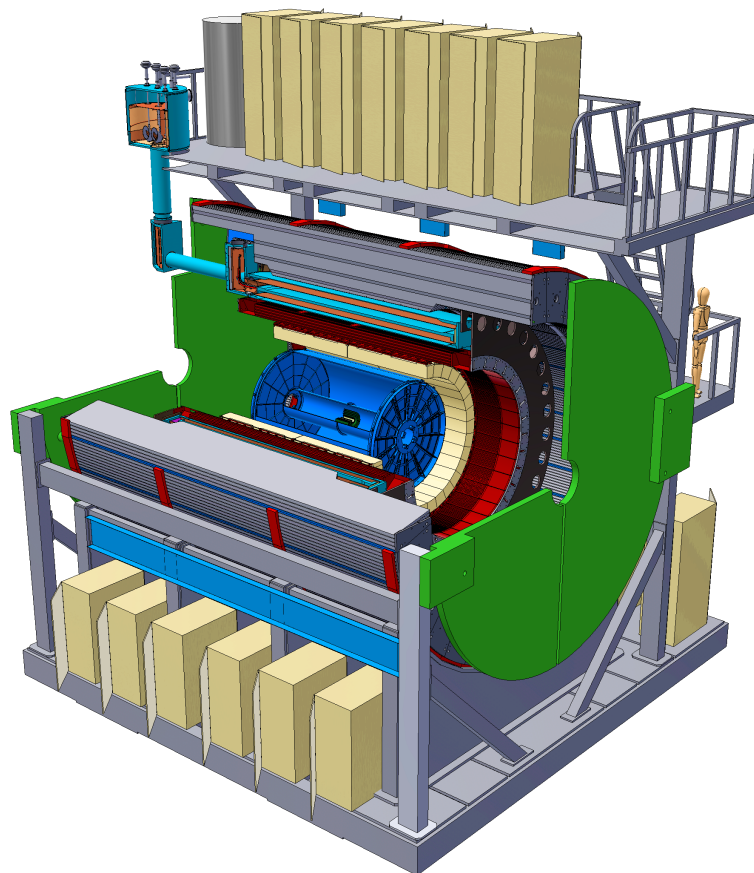




sPHENIX Conceptual Design Report

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Executive Summary

sPHENIX[1] is a proposal for a major upgrade to the PHENIX experiment at RHIC capable of measuring jets, jet correlations and upsilons to determine the temperature dependence of transport coefficients of the quark-gluon plasma. The detector needed to make these measurements require electromagnetic and hadronic calorimetry for measurements of jets, a high resolution and low mass tracking system for reconstruction of the Upsilon states, and a high speed data acquisition system.

This document describes a design for a detector capable of carrying out this program of measurements built around the BaBar solenoid. As much as possible, the mechanical, electrical, and electronic infrastructure developed for the PHENIX experiment from 1992-2016 is reused for sPHENIX. The major new systems are the superconducting magnet, a high precision tracking system, and electromagnetic and hadronic calorimeters.

The central tracking system consists of a small Time Projection Chamber with up to four layers of silicon strip detector within the inner radius. The feasibility of the detector and electronics is being evaluated through simulation, design, and prototyping.

The electromagnetic calorimeter is a compact tungsten-scintillating fiber design located inside the solenoid. The outer hadronic calorimeter consists of of steel and scintillator in a somewhat novel arrangement in which scintillator tiles with light collected by wavelength shifting fiber are sandwiched between tapered absorber plates that project nearly radially from the interaction point. The calorimeters use a common set of silicon photomultiplier photodetectors and amplifier and digitizer electronics.

The detector is being designed with an eye on upgrades and enhancements which can extend the physics reach of the detector. The presently expected DOE funding is only sufficient for approximately 75% of the electromagnetic calorimeter, although outside contributions appear likely to restore the full scope. The design of a precision silicon vertex detector which enables a large menu of physics, has been developed by a consortium of institutions, and the design of an additional longitudinal layer of hadronic calorimetry has been developed so that it could be instrumented if additional funding becomes available.

The detector design has been evaluated by means of GEANT4 simulation and measurements with a continuing program of bench and beam tests prototypes of the detectors. Simulation, prototyping, and testing of components is continuing to finalize the baseline design.

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Chapter 1

Scientific Objective and Performance

Results from RHIC and the LHC indicate that a new state of matter is formed in ultra-relativistic collisions of heavy nuclei. Initial temperatures $T > 300$ MeV [2] at RHIC and $T > 420$ MeV [3] at the LHC have been extracted from the spectrum of directly-emitted photons from the system. The formation of this state, called the quark-gluon plasma (QGP), was predicted by Lattice QCD and various models and to have existed at similar temperatures prior to the formation of hadrons just microseconds after the Big Bang.

The temperature scales at RHIC and LHC result in an intrinsically non-perturbative system. The difference in the initial temperature created in RHIC and LHC collisions is expected to be associated with changes in the nature of the QGP being probed. Such changes in the properties of the system must be determined in order to properly characterize the new QGP state of matter. Furthermore, to understand the many-body collective effects in the QGP and their temperature dependence near the transition temperature requires considerable further investigation.

The scientific objective of the sPHENIX experiment [1] is to gain an understanding of the evolution of the system and its coupling strength at RHIC from the initial high temperatures, where short distance scales prevail, through expansion and cooling to the transition temperature and longer distance scales. This will be accomplished by using hard-scattered partons that traverse the medium and the Upsilon states to investigate the medium at the different length scales. The fragmentation products of partons in the form of jets and the three Upsilon states, which span a large range in binding energy and size, are complementary and excellent probes for this purpose. The variables in this investigation are the temperature of the QGP, the length scale probed in the medium, and the virtuality of the hard process.

The QGP is expected to transform from a weakly-coupled system at high temperature to a more strongly-coupled system near T_c . In general, for many systems a change in coupling strength is related to quasi-particle excitations or strong coherent fields. To study these phenomena usually requires that the medium be investigated at a variety of length scales. The collisions at RHIC and the LHC involve a time evolution during

244 which the temperature decreases as the QGP expands. Determination of the temperature
 245 dependence of the properties of the QGP is expected to come from calculations that describe
 246 simultaneously all observables measured at both energies. Typically, all the non-scaling
 247 behavior is found near the transition. It is therefore crucial to perform measurements near
 248 the phase transition and compare with results from experiments done farther above T_c .

249 These measurements at RHIC will provide information complementary to those at the LHC.
 250 The measurement of jets over the broadest possible energy scale is key to investigating the
 251 potential quasi-particle nature of the QGP. Jets at the LHC reach the highest energies, the
 252 largest initial virtualities, and large total energy loss to probe the shortest distance scales.
 253 The lower underlying event activity at RHIC will allow extension of jet measurements to
 254 lower energies and lower initial virtualities than at LHC, thus probing the important longer
 255 distance scales in the medium. Figure 1.1 (left), which will be discussed in more detail in
 256 Section 1.4, displays as a function of temperature the expected evolution of virtuality in
 257 vacuum, from medium contributions, and combined for a QGP. Figure 1.1 (right) shows a
 258 scenario for what may be resolved in the QGP by probing at the length scales indicated
 259 by the magnifying glasses on the left. In addition to the investigation of jets, precision
 260 measurements of the three Upsilon states will allow further insight and understanding of
 261 the behavior on different distance scales.

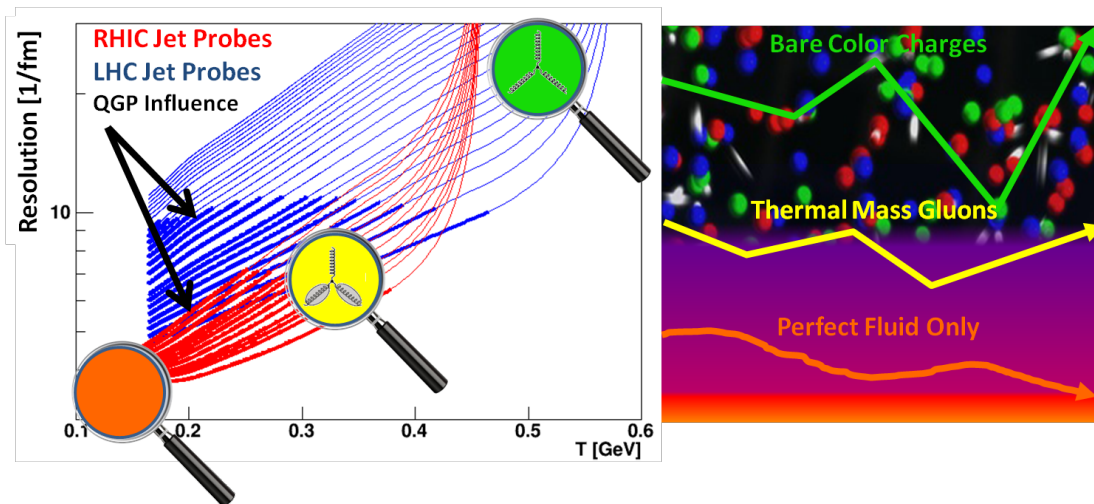


Figure 1.1: Virtuality evolution as a function of temperature as represented (left) by the resolution of jet probes at the LHC (blue curves) and at RHIC (red curves). The potential range of influence of the QGP that is being investigated is represented by the bolder curves for each case. The magnified views are meant to represent pQCD scattering from bare quarks and gluons in the medium (green), scattering from thermal gluons (yellow), and a final state integration over all possible objects probed in the medium (orange). (right) Graphical depiction of the objects being probed at the various resolutions on the left.

262 In this Chapter we start by presenting our current understanding of the role of the coupling
 263 strength in the QGP, how it can be probed at different length scales, the temperature

264 dependence of a few observables of the QGP and the evolution of parton virtuality in the
 265 QGP. We then present the case for utilizing hard-scattering (parton) probes to constrain
 266 theories and compare a few examples of theoretical calculations with recent LHC data
 267 and their differing predictions for RHIC. We relate these aspects to specific observables
 268 that can be measured with sPHENIX. These include fragmentation functions from photon-
 269 jet correlations, hadron-jet and di-jet measurements, open heavy flavor jets and beauty
 270 quarkonia. We conclude with the rates and other performance measures of sPHENIX
 271 that will enable precision measurements to be made across a comprehensive jet and
 272 quarkonium program at RHIC.

273 1.1 Towards Understanding the Coupling Strength of the QGP

274 It was originally thought that even at temperatures as low as $2-5 T_c$, the QGP could be
 275 described by a weakly-coupled perturbative approach, despite being quite far from energy
 276 scales typically associated with asymptotic freedom. One very surprising result discovered
 277 at RHIC was the fluid-like flow of the QGP [4], in stark contrast to some expectations that
 278 the QGP would behave as a weakly-coupled gas of quarks and gluons. RHIC and LHC
 279 heavy ion experiments have since provided a wealth of data for understanding the physics
 280 of the QGP.

281 The QGP created in heavy ion collisions expands and cools, eventually passing through the
 282 phase transition to a state of hadrons, which are then measured by experiment. Extensive
 283 measurements of the radial and flow coefficients of various hadrons, when compared to
 284 hydrodynamics calculations, imply a very small ratio of shear viscosity to entropy density,
 285 η/s [5]. In the limit of very weak coupling (i.e., a non-interacting gas), the shear viscosity is
 286 quite large as particles can easily diffuse across a velocity gradient in the medium. Stronger
 287 inter-particle interactions inhibit diffusion to the limit where the strongest interactions
 288 result in a very short mean free path and thus almost no momentum transfer across a
 289 velocity gradient, resulting in almost no shear viscosity.

290 The shortest possible mean free path is of order the de Broglie wavelength, which sets
 291 a lower limit on η/s [6]. A more rigorous derivation of the limit $\eta/s \geq 1/4\pi$ has been
 292 calculated within string theory for a broad class of strongly coupled gauge theories by
 293 Kovtun, Son, and Starinets (KSS) [7]. Viscous hydrodynamic calculations assuming η/s to
 294 be temperature independent through the heavy ion collision time evolution are consistent
 295 with the experimental data where η/s is within 50% of this lower bound for strongly
 296 coupled matter [5, 8, 9, 10, 11, 12]. Even heavy quarks (i.e., charm and beauty) are swept
 297 up in the fluid flow and theoretical extractions of the implied η/s are equally small [13].

298 Other key measures of the coupling strength to the medium can be found in the passage of a
 299 hard-scattered parton through the QGP. As the parton traverses the medium it accumulates
 300 transverse momentum as characterized by $\hat{q} = d(\Delta p_T^2)/dt$ and transfers energy to the
 301 medium via collisions as characterized by $\hat{e} = dE/dt$. Once in vacuum, the hard-scattered

parton creates a conical shower of particles referred to as a jet. In the QGP, the lower energy portion of the shower may eventually be equilibrated into the medium, thus giving a window on the rapid thermalization process in heavy ion collisions. This highlights part of the reason for needing to measure the fully reconstructed jet energy and the correlated particle emission with respect to the jet at all energy scales. In particular, coupling parameters such as \hat{q} and \hat{e} are scale dependent and must take on weak-coupling values at high enough energies and strong-coupling values at thermal energies.

Continued developments in techniques for jet reconstruction in the environment of a heavy ion collision have allowed the LHC experiments to reliably recover jets down to 40 GeV [14, 15], which is well within the range of reconstructed jet energies at RHIC in the future. This overlap opens the possibility of studying the QGP at the same scale but under different conditions of temperature and coupling strength.

Apart from the temperature and coupling strength differences in the medium created at RHIC and the LHC, the difference in the steepness of the hard scattering p_T spectrum plays an important role. The less steeply falling spectrum at the LHC has the benefit of giving the larger reach in p_T with reconstructed jets expected up to 1 TeV. At RHIC, the advantage of the more steeply falling spectrum is the greater sensitivity to the medium coupling and QGP modifications of the parton shower. This greater sensitivity may enable true tomography in particular with engineering selections for quarks and/or gluons with longer path length through the medium. In addition, for correlations, once a clean direct photon or jet tag is made, the underlying event is 2.5 times smaller at RHIC compared to the LHC thus giving cleaner access to the low energy remnants of the parton shower and possible medium response. Therefore one focus of this proposal is the measurement of jet probes of the medium as a way of understanding the coupling of the medium, the origin of this coupling, and the mechanism of rapid equilibration.

1.2 Probing Different Length Scales in the QGP

In electron scattering, the length scale is set by the virtuality of the exchanged photon, Q^2 . By varying this virtuality one can obtain information over an enormous range of scales: from pictures of viruses at length scales of 10^{-5} meters, to the partonic make-up of the proton in deep inelastic electron scattering at length scales of less than 10^{-18} meters.

For the case of hard-scattered partons in the quark-gluon plasma, the length scale probed is initially set by the virtuality of the hard-scattering process. Thus, at the highest LHC jet energies, the parton initially probes a very short length scale. Then as the evolution proceeds, the length scale is set by the virtuality of the gluon exchanged with the color charges in the medium, as shown in the circular diagram on the right of Figure 1.2. However, if the exchanges are coherent, the total coherent energy loss through the medium may set the length scale.

If the length scale being probed is very small then one expects scattering directly from

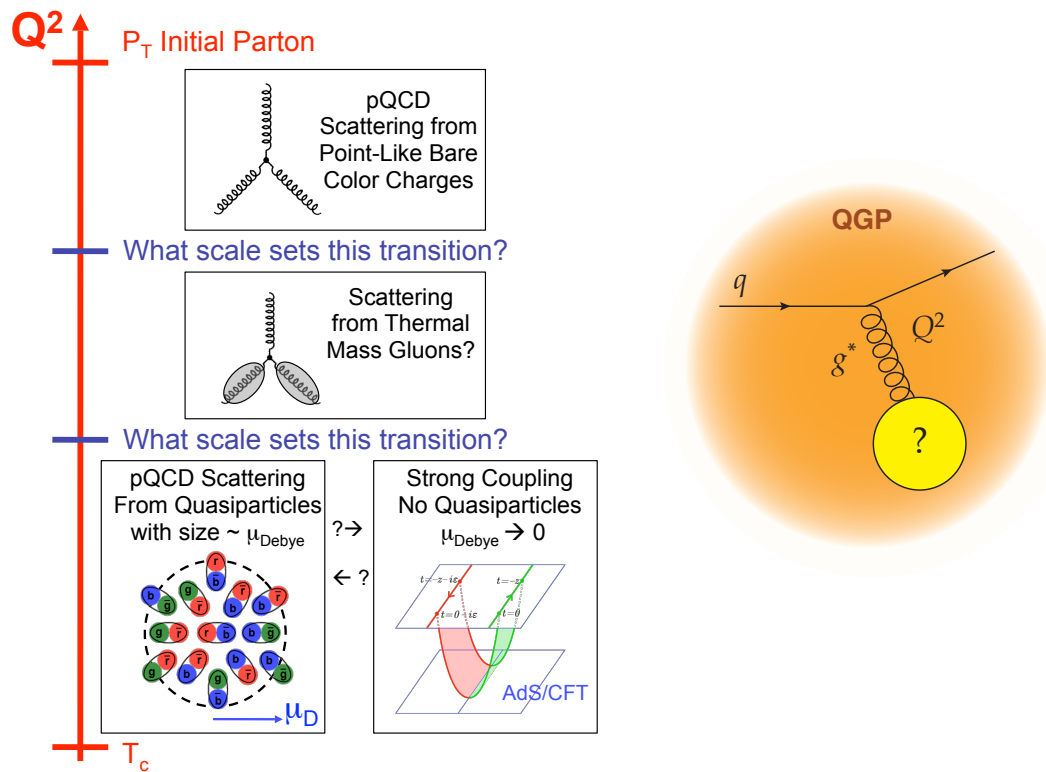


Figure 1.2: Interaction scale for the interaction of partons with the QGP and possibilities for the recoil objects. (left) Diagram of the net interaction of a parton with the medium and the range of possibilities for the recoil objects as a function of Q^2 . (right) Diagram for a quark exchanging a virtual gluon with an unknown object in the QGP. This highlights the uncertainty for what sets the scale of the interaction and what objects or quasiparticles are recoiling.

340 point-like bare color charges, most likely without any influence from quasiparticles or
 341 deconfinement. This can be seen in Figure 1.2 (left). As one probes longer length scales, the
 342 scattering may be from thermal mass gluons and eventually from possible quasiparticles
 343 with size of order the Debye screening length (lower in Figure 1.2). In Ref. [16], Rajagopal
 344 states that “at some length scale, a quasiparticulate picture of the QGP must be valid, even
 345 though on its natural length scale it is a strongly-coupled fluid. It will be a challenge to
 346 see and understand how the liquid QGP emerges from short-distance quark and gluon
 347 quasiparticles.” This is the challenge to be met by sPHENIX.

348 The extension of jet measurements over a wide range of energies and with different
 349 medium temperatures again gives one the largest span along this axis. What the parton
 350 is scattering from in the medium is tied directly to the balance between radiative energy
 351 loss and inelastic collisional energy loss in the medium (encoded in \hat{q} and \hat{e}). In the limit
 352 that the scattering centers in the medium are infinitely massive, one only has radiative
 353 energy loss—as was assumed for nearly 10 years to be the dominant parton energy loss

354 effect. In the model of Liao and Shuryak [17], the strong coupling near the quark-gluon
 355 plasma transition is due to the excitation of color magnetic monopoles, and this should
 356 have a significant influence on the collisional energy loss and equilibration of soft partons
 357 into the medium.

358 In a model by Coleman-Smith [18, 19] consisting of parton showers propagating in a
 359 medium of deconfined quarks and gluons, one can directly vary the mass of the effective
 360 scattering centers and extract the resulting values for \hat{e} and \hat{q} . Figure 1.3 shows $T\hat{e}/\hat{q}$ as a
 361 function of the mass of the effective scattering centers in the medium in this model. In the
 362 limit of infinitely massive scattering centers, the interactions are elastic and no energy is
 363 transferred to the medium.

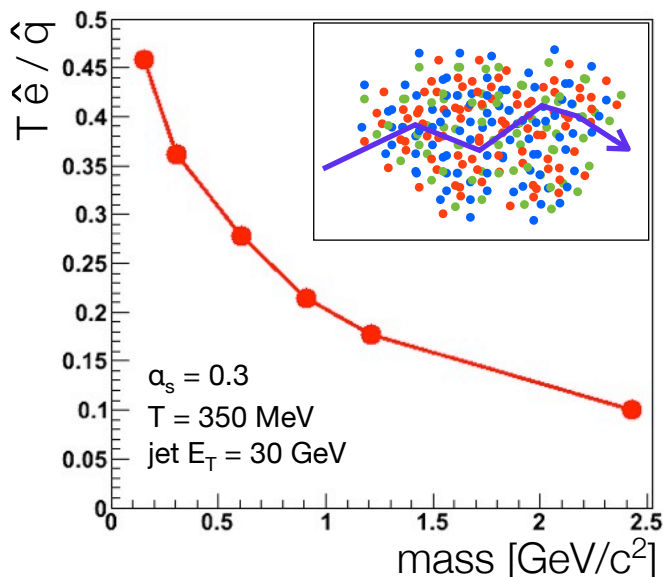


Figure 1.3: $T\hat{e}/\hat{q}$ as a function of the mass of the effective scattering centers in the medium. As the mass increases, the parton is less able to transfer energy to the medium and the ratio drops.

364 1.3 The Temperature Dependence of the QGP

365 1.3.1 Shear viscosity to entropy density ratio

366 It is well known that near a phase boundary familiar substances governed by quantum
 367 electrodynamics demonstrate interesting behavior such as the rapid change in the shear
 368 viscosity to entropy density ratio, η/s , near the critical temperature, T_c . This is shown in
 369 Figure 1.4 (left) for water, nitrogen, and helium [20]. Despite the eventual transition to
 370 superfluidity at temperatures below T_c , η/s for these materials remains an order of magni-
 371 tude above the conjectured quantum bound of Kovtun, Son, and Starinets (KSS) derived

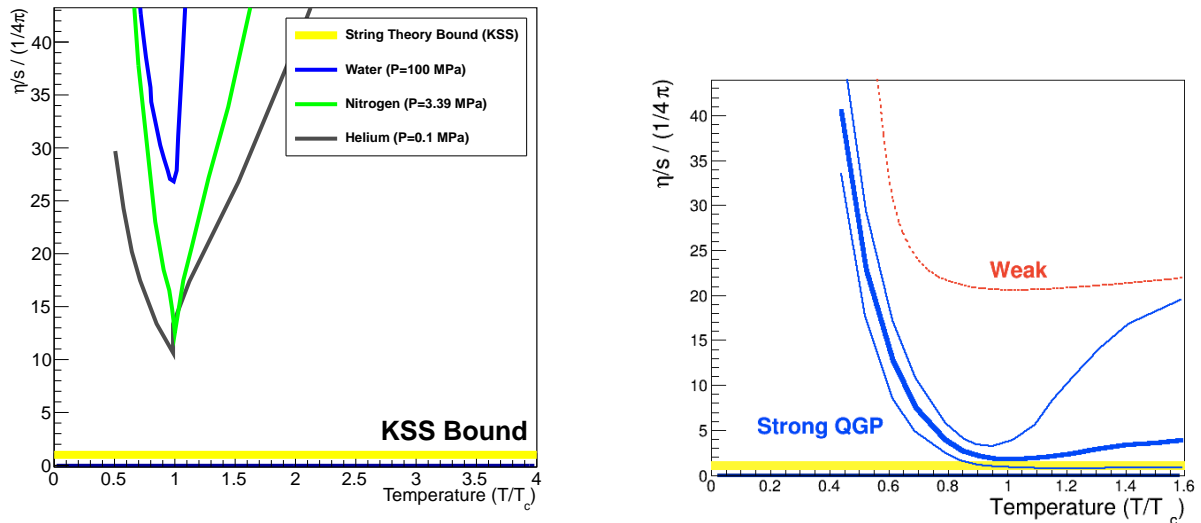


Figure 1.4: (left) The ratio of shear viscosity to entropy density, η/s , normalized by the conjectured KSS bound as a function of the reduced temperature, T/T_c , for water, nitrogen, and helium. The cusp for Helium corresponds to the case at the critical pressure. (right) Calculation for a weakly-coupled system (pQCD) and for various models of a strongly-coupled QGP.

372 from string theory [7]. Such observations provide a deeper understanding of the nature
 373 of these materials: for example the coupling between the fundamental constituents, the
 374 degree to which a description in terms of quasiparticles is important, and the description
 375 in terms of normal and superfluid components.

376 The dynamics of the QGP are dominated by Quantum Chromodynamics and the exper-
 377 imental characterization of the dependence of η/s on temperature will lead to a deeper
 378 understanding of strongly coupled QCD near this fundamental phase transition. Theoret-
 379 ically, perturbative calculations in the weakly-coupled limit indicate that η/s decreases
 380 slowly as one approaches T_c from above, but with a minimum still a factor of 20 above the
 381 KSS bound [21].

382 Hydrodynamic modeling of the bulk medium does provide constraints on η/s , and recent
 383 work has been done to understand the combined constraints on η/s as a function of
 384 temperature utilizing both RHIC and LHC flow data sets [22, 23, 24, 25] and result in
 385 values near the KSS bound around T_c as seen in Figure 1.4 (right).

386 1.3.2 Jet probe parameters

387 The above discussion was focused on η/s as the measure of the coupling strength of the
 388 QGP. However, both η/s and jet probe parameters such as \hat{q} and \hat{e} are sensitive to the

389 underlying coupling of the matter, but in distinct ways. Establishing for example the
 390 behavior of \hat{q} around the critical temperature is therefore essential to a deep understanding
 391 of the QGP. Hydrodynamic modeling may eventually constrain $\eta/s(T)$ very precisely,
 392 though it will not provide an answer to the question of the microscopic origin of the strong
 393 coupling (something naturally available with jet probes).

394 Since the expected scaling of \hat{q} with temperature is such a strong function of temperature,
 395 jet quenching measurements should be dominated by the earliest times and highest
 396 temperatures. In order to have sensitivity to temperatures around $1-2 T_c$, measurements at
 397 RHIC are needed in contrast to the LHC where larger initial temperatures are produced,
 398 as depicted graphically in Figure 1.1. In addition, the ability of RHIC to provide high
 399 luminosity heavy-ion collisions at a variety of center of mass energies can be exploited to
 400 probe the detailed temperature dependence of quenching right in the vicinity of T_c .

401 Theoretical developments constrained simultaneously by data from RHIC and the LHC
 402 have been important in discriminating against some models with very large \hat{q} , see Ref. [26]
 403 and theory references therein. Models such as PQM and ASW with very large values of \hat{q}
 404 have been ruled out by the combined constraint. Shown in the left panel of Figure 1.5 is a
 405 recent compilation of four theoretical calculations with a directly comparable extraction
 406 of \hat{q} . It is notable that a number of calculations favor an increased coupling strength
 407 near the transition temperature. Developments on the theory and experimental fronts
 408 have significantly narrowed the range of \hat{q} [27]. This theoretical progress lends credence
 409 to the case that the tools will be available on the same time scale as sPHENIX data to
 410 have precision determinations of \hat{q} and then ask deeper additional questions about the
 411 quark-gluon plasma and its underlying properties.

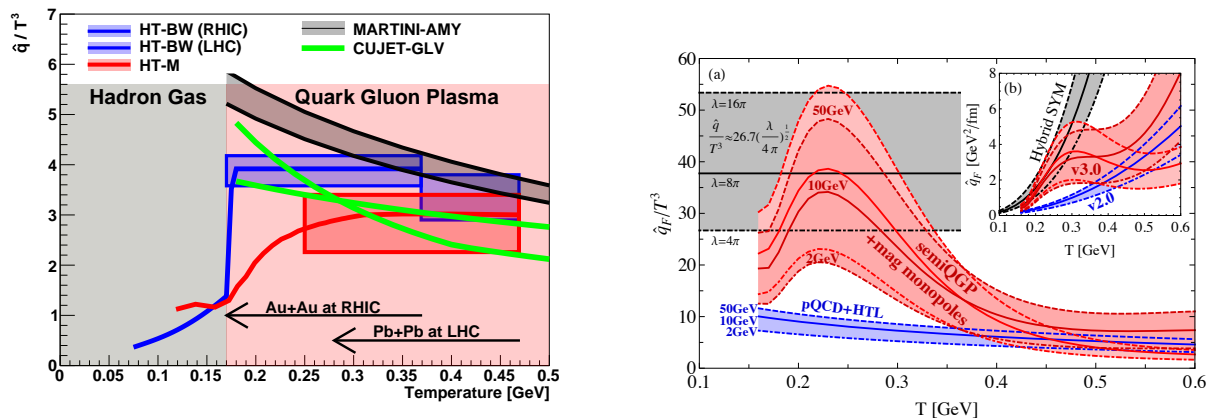


Figure 1.5: Calculations of \hat{q}/T^3 vs temperature, constrained by RHIC and LHC R_{AA} data — including near T_c enhancement scenarios of \hat{q}/T^3 . (left) Calculations from four jet quenching frameworks constrained by RHIC and LHC R_{AA} data with results for \hat{q}/T^3 as a function of temperature. Details of the calculation are given in Ref. [27]. (right) Results from calculations within CUJET 3.0 with magnetic monopole excitations that result in enhanced coupling near T_c . Plotted are the constraints on \hat{q}/T^3 as a function of temperature as shown in Ref. [28]

412 Ref. [29] states that “Comparing weak coupling scenarios with data, NTC [near T_C en-
 413 hancement] is favored. An answer to this question will require a systematic picture across
 414 several different high p_T observables.” In Ref. [17], Liao and Shuryak use RHIC mea-
 415 surements of single hadron suppression and azimuthal anisotropy to infer that “the jet
 416 quenching is a few times stronger near T_c relative to the quark-gluon plasma at $T > T_c$.”

417 Most recently this strong coupling picture with color magnetic monopole excitations
 418 has been implemented within CUJET 3.0 for a broader comparison with experimental
 419 observables and previous theory calculations [28]. Shown in Figure 1.5 (right panel) are
 420 results from their constrained RHIC and LHC data fit for the temperature dependence of
 421 the scaled quenching power \hat{q}/T^3 .

422 Within the jet quenching model WHDG [30], the authors constrain \hat{q} by the PHENIX π^0
 423 nuclear modification factor. They find the prediction scaled by the expected increase in the
 424 color charge density created in higher energy LHC collisions when compared to the ALICE
 425 results [31] over-predicts the suppression. This over-prediction based on the assumption
 426 of an unchanging probe-medium coupling strength led to the title of Ref. [30]: “The
 427 surprisingly transparent sQGP at the LHC.” They state that “one possibility is the sQGP
 428 produced at the LHC is in fact more transparent than predicted.” Similar conclusions have
 429 been reached by other authors [32, 33, 34]. Recently work has been done to incorporate the
 430 running of the QCD coupling constant [35].

431 It is important to note that most calculations predict a stronger coupling near the transi-
 432 tion, even if just from the running of the coupling constant α_s . The goal is to determine
 433 experimentally the degree of this effect. Lower energy data at RHIC also provides impor-
 434 tant constraints – see for example Refs. [36, 37]. The full set of experimental observables
 435 spanning the largest range of collision energy, system size, and path length through the
 436 medium is needed to determine the coupling strength as a function of temperature.

437 1.4 Evolution of Parton Virtuality in the QGP

438 The initial hard-scattered parton starts out very far off-shell and in e^+e^- , $p+p$ or $p+\bar{p}$ col-
 439 lisions the virtuality evolves in vacuum through gluon splitting down to the scale of
 440 hadronization. In heavy ion collisions, the vacuum virtuality evolution is interrupted
 441 at some scale by scattering with the medium partons which increase the virtuality with
 442 respect to the vacuum evolution. Figure 1.1 (left) shows the expected evolution of virtuality
 443 in vacuum, from medium contributions, and both combined (in a QGP).

444 If this picture is borne out, it “means that [a] very energetic parton hardly notices the
 445 medium for the first 3–4 fm of its path length [38].” Spanning the largest possible range of
 446 virtuality (initial hard process Q^2) is very important, but complementary measurements at
 447 both RHIC and LHC of produced jets at the same virtuality (around 50 GeV) will test the
 448 interplay between the vacuum shower and medium scattering contributions.

449 In some theoretical frameworks — for example Refs [39, 40, 41] — the parton splitting is
 450 simply dictated by the virtuality and in vacuum this evolves relatively quickly from large
 451 to small scales. The Q evolution means that the jet starts out being considerably off mass
 452 shell when produced, and this off-shellness is reduced by successive splits to less virtual
 453 partons. In these calculations, the scattering with the medium modifies this process of
 454 parton splitting. The scale of the medium as it relates to a particular parton is \hat{q} times the
 455 parton lifetime (this is the mean transverse momentum that the medium may impart to the
 456 parent and daughter partons during the splitting process). When the parton's off-shellness
 457 is much larger than this scale, the effect of the medium on this splitting process is minimal.
 458 As the parton drops down to a lower scale, the medium begins to affect the parton splitting
 459 more strongly.

460 Shown in Figure 1.6 (left) is the single hadron R_{AA} measured in central Au+Au collisions
 461 at 200 GeV and in heavy ion collisions at other beam energies. One can see in Figure 1.6
 462 (right) that inclusion of the virtuality evolution for the YAJEM calculation leads to a 50%
 463 rise in R_{AA} from 20–40 GeV/c, and a 100% rise in the HT-M calculation. A strong rise in
 464 R_{AA} measured at higher p_T at the LHC has been observed, and measurement of the effect
 465 within the same framework at RHIC is a key test of this virtuality evolution description.
 466 It is notable that the JEWEL calculation, which accurately describes the rising R_{AA} at the
 467 LHC [42], results in a nearly flat R_{AA} over the entire p_T range at RHIC. As detailed in
 468 Ref. [43, 44], many formalisms assuming weakly coupled parton probes are able to achieve
 469 an equally good description of the single-inclusive hadron (R_{AA}) data at RHIC and the
 470 LHC. The single high p_T hadron suppression constrains the \hat{q} value within a model, but is
 471 not able to discriminate between different energy loss mechanisms and formalisms for the
 472 calculation. sPHENIX will perform precision measurements of charged hadrons over an
 473 extended p_T range, as shown in the projected uncertainties, that will strongly discriminate
 474 between the various energy loss mechanisms and model assumptions about the virtuality
 475 evolution in the medium.

476 1.5 Current Jet Probe Measurements

477 Jet quenching (i.e., the significant loss of energy for partons traversing the QGP) was
 478 discovered via measurements at RHIC of the suppression of single hadron yields compared
 479 to expectations from $p+p$ collisions [45, 46]. Since the time of that discovery there has been
 480 an enormous growth in jet quenching observables that have also pushed forward a next
 481 generation of analytic and Monte Carlo theoretical calculations to confront the data.

482 Two-hadron correlations measure the correlated fragmentation between hadrons from
 483 within the shower of one parton and also between the hadrons from opposing scattered
 484 partons. These measurements, often quantified in terms of a nuclear modification I_{AA} [47,
 485 48, 49], have been a challenge for models to describe simultaneously [50].

486 The total energy loss of the leading parton provides information on one part of the parton-

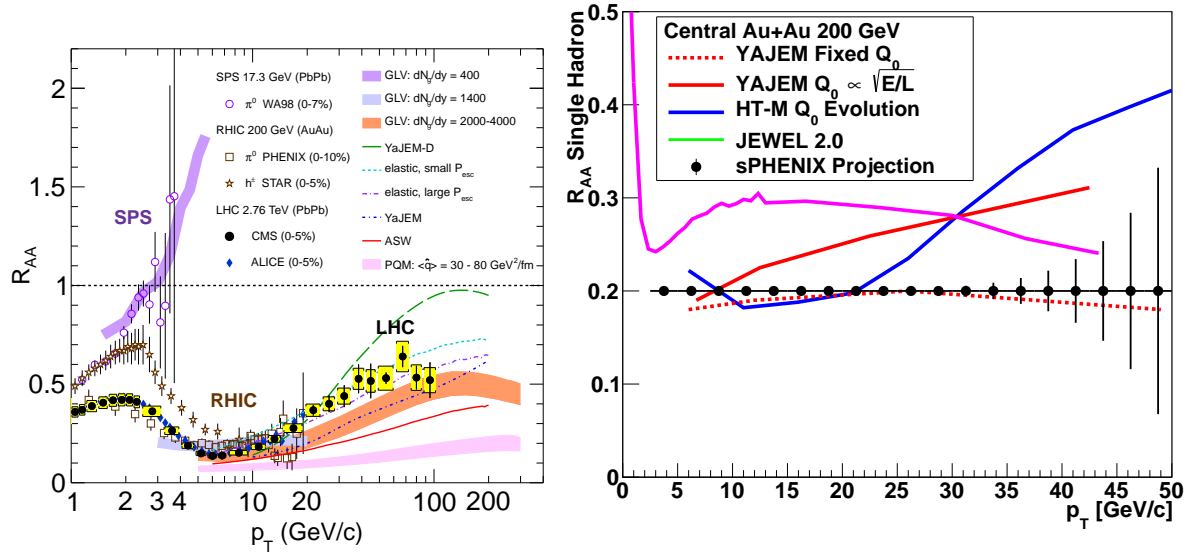


Figure 1.6: (left) The nuclear modification factor R_{AA} as a function of transverse momentum in A+A collisions at the SPS, RHIC, and LHC. Comparisons with various jet quenching calculations as detailed in Ref. [26] and references therein are shown. The simultaneous constraint of RHIC and LHC data is a powerful discriminator. (right) Predictions of R_{AA} for single hadrons to $p_T \sim 50$ GeV/c in central Au+Au at 200 GeV. Also shown are the projected sPHENIX uncertainties.

487 medium interaction. Key information on the nature of the particles in the medium being
 488 scattered from is contained in how the soft (lower momentum) part of the parton shower
 489 approaches equilibrium in the QGP. This information is accessible through full jet recon-
 490 struction, jet-hadron correlations, di-jets and γ -jet correlation observables.

491 The measurements of fully reconstructed jets and the particles correlated with the jet (both
 492 inside and outside the jet) are crucial to testing the various models and their energy loss
 493 mechanisms. Not only does the strong coupling influence the induced radiation from the
 494 hard parton (gluon bremsstrahlung) and its inelastic collisions with the medium, but it
 495 also influences the way soft partons are transported by the medium outside of the jet cone
 496 as they fall into equilibrium with the medium. Thus, the jet observables combined with
 497 correlations are a means to access directly the coupling of the hard parton to the medium
 498 and the parton-parton coupling for the medium partons themselves.

499 1.5.1 LHC results

500 The first results from the LHC based on reconstructed jets in heavy ion collisions were the
 501 centrality-dependent dijet asymmetries measured by ATLAS [51] and CMS [52] as shown

502 on the left panels of Figures 1.7 and 1.8. The measured dijet asymmetry A_J is defined by
 503 ATLAS as $A_J = (E_1 - E_2)/(E_1 + E_2)$ and $A_J = (p_1 - p_2)/(p_1 + p_2)$ by CMS. These results
 504 indicate a substantial broadening of the dijet asymmetry A_J distribution for increasingly
 505 central Pb+Pb collisions and a lack of modification to the dijet azimuthal correlations (not
 506 shown). The broadening of the A_J distribution points to substantial energy loss for jets
 507 and the unmodified azimuthal distribution shows that the opposing jet $\Delta\phi$ distribution is
 508 not broadened as it traverses the matter.

509 Direct photon-jet measurements are also a powerful tool to study jet quenching. Unlike
 510 dijet measurements the photon passes through the matter without losing energy, providing
 511 a cleaner measure of the expected jet p_T [53]. CMS has results for photons with $p_T >$
 512 $60 \text{ GeV}/c$ correlated with jets with $p_T > 30 \text{ GeV}/c$ [54]. Though with modest statistical
 513 precision, the measurements indicate energy transported outside the $R = 0.3$ jet cone
 514 through medium interactions. Similar results from the ATLAS experiment again indicate a
 515 shift of the energy outside the opposing jet cone.

516 Reconstructed jets have significantly extended the kinematic range for jet quenching
 517 studies at the LHC, and quenching effects are observed up to the highest reconstructed jet
 518 energies ($> 300 \text{ GeV}$) [55]. They also provide constraints on the jet modification that are
 519 not possible with particle-based measurements. For example, measurements from ATLAS
 520 constrain the modification of the jet fragmentation in Pb+Pb collisions from vacuum
 521 fragmentation to be small [56]. CMS results on jet-hadron correlations have shown that
 522 the lost energy is recovered in low p_T particles far from the jet cone [52]. The lost energy
 523 is transported to very large angles and the remaining jet fragments as it would in the
 524 vacuum.

525 1.5.2 RHIC results

526 There are preliminary results on fully reconstructed jets from both STAR [57, 58, 59, 60] and
 527 PHENIX experiments [61, 62]. However, a comprehensive jet detector, such as sPHENIX,
 528 with large, uniform acceptance and a high-rate capability can be combined with the newly
 529 completed increase in RHIC luminosity to perform these key measurements definitively to
 530 access this important physics. In addition to extending the RHIC observables to include
 531 fully reconstructed jets and γ -jet correlations, theoretical development is required for
 532 converging to a coherent 'standard model' of the medium coupling strength and the nature
 533 of the probe-medium interaction. In the next section, we present predictions for a sample
 534 of future RHIC measurements based on theory that has been calibrated through successful
 535 reproduction of recent LHC measurements.

1.6 Using Jets at RHIC to Constrain Theoretical Calculations

The theoretical community is actively working to understand the details of probe-medium interactions. Much work has been carried out by the Topical Collaboration on Jet and Electromagnetic Tomography of Extreme Phases of Matter in Heavy-ion Collisions [63]. The challenge is to understand not only the energy loss of the leading parton, but how the parton shower evolves in medium and how much of the lost energy is re-distributed in the QGP. Monte Carlo approaches have been developed (as examples [64, 65, 66, 19, 67, 68]) to overcome specific theoretical hurdles regarding analytic parton energy loss calculations and to couple these calculations with realistic models of the QGP space-time evolution. Theoretical calculations attempting to describe the current data from RHIC and LHC have yet to reconcile some of the basic features. Some models include large energy transfer to the medium as heat (for example [69]) while others utilize mostly radiative energy loss (for example [70, 71]). Measurements at RHIC energies with jets over a different kinematic range allow specific tests of the different mechanisms.

Jets provide a rich spectrum of physics observables, ranging from single-jet observables such as R_{AA} , to correlations of jets with single particles and correlations of trigger jets with other jets in the event. Triggers ranging from single hadrons to ideally reconstructed jets are used to form correlations with hadrons or another jet in the event. Different triggers demonstrate different degrees of surface bias in the production point of the “dijet”, i.e. the hard-scattering vertex location, and this bias itself has been used as leverage in the investigation of the properties of the medium. Examples of different trigger biases that can be exploited have been presented in calculations by Renk [72].

In this section, we present a brief review of a subset of calculations that employ different mechanisms for jet-medium interactions. These are compared to jet observables that still need to be measured at RHIC, with an emphasis on their particular sensitivity to the underlying physics, and represent the potential constraining power of a comprehensive jet physics program by sPHENIX at RHIC.

1.6.1 Di-jet Asymmetry

Results of calculations from Coleman-Smith and collaborators [18, 19] for the dijet asymmetry A_J at the LHC are presented along with the data in Figure 1.7 (left) [18]. The parton showers are extracted from PYTHIA (with hadronization turned off) and then embedded into a deconfined QGP, modeled at constant temperature using the VNI parton cascade [73] with fixed $\alpha_s = 0.3$. One feature of the calculation is that it provides the ability to track the time evolution of each individual parton, not only the scattered partons from the shower, but also partons from the medium, which through interactions can contribute particles to the reconstructed jets. Jets in the calculation are reconstructed with the anti- k_T algorithm with radius parameter $R = 0.5$ and then smeared by a simulated jet resolution of $100\%/\sqrt{E}$, and with requirements of $E_{T1} > 120$ GeV and $E_{T2} > 50$ GeV on the leading

574 and sub-leading jet, respectively. The calculated A_J distributions reproduce the CMS
 575 experimental data [52].

576 In Figure 1.7 (right panel) the calculation is repeated with a medium temperature appropri-
 577 ate for RHIC collisions and with RHIC observable jet energies, $E_{T1} > 20$ GeV and $R = 0.2$.
 578 The calculation is carried out for different coupling strengths α_s between partons in the
 579 medium themselves and the parton probe and medium partons. The variation in the value
 580 of α_s should be viewed as changing the effective coupling in the many-body environment
 581 of the QGP. It is interesting to note that in the parton cascade BAMPS the authors find that
 582 an effective coupling of $\alpha_s \approx 0.6$ is required to describe the bulk medium flow [74]. These
 583 results indicate sizable modification to the dijet asymmetry and thus excellent sensitivity
 584 to the effective coupling to the medium at RHIC energies.

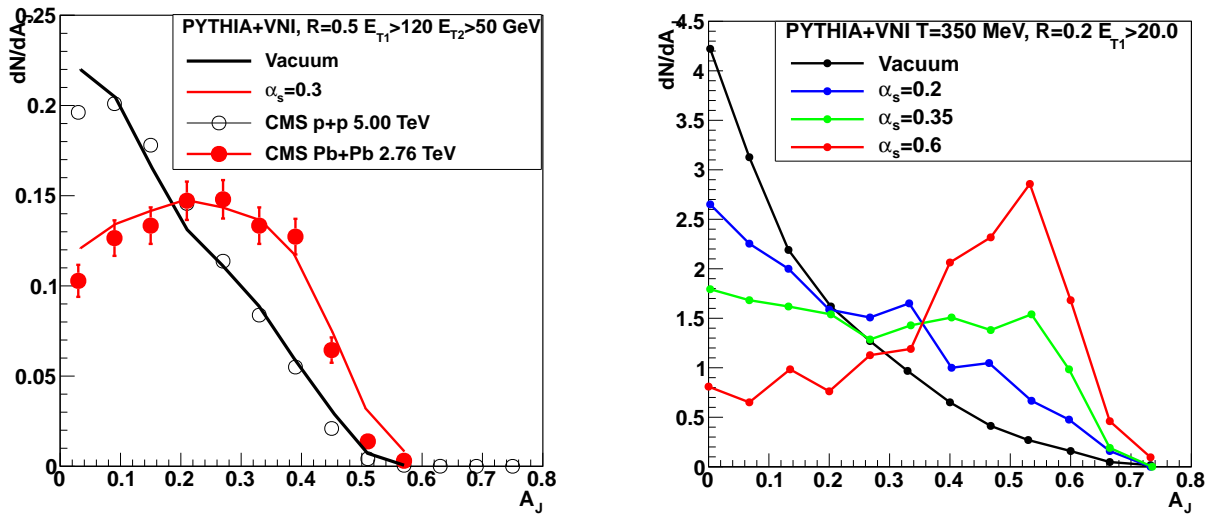


Figure 1.7: (left) Calculation in VNI parton cascade of dijet A_J with $T = 0.35$ GeV and $\alpha_s = 0.3$ compared to the CMS data [18]. (right) Calculation for RHIC jet energies, $E_{T1} > 20$ GeV, for a circular geometry of radius 5 fm of A_J for different values of α_s increasing to $\alpha_s = 0.6$ (red line) [75].

585 The results of calculations for A_J from two other groups are presented in Figure 1.8. In the
 586 calculation of Qin and collaborators [76, 77] a differential equation governing the evolution
 587 of the radiated gluon distribution is solved to predict the propagation of the jet through
 588 the medium. Energy contained inside the jet cone is lost by dissipation through elastic
 589 collisions and by scattering of shower partons to larger angles. The model calculations
 590 of Young, Schenke and collaborators [66] utilize a jet shower Monte Carlo, referred to as
 591 MARTINI [78], and embed the shower on top of a hydrodynamic space-time background,
 592 using the model referred to as MUSIC [79]. Each of the above approaches reproduce the
 593 A_J data measured at LHC quite well [80, 76] as shown in Figure 1.8 (left). Figure 1.8
 594 (right) shows the jet energy dependence of A_J predicted for RHIC energy di-jets with

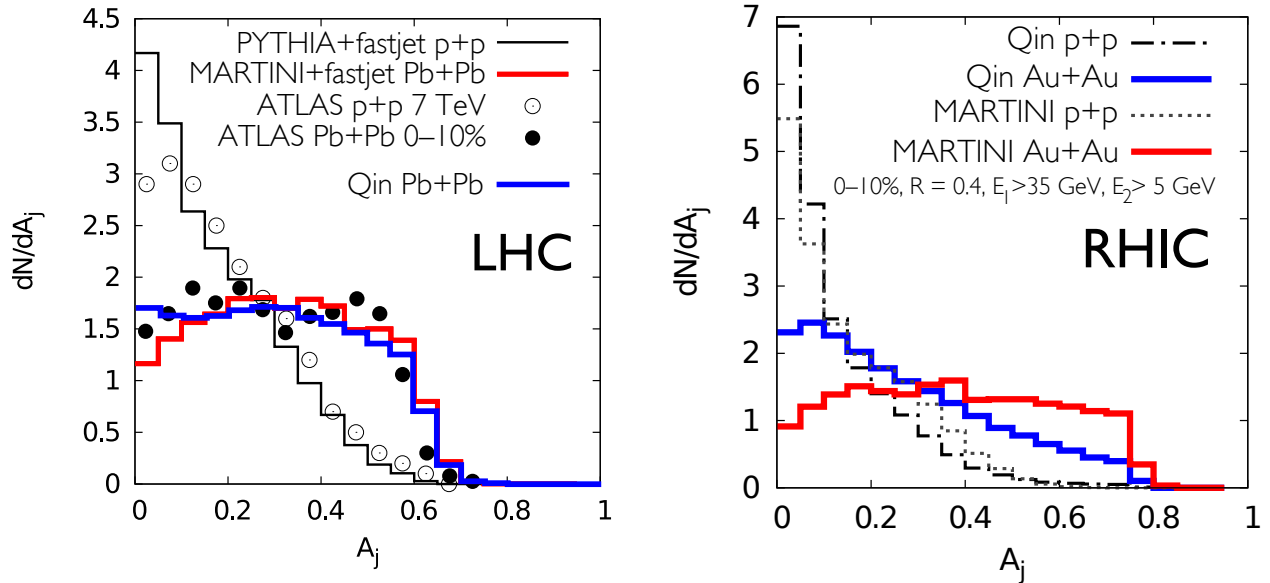


Figure 1.8: A_j distributions in MARTINI+MUSIC [81] and the model of Qin et al. [77]. (left) Comparison of A_j calculations in MARTINI+MUSIC and by Qin et al for Pb+Pb collisions at 2.76 TeV (red line, Qin et al; blue line, MARTINI+MUSIC). Both calculations show a similar broad A_j distribution. (right) Same as left panel, but for Au+Au collisions at 200 GeV (with leading jet $E_T > 35$ GeV). These results indicate a substantially different modification predicted by these models for di-jets propagating through the QGP at RHIC.

595 $E_{T1} > 35$ GeV with $E_{T2} > 5$ GeV by the two model calculations. A significant difference
 596 in shape is observed between the two models at RHIC energy with a peak developing at
 597 small A_j in the Qin et al. model while the MARTINI+MUSIC calculation retains a shape
 598 similar to those seen at the LHC energy.

599 1.6.2 Jet Shapes

600 Calculations from Vitev and collaborators [82, 83, 84] predict a jet radius R and energy
 601 dependence for inclusive jet R_{AA} , in contrast to the results from Qin et al. Vitev et
 602 al. utilize a Next-to-Leading-Order (NLO) calculation and consider not only final-state
 603 inelastic parton interactions in the QGP, but also parton energy loss effects from the cold
 604 nuclear matter. This can be seen in Figure 1.9, which exhibits significant radius and energy
 605 dependences. Because the high energy jets originate from hard scattering of high Bjorken
 606 x partons, a modest energy loss of these partons results in a reduction in the inclusive jet
 607 yields. At RHIC cold nuclear matter measurements will be made with $p+Au$ running in
 608 sPHENIX at the same collision energy to determine the strength of cold nuclear matter
 609 and any other effects as a baseline to the heavy ion measurements.

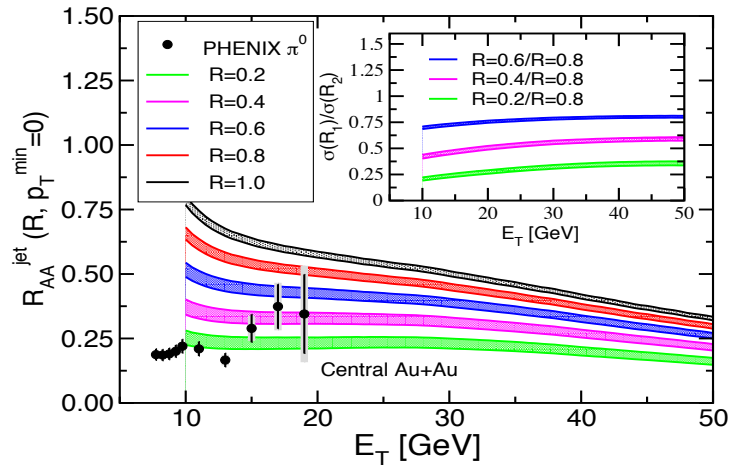


Figure 1.9: Calculations from Vitev et al. for the inclusive jet R_{AA} as a function of the jet energy and radius. Also shown for reference are PHENIX π^0 R_{AA} results. Inset presents ratios for jets of various radii relative to those measured with $R = 0.8$.

1.7 Fragmentation Functions

1.7.1 Direct photon-jet correlations

Ideally, one would like to understand how a quark or gluon of known energy interacts while traversing the QGP and the redistribution of energy and particles both longitudinal and transverse to the initial parton direction. The initial quark energy can be identified from binary scattering kinematics by measuring its direct photon [53] scattering “partner” on the opposite side. One can study fully reconstructed jets opposite the photon for various jet radii to investigate the redistribution in transverse energy. ATLAS has presented results on photon-jet R_{AA} . A suppression of the away-side jet is observed for two different jet-radius parameters.

Figure 1.10 presents the result of calculations of the event distribution of the ratio of the reconstructed jet energy (with $R = 0.3$) relative to the direct photon energy [85]. The authors note: “The steeper falling cross sections at RHIC energies lead not only to a narrow $z_{J\gamma}$ distribution in $p+p$ collisions but also to a larger broadening and shift in $\langle z_{J\gamma} \rangle$ in A+A collisions.” This results in a greater sensitivity to the redistribution of energy, which is again sensitive to the balance of processes including radiative and collisional energy loss. With an underlying event energy at RHIC that is a factor of 2.5 lower than that at the LHC, sPHENIX will be able to reconstruct jets over a very broad range of radii and energies opposite the direct photons. Shown in Figure 1.11 are the projected sPHENIX photon - jet correlation uncertainties measured differentially with respect to the path length through the QGP.

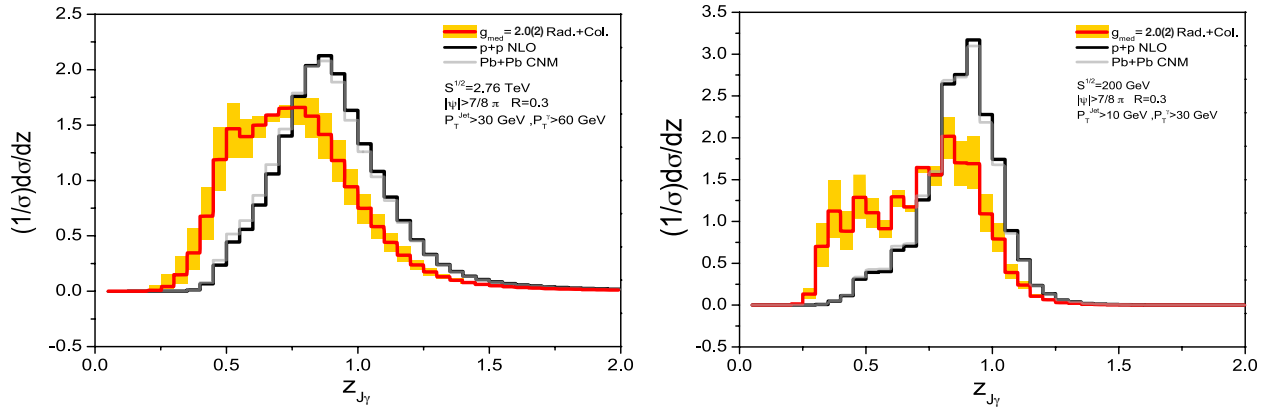


Figure 1.10: Calculations by Vitev et al. of the vacuum and medium-modified z_{J_γ} distributions for direct photon-triggered reconstructed jet events at LHC (left) and RHIC (right) energies [85].

631 With charged particle tracking one can also measure the longitudinal redistribution of
 632 hadrons opposite the direct photon. sPHENIX will have excellent statistical reach for such
 633 direct photon measurements.

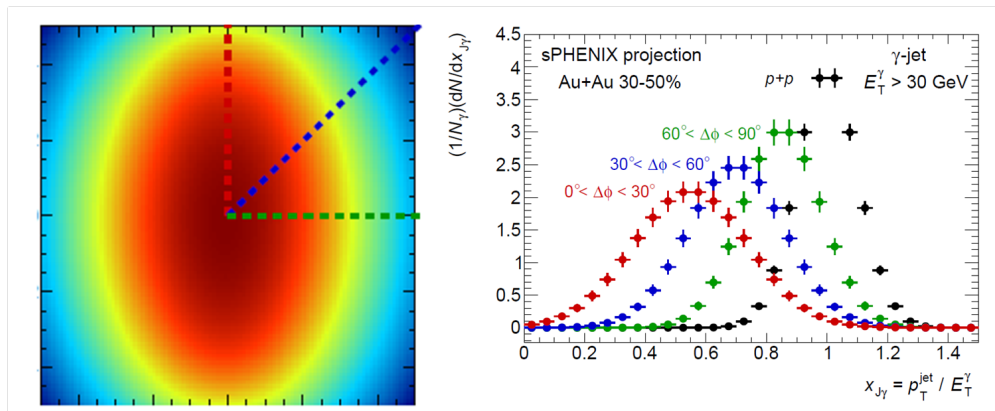


Figure 1.11: Schematic of different potential path lengths through the QGP (left) and projected sPHENIX uncertainties in the photon-jet channel for these different length scales traversed in the QGP.

634 At the same time, it is advantageous to measure modified fragmentation functions within
 635 inclusive reconstructed jets and via correlations as well. The original predictions of jet
 636 quenching in terms of induced forward radiation had the strongest modification in the
 637 longitudinal distribution of hadrons from the shower (i.e., a substantial softening of the
 638 fragmentation function). One may infer from the nuclear suppression of π^0 in central
 639 Au+Au collisions $R_{AA} \approx 0.2$ that the high z (large momentum fraction carried by the
 640 hadron) showers are suppressed.

641 1.7.2 Hadron-jet correlations

642 In sPHENIX, fragmentation functions via precision charged-track measurements are avail-
 643 able from high- z , where the effects are predicted to be largest, to low- z where medium
 644 response and equilibration effects are relevant. The independent measurement of jet
 645 energy (via calorimetry) and the hadron p_T via tracking is important. This independent
 646 determination also dramatically reduces the fake-track contribution by the coincidence
 647 required with a high energy jet.

648 One can also access somewhat less directly this transverse and longitudinal redistribution
 649 of energy and particles via trigger high p_T hadrons and narrow reconstructed jets. Such
 650 measurements have been undertaken by STAR [86]. The large kinematic reach of sPHENIX
 651 will provide very high statistics observables that span a reach where the opposing parton
 652 is mostly a gluon near 20 GeV with increasing quark fraction for higher energy triggers.
 653 This is another complement between the kinematics at RHIC and the LHC as shown in Fig-
 654 ure 1.12 that compares the quark-quark, quark-gluon, gluon-gluon relative contributions
 655 as a function of p_T .

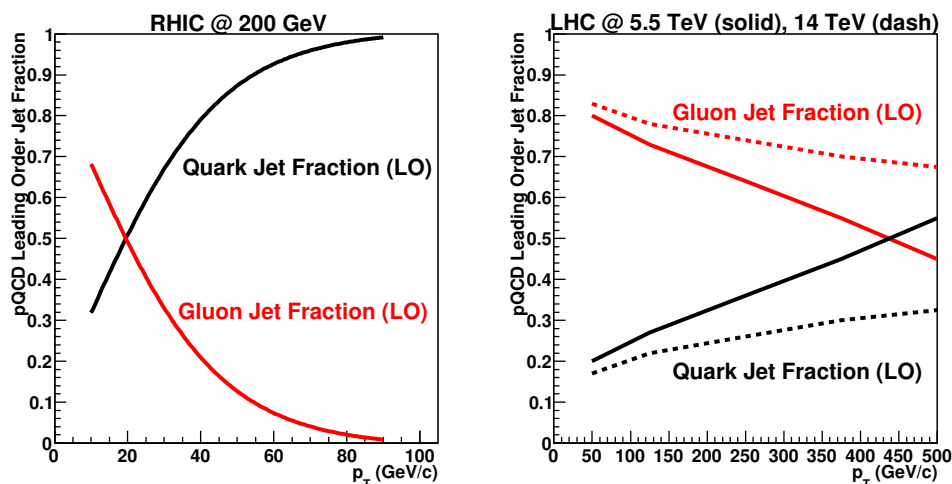


Figure 1.12: Comparison of the fraction of quark and gluon jets from leading order pQCD calculations as a function of transverse momentum for RHIC (left) and LHC (right) energies.

656 1.8 Heavy Quark Jets

657 The motivation for studying heavy flavor jets in heavy ion collisions is to understand the
 658 processes involved in parton-medium interactions and to further explore the issue of *strong*
 659 *versus weak* coupling [87]. As elaborated in Section 1.2, a major goal is understanding
 660 the constituents of the medium and how fast partons transfer energy to the medium.

661 Heavy quarks are particularly sensitive to the contribution of collisional energy loss, due
 662 to suppressed radiative energy loss from the “dead cone” effect [88]. Measurements of
 663 beauty-tagged jets and reconstructed D mesons over the broadest kinematic reach will
 664 enable the disentangling of \hat{q} and \hat{e} .

665 There are important measurements currently being made of single electrons from semilep-
 666 tonic D and B decays and direct D meson reconstruction with the current PHENIX VTX and
 667 STAR Heavy Flavor Tracker (HFT). The sPHENIX program can significantly expand the
 668 experimental acceptance and physics reach of this program with its ability to reconstruct
 669 full jets with a heavy flavor tag. The rates for heavy flavor production from perturbative
 670 QCD calculations [89] are shown in Figure 1.13.

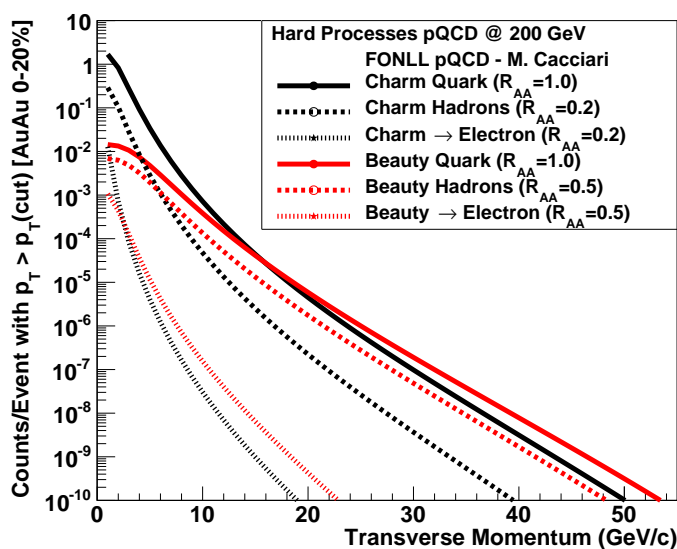


Figure 1.13: FONLL calculations [89] for heavy flavor (charm and beauty) jets, fragmentation hadrons (D, B mesons primarily), and decay electrons as a function of transverse momentum. The rates indicate expected counts for p_T above a minimum transverse momentum threshold, $p_T(\text{cut})$, as a function of $p_T(\text{cut})$ for Au+Au 0–20% central collisions.

671 Calculations including both radiative and collisional energy loss for light quark and gluon
 672 jets, charm jets, and beauty jets have been carried out within the CUJET 2.0 framework [90].
 673 The resulting R_{AA} values in central Au+Au at RHIC and Pb+Pb at the LHC for π, D, B
 674 mesons are shown as a function of p_T in Figure 1.14. The mass orderings are a convolution
 675 of different initial spectra steepness, different energy loss mechanisms, and the final
 676 fragmentation. Measurements of D mesons to high p_T and reconstructed beauty-tagged
 677 jets at RHIC will provide particularly sensitive constraints in a range where, due to their
 678 large masses, the charm and beauty quark velocities are not near the speed of light.

679 The tagging of charm and beauty jets has an extensive history in particle physics experi-
 680 ments. There are multiple ways to tag heavy flavor jets. First is the method of tagging via

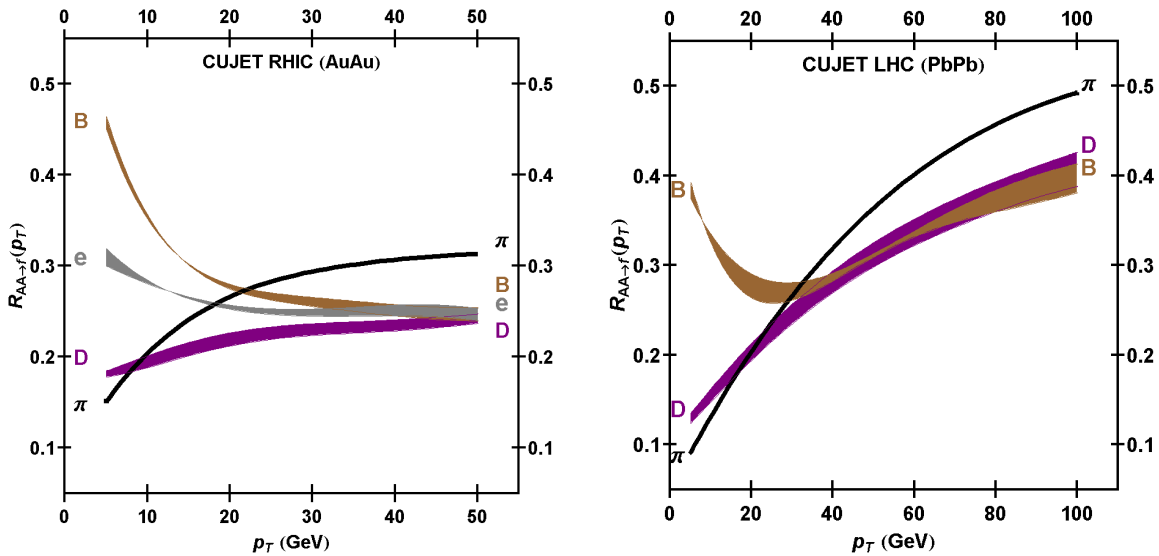


Figure 1.14: Calculations within the CUJET 2.0 [90] framework of the R_{AA} in central Au+Au collisions at RHIC (left) and Pb+Pb collisions at the LHC (right), with light, charm and beauty hadrons and electrons shown as separate curves.

681 the selection of a high p_T electron with a displaced vertex inside the jet. In minimum bias
 682 Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the fraction of inclusive electrons from D and B
 683 meson decays is already greater than 50% for $p_T > 2$ GeV/c. The sPHENIX tracking can
 684 confirm the displaced vertex of the electron from the collision point, further enhancing
 685 the signal. Since the semileptonic branching fraction of D and B mesons is approximately
 686 10%, this method provides a reasonable tagging efficiency. Also, the relative angle of the
 687 lepton with respect to the jet axis provides a useful discriminator for beauty jets as well,
 688 due to the decay kinematics. Second, the direct reconstruction of D mesons is possible
 689 within sPHENIX (see Figure 4.37 of Ref. [1]).

690 The third method utilizes jets with many tracks that do not point back to the primary
 691 vertex. This technique is detailed by the $D0$ collaboration to identify beauty jets at the
 692 Tevatron [91, 92], and employed with variations by ATLAS and CMS at the LHC. This
 693 method exploits the fact that most hadrons with a beauty quark decay into multiple
 694 charged particles all with a displaced vertex. The performance metrics for tagged beauty
 695 jets are given in Section 4.7 of Ref. [1]).

696 Measurements at the LHC provide tagging of heavy flavor probes as well – initial results
 697 on beauty tagged jets from CMS are shown in Figure 1.15. As detailed in Ref. [93], beauty
 698 tagged jets at the LHC come from a variety of initial processes. In fact, most often a
 699 tagged beauty jet does not have a back-to-back partner beauty jet. At RHIC energies the
 700 pair creation process represents $\sim 35\%$ of the beauty jet cross-section, which is a larger
 701 fractional contribution than at the LHC, though flavor excitation still produces $\sim 50\%$ of
 702 all b -jets at RHIC. Measurements at RHIC offer a different mixture of initial processes, and

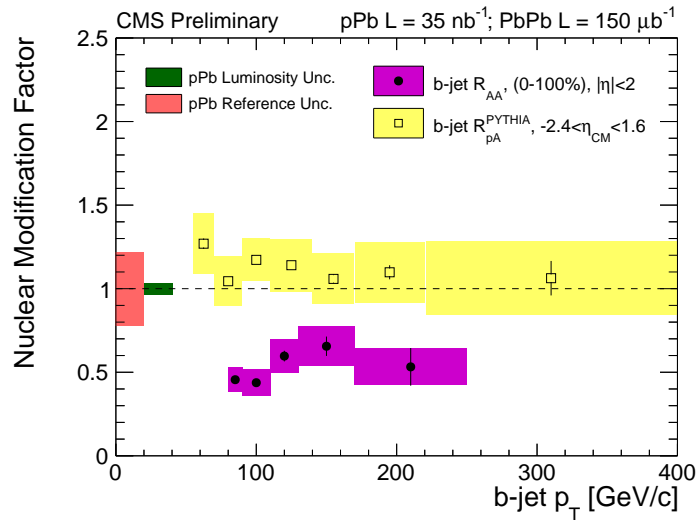


Figure 1.15: CMS results on the R_{AA} for beauty tagged jets in Pb+Pb collisions at the LHC.

703 thus kinematics, when looking at correlated back-to-back jets including heavy flavor tags,
 704 and will complement similar measurements at the LHC to constrain theories.

705 1.9 Quarkonia in the QGP

706 Motivated by a desire to observe the suppression of J/ψ production by color screening
 707 in the QGP an extensive program of J/ψ measurements in A+A collisions has been
 708 carried out at the SPS ($\sqrt{s_{NN}} = 17.3 \text{ GeV}$) and RHIC ($\sqrt{s_{NN}} = 200 \text{ GeV}$) and the LHC
 709 ($\sqrt{s_{NN}} = 2.76 \text{ TeV}$). Strong suppression is observed at all three energies, but it has become
 710 clear that the contribution of color screening to the observed modification cannot be
 711 uniquely determined without a good understanding of two strong competing effects.

712 The first of these, the modification of the J/ψ production cross section in a nuclear target,
 713 has been addressed at RHIC using d +Au collisions and at the SPS using p +Pb collisions,
 714 and is being addressed at the LHC using p +Pb collisions. A more recently recognized
 715 complicating effect arises from the possibility that previously unbound heavy quark pairs
 716 could coalesce into bound states due to interactions with the medium. This introduces
 717 the possibility that if a sufficient density of heavy quark pairs is produced initially, then
 718 coalescence of heavy quarks may increase the production cross section beyond the initial
 719 population of bound pairs [94].

720 Using p +Pb and d +Au data as a baseline, and under the assumption that cold nuclear
 721 matter (CNM) effects can be factorized from hot matter effects, the suppression in central
 722 collisions due to the presence of hot matter in the final state has been estimated to be about
 723 25% for Pb+Pb at the SPS [95], and about 50% for Au+Au at RHIC [96], both measured
 724 at midrapidity. The first J/ψ data in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ have been

725 measured from ALICE [97]. Interestingly, the suppression in central collisions is far greater
 726 at RHIC than at the LHC. This is qualitatively consistent with a predicted [94] strong
 727 coalescence component due to the very high $c\bar{c}$ production rate in a central collision at
 728 LHC. There is great promise that, with CNM effects estimated from p +Pb data, comparison
 729 of these data at widely spaced collision energies will lead to an understanding of the role
 730 of coalescence.

731 1.9.1 Upsilon State Measurements

732 Upsilon measurements have a distinct advantage over charmonium measurements as a
 733 probe of deconfinement in the quark-gluon plasma. The $Y(1S)$, $Y(2S)$ and $Y(3S)$ states can
 734 all be observed with comparable yields via their dilepton decays. Therefore, it is possible
 735 to compare the effect of the medium simultaneously on three bottomonium states—all of
 736 which have quite different radii and binding energies.

737 At the LHC, CMS has measured Upsilon modification data at midrapidity in Pb+Pb
 738 collisions at 2.76 TeV that indicate strong differential suppression of the 2S and 3S states
 739 relative to the 1S state [98]. ALICE has measured the $Y(1S)$ modification at forward
 740 rapidity in Pb+Pb collisions at 2.76 GeV [99], and in p +Pb collisions at 5.02 TeV [100].
 741 With longer Pb+Pb runs, and corresponding p +Pb modification data to establish a CNM
 742 baseline, the LHC measurements will provide an excellent data set within which the
 743 suppression of the three upilon states relative to p +Pb can be measured simultaneously
 744 at LHC energies.

745 At RHIC, upilon measurements have been hampered by a combination of low cross
 746 sections and acceptance, and insufficient momentum resolution to resolve the three states.
 747 So far, there are measurements of the modification of the three states combined in Au+Au
 748 by PHENIX [101] and STAR [102]. However a mass-resolved measurement of the modifi-
 749 cations of the three upilon states at $\sqrt{s_{NN}} = 200$ GeV would be extremely valuable for
 750 several reasons.

751 First, the core QGP temperature is approximately $2T_c$ at RHIC at 1 fm/ c and is at least
 752 30% higher at the LHC (not including the fact that the system may thermalize faster) [103].
 753 This temperature difference results in a different color screening environment. Figure 1.16
 754 shows the temperature as a function of time for the central cell in Au+Au and Al+Al
 755 collisions at 200 GeV and Pb+Pb collisions at 2.76 TeV from hydrodynamic simulations that
 756 include earlier pre-equilibrium dynamics and post hadronic cascade [104]. Superimposed
 757 are the lattice expected dissociation temperatures with uncertainties for the three upilon
 758 states. The significant lever arm in temperature between RHIC and LHC, and the use of
 759 either centrality or system size, allow one to bracket the expected screening behavior.

760 Second, the bottomonium production rate at RHIC is lower than that at the LHC by
 761 ~ 100 [96]. As a result, the average number of $b\bar{b}$ pairs in a central Au+Au collision
 762 at RHIC is ~ 0.05 versus ~ 5 in central Pb+Pb at the LHC. Qualitatively, one would

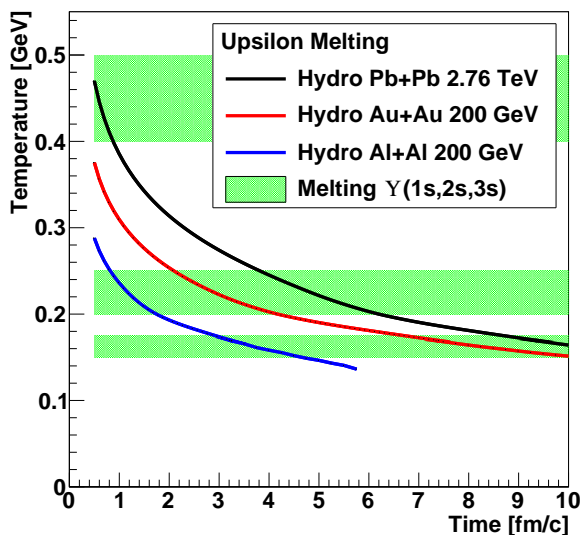


Figure 1.16: Temperature as a function of time for the central cell in Au+Au and Al+Al collisions at 200 GeV and Pb+Pb collisions at 2.76 TeV from hydrodynamic simulations that include earlier pre-equilibrium dynamics and post hadronic cascade [104]. Superimposed are the lattice expected dissociation temperatures with uncertainties for the three upsilon states.

763 expect this to effectively remove at RHIC any contributions from coalescence of bottom
 764 quarks from different hard processes, making the upsilon suppression at RHIC dependent
 765 primarily on color screening and CNM effects. This seems to be supported by recent
 766 theoretical calculations [105] where, in the favored scenario, coalescence for the upsilon is
 767 predicted to be significant at the LHC and small at RHIC.

768 Finally, it is of interest at RHIC energy to directly compare the modifications of the J/ψ and
 769 the $Y(2S)$ states as a way of constraining the effects of coalescence by studying two states -
 770 in the same temperature environment - that have very similar binding energies and radii,
 771 but quite different underlying heavy quark populations.

772 An example theoretical calculation for both RHIC and the LHC is shown in Figure 1.17
 773 indicating the need for substantially improved precision and separation of states in the
 774 temperature range probed at RHIC.

775 STAR has constructed a Muon Telescope Detector (MTD) to measure muons at midra-
 776 pidity [106]. The MTD has coverage over $|\eta| < 0.5$, with about 45% effective azimuthal
 777 coverage. The MTD will have a muon to pion enhancement factor of 50–100, and the mass
 778 resolution will provide a clean separation of the $Y(1S)$ from the $Y(2S+3S)$, and likely the
 779 ability to separate the $Y(2S)$ and $Y(3S)$ by fitting. While STAR has already taken data in
 780 the 2014 run with the MTD installed, the upgrade to sPHENIX will provide better mass
 781 resolution and approximately 10 times higher yields per run for upsilon measurements as

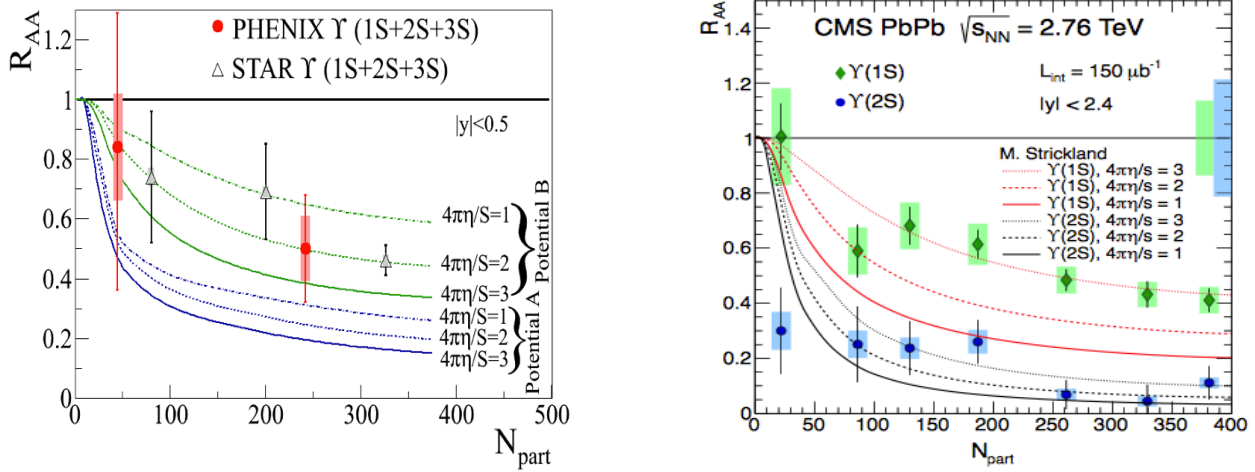


Figure 1.17: Calculations for Upsilon state suppression at RHIC and LHC energies as a function of collision centrality. The current state of measurements are also shown from PHENIX, STAR and CMS.

782 shown in Figure 1.18. In concert with the expected higher statistics results from the LHC
 783 experiments, sPHENIX data will provide the required precision to discriminate models of
 784 breakup in the dense matter and the length scale probed in the medium.

785 **1.9.2 Quarkonia in $p(d) + A$ collisions**

786 Measurements of quarkonia production in proton-nucleus collisions have long been con-
 787 sidered necessary to establish a cold nuclear matter baseline for trying to understand
 788 hot matter effects in nuclear collisions. It has become clear, however, that the physics of
 789 $p+A$ collisions is interesting in its own right [96]. Modification of quarkonia production
 790 in a nuclear target has been described by models that include gluon saturation effects
 791 (see for example [107]), breakup of the forming quarkonia by collisions with nucleons in
 792 the target [108, 109], and partonic energy loss in cold nuclear matter [110]. These mecha-
 793 nisms, which are all strongly rapidity and collision energy dependent, have been used, in
 794 combination, to successfully describe J/ψ and $Y(1S)$ data in $p(d)+A$ collisions.

795 The observation of what appears to be hydrodynamic effects in $p+Pb$ collisions at the
 796 LHC [111, 112, 113] and $d+Au$ collisions at RHIC [114] has raised questions about the
 797 longstanding assumption that $p(d)+A$ collisions are dominated by cold nuclear matter
 798 effects. For quarkonia, it raises the obvious question: does the small hot spot produced in
 799 the $p(d)+A$ collision affect the quarkonia yield? Recent measurements of the modification
 800 of quarkonia excited states in $p(d)+A$ collisions have produced unexpected and puzzling
 801 results.

802 The situation has become more interesting with the release of data from CMS on produc-

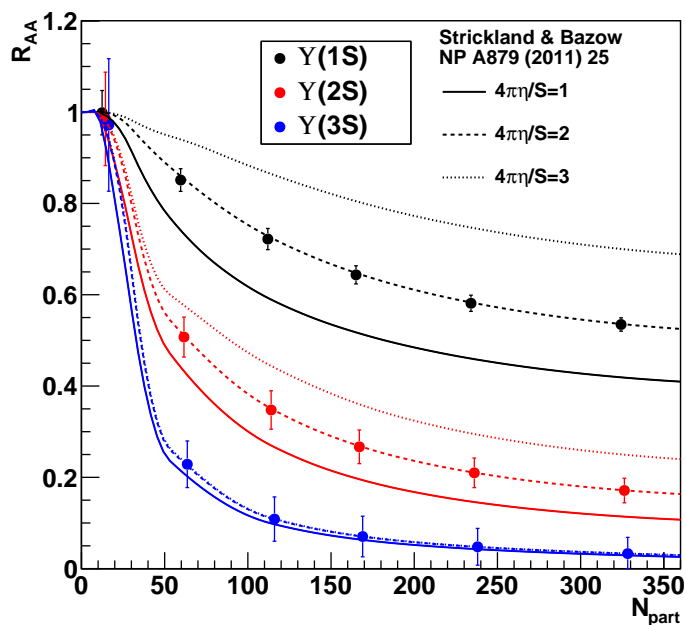


Figure 1.18: Estimate of the statistical precision of a measurement of the Y states in Au+Au collisions using sPHENIX, assuming that the measured R_{AA} is equal to the results of a recent theory calculation by Strickland & Bazow referenced in the legend. The yields assume 100 billion recorded Au+Au events.

803 tion of Upsilon excited states in p +Pb collisions. They find that the Y(2S) to Y(1S) ratio is
 804 suppressed by about 20% in minimum bias p +Pb collisions, while for the Y(3S) the differ-
 805 ential suppression in minimum bias collisions is about 30%. The effect will be considerably
 806 larger in the most central collisions, but data showing the centrality dependence are not
 807 released yet.

808 A comprehensive p +A collision program with sPHENIX will provide Upsilon measure-
 809 ments in p +Au collisions at RHIC energy with all three states resolved from each other.

810 1.10 Jet Rates and Physics Reach

811 In order to realize the proposed comprehensive program of jet probes, direct photon-tagged
 812 jets, and Upsilon measurements requires very high luminosities and the ability to sample
 813 events without selection biases.¹ In addition to the Upsilon capabilities summarized
 814 in Figure 1.18, the extensive set of reconstructed jet measurements made available by

¹The effect of the completed stochastic cooling upgrade to the RHIC accelerator [115] has been incorporated into the RHIC beam projections [116]. Utilizing these numbers and accounting for accelerator and experiment uptime and the fraction of collisions within $|z| < 10$ cm, the nominal full acceptance range for

815 sPHENIX will provide detailed information about the quark-gluon plasma properties,
 816 dynamics, time evolution, and structure at $1-2 T_c$. The theoretical bridgework needed
 817 to connect these measurements to the interesting and unknown medium characteristics
 818 of deconfined color charges is under active construction by many theorists. Combining
 819 this work with new results from the flexible and high luminosity RHIC collider facility
 820 can produce new discoveries in heavy ion collisions with an appropriate set of baseline
 821 measurements provided sPHENIX apparatus is constructed. The sPHENIX jet detector at
 822 RHIC is best able to take advantage of these opportunities.

823 1.10.1 Inclusive jet rates

824 The inclusive jet yield within $|\eta| < 1.0$ in 0–20% central Au+Au collisions at 200 GeV
 825 has been calculated for $p+p$ collisions by Vogelsang in a Next-to-Leading-Order (NLO)
 826 perturbative QCD formalism [117] and scaled by the expected number of binary collisions.
 827 This is presented in Figure 1.19. Also shown are results from the calculation for π^0 and
 828 direct and fragmentation photon yields. The bands correspond to the renormalization scale
 829 uncertainty in the calculation (i.e., $\mu, \mu/2, 2\mu$). Figure 1.19 provides the counts per event
 830 with p_T larger than the value on the x-axis for the most central 20% Au+Au collisions at
 831 $\sqrt{s_{NN}} = 200$ GeV. With 20 billion events per RHIC year for this centrality selection, this
 832 translates into jet samples from 20–80 GeV and direct photon statistics out beyond 40 GeV.
 833 It is notable that within the acceptance of the sPHENIX detector, over 80% of the inclusive
 834 jets will also be accepted dijet events. The necessary comparable statistics are available
 835 with 10 weeks of $p+p$ and 10 weeks of $p+Au$ running.

836 1.10.2 Constraining the path length through the medium

837 An observable that has been especially challenging for energy loss models to be able to
 838 reproduce is the azimuthal anisotropy of π^0 production with respect to the reaction plane.
 839 A weak dependence on the path length in the medium is expected from radiative energy
 840 loss. This translates into a small elliptic flow v_2 value for high p_T particles, and thus would
 841 represent only a modest difference in parton energy loss when traversing a short versus
 842 long path length in the QGP.

843 A strong path length dependence is naturally described by strongly-coupled energy-loss
 844 models [118, 119]. Note that one can obtain a larger v_2 by using a stronger coupling, larger
 845 \hat{q} , but at the expense of over-predicting the average level of suppression. New strong

the detector, the sPHENIX detector can record 100 billion Au+Au minimum bias collisions in a one-year 22 week run. With the latest luminosity projections, for the purely calorimetric jet and γ -jet observables with modest trigger requirements, one can sample 0.6 trillion Au+Au minimum bias collisions. Note that the PHENIX experiment has a nearly dead-timeless high-speed data acquisition and trigger system that has already sampled tens of billions of Au+Au minimum bias collisions, and maintaining this high rate performance with the additional sPHENIX components is an essential design feature.

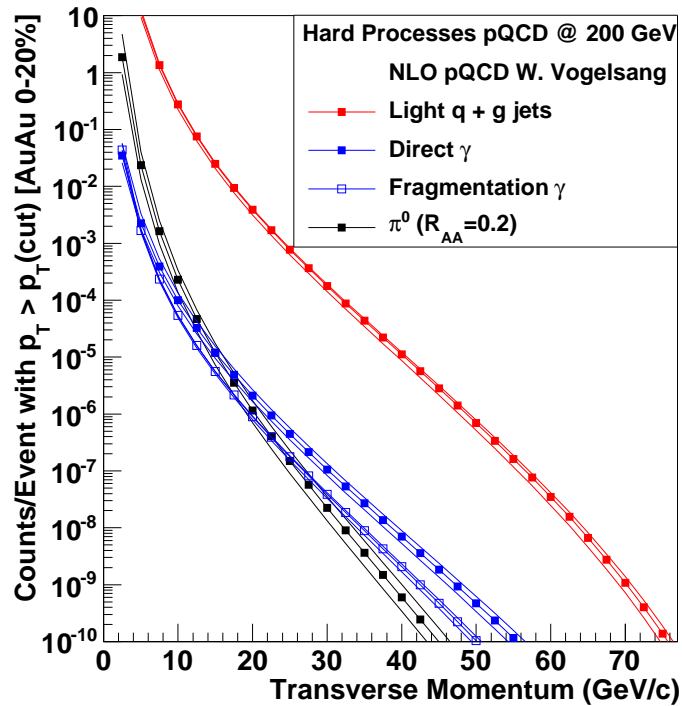


Figure 1.19: Jet, photon and π^0 rates for $|\eta| < 1.0$ from NLO pQCD [117] calculations scaled to Au+Au central collisions for $\sqrt{s_{NN}} = 200$ GeV. The scale uncertainties on the pQCD calculations are shown as additional lines. Ten billion Au+Au central collisions correspond to one count at 10^{-10} at the bottom of the y-axis range. A nominal 22 week RHIC run corresponds to 20 billion central Au+Au events.

846 coupling models [120, 121] will need to confront the full set of observables measured at
 847 RHIC.

848 The measurement of jet quenching observables, as a detailed function of orientation with re-
 849 spect to the reaction plane, is directly sensitive to the coupling strength and the path length
 850 dependence of any modification to the parton shower. In addition, medium response may
 851 be optimally measured in mid-central collisions where there is a lower underlying event
 852 and where the medium excitations are not damped out over a longer time evolution as
 853 in more central collisions or which may be the case also at LHC. Shown in Figure 1.20
 854 are projected uncertainties from sPHENIX for the direct photon and reconstructed jet
 855 observables in three orientation selections. One expects no orientation dependence for
 856 the direct photons and the question is whether the unexpectedly large dependence for
 857 charged hadrons persists in reconstructed jets up to the highest p_T . Note that the same
 858 measurements can be made for beauty tagged jets, charged hadrons up to 50 GeV/c, and a
 859 full suite of correlation measurements including jet-jet, hadron-jet, γ -jet.

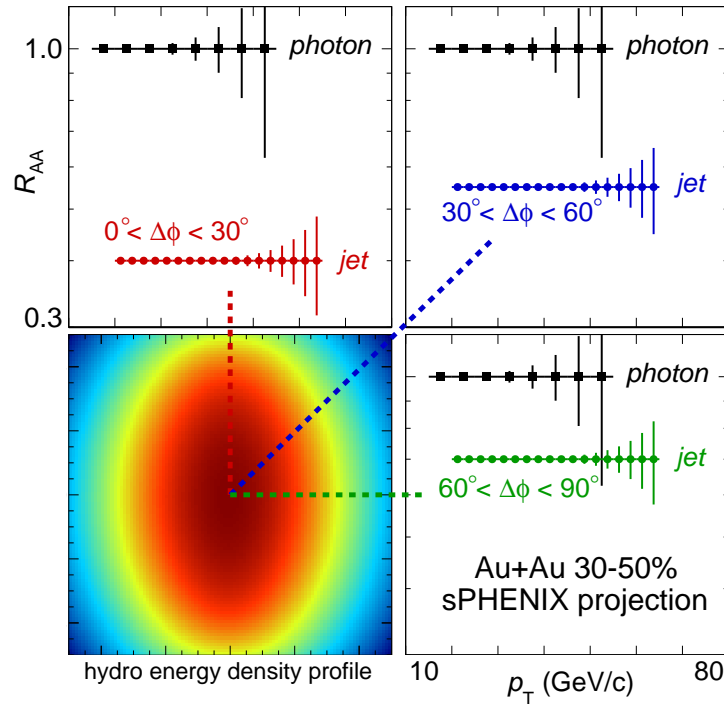


Figure 1.20: Demonstration of the statistical reach for azimuthally-sensitive hard probes measurements in sPHENIX. Each panel shows the projected statistical uncertainty for the R_{AA} of inclusive jets and photons, with each a panel a different $\Delta\phi$ range with respect to the reaction plane in 30–50% Au+Au events. sPHENIX would additionally have tremendous statistical reach in the analogous charged hadron R_{AA} .

860 All measurements in heavy ion collisions are the result of emitted particles integrated
 861 over the entire time evolution of the reaction, covering a range of temperatures. Similar
 862 to the hydrodynamic model constraints, the theory modeling for jet probes requires a
 863 consistent temperature and scale dependent model of the quark-gluon plasma and is only
 864 well constrained by precision data through different temperature evolutions, as measured
 865 at RHIC and the LHC.

866 1.10.3 Rates for Direct Photons

867 Measurement of direct photons requires them to be separated from the other sources of
 868 inclusive photons, largely those from π^0 and η meson decay. The left panel of Figure 1.21
 869 shows the direct photon and π^0 spectra as a function of transverse momentum for both
 870 $\sqrt{s} = 200$ GeV and 2.76 TeV $p+p$ collisions. The right panels show the γ/π^0 ratio as a
 871 function of p_T for these energies with comparison PHENIX measurements at RHIC. At the
 872 LHC, the ratio remains below 10% for $p_T < 50$ GeV while at RHIC the ratio rises sharply
 873 and exceeds one at $p_T \approx 30$ GeV/c. In heavy ion collisions the ratio is further enhanced

874 because the π^0 s are significantly suppressed. Taking the suppression into account, the
 875 γ/π^0 ratio at RHIC exceeds one for $p_T > 15$ GeV/c. The large signal to background means
 876 that it will be possible to measure direct photons with the sPHENIX calorimeter alone,
 877 even before applying isolation cuts. Beyond measurements of inclusive direct photons,
 878 this enables measurements of γ -jet correlations and γ -hadron correlations.

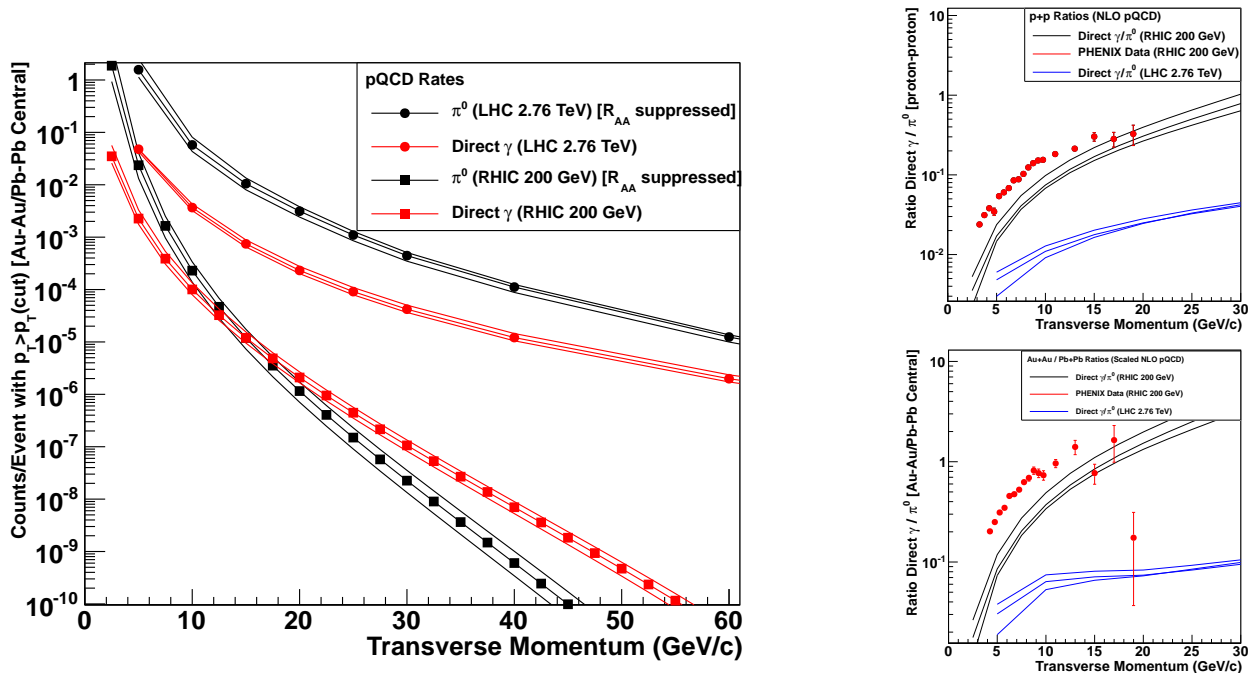


Figure 1.21: NLO pQCD calculations of direct photons and π^0 for RHIC and LHC. The plot on the left shows the counts per event in Au+Au or Pb+Pb collisions (including the measured R_{AA} suppression factor for π^0). The upper (lower) panel on the right shows the direct γ to π^0 ratio in $p+p$ (Au+Au or Pb+Pb) collisions, in comparison with measurements from the PHENIX experiment at RHIC [122, 123].

879 1.10.4 Hard probe statistics and range in p_T

880 Figure 1.22 summarizes the current and future state of hard probes measurements in A+A
 881 collisions in terms of their statistical reach, showing the most up to date R_{AA} measurements
 882 of hard probes in central Au+Au events by the PHENIX Collaboration plotted against
 883 statistical projections for sPHENIX channels measured after the first two years of data-
 884 taking. While these existing measurements have greatly expanded our knowledge of
 885 the QGP created at RHIC, the overall kinematic reach is constrained to < 20 GeV even
 886 for the highest statistics measurements. Figure 1.23 shows the expected range in p_T for
 887 sPHENIX as compared to measurements at the LHC. Due to the superior acceptance,
 888 detector capability and collider performance, sPHENIX will greatly expand the previous
 889 kinematic range studied at RHIC energies (in the case of inclusive jets, the data could

890 extend to 80 GeV/c, four times the range of the current PHENIX π^0 measurements) and
 891 will allow access to new measurements entirely (such as fully reconstructed b -tagged jets).

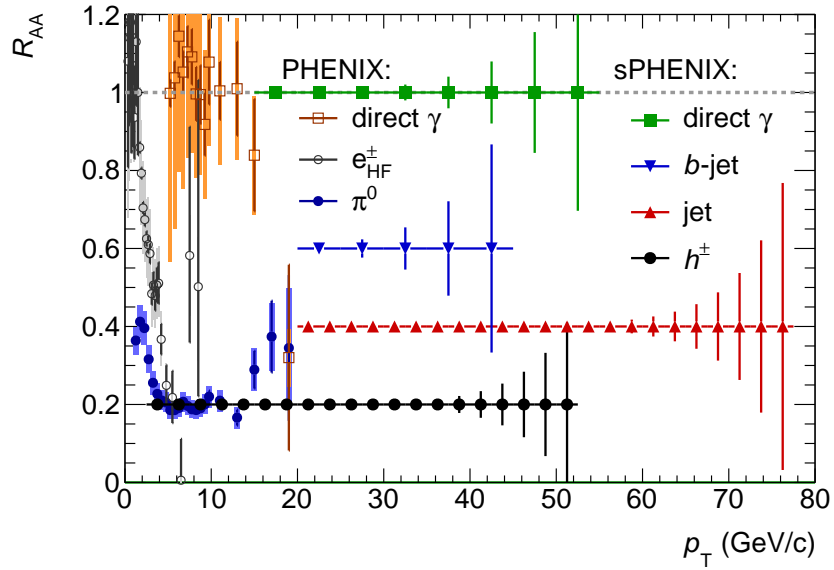


Figure 1.22: Statistical projections for the R_{AA} of various hard probes vs p_T in 0-20% Au+Au events with the sPHENIX detector after two years of data-taking, compared with a selection of current hard probes data from PHENIX.

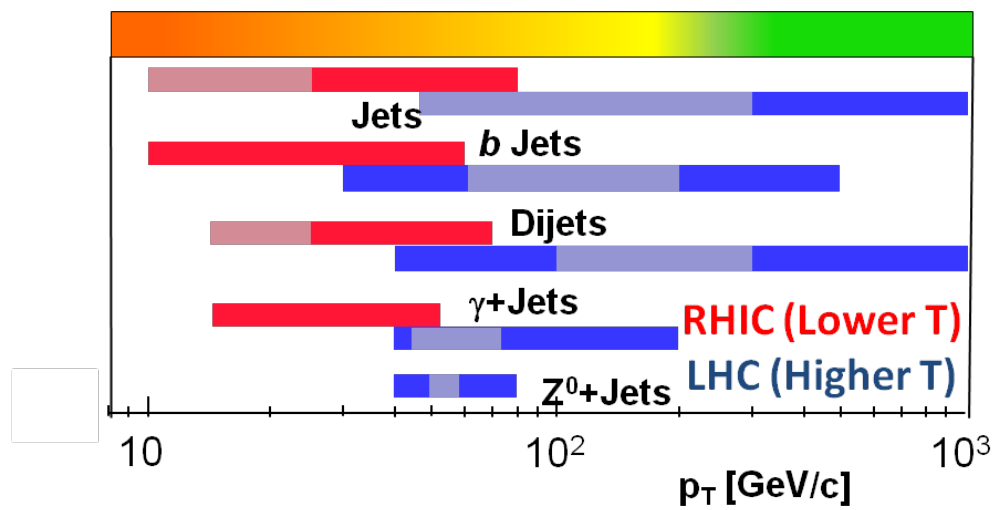


Figure 1.23: Anticipated range in p_T of various hard probe measurements using sPHENIX at RHIC (red) and measurements made at the LHC (blue). The color strip across the top corresponds to the regions presented initially in Figure 1.1 (left) for scattering in the medium from bare quarks and gluons (green), from thermal gluons (yellow), and integration over all possible objects that are probed (orange).

Chapter 2

Detector Overview

The sPHENIX Detector is a cylindrical detector covering $|\eta| \leq 1.1$ and the full azimuth. It is designed to use the former BaBar superconducting solenoid to contain an inner tracking system out to 80 cm in radius followed by a electromagnetic calorimeter and the first of two longitudinal segments of a hadronic calorimeter. The second longitudinal segment of the hadronic calorimeter, which also serves as the magnet flux return, surrounds the magnet cryostat.

sPHENIX has been designed to collect a large sample of events in Au+Au and $p+p$ collisions at RHIC to measure jets, jets correlations, and Upsilon production and decay and satisfy a set of performance requirements that are needed to carry out the physics program described in Chapter 1. The sPHENIX physics program rests on several key measurements, particularly measurements of jets with calorimetry and tracking which can cleanly separate the Upsilon states; the requirements that drive any particular aspect of the detector performance come from a broad range of considerations related to those measurements. A comprehensive assessment of the physics requirements has led to the development of the reference design shown in Figure 2.1.

The primary components of the sPHENIX reference design are as follows.

Magnetic Solenoid Built for the BaBar experiment at SLAC, the magnet became available after the termination of the BaBar program. The cryostat has an inner radius of 140 cm and is 33 cm thick, and can produce a central field of 1.5 T.

Tracking system The tracking system consist of three components:

Time Projection Chamber A TPC with an outer radius of about 80 cm measures space points on charged tracks which provides momentum resolution which can separate the Upsilon states in decays to e^+e^- .

Intermediate Tracking The Intermediate Tracker is a silicon strip detector consisting of up to four layers which can measure space points on charged tracks inside

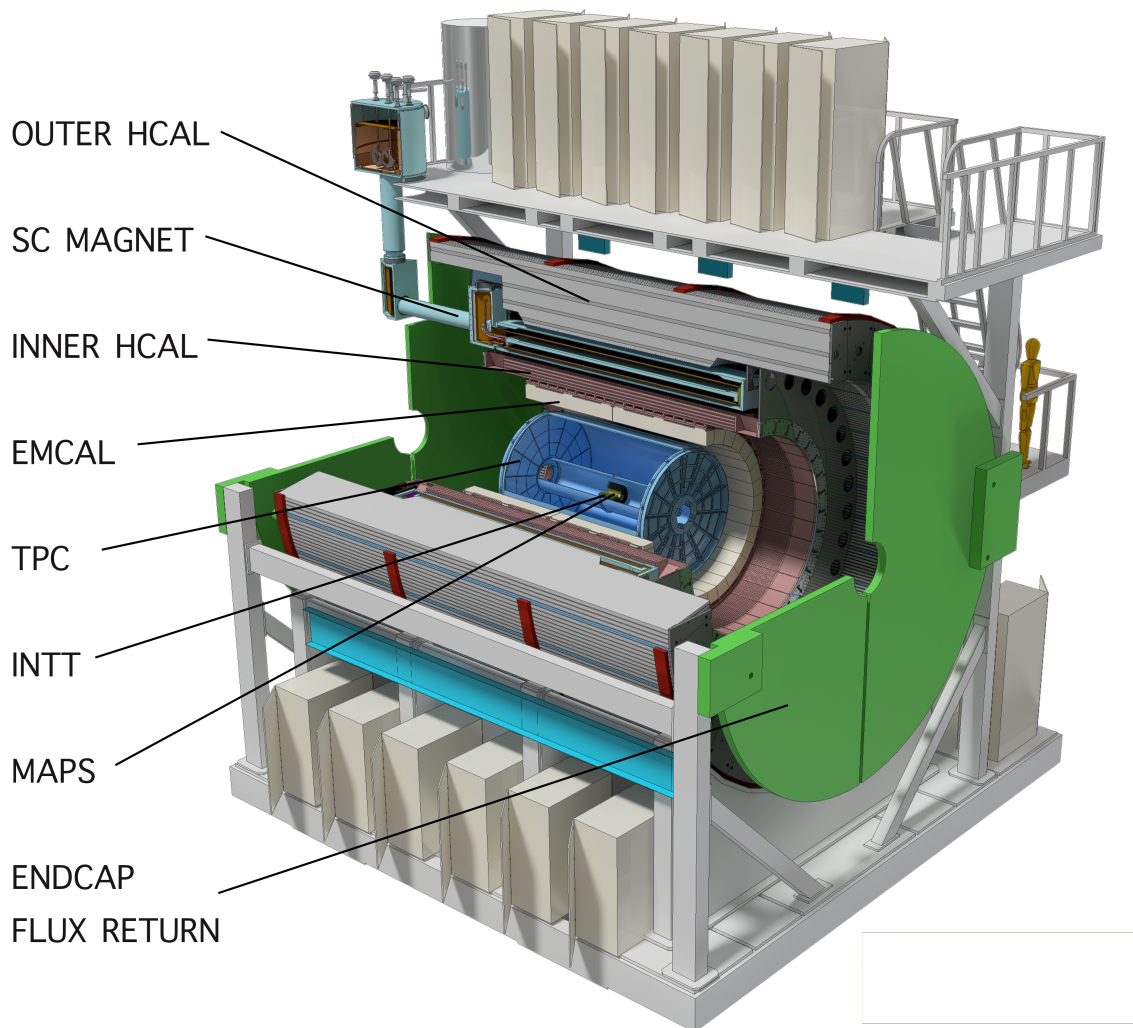


Figure 2.1: View of the sPHENIX detector with its component subdetectors.

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the inner radius of the TPC for robust tracking even in a high multiplicity heavy ion collision with time resolution that can separate pileup in the TPC. This detector is based on commercial silicon sensors read out with the FPHX ASIC developed for the PHENIX FVTX detector and is a RIKEN and RIKEN-Brookhaven Research Center contribution to the sPHENIX experiment.

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MAPS Vertex Detector A Monolithic Active Pixel (MAPS) vertex detector in close proximity to the beam pipe is to provide high precision vertex measurements for measurement of displaced vertices from decays of particles containing b and c quarks, and provide additional precisely measured space points for charged particle tracking. This detector is being proposed and developed as a separate upgrade to the sPHENIX proposal, based on duplicating as much as possible

930 the ALICE Inner Tracking System (ITS) detector.

931 **Electromagnetic Calorimeter** Tungsten-scintillating fiber sampling calorimeter inside the
 932 magnet bore read out with silicon photo-multipliers. The calorimeter has a small
 933 Molière radius and short radiation length. allowing for a compact design.

934 **Inner Hadronic Calorimeter** Sampling calorimeter of non-magnetic metal and scintillator
 935 located inside the magnet bore, which is not part of the DOE funded proposal, but
 936 which could be instrumented at a later time with non-DOE funding.

937 **Outer Hadronic Calorimeter** Sampling calorimeter of magnet steel scintillator located
 938 outside the cryostat which doubles as the flux return for the solenoid.

939 In the following list we provide a high-level mapping between physics aims and various
 940 detector requirements. The justification for these requirements is then discussed in more
 941 detail in subsequent sections.

942 **Upsilon** The key to the physics is high statistics $p+p$, $p+A$, and $A+A$ data sets, with
 943 mass resolution and signal-to-background sufficient to separate the three states of
 944 the Y family.

- 945 • large geometric acceptance ($\Delta\phi = 2\pi$ and $|\eta| < 1.1$)
- 946 • high rate data acquisition (15 kHz)
- 947 • trigger for electrons from $Y \rightarrow e^+e^-$ ($> 90\%$ efficiency) in $p+p$ and $p+A$
- 948 • track reconstruction efficiency $> 90\%$ and purity $> 90\%$ for $p_T > 3$ GeV/c
- 949 • momentum resolution of 1.2% for p_T in the range 4-10 GeV/c.
- 950 • electron identification with efficiency $> 70\%$ and charged pion rejection of 90:1
 951 or better in central Au+Au at $p_T = 4$ GeV/c.

952 **Jets** The key to the physics is to cover jet energies of 20–70 GeV, for all centralities, for a
 953 range of jet sizes, with high statistics and performance insensitive to the details of jet
 954 fragmentation.

- 955 • energy resolution $< 120\%/\sqrt{E_{\text{jet}}}$ in $p+p$ for $R = 0.2$ –0.4 jets
- 956 • energy resolution $< 150\%/\sqrt{E_{\text{jet}}}$ in central Au+Au for $R = 0.2$ jets
- 957 • energy scale uncertainty $< 3\%$ for inclusive jets
- 958 • energy resolution, including effect of underlying event, such that scale of un-
 959 folding on raw yields is less than a factor of three
- 960 • measure jets down to $R = 0.2$ (segmentation no coarser than $\Delta\eta \times \Delta\phi \sim$
 961 0.1×0.1)

- 962 • underlying event influence event-by-event (large coverage HCal/EMCal) (AT-
 - 963 LAS method)
 - 964 • energy measurement insensitive to softness of fragmentation (quarks or gluons)
 - 965 — HCal + EMCal
 - 966 • jet trigger capability in $p+p$ and $p+A$ without jet bias (HCal and EMCal)
 - 967 • rejection ($> 95\%$) of high p_T charged track backgrounds (HCal)
-

968 **Dijets** The key to the physics is large acceptance in conjunction with the general require-
 969 ments for jets as above

- 970 • $> 80\%$ containment of opposing jet axis
 - 971 • $> 70\%$ full containment for $R = 0.2$ dijets
 - 972 • R_{AA} and A_J measured with $< 10\%$ systematic uncertainty (also key in $p+A$,
 - 973 onset of effects)
-

974 **Fragmentation functions** The key to the physics is unbiased measurement of jet energy

- 975 • excellent tracking resolution out to $> 40 \text{ GeV}/c$ ($dp/p < 0.2\% \times p$)
 - 976 • independent measurement of p and E ($z = p/E$)
-

977 **Heavy quark jets** The key to the physics is tagging identified jets containing a displaced
 978 secondary vertex

- 979 • precision DCA (< 100 microns) for electron $p_T > 4 \text{ GeV}/c$
 - 980 • electron identification for high $p_T > 4 \text{ GeV}/c$
-

981 **Direct photon** The key to the physics is identifying photons

- 982 • EMCal segmentation $\Delta\eta \times \Delta\phi \sim 0.024 \times 0.024$
 - 983 • EMCal resolution for photon ID ($< 15\%/\sqrt{E}$)
 - 984 • EMCal cluster trigger capability in $p+p$ and $p+A$ with rejections > 100 for
 - 985 $E_\gamma > 10 \text{ GeV}$
-

986 **High statistics** Ability to sample high statistics for $p+p$, $p+A$, $A+A$ at all centralities —
 987 requires high rate, high throughput DAQ (15 kHz).

988 In the following sections, we detail the origin of key requirements.

2.1 Acceptance

The large acceptance and high rate of sPHENIX are key enablers of the physics program detailed in Chapter 1. The total acceptance of the detector is determined by the requirement of high statistics jet measurements and the need to fully contain both single jets and dijets. To fully contain hadronic showers in the detector requires both large solid angle coverage and a calorimeter deep enough to fully absorb the energy of hadrons up to 70 GeV.

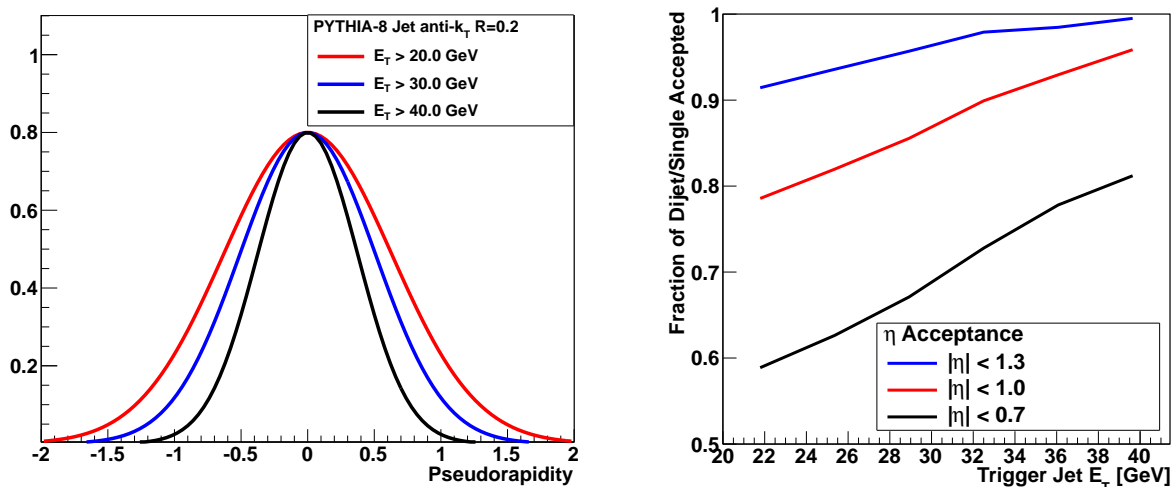


Figure 2.2: (Left) Pseudorapidity distribution of PYTHIA jets reconstructed with the FASTJET anti- k_T and $R=0.2$ for different transverse energy selections. (Right) The fraction of PYTHIA events where the leading jet is accepted into a given pseudorapidity range where the opposite side jet is also within the acceptance. Note that the current PHENIX acceptance of $|\eta| < 0.35$ corresponds to a fraction below 30%.

The PYTHIA event generator has been used to generate a sample of $p+p$ at 200 GeV events which can be used to demonstrate the pseudorapidity distribution of jets. The left panel in Figure 2.2 shows the pseudorapidity distribution of jets with E_T above 20, 30, and 40 GeV. The right panel in Figure 2.2 shows the fraction of events where a trigger jet with E_T greater than a given value within a pseudorapidity range has an away side jet with $E_T > 5$ GeV accepted within the same coverage. In order to efficiently capture the away side jet, the detector should cover $|\eta| < 1$, and in order to fully contain hadronic showers within this fiducial volume, the calorimetry should cover slightly more than that. Given the segmentation to be discussed below, the calorimeters are required to cover $|\eta| < 1.1$.

It should be noted that reduced acceptance for the away-side jet relative to the trigger suffers not only a reduction in statistics for the dijet asymmetry and γ -jet measurements but also results in a higher contribution of low energy fake jets (upward fluctuations in the background) in those events where the away side jet is out of the acceptance. For the latter effect, the key is that both jet axes are contained within the acceptance, and then events

1009 can be rejected where the jets are at the edge of the detector and might have partial energy
1010 capture.

1011 2.2 Segmentation

1012 Jets are reconstructed from the four-vectors of the particles or measured energies in the
1013 event via different algorithms, and with a typical size $R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$. In order to recon-
1014 struct jets down to radius parameters of $R = 0.2$ a segmentation in the hadronic calorimeter
1015 of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ is required. The electromagnetic calorimeter segmentation should
1016 be finer as driven by the measurement of direct photons for γ -jet correlation observables.
1017 The compact electromagnetic calorimeter design being considered for sPHENIX has a
1018 Molière radius of ~ 15 mm, and with a calorimeter at a radius of about 100 cm, this leads
1019 to an optimal segmentation of $\Delta\eta \times \Delta\phi = 0.024 \times 0.024$ in the electromagnetic section.

1020 2.3 Energy Resolution

1021 The requirements on the jet energy resolution are driven by considerations of the ability
1022 to reconstruct the inclusive jet spectra and dijet asymmetries and the fluctuations on the
1023 fake jet background. The total jet energy resolution is typically driven by the hadronic
1024 calorimeter resolution and many other effects including the bending of charged particles
1025 in the magnetic field out of the jet radius. Expectations of jet resolutions approximately 1.2
1026 times worse than the hadronic calorimeter resolution alone are typical.

1027 In a central Au+Au event, the average energy within a jet cone of radius $R = 0.2$ ($R = 0.4$)
1028 is approximately 10 GeV (40 GeV) resulting in an typical RMS fluctuation of 3.5 GeV
1029 (7 GeV). This sets the scale for the required reconstructed jet energy resolution, as a much
1030 better resolution would be dominated by the underlying event fluctuations regardless.
1031 A measurement of the jet energy for $E = 20$ GeV with $\sigma_E = 120\% \times \sqrt{E} = 5.4$ GeV
1032 gives a comparable contribution to the underlying event fluctuation. A full study of the
1033 jet energy resolution with a GEANT4 simulation of the detector configuration has been
1034 performed and is discussed in the sPHENIX proposal required and is presented in the
1035 Physics Performance chapter of the sPHENIX Proposal [1].

1036 Different considerations set the scale of the energy resolution requirement for the EMCal.
1037 The jet physics requirement is easily met by many EMCal designs. For the direct γ -jet
1038 physics, the photon energies being considered are $E_\gamma > 10$ GeV where even a modest
1039 $\sigma_E/E = 12\%/\sqrt{E}$ represents only a blurring of 400 MeV. In Au+Au central events, the
1040 typical energy in a 3×3 tower array is also approximately 400 MeV. These values represent
1041 a negligible performance degradation for these rather clean photon showers even in central
1042 Au+Au events.

1043 Most of these physics measurements require complete coverage over a large range of
1044 rapidity and azimuthal angle ($\Delta\eta \leq 1.1$ and $\Delta\phi = 2\pi$) with good uniformity and minimal
1045 dead area. The calorimeter should be projective (at least approximately) in η . For a
1046 compact detector design there is a trade-off in terms of thickness of the calorimeter and
1047 Molière radius versus the sampling fraction and, therefore, the energy resolution of the
1048 device. Further optimization if these effects will be required as we work towards a final
1049 design.

1050 2.4 Tracking

1051 The requirements on tracking capabilities are tied to three particular elements of the
1052 sPHENIX physics program. The measurement of the upsilon family of quarkonia states,
1053 heavy flavor tagged jets, and fragmentation functions at high and at low z , together set the
1054 performance specification for the sPHENIX Tracker.

1055 To fully utilize the available luminosity, the tracking systems should have large, uniform
1056 acceptance and be capable of fast readout. Measuring fragmentation functions at low z
1057 means looking for possibly wide angle correlations between a trigger jet and a charged
1058 hadron. This places only moderate requirements on the momentum resolution ($\Delta p/p \simeq$
1059 $1\% \cdot p$), but reinforces the requirement of large acceptance.

1060 Fragmentation functions at high z place more stringent requirements on momentum
1061 resolution and can be a design constraint at momenta well above 10 GeV/c. In order to
1062 unfold the full fragmentation function, $f(z)$, the smearing due to momentum uncertainty
1063 should be very small compared to the corresponding smearing due to the calorimetric jet
1064 measurement for a cleanly identified jet. For a 40 GeV jet this condition is satisfied by a
1065 tracking momentum resolution of $\Delta p/p \simeq 0.2\% \cdot p$ or better.

1066 The measurement of the Y family places the most stringent requirement on momentum
1067 resolution below 10 GeV/c. The large mass of the upsilon means that one can focus
1068 primarily on electrons with momenta of $\sim 4 - 10$ GeV/c. The Y(3S) has about 3% higher
1069 mass than the Y(2S) state; to distinguish them clearly one needs invariant mass resolution
1070 of ~ 100 MeV, or $\sim 1\%$. This translates into a momentum resolution for the daughter e^\pm of
1071 $\sim 1.2\%$ in the range 4 – 10 GeV/c.

1072 The Y measurement also generates requirements on the purity and efficiency of electron
1073 identification. The identification needs to be efficient because of the low cross section
1074 for Y production at RHIC, and it needs to have high purity against the charged pion
1075 background to maintain a good signal to background ratio. Generally speaking, this
1076 requires minimizing track ambiguities by optimizing the number of tracking layers, their
1077 spacing, and the segmentation of the strip layers. Translating this need into a detector
1078 requirement can be done only by performing detailed simulations with a specific tracking
1079 configuration, followed by evaluation of the tracking performance.

1080 Tagging heavy-flavor jets introduces the additional tracking requirement of being able
1081 to measure the displaced vertex of a D or B meson decay. The $c\tau$ for D and B decays is
1082 $123 \mu\text{m}$ and $457 \mu\text{m}$, respectively, and the displaced vertex needs to be identified with a
1083 resolution sufficient to distinguish these decays against backgrounds.

1084 2.5 Triggering

1085 The jet energy should be available at the Level-1 trigger as a standard part of the PHENIX
1086 dead-timeless Data Acquisition and Trigger system. This triggering ability is important
1087 as one requires high statistics measurements in proton-proton, proton-nucleus, light
1088 nucleus-light nucleus, and heavy nucleus-heavy nucleus collisions with a wide range of
1089 luminosities. It is important to have combined EMCal and HCal information available so
1090 as to avoid a specific bias on the triggered jet sample.

Chapter 3

TPC

3.1 Physics requirements

Four elements of the sPHENIX physics program drive the performance parameters of sPHENIX tracking. Three of these, the measurement of the Upsilon family of quarkonia states, fragmentation functions at high and at low z , and heavy flavor tagged jets together set the momentum resolution spec for the tracker. The fourth element, the tagging of heavy-flavor jets, requires that the inner tracking system has the ability to measure the displaced vertex of a D or B meson decay. In addition, to fully utilize the available RHIC luminosity the tracking systems should have large, uniform acceptance and be capable of fast readout.

The measurement of the Y family places the most stringent requirement on momentum resolution at lower momentum. The large mass of the Upsilon means that one can primarily focus on electrons with momenta of $\sim 4 - 8 \text{ GeV}/c$. The Y(3S) has about 3% higher mass than the Y(2S) state and to distinguish them clearly one needs invariant mass resolution of $\sim 100 \text{ MeV}$, or $\sim 1\%$. This translates into a momentum resolution for the daughter e^\pm of $\sim 1.2\%$ in the range $4 - 8 \text{ GeV}/c$.

The Y measurement also generates requirements on the purity and efficiency of electron identification. The identification needs to be efficient because of the low cross section for Y production at RHIC, and it needs to have high purity against the charged hadron background to maintain a good signal to background ratio. This requires minimizing track ambiguities. For a continuous tracking device such as a TPC one must optimize the two-track separation through the appropriate choice of granularity of the readout plane, and control of space charge and pile-up effects. Translating this need into a detector requirement can be done only by performing detailed simulations with a specific tracking configuration, followed by evaluation of the tracking performance.

Fragmentation functions at high z also place stringent requirements on momentum resolution and at larger momentum than the Y reconstructions. In order to unfold the full

1119 fragmentation function, $f(z)$, the smearing due to momentum uncertainty should be very
1120 small compared to the corresponding smearing due to the calorimetric jet measurement for
1121 a cleanly identified jet. For a 40 GeV jet this condition is satisfied by a tracking momentum
1122 resolution of $\Delta p/p \simeq 0.2\% \cdot p$ or better.

1123 Measuring fragmentation functions at low z requires looking for possibly wide angle
1124 correlations between a trigger jet and a charged hadron. This places only moderate
1125 requirements on the momentum resolution ($\Delta p/p \simeq 1\% \cdot p$), but reinforces the requirement
1126 of large acceptance.

1127 Tagging heavy-flavor jets introduces the additional tracking requirements. At minimum
1128 this demands the ability to measure the displaced track originating from a D or B meson
1129 decay. The $c\tau$ for D and B decays is 123 μm and 457 μm , respectively, and the displaced
1130 track would need to be identified with a resolution sufficient to distinguish these decays
1131 against backgrounds. Furthermore, heavy-flavor jet identification algorithms such as
1132 DCA-counting methods require multiple large DCA tracks to be found simultaneously
1133 within a jet and will require a large single track efficiency to keep the overall identification
1134 suitably efficient. Other heavy flavor jet identification methods such as those based on
1135 fully reconstructing individual secondary vertices can place additional demands on the
1136 individual track position resolution and impact the inner pixel segmentation.

1137 3.2 General Remarks about Tracking

1138 3.2.1 Magnetic Field

1139 The field produced by the Babar magnet is shown in Figure 3.1. The sPHENIX application
1140 of this coil is rather close to the original BaBar design with an EMCAL inside the coil and
1141 tracking extending to ~ 78 cm. A standard solenoid with length equal to diameter has
1142 significant radial magnetic field components at each end and thereby does not produce an
1143 idealized field shape. A return yoke with a small opening (*e.g.* STAR) will compensate for
1144 this shortcoming while severely limiting possibilities for upgrades in the forward direction.
1145 The BaBar magnet attacks this classic problem by using an increased winding density
1146 at each end, thereby sacrificing uniformity of the field at large radius, for an extended
1147 “sweet spot” of field in the middle. Thus the region in which sPHENIX plans to install
1148 tracking features a close-to-ideal magnetic field shape. It should further be noted that the
1149 calculations of Figure 3.1 are done with a return yoke that allows for future upgrades in
1150 the forward direction.

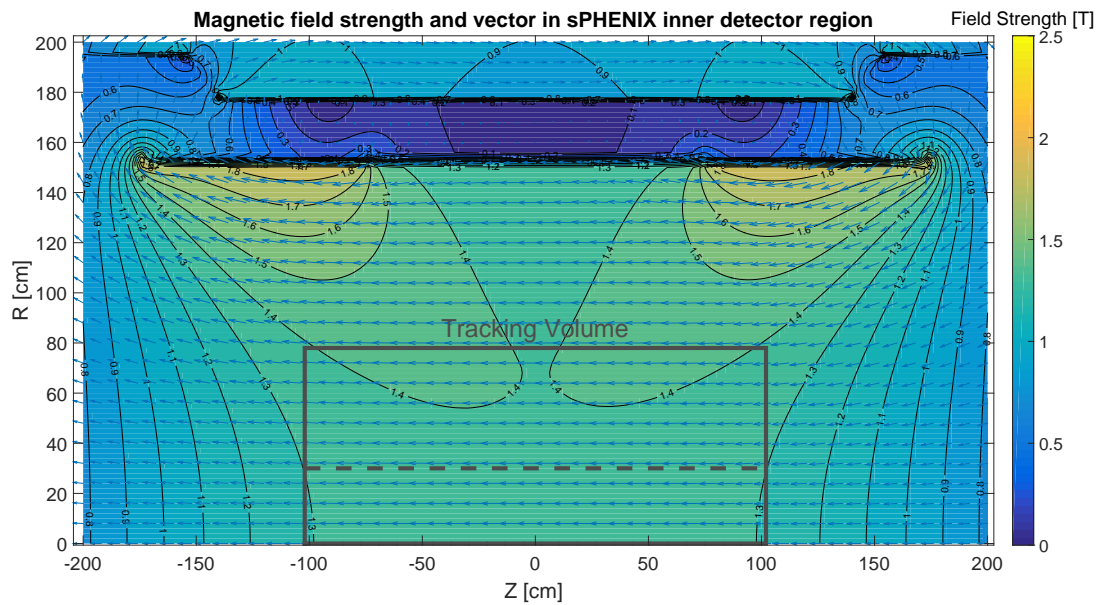


Figure 3.1: The BaBar magnet field superimposed with the dimensions of the tracker volume. This calculation includes the effect of the field return as envisioned for future upgrades (forward arm spectrometer). The dashed line indicates the inner radius of the TPC tracking volume.

1151 3.3 TPC Design Overview

1152 The TPC design follows the classical cylindrical double-sided TPC layout used in sev-
 1153 eral other experiments, with a central membrane electrode located at the middle of the
 1154 interaction region dividing the TPC into two mirror-symmetric volumes, as shown in
 1155 fig. 3.2.

1156 In each such volume the readout plane is located on the endcap inner surface, facing the
 1157 gas volume. The electric field, transporting primary ionization to the readout plane is
 1158 formed by the membrane electrode set to the highest voltage bias on one side and by the
 1159 the readout plane at ground potential on the other. The electrical drift field is constrained
 1160 by the field cage along the inner and the outer cylindrical surfaces of the TPC.

1161 The two mirror-symmetric parts of the TPC form a common gas volume filled with the gas
 1162 mixture, which transports primary ionization to the readout plane on each TPC endcap
 1163 surface. The same gas that transports primary ionization also serves as the medium for the
 1164 amplification elements located in front of the readout planes. These amplification elements
 1165 are built based on several layers of micropattern gaseous detectors.

1166 Other TPC subsystems directly related to the main volume are the channel readout system;
 1167 high voltage distribution systems for the drift field and for the amplification elements;
 1168 gas circulation, control and purification system; TPC calibration systems. Operation and

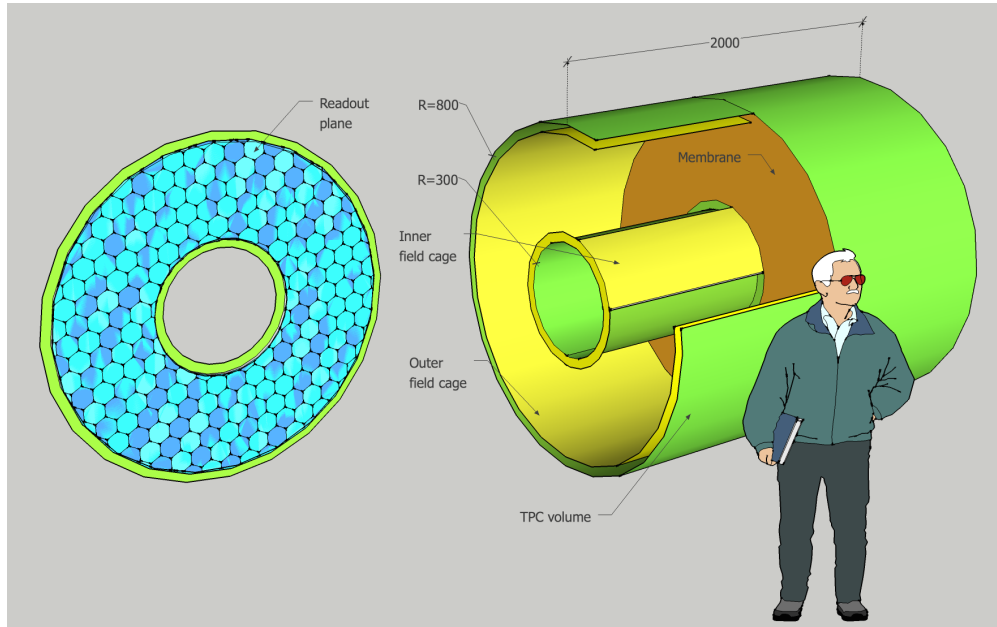


Figure 3.2: Schematic layout of TPC main elements.

Size	end/TPC	sector/end	cards/sector	channels/card	channels/TPC
R1	2	12	5	256	30720
R2	2	12	8	256	49152
R3	2	12	12	256	73728
TOTAL					153600

Table 3.1: Table summarizing TPC module and channel counts.

1169 readout of different service subsystems requires a TPC slow control system.

1170 Each end of the TPC will be divided into 12 azimuthal segments and three radial segments.
 1171 This size of GEM chamber is well established in multiple experiments and should lead to
 1172 stable and reliable operation. Charge from individual pads will be collected by SAMPA
 1173 chips (developed by ALICE) on the so-called FEE cards. Each FEE will house 8 SAMPA
 1174 chips and thereby 256 channels. The R1, R2, and R3 modules support 5, 8, and 12 FEE cards
 1175 respectively. Thus, the total number of channels for the TPC is 153,600. These channel
 1176 counts are summarized in Table 3.1

1177

1178 Data flowing from each TPC sector (25 cards) will be collected into a Data Aggregation
 1179 Module (DAM) wherein clustering algorithms will be performed prior to the data entering
 1180 the main sPHENIX DAQ stream.

3.4 TPC Simulations

The TPC simulations we have performed target a realistic representation of the cluster size and two-hit resolution based on design parameters *which are consistent with those described in the previous section*.

At the very high luminosities expected during sPHENIX operation, the charge collection time in the TPC causes charge from multiple different collisions to be drifting in the TPC at any given time. The time window for the configuration used for these simulations is $\pm 13.2 \mu\text{s}$. At a Au+Au collision rate of 200 kHz the number of "pileup" events is typically 3 to 8, and they add very substantially to the occupancy in the TPC. In p+p collisions it is far higher, but the multiplicity per event is much lower. The simulation results presented here are for Au+Au, and to simulate the detector performance in high luminosity events we use central (0-4 fm impact parameter) Au+Au collisions as the triggered event, and a 200 kHz minimum bias collision rate to add pileup event charge.

GEANT4 is used to record energy deposits in a cylindrical volume of gas. In the results shown below, the volume was filled with a Ne:CF₄ mixture (90:10) operated with a drift voltage of 400 V/m and a drift speed of 8 cm/ μs . The energy deposits are recorded in discrete radial regions of the cylindrical volume. For each region, a Poissonian random number of ionization electrons are produced along the track trajectory according to measured values of the average ionization per energy deposit for the simulated gas. Because highly angled tracks deposit energy along an extended path in z within each radial layer, they have an important effect on the occupancy in the TPC. Therefore the primary ionization is broken up into segments in z that are drifted independently. Each segment of the primary ionization is then randomly diffused in 3 dimensions. The average diffusion is then added in quadrature with a constant diffusion to emulate diffusion during the amplification stage of readout.

The $r - \phi$ readout is simulated using a plane of rectangular pads. The rectangular pads have twice the density in $r\phi$ of the chevron pads that are planned, to achieve adequate charge division between pads. The charge distribution at the pad plane from each drifted z segment is divided between pads by integrating it between the pad ϕ limits. For the z direction, the analogue timing response of the SAMPA chip is simulated with different rise and fall times that approximate the measured response of the chip. In these simulations a SAMPA peaking time of 40 ns is assumed. The resulting time distribution is broken up into ADC time bins, and the bins are assigned a z location based on the drift velocity. The charge is digitized into a 12-bit ADC for each pad, directly in proportion to the number of diffused electrons reaching the pad (gain fluctuations are not currently simulated).

After the pad ADC has been recorded in each time bin, clustering is performed to group (pad,time-bin) pairs into 3-dimensional detector hits to be passed to the track-finding algorithm. The current cluster finding algorithm is designed to operate in a high occupancy environment and can separate overlapping clusters as long as the cluster centroids are separated approximately 1.5 sigma of the cluster width. This performance is sufficient to

1221 guarantee close to 100% cluster reconstruction efficiency in high pile-up Au+Au events up
 1222 to a channel occupancy of $\approx 40\%$.

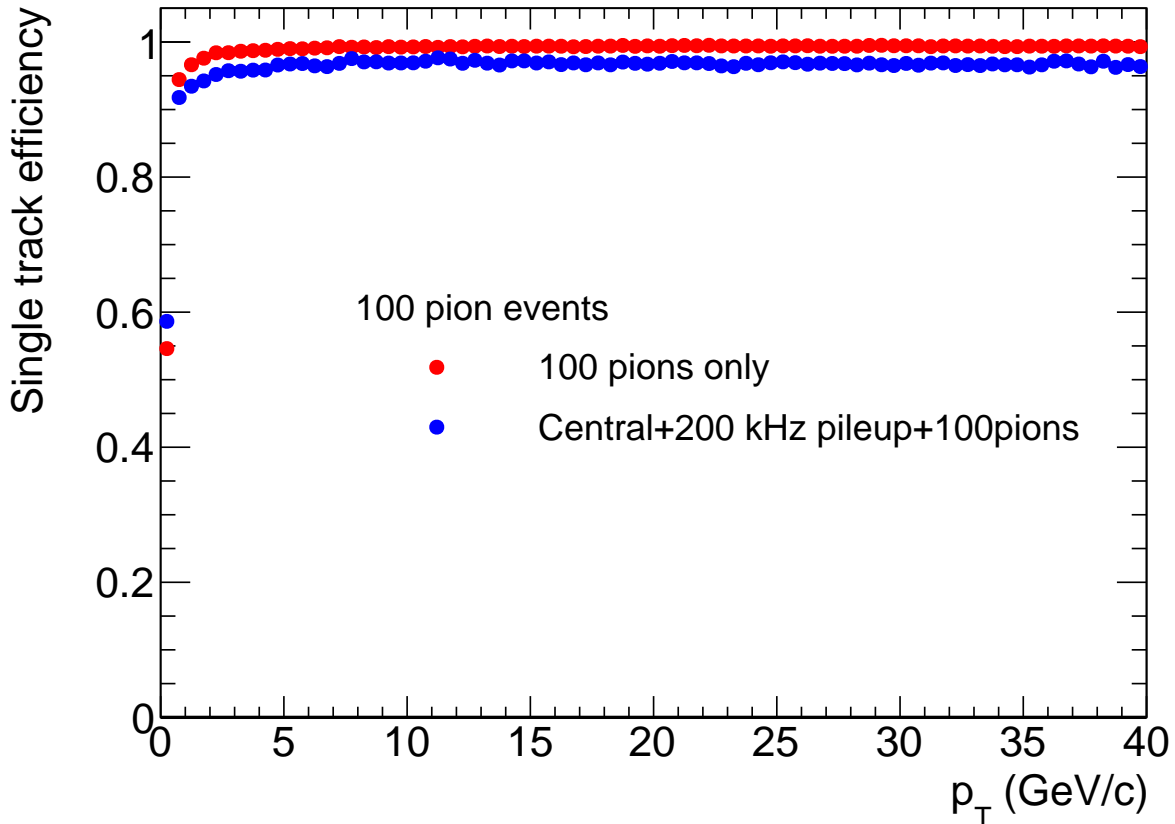


Figure 3.3: comparison of the track reconstruction efficiency for the simulated TPC for pions between 0 and 40 GeV/c in standalone 100 pion events, and embedded in central (0-4 fm) Au+Au collisions with event pileup from 200 kHz Au+Au collision rate. Even in the very high occupancy environment the tracking efficiency remains above 95%.

1223 In addition to the TPC, the silicon inner layers are included in the tracking setup. The
 1224 clustering is performed on the silicon hits by finding groups of contiguous pixels or strips
 1225 within a sensor.

1226 From the clusters charged particle trajectories are reconstructed by a seeded kalman filter
 1227 based algorithm comprised of the following steps:

- 1228 • A 5-dimensional Hough transform is employed to locate clusters from helical hit
 1229 patterns in the TPC arising from tracks bending through the solenoid field to seed
 1230 the track reconstruction.
- 1231 • Track seeds are propagated outside-in from the TPC. to the optional inner silicon
 1232 based detectors by a Kalman filter [124] based pattern recognition algorithm.

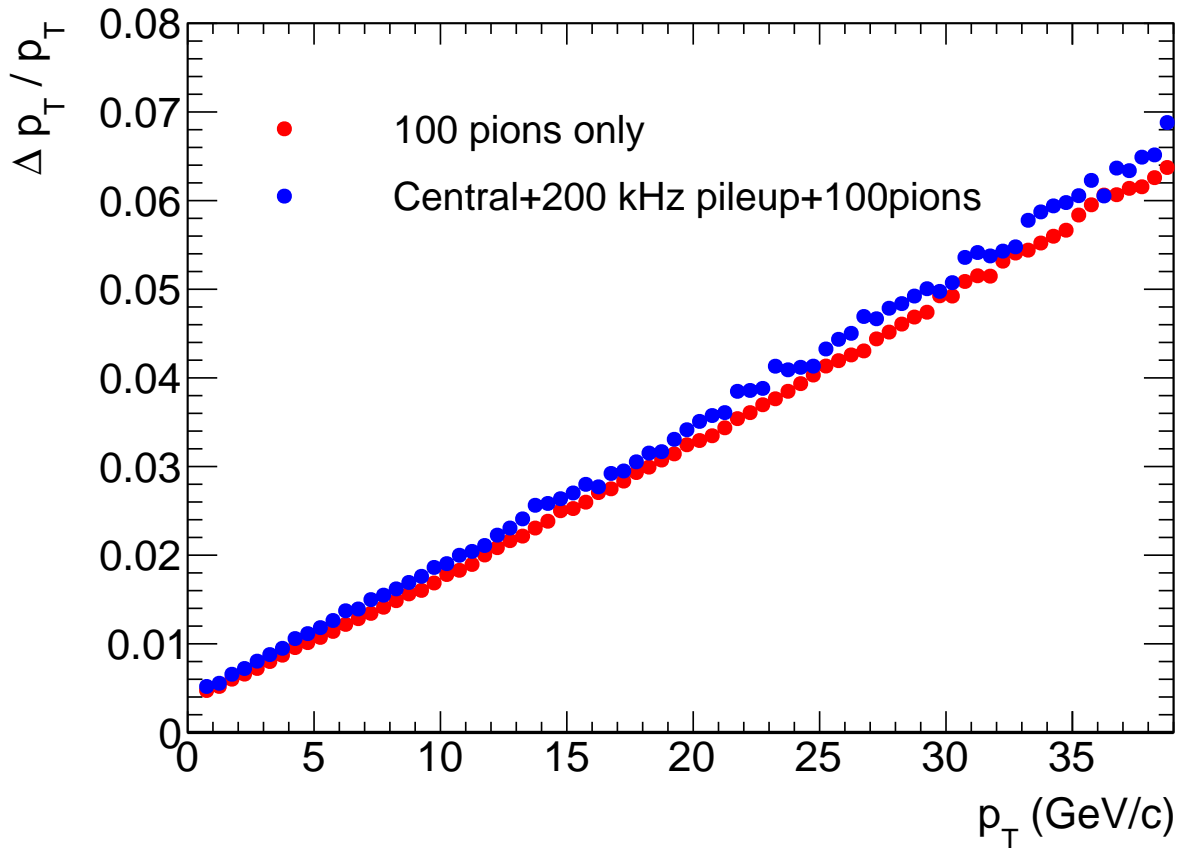


Figure 3.4: comparison of the momentum resolution of the simulated TPC for pions between 0 and 40 GeV/c in standalone 100 pion events, and embedded in central (0-4 fm) Au+Au collisions with event pileup from 200 kHz Au+Au collision rate.

- 1233 • Iteration of the first two steps using looser seeding criteria in subsequent iterations.
- 1234 • Clusters belonging to the same track are fit using a Kalman-filter-based generic
- 1235 track-fitting toolkit [125], to extract track parameters including displacement at the
- 1236 vertex and the momentum vector at vertex.
- 1237 • All tracks are fed into a generic tracking fitting toolkit, RAVE [126], to determine the
- 1238 locations of the primary and secondary vertices's.

1239 The performance of the detector in simulations is illustrated here by several figures. Fig-
 1240 ure 3.3 provides a comparison of track reconstruction efficiency for simulated events
 1241 consisting of a central (0-4 fm impact parameter) HIJING collision, plus pileup from mini-
 1242 mum bias HIJING collisions assuming a collision rate of 200 kHz. The track reconstruction
 1243 efficiency is evaluated for 100 pions ($p_T = 0-40$ GeV/c) embedded in the central event.
 1244 Reconstructed tracks are required to have a reconstructed p_T within 4σ of the truth p_T .
 1245 The track efficiency is compared with that for low occupancy events, containing only

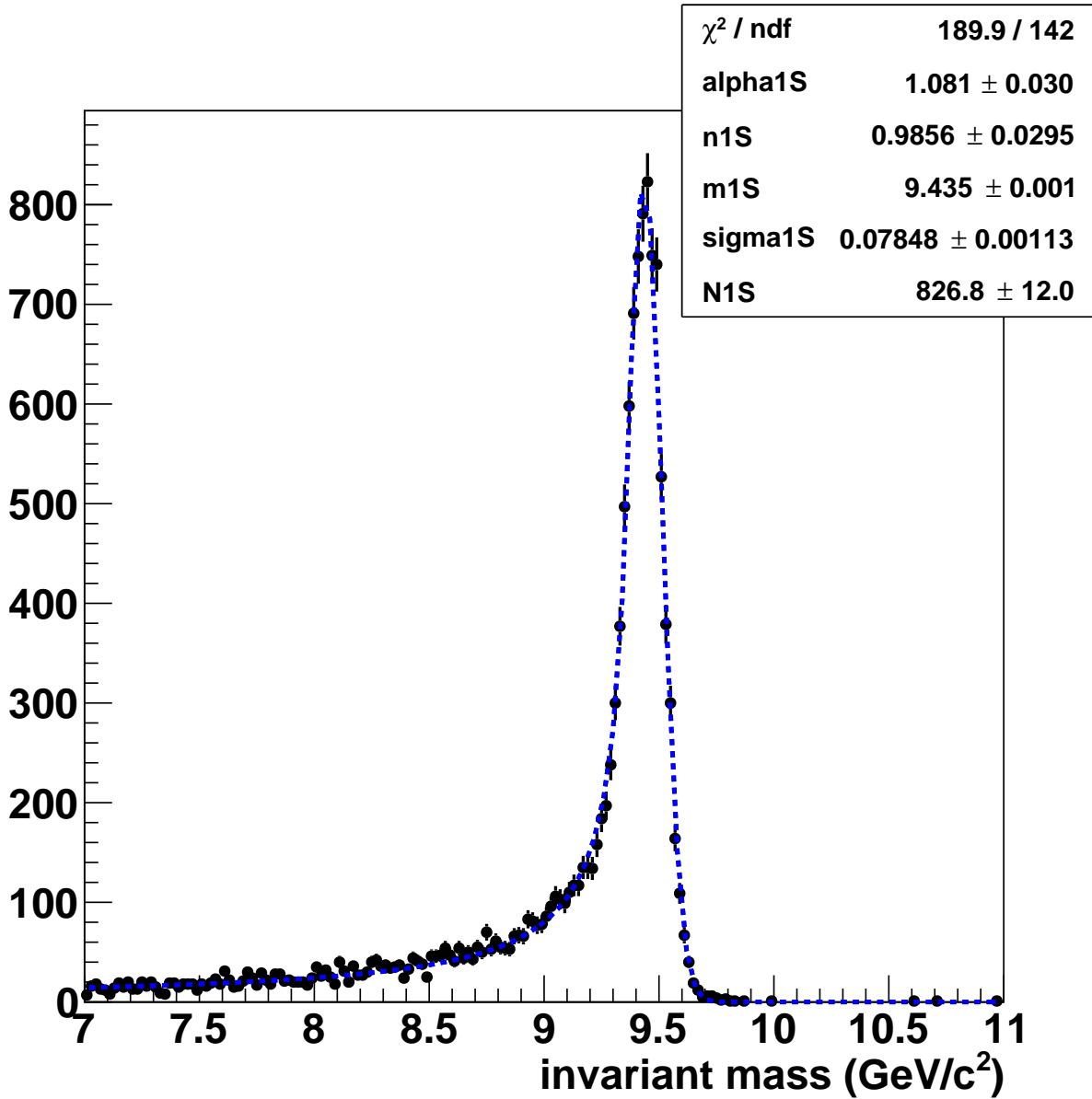


Figure 3.5: Upsilon 1S mass spectrum and resolution for the simulated TPC in low multiplicity events (100 pions). The mass resolution is about 80 MeV.

1246 the 100 pions. Figure 3.4 compares p_T resolution at low and high occupancies obtained
 1247 from the same simulations. Figure 3.5 shows the mass spectrum for reconstructed $Y(1S)$
 1248 decays, where the Upsilon's were embedded in low occupancy 100 pion events. The mass
 1249 resolution of about 80 MeV is well within our acceptable range.

1250 We have also tested the effect of high TPC occupancy on the performance of the tracking
 1251 system if the proposed MVTX detector is added to sPHENIX. The goal is to understand
 1252 whether the TPC as a tracker will work well in high occupancy events with a displaced

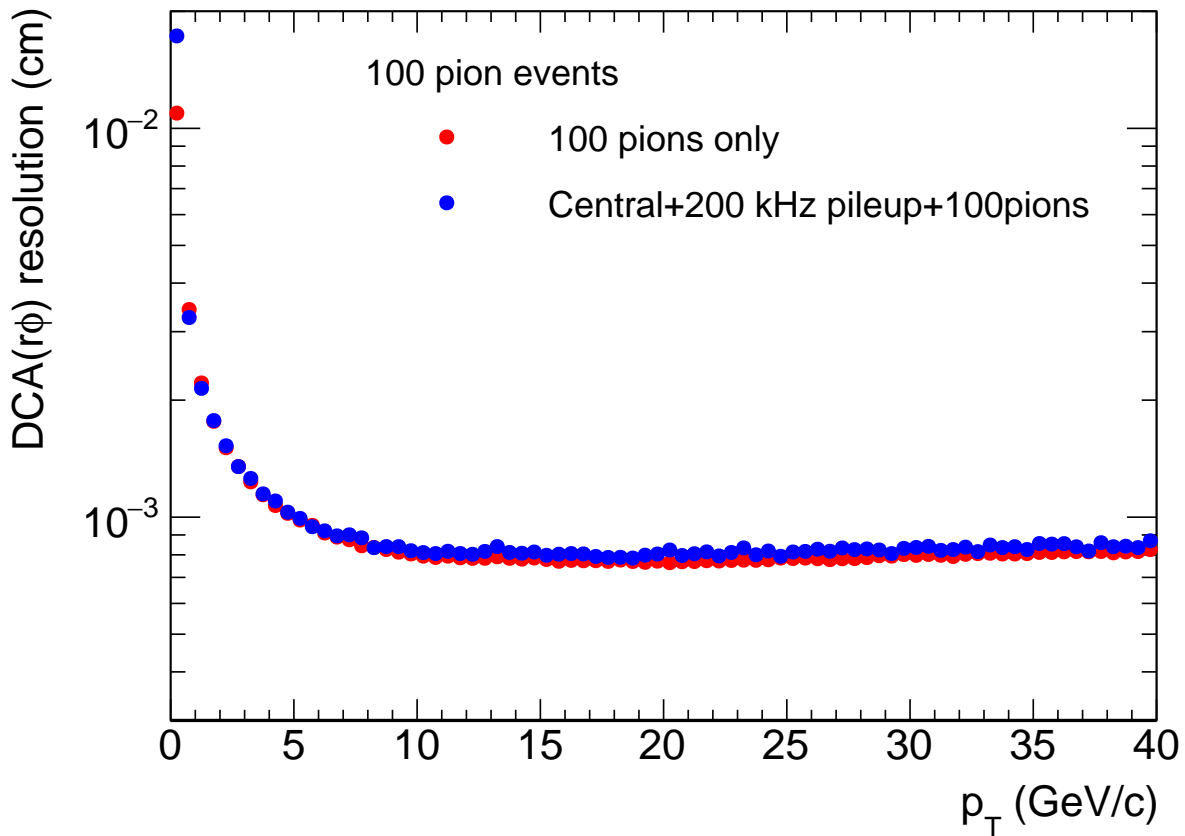


Figure 3.6: comparison of the DCA resolution in the $r\phi$ plane for a tracker consisting of the TPC and the proposed MVTX pixel barrel and the INTT silicon strip detectors. The comparison is for pions between 0 and 40 GeV/c in standalone 100 pion events, and embedded in central (0-4 fm) Au+Au collisions with event pileup from 200 kHz Au+Au collision rate.

1253 vertex detector. The results for the $r\phi$ track vertex resolution are shown in Figure 3.6.
 1254 Results for the track vertex resolution in the z direction are shown in Figure 3.7. The track
 1255 vertex resolution shows little effect from the high occupancy except for the DCA resolution
 1256 in the z direction at high momentum, where it is nevertheless still very good.

1257 3.5 TPC Design Details

1258 3.5.1 Design Drivers

1259 The TPC system must supply sPHENIX with excellent pattern recognition and excellent
 1260 momentum resolution in order to meet all the physics goals. As detailed below, this is
 1261 a challenging task, but not insurmountably so. Figure 3.8 shows in 3D model form the

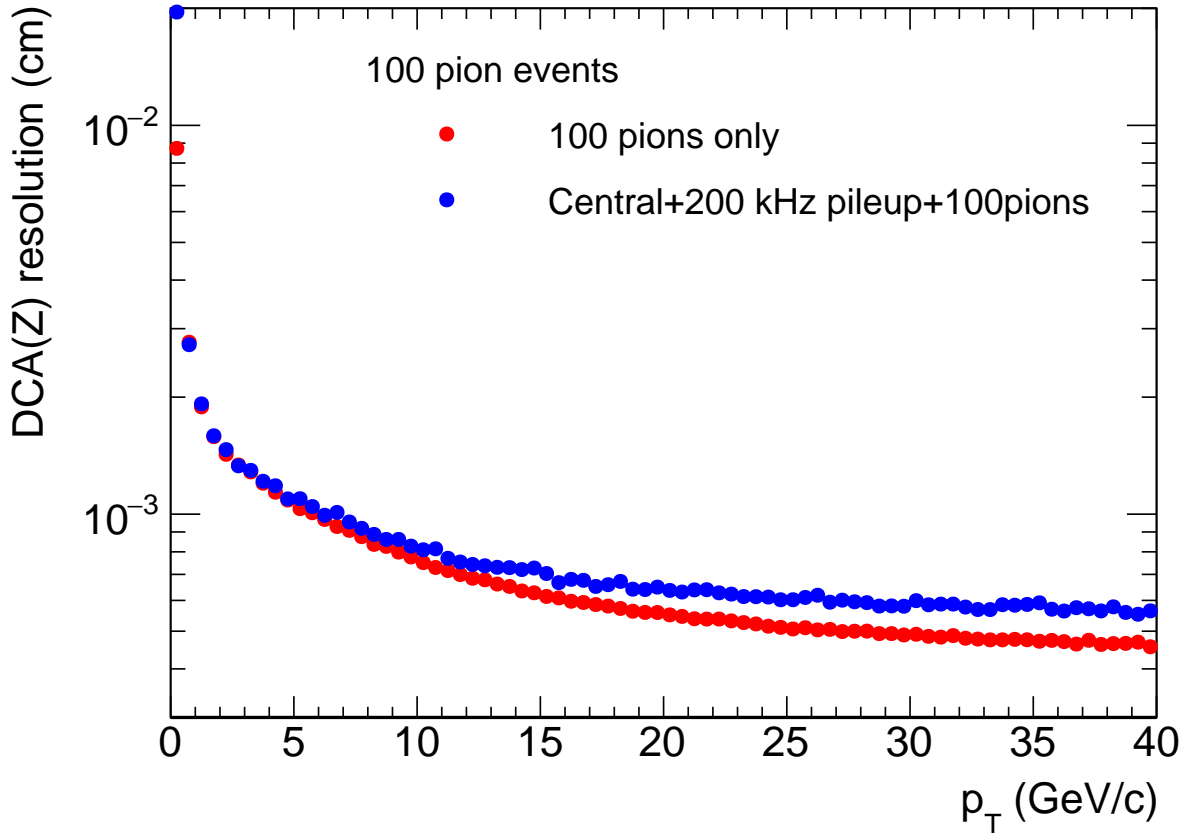


Figure 3.7: comparison of the DCA resolution in the z direction for a tracker consisting of the TPC and the proposed MVTX pixel barrel and the INTT silicon strip detectors. The comparison is for pions between 0 and 40 GeV/c in standalone 100 pion events, and embedded in central (0-4 fm) Au+Au collisions with event pileup from 200 kHz Au+Au collision rate.

1262 location of the TPC. Because the TPC is sandwiched between the EMCAL on the outside
 1263 radius and the silicon detectors on the inside, the radial extent of the TPC is limited to
 1264 $20\text{ cm} \rightarrow 78\text{ cm}$.

1265 The radial extent along with the polar angle direction ($\eta < \pm 1.1\text{ units}$) defines the TPC
 1266 envelope as indicated in Figure 3.9, compliant with the sPHENIX envelope control speci-
 1267 fications. As compared to prior TPC detectors used in heavy ion physics (STAR, ALICE) the
 1268 sPHENIX will be rather small and is thereby referred to as a "compact" TPC. while aspects
 1269 of being compact simplify the detector construction (*e.g.* not requiring a scaffold to reach
 1270 the detector top), others present challenges. In particular, a short gas length adversely
 1271 affects the $\frac{dE}{dx}$ resolution and yields a small lever arm for momentum measurements.

1272 Figures 3.3, 3.4 and 3.5 show simulations of the performance of the TPC and indicate that,
 1273 as simulated, we meet or exceed all specifications. This performance is despite the short
 1274 lever arm, but requires that the end-of-day resolution of the TPC should be better than

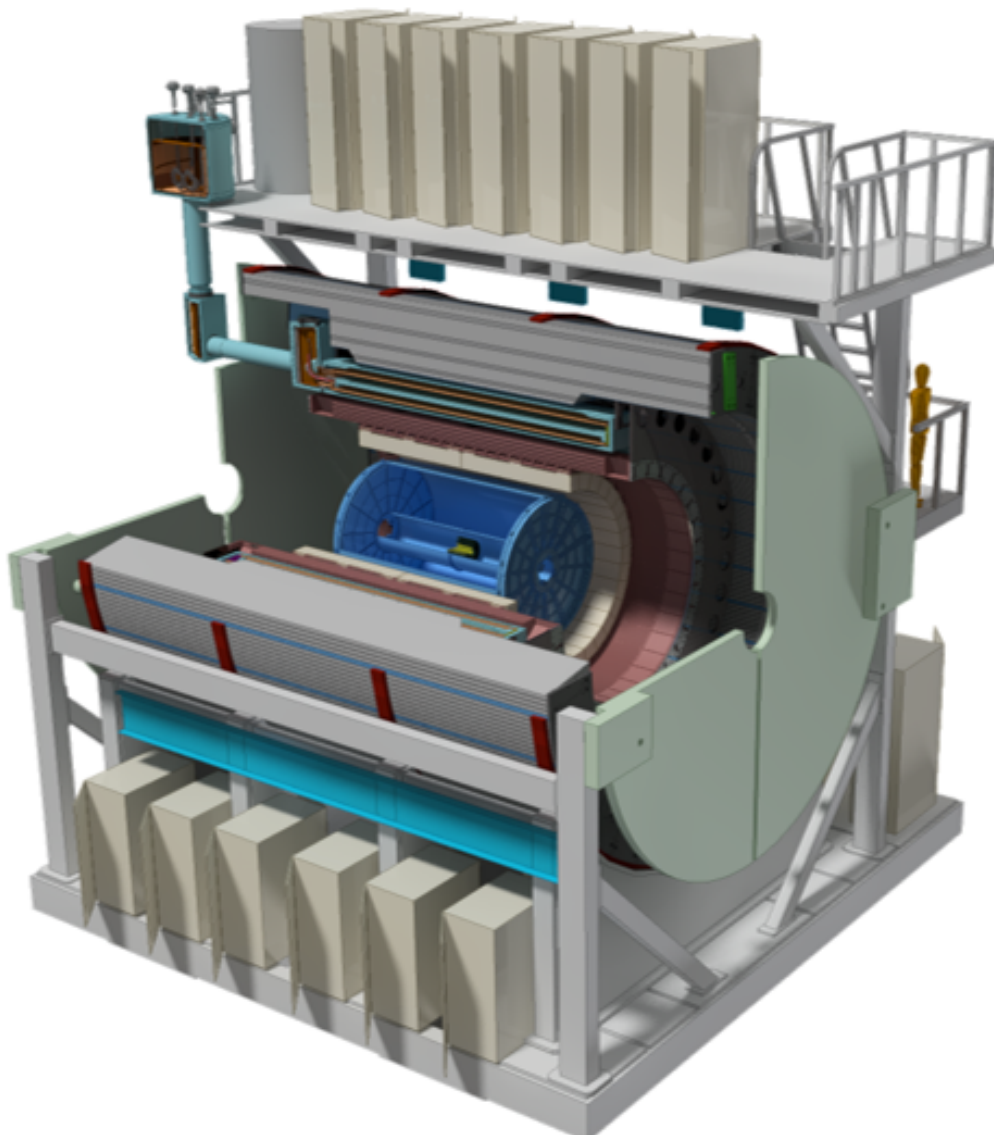


Figure 3.8: Schematic layout of the sPHENIX experiment. The TPC is presented as the central blue cylinder.

1275 $200 \mu\text{m}$ in the $r - \phi$ direction. While not significantly beyond the bounds of what has been
1276 previously achieved, we must maintain this performance in the face of high collision rates
1277 and possibly high space charge effects.

1278 3.5.2 Limiting Space Charge Effects

1279 Figure 3.10 summarizes the geometrical overview of the TPC. Tracking is accomplished by
1280 digitizing the after-avalanche electron clouds that impinge upon the amplification stage

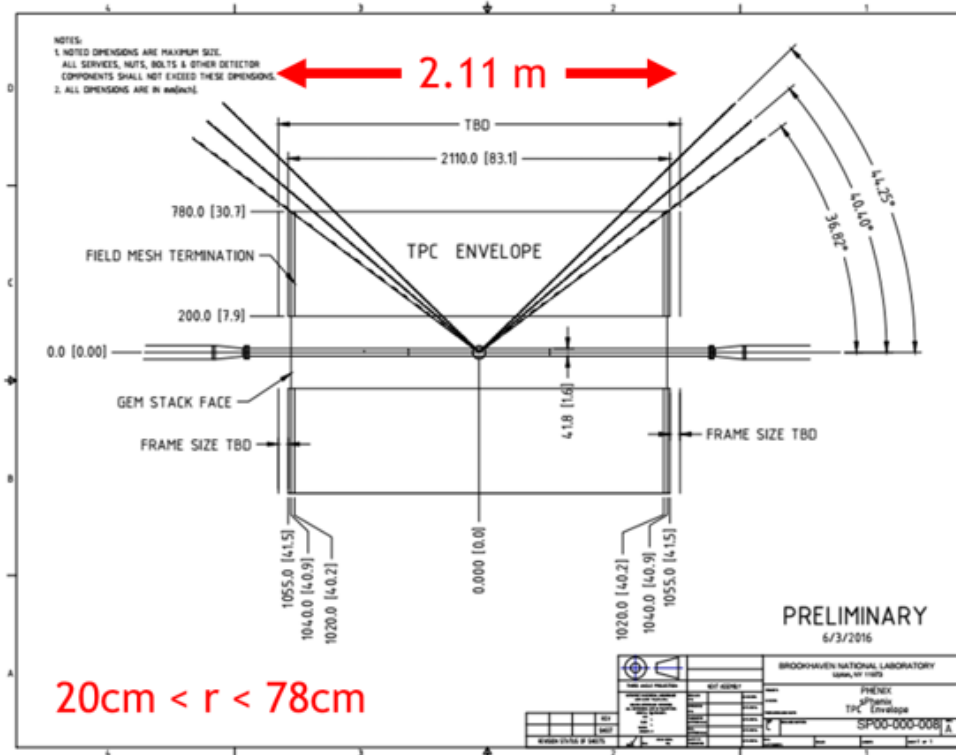


Figure 3.9: The outer limit of the TPC radial space (20 cm to 78 cm) is bounded by the INTT and EMCAL detectors and allows for an as-yet-unspecified future 10 cm PID upgrade device. The length is defined by the $\eta < \pm 1.1$ sPHENIX aperture.

1281 after having drifted away from the central membrane. Because of the enormous positive
 1282 charge left in the gas volume following avalanche (here expected to be 2000X the primary
 1283 charge), any TPC design must specifically deal with the positive ions to eliminate or at
 1284 least minimize their impact on the TPC drift field. Traditionally this issues is handled by a
 1285 so-called "gating grid" whose bias can be set to either allow the flow and electrons (and
 1286 ions) or deny this flow. A traditional TPC therefore operates by opening the gating grid
 1287 upon receipt of a trigger, holding it open for a time sufficient to collect electrons with the
 1288 largest drift time (*i.e.* those originating near the central membrane), and then closing it for
 1289 a time period sufficient to block all avalanche-induced positive ions from entering the main
 1290 TPC gas volume. Because of the "off-time" for responding to positive ions, traditional
 1291 TPC's are considered somewhat slow devices.

1292 A new concept in limiting Ion Back Flow (IBF, or avalanched-induced positive ions) has
 1293 been pioneered by the ALICE collaboration and is expected to be brought online by
 1294 them prior to first data-taking with sPHENIX. With the advent of MPGD (Micro-Pattern
 1295 Gas Detector) technology a breakthrough is possible in IBF handling. As indicated in
 1296 Figure 3.11, the avalanche stage of a gas detector can be made using a stack of Gas-Electron
 1297 Multiplier (GEM) foils. Each foil contributes a small fraction of the total gain, which
 1298 is achieved only when avalanching through the full stack. However, through clever

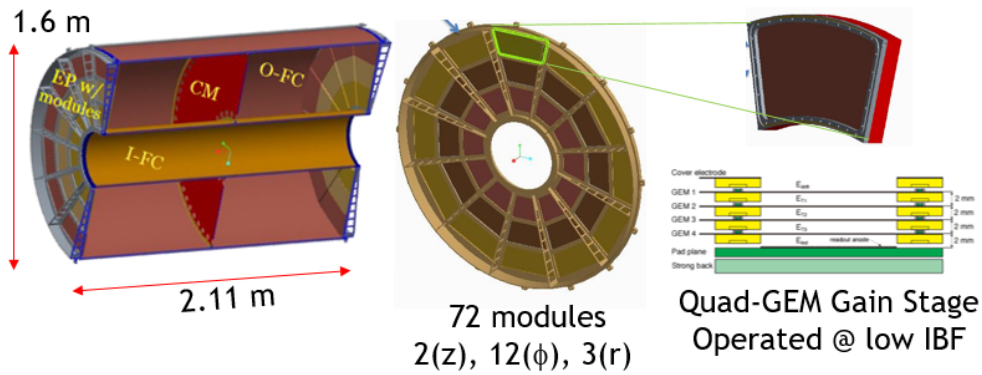


Figure 3.10: Ionization drifts away from the central membrane of the TPC and impinges upon the avalanche chambers located at each end. The end plates are segmented into 12 azimuthal and 3 radial segments, making a total of 72 modules in total. Each module is a quad-GEMstack operated in a low IBF configuration.

1299 manipulation of the electric fields between GEM foils ("transfer" fields) one can generate a
 1300 condition whereby only a very small fraction of the positive ions are able to drift back into
 1301 the main detector volume. In this way, the detector can be kept fully live at all times.

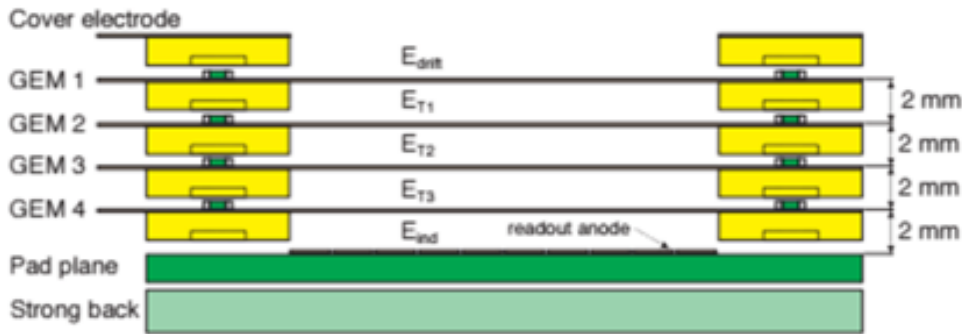


Figure 3.11: This figure shows the final design of the ALICE avalanche modules using a quad-GEMstack. We expect to operate similar chambers or perhaps a hybrid μ MEGA arrangement.

1302 Unfortunately, the MPGD-based avalanche scheme is not 100% effective at blocking posi-
 1303 tive ions from entering the gas volume. Figure 3.12 illustrates the problem. charge from the
 1304 primary ionization (indicated by blue lines) is released into the gas volume. The positive
 1305 ions will drift toward the central membrane with some having short paths and others
 1306 longer. Conversely, all IBF positive ions begin at the avalanche chambers and therefore
 1307 drift through the entire TPC gas volume. Because of the large disparity in drift velocity
 1308 between the fast electrons and slow ions, the TPC effectively "stores" a past time history of
 1309 ionization in the form of pancakes of charge that slowly drift toward the central membrane.
 1310 Even in the case of upgraded ALICE working optimally, when operating at a gain of 2000
 1311 and an IBF fraction of 1%, the IBF positive charge will exceed the primary by a factor of

1312 20X. Thus, all possible precautions and design considerations must be applied to the IBF
 1313 issue.

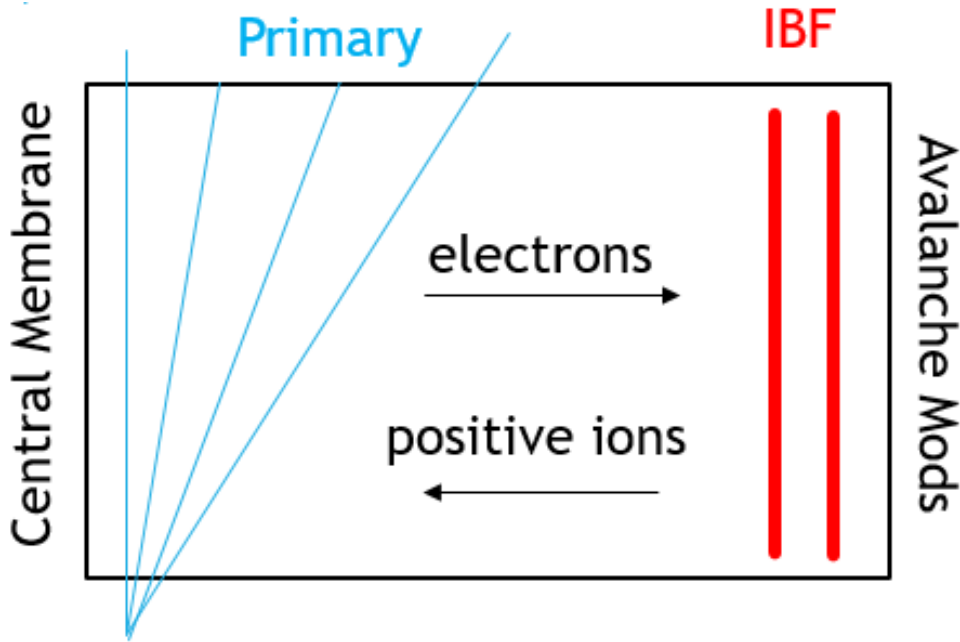


Figure 3.12: All ionization produces both signal electrons and positive ions. Primary ionization sets the lower limit to TPC space charge. However, even small percentage back flows from the avalanche stage (here represented by the red “pancakes” of drifting charge) contribute significantly to the overall space charge and will likely be the dominant source.

1314 The analytical expression for space charge density in radius and z, developed by STAR,
 1315 has the form:

$$\rho(r, z) \propto \frac{I \cdot M \cdot R}{v_{ion}} \left[\frac{1 - \frac{z}{Z_{tot}} + e}{r^2} \right] \quad (3.1)$$

1316 where $1 - \frac{z}{Z_{tot}}$ accounts for primary ionization and e accounts for IBF. Figure 3.13 shows
 1317 the relative contributions of the two forms of space charge. The left panel shows the result
 1318 from only primary ionization. The right panel shows the effect of adding only 1% IBF at a
 1319 gain of 2000X. The space charge comes overwhelmingly from the non-absorbed fraction of
 1320 avalanche charge. For this reason, we put our initial TPC design efforts into minimizing
 1321 IBF. The following sections summarize each of the design steps we have used to combat
 1322 and minimize IBF.

1323 Ion Drift Velocity

1324 In general, the ion drift velocity is given by the expression:

$$v_{ion}^{\vec{}} = K\vec{E} \quad (3.2)$$

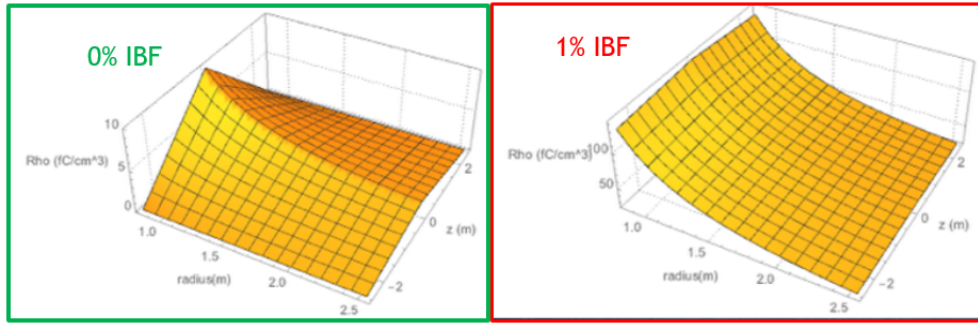


Figure 3.13: The left panel shows the anticipated space charge in the TPC resulting from only primary charges with a minimum bias collision rate of 100 kHz. The right panel shows the result if one assumes 1% IBF from the avalanche stage operating with a gain of 2000.

1325 where K is the ion mobility and \vec{E} is the electric field. Although the ion mobility is,
 1326 in principle, a function of the applied field, for all practical values of drift field, the ion
 1327 mobility is a constant. Therefore, the initial attack on space charge involves maximizing the
 1328 ion drift velocity by maximizing both the mobility and electric field strength. Figure 3.14
 1329 shows the ion mobility in pure gases as a function of mass. Clearly the fastest gases have
 1330 the lowest mass, driving us toward Ne as the principle noble gas component for sPHENIX.
 1331 The right hand plot in the same Figure shows the accuracy by which one can predict ion
 1332 drift velocity in gas mixtures using Blanc's Law:

$$\frac{1}{K_{tot}} = \frac{f_1}{K_1} + \frac{f_2}{K_2} + \frac{f_3}{K_3} + \dots \quad (3.3)$$

1333 Blanc's law is analogous to the formula for resistors in parallel. We can apply law to
 1334 compare ion drift velocities across experiments as shown in the table below:

Gas	$K (\frac{cm^2}{Volt \cdot sec})$	$v_D (E = 130 \frac{V}{cm})$	$v_D (E = 400 \frac{V}{cm})$
Ar	1.51	196	604
Ar-CH ₄ 90:10	1.56	203(STAR)	624
Ar-CO ₂ 90:10	1.45	189	582
Ne	4.2	546	1680
Ne-CH ₄ 90:10	3.87	503	1547
Ne-CO ₂ 90:10	3.27	425	1307(ALICE)
He	10.2	1326	4080
He-CH ₄ 90:10	7.55	981	3019
He-CO ₂ 90:10	5.56	722	2222
T2K	1.46	190(ILC)	584

1335 It is clear that the space charge issues in STAR and ALICE are of an entirely different
 1336 nature. in STAR, the ion mobility is low enough that the positive argon ions from the
 1337

1338 primary charge generate track distortions. In ALICE, both the noble gas choice (Ne instead
 1339 of Ar) and the high drift field, dramatically reduce the distortions due to the space charge
 1340 from the primary ionization. After upgrade, ALICE will struggle primarily with the ion
 1341 back flow from the amplification stage.

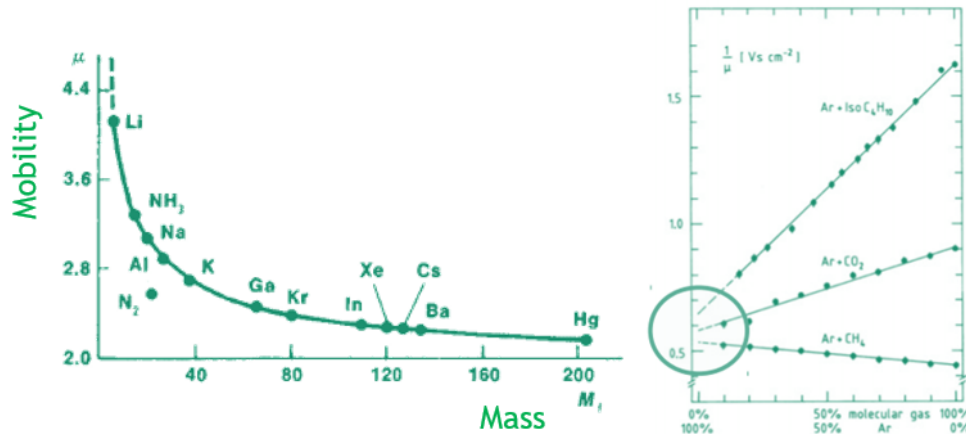


Figure 3.14: The left panel shows the mass dependence of positive ion mobility, clearly favoring light gases for high mobility and thereby low space charge. The right panel shows the effectiveness of Blanc’s Law for calculating ion mobility in gas mixtures.

1342 GEMstack Operating Point

1343 ALICE has done extensive studies of the characteristics of IBF using a quad GEMstack.
 1344 Their results are summarized in Figure 3.15. The vertical axis is an energy resolution
 1345 measure based upon ⁵⁵Fe measurements. The 5.6 keV gamma from ⁵⁵Fe would be expected
 1346 to have a fractional width $\frac{\sigma}{mean}$ of roughly 8%. However, one sees that in the limits of lowest
 1347 ion back flow, the resolution worsens significantly. Understanding this effect is simple. In
 1348 the ALICE configuration, any positive ions created by the top GEM will be coupled directly
 1349 in to the drift volume. Therefore, lowering the gain in the first GEM is the most effective
 1350 way to lower the IBF. However, fractional gain fluctuations are maximized at low gain,
 1351 thereby spoiling energy resolution. Despite the many different running configurations
 1352 represented in this plot, all fall basically atop the energy resolution vs IBF compromise
 1353 curve.

1354 For ALICE this is a critical consideration since their TPC’s main function is the measure-
 1355 ment of specific ionization, $\frac{dE}{dx}$. For sPHENIX the case is significantly simpler since our
 1356 physics goals do not require a precision $\frac{dE}{dx}$ measurement. We therefore choose to operate
 1357 our GEMstacks at the lowest point measured by ALICE, 0.3% IBF.

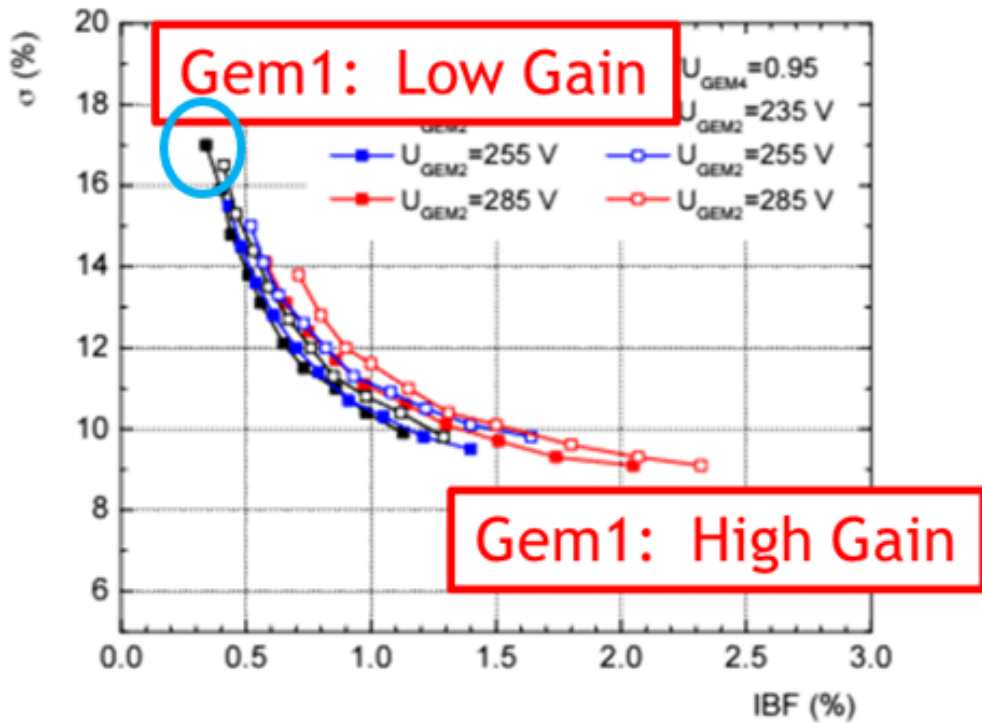


Figure 3.15: Results from R&D for the ALICE experiment indicate a “universal” trend. Configurations with the lowest IBF suffer from poor energy resolution. The principle reason for this trend is the contribution of the first GEM to the overall gain.

1358 Field Cage Entrance Window

1359 The finger-physics explanation of the effects of space charge in the TPC volume is simple:
 1360 Positive ions attract electrons and thereby distort their trajectories toward the “middle”
 1361 radius of the TPC. A more careful consideration reminds us that if space were filled with
 1362 a uniform charge density, that there would be no net force on the electron. Therefore we
 1363 are lead to the simple picture that space charge distortions maximize at both the inner
 1364 and outer field cages where the space charge density has a discontinuity. Indeed, full
 1365 calculations of space charge distortions for sPHENIX are shown in Figure 3.16. The blue
 1366 curve indicates a calculation for a TPC spanning the radial range 30-80 cm. The maximum
 1367 distortion is 2 cm found exactly at the inner radius. Notice, however, the red curve for a
 1368 TPC spanning 20-80 cm. At the lowest radius, the distortion is indeed severe (3 cm, 50%
 1369 worse than before), however the distortion of the track at 30 cm is drastically reduced to
 1370 only 3 mm!. Thus, by modifying our TPC design from the originally-proposed version
 1371 (30-80 cm) to a new version that spans (20-80 cm), can can easily and dramatically reduce
 1372 space charge to under 1 cm.

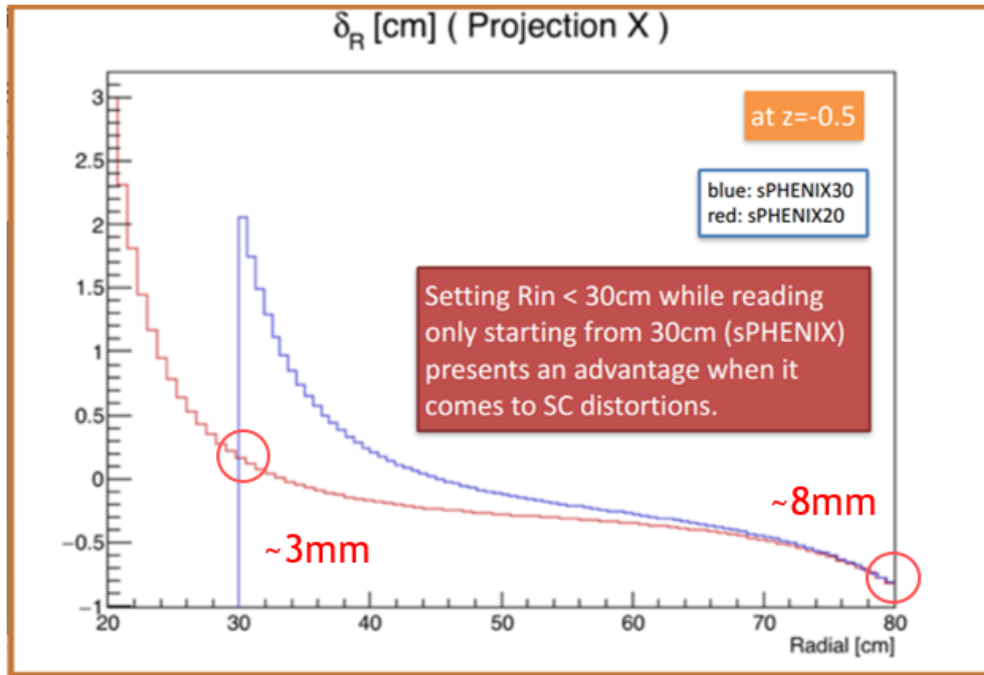


Figure 3.16: Electron paths are primarily influenced by the charge density closest to the electron. Necessarily, the greatest deflections from the ideal trajectory are found closest to the field cage. By moving the field cage entrance window from 30 cm to 20 cm, we are able to drastically reduce the deflection due to IBF to reasonably manageable levels.

1373 Passive Mesh for IBF Reduction

1374 Although our current proposal for IBF reduction (Ne gas; High E-field; Low IBF Op
 1375 Point; Moved Inner Field Cage), makes our distortions manage-ably small, there is still
 1376 significantly more that can be done to reduce IBF. Such a reduction would allow us to, for
 1377 example, change the operation point of the GEMstack to regain much of the lost resolution.
 1378 To understand the technique we must first gain insight on how IBF reduction in an MPGD
 1379 detector works.

1380 Figure 3.17 shows the electric field lines of a GEM under operation in the left panel. Notice
 1381 that the density of field lines below the GEM is greater than above, indicating the the
 1382 transfer field exceeds the drift field. The right hand panel shows the limit in which we
 1383 ignore diffusion during transport. The violet region indicates the field lines passing from
 1384 above the GEM to below. The blue "halo" region surrounds the "core". Electrons beginning
 1385 above the GEM will all be transported through the holes. However, ions beginning below
 1386 the GEM will distribute themselves among the core and halo, thereby having only a
 1387 fractional transmission.

1388 This effect is quite similar to that which induces the so-called "Sauli Point" (Figure 3.18)
 1389 for GEM transparency at low avalanche field. Indeed, this phenomenon has served as the
 1390 basis for design of the gating GEM anticipated for use the the ILC TPC. Inspired by that

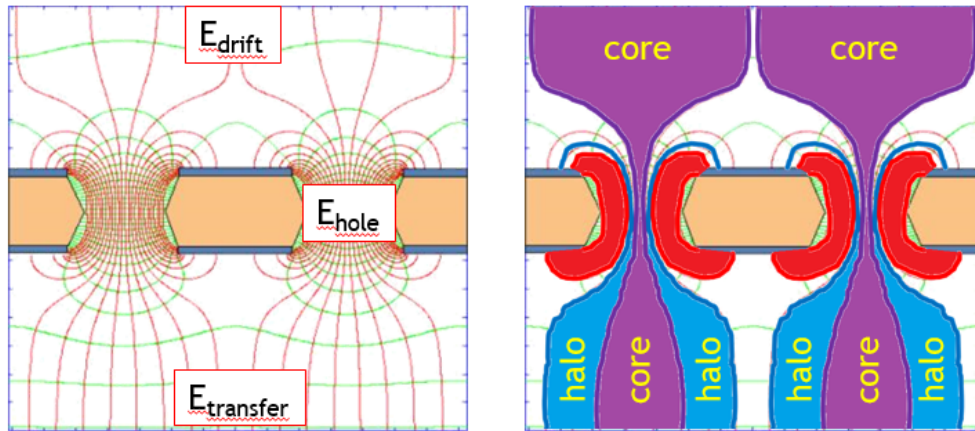


Figure 3.17: In the limit of zero diffusion, one can easily visualize the mechanism behind IBF suppression. When the exit field of a GEM significantly exceeds the entrance field, near 100 % electron transmission is achieved while many or most of the ions terminate instead on the GEM itself.

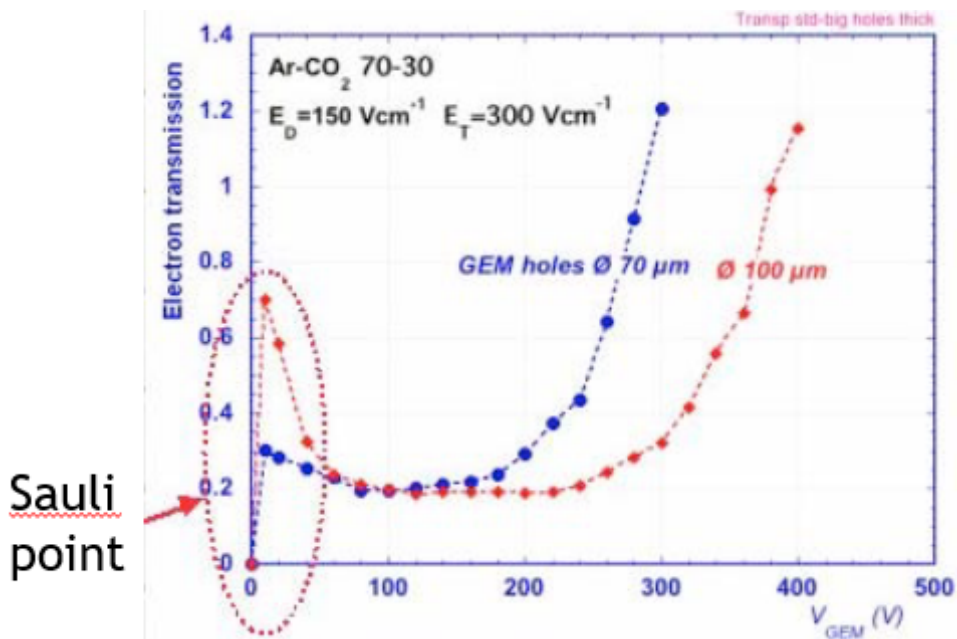


Figure 3.18: The so-called “Sauli Point” for a GEM is a spike in electron transmission at very low dV . sPHENIX has proposed and simulated using either a low ΔV GEM operating at the Sauli Point or even a simple mesh to create an electron-transparent but ion-blocking shield.

1391 possibility and further encouraged by a private suggestion that the same might be accom-
 1392 plished by a passive mesh (H. Appelshäuser, ALICE), we began a second consideration of
 1393 methods to combat IBF without compromising energy resolution.

1394 Figure 3.19 summarizes the approach. The well understood degradation in energy resolu-
 1395 tion with decreasing IBF comes from fluctuations at low gain the the first GEM. Indeed,

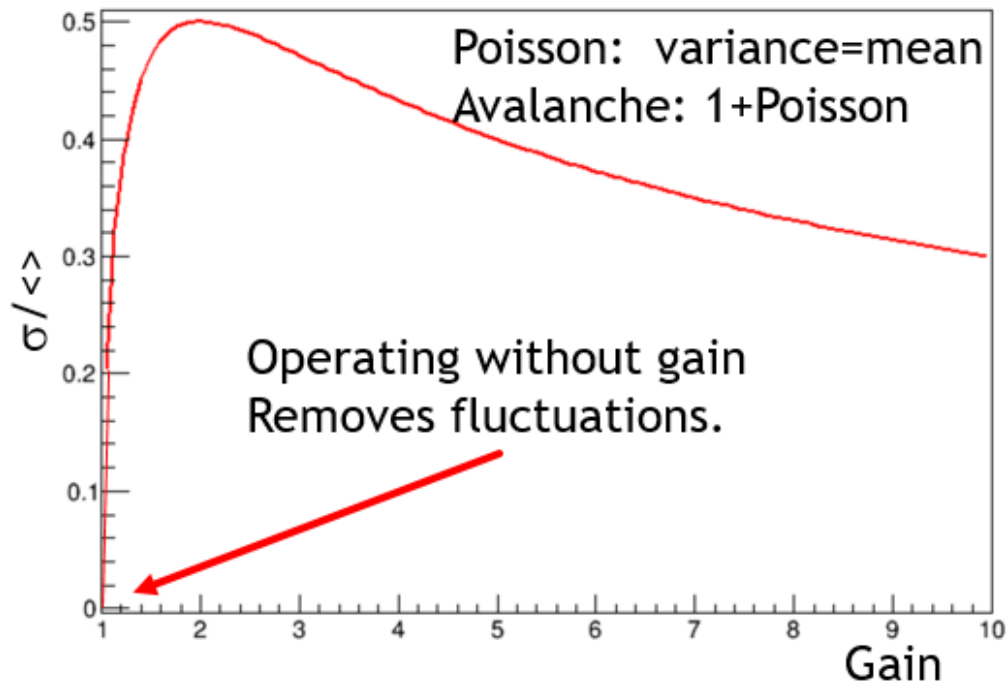


Figure 3.19: Electron gain differs from simple statistical calculations (*e.g.* Poisson) because even without gain, at the very least the electron that enters the avalanche exits as well. Therefore the fluctuations (measured as $\frac{\sigma}{mean}$) vanish in the low gain limit.

1396 statistical distributions enforce this tendency, for example Poisson distributions have the
 1397 variable equal to the mean. However, an avalanche is different. At the very least the
 1398 primary electron in the avalanche will be present at small gain ~ 1 . For this reason, an
 1399 avalanche stage with full transparency and no gain introduces no fluctuations. If such a
 1400 structure were placed with asymmetric entrance and exist field, it is natural to assume that
 1401 the electric fields would dictate high transparency and low IBF.

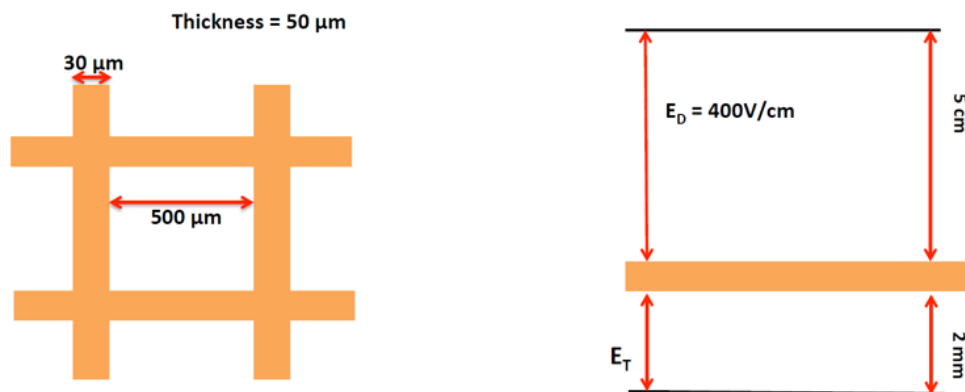


Figure 3.20: Full GARFIELD simulations including magnetic field in the idealized mesh shape shown here, square holes photographically etched into flat metal.

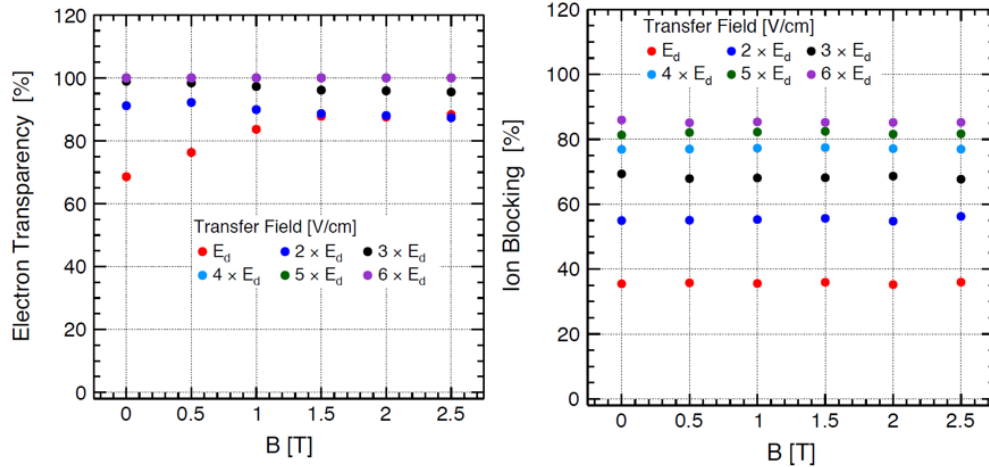


Figure 3.21: GARFIELD results indicate that for reasonable ratios of $\frac{E_{exit}}{E_{entrance}}$ near perfect electron transmission can be achieved while blocking 70-80% of the ions produced in the avalanche stage.

1402 Full GARFIELD simulations indicate that this configuration should be viable. Many
 1403 different mesh geometries have been modeled by sPHENIX, one of which is summarized
 1404 in Figures 3.20 and 3.21. Both the electron transmission (forward direction) and the ion
 1405 blocking (backward direction) have been measured using GARFIELD in our operating
 1406 gas and as a function of magnetic field in the TPC. Clearly, for quite reasonable ratios of
 1407 drift and transfer fields, one can achieve nearly 100% electron transmission while blocking
 1408 about 80% of the positive ions. This would, in principle allow for much more favorable
 1409 operating points with very low IBF and good energy resolution. Future R&D will confirm
 1410 these findings.

1411 3.5.3 Diffusion and Resolution

1412 The prior section justified our choices for minimization of IBF effects on the TPC:

- 1413 • Use a low mass gas (Ne) to increase ion drift velocity.
- 1414 • Use a high drift field to increase drift velocity.
- 1415 • Select a GEM operating point for intrinsically low IBF.
- 1416 • Move the inner field cage closer to the interaction point to counteract space charge.
- 1417 • Adjust the field strengths on both sides of the field termination mesh to allow for
 1418 passive IBF rejection.

1419 These steps, will surely minimize the IBF distortions or a manageable level. This, our next
 1420 consideration must be resolution.

1421 The single point resolution of a gas chamber can be expressed as the quadrature sum of
 1422 several terms:

$$\sigma_x^2 = \sigma_{pad}^2 + \frac{D_T^2 L}{N_{eff}} + \sigma_{sc}^2 \quad (3.4)$$

1423 Here σ_x is the position resolution, σ_{pad} is the intrinsic resolution of the pad plane, D_T is the
 1424 transverse diffusion constant, L is the drift length, N_{eff} is the effective number of electrons,
 1425 and σ_{sc} is the uncertainty due to space charge distortion. The character of the diffusion
 1426 constant reflects the random walk process. Clearly the lowest diffusion gas will give us
 1427 the best precision so long as we achieve charge sharing among pads (so as to not ruin the
 1428 pad term).

1429 Although the N_{eff} term looks like simple counting statistics, it is somewhat more compli-
 1430 cated. Two principle factors reduce the effective number of electrons as compared to the
 1431 average number of ionization electrons. The first factor is only relevant when the number
 1432 of electrons is very small on average. This one notes that:

$$\langle N \rangle \neq \left(\left\langle \frac{1}{N} \right\rangle \right)^{-1} \quad (3.5)$$

1433 Although significant for numbers of primary electrons below 10, this correction is only
 1434 a few % for our case. The second factor is more subtle and more significant. Since each
 1435 electron's avalanche is of different strength, the error on the mean is larger than the error of
 1436 a single measurement over \sqrt{N} . This calculated by Kobayashi for a Polya gain distribution
 1437 with parameter θ as:

$$R = 1 + \frac{1}{1 + \theta} \quad (3.6)$$

1438 The the gases currently under consideration by sPHENIX this reduction in N_{eff} is between
 1439 a factor of 1.5 and 2.

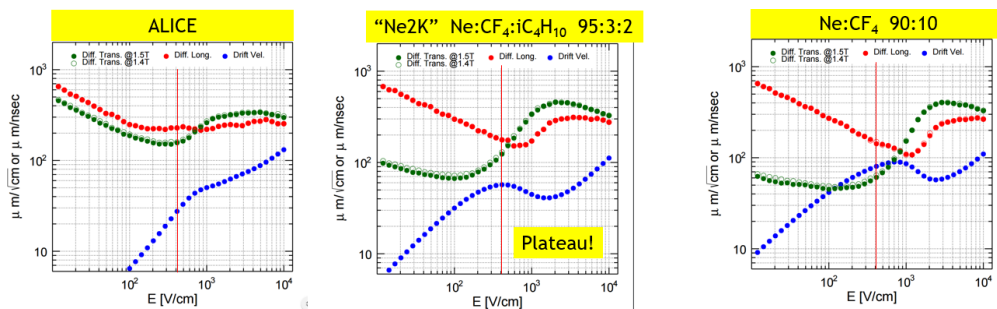


Figure 3.22: Three types of gases are analyzed for longitudinal diffusion (red), transverse diffusion (blue), and drift velocity (black). The left panel shows the original ALICE gas (Ar:CO₂), "Ne2K" (as described in the text), and our current leading choice (Ne:CF₄ 90:10).

Gas	N_{eff}	D_T	$\frac{D_T\sqrt{L}}{\sqrt{N_{eff}}}$	v_{drift}	T_{drift}	$\sigma_\tau(chr)$
Ne2K	31.4	$120 \frac{\mu m}{\sqrt{cm}}$	$214 \mu m$	$56 \frac{\mu m}{nsec}$	$18 \mu sec$	$32 nsec$
Ne:CF ₄ 90:10	32.1	$60 \frac{\mu m}{\sqrt{cm}}$	$106 \mu m$	$80 \frac{\mu m}{nsec}$	$12.5 \mu sec$	$17.5 nsec$

Table 3.2: Resolution comparison for Ne2K and Ne:CF₄ gases.

1440 Figure 3.22 shows calculations of diffusion and drift velocity for several gas choices.
 1441 The red curve is longitudinal diffusion, the green curve is transverse diffusion, and the
 1442 blue curve (different scale) is drift velocity. Table 3.2 summarizes the diffusion-driven
 1443 resolution.

1444

1445 Pure resolution considerations obviously favor the *Ne : CF₄* gas mixture over Ne2K,
 1446 however, the plateau at our exact drift velocity in Ne2K makes this remain an attractive
 1447 choice. Both gases will be investigated moving forward.

1448 3.5.4 TPC Electronics

1449 sPHENIX benefits tremendously from the developments in ALICE for their own TPC
 1450 upgrade. In many ways, our detector is based upon theirs. It is therefore worthwhile to
 1451 summarize their design before moving to the particulars of sPHENIX/

1452 The ALICE TPC at the LHC is to read out continuously at 50 kHz in Pb+Pb collisions, a
 1453 reasonable match to requirements at RHIC. Figure 3.23 shows the block diagram of signal
 processing based on the ALICE TPC upgrade electronics. Starting from the end of the

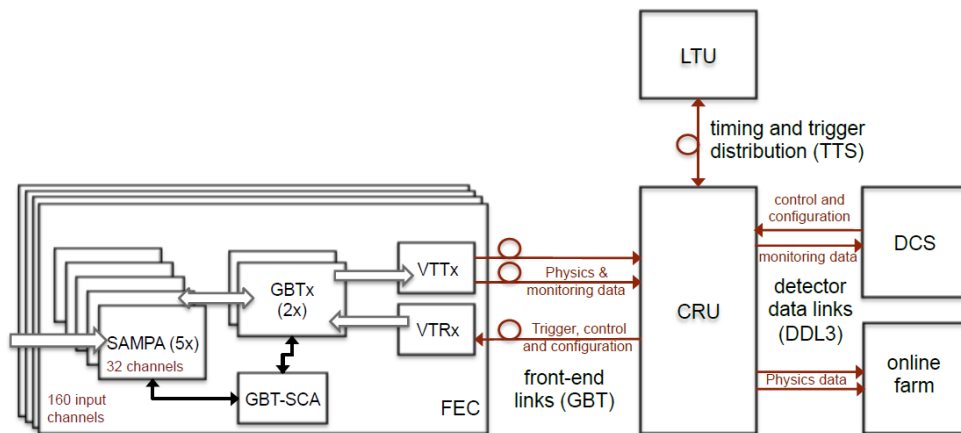


Figure 3.23: Block diagram of signal processing for ALICE TPC upgrade

1454 signal processing chain, the Data Control System (DCS) and online farm is the computer
 1455 system where the data are stored and processed for analysis. The LTU provides the timing
 1456 and trigger signal to the Common Readout Unit (CRU), which is the post-processing
 1457 system where some online calibrations and event reconstruction are performed.
 1458

1459 The Front End Card (FEC) consists of SAMPA chips which amplify and shape the analog
 1460 signals and digitize them. The DSP (data processing unit) is also on the chip. This
 1461 formats the digital data into a data packet (it also performs baseline suppression, i.e.,
 1462 zero-suppression of the raw data). The packet is then sent to GBTx followed by VTTx.
 1463 They convert the data packet into optical signals. In the PHENIX case, DCM-II is defined
 1464 as the destination of the data to be sent optically. Since, we don't perform calibration or
 1465 reconstruction online, we wouldn't need CRU as long as the data format for DCM-II is
 1466 simple enough that the DSP can fully handle it.

The block diagram of the SAMPA chips is shown in Figure 3.24. In the ALICE design, there

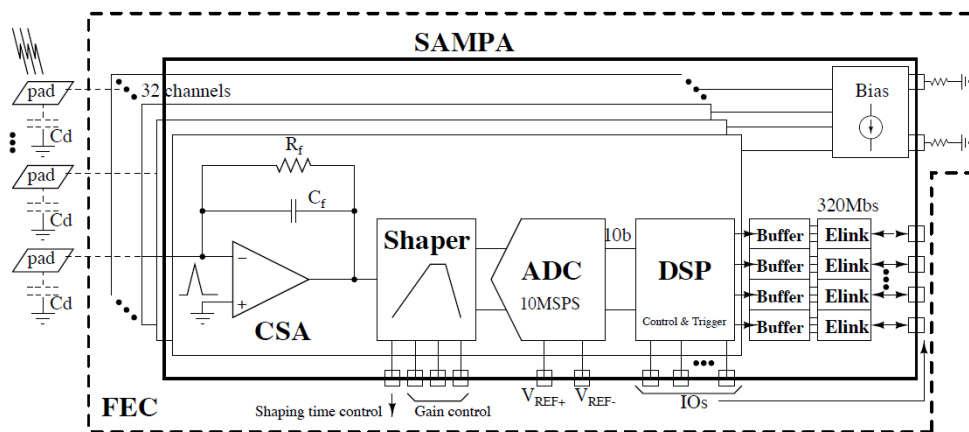


Figure 3.24: Block diagram of ALICE SAMPA chip

1467 will be 5 SAMPA chips multiplexed by 2GBTx ASICs. One SAMPA chip accepts 32 inputs,
 1468 therefore one FEC can process 160 inputs. The ALICE TPC will have 121 FECs per readout
 1469 segment module. The TPC will be equipped with 18 segments in each side, 36 segments in
 1470 total.
 1471

1472 By contrast, the sPHENIX system is summarized in Figure 3.25. The sPHENIX FEE cards
 1473 will each carry 8 SAMPA chips and thereby readout 256 channels on each FEE. Going
 1474 outward in radius, the sPHENIX modules carry 5, 8, and 12 FEE cards respectively. This
 1475 results in 153,600 active channels for the entire TPC system. Each sector of 25 FEE cards
 1476 is serviced by a single PCI-express-based FPGA card, Data Aggregation Module (DAM),
 1477 which is hosted on a server, Event Buffering and Data Compressor (EBDC). The DAM
 1478 is responsible for event alignment and clustering. Furthermore, present calculations
 1479 indicate that we can create false event boundaries from our continuous readout by copying
 1480 ambiguous data into both triggered events. Then the result sub-event is compressed on

1481 EBDC and send to the sPHENIX event builder via Ethernet.

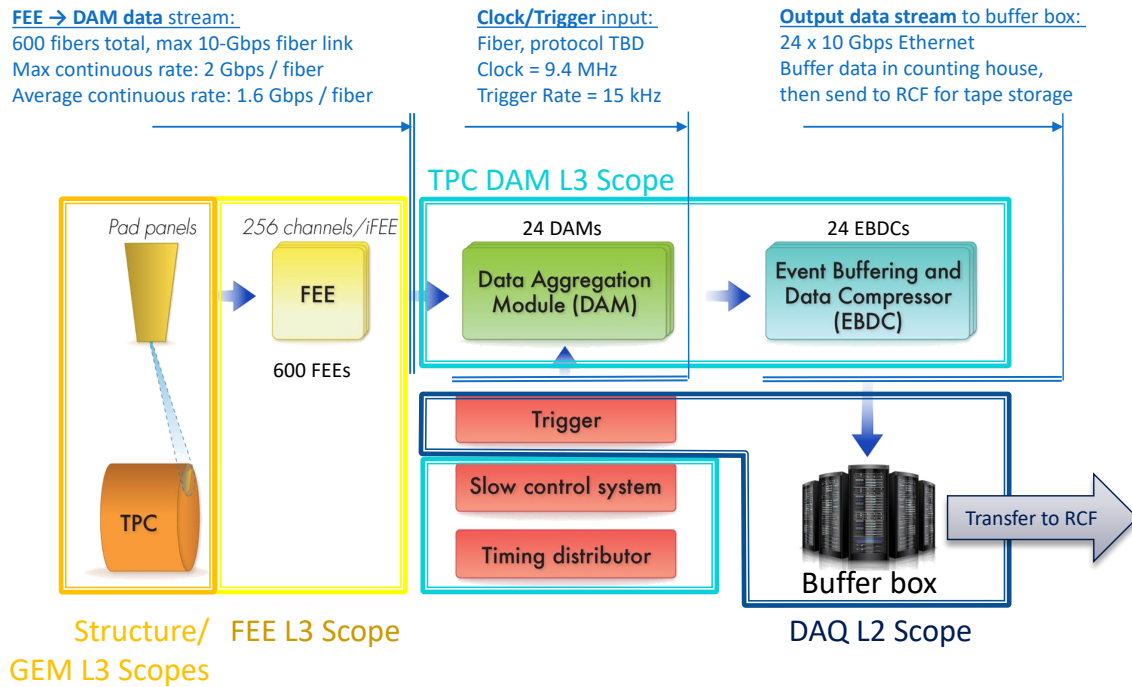


Figure 3.25: An overview of the TPC electronics chain. FEE cards housing SAMPA chips are located on board of the detector. Zero suppressed, untriggered data flows to Data Aggregation Modules (DAMs) hosted on Event Buffering and Data Compressors (EBDCs) located in the counting house. From there, the TPC data joins the main stream flow of the sPHENIX DAQ.

1482 Figure 3.26 shows the current leading implementation for the DAM device: using the
 1483 ATLAS FELIX board. Because the DAM is a digital-in and digital-out board with on board
 1484 programmable processing power, multiple already available options for implementation of
 1485 the DAM exist. While the CRU unit from ALICE can be paired with a SAMPA datastream,
 1486 the FELIX board is being developed with the help of the BNL Instrumentation Division
 1487 and ATLAS experiment since it appears likely to satisfy all the requirements, and local
 1488 expertise will provide a stable platform for the DAM operations in the long term. The rate
 1489 through put of the DAM-EBDC system and at each processing stage is summarized in
 1490 Table 3.4.

1491 The SAMPA chip has reached a mature stage as evidenced by the waveform from the
 1492 MPW2 test run. This waveform was obtained directly from the silicon in the ORNL
 1493 laboratory of Chuck Britton. One should note that the SAMPA chip's rise time is on the
 1494 slow side for sPHENIX. Our drive towards low diffusion to meet the resolution spec
 1495 has necessitated the use of a "cold" gas (namely CF_4) which has also increased the drift
 1496 velocity. In principle, one should match the charge collection time to the time constant
 1497 of the amplifier. With low diffusion and high drift velocity, there is a mis-match with the
 1498 electronics time constant being longer than we would prefer. This increases the occupancy,

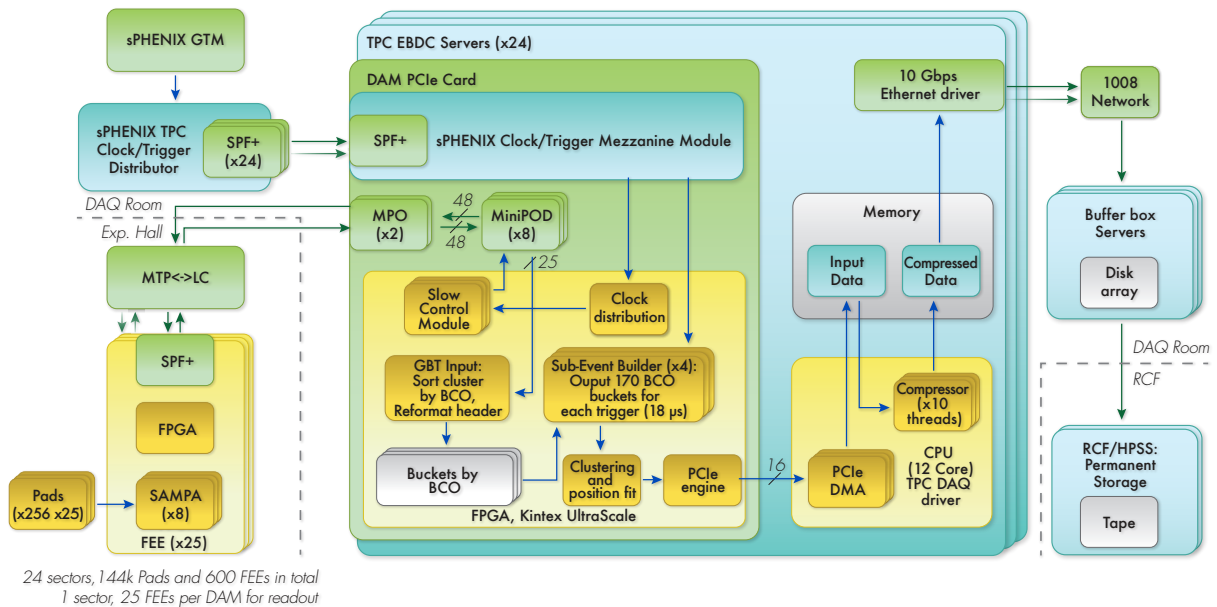


Figure 3.26: Block diagram for DAM and EBDC. Estimation of the DAM performance as realized using the FELIX board have been performed following this architecture assumption detailed in these diagrams. These studies indicate that not only can the FELIX card handle the desired throughput, but it can additionally assert “trigger coincidence” criteria by copying data from overlapping triggers into both events.

1499 but not to the point that the tracking efficiency is expected to suffer.

1500 At the time of this writing we have received several SAMPA chips for testing. We have

1501 developed a utility test board that serves a list of important functions:

- 1502 • The board opens multiple diagnostic channels to allow a complete evaluation of the
- 1503 SAMPA chip.
- 1504 • The board interfaces directly to existing GEM modules at BNL and Stony Brook so
- 1505 that physics signals (^{55}Fe , generated soft X-rays, cosmic rays) can be used to excite
- 1506 the GEMstack and read out through a SAMPA-based chain.

1507 The experience of the test board should put us in an excellent position to develop the

1508 8-SAMPA version of the board that will be compatible with modules on the main TPC.

1509 Figure 3.29 indicates a comparative study of the ALICE CRU module to the ATLAS FELIX

1510 module. Either of these devices fulfills the DAM throughput specification. We currently

1511 consider the FELIX board as our first choice simply because of the local (aka BNL) expertise

1512 in programming and operating that card. We have also acquired via loan a FELIX version

1513 1.5 card that is being used to study the throughput and verify the simulation results.

Table 3.3: Raw data rate estimate for sPHENIX TPC and ALICE TPC cases

Parameters	sPHENIX (Au+Au 200 GeV)	ALICE (Pb+Pb 5.5 TeV)	Notes
dN/dy (Minbias)	180	500	
η coverage of TPC	2.2 ($ \eta < 1.1$)	1.8 ($ \eta < 0.9$)	
# of tracks in TPC	396	900	
Effective # of tracks in TPC (accounted for r -dep. η coverage change)	560	1690	note 1
Effective factor for track # increase for accounting albedo background	2	2	note 2
# of measurements in r	40	159	
# of samples in ϕ	3	2	$\phi \times \text{time} \sim 20$ bins for ALICE (from TDR)
# of samples in timing	5	10	
# of bits of each sample	10	10	
Data volume increase fac- tor by SAMPA header	1.4	1.4	Absolute maximum
Data volume/event (bits)	9.41×10^6	1.50×10^8	note 3
Data volume/event (bytes)	1.18×10^6	1.88×10^7	
Collision rate [kHz]	100	50	
Total data rate (bits/sec)	9.41×10^{11}	7.52×10^{12}	
Total data rate (bytes/sec)	1.18×10^{11}	9.41×10^{11}	

note 1: ALICE didn't estimate from first principle. We estimated for them.

note 2: We doubled the number of tracks to account for the background, based on STAR's experience.

note 3: Product of the previous seven rows. ALICE estimated the data volume as 160 Mbits/evt.

1514 3.5.5 TPC readout plane

1515 One consequence of pushing resolution through low diffusion regards the size of the cloud
1516 that hits the pad plane. The advantages of a charge-division pad plane are entirely lost if
1517 the charge from a single avalanche is confined to 1 single pad. This this reason, "chevron"
1518 or "zig-zag" pads have been developed as a means of ensuring charge division for even
1519 narrow avalanches.

1520 Figure 3.30 indicates the chevron segmentation style applied to our pad planes. Charge
1521 sharing is driven by the fine part of the zig-zag pattern, while channel count is driven by
1522 the macroscopic pad-to-pad spacing.

1523 The radial pad size is ~ 1 cm. The transverse dimension of the pads varies with ~ 1 mm

Table 3.4: TPC DAM and EBDC average data rate for the default TPC configuration. For various design scenarios of drift speed and collision rate that are considered for TPC operation, the recorded data rate varies from 50–140 Gbps.

	Unit count	Rate per unit	Total rate	Assumptions and comments
Data on FEE Fibers	600 fibers	1.5 Gbps	880 Gbps	40-radial layer TPC and 100kHz Au+Au collision assumed. Rate is radial position dependent. The max data rate is 2 Gbps for the inner-radius FEEs.
BCO-buckets	24 DAMs	36 Gbps	900 Gbps	Unpack SAMPAs data and add two 10-bit header per wavelet
After triggering	24 DAMs	10 Gbps	240 Gbps	On-DAM event builders collect 13 μ s of hits after each trigger. This reduce data to 27%
After clustering	24 DAMs	5 Gbps	120 Gbps	Cluster finding and fitting on DAM FPGA. Expecting a reduction of total data volume to 50% based on STAR and ALICE experience.
After compression	24 EBDCs	3 Gbps	70 Gbps	Lossless compression on EBDC CPUs. Assuming the PHENIX experience of a reduction of total data volume to 60%
Buffer box logging	Buffer box system	70 Gbps	70 Gbps	Logging TPC data to disk in buffer box system in sPHENIX counting house.

1524 spacing of rectangular pads in the R1 module and ~ 2 mm spacing for the R2 and R3
1525 modules.

1526 The TPC amplification element is based on several layers of Gas Electron Multiplier
1527 (GEM) detectors. Traditional Muti-Wire Proportional Chamber (MWPC) technology is not
1528 considered because it a) cannot provide desired $r\phi$ resolution of 100 μ m and b) the MWPC
1529 requires gating to stop ion back flow, and that significantly limits the data taking rate.

1530 Four GEM layers are considered in the current scheme of the amplification element. Each
1531 GEM will provide gain in the range of typically a few thousand, suitable for the readout
1532 electronics considered for the TPC. The gain range is driven by two competing factors.
1533 Higher gains will improve the signal:noise and improve $\frac{dE}{dx}$ results, but will also increase
1534 the Ion Back Flow (IBF). ALICE intends to run at a gain of 2000 with SAMPAs chip readout.
1535 ALICE results also demonstrate high stability of GEM operation in the environment of
1536 high energy heavy ion collisions.

1537 The amplification element is shown in fig. 3.31.

1538 The development of the sPHENIX TPC is greatly aided by the multi-year effort put into

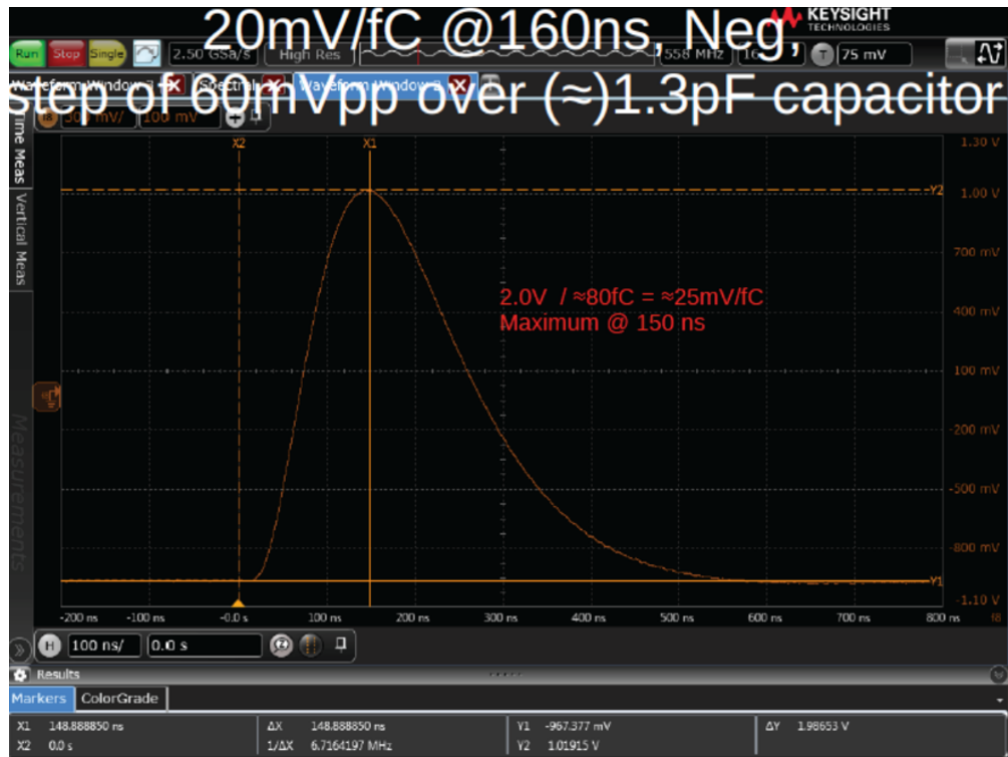


Figure 3.27: Wafer measurements at ORNL for ALICE capture the waveform coming from the SAMPA shaper in response to a delta-function excitation. The indicated peaking time of 150 nsec, while on the slow side for sPHENIX needs, is nonetheless OK for meeting our performance specifications.

1539 development of detector technologies for the EIC. In particular, this program has allowed
 1540 studies of the complete suite of gas properties for all our candidate gases and many others
 1541 that would be suitable for EIC, but not so much for RHIC.

1542 Figure 3.32 shows the response of quad-GEM chambers to an X-ray source (^{55}Fe) in both
 1543 the Ne2K and Ne:CF₄ gases current leading our choices. Experience in the lab showed
 1544 excellent stability for both these gases over log running periods.

1545 Furthermore, our R&D efforts have opened the door to BF measurements. Figure 3.33
 1546 shows an overlay of sPHENIX results on Ion Back Flow superimposed upon the iconic
 1547 plot from ALICE, The agreement is excellent, opening the door to bench verification of
 1548 some of the new ideas we have had for IBF suppression including the passive mesh
 1549 concept. Currently we have **NOT** taken credit for this new effect in our simulations as
 1550 a conservative measure to ensure that we do not over estimate the performance of our
 1551 design.

1552 One issue for all chevron pattern detectors is that of differential non-linearity. Typically the
 1553 shape of the charge cloud folder with the segmentation of the pad plane does not produce
 1554 a linear response with position. Indeed, as shown explicitly in Figure 3.34 the correlation
 1555 between true position and measured position shows a saw-tooth pattern whose spatial

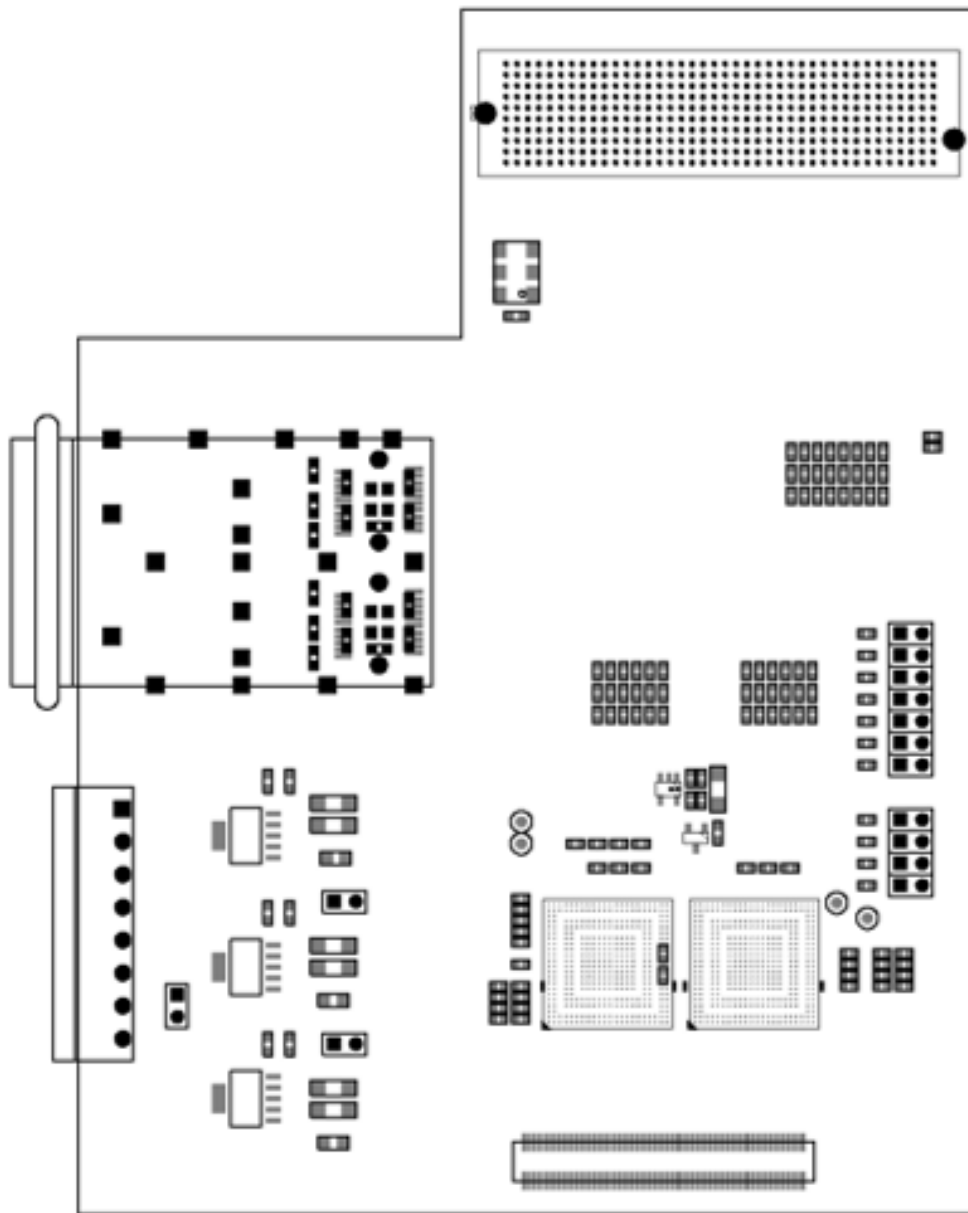


Figure 3.28: The first sPHENIX SAMPA prototype board is designed to house 2 SAMPA chips (similar to the iTPC for STAR) and a variety of diagnostic access points. The board is ordered. Delivery and firsts tests are anticipated for May 2017.

1556 period matches the pad spacing. Although our R&D shows that the troublesome response
 1557 can be removed from the data by simple and self-calibrating means, it is nonetheless quite
 1558 desirable to design a pad plan that a priori would have little to no differential non-linearity.

1559 Again under the guise of EIC R&D we have studied at a theoretical level that issue of
 1560 non-linearity as a function of pad shape. Figure 3.35 shows the anticipated response of our
 1561 new design. Unfortunately the line spacings used in simulation are not possible in industry

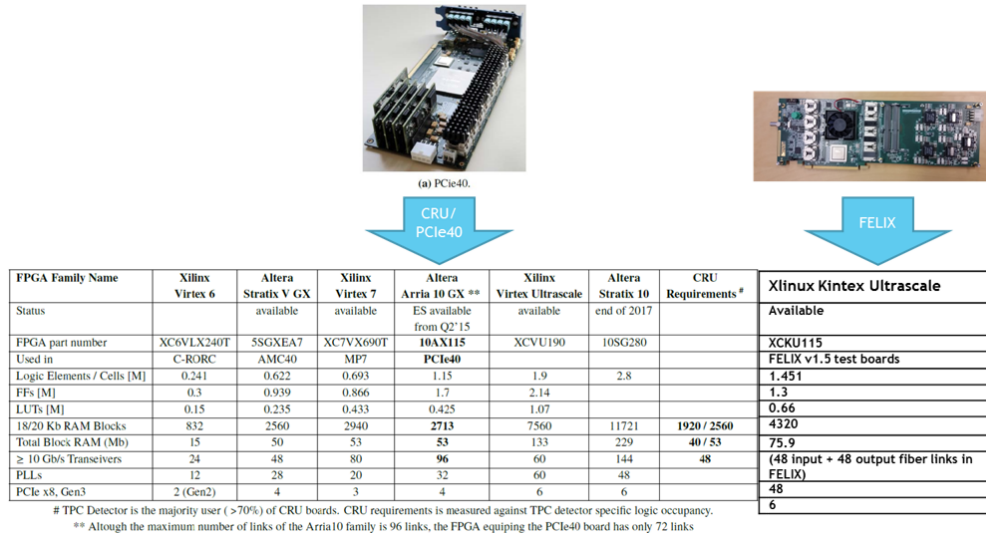


Figure 3.29: The DAM acts as a bridge from SAMPA data to the sPHENIX DAQ and simply applies digital horsepower to high speed digital input and output streams. As such, we can leverage developments of other experiments such as ALICE (left panel) and ATLAS (right panel). We currently favor the ATLAS-based solution using the so-called FELIX 2.0 card.

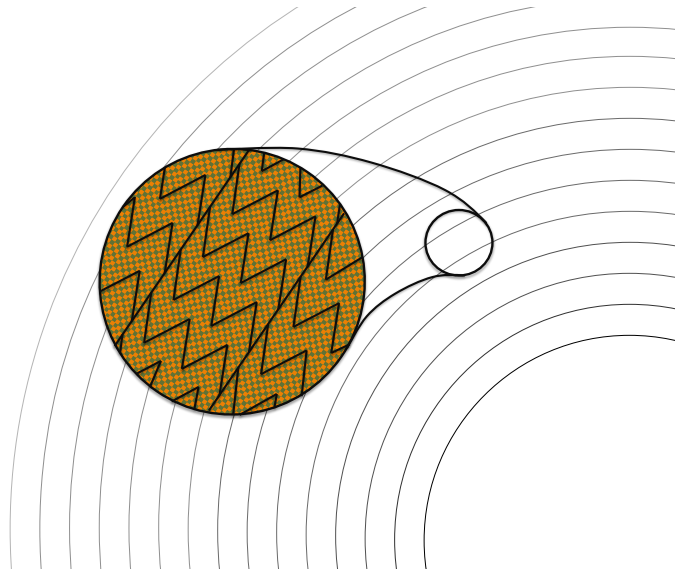


Figure 3.30: Schematic layout of the TPC pad rows and chevron pads.

1562 at the present time and so a compromise was made to the best that can be manufactured
 1563 today. This new pad board is in house and expected to produce DNL results very soon.

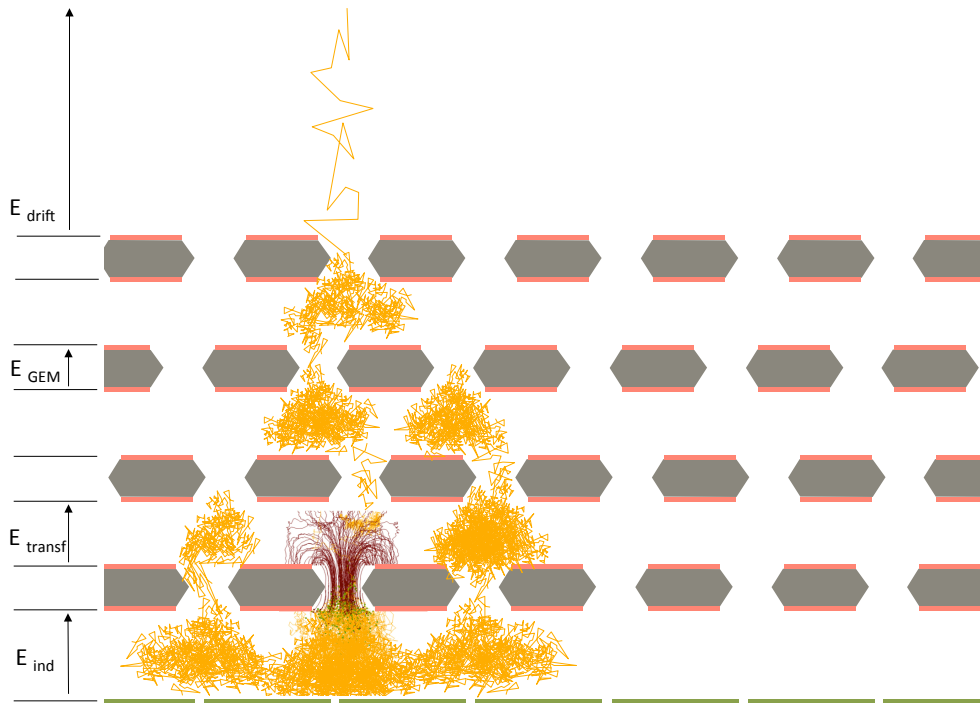


Figure 3.31: Schematic view not to scale of the readout element built with four layers of GEMs. Yellow lines show electron paths, brown lines show the ion paths for one single hole (simulation).

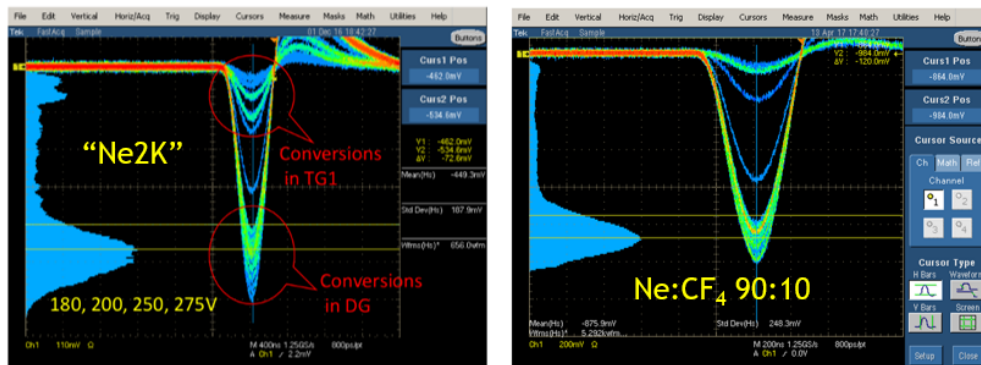


Figure 3.32: R&D results on our candidate gas mixtures (Ne:CF₄:iC₄H₁₀ demonstrate good energy resolution and excellent stability when operated with a quad-GEMstack).

1564 **3.5.6 TPC field cage**

1565 The basic function of the TPC field cage is to provide a uniform drift field from the central
 1566 membrane to the detector modules at each end. This field cage is traditionally defined by
 1567 a series of conducting rings held at uniformly decreasing potential by a precision-matched
 1568 chain of resistors. The field cage is then surrounded by a gas enclosure. Both for safety

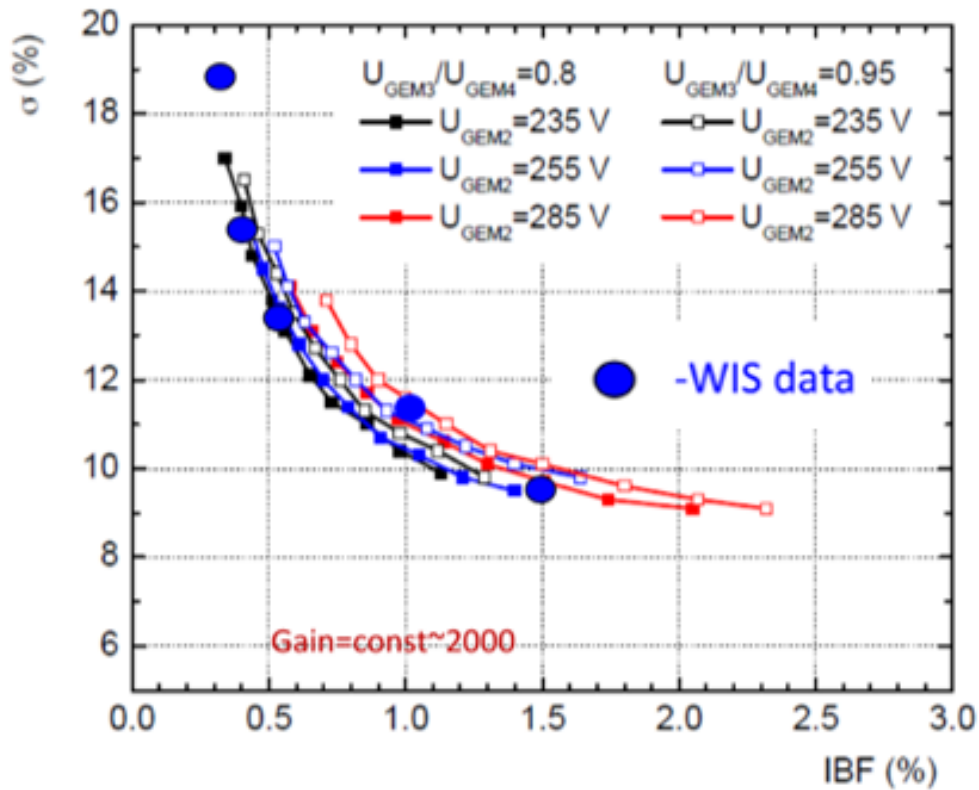


Figure 3.33: This figure shows results obtained on our labs (Weizmann Institute of Science) overlaid with the iconic ALICE results on IBF. These indicate that we are well positioned to experimentally investigate .

1569 considerations and to avoid stray electric fields in neighboring detectors, the gas enclosure
 1570 is usually grounded. Figure 3.36 shows the configuration found on the outer shell of the
 1571 STAR TPC. Both the field cage and the gas enclosure are made structurally rigid using a
 1572 hex cell honeycomb sandwich structure.

1573 The field cage electrodes are made as a double-layer of staggered rings, one facing the
 1574 operating gas and the other embedded in the field cage wall. The latter ring serves to
 1575 shape the field and minimize nonuniformities in the drift volume. Dry nitrogen gas flows
 1576 through the 5.7 cm gap, exceeding by slightly more than a factor of two the "rule of thumb"
 1577 gap dielectric strength of $1 \frac{kV}{mm}$ when operating at a central potential of 27 kV. Although
 1578 in STAR the inner gas enclosure is skipped (exposing the field cage strips to outside air
 1579 and stressing inner detectors with electric field) in the sPHENIX application we have more
 1580 than enough room between the inner silicon pixels and the TPC active volume for an inner
 1581 gas enclosure. Scaling to an identical safety factor as used by STAR, we would require a
 1582 $5.7cm \frac{34kV}{27kV} = 7.2cm$ gap.

1583 An "air" gap of this size would be undesirable for the outer TPC wall since it would limit
 1584 the active volume and degrade the momentum resolution. Because the TPC is followed by

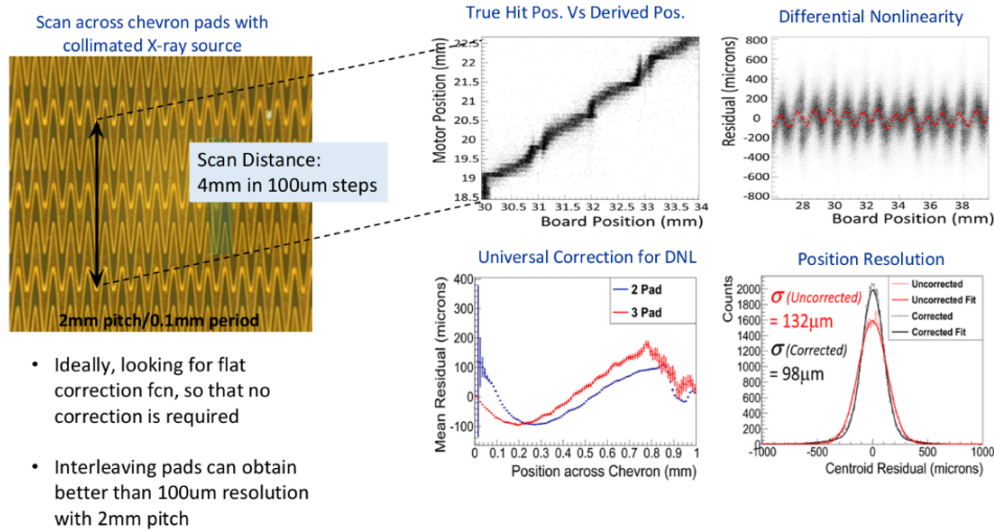


Figure 3.34: Extensive studies of various pad shapes have been performed to quantify and test reduction of differential non-linearity. These tests shows that after correction, resolution of the pad plane are easily achieved to better than 100 μ m.

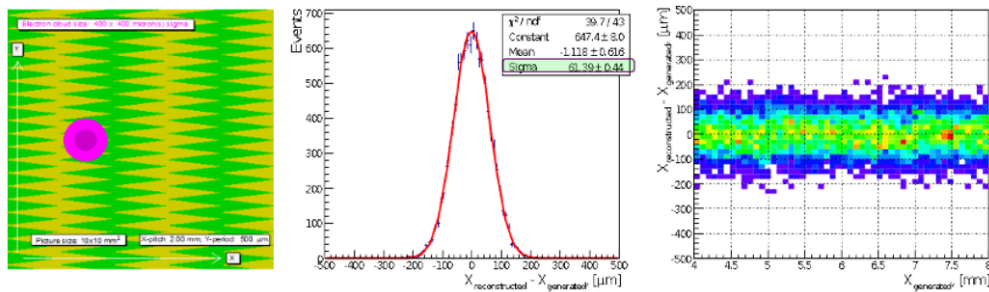


Figure 3.35: Theoretical studies of pad shape have been performed and indicate that significantly reduced non-linearity is achievable.

1585 the EMCAL, we can safely afford to solve the field issue using a solid of high dielectric
 1586 strength. The concern over this solution is two-fold. First, the dielectric field strength
 1587 of common materials is found to reduce with time in a variety of materials as shown in
 1588 Figure 3.37. Much of this variation (e.g. FR4) is dominated by micro-gas bubbles within
 1589 the material which can carbonize over time. Secondly, dependent upon material, solid
 1590 material high voltage gaps, can be subject to permanent failure during a discharge event
 1591 or over-time corona current.

1592 sPHENIX is working with the Sierra Proto Express company to develop a robust solid core
 1593 solution for the outer field cage that would maximize the reliability and longevity of the
 1594 device. Although a multi-material, layered ultimate design is likely, the table below shows
 1595 the required thicknesses for safety factors of 3X and 5X in the design assuming a single
 1596 material type and neglecting contributions other than the insulator itself. Calculations
 1597 here use the worst-case aging estimates from Sierra for each material type. These initial

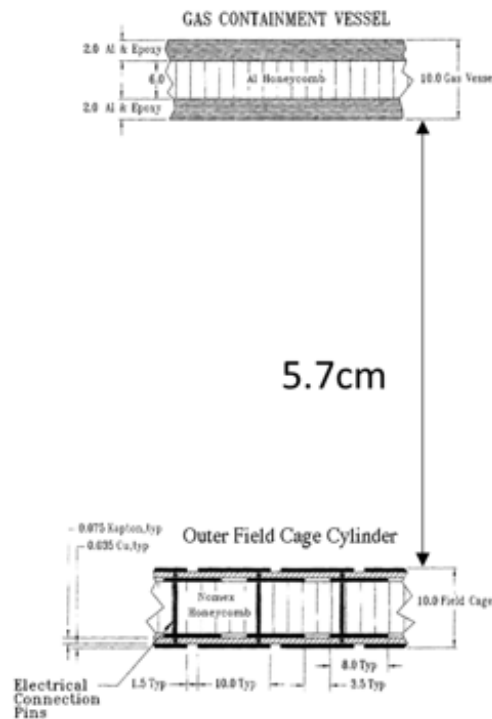


Figure 3.36: Scale drawing of the outer field cage and gas enclosure for the STAR TPC.

Material Type	Max. Operating Temperature (°C)	T/G °C	Voltage (V/mil) Note 1	Aged rating (V/mil)	W°C/m
FR4	105-130	160	800	300/150	0.21
FR4 Hi-Temp.	130-150	170	800	300/150	0.22
BT Epoxy	140-160	180	1300	600/400	0.40
Polyimide	150-190	200	900	700/500	0.25
HVPF*	180-200	210	3000 to 7000	3000/2000	0.28

*HVPF is a trademark of Sierra proto express.

Figure 3.37: Dielectric strengths of various common circuit card materials, reproduced from figures by Sierra Proto Express, a Palo Alto-based circuitry company specializing in high voltage circuit card for both terrestrial and satellite applications.

1598 calculations seem promising, meaning that the "air gap" solution is presently considered
 1599 only as a fallback option. If the solid option realization has a sufficiently small radiation
 1600 length, it can also be considered for the entrance window, thereby simplifying the design.

Material	χ_0 (cm)	Volt/mil	3X Safety	5X Safety
FR4	16.76	150	1.72 cm (10.3% χ_0)	2.88 cm(17.2% χ_0)
Kapton	28.58	500	0.52 cm (1.8% χ_0)	0.86 cm(3.0% χ_0)
HVPF	28.57	2000	0.13 cm (0.45% χ_0)	0.22 cm(0.75% χ_0)

1602 After a complete suite of successful tests of the HVPF product we were disappointed to
 1603 learn that Sierra could not expend their production process to pieces larger than 8" x 8"

1604 tiles. Fearing the worst for the many seams between these tiles we instead turned in the
 1605 direction of lamination-in-place of multi-layer Kapton of the same base stock as is used for
 1606 HVPF. Lab tests indicate that our design has a very large safety margin. We have designed
 1607 a lamination tensioner system that will provide Kapton to the TPC shall at uniform tension
 1608 to avoid trapper air pockets in the laminate.

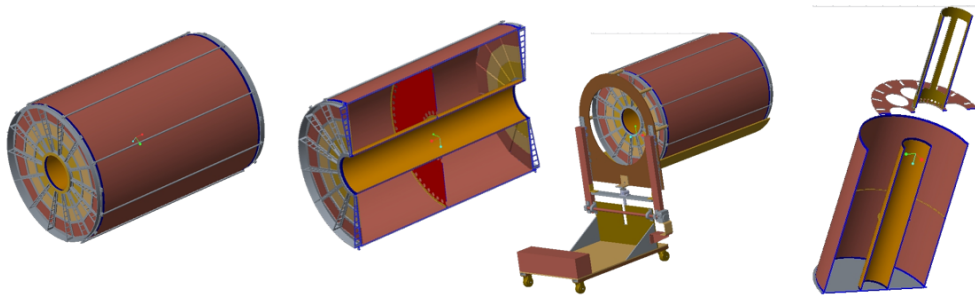


Figure 3.38: Mechanical modeling of the TPC is in an advanced stage including the device itself and also transportation/handling fixtures and assembly fixtures.

1609 Mechanical designs for the TPC have reached an advanced stage. This advancement has
 1610 been partly driven by our wise choice to prototype the TPC field cage at full size. Our
 1611 budget allows for two complete field cage construction projects (prototypes v1 & v2),
 1612 however, if the v1 device proves suitable for our needs the cost savings can be recovered.
 1613 Figure 3.38 shows the advanced model concepts for the overall TPC including handling
 1614 cart and central membrane installation tooling.

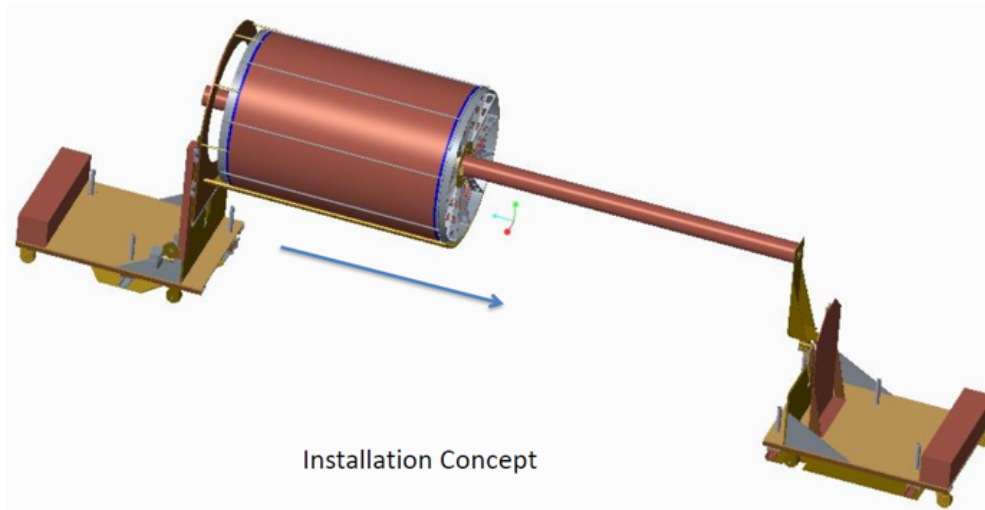


Figure 3.39: Installation of the TPC will include use of the handling cart and a second cart. The device will roll on temporary fixtures into place inside the already-assembled EMCAL.

1615 Figure 3.39 shows the plan for installation of the TPC into sPHENIX. Each wagon wheel has
 1616 fittings for a rolling brace that will allow the TPC to roll in supported by a long cylindrical

1617 tube. The two ends of the tube will be held up by both the handling cart (delivery vehicle
 1618 for the TPC and a second similar cart at the far end. The Handling cart falls within the
 1619 scope and budget of the TPC, whereas the second cart is costed in the installation work
 1620 package.

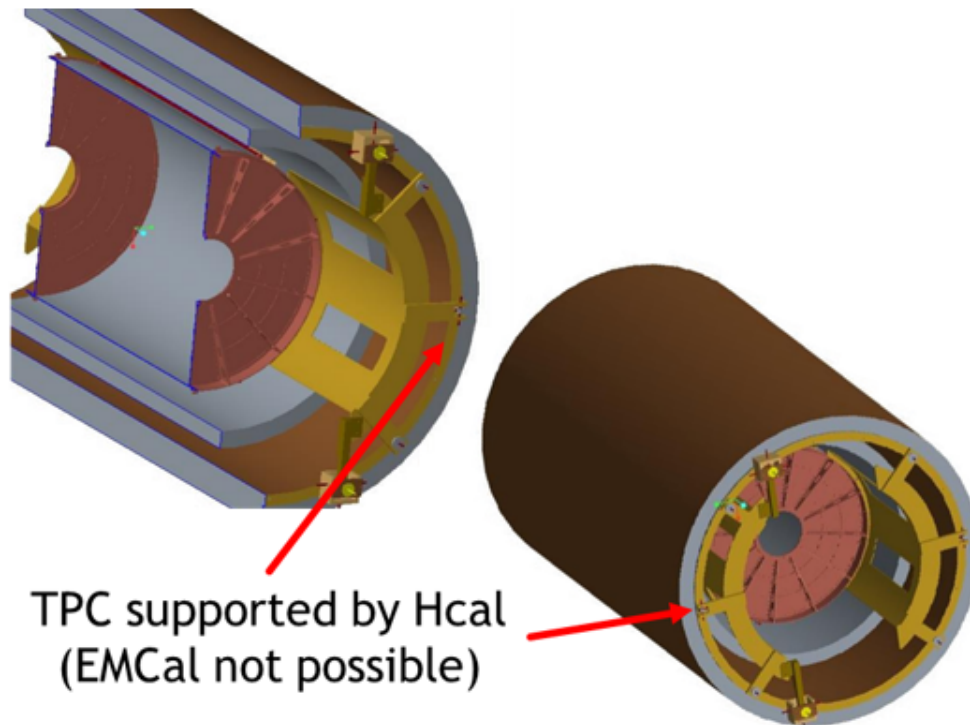


Figure 3.40: Because the EMCAL external structure does not provide sound support points for the TPC, we envision supporting the device from the inner HCAL.

1621 A conceptual holding fixture is also modeled for the TPC. We choose to hang the TPC from
 1622 the HCAL since the EMCAL walls are thinner material to reduce radiation length. Each side
 1623 of the TPC accepts a "1.4 top-hat" shape. Two top-hats (east and west) are used to hang
 1624 the TPC from the HCAL and thereby in the sPHENIX aperture.

1625 Because our momentum resolution depends critically upon the lever arm of the TPC track-
 1626 ing we wish to track as close to the TPC field cage as possible. One realizes immediately,
 1627 however, that a step-function approximation to a uniformly decreasing potential creates
 1628 non-uniformities in the electric field. These non-uniformities have a pitch that matches the
 1629 segmentation of the electrode rings (colloquially called "stripes") and also a radial extent
 1630 that varies linearly with the pitch. It is therefore important to minimize the pitch of the
 1631 striped electrodes.

1632 Figure 3.41 shows the pattern we have chosen. Here a pitch of 2.8 mm is chosen and the
 1633 resistive divider chains are made from surface mount components. Although physically
 1634 small resistor packages are traditionally considered a failure risk, the resistors we have
 1635 chosen are of a new type known as HVPW or High Voltage pulse Withstanding resistors.

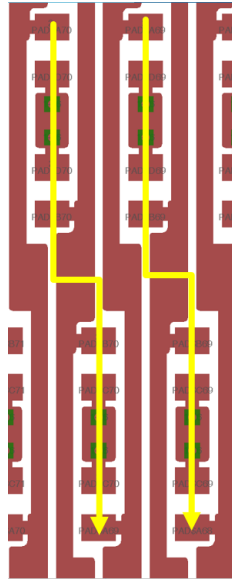


Figure 3.41: To improve field uniformity and bring the useful gas region as close as possible to the field cage, we have chosen a very fine field cage pitch (2.8 mm). This pitch is realized using SMD resistors of the HVPW (High Voltage Pulse Withstanding) variety. Current flow follows the yellow arrows.

1636 Each of the 1500 resistors in our multiple chains is rated to survive a 15 kV surge.

1637 TPC Mechanical Tolerances

1638 We have undertaken and completed an exhaustive simulation program to allow us to
 1639 accurately specify the mechanical tolerances for the TPC field cage. For each variant of
 1640 "mis-construction" (see Figure 3.42, we have used Ansys to create a full field map. Two
 1641 such variants include modules that are out of plane from their desired alignment and
 1642 having the central membrane out-of-plane.

1643 Once the electric field distortions are known, we use GARFIELD with the distorted electric
 1644 field map and an ideal magnetic field map to measure the average position error from the
 1645 pad plane by allowing the electric field distortions to go uncorrected. The net result of this
 1646 lengthy procedure is that we are able to derive a complete suite of mechanical tolerances
 1647 to which the field cage must conform in order to minimize tracking errors. Examples of
 1648 these distortions for different electron launch points under the condition of 1 mm tilt of
 1649 the central membrane are shown in Figure 3.43. An interesting output from this study is
 1650 the discovery of a local minimum in the field-induced distortions of the TPC us run under
 1651 the conditions $v_{drift} \times \vec{B} \sim E_{drift}$. We are lucky at or very near this condition in both our
 1652 candidate gases.

1653 Another substantive issue for the TPC is the size of the gas volume and maintaining
 1654 cleanliness of the gas. Although it is true the PHENIX constructed an exceptional gas

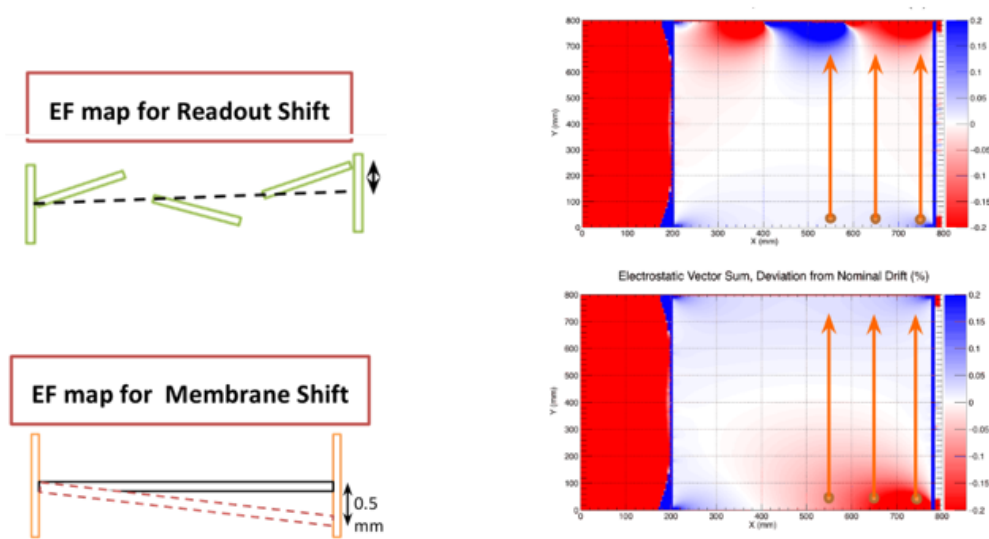


Figure 3.42: Ansys calculations have been performed to compare the electric field of an ideal TPC to that of a TPC build with manufacturing errors. These field calculations assist in defining the production tolerances.

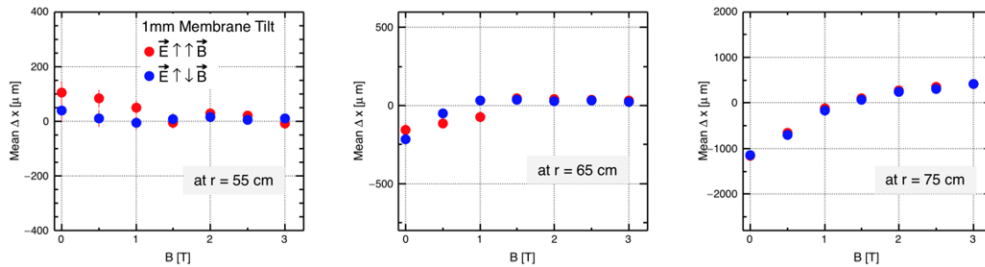


Figure 3.43: For each mechanical error calculated by Ansys, the distorted field is fed into GARFIELD so that position measurement errors can be deduced. Calculations not only yield a quantitative impact study of field cage errors, they also demonstrate a local minimum in tracking error when $v_{drift} \times \vec{B} \sim E_{drift}$, as is the case for Ne2K gas.

1655 system for the old HBD detector (below 5 ppm and O_2 and H_2O at all times, the sPHENIX
 1656 TPC is a much larger gas volume and will require special care in defining its fittings.

1657 Our designs that are presently under construction for the full-scale prototype call out
 1658 making both the wagon wheels and their mating pieces from solid Al block. Although this
 1659 is by no means inexpensive, it allows for vacuum-quality seals at all places.

1660 Figures 3.44 and 3.45 show the details for completing the seals. The wagon wheels shall
 1661 seal to the field cages using spring-energized elastomer gland seals. These will proceed
 1662 for simple insertion thereby eliminating the need to excessive force applied to the field
 1663 cage cylinders during assembly. Furthermore, each TPC avalanche module will achieve an
 1664 O-ring seal against the wagon wheel pieces.

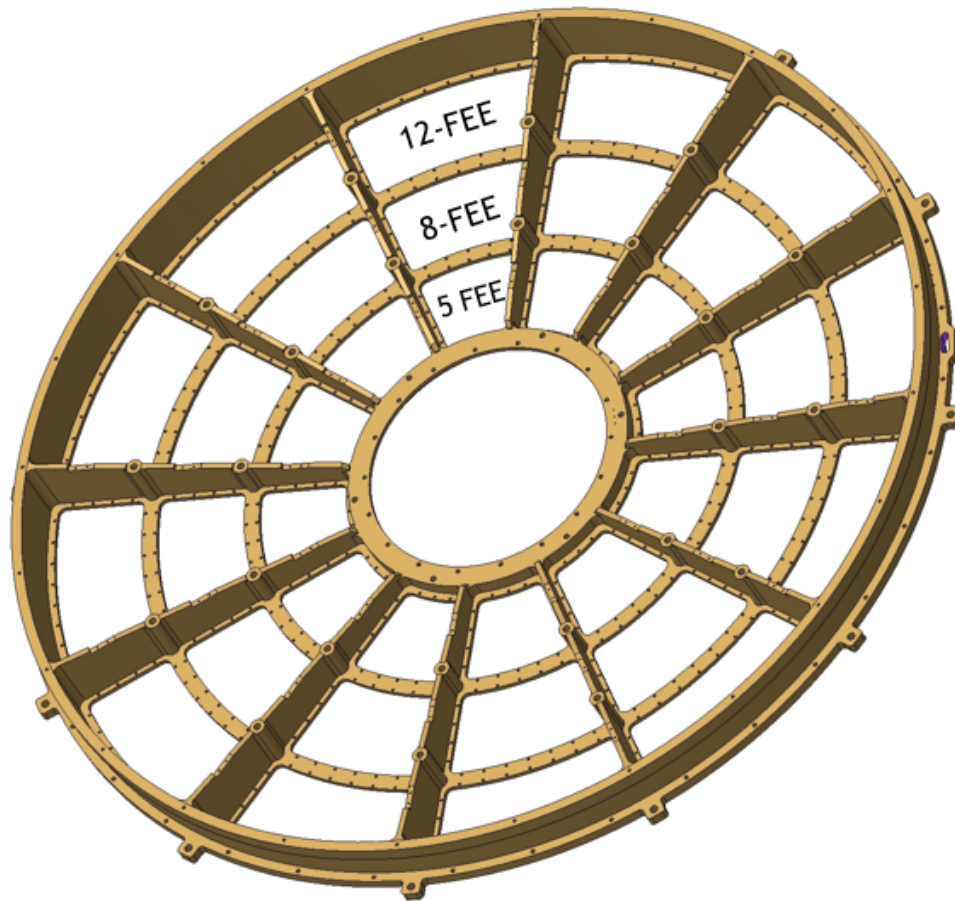


Figure 3.44: The TPC “wagon wheel” shall be machined from single piece Al to eliminate cracks and minimize leaks.

1665 TPC Fabrication

1666 Because of the size of the TPC, the fabrication of all parts could, in principle, be accom-
 1667 plished at any of our collaborating institutions worldwide. That said, it would nonetheless
 1668 be simplest if the field cage assembly was done locally, with smaller parts made around the
 1669 world. This model proved quite effective in building the PHENIX Hadron Blind Detector,
 1670 wherein the individual parts were manufactured at the Weizmann Institute of Science in
 1671 Israel, and the assembly was accomplished at Stony Brook University.

1672 Because of the need to maintain active area to the largest radius, our designs for the TPC
 1673 field cage and gas enclosure will be biased toward the thinnest of robust designs. Thus, the
 1674 STAR and ILC field cage designs are the most appropriate as models for our work. Those
 1675 devices were manufactured using large mandrels upon which layers of flexible circuit
 1676 card and honeycomb were applied. Each mandrel is designed to release by “collapsing”
 1677 to smaller radius after the TPC shell is cured, thereby releasing the shell. The completed
 1678 shells are then outfitted with aluminum spoke-like end caps and a central membrane to

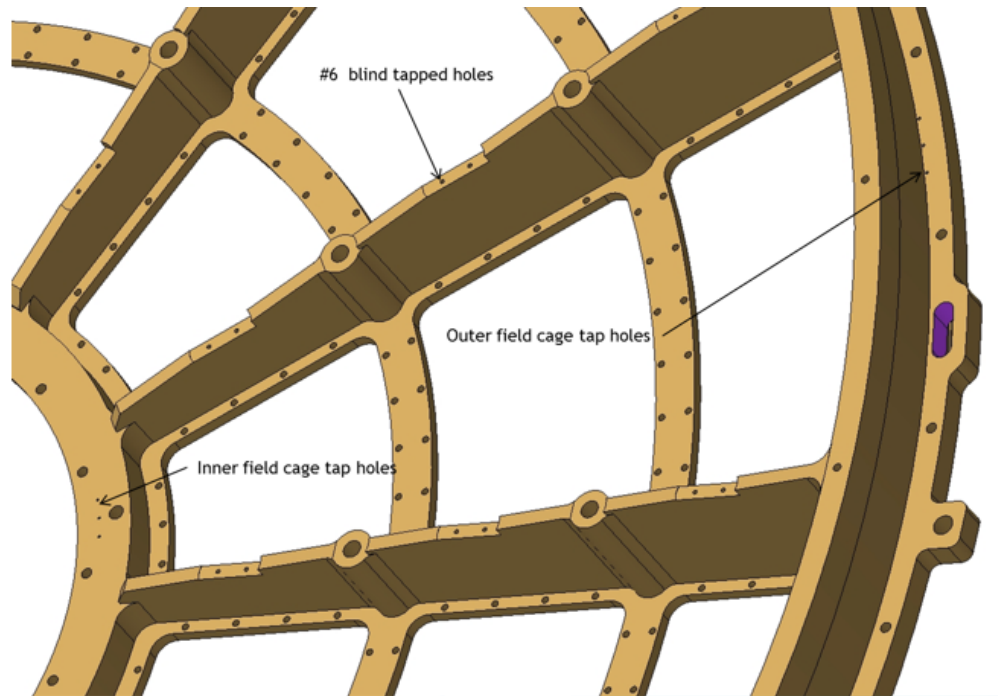


Figure 3.45: The “wagon wheel” includes allowances for all services, feedthroughs, installation fixtures, and support fixtures.

1679 form the completed field cage. We intend to design the field cage to safely hold the highest
 1680 potential currently under investigation (ALICE gas ~ 37 kV).

1681 The open ports between the spokes of the end caps will be filled with “mechanical blank”
 1682 modules to allow the field cage to become gas tight during the prototyping stage. This
 1683 will allow full testing of the high voltage stability of the field cage without any of the gain
 1684 stage modules in place.

1685 During the prototyping stage, single items of the prototype gain stage module will be
 1686 built. Because of the finite size of these units, there is a list of institutions that are capable
 1687 of prototype construction, including Weizmann, Stony Brook, BNL, PNPI, Temple, and
 1688 Vanderbilt. All of these institutions have past experience in the PHENIX HBD construction,
 1689 or in the ongoing construction of the inner TPC layers for the ALICE upgrade. We envision
 1690 two full sized prototypes whose design is driven by results from our ongoing TPC gain
 1691 stage R&D, which has been funded by the EIC R&D program. As described below, we
 1692 have already garnered extensive experience in multiple gain stage technologies, as well as
 1693 a number of clever readout scheme applications.

1694 The so-called “pre-production prototype” will be the third and final stage of full sized
 1695 prototype construction. Barring any discovered deficiencies, “production” would involve
 1696 the manufacture of the remaining gain stage modules as well as spare units. As with the
 1697 prior work, it is likely that much of this effort will take place “off site” from the location of
 1698 the field cage itself, with working modules shipped via clean, dust-free packaging.

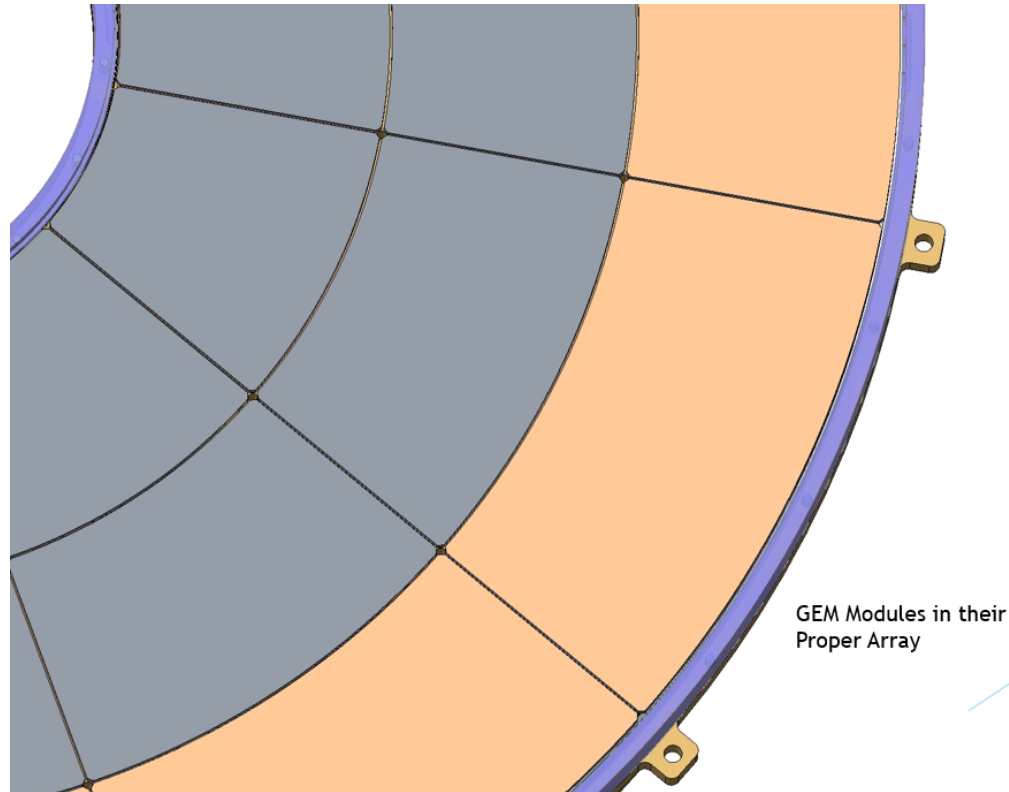


Figure 3.46: TPC modules have only $\frac{1}{16}$ " gap and localize penetration services (gas, laser, temp, pressure, ...) at the "corner points".

1699 Figure 3.46 shows the fit of the modules after assembly. a $\frac{1}{6}$ " gap is standard between all
 1700 modules Furthermore at each corner junction, the modules allow for $\frac{1}{4}$ " feed-through
 1701 allowing for gas in/out and laser signals.

1702 Figures 3.47 and 3.48 highlight the gland seals.

1703 3.5.7 TPC cooling and cabling

1704 Our cooling requirements for the TPC electronics will be significant. Although we are only
 1705 cooling $\frac{1}{2}$ as many channels as ALICE, these channels are distributed over only $\frac{1}{10}$ as much
 1706 surface area. Therefore the power required from our cooling plant will be smaller overall,
 1707 but we will need to design for very effective heat transfer to the cooling lines.

1708 Figure 3.49 shows the configuration of the cooling plant currently in use by the ALICE
 1709 experiment. The key feature of this cooling plant is that the coolant is delivered at pressures
 1710 below one atmosphere so that in the event of a leak, gas is introduced into the coolant rather
 1711 than coolant introduced into the gas. The ALICE resistor chains dissipate a significant
 1712 amount of power (8W in each of 4 resistor bars). Higher power in the resistor chain is
 1713 driven by the need for robust performance in the face of stray currents due to nearby

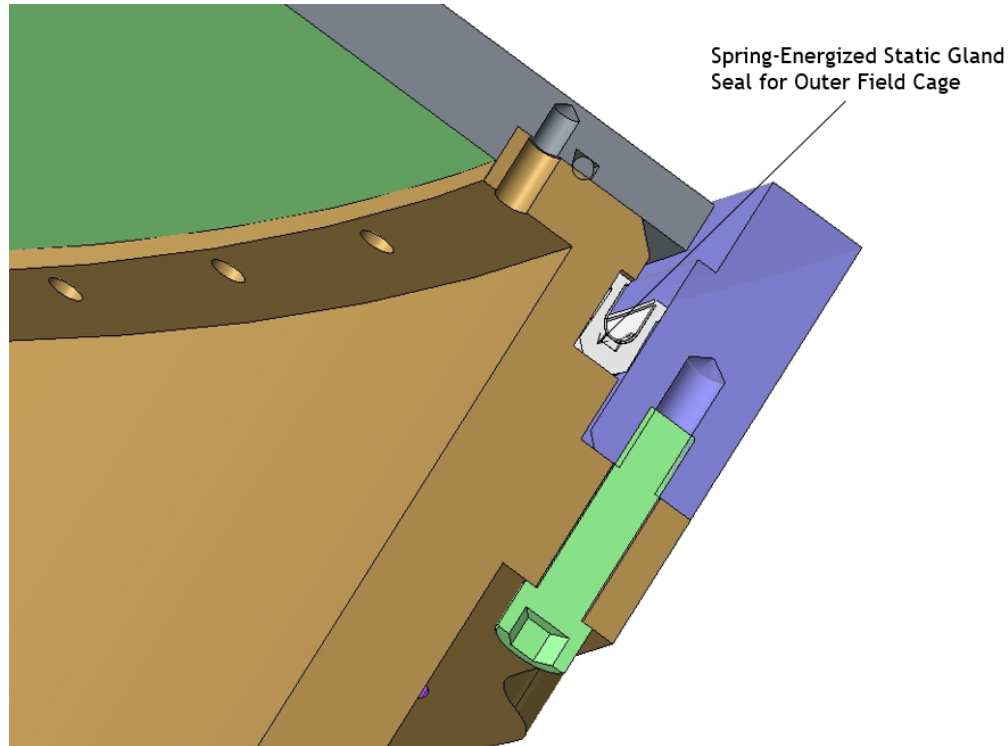


Figure 3.47: Both the inner and outer field cages avoid O-ring-induced distortions of the wagon wheel by making an annular seal. Stresses are further minimized using a spring-energized gland seal.

1714 ionization. Although the track density in sPHENIX and ALICE are very similar, the charge
 1715 load onto the ALICE TPC frame is much higher. Among STAR, ALICE, and ILC, only
 1716 ALICE water cools their resistor chain. Since our power dissipation will be the least of
 1717 these three applications, we are safest to not water cool the resistor chain, and thereby
 1718 preclude from the outset the risk of water leaking into the chamber. Our resistor chain
 1719 design dissipates ~ 1 Watt.

1720 The cable plant for the TPC includes a pair of shielded coaxial high voltage leads whose
 1721 diameter will be under $\frac{1}{2}$ " (e.g. Dielectric Sciences 2125: 100 kV; \varnothing 0.4"). Each sector will
 1722 receive bias for the GEMstack as 8 independent voltages. The readout cards, will receive
 1723 DC power input, optical connections for slow control and optical connections for data
 1724 output. To the extent possible, this significant cable plant will be localized so as to align
 1725 with the end cap spokes, to minimize the radiation depth for the end cap detector systems.

1726 3.6 TPC installation and calibration

1727 The assembly order for sPHENIX specifies that the TPC will be inserted from the end after
 1728 the calorimeters have already been installed onto the magnet.

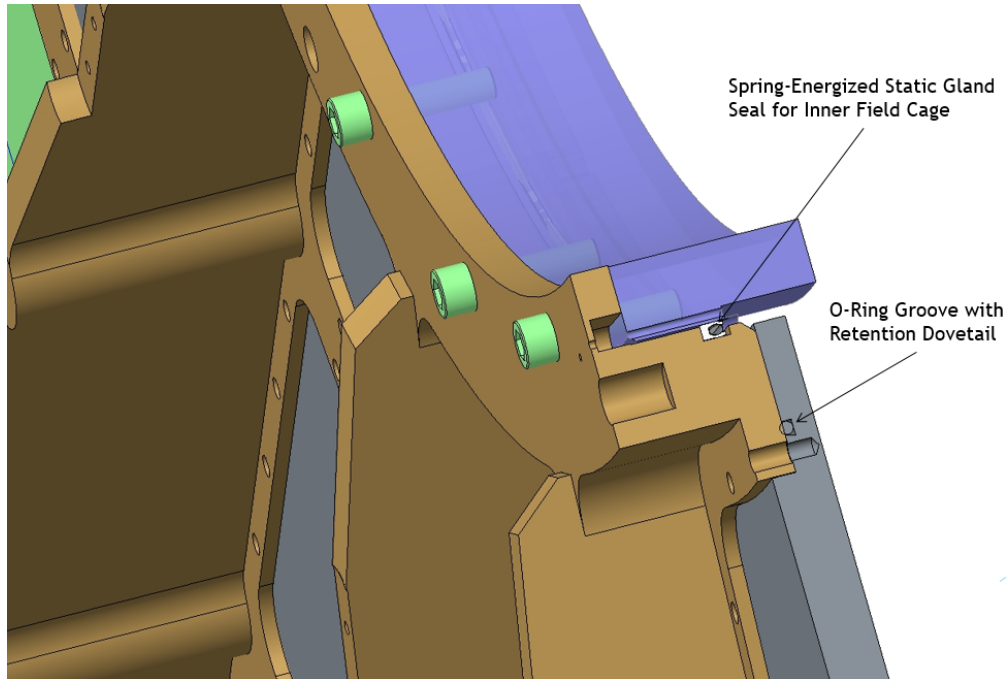


Figure 3.48: Schematic layout of TPC main elements.

1729 TPC calibration will be achieved using a laser system, similar in philosophy to that used
 1730 by STAR and prototypes for the ILC. Because the work function of aluminum is low, a
 1731 UV flash will release electrons. Both the STAR TPC and the ILC TPC prototype used a
 1732 pattern of aluminum applied to the central membrane to produce these reference tracks.
 1733 The pattern used by STAR consists of lines shown in Figure 3.50, whereas that of the
 1734 ILC was a pattern of dots. The laser system will not only provide an initial reference
 1735 calibration, but can be fired at regular intervals (PHENIX fires their EMCAL laser at 1 Hz)
 1736 during data collection to provide a continuous calibration of the drift velocity and space
 1737 charge distortions. Gain calibrations can be roughly estimated using cosmic rays, but final
 1738 calibration will use collision data. In addition to the central membrane pattern, we will
 1739 shoot lasers directly through the gas at angles from the access points provides in the corner
 1740 module meeting places.

1741 3.7 Alternate TPC readout plane options

1742 As discussed previously, we are currently investigating a list of possible alternate technolo-
 1743 gies for the readout plane. These alternatives include both the possibility of changing a
 1744 classic gating grid to implement a prompt flush for positive ions (possibly resulting in a
 1745 TPC with zero ion back flow, at the cost of adding a “duty cycle”) and variations of the
 1746 scheme for the MPGD-based gas amplification stage. Already discussed is the ongoing
 1747 work to implement a hybrid μ MEGA/GEM detector that would benefit from the superior

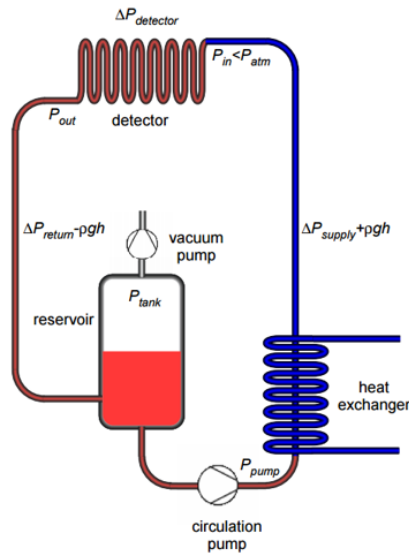


Figure 3.49: Diagram of the cooling plant in use the the ALICE TPC. The cooling plant is an under pressure system so that any leak results in gas bubbling into the coolant rather than coolant dripping into the detector.



Figure 3.50: Photograph of the central membrane of the STAR TPC. The pattern of Aluminum strips is used to release electrons via laser flash as a calibration signal.

1748 ion back flow characteristics of the μ MEGA and achieve remarkable stability by lowering
 1749 the μ MEGA gain requirements via the assistance of the GEMstack.

1750 A unique suggestion has been tested at WIS. In this case, small self-supporting hexagonal

1751 GEM stacks were developed that could be used to populate any large surface. These
1752 devices would feature the robust performance of smaller GEMs while still maintaining a
1753 nearly hermetic acceptance. The first results with the prototypes show high mechanical
1754 rigidity of the elements, not affected by the transfer electric fields.

1755 Besides providing nearly hermetic acceptance the modular solution requires a large num-
1756 ber of small GEMs that allow one to reduce the overall cost of the readout plane, but
1757 more importantly such an approach benefits from a very stringent quality control at the
1758 production stage that insures high gain and residual ion backflow uniformity across the
1759 area of the reaction plane.

Chapter 4

Electromagnetic Calorimeter

4.1 Physics Requirements

The EMCal performance is central to the direct photon and upsilon measurements and it is also a key component, along with the hadronic calorimeter, of the calorimetric jet reconstruction. In this section the photon and upsilon requirements for the EMCal are discussed.

Direct photons and their correlation with jets are a unique probe of partonic interactions in the QGP. Photons can be the result of a hard scatter (for example $gq \rightarrow \gamma q$). The photon, not carrying color charge, does not interact strongly with the QGP and thus provides a direct measure of the momentum transfer of the hard scatter itself that is accessible in the final state. This is in contrast to dijet systems where both jets interact strongly with the QGP. Direct photon measurements in heavy ion collisions are limited by the rate of the photon production and the efficiency and purity with which the photon can be identified. Therefore, the main requirements on the EMCal from photon measurements are on the size of the acceptance and the contamination of the photon candidate cluster by energy deposited near the photon from the underlying event. As illustrated in Fig. 1.21, the photon/ π^0 discrimination is not a driver of the calorimeter performance at the momenta of interest at RHIC.

For heavy ion collisions, one goal is that the detector resolution and segmentation not be a limitation on the electron cluster reconstruction compared to the underlying event background in a central heavy ion event. A typical cluster size (a 3x3 tower array) contains about 340 MeV of underlying event energy in the EMCal (see Fig. 4.23). Using a typical Y-electron cluster of 5 GeV and the underlying event blurring to set the magnitude of the energy resolution leads to required resolution of approximately $\Delta E/E \leq 15\%/\sqrt{E}$.

For the Y, the EMCal requirements are driven by the need to reject hadrons by a matching condition between the track momentum and the EMCal energy. Hadrons misidentified as electrons will lead to an increased combinatoric background in the Y mass distribution.

1788 The design goal is to optimize the electron identification efficiency with respect to the
1789 pion rejection by the calorimeter energy matching condition. As in the photon case,
1790 central Au+Au collisions are the most challenging environment and drive the detector
1791 specifications. The physics requirement is to be able to have sufficient statistical precision
1792 to measure the suppression of the three Y states separately.

1793 4.2 Detector Design

1794 4.2.1 Design Requirements

1795 The design requirements for the sPHENIX electromagnetic calorimeter are based on the
1796 physics requirements described in the previous section. The calorimeter will play a
1797 major role in both the measurement of jets and single photons out to high p_T , as well as
1798 identifying and measuring the energies of the electrons from Y decays. In addition, the
1799 calorimeter must fit inside the BaBar magnet and allow space for the tracking system that
1800 will reside inside the calorimeter. The calorimeter should also be as compact as possible in
1801 order to minimize the overall size and cost of the hadronic calorimeter. The basic detector
1802 design requirements can be summarized as follows:

- 1803 • Large solid angle coverage (± 1.1 in η , 2π in ϕ)
- 1804 • Moderate energy resolution ($\leq 15\%/\sqrt{E}$)
- 1805 • Fit inside BaBar magnet
- 1806 • Occupy minimal radial space (short X_0 , small R_M)
- 1807 • High segmentation for heavy ion collisions
- 1808 • Minimal cracks and dead regions
- 1809 • Projective (approximately)
- 1810 • Readout works in a magnetic field
- 1811 • Low cost

1812 The requirement for large solid angle coverage is driven by the need to accumulate high
1813 statistics for measuring jets and single photons out to the highest p_T possible in an unbiased
1814 way using full jet reconstruction over the entire central rapidity region. The requirement
1815 for the energy resolution is determined by achieving the best resolution possible consistent
1816 with the contribution to the energy resolution from the underlying event in central heavy
1817 ion collisions. The energy from the underlying event also requires the tower size to be

1818 small ($\sim 1 R_M^2$) in order to minimize the background contribution for measuring the jet
 1819 energy or the electron energy from Υ decays. This then also determines the minimum
 1820 inner radius of the calorimeter and the required level of segmentation. The current design
 1821 places the inner radius of the calorimeter at 90 cm and has a segmentation of 0.025×0.025
 1822 in $\Delta\eta \times \Delta\phi$, which leads to $96 \times 256 = 24,596$ towers over the full rapidity and ϕ range.
 1823 Figure 4.1 shows the energy deposition in the sPHENIX calorimeter system as a function
 1824 of the geometric position in the detector. In Figure 4.23, this is quantified in terms of
 1825 the distribution of energy in single calorimeter towers and in 3×3 tower sums for central
 1826 Au+Au HIJING events. The average energy for the tower sum is ~ 340 MeV.

1827 The requirement for minimal gaps and dead regions is driven by the need to measure jets
 1828 over a large solid angle with good uniformity. Gaps are particularly undesirable since they
 1829 can lead to missing energy for the electromagnetic component of the shower.

1830 Projectivity in two dimensions (2-D proj.) is desired for the upsilon program. With a
 1831 one dimensionally projective calorimeter (i.e., projective in ϕ only, or 1-D projective), the
 1832 pion rejection at fixed electron efficiency degrades with increasing $|\eta|$, as electrons enter
 1833 the calorimeter at increasing angles. The resulting shower is spread through a larger
 1834 number of towers (Figure 4.20) and thus has higher contributions from the underlying
 1835 event overlapping with the cluster, blurring the electron/hadron separation. At 70%
 1836 electron efficiency the pion rejection degrades from a factor of 100 in the two dimensionally
 1837 projective case to 60 for $0.7 < |\eta| < 0.9$ (see the discussion of Figure 4.25). This results in an
 1838 increase in the combinatoric background and a corresponding decrease in the statistical
 1839 power of the upsilon measurements from that shown in Figure 1.18

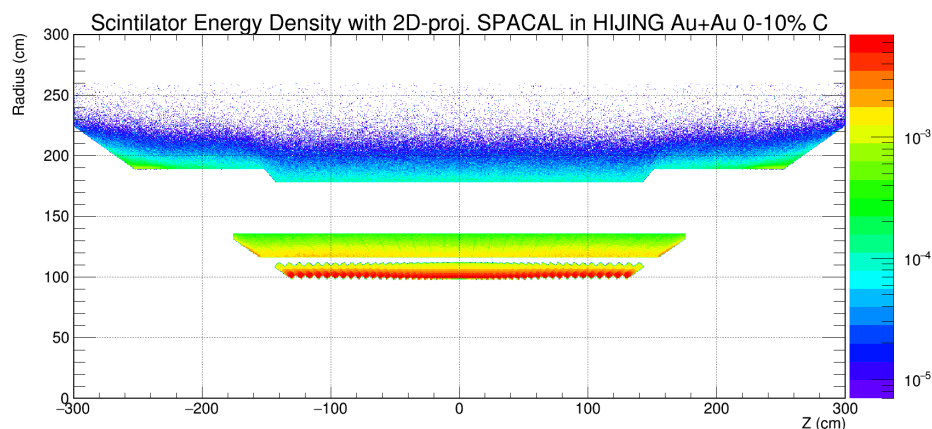


Figure 4.1: Visible energy density in the sPHENIX calorimeter systems in central Au+Au collisions. The electromagnetic calorimeter at radius of ~ 100 cm observes a high amount of background energy density, which is quantified in Figure 4.23 in a later section. Each block of the EMCAL consists of two towers in the z -direction.

1840 The technology chosen for the EMCAL utilizes an absorber consisting of a matrix of

1841 tungsten powder and epoxy with embedded scintillating fibers (W/SciFi), similar to
1842 the SPACAL design that has been used in a number of other experiments [127, 128, 129,
1843 130, 131]. In order to work inside the magnetic field, the readout will utilize silicon
1844 photomultipliers (SiPMs), which provide high gain and require minimal space. The
1845 readout will digitize the SiPM signals and also provide a trigger for high energy electrons
1846 and photons. The W/SciFi absorber matrix was developed at UCLA and has been tested
1847 several times in test beams at Fermilab [132, 133]. The matrix is formed by preparing
1848 an assembly of 0.47 mm diameter scintillating fibers, held in position by a set of metal
1849 meshes. The nominal center to center spacing of the fibers is 1.0 mm. The fiber assembly is
1850 encapsulated in a mixture of tungsten powder and epoxy, which is compacted by vibration
1851 to achieve a density $\sim 9\text{-}10\text{ g/cm}^3$. This results in a sampling fraction $\sim 2.3\%$ with a
1852 radiation length $X_0 \sim 7\text{ mm}$ and a Molière radius $R_M \sim 2.3\text{ cm}$.

1853 The design of the EMCal is being developed with the use of simulations, tests of individual
1854 calorimeter components, development of a complete mechanical design, and the construc-
1855 tion and evaluation of several prototype calorimeters that are being studied along with the
1856 hadronic calorimeter in a series of beam tests. These various efforts of the EMCal design
1857 are described in the sections below.

1858 4.2.2 Block Design and Construction

1859 The full scope of the EMCal will require a total of 24576 towers, in 6144 blocks, each
1860 of which contains 2×2 towers. The manufacturing of such a large number of blocks is
1861 at an industrial scale. The Nuclear Physics Group at UIUC has significant production
1862 capabilities and expertise in producing detector components of this type. They have, in
1863 fact, built a similar tungsten-scintillating fiber calorimeter in the past in connection with
1864 the g-2 experiment [134]. Through our R&D program they have now developed extensive
1865 expertise and experience in producing the absorber blocks (see Section 4.4).

1866 The procedure to fabricate the blocks is as follows. First the fibers are cut to the desired
1867 length. Then the fibers are filled into the screens (see Figure 4.2 for a drawing of a typical
1868 screen) as they are supported by a 3D printed holder placed at the top of a plastic cup
1869 which is used as a support structure (see Figure 4.3). Each block contains 2668 fibers. When
1870 the screens have been verified to be filled the fiber assembly is placed in a mold with
1871 machined slots to hold the screens in the proper place. The fibers are brought away from
1872 the edges of the mold near the read out end in order to make the area of the light collecting
1873 surface the same for all the block shapes (see Figure 4.4). This improvement allows for
1874 a single light guide size to be used for all block shapes. Additionally, it brings the fibers
1875 away from the edges of the light guides where the light collection efficiency is lower. The



Figure 4.3: Photo of the fiber filling assembly.

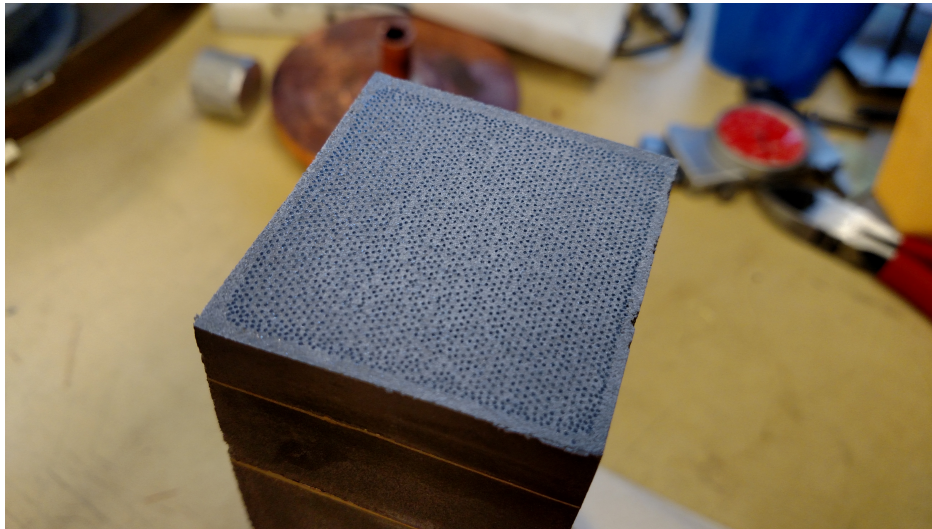


Figure 4.4: Photo of a cast block with the fibers on the read out end of the block moved away from the edge of the block to make the size of the light collection area the same for all block shapes.

1889 4.2.3 Module and Sector Design

1890 The EMCal will consist of 64 sectors (32 azimuthal \times 2 longitudinal) that are supported by
1891 the inner HCal. Figure 4.7 shows the installation of an EMCAL sector on the Inner HCal.
1892 Each sector will subtend 11.2 deg in ϕ and cover 1.1 units in η . They will be supported by

Material	Property	Value
Tungsten powder	THP Technon 100 mesh	
	Particle size	$\leq 100 \mu\text{m}$
	bulk density (solid)	$\geq 18.50 \text{ g/cm}^3$
	tap density (powder)	$\geq 11.25 \text{ g/cm}^3$
	purity	≥ 99.9 percent W
Scintillating fiber	impurities (≤ 0.1 percent)	Fe, Ni, O ₂ , Co, Cr, Cu, Mo
	Kuraray SCSF78 (blue)	
	fiber diameter	0.47 mm
	cladding	single
	core material	polystyrene
	cladding material	polymethylmethacrylate
	emission peak	450 nm
	decay time	2.8 ns
	attenuation length	≥ 4.0 m
	Epoxy	Epo-Tek 301
pot life		1-2 hours
index of refraction		1.519 at 589 nm
spectral transmission		≥ 99 % at 382-980 nm

Table 4.1: EMCal module component materials



Figure 4.6: 2D projective block produced at Illinois.

1908 $0.83\lambda_{int}$.

1909 Figure 4.9 shows the layout of the absorber blocks inside an EMCAL sector along with
 1910 the internal electronics and cooling. Each module forms a slice in ϕ that gradually tilts
 1911 along the z axis in order to project back to a position near the vertex at larger rapidity. The
 1912 96 blocks for each sector are glued to a sawtooth support structure, shown in Fig. 4.10,

Parameter	Units	Value
Inner radius (envelope)	mm	900
Outer radius (envelope)	mm	1161
Length (envelope)	mm	$2 \times 1495 = 2990$
tower length (absorber)	mm	144
Number of towers in azimuth ($\Delta\phi$)		256
Number of towers in pseudorapidity ($\Delta\eta$)		$2 \times 48 = 96$
Number of electronic channels (towers)		$256 \times 96 = 24576$
Number of SiPMs per tower		4
Number of towers per module		$2 \times 8 = 16$
Number of modules per sector		24
Number of towers per sector		384
Number of sectors		$2 \times 32 = 64$
Sector weight (estimated)	kg	326
Total weight (estimated)	kg	20890
Average sampling fraction		2.3%

Table 4.2: Key parameters of the EMCal modules and sectors

1913 that is attached to a metal plate (strong back) that is attached to the rail system which is
 1914 mounted on the inner surface of the Inner HCal. The entire sector is enclosed in a thin
 1915 walled stainless steel box that provides overall support and light tightness. Figure 4.11
 1916 shows a cross section of the sector showing the location of the absorber, the light guides,
 1917 front end electronics and cabling. The towers are read out from the front at the inner radius
 1918 of the detector. This allows access to the electronics from inside the magnet through a
 1919 removable cover on the sector enclosure.

1920 4.2.4 Light Guides

1921 Light guides are used to optically couple the SiPMs to the readout surface of the calorimeter
 1922 blocks. Each light guide will define a readout tower. The surface area of a single tower is
 1923 roughly $19.8 \text{ mm} \times 19.8 \text{ mm} = 392 \text{ mm}^2$, while the combined active area of the 4 SiPMs
 1924 is $4 \times (3 \text{ mm} \times 3 \text{ mm}) = 36 \text{ mm}^2$, so only 9 % of the active area is covered by the optical
 1925 sensors. The severe space limitations inside the sector require the use of a very short light
 1926 guide, and considerable effort was spent by using optical ray tracing simulations and
 1927 actual measurements in the lab to optimize its design. In the end, it was found that a simple
 1928 trapezoidal design gave the best overall light collection efficiency ($\sim 15 \%$ for the 4 SiPMs)
 1929 and was the simplest to construct. Figure 4.12 shows the final design of the light guide.

1930 However, because we require $\sim 25\text{K}$ individual light guides for all the towers, and the
 1931 cost for machining such a larger number was prohibitive, it was necessary to find a cost
 1932 effective method for producing them. The solution in the end was to produce them by

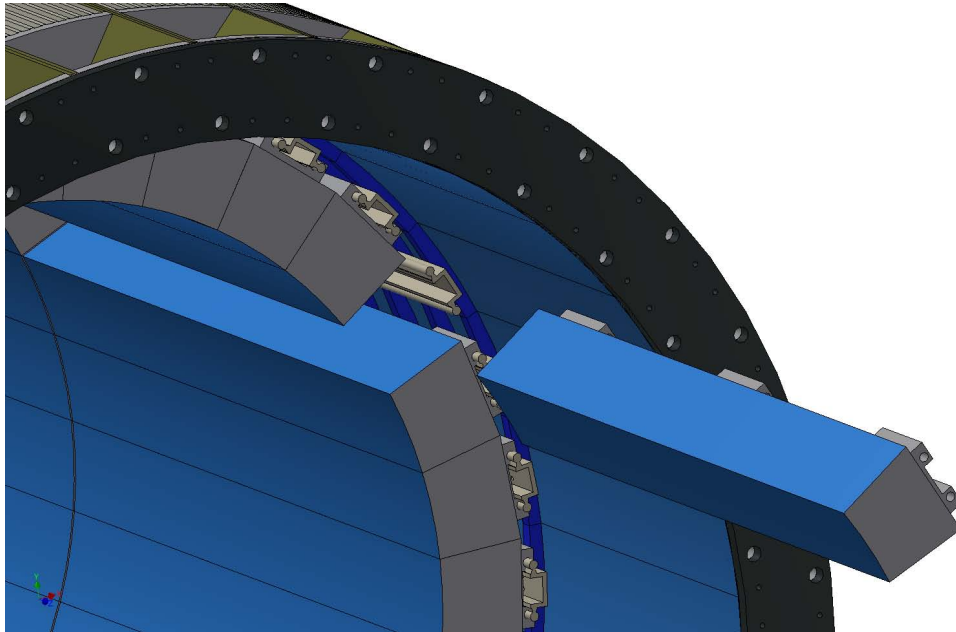


Figure 4.7: EMCal sector showing installation on the Inner HCAL.



Figure 4.8: Drawings showing the projectivity of the EMCal blocks along the beam direction (left) and in ϕ (right).

1933 injection molding using a UV transmitting acrylic, but it required a very specialized process
 1934 to produce optical quality parts using this method. This process was finally successfully
 1935 developed by a company that specializes in high precision injection molding (NN, Inc. in
 1936 East Providence, RI). The result was very high quality light guides at a price of \sim \$10 a
 1937 piece. Figure 4.13 shows some samples of the light guides after they are produced with the
 1938 injection molding sprue still attached, after machining and finally glued onto the absorber
 1939 block. Silicone cookies are then used to optically couple the SiPMs to the light guides.

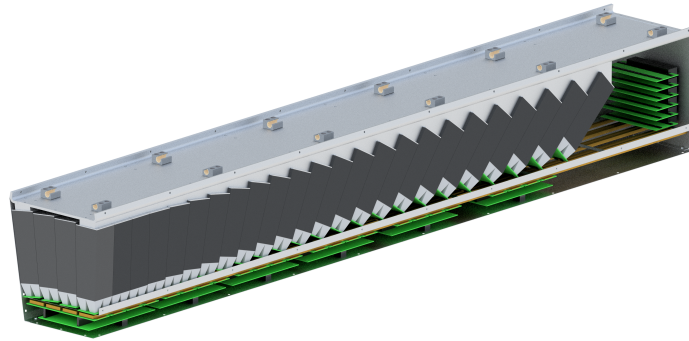


Figure 4.9: EMCAL sector showing internal block layout, electronics and cooling.

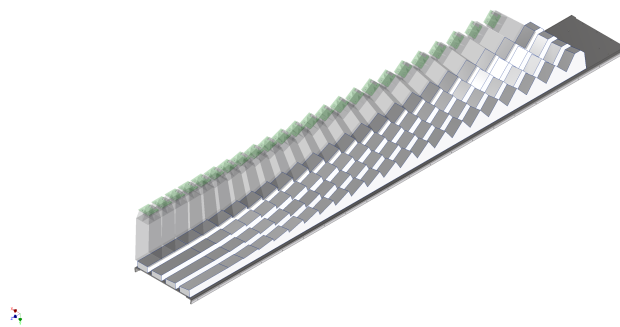


Figure 4.10: Sawtooth support structure used to support the blocks inside the EMCAL sector.

1940 4.2.5 Sensors

1941 The photosensor selected for the EMCAL is the Hamamatsu S12572-015P SiPM, or Multi
 1942 Pixel Photon Counter (MPPC), described in detail in the Electronics - 6.1 Optical Sensors
 1943 section of this document. This device will be used for both the HCal and EMCAL. The
 1944 EMCAL will use a 2x2 arrangement of 4 SiPMs per tower, passively summed into one
 1945 preamp/electronics readout channel. Figure 4.14 The 4 SiPMs will be gain-matched
 1946 (selected) and will share a common bias voltage.

1947 4.2.6 Electronics

1948 The readout electronics for the EMCAL consists of the analog front end, slow controls,
 1949 digitizers and power distribution system. The EMCAL Preamp Board consists of an 8×2

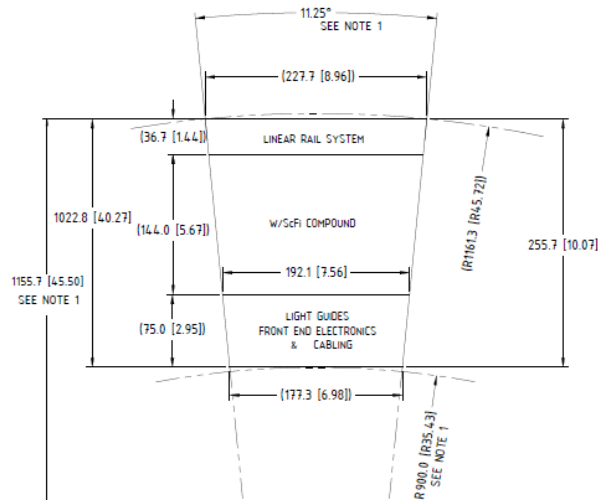


Figure 4.11: Cross sectional drawing of an EMCal sector.

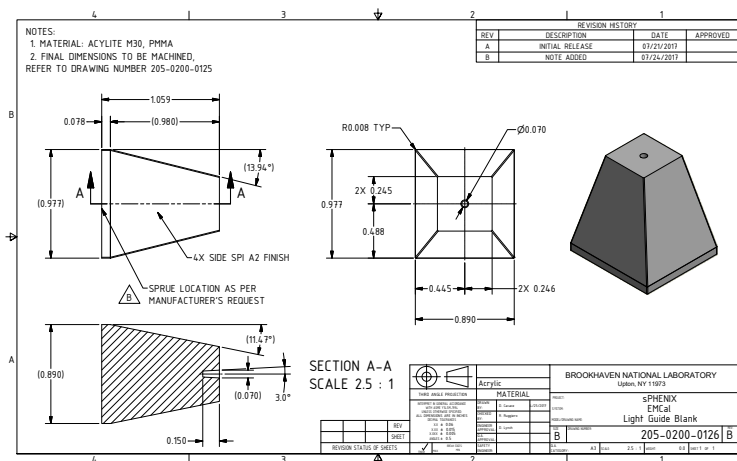


Figure 4.12: Final design for the EMCal light guides.

1950 array of preamplifier circuits that are laid out to match the geometry of the light guides.
 1951 The Preamp Boards are mounted directly to the light guides. The analog signals from each
 1952 of the four SiPMs associated with an EMCal tower are passively summed into one readout
 1953 channel. The analog sum signal is amplified with a common-base transistor amplifier,
 1954 shaped with a 30 ns peaking time and driven differentially to digitizer electronics located
 1955 near the detector. The analog signals are digitized with a Flash ADC operating at 6 times
 1956 the beam crossing (BCO) frequency and stored in a digital pipeline with a 40 BCO latency.
 1957 Upon receipt of a Level-1 (L1) trigger, the digital wave form is transferred to a readout
 1958 buffer capable of buffering up to 5 events for readout to the data acquisition system via a

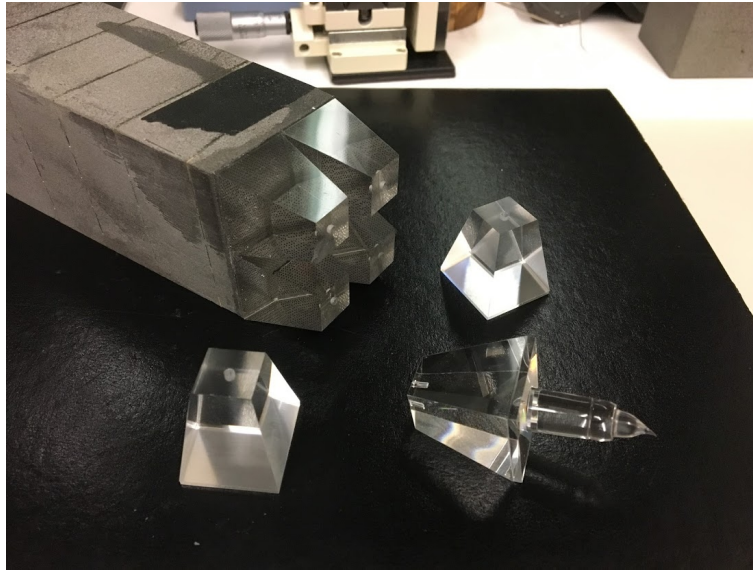


Figure 4.13: Light guides produced by injection molding showing parts after removal from the mold, after machining and finally glued onto absorber block.

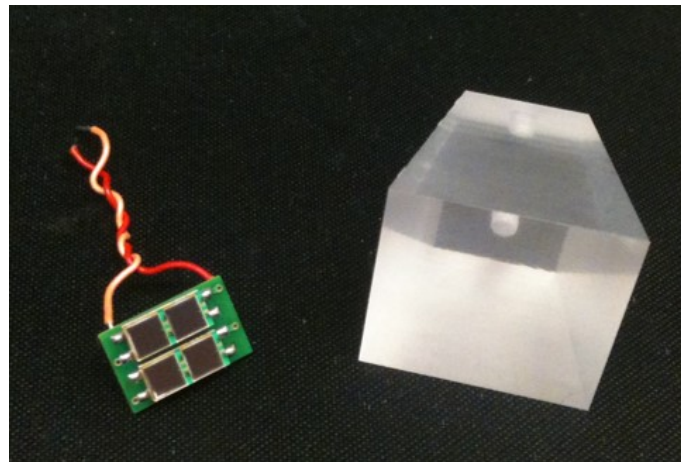


Figure 4.14: Four-SiPM PCB and lightguide. The SiPMs will be optically coupled to the narrow end of the light guide using a clear silicone adhesive.

1959 high speed optical link. The digitizer boards also compute trigger primitives which are
 1960 transmitted to the Level-1 trigger system through independent optical fiber links. Full
 1961 details of the calorimeter electronics can be found in Chapter 6.

1962 4.2.7 LED Calibration

1963 Pulsed LEDs (450 nm), mounted on the SiPM side of the preamp PCB, and projecting light
1964 into the lightguides, will be used to calibrate the detector channels and monitor gain drift.

1965 4.2.8 Cooling

1966 The gain of the SiPMs have a strong dependence on temperature and we therefore need to
1967 stabilize and monitor their temperature during operation. In addition, we expect the dark
1968 current in the SiPMs to increase significantly due to exposure to neutrons over the course
1969 of running for several years. From measurements done in the PHENIX experimental hall,
1970 we expect that the total neutron exposure in a year of running may reach $\sim 10^{10}$ n/cm²
1971 and the dark currents to reach up to several hundred μ A per device. We therefore need to
1972 provide additional cooling to reduce the noise as it increases over time. A liquid cooling
1973 system is being designed that will cool both the preamps and the SiPMs themselves This
1974 system is integrated with the readout electronics and cabling scheme inside the sector and
1975 is designed to fit in the ~ 7 cm of radial space, as shown in Fig 4.11. A prototype version
1976 of this cooling system has been designed and implemented in the V2.1 EMCAL prototype
1977 described below and will be tested along with the detector in the test beam.

1978 4.3 Simulations

1979 4.3.1 Introduction

1980 Both the 2D and the 1D SPACAL designs have been implemented in detail using the
1981 sPHENIX analysis framework and GEANT4. The 1D implementation allows for verifying
1982 the simulation with existing test beam data. A large set of calorimeter simulations has
1983 been run with the aim of defining design goals and quantifying detector and physics
1984 performance. The basic features of the simulation setup are as follows:

- 1985 • Both the 1D and 2D projective EMCAL designs are implemented in a full detector
1986 simulation of sPHENIX. The structure of the SPACAL in simulation is detailed to
1987 each of the 20M fibers (including core and cladding) to properly study the shower
1988 sampling.
- 1989 • The simulation is based on GEANT4 v4.10 [135] with the QGSP_BERT_HP physics
1990 list.
- 1991 • The default GEANT4 Birks correction model for scintillation light production [135]
1992 with Birks constant $k_B = 0.0794$ mm/MeV [136] is implemented.

- 1993 • The mean number of photoelectrons per GeV of total energy deposit is 500. The
1994 observed number of photoelectrons follows a Poisson distribution.
- 1995 • The pedestal width is taken to be 8 photoelectrons with a zero-suppression of 16
1996 photoelectrons per EMCal tower, based on the experience of the EIC eRD1 beam test
1997 with the SPACAL [132].
- 1998 • The sPHENIX offline analysis framework is used to handle the conversion of the
1999 ADC value to measured energy, group towers into EMCal clusters, and match with
2000 tracks.

2001 Event displays for a single tower and full EMCal are shown in Figure 4.15 and 4.16,
2002 respectively.

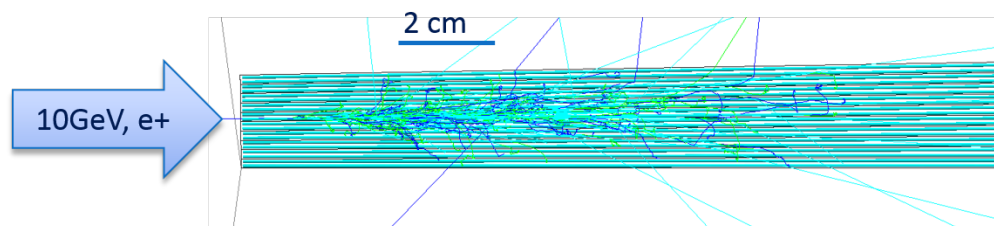


Figure 4.15: Event display of a 10 GeV positron shower in a single SPACAL tower. Scintillation fibers as embedded in the module are also shown, while the absorber material is not displayed.

2003 4.3.2 Verification of Simulation

2004 The simulation was initially verified with data from the EIC eRD1 beam test of the 1D
2005 projective SPACAL prototype [132]. As shown in Figure 4.17, the simulation and data
2006 agree quite well for three choices of beam energies:

- 2007 • The measured energy resolution for electron showers is reproduced in simulation
2008 within 10%.
- 2009 • A 10% contribution of muons is expected in the test beam with a “non-electron”
2010 Čerenkov cut. Likewise a small amount of electrons and other beam background are
2011 suggested by the data.
- 2012 • The simulated hadronic shower response is consistent with data within a factor of 2
2013 across all energy bins.

2014 Even though good agreement has already been achieved with default tuning of the sim-
2015 ulation, further improvements were made to improve the fidelity of measurements to
2016 simulation:

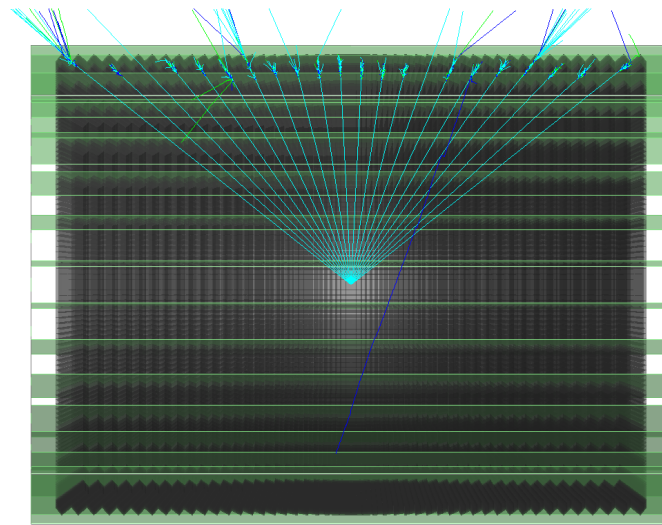


Figure 4.16: Simulation display of a half cut view of the 2D projective EMCAL. The SPACAL modules (2x8 towers each) are display in gray; the stainless steel enclosure box is displayed in green.

- 2017 • The Birks constant for the fiber core material has been tuned. Preliminary tests
2018 showed that a higher Birks constant than the one found by the CALICE experi-
2019 ment [137] can significantly improve the agreement for the hadronic shower compo-
2020 nent.
- 2021 • Implementation of fiber-to-fiber light collection efficiency variations which account
2022 for measured variation in the response of the calorimeter as a function of the position
2023 of the incident particle.

2024 An extensive beam test of a section of a prototype sPHENIX electromagnetic calorimeter
2025 around zero pseudorapidity has been carried out the Fermilab Test Beam Facility with a
2026 wide variety of incident particles, energies, and track position and angle. These results
2027 have been submitted for publication[138] and have shown excellent agreement between
2028 simulation and measurements. A beam test of a higher pseudorapidity slice of the EMCAL
2029 has been carried out in February, 2017, and a second paper is being prepared on the results,
2030 but preliminary analysis has demonstrated equally good agreement with simulation.

2031 4.3.3 Sampling Fraction

2032 In the W-epoxy and scintillator fiber structure, only energy deposition in the core of fiber
2033 is visible via detection of scintillation light, which represent a small fraction of the total
2034 shower energy. The sampling fraction is around 2.4% as shown in Figure 4.18 with two

2035 choices of typical showers: 4 GeV electrons as typical Y decay products; and 24 GeV
2036 photons as typical for γ -jet measurements. The higher energy showers are sampled with
2037 lower sampling fraction as the shower moves deeper into the calorimeter, where the fibers
2038 have larger spacing due to the projectivity.

2039 4.3.4 Lateral Shape of Showers

2040 To study the property of EM shower in the W-epoxy and scintillator fiber structure, the
2041 lateral extension of the EM shower is quantified in Figure 4.19, by histogramming all
2042 scintillator GEANT4 hits with their distance to the projection of the incoming 4 GeV
2043 electrons (as typical Y decay products in the central pseudorapidity). The Molière radius is
2044 about 2 cm in order to contain 90% of the EM shower. A 3×3 EMCal tower-cluster contains
2045 about 95% of the EM shower. For pion showers in the EMCal, which the calorimeter system
2046 is designed to reject, the same 3×3 EMCal tower-cluster contains about 50% of the shower
2047 energy, which helps to improve the efficiency of the E/p cut. The inner hadron calorimeter
2048 (HCal) immediately behind the EMCal is used to catch the tails of the pion shower in
2049 order to veto hadrons. A 3×3 inner HCal tower-cluster can contain 60% of the energy
2050 of the pion shower tail. These simulation served as a guild line for the choice of tower
2051 size for both EMCal and inner HCal, as the choice of tower segmentation is optimized for
2052 the shower containment in 3×3 tower-clusters, and a finer towering structure would not
2053 significantly improve the clustering.

2054 The shower size is also quantified using towers of 1-D and 2-D SPACAL as shown in
2055 Figure 4.20. For a 2-D projective SPACAL, despite the fact that the towers are shifted along
2056 the longitudinal direction (as illustrated in Figure 4.1 and ??), a circular distribution of
2057 towers for the EM shower is observed around the track projection for both central and
2058 forward pseudorapidity. This leads to a round-shaped cluster with a minimal number of
2059 towers necessary to contain an EM shower. In comparison, a shower in the 1-D projective
2060 SPACAL is spread into multiple towers along the polar direction, which leads to an
2061 elongated cluster covering more towers, as quantified in the right panel of Figure 4.20.

2062 4.3.5 Single EM Shower Performance

2063 The linearity and energy resolution for photon clusters as simulated through the full
2064 sPHENIX detector and analysis chain are presented in Figure 4.21 and 4.22.

2065 For sPHENIX γ -jet measurements, the photon clusters were simulated with the full
2066 sPHENIX detector, which produces an energy resolution better than $\sim 14\%/\sqrt{E}$ as shown
2067 on the left side of Figure 4.21. For the 1D projective SPACAL, the energy resolution im-
2068 proves as the photon shifts toward forward rapidity and the shower deposits more energy
2069 at a smaller radius and becomes better sampled.

2070 For possible use of the calorimeter in a future EIC experiment with a much thinner

2071 tracking detector, the single electron resolution without the sPHENIX silicon tracker was
2072 also simulated as on the right panel of Figure 4.21. The electron energy resolution is better
2073 than $\sim 12\%/\sqrt{E}$, which benefits from the bending of low energy electrons in the magnetic
2074 field and radially shallower showers compared with photons.

2075 As shown in Figure 4.22, the linearity for both SPACAL options is better than 3.5%, as
2076 defined as the relative deviation from $E_{\text{reco}}/E = 1$ at the maximum photon energy of
2077 $E = 50$ GeV. The linearity is improved to better than 2.0% when photons are in the forward
2078 rapidity direction, where the SPACAL becomes thicker along the path of the photon, and
2079 therefore lower back-leakage occurs. The 1D projective SPACAL yields better linearity,
2080 since the variation of the fiber density and the sampling fraction along the depth of the
2081 shower is lower.

2082 4.3.6 Occupancy

2083 The occupancy in central Au+Au collisions (the highest background event) is illustrated in
2084 Figure 4.1 and quantified in Figure 4.23. For a typical 3×3 EMCal tower-cluster in the
2085 2-D projective SPACAL, the mean background energy is 340 MeV. For the 1-D projective
2086 SPACAL at forward rapidity, a significantly larger underlying event (about 550 MeV)
2087 would be included in a cluster since electron showers would spread into more towers (as
2088 illustrated in the right panel of Figure 4.20). Meanwhile, this background presents a large
2089 tail extending to higher energy, which leads to a challenge of rejecting hadron shower for
2090 electron-ID as the logarithmically dropping hadron shower tail is shifted up in energy by
2091 this background.

2092 4.3.7 Electron Identification

2093 One key function of the EMCal is to identify the electron/positron tracks within the hadron
2094 background for the Y measurement. The energy of the electron/positron from the Y decay
2095 range from 2-10 GeV, with averages of 4.8 GeV in the central pseudorapidity to 5.7 GeV in
2096 the forward direction ($0.7 < \eta < 0.9$). The primary method of electron-identification (eID)
2097 is to match the measured track momentum with the measured cluster energy in the EMCal.
2098 Furthermore, the inner hadron calorimeter can improve the eID by vetoing track candidates
2099 with a large leakage behind the EMCal. For each track, cluster energy information from
2100 both the EMCal and inner HCal is analyzed using a likelihood method, by comparing the
2101 observed cluster energy with the EMCal-HCal two-dimensional probability distributions
2102 extracted from template samples of pure electrons and hadrons. By selecting tighter or
2103 looser cuts, the hadron rejection versus electron efficiency curves can be mapped out for
2104 each combinations of track rapidity, track momentum and SPACAL configurations.

2105 The reference electron identification performance is shown in Figure 4.24 in the single
2106 particle simulations (expected performance in $p+p$ collisions) and 4.25 in the most central

2107 Au+Au collisions (top 0-10% in centrality). These reference eID performance curves are
2108 simulated with a 1-D projective SPACAL fiber structure. Then hits in GEANT4 can be
2109 grouped around the track projection into clusters in order to estimate the performance
2110 for the 2-D projective SPACAL, or grouped radially in order to estimate the performance
2111 for the 1-D projective SPACAL. The cluster energy is sum over all energy deposition in
2112 the fiber core (prior to the Birks correction model for scintillation light production [135]),
2113 which is then scaled to the measured energy in the calorimeter with a scaling constant of
2114 $1/(\text{sampling fraction})$.

2115 In these reference studies, the 2-D projective SPACAL provided better than 100:1 pion
2116 rejection at 95% efficiency for 4 GeV electrons in $p+p$ collisions (Figure 4.24), and better
2117 than 90:1 pion rejection at 70% efficiency for 4 GeV electrons in the most-central Au+Au
2118 collisions (left panel of Figure 4.25). These pion rejection and electron efficiency values
2119 has been used to for the estimates of the Y in our reference design. We also estimate that
2120 if a 1-D projective SPACAL is used, the pion rejection at large pseudorapidities will be
2121 reduced due to the larger cluster size necessary to contain the EM-shower, as shown in the
2122 right side of Figure 4.25.

2123 Significant simulation effort has also been invested into updating these projections with
2124 a realistic setup of the SPACAL as shown in Figure 4.16, including incorporating the
2125 support/enclosure structures and the longitudinal offsets of the modules, and improved
2126 shower simulation (including the Birks scintillation model [135], photon fluctuations, and
2127 pedestal widths, which are cross-checked with test beam results as shown in Figure 4.17.
2128 When compared with the reference performance, preliminary results show improved
2129 eID performance with the suppressed hadron response in the default GEANT4 Birks
2130 scintillation model.

2131 4.3.8 Dynamic range

2132 The dynamic range required for the ADC system is studied by comparing the maximum
2133 energy deposition in a tower to the pedestal width. For a 50 GeV photon shower, a
2134 maximum of 22k photoelectrons were observed in a single tower as shown in Figure 4.26
2135 (assuming a high pixel count SiPM). To encode this maximum photoelectron count down
2136 to the pedestal noise of 8 photoelectrons, a 12-bit ADC is required. The EMCal electronics,
2137 which provides a 14-bit ADC, will satisfy this requirement.

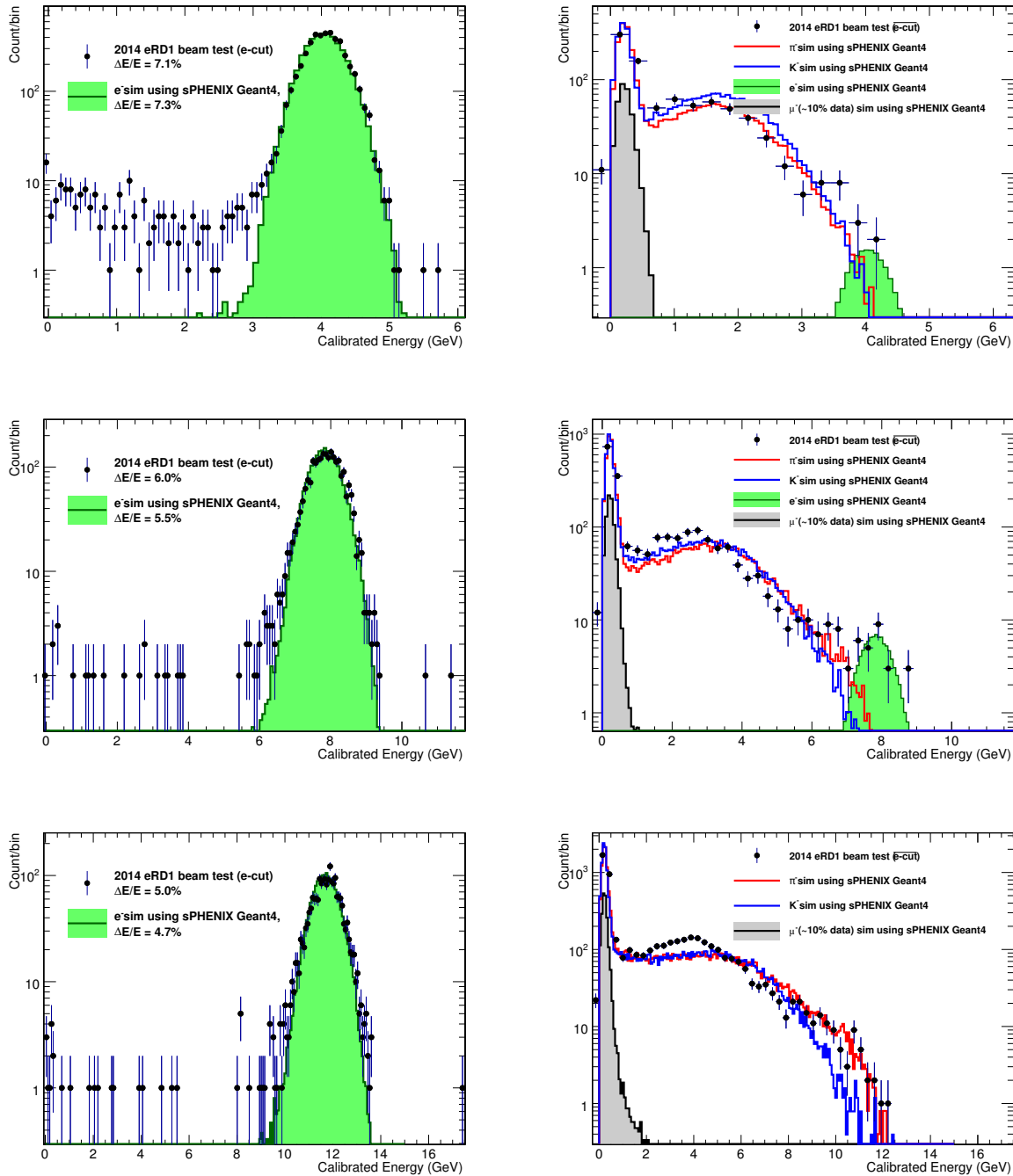


Figure 4.17: Comparison of the eRD1 beam test data and sPHENIX GEANT4 simulation for three choices of beam energies: 4.12 GeV (top), 8.0 GeV (middle) and 12.0 GeV (bottom). The left column data (black points) are with an electron requirement based on a beam Cherenkov detector, and the right column with a non-electron requirement. Curves represent simulated electrons (green), pions (red), kaons (blue) and muons (black).

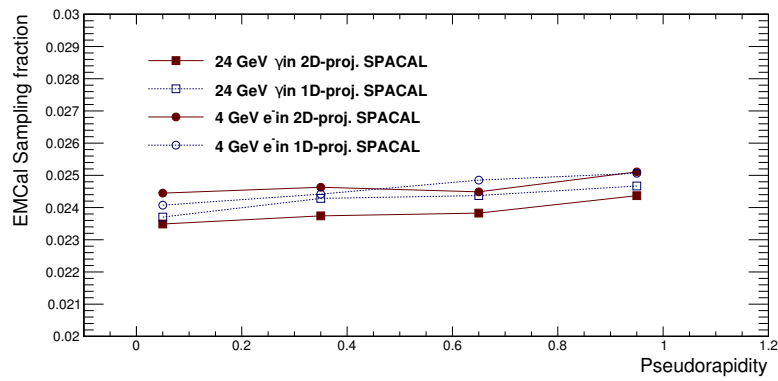


Figure 4.18: The sampling fraction of the 1D and 2D projective SPACAL as a function of pseudorapidity. Two energy ranges were chosen: the circles represent electron showers at 4 GeV, which is a typical energy for Y measurements; the squares represent photon showers at 24 GeV, which is a typical energy for γ -Jet measurements.

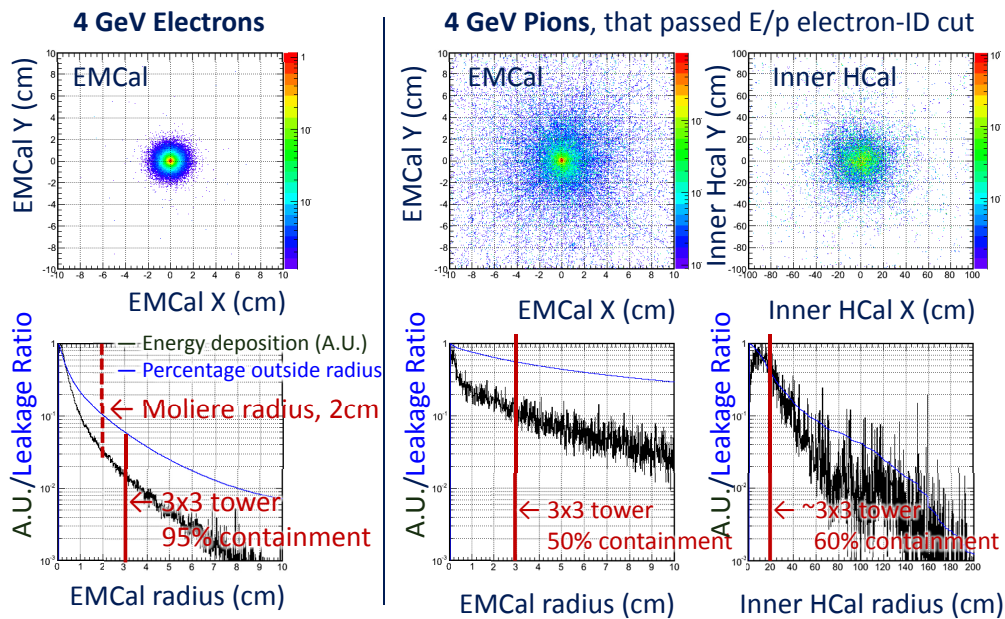


Figure 4.19: The lateral expansion of 4 GeV electron showers in the EMCAL (left column), which is compared with 4 GeV negatively charged pion showers in the EMCAL (middle column) and in the inner HCal (right column). The center, $(X, Y) = (0, 0)$ cm, denotes the projection of the electron track. Then the energy deposition of all scintillator hits in GEANT4 is histogrammed versus the lateral distance from the track projection. The top row shows the energy deposition density in the 2-D lateral dimension, and the bottom row shows the energy density (black) and the shower leakage ratio (blue) vs. lateral radial distance.

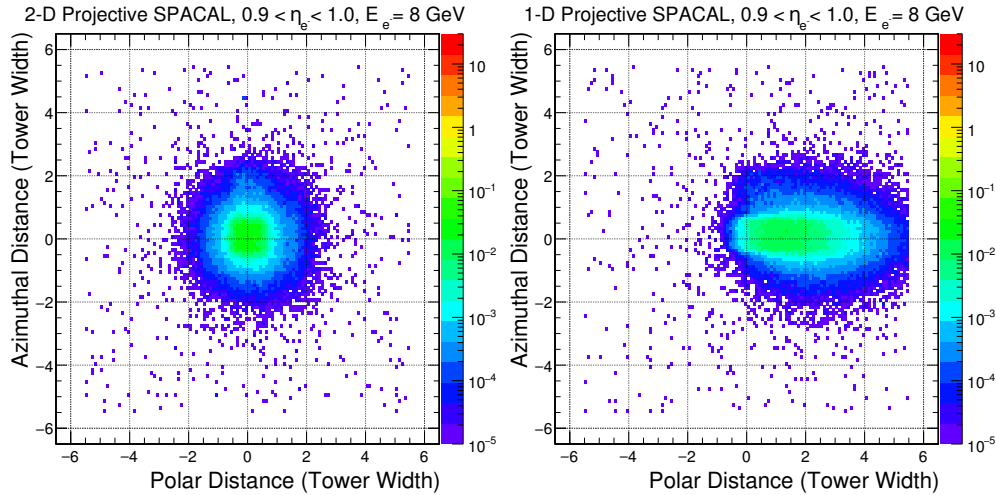


Figure 4.20: For very forward pseudorapidity, the lateral distribution of 8 GeV electron showers as observed in the 2-D projective (left) and 1-D projective (right) SPACAL towers. The polar (X-axis) and azimuthal (Y-axis) distances are defined as the distance between the tower and the electron track projection, in the unit of tower width.

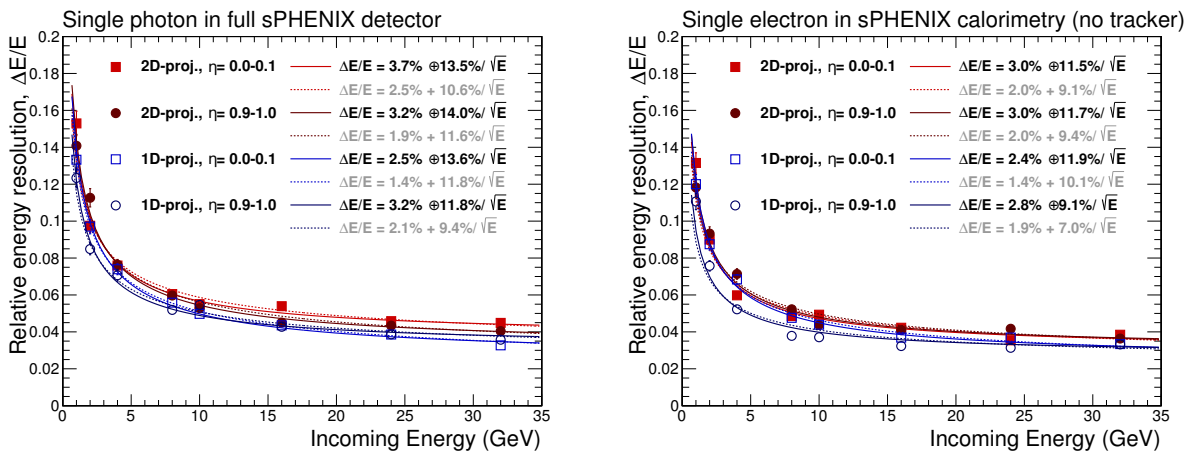


Figure 4.21: Left: the energy resolution for single photon clusters as reconstructed with the fully simulated sPHENIX detector, right: the energy resolution for single electron clusters as reconstructed with the sPHENIX calorimeters only (no silicon detector before ECal). Two formulas were used to fit the resolution points: a quadratic sum of linear and statistical terms (solid line) and a linear sum of the two (dash line). Both 1D (blue curves and open points) and 2D (red curves and closed points) SPACAL options are presented.

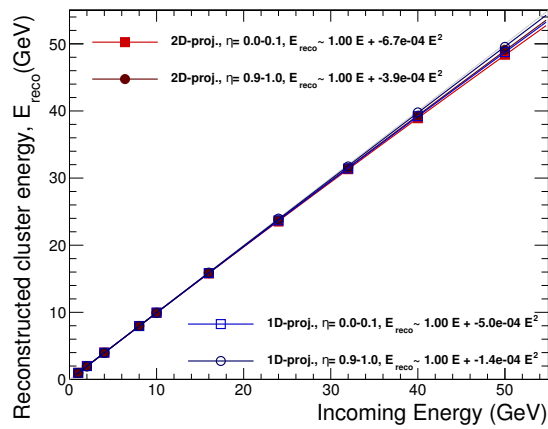


Figure 4.22: Linearity for single photon clusters as reconstructed with the full sPHENIX detector simulation and analysis chain. The linearity is calibrated for each pseudorapidity region to 1 at the low energy end, while the non-linearity towards the high energy end is quantified via a quadratic fit.

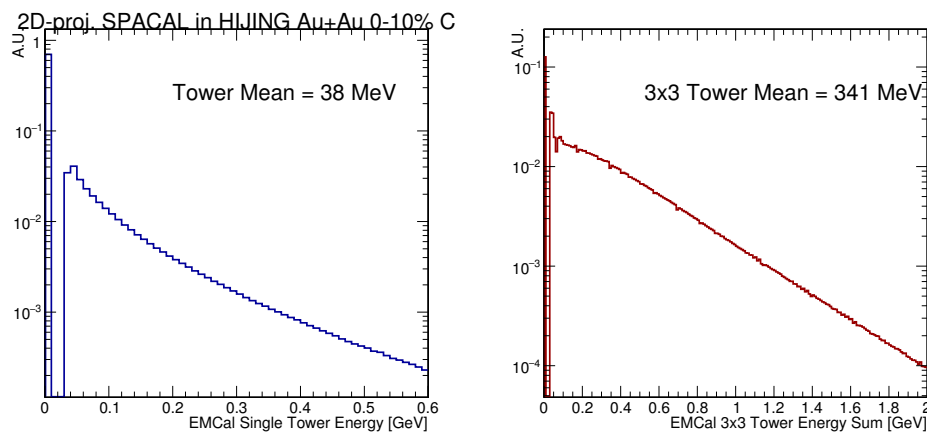


Figure 4.23: a) Energy per tower ($\sim 1R_M^2$) for central Au+Au HIJING events, b) Mean energy for a 3×3 EMCal tower-cluster. The 2-D projective SPACAL configuration is shown here.

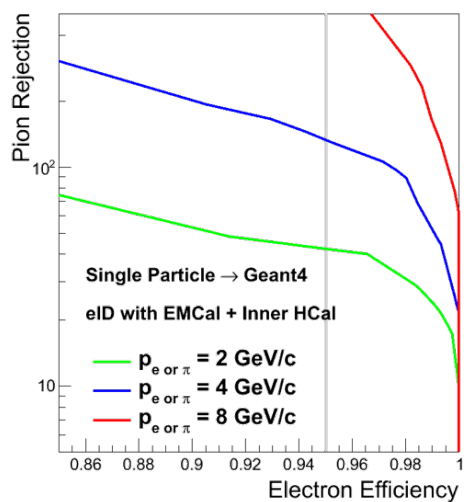


Figure 4.24: Pion rejection vs. electron identification efficiency for a single particle simulation for the 2-D projective SPACAL, which represents the performance for $p+p$ and EIC collisions.

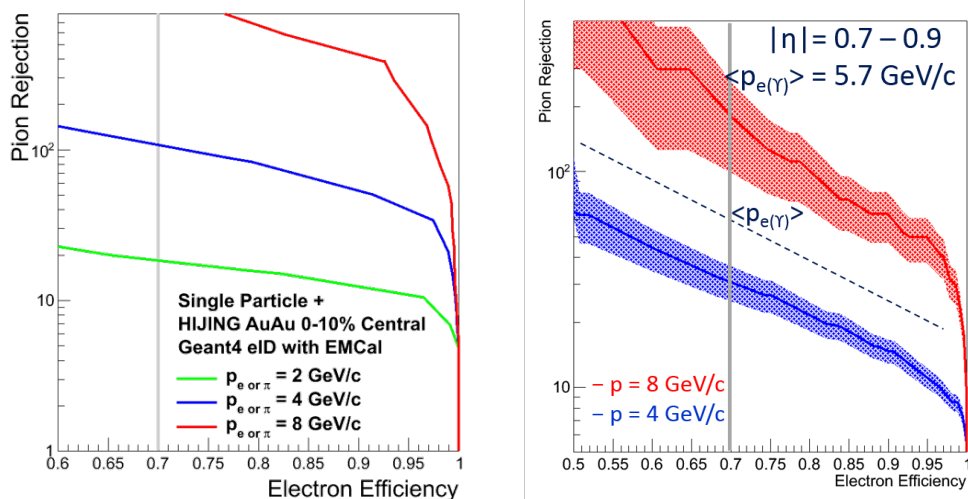


Figure 4.25: The pion rejection vs electron identification efficiency for the 2-D projective (left) and 1D-projective (right) SPACAL in central Au+Au collisions (0-10% central).

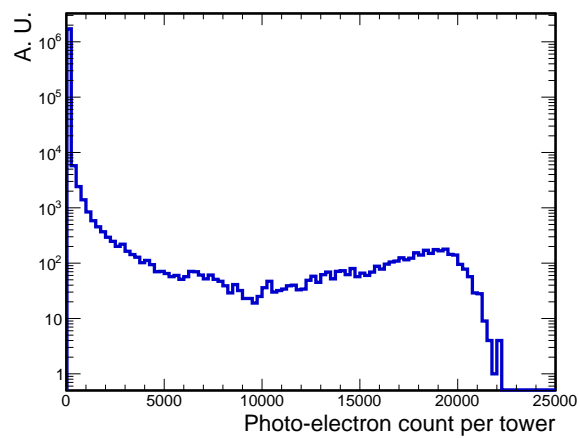


Figure 4.26: Number of photoelectrons per tower for 50 GeV photons as the maximum energy shower targeted by this calorimeter system. To encode the maximum photoelectron count down to the pedestal noise level, a 12-bit ADC is required.

2138 4.4 Prototyping and Testing

2139 Over the past 3 years, several prototypes of the EMCAL have been built and tested in
2140 order to study its design and improve its performance. These prototypes have evolved
2141 from the original 1D projective UCLA design to the 2D projective design that is in the
2142 current design of the sPHENIX detector. Each of these prototypes was tested in the beam
2143 at the Fermilab Test Beam Facility (FTBF) in order to measure their energy resolution,
2144 linearity and other key performance parameters. They each were tested in a stand alone
2145 configuration where the EMCAL prototype was studied in detail by itself, and also in
2146 combination with prototypes of the Inner and Outer HCALs to simulate the final sPHENIX
2147 configuration. The sections below give a brief summary of the results from these tests.

2148 4.4.1 1D Projective Prototype (V1)

2149 The first EMCAL prototype (V1) consisted of 1D projective blocks similar to the blocks that
2150 will be used in the detector for the most central rapidity range. The blocks were essentially
2151 copied from the original UCLA design and consisted of a combination of blocks produced
2152 at UIUC and by the company that supplied the tungsten powder for all of the blocks we
2153 produced so far (Tungsten Heavy Powder). The prototype consisted of an 8×8 array of 64
2154 towers made up of 1×2 tower 1D projective blocks. The detector was tested in at the FTBF
2155 in the winter of 2016 and the results have been summarized and submitted for publication
2156 [138]. As an overall summary of the results, Figure 4.27 shows the energy resolution
2157 measured for this prototype for the beam centered on a single tower. For the UIUC blocks
2158 at an incident beam angle of 10° , the measured energy resolution was $12.7\%/\sqrt{E} \oplus 1.6\%$
2159 after unfolding a 2% momentum spread of the beam, which agrees well with tests done by
2160 the UCLA group with similar prototypes of their design [132, 133].

2161 4.4.2 2D Projective Prototypes (V2 and V2.1)

2162 The second EMCAL prototype (V2) consisted of 2D projective blocks that represented
2163 the large rapidity region ($\eta \sim 1$) of the sPHENIX calorimeter. It consisted again of an
2164 8×8 array of 64 towers which was made up of 16 2D projective blocks, each having 2×2
2165 towers. These were the first 2D projective blocks ever produced and allowed us to develop
2166 the numerous new procedures required to produce these blocks. The prototype was
2167 tested at Fermilab in 2017, again in stand alone mode to measure its detailed performance
2168 parameters, and also in combination with prototypes of the Inner and Outer HCAL. These
2169 results have been presented at various conferences and appear in the proceedings [139].

2170 We observed a strong position dependence to the shower response due to non-uniformities
2171 in the light collection and dead material near the block boundaries. We corrected for this
2172 using two methods. One was using a scintillation hodoscope in the beam to measure the

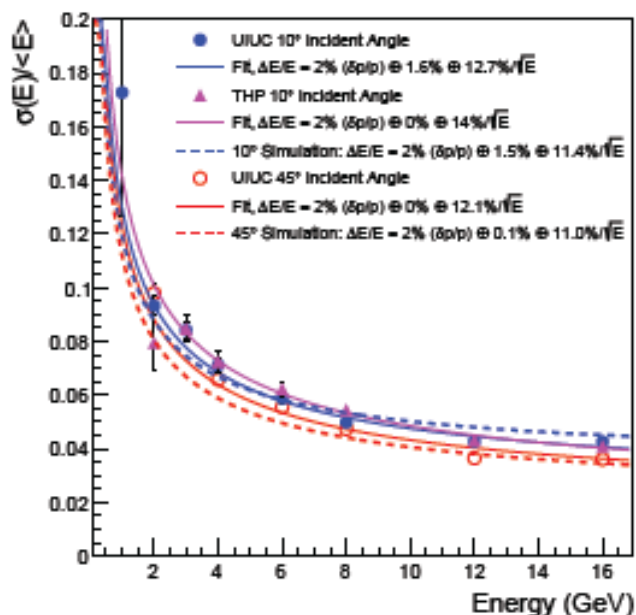


Figure 4.27: Energy resolution measured for the first EMCAL prototype (V1) consisting of 1D projective with the beam centered on a single tower.

2173 beam position and the other was to use the measured shower position from the calorimeter
 2174 itself. Both methods gave similar results and are shown in Fig.4.28 The energy resolution
 2175 measured over a 4×4 cm region of one of the blocks, which included the boundaries
 2176 between 4 light guides but not the boundaries between different blocks, was $\sim 13.0\% / \sqrt{E}$
 2177 $\oplus 1.5\%$ after unfolding a 2% momentum spread of the beam at an incident beam angle of
 2178 10° , which is well within the sPHENIX specs. However, when the block boundaries were
 2179 included, the energy resolution degraded to slightly more than $15\% / \sqrt{E}$ with a constant
 2180 term $\sim 4\%$. We believe this was mainly due to initial problems in producing the first 2D
 2181 projective blocks that have now been corrected, and we have also implemented additional
 2182 improvement in the light collection as well. We now plan to test a new version of the 2D
 2183 projective prototype (V2.1) with the improved blocks in the test beam at Fermilab in early
 2184 2018.

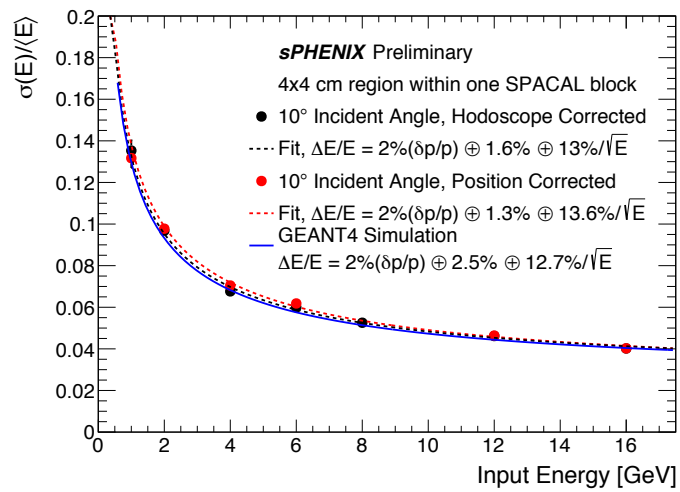


Figure 4.28: Energy resolution measured for the second EMCAL prototype (V2) consisting of 2D projective towers with the beam centered on a region containing several towers but excluding block boundaries. Curves show two methods used for position dependent corrections

Chapter 5

Hadronic Calorimeter

The hadronic calorimeter (HCal), essential for the measurement of jets, is a steel-scintillator sampling calorimeter with two longitudinal segments, one inside and one outside the magnet. As the result of a recent descoping effort, however, the current baseline replaces the inner longitudinal segment (called the Inner HCal) with an uninstrumented aluminum frame. The collaboration is actively pursuing different options to restore the Inner HCal. The outer longitudinal segment (called the Outer HCal) also serves as the flux return of the solenoid and provides mechanical support for the solenoid and the detector components inside the solenoid. This chapter describes the reference design of the HCal detectors, prototypes of these detectors, test beam performance, simulation results, and progress toward the development of a complete detector design. As the descoping exercise only concluded in December 2017, most performance plots presently at hand—and shown here in the document—are with the configuration that has the Inner HCal. Since the Inner HCal only comprises 0.55λ (compared to 3.8λ in the Outer HCal), those plots serve as reasonable proxies for the descoped version of the detector. Studies on the impact of the uninstrumented aluminum frame are presented in Section 5.3 (Simulations).

5.1 HCal Requirements and Overview

The performance requirements for the sPHENIX HCal are driven by the physics requirements related to measuring jets in relativistic heavy ion collisions and the need to realize the HCal in an efficient, cost-effective manner.

A uniform, hermetic acceptance is required between $-1.1 < \eta < 1.1$ and $0 < \phi < 2\pi$ to minimize the systematic errors associated with energy that is not measured by the detector. For similar reasons, the calorimeter system is required to absorb $>95\%$ of the incident hadronic energy, which sets the required depth of the calorimeter system to 4.9 nuclear

2210 interaction lengths¹. The modest single hadron energy resolution requirement of $\frac{\sigma}{E} \sim \frac{100\%}{\sqrt{E}}$
2211 for the HCal is adequate in heavy ion collisions since, for low energy jets, the jet energy
2212 resolution is dominated by the subtraction of the underlying event and not the energy
2213 resolution of the HCal.

2214 Key design aspects of the HCal are determined by the mechanical and practical limitations.
2215 To limit civil construction in the 1008 interaction region at RHIC, it is highly desirable
2216 that the sPHENIX detector fit through the existing shield wall opening. In addition, the
2217 engineering challenge of supporting the HCal increases with the radius of the detector,
2218 which drives a design that makes use of the Outer HCal as the magnet flux return and
2219 places the Inner HCal segment or replacement aluminum frame inside the solenoid magnet
2220 where it also supports the EMCal. For these reasons we have chosen a novel tilted plate
2221 calorimeter design, which is described more fully in the following sections.

2222 5.2 Detector Design

2223 The design of the hadronic calorimeter has been developed by a program of simulation and
2224 prototyping which is continuing to optimize the design. The reference design consists of
2225 two longitudinal compartments. As the result of a descoping process at the end of 2017, the
2226 Inner HCal, located inside the solenoid, is replaced an uninstrumented 0.25λ aluminum
2227 frame, the design of which is taken from the Inner HCal. Engineering finite element
2228 analysis has shown that an Al version of the Inner HCal design is capable of supporting
2229 the EMCal within safety margins. The collaboration is actively pursuing different options
2230 to restore the Inner HCal, which comprises 0.55 nuclear interaction lengths (as originally
2231 designed in stainless steel). This would provide more information on the longitudinal de-
2232 velopment of electromagnetic showers, thus providing additional discrimination between
2233 electrons and hadrons beyond determination of E/p in the electromagnetic shower. The
2234 larger Outer HCal provides the remaining interaction lengths (3.8λ) needed to achieve the
2235 required energy resolution and serves as flux return for the solenoid magnet. In order to
2236 keep cost low, the Inner HCal uses a very similar design as the outer one.

2237 The basic calorimeter concept is a sampling calorimeter with absorber plates tilted from the
2238 radial direction. This design provides more uniform sampling in azimuth and gives some
2239 information on the longitudinal shower development. The current design uses tapered
2240 plates for the Outer HCal. The Inner HCal would not require tapered plates as studies
2241 showed that tapering the shorter Inner HCal plates was not necessary, and tapering them
2242 increased the machining cost. Extruded tiles of plastic scintillator with an embedded
2243 wavelength shifting fiber are interspersed between the absorber plates and read out at
2244 the outer radius with silicon photomultipliers (SiPMs). The tilt angle is chosen so that
2245 a radial track from the center of the interaction region traverses at least four scintillator
2246 tiles. Each tile has a single SiPM, and the analog signal from each tile in a tower (five for

¹for a typical 30 GeV jet where the leading particle carries 2/3 of the jet energy

2247 the Outer HCal, four for the Inner HCal) are ganged to a single preamplifier channel to
 2248 form a calorimeter tower. Tiles are divided in slices of pseudorapidity so that the overall
 2249 segmentation is $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$.

2250 5.2.1 Scintillator

Property	
Plastic	Extruded polystyrene
Scintillation dopant	1.5% PTP and 0.01% POPOP
Reflective coating	Proprietary coating by surface exposure to aromatic solvents
Reflective layer thickness	50 μ
Wrapping	one layer of 100 μ Al foil, one layer of 30 μ cling-wrap, one 100 μ layer of black Tyvek
Attenuation length in lateral (with respect to extrusion) direction	~ 2 -2.5 m
Wavelength shifting fiber	Single clad Kuraray Y11
Fiber size	1 mm round
Fiber core attenuation length	> 2 m
Optical cement	EPO-TEK 3015

Table 5.1: Properties of HCal scintillating tiles.

2251 The scintillating tiles are similar to the design of scintillators for the T2K experiment by the
 2252 INR group (Troitzk, Russia) who designed and built 875 mm long scintillation tiles with a
 2253 serpentine wavelength shifting fiber readout [140]. The MINOS experiment developed
 2254 similar extruded scintillator tiles. The properties of the HCal scintillating tiles are listed in
 2255 Table 5.1.

2256 We have considered two wavelength shifting (WLS) fiber manufacturers: Saint-Gobain
 2257 (formerly BICRON), product brand name BCF91A [141], and Kuraray, product name
 2258 Y11 [142]. Both vendors offer single and double clad fibers. The Kuraray single clad fiber
 2259 was chosen due to its flexibility and longevity, which are critical in the geometry with
 2260 multiple fiber bends. The properties of the HCal wavelength shifting fibers are listed in
 2261 Table 5.2.

2262 The scintillator emission spectrum and the fiber absorption spectrum are shown in Fig-
 2263 ure 5.1. The fiber routing was designed so that all energy deposited in the scintillator is
 2264 within 2.5 cm of a WLS fiber, and the bend radius of any turn in the fiber has been limited
 2265 to 35 mm based on T2K and our own empirical experience with test tiles. The two ends
 2266 of a fiber are brought to the outer radius of a tile where a small plastic holder carries a
 2267 3×3 mm SiPM at 0.75 mm from the end of the polished fibers. Both the Inner and Outer

Property	
Fiber diameter	1.0 mm
Formulation	200, K-27, S-Type
Cladding	single
Cladding thickness	2 percent of d (0.02 mm)
Numerical Aperture (NA)	0.55
Emission angle	33.7 °
Trapping Efficiency	3.1 percent
Core material	polystyrene (PS)
Core density	1.05 g/cc
Core refractive index	1.59
Cladding material	Polymethylmethacrylate (PMMA)
Cladding density	1.19 g/cc
Cladding refractive index	1.49
Color	green
Emission peak	476 nm
Absorption Peak	430 nm
Attenuation length	> 3.5 m
Minimum bending radius	100 mm

Table 5.2: Properties of Kuraray Y-11 (200) wavelength shifting fibers.

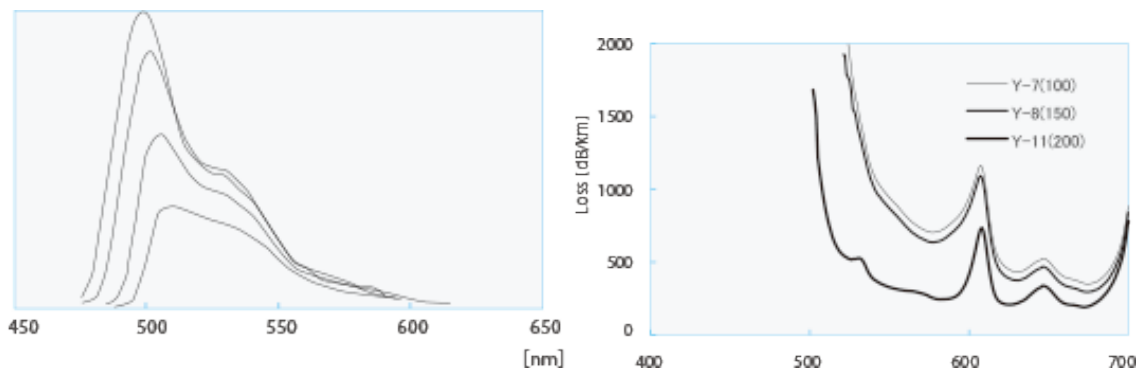


Figure 5.1: Y-11 (200) WLS fiber emission spectrum for various fiber lengths (10, 30, 100, 300 cm, from top to bottom) (left) and transmission loss (right).

2268 HCal are north-south symmetric and require 24 tiles along the η direction. The design
 2269 requires 12 different shapes for tiles for each longitudinal segment. As an example, Fig. 5.2
 2270 shows the tile and embedded fiber pattern for the Outer HCal.

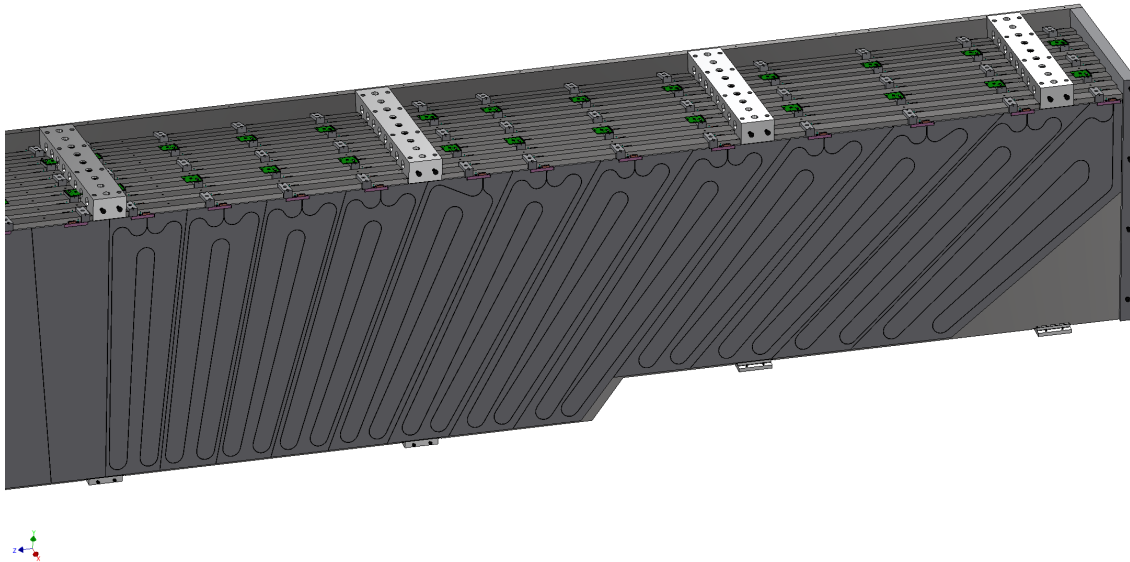


Figure 5.2: Scintillator tiles in a layer of the Outer HCal.

2271 5.2.2 Outer HCal

2272 The major components of the Outer HCal are tapered steel absorber plates and 7680
 2273 scintillating tiles which are read out with SiPMs along the outer radius of the detector.
 2274 The detector consists of 32 modules, which are wedge-shaped sectors containing 2 towers
 2275 in ϕ and 24 towers in η equipped with SiPM sensors, preamplifiers, and cables carrying
 2276 the differential output of the preamplifiers to the digitizer system on the floor and upper
 2277 platform of the detector. Each module comprises 9 full-thickness absorber plates and 2
 2278 half-thickness absorber plates, so that as the modules are stacked, adjoining half-thickness
 2279 absorber plates have the same thickness as the full-thickness absorber plates. The tilt angle
 2280 is chosen to be 12 degrees relative to the radius, corresponding to the geometry required
 2281 for a ray from the vertex to cross four scintillator tiles. Table 5.3 summarizes the major
 2282 design parameters of the Outer HCal, which is illustrated in Figure 5.3.

2283 Since the Outer HCal will serve as the flux return of the solenoid, the absorber plates are
 2284 single, long plates running along the field direction. The Outer HCal SiPM sensors and
 2285 electronics are arranged on the outer circumference of the detector.

2286 5.2.3 Inner HCal

2287 The Inner HCal (or the replacement aluminum frame) occupies a radial envelope bounded
 2288 by a 50 mm clearance inside the solenoid cryostat and the outer radius of the electromag-

Parameter	Units	Value
Inner radius (envelope)	mm	1820
Outer radius (envelope)	mm	2700
Length (envelope)	mm	6316
Material		1020 low carbon steel
Number of towers in azimuth ($\Delta\phi$)		64
Number of tiles per tower		5
Number of towers in pseudorapidity ($\Delta\eta$)		24
Number of electronic channels (towers)		$64 \times 24 = 1536$
Number of optical devices (SiPMs)		$5 \times 1536 = 7680$
Number of modules (azimuthal slices)		32
Number of towers per module		$2 \times 24 = 48$
Total number of absorber plates		$5 \times 64 = 320$
Tilt angle (relative to radius)	$^\circ$	12
Absorber plate thickness at inner radius	mm	10.2
Absorber plate thickness at outer radius	mm	14.7
Gap thickness	mm	8.5
Scintillator thickness	mm	7
Module weight	kg	12247
Sampling fraction at inner radius		0.037
Sampling fraction at outer radius		0.028
Calorimeter depth	λ	3.8

Table 5.3: Design parameters for the Outer Hadronic Calorimeter.

2289 netic calorimeter. The skin on the inner radius provides support for the electromagnetic
2290 calorimeter and the HCal, while steel rings at either end carry the load to the Outer HCal.

2291 Table 5.4 shows the basic mechanical parameters of the Inner HCal reference design. The
2292 detector would be built in 32 modules, which would be wedge-shaped sectors comprising
2293 8 gaps with 7 full-thickness plates and 2 half-thickness plates (so that as the modules
2294 are stacked, adjoining half-thickness plates have the same thickness as the full-thickness
2295 plates). The modules contain 2 towers in ϕ and 24 towers in η equipped with SiPM
2296 sensors, preamplifiers, and cables carrying the differential output of the preamplifiers to
2297 the digitizer system on the floor and upper platform of the detector. The instrumentation
2298 consists of 6144 scintillating tiles and optical devices, 1536 preamps, and cabling. Figure
2299 5.4 shows the arrangement of absorber plates in a sector with scintillator tiles sandwiched
2300 between stainless steel absorber plates. To preserve the “four crossing” geometry, the tilt
2301 angle is chosen to be 32 degrees relative to the radius.

2302 In the current baseline, the Inner HCal is replaced with a design that clones the steel frame
2303 of the Inner HCal design and uses a hardened aluminum alloy for the material. Studies
2304 have demonstrated that this frame provides the mechanical support necessary for the inner

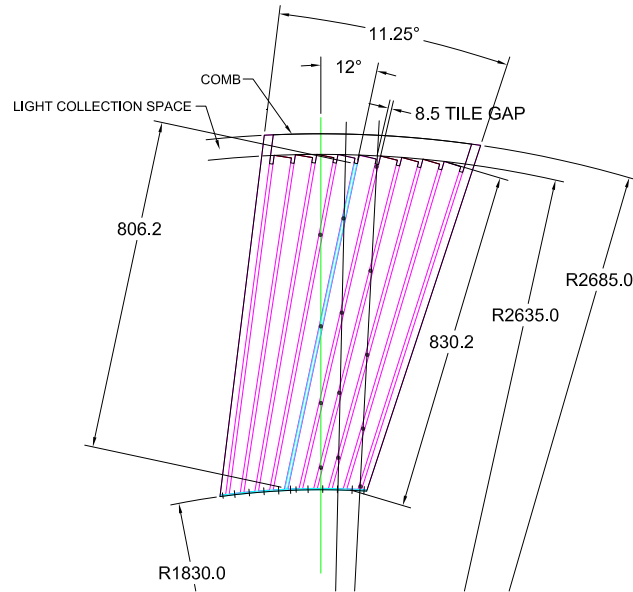


Figure 5.3: Transverse cutaway view of an Outer HCal module, showing the tilted tapered absorber plates. Light collection and cabling is on the outer radius at the top of the drawing.

Parameter	Units	Value
Inner radius (envelope)	mm	1157
Outer radius (envelope)	mm	1370
Length (envelope)	mm	4350
Material		310 stainless steel
Number of towers in azimuth ($\Delta\phi$)		64
Number of towers per module		$2 \times 24 = 48$
Number of tiles per tower		4
Number of towers in pseudorapidity ($\Delta\eta$)		24
Number of electronic channels (towers)		$64 \times 24 = 1536$
Number of optical devices (SiPMs)		$4 \times 1536 = 6144$
Total number of absorber plates		$4 \times 64 = 256$
Tilt angle (relative to radius)	$^\circ$	32
Absorber plate thickness	mm	13
Gap thickness	mm	8.5
Scintillator thickness	mm	7
Number of modules (azimuthal slices)		32
Module weight (SS310)	kg	907.19
Sampling fraction		0.076
Calorimeter depth	λ	0.55

Table 5.4: Design parameters for the Inner Hadronic Calorimeter.

2305 detectors. As discussed above, the collaboration is actively pursuing options to restore the
 2306 Inner HCal.

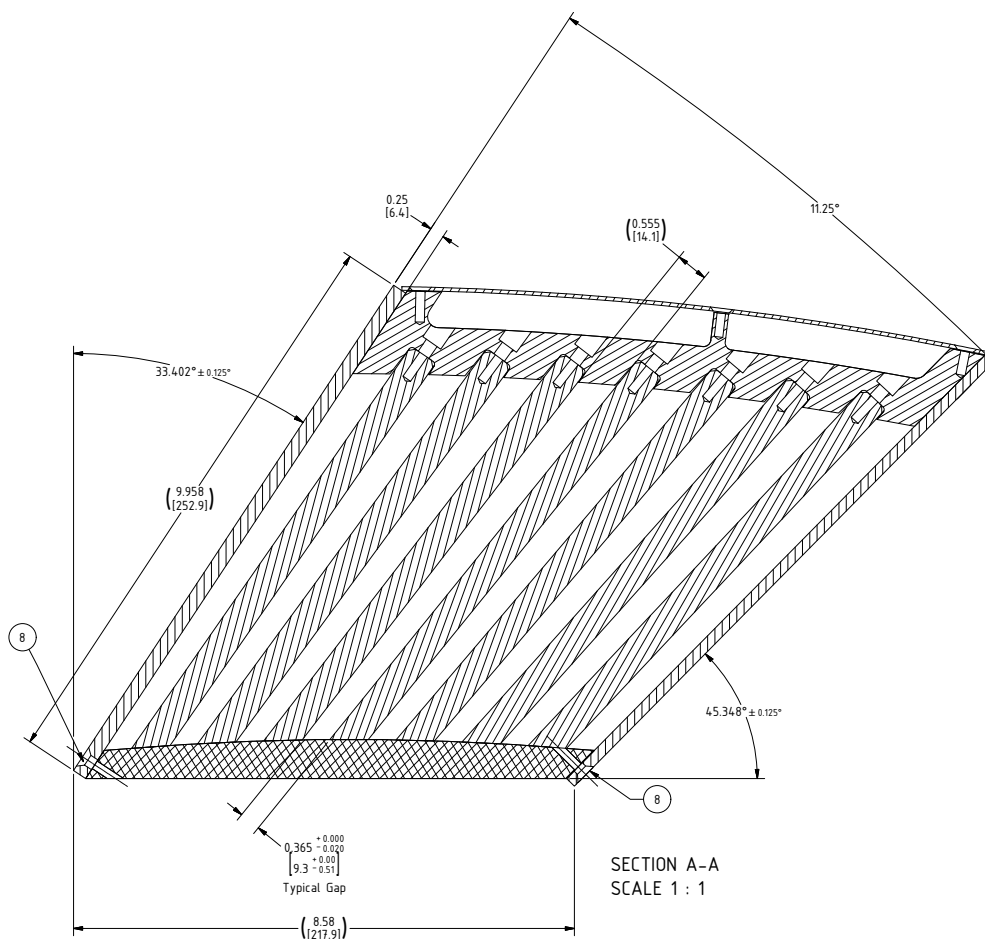


Figure 5.4: Transverse cut of an Inner HCal module, showing the tilted tapered absorber plates. Light collection and cabling is on the outer radius at the top of the drawing.

2307 The Inner HCal (or aluminum frame) modules are to be bolted together with spacers
 2308 maintaining the 8.5 mm gap between plates for inserting the scintillator tiles. The plates
 2309 would be assembled into mechanically complete modules at the raw material (steel or
 2310 aluminum) vendor, at BNL, or at a collaborating institution. In parallel, scintillating tiles
 2311 would be prepared with their SiPMs and LED flashers, and tested with cosmic rays before
 2312 installation into the Inner HCal modules. A potential assembly sequence for the Inner
 2313 HCal modules is shown in Figure 5.5.

2314 The SiPMs attached to the tiles in a given tower must be gain matched, because we plan to
 2315 provide the same bias voltage on all five of the SiPMs in a tower. This should be possible
 2316 by sorting the SiPMs according to the manufacturer’s measurements. The SiPM sensors,
 2317 preamplifiers, and cables are arranged on the outer circumference of the Inner HCal, with

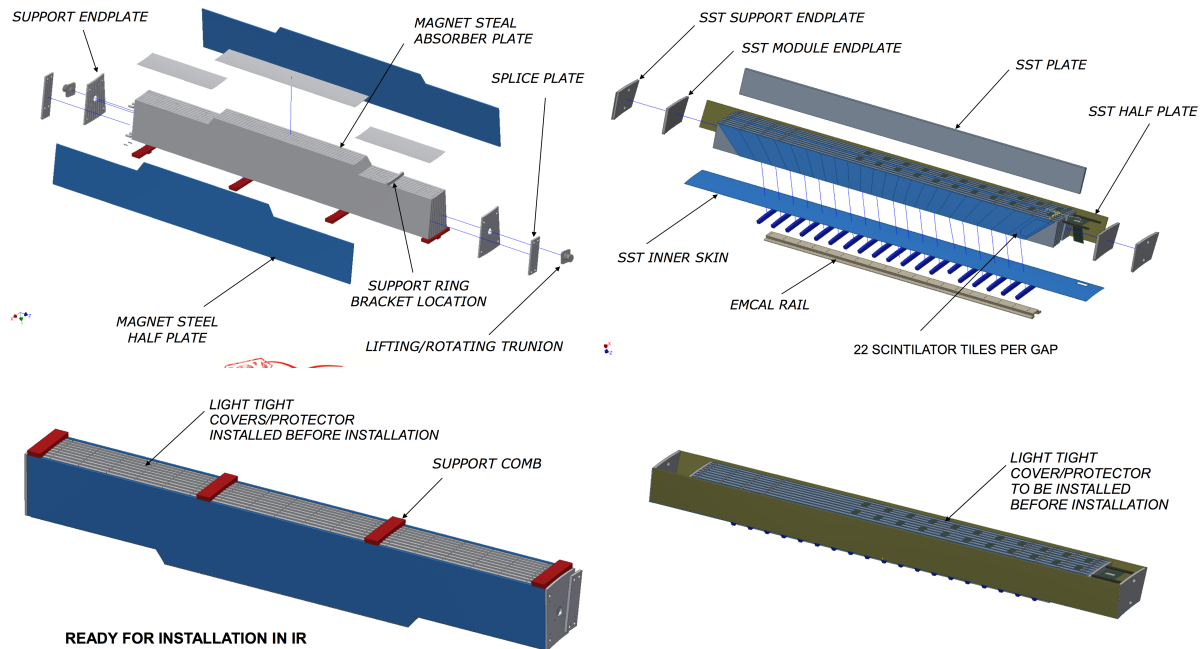


Figure 5.5: Assembly of Inner HCal modules.

2318 cables exiting the two ends of the modules. Interface boards mounted at the ends of the
 2319 modules monitor the local temperatures and leakage currents, distribute the necessary
 2320 voltages, and provide bias corrections for changes in temperature and leakage current.
 2321 As part of the production QA, we have a requirement that tile plus SiPM pairs in each
 2322 tower must have a response within 10% of each other. The current design plan is shown in
 2323 Figure 5.6.

2324 The Inner HCal is designed to be inserted as a complete unit into the solenoid cryostat,
 2325 and access to the on-detector electronics and cables would require both the EMCal and
 2326 Inner HCal to be removed from their positions inside the solenoid cryostat. Therefore, it is
 2327 important that any Inner HCal on-detector electronics be thoroughly tested and burned in
 2328 before completing the assembly of the detector in the magnet.

2329 5.2.4 Mechanical Design

2330 The current mechanical design concept for the outer and inner hadronic calorimeter
 2331 subsystems relies on a load transfer scheme where the tilted steel plates in the Inner and
 2332 Outer HCal form the primary structural members for transferring loads. The concept
 2333 further requires the Inner HCal to support the EMCal, and the Outer HCal must support
 2334 the inner HCal and the superconducting solenoid magnet independently. The Inner HCal
 2335 comprises 32 independent sectors joined at its longitudinal ends by stainless steel rings

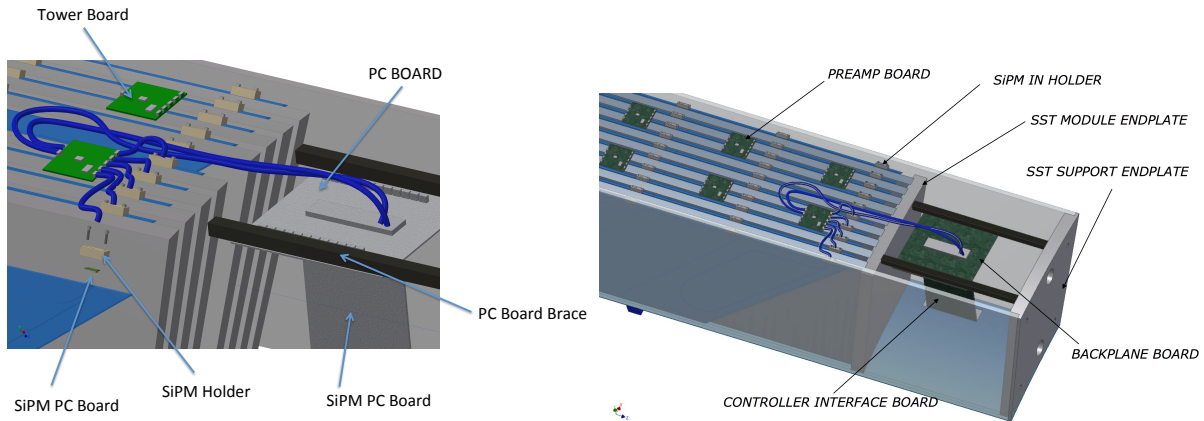


Figure 5.6: The design for electronics and cable routing from an Inner HCal sector. The SiPM holders are mounted directly on the end of the tile with a single preamplifier/shaper/driver board mounted nearby. An Interface Board at the end of the sector, provides power and bias voltage distribution and local monitoring.

2336 to integrate the sectors into a single entity, which in turn is installed inside and through
 2337 the solenoid magnet and mounted to the Outer HCal by mounting rings on either end.
 2338 The outer HCal sectors are joined at their longitudinal ends by steel splice plates between
 2339 adjacent sectors into a single unit, which is mounted on the Central Platform. The reference
 2340 design for the Inner and Outer HCal support structure is shown in Figure 5.7.

2341 Validation of this mounting scheme has been demonstrated using finite element modeling
 2342 and analysis to calculate the stresses and displacements of the design concept. Analyses of
 2343 the Inner HCal structure with and without the EMCal load has been performed and an
 2344 example of the results is shown in Figure 5.8, showing that the final assembly deformation
 2345 is within the tolerance necessary ensure that scintillator tiles are not compressed. Similarly,
 2346 analyses of the Outer HCal structure and multiple Inner HCal installation procedures have
 2347 been performed to validate the concepts.

2348 5.3 Simulation

2349 The GEANT4 simulation toolkit [135] is employed for simulation studies of the HCal
 2350 system. The GEANT4 QGSP_BERT_HP was selected as the default physics processes
 2351 list, which is recommended for high energy detector simulations like the LHC experi-
 2352 ments [143]. Figure 5.9 shows an example event display of a 10 GeV pion shower in the
 2353 GEANT4 Monte Carlo.

2354 After the GEANT4 simulation stage, digitization was implemented with the following four
 2355 steps:

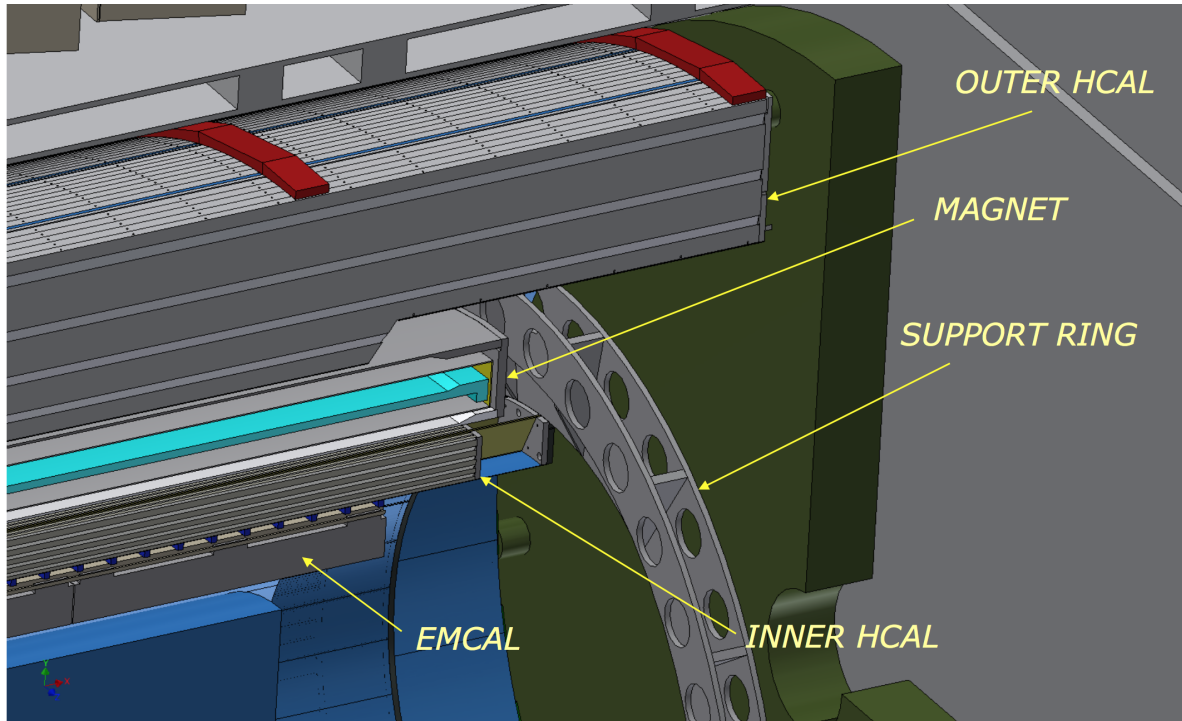


Figure 5.7: Inner and Outer HCal with support structure.

- 2356 1. Energy depositions for each GEANT4 tracklet in the scintillation volume are collected
2357 in the sPHENIX analysis framework.
- 2358 2. The Birks' law of scintillator non-linearity [144] with a default Birks' constant of
2359 $k_B = 0.0794 \text{ mm/MeV}$ [136] is implemented to convert ionizing energy deposition to
2360 visible energy that is proportional to the expected number of photons produced in
2361 the scintillator.
- 2362 3. The visible energy in each calorimeter tower is summed in a timing window of
2363 0-60 ns to calculate the mean number of active pixels in the SiPM readout. The
2364 scale of the mean number of active pixels is set by the mean active pixel count as
2365 measured in cosmic tests of the HCal. The actual active pixel number is a random
2366 number following a Poisson distribution using the mean number of active pixels as a
2367 parameter.
- 2368 4. In the last step, the ADC for each readout channel is proportional to the sum of the
2369 actual active pixel number and a random number following the pedestal distribution.
2370 The sum is scaled to an ADC value using measured pixel/ADC value from cosmic
2371 tests and discretized to integer ADC value.

2372 The sPHENIX simulations have been integrated with the sPHENIX software frame-
2373 work [145], enabling the same analysis software setup to be used to analyze the full

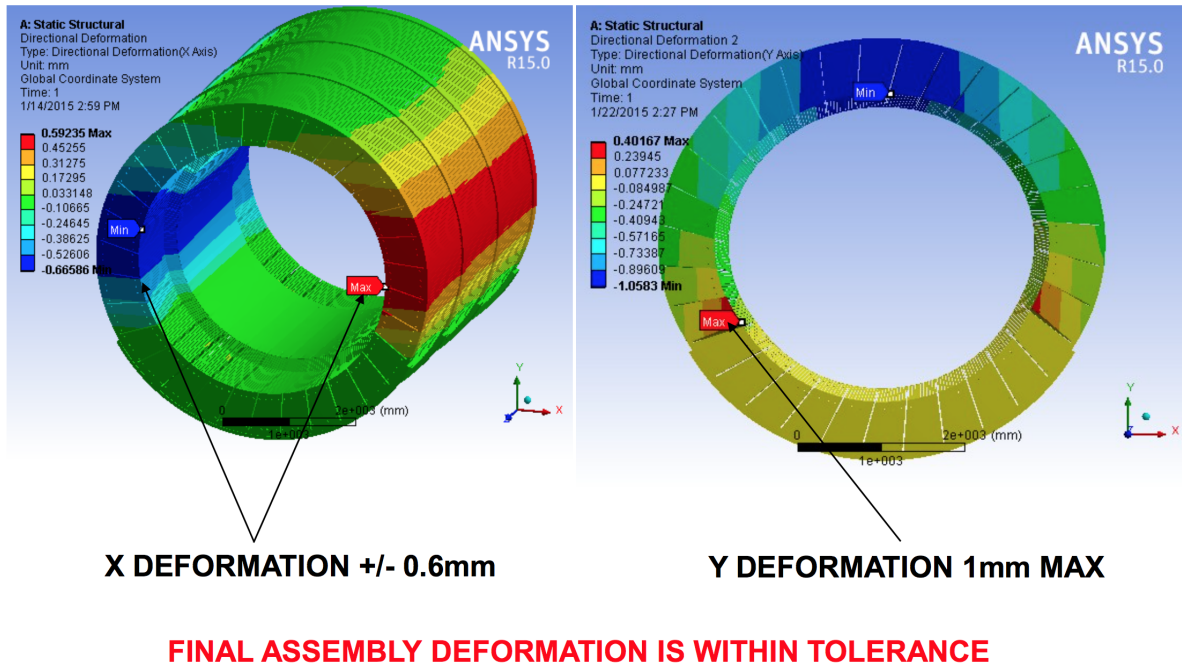


Figure 5.8: Results of finite element analysis of Outer HCal after final assembly, showing the maximum deformation of the structure.

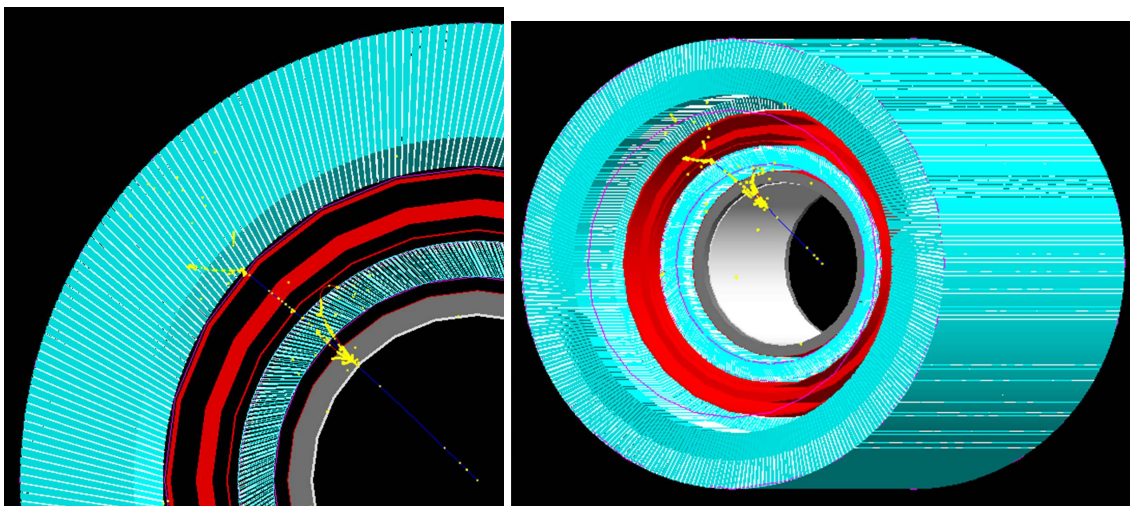


Figure 5.9: GEANT4 event display of a 10GeV π shower in the sPHENIX calorimeter system.

2374 simulations with all the other detector subsystems. Magnetic field maps for the BaBar
 2375 magnet have been imported from OPERA calculations. The magnetic field map in the
 2376 region of the Outer HCal takes its geometry into account with the field concentrated in the
 2377 steel plates and the scintillators in a field free region.

2378 The implementation of the hadronic calorimeters is highly configurable. This allows for the
 2379 investigation of different design choices (inner and outer radius, plate tilt angle, gap size
 2380 for scintillator, scintillator thickness, pseudo rapidity coverage, etc.) The superconducting
 2381 magnet is simulated with the proper location and material of the cryostat. All simulated
 2382 tracks which reach a layer 10 cm outside the outer HCal are aborted and their energy
 2383 recorded to yield an estimate of the leakage from the back of the Outer HCal.

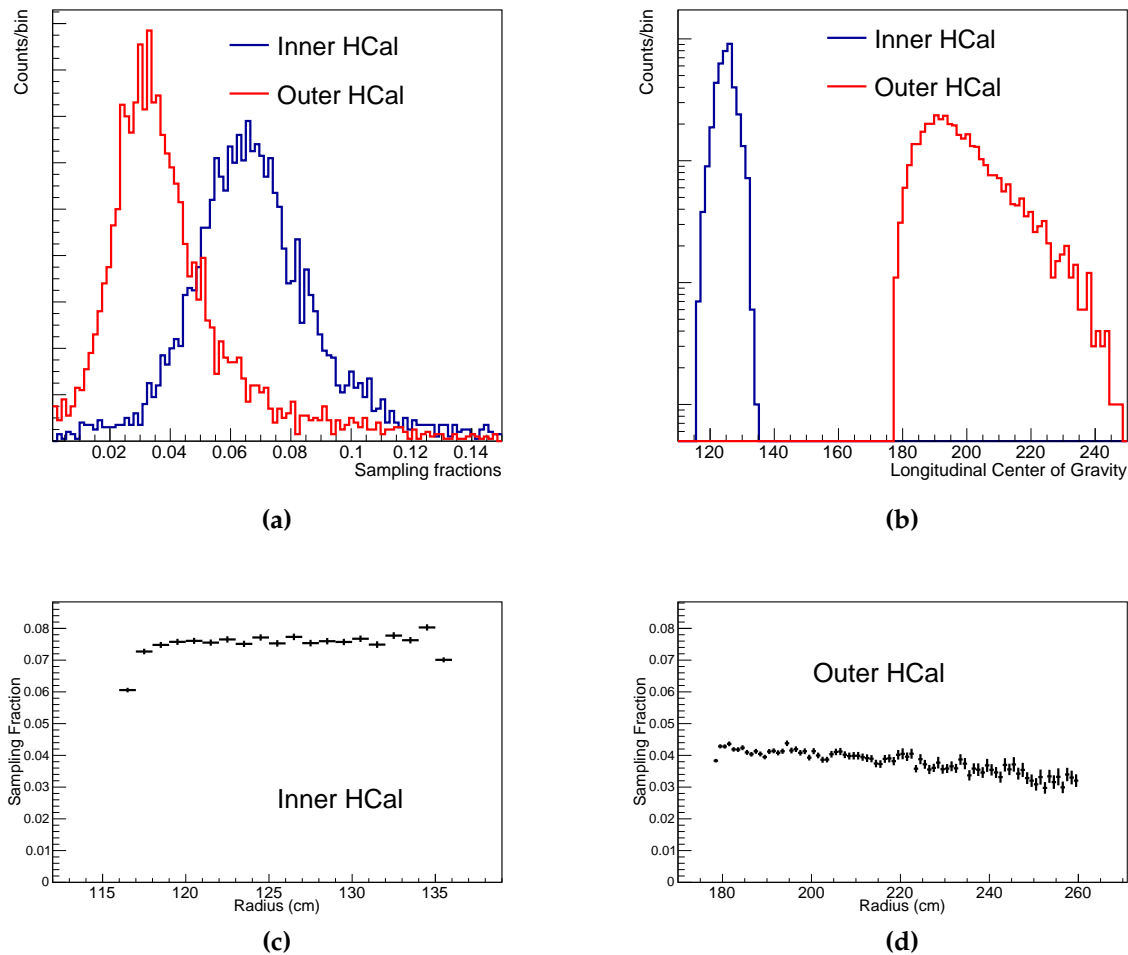


Figure 5.10: GEANT4 simulations of (a) HCal sampling fractions and (b) longitudinal center of gravity for the inner and outer sections. The longitudinal center of gravity shows where the hadronic shower begins to develop in the calorimeter. Also shown are GEANT4 simulations of (c) sampling fraction in the Inner and (d) Outer HCal as a function of depth along the radius, showing it is uniform for inner but decreases for the outer as expected from the tapered plate design.

2384 To elucidate the effect of design choices, single particle simulations were performed using
 2385 fixed momenta with random pseudorapidity $0 < \eta < 0.1$ and random azimuthal angle

2386 $0 < \phi < 2\pi$. The vertex was randomized along the beam axis within ± 10 cm. A reference
 2387 configuration of the HCal as described in the previous section was chosen. In particular,
 2388 the Inner HCal tilt angle is 32 degrees and the Outer HCal tilt angle is 12 degrees. The
 2389 energy deposited in the scintillator and absorber are recorded. This information is used to
 2390 calculate the sampling fraction. Figure 5.10 (a) shows the pion sampling fractions in both
 2391 inner and outer sections of the HCal. The average sampling fractions were estimated to be
 2392 6.7% for the inner and 3.5% for the Outer HCal. Using the average sampling fractions, the
 2393 summed energy in each compartment was corrected and combined to yield the calorimeter
 2394 response. The longitudinal center of gravity (LCG) is a good measure of the depth of the
 2395 hadronic showers inside a calorimeter. The LCG is defined as

$$\text{LCG} = \frac{\sum \text{G4Hits} E_{dep} \frac{(r_{in} + r_{out})}{2}}{\sum \text{G4Hits} E_{dep}}, \quad (5.1)$$

2396 where E_{dep} is the GEANT4 hit energy deposited in the scintillators, and r_{in} and r_{out} are the
 2397 inner and outer radius of the hits, respectively. Figure 5.10 (b) shows the LCG for the pion
 2398 showers inside Inner and Outer HCal.

2399 We examined the effect of the sampling fraction variation as a function of depth in the
 2400 Inner and Outer HCal compartments. As noted previously, while the steel plates in the
 2401 Inner HCal are have a uniform thickness, the steel plates in the Outer HCal widen with
 2402 the radius, which causes the sampling fraction for the Outer HCal to be reduced as a
 2403 function of radius, since the scintillator tiles maintain a constant thickness. This effect
 2404 is demonstrated in Figure 5.10 (c), (d) which shows the sampling fraction for the Inner
 2405 HCal is constant as a function of depth along the radius while it decreases for the Outer
 2406 HCal. An extensive study was performed to investigate its impact on the energy resolution.
 2407 A correction factor was applied to the scintillator tiles modifying the light response in
 2408 order to even out decreasing sampling fraction as a function of depth. This step was
 2409 applied at the GEANT4 step level. Only a very modest improvement was seen in the
 2410 energy resolution. The small improvement would likely be lost in a realistic device when
 2411 towering and clustering are included. Therefore, from this study we conclude that the
 2412 variation in the Outer HCal sampling fraction as a function of depth is not a significant
 2413 contributor to the HCal energy resolution.

2414 Finally, the energy response of the combined HCal is calculated by adding the energy
 2415 deposited in the scintillators and corrected by the sampling fractions. Figure 5.11 shows
 2416 the energy reconstruction for pions in the HCal. An event selection was applied to select
 2417 showers that pass through the EMCal with minimum ionizing energy loss. Deposited
 2418 energy from showers are shared between the Inner and Outer HCal. As seen from the
 2419 figure most of the energy is deposited in the Outer HCal. The combined energy response
 2420 from the two sections shows the peak for the fully reconstructed 12 GeV pions.

2421 As one of the main physics goals of the HCal is the measurement of jets, the performance of
 2422 jet reconstruction has been investigated through the full GEANT4 simulation incorporating
 2423 all the other detector subsystems. Dijet events were generated using PYTHIA 8 to simulate
 2424 the proton-proton collisions. Jets are reconstructed by clustering calorimeter towers with

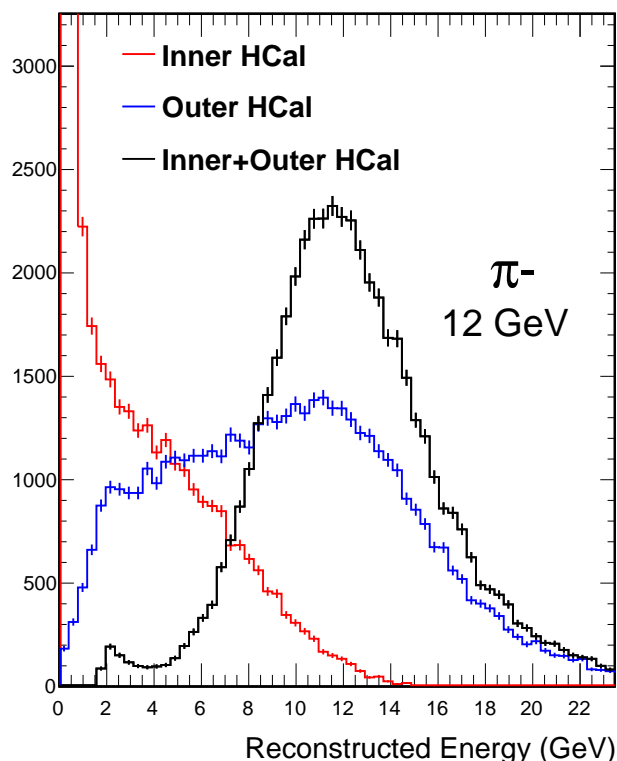


Figure 5.11: Pion reconstruction in the HCal. The energy deposited by 12 GeV π^- showers in two compartments of HCal. Energy deposited in the scintillators are corrected by the sampling fractions and added together for total energy.

2425 the anti- k_T jet finding algorithm in the FastJet package. Generated particles are put through
 2426 the same package to determine the truth jet.

2427 Figure 5.12 shows the ratio of reconstructed to truth jet transverse momenta, p_T^{reco} / p_T^{truth} ,
 2428 with the Inner HCal and the uninstrumented aluminum frame discussed in Section 5.2.3.
 2429 Truth jets are selected to be in the central region of $|\eta| < 0.6$ and $p_T > 50$ GeV/c. Jets are
 2430 reconstructed with different values of anti- k_T jet radius parameter, R , between 0.2–0.5 and
 2431 associated with the closest truth jet, additionally requiring the distance between truth and
 2432 reconstructed jet is smaller than the radius. The p_T^{reco} / p_T^{truth} distributions are fitted by a
 2433 Gaussian distribution, and the mean and width represent the Jet Energy Scale (JES) and Jet
 2434 Energy Resolution (JER), respectively.

2435 Figure 5.13 summarizes the R dependence of JES and JER. The aluminum frame shows
 2436 poorer performance than the Inner HCal as the energy deposited in the frame cannot be
 2437 reconstructed and combined into the total jet energy. The bottom panel of Figure 5.13
 2438 shows the ratio of the response with aluminum frame to one with Inner HCal. The flatness

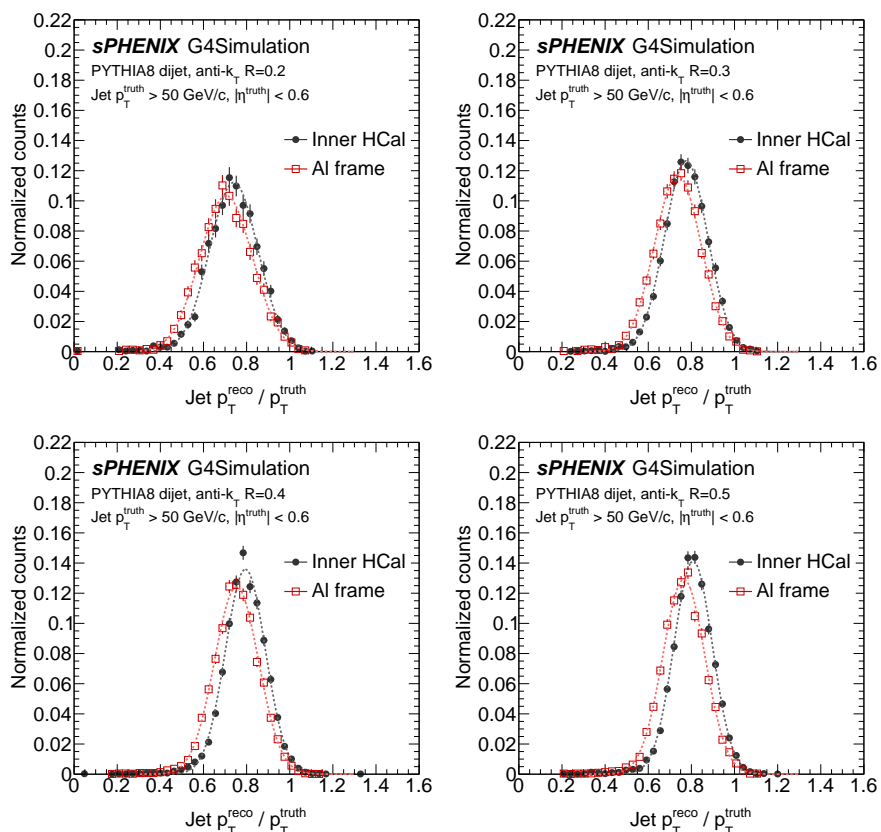


Figure 5.12: The ratio of reconstructed to the truth jet p_T distributions from simulated proton-proton events with the Inner HCal (closed circles) and the aluminum frame (open squares). The total area under each histogram is normalized to unity. Each plot shows the jets reconstructed with different parameters, $R = 0.2, 0.3, 0.4,$ and $0.5,$ respectively.

2439 of these ratios indicates that the relative performance of the Inner HCal and the aluminum
 2440 frame does not depend on the choice of R . Obtaining the optimal energy resolution for
 2441 jets will require a calibration procedure that takes into account energy scale differences
 2442 between the calorimeter compartments. We have developed such a procedure in the
 2443 analysis of single-hadron showers in test beam data (see Section 5.5.1) and work is ongoing
 2444 to develop a similar calibration procedure for jets.

2445 5.4 Prototype construction

2446 To verify the design performance, HCal prototypes have been assembled at Brookhaven
 2447 National Laboratory and tested at the Fermilab Test Beam Facility (FTBF) as experiment
 2448 T-1044.

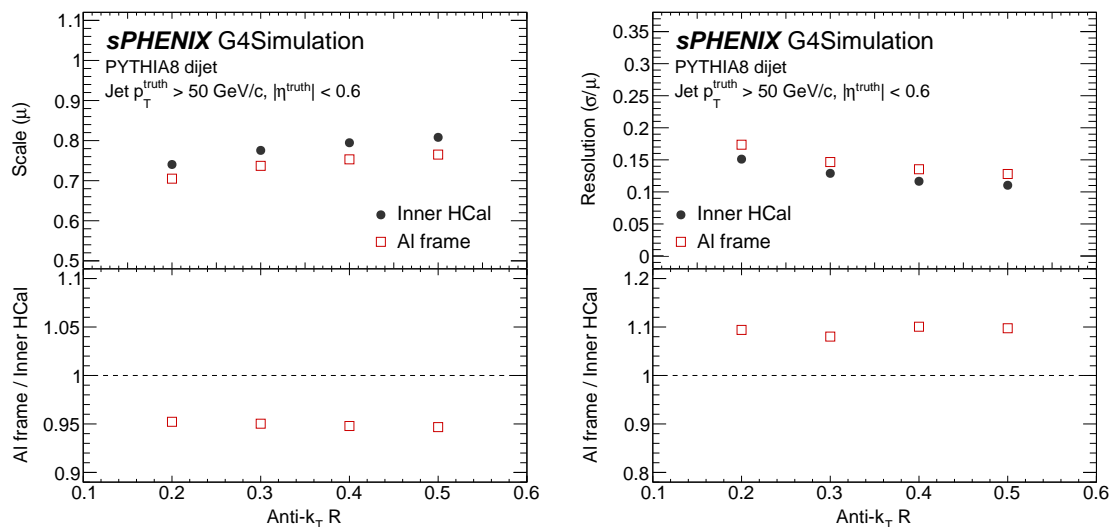


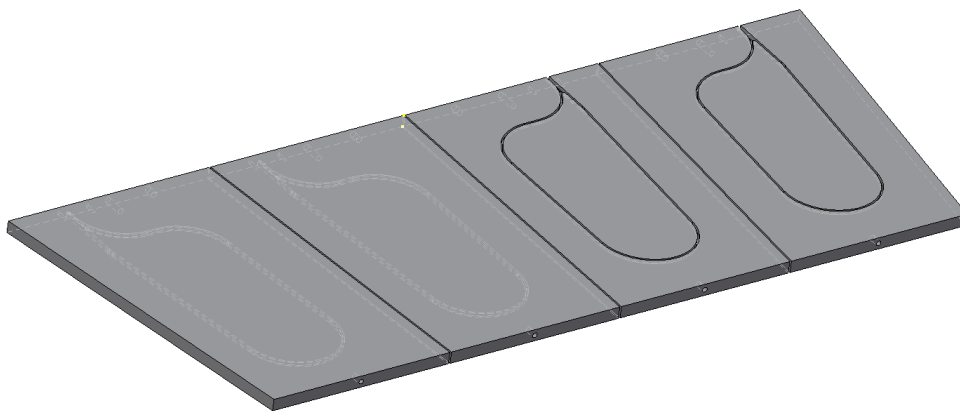
Figure 5.13: Jet energy scale (left) and resolution (right) as a function of parameter R of the reconstructed jets in simulated proton-proton events with the Inner HCal and the aluminum frame, obtained by fitting the distributions in Figure 5.12 with a Gaussian function.

- 2449 • The first beam test was performed in February of 2014. It was during the prelimi-
2450 nary stage of the detector development. The goals included characterization of the
2451 light yield of the full detector for hadronic showers, as well as an investigation of
2452 the energy response and calibration procedures. This prototype reflects an earlier
2453 iteration of the design, where both the Inner and Outer HCal were located outside
2454 of the solenoid magnet. In addition, fiber routing from this earlier design has since
2455 been further optimized.
- 2456 • The second beam test was performed in April of 2016. The prototype configura-
2457 tion was intended for mid-rapidity configuration in the sPHENIX detector and reflects
2458 the current positions of the Inner and Outer HCal.
- 2459 • The third beam test was performed in January 2017. The calorimeter was config-
2460 ured in a manner that mimics the high-rapidity configuration of sPHENIX. The same steel
2461 was used as in the 2016 test. The main goal for this phase was to understand the
2462 performance in the high-rapidity configuration.

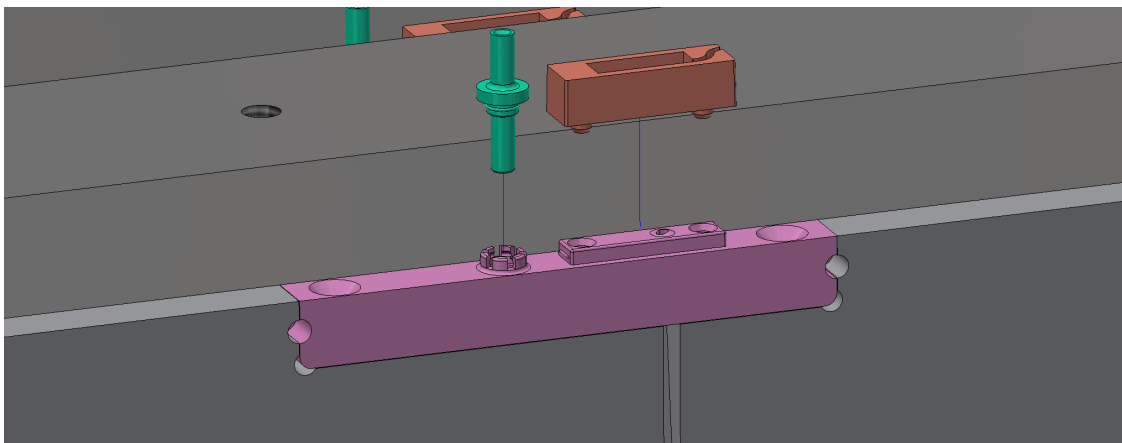
2463 This section will focus on the set-up and results from the 2016 and 2017 prototype tests. The
2464 T-1044 test beam configurations include both sections of Inner and Outer HCal prototypes
2465 as well as an EMCAL prototype. The Inner and Outer HCal prototypes are constructed
2466 as a small pseudorapidity and azimuthal segment ($\Delta\eta \times \Delta\phi = 0.4 \times 0.4$) of the full scale
2467 sPHENIX design. A mock cryostat, comprising three vertical plates of aluminum, was
2468 placed between the Inner and Outer HCal to provide as many radiation lengths of material
2469 as a particle would encounter traversing the sPHENIX solenoid (approximately $1.4 X_0$).



(a) Inner HCal scintillator tiles at different stages of production. The tiles shown are after the extruded scintillator is cut to size (left), after application of the reflective coating (middle) and after the groove for the fiber is cut.



(b) Inner HCal tile design patterns



(c) Plastic coupler to attach the SiPM at the fiber exit

Figure 5.14: HCal tile production. (a) Inner HCal scintillating tiles in several stages of production. From left to right tiles are machined, then coated and embedded with WLS fiber. (b) 4 scintillating tiles arranged symmetrically around $\eta = 0$ to be inserted between the steel absorber plates. (c) SiPM installation at the fiber exit using a plastic coupler.

2470 5.4.1 Tile Construction

2471 Figure 5.14 (a) shows the tile production steps for the Inner HCal. The design of the Outer
2472 HCal tiles are similar, but the Outer HCal tiles are larger to accommodate the larger radius
2473 of the Outer HCal. The scintillation light produced in the tiles by ionization from charged
2474 particles is contained within the tile and reflected diffusely by a reflective coating and
2475 reflective tile wrapping. The light is absorbed by the fiber embedded in the scintillator.
2476 Figure 5.14 (b) shows the fiber routing patterns for the tiles used in the 2016 study. As
2477 shown in Figure 5.14 (c), the two ends of the fiber are brought together at the outer radius
2478 of the tile where a small plastic mount supports a $3 \times 3 \text{ mm}^2$ SiPM at the fiber exit. The
2479 fiber exit is orthogonal to the tile edge and glued at a depth in the tile that allows for
2480 installation of the SiPM centered around the fiber exits. The air gap between the fiber
2481 ends and the face of the SiPM allows the emitted light to spread over the face of the SiPM,
2482 reducing the probability of optical saturation resulting from the two or more photons
2483 impinging on the same pixel. A gap of 0.75 mm satisfies the following two requirements:
2484 (1) there be no more than a 5% variation in the SiPM response when fibers and SiPM are
2485 misaligned by 0.2 mm; (2) no more than 20% loss of light outside of SiPM sensitive area.

2486 Scintillating tiles for the calorimeter are manufactured by the Uniplast Company in
2487 Vladimir, Russia. A dry mix of polystyrene granules, PTP, and POPOP is melted and
2488 extruded, producing a continuous band of hot scintillating plastic 25 cm wide. The
2489 scintillator is then cut into 2 m long pieces. After passing inspection for defects and
2490 discolorations, these pieces are mechanically machined into the tiles according to the
2491 specified dimensions. The tiles are then placed in a bath of aromatic solvents resulting
2492 in the development of a white diffuse reflective coating over the whole tile surface with
2493 an average thickness of $50 \mu\text{m}$. This process also removes microscopic non-uniformities
2494 normally present on the surface of extruded plastic, which decreases aging and improves
2495 the ability of the tile to withstand pressure without crazing. It also enhances the efficiency
2496 of light collection in tiles with embedded fibers. The coated tiles are then grooved and
2497 WLS fibers are embedded. The fibers are glued using optical epoxy (EPO-TEK 301) with
2498 special care given to the fiber position at the exit from the tile. The fibers are cut at the tile
2499 edge and polished by hand.

2500 5.4.2 Tile Testing

2501 To determine the light response across the tiles, various studies have been performed. In
2502 one study, an LED with a collimator is attached to a mount on a two-dimensional rail
2503 system with very accurate stepper motors. This allows an automated analysis with very
2504 high positional precision. The LED scans of the Outer HCal tiles consist of 174 points in
2505 the long direction (X) and 54 points in the short direction (Y) for a total of 9,396 points.
2506 The scan positions are 0.5 cm (approximately the LED spot size) apart in each direction.
2507 The principal disadvantage of an LED scan is that light is inserted into the tile directly
2508 rather than being induced by ionizing radiation. During the FTBF test beam running, a

2509 “tile mapper” was constructed and placed on a two-dimensional motion table. The motion
 2510 table moves up/down and left/right, keeping the position along the beam direction fixed.
 2511 The tile mapper included four Outer HCal tiles placed perpendicular to the beam direction,
 2512 so that movement on the motion table corresponds to different positions on the tile face.
 2513 Each tile is read out individually, which enables a detailed study of the light response as a
 2514 function of position. The scan consists of 20 total positions, 10 positions focused on the
 2515 inner part of the tile and 10 focused on the outer part of the tile. A few of the outer scan
 2516 positions fall near the edge and are excluded from the analysis. This study was performed
 2517 with a 16 GeV negative pion beam.

2518 Figure 5.15 shows the LED scan of an Outer HCal tile using a 405 nm UV LED. Additional
 2519 scans were performed using 375 and 361 nm UV LEDs with similar results. The overlaid
 2520 black circles indicate the positions on the tiles used in beam scan described in the previous
 2521 paragraph. The relative positional accuracy of the points is 0.2-0.3 cm. The numbers show
 2522 the ratio of the average ADC value of the 16 GeV pion data to the average ADC value of
 2523 the LED scan for that position. Note that the same tile was not used the two studies and
 2524 the normalization is arbitrarily chosen so that the numerical values are near unity.

2525 Most of the points have ratio values close to unity, indicating good agreement between the
 2526 16 GeV pion data and the LED data. The points close to the SiPM, which can be seen as
 2527 the red region in the upper left, show a downward trend in the ratio values, suggesting
 2528 that the intense bright spot in the LED data is not as significant in the 16 GeV pion data.
 2529 Additionally, the set of five points near 150 mm in the Y position and less than 200 mm
 2530 in the X position, are systematically lower than the LED data and their positions appear
 2531 to overlap the embedded WLS fiber. This is most likely due to the fact that, in the LED
 2532 scan, some of the light from the LED is captured directly by the fiber, so there is a modest
 2533 enhancement at the fiber that is not present in the 16 GeV pion data. Both sets of five inner
 2534 points, however, show a decreasing trend as the points get close to the SiPM.

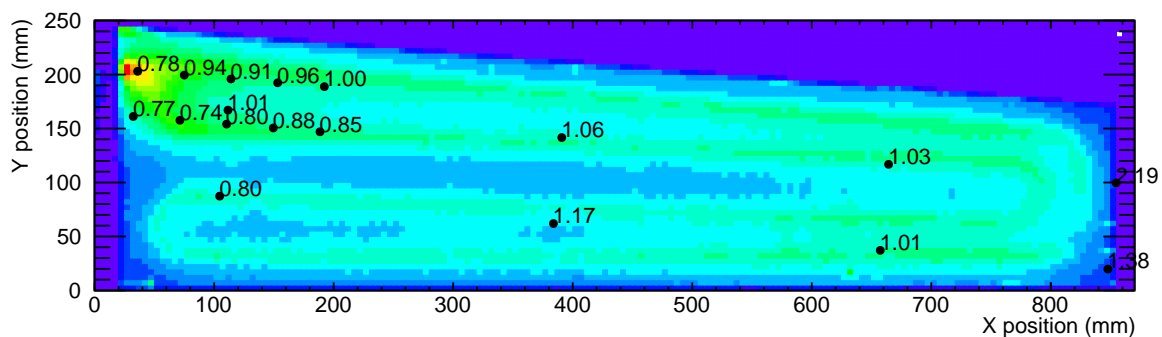


Figure 5.15: LED response of a scintillation Outer HCal tile with tile mapper scan data overlaid as black points. The numerical value shown at each point is the normalized ratio of the LED response to the tile mapper response.

2535 Figure 5.16 shows the average ADC value for each scan position as a function of the dis-

2536 tance from the SiPM. While the 16 GeV pion data do not show as much of an enhancement
 2537 near the SiPM as the LED scan, it can be seen that for points less than 15 cm away from the
 2538 SiPM that there is a strong rise in the average ADC as the distance to the SiPM decreases.
 2539 This is most likely due to the fact that some of the light in the fiber is carried in the cladding,
 2540 which has a very short attenuation length, and is therefore lost for most positions in the tile.
 2541 Studies of small double-ended scintillating tiles have indicated that up to 50% of the light
 2542 is carried in the cladding, though this is with LED light rather than scintillation light. Here
 2543 the results indicate that about 33% of the light is carried in the cladding. The area in which
 2544 more light is collected due to light being present in the cladding is of order 5 cm² right
 2545 around the SiPM mounting, which is at the back of the calorimeter. The spatial density of
 2546 shower particles is lowest at the back of the calorimeter and therefore this small amount of
 2547 additional light has a negligible effect on the determination of the shower energy.

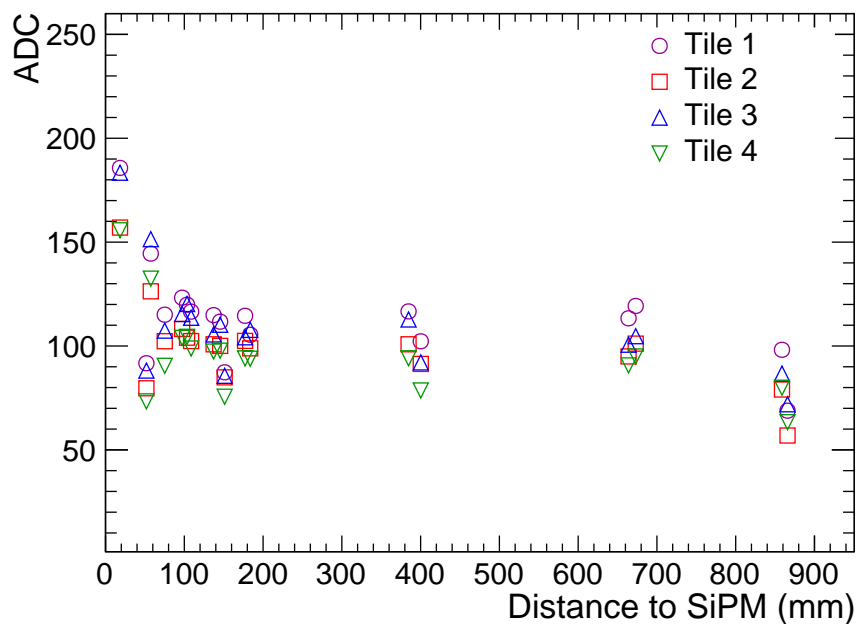


Figure 5.16: Outer HCal tile scan using 16 GeV pion beam. Average ADC value in the tile plotted as a function of distance from the SiPM. The points below 150 mm indicate an enhancement close to the SiPM.

2548 5.4.3 Assembly

2549 Figure 5.17 (a), (b) shows the fully assembled Inner and Outer HCal prototypes. The major
 2550 components are 20 steel absorber plates and 80 scintillating tiles which are read out with
 2551 SiPMs along the outer radius of the detector. The 2016 and 2017 prototype Inner HCal was

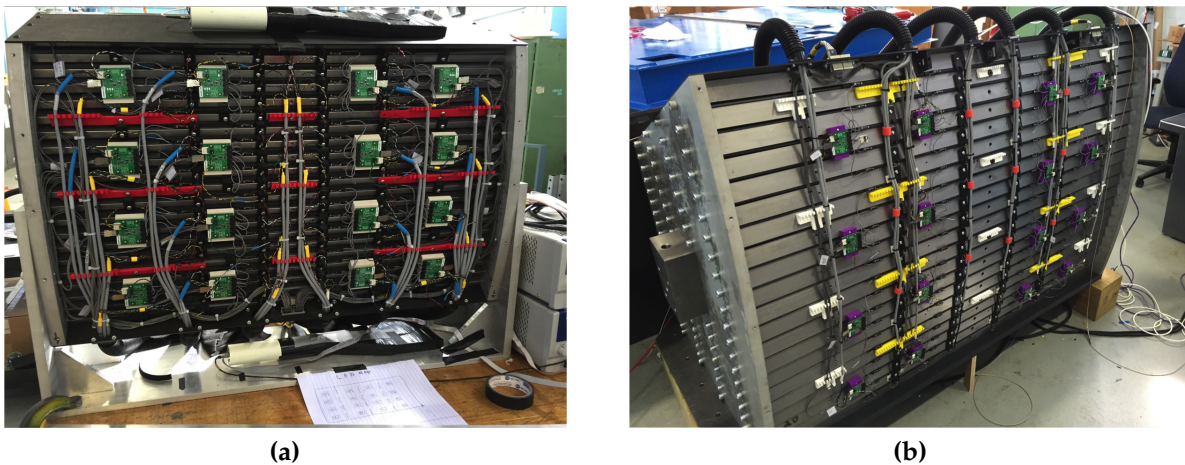


Figure 5.17: Fully assembled (a) Inner and (b) Outer HCal test beam prototypes. Each section has 20 steel absorber plates stacked together and 80 scintillating tiles are inserted between them. SiPM read out from five tiles are ganged together as a tower. This results in a total of 16 towers equipped with SiPM sensors, preamplifiers, and cables carrying the differential output of the preamplifiers to the digitizer system.

2552 based on an earlier design with tapered plates and five tiles per tower. The 2018 prototype
 2553 will test the final design for the Inner HCal with flat plates and four tiles per tower. The
 2554 Outer HCal prototype is unchanged.

2555 The SiPMs from five tiles are connected passively to a preamplifier channel. This resulted
 2556 in a total of 16 towers, 4 in ϕ by 4 in η , equipped with SiPM sensors, preamplifiers, and
 2557 cables carrying the differential output of the preamplifiers to the digitizer system. Sixteen
 2558 preamplifier boards corresponding to the 16 towers are visible. In order to make the whole
 2559 system light tight, the front and back sides were covered with electrically conductive
 2560 ABS/PVC plastic. This material quickly diverts damaging static charges if there is a
 2561 buildup. Corners were sealed with light tight black tape. No light leaks were observed
 2562 during the entire data taking period.

2563 Since the same bias voltage is supplied to all five SiPMs in a given tower, the SiPMs
 2564 must be gain matched so that their responses are the same. The SiPMs are sorted and
 2565 grouped to towers according to the manufacturer's measurements. The SiPM sensors,
 2566 preamplifiers, and cables are arranged on the outer radius of the Inner HCal. The interface
 2567 boards mounted on the side of the modules monitor the local temperatures and leakage
 2568 currents, distribute the necessary voltages, and can provide bias corrections for changes in
 2569 temperature and leakage current.

2570 5.4.4 Prototype Calibration

2571 The initial HCal calibration was performed using cosmic MIP events in order to equalize
 2572 the response of each tower. A set of cosmic MIP events was recorded prior to the test beam
 2573 data taking in order to calibrate the detector. The cosmic MIP events were triggered with
 2574 scintillator paddles positioned at the top and bottom of the HCal (in the ϕ direction as
 2575 seen from the interaction point). In each run, four vertical towers are scanned from top
 2576 to bottom (e.g. Tower 0-3 in Figure 5.18). This yields eight individual runs in order to
 2577 fully calibrate both the Inner and Outer HCal sections. Figure 5.18 (a) shows the ADC
 2578 distributions in the 4×4 Inner HCal towers. Each spectrum is fit with a function that
 2579 is the sum of an exponential and a Landau distribution, where the exponential function
 2580 corresponds to the background and the Landau function represents the MIP events. As
 2581 seen in Figure 5.18, the background component is relatively small. Clear cosmic MIP peaks
 2582 are observed in all towers.

2583 The corresponding simulation of cosmic muons is performed with 4 GeV muons (the mean
 2584 muon energy at sea level) moving from the top to bottom of the HCal prototype with the
 2585 standard GEANT4 setup discussed in Section 5.3. Figure 5.18 (b) shows energy deposition
 2586 in only one column of towers. The mean energy deposited by the cosmic muons in each
 2587 tower is approximately 8 MeV for the Inner HCal. Because of the tilted plate design, towers
 2588 at the bottom of the Inner HCal have more deposited energy than the top ones. This feature
 2589 was first observed in data and then confirmed by the simulations. This simulation was
 2590 used to calibrate the ADC signal in each tower to the corresponding energy loss in the test
 2591 beam. Once the ADC signal height, $I(ch)$, is determined by a functional fit to the ADC
 2592 timing samples, the energy deposited is calculated by:

$$E(ch) = I(ch) \frac{E_{dep}^{cosmic}(ch)}{E_{dep}^{ADC}(ch) \times SF(muon)}, \quad (5.2)$$

2593 where $E_{dep}^{cosmic}(ch)$ is the total deposited energy extracted from the GEANT4 simulations,
 2594 $E_{dep}^{ADC}(ch)$ is the ADC signal height measured from cosmic data, and $SF(muon)$ is the muon
 2595 sampling fraction.

2596 5.5 Prototype performance

2597 5.5.1 HCal Standalone Measurements

2598 The HCal standalone data are collected with only the inner and outer sections of the HCal
 2599 in the beam line and no EMCal in front. In this configuration, electromagnetic showers
 2600 generally start earlier in the calorimeter and deposit most of their energy in the Inner
 2601 HCal. The hadronic showers, however, are typically deeper than the electromagnetic

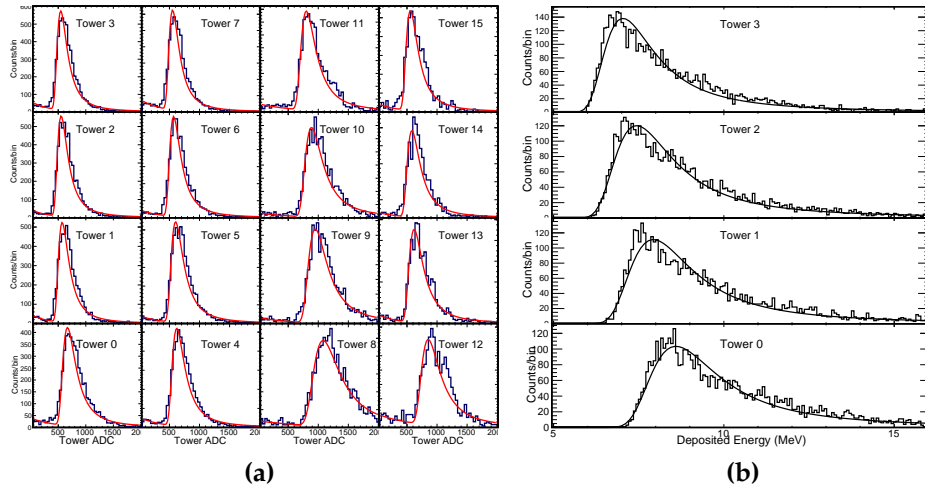


Figure 5.18: Tower to tower calibration for the Inner and Outer HCal was done with cosmic muons. (a) Measured raw ADC spectra of cosmic ray muon events in the Inner HCal. (b) Inner HCal cosmic muon energy deposition in simulation in one column. Muons were simulated at 4 GeV moving from the top to the bottom. Energy depositions in the bottom towers are higher due to the tilted plate design where muons have to go through a longer path through the scintillating tiles.

2602 showers and deposit most of their energy in the Outer HCal. The beam is adjusted to
 2603 be in the middle of the prototypes in order to maximize the hadron shower containment
 2604 in the 4×4 Inner and Outer HCal towers. Data were collected with negatively charged
 2605 particle beams with energies between 2 GeV and 32 GeV, which contain an admixture of
 2606 mainly electrons and pions. Electron and pion events were tagged using the two beamline
 2607 Cherenkov counters. Hodoscope and veto cuts based on the beam location were applied
 2608 but no significant effect on the energy resolution due to the beam position was found. Both
 2609 high and low gain signals from the HCal towers were collected but only low gain channels
 2610 are used for analysis.

2611 The energy from all of the towers of both the Inner and Outer HCal are summed to
 2612 determine the reconstructed energy:

$$E_{HCAL} = Gain_{inner} E_{inner} + Gain_{outer} E_{outer}, \quad (5.3)$$

2613 where E_{inner} and E_{outer} are the sum of the calibrated tower energy ($\sum_{ch} E(ch)$) of the Inner
 2614 and Outer HCal, respectively. The asymmetry between the two sections is defined as

$$A_{HCAL} = \frac{E_{inner} - E_{outer}}{E_{inner} + E_{outer}}. \quad (5.4)$$

2615 The gain calibration constants, $Gain_{inner}$ and $Gain_{outer}$, are determined in order to minimize
 2616 the dependence of E_{HCAL} on A_{HCAL} and the deviation of E_{HCAL} from the beam energy.
 2617 The same gain calibration constants are used in analysis of all beam energies.

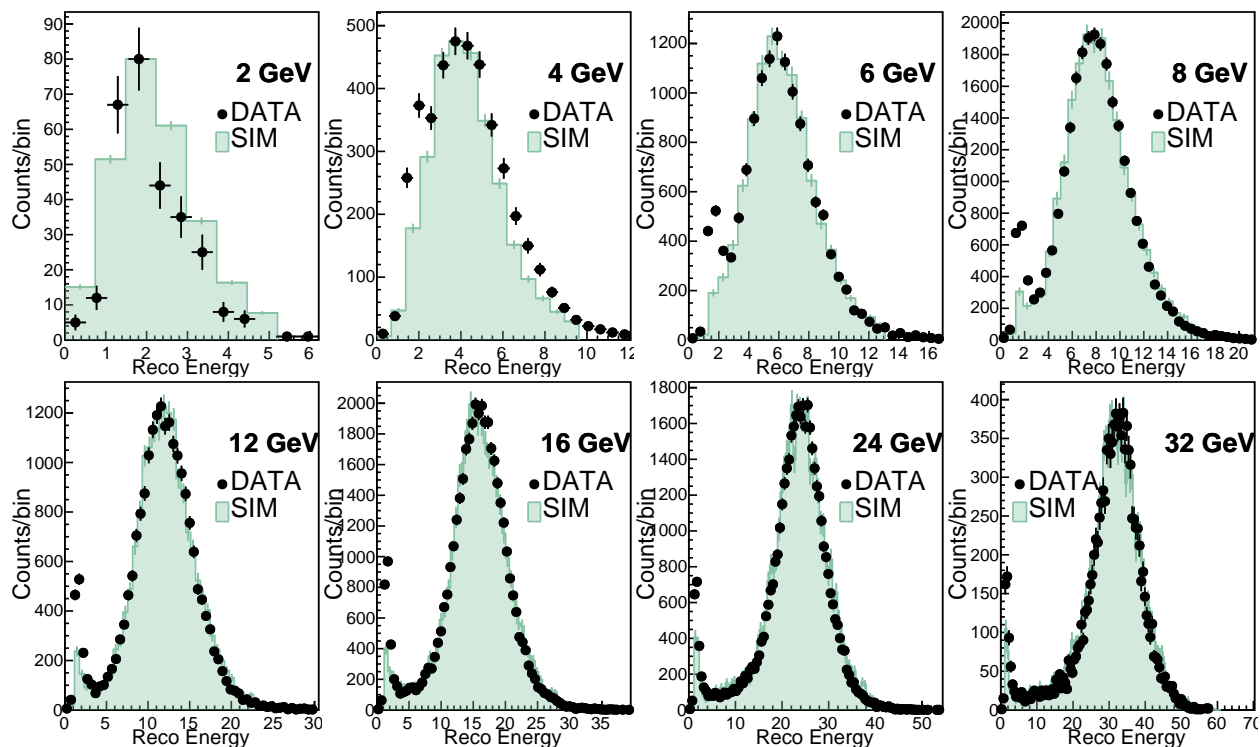


Figure 5.19: Hadron reconstruction in the standalone HCal setup. Calibrated 4×4 tower energies were added together from the inner and the Outer HCal. The simulation is shown by the filled histogram and the solid points are the data. Both are in good agreement. The peak at the lower energies in the data corresponds to the small fraction of muon events that pass through the HCal leaving only the minimum ionizing energy, which were not simulated.

2618 Figure 5.19 shows a comparison of the reconstruction hadron energy between data and
 2619 simulation. The simulation (filled histogram) and data (solid points) are in excellent agree-
 2620 ment for 6-32 GeV beam energies. The data has a beam momentum spread of 2% which
 2621 has been included in the simulations as well. At lower energies, hadron measurements are
 2622 poor due to lower fractions of hadrons in the beam as well as the increased beam size. The
 2623 peak at the lower energies in the data corresponds to the small fraction of muons events
 2624 that pass through the HCal leaving only the minimum ionizing energy. The corresponding
 2625 energy resolution and linearity for hadrons are shown in Figure 5.20. The data are fit with
 2626 the function, $\Delta E/E = \sqrt{(\delta p/p)^2 + a^2 + b^2/E}$, as labeled on the plot. A beam momentum
 2627 spread ($\delta p/p \approx 2\%$) is unfolded and included in the resolution calculation. The hadron
 2628 energy resolution is $11.8 \oplus 81.1\%/\sqrt{E}$, which matches the expected resolution from simu-
 2629 lations very well. The HCal was calibrated for hadronic showers and then used to measure
 2630 electron showers. The electron resolution for the standalone HCal is $8.1 \oplus 31.3\%/\sqrt{E}$.
 2631 This demonstrates that the HCal can assist the EMCal by measuring the electron energy
 2632 leaking from the EMCal into the HCal.

2633 As seen in Figure 5.20 (a), the hadron energy response is well described by a linear fit
 2634 where the reconstructed energy is the same as the input energy. The bottom panel shows

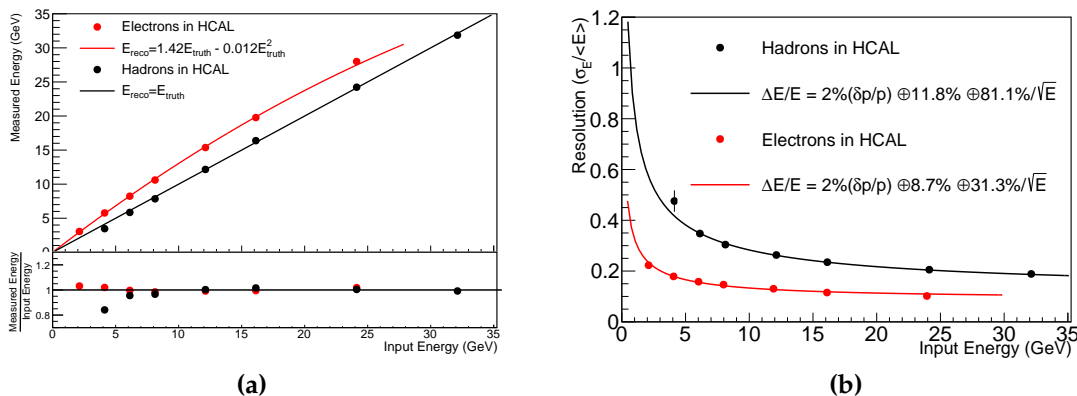


Figure 5.20: HCal standalone measurements without the EMCal in front. (a) HCal linearity for electrons and hadrons. The lower panel shows the ratio of reconstructed energy and the fits. (b) Corresponding HCal resolution for hadrons and electrons. The beam momentum spread ($\delta p/p \approx 2\%$) is unfolded and included in the resolution calculation.

2635 the ratio between the reconstructed energy and the fit. The 4 GeV hadron measurement is
 2636 poor because the hadron peak is difficult to distinguish from the muon MIP peak due to
 2637 their proximity, as seen in Figure 5.19. The response of the electrons is described well with
 2638 a second order polynomial due to non-linear e/h response.

2639 5.5.2 Hadron Measurement With The Full Calorimeter System (sPHENIX 2640 Configuration)

2641 The full hadron measurement is done with the sPHENIX configuration, which includes all
 2642 three segments of calorimeters including the EMCal in front of the HCal. In this configura-
 2643 tion the total energy will be reconstructed by summing up the digitized data from both
 2644 the EMCal and the HCal. The development of hadronic showers is a complicated process
 2645 with significant fluctuations in the reconstructed energy compared to electromagnetic
 2646 showers. Determining the shower starting position helps to understand the longitudinal
 2647 shower development fluctuations. Therefore, in this analysis, the events are sorted into
 2648 three categories depending on their longitudinal shower profile:

- 2649 • **HCALOUT:** Events where hadrons pass through the EMCal and Inner HCal and
 2650 primarily shower in the Outer HCal alone or pass through the full calorimeter system
 2651 without showering. These events are shown as the blue points in Figure 5.21.
- 2652 • **HCAL:** Events where hadrons pass through the EMCal. In these events, hadron show-
 2653 ers start in the Inner HCal, or the Outer HCal, or pass through all three calorimeters.
 2654 These events are shown as red points in Figure 5.21.

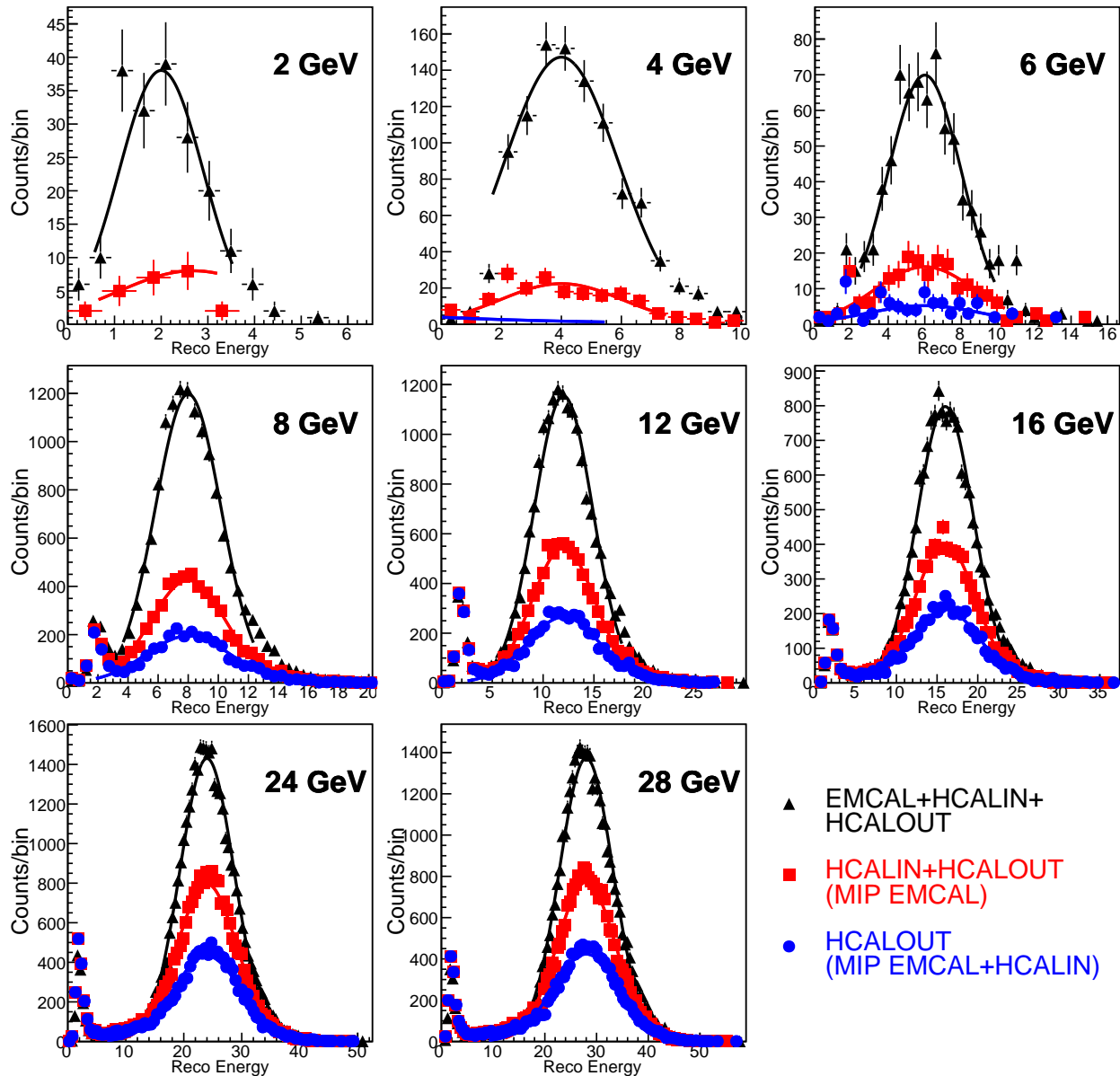


Figure 5.21: Hadron energy measurements with combined EMCal+HCal detector. Events were sorted into three categories: 1) HCalOUT where particles pass through the EMCal and Inner HCal and then shower in the Outer HCal; 2) HCalIN+HCalOUT where particles pass through the EMCal and then shower in either HCal; 3) EMCAL+HCalIN+HCalOUT which includes all showers irrespective of their starting position.

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- FULL: This represents all hadrons irrespective of when they start showering. They are shown as black points in Figure 5.21. These include hadron showers that start in the EMCal, Inner HCal, Outer HCal, or pass through all three calorimeter systems.

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These event categories help diagnose each calorimeter independently as well as improve our understanding of the leakage variations, shower containment, and longitudinal fluc-

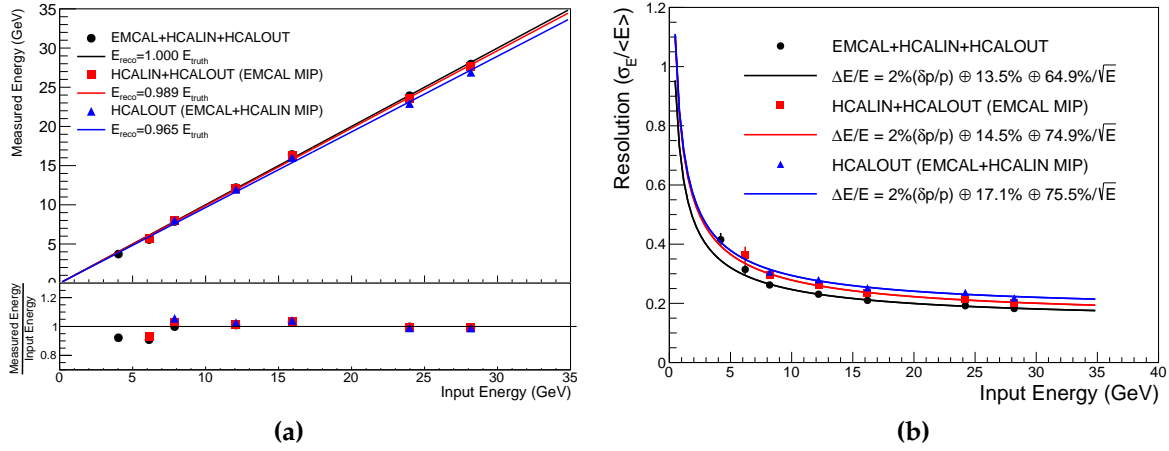


Figure 5.22: Hadron (a) linearity and (b) resolution measured with the combined EM-Cal+HCal (sPHENIX configuration) detector setup. Three sets of data points corresponds to the event categories shown in Figure 5.21. The bottom panel of (a) shows the ratio of the measured energy and corresponding fits.

2660 tuations of particle showers depending on their starting position. The EMCal energy
 2661 was balanced with respect to the HCal in a similar way, by changing the gain factors
 2662 described in the previous section. As expected, Figure 5.21 shows the fraction of HCAL
 2663 or HCALOUT events increases as a function of beam energy. The peaks at the lower
 2664 measured energy correspond to the small fractions of muon events that pass through the
 2665 calorimeters leaving only the minimum ionizing energy.

2666 The corresponding hadron resolution is shown in Figure 5.22 (b). Data are fit in a similar
 2667 manner with $\Delta E/E = \sqrt{(\delta p/p)^2 + a^2 + b^2}/E$, i.e. with a fixed beam momentum spread
 2668 term of $\delta p/p \approx 2\%$ subtracted from the constant term in quadrature. HCALOUT showers
 2669 that pass through the EMCal and Inner HCal have a resolution of $17.1 \oplus 75.5\%/\sqrt{E}$. HCAL
 2670 showers that pass through through the EMCal have a resolution of $14.5 \oplus 74.9\%/\sqrt{E}$.
 2671 A combined resolution of all the showers irrespective of their starting position (FULL)
 2672 is $13.5 \oplus 64.9\%/\sqrt{E}$. The hadron resolution improves without the MIP cuts because it
 2673 reduces the overall shower fluctuations and leakages.

2674 The linearity is shown in Figure 5.22 (a). The bottom panel shows the ratio of the measured
 2675 energy and the corresponding fits. The FULL reconstructed showers are normalized
 2676 to the input energy. This results in the HCAL and HCALOUT reconstructed showers
 2677 linearity slightly below the input energies, due to higher leakage in those event categories.
 2678 In all cases the single hadron energy response is exceeds the sPHENIX performance
 2679 specifications.

2680 5.6 Ongoing developments

2681 5.6.1 Test Beam in 2018

2682 Building on the success of the three HCal prototypes, we plan to construct a fourth
2683 prototype for testing in the FNAL test beam in 2018. In addition to a new EMCal prototype
2684 and the same Outer HCal reused from the 2017 beam test, the 2018 prototype will consist of
2685 two prototype Inner HCal sectors with the flat plate design, one with hardened aluminum
2686 alloy and the other with steel. Previous beam tests used the tapered plates for the Inner
2687 HCal prototype, as it was designed and built prior to the design change to flat plates and
2688 four tiles per tower. Simulations studies have demonstrated the change from tapered
2689 to flat plates has little effect on the performance; nevertheless, such a change in design
2690 warrants confirmation with a beam test. The 2018 beam test will test the final designs for
2691 all components of the calorimeter system and is expected to be the final beam test.

2692 5.6.2 Self Trigger

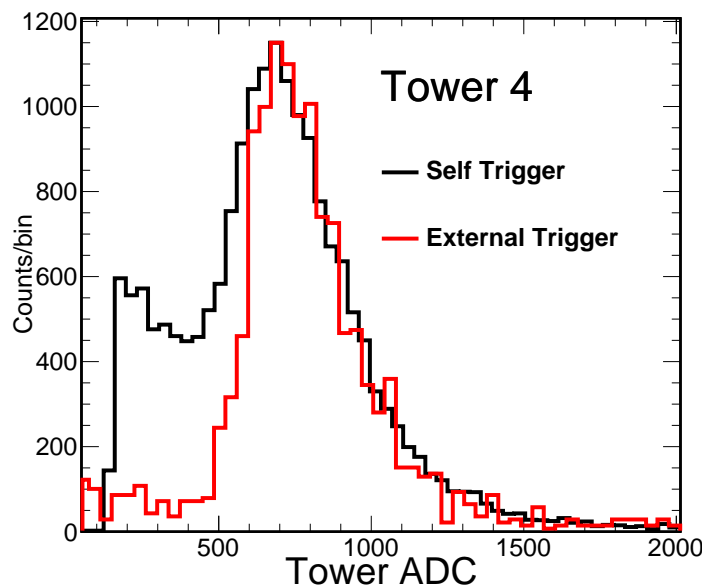


Figure 5.23: ADC distribution in a inner HCal tower for cosmic muons. Two trigger configurations are compared: the two scintillator paddle cosmic trigger and the self trigger.

2693 The prototype was calibrated with cosmic muon events triggered with external scintillator
2694 paddles positioned at the top and bottom of the HCal. As noted in the previous section,
2695 this procedure successfully equalized the response of each tower. The calibrated energy

2696 sum agrees with the simulation very well. However, because of the cylindrical geometry
2697 of the completed sPHENIX and the time required for collecting enough cosmic ray events,
2698 this triggering method can not easily be scaled to the full geometry, which includes 1536
2699 towers (64 in $\phi \times 24$ in η) for each HCal.

2700 A self trigger configuration has been tested with the HCal prototype. This trigger con-
2701 figuration removes the single tower backgrounds, improving the rejection factor. The
2702 algorithm is based on requiring at least N towers with signal greater than some threshold,
2703 thus removing a lot of single tower noise events. The trigger algorithm is executed by the
2704 FPGA on the data buffer. The steps of the algorithm is follows:

- 2705 • Get an 8 bit signal amplitude. For each tower in the HCal, take the 12 bit post sample
2706 minus the pre sample to get a signal amplitude. The separation of the post and pre
2707 samples is user definable, but was set to be 5 samples. If the amplitude is below 0, it
2708 is set to 0. If the amplitude is above 2040, it is set to 255. Otherwise, the bottom 3 bits
2709 are dropped from the amplitude to produce a 8 bit amplitude value. Note that since
2710 we use a bipolar ADC, the 12 bits is effectively only 11 bits. The above 0 and 2040
2711 limits are to check for over and underflow of those 11 bits, which can happen since
2712 we operate on 12 bits.
- 2713 • Get the number of towers above single tower threshold. Sum up the number of
2714 towers above the single channel threshold.
- 2715 • Scale by the gain factors. Scale the 8 bit amplitude for each tower by the gain scale
2716 factors. The gain factor allows one to gain-balance the towers at the trigger level.
2717 After the scaling, the amplitude is a 16 bit value. To return to an 8 bit value, the top 2
2718 bits and bottom 6 bits are dropped, i.e. the amplitude is divided by 64.
- 2719 • Sum tower amplitudes. Sum up all the tower amplitudes to get the total sum in a
2720 HCal module. Since the sum is a 8 bit number, if the sum is above 255 it gets set to
2721 255.

2722 The above algorithm is run for Inner and Outer HCal independently. We require at least
2723 three out of the sixteen towers to be higher than a common threshold to define a self trigger.
2724 Figure 5.23 shows a comparison of the energy deposited in a tower when triggered with
2725 self trigger and external trigger. A clear Landau distribution is seen in both setups. The
2726 self trigger configuration contains a small number of noise events which can be further
2727 cleaned with appropriate geometry cuts. This method also confirmed our calibrations for
2728 both sections of the HCal prototypes. While this is still in a developmental phase, the self
2729 trigger can be very useful calibrating the full HCal detector.

2730 5.6.3 LED System

2731 A LED pulser system has been developed for tracking short term gain changes caused by
2732 temperature compensation of the SiPMs and effects of increased leakage current caused

2733 by radiation damage. The system has been integrated into the Slow Controls system to
2734 eliminate additional cabling and circuitry on the detector. In the HCal prototype from
2735 January 2017, five UV LEDs were located on the controller. Since each tower has five
2736 individual tiles, each tile was connected to distinct LEDs via optical fibers. The tower
2737 response was measured when each tile was illuminated separately or in some combination.
2738 It helps to quickly identify the dead channels and stability of their light outputs during
2739 data taking.

2740 5.6.4 Tile testing setup

2741 Since the first prototype productions of tiles, the need for additional quality control tests
2742 at Uniplast was realized. The final thickness of each tile produced for the 2017 prototype
2743 was measured and recorded at several locations along the tile to ensure they satisfied
2744 the tolerance requirements to fit cleanly between the steel plates. Additional quality
2745 control tests to ensure fibers were not damaged and could provide light output were also
2746 performed. The results of each test were provided to BNL along with the tiles.

2747 In addition, a tile tester is being prepared by collaborators at Georgia State University and
2748 Debrecen which will further test the light output by the fibers at Uniplast prior to shipping.
2749 The tester will measure the signal output by a particular set of SiPMs when cosmic rays
2750 pass through a stack of tiles. This will allow Uniplast to confirm that the tiles and fibers
2751 are emitting a consistent amount of light throughout the final production.

2752 Chapter 6

2753 Calorimeter Electronics

2754 The sPHENIX reference design for electronics is based on a common electronics design for
 2755 both the EMCal and HCal detectors using off the shelf components. This approach will
 2756 reduce the overall cost and minimize the design time for the electronics. A block diagram
 2757 of the calorimeter readout chain is shown in Fig. 6.1. The technical specifications for the
 2758 calorimeter electronics are set by physics requirements and are summarized in Table 6.1.
 2759 For the EMCal, the expected energy range for photons is expected to be 1 GeV to 50 GeV.
 2760 For a 1 GeV photon incident on the center of an EMCal tower, 80% of the energy will be
 2761 deposited in the central tower with 20% of the energy shared among the 8 surrounding
 2762 towers. This implies a minimum energy of 25 MeV and a dynamic range of 10^3 to cover
 the range of expected energy deposition in a single tower of the EMCal.

Table 6.1: Technical Specifications for the Calorimeter Electronics.

Component	Requirement	Specification
Optical Sensor	Pixel Size	$15 \times 15 \mu m^2$
	Dynamic Range	10^4
	PDE	25%
	Gain	10^4
	Pixels/GeV: EMCal	1600
	Pixels/GeV: HCal	
Amplifier/Shaper	Gain	100 mV/pC
	Signal-to-Noise	10:1
	Peaking time	30nSec
Digitizer	Resolution	14 Bit (13 Bit effective)
	Maximum Sampling Frequency	65 MHz
	Latency	40 BCO
	Multi-event Buffering	5 Events

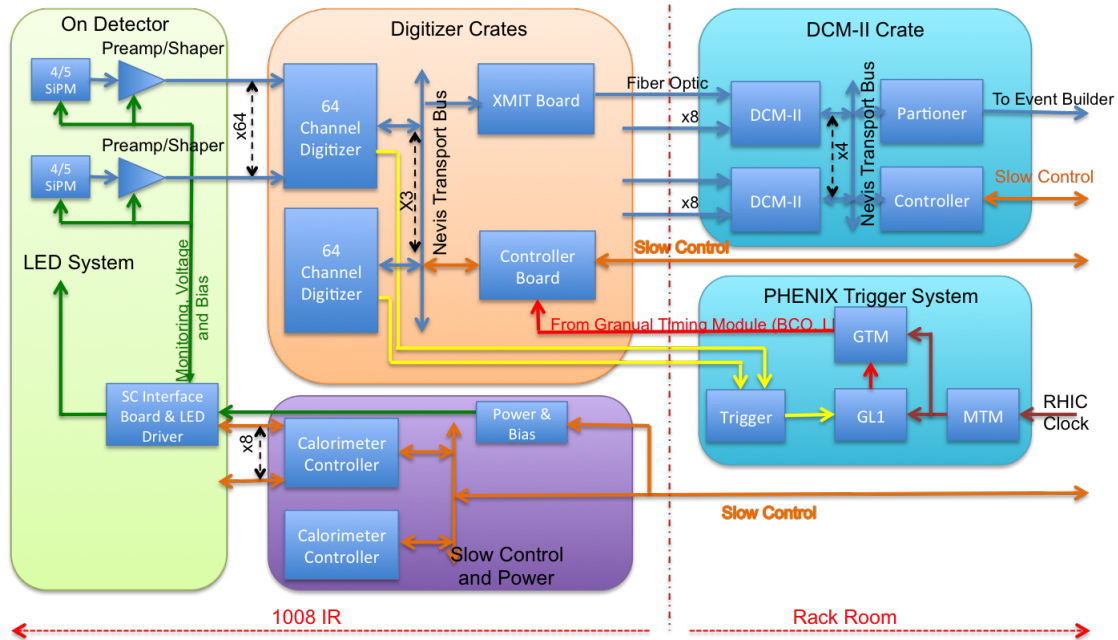


Figure 6.1: Block diagram of the calorimeter readout chain. The optical signals are amplified locally and driven as differential analog signals to the digitizers located near the detector. Upon receipt of a level one trigger, the digital data for triggered event is transmitted via optical fiber to the sPHENIX data acquisition system. for recording.

2763 The reference design uses multiple Silicon Photomultipliers (SiPMs) as the optical sensors
 2764 for the calorimeters. The Analog signals from the SiPMs associated with a single tower
 2765 in the calorimeters are passively summed, amplified, shaped and differentially driven
 2766 to digitizer boards located in racks near the detector. The differential analog signals are
 2767 received by 64 channel digitizer boards and digitized by a 14 bit ADC operating at a
 2768 sampling rate 6 times the beam crossing frequency. Upon receipt of a Level-1 (L1) trigger
 2769 signal, the digitized data is optically transmitted to the PHENIX DAQ.

2770 The EMCal front end electronics for an EMCal sector module consists of 2x2 SiPM Daugh-
 2771 ter Boards which mount directly on the EMCal light guides for 4 towers, 2 × 8 Preamplifier
 2772 Boards which connect to 4 SiPM Daughter Boards via flex cable, and an Interface Board
 2773 which plugs into 4 Preamplifier Boards. Located in a crate near the detector are the
 2774 Calorimeter Controllers, capable of controlling 8 Interface Boards. The amplified differ-
 2775 ential analog signals are driven directly to the nearby digitizers. There are a total of 384
 2776 EMCal front end channels in a EMCal 1/2 sector module.

2777 The HCal front end electronics for an HCal module consists of SiPM Daughter Boards with
 2778 a single SiPM which couples directly to a an HCal tile fiber and an HCal single channel
 2779 Preamplifier Board mounted next to the tower. Mounted on each end of an HCal module
 2780 are Interface and Backplane boards which provides the voltage distribution, monitoring

2781 and gain corrections, and an LED Driver board that distributes a calibration/monitoring
 2782 light pulse via optical fiber to each of the tiles in an HCal module. The differential analog
 2783 signals are brought directly to connectors located on the ends of the HCal module

2784 The analog analog signals from both the EMCal and HCal are waveform digitized using
 2785 identical electronics. The digitizer system consists of a 64 channel digitizer board with 14
 2786 bit ADCs running at 6 times the beam crossing frequency (BCO), a crate controller which
 2787 provides slow control for the crate, and an XMIT module which transmits the triggered
 2788 data from the digitizer boards to the sPHENIX Data Acquisition System. The system is
 2789 designed to read an event out in $40\mu\text{Sec}$ and operate at a level 1 trigger rate up to 15kHz.
 2790 In addition to digitizing all the channels, the digitizer board is capable of producing trigger
 2791 primitives which are transmitted over dedicated optical links to the sPHENIX trigger
 2792 system.

2793 Detailed descriptions of each of the modules for the EMCal and HCal front end electronics
 2794 and digitizer system are given in the following sections. A summary of the number of
 boards for the full detector is given in Table 6.2.

Table 6.2: Electronics Component Count.

EMCal Front End Electronics	SiPMs	98304
	SiPM Daughter Boards	6144
	Preamp Boards	1536
	Interface Boards	384
	Controller Boards	64
	Controller Crates	4
HCal Front End Electronics	SiPMs	13824
	Preamp Daughter Boards	3072
	Interface Boards	128
	LED Driver Boards	128
	Controller Boards	16
	Controller Crates	2
Digitizer Electronics Electronics	Signal Cables	1728
	Digitizer Boards	432
	XMIT Modules	144
	Controller Boards	36
	Clock Master	36
	Crates	36

2796 6.1 Optical Sensors

2797 The compact nature of the EMCal and HCal detectors and the location of the EMCal and
 2798 Inner HCal being inside the 1.5T solenoidal field require that the optical sensors be both
 2799 physically small and immune to magnetic effects. A device with large gain is also desirable
 2800 in order to reduce the demands on the performance specifications of the front end analog
 2801 electronics. For both the EMCal and HCal detectors, silicon photo-multipliers (SiPMs)
 2802 from Hamamatsu have been chosen as the reference design optical sensor. SiPMs have the
 2803 advantage that they are immune to magnetic fields, have large gain and are small in size.

2804 6.1.1 Device Characteristics

2805 SiPMs are inherently limited in their dynamic range by the number of micro-pixels in the
 2806 device, as shown in Figure 6.2. Due to the digital nature of the SiPM, the usable dynamic
 2807 range is significantly less than the the total number of micro-pixels. Each micro-pixel
 2808 fires once per event regardless of how many photons hit it. Distributing the incident light
 2809 uniformly across the active area maximizes the useful range, but for large signals it is still
 2810 limited by optical saturation, that is more than one photon hitting the same micro-pixel.
 2811 While increasing the number of micro-pixels would increase the dynamic range, there
 2812 are trade-offs in that more micro-pixels typically means lower gain and lower photon
 detection efficiency, PDE.

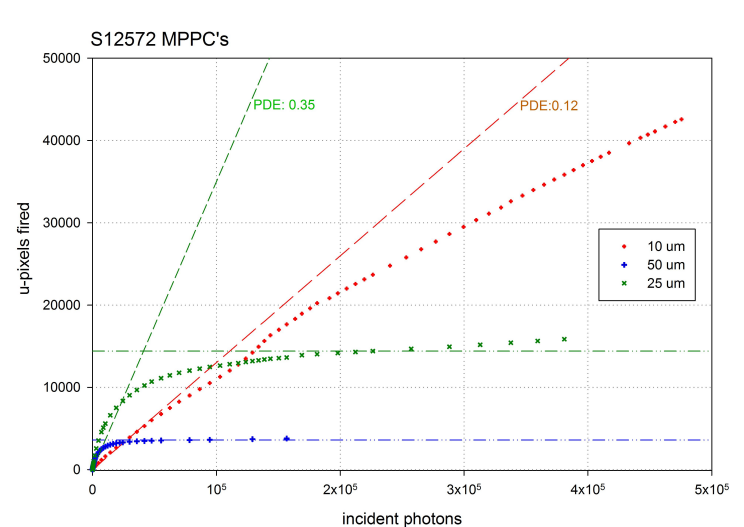


Figure 6.2: Optical saturation in Hamamatsu S12572 MPPCs. 10 μm , 25 μm , and 50 μm micro-pixels

2813

2814 In order to achieve the required dynamic range, a device with a large number of micro-cells
 2815 is required, which limits the number of devices that meet the technical specifications for
 2816 the optical sensors. Hamamatsu has a number of devices with high pixel counts, high

2817 gain, and good PDE which meet the sPHENIX technical requirements. For both the EMCal
 2818 and HCal detectors, the reference design is based on the Hamamatsu S12572-33-015P
 2819 MultiPixel Photon Counters (MPPC). The device is a $3 \times 3 \text{ mm}^2$ device with 40K pixels
 2820 each $15 \times 15 \mu\text{m}^2$ in size. A photograph of the device is shown in Figure 6.3 and a technical
 drawing is shown in Figure 6.4. The properties of this device are summarized in Table 6.3.

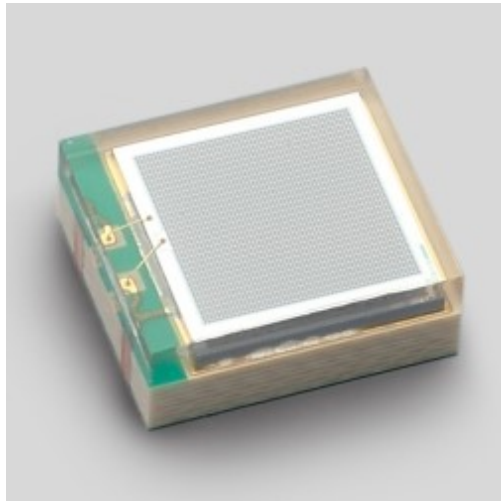


Figure 6.3: Hamamatsu S12572 MPPC (SiPM). The device is $3 \times 3 \text{ mm}^2$ with 40,000 pixels $15 \mu\text{m}^2$.

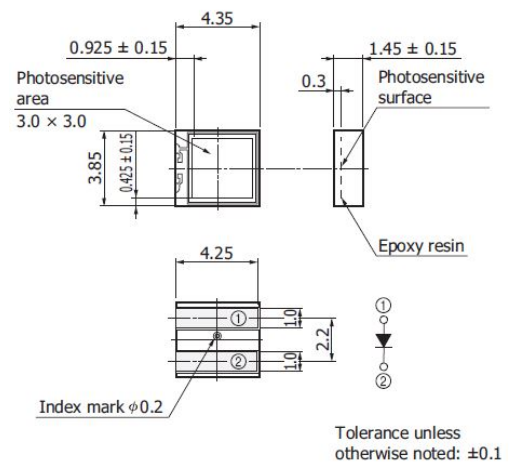


Figure 6.4: Hamamatsu S12572 MPPC surface mount package dimensions.

2821 The 40K pixels of the Hamamatsu S12572-15P device limit the dynamic range of device
 2822 to be $\sim 10^4$. However, the optical saturation at the upper end of the range is difficult
 2823 to correct for as the device response deviates from linearity as the number of activated
 2824 pixels approaches the total number of pixels in the device, so the effective pixel count is
 2825 significantly less than 40K. With a PDE of $\sim 25\%$ it should therefore be possible to adjust
 2826 the light level to the SiPM using a mixer to place the full energy range for each tower (\sim
 2827 25 MeV–50 GeV) in its useful operating range. For example, if the light levels were adjusted
 2828 to give 10,000 photoelectrons for 50 GeV, this would require only 200 photoelectrons/GeV,
 2829 which should be easily achieved given the light level from the fibers entering the mixer.
 2830

2831 The performance of a SiPM is affected by the temperature of the device. SiPMs show an
 2832 increasing dark current and a diminishing gain with increasing temperature. Figure 6.5
 2833 shows the dependence of gain on temperature for different SiPMs and the dependence of
 2834 device leakage current on temperature for Hamamatsu S12572 SiPMs of different pixel sizes.
 2835 Devices with larger pixel sizes typically have higher gain, but also higher leakage current.
 2836 The leakage current increases rapidly above 30°C , suggesting the benefit of operating in
 2837 $5\text{--}20^\circ\text{C}$ range. While in principle cooling could be used to mitigate the increased dark
 2838 current due to radiation damage, the scale of the increase (orders of magnitude) greatly
 2839 exceeds the potential benefits of cooling (factors of 2) over the temperature range $0\text{--}40^\circ\text{C}$.
 2840 Figure 6.6 shows the leakage current, signal amplitude, and signal noise performance of a
 2841 S12572-015P SiPM and an sPHENIX preamp as a function of temperature.

Property	
active area	3mm x 3mm
number of micro-pixels	40,000
micro-pixel pitch	15 μ m
geometric fill factor	0.53
package	surface mount
window	epoxy resin
window refractive index	1.55
operating temperature	0-40 deg C
spectral response range	320-900 nm
peak sensitivity wavelength	460 nm
photon detection efficiency (PDE)	0.25
Dark Count Rate (typ)	1 Mcps
Terminal capacitance	320 pF
Gain	230,000
Gain temp coefficient	3500 / $^{\circ}$ C
Breakdown voltage (V_{br})	65 ± 10 V
Recommended Operating Voltage	$V_{br} + 4$ V
Temp coeffic at V_{op}	60 mV / $^{\circ}$ C

Table 6.3: Properties of Hamamatsu S12572-015P MPPC.

2842 6.2 Readout Electronics

2843 The EMCal and HCal readout electronics consist of the analog front end electronics
 2844 mounted directly on the detectors, and the digital back end system mounted in racks
 2845 near the detector in the sPHENIX Interaction Region. The analog front end system consists
 2846 of the SiPM daughter boards, Preamplifier boards, calibration and monitoring systems,
 2847 and power distribution. The analog front end electronics is functionally the same for both
 2848 the EMCal and HCal detectors with different packaging to account for differences in the
 2849 mechanical design of the 2 detector subsystems. The digitizer and power systems are
 2850 common to both subsystems

2851 6.2.1 HCal Electronics

2852 An HCal module consists of 2×24 towers covering the full range in η and 2ϕ slices with
 2853 2×12 towers readout on each end of the module. Each of the tiles that form a tower (4 for
 2854 the Inner HCal and 5 for the Outer HCal) have single SiPM mounted on the SiPM Daughter
 2855 Board that is attached to the edge of the tile where the wave shifting fiber ends are. The
 2856 SiPMs for a tower are connected to a Preamplifier Board located on the outer radius, in
 2857 the center of the tower with a shielded cable. The signals are received on the Preamplifier

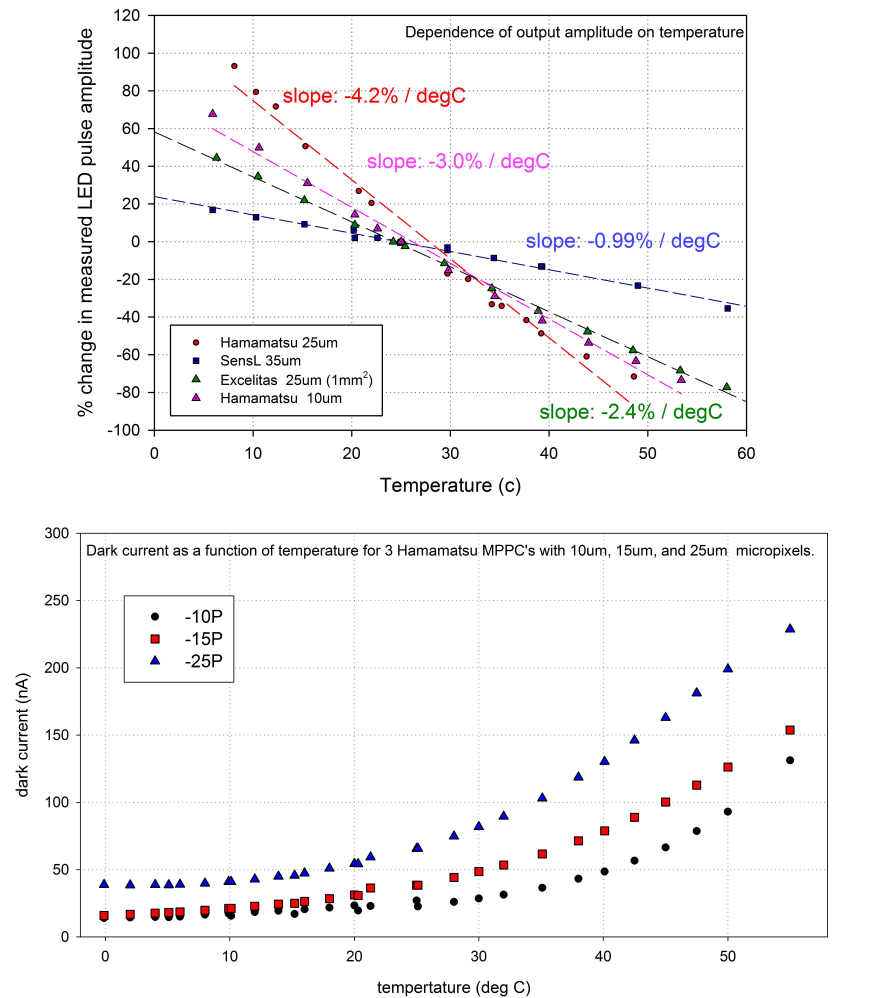


Figure 6.5: Percent change in LED signal amplitude vs temperature for Various SiPMs. (top) and Dependence of leakage current on Temperature in Hamamatsu S12572 MPPCs with 10 μ m, 15 μ m, and 25 μ m micro-pixels (bottom).

2858 Board where they are passively summed, amplified, shaped and driven differentially to
 2859 the digitizer system. Located on each end of the HCal module are the HCal Backplanes,
 2860 Interface Boards and LED Driver Boards. The Interface Board distributes the SiPM bias
 2861 voltage and low voltage to the Preamp Boards for 24 of the towers in an HCal module. The
 2862 HCal Interface Board also has ADCs for monitoring the SiPM temperatures, bias currents
 2863 and voltages. The HCal Interface Board also has 24 DAC channels, 1 per tower, that is used
 2864 to provide a voltage adjustment to the SiPM bias voltage to compensate for temperature
 2865 variations and changes in the bias current due to increased leakage current as a result of
 2866 neutron damage to the SiPM. The Interface Board plugs directly into an HCal Backplane
 2867 Board, which is a passive board containing the cable connections for 24 towers. This
 2868 arrangement allows for an HCal Interface Board to be replaced with minimal disturbance
 2869 to the preamp power cables. Also connected to the HCal Interface Board is an LED Driver

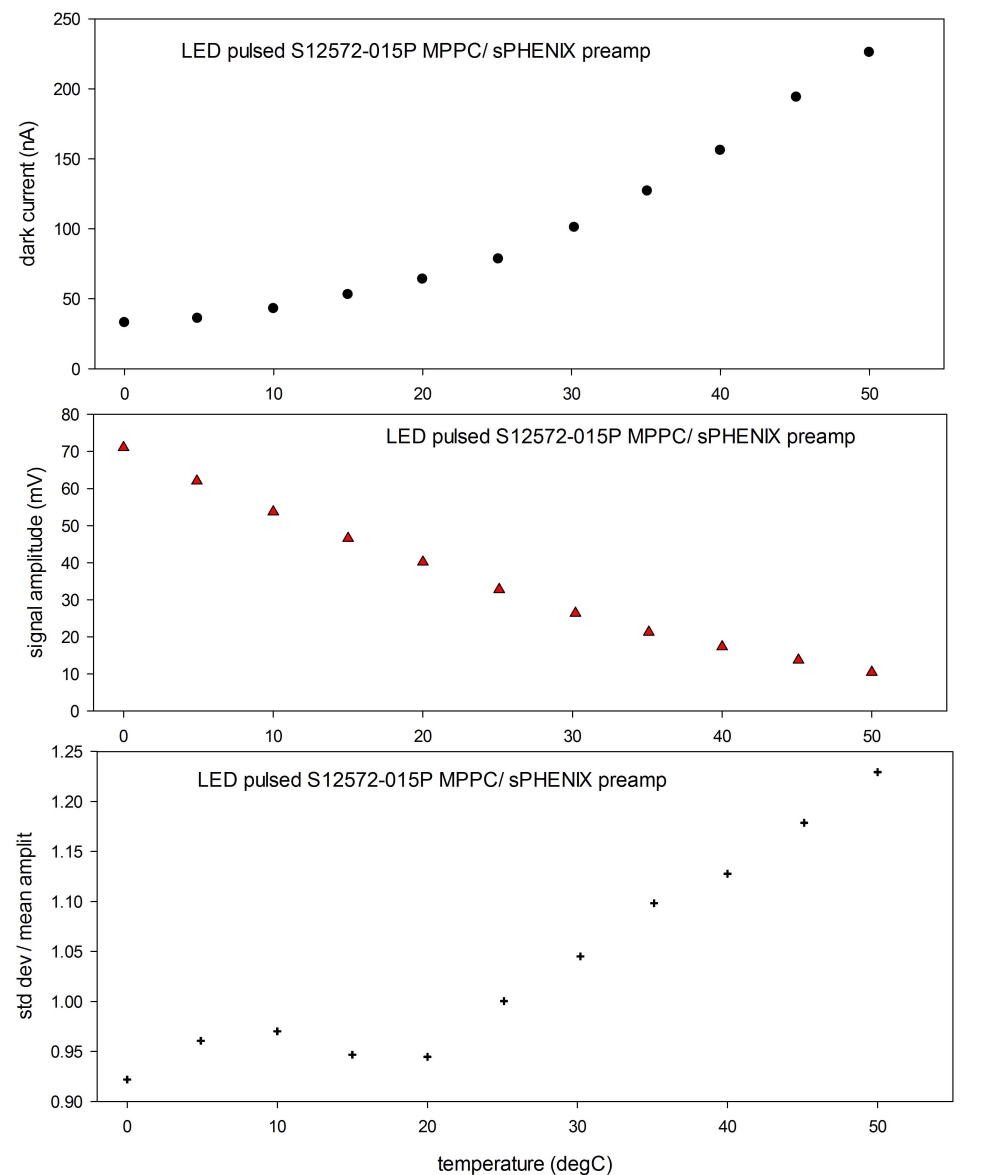


Figure 6.6: Performance as a function of temperature - Hamamatsu S12572-015P MPPCs with an sPHENIX preamp. Dark current as a function of temperature (top), signal (LED pulse) amplitude vs temperature (center), and for the LED signal, stddev/mean vs temperature (bottom)

2870 Board. The LED Driver Board consists of an LED driver circuits, 5 LEDs, and light mixing
 2871 blocks. Twenty-four light fibers, one per tile per tower are connected to a light mixing
 2872 block. Digital circuitry allows selection of which LED is pulsed and the pulse amplitude.
 2873 This arrangement allows for a single tile in each of 24 towers to be illuminated independent
 2874 of the other tiles in a tower for testing and calibration purposes. A bi-directional serial
 2875 link connects the HCal Interface Board to a Calorimeter Controller board in a nearby crate.

2876 The Controller board transmits to the Interface Board the parameters for the temperature
 2877 compensation and gain control, LED enables, pulse amplitudes and pulse triggers, and
 2878 reads back the monitoring information from the Interface Board. Each Controller is capable
 2879 of controlling 8 HCal Interface Boards. Each Controller board has an Ethernet connection
 2880 for communications with the sPHENIX Slow Control computer. A block diagram of the
 HCal electronics chain is shown in Figure 6.7.

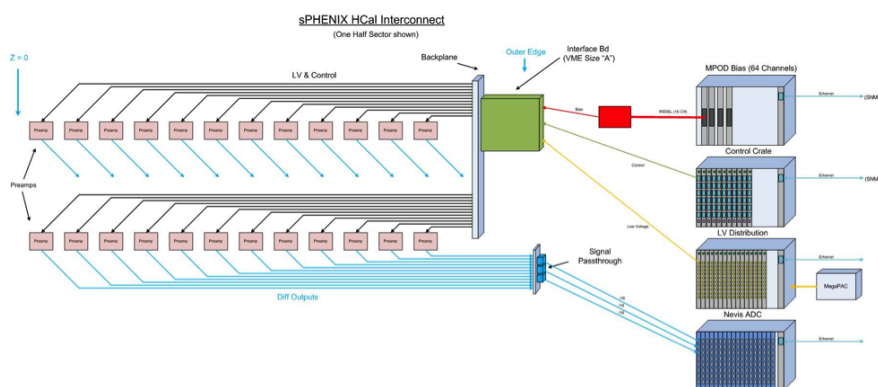


Figure 6.7: A block diagram showing the overall design of the HCal electronics for one half sector of the HCal. There are a total of 128 half sectors for the inner and outer HCal combined. Not shown are the connections for the LED monitoring system.

2881

2882 6.2.2 EMCal Electronics

2883 A half sector of the EMCal consists of 384 towers in a 8×48 ($\phi \times z$) configuration. To match
 2884 the mechanical layout of the EMCal towers, the EMCal analog channels are arranged in a
 2885 8×2 array on a Preamp Board matching the EMCal tower geometry. The 16 SiPMs (4 per
 2886 tower) for a 2×2 array of towers are surfaced mounted on a small daughter board that
 2887 also has an LED mounted in the center of the 4 towers and a thermistor for monitoring the
 2888 local temperature. Four SiPM daughter boards are connected to a Preamp Board by a short
 2889 flex cable. The signals from the 4 SiPMs associated with an EMCal tower are passively
 2890 summed, amplified, shaped and differentially driven over shielded cable to the digitizer
 2891 system located in nearby racks. Four EMCal Preamp Boards plug into an EMCal Interface
 2892 Board which distributes the bias voltage and preamp low voltage. The EMCal Interface
 2893 board also provides monitoring for the voltages, currents, and temperatures, along with 64
 2894 DAC channels for bias gain adjustment and programmable LED drivers. The six EMCal
 2895 Interface boards in a half sector are connected with a bi-directional serial connection to a
 2896 Calorimeter Controller board. The EMCal control system is identical to the HCal control
 2897 system described earlier. A block diagram of the front end electronics for one EMCal half
 2898 sector is shown in Figure 6.8.

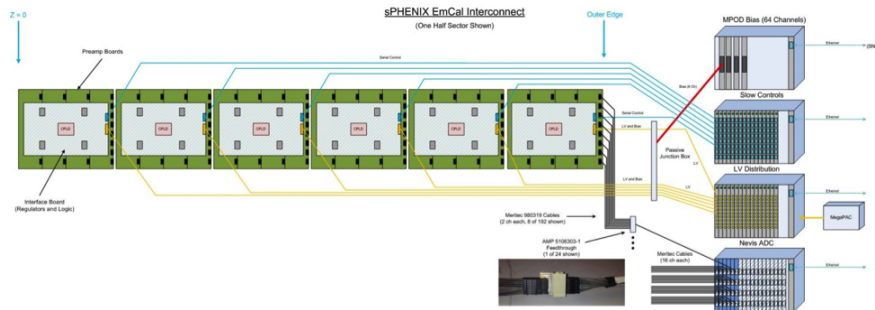


Figure 6.8: A block diagram showing the overall design for the EMCAL electronics for one half sectors for the EMCAL. There are a total of 384 towers per half sector and 32 half sectors for the EMCAL.

2899 6.2.3 Amplifier, Shaper Driver Circuit

2900 To improve light collection, four SiPMs will be used in parallel for the EMCAL and the Inner
 2901 HCal, and five for the Outer HCal. This paralleling of devices also leads to a total input
 2902 capacitance into the Preamplifier that can exceed 1.5nF. Preamp circuits that use feedback
 2903 to obtain linearity are prone to oscillation due to the significant input pole presented by
 2904 this source capacitance. Other approaches which amplify signal voltage developed across
 2905 a source resistor produce nonlinearity due to the inherent dynamic source impedance of
 2906 SiPMs and an excessively long wave shape. A common-base transistor amplifier (CBA)
 2907 was chosen to address these concerns. The CBA acts as a transresistance amplifier or
 2908 current to voltage transformer without the need for feedback. The result is a stable circuit
 2909 with an input impedance of less than 4 ohms.

2910 A differential output amplifier is required to drive the signals through 10 meter Meritek
 2911 cables to the inputs of the Digitizer Boards which are located in rack mounted crates
 2912 near the detector. The shaper/driver is a differential driver amplifier configured as a
 2913 multiple-pole feedback filter with a corner frequency of 5 MHz which provides a peaking
 2914 time of 30 nS for ADC sampling at 65 MHz. In order to observe signals from Minimum
 2915 Ionizing Particles for calibration of the EMCAL and HCal detectors, a second high gain
 2916 output stage is provided. This stage is identical to the normal gain output stage with the
 2917 exception of the stage gain. Selection of which output stage is used, is determined through
 2918 the slow control system at the time the readout is initialized for readout, providing control
 2919 on a run-by-run basis. A schematic diagram of the front end amplifier/driver circuit is
 2920 shown in Figure 6.9.

2921 The SiPM delivers nominally 37 fC for a single micro-cell fired and the CBA produces an
 2922 Equivalent Noise Charge of about 43 fC, as shown in Figure 6.10, so the signal to noise
 2923 ratio is approximately 0.86 at the single micro-cell level. A Minimum Ionizing Particle is
 2924 expected to produce approximately 35 photoelectrons which would yield 9 micro-cells
 2925 fired given a PDE of $\sim 25\%$.

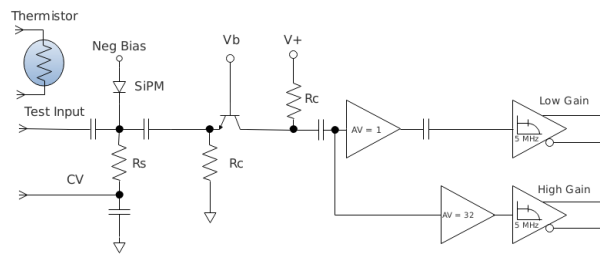


Figure 6.9: Schematic diagram of the EMCAL and HCal Preamplifier/shaper/driver circuit. Selection of the normal gain or high gain output is made through the slow control system (not shown) at the time the system is configured for data taking. For standard data taking, the normal gain is used.

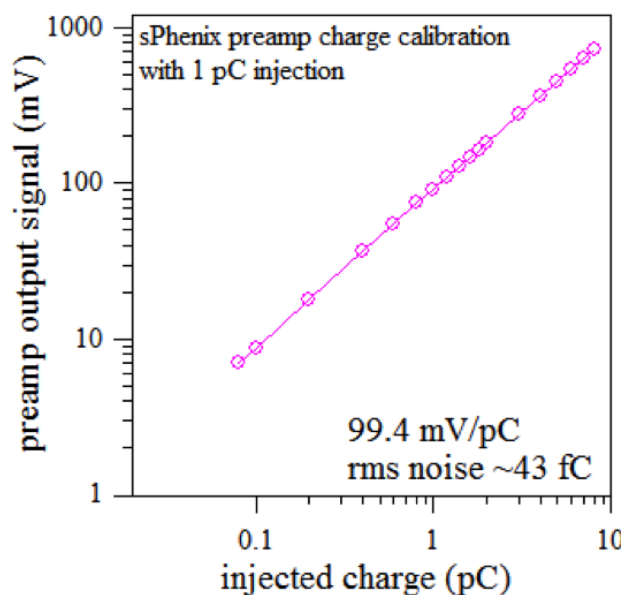


Figure 6.10: The response of the common-base transistor amplifier as a function of the injected charge as measured in the lab. The measured RMS noise is ~ 43 fC which matches the charge injected by a single micro-cell of the SiPM firing.

2926 6.2.4 Gain Stabilization

2927 The SiPM reverse breakdown voltage, V_{br} , is proportional to temperature and increases
 2928 nominally by $60\text{mV}/^\circ\text{C}$. As the SiPM bias increases over V_{br} , the SiPM begins to operate
 2929 in Geiger mode with a gain up to 2.75×10^5 and is linearly proportional to the bias over-
 2930 voltage, V_{ov} . The range of this over-voltage is typically 4 Volts and represents the useful
 2931 gain range of the device. In order to compensate for temperature variations and maintain
 2932 a stable gain, a closed feedback loop consisting of a thermistor, ADC, logic and a DAC will
 2933 be used to adjust V_{ov} and stabilize the voltage as shown in Figure 6.11. The thermistor
 2934 is located near the SiPMs and is measured by 16 bit ADC located on the Interface Board.
 2935 The digitized where a local processor computes an offset for the bias voltage to correct for

2936 temperature variations. The 12 bit correction is transmitted back to the Interface Board
 2937 where a 12 bit DAC provides an offset voltage to adjust the SiPM bias voltage for the
 2938 desired gain.

2939 One effect of the increase in leakage current resulting from neutron damage is that voltage
 2940 drop across the current limiting resistor for the bias supply changes as function of time. In
 2941 order to compensate for this changing voltage, the bias current for SiPMs in an EMCAL or
 2942 HCal tower is monitored. The measured bias current, combined with the known value of
 2943 the limiting resistors is used to compute an additional correction to the bias that is added
 2944 to the bias correction required for temperature variations in order to maintain a stable gain.

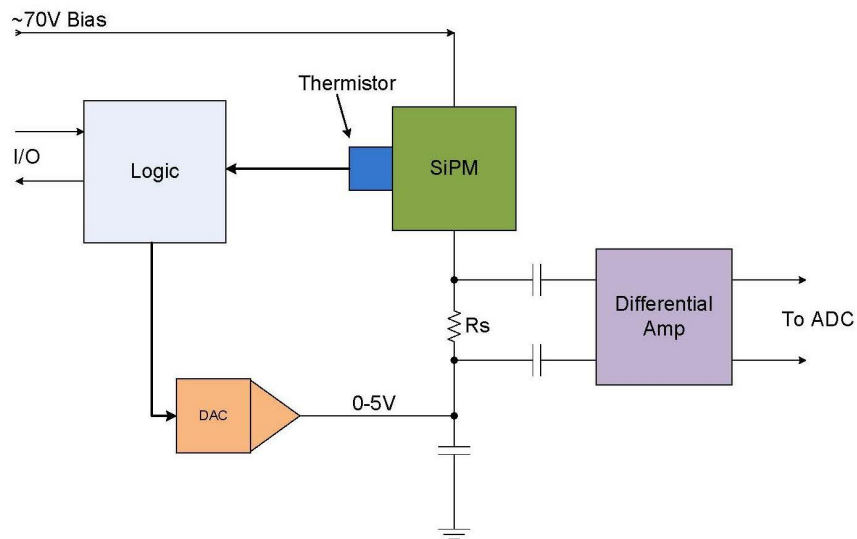


Figure 6.11: Block diagram of a temperature compensating circuit for SiPMs

2945 6.2.5 Slow Control and Monitoring

2946 The slow control and monitoring for the EMCAL and HCal electronics consists of the
 2947 Interface Board and Controller Board. The Interface Board mounts directly on the detector,
 2948 with the Controller located in a rack mounted crate nearby. A block diagram of the
 2949 slow control and monitoring system for the EMCAL and HCal detectors is shown in
 2950 Figure 6.12. The Interface Board contains a Xilinx®CoolRunner-II™ CPLD, 16 bit ADC
 2951 and multiplexers to monitor voltages, leakage currents and temperatures. The CPLD
 2952 runs a state machine that selects each of the analog channels to be monitored, reads
 2953 out the associated ADC information and updates the bias DACs when new settings
 2954 are transmitted to it from the Controller Board. A single Interface Board is capable of
 2955 monitoring 24 towers for the HCal and 64 Towers for the EMCAL. The data is transmitted
 2956 serially to the Controller Board which is capable of controlling up to 8 Interface boards.
 2957 A processor on the Controller Board uses the temperatures measured by the thermistors
 2958 next to the SiPMs to determine the individual DAC settings to correct the bias voltage

2959 to compensate for temperature variations and maintain a stable gain. The DAC settings
 2960 are transmitted back to the CPLD on the interface board and loaded into the appropriate
 2961 DACs. All digital data is transmitted to the slow control monitoring system via the crate
 back plane and crate controller.

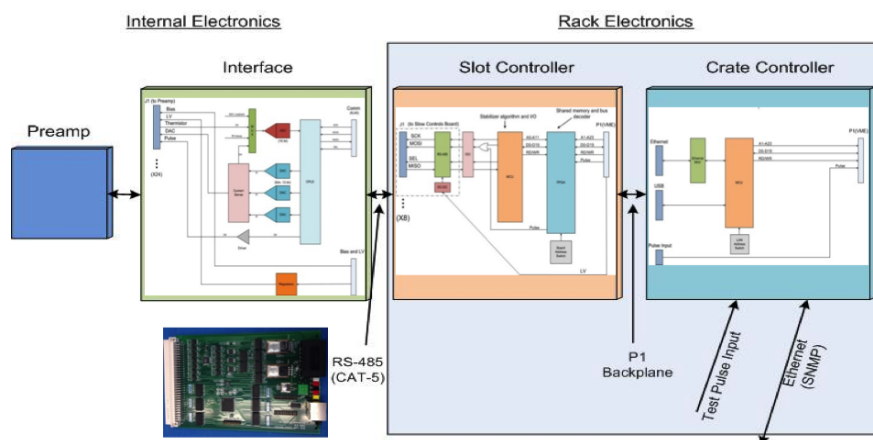


Figure 6.12: Block diagram of the slow controls for the calorimeter front end electronics. The inset picture shows a prototype module of the HCal Interface board that will be used on the HCal Beam Test prototype.

2962

2963 6.3 Digitizers Electronics

2964 The reference design digitizer electronics for sPHENIX is based on the digitizer system
 2965 built for the PHENIX Hadron Blind Detector (HBD) [146] and modified for the PHENIX
 2966 Muon Piston Calorimeter (MPC) detector. A block diagram of the Digitizer Board is shown
 2967 in Figure 6.13. Differential signals from the preamplifiers are received over a 10 meter
 2968 Hard Metric cable by an Analog Device AD8132 differential receiver which also serves
 2969 as the ADC driver. The signals for 8 towers are digitized by an Analog Device AD9257 8
 2970 channel, 14 bit ADC operating at 6x the Beam Crossing Clock (BCO). The serialized data
 2971 from the ADC is received by an Altera Arria V GX FPGA which provides digital pipeline
 2972 that is 85 BCOs deep to provide a trigger latency of up to $\sim 85 \mu\text{s}$. Upon receipt of a Local
 2973 Level 1 (LL1) trigger, up to 31 time samples (set during system configuration) for each
 2974 channel is buffered in an event buffer for readout. The ADC board is capable of buffering
 2975 up to 5 events.

2976 The LL1 data from Digitizer Boards are received by an XMIT Board using token passing to
 2977 control the readout from the Digitizer Boards over the back plane. The data is formatted
 2978 into a standard sPHENIX data packet. Formatted data is sent by 1.6 GBit optical links
 2979 using 8Bit/10Bit encoding to the sPHENIX second generation Data Collection Modules
 2980 (DCM-IIs). In order to meet the sPHENIX readout requirement of $\leq 40 \mu\text{s}$ 3 Digitizer

3003 which are individually switched and monitored. Control of the system is provided via
 3004 MODBUS/TCP and client software such as Iconics Graphworx. All low voltage will be
 3005 locally regulated on the detector. For the digitizers, low voltage power will be supplied by
 3006 local bulk supplies and DC-to-DC converters located in the crates. Local monitoring of the
 3007 digitizer voltages will be done using a monitoring system similar to PHENIX monitoring
 3008 system based on ADAMS modules by Advantech using a MODBUS/TCP interface.

3009 Bias power for the SiPMs will be provided by commercial power supplies such as the
 3010 WEINER-ISEG system proposed for Hall-D at Jefferson Lab. Bias voltage from single
 3011 channel of the WEINER-ISEG system is fanned out multiple SiPMs with all the SiPMs for a
 3012 tower receiving a common bias voltage that has been adjusted for temperature variations
 3013 and leakage current effects.

3014 The estimated power consumption for the different components of the EMCal and HCal
 readout electronics is summarized in Table 6.4.

Table 6.4: Summary of the estimated power consumption for the EMCal and HCal readout electronics. For the SiPM Daughter Boards, power is after radiation damage.

Board	Board	Sector	Total Power
EMCal On Detector Front End Electronics			
SiPM Daughter Boards	280 mW	26.7 W	1.71 kW
Preamplifier Boards	5 W	120.0 W	7.68 kW
Interface Boards	4.5 W	27.0 W	1.75 kW
Total On-Detector Power		173.7 W	11.2 kW
HCal On-Detector Front End Electronics			
SiPM Daughter Boards (Inner)	17 mW	3.4 W	108.8 W
SiPM Daughter Boards (Outer)	17 mW	4.2 W	134.4 W
Preamplifier Boards	020 mW	14.4 W	921.6 W
Interface/LED Boards	3.5 W	3.5 W	224.0 W
Total On-Detector Power		21.7 W	1.39 kW

3015

3016 Critical to minimizing the noise and maintaining the requirements for the signal-to-noise
 3017 is a well developed grounding plan. Preliminary work has started on defining such a plan.
 3018 It is a star grounding plan with the reference point defined near the front end electronics.
 3019 All electronics will be electrically isolated from the mechanical components of the detector
 3020 which are separately connected to the experimental ground. All power supplies will have
 3021 isolated returns decoupling them from the AC power ground. A preliminary grounding
 3022 plan is shown in Figure 6.14.

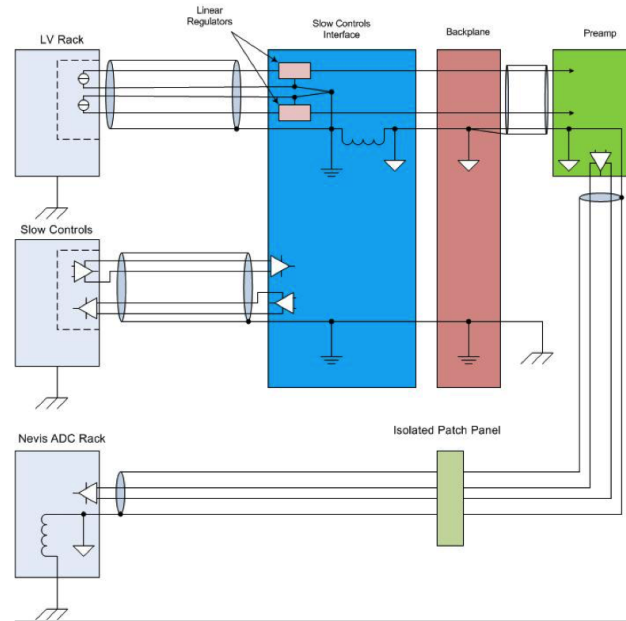


Figure 6.14: Preliminary grounding plan for calorimeter electronics which is based on a star grounding configuration. Not shown is the grounding of the mechanical parts of the calorimeters.

6.5 Electronics Cooling

3023

3024 The power requirements for the front end electronics is summarized in Table 6.4. For the
 3025 Inner and Outer HCal detectors the resulting heat load is not anticipated to be a problem;
 3026 however, for the EMCAL sectors the heat generated by the SiPms and EMCAL front end
 3027 electronics must be removed. As a whole, the subsystem can eventually generate 11 kW
 3028 of heat while operating. The plan is to use a water or water/glycol mixture to provide
 3029 cooling for the system and maintain its temperature to slightly below ambient (20°C). The
 3030 cooling concept is shown in the cooling circuit layout in Figure 6.15. Since the detector
 3031 will be inaccessible while running, the filling, bleeding and draining operations must
 3032 be able to be done from remote areas. Because of the location of the system, it must be
 3033 monitored remotely for performance and failures. In addition, redundancy must be built
 3034 into it provide continuous uninterrupted service throughout the run. The number of active
 3035 components installed inside the active area in these areas must be reduced to a minimum
 3036 to reduce failure rates. If the fluid used is water, the consequences of leaks is damage to the
 3037 detectors electronics, while if fluorocarbons are used, the cost of leaks can quickly become
 3038 prohibitive. In order to minimize the risk of leaks, the number internal connections needs
 3039 to be minimized, type of connection optimized to reduce the probability of leaks occurring.

3040

3041 To remove heat from the EMCAL Pre-amplifier Boards, a custom cold plate will be designed
 3042 that will be coupled to each Pre-amplifier Board with a Gap Pad thermal interface. Multiple

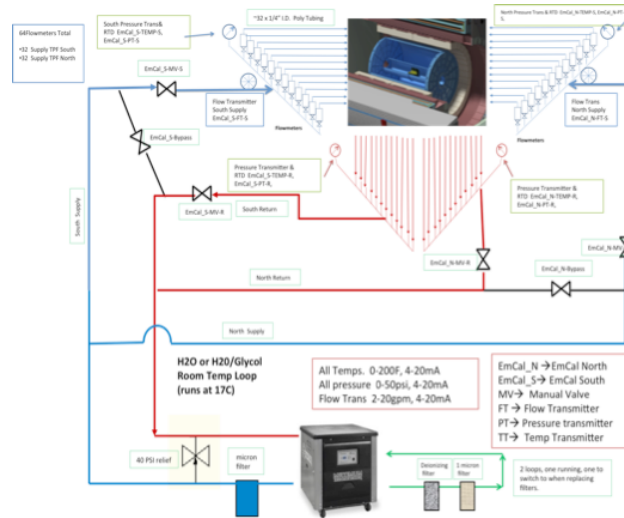


Figure 6.15: Conceptual design of the the cooling system for the EMCAL front end electronics.

3043 cooling loops connect the cold plates and will also provide the mechanical support for
 3044 the Preamplifier Boards. A conceptual design of the preamplifier cold plates and cooling
 3045 for an EMCAL Sector is show in Figure 6.16. The cold plate will also have four copper
 3046 thermal straps to transfer the heat from the associated SiPM Daughter Boards to the same
 3047 cold plate. Prototypes of cold plates being tested are shown in Figure 6.17. Fluid for each
 3048 EMCAL sector is provided from a multi channel manifold control box outside the solenoid.
 3049 The control box will have the capability of balancing flowers to each of the sectors as well
 3050 as monitor the pressure, temperature and flows to each side of the EMCAL. A total of 64
 3051 cooling loops will be used to insure proper balancing for the removal of heat in throughout
 3052 the system.

3053 6.5.1 Cooling Plant

3054 The chillers for the EMCAL will be located some 125 feet away from the detector. Independen-
 3055 dent lines and chillers will be installed for both manifold control boxes (North and South).
 3056 This will be run to allow either side of the EMCAL to be operated independently of the
 3057 other. In addition, a third chiller will be plumbed into the system to be used as a back-up
 3058 and ready to be switched over in a moments notice. Since the detector will be located in
 3059 an area with limited accessibility, active components inside the interaction area must be
 3060 reduced. In addition, the filling, bleeding and draining operations must be performed
 3061 remotely.

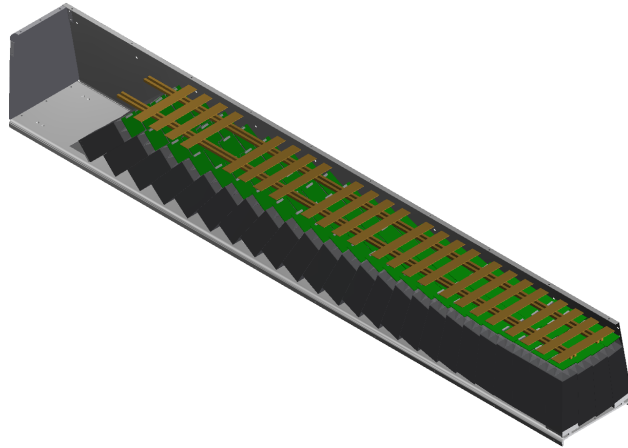


Figure 6.16: Conceptual design of the cooling plates and channels for an EMCAL Sector. Connections to the cooling supply lines are made at the high η end of the EMCAL Sector.

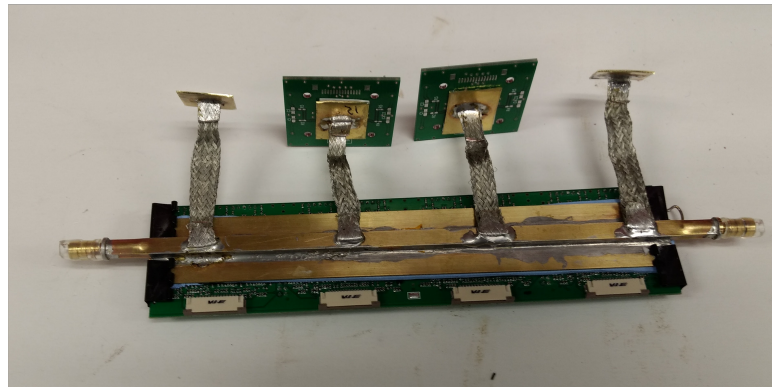


Figure 6.17: Prototype cooling plates for the EMCAL SiPM Daughter Boards used for proof of principle. Design concept is to use a thermal connector to simplify installation.

3062 6.5.2 Monitoring and Safety System

3063 Each cooling loop will have remote sensors installed so that health of the system can be
3064 monitored. The flow, temperature and pressure of the supply and return of each control

3065 box will be recorded and alarmed in case of change for normal operation parameters.
3066 The low voltage and bias voltage of the EMCal will be interlocked to this monitoring to
3067 prevent equipment damage in case of cooling system failure. Active components in the
3068 interaction area must be kept to a minimum for reduce the risk of failure. In addition, only
3069 robust industrial components should be selected for inaccessible components. Water trace
3070 monitors should be installed in several locations to monitor for potential leaks during
3071 times of inaccessibility.

3072 6.6 Radiation Tolerance

3073 6.6.1 Neutron Radiation Effects

3074 Silicon photo-multipliers have been found to be susceptible to damage from neutron
3075 radiation. Matsumura et.al. as part of the T2K collaboration found that exposure to
3076 protons resulted in an increase in the device leakage current, increased noise, and reduced
3077 single photoelectron resolution [147]. Qiang et.al. of the GlueX experiment has also
3078 measured increased leakage current after neutron irradiation [148]. Musienko et.al. of
3079 the CMS HB/HE Calorimeter Upgrade also studied radiation damage and worked with
3080 manufacturers to develop more radiation-hard SiPMs [149]. Simulations to estimate
3081 neutron fluences in the sPHENIX IR based on studies of the current STAR and PHENIX IRs
3082 at RHIC [150] suggest that the expected neutron fluence is approximately 2×10^{10} n/cm²
3083 per Run year. Based on the measurements of increase in leakage current due to neutron
3084 damage and the expected neutron rates in the sPHENIX interaction region and number
3085 of studies on the impact to SiPM performance in context of the sPHENIX calorimeter
3086 requirements have been carried out.

3087 Studies of SiPMs were conducted in the current PHENIX IR during Run 14 and Run 15
3088 to observe the effects of neutron radiation on a sample SiPMs of various pixel size, in the
3089 approximate sPHENIX environment. Figure 6.18 shows leakage currents measured from
3090 different Hamamatsu devices during Run 15 as a function of fluence. Part of this study
3091 done in the PHENIX IR during Run 15 was to investigate whether thermal neutrons were
3092 causing some of the damage to the SiPMs. Two groups of identical devices, positioned at
3093 the same location in the IR, were compared; 2 SiPMs were placed inside a Gadolinium-
3094 shielded box to eliminate thermal neutrons, the other 2 SiPMs were left un-shielded. Both
3095 groups of SiPMs showed a similar increase in leakage current. There was no obvious
3096 difference in the damage to the 2 groups based on the leakage current measurements,
3097 suggesting that the observed damage was not caused by thermal neutrons. The data for
3098 these devices is included in Figure 6.18.

3099 As a follow-up to the PHENIX IR measurements, with a more controlled, neutron source,
3100 we irradiated additional SiPMs at the BNL Solid State Physics Irradiation Facility. A
3101 deuterium-tritium neutron source was used to generate 14 MeV neutrons. We exposed

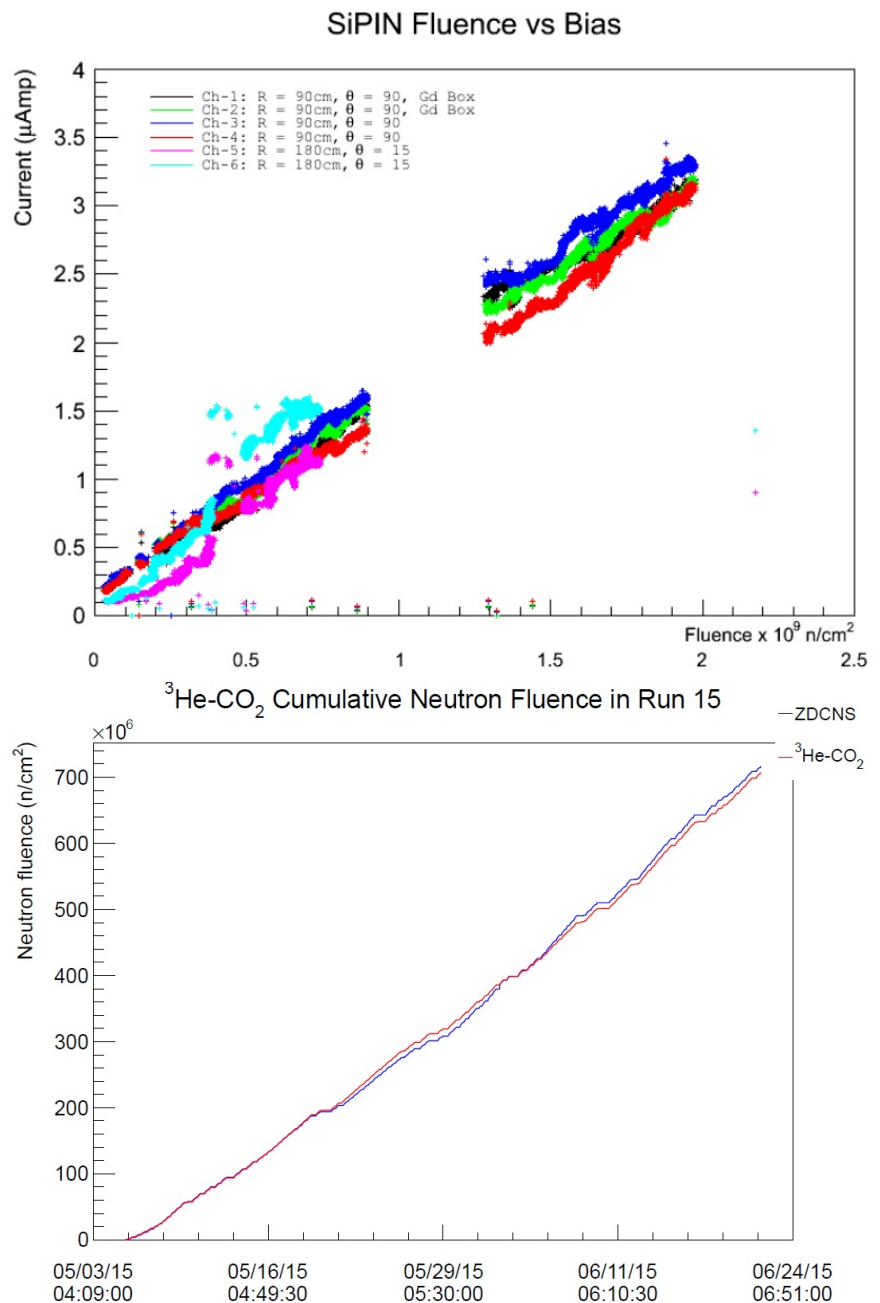


Figure 6.18: SiPMs in the PHENIX IR during Run 15 p-p running. The devices – Hamamatsu S12572-025P, -015P, and -010P all showed a steady increase in leakage current with cumulative neutron fluence during Run 15.

3102 the devices to neutrons at a flux rate of 10^5 n/cm^2 . The SiPMs were characterized before
 3103 and after irradiation. Figure 6.19 shows a plot of the increasing leakage current versus
 3104 exposure time for the SiPMs tested.

3105 Two additional studies have been done to understand the effects of neutron irradiation

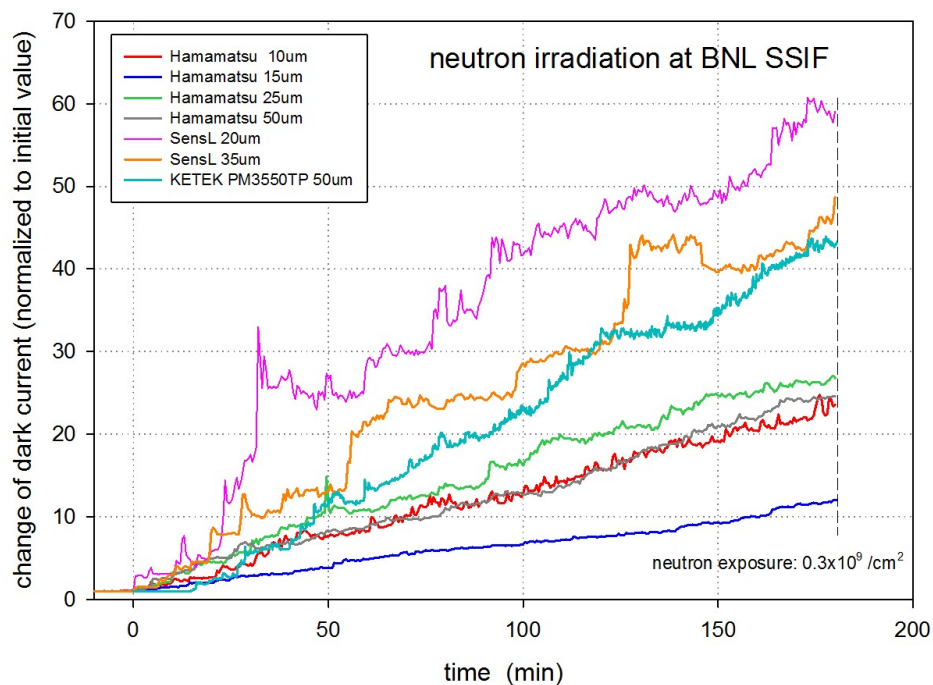


Figure 6.19: Various SiPMs studied at BNL SSGRIF facility. Increasing leakage current vs time during neutron exposure.

3106 on SiPM devices using neutron sources at National Laboratories. In the first, SiPMs
 3107 were exposed to neutron fluences at the University of Indiana Low Energy Neutron
 3108 Source (LENS) facility, equivalent to about 2 orders of magnitude higher than what is
 3109 anticipate over their sPHENIX lifetime at RHIC. These results are shown in Figure 6.20. In
 3110 the second test, Hamamatsu SiPMs were irradiated at the Los Alamos LANSCE facility
 3111 to the approximate fluences expected over the expected lifetime in sPHENIX (about
 3112 $7 \times 10^{10} \text{ n/cm}^2$). The leakage current versus V_{bias} curves for the devices before and after
 3113 irradiation are shown in Figure 6.21. The S12572-015P shows an increase from 50nA to
 3114 $250\mu\text{A}$ at its operating voltage.

3115 In summary the following radiation damage studies of SiPMs have been done:

- 3116 • PHENIX IR RUN14 (200 GeV Au-Au, h-Au), 2 Hamamatsu -025P SIPMs-about 3
 3117 weeks of beam running time.
- 3118 • PHENIX IR RUN15 (200 GeV p-p, p-Au, p-Al) 30 Hamamatsu -010P, -015P, -025P
 3119 SIPMs - about 8 weeks of beam running time.
- 3120 • Neutron generator irradiation studies at BNL SSGRIF SiPMs from Hamamatsu,
 3121 SensL, AdvanSiD, Excelitas, and KETEK of various μ -pixel sizes cumulative expo-
 3122 sures to 10^9 n/cm^2 .

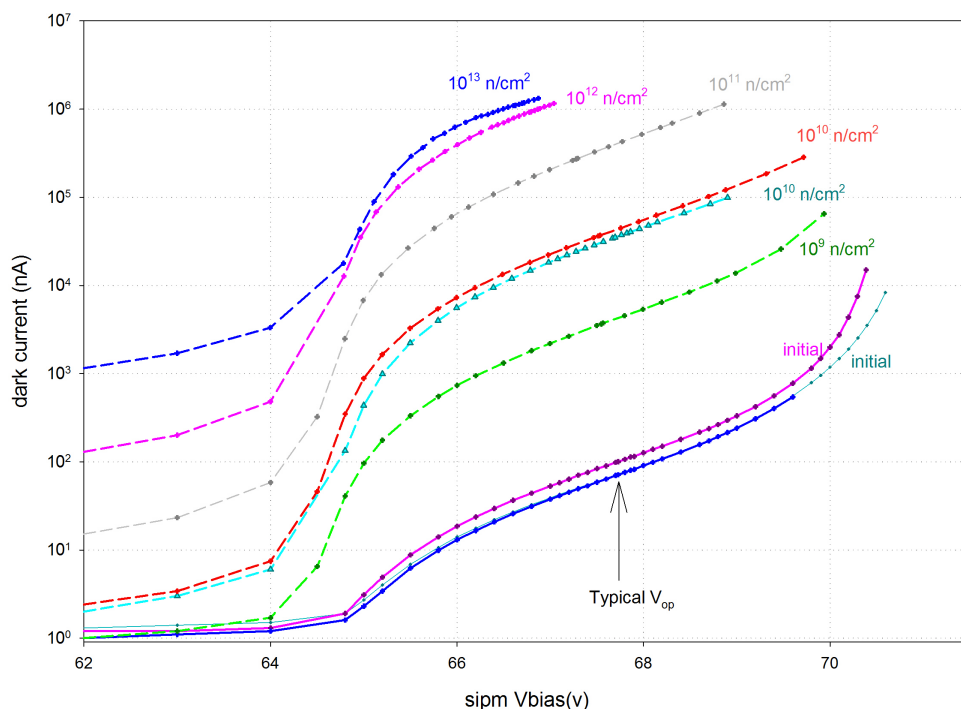


Figure 6.20: Neutron damage in Hamamatsu MPPCs exposed at Indiana Univ LENS facility

- 3123 • Neutron Irradiation studies at Indiana University LENS Facility Hamamatsu -025P
3124 MPPCs cumulative exposures up to 10^{13} n/cm².
- 3125 • Neutron Irradiation studies at Los Alamos (LANSCE) - Hamamatsu MPPCs of
3126 various μ -pixel size -Cumulative exposures to about 7×10^{10} n/cm².

3127 The increase in leakage current due to neutron damage poses a technical challenge for
3128 maintaining a constant gain, however, the gain stabilization circuit as described in Sec-
3129 tion 6.2.4 is designed to compensate for the increased leakage current. While the increase in
3130 the leakage current will limit the ability to observe single photo-electron peaks, the leakage
3131 current increases that are expected in 3 years of sPHENIX running will not significantly
3132 impact the signals that are of interest for sPHENIX, As part of the on going R&D effort,
3133 studies will continue to understand the impact of the neutron damage in context of the
3134 sPHENIX requirements.

3135 In addition to the effects of neutron damage to the SiPMs, there the also the possibility of
3136 damage to the electronics components due to ionizing radiation. During the past several
3137 runs of PHENIX, the radiation levels at several locations in PHENIX interaction region that
3138 correspond the approximate locations of where the front end electronics will be located
3139 has been measured. The total ionizing dosage (TID) measured per run is dependent
3140 on the beam species and energies, but typical values range from 2 kRad to 10 kRad per
3141 run with the highest dosage coming during the 510 GeV p+p running periods. While

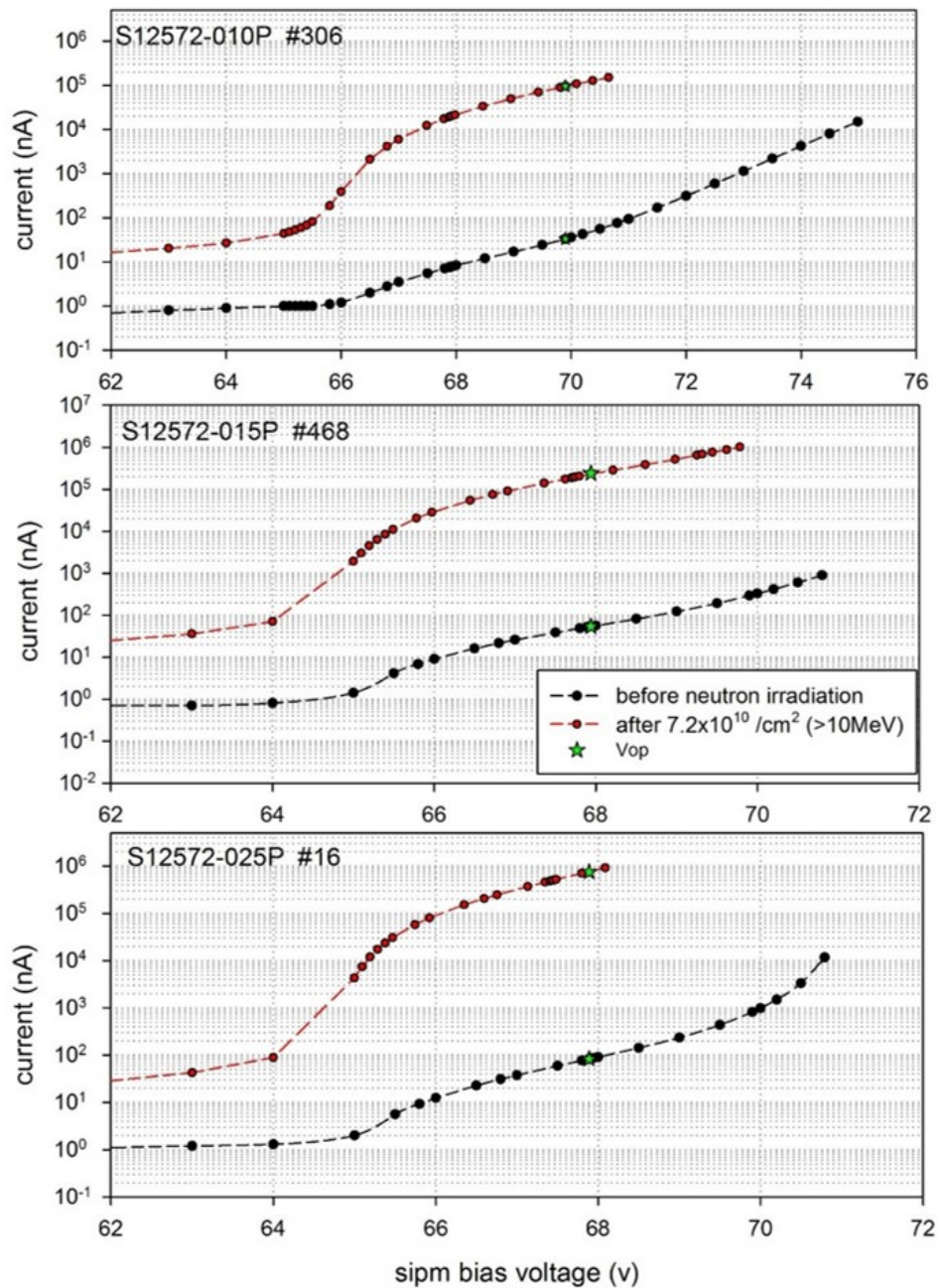


Figure 6.21: Neutron damage in Hamamatsu MPPCs exposed at Los Alamos LANSCE facility

3142 these dosages are several orders of magnitude lower than what is experienced at the LHC
 3143 experiments, it is still necessary to consider the effects of radiation damage on the front
 3144 end components. The three areas of concern are the analog devices (amplifiers, DACs and
 3145 ADCs), the voltage regulators and the CPLD used for temperature compensation, gain

3146 corrections and monitoring. For the analog components and regulators, when possible,
3147 devices certified as radiation tolerant for CERN LHC applications will be chosen. In cases
3148 where devices can not be identified that have been LHC certified, testing will be done to
3149 evaluate their radiation tolerance and the impact of failure due to irradiation.

3150 In the reference design, the Xilinx®CoolRunner-II™ CPLD technology has been chosen.
3151 This device has been tested for radiation effects up to an integrated TID of 22 kRad [151].
3152 There were no Single Event Errors (SEE) observed in the flash memory, allowing the device
3153 to be recovered at any time by powering device off and back on. The SRAM cells are
3154 sensitive to protons with energies greater than 15 MeV with a MTBF of 11 days in the
3155 worst case. The actual MTBF in real applications will be higher since only a small fraction
3156 of the Single Event Upsets (SEU) will generate a functional error.

Chapter 7

Minimum Bias Trigger Detector

The sPHENIX Minimum Bias Trigger Detector (MBD) is responsible for providing the primary Level-1 trigger for heavy-ion collisions. The trigger should have good efficiency for hadronic collisions and a z-vertex resolution of a few cm, while minimizing background triggers. The z-vertex measurement is necessary to select for collisions within $|z| < \pm 10$ cm, which is the nominal region which the sPHENIX silicon tracking system is designed to cover. The PHENIX Beam-beam Counters (BBC) served very successfully as the MBD for PHENIX, and sPHENIX plans to pursue reusing the BBC detector. The BBCs operated very successfully for 16 years in PHENIX, and with the long experience of its operation, and extensive understanding of its maintenance, cooling, and calibration needs, it serves as an ideal detector for the MBD in sPHENIX.

7.1 Reuse of the PHENIX BBC in sPHENIX

The PHENIX BBCs consists of two identical sets of 64 counters installed on both sides of the collision point along the beam axis, one on the North side and the other on the South side [152, 153]. Each counter is composed of one-inch diameter mesh-dynode photomultiplier tubes (Hamamatsu R6178) equipped with 3 cm thick quartz on the head of the PMT as a Cherenkov radiator (see fig. 7.1). Quartz is chosen as the radiator since a radiation hard design is needed for the BBC, which sits close to the beam-pipe in the forward regions where radiations levels are among the highest in PHENIX. Since the PMTs are inherently tolerant to radiation, the BBC system is radiation hard. Over 16 years of running, no significant degradation of the BBC performance has been noticed.

In PHENIX the BBCs were placed 144 cm from the center of the interaction diamond, just around the beam pipe, where the magnetic field was about 0.3T. The inner and outer edges of the BBC are at radii of 5 and 15 cm, respectively, and corresponds to a pseudorapidity range from 3.0 to 3.9, with coverage over the full azimuth. While the mesh-dynode PMTs are designed to operate in moderate magnetic fields, the field strength in sPHENIX will

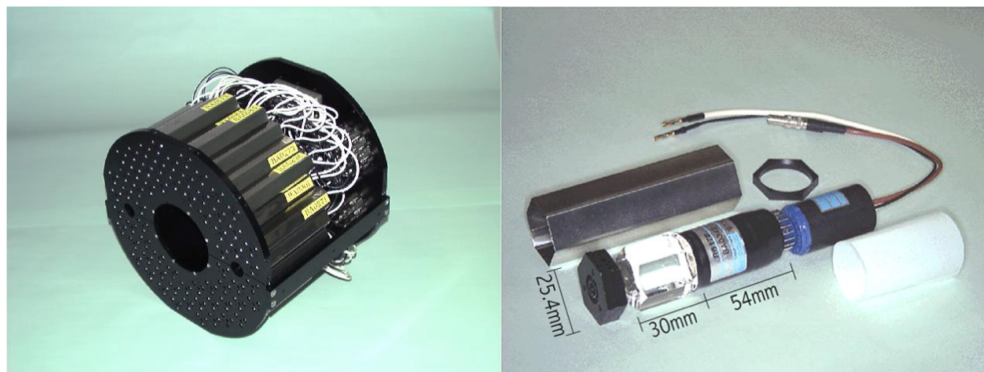


Figure 7.1: (left) The BBC array mounted on the BBC mechanical frame. (right) The individual bbc counter module.

3184 be much higher at $|z| = 144$ cm than it was in PHENIX. Thus, the BBC's will have to be
 3185 moved in sPHENIX to a z location where the effect on the magnetic field will be tolerable
 3186 to the BBC PMTs.

3187 Table 7.1 shows the pseudorapidity coverage and longitudinal magnetic fields for differ-
 3188 ent z -positions in sPHENIX. The min-bias efficiencies in the table were evaluated from
 3189 PYTHIA6 and Hijing Monte Carlo studies. At $z = 144$ cm, the field is 1.11T, which would
 3190 result in 2 orders of magnitude lower gain in the PMT. Thus, the BBCs can only reliably
 3191 operate at $|z| > 250$ cm, where the fields are roughly similar to what it operated under in
 3192 PHENIX. Here, the PMT gains are reduced by less than a factor of 2, which can be compen-
 3193 sated by running at voltages of 100-200 V higher. Note that since the BBCs already were
 3194 designed to operate in moderate magnetic fields, the mechanical frame and everything
 3195 connected to the BBC are already made of non-magnetic materials, so the BBC housing
 3196 can be re-used.

z (cm)	η_{min}	η_{max}	B_Z (T)	PMT Rel. Gain	Au+Au MB Eff (%)	p+p MB Eff (%)
144	3.0	3.9	1.11	0.01	90	39
200	3.33	4.23	0.75	0.15	89	36
250	3.56	4.45	0.50	0.5	88	34
300	3.74	4.63	0.32	0.9	87	32

Table 7.1: Parameters for the MBD at different z -vertex locations. The gains are taken from the Hamamatsu R5505 datasheet (and verified in the lab). The trigger efficiency is determined from HIJING and PYTHIA6 Monte Carlo for 200 GeV Au+Au and p+p events.

3197 The PMT gain as a function of magnetic field is taken from the Hamamatsu R5505 datasheet,
 3198 which is a similar PMT to the R6178 used in the BBCs. The R6178 was never widely adopted
 3199 and the datasheet is not publicly available. However, the BBC PMTs were tested in fields
 3200 of 0.3T before installation in PHENIX and the results are consistent with the datasheet
 3201 for the R5505. Also, a spare BBC PMT was tested in the dipole magnet facility in BNL's

3202 Instrumentation Dept., and a gain curve was mapped out up to 0.5T. The gain curve was
3203 found to be consistent with the R5505 datasheet.

3204 Estimates for the efficiencies for triggering are given in the last two columns of table 7.1.
3205 The efficiencies were estimated from Hijing events for 200 GeV Au+Au, and Pythia 6.4.28
3206 events for 200 GeV p+p. A trigger is accepted when at least two charged particles are
3207 in the acceptance of both BBCs for Au+Au collisions, while in p+p the requirement is
3208 one charged particle in each arm. The efficiency percentages for the $z = 144$ cm case are
3209 consistent within a few percent of what has been observed in PHENIX, with the difference
3210 due to the fact that conversions of photons in the beam-pipe and other upstream material
3211 can boost the efficiency slightly. The efficiency for Au+Au collisions drops by only 3%
3212 relative to what has been seen in PHENIX even if moving the BBCs out to $z = 300$ cm.
3213 This is expected since the multiplicity drop is not very large when going to the more
3214 forward pseudorapidity, and also because in Au+Au collisions the efficiency is largely
3215 determined by the multiplicity fluctuations in only the most peripheral events. Starting
3216 from mid-peripheral collisions enough particles are created that the efficiency is 100%.

3217 The situation for p+p collisions is a bit worse, since the multiplicities are much lower. Here
3218 the BBC efficiency will be $\sim 20\%$ lower than the PHENIX case. However, in p+p the MB
3219 efficiency is much less important since a minimum bias p+p event are dominated by largely
3220 uninteresting soft collision events. The trigger rates for min-bias p+p events were often
3221 prescaled by a factor of 10^4 or more in PHENIX. Thus, the location that optimizes min-bias
3222 efficiency while still allowing for operation of the BBC in sPHENIX is at $|z| = 250$ cm.

3223 The BBCs are designed to handle the maximum expected multiplicity in PHENIX, which
3224 is about 30 particles, and thus there are no questions about it's performance in this regard
3225 to sPHENIX. This is important when using the BBC as a reaction-plane detector, which
3226 uses the multiplicity of particles as a function of position to determine the event-plane of
3227 the heavy ion collision.

3228 7.2 MBD FEE Upgrade

3229 While the existing BBC FEMs are available and could work for the MBD readout in
3230 sPHENIX, it would be far preferable to upgrade to modern electronics. The BBC FEMs rely
3231 on many legacy Trigger and DAQ systems, such as the Arcnet slow control system, the
3232 FE2 DCM, the JSEB-I, and the BBC Local Level1 trigger system, which are now 18 years
3233 old and would require extra manpower to maintain.

3234 Fortunately, the BBCs can be read out with one modification to the proposed sPHENIX
3235 Front-End Electronics system for the calorimeters. A discriminator/shaper (D/S) board
3236 needs to be developed, as shown in Fig. 7.2. The discriminator/shaper board is needed to
3237 shape the 2 ns wide signals from the BBC PMTs so that it can be digitized at the 16.7 ns
3238 sampling time of the sPHENIX digitizers. In addition, the raw signal will be split, with
3239 the split signal being used to provide a fast time measurement of better than 120 ps that is

3240 needed to make the vertex measurement for the minimum bias trigger.

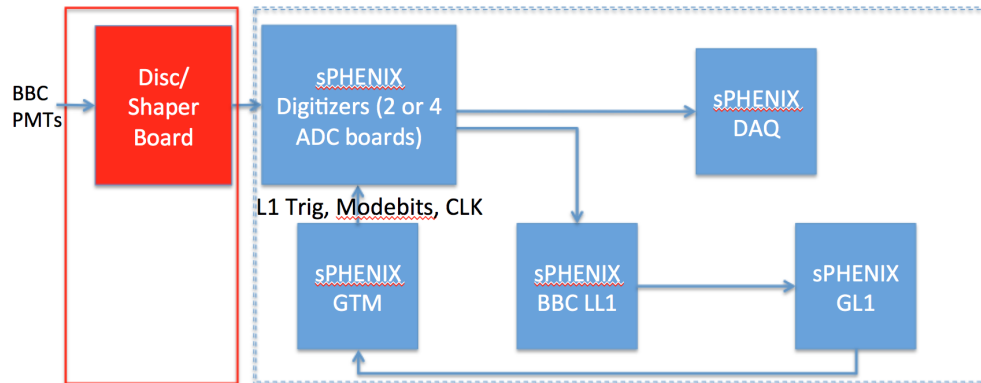


Figure 7.2: Readout diagram for the sPHENIX MBD. The items in the right box are common to the rest of the sPHENIX Calorimeter FEE and DAQ.

3241 To accomplish the timing measurement, the D/S board will discriminate the BBC signal,
 3242 and generate a 1 volt square pulse (less than one RHIC clock wide) to the sPHENIX
 3243 digitizers. The time of arrival can be extracted from this discriminator pulse. The time
 3244 resolution of the sPHENIX digitizers have been measured to be better than 13 ps by using
 3245 a passively split signal similar to the discriminator pulse, and then comparing the time
 3246 measurement between the two split pulses. The D/S board is under development and will
 3247 be tested for its contribution to the overall time resolution.

3248 As a backup solution, a time-to-analog converter (TAC) could be used to generate a linearly
 3249 rising analog voltage until it is stopped by discrimination from a signal. This amplitude is
 3250 then digitized by the sPHENIX digitizer ADC and represents the time of arrival. The TAC
 3251 is reset every RHIC clock to provide a time measurement every crossing. At 12 ENOB, the
 3252 sPHENIX digitizers should be capable of 26 ps/bin.

3253 Whichever scheme is chosen for the discriminator, the sPHENIX digitizers will be able
 3254 to determine the time of hit on each channel, the amplitude, and whether there was a hit
 3255 or not using the on-board FPGA. This information, which form the basis of the trigger
 3256 primitives from the MBD, will be sent each crossing to the MB Level-1 trigger board for
 3257 further processing, as detailed in section 8.3.1.

Chapter 8

Data Acquisition and Trigger

8.1 The Data Acquisition

In this section we detail the architecture of the sPHENIX data acquisition and how to satisfy the requirements to achieve a 15 kHz data accept rate with a livetime greater than 90% in a high-multiplicity environment. The estimates are based on the the RHIC Collider Projections as documented in Ref. [116]. Compared to the luminosity achieved in 2014, we expect an increase of up to about a factor of two of the rates of interaction which take place within a z-vertex range $|z| < 10$ cm for Au+Au collisions at 200 GeV. The $|z| < 10$ cm vertex is inside the coverage of the sPHENIX tracking system. In the case of Au+Au collisions, we expect to record minimum bias triggers mostly (i.e. a simple interaction trigger), and expect to collect in the order of 100 billion events in a typical 22-week running period. There are also selective jet and photon triggers that can sample additional physics from the entire accessible vertex range $|z| < 30$ cm. In $p+p$ and $p+A$ collisions, more selective triggers utilize the EmCal, the HCal, and the tracking system. Select results from simulation studies are given in the sPHENIX proposal [1].

The operation of the DAQ system is governed by the *Global Level-1 Trigger (GL1)* and the *Timing System*, which instructs the front-end electronics to “select” (or accept) the data from a given collision, or not. If accepted, the data are sent up from the front-end and are eventually stored on disk and tape. This operation is commonly referred to as “triggering”.

The GL1 decision to accept the data from a given collision is based on the input from a number of *Local Level-1* systems (LL1), which examine the data from various detector systems and communicate a number of key properties to the GL1. A good example of such a property is the aforementioned collision vertex. We will select collisions that take place very close (± 10 cm) to the center of the sPHENIX detector, and discard most of the others. After taking the various LL1 inputs, the overall “busy” state of the DAQ system, and several other factors into account, the GL1 either accepts or rejects the data of the collision in question. It takes this decision for every beam crossing.

3286 Once a collision is accepted, the GL1 instructs the Timing System to inform the Front-end
3287 of this fact. The Timing Systems then sends this information in a detector-specific way and
3288 format (which varies from system to system), and the front-end then sends the data.

3289 The front-end electronics operates in lockstep with the RHIC accelerator clock. The current
3290 design sets the basic clock frequency to 6 times the beam crossing rate, at about 55MHz. The
3291 Timing System gets its name from the fact that it distributes this clock to the various Front-
3292 End Modules (FEMs) and other components of the DAQ. The detector-specific aspects will
3293 include the adjustment of the clock phases to compensate for different propagation times,
3294 and the selection of the right beam crossing. As an example, the calorimeter electronics
3295 digitizes the data from each beam crossing and retains 64 such data sets. The timing system
3296 then instructs the front-end to go back a certain number of crossings and select the data
3297 from the right collision. The required information can vary from system to system.

3298 This chapter is structured in the following way. We will first detail the the core Data
3299 Acquisition system, the Local Level 1 system, and then the GL1 and Timing System.

3300 8.2 The Core DAQ System

3301 Table 8.1 shows a breakdown of the expected data sizes per subsystem. The estimate for
3302 the readout of the calorimeters is based on 16 samples from each channel, and assumes
3303 an occupancy of 25% for the EmCal (estimated from HIJING Monte Carlo and plausible
3304 expectations for pedestal noise), and 100% for the HCal and the BBC. The estimate for the
3305 VTX-pixels, the only detector that has been used previously, is derived from data from the
3306 PHENIX Run 14, where the pixel configuration consisted of two layers at 25 and 50 mm
3307 radius, respectively, with 10 and 20 ladders. In sPHENIX, the pixel layers will be at 24
3308 and 44 mm, with a total number of 36 ladders. The average data size of approximately 42
3309 kbytes per minimum bias event in Run 14 200 GeV Au+Au is scaled by 36/30 to account
3310 for the increased number of ladders to achieve full azimuthal coverage, and then by 1.1 to
3311 account for the smaller radial positions of the layers.

3312 The architecture is a fully pipelined design, which allows the next event to be triggered
3313 without waiting for the previous event to be fully processed. The design allows for a depth
3314 of 4 such events to be buffered in front end modules before transmission. This multi-event
3315 buffering is the key concept to achieve the design event rate of 15 kHz while preserving
3316 livetime.

3317 The different detector systems use two conceptually very different readout strategies.
3318 The calorimeters, the minimum bias detector, and the Intermediate Tracker use existing
3319 DAQ hardware. Those system are read out in a “triggered” fashion, that is, the front-end
3320 electronics generates data only when it receives a trigger. The readout of these systems
3321 closely follows the design of the PHENIX DAQ [154].

3322 Conversely, the front-end electronics for the TPC and the future MAPS detector will read

Table 8.1: Counts of channels, fibers, and readout components for the subsystems from the reference design. The last column is the estimated data size from that subsystem per event in Au+Au collision at 200 GeV. In the case of the VTX, the only subsystem that has been in use previously, the data are from the Au+Au part of the PHENIX Run 14, scaled for full azimuthal coverage and smaller radial positions.

subsystem	channels	occupancy	data size (kbytes)
EmCal	24,576	25%	150
HCal inner	1,536	100%	100
HCal outer	1,536	100%	100
INTT	4,700,000	n/a	55.5 ****check****
BBC	512	100%	3.5

3323 data in a *continuous*, or *streaming* mode. It will sample and send up the sampled waveform
 3324 data continuously. Subsequent processing will select the parts of the waveform that
 3325 correlate with triggered events.

3326 The two readout modes differ in the way the data are read in the front-end. In the case
 3327 of the triggered detector systems, the Front-End Module (FEM) digitizes the data from
 3328 the connected detector channels. The data selected by the triggered system flow from the
 3329 FEMs to Data Collection Modules (DCM's). The second generation of DCMs, the DCM2,
 3330 was developed for the PHENIX silicon vertex detectors and runs detector-specific FPGA
 3331 code to zero-suppress and package the data. This provides the freedom to change the data
 3332 format as necessary by loading a new version of the FPGA code. A DCM2 has inputs for 8
 3333 data fibers.

3334 A group of DCM2s interface with commodity computers called Sub-Event Buffers (SEBs)
 3335 via 1.6 GBit/s serial optical links through a custom PCIe interface card, the JSEB-II. Due to
 3336 overhead in the data encoding, the effective bandwidth through the fiber is 1.28 GBit/s.
 3337 This 4-lane PCIe card is capable of sustaining 500 MB/s input into the SEB. This bandwidth
 3338 is needed to achieve the envisioned event rate of about 15 kHz.

3339 The TPC data are sampled by front-end cards that interface to a high-end FPGA PCI-
 3340 Express card, the *Data Aggregation Module* (DAM), which provides up to 48 fiber inputs.
 3341 The processing of the streaming data will be performed by a combination of the FPGAs
 3342 and the CPUs of the servers that host these readout cards. Those *Event Buffering and*
 3343 *Data Compressor* machines (EBDC) have functionality similar to the Sub-Event Buffers of
 3344 the triggered systems in that they hold the data from the respective subset of connected
 3345 readout channels. This is shown in the top part of Fig. 8.2, which shows the samples
 3346 waveform of a given TPC channel. In the second part of Fig. 8.2 we show regions of
 3347 interest derived from samples above a threshold. Those regions are then correlated with
 3348 events that have been triggered for readout with the other detectors, and only those regions
 3349 are kept.

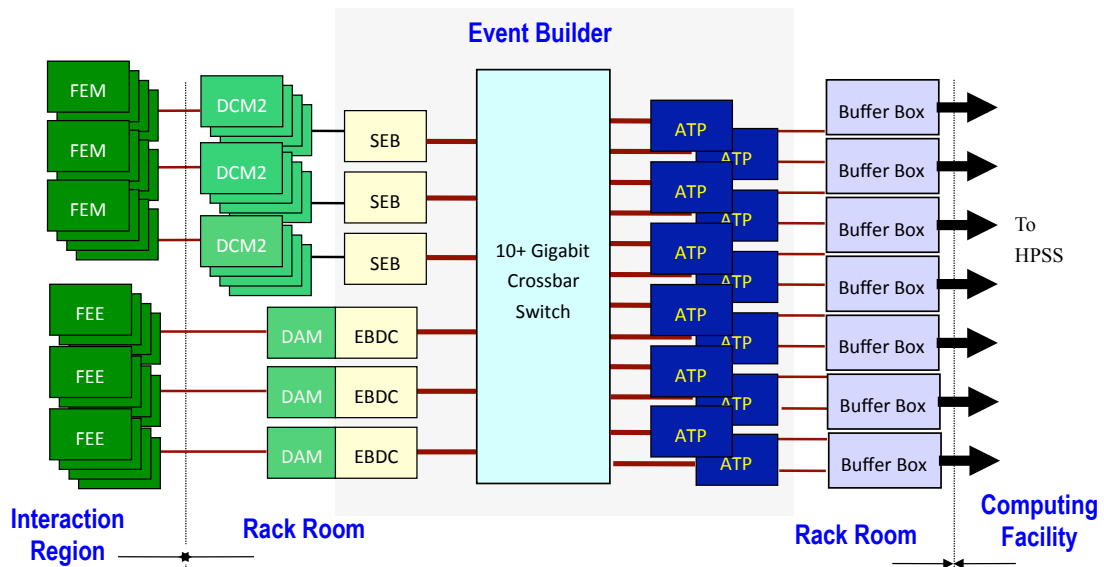


Figure 8.1: Overview of the event builder design. The data are digitized in the Front-End Modules and zero-suppressed and packaged in the Data Collection Modules. The data from a given collision are initially distributed over many SEBs and EBDCs. The data from one collision are collected in the ATP's, which sees the full complement of data of that collision for the first time. The ATP compresses the data before transmitting them to the *Buffer Boxes*, from where the data are transferred to a long-term storage system.

3350 In both cases, those *sub-events* still need to be combined into a full event that contains all
 3351 the data from one collision collected from the SEBs and EBDCs.

3352 This task is performed by the Event Builder, which consists entirely of commodity PCs
 3353 running Linux. The SEBs and EBDCs are connected to a high-end network switch, which
 3354 is central to the Event Builder. It must be able to sustain the aggregated bandwidth in a
 3355 non-blocking fashion. Non-blocking means that data can flow at line speeds between two
 3356 arbitrary ports, while at the same time line-speed data is being transferred between any
 3357 other two ports. Network equipment is subject to rapid improvements and price drops.
 3358 While viable options do currently exist, we expect that a wide selection of commodity-
 3359 priced network switches will be available at commissioning time.

3360 Also connected to the switch are a number of *Assembly and Trigger Processors (ATPs)*.
 3361 Through the network switch, each ATP receives the sub-events from a given collision and
 3362 combines them into a fully assembled event.

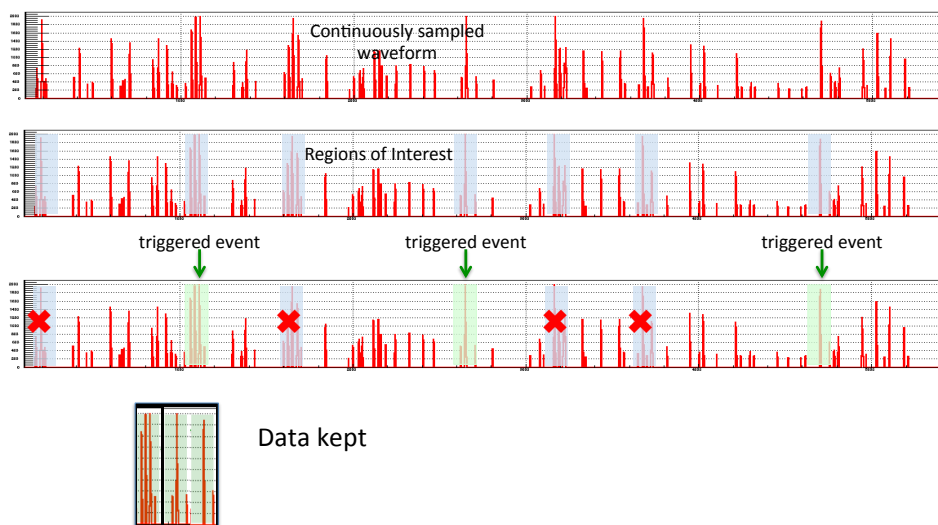


Figure 8.2: A conceptual overview of the TPC “streaming” readout. The front-end electronics continuously samples the waveforms. A processing system selects “regions of interest”, indicated in this example as amplitudes above a threshold. Further processing selects those regions that correlate with triggered events.

3363 8.2.1 TPC Readout

3364 The front-end electronics of the TPC is detailed in chapter 3. The DAQ obtains the data
 3365 and meta-information from about 20 EBDC machines (fig. 8.1). Those provide the TPC data
 3366 event-by-event to the Event Builder. The streaming-mode readout relies on a significant
 3367 data reduction in the DAM and the EBDC by correlating the TPC waveforms with triggered
 3368 events and subsequent clustering. However, the clustering under full load has not yet been
 3369 demonstrated, and we are budgeting the data volume from the TPC to be up to 80 Gbit/s.
 3370 We expect the clustering to reduce the data volume by a factor of two.

3371 8.2.2 Calorimeter Readout

3372 The current layout for the EmCal, the largest source of calorimeter data, is to read out
 3373 3 digitizers (3×64 channels) through one data fiber, resulting in a total number of 128
 3374 data fibers. With 8 inputs per DCM2 we need 16 DCM2s. These 16 DCM2s would connect
 3375 in groups of 4 (a *DCM group*) to 4 SEBs. This is similar in scope to the PHENIX silicon

3376 detectors.

3377 Table 8.2 breaks down the counts of the various components by subsystem.

Table 8.2: Counts of channels, fibers, and readout components for the subsystems from the reference design.

subsystem	channels	fibers	DCM2s	SEBs
EmCal	24,576	128	16	4
HCal inner	1,536	12	2	2
HCal outer	1,536	12	2	2
INTT	n/a	32	8	4 *** check****
MBD	256	2	1/2	1

3378 There is freedom to configure the mapping of DCM2s to SEBs differently, and vary the
 3379 number of DCM2s that send their data to a given SEB. In this way, we could obtain more
 3380 bandwidth by using more SEBs which connect to fewer DCM2s each, or save SEBs by
 3381 connecting more DCM2s to fewer SEBs.

3382 8.2.3 Data Compression

3383 While the number of SEBs and EBDCs is determined by the topology of the front-end and
 3384 fixed for a given configuration, the number of ATPs is not fixed and can be adjusted to
 3385 match the load. We use the ATPs to perform a late-stage, distributed compression of the
 3386 data before they are sent to the so-called *Buffer Boxes* that receive the data from the ATPs
 3387 and provide local storage capacity. The compression has traditionally yielded savings of
 3388 45% – 100GB of data shrink, on average, to 65GB.

3389 Fig. 8.3 shows the principle of the late-stage compression. Naively one would think that
 3390 we use existing tools (such as *gzip*) to compress a file on disk. However, this would
 3391 require an uncompressed file to be written in the first place, thereby negating most of
 3392 the speed advances in both the network and storage system. In addition, this file would
 3393 need to be unpacked in its uncompressed state to disk on readback, again negating most
 3394 benefits of the compression. What is needed is a compressed data format that can be
 3395 generated in-memory and be written out, and be read back directly. This is accomplished
 3396 through the concept of a *buffer structure*, which is strictly a storage-technology feature and
 3397 generally invisible to the other software layers. A *PHENIX Raw Data File* (PRDF) is simply
 3398 a concatenation of such self-contained buffer structures. At its core, the buffer structure is
 3399 a means to improve the data throughput through network links, which are generally more
 3400 efficient for larger data quantities due to the lower ratio of network overhead to payload.
 3401 While a buffer with data from just one event is valid, the sizes are chosen such that a
 3402 buffer contains about 50 to 100 events. This buffer structure also facilitates the compression
 3403 through the concept of a compressed buffer.

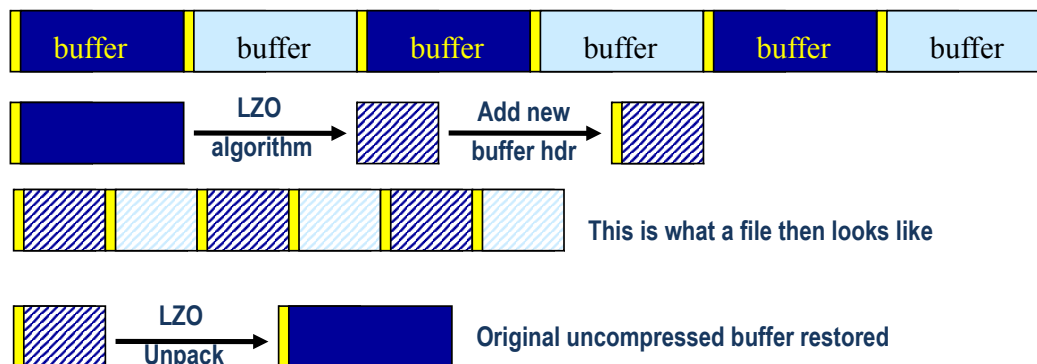


Figure 8.3: The principle of the raw data compression. The event data are organized in so-called buffers typically holding 50-100 events. Instead of sending this buffer to storage, the ATP compresses the entire buffer, and adds a new buffer header to the binary blob of compressed data, which is then sent to storage. On readback, the compressed payload is restored into the original buffer, which is passed on to the next software layer as if it had been read from storage this way. The compression functionality is entirely confined to the lowest I/O layers of the software.

3404 The ATP creates a buffer that could be sent to the Buffer Boxes and written out as-is. The
 3405 header of such a buffer, indicated in yellow in fig. 8.3, holds the length of the buffer and
 3406 other meta-information, and in addition indicates that the payload contains actual event
 3407 data. Rather than sending this buffer to the buffer boxes, the ATP uses the LZO [155]
 3408 algorithm to compress the entire buffer in a loss-less manner. The resulting binary blob
 3409 of data receives a new buffer header, this time indicating that the payload is an entire
 3410 compressed buffer. Due to the presence of the header, the result is again a legitimate buffer
 3411 structure that can be sent to the buffer boxes and written to disk just like the original,
 3412 uncompressed buffer.

3413 On readback, the I/O software layer examines the buffer header and learns that the
 3414 payload is a compressed buffer. It reverses the compression and so restores the original
 3415 buffer, which is then passed on to the next software layer as if this buffer had been read
 3416 from disk in this form. In this way, the entire compression functionality is confined to the
 3417 lowest I/O layer and transparent to user code.

3418 The Buffer Boxes are designed to limit the number of concurrently written output files to a
 3419 reasonably small value by receiving the compressed buffers from the ATPs and writing
 3420 them to disk. They provide about 80 hours of local storage capacity, which will help us
 3421 to ride out short-term outages of the tape storage system without the need to stop taking
 3422 data. In addition, the local buffering levels the changing data rates of the experiment and
 3423 allows us to transfer the *average*, rather than the peak, data rate of the experiment to the
 3424 long-term HPSS tape storage system located at the RHIC computing facility. This improves

3425 the utilization of the tape drives, and in general reduces the load on the network fibers and
 3426 switches. The already transferred files can stay on disk for 2 or 3 days and are available
 3427 to a local computing cluster for online monitoring and calibration purposes. Especially
 3428 the calibration processes typically require access to all files of a given run, and we take
 3429 advantage of the availability of the files on the buffer boxes. By the time the oldest data
 3430 files need to be deleted from the local storage system, the calibration constants required
 3431 for reconstruction will be available.

3432 8.2.4 Data Acquisition Performance

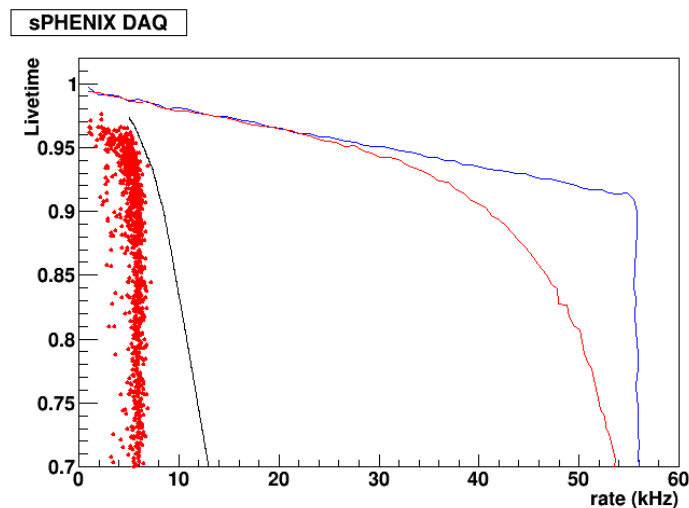


Figure 8.4: Livetime as a function of DAQ accepted event rate. The points are measurements from Run 14 Au+Au running in PHENIX, the black line is the measured performance from one older PHENIX system, the red line shows the simulated performance with 4 event buffering with the sPHENIX calorimeter ADC system, and the blue line shows the expected behavior with 100 events buffered in the front end.

3433 The sPHENIX data acquisition system eliminates the slower DCM I modules, and also uses
 3434 the TI TLK2501 optical links to transmit data from the front end modules to the DCM II at
 3435 1.28 Gbps. These changes, along with 4 event buffering in the front end modules, result in
 3436 a predicted livetime as a function of DAQ rate following the solid red line in Figure 8.4
 3437 showing good livetime at 15 kHz.

3438 8.3 Trigger

3439 The goal of the sPHENIX trigger system is to sample the key physics from the delivered
 3440 luminosity and reduce the selected event rate below the specified 15 kHz sPHENIX data

3441 acquisition bandwidth. This goal is achieved with a Level-1 trigger system providing
3442 decisions within a specified 4-5 microsecond latency during which detectors are able to
3443 buffer data output.

3444 Tables 8.3, 8.4 and 8.5 show the Collider-Accelerator Detector group's projections for
3445 luminosities delivered and peak collision rates for Au+Au, $p+p$, and $p+Au$ at 200 GeV,
3446 respectively. The sPHENIX schedule includes five years of physics running labeled Year-1
3447 through Year-5. The Level-1 triggers need to be able to handle the highest projected rates
3448 and so we show the maximum projected values at the peak (beginning) of the store. These
3449 quantities are shown for all collisions and for the fraction of collisions – denoted f_{z10} –
3450 which lie within the restricted $|z| < 10$ cm range over which sPHENIX has optimal tracking
3451 coverage for pseudorapidity $|\eta| < 1.0$.

Table 8.3: Summary of C-AD key values for Au+Au at 200 GeV running.

Mode	nb ⁻¹ /wk [min]	nb ⁻¹ /wk [max]	f_{z10} [min]	f_{z10} [max]	ave/peak	peak rate [max]	peak rate $\times f_{z10}$ [max]
Au+Au (Year-1)	3	4.75	0.19	0.3	0.6	1.5E5	4.5E4
Au+Au (Year-3)	3	7.02	0.3	0.3	0.6	2.2E5	6.6E4
Au+Au (Year-5)	3	7.51	0.3	0.3	0.6	2.4E5	7.1E4

Table 8.4: Summary of C-AD key values for $p+p$ at 200 GeV running.

Mode	pb ⁻¹ /wk [min]	pb ⁻¹ /wk [max]	f_{z10} [min]	f_{z10} [max]	ave/peak	peak rate [max]	peak rate $\times f_{z10}$ [max]
$p+p$ (Year-2)	25	64	0.16	0.19	0.6	1.2E7	2.4E6
$p+p$ (Year-4)	25	64	0.19	0.19	0.6	1.2E7	2.4E6

Table 8.5: Summary of C-AD key values for $p+Au$ at 200 GeV running.

Mode	pb ⁻¹ /wk [min]	pb ⁻¹ /wk [max]	f_{z10} [min]	f_{z10} [max]	ave/peak	peak rate [max]	peak rate $\times f_{z10}$ [max]
$p+Au$ (Year-2)	0.14	0.35	0.17	0.25	0.6	2.8E6	6.9E5

3452 8.3.1 Physics Driven Trigger Requirements

3453 This section details the various physics based trigger requirements. We discuss five types
 3454 of triggers below: (1) minimum bias trigger, (2) photon trigger, (3) jet trigger, (4) hadron
 3455 trigger, and (5) Upsilon trigger.

3456 (1) *Minimum bias trigger.* In the case of Au+Au collisions at 200 GeV, most of the physics is
 3457 delivered by simply triggering on inelastic collisions - a minimum bias trigger (MBT). We
 3458 expect to utilize the majority of the 15 kHz bandwidth for recording minimum bias Level-1
 3459 triggered events. The key requirements of this MBT are to fire on a large fraction of the 7.2
 3460 barn Au+Au inelastic cross section and to provide a selection on collisions with vertex
 3461 $|z| < 10$ cm. The minimum bias detector (MBD) described in Chapter 7.1, and based on
 3462 the existing PHENIX Beam-Beam Counter modules, meets these specifications.

3463 In the case of $p+p$ and $p+Au$ at 200 GeV, it is critical to sample the luminosity via more
 3464 selective Level-1 triggers to ensure high statistics for single high p_T jets, high p_T hadrons,
 3465 high p_T photons, and Upsilon's decaying to dielectrons. From the rates shown in the Tables
 3466 above, rejection factors of order 5,000-10,000 are needed in $p+p$ collisions at 200 GeV in
 3467 order for individual Level-1 triggers to be allocated 1-2 kHz of bandwidth. All such Level-1
 3468 triggers are based on information from the Electromagnetic and Hadronic calorimeters.

3469 We briefly recap the requirements for calorimetric-based triggering on single jet, single
 3470 hadron, photon, and Upsilon's in $p+p$ and $p+Au$ collisions (where they are crucial to
 3471 complete the scientific mission of sPHENIX). Expected trigger efficiencies and rejection
 3472 factors are presented below using GEANT4 simulations of $p+p$ collisions in sPHENIX. For
 3473 the case of $p+Au$ collisions, it is expected that achievable trigger efficiencies will be similar
 3474 to those in $p+p$ collisions. Additionally, the mean number of binary collisions in $p+Au$
 3475 collisions is $\langle 4.6 \rangle$, thus somewhat lowering the rejection factors at a fixed window energy
 3476 threshold. However, this decreased rejection is expected to match the data acquisition
 3477 bandwidth since the peak rate in $p+Au$ running is projected to be a factor of 3–5 lower
 3478 than that in $p+p$ running (see Tables 8.4 and 8.5 above). Full simulations of the expected
 3479 trigger performance in $p+Au$ collisions are expected to confirm this. Furthermore, it is
 3480 notable that in Au+Au at 200 GeV collisions, a subset of these triggers may still be useful
 3481 to enhance the minimum bias data sample described above.

3482 (2) *Photon trigger.* Collision events with a high- p_T photon can be selected by requiring that
 3483 some amount of energy is deposited into a small set of EMCal towers above threshold. Due
 3484 to the precise nature of the experimental signature (large amount of electromagnetic energy
 3485 deposited in a small region), this trigger is likely to achieve large rejections for even modest
 3486 p_T thresholds while maintaining an excellent efficiency. In $p+p$ collisions, an unprescaled
 3487 trigger which is efficient for $p_T^\gamma > 10$ GeV photons will be crucial for enabling sPHENIX to
 3488 collect the necessary comparison data for photon-tagged measurements of (jet and hadron)
 3489 energy loss in Au+Au collisions, as well as for high- p_T photon production measurements
 3490 which will serve as a reference for tests of binary-collision scaling in Au+Au collisions.
 3491 Similarly, a $p_T^\gamma > 10$ GeV photon trigger in $p+Au$ collisions would enable measurements
 3492 of cold nuclear effects on hard process rates and on photon–hadron correlations. In both
 3493 cases, the trigger could be configured with multiple thresholds, such that auxiliary lower-
 3494 threshold triggers operated with a prescale could be used to determine the efficiency of
 3495 the higher-threshold trigger with good efficiency.

3496 Figure 8.5 demonstrates the simulated trigger efficiency curves and rejection factors for
 3497 such a photon trigger, based on requiring some minimum energy in overlapping 4×4
 3498 EMCal tower windows, in GEANT4-simulated $p+p$ events. The simulations show that
 3499 even a 5 GeV window trigger threshold will achieve a rejection factor of over 10^4 .

3500 For potential high-luminosity Au+Au running, a trigger which is efficient for $p_T^\gamma > 10$ GeV
 3501 photons would utilize the full luminosity which can be delivered by RHIC. In particular,
 3502 this would have the largest benefit for measurements which do not require the vertex to lie
 3503 within the narrow 10 cm range, such as photon spectra or photon-jet balance (where the jet
 3504 is measured purely calorimetrically). Since the effect of the underlying event in Au+Au
 3505 collisions is small in small-sized windows of EMCal towers, it is likely the trigger could
 3506 avoid the need for a subtraction or estimation of this background.

3507 (3) *Jet trigger.* Collision events with a high- p_T jet can be selected by requiring that some
 3508 amount of energy is deposited into a moderate-sized patch of the EMCal and HCal (a “jet
 3509 patch” or FullCalo trigger). By using information from both the EMCal and HCal, the

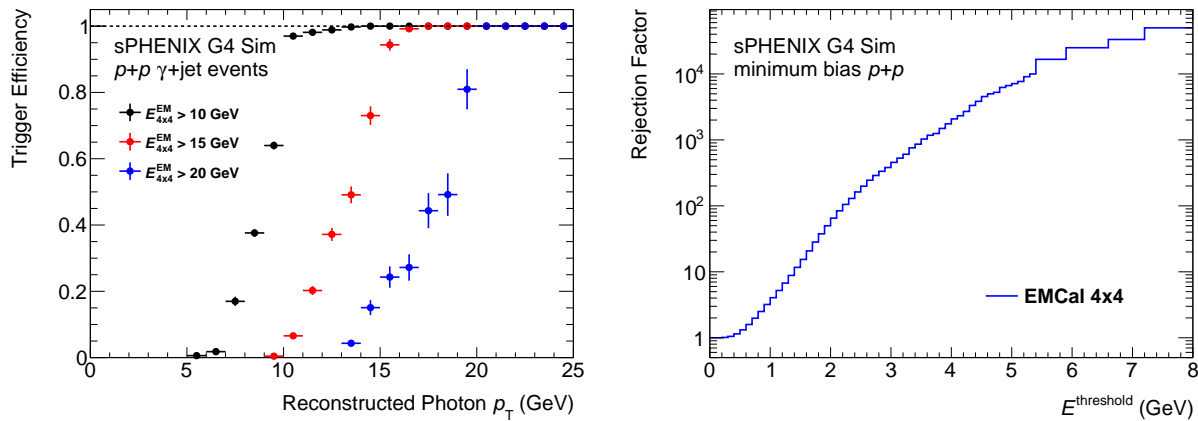


Figure 8.5: *Left:* Trigger efficiency for photons with respect to the reconstructed photon p_T . For this plot, PYTHIA 8 events with the prompt photon switch turned on and $\hat{p}_T > 8$ GeV were used. The efficiency is shown for three different energy thresholds using the EMCAL 4x4 trigger. *Right:* Rejection factors in minimum bias $p+p$ collisions for EMCAL 4x4 energy thresholds.

3510 trigger can avoid being biased by the fragmentation pattern or flavor of the jet and can
 3511 operate with a high efficiency. In addition, the trigger could be configured to examine the
 3512 total energy in different-sized patches (for example square patches which enclose circular
 3513 jets with radius $R = 0.3$ and $R = 0.4$).

3514 In $p+p$ collisions, a jet patch trigger which is efficient for $p_T > 20$ GeV jets will allow
 3515 sPHENIX to collect necessary comparison data for inclusive jet, dijet, jet structure, and
 3516 other jet-based measurements of energy loss in Au+Au collisions. In $p+Au$ collisions,
 3517 such a trigger would enable the benchmarking of cold nuclear matter effects on jet and
 3518 hadron production, especially at moderate and large p_T . Given the large collision rates
 3519 projected for $p+p$ and $p+Au$ data-taking, the jet trigger must be configured to achieve a
 3520 sufficiently large rejection for minimum bias events, setting a lower limit on the minimum
 3521 p_T at which the trigger could record events unprescaled. Additionally, the trigger could
 3522 also be configured with lower p_T thresholds and a finite prescale to provide events which
 3523 are used to determine the efficiency turn-on curve for the unprescaled, high threshold- p_T
 3524 jet trigger. The segmentation of the calorimeter available at Level-1 is shown in Figure 8.6.

3525 Figure 8.7 demonstrates the simulated trigger efficiency curves and rejection factors for
 3526 the FullCalo Jet trigger in GEANT4-simulated $p+p$ events. The simulations show that a
 3527 12 GeV window trigger threshold will achieve a rejection factor of over 10^4 .

3528 In Au+Au data-taking at high luminosity, a jet trigger could complement the number
 3529 of high- p_T jet events recorded for offline analysis. This would have a particularly large
 3530 impact for measurements which do not require a narrow selection on the collision vertex
 3531 and would, for example, allow sPHENIX to explore the quenching of jets near the kinematic
 3532 limit and at very large initial virtuality ($\gtrsim 60$ GeV). However, the presence of the

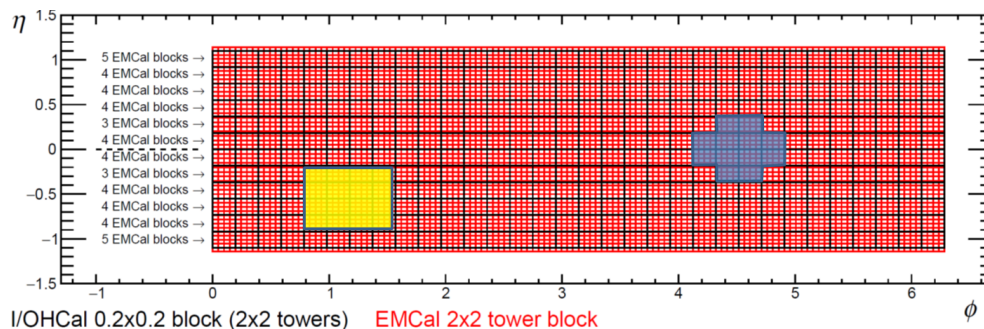


Figure 8.6: Diagram showing the calorimeter segmentation for use in the Level-1 jet patch trigger. There are 384 effective combined calorimeter energies available (in $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ regions). This grid is comprised of 12 elements in η and 32 elements in ϕ . Shown on top are the default 0.8×0.8 square jet patch region and an alternative with the corner energies removed.

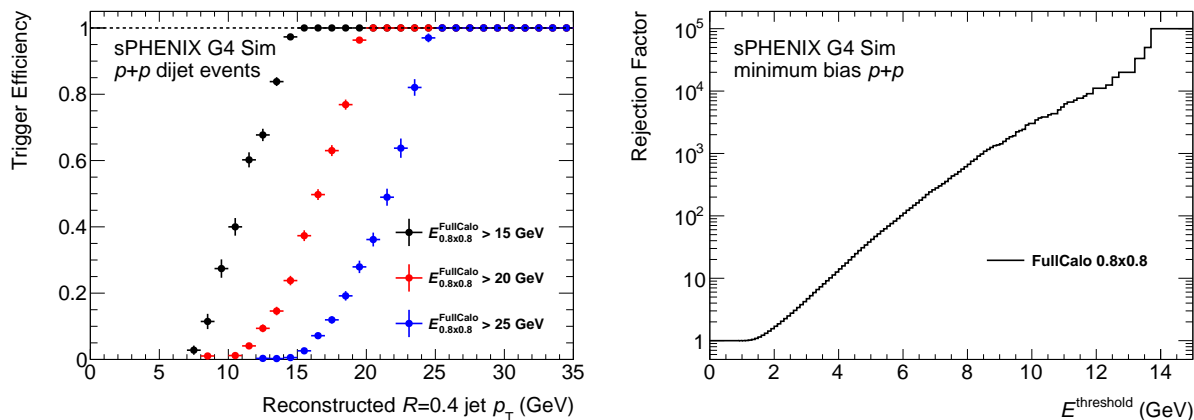


Figure 8.7: *Left:* Trigger efficiency for jets with respect to the (offline) reconstructed anti- k_t $R = 0.4$ jet p_T , based on requiring a minimum energy in a $\Delta\eta \times \Delta\phi = 0.8 \times 0.8$ region of the calorimeters. For this plot, PYTHIA 8 events with the hard QCD switch turned on and $\hat{p}_T > 20$ GeV were used. The efficiency is shown for three different window energy thresholds. *Right:* Rejection factors in minimum bias $p+p$ collisions for FullCalo 0.8×0.8 window energy thresholds.

3533 underlying Au+Au event, which fluctuates over a large dynamic range every collision,
 3534 will reduce the performance of a calorimeter-based jet patch trigger. For best operational
 3535 efficiency, some estimation and subtraction of the underlying event should be performed
 3536 at the trigger level. Even after this, localized underlying event fluctuations would reduce
 3537 the ability of the trigger to reject minimum bias events. While a narrower jet patch area
 3538 may reduce the per-event rate of such fluctuations (thus allowing a lower unprescaled p_T
 3539 threshold), this may impose a selection bias on the profile of triggered jets. Thus, relative
 3540 to $p+p$ collisions, these issues limit the minimum p_T threshold above which a trigger

3541 can select hard-scattering jets with high efficiency while having sufficient rejection for
 3542 underlying event fluctuations, for example to $p_T > 40$ GeV.

3543 (4) *Hadron trigger*. In addition to the FullCalo jet trigger above, events containing high- p_T
 3544 hadrons can be selected by requiring an energy deposit above threshold in a narrower
 3545 $\Delta\eta \times \Delta\phi$ region of the calorimeters. In $p+p$ and $p+Au$ collisions, such a trigger could
 3546 enhance the statistics for intermediate- p_T hadrons, extending the $p+p$ and cold nuclear
 3547 matter references for hadron-based measurements to a lower hadron p_T range than would
 3548 naturally be selected with a (higher- p_T) jet trigger. In addition, such a trigger could be
 3549 useful in selecting events with leading hadrons from heavy flavor quark jets: since these
 3550 hadrons have a higher typical z than light jets, they would not fire the jet trigger until
 3551 they reach substantially higher hadron p_T . Figure 8.8 demonstrates the simulated trigger
 3552 efficiency curves for the FullCalo $\Delta\eta \times \Delta\phi = 0.4 \times 0.4$ hadron trigger in GEANT4-simulated
 3553 $p+p$ events. The simulations show that a 10 GeV window trigger threshold will achieve a
 3554 rejection factor of over 10^4 .

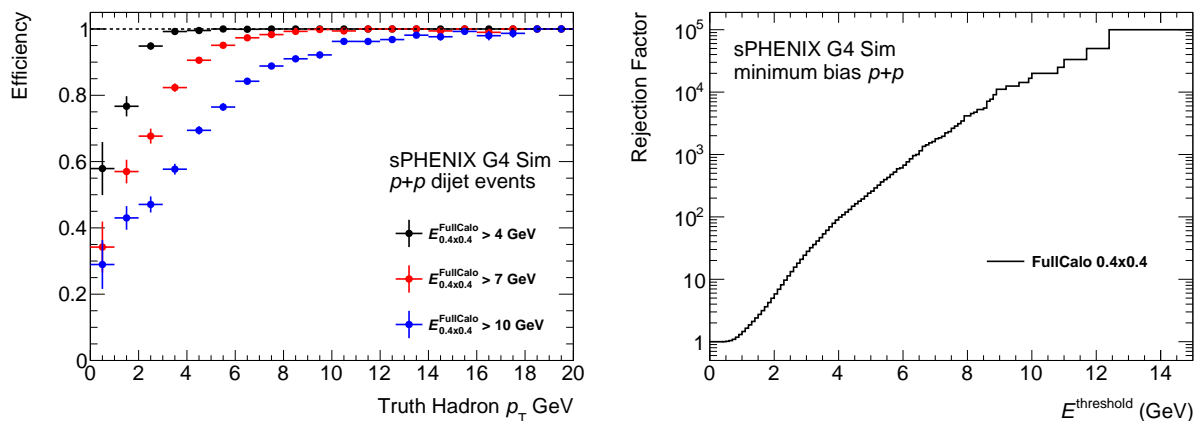


Figure 8.8: *Left:* Trigger efficiency for high- p_T hadrons with respect to the truth-level hadron p_T . The efficiency is shown for three different window energy threshold using the the FullCalo $\Delta\eta \times \Delta\phi = 0.4 \times 0.4$ hadron trigger. For this plot, the efficiency is determined in the same PYTHIA 8 hard-QCD $\hat{p}_T > 20$ GeV samples used to determine the jet trigger efficiency. In this case, for the purposes of firing the trigger, a hadron benefits from the fact that it is likely to be in close proximity to other hadrons in the jet which contribute to the energy in the FullCalo sliding windows. Thus, this estimate of the efficiency is most appropriate for the case of hadrons inside moderate- p_T quark or gluon jets (e.g. a separate study is needed to estimate the trigger efficiency for hadrons in charm or beauty jets). *Right:* Rejection factor in minimum bias $p+p$ collisions for FullCalo 0.4×0.4 window energy thresholds.

3555 (5) *Upsilon trigger*. Upsilon states decaying through the di-electron channel can be identified
 3556 with a calorimeter-based trigger which requires a high-energy deposit in the EMCal
 3557 consistent with an electron. For decays of the Y states, the large mass of the parent
 3558 particle sets a lower limit on the energy of its highest-energy electron daughter, potentially
 3559 allowing a single-electron trigger to sample the full Upsilon production cross-section at

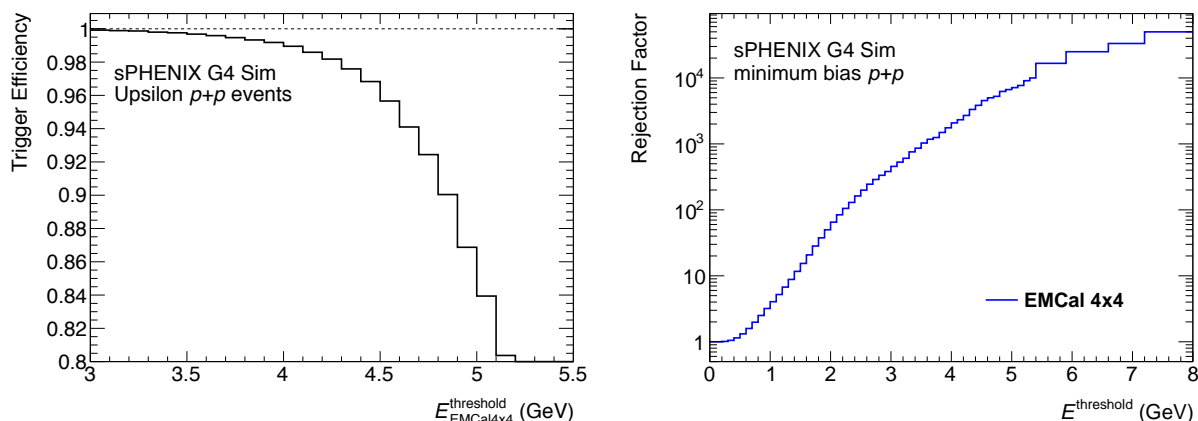


Figure 8.9: *Left:* Trigger efficiency for Upsilon decaying to two electrons, both of which are in the sPHENIX acceptance. The event sample used is PYTHIA 8 events with generator-level filtering on the decay electron and positron kinematics. The efficiency is shown as a function of the required EMCal 4x4 window threshold. *Right:* Rejection factor in minimum bias $p+p$ collisions for EMCal 4x4 window energy thresholds (same as the right plot in Fig. 8.5).

3560 all kinematics for which the sPHENIX detector has acceptance. In $p+p$ collisions, an Y
 3561 trigger will be critical to provide reference data for quarkonia melting measurements in
 3562 Au+Au collisions. In $p+Au$ collisions, such a trigger could help provide a high-statistics
 3563 calibration of cold nuclear matter effects on Y production. Since it is challenging to identify
 3564 electrons at the trigger level in sPHENIX, it will be important to demonstrate that the
 3565 rejection power of such a trigger is sufficient in high-rate $p+p$ and $p+Au$ running to fit
 3566 within the allocated bandwidth.

3567 Figure 8.9 demonstrates the simulated trigger efficiency curves and rejection factors for
 3568 such an Upsilon trigger, based on requiring some minimum energy in a 4×4 EMCal tower
 3569 window, in GEANT4-simulated $p+p$ events. At a threshold of 4.5 GeV, where the trigger is
 3570 still efficient, the rejection factor for minimum bias events is ≈ 4000 . While this is slightly
 3571 lower than the nominal specification of 5,000 to 10,000, this trigger could be allocated
 3572 additional bandwidth, or a trigger based on reconstructing the Upsilon invariant mass
 3573 could be considered. Simulation results indicate an electron pair trigger with an invariant
 3574 mass cut > 6 GeV results in a very good efficiency and a rejection in $p+p$ events of greater
 3575 than 30,000.

3576 In Au+Au collisions, an Y trigger would allow sPHENIX to take advantage of high-
 3577 luminosity running to collect additional statistics for differential quarkonia melting mea-
 3578 surements. This is especially valuable for increasing the available statistics for the highest
 3579 Y states (which are suppressed below sensitivity at the LHC) and in peripheral collisions,
 3580 which are the most statistically limited.

3581 In addition to the considerations for an Y trigger described above, a single-electron trig-
 3582 ger would have partial acceptance for (predominantly high- p_T) J/ψ and $\psi(2S)$ mesons.

3583 Another possibility is the use of a di-electron triggers, which selects events based on the
3584 presence of two electrons with an invariant mass in the region of the Y mass.

3585 Calorimeter Trigger

3586 The ElectroMagnetic Calorimeter has 24,576 channels that are read out via the Front End
3587 Electronics (FEE) in groups of 64 channels. The FEE will perform a first pass pedestal
3588 subtraction and gain correction, and then sum the energies from adjacent 2×2 non-
3589 overlapping towers. The detector to FEE cabling will ensure that the 64 channels contain a
3590 contiguous set of nearest neighbor 2×2 towers. The trigger primitive output is bandwidth
3591 limited to 8 bits for each 2×2 sum, and these are transmitted every beam crossing through
3592 a small transition module mounted on the rear of the FEE system backplane. Including
3593 header and spacer words, the data output for the trigger primitives is ten 16-bit words per
3594 beam crossing. This fits within the bandwidth of 2 Gigabits/second for the optical output.

3595 The Hadronic Calorimeter including both inner and outer detectors has 3,072 channels that
3596 are read out via the same FEE as the EMCal, again in groups of 64 channels. As detailed
3597 above for the EMCal, the HCal FEE will pedestal subtract, gain correct, energy sum 2×2
3598 non-overlapping towers, and transmit 8-bit energy values via optical output. Note that for
3599 the HCal this means that the finest granularity for energies available at the Level-1 trigger
3600 are $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ (which matches the physics performance requirements).

3601 There are several methods to collect the trigger primitives for Level-1 algorithm operations.
3602 One can directly couple primitives to the L1 boards or one can concentrate the data first to
3603 boost the optical bandwidth. Field Programmable Gate Arrays (FPGAs) available on the
3604 market, both from Altera and Xilinx, already achieve greater than 10 Gbits/sec serial speed
3605 (in the current mid-range cost FPGA) and with more than 40 link per chip. Even the new
3606 low-range cost FPGA will soon reach greater than 10 Gbits/sec serial speed, for example
3607 the Altera Cyclone 10. We find that concentrating primitives first to a higher speed may
3608 turn out to be a better match with available technology. Conservatively we can merge
3609 4 ADC trigger primitives cables into one high speed optical cable. After removing the
3610 duplicate header words, the bandwidth will be around 7 Gbits/sec. The total number of
3611 trigger primitives cables will then be 96. If we divide the detector into 4 region, each region
3612 will only host 24 optical cables. Even with optional cross-stitching of the detector, the
3613 topology will match much better to available FPGA technology. The number of registers
3614 in the FPGA will be around 0.5 million or more. It should be enough for working multiple
3615 trigger algorithms. The outputs of the trigger calculation will be sent out via optical cable.
3616 We refer to these modules as Level-1A trigger modules, as shown in Figure 8.10.

3617 The Level-1A boards will perform the 4×4 overlapping energy sums for the EMCal. The
3618 Level-1A main FPGA has more than enough register capacity for these calculations. The
3619 highest three energy sums are transmitted to the Level-1B board. The Level-1B board can
3620 then also make global combinations of pairs to potentially enhance the Upsilon trigger
3621 rejection with a simple invariant mass selection. From the $p+p$ event trigger simulations,

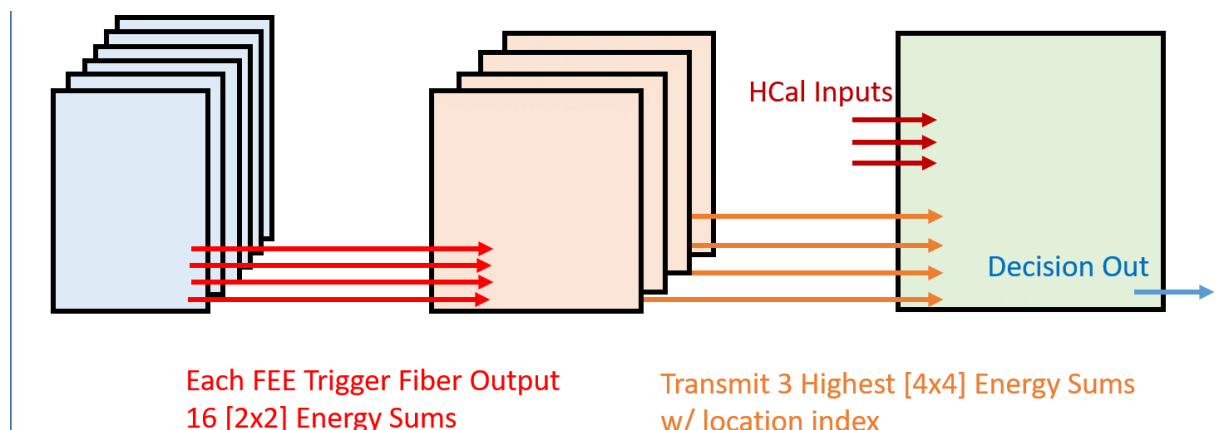


Figure 8.10: Schematic for the calorimeter Level-1 trigger systems. The FEE sends primitives with 2×2 non-overlapping tower energies to the Level-1A modules. The Level-1A modules may contain data from approximately 25% of the entire detector. The Level-1A modules then send non-overlapping energy sums in $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ regions to the Level-1B board for full jet trigger algorithm processing, where the entire detector coverage is needed. The Level-1A modules also send out a truncated list of the highest energy EMCal 4×4 overlapping towers.

3622 this additional mass selection is not necessary but it may, for example, enable some Upsilon
3623 statistics enhancement in peripheral Au+Au collisions.

3624 The Level-1A boards will also perform non-overlapping sums for the EMCal and HCal
3625 into $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ regions. The total number of such sums for the EMCal, Inner, and
3626 Outer HCal is $384+384+384$. These energies are transmitted to the Level-1B board where
3627 jet trigger algorithms are applied and can utilize the complete event within the sPHENIX
3628 calorimeter acceptance.

3629 The trigger simulations results shown earlier in this Section are full GEANT4 simulations
3630 of the detector performance and tower segmentation and summing. However, they do not
3631 yet include an emulation of the detailed Level-1 trigger primitives and 8-bit bandwidth
3632 matching requirement. An initial extension of the simulations to include the 8-bit ADC
3633 truncation is detailed below.

3634 The performance of possible electron triggers for selecting di-electron Υ decays in high-
3635 luminosity $p+p$ running in sPHENIX has been extended to mimic the first stage of the
3636 Level-1 trigger primitive processing. These triggers are based on energy sums in the
3637 electromagnetic calorimeter, and have been examined with a full event PYTHIA 8 and
3638 GEANT4 simulation of the whole sPHENIX detector. Two-dimensional projective SPACAL
3639 towers were collected into sliding tower windows made from 4×4 towers via a trigger
3640 logic emulator ($\Sigma_{4 \times 4}[E_{\text{Tower}}]$). The top 8-bit ADC value for each tower was used in the
3641 sum in order to model the constraint from the trigger data bandwidth. The distribution of
3642 largest energy sums in minimum bias PYTHIA events was used to determine the rejection

3643 factors for the trigger. The efficiency for Y events was determined using a cut on the largest
 3644 energy sums in PYTHIA events, which contain at least one $Y(1S)$ particle that decayed into
 3645 di-electrons and was reconstructed by the full tracking detector to be within an invariant
 3646 mass window of $M_{Y(1S)} \pm 200$ MeV ($M_{Y(1S)} \pm 2\sigma$). Figure 8.11 summarizes the performance
 3647 of such an electron trigger by simultaneously plotting the rejection factor for minimum
 3648 bias events and the efficiency for Y events as a function of the minimum energy required
 3649 in the electromagnetic calorimeter tower windows using both the full ADC bit-width and
 3650 the top 8-bit truncated ADC information. In particular, the vertical gray band in the figure
 3651 at $\Sigma_{4 \times 4}[E_{\text{Tower}}] = 4.3$ GeV gives an example of a choice of minimum threshold energy in
 3652 4×4 windows for which the rejection factor is better than $\approx 5 \times 10^3$ while maintaining
 3653 an Y efficiency of 98% in both ADC bit-width choices. The result is quite comparable to
 3654 the GEANT4 simulation without 8-bit truncation. This demonstrates the feasibility of an
 3655 electron trigger for the Upsilon program in high-luminosity $p+p$ data-taking. Extending
 3656 these trigger emulated studies to the full physics channel set goes hand in hand with
 3657 further specification of the trigger algorithms.

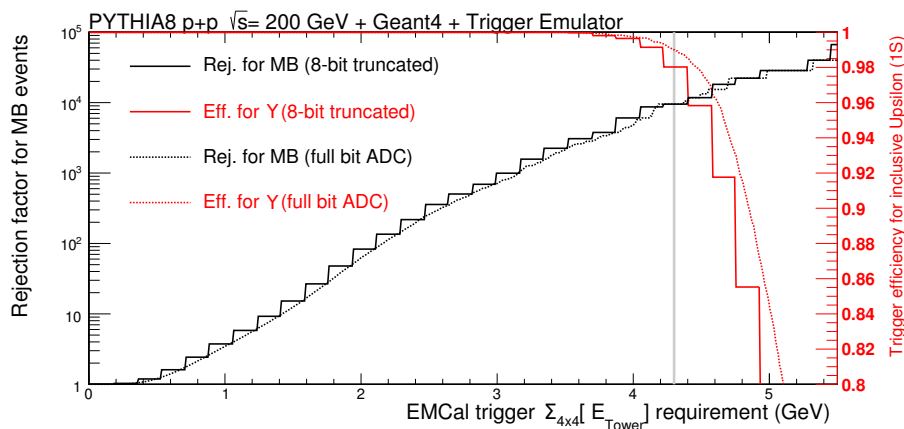


Figure 8.11: Rejection factor and efficiency for an Y -electron trigger, which requires some minimum amount of energy in a 4×4 -tower of the 2D projective SPACAL ($\Sigma_{4 \times 4}[E_{\text{Tower}}]$). Results are shown for a full PYTHIA and GEANT4 simulation of the detector response. The rejection factor for minimum bias $p+p$ events (black lines) and the efficiency for Y (red lines) are plotted as a function of the required energy $\Sigma_{4 \times 4}[E_{\text{Tower}}]$. For the dashed lines, full bit-width ADC values were used in the trigger sum, while the solid line shows trigger performance when only the top 8-bit ADC information is used.

3658 Minimum Bias Trigger

3659 The MBD consists of two identical arms of detectors around the beam-pipe, located both
 3660 forward and backward of the collision point. Each arm consists of 64 channels, and are
 3661 referred to as the North and South arms. For full details see Chapter 7.1. On every RHIC

3662 crossing, the MB LL1 trigger board will receive the following trigger primitives over 4
3663 fibers from each of the 4 ADC boards used by the MBD:

- 3664 • The mean time of all hits in one MBD ADC Board (10-12 bits)
- 3665 • The number of hit channels in one MBD ADC Board (6 bits)
- 3666 • The total charge sum in one MBD ADC Board (12-16 bits)

3667 The ranges of bits in the above are determined by the lower and upper bounds on the
3668 resolution we expect to be able to achieve in the system, and will be finalized after further
3669 study. Since each ADC board reads out half of one MBD arm, it represents the data from
3670 the left or right half of an arm, which will allow scaling of left-right asymmetries during
3671 transversely polarized proton running. The MB Local Level 1 trigger will calculate the
3672 z-vertex position of the collision using the difference in the times from the two arms, and
3673 can make a cut on the collision vertex [154]. The nominal selection for sPHENIX is $|z| < 10$
3674 cm since this is the fiducial acceptance for the silicon tracking systems. However, multiple
3675 vertex selections are possible. In PHENIX, for example, three MB triggers were defined:
3676 $|z| < 10$ cm, $|z| < 30$ cm, and the “wide” trigger in which collisions from any vertex
3677 location are accepted. With 120 ps time resolution, one expects a z-vertex resolution of
3678 about 2.5 cm for the most peripheral heavy ion events. As the centrality of the collision
3679 increases, this resolution will improve due to the statistical improvement from the larger
3680 number of hits.

3681 The electronics upgrade allows the possibility of a couple of new features that were
3682 not available in PHENIX. The centrality of the collision can be estimated using the the
3683 number of hits or energy sums in the MBD, allowing for a trigger selection on centrality.
3684 Additionally, since the time and charge are extracted simultaneously on the ADC Board,
3685 a slew correction can be applied to the time determination, which will improve the time
3686 resolution in the Level-1 trigger compared to PHENIX.

3687 8.4 The Global Level-1 and Timing System

3688 At its core, the GL1 functionality is implemented in a FPGA that receives, for each beam
3689 crossing, inputs from the LL1s. After examining the input data, it arrives at a decision
3690 whether or not to accept the data from the beam crossing in question. In the end, a given
3691 crossing fulfills one or more classifications, which are usually referred to as different *trigger*
3692 *inputs*. For example, a collision could be characterized as (likely) containing an Upsilon
3693 signal, a high-momentum photon, or a jet, high centrality, or any of the trigger algorithms
3694 described in the previous chapter. Those properties are not exclusive; a given crossing can
3695 (and often does) fulfill more than one.

3696 One would give priority to the most “interesting” events, usually the ones that fulfill a
 3697 dedicated LL1 criterion. The least interesting crossing is one where no actual collision took
 3698 place. In order to facilitate consistency checks and normalizations of the calculated cross
 3699 sections, one still adds a very small fraction of those “clock” triggers to the mix.

3700 8.4.1 Trigger Scaledowns

3701 A given trigger mix is implemented by a set of *scaledown values*. To use an example
 3702 from the PHENIX experiment, one particular run saw 18635569 collisions that satisfied
 3703 the Minimum Bias criterion. Of those, 3218134 collisions happened within the desired
 3704 narrow central vertex range. Obviously, we want to collect as many of the latter type as
 3705 possible; however, one still needs to collect a small fraction of the former (about 0.5% of
 3706 the total number of events) of the “wide vertex” collisions for normalization purposes and
 3707 consistency checks.

3708 The scaledown system counts how often a trigger signal arrives at a given trigger input
 3709 while the data acquisition is not busy. If the scaledown is, for example, 10, only every 10th
 3710 such collision is accepted, all others are discarded. It is of the utmost importance that the
 3711 system only counts trigger signals that arrived while the DAQ system was live. In this
 3712 way, the one accepted (and recorded) collision represents, other than itself, 9 others of the
 3713 same statistical significance *that could have been taken*. In the analysis phase, the data from
 3714 this collision must be weighted by a factor of 10 to account for the scaledown. Conversely,
 3715 if that scaledown is set to 1 (no rate reduction), each triggered collision is getting accepted,
 3716 and its weight is 1.

3717 In the PHENIX run shown above, of the 18635569 minimum bias collisions, 16738539
 3718 arrived while the DAQ system was live. The scaledown for this trigger input was set to
 3719 1333, resulting in 12547 accepted collisions.

3720 Of the 3218134 collisions in the narrow vertex range, 2891906 triggers arrived while the
 3721 DAQ was live, and, with a scaledown of 1, all of them were accepted and recorded. In this
 3722 way, the desired small admixture of 0.43% (12547/2891906) minimum bias events without
 3723 a vertex cut was accomplished.

3724 Similarly, a small fraction of clock triggers (7067399912 raw, 6362534485 live, 19087 ac-
 3725 cepted) was selected by a scaledown of 1/3 million (333,333). The following table summa-
 3726 rizes those numbers:

trigger	raw count	live count	scaledown	accepted
clock	7067399912	6362534485	333333	19087
minimum bias	18635569	16738539	1333	12547
narrow vertex	3218134	2891906	1	2891906

3728 Without the dedicated “narrow vertex” trigger, we could have taken about 2904453
 3729 (2891906 + 12547) minimum bias events in that run, but only 501563 of them, rather

3730 than 2891906, would have been in the narrow vertex. By implementing the narrow ver-
3731 tex trigger, and adjusting the scaledown settings properly, we were able to enhance the
3732 statistics of the most valuable collisions by almost a factor of 6.

3733 The entire latency for the Level-1 trigger system is specified at 4.0-5.0 microseconds.

3734 8.4.2 Timing System

3735 The sPHENIX Timing System performs distribution of the timing information to the front
3736 end modules (FEM) for the various detector subsystems. The front-end electronics needs
3737 to be aware of the RHIC clock in order to synchronize the sampling frequencies with the
3738 arrival of the signals.

3739 The module is housed in a 1U rack mount enclosure and interfaces with the controls
3740 network via TCP/IP over gigabit Ethernet. The actual timing information is transmitted
3741 via dedicated fiber interfaces.

3742 The timing module performs three primary functions.

3743 First, it provides low jitter distribution and generation of timing signals, namely the Beam
3744 Clock, Beam Clock $\times 6$ (generated on board via PLL), and LVL-1 Accept. The Timing
3745 System distributes a copy of the generated $6 \times$ the RHIC clock to the front-end.

3746 Second, it provides readout enable strobes to the FEM's, and monitors the number of level-
3747 1-accepts generated by the level1 system.

3748 Third, it is a mode bit scheduler, which outputs predetermined mode commands on a
3749 crossing-by-crossing basis to the FEM's. RHIC has 120 "buckets" in each ring that can hold
3750 beam bunches (or can be empty), giving the collider a period of 120 bunch crossings, after
3751 which the same pattern of crossings repeats itself. The bunches cross about every 110 ns,
3752 although the exact value varies slightly with the ion species that is being stored, and also
3753 changes during the acceleration phase of a RHIC store.

3754 The scheduler always operates as multiples of a sequence of 120 values, one for each
3755 crossing in one period, which is a full rotation of a particular bunch around the ring, which
3756 takes about 1.3 microseconds.

3757 The Timing System needs to know the RHIC bunch crossing number. The Collider provides
3758 a "fiducial tick", a hardware signal that denotes the passing of bunch number 1, which
3759 the GL1 and Timing System uses to get in sync with the accelerator state. At the start of
3760 the GL1 and Timing System operation, all its internal counters are held at reset. At the
3761 next crossing of bunch 1, the systems start counting and remain in sync with the bunch
3762 numbers.

3763 For each beam crossing, the various front-end systems need to receive some information.
3764 Most importantly, it needs to know whether or not to prepare the data from a given
3765 collision for transmission, but there are other types of information that can be sent. For

3766 example, it would be possible to instruct the front-end to set a certain bit that results in the
 3767 zero-suppression getting switched off for a small fraction of events. In this way it would
 3768 be possible to acquire, for example, special events with a very low rate that can be used to
 3769 check the proper settings of the pedestal subtraction (“in-beam pedestal”).

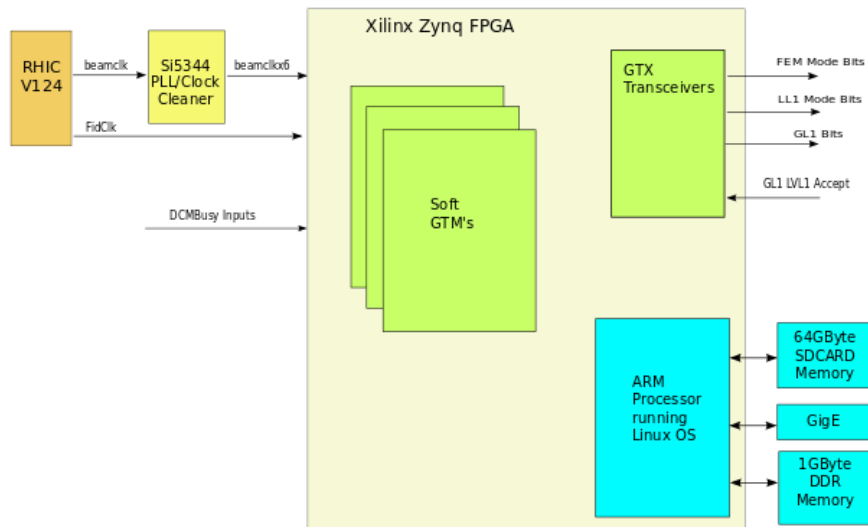


Figure 8.12: Block diagram of the Timing system, which contains a number of virtual *Granule Timing Modules* (GTM's) implemented in firmware on a FPGA. The board receives the RHIC clock from the accelerator system, as well as a *fiducial tick*, denoting the passing-by of bunch 1 in the ring. The GTM's distribute the timing and trigger information in a detector-specific way, and maintain the busy state of the DAQ.

3770 At the core of the timing system are multiple copies of a virtual *Granule Timing Module*
 3771 implemented in firmware (Fig. 8.12). A granule refers to a set of FEMs that receive identical
 3772 timing information. This is most often a section of a detector system, such as the north-
 3773 or south half of the electromagnetic calorimeter. Since it is possible to operate a granule
 3774 in a standalone fashion during testing and debugging of the detector readout, we will
 3775 likely split large detector systems up into more granules than strictly necessary just from a
 3776 timing information perspective.

3777 Each virtual GTM implements its own scheduler. The scheduler can hold 32 different
 3778 sequences (internally called “mode bit groups”) of 120 per-crossing “modes” that usually
 3779 repeat many times. In order to be able to execute a special sequence occasionally, as with
 3780 the example of in-beam pedestals, or only one time, the GTM holds a 128 entries deep
 3781 section of *scheduler memory* that schedules the proper sequences for execution. For example,
 3782 sequence *A* might contain an instruction on bunch crossing 1 for the FEMs to reset their
 3783 counters and clear their memory. Sequence *B* would then encode the standard operation
 3784 for each rotation. In that case, one would execute sequence *A* once at the start of data
 3785 taking, and then repeat sequence *B* indefinitely until the data taking ends.

3786 Let's now assume that another pattern *C* contains a special instruction that injects an
 3787 in-beam pedestal event, and that such an event should occur every 15 seconds. Now one
 3788 would schedule sequence *A* once at the start as before, followed by an indefinite loop of
 3789 11538 repetitions (about 15s worth) of the standard sequence *B* and then one sequence *C*.

3790 Each entry in the scheduler memory is 32 bits wide, and mean

31	30...5	4...0
reset	repeat count	sequence address

3792 The entries are executed in order. The repeat count specifies how often a given sequence is
 3793 repeated. The reset bit causes the scheduler to jump back to the start position after finishing
 3794 the entry's execution, making it possible to program indefinite execution sequences.

3795 To program the above example, sequence *A* might be stored at address 0, *B* at address 1,
 3796 and *C* at address 2. Then the scheduler memory would be

31	30...5	4...0	
0	1	0	initialization
0	11538	1	15s standard operation
1	1	2	in-beam pedestal injection

3798 A candidate board for the Timing system is shown in Fig. 8.13. The board has a Xilinx
 3799 Zynq FPGA. The board has 14 individual fiber transceivers and can support 14 different
 3800 granules. The Zynq FPGA has several CPU cores, and a Debian implementation for the
 3801 board exists. This provides access to a standard ethernet port. The board can be configured
 3802 through the network, which can also provide aggregate information such as counters.

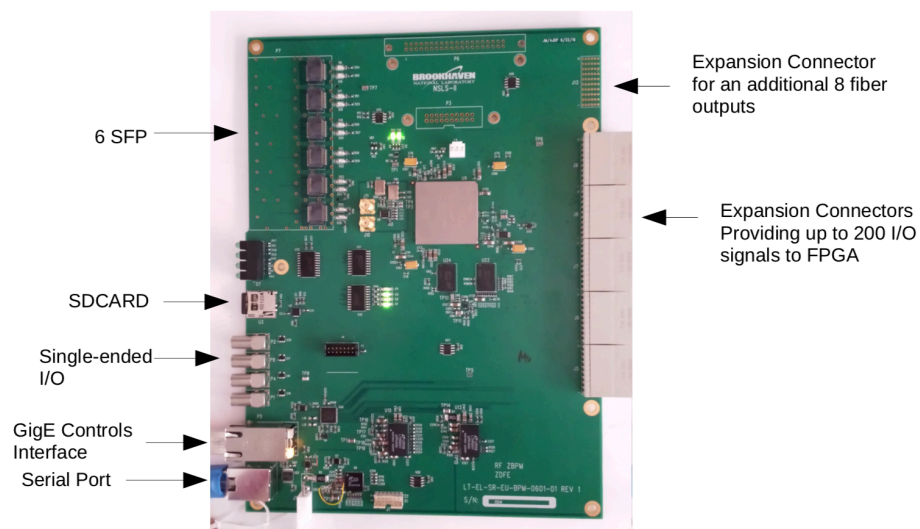


Figure 8.13: A picture of a candidate board to run the Timing System. The board has a Xilinx Zynq FPGA which, in addition to the FPGA portion, has ARM CPU cores that can run Linux and provide the slow controls interface, as well as access to aggregate information.

3803 Appendix A

3804 Superconducting Magnet

3805 The magnet and tracking system should be capable of order of 1% momentum resolution
3806 at 10 GeV/c over $|\eta| < 1.1$ and the full azimuth. The BaBar solenoid, with a central field
3807 of ~ 1.5 T and an inner radius of ~ 140 cm, is an excellent match to the sPHENIX physics
3808 requirements. The magnet became available in late 2012, and the ownership of the coil
3809 and related equipment have been transferred to BNL.

3810 A.1 Magnet Mechanical Design

3811 The superconducting solenoid magnet was manufactured by Ansaldo and delivered to
3812 the BABAR experiment at SLAC in 1997. The magnet was successfully commissioned in
3813 1998, and it was operated and remained in good condition through the end of the BaBar
3814 experiment in April 2008. The solenoid was then shipped to BNL in February 2015. Upon
3815 installation in sPHENIX at BNL, the magnet will remain unchanged except for an extension
3816 to the connection to the exiting power leads and cryogenic line structure (referred to as the
3817 valve box) to eliminate interference with the sPHENIX outer calorimeter.

3818 Partly to simplify track finding and fitting, the magnitude of the magnetic field within the
3819 tracking volume should be constant within a few percent. The field will be measured to
3820 better than 1% in the whole cryostat area to correct for nonuniformities, especially close to
3821 the plug doors.

3822 A.1.1 Conductor

3823 The conductor is composed of a niobium titanium “Rutherford-type” superconducting
3824 cable which was co-extruded with an outer aluminum matrix. The cable is made of sixteen
3825 strands of 0.8 mm diameter wire with a copper to superconductor ratio of 1:1, filament size
3826 less than $40 \mu\text{m}$, and twist pitch of $25 \mu\text{m}$. The final superconducting cable is rectangular in

3827 shape and 1.4 mm by 6.4 mm in size. The aluminum matrix into which the superconductor
 3828 is co-extruded is of two sizes; 8.49 mm thick by 20 mm wide in the body of the magnet, and
 3829 4.93 mm thick by 20 mm wide in the coil end regions. The thinner aluminum matrix in the
 3830 ends permits higher current density in the coil ends to extend the axial region of uniform
 3831 solenoid field. The critical current of the conductor is 12,680 A at 2.5 T and 4.2 K, which
 3832 provides a safety margin of 2.75 over the operating current of 4,596 A. The conductor is
 3833 wrapped with fiberglass cloth which is later impregnated with epoxy, the combination of
 3834 which provides both electrical insulation for the conductor and mechanical support for the
 3835 completed coil.

3836 A.1.2 Coil

3837 The solenoid coil consists of two conductor layers. Both conductor layers were internally
 3838 wound inside an aluminum support mandrel — first the outer layer and then the inner
 3839 layer. Winding was started at the end where the conductor leads would ultimately exit the
 3840 coil, using the narrow conductor. After a specified number of windings the narrow con-
 3841 ductor was spliced to the thick conductor using two 30 cm long soldered lap connections,
 3842 spaced 20 cm on either side of a 1.5 m long region where the edges of the overlapping thin
 3843 and thick aluminum matrices were welded together (Figure A.1). The completed splice
 3844 region was hand wrapped with fiberglass cloth when complete and winding using the
 3845 thick conductor was completed to a specified number of turns, after which a similar splice
 3846 back to thin conductor was installed and the winding of the outer layer completed to the
 3847 desired dimensions. A third splice, this one to connect to the inner coil layer, was installed,
 3848 and inner layer winding was completed in a fashion similar to the outer layer using thin,
 3849 then thick, a finally thin, conductor. The number of thin and thick conductor windings, for
 3850 the inner (outer) layer, counting from the exiting lead end of the coil, are 184, 164, and 183
 3851 (188, 159, and 189). When the winding was completed, the coil was impregnated using
 3852 epoxy to create a rigid structure. G-10 parts were used in transition locations and to adjust
 the overall length of the coil to meet the aluminum support mandrel end flanges.

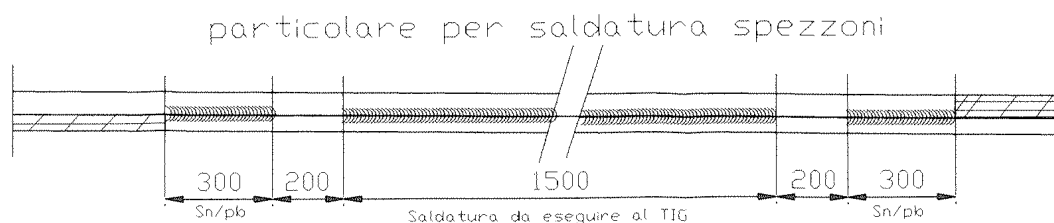


Figure A.1: Internal splices (extracted from the original Ansaldo drawing): 1500 mm weld of aluminum edges + 200 mm gap + 300 mm solder of aluminum faces on both sides of the weld. The welding was done with the TIG (Tungsten Inert Gas) technique.

3854 A.1.3 Cold Mass and Cryostat

3855 The aluminum support mandrel provides both mechanical support and cooling to the
3856 solenoid coil (Figure A.5). Conductive cooling is provided via helium which circulates in
3857 lines welded to the outside surface of the support mandrel. An outer heat shield which is
3858 actively cooled to 40 K using helium gas from the cold mass cooling line boil-off that is
3859 returned to the helium reservoir, along with conductively cooled heat shield end plates
3860 and inner heat shield (connected to the outer shield) assist with maintaining a uniform 4 K
3861 coil temperature. Support from outward radial and axial Lorentz forces is provided by the
3862 strength of the aluminum cylinder. Gravity loads, as well as magnetic field alignment, are
3863 provided by a system of tangential and axial Inconel tie rods which develop tension on
3864 cool down to 4 K. Tie rods connect the coil support cylinder directly to the aluminum outer
3865 cryostat (Figure A.6) but are heat stationed to the outer heat shield. The coil is positioned
3866 with a 30 mm axial offset toward the lead end with respect to the outer cryostat. The
3867 outer heat shield is independently supported by the outer cryostat by separate tie rods
3868 (Figures A.7 and Figures A.8).

3869 A.1.4 Valve Box

3870 The cryostat connects to a vertical tower (valve box, Figure A.2), which contains all the
3871 electrical (vapor cooled) power leads, instrumentation wire leads, helium supply and
3872 return lines for coil and heat shield, and vacuum connections. During installation in
3873 sPHENIX this valve box will be extended away from the magnet to provide clearance
3874 for the outer calorimeter, by adding a 1 m transfer line extension which carries all of the
3875 aforementioned lines from magnet to valve box.

3876 Figures A.2 and A.3 show the placement of the cryostat, the extension and the valve box.
3877 Figure A.4 shows different portions of the extension that is connected to the valve box.

3878 A.2 Cryogenics

3879 A.2.1 Magnet Cryostat System

3880 The coil of the magnet is attached to a cylindrical aluminum mandrel which is cooled
3881 by boiling liquid helium in eleven parallel aluminum tubes welded to the mandrel. A
3882 separate valve-box cryostat located above the solenoid cryostat, outside the return flux
3883 iron serves to interface the power and cryogenics to the solenoid. The valve-box contain
3884 the cryogenic valves, the siphon phase separator vessel, current leads, and relief devices. A
3885 vacuum jacketed interconnect containing the cryogenic lines and superconducting current
3886 cables, and instrument wiring, connects the solenoid cryostat to the valvebox.

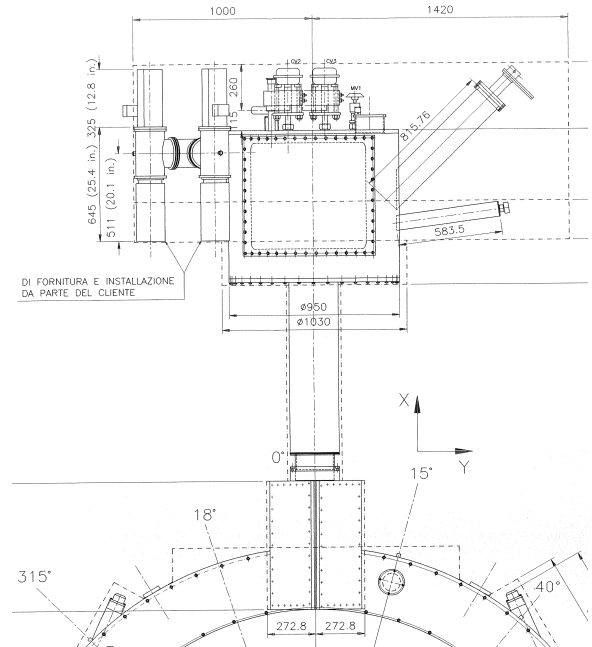
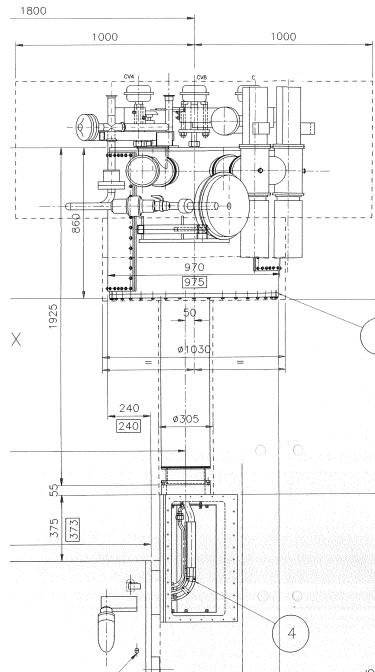


Figure A.2: Original Ansaldo drawing of the valve box.

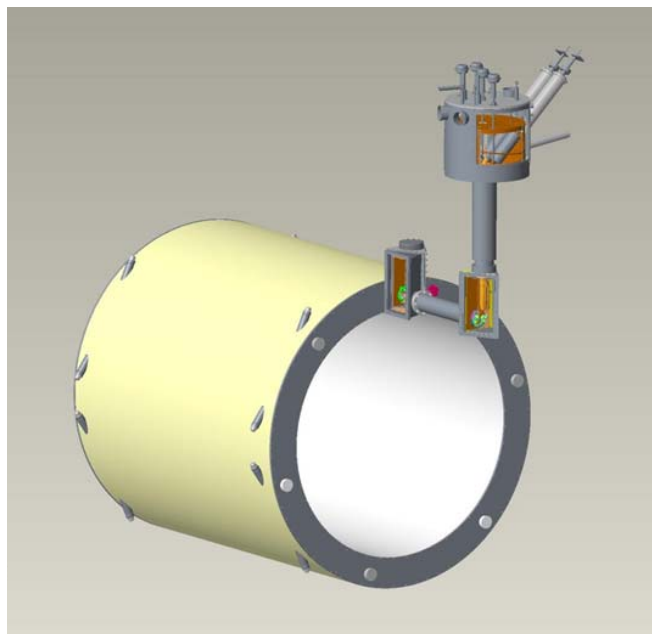


Figure A.3: The cryostat, the extension and the valve box.

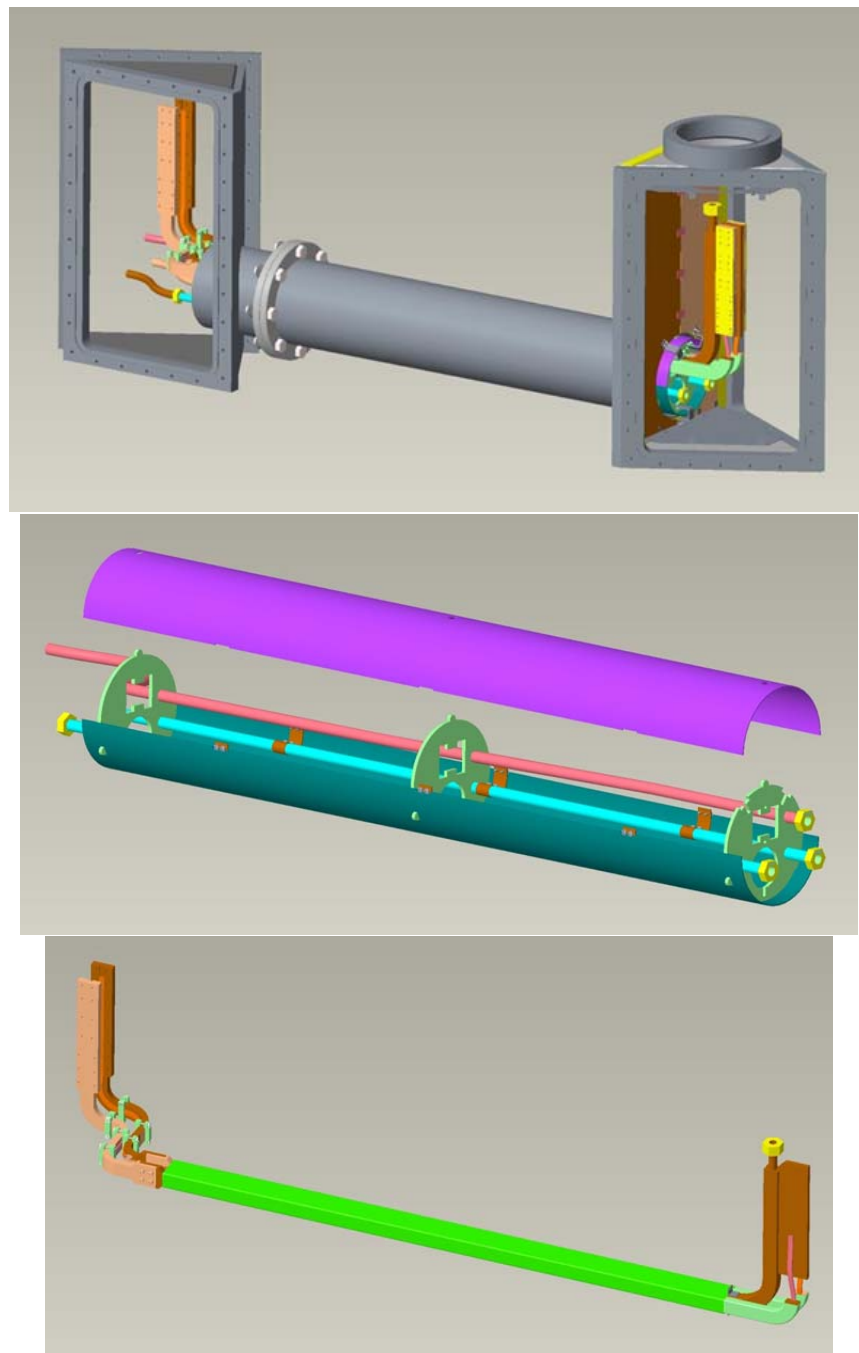


Figure A.4: Top: from the junction box (at the cryostat) to the valve box; Middle: coil helium supply line and heat shield; Bottom: extension lead assembly with flexible (laminated copper) connections to accommodate thermal contraction on the left and coil return helium to cool exiting leads on the right.

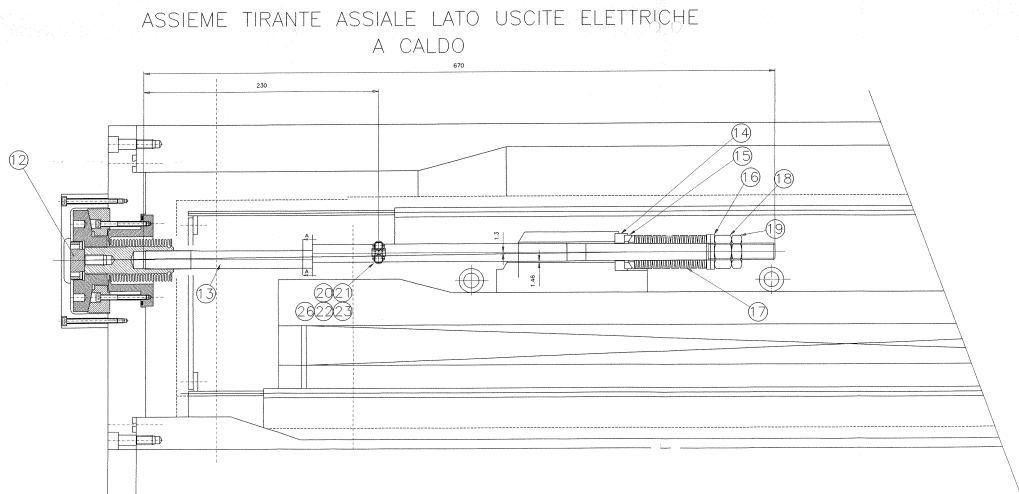


Figure A.6: Original Ansaldo drawing: Axial Tie Rod Assembly

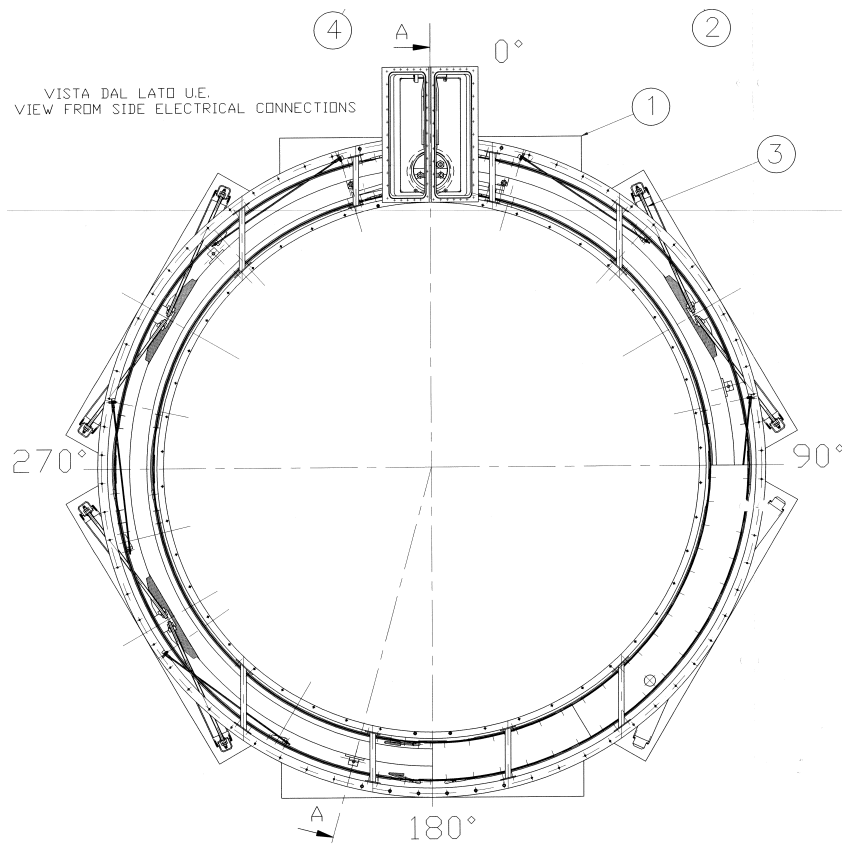


Figure A.7: Original Ansaldo drawing: Cryostat Assembly



Figure A.8: (Left) Exiting leads — aluminum removed and niobium titanium soldered to heavy copper stabilizer leads (overlapping aluminum); (Right) Outer heat shield.

3887 A.2.2 Magnet 4.5 K Cooling

3888 The originally design of the cooling loop is a thermo-siphon loop in which liquid is drawn
 3889 from the phase separator vessel and fed to the bottom of solenoids cooling loop and
 3890 returns back to the phase separator. It has not been operated in the thermo-siphon for
 3891 most if its normal operating life at its previous facility. The magnet was cooled by, instead
 3892 of feeding the liquid to the phase separator, the liquid helium was fed directly from the
 3893 cryogenic supply to the solenoids cooling loop, with the return flow still coming back to
 3894 the valve-box phase separator. This operating point was still sub-critical, and thus nucleate
 3895 boiling still occurred and the flow is two phase returning to the phase separator.

Table A.1: Steady State Loads

Solenoid Valvebox Loads	Original Design / Nominal Load	Forced 2 Phase Flow Operation and Design Load
Magnet load and valvebox	35 W @ 4.5 [siphon mode]	7.5 g/s, 145W [with Valvebox separator loading heaters]
Shield	0.35 g/s, from 4.5K to 50K, 110W	0.5 g/s, from 4.5K to 50K
Vapor cooled leads	0.51 g/s, 4.5K to 300K	0.51 g/s, 4.5K to 300K
Vapor cooled leads	0.51 g/s, 4.5K to 300K	0.51 g/s, 4.5K to 300K

3896 A.2.3 Superconducting Current Leads

3897 The two superconducting current (SC) leads, after exiting the coil are cooled by conduction
 3898 to the 2-phase flow return tube. The superconducting lead cables are attached to copper
 3899 bars, which are cooled by this return line going back to the valve box. The SC leads
 3900 terminate at the lead pots, which each contain the normal conducting copper vapor cooled
 3901 current lead, that transitions to the room temperature connection for the external power
 3902 supply. The lead pot is cooled by liquid drawn from the main siphon phase separator.
 3903 The entire lead pot is electrically hot, and isolation is done with an isolator at the tubing
 3904 connections that feed liquid and return cold vapor, and on the tubing connection where
 3905 the lead cooling exit the warm end of the current lead, with the actual pot vessel isolated
 3906 with a G-10 spacer at the flange on the warm end of the lead pot vessel. The nominal lead
 3907 cooling flow is 0.2 g/s controlled by a 0.5 g/s thermal mass flow controller.

3908 A.2.4 Thermal Shield

3909 Thermal shields surround the solenoid coil/mandrel assembly in both annular spaces
 3910 (inner and out diameter) between the coil and the cryostat vacuum vessel. Some of the
 3911 4.5 K cold vapor from the separator vessel is taken through the shield loop and returns
 3912 back to the cryosystem to a warmup heater (liquefaction load on the plant) or returns cold
 3913 at approximately 40 K to the cryo plants coldbox. Nominal shield flow is 0.35 g/s with a
 3914 return temperature of around 60 K for a load of 110 W.

3915 A.2.5 Valve Box

3916 The existing valve box serves as the cryogenic, power supply, vacuum, and instrumenta-
 3917 tion interface between the solenoid and the rest of the facility. It contains the following
 3918 equipment on the valve box and interfaces: cryogenic control valves, the relief devices, the

3919 electrical feedthroughs for all the solenoid instrumentation, turbo vacuum pump, vacuum
3920 gages, pressure sensors, TE, SC level, LHe bath heaters.

3921 A.2.6 Relief Devices

3922 The helium volume is protected by an ASME relief valve and ASME burstdisk, and a
3923 cryogenic dump globe valve from a relief line originating from the phase separator. The
3924 reliefs were sized to handle a full magnet quench and loss of insulating vacuum to air.

3925 A.2.7 Cryogenic Supply System

3926 The magnet will be cooled by tie-in to RHIC cryogenic distribution system. There will be
3927 one supply line that will tie-in to the S header and the H header of the cryo distribution
3928 system. This allows liquid helium supply during 4.5K operations and ability to draw from
3929 the heat shield header during cooldown.

3930 Cold vapor returns via a return line to the U header on RHIC distribution system. The
3931 solenoid shield returns on a separate shield return which will also be used to shield the
3932 cryogenic transfer line for this interface transfer line system. The shield flow will return to
3933 the RHIC U-header or WR header. The current lead flow returns will be returned as warm
3934 gas to RHICs WR header, operating at 1.2 bar.

3935 Thus RHIC operating conditions on the cryo distribution system will set the operating
3936 condition for the SC Solenoid.

Header name	Pressure [bar]	Temperature [K]
S	3,4	5.0
H	12-14	50-80
R/U	1.22	4.6
WR	1.19	293

3938 Magnet operating temperature is actually set by the return pressure on the RHIC cryogenic
3939 distribution system at 8 O'clock / 1008. The pressure in RHICs 4.5 K vapor line R or U
3940 header is around 1.22 bar during normal operation. In order to operate the solenoid helium
3941 at 4.5 K, the boiling point pressure needs to be 1.300 bar. This sets the 4.5 K pressure drop
3942 budget between the solenoid and R header at 80 mbar.

3943 Tie-in from the RHIC cryogenic distribution system will occur at the valvebox via the
3944 tee-ins from the main header to the individual relief transition feedthrough lines located at
3945 one end [sextant 8/9 end] of the valvebox. The valvebox is located inside 1008B service
3946 building. The transfer line system exits the 1008 building and will penetrate the IP8 Hall
3947 via the south wall and suspends across the Hall to the platform. Cryogenic line jumpers
3948 with bayonets interface to the new interface box.

Table A.2: 4.5K loop vapor return pressure drop budget [10 g/s vapor]

Item	Pressure [bar]	DP budget [mbar]
Bath pressure	1.300	
Tubing run to valve	1.295	5
Vapor return valve	1.279	16 [$C_v = 2.8$]
Tubing run to bayonet	1.275	4
Return line to heater	1.270	5
Heater	1.250	20
Return line to RHIC tap, 1 NPS, sch10	1.240	10
Isolation valves, two	1.226	14 [$C_v = 4$]
Margin/Balance	1.216	4
U header, 5K	1.220	[overall: 80]

3949 A.2.8 Interfacebox

3950 The interfacebox will be located next to the solenoid valvebox and will contain the follow-
3951 ing components:

1	Liquid helium reservoir, 400L	Sufficient for magnet rampdown in 1 hour if LHe supply is interrupted
2a 2b	LN2 Boiler / Helium exchanger GN2 / Helium exchanger	LN2 exchangers to hold the magnet at 100K during shutdown using the helium circulating compressor at 1010B. LN2 Boiler and sensible heat recovery exchanger from 80K to 300K.
3a 3b 3c	heater or recovery heatexchanger*	20 kW Heater to warmup cold gas from the RHIC distribution for controlled cooldown and controlled warmup. * Recovery heatexchanger option: acts as recovery heat exchanger between solenoid helium stream and RHIC distribution system to control gradient across solenoid during cooldown and warmup
4a	Reservoir Vapor return control	Back pressure on reservoir to develop pressure difference to transfer flow to the solenoid valvebox supply
4b	Reservoir Liquid supply control	Controls liquid Helium into the reservoir from RHIC supply
4c	External dewar Liquid supply control	Controls liquid Helium into the reservoir from external dewar
4d	Heater Supply isolation	Isolates heater inlet from RHIC Helium supply
4e	Heater Exit to return side control	Controls warm Helium gas bypass to return side
4f	LN2 supply to Boiler Exchanger	Controls LN2 into LN2 boiler
4g	LN2/He HX Cooldown supply control	Controls 80K Helium flow into reservoir
5	Reliefs	Liquid helium reservoir and LN2 boiler bath, and trapped volumes
6	Temperature sensors	Reservoir, heater exit, LN2 Boiler exit
7	Pressure sensors	Liquid helium reservoir, Heater volume and LN2 boiler bath
8	Level sensors	Liquid helium reservoir and LN2 boiler bath

3952

3953 A 400 Liter ASME U-Stamped liquid helium reservoir will serve as the buffer to allow
 3954 rampdown of the magnet in the event there is interruption from the liquid helium supply,
 3955 it also serves as the phase separator to do the phase separation from the supercritical
 3956 helium supplied from RHIC cryogenic distribution S-header which is slightly warmer than
 3957 RHICs main M line flow. Supercritical helium at 3.55 bar and 4.8K is supplied from the
 3958 S-header via shielded transfer line bundle into the 400L liquid helium reservoir and from

3959 there liquid helium at 1.4 bar, 4.6K is supplied to the solenoids valvebox. An additional
3960 bayonet is also provided to allow supply from a 500L portable liquid helium dewar from
3961 the superstructure platform. The reservoir will need to have a net liquid inventory of 300
3962 Liters to allow liquid draw of 7.5 g/s and 1.3 g/s of vapor generation (8.8 g/s = 264 LPH)
3963 to allow rampdown of the magnet within 1 hour. [from 4600 A @1.5A/s].

3964 The Interface box will also include the LN2/He exchanger for keeping the solenoid cold at
3965 100K during RHIC shutdown. To handle the controlled gradient cooldown with no warm
3966 helium gas supply source available during RHIC operation, either a heater configuration
3967 or a He/He heat-exchanger and a small heater configuration is required. When the RHIC
3968 plant is not running the capability exists to use a small 18 g/s compressor located at 1010B
3969 to supply helium for circulation.

3970 A.2.9 Liquid Nitrogen Supply Line

3971 Liquid nitrogen is supplied to the interface valvebox for use during the shutdown to
3972 maintain the magnet at 100K. The LN2 is supplied a 500 ft long cryogenic transfer line from
3973 the liquid nitrogen storage dewar located in the front of the experimental hall building.

3974 A.2.10 Warm Piping

3975 N2 vent line to vent room temperature N2 to outside of the building will be run from the
3976 interface box to outside.

3977 A.2.11 Utilities

3978 A.2.12 Utilities Instrument Air is supplied via RHICs Cryogenic systems Instrument air
3979 system capable of providing -60C dewpoint at 90 psig.

3980 120VAC and 480VAC power is required for the heater and controls at the solenoid and in
3981 1008B service building.

3982 A.2.12 Controls

3983 Controls of the solenoid valvebox, the interfacebox will be done by a Modicon 340 series
3984 PLC and I/O chassis, located in two (2) 19 rack along with the temperature sensors
3985 controllers, SC level probe controllers and vacuum pump controllers. The PLC is interfaced
3986 to the RHIC Cryogenic Systems DCS/HMI control system via Ethernet on its own subnet.

3987 Figure A.9 presents a flow-chart of the cryogenic control system.

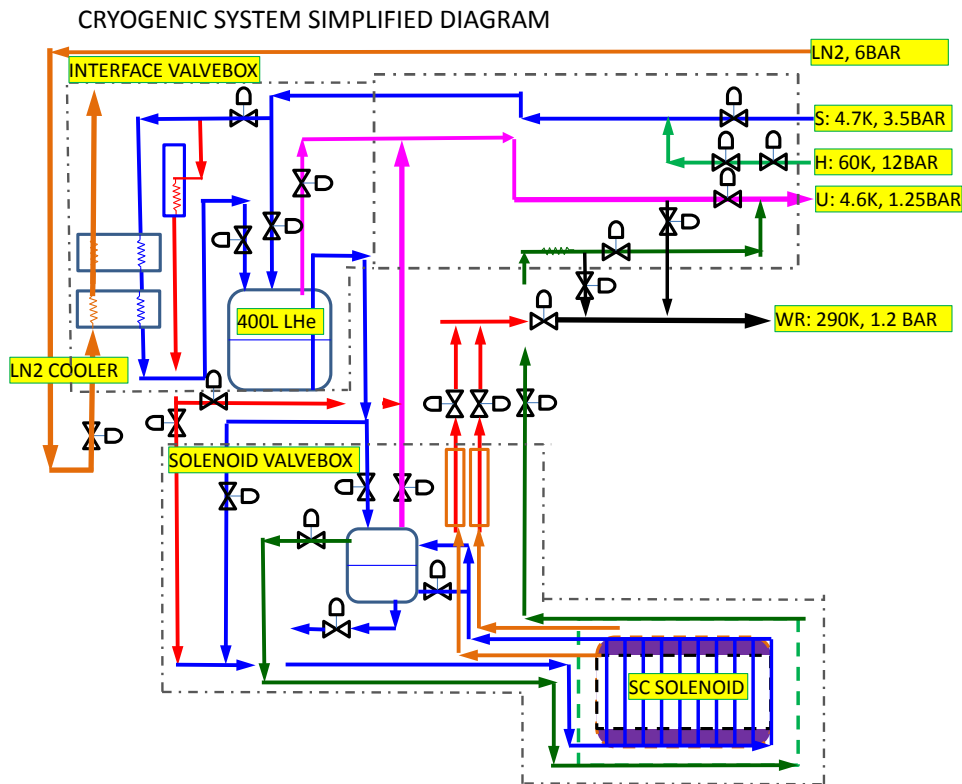


Figure A.9: sPHENIX Magnet Cryogenic Control System

3988 **A.3 Magnet Power Supply**

3989 **A.3.1 Elements of the Power Supply System**

3990 Figure A.10 shows the main elements of the sPHENIX Magnet powering system.

3991 **L Solenoid = 2.5 Hy** The solenoid is represented as two inductors in series, as it con-
 3992 structed in two layers. The connection between the two layers is brought outside the
 3993 solenoid, to be used by the quench protection system. It is close, but not exactly, a
 3994 true center tap. The two layers have slightly different number of turns (531 vs 536),
 3995 and the inner winding has greater capacitive coupling to the support cylinder.

3996 **Rd = 68 mΩ** Rd is energy dump resistor, used to quickly reduce the current in the solenoid
 3997 if a quench is detected. This minimizes the energy absorbed within the solenoid. It is
 3998 split in two, with a soft reference to ground at the center point. With this split, the
 3999 voltage on either side of the solenoid to ground is only half the full dump voltage.

4000 **Rg = 67 mΩ** Rg limits the ground current, should the coil fault to ground. The voltage

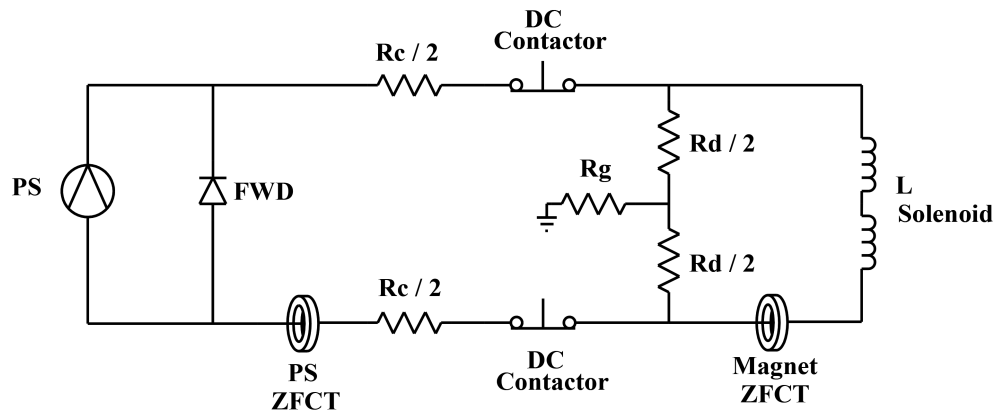


Figure A.10: sPHENIX Magnet powering system

4001 across R_g is monitored by a ground fault detector.

4002 **Magnet ZFCT** The magnet zero flux current transducer (ZFCT) accurately measures the
 4003 current into the solenoid. It differs from the power supply current by the current
 4004 flowing through the dump resistor. For this reason, this is the ZFCT used to regulate
 4005 the current in the power supply.

4006 **DC Contactor** In the event of a quench, the DC contactors are opened, and the power
 4007 supply is disconnected from the solenoid. The full solenoid current is then directed
 4008 through the energy dump resistor.

4009 **$R_c = 1.25 \text{ m}\Omega$ (SLAC Configuration)** R_c is the cable resistance. It determines the time to
 4010 ramp down the current through the freewheeling diode (FWD) when the power
 4011 supply turns off.

4012 **PS ZFCT** The power supply ZFCT is for testing purposes, as it does not represent the
 4013 solenoid current as accurately as the magnet ZFCT.

4014 **FWD** The freewheeling diode (FWD) provides a current path when the power supply is
 4015 turned off or trips.

4016 **PS** The power supply (PS) nominally operates 4.6 kA and less than 20 V. The unit is
 4017 manufactured to operate up to 8 kA and 40 V. Taps on the input transformer are used
 4018 to reduce the maximum operating voltage.

4019 A.3.2 Operating Conditions

4020 1. Ramping Up to Full Current

4021

4022 Under the conditions where the current is ramped from zero to 4.6 kA at a rate
4023 of 2.5 A/sec:

4024 (a) The time to reach full current is $(4,600 \text{ A}) / (2.5 \text{ A/sec}) = 1,840 \text{ seconds}$
4025 $= 30.7 \text{ minutes}$.

4026 (b) The voltage across the magnet is $V_m = L di/dt = 2.5 \text{ Hy} \times 2.5 \text{ A/sec} = 6.25 \text{ V}$.

4027 (c) The current through R_d is $V_m / R_d = 6.25 \text{ V} / 68 \text{ m}\Omega = 92 \text{ Amps}$

4028 (d) The peak power supply voltage is $R_c (I_m + I_d) + V_m$
4029 $= 1.25 \text{ m}\Omega (4,600 + 92) + 6.25 = 12.1 \text{ V}$.

4030 2. Slow Discharge through FWD and R_c

4031 (a) Time constant $\tau = L / R_c = 2.5 \text{ Hy} / 1.25 \text{ m}\Omega = 2,000 \text{ seconds} = 33.3 \text{ minutes}$

4032 (b) Time to decay from 4.6 kA to 100 A (as an example),
4033 $T_d = -\tau \ln(I / I_0) = -33.3 \ln(100 / 4,600) = 127.5 \text{ minutes} = 2.1 \text{ hours}$

4034 3. Fast Discharge through Dump Resistor

4035 (a) Time constant $\tau = L / R_d = 2.5 \text{ Hy} / 68 \text{ m}\Omega = 36.76 \text{ seconds}$

4036 (b) Time to decay from 4.6 kA to 100 A (as an example),
4037 $T_d = -\tau \ln(I / I_0) = -36.76 \ln(100 / 4,600) = 140.4 \text{ seconds} = 2.34 \text{ minutes}$

4038 A.3.3 Monitoring the Solenoid

4039 The change in state of a conductor from superconducting to resistive is called a quench.
4040 The function of the quench detector is to measure small values of resistance by the voltage
4041 they create. Figure A.11 shows the wires connected to parts of the solenoid to sense internal
4042 voltages.

4043 Quench Detection During Ramping

4044 The quench detector should be sensitive to a voltage rise of about 100 mV. This is simple
4045 when the current in the solenoid is constant. But, when the current is ramping up or
4046 down, the induced voltage, $V = L di/dt$, is much greater than 100 mV. With a ramp rate of
4047 2.5 A/sec, $V = 6.25 \text{ V}$.

4048 There is a voltage tap at the connection between the inner and outer solenoid windings.
4049 During ramping, if the inductance of these windings were identical, the voltage across the
4050 top coil (VT05 with respect to VT07) would be exactly negative of the voltage across the
4051 bottom coil with respect to the same point (VT10 with respect to VT09).

4052 The sum of these two voltages would add to zero. An imbalance caused by a 100 mV
4053 quench voltage can then be detected in the sum.

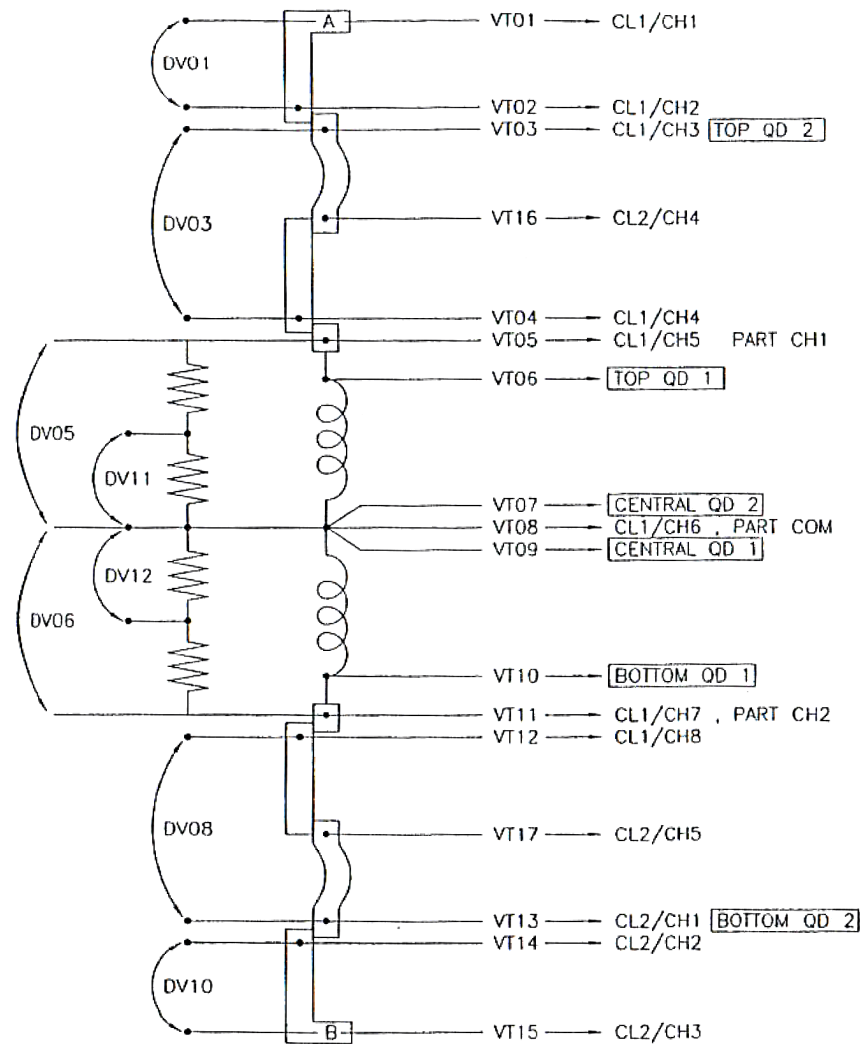


Figure A.11: sPHENIX Magnet voltage taps

4054 Practical Considerations

4055 The inner and outer coil inductances are not identical.

- 4056 1. The winding turns are not equal. The number is slightly different, 531 vs 536. This
4057 can be corrected by scaling the voltage tap value slightly before summing the two
4058 halves of the solenoid voltages.
- 4059 2. The inner coil has greater capacitive coupling to the supporting cylinder than the
4060 outer coil. Even if the coils had identical initial inductances, this coupling imbalance
4061 will cause an imbalance in induced voltage. This is effect is a function of ramp rate.
4062 To reduce this effect, the summing correction for the static inductance difference is
4063 adjusted for a given ramp rate.

4064 Energy Extraction

4065 When a quench is detected, DC contactors are opened, removing the power supply from
4066 the load and directing the load current through the energy dump resistor.

4067 The energy dump resistor causes the current in the solenoid to decay with a time constant
4068 of 36.8 seconds. This minimizes the heating of the quenched portion of the magnet. The
4069 peak voltage across the magnet is approximately 640 V, which due to the center ground
4070 reference at the energy dump resistor, is a maximum of 320 V with respect to ground on
4071 either side of the solenoid. By comparison, the time constant for a slow decay through the
4072 freewheeling diode for a normal shut down is 33.3 minutes.

4073 The quench protection of the BaBar magnet was externally reviewed in October 1996. At
4074 the end of that review, additional information was requested and a second review was
4075 held in January 1997. The final report was delivered in March 1997. The report concluded
4076 that the quench analysis was complete. Based on this analysis it was shown that, even
4077 without a fast discharge, a quench would not develop temperatures that would cause a
4078 catastrophic magnet failure. As a key component of the fast discharge, the energy dump
4079 resistor was also studied, and found to provide adequate protection for the magnet.

4080 Development of a New Quench Detector

4081 Fifteen years have passed since the original quench detection system in the BaBar experi-
4082 ment has been designed and implemented. In the future implementation which will be
4083 done by the cooperation of Superconducting Magnet Division and the Collider-Accelerator
4084 Department, new hardware and software will make more accurate and reliable quench
4085 detection possible for this Magnet.

4086 A.3.4 Magnetic Field Simulations

4087 As the return yoke in sPHENIX is very different than the original BaBar configuration,
4088 detailed field simulations are needed to understand the changes in shape and strength of
4089 the field. In a first step 2D simulations were done using the standard commercial opera
4090 software package.

4091 These 2D simulations, Fig. A.12, assume a rotational symmetry of the setup and are a
4092 starting point for GEANT4 detector and physics simulations.

4093 As the field depends on the dimensions and shape of the return yoke, which is not
4094 completely symmetric, and specifically on the distance of the two plug-doors with the
4095 beam openings, more detailed 3D simulation are necessary. To simplify the simulations
4096 the return yoke was first replaced by a solid cylinder of magnet steel with the appropriate
4097 density, Fig. A.13. The calculated magnetic field through this structure, at 4596 A, along

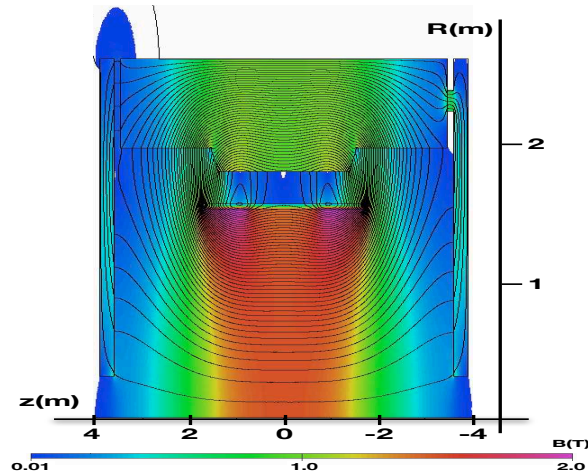


Figure A.12: 2D opera simulations of the sPHENIX setup

4098 the longitudinal axis (beam direction) is shown in Fig. A.14.

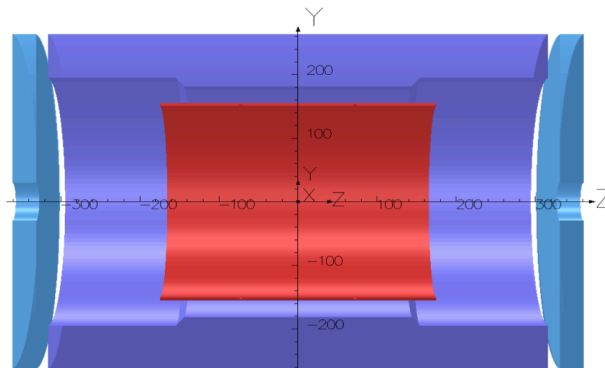


Figure A.13: 3D opera Model

4099 These simulations can also be used to calculate the forces on the solenoid. Apart from the
 4100 mechanical forces due to the cool down, the dimensions and shape of the yoke and plug
 4101 doors as well as the position of the coil within the return yoke creates sizable forces on the
 4102 coil.

4103 The plate structure of the return yoke is a challenging setup for the finite-element analysis,
 4104 but these details are needed for understanding possible changes in the shower shape due
 4105 to the scintillator gaps, Fig. A.15.

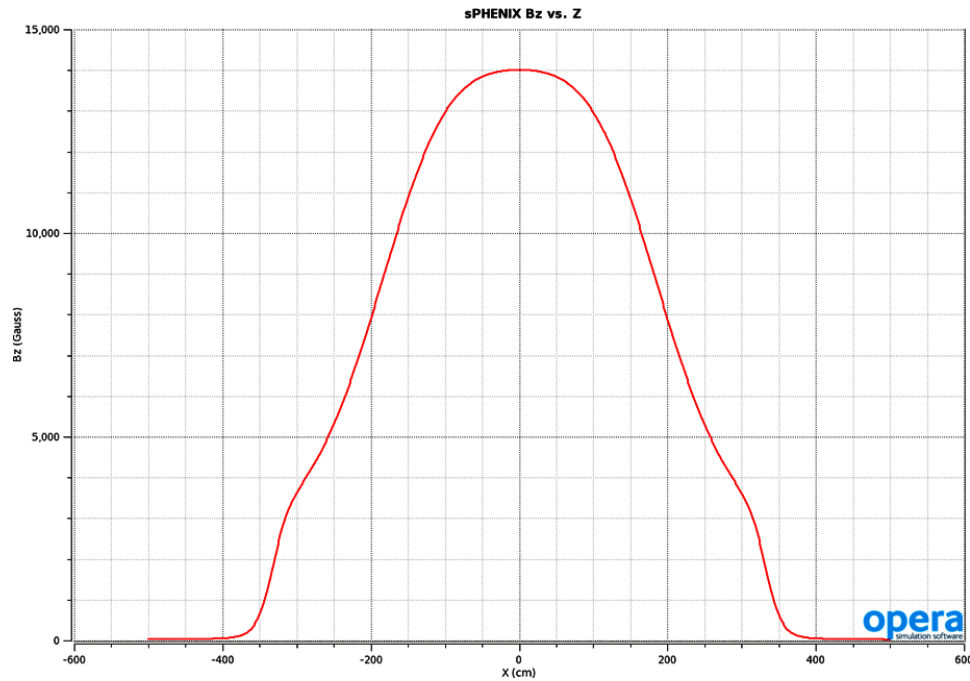


Figure A.14: Calculated magnetic field along the longitudinal axis (beam direction) for the symmetric return yoke model

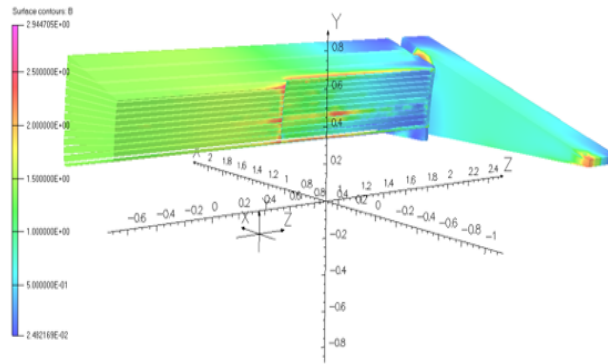


Figure A.15: 3D OPERA model detail of the field in the HCal plates

4106 **A.3.5 Magnetic Force Simulations**

4107 The BaBar superconducting coil will be placed inside a non-symmetric flux return yoke as
 4108 a part of the sPHENIX magnet assembly. This can give rise to axial offset forces on the coil.
 4109 Simulations with OPERA have been run to understand what these forces and torques will
 4110 be on the coil during its operation at 4596 A, where the central field is about 1.4 T.

4111 Figure A.16 shows the non-symmetric model for the sPHENIX flux return yoke in the

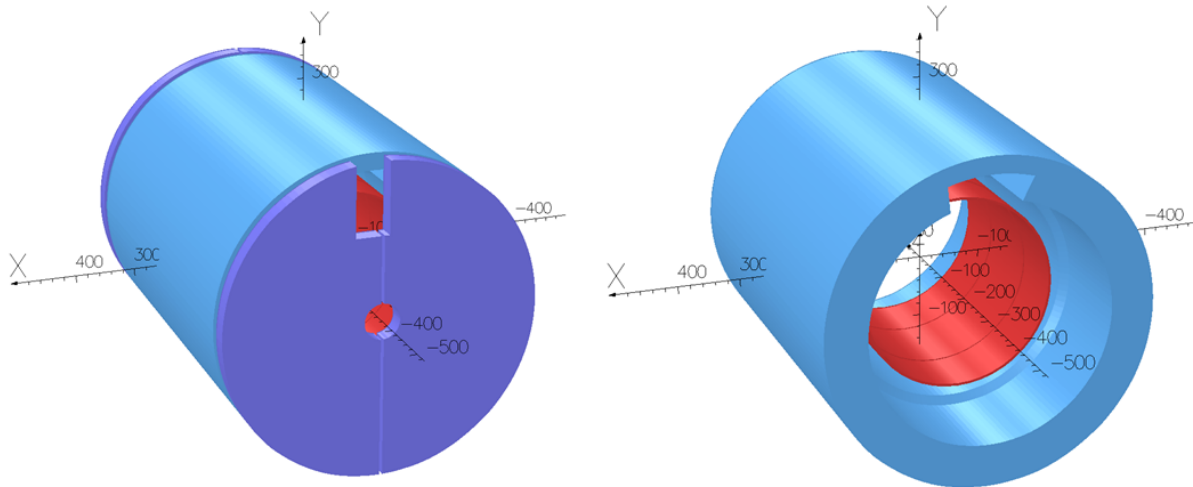


Figure A.16: Yoke and end-cap cuts from the OPERA Model, as viewed from the "south" or the "lead" end.

4112 OPERA simulation, it is modelled using 1006 steel. The notch in the south end door is to
 4113 allow for the valve box, as previously shown in Figure A.3.

4114 In the symmetric model the forces along the beam axis are symmetric, the simulation for
 4115 the total forces are balanced at about $\pm 5.65 \times 10^6$ N. The calculated forces on the two end
 4116 doors are about $\pm 8 \times 10^5$ N.

4117 From the simulations of this model, the magnetic forces and torques at the yoke center due
 4118 to the coils being misaligned are shown in Table A.3.

Table A.3: Magnetic forces (F_x, F_y, F_z) and torques (T_x, T_y, T_z) in the non-symmetric model.

	F_x [N]	F_y [N]	F_z [N]	T_x [N-cm]	T_y [N-cm]	T_z [N-cm]
No misalignments	-1043	-14072	15640	335007	160904	0
Coils shift, $dx=2$ mm	9412	-14077	15647	335345	157079	-2815
Coils shift, $dz=3$ mm	-1033	-13903	21207	354464	159326	0

4119 A.3.6 Field Mapping

4120 To achieve the required momentum resolution the solenoid field has to be known in detail,
 4121 specially towards the edges of the tracker acceptance where deviations from the ideal
 4122 solenoidal field are expected.

4123 There will be three separate monitoring tasks. The low and full field tests scheduled for
 4124 2016 and 2017 will just be a monitoring task where we plan to use a few commercial hall

4125 probes. For the low field test we installed a 3D probe close to the center of the magnet
4126 monitoring the expected field of a few hundred Gauss.

4127 For the full field test at a current of 4596 A more commercial high resolution NMR probes
4128 will be installed in the magnet. The NMR probes will provide a high resolution measure-
4129 ment of the field and will later be installed as permanent monitoring probes in the final
4130 setup.

4131 For the final setup we currently plan to install a series of NMR probes on the outside of
4132 the mapping detectors and rely on detailed field simulations.

4133 A.4 Tests for the Superconducting Solenoid Magnet

4134 There were a series of tests done at room temperature in April 2015 for the initial inspection
4135 and acceptance of the superconducting solenoid after it was shipped to BNL. The high
4136 potential (hipot) tests (up to 520 V) recorded a leakage current of $0.15 \mu\text{A}$. The impulse
4137 test done at 400 V was successful in that the waveform measured didn't indicate any
4138 turn-to-turn short in the magnet coils. We also ramped the current across the solenoid
4139 slowly from 0 to 2 A and 5 V to measure the inductance of the solenoid to be about 2.3 H
4140 (very close to 2.2 H that was measured in 1997). In addition, we have also performed a
4141 leak check which found no noticeable leaks and a 6.6 bar pressure test which was also
4142 successful (even up to 85 psi).

4143 In March 2016, a low-field and low-current test has been performed for the superconduct-
4144 ing solenoid. We have cooled the magnet with helium down to about 4.5 K and brought
4145 the current to 100 A. This was as much a test for the entire cryogenic system as it was to
4146 test and verify the expected magnetic field (about 300 Gauss in the center). P. Joshi has
4147 also tested his quench protection system that he had used in the Superconducting Magnet
4148 Division for other purposes.

4149 In 2017, we further plan to perform a high-field and high-current test for the magnet. Then,
4150 we will raise the current gradually to 4596 A which was the nominal operating current
4151 that the BaBar experiment has used for this magnet during their years of operation. The
4152 entire solenoid cryostat will be surrounded by steel plates, in a box configuration, which
4153 serves as the media for the return field. The above-mentioned quench protection system
4154 will have its realistic test and usage in this high-field test.

4155 Appendix B

4156 Infrastructure

4157 The sPHENIX detector will be located in the RHIC building 1008 complex Major Facility
4158 Hall (MFH). It consists of a central hall and two expanded tunnel areas. Adjacent to the
4159 MFH is a 3700 square ft. Assembly Building, a Counting House, and Rack Room. Concrete
4160 block shielding is provided between the MFH and the assembly building. The central
4161 hall is 57 ft. long by 61 ft. wide and 47 ft. high with a 12 ton overhead crane and (2)
4162 1-ton auxiliary cranes. A 40 ton crane is installed is installed over the assembly area. The
4163 expanded concrete tunnel areas on either side of the Central Hall are 53 ft. long by 30 ft.
4164 wide and 21.5 ft. high with a 9 6 concrete platform to raise the floor level. The Assembly
4165 Hall is steel frame with metal siding. See Figure B.1 for a plan view of the structures.

4166 All buildings are connected to the BNL 13.8 KV AC distribution system. The electrical
4167 substations at buildings 1008A and 1008B convert 13.8 KV to 480 volts AC for distribution
4168 into the downstream distribution network of 480 V to 208/120 volt transformers and
4169 panels.

4170 B.1 Auxiliary Buildings at the Experimental Site

4171 Auxiliary Buildings 1008B and 1008 C contain cooling water pumping stations and HVAC
4172 equipment to service the MFH, Assembly building, and Counting House.

4173 B.2 Cradle Carriage

4174 The Cradle Carriage will support the sPHENIX Main Magnet. Four detector systems will
4175 be constructed in the inner and outer radius of the magnet. The Beam Pipe passes axially
4176 through the magnet/detector center.

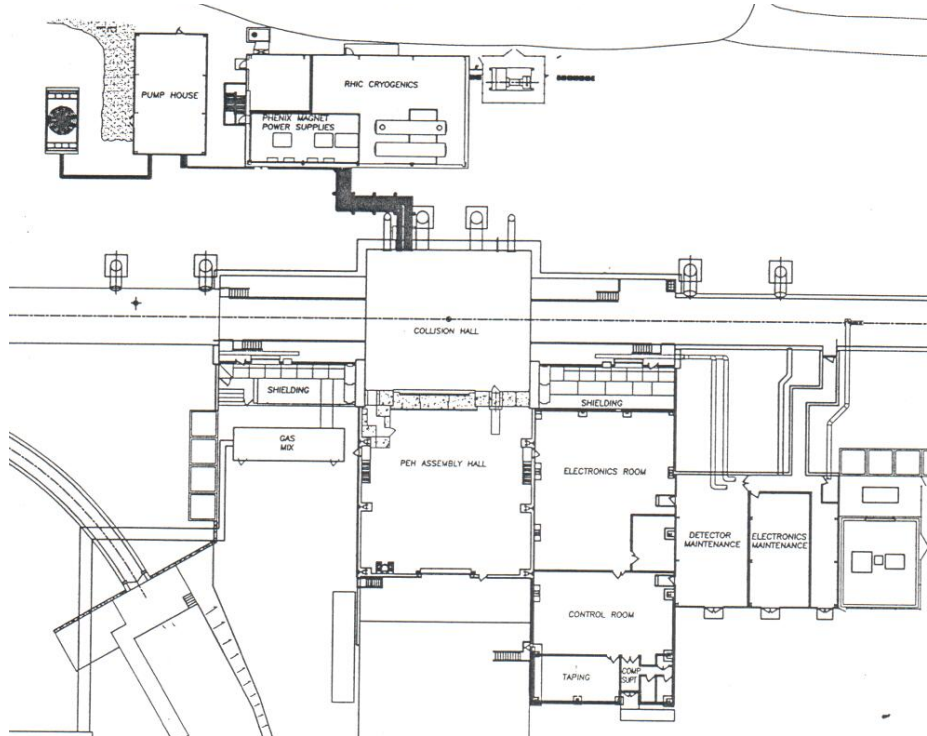


Figure B.1: sPHENIX Major Facility Hall and Auxilliary Buildings

4177 B.3 Electronics Racks

4178 Electronics racks for the detectors will be mounted on the Cradle Carriage and in the
4179 Counting House Rack Room. They will be fully enclosed and contain water cooled heat
4180 exchangers to remove heat. They will each contain a safety interlock system to shut their
4181 electric power & cooling water flow off during conditions such as over-temperature, smoke
4182 or water leak detected. Permanent walkways, platforms and ladders, mounted on the
4183 Central Pedestal allow for access to the racks. All will be equipped with appropriate safety
4184 railings and kick plates.

4185 B.4 Beam Pipe

4186 The sPHENIX Beam Pipe is a cylindrical tube with overall length of 101.2 inches. It is made
4187 up from a central 31.5 inch long beryllium section 0.030 inch thick which was gun-drilled
4188 from beryllium rod then e-beam welded to the aluminum extension pipes which were TIG
4189 welded to 2.75 inch conflat explosion bonded aluminum/stainless flanges. The flanges
4190 are bolted to the corresponding flanges on the upstream and downstream beam tube
4191 transition sections which increase the beam pipe diameter to 5 inch outside diameter in 2
4192 steps. The sPHENIX beam pipe will be supported from the flanges and also within the
4193 central pedestal by low mass supports. sPHENIX will reuse the existing central Be section
4194 and modify the transition sections as necessary to accommodate the sPHENIX detectors.
4195 In addition, gate valves and pumping ports will be added to allow removal of the central
4196 beam pipe sections.

4197 B.5 Shield Walls and Openings

4198 The sPHENIX shield wall is approximately 61 wide by 48 high by 5 6 deep, made from
4199 light concrete blocks. A large rolling shield block door measures 30 wide by 36 high. The
4200 shield blocks are 20 tons each. The wall is built on a rolling platform that rides on a number
4201 of 200 ton each rated Hillman rollers. This wall can be moved away from its opening to
4202 allow large detector pieces or other equipment into and out of the MFH. There is a rolling,
4203 motor driven personnel door and emergency egress labyrinth separate from the main
4204 rolling shield door. There are PVC pipe penetrations for utilities from the assembly hall
4205 into the MFH embedded into a concrete sill . Two 3 tubes for cooling water services, twelve
4206 4 tubes for electrical power cables, and eighteen tubes for signal cables are provided. No
4207 major modification to the PHENIX shielding configuration is anticipated for sPHENIX.

4208 B.6 Electrical Power

4209 Numerous distribution transformers are supplied by a 480 volt 1200 amp bus that contains
4210 eight molded case circuit breakers. This is the primary Normal Power distribution supply
4211 that powers all experimental and non-experimental loads. An emergency backup diesel
4212 generator provides 150 KW of power to critical loads in the event of on or off site power
4213 interruption. A 30 KVA Uninterruptible Power Supply (UPS) supplies battery backed-up
4214 208/120 VAC power primarily to critical computer loads. A 3 KVA UPS supplies backup
4215 power to critical safety instruments protecting the experiment. sPHENIX will utilize the
4216 existing PHENIX power infrastructure, however, some modifications to the distribution
4217 system will be required at the 480/220 volt level.

4218 B.7 Safety System and Control Room Monitoring & Alarm Sys- 4219 tem

4220 SPHENIX will have a real time, monitoring and control system that will take inputs
4221 from smoke and fire detection systems as well as crash buttons. Upon detection of an
4222 off normal situation from any input, safe shutdown of the experiment will be initiated.
4223 Existing PHENIX systems will be utilized to the maximum extent possible, although new
4224 components will be necessary to integrate new safety systems for potential new hazards,
4225 like oxygen deficiency.

4226 B.8 Cooling Water

4227 Chilled water is required at 20 degrees C for cooling the detector electronics. Pumping
4228 capacity is 300 gallons per minute (GPM). The existing cooling towers and chilled water
4229 system at the 1008 complex has the capability to meet these specifications. sPHENIX will
4230 utilize the existing PHENIX chilled water infrastructure, however, some modifications
4231 to the distribution system will be required at the rack level and to satisfy any other new
4232 water cooling needs.

4233 B.9 Climate Control

4234 Conventional heating, ventilation and air conditioning (HVAC) is required. Approximately
4235 100 tons capacity currently is in use, 40 tons in the IR, 50 tons in the rack room and the
4236 remainder serving the rest of the complex. sPHENIX will utilize the existing HVAC system,
4237 with minor additions and upgrades as necessary.

4238 B.10 Cryogenics

4239 A cryogenics supply system is required for the sPHENIX superconducting solenoid magnet.
4240 This system is described in the Magnet section of this report.

4241 Appendix C

4242 Installation and Integration

4243 sPHENIX has been conceived to be straightforward to manufacture and assemble, but it
4244 still requires significant and well thought out integration and assembly schemes to achieve
4245 the specified alignment and positioning requirements of the component detectors. In
4246 addition, the design must allow for appropriate access for maintenance and servicing
4247 of the functional components of these detectors and to optimize the integration and
4248 installation concept. The goal is to balance design tradeoffs while considering the effects
4249 on performance, cost, schedule, and reliability. Figure C.1 illustrates the overall design
4250 concept for the installed sPHENIX experiment. The following sub sections of this topic
4251 indicate how these factors will be addressed in the sPHENIX project.

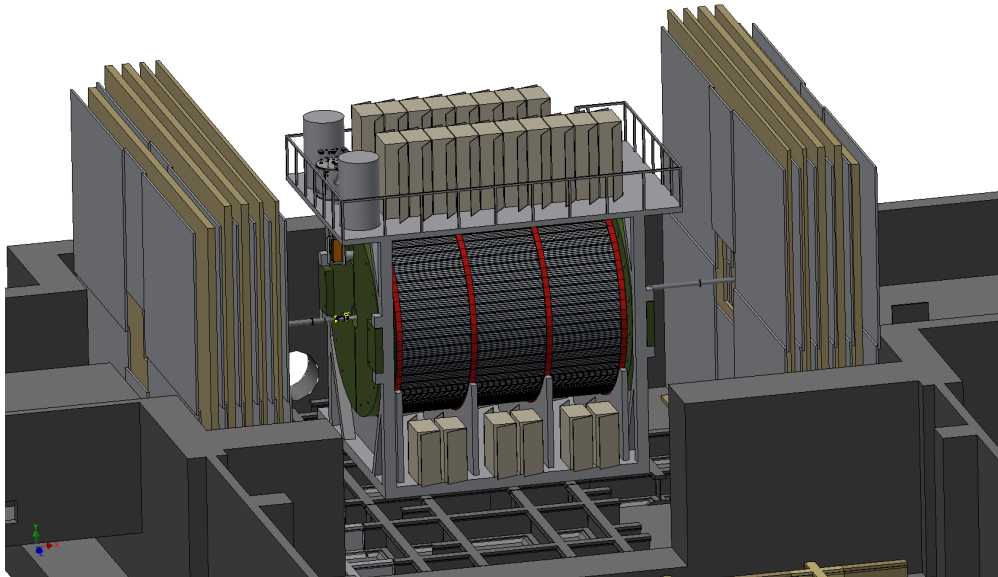


Figure C.1: sPHENIX in IR

4252 C.1 Specifications and Requirements

4253 C.1.1 General Limits and Requirements

4254 The following are the key general requirements that guide the integration, inter detector
 4255 assembly and installation of the sPHENIX components comprising the overall sPHENIX ex-
 4256 perimental apparatus. Requirements may be superseded by individual detector subsystem
 4257 requirements (see subsystem sections).

Table C.1: sPHENIX General Limits and Requirements

Item	General Requirements
Location for final assembly/ Installation	PHENIX Assembly Hall
Assembly Hall ("AH") Crane	rated at 40 tons
Interaction region ("IR") Crane limit	12 tons plus 2 auxiliary, 1 ton cranes
Floor Loading Limit	4000 psi max
Assembly support surface	existing PHENIX rail system
Clearance requirements	2 inches (50 mm), between subsystems
Positional precision	0.1 mm
Angular precision	10 milliradian (roll, pitch and yaw)
Positional stability	0.5 mm
Angular stability	10 milliradian (roll, pitch and yaw)
Positional repeatability	1.0 mm
Angular repeatability	10 milliradian (roll, pitch and yaw)
Positional tolerance	(see individual detector specifications)
Angular tolerance	(see individual detector specifications)
Temperature and humidity	-10 to 50 deg C and 0-100 percent R.H.
Magnetic field	0–2T inside magnet, 0–100 Gauss field outside
Radiation environment	to be specified
Detector cooling requirements	(see individual detector subsystems)
Rack cooling requirements	2.0 gpm @ 50 deg F, for 2 kW per rack
Cryo requirements	(see Magnet Section)
Monitoring and safety system requirements	(see Infrastructure Section)
Overall size requirements	fit through the sPHENIX sill on existing rail system (see Figure C

4258 C.1.2 Configuration Management and Control

4259 In order to assure that the various subsystems of the sPHENIX experiment honor the space
 4260 requirements for all other components, not interfere with other subsystem and/or infras-
 4261 tructure features of the sPHENIX experimental location, and assure that the integration
 4262 and installation concepts are achievable, outline/interface drawings will be prepared for

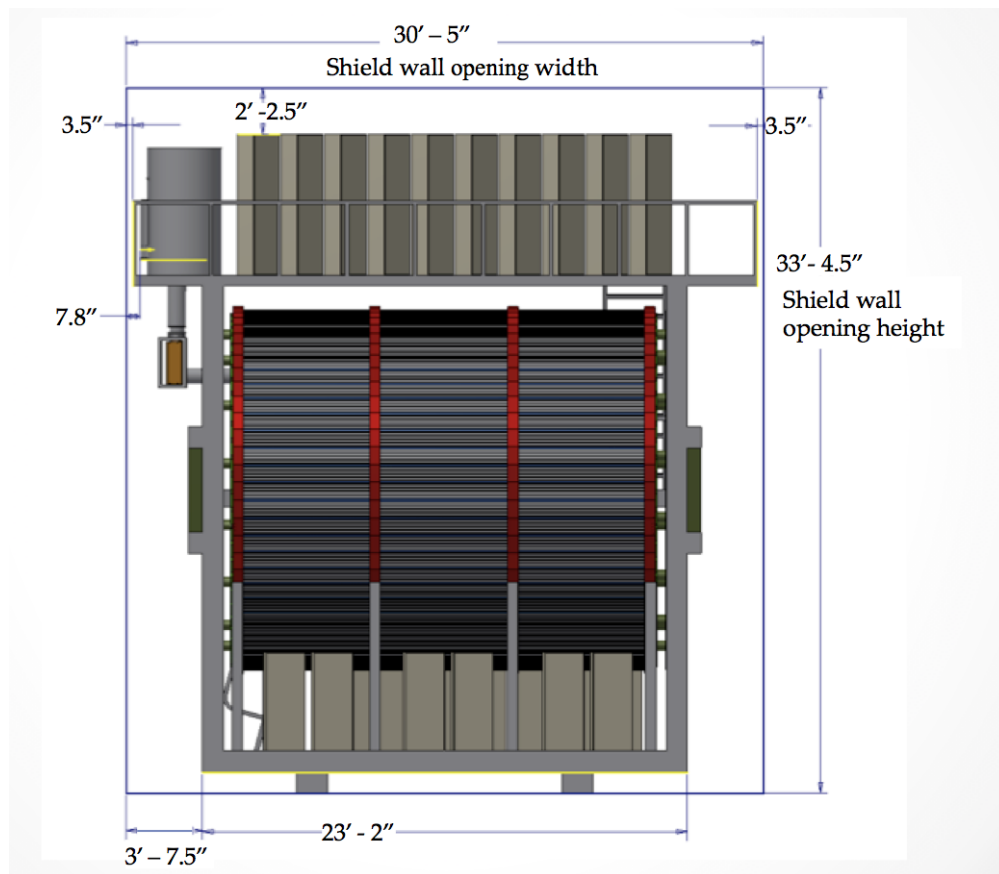


Figure C.2: sPHENIX Overall size

4263 each detector subsystem and an overall envelope control drawing will be prepared for the
 4264 integrated sPHENIX experiment.

4265 Subsystem outline/interface drawings will provide the defining exterior envelope in to
 4266 which the subsystem components fit, key dimensions for subsystem components which
 4267 interface with other subsystems and/or infrastructure, and any other information pertinent
 4268 to the space to be occupied by the subsystem and its relationship to adjacent subsystems
 4269 and infrastructure. Figure C.3 is the subsystem outline/interface drawing for the EMCal
 4270 detector subsystem.

4271 Subsystem outline/interface drawings will provide the defining exterior envelope in to
 4272 which the subsystem components fit, key dimensions for subsystem components which
 4273 interface with other subsystems and/or infrastructure, and any other information pertinent
 4274 to the space to be occupied by the subsystem and its relationship to adjacent subsystems
 4275 and infrastructure. Figure C.3 is the subsystem outline/interface drawing for the EMCal
 4276 detector subsystem.

4277 The overall envelope control drawing will provide the limiting space allocations for each
 4278 of the detector subsystems, as well as space allocations for structural support, integrating

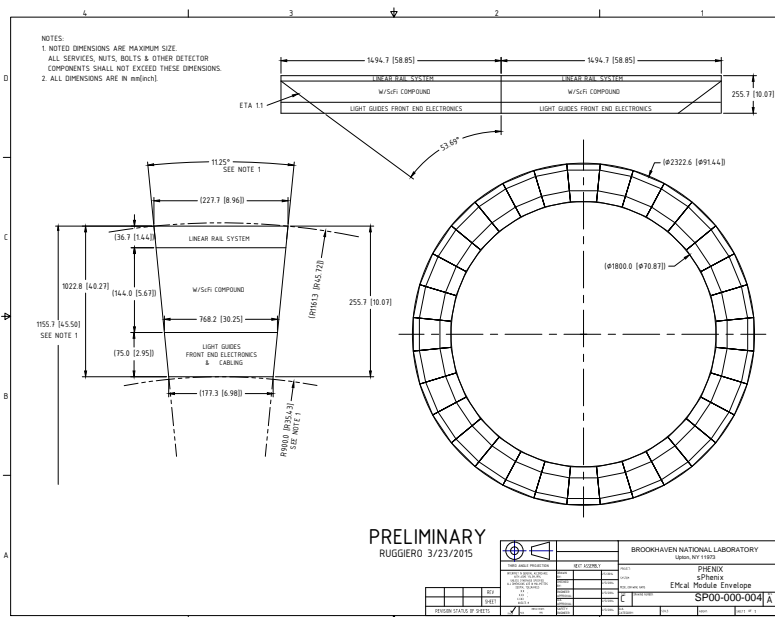


Figure C.3: EMCal Envelope Control Drawing

4279 interfaces and all services.

4280 Figure C.4 is the overall envelope control drawing for the sPHENIX experiment.

4281 All subsystem design drawings, fabrication and assembly procedures and all other docu-
 4282 mentation which define the sPHENIX assembly, installation and component subsystems
 4283 will comply with BNL and DOE requirements that will be governed by sPHENIX con-
 4284 trolled documents for Configuration Management and Documentation Control Systems.

4285 C.1.3 Weight Estimates

4286 In order to properly evaluate the design and adequacy of the integration and installation
 4287 conceptual design which will proceed parallel to the detailed design of the component
 4288 detector subsystems and infrastructure, it is necessary to have reasonable estimates of
 4289 weights for the major components. The following table provides the estimated weights for
 4290 the major subsystem components for sPHENIX.

4291 C.1.4 Alignment Requirements

4292 Alignment of the detector subsystems to each other and to the RHIC nominal beam
 4293 path, as reflected by the positional and angular orientations relationship of the detector
 4294 subsystem components to each other and to the sPHENIX global coordinate is essential to

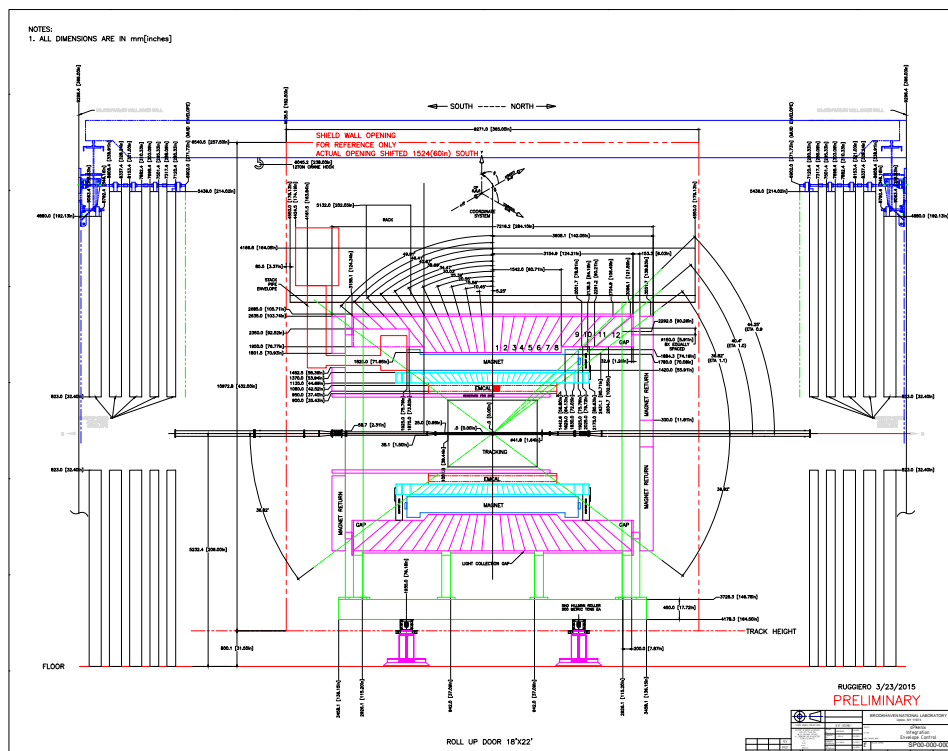


Figure C.4: sPHENIX Envelope Control Drawing

4295 the proposed performance of the sPHENIX experiment. Internally, each detector subsystem
 4296 component is aligned to the subsystem's own coordinate system as defined by each
 4297 subsystem. This alignment is then reflected to the global system by means of inspection
 4298 of dimensional data with respect to reference points ("fiducials") to be established on
 4299 the exterior of each component. These reference points are used in the assembly and
 4300 installation process to establish position and orientation of these components and by
 4301 extension the internal features of each component to the sPHENIX global coordinate
 4302 system.

4303 Each component, as it is assembled and installed into the sPHENIX support structure, is
 4304 to be aligned by means of built-in adjustment to achieve specified precision with respect
 4305 to the experiment support structure (i.e. the Cradle Carriage) which shall have fiducial
 4306 references related by survey. After the Cradle Carriage is assembled with all subsystems
 4307 except the Min Bias, INTT and MVTX detectors and is moved to the Interaction Region
 4308 ("IR"), THE CC is to be positioned and aligned to the sPHENIX global coordinate system
 4309 at the nominal Interaction Point ("IP").

4310 The sPHENIX global coordinate system is related to the RHIC coordinate system from the
 4311 Interaction Point the center of the RHIC ring and the straight line of the RHIC ring orbit
 4312 through the sPHENIX IP.

Table C.2: sPHENIX Estimated Weights of Major Components

Subsystem	Weight	Notes
Inner HCal	64,000 lb, 32 ton	2000 lb/sector
Outer HCal	854,000 lb, 427 ton	27,000 lb/sector
EMCal (with mounting)	61,000 lb, 31 ton	900 lb/sector
Inner HCal Assy Rings	1650 lb, 1 ton	total, 2 rings
Inner to Outer load transfer rings	6400 lb, 3.5 ton	total, 2 rings
Flux return end caps	226,000 lb, 113 ton	
Magnet + stack wt	42,000 lb, 21 ton	
TPC	1000 lb, 1/2 ton	
Min Bias	68 lb, 1/30 ton	17 lb/quadrant
INTT	500 lb, 1/4 ton	
MVTX	200 lb, 1/10 ton	
Detector services and support equipment	5000 lb, 2.5 tons	
Total Detector load on Cradle Carriage (CC)	1,261,000 lb, 631 tons	
CC weight without magnet and detectors	250,000 lb, 125 tons	
Total Detector load on Cradle Carriage (CC)	1,261,000 lb, 631 tons	
CC weight without magnet and detectors	250,000 lb, 125 tons	

4313 Positional precision and alignment tolerances for the individual detector subsystem compo-
 4314 nent internal features are established for each individual detector subsystem independently
 4315 (see the appropriate subsystem for details). The subsystem components and/or the sup-
 4316 port structure will be designed with appropriate adjustment capability to achieve the
 4317 specifications indicated in the previous section.

4318 Precision is determined by combining the accuracy of the measurement method (survey)
 4319 for locating the individual fiducial points for subsystem components directly with the
 4320 fineness of adjustment provided in the subsystem mounting system.

4321 Stability is the tendency for the assembly and its components to remain in the same
 4322 location over a period of time, under normally varying environmental conditions for both
 4323 operational and non-operational conditions.

4324 Repeatability is the tendency of the assembly and its components to return to the same
 4325 location after maintenance operations requiring disassembly and reassembly and/or
 4326 temporary displacement and return of the entire assembly or any of the components
 4327 (usually for maintenance purposes).

4328 Tolerance is the amount by which a measured position or angle can vary from its nominal
 4329 "exact" position or angle. This is the sum of measured variance plus the measurement
 4330 precision, repeatability and stability. For internal components of subsystems, the tolerance
 4331 with respect to global coordinates is calculated from a combination of the tolerance of the
 4332 external fiducial points and the tolerance of the relative dimensional feature of internal
 4333 features to the external fiducials. In some cases the tolerance calculations might require

4334 combining multiple relative tolerances.

4335 C.1.5 Service Requirements

4336 Adequate space is to be provided to route appropriate services to all of the detectors
4337 including power, signal and monitoring cables, cooling channels (air cooling) and piping
4338 (liquid cooling) for removal of heat generated by detector electronics and distribution
4339 equipment for branching and integrating electronics signals, electric power and cooling
4340 from detector service racks to module/sector front end electronic distribution panels and
4341 flow distribution manifolds to the installed detector components. Within the components
4342 these services are to be distributed to individual active components as described in the
4343 subsections describing the individual detector subsystems.

4344 In addition, space is to be provided for cooling services and power to the subsystem
4345 racks from the cooling source(s) and line power breaker boxes, respectively. Space is to
4346 be provided as well to route signals to the rack room. Refer to the infrastructure for more
4347 detailed information on service requirements.

4348 During the research and development process for each of the detector subsystems, proto-
4349 type mockups (dimensionally accurate, non-functional) are to be developed to assist in
4350 planning the design of adequate space for services. A mockup of an Inner HCal half-sector
4351 is shown in Figure C.5.

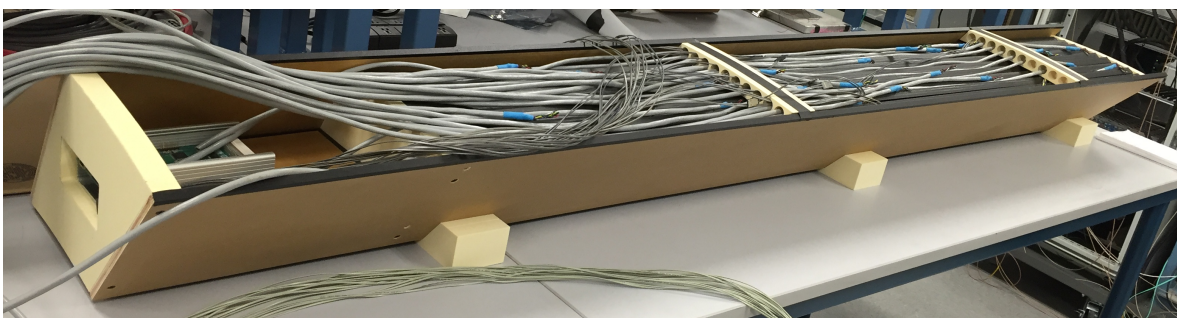


Figure C.5: Inner HCal Half-sector mockup

4352 C.1.6 Accessibility

4353 The sPHENIX detector subsystems will be designed to operate without maintenance for
4354 extended periods. Maintenance of the active detector components and the magnet is not
4355 possible during a run, except that access is provided to the subsystem rack electronics on all
4356 levels, to the magnet valve box and to power and cooling sources and primary distribution
4357 equipment. Limited access to the outer HCal detector electronics is possible, but it is not

4358 a requirement. Limited access to external interface electronics on all of the detectors is
4359 possible during an extended access period during a run (on the order of one or more weeks
4360 in duration), but any individual internal component of any detector subsystem is only
4361 accessible during a major shutdown of three or more months by reversing the assembly
4362 process described later in this report.

4363 C.1.7 Quality Control

4364 sPHENIX engineering will implement the full quality assurance program described else-
4365 where in this document by establishing procedures to assure that the design of sPHENIX
4366 meets the requirements of BNL, DOE and industry best practices, including implement-
4367 ing the appropriate configuration management, documentation control, work planning,
4368 quality control testing and inspection and performance verification.

4369 C.2 Component Integration

4370 C.2.1 General Integration Concepts

4371 sPHENIX is designed to be integrated into a single structural assembly wherein a central
4372 support structure, the cradle carriage ("CC"), provides a base on a set of roller bearings,
4373 which in turn supports a set of four structural arcs ("cradles") to support the Outer
4374 HCal detector subsystem and pillars to support an intermediate level platform, an upper
4375 platform and the north and south flux return end caps/pole tips.

4376 The superconducting solenoid magnet is support by 12 mounting feet, six each equally
4377 distributed at the north and south ends of the magnet in the annular space between the
4378 magnet outer diameter and the Outer HCal inner diameter. These mounting feet also
4379 provide alignment adjustment for the magnet in all directions. The Outer HCal provides
4380 two additional support rings on its interior diameter onto which the interior Inner HCal
4381 and Tracking detector subsystems (TC, INTT and MVTX) are mounted. The EMCal
4382 detector subsystem is divided into 64 (32 north and 32 south) sectors which are individually
4383 mounted to adjacent Inner HCal sectors by bearing rails.

4384 There will be two sets of four roller bearings under the base platform. They will be
4385 rotatable to allow the entire experiment assembly to move east or west and, when rotated
4386 90 degrees, north or south. Relocation of the assembly in these directions is accomplished
4387 on the existing PHENIX rail system and allows for repositioning of the assembly in the IR
4388 and moving from the AH to the IR for installation, maintenance and upgrade operations.
4389 The 2 sets of rollers are positioned with a hydraulic lifting piston on each of the 4 points
4390 corresponding to intersection crosses of the sPHENIX rail system. This allows the entire CC
4391 to be lifted at 4 points to change the orientation of the roller bearing sets from north/south

4392 to east/west and back. Figure C.6 shows an exploded view of the detectors which
 4393 comprise sPHENIX.

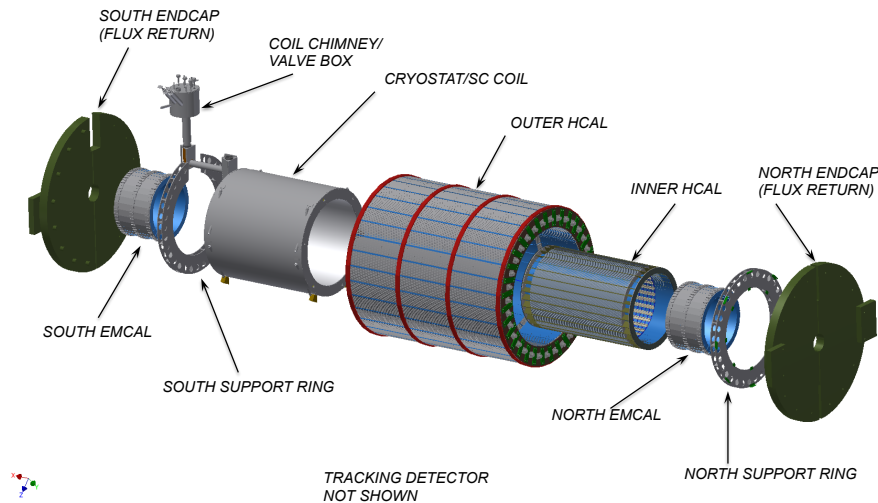


Figure C.6: sPHENIX exploded view

4394 C.2.2 Structural Load Support

4395 Roller bearings for the CC are to be sized for approximately twice the estimated load of
 4396 the fully assembled sPHENIX experiment. The CC base will be built of structural steel
 4397 and support the four cradles and four pillars which will be welded to the base as well as
 4398 provide the lower level platform for detector electronics racks. The Outer HCal will be
 4399 fully supported by the cradles while the mid and upper platforms and magnet flux return
 4400 end caps will be supported by the pillars.

4401 The outer HCal is comprised of 32 sectors which are tied together at their north and south
 4402 ends by splice plates. The loads of each of these sectors is transferred through the splice
 4403 plates to the cradles. Interior to the Outer HCal will be the magnet mounting feet and
 4404 Inner HCal support rings which will transfer the magnet and inner detector structural
 4405 loads separately to the base through the Outer HCal.

4406 The Inner HCal is comprised of 32 sectors each of which has mounting provisions on its
 4407 inner diameter for two EMCAL sectors. Each of the 32 Inner HCal sectors is mounted on
 4408 its north and south end plate to end rings. The north and south end rings that tie the 32
 4409 sectors together are then mounted to the north and south structural rings which transfer
 4410 the load of the Inner HCal sectors plus the EMCAL sectors to the Outer HCal and through
 4411 the Outer HCal to the cradles to the base to the roller bearings to the rails and finally to the
 4412 floor.

4413 The TPC subsystem will also have a support structure which attaches to the north and
4414 south structural rings that will transfer its load in a similar manner.

4415 The MVTX and INTT will be integrated into a dual hemisphere support frame (upper and
4416 lower). Each frame hemisphere will have a 3 point support onto a dual rail and bearing
4417 system in which the bearings will slide along pathways on the rail which allows the upper
4418 and lower frames to ride in separately and moved away from the beampipe until the
4419 frames have cleared the beampipe flanges. The lower frame is positioned first then the
4420 rail is adjusted in 3 dimensions to achieve the alignment precision required. Then the
4421 upper frame is brought into position and is mated to the lower frame by kinematic mounts.
4422 Figure C.7 shows the load path through the support structures.

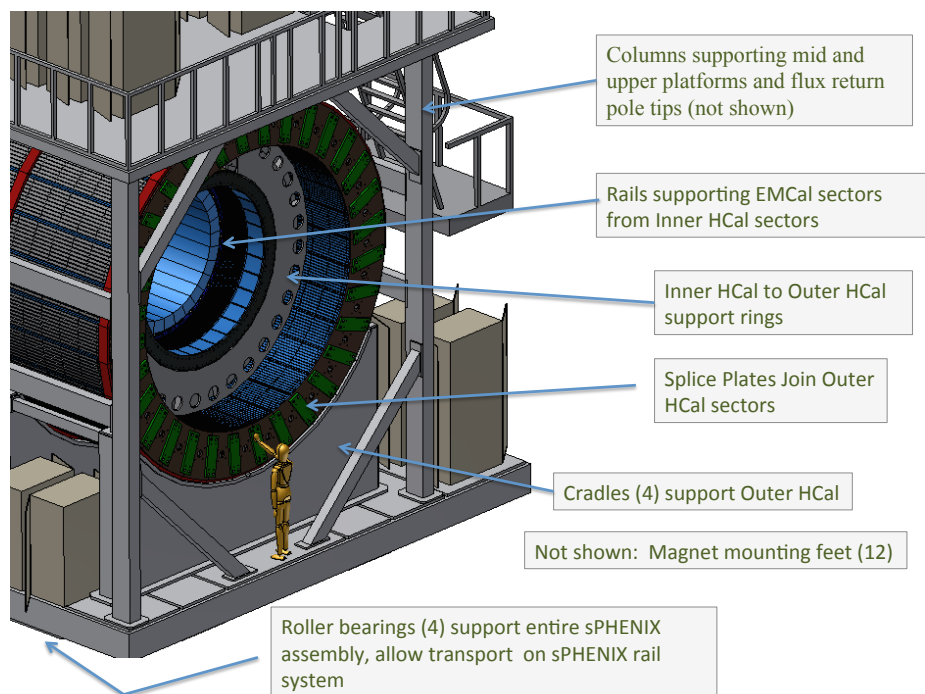


Figure C.7: sPHENIX Structural Support

4423 C.2.3 Alignment

4424 The sPHENIX overall alignment concept will be as follows:

- 4425 • Internal alignment of detector subsystem components in the interior of the detector
4426 subsystem will be aligned as required by the subsystem at the subsystem subassem-
4427 bly level in accordance with the subsystem requirements, related to a set of external

4428 fiducials on the subassembly sectors/modules which are deliverables from the sub-
 4429 system to the sPHENIX AH where final installation will take place. These fiducials
 4430 will be documented to enable analytical reconstruction of the internal relevant fea-
 4431 tures and to define a nominal axis and centerpoint relationship to the fiducials for
 4432 each of the subassembly modules.

- 4433 • The CC base and cradle assembly will be provided with adequate precision align-
 4434 ment features (reference fiducials and adjustment features) to define the nominal
 4435 experiment axis and center point and the position of the initial Outer HCal sector
 4436 to align its reference axis and center point to that of the CC Base and cradle assem-
 4437 bly. Survey and shimming will be employed to fix the position of the initial Outer
 4438 HCal sector within the tolerance specifications indicated in the general requirements
 4439 section, above.
- 4440 • As each additional Outer HCal Sector is installed it will be surveyed, adjusted and
 4441 shimmed into place with respect to the required tolerances, until the lower half of the
 4442 Outer HCal is completed. Figure C.8 shows the initial Outer Hcal sector installed
 and aligned.

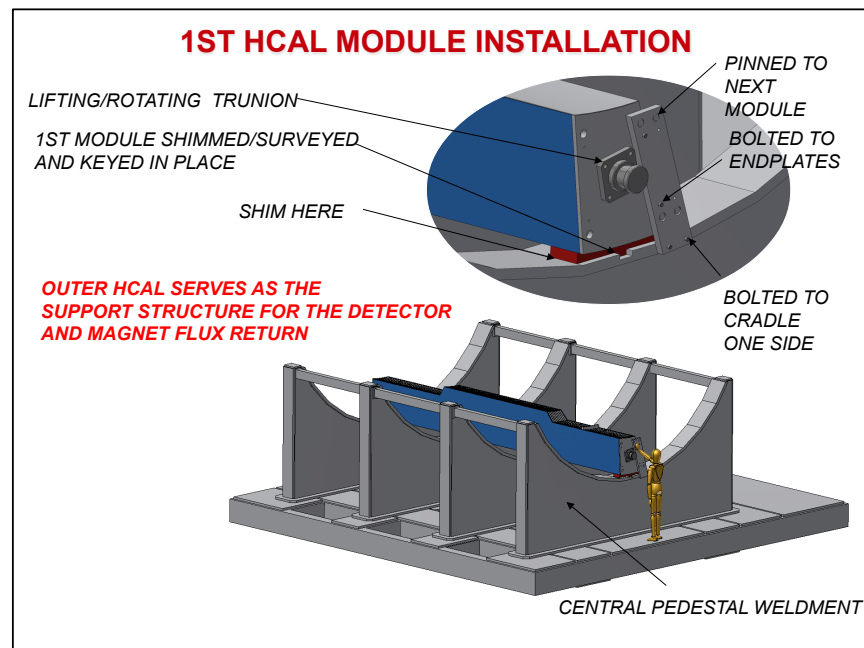


Figure C.8: sPHENIX Initial Alignment

4443

4444

4445

- The Superconducting solenoid magnet will have been surveyed and been sufficiently tested to establish a nominal magnetic axis and centerpoint which will have been

4446 related to external fiducial points on the magnet and those relationships recorded.
4447 The magnet will have 12 adjustable mounting supports attached to position and
4448 secure the magnet onto the inner surface of the Outer HCal.

4449 • After the lower half of the Outer HCal installation is completed, the magnet shall
4450 be mounted, surveyed, aligned and secured to the Outer HCal in accordance with
4451 requirements.

4452 • The remaining Outer HCal Sectors are installed, surveyed, adjusted and shimmed
4453 into place with respect to the required tolerances, until the upper half of the Outer
4454 HCal is completed.

4455 • The Inner HCal sectors are installed into a complete detector aligned using mechani-
4456 cal precision features, survey and shimming to achieve the desired alignment of each
4457 of the sectors to each other and external fiducial points. The entire assembly is then
4458 surveyed, aligned and secured onto the Inner HCal to Outer HCal support rings.

4459 • Each of the 64 EMCal sectors is then installed onto the rail systems on each of their
4460 respective Inner HCal sectors, surveyed, positioned, adjusted and secured into place
4461 in accordance with required tolerances. Figure C.9 shows the installation of an
EMCal sector.

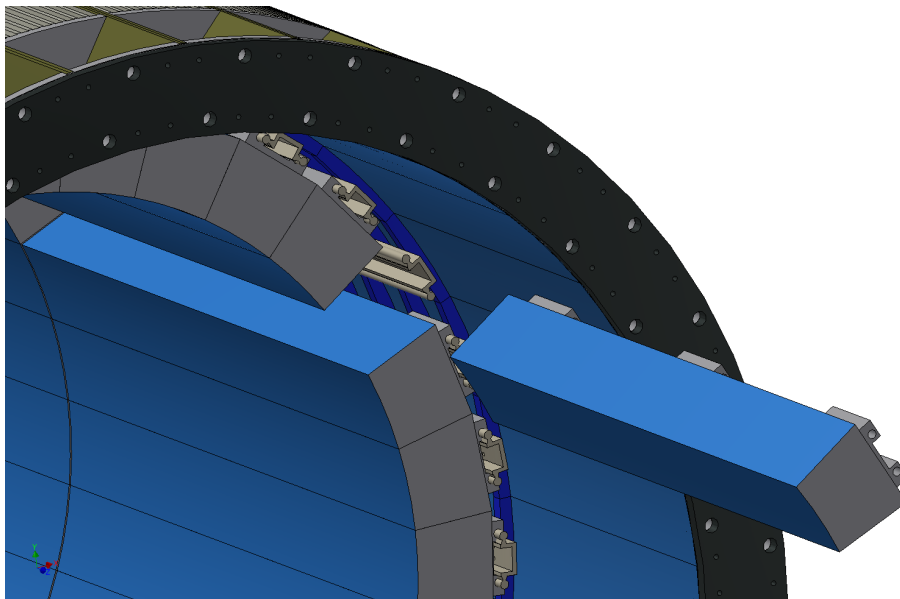


Figure C.9: EMCal Sector Installation

4462

4463 • The detector assembly on the CC support structure in the AH is completed by
4464 installing and aligning the TPC subsystem with the nominal axis and centerpoint
4465 using the alignment adjustments designed into the support brackets.

- 4466 • Next, the entire CC is moved west on the sPHENIX rail system to the IR until its
4467 nominal axis is coaxial with the nominal RHIC beam axis then north until the CC
4468 assembly's nominal center point coincides with the sPHENIX nominal interaction
4469 point ("IP"). Survey and built in adjustments to the CC assembly are used to bring
4470 the entire assembly into tolerance as required.

4471 The following alignments take place after the cradle carriage is moved into the
4472 Interaction Region (IR).

4473 The beampipe is installed and surveyed into place by using the beampipe survey
4474 fixture and making adjustments on the beampipe stands. The MVTX and INTT will
4475 be integrated into a dual hemisphere support frame (upper and lower) with the
4476 upper and lower halves relatively aligned on the bench prior to installation such that
4477 mating kinematic mounting features are fully adjusted in a simulated installation.
4478 Each frame hemisphere will have a 3 point support onto a dual rail and bearing
4479 system in which the bearings will slide along pathways on the rail which allows the
4480 upper and lower frames to ride in separately and moved away from the beampipe
4481 until the frames have cleared the beampipe flanges. The lower frame is positioned
4482 first then the rail is adjusted in 3 dimensions to achieve the alignment precision
4483 required. Then the upper frame is brought into position and is mated to the lower
4484 frame by kinematic mounts.

4485 The final detector to be installed and aligned is the Min Bias detector. It will be
4486 mounted on alignment rails which in turn mounted to horizontal and vertical brack-
4487 ets anchored to the Outer HCal inboard of the end caps/pole tips. These will allow
4488 X-Y-Z and angular adjustments as required.

4489 C.2.4 Routing of Services

4490 All services to the detectors are routed from the north or south of the overall experimental
4491 assembly to service distribution points at the north and south end of each subassembly
4492 sector/module. From that point services are routed to source points (e.g. electronics racks,
4493 cooling manifolds, etc.) which will be generally segmented into quadrants at each end for
4494 the MVTX all services are routed to the south end.

4495 All manifolds and patch panels will be rack mounted on the Cradle Carriage platforms
4496 outside of the detector areas. In general, the services will be layered such that the outermost
4497 detector (Outer HCal) has the inner most services routes, with the Inner HCal on top of
4498 those, then the EMCAL services and finally the Tracking services.

4499 C.3 Installation

4500 Installation is defined as the final assembly of detector support structure and detector
4501 components that will take place at the sPHENIX Assembly Hall and/or in the Interaction
4502 Region, QA testing of components at predetermined points during assembly, the relocation
4503 of the final assembly to the sPHENIX IR to its Operational location at the sPHENIX
4504 IP, installing and integrating infrastructure services, ready for final commissioning and
4505 operation.

4506 C.3.1 Installation Concept

4507 The Installation Concept for sPHENIX is as follows:

- 4508 • Internal alignment of detector subsystem components in the interior will be com-
4509 pleted as described in the previous section and the individual sectors or modules of
4510 the detector subsystems will be operationally tested and ready for installation when
4511 shipped to the sPHENIX AH for installation, as described in the relevant subsystem
4512 section of this report.
- 4513 • The subsystem sectors/modules will be provided with handling fixtures as indicated
4514 in the tooling and support equipment section below.
- 4515 • As each additional Outer HCal Sector is installed it will be surveyed, adjusted and
4516 shimmed into place with respect to the required tolerances, until the lower half of
4517 the Outer HCal is completed.
- 4518 • The Superconducting solenoid magnet will have been surveyed and been sufficiently
4519 tested to establish a nominal magnetic axis and centerpoint which will have been
4520 related to external fiducial points on the magnet and those relationships recorded.
4521 The magnet will have 12 adjustable mounting supports attached to position and
4522 secure the magnet onto the inner surface of the Outer HCal. Figure C.10 shows the
4523 Outer HCal with 32 sectors installed ready for the superconducting magnet to be
4524 mounted.
- 4525 • After the lower half of the Outer HCal is completed, the magnet shall be mounted
4526 surveyed, aligned and secured to the OuterHCal in accordance with requirements.
- 4527 • The remaining Outer HCal Sectors are installed, surveyed, adjusted and shimmed
4528 into place with respect to the required tolerances, until the upper half of the Outer
4529 HCal is completed.
- 4530 • The pillars for supporting the upper platform and flux return end caps and are then
4531 installed followed by the installation of the upper platform and end caps themselves.

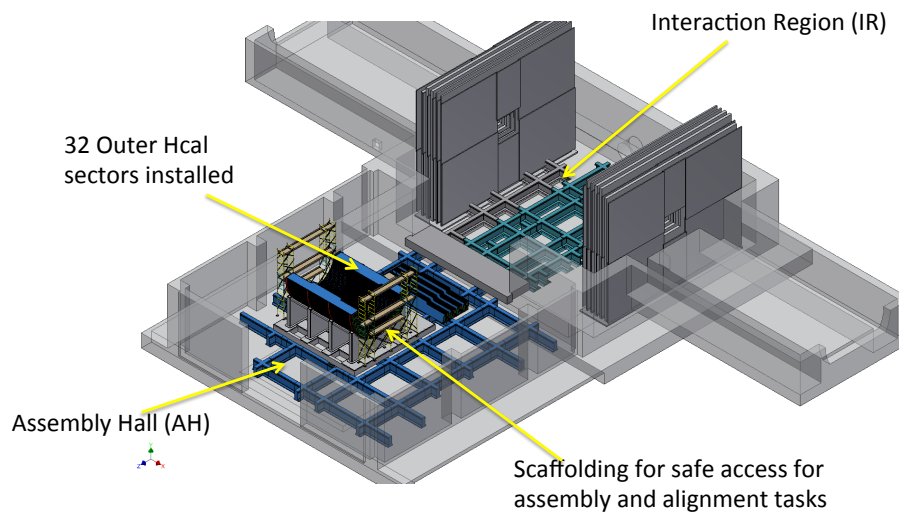


Figure C.10: Outer HCal Installation, lower half

- 4532 • The Magnet valve box with extension is installed. Outer HCal services are then
4533 installed.

4534 The Inner HCal sectors are to be assembled into a complete detector on its dedicated
4535 assembly fixture, aligned using mechanical precision features, survey and shimming
4536 to achieve the desired alignment of each of the sectors to each other and to external
4537 fiducial points. The entire assembly is then surveyed, aligned and secured to the
4538 Inner HCal-to-Outer HCal support rings and services are installed. Figure C.11 shows
4539 the Inner HCal nearing assembly completion and mounted on the installation fixture

- 4540 • Each of the 64 EMCal sectors is then installed onto the rail systems on each of their
4541 respective Inner HCal sectors, surveyed positioned, adjusted and secured into place
4542 in accordance with required tolerances. EMCal services are then installed.

- 4543 • The detector assembly on the CC support structure is made ready for movement by
4544 installing and aligning the Tracking subsystem with the nominal axis and centerpoint.
4545 The pillars for supporting the upper platform and flux return end caps/pole tips are
4546 then installed followed by the installation of the upper platform and end caps/pole
4547 tips themselves.

- 4548 • Next, the entire CC is moved west on the sPHENIX rail system to the IR until its
4549 nominal axis is coaxial with the nominal RHIC beam axis then north until the CC
4550 assembly's nominal center point coincides with the sPHENIX nominal interaction
4551 point ("IP"). Survey and built in adjustments to the CC assembly are used to bring
4552 the entire assembly into tolerance as required. Once the CC is positioned and aligned
4553 in its run position, the MVTX and INTT are installed as separate detectors on a

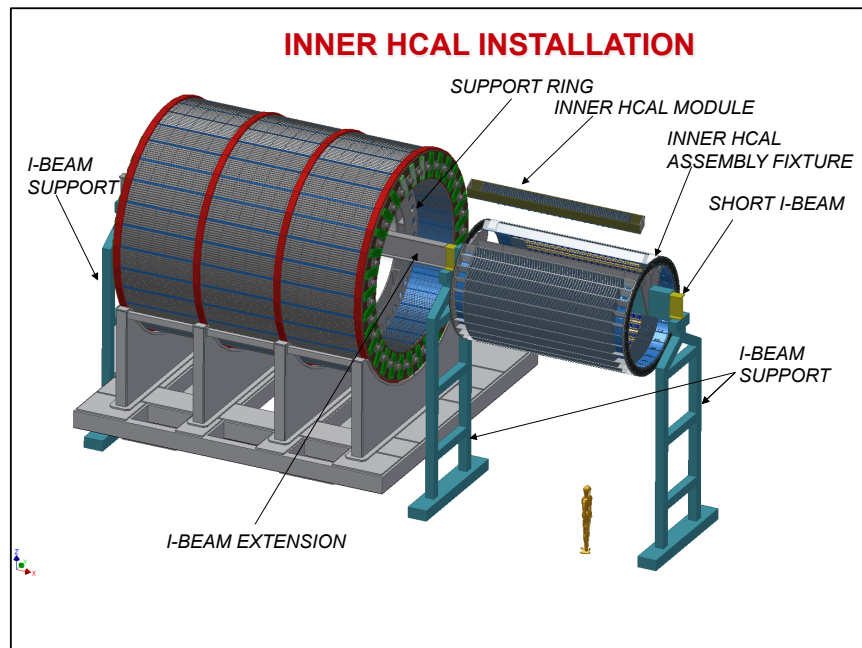


Figure C.11: Inner HCal Installation

4554 common support structure. (Note, if necessary either of these 2 detectors could be
4555 installed without the other.) Services for the MVTX and INTT are then installed.

- 4556 • Finally, the min Bias detector and its services are installed.

4557 C.3.2 Tooling and Support Equipment Requirements

4558 The following are the most significant tooling and support equipment needs for integration
4559 and installation:

- 4560 • Central Pedestal (CC): standard lifting tools for CC base and rollers, cradle, support
4561 posts, bridge platform, access stairs), alignment tools for rollers and cradle.
- 4562 • Outer HCal: module holding fixtures (4), indexed lifting/installation fixture, align-
4563 ment tools, temporary inner and outer assembly support fixtures
- 4564 • Inner HCal: module holding fixtures (4), module lifting fixture, assembly in-
4565 dexed/rotating fixture and insertion beam and insertion beam lifting fixture, align-
4566 ment tools

- 4567 • EMCal: module handling fixtures (8), rail alignment tool, indexed lifting/installation
4568 fixture
- 4569 • TPC: Handling fixtures (2), alignment tool, installation tool
- 4570 • INTT: Handling fixture, alignment tool, installation tool (common with MVTX)
- 4571 • MVTX: Handling fixture, alignment tool, installation tool (common with INTT)
- 4572 • Min Bias: Handling fixture, alignment tool, installation tool (common with MVTX)
- 4573 • SC Magnet: Lifting fixture (spreader bar), alignment tool, stack handling/lifting tool
- 4574 • Infrastructure: beampipe alignment tools/fixtures, bakeout tools/fixtures

4575 Note: some of the tools/fixtures described above will be used in subsystem sector/module
4576 assembly operations as described in their respective sections of this report prior to being
4577 used for final installation.

4578 C.4 Testing and Commissioning

4579 C.4.1 Magnet

4580 The superconducting solenoid magnet will be QA tested for integrity and function as
4581 described in the Magnet section of this report. After transport to the AH for assembly and
4582 again after installation into the CP, the magnet will be QA tested to assure that no damage
4583 has been done in transportation and installation. See the magnet section of this report for
4584 more details on magnet testing.

4585 C.4.2 Detector Subsystem Commissioning

4586 All detector subsystem sectors/modules are QA tested at their point of assembly, as
4587 described in the relevant subsystem sections of this report, prior to transporting the
4588 sectors/modules to the AH for installation. After transport to the AH for assembly and
4589 again after installation into the CC, the sectors/modules will be QA tested to assure that
4590 no damage has been done in transportation and installation.

4591 The complete detector subsystems will be tested to demonstrate their operational readiness,
4592 to calibrate the detector components as necessary and to verify the chains of signals from
4593 the detector elements through to the data acquisition system. In addition, all services will
4594 be tested to demonstrate performance in accordance with requirements.

4595 C.5 Alternative Integration/Installation Concepts Considered

4596 The evolution of the integration and installation concept is largely driven by the design
4597 evolution of the component detector subsystems. Several alternative integration and
4598 Installation concepts have been considered during this process independent of the detec-
4599 tor subsystems. Some of the more interesting considerations are described below, with
4600 explanation of why they have been rejected.

4601 Multiple carriages instead of one unified Cradle Carriage. This option was considered early
4602 on, but it was rejected as unnecessarily expensive and it increases alignment difficulty.

4603 Separate carriages for the flux return end caps. The current concept has hinged flux return
4604 caps to minimize cost, and simplify assembly.

4605 Sliding door flux return end caps (both vertical and horizontal sliding), instead of hinged
4606 end caps. This concept was rejected because it increases space requirements for main-
4607 tenance, increases cost and (in the case of the vertical sliding end caps) handling safety
4608 considerations.

4609 Installing the EMCal as a complete detector instead of 64 separately supported sectors.
4610 This would require an assembly structure and complicated installation tooling fixtures,
4611 adding to cost. It also decreases the accessibility for maintenance.

4612 Completing the assembly of the Inner HCal remotely and transporting the completed
4613 assembly to the AH for installation. This would require a complicated transport fixture
4614 added risk for damage during transportation and additional logistical considerations
4615 (additional assembly space). There are some merits to this alternative procedure and it
4616 may be revisited, if appropriate, after subsystem designs are finalized.

4617 Using rail mounted gantry cranes to install the Inner HCal instead of a monorail system.
4618 Increased complexity and cost. There are some merits to this alternative procedure and it
4619 may be revisited, if appropriate, after subsystem designs are finalized.

4620 Using separate pillars and rails to support the Inner HCal, instead of the load transfer
4621 rings. This is a more complicated design, which would increase cost and complexity of
4622 installation.

4623 Having separate supports for the magnet instead of supporting the magnet with the Outer
4624 HCal. This was rejected due to increased complexity and cost.

4625 Appendix D

4626 Intermediate Silicon Strip Tracker

4627 D.1 Detector description

4628 The INtermediate Tracker (INTT) is part of the charged particle tracking systems of
4629 sPHENIX. The INTT consists of four layers of barrel silicon semiconductor strip detectors.
4630 The layers are noted by Layer-0, 1, 2, and 3 from the most inner to outer and the distance in
4631 radii of each layer from the interaction point is 6, 8, 10, and 12 cm, respectively. Each layer
4632 is composed of several ladders cylindrically covering rapidity range of approximately
4633 $-1.1 < \eta < 1.1$. To achieve hermeticity, alternate support and cooling structures are
4634 staggered in radius and offsets in azimuthal angle so that the alternating sensor modules
4635 overlap in azimuth as shown in Figure. D.1. Number of ladders in each layer is presented
on Table D.1. Each ladder is made of two silicon modules mounted on the same Carbon-

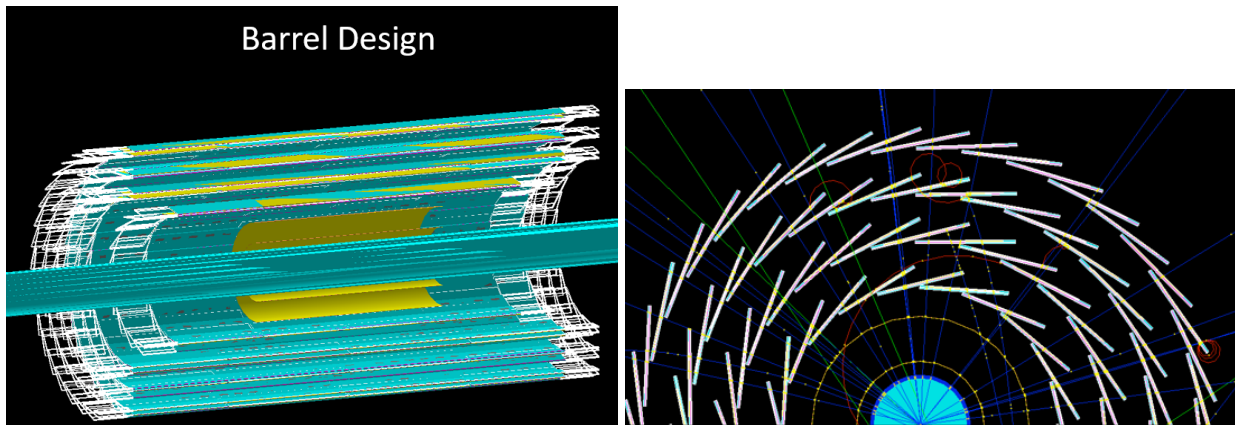


Figure D.1: The INTT tracker drawing: side view (left), and front view (right).

4636
4637 Fiber-Composite stave. Each silicon module is read out from one side and is composed of:
4638 (1) Two AC coupled, single-sided silicon strip sensors produced by Hamamatsu Photonics

Table D.1: Radius and number of ladders of each layers of barrel silicon strip detectors.

layer	radius [cm]	number of ladders
0	6	20
1	8	26
2	10	32
3	12	38
Total	-	116

Table D.2: Dimensions of silicon sensors (not active region) to parallel to the beam (z-) direction. The last line of the table is the $|z|$ position of $\eta = 1.1$ at the distance of each layers (6,8,10, and 12cm).

		Layer-0	Layer-1	Layer-2	Layer-3
type-A	z-length/block[mm]	18		16	
	# of blocks	5		8	
	z-length [mm]	90		128	
type-B	z-length/block[mm]	18		20	
	# of blocks	5		5	
	z-length [mm]	90		100	
type-(A+B)	z-length [mm]	180		228	
	$ z @ \eta = 1.1$ [mm]	174	198	223	247

4639 Co. (HPK) and (2) One flexible circuit board, called the High Density Interconnect (HDI);
 4640 each HDI provides power, and bias input lines as well as slow control and data output
 4641 lines. The HDI was designed, manufactured and tested by Yamashita Materials Co. (3)
 4642 On top of each HDI, twenty and twenty six FPHX chips[156] are mounted for ladders
 4643 of layer 0 and layers 1, 2 and 3, respectively. The FPHX chip consists of a 128-channel
 4644 front-end ASIC, and was designed by Fermilab for the FVTX detector[157]. The chip was
 4645 optimized for fast trigger capability, a trigger-less data push architecture, and low power
 4646 consumption (64 mW/chip). The HDI ends will be connected to an extender cable which
 4647 is connected at the other end to a FVTX ROC used in PHENIX previously. The extender is
 4648 1.2 m long (and possibly longer) to reach the ROCs, which are in a big wheel arrangement
 4649 on the inner part of the TPC endcap.

4650 The basic design of INTT is derived from the PHENIX Forward VTX (FVTX) detector[157].
 4651 In fact, the FPHX readout chip is employed for the INTT and thus the readout chain of
 4652 FVTX can be re-used for INTT. In order to avoid production of extra readout electronics
 4653 beyond FVTX resources, number of readout channels are designed to be less than that of
 4654 FVTX. The INTT silicon strip sensor uses conservative technology design; it is a silicon
 4655 strip single sided, AC coupled, double-metal layer to route the signal from the strip to
 4656 the bonding area at the edge of the sensor. In summary, The INTT tracker is driven by

4657 several ideas which it is conservative design, low risks, low-cost and high optimization for
4658 physics.

4659 The dimensions of silicon sensors (not active region) to parallel to the beam (z-) direction
4660 are tabulated in Table D.2. The total z-coverage of Layer-0 and Layer-1 to 3 are 180 mm
4661 and 228 mm, respectively. As tabulated in the bottom of the table, the Layer-0, 1, and 2
4662 fully cover more than $\eta = 1.1$, while z-coverage of Layer-3 is short by 19 mm from the
4663 $|z|=247$ mm where $\eta = 1.1$ at the distance of 12 mm from the beam line. The effect in the
4664 acceptance is discussed in subsection D.2.

4665 D.2 Acceptance and efficiency

4666 Geometrical acceptance and detection efficiency of each INTT layer are summarized in
4667 Table. D.3. Geometrical acceptance is estimated for two types of z-vertex values ($vtxz$):
4668 $vtxz < 0$ cm and $vtxz < 10$ cm. Detection efficiencies in the two rapidity regions, $|\eta| = 0$
4669 and $|\eta| < 1$, are calculated using single electron simulation events fired from the vertex
(0,0,0) cm.

Table D.3: Summary of the geometrical acceptance and detection efficiency for each INTT layer.

Layer	Acceptance		Efficiency	
	$ vtxz < 0$ cm	$ vtxz < 10$ cm	$ \eta = 0$	$ \eta < 1$
L0	$\eta < 1.83$	$\eta < 1.12$	100 %	> 99 %
L1	$\eta < 1.79$	$\eta < 1.28$	100 %	> 99 %
L2	$\eta < 1.58$	$\eta < 1.09$	> 99 %	> 99 %
L3	$\eta < 1.41$	$\eta < 0.95$	100 %	> 99 %

4670

4671 D.3 Silicon strip sensors

4672 The sensors are single sided, AC coupled sensors. For Layer-1 to 3, the active area of the
4673 type-A and type-B sensors are 128 mm \times 19.96 mm and 100 mm \times 19.96 mm, respectively.
4674 The active area of the type-A (type-B) sensor is divided into 8 \times 2 (5 \times 2) blocks. Each
4675 block has 128 short strips that are 78 μ m in pitch and 16.0 mm (type-A) or 20 mm (type-B)
4676 long, and run parallel to the z (beam) direction (Table D.4). In Figure D.2, the strip runs
4677 horizontally. The read-out lines of the strips, run perpendicular to the strips and bring the
4678 signals to the read-out chips placed on the HDI at the upper and the lower edge of the
4679 sensor.

Silicon strip sensors

Intermediate Silicon Strip Tracker

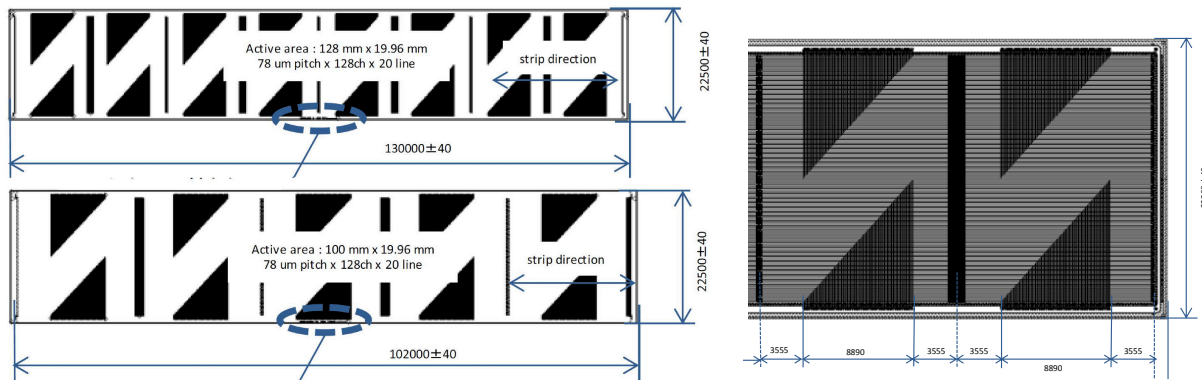


Figure D.2: The silicon strip sensor drawings of layer 1 to 3 made by HPK. (Top left) type-A, (bottom left) type-B, and (right) part of type-A sensor.

Table D.4: Silicon sensor dimensions of Layer-1 to 3.

Type	number of blocks	active area dimension	strip pitch
A	8	128 mm × 19.96 mm	78 μm
B	5	100 mm × 19.96 mm	78 μm

4680 The silicon sensors are manufactured by Hamamatsu Photonics Co (HPK). In order to
 4681 reduce the material in the tracking system, a thinner silicon sensor is under development.
 4682 The thinner silicon sensors are manufactured by grinding their standard thick (320 μm)
 4683 silicon down to 200 to 240 μm as a trade off of the increasing dark current. The final design
 4684 of the silicon thickness will be optimized based on the signal to noise ratio performance.
 4685 Shown in Figure D.3 is the prototype silicon sensor B for Layer-1,2,3.

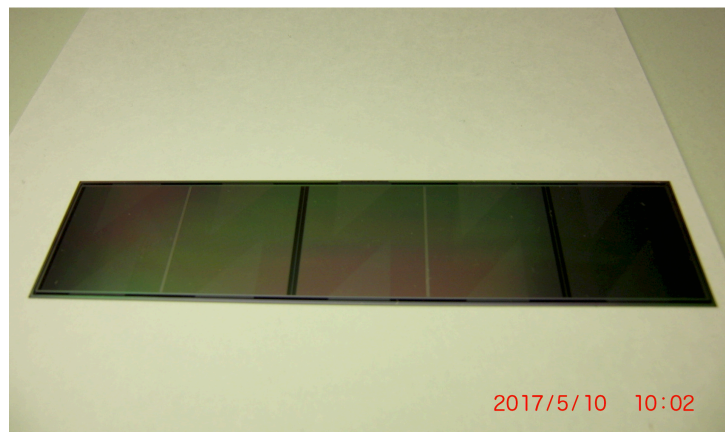


Figure D.3: The photograph of the type-B silicon sensor prototype for Layer-1,2,3.

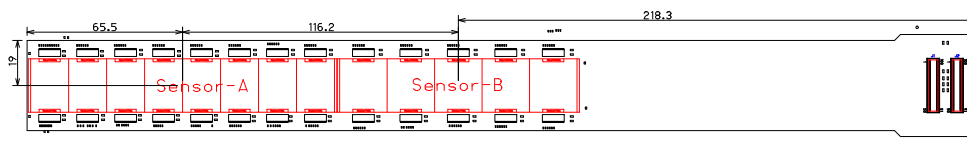


Figure D.4: Dimension of HDI for layer-1 to 3 and layout of silicon sensors, FPHX readout chips and other components.

4686 D.4 HDI

4687 The HDI is a seven layer flexible circuit board to read-out two silicon sensors. The basic
 4688 layer structure design of HDI is derived from the PHENIX FVTX. On the other hand, some
 4689 of parameters are slightly different particularly for those close to technological limit in
 4690 FVTX are somewhat relaxed in INTT. The copper line width and pitch between copper
 4691 lines are 60 ± 10 and $120 \mu\text{m}$, respectively. Each copper line pairs are spaced greater than
 4692 $180 \mu\text{m}$ at least. The impedance is well controlled to be 50Ω . The HDI will be manufactured
 4693 by Yamashita Materials Co. Shown in Figure D.4 shows the dimension of HDI for layer-1
 4694 to 3 and layout of silicon sensors and FPHX chips. The width of HDI is 38mm in sensor
 4695 part while 43mm in the connector end. The length is 400mm which is the longest limit of
 4696 multilayer flexible cable.

4697 Shown in Figure D.5 is the 7 layer structure of HDI. The total thickness is $493 \mu\text{m}$. The total
 4698 thickness governed by copper layers is $68 \mu\text{m}$ which is the major source of the material
 4699 budget of INTT layers. In order to reduce the material budget, a mesh pattern is introduced
 4700 in ground and bias copper layers for prototype model. As shown in Figure D.7, the copper
 4701 line width is $300 \mu\text{m}$ and space between copper lines was kept 1.7 mm. This pattern leaves
 4702 residual copper rate of 30% saving 70% of material compared to the solid copper ground.
 4703 Since the main purpose of having signal layers sandwiched by ground/bias layers is to
 4704 shield incoming/outgoing noise to/from signal lines, meshed design is trade off of the
 4705 noise shielding performance and reducing the material. In order to minimize the noise
 4706 shielding effect, the mesh design is only introduced in the area where signal lines are
 4707 not running in adjacent signal layer as can be seen in Layer-2,4, and 6 in Figure D.6. The
 4708 residual Copper rates for these layers are summarized in Table ???. The final design will be
 4709 optimized based on its performance by comparing prototype models between meshed and
 4710 solid ground designs. Some signal lines running in sensor region in L7 is not succeeded
 4711 design from FVTX. This signal lines were bi-product of saving HDI width as narrow as
 4712 possible and thus couldn't fit within the signal layers. Since L7 is not shielded by the
 4713 ground layers, the signal lines are exposed to the external environment, the length of the
 4714 lines were kept as short as possible ($<$ a few cm).

4715 FPHX chips[156], which was used for the FVTX silicon tracker of PHENIX[157], are
 4716 mounted on HDI to read-out the sensor. A FPHX chip has 128 channels of 3 bit ADCs

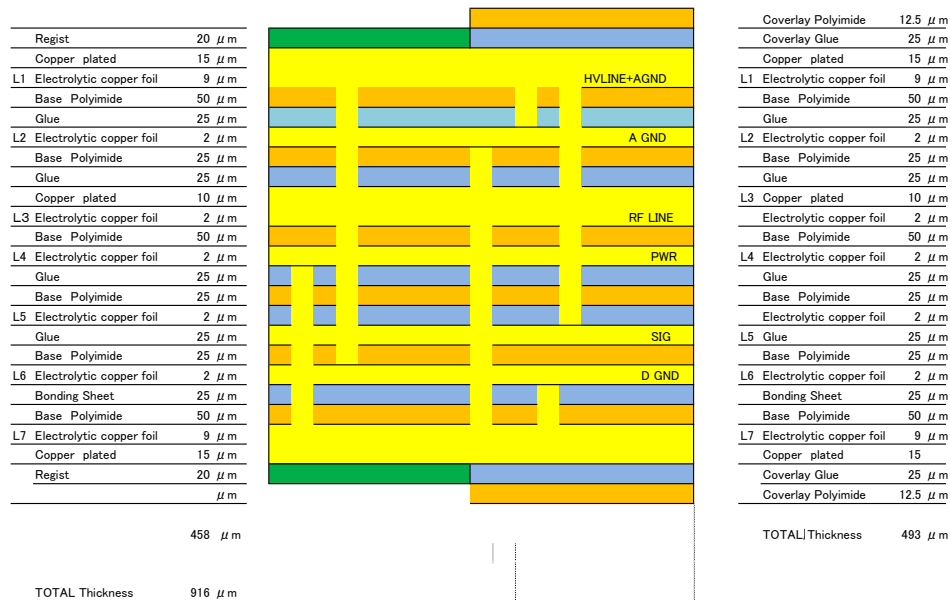


Figure D.5: 7 layer structure of HDI.

Table D.5: Residual Copper rate for ground and bias layers of HDI.

Layer	residual Copper %
2	53.99
4	62.66
6	71.92

4717 and it can read out 128 mini-strips in one block of the sensor. The read-out pad pitch
 4718 of the sensor is thus matched to that of FPHX chip (78 μm). FPHX chip has low power
 4719 consumption, about 64 mW per chip, which reduces the need for cooling for the sensor
 4720 module. The analog signal of each strip is digitized in the FPHX chip, and the digitized
 4721 data of 128 channels are sent out through the 200 MHz data-out port of the FPHX chip.

4722 D.5 Bus Extender

4723 The bus extender is a cable to connect between the ROC board and the INTT ladder, and
 4724 to bring all the signals from the ladder to the ROC board and power and the control
 4725 commands from the ROC board to the ladders.

4726 The requirements of the bus extender are following: (1) 1.2m long, (2) signal integrity of
 4727 200 MHz clock rate with LVDS lines, (3) small available space in the TPC. Figure D.8 shows

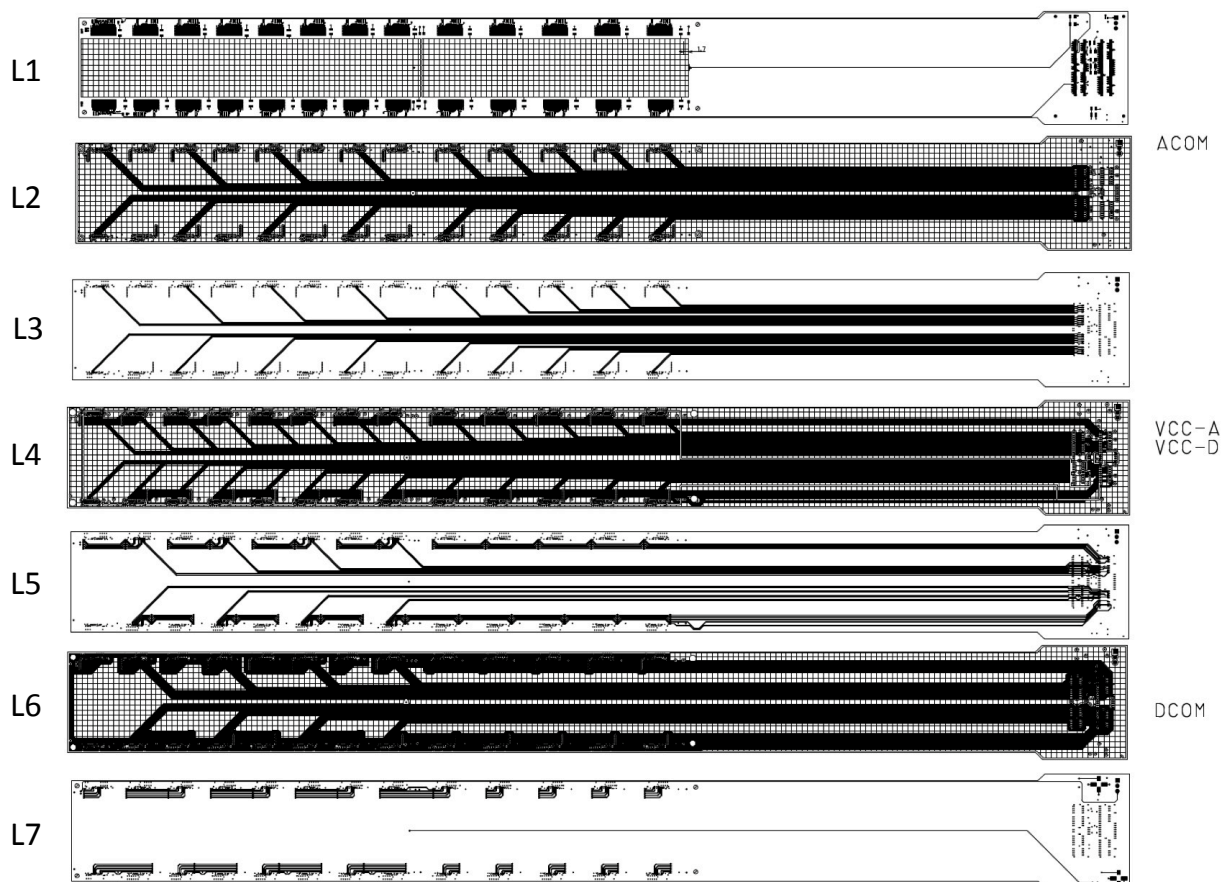


Figure D.6: 7 layer structure of HDI.

4728 the sPHENIX tracking system. INTT detector is placed at the center of the TPC barrel and
 4729 the ROC boards are outside of the barrel. The distance between the INTT ladder and the
 4730 ROC boards is 1.2 m. The available space near INTT region is small. the MAPS detector
 4731 has a heavy cabling systems with the mechanical support. In addition, the front edge of
 4732 the the forward sPHENIX detector is rolled in to the TPC barrel and is placed near the
 4733 INTT detector.

4734 One way to meet these requirement is that the bus extender is made from a flexible PC
 4735 board with having a similar stack-up design to the INTT HDIs. The flexible PCB is thin
 4736 and can be arranged by bending along with the TPC barrel. The FVTX bus extender was
 4737 built with the flexible PCB with multiple layers, as shown in Figure D.9. The parameters
 4738 of the FVTX bus extender is summarized in Table D.6. Therefore, It is good to start with
 4739 the design of the FVTX extender. It is challenging to build the extender with 1.2 m long in
 4740 terms of a good signal integrity and making the long flexible PCB. We plan to do 3 steps
 4741 R&D to make the extender: First, the long cable with single layer to test the signal transfer
 4742 with 1.3m. Second, the long cable stacked with multiple layers for checking the multi-layer

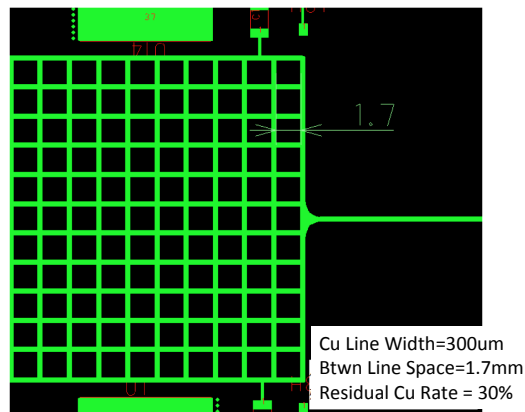


Figure D.7: Close view of the mesh pattern of the ground layer.

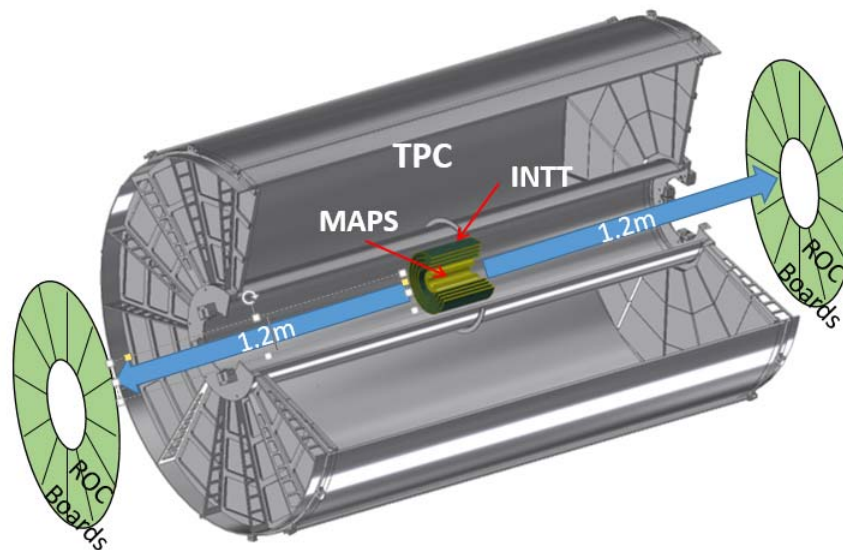


Figure D.8: sPHENIX tracking system. The bus extender should be at least 1.2m to connect between the INTT ladders and ROC boards.

4743 cable. Third, the proto-type cable with actual 62 LVDS lines for total verification. The R&D
4744 is in progress.

4745 D.6 Sensor module

4746 Figure D.10 illustrates the conceptual design of the sensor module of the layer-0 (top) and
4747 layer-1 to 3 (bottom) of the INTT tracker. Each of the silicon strip module is made:

4748 (1) Two pieces of silicon sensors type-A and type-B for layer-1 to 3, and two pieces of



Figure D.9: The bus extender for FVTX.

Table D.6: The set of parameters of the FVTX bus extender.

length	27 cm
width	2cm
Layer	7
LVDS lines	62
Powers	power, bias, GND

4749
4750
4751
4752
4753
4754

silicon sensors type-B for layer-0. As reminder (see silicon sensor section for more details), the active area of the type-A and type-B sensors are $128\text{ mm} \times 19.96\text{ mm}$ and $100\text{ mm} \times 19.96\text{ mm}$, respectively. The active area of the type-A (type-B) sensor is divided into 8×2 (5×2) blocks. Each silicon sensor is an AC coupled silicon strip sensor single side, double-metal layer to route the signal from the strip to the bonding area at the edge of the sensor, and a strip pitch sensor of $78\text{ }\mu\text{m}$ (in ϕ). The

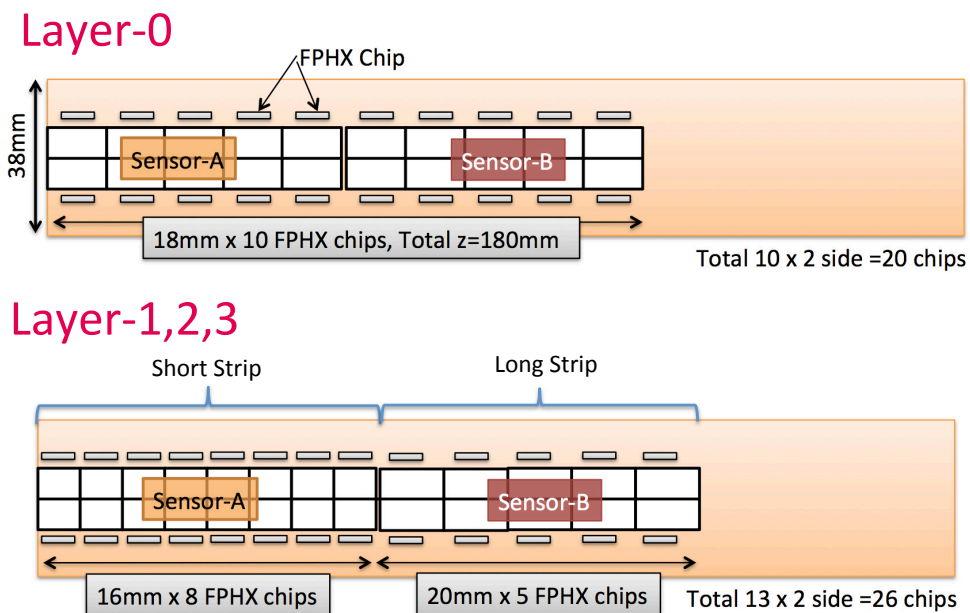


Figure D.10: Conceptual design of the Sensor Module for Layer-0 (top) Layer-1 to 3 (bottom) of the INTT detector.

- 4755 silicon sensors were produced by Hamamatsu Photonics Co. (HPK).
- 4756 (2) One flexible circuit board, called High Density Interconnect (HDI); each HDI provides
4757 power, and bias input lines as well as slow control and data output lines. The HDI is
4758 manufactured and tested by Yamashita Materials Co.
- 4759 (3) Signals from strip sensors are digitized by 20 and 26 FPHX chips mounted on HDI for
4760 Layer-0 and Layer-1 to 3, respectively. The FPHX chip consists of a 128-channel front-
4761 end ASIC, and was designed by Fermilab for the FVTX/PHENIX detector. The chip
4762 was optimized for fast trigger capability, a trigger-less data push architecture, and
4763 low power consumption (64 mW/chip). The from-end of each chip (128 channels)
4764 is a wire-bond to the silicon sensor, and the back-end of the chip (32 channels) is
4765 wire-bonded to the HDI. All wire-bonding are encapsulated for protection.
- 4766 (4) It should be point out that each sensor module contains two temperature sensors.
4767 Each ladder contains two thermistors (NCP15XH103D03) allowing us to read the
4768 temperature of each sensor module. The thermistors are part of the HDI (built in) and
4769 they are read out from the edge of the HDI. From each HDI, we will have one cable
4770 going to a readout board. The thermistors and readout board have been determined
4771 by engineer using them currently and planned to be used in sPHENIX.

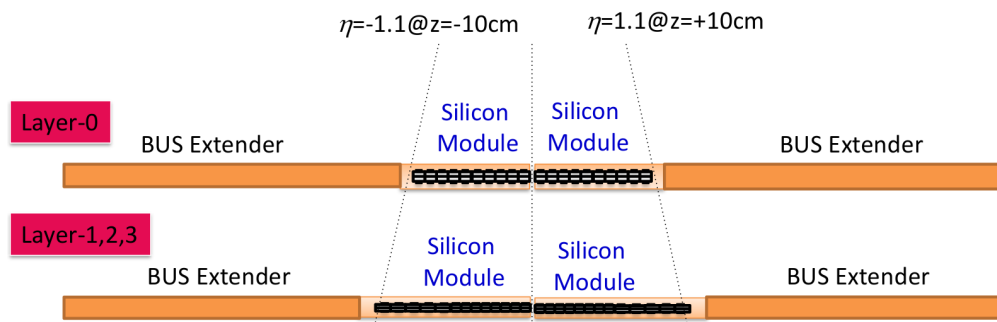


Figure D.11: Conceptual design of ladder for Layer-0 (top) Layer-1 to 3 (bottom).

4772 D.7 Ladder

4773 For Layer-0 to 3, each ladder is build as following:

- 4774 (1) One mechanical support made of Carbon-Fiber-Composite skins called stave. The
4775 area of the stave for layer-0 (layer-1 to 3) is 40 cm × 3.3 cm (50 cm × 3.3 cm), as shown
4776 in figure D.12. Each stave contains a graphite sheet (to enhance thermal conductivity)
4777 which carries out the heat of each ladder to the top edges of the stave. Each edge
4778 of the stave is connected to a Ring which is cooled down. The temperature of each

- 4779 ladder should be at 10 degrees Celsius during operation. The heat load expected
 4780 from each half ladder is: $390 \mu\text{W} \times 128\text{ch} \times 26 \text{ chips} = 1.3 \text{ W} \simeq 2 \text{ W}$ (including
 4781 power). (including power). The total heat load over the entire INTT is 300 W.
- 4782 (2) Each stave carried out on top two sensor modules. Each sensor module is read out in
 4783 one edge of the ladder through the HDI bus extender as shown in figure D.11. The
 4784 HDI ends will be connected to an extender cable which is connected at the other end
 4785 to a FVTX ROC used in PHENIX. The extender has to be at least 1.2 m long (and
 4786 and possibly longer) to reach the ROCs, which are in a big wheel arrangement on the
 4787 inner part of the TPC endcap.
- 4788 (3) Number of ladders per layer of barrel is presented on Table D.7. We have four layers
 4789 of barrels silicon strip detectors made of 116 ladders in total.
- 4790 (4) The four layers (layer-0 to 3) barrels silicon strip detectors will be integrated into
 4791 a dual hemisphere support frame (upper and lower). Each frame hemisphere will
 4792 have a 3 point support onto a dual rail and bearing system in which the bearings
 4793 will slide along pathways on the rail which allows the upper and lower frames to
 4794 ride in separately and move away from the beam pipe until the frames have cleared
 4795 the beam pipe flanges. The lower frame is positioned first, then the rail is adjusted
 4796 in 3 dimensions to achieve the alignment precision required. Then the upper frame
 4797 is brought into position and is mated to the lower frame by kinematic mounts. It is
 4798 almost certain that the same external supports and rail system will need to hold both
 4799 the INTT and the MVTX. As a result, it will not be possible to install or remove either
 4800 detector while the other is already installed. However, the support system should
 4801 allow installing either of the detectors alone in the absence of the other.

Table D.7: Number of ladders per layer of barrel silicon strip detectors.

layer	number of ladders
0	20
1	26
2	32
3	38
Total	116

4802 D.8 Electronics, LV&HV systems

4803 As briefly described in the detector description section, the readout, slow control, LV, HV
 4804 supply electronics chains composed by re-use boards of FVTX. These boards are mostly
 4805 functional in the last year of FVTX operation and known to be kept in reasonably good

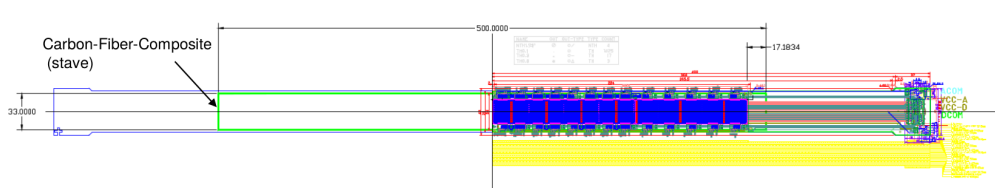


Figure D.12: Auto-Cad drawing of one stave, one silicon module, one HDI extender bus of one ladder.

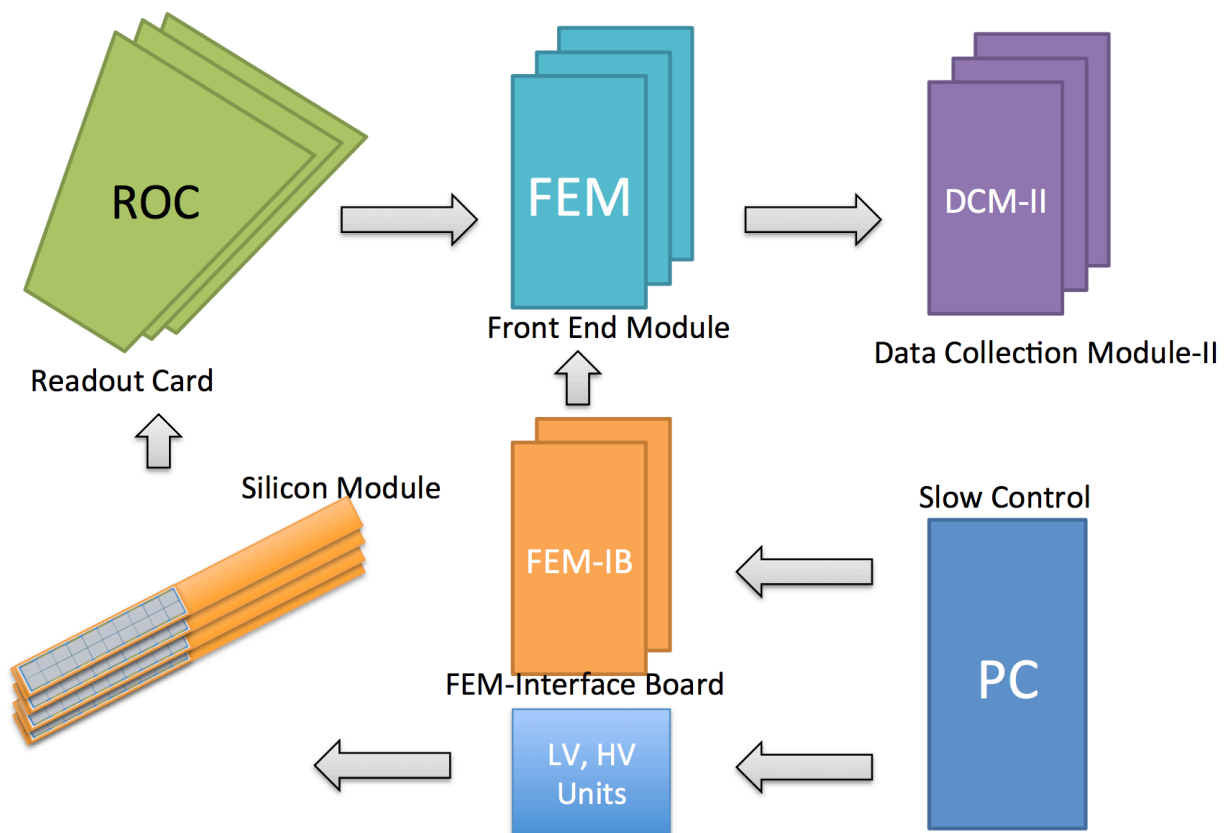


Figure D.13: Readout electronics chain for INTT. Any electronics downstream of ROC boards are re-use of resources from FVTX.

4806 condition. However, each boards are to be tested before the INTT installation and repaired
 4807 up on necessity. Shown in Figure D.13 is the schematics of the readout and slow control
 4808 chains for INTT.

4809 D.9 Justification of design choices

4810 The momentum resolution is weakly affected by multiple scattering in the material. Thus
4811 the amount of material in INTT is kept as small as possible. The design choices being
4812 pursued to minimize the material budget are as follows.

- 4813 1. High thermal conductivity plate cooling.
- 4814 2. Thinner Silicon Sensor.
- 4815 3. Mesh pattern ground and bias layers of HDI.
- 4816 4. Long multilayer bus extender.

4817 High thermal conductivity plate cooling

4818 The biggest advantage of the FPHX chip is the small heat generation, which allowed FVTX
4819 to avoid running cooling tubes into the acceptance. The heat generated by the wedge
4820 assemblies is conducted through the wedge carbon composite backplane to the outer
4821 radius (outside acceptance) cooling tubes which is away from the inner most chip by 5
4822 cm (station-0) and 12 cm (station-1,2,3). The wedge carbon composite has relatively high
4823 thermal conductivity of 650 W/mK. The number of FPHX chips per HDI is identical with
4824 FVTX for Layer-0 and Layer-1 to 3 and therefore the total heat generation per HDI will be
4825 also same as FVTX. However, the spacing between adjacent chips are not as dense as FVTX.
4826 As a consequence, the distance from the chip closest $z = 0$ to the outside the acceptance is
4827 much longer in INTT (18 cm to 25 cm). Therefore the heat generated by the chip needs
4828 to be conducted longer distance and more efficiently to the location of cooling tube. The
4829 performance of high thermal conductivity 1000 ~ 1500 W/mK sheets are under testing. It
4830 will be used in combination with the carbon composite backplane to conduct the heat.

4831 Thinner silicon sensor

4832 The thinner silicon sensors are manufactured by grinding their standard thick ($320\mu\text{m}$)
4833 silicon down to 200 to 240 μm as a trade off of the increasing dark current. The final design
4834 of the silicon thickness will be optimized based on the signal to noise ratio performance.

4835 Mesh pattern ground and bias layers of HDI.

4836 Two types of prototype HDI are under production and to be compared their noise shielding
4837 performance. An electromagnetic field simulation is to be also executed and verify the
4838 actual observation.

4839 Long multilayer bus extender

4840 The length of the bus extender cable of FVTX is less than 30cm. As far as we investigated
4841 within the Japanese industrial market, the length of the multilayer flexible cable is only
4842 available up to around 40 cm, while required length is approximately 1.2 meter. As
4843 discussed in subsection D.5, we established collaborative R&D contract between Tokyo
4844 Metropolitan Industrial Technology Research Institute and REPIC Co and will develop the
4845 technology within 1.5 year. In the case of unsuccessful result, the back-up solutions are
4846 1) concatenate multiple multilayer bus extender up to 1.2 meter, 2) use single layer cable
4847 using cable adapters in both HDI and ROC board ends. The latter two has to overcome the
4848 following additional difficulties, i.e. additional connector joint can introduce new worry of
4849 unstable connection over the course of time, and spacial constraint to accommodate the
4850 cable adapter, especially in HDI side.

4851 **D.10 R&D**

4852 The first prototype INTT modules have been assembled successfully at BNL with the
4853 silicon sensors and HDI sent from Japan. The thickness of the silicon sensors used for the
4854 prototype modules are 240 and 320 μm . Figure D.14 shows the prototype module with
4855 320 μm -thick silicon sensors. HDIs are connected one either side of the silicon sensors and
4856 10 FPHX chips are mounted on each HDI. The silicon sensors are mechanically separated
4857 at the middle and the FPHX chips are wire-bonded to the sensors.

4858 Tests of the prototype modules have been made with calibration pulses and the test result
4859 for a single FPHX chip on the HDI is shown in Fig. D.15. A clear correlation between
4860 calibration pulse amplitude and ADC values can be seen and all 128 channels on the chip
4861 look working correctly. Further tests with prototype modules are scheduled using cosmic
4862 rays and an available beta source.

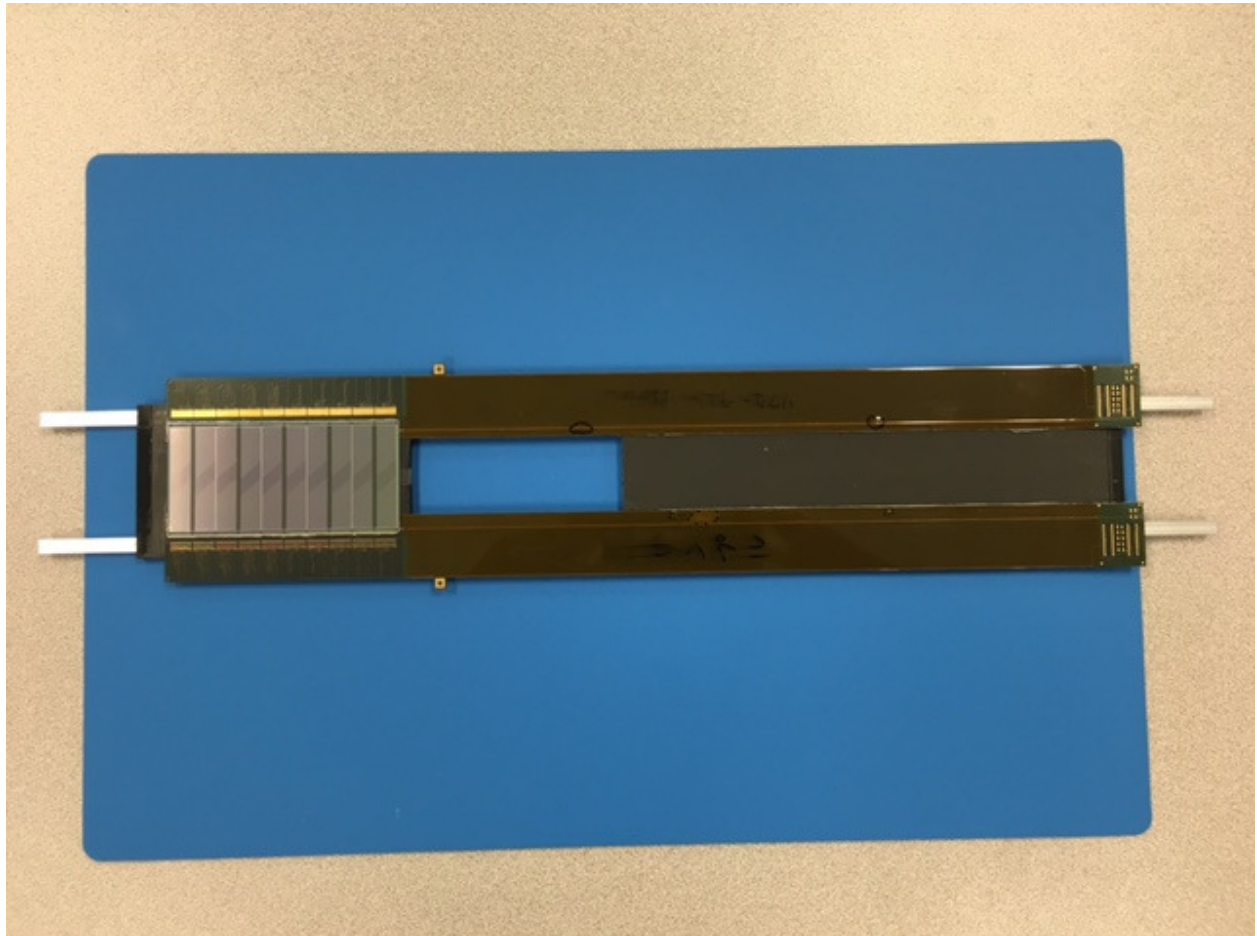


Figure D.14: The prototype module with $320\ \mu\text{m}$ -thick silicon sensors.

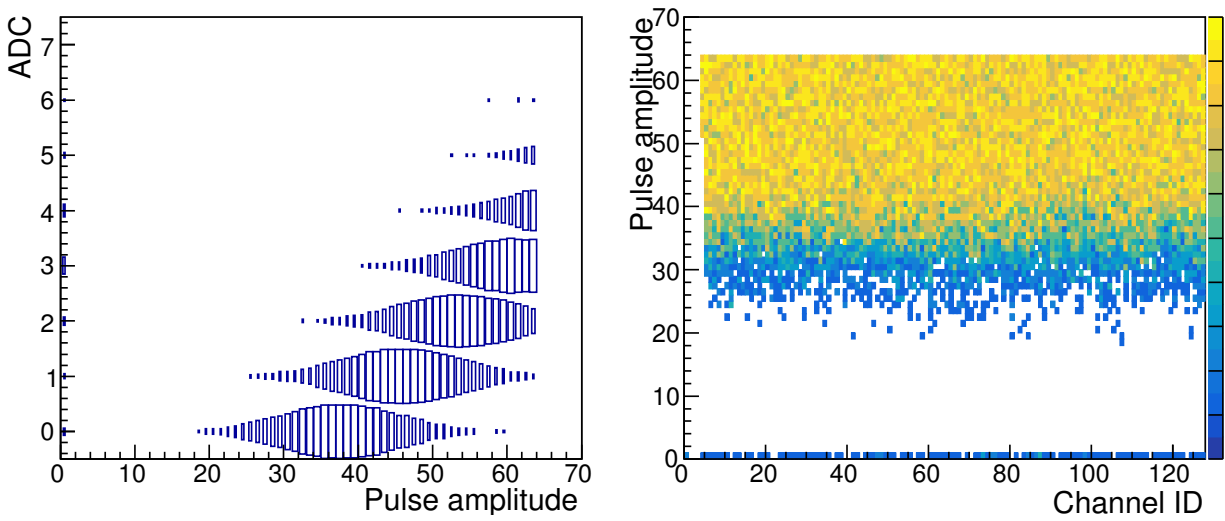


Figure D.15: The correlation between calibration pulse amplitude and ADC values (Left) and responses with the calibration pulses for all channels on the chip (Right).

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 5008 collisions with event pileup from 200 kHz Au+Au collision rate. 50

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5011 3.9 The outer limit of the TPC radial space (20 cm to 78 cm) is bounded by the
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 5013 10 cm PID upgrade device. The length is defined by the $\eta < \pm 1.1$ sPHENIX
 5014 aperture. 52

5015 3.10 Ionization drifts away from the central membrane of the TPC and impinges
 5016 upon the avalanche chambers located at each end. The end plates are
 5017 segmented into 12 azimuthal and 3 radial segments, making a total of 72
 5018 modules in total. Each module is a quad-GEMstack operated in a low IBF
 5019 configuration. 53

5020 3.11 This figure shows the final design of the ALICE avalanche modules using a
 5021 quad-GEMstack. We expect to operate similar chambers or perhaps a hybrid
 5022 μ MEGA arrangement. 53

5023 3.12 All ionization produces both signal electrons and positive ions. Primary
 5024 ionization sets the lower limit to TPC space charge. However, even small
 5025 percentage back flows from the avalanche stage (here represented by the red
 5026 "pancakes" of drifting charge) contribute significantly to the overall space
 5027 charge and will likely be the dominant source. 54

5028 3.13 The left panel shows the anticipated space charge in the TPC resulting from
 5029 only primary charges with a minimum bias collision rate of 100 kHz. The
 5030 right panel shows the result if one assumes 1% IBF from the avalanche stage
 5031 operating with a gain of 2000. 55

5032 3.14 The left panel shows the mass dependence of positive ion mobility, clearly fa-
 5033 voring light gases for high mobility and thereby low space charge. The right
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 5035 gas mixtures. 56

5036 3.15 Results from R&D for the ALICE experiment indicate a "universal" trend.
 5037 Configurations with the lowest IBF suffer from poor energy resolution. The
 5038 principle reason for this trend is the contribution of the first GEM to the
 5039 overall gain. 57

5040	3.16	Electron paths are primarily influenced by the charge density closest to the	
5041		electron. Necessarily, the greatest deflections from the ideal trajectory are	
5042		found closest to the field cage. By moving the field cage entrance window	
5043		from 30 cm to 20 cm, we are able to drastically reduce the deflection due to	
5044		IBF to reasonably manageable levels.	58
5045	3.17	In the limit of zero diffusion, one can easily visualize the mechanism behind	
5046		IBF suppression. When the exit field of a GEM significantly exceeds the	
5047		entrance field, near 100 % electron transmission is achieved while many or	
5048		most of the ions terminate instead on the GEM itself.	59
5049	3.18	The so-called "Sauli Point" for a GEM is a spike in electron transmission	
5050		at very low dV. sPHENIX has proposed and simulated using either a low	
5051		ΔV GEM operating at the Sauli Point or even a simple mesh to create an	
5052		electron-transparent but ion-blocking shield.	59
5053	3.19	Electron gain differs from simple statistical calculations (<i>e.g.</i> Poisson) be-	
5054		cause even without gain, at the very least the electron that enters the	
5055		avalanche exits as well. Therefore the fluctuations (measured as $\frac{\sigma}{mean}$) vanish	
5056		in the low gain limit.	60
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5058		shape shown here, square holes photographically etched into flat metal. . .	60
5059	3.21	GARFIELD results indicate that for reasonable ratios of $\frac{E_{exit}}{E_{entrance}}$ near perfect	
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5061		produced in the avalanche stage.	61
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5063		diffusion (blue), and drift velocity (black). The left panel shows the original	
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5072		TPC data joins the main stream flow of the sPHENIX DAQ.	65

5073	3.26	Block diagram for DAM and EBDC. Estimation of the DAM performance as realized using the FELIX board have been performed following this architecture assumption detailed in these diagrams. These studies indicate that not only can the FELIX card handle the desired throughput, but it can additionally assert "trigger coincidence" criteria by copying data from overlapping triggers into both events.	66
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5133 3.45 The "wagon wheel" includes allowances for all services, feedthroughs,
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