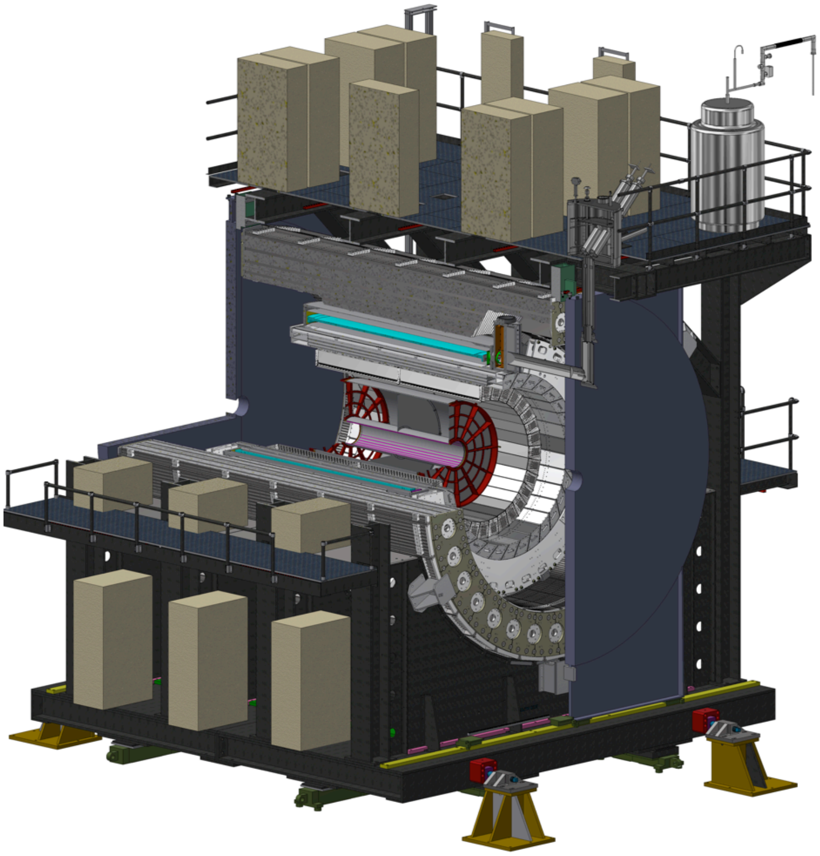

DRAFT from December 12th 2022

Final Project Closeout Report
for the
Super Pioneering High Energy Ion eXperiment (sPHENIX)
Project at
Brookhaven National Laboratory

Office of Nuclear Physics

Office of Science

U.S. Department of Energy

Date Approved:

December 2022

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Brookhaven National Laboratory

List of Acronyms

ALD	Associate Laboratory Director
AS	Acquisition Strategy
ASE	Accelerator Safety Envelope
AY	Actual Year Dollars
BHSO	Brookhaven Site Office
BNL	Brookhaven National Laboratory
BSA	Brookhaven Science Associates
C-AD	Collider-Accelerator Division
CAM	Control Account Manger
CCB	Change Control Board
CD	Critical Decision
CDR	Conceptual Design Report
CERN	European Council for Nuclear Research
CR	Continuing Resolution
CY	Calendar Year
DAM	Data Aggregation Module
DAQ	Data Acquisition
DOE	U.S. Department of Energy
EIA	Electronic Industries Alliance
EMCal	Electromagnetic Calorimeter
ES&H	Environment, Safety and Health
EVMS	Earned Value Management System
FPM	Federal Program Managers
FY	Fiscal Year
Gbps	Gigabits-per-second
GEM	Gas-Electron Multiplier
HCal	Hadronic Calorimeter
HQ	DOE Headquarters
IHCal	Inner Hadron Calorimeter
INTT	Intermediate Silicon Strip Tracker
IPR	Independent Project Review
ISM	Integrated Safety Management
ISMS	Integrated Safety Management System
KPP	Key Performance Parameter
kHz	kilohertz
L2	Level 2
L3	Level 3
LCC	Life Cycle Costs
LHC	Large Hadron Collider
LRP	Long Range Plan
MBD	Minimum Bias Trigger Detector
MIE	Major Item of Equipment
MOA	Memorandum of Agreement
NEPA	National Environmental Policy Act
NP	Nuclear Physics
NPP	Nuclear and Particle Physics
NSAC	Nuclear Science Advisory Committee
OHCal	Outer Hadron Calorimeter
ONP	DOE’s Office of Nuclear Physics
OPC	Other Project Costs
OPPO	Office of Project Planning and Oversight
OPS	Operations Program
OSH	Occupational Safety and Health
PB	Performance Baseline
PC	Project Controls
PCR	Project Change Request

PD	Project Decision
PMP	Project Management Plan
HAR	Hazard Analysis Report
PHENIX	Pioneering High Energy Nuclear Interaction experiment
PMG	Project Management Group
PMT	Project Management Team
POB	Project Oversight Board
QA	Quality Assurance
QAP	Quality Assurance Plan
QCD	Quantum Chromodynamics
QGP	Quark Gluon Plasma
R&D	Research & Development
RHIC	Relativistic Heavy Ion Collider
RLS	Resource Loaded Schedule
RM	Risk Management
RMP	Risk Management Plan
SAD	Safety Assessment Document
SBMS	Standards Based Management System
SC	Office of Science
SC Magnet	Superconducting Magnet
SiPM	Silicon Photomultipliers
SOW	Statement of Work
sPHENIX	Super Pioneering High Energy Nuclear Interaction experiment
STAR	Solenoidal Tracker at RHIC
SVAR	Security Vulnerability Assessment Report
TEC	Total Estimated Cost
TPC	Time Projection Chamber
UPP	Ultimate Performance Parameters
USI	Unreviewed Safety Issue
WBS	Work Breakdown Structure
WP	Work Packages

Project Closeout Report for the
sPHENIX MIE Project at the
Brookhaven National Laboratory

1.0 EXECUTIVE SUMMARY

2.0 INTRODUCTION

This is the final project closeout report for the sPHENIX project, an upgrade to the PHENIX experiment at the Relativistic heavy Ion Collider.

1.1 Project Background

The sPHENIX MIE is a major upgrade to the PHENIX experiment that will enable the precision characterization of jets produced in nucleus+nucleus (AA), proton+nucleus (pA) and proton+proton (pp) collisions at the Relativistic Heavy Ion Collider (RHIC) located at Brookhaven National Laboratory (BNL). The experiment will also collect a large sample of upsilons with a mass resolution that allows for their separation into three mass states, and the study of their behavior on different distance scales. sPHENIX provides excellent opportunities complementary to measurements being made at the Large Hadron Collider (LHC) at CERN and extends the RHIC physics program in ways that fully exploits RHIC's unique performance capabilities.

1.2 Justification of Mission Need

The mission of the Office of Science (SC) is to deliver the scientific discoveries and major scientific tools that transform our understanding of nature and advance the energy, economic, and national security of the United States. SC accomplishes this mission through the direct support of research, construction, and operation of national scientific user facilities, and the stewardship of ten world-class national laboratories. The SC national laboratories collectively comprise a preeminent federal research system that develops unique, often multidisciplinary, scientific capabilities beyond the scope of academic and industrial institutions, to benefit the nation's researchers and national strategic priorities.

The Nuclear Physics (NP) program plans, constructs, and operates major scientific user facilities and fabricates experimental equipment to serve researchers at universities, national laboratories, and industrial laboratories as part of its strategic mission. The program provides world-class, peer- reviewed research results in the scientific disciplines encompassed by the NP mission areas under the mandate provided in Public Law 95-91 that established the Department of Energy (DOE).

The DOE NP program addresses three broad, interrelated scientific thrusts in pursuit of its mission: Quantum Chromodynamics (QCD), Nuclei and Nuclear Structure and Astrophysics, and investigations of Fundamental Symmetries using neutrons and nuclei. sPHENIX addresses goals within the "QCD investigations" within the NP program. Over the last two decades, the heavy ion nuclear physics component of the QCD scientific thrust has focused on the discovery and characterization of the Quark Gluon Plasma (QGP): a form of matter believed to have last naturally existed in the universe approximately one microsecond after the Big Bang. Since the discovery of the QGP at the BNL RHIC over ten years ago, and subsequent confirmation by experiments at CERN's LHC, a number of important characteristics of the QGP have been measured. Though great progress has been made over the last twenty years, the 2015 Nuclear Science Advisory Committee (NSAC) Long Range Plan (LRP) identified a vital QGP-related research question that remains unaddressed. The field must "probe the inner workings of the quark gluon plasma by resolving the properties at shorter and shorter length scales." A virtually identical goal was recommended in the 2010 National Academy Study," Nuclear Physics, Exploring the Heart of Matter." The sPHENIX MIE enables the pursuit of this directive at RHIC. The LRP states: "This program requires large samples of jets in different energy regimes, with tagging of particular initial states, for example, in events with a jet back-to-back with a photon. The full power of this new form of microscopy will only be realized when it is deployed at both RHIC and the LHC, as jets in the two regimes have complementary resolving power and probe QGP at different temperatures, with different values of the length scale at which bare quarks and gluons dissolve into a near perfect liquid". sPHENIX is needed to make these measurements feasible. Neither the existing STAR nor PHENIX experiments can make the required measurements with the necessary sensitivity.

Obtaining the scientific goals of sPHENIX has been identified by both the recent NSAC LRP and the National Academy study as needed to carryout NP's scientific mission. There is currently a gap in capabilities that needs to be addressed in order to reach those goals.

The scope baseline for the sPHENIX Project is:

- A Time Projection Chamber (TPC), Electromagnetic Calorimeter (EMCal), and a Hadronic Calorimeter (HCal) all covering 2π in azimuth. The TPC and HCal have pseudorapidity coverage of $-1.1 \leq \eta \leq 1.1$. The EMCal has pseudorapidity coverage of $-0.85 \leq \eta \leq 0.85$.
- A Minimum Bias Trigger Detector (MBD).
- Readout electronics to fully instrument the TPC, EMCal, HCal and MBD.
- A data acquisition (DAQ) system with the capability to readout the TPC, EMCal, HCal and MBD with an event rate and data-logging rate commensurate with the sPHENIX physics goals.
- A DAQ/Trigger system that can provide minimum bias and energy cluster triggers at a rate necessary to carry out the sPHENIX physics program in AA, pA and pp collisions at RHIC.
- Project Management to carry the project scope through to a successful on time and on budget completion.

This project will be declared complete when the defined scope is delivered to BNL and the Threshold KPPs are satisfied through bench tests. Installation and integration of these delivered components and parallel activities associated with this sPHENIX MIE are not part of this project's scope to be delivered at Approval of Project Completion.

3.0 ACQUISTION APPROACH

The acquisition strategy is detailed in the Acquisition Strategy (AS) Project Document approved August 2018. DOE acquired design and fabrication of the sPHENIX MIE through the Management and Operating (M&O) Contractor for BNL. The M&O Contractor is responsible to DOE to manage and complete the construction of MIE components. The basis for this choice and strategy is that:

BNL has a DOE approved procurement system with established processes and acquisition expertise needed to obtain the necessary components and services to build the component required for this upgrade

BNL has extensive experience in managing complex construction, fabrication, and installation projects involving multiple National Laboratories, Universities and other partner institutions, including construction of the original PHENIX detector.

BNL directed the sPHENIX project management team in the execution of the project and delegated to the team its authority for project execution. The BNL sPHENIX Project Office managed the distribution-to and expenditure-of DOE funds including collaborating sPHENIX institutions. The project scope accomplished at collaborating institutions was documented in Memoranda of Agreements between BNL and collaborating institutions. Statements of Work between BNL and the collaborating institutions, including frequent milestones, were used to track progress of their contributions to the project. The acquisition approach for the project is described in detail in the sPHENIX Acquisition Strategy (AS) prepared at CD-1.

BNL collaborates and works with many institutions, including other DOE National Labs and Universities (i.e. Stony Brook University). BNL was responsible for overall project management but collaborators have held key roles as the WBS Level 2 Managers, Level 3 Managers and Control Account Managers.

4.0 MANAGEMENT ORGANIZATION AND STRUCTURE

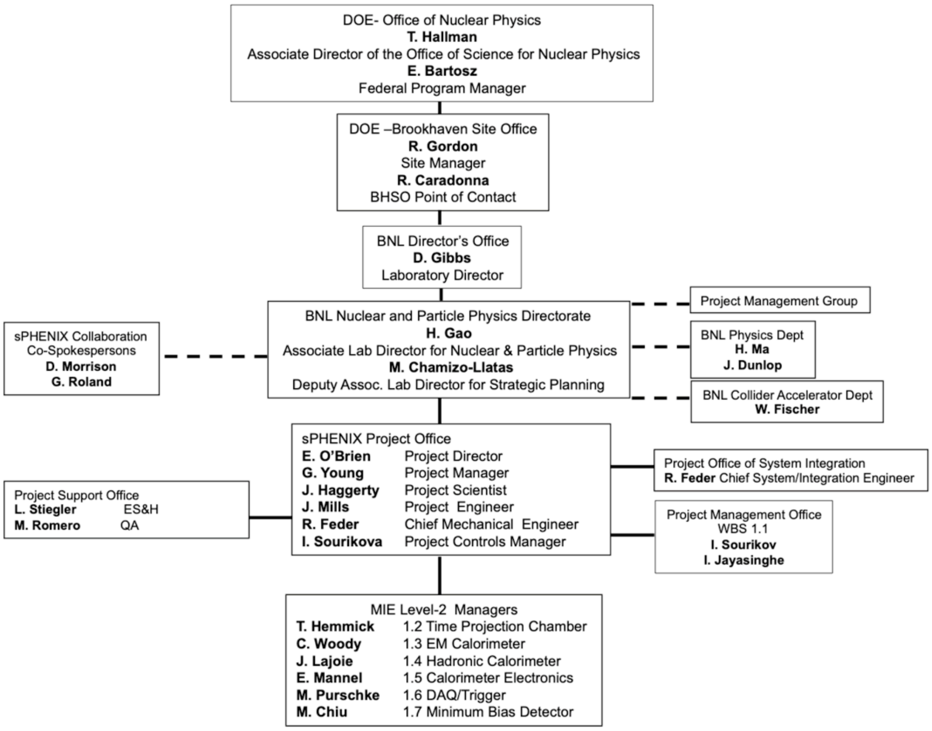


Figure 1: The sPHENIX Organization Chart

The sPHENIX MIE organization from an agency perspective is shown in the upper section of Figure 1, including representatives from the DOE Office of Nuclear Physics in the DOE Office of Science, the DOE Brookhaven Site office (BHSO), the BNL Director's office, and the BNL Directorate for Nuclear and Particle Physics. The sPHENIX Project Office reports to the Directorate for Nuclear and Particle Physics and keeps that office informed as well as other key parties including the sPHENIX Collaboration co-Spokesmen, the BNL Physics Department office, the BNL Collider-Accelerator Department office, and the Project Management Group.

The organization of the sPHENIX project is shown in the lower part of Figure 1 and includes the sPHENIX Project Office, the Control Account Managers, the Project Support Office, the Project Office of System Integration, and the Project Management Office.

The sPHENIX effort divides into the seven WBS elements shown in Table 2 that are known as the Level 2 deliverables. The organization of Level 2 Managers, Level 3 Managers and Control Accounts can be seen in Figure 2. Level 2 managers are each responsible for one of the seven elements. They report directly to the sPHENIX Project Management team. The Project Management team reports directly to the BNL Associate Lab Director for Nuclear and Particle Physics who reports to the BNL Laboratory Director.

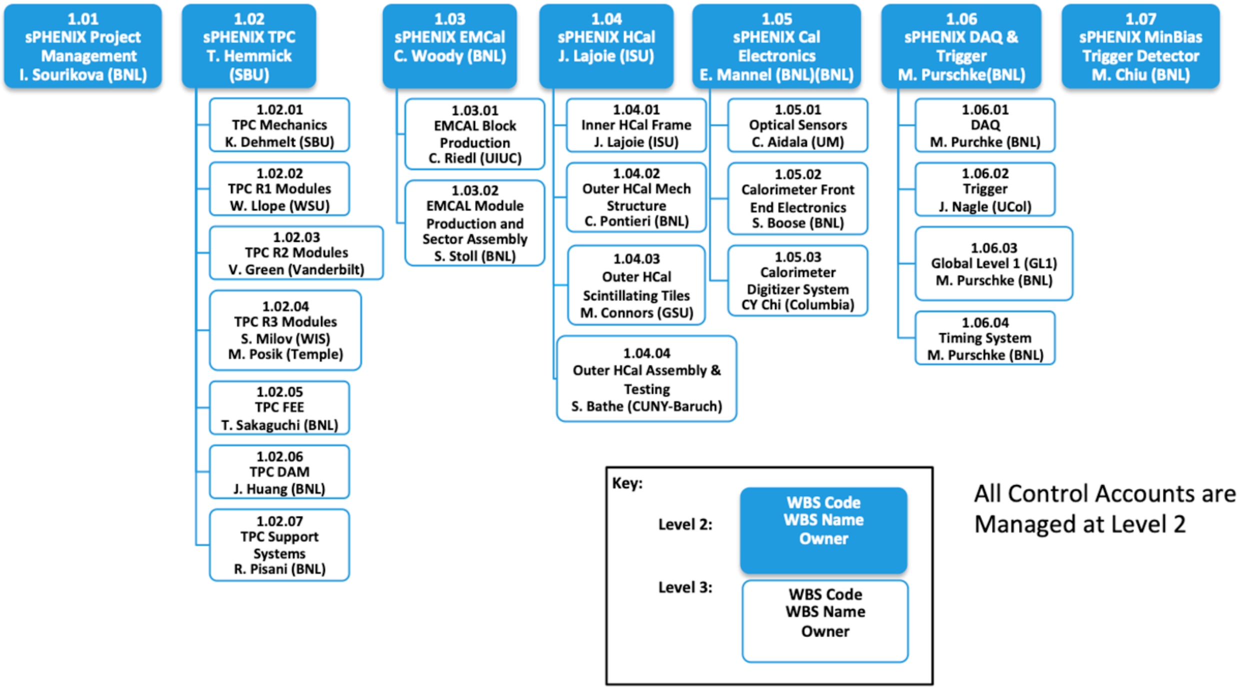


Figure 2: The Level 2 and Level 3 Work Breakdown Structure for sPHENIX MIE

5.0 PROJECT BASELINE AT COMPLETION

This section documents the project's Performance Baseline (PB) that consists of the scope, cost, schedule (time line to the Project Closeout date), funding profile, and other related information. Lower tier documents will capture the details and plans for resource cost/schedule/scope and project life cycle from the project initiation through the start of operations to the project closeout.

5.1 Scope Baseline

The scope baseline for the sPHENIX Project is:

- A Time Projection Chamber (TPC), Electromagnetic Calorimeter (EMCal), and a Hadronic Calorimeter (HCal) all covering 2π in azimuth. The TPC and HCal have pseudorapidity coverage of $-1.1 \leq \eta \leq 1.1$. The EMCal has pseudorapidity coverage of $-0.85 \leq \eta \leq 0.85$.
- A Minimum Bias Trigger Detector (MBD).
- Readout electronics to fully instrument the TPC, EMCal, HCal and MBD.
- A data acquisition (DAQ) system with the capability to readout the TPC, EMCal, HCal and MBD with an event rate and data-logging rate commensurate with the sPHENIX physics goals.

- A DAQ/Trigger system that can provide minimum bias and energy cluster triggers at a rate necessary to carry out the sPHENIX physics program in AA, pA and pp collisions at RHIC.
- Project Management to carry the project scope through to a successful on time and on budget completion.

This project will be declared complete when the defined scope is delivered to BNL and the Threshold KPPs are satisfied through bench tests. Installation and integration of these delivered components and parallel activities associated with this sPHENIX MIE are not part of this project's scope to be delivered at Approval of Project Completion.

The KPPs are shown in Table 1. The Threshold KPPs are the minimum parameters against which the project performance is measured at the Project Closeout Review (PD-4). The Objective KPPs are the stretch performance parameters that will be achievable within the Performance Baseline project scope, cost and schedule performance baseline when established. The KPPs are chosen because they comprise a set of minimum test results that once demonstrated, will allow one to conclude with confidence that sPHENIX will be able to meet its mission need after a period of commissioning, calibration and data-taking. The KPPs define tests for each of the sPHENIX Level 2 deliverables. The tests will establish that the subsystems are working at a performance level that is consistent with their design. The difference between the Threshold and Objective KPPs is essentially the difference between the expected Level 2 subsystem performance soon after initial power-up and the performance after a period of debugging and maintenance.

System	**Demonstration or Measurement**	**Threshold KPP's**	**Objective KPP's**
Time Projection Chamber	Preinstall, Bench Test	≥ 90% live channels based on laser, pulser, cosmics	≥ 95% live channels based on laser, pulser, cosmics
Time Projection Chamber	Preinstall, Bench Test	Ion Back Flow ≤ 2% per GEM Module averaged over the active area of ea GEM Mdule	Same
Time Projection Chamber	Preinstall, Bench Test w/cosmics	≥ 90% single hit efficiency / mip track, averaged over the active TPC volume	≥ 95% single hit efficiency / mip track
Time Projection Chamber Front End Electronics	Preinstall, FEE Stand-alone Bench Test	Cross talk ≤ 2% per channel, averaged over all channels	Same
EM Calorimeter	Preinstall, Bench Test	≥ 90% live channels based on LED, cosmics	≥ 95% live channels based on LED, cosmics
Hadronic Calorimeter	Preinstall, Bench Test	≥ 90% live channels based on LED, cosmics	≥ 95% live channels based on LED, cosmics
EM Calorimeter	Preinstall, Bench Test	Each sector with an absolute energy pre-calibration to a precision of ≤ 35% RMS	Same

Hadronic Calorimeter	Preinstall, Bench Test	Each sector with an absolute energy pre-calibration to a precision of ≤ 20% RMS	Same
Min Bias Trigger Detector	Preinstall, Bench Test	≥ 90% live channels based on laser. 120 ps/channels timing resolution w/ Bench Test	≥ 95% live channels based on laser. 100 ps/channels timing resolution w/ Bench Test
DAQ/Trigger	Event rate	10 kHz with random pulser	15 kHz with random pulser
DAQ/Trigger	Data Logging Rate	10 GBit/s with pulser	Same

Table 1: Table of Key Performance Parameters

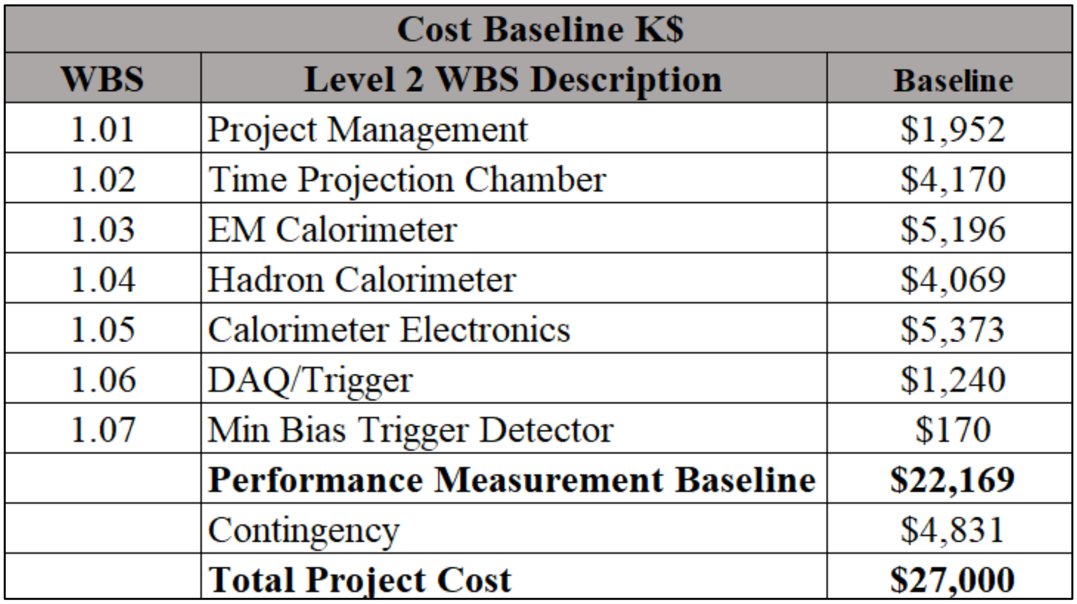
In addition to these KPPs, Ultimate Performance Parameters (UPPs) have been defined. The UPPs are listed in Table 1a and describe the performance needed after project completion to realize the scientific goals of the project. These parameters are outside the project's scope.

Ultimate Performance Parameters
Upsilon (1S) mass resolution ≤ 125 MeV
≥ 90% Tracking Efficiency
≤ 10% momentum resolution at 40 GeV /c
≤ 150% / $\sqrt{E_{jet}}$ jet-energy resolution for R=0.2 jets
≤ 8% single photon energy resolution at 15 GeV

Table 1a: Ultimate Performance Parameters. UPPs for measurements made at 10% central Au+Au RHIC events at the average RHIC store luminosity

5.2 Cost Baseline

The Total Project Cost of the sPHENIX MIE is $27.0 million AY dollars ($). The breakdown by WBS Level 2 can be seen in Table 2. The cost baseline includes the contingency estimate of an overall average cost contingency of 27.5% on "to go" activities. The contingency was based on a bottom-up contingency estimate that included a graded contingency rating given to each WBS element where the grade applied was determined from the confidence in the choice of a specific item, source of pricing information, maturity of the design, and other similar factors in addition to a project risk assessment on all activities.



Cost Baseline K$		
WBS	**Level 2 WBS Description**	**Baseline**
1.01	Project Management	$1,952
1.02	Time Projection Chamber	$4,170
1.03	EM Calorimeter	$5,196
1.04	Hadron Calorimeter	$4,069
1.05	Calorimeter Electronics	$5,373
1.06	DAQ/Trigger	$1,240
1.07	Min Bias Trigger Detector	$170
	Performance Measurement Baseline	**$22,169**
	Contingency	$4,831
	Total Project Cost	**$27,000**

Table 2: sPHENIX MIE Total Project Cost in AYk$ approved at PD-2/3. The baseline budget and associated project scope were reduced by $501k in FY23 based on an agreement between the sPHENIX Project, BNL and DOE.

5.3 Schedule Baseline

The Level 1 Project milestones of the Major Item of Equipment (MIE) are seen in Table 3. The MIE Approve PD-4 Project Completion date is Q1 FY2023, which includes 14 months of schedule contingency. The Project Schedule Milestones not included in the Level 1 milestones are shown in Table 4. The sPHENIX Project Summary Schedule is shown in Figure 1. The Project early completion date is October 2021. The major technical milestones of the Level 2 subsystem that are the MIE deliverables can be seen in Table 5. The integrated Resource-Loaded Schedule (RLS) has a Critical Path (CP) that goes through the procurement, fabrication and assembly of the EMCal prototype. It proceeds through Calorimeter Electronics procurement, fabrication and assembly of the Silicon Photomultipliers (SiPM). Finally, the CP runs through EMCal Module/Sector (production) fabrication and assembly, followed by EMCal sector testing. The RLS CP is shown in Figure 1.

The project requested and received CD-1/3A approval on August 16, 2018. The scope of the CD-3A long lead procurements (LLPs) is: Scintillating Tiles for the HCal, SiPMs for the EMCal and HCal readout, Scintillating Fibers Production order for the EMCal, Tungsten Powder Production Order for the EMCal and the cost is $5.850 million including 30% contingency. These are long lead procurements because they are on or near the critical path or are part of components/systems on or near the critical path or are a challenging procurement from a foreign vendor.

Project Decisions PD-2, PD-3 and PD-4 will require the approval of the BNL Laboratory Director and the concurrence of the BHSO Site Manager and the Associate Director of the Office of Science for NP. PD approvals will be based on results from IPRs, the clearing of pre-approval action items resulting from those reviews, and the approval of documentation provided by the sPHENIX Project to the Lab Director such as the Project Management Plan, Technical Design Report, Basis of Estimate documents, etc. A PD-3 approval was requested by sPHENIX at the same time as the PD-2 approval. The plan was based on the assessment by the project team that the technical design and R&D of all Level 2 systems was 90% complete in the aggregate at the time of the PD-2/3 Review.

Milestone Level 1	Schedule Date
CD-0, Approve Mission Need	9/16/2016 (A)
CD-1/3A, Approve Conceptual Design, Alternative Selection and Cost Range, and Long Lead Procurements	8/16/2018 (A)
Approve PD-2/3, Approve Performance Baseline/Approve Project Production	Q4 FY 2019
Approve PD-4, Approve Project Completion	Q1 FY 2023

Table 3: Table of sPHENIX MIE Project Decision Milestones at the time of PD-2/3

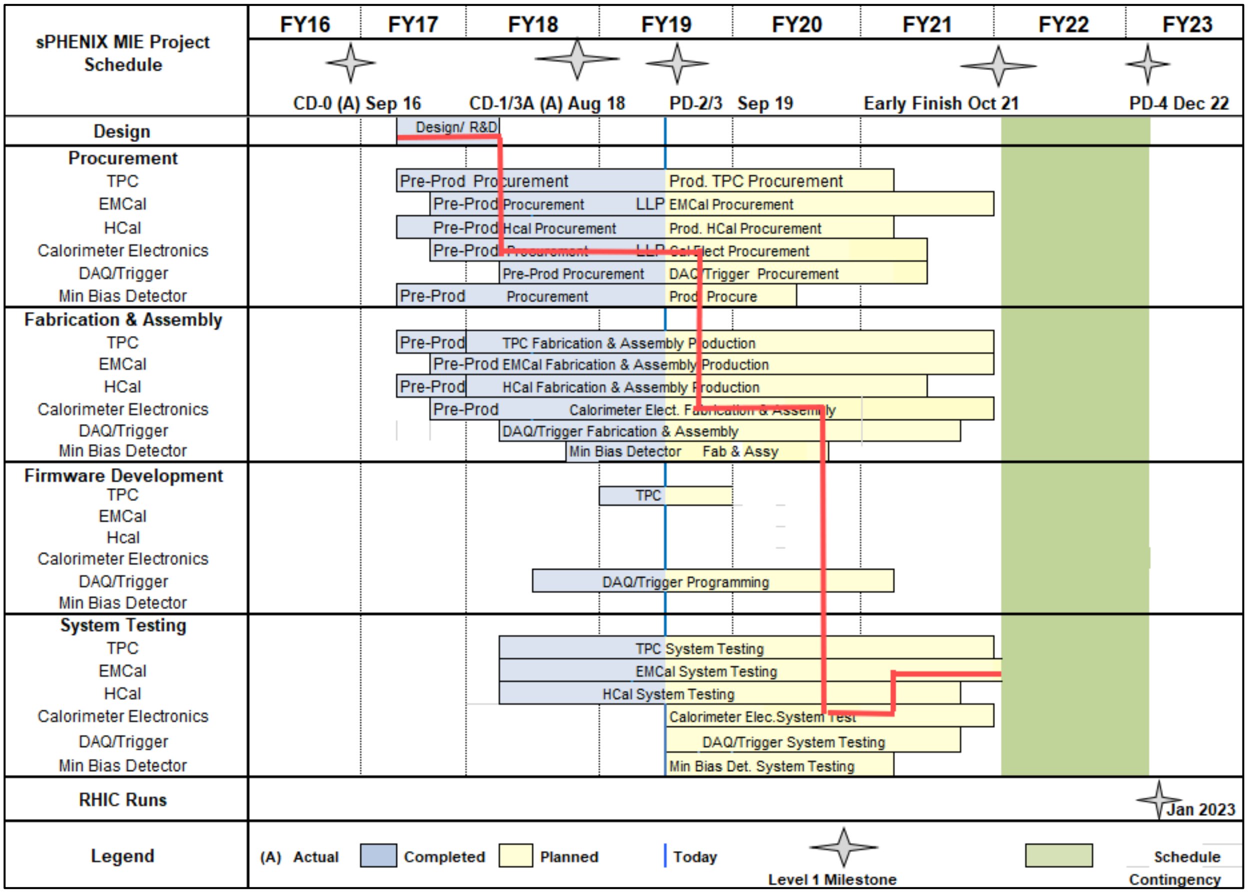
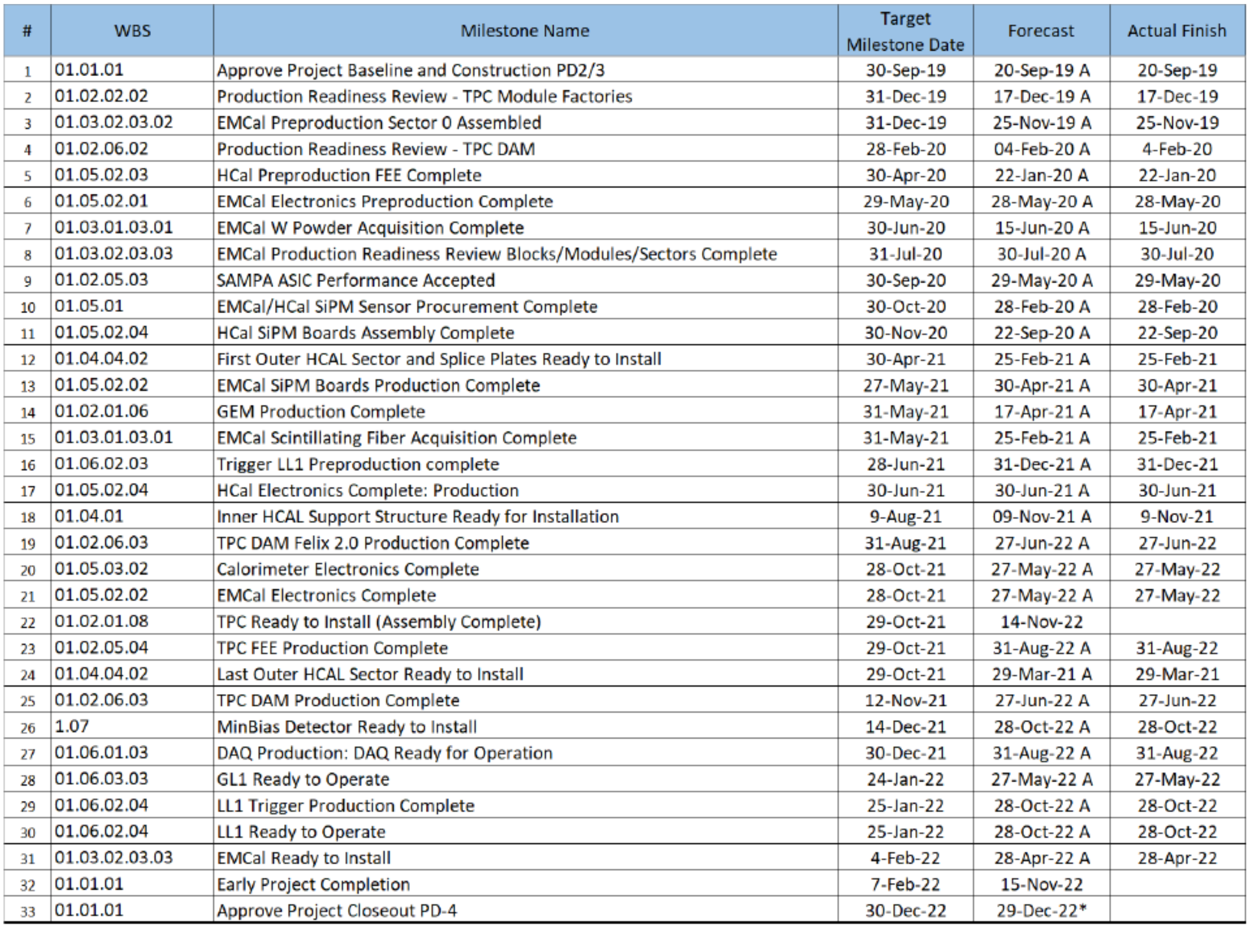


Figure 3: sPHENIX MIE Summary Schedule at the time of PD-2/3 Approvl. The red line shows the project critical path.



#	WBS	Milestone Name	Target Milestone Date	Forecast	Actual Finish
1	01.01.01	Approve Project Baseline and Construction PD2/3	30-Sep-19	20-Sep-19 A	20-Sep-19
2	01.02.02.02	Production Readiness Review - TPC Module Factories	31-Dec-19	17-Dec-19 A	17-Dec-19
3	01.03.02.03.02	EMCal Preproduction Sector 0 Assembled	31-Dec-19	25-Nov-19 A	25-Nov-19
4	01.02.06.02	Production Readiness Review - TPC DAM	28-Feb-20	04-Feb-20 A	4-Feb-20
5	01.05.02.03	HCal Preproduction FEE Complete	30-Apr-20	22-Jan-20 A	22-Jan-20
6	01.05.02.01	EMCal Electronics Preproduction Complete	29-May-20	28-May-20 A	28-May-20
7	01.03.01.03.01	EMCal W Powder Acquisition Complete	30-Jun-20	15-Jun-20 A	15-Jun-20
8	01.03.02.03.03	EMCal Production Readiness Review Blocks/Modules/Sectors Complete	31-Jul-20	30-Jul-20 A	30-Jul-20
9	01.02.05.03	SAMPA ASIC Performance Accepted	30-Sep-20	29-May-20 A	29-May-20
10	01.05.01	EMCal/HCal SiPM Sensor Procurement Complete	30-Oct-20	28-Feb-20 A	28-Feb-20
11	01.05.02.04	HCal SiPM Boards Assembly Complete	30-Nov-20	22-Sep-20 A	22-Sep-20
12	01.04.04.02	First Outer HCAL Sector and Splice Plates Ready to Install	30-Apr-21	25-Feb-21 A	25-Feb-21
13	01.05.02.02	EMCal SiPM Boards Production Complete	27-May-21	30-Apr-21 A	30-Apr-21
14	01.02.01.06	GEM Production Complete	31-May-21	17-Apr-21 A	17-Apr-21
15	01.03.01.03.01	EMCal Scintillating Fiber Acquisition Complete	31-May-21	25-Feb-21 A	25-Feb-21
16	01.06.02.03	Trigger LL1 Preproduction complete	28-Jun-21	31-Dec-21 A	31-Dec-21
17	01.05.02.04	HCal Electronics Complete: Production	30-Jun-21	30-Jun-21 A	30-Jun-21
18	01.04.01	Inner HCAL Support Structure Ready for Installation	9-Aug-21	09-Nov-21 A	9-Nov-21
19	01.02.06.03	TPC DAM Felix 2.0 Production Complete	31-Aug-21	27-Jun-22 A	27-Jun-22
20	01.05.03.02	Calorimeter Electronics Complete	28-Oct-21	27-May-22 A	27-May-22
21	01.05.02.02	EMCal Electronics Complete	28-Oct-21	27-May-22 A	27-May-22
22	01.02.01.08	TPC Ready to Install (Assembly Complete)	29-Oct-21	14-Nov-22	
23	01.02.05.04	TPC FEE Production Complete	29-Oct-21	31-Aug-22 A	31-Aug-22
24	01.04.04.02	Last Outer HCAL Sector Ready to Install	29-Oct-21	29-Mar-21 A	29-Mar-21
25	01.02.06.03	TPC DAM Production Complete	12-Nov-21	27-Jun-22 A	27-Jun-22
26	1.07	MinBias Detector Ready to Install	14-Dec-21	28-Oct-22 A	28-Oct-22
27	01.06.01.03	DAQ Production: DAQ Ready for Operation	30-Dec-21	31-Aug-22 A	31-Aug-22
28	01.06.03.03	GL1 Ready to Operate	24-Jan-22	27-May-22 A	27-May-22
29	01.06.02.04	LL1 Trigger Production Complete	25-Jan-22	28-Oct-22 A	28-Oct-22
30	01.06.02.04	LL1 Ready to Operate	25-Jan-22	28-Oct-22 A	28-Oct-22
31	01.03.02.03.03	EMCal Ready to Install	4-Feb-22	28-Apr-22 A	28-Apr-22
32	01.01.01	Early Project Completion	7-Feb-22	15-Nov-22	
33	01.01.01	Approve Project Closeout PD-4	30-Dec-22	29-Dec-22*	

Table 4: Level 2 Subsystem technical milestones of the sPHENIX MIE

5.4 Detailed Control Account Performance

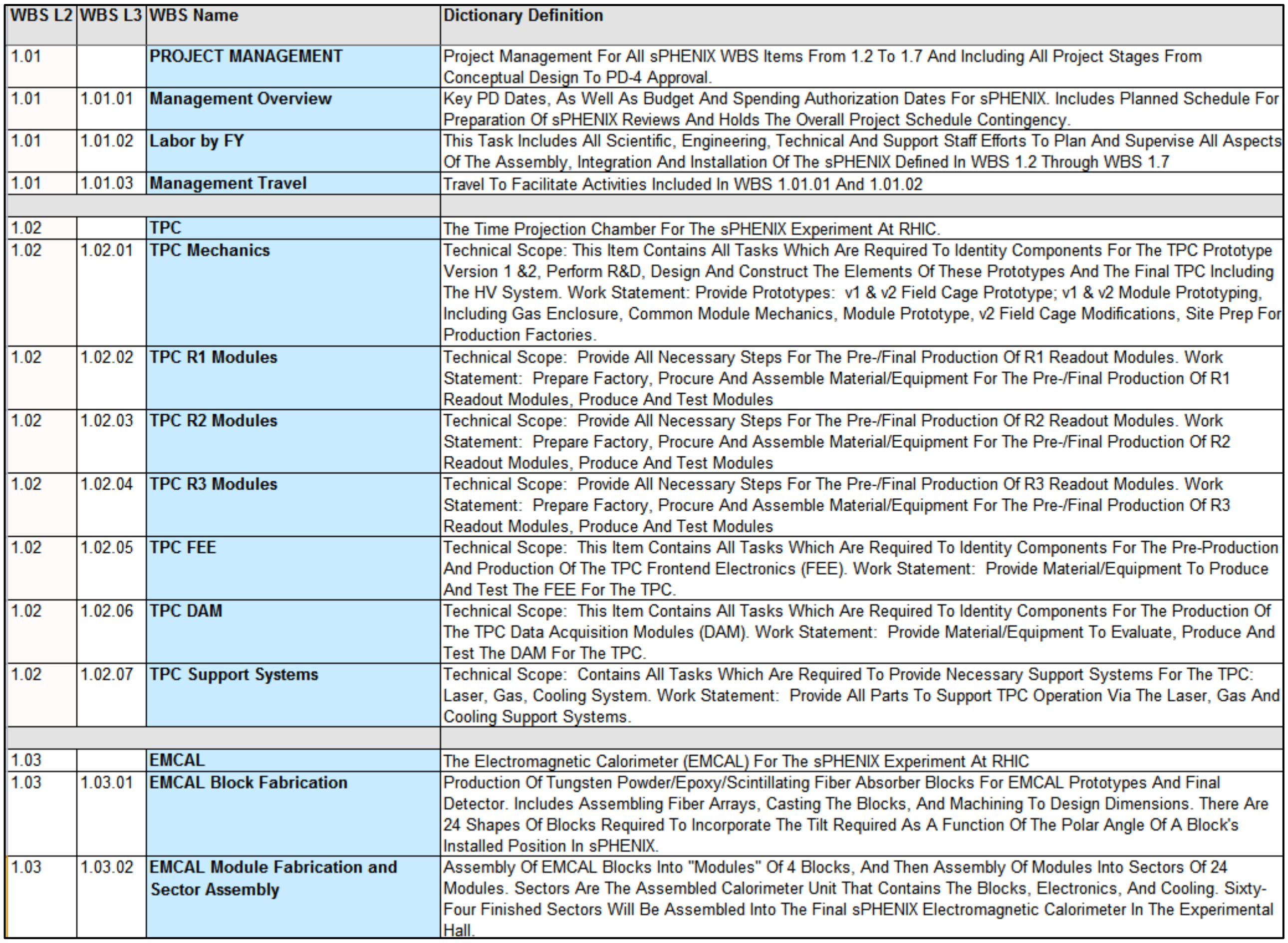
The Scope Verification documents give the final financial performance by Level-2 Control Account. They are in the sPHENIX Document Archives (and posted to the Indico review site).

The final sPHENIX schedule performance against the PD-2/3 Performance Baseline is in the final P6 Progress file printout, also filed in the sPHENIX Document archives (and posted to the Indico Review site). All activities are complete thus the SPI is 1.0 by definition. (Note added: The P6 Progress file on the Indico page has a Data Date of November 30, 2022. The final JACK boards arrived on December 7, 2022. Thus, activity S143285 for the JACK boards will be claimed complete in the final progress taken on December 31, 2022.)

5.5 Work Breakdown Structure

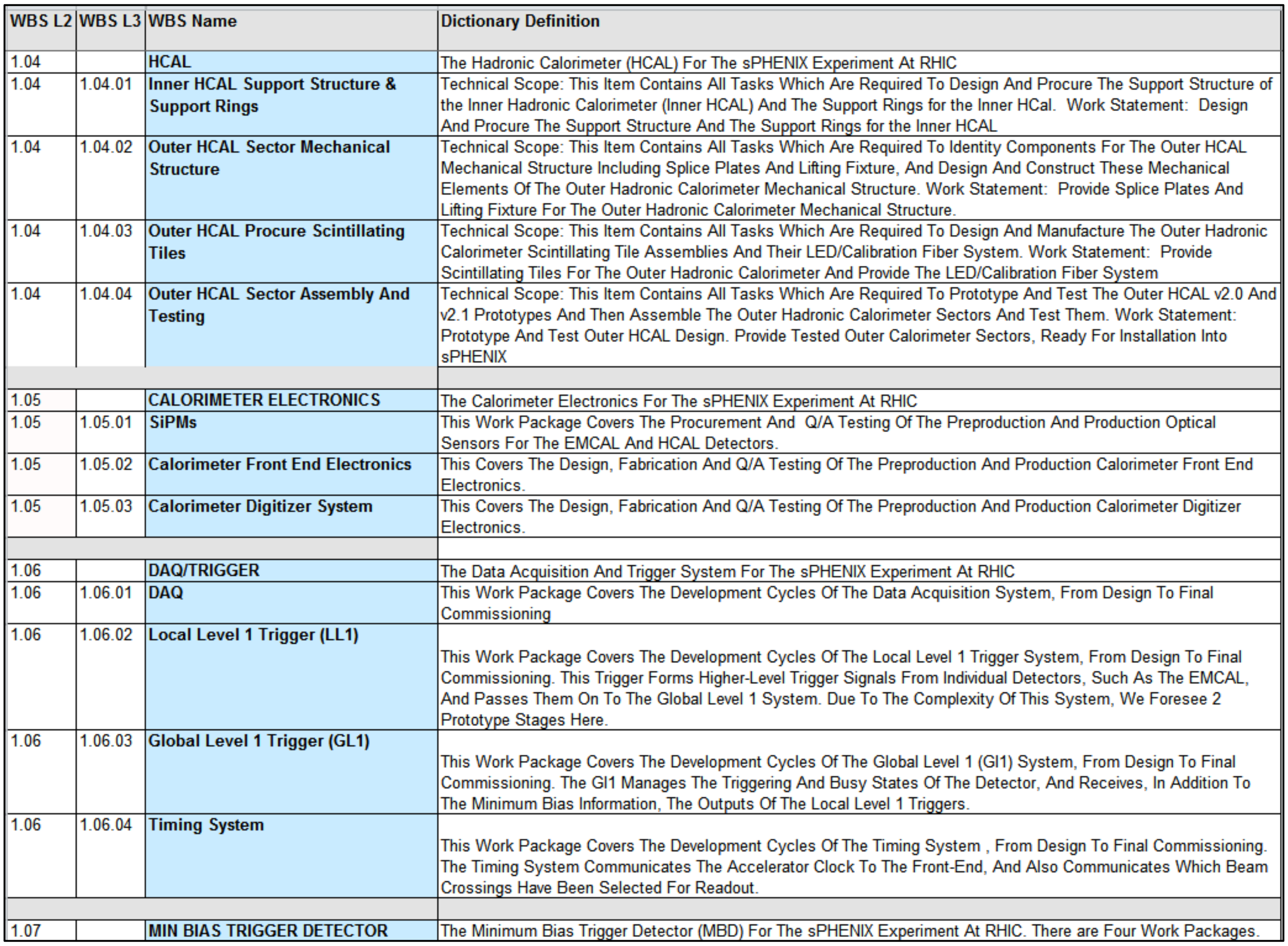
The sPHENIX MIE has been organized into a WBS with seven Level-2 items and that is documented in the WBS dictionary. The WBS Dictionary to Level-3 is shown in Table 5a and Table 5b. The full WBS Dictionary, to level 5 is included in the sPHENIX Archival material.

Figure 4: The Level 2 and Level 3 Work Breakdown Structure for sPHENIX MIE



WBS L2	WBS L3	WBS Name	Dictionary Definition
1.01		**PROJECT MANAGEMENT**	Project Management For All sPHENIX WBS Items From 1.2 To 1.7 And Including All Project Stages From Conceptual Design To PD-4 Approval.
1.01	1.01.01	**Management Overview**	Key PD Dates, As Well As Budget And Spending Authorization Dates For sPHENIX. Includes Planned Schedule For Preparation Of sPHENIX Reviews And Holds The Overall Project Schedule Contingency.
1.01	1.01.02	**Labor by FY**	This Task Includes All Scientific, Engineering, Technical And Support Staff Efforts To Plan And Supervise All Aspects Of The Assembly, Integration And Installation Of The sPHENIX Defined In WBS 1.2 Through WBS 1.7
1.01	1.01.03	**Management Travel**	Travel To Facilitate Activities Included In WBS 1.01.01 And 1.01.02
1.02		**TPC**	The Time Projection Chamber For The sPHENIX Experiment At RHIC.
1.02	1.02.01	**TPC Mechanics**	Technical Scope: This Item Contains All Tasks Which Are Required To Identity Components For The TPC Prototype Version 1 &2, Perform R&D, Design And Construct The Elements Of These Prototypes And The Final TPC Including The HV System. Work Statement: Provide Prototypes: v1 & v2 Field Cage Prototype; v1 & v2 Module Prototyping, Including Gas Enclosure, Common Module Mechanics, Module Prototype, v2 Field Cage Modifications, Site Prep For Production Factories.
1.02	1.02.02	**TPC R1 Modules**	Technical Scope: Provide All Necessary Steps For The Pre-/Final Production Of R1 Readout Modules. Work Statement: Prepare Factory, Procure And Assemble Material/Equipment For The Pre-/Final Production Of R1 Readout Modules, Produce And Test Modules
1.02	1.02.03	**TPC R2 Modules**	Technical Scope: Provide All Necessary Steps For The Pre-/Final Production Of R2 Readout Modules. Work Statement: Prepare Factory, Procure And Assemble Material/Equipment For The Pre-/Final Production Of R2 Readout Modules, Produce And Test Modules
1.02	1.02.04	**TPC R3 Modules**	Technical Scope: Provide All Necessary Steps For The Pre-/Final Production Of R3 Readout Modules. Work Statement: Prepare Factory, Procure And Assemble Material/Equipment For The Pre-/Final Production Of R3 Readout Modules, Produce And Test Modules
1.02	1.02.05	**TPC FEE**	Technical Scope: This Item Contains All Tasks Which Are Required To Identity Components For The Pre-Production And Production Of The TPC Frontend Electronics (FEE). Work Statement: Provide Material/Equipment To Produce And Test The FEE For The TPC.
1.02	1.02.06	**TPC DAM**	Technical Scope: This Item Contains All Tasks Which Are Required To Identity Components For The Production Of The TPC Data Acquisition Modules (DAM). Work Statement: Provide Material/Equipment To Evaluate, Produce And Test The DAM For The TPC.
1.02	1.02.07	**TPC Support Systems**	Technical Scope: Contains All Tasks Which Are Required To Provide Necessary Support Systems For The TPC: Laser, Gas, Cooling System. Work Statement: Provide All Parts To Support TPC Operation Via The Laser, Gas And Cooling Support Systems.
1.03		**EMCAL**	The Electromagnetic Calorimeter (EMCAL) For The sPHENIX Experiment At RHIC
1.03	1.03.01	**EMCAL Block Fabrication**	Production Of Tungsten Powder/Epoxy/Scintillating Fiber Absorber Blocks For EMCAL Prototypes And Final Detector. Includes Assembling Fiber Arrays, Casting The Blocks, And Machining To Design Dimensions. There Are 24 Shapes Of Blocks Required To Incorporate The Tilt Required As A Function Of The Polar Angle Of A Block's Installed Position In sPHENIX.
1.03	1.03.02	**EMCAL Module Fabrication and Sector Assembly**	Assembly Of EMCAL Blocks Into "Modules" Of 4 Blocks, And Then Assembly Of Modules Into Sectors Of 24 Modules. Sectors Are The Assembled Calorimeter Unit That Contains The Blocks, Electronics, And Cooling. Sixty-Four Finished Sectors Will Be Assembled Into The Final sPHENIX Electromagnetic Calorimeter In The Experimental Hall.

Table 5a: WBS Dictionary at the Level 2 and Level 3 Work Breakdown Structure for the sPHENIX MIE. The WBS Dictionary describes the project scope to Level 3 of the WBS 1.1 – 1.3.



WBS L2	WBS L3	WBS Name	Dictionary Definition
1.04		**HCAL**	The Hadronic Calorimeter (HCAL) For The sPHENIX Experiment At RHIC
1.04	1.04.01	**Inner HCAL Support Structure & Support Rings**	Technical Scope: This Item Contains All Tasks Which Are Required To Design And Procure The Support Structure of the Inner Hadronic Calorimeter (Inner HCAL) And The Support Rings for the Inner HCal. Work Statement: Design And Procure The Support Structure And The Support Rings for the Inner HCAL
1.04	1.04.02	**Outer HCAL Sector Mechanical Structure**	Technical Scope: This Item Contains All Tasks Which Are Required To Identity Components For The Outer HCAL Mechanical Structure Including Splice Plates And Lifting Fixture, And Design And Construct These Mechanical Elements Of The Outer Hadronic Calorimeter Mechanical Structure. Work Statement: Provide Splice Plates And Lifting Fixture For The Outer Hadronic Calorimeter Mechanical Structure.
1.04	1.04.03	**Outer HCAL Procure Scintillating Tiles**	Technical Scope: This Item Contains All Tasks Which Are Required To Design And Manufacture The Outer Hadronic Calorimeter Scintillating Tile Assemblies And Their LED/Calibration Fiber System. Work Statement: Provide Scintillating Tiles For The Outer Hadronic Calorimeter And Provide The LED/Calibration Fiber System
1.04	1.04.04	**Outer HCAL Sector Assembly And Testing**	Technical Scope: This Item Contains All Tasks Which Are Required To Prototype And Test The Outer HCAL v2.0 And v2.1 Prototypes And Then Assemble The Outer Hadronic Calorimeter Sectors And Test Them. Work Statement: Prototype And Test Outer HCAL Design. Provide Tested Outer Calorimeter Sectors, Ready For Installation Into sPHENIX
1.05		**CALORIMETER ELECTRONICS**	The Calorimeter Electronics For The sPHENIX Experiment At RHIC
1.05	1.05.01	**SiPMs**	This Work Package Covers The Procurement And Q/A Testing Of The Preproduction And Production Optical Sensors For The EMCAL And HCAL Detectors.
1.05	1.05.02	**Calorimeter Front End Electronics**	This Covers The Design, Fabrication And Q/A Testing Of The Preproduction And Production Calorimeter Front End Electronics.
1.05	1.05.03	**Calorimeter Digitizer System**	This Covers The Design, Fabrication And Q/A Testing Of The Preproduction And Production Calorimeter Digitizer Electronics.
1.06		**DAQ/TRIGGER**	The Data Acquisition And Trigger System For The sPHENIX Experiment At RHIC
1.06	1.06.01	**DAQ**	This Work Package Covers The Development Cycles Of The Data Acquisition System, From Design To Final Commissioning
1.06	1.06.02	**Local Level 1 Trigger (LL1)**	This Work Package Covers The Development Cycles Of The Local Level 1 Trigger System, From Design To Final Commissioning. This Trigger Forms Higher-Level Trigger Signals From Individual Detectors, Such As The EMCAL, And Passes Them On To The Global Level 1 System. Due To The Complexity Of This System, We Foresee 2 Prototype Stages Here.
1.06	1.06.03	**Global Level 1 Trigger (GL1)**	This Work Package Covers The Development Cycles Of The Global Level 1 (Gl1) System, From Design To Final Commissioning. The Gl1 Manages The Triggering And Busy States Of The Detector, And Receives, In Addition To The Minimum Bias Information, The Outputs Of The Local Level 1 Triggers.
1.06	1.06.04	**Timing System**	This Work Package Covers The Development Cycles Of The Timing System , From Design To Final Commissioning. The Timing System Communicates The Accelerator Clock To The Front-End, And Also Communicates Which Beam Crossings Have Been Selected For Readout.
1.07		**MIN BIAS TRIGGER DETECTOR**	The Minimum Bias Trigger Detector (MBD) For The sPHENIX Experiment At RHIC. There are Four Work Packages.

Table 5b: WBS Dictionary at the Level 2 and Level 3 Work Breakdown Structure for the sPHENIX MIE.
The WBS Dictionary describes the project scope to Level 3 of the WBS 1.4 – 1.7.

5.6 Funding Profile

The Total Project Cost for sPHENIX is $26.499M as shown in Table 6. This project is implemented with existing funding from within the RHIC facility operations budget provided by US Department of Energy Office of Nuclear Physics (DOE-ONP).

Funding Profile At Year k$								
	FY17	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**Total**
R&D	1,513	4,260	350					**6,123**
CDR	100	200						**300**
PED								
Pre-ops								
OPC (R&D+CDR)	**1,613**	**4,460**	**350**					**6,423**
TEC			**5,310**	**9,524**	**5,530**	**213**	**-501**	**20,076**
Total Project Cost	**1,613**	**4,460**	**5,660**	**9,524**	**5,530**	**213**	**-501**	**26,499**

Table 6: sPHENIX Baseline Funding Profile

5.7 Environmental Requirements/Permits

In accordance with NEPA (required by DOE Order 451.1B), an Environmental Evaluation Notification Form has been completed for the sPHENIX MIE by the BNL Environmental Protection Division. This document was submitted to DOE- BHSO on April 16, 2016 for review and NEPA determination as required by 10 CFR 1021 which are DOE's Rules for Implementing NEPA. The Categorical Exclusion was approved. A Hazard Analysis Report has also been developed. The report concludes that all hazards identified are similar in nature and magnitude to those already found in other types of nuclear or particle physics projects. The impact of any hazard will be minor off-site and negligible on-site. The Hazard Analysis Report will be updated as required.

The ES&H requirements for the proposed sPHENIX Experiment begin with BNL's Institutional Assessment Process as related to Accelerator Safety. These requirements are delineated by DOE Order 420.2C "Safety of Accelerator Facilities". Oversight is conducted by the Operations Management Division of the DOE Site Office (BHSO). This is not limited to just ionizing radiation hazards from beams or sources. It is for analysis of the other two non-standard industrial safety hazards, namely, large volumes of flammable gas and the potential for oxygen deficiency from helium, nitrogen, or other inert gases.

The BNL organizational requirements for compliance with ES&H are implemented by the Collider Accelerator Department (C-AD), Occupational Safety and Health (OSH), and Environmental programs. They are employed at the job level, are described in detail on the C-AD ES&H webpage and are compared to the ISMS for DOE. Additionally, guidance is also provided by the BNL SBMS in the Accelerator Safety subject area. The DOE O 420.2C Accelerator Safety Program must include a Safety Assessment Document (SAD), Accelerator Safety Envelope (ASE) and Unreviewed Safety Issue (USI) process. The sPHENIX Experiment is planned to be constructed in the existing RHIC 1008 Facility following PHENIX removal and repurposing. The designs, thus far, reveal that sPHENIX will be a similar experiment to PHENIX, from an ES&H perspective, of lesser scope with the added feature of a superconducting main magnet. Therefore, the hazards and controls for sPHENIX are expected to be similar to those previously included in the C-AD 2011 SAD (up for 2016 revision).

Nevertheless, mainly due to the addition of helium cooling, sPHENIX shall undergo a USI screening, evaluation and disposition workflow. By definition, a USI is a significant increase in the probability of, or consequences from: 1) A planned modification that creates a previously unanalyzed postulated accident or condition that could result in a significant adverse impact; or 2) A previously analyzed postulated accident or condition. The USI process starts by using a C-AD USI Checklist that asks a set of questions. Once answered, the checklist returns an evaluation with either a positive or negative result. A negative result requires no further action in regard to the SAD or ASE. If positive, a Hazard Analysis Report (HAR) is then sent to the Accelerator Safety Committee, the Experimental Safety Committee, and eventually DOE for approval. After BHSO approval, any resulting affects to the SAD and ASE are first added as appendices to the SAD prior to its five-year revision cycle.

In accordance with NEPA (required by DOE Order 451.1B), an Environmental Evaluation Notification Form has been completed for the sPHENIX MIE by the BNL Environmental Protection Division. This document was submitted to DOE- BHSO on April 16, 2016 for review and NEPA determination as required by 10 CFR 1021 which are DOE’s Rules for Implementing NEPA. The Categorical Exclusion was approved. A Hazard Analysis Report has also been developed. The report concludes that all hazards identified are similar in nature and magnitude to those already found in other types of nuclear or particle physics projects. The impact of any hazard will be minor off-site and negligible on-site. The Hazard Analysis Report will be updated as required.

5.8 Safety Record

The plan for equipment safeguards and cyber-security at the 1008 facility during the construction and operation of the sPHENIX MIE was evaluated by the BNL Protection Division and Information Technology Department. The assessment of both groups was that our equipment safeguards, and cyber-security plans are valid, and meet the BNL criteria established for both areas. The safeguards and security issues for this project are considered small and manageable with standard BNL practices currently in place. The project does not require a Security Vulnerability Assessment Report (SVAR) or additional security requirements that are not already addressed by current Brookhaven policies and procedures. The project uses the existing program and policy that is already approved by DOE.

6.0 CLOSEOUT STATUS

The Scope Verification documents for all seven of the Level-2 WBS areas have been prepared and signed, using budget information available as of the end of November 2022. All scope noted in the WBS Dictionary has been accomplished. The Scope Verification documents do note two cases where possible enhancements to the scope were not completed, namely the diffuse lasers and fiber bundles for the TPC and the added DCM-II capability for the DAQ system. These do not compromise the attainment of the KPPs nor the completion and delivery of all items noted in the WBS Dictionary.

Final invoices are still due for some completed work. A list of the relevant Purchase Orders has been submitted to the BNL financial office for assistance in obtaining and paying the needed invoices. No open purchases with incomplete deliverables remain.

7.0 LESSONS LEARNED

- Plan for possible significant shutdowns (COVID-19)
- Plan for supply disruptions (ongoing supply chain issues) (We actually did plan for a 3-month disruption, but COVID-19 overachieved there.)
- Continue all QC checks throughout multiyear procurements. We have two big examples - the change in tungsten powder size distribution for EMCal and the amine-blush issue for the HCal scintillating tiles. Both these took many weeks to identify and resolve.

- Allow for large increases in component lead times, in particular for electronics, where there are notable reliances on non-US supplies
- Vet all designs and also the planned fabrication timelines for component end-of-production timelines and issues, in particular for electronics and computer-related hardware
- Vet all consumable choices against potential supply interruptions and have a backup plan. Our big example is the loss of access to Neon gas for the TPC and the need to tweak designs of TPC HV components and re-evaluate expected rate and space-resolution performance.
- Complete prototyping in realistic conditions. The advanced calorimeter, TPC, calorimeter FEE and TPC FEE prototypes that could be exposed to tagged particle beams at FNAL were invaluable in certifying designs for production before final engineering drawings needed to be issued.
- Arrange for test stands as soon as possible for any ASICs to be developed. We relied on stands developed for ALICE, made possible by pursuing a parallel development of the SAMPA v5 based on the version SAMPA v4 developed for ALICE, but with improvements and specializations adapted for sPHENIX.
- Budget adequate time for ASIC trial runs and testing of the resulting prototypes, and budget time for a pre-production run of the actual design followed by extensive performance testing
- Strive for a stable personnel base for series production. Training and startup effort for a constantly changing personnel base are highly detrimental to keeping schedule.
- Include realistic calendars for scheduling contributed labor for production and testing. This must take into account the relevant university exam and teaching schedules and other laboratories' operating schedules.
- Plan procurement workloads to have enough officers and lead time to pursue multiple complex procurements in parallel. Assign at least one procurement liaison officer and have a tracking method that keeps all procurements up to date and avoids having any being lost in the shuffle.
- Define all detector monitoring systems by the time of CD-3 including technology and control methods, in order to budget adequate development time, testing time, and procurement time.
- Set up a system for handling, and if possible accruing, the inevitable tardy invoices, in order to keep track of cost performance of the project. sPHENIX relied heavily on a monthly accounting of the Estimate to Complete (ETC) and Estimate at Completion (EAC) that in turn relied extensively on a monthly accounting of incomplete procurements, where incomplete refers to the invoicing as well as actual material production.

8.0 KPP ACHIEVEMENT

There were eleven KPPs developed for the sPHENIX MIE. All have been met. The various KPPs, both threshold and Objective, and the measurements taken to show that they are met, are discussed in the following sections. We note that WBS 1.1 Management and WBS 1.5 Calorimeter Electronics were not assigned KPPS.

8.1 Time Projection Chamber (WBS 1.2)

Time Projection Chamber KPP – Live Channels

- Demonstration or Measurement: **Preinstall, bench tests**
- Threshold KPP's: ≥ **90% live channels based on Laser, pulser, cosmics**
- Objective KPP's: ≥ **95% live channels based on Laser, pulser, cosmics**

We report on live channel count through feeding pulse to the bottom side of the GEMs that are facing to the padplane. The pulses are then propagated to padplane through capacitive coupling. We went through all the readout channels at both ends, i.e., all 159,744 channels. Below are signal amplitudes for all the channels. The low ADU values (~50 ADU) corresponds to R1 section (most inner part) of a sector where the pad sizes are about half of those in R2 and R3. The channels whose amplitude is less than 20 ADU were defined as dead channels.

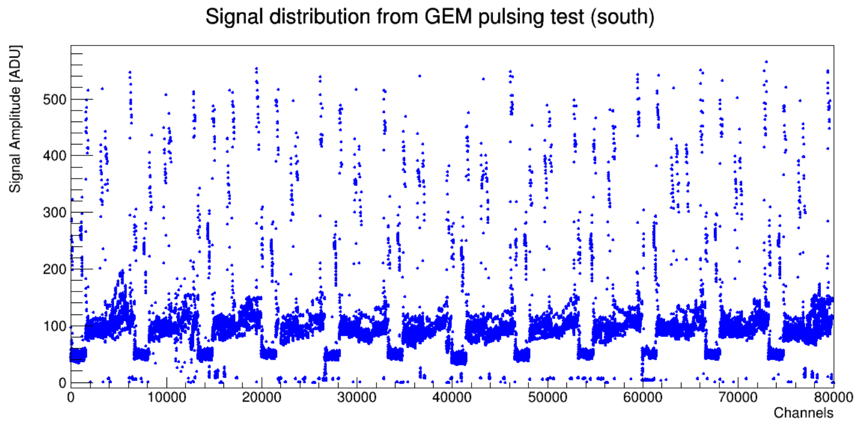
We observed 3746 channels out of 79872 in south are dead and that 2172 channels out of 79872 in north are dead. This results in a live channel percentage of:

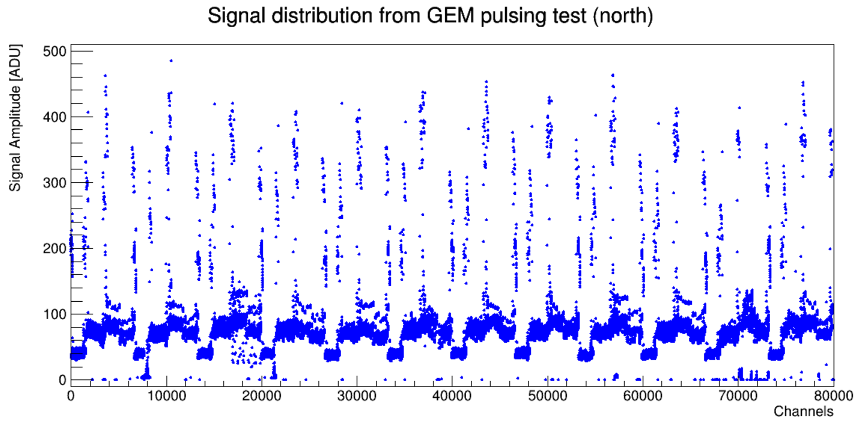
$$1 - (3746+2172)/(79872*2) = 0.963 \text{ (96.3\% alive)}$$

We found that 3136 out of 3746 in north and 1536 out of 2172 in south are due to SAMPA configuration issues or incomplete insertion of FEE cards. They are fixable, and if they are all fixed, the percentage will become:

$$1 – (610+626)/(79872*2) = 0.992 \text{ (99.2\% alive)}$$

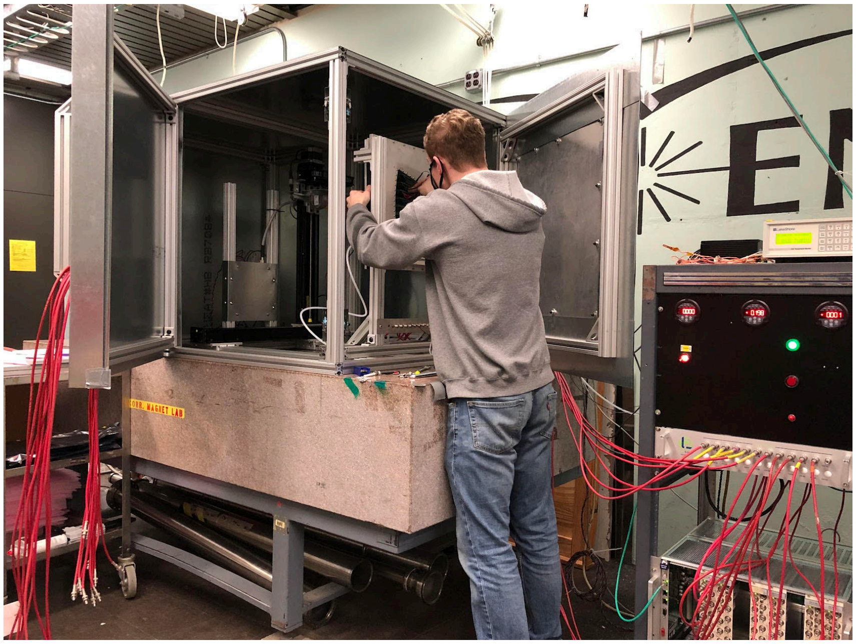
In any case, the live channel count exceeds the threshold KPP (90% live) and the objective KPP (95% live).


Signal distribution from GEM pulsing test (south)

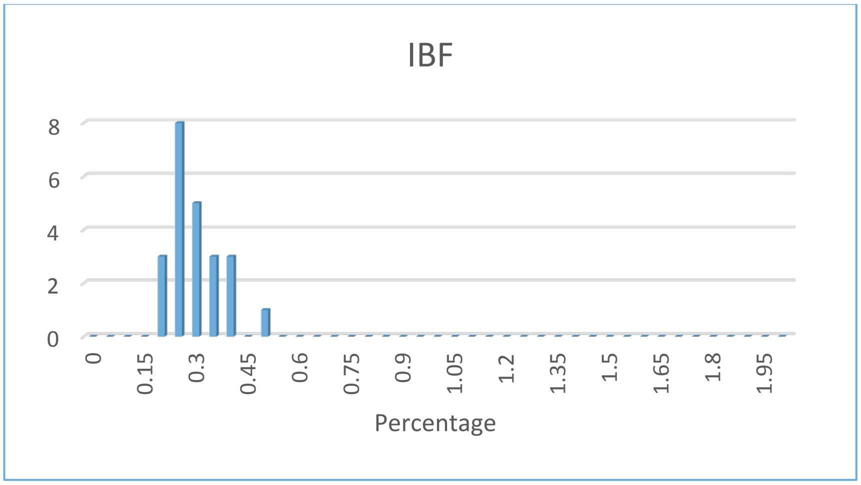

Signal distribution from GEM pulsing test (north)

Time Projection Chamber KPP – Ion Back Flow

- Demonstration or Measurement: **Preinstall, bench tests**
- Threshold KPP's: **Ion back flow ≤ 2% per GEM module averaged over the active area of each GEM module**
- Objective KPP's: **Same**



IBF measurements were performed using the gain characterization apparatus, with minor modifications to measure the very small induced current on the cathode plane. Measured IBF fractions were significantly better than required by the KPP as seen in the plot below.



Acceptable modules would have an IBF below 2%.
All modules passed this threshold very easily.

Time Projection Chamber KPP – Single Hit Efficiency

- Demonstration or Measurement: **Preinstall, bench tests w/cosmics**
- Threshold KPP's: **≥ 90% single hit efficiency/mip track, averaged over active TPC volume**
- Objective KPP's: **≥ 95% single hit efficiency/mip track, averaged over active TPC volume**

MIPs can be seen with one sector FEE and the HV, gas and cooling, all of which are now in hand and in place. Results expected by mid-November for the actual TPC. Earlier results exist but for test chambers hooked to actual TPC FEE.

The single hit efficiency per MIP track was measured using comic ray tracks triggered by coincidence of two scintillation counters which cover the acceptance of a TPC sector of interest.

Setup and condition:

We used the R2 (middle section in R) of the bottom sector for assessing the efficiency. Two of 140cm x 16cm scintillation counters were used to trigger cosmic rays. One scintillation counter was placed at the center of the TPC, and the other was placed on the floor below the TPC. The coincidence of the signal from two counters will ensure that the cosmic rays pass through the volume in R and phi space, but not in z. For evaluating the hit efficiency, we chose the tracks that made hits at the first and the last pad in R-cells (R-cells run from 0 to

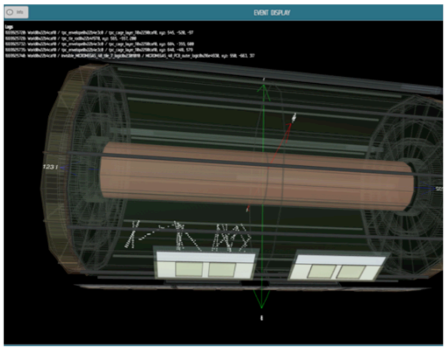
15). We applied high enough signal amplitude cut of ADU>25 on each pad to ensure the signals are real.

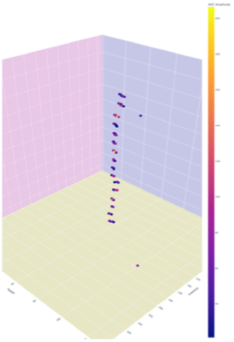
We counted the number of missing hits int R-cells for efficiency calculation. The resulting number of good tracks was 239.

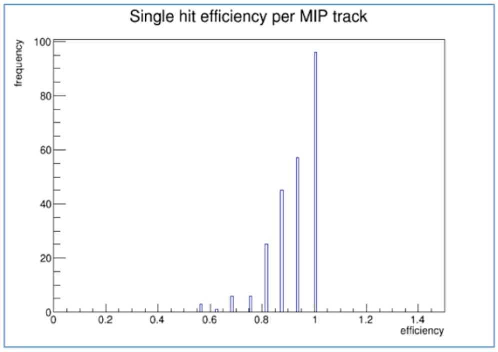
Result:

An example of over-laid MIP tracks triggered by the scintillation counters is shown in the figure below (left). Several tracks are accumulated and shown with TPC gas volume in outline. A single MIP track in the TPC can be seen in the middle figure.

Based on a sample of 239 cosmic tracks, 303 missing hits in R-cells were found in 239 tracks. This gives us the single hit efficiency as: 1-303/(239 * 16) = 0.92 (92%).





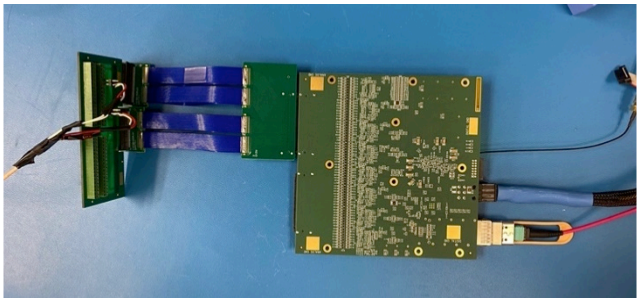


The single hit efficiency distribution is shown above (right). The track and signal pad selections are very tight, which would have decreased the efficiency significantly. Still, the efficiency is higher than 90%, which meets the threshold KPP. Measurements are continuing for the objective KPP, which seeks 95%.

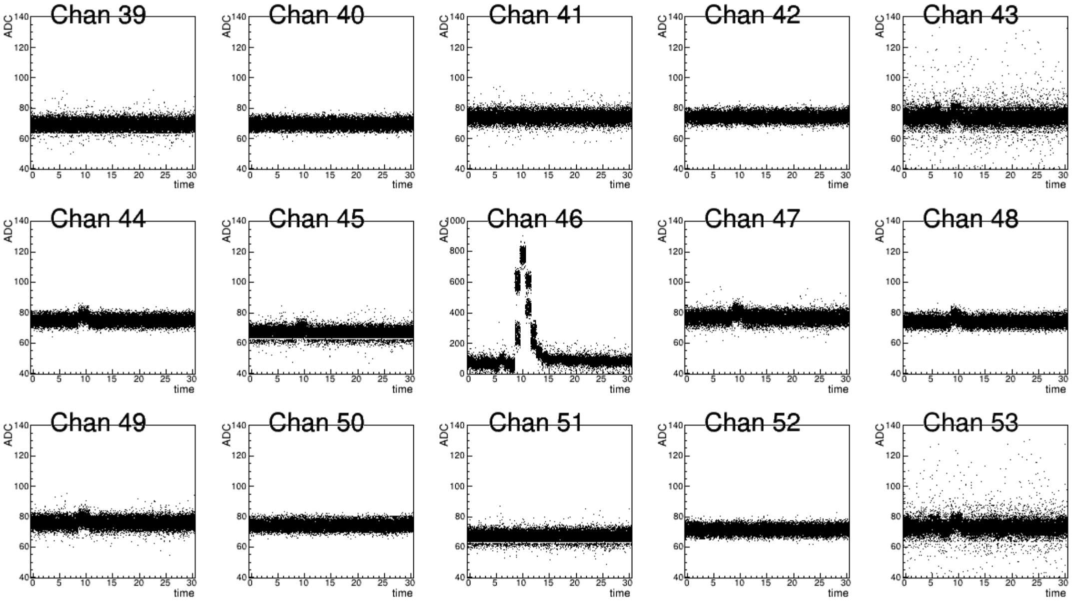
Time Projection Chamber KPP – Cross Talk

- Demonstration or Measurement: **Preinstall, FEE stand alone bench tests**
- Threshold KPP's: **Cross talk ≤ 2% per channel averaged over all channels**
- Objective KPP's: **Same**

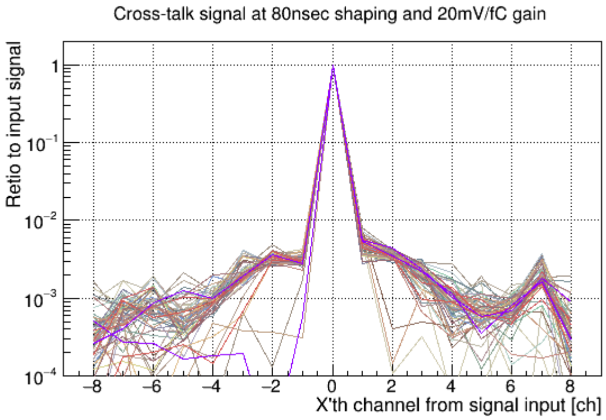
We injected signal charges into two channels only out of 128 manually at a time using the setup shown. The two channels are separated by 16 channels. We repeated this measurement 32 times, thus 64 channels out of 128 channels were measured in total. This is sufficient to assess the crosstalk level on the FEE.

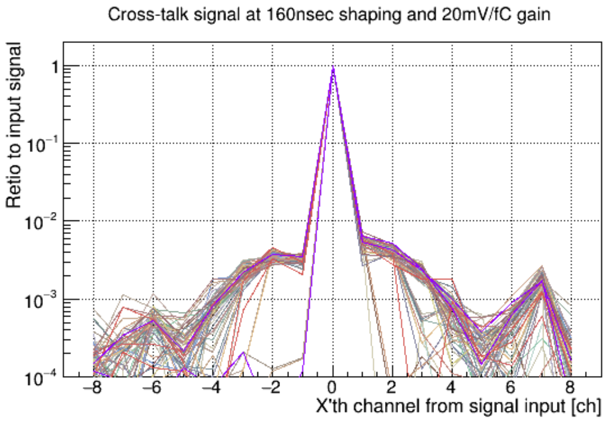


The input signal is adjusted so that it yields an ADC count of 900-1000 out of the full ADC range of 0-1024, making the crosstalk in the neighboring channels maximally measurable. The figure shows the ADC vs sampling time for the channel (Ch. 46) where charges are fed in and for the +/- 7 neighboring channels. Note the vertical scale is set to 0-1000 for the signal channel, and 40-140 for neighboring channels, respectively.



We quantified the level of crosstalk in a given channel with respect to the magnitude of signal channel by the ratio of their respective ADC counts. The figures below show the level of crosstalk for neighboring +/-8 channels for two shaping times (80 and 160 nsec). Both gains are 20mV/fC. It is seen that the crosstalk is a little larger in the 80nsec case than that of the 160nsec case (as seen by the difference in the width of the distributions). This trend is consistent with expectation. <u>It was found that no channel has crosstalk level larger than 1% in either case.</u>





8.2 Electromagnetic Calorimeter (WBS 1.3)

Electromagnetic Calorimeter KPP – Live Channels

- Demonstration or Measurement: **Preinstall, bench tests**
- Threshold KPP's: ≥ **90% live channels based on LED, cosmics**
- Objective KPP's: ≥ **95% live channels based on LED, cosmics**

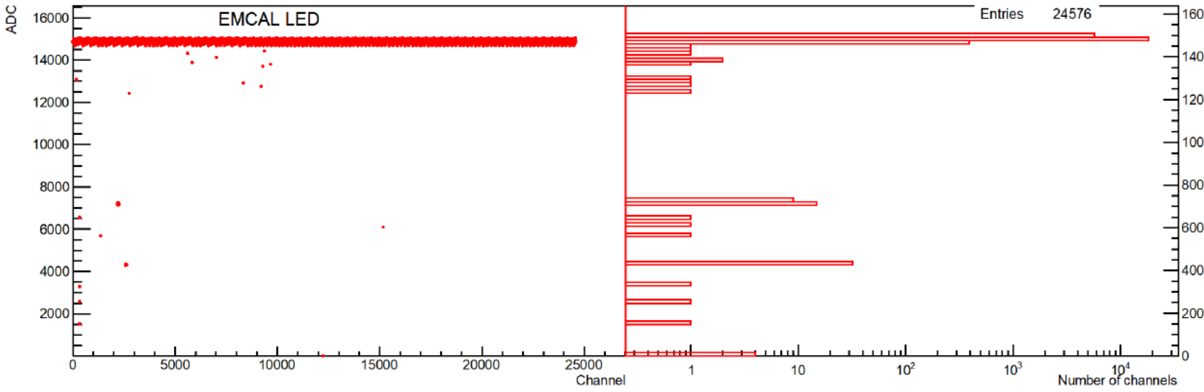
The LEDs are driven by a variable pulse width driver that can vary the amplitude of the LED signal from each channel.

Due to variations in the amount of LED light seen by each channel, no single pulse width can put the LED signal in the nominal ADC range for all channels simultaneously. However, there is an appropriate pulse width for each channel that can be used to calibrate and monitor each channel during normal data taking.

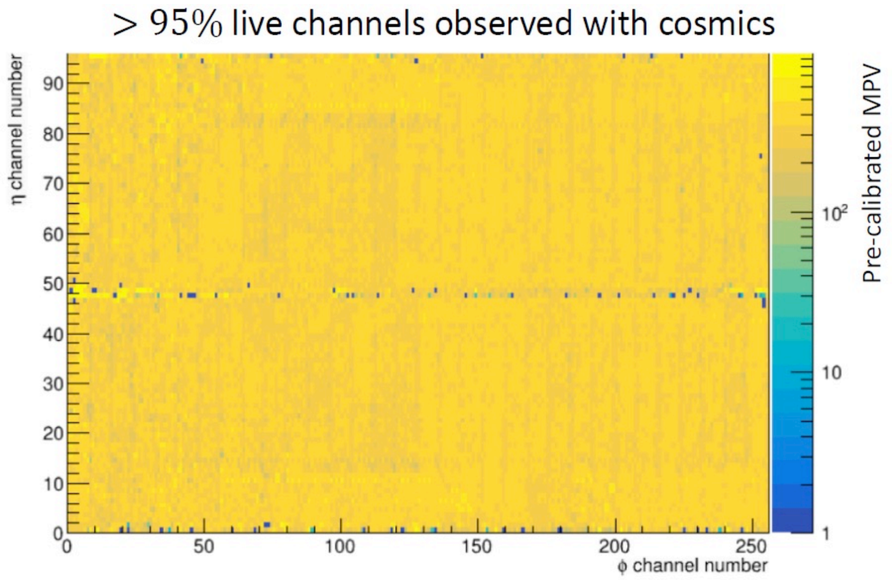
For the purpose of satisfying the EMCAL KPPs using the LEDs, all channels were driven into saturation using a long pulse width. An example of several channels being driven into saturation is shown in the next plot.

Left hand plot shows ADC value vs channel number when the LEDs are driven into saturation

Right hand plot is a frequency histogram showing most channels are driven into ADC saturation, and are thus "live". Fewer than 80 channels, or 0.3%, do not show full ADC response



Live channels can also be checked by observing the amplitude of cosmic ray peaks in individual towers. The plot below shows better than 95% of channels respond.



Extreme values measured at η channel numbers ~ 0, ~ 48, ~ 96 are due to limited scintillator panel coverage

Electromagnetic Calorimeter KPP – Absolute Energy Precalibration

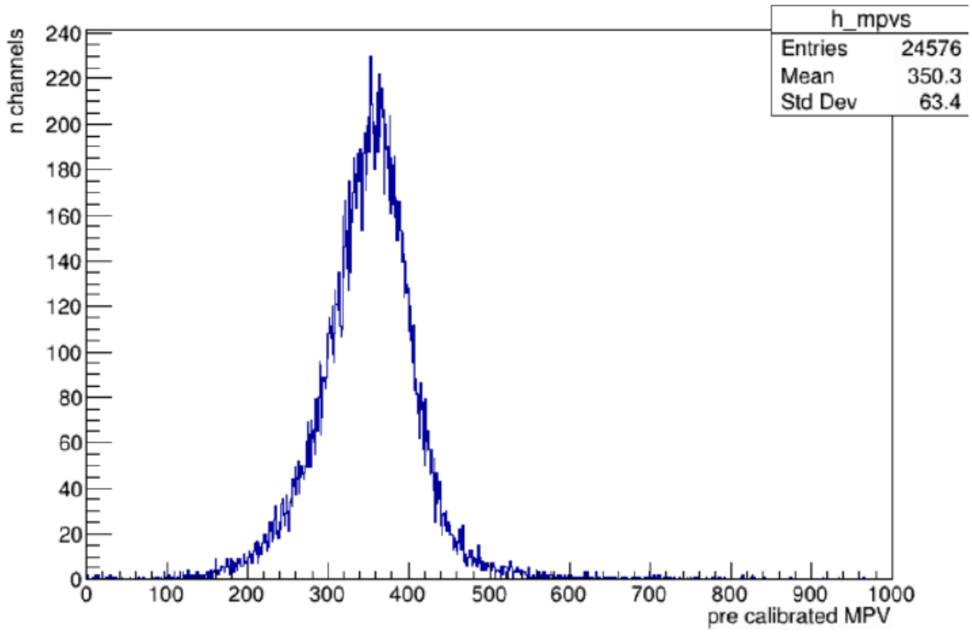
- Demonstration or Measurement: **Preinstall, bench tests**
- Threshold KPP's: **Each sector w/ an absolute energy precalibration of ≤ 35% RMS**
- Objective KPP's: **Same**

Individual towers were pre-calibrated following a two-step process:

1. Each channel MPV is corrected for differences in gain observed in the single pixel gap (spg) measurements; Correction factor = 30 / measured spg

2. Each channel MPV is corrected for differences in the observed light output from different scintillating fiber production batches. Correction factor = 350 / $\langle MPV \rangle$ determined for each fiber batch.

Once the simulation study completes a third correction factor will be applied to convert from ADC to energy for MIPs. Will be position dependent and is expected to further reduce the RMS. For the full 24,576 channels in the EMCal the RMS/mean for the pre-calibrated MPVs is 18.1%. Pre-calibration is about a factor 2 below the KPP requirement of precalibration for each sector to within an RMS of 35%



8.3 Hadronic Calorimeter (WBS 1.4)

Hadronic Calorimeter KPP – Live Channels

- Demonstration or Measurement: **Preinstall, bench tests**
- Threshold KPP's: ≥ **90% live channels based on LED, cosmics**
- Objective KPP's: ≥ **95% live channels based on LED, cosmics**

All towers in all sectors were verified with electronics test pulse, LED test pulse, and cosmic rays at assembly.

In addition, all towers in all sectors were verified using an LED test pulse after barrel assembly in 1008.

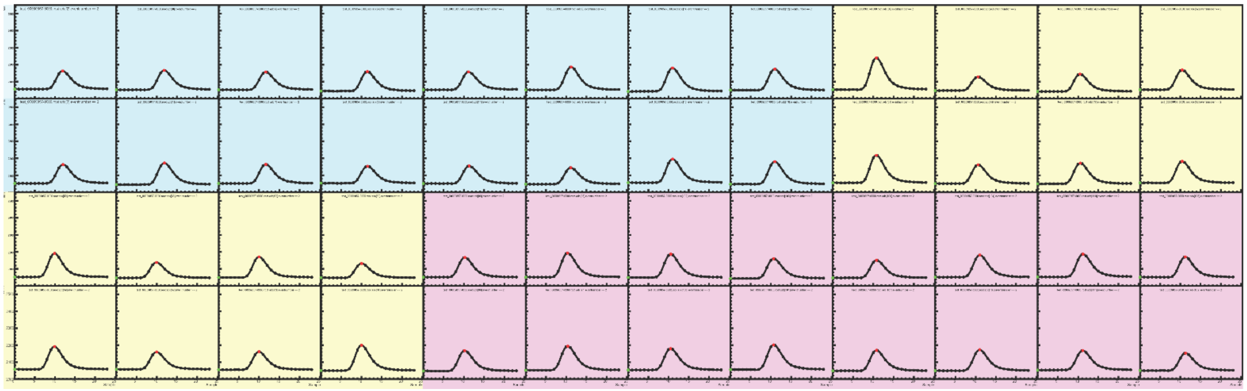
All towers in all sectors were verified with electronics test pulse, LED test pulse, and cosmic rays at assembly.

In addition, all towers in all sectors were verified using an LED test pulse after barrel assembly in 1008.

As of 5/17/2022 all oHCAL towers are fully functional – the oHCAL has 100% live towers.

All sector test data is archived at: https://sphenix-intra.sdcc.bnl.gov/WWW/subsystem/hcal/test/sector/

As an example, below is the LED test data for Sector 12:



-

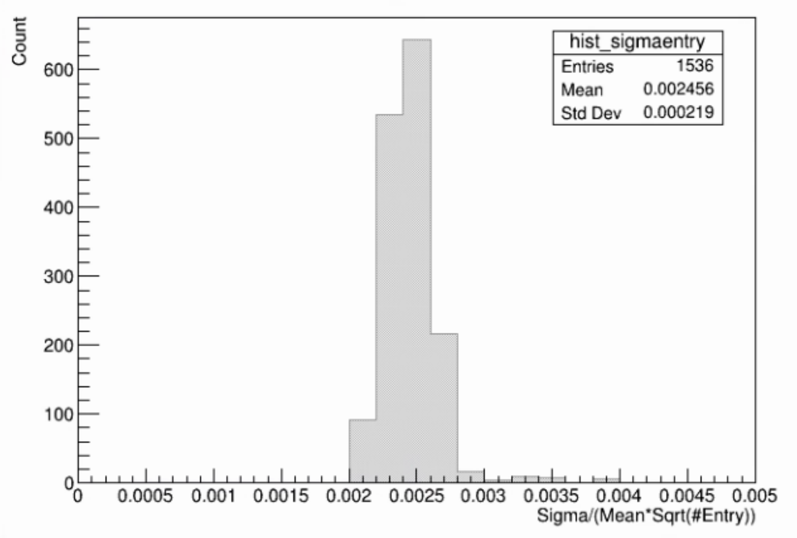
8.3.2 Hadronic Calorimeter KPP – Absolute Energy Precalibration

- Demonstration Measurement: **Preinstall, bench tests**
- Threshold KPP's: **Each sector w/ an absolute energy precalibration of ≤ 20% RMS**
- Objective KPP's: **Same**

All towers are precalibrated initially using the Landau peak in cosmic ray data. The location of this peak is used to normalize the gains between the towers and fix the initial absolute energy scale. The accuracy of this precalibration is determined by how well we know the location of the Landau peak.

All towers are precalibrated initially using the Landau peak in cosmic ray data. The location of this peak is used to normalize the gains between the towers and fix the initial absolute energy scale. The accuracy of this precalibration is determined by how well we know the location of the Landau peak.

We estimate this by plotting the ratio of the error on the mean to the mean for every HCAL tower. This ratio is less than a percent for all towers, indicating we have achieved the threshold and objective KPP of <20%.



8.4 Calorimeter Electronics (WBS 1.5)

There are no KPPs required for the Calorimeter Electronics WBS. All items produced were used in conjunction with items produced in other Level-2 WBS.

8.5 Data Acquisition/Trigger (WBS 1.6)

DAQ/Trigger KPP – Event Rate

- Demonstration or Measurement: **Event Rate**
- Threshold KPP's: **10 kHz w/ random pulser**
- Objective KPP's: **15 kHz w/ random pulser**

The event-rate limit results from re-use of the existing DCM-2 modules to read out the calorimeter digitizers. This is a legacy backplane-based system, which in turn is read out via the legacy "jSEB2" readout card, which is a 4-lane PCIExpress "Generation 1" device.

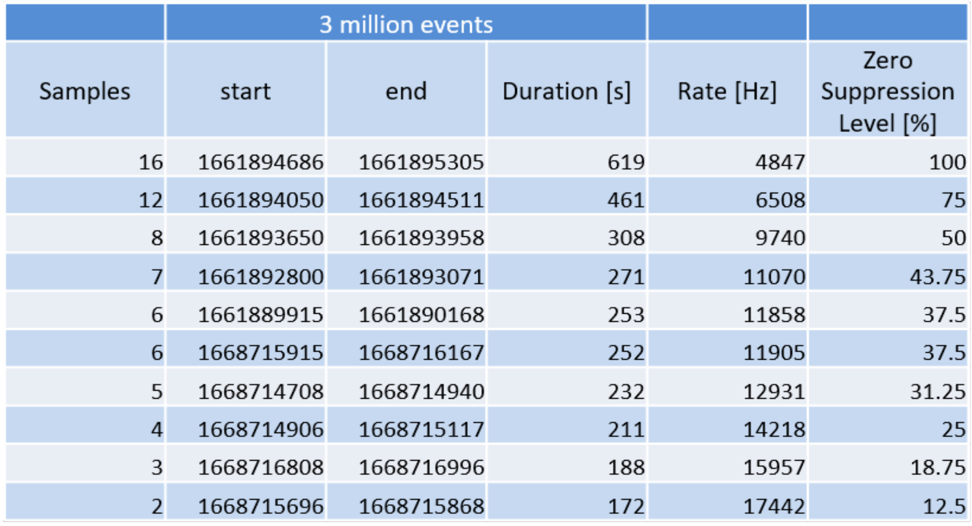
We used both a BNC pulser that can generate random pulses for a random trigger, as well as a large scintillator paddle connected to a Constant Fraction Discriminator (CFD). The CFD threshold was adjusted to generate random triggers at a rate of about 30KHz.

We used the number of samples that we read out as a **proxy** for the achieved level of zero-suppression. We will nominally read out 16 waveform samples. The achievable zero-suppression with an occupancy of about 25% in the electromagnetic calorimeter corresponds to a reduction to **4 readout samples**.

We note here that **25% is higher than the expected occupancy**.

We did not adjust the number of samples in the demonstration test to below 6, corresponding to an occupancy of about 35%, which is a very conservative assumption for the operation of the sPHENIX detectors.

For each number of waveform samples, we took exactly 3 million events and measured how long this takes. For the full 16 samples for each event, this took 619 seconds, resulting in an event rate of 4.8 KHz. The table shows the measure rated as a function of the number of waveform samples, with the start and ending times measured in terms of the readout PC's Unix time. We cross the 10KHz event rate threshold between 8 and 7 samples, corresponding to zero-suppression levels of 50% and 44%, respectively.



	3 million events				
Samples	start	end	Duration [s]	Rate [Hz]	Zero Suppression Level [%]
16	1661894686	1661895305	619	4847	100
12	1661894050	1661894511	461	6508	75
8	1661893650	1661893958	308	9740	50
7	1661892800	1661893071	271	11070	43.75
6	1661889915	1661890168	253	11858	37.5
6	1668715915	1668716167	252	11905	37.5
5	1668714708	1668714940	232	12931	31.25
4	1668714906	1668715117	211	14218	25
3	1668716808	1668716996	188	15957	18.75
2	1668715696	1668715868	172	17442	12.5

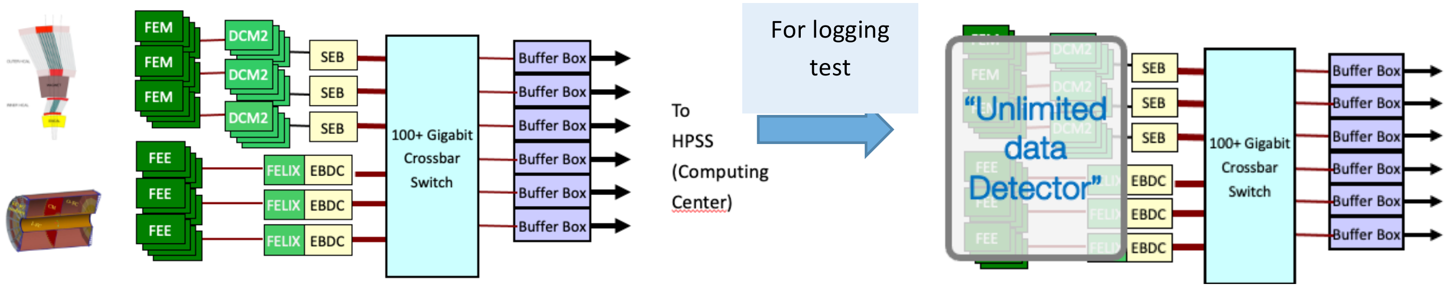
The table shows achieved readout rates with different number of samples, corresponding to various levels of achieved zero-suppression in the calorimeters. We cross the 10KHz threshold between 8 and 7 samples, corresponding to zero-suppression levels of 50% and 44%, respectively.

DAQ/Trigger KPP – Data Logging Rate

- Demonstration or Measurement: **Data Logging Rate**
- Threshold KPP's: **10 Gbit/s with pulser**
- Objective KPP's: **Same**

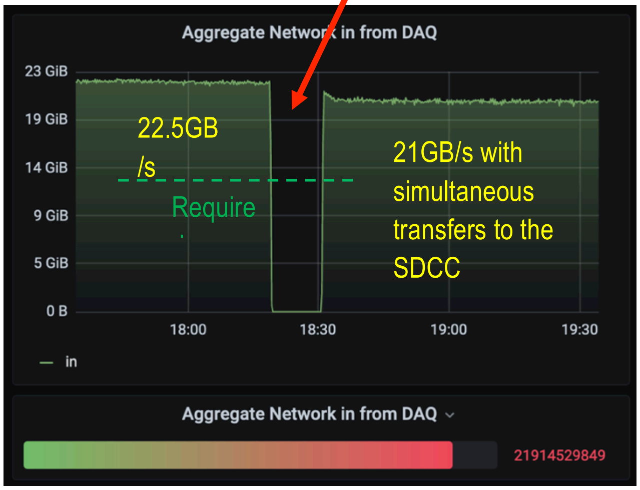
To demonstrate this, we configured the data acquisition system for a special running mode where the actual detector (that is not yet available in its entirety) is replaced with a setup that delivers data as the real detector would, just without any practical limits on the rate of delivered events. This setup, informally called "unlimited data detector", therefore tests the capabilities and limits of the network and data logging system. It uses 42 SEBs/EBDCs, 7 per Buffer Box, same load for each Buffer Box.

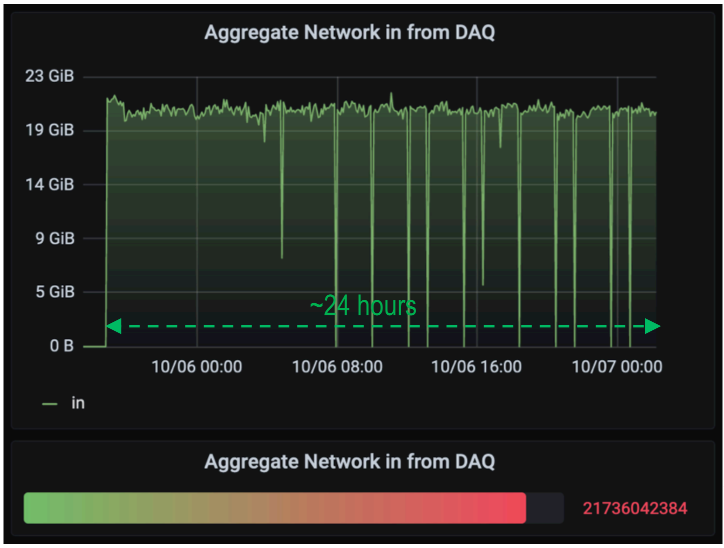
The data logging system consists of 6 so-called "Buffer Boxes", high-end file servers that collectively provide 6PB of RAID disk space. The detectors are read out with Front-End Modules (FEM/FEE) that in turn are read out with DCM2 modules or FELIX cards, that in turn transfer data to buffer boxes that temporarily store the data before sending them to the SDCC computing center for permanent storage. The buffer boxes level the variable data rate from the detector; this rate changes during a RHIC store with the available RHIC luminosity. The buffer boxes also allow us to ride out a storage system downtime at the SDCC side for about 4-5 days. The right-side figure shows how the actual detector readout is replaced with the "unlimited data detector". This system still uses all parts of the DAQ system, except the actual detector front-ends.



The achieved aggregate logging rate to the buffer boxes when running the "unlimited data detector" configuration is shown. The test runs for over an hour. After the first run shown earlier, we started transferring the data to the SDCC, and started a new DAQ run. This is the actual way we will operate the system, take new data while transferring the older data. The achieved logging rate with concurrent access of previously acquired data to transfer to the SDCC is shown. (Left: 90 minutes; Right: 24 hours)

Gap to start simultaneous data-taking and transfer to SDCC





Expanded scale to show even transfer gaps. Artificial 3-min breaks between 1hr runs.

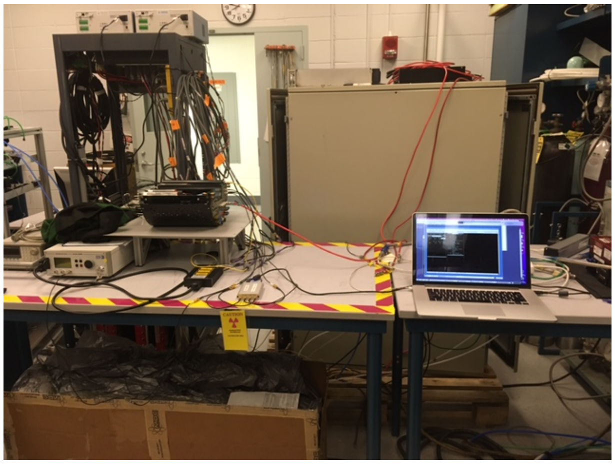
8.6 Minimum Bias Trigger Detector (WBS 1.7)

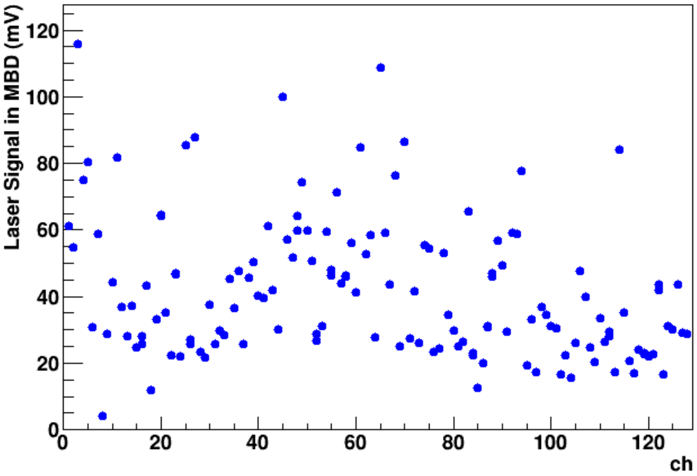
8.6.1 Min Bias Trigger Detector KPP – Live Channels, Timing

- Demonstration or Measurement: **Preinstall, bench tests**
- Threshold KPP's: ≥ **90% live channels based on laser. 120 ps/channel timing resolution w/ bench test**
- Objective KPP's: ≥ **95% live channels based on laser. 100 ps/channel timing resolution w/ bench test**

Each of the 128 MBD PMTs was flashed with a laser and the mean amplitude recorded.

The figure on the right shows these amplitudes vs channel number. The variation comes from the differences in the laser split to each channel. All 128 channels (100%) are alive and show good signal.

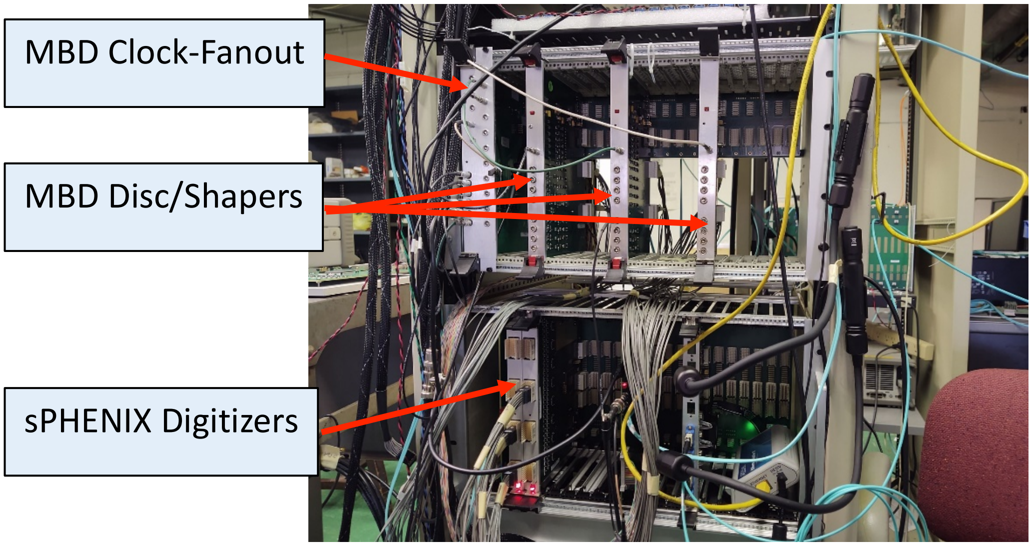


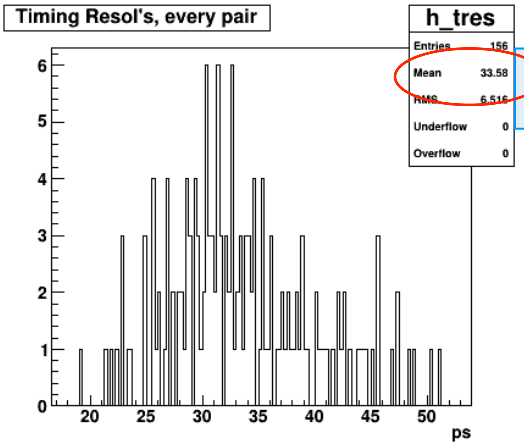


Using the time difference between two channels seeing a passively split signal, we determined a range for the time resolution of the electronics from 20-50 ps

The time extraction technique uses the same algorithm that will be used by the LL1 trigger

Combined with the known time resolution of the PHENIX BBC PMTs of 40 ps, we will get a total time resolution of at most 64 ps.

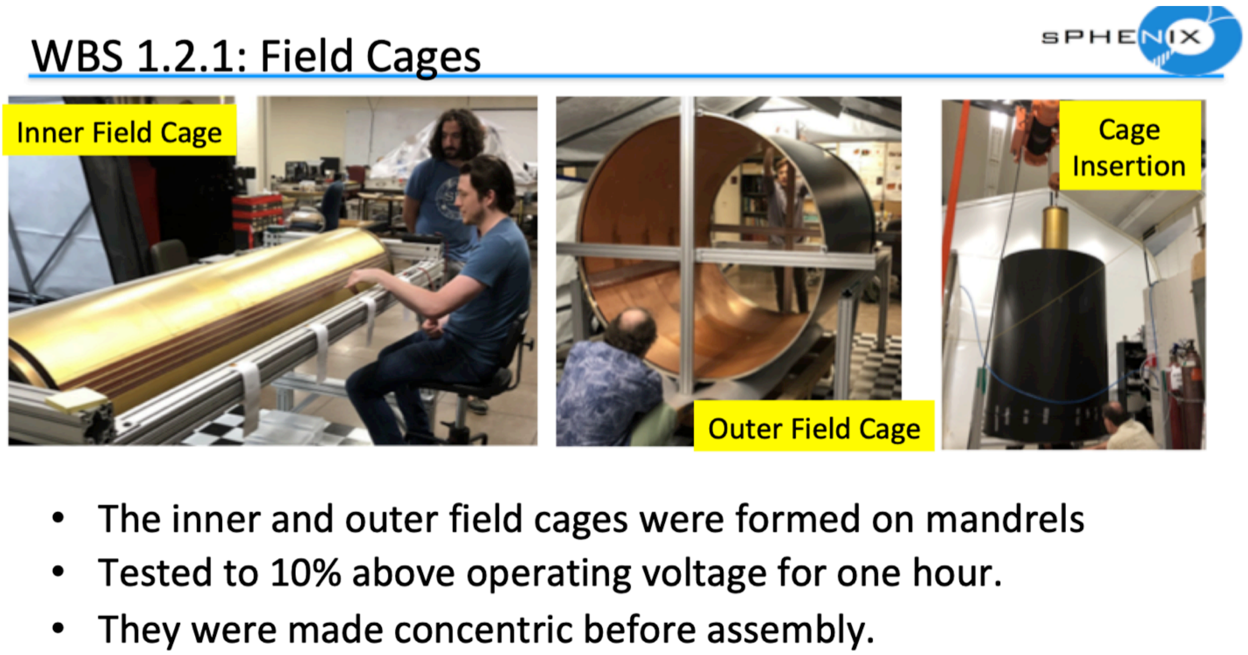




Mean timing resolution is 33.6 ps. Objective KPP is 100 ps.

9.0 Photos of WBS Elements

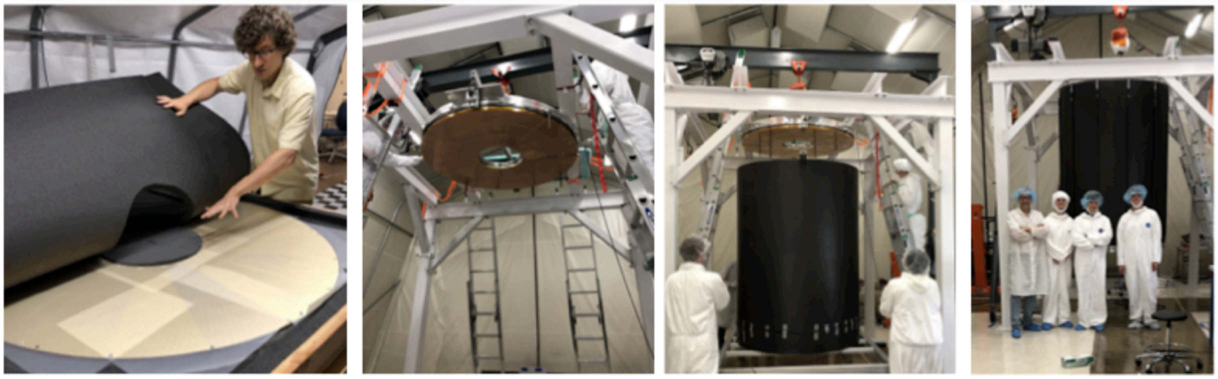
9.1 Time Projection Chamber Photos



WBS 1.2.1: Field Cages

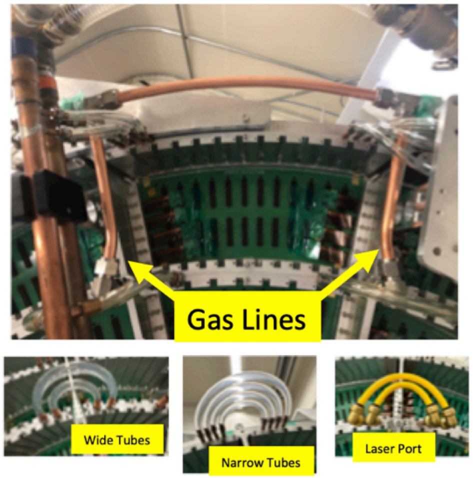
- The inner and outer field cages were formed on mandrels
- Tested to 10% above operating voltage for one hour.
- They were made concentric before assembly.

WBS 1.2.1: Central Membrane and Full TPC



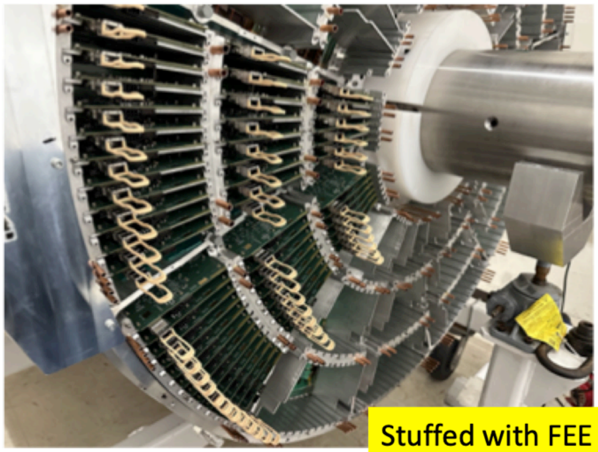
- Central Membrane with evaporated Aluminum stripes
- TPC Assembly in vertical orientation.

WBS 1.2.1: Wagon Wheel with Cooling and Gas

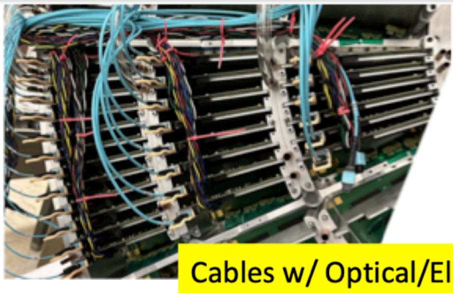


- No water leaks.
- 99.4% gas return at full flow.

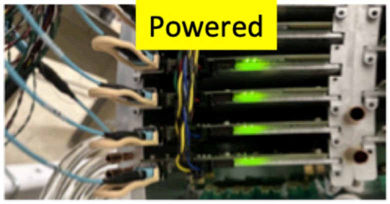
WBS 1.2.1: TPC Instrumented with FEE Cards



Stuffed with FEE Cards



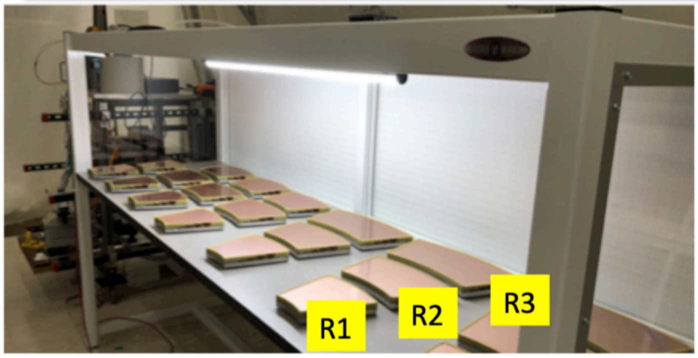
Cables w/ Optical/Electrical



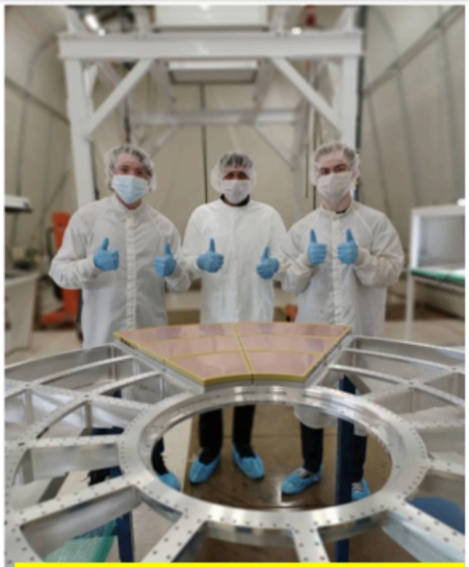
Powered

- FEE cards are cooled by cooling blocks.
- FEE cards require one optical and one LV connector.

WBS 1.2.2, 1.2.3, 1.2.4: R1, R2, R3 GEM Modules



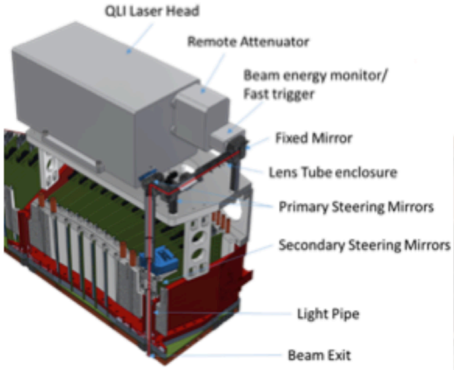
- Earliest Completed TPC Modules.
- 72 Modules total
- Three sizes: R1, R2, R3
- Gain * IBF Mapped using X-ray Source.

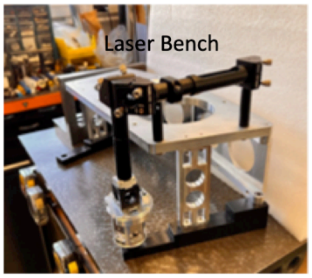


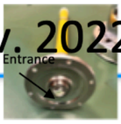
Module Test Fit to Wagon Wheel

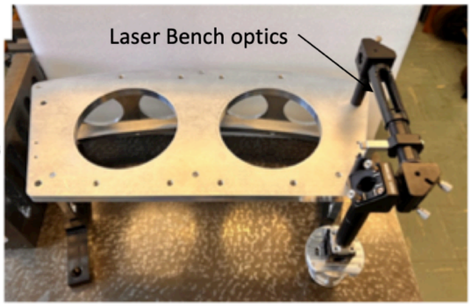
WBS 1.2.7.1: TPC Line Laser Status - Nov. 2022

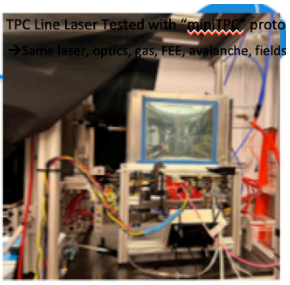
- All design work complete
- All lasers stress tested
- Proof of concept successful
- Procurement of parts ~95%
- Assembly to be completed by Dec. 2022

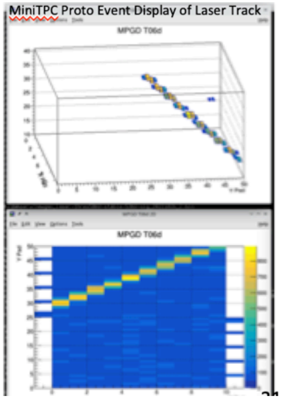






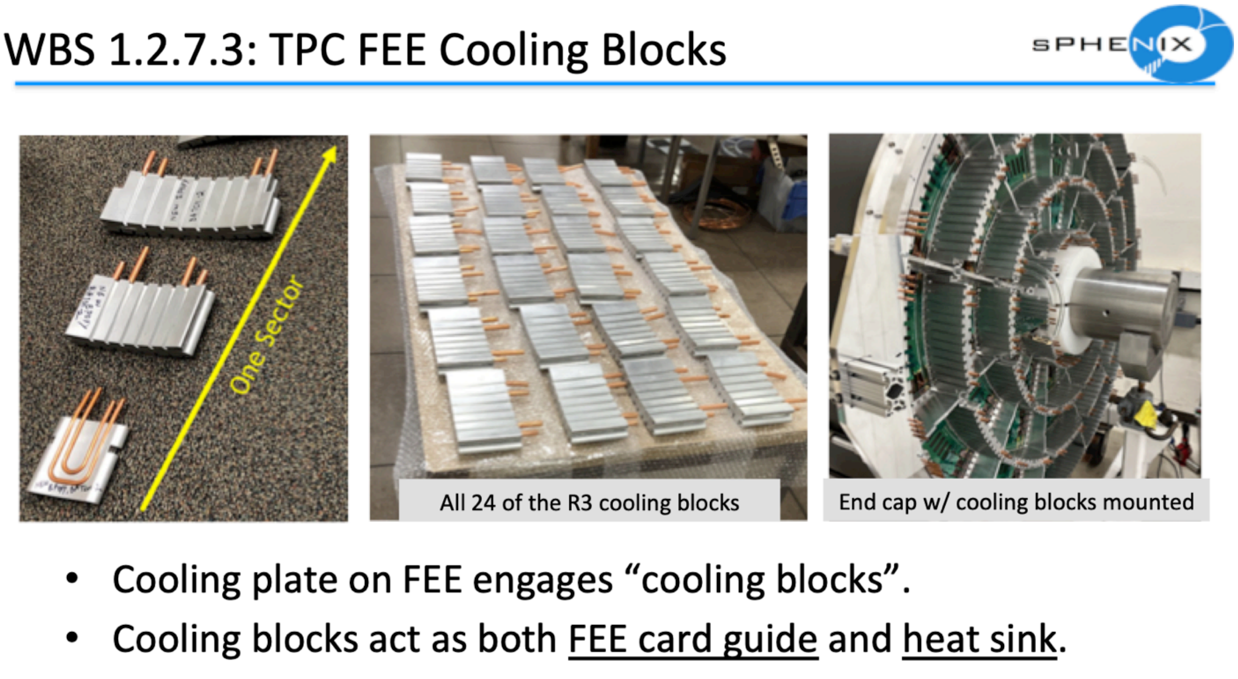



TPC Line Laser Tested with "miniTPC" proto
→Same laser, optics, gas, FEE, avalanche, fields


MiniTPC Proto Event Display of Laser Track

WBS 1.2.7.2: TPC Gas Rack Status

- All design work complete
- All Major components mounted and plumbed
- Flow controllers, Gas Analyzer, H20 Monitor, O2 Meter, Pumps, etc
- Purifiers and Driers built.



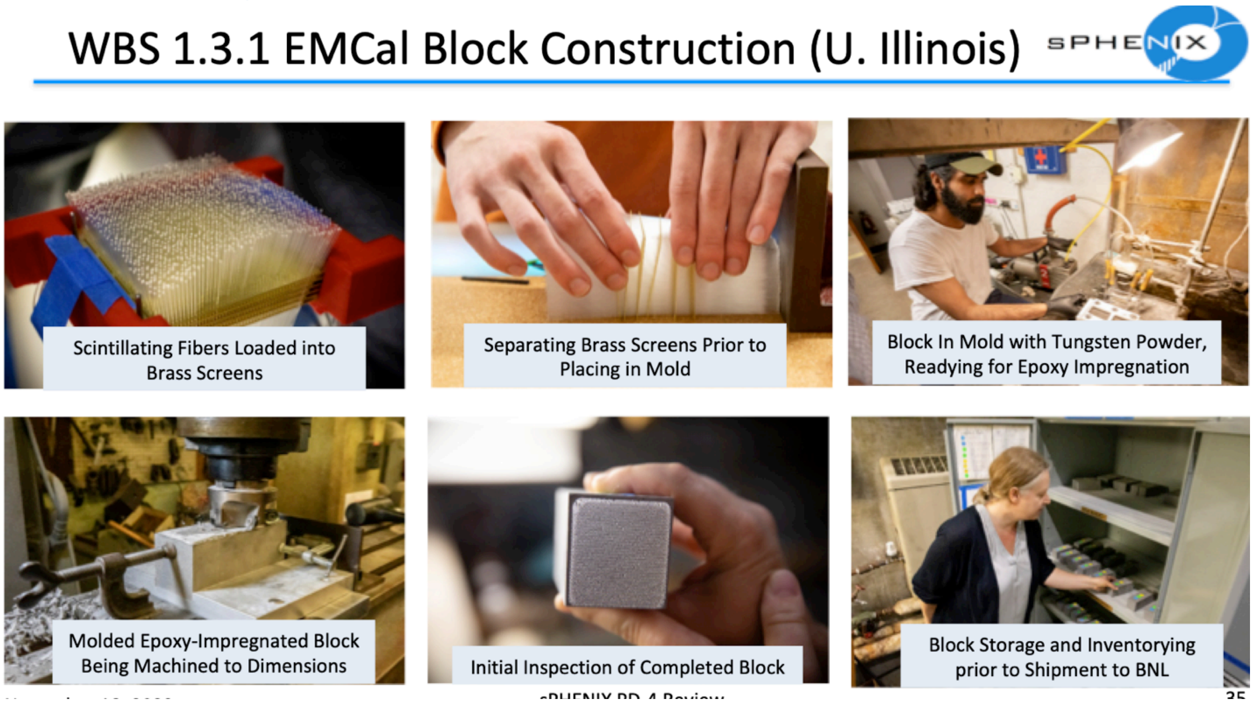
WBS 1.2.7.3: TPC FEE Cooling Blocks

All 24 of the R3 cooling blocks

End cap w/ cooling blocks mounted

- Cooling plate on FEE engages “cooling blocks”.
- Cooling blocks act as both FEE card guide and heat sink.

9.2 Electromagnetic Calorimeter Photos



WBS 1.3.1 EMCal Block Construction (U. Illinois)

Scintillating Fibers Loaded into Brass Screens

Separating Brass Screens Prior to Placing in Mold

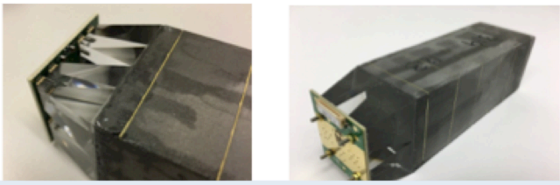
Block In Mold with Tungsten Powder, Readying for Epoxy Impregnation

Molded Epoxy-Impregnated Block Being Machined to Dimensions

Initial Inspection of Completed Block

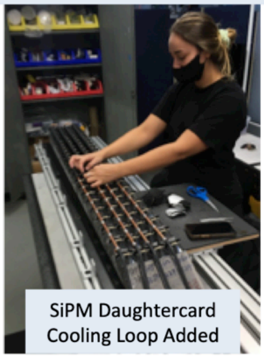
Block Storage and Inventorying prior to Shipment to BNL

WBS 1.3.2 EMCal Module & Sector Construction (1)

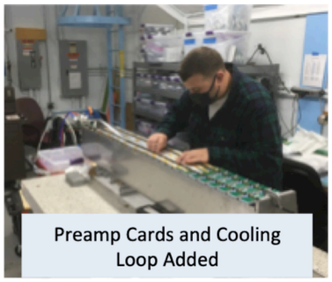


Block with 4 Lightguides (thus 4 towers) and 4 SiPM Daughtercards (16 SiPMs total)

Blocks Epoxied onto Strongbacks



SiPM Daughtercard Cooling Loop Added

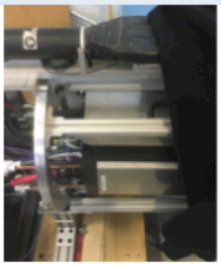


Preamp Cards and Cooling Loop Added

Cables and Interface Cards Added; Ready for Outer Skins

WBS 1.3.2 EMCal Module & Sector Construction (2)

Finished Sectors in the Rotating Test Fixture for Cosmic Tests



Completed Sectors under Extended Burn-In Test

Finished Sectors in Bldg 510 Awaiting Installation

9.3 Hadronic Calorimeter Photos

WBS 1.4: Hadronic Calorimeter Deliverables

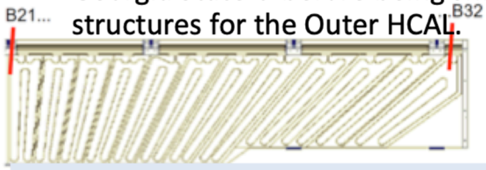
- 32 assembled, tested and calibrated Outer HCAL sectors
- InnerHCAL support structure (32 sectors)
- All deliverables completed and installed in sPHENIX

Outer HCAL instrumented sectors assembled into barrel on sPHENIX platform. (32 sectors) Installation completed 3/2022

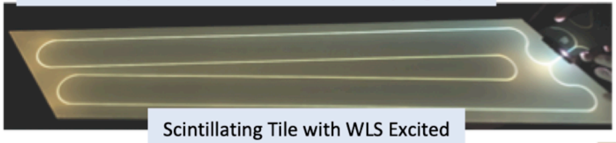
Inner HCAL assembled support structure being installed in sPHENIX (32 sectors)
Inner HCAL detector instrumentation supplied by separate capital project
Completed 4/2022

WBS 1.4: Hadronic Calorimeter components

- Scintillator tiles with embedded WLS fibers are used to instrument the steel absorber of the Outer HCAL. The tiles were produced by UNIPLAST and checked at Georgia State U before being shipped to BNL for insertion in the steel absorber structures for the Outer HCAL.

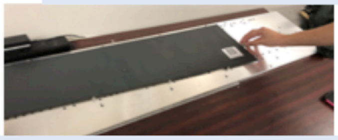


Tile/WLS layout for half of one OHCal Sampling Layer



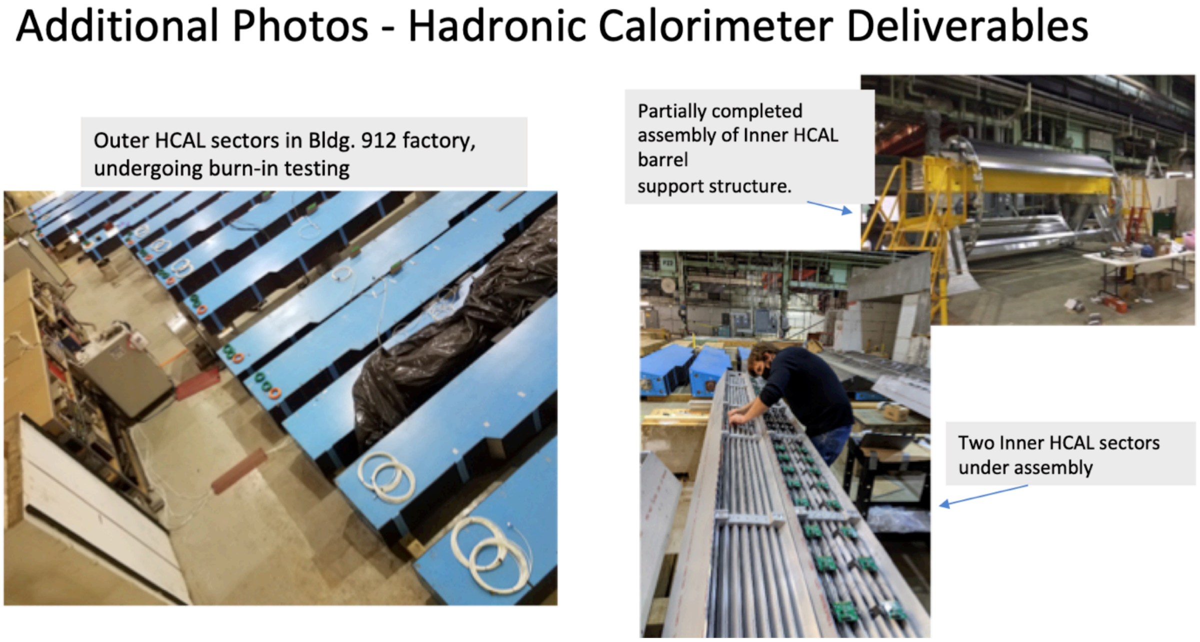
Scintillating Tile with WLS Excited

Scintillating Tile exit edge at SiPM location



Nc Wrapped Scintillating Tile being dimension checked

Several Wrapped Scintillating Tiles being checked in the cosmic ray test fixture



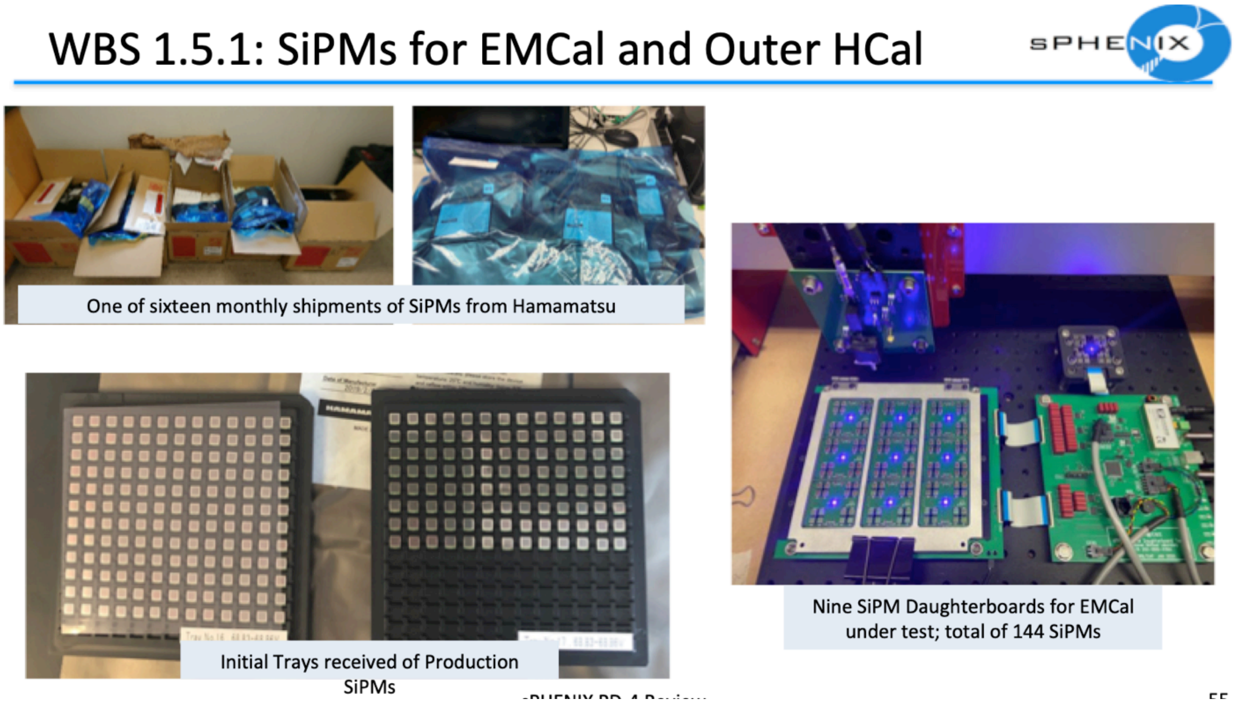
Additional Photos - Hadronic Calorimeter Deliverables

Outer HCAL sectors in Bldg. 912 factory, undergoing burn-in testing

Partially completed assembly of Inner HCAL barrel
support structure.

Two Inner HCAL sectors under assembly

9.4 Calorimeter Electronics Photos



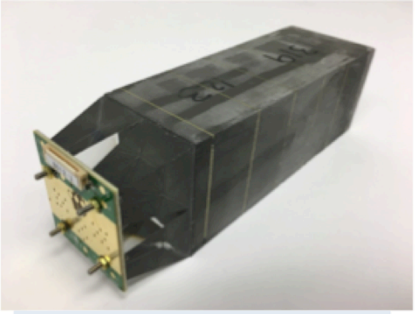
WBS 1.5.1: SiPMs for EMCal and Outer HCal

One of sixteen monthly shipments of SiPMs from Hamamatsu

Initial Trays received of Production SiPMs

Nine SiPM Daughterboards for EMCal under test; total of 144 SiPMs

WBS 1.5 Details – EMCAL FEE example items in use



EMCal Block (4 Towers) with SiPMs and SiPM Daughterboards Mounted

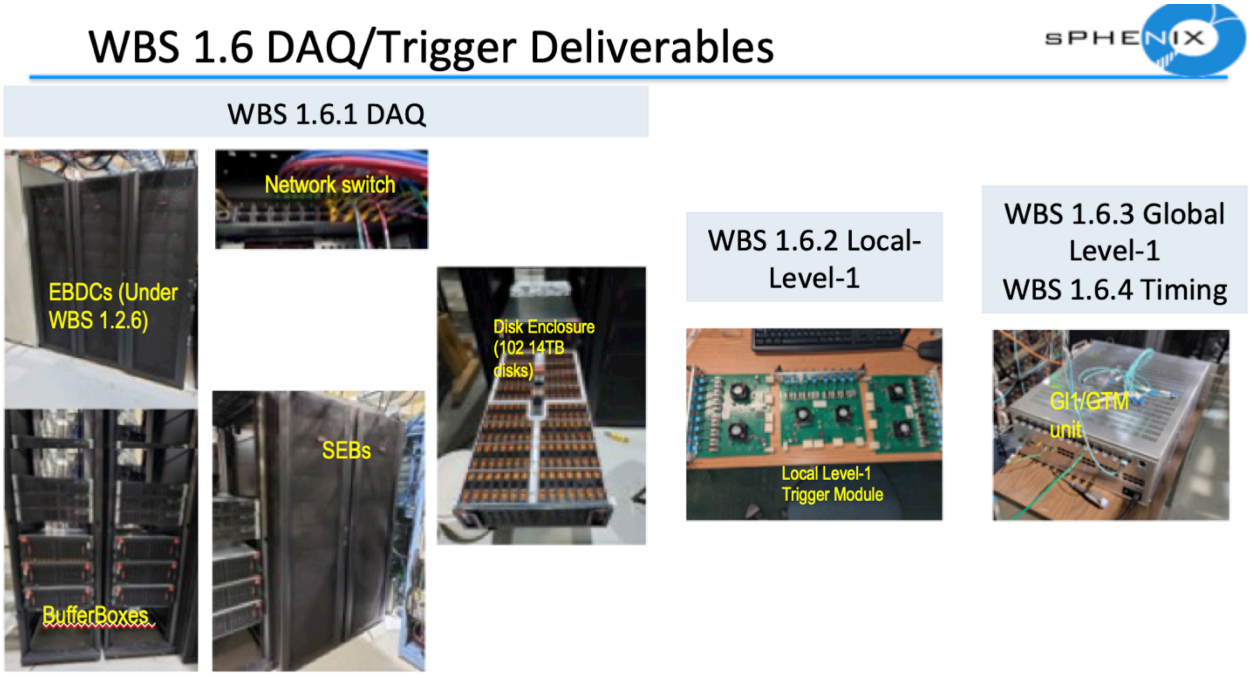
EMCal Sector (96 Towers) with SiPMs and SiPM Daughterboards Mounted

EMCal Sector (96 Towers) with PreAmps, Interface Boards and Cabling Mounted

WBS 1.5.3: Digitizers – EMCal and Outer HCal

Full Rack of sPHENIX Digitizers assembled and under test

9.5 Data Acquisition/Trigger Photos



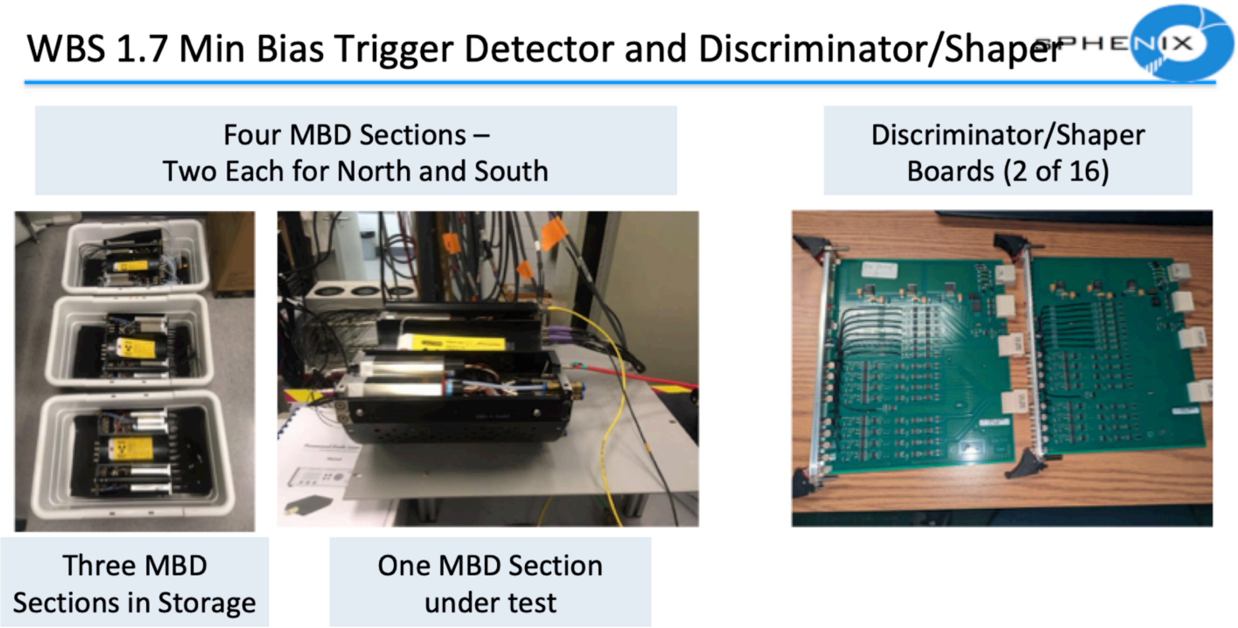
WBS 1.6 DAQ/Trigger Deliverables

WBS 1.6.1 DAQ

WBS 1.6.2 Local-Level-1

WBS 1.6.3 Global Level-1
WBS 1.6.4 Timing

9.6 Minimum Bias Trigger Detector Photos



WBS 1.7 Min Bias Trigger Detector and Discriminator/Shaper

Four MBD Sections –
Two Each for North and South

Discriminator/Shaper
Boards (2 of 16)

Three MBD
Sections in Storage

One MBD Section
under test

10.0 PROJECT DOCUMENT ARCHIVES AND LOCATION

Links to archival documents will be posted on a BNL SharePoint site that will be made available to BNL and DOE.

11.0 TRANSITION TO OPERATIONS

The sPHENIX MIE deliverables shall include all scope delineated in Section 2, including all deliverable listed items and tasks mentioned in the WBS with performance satisfying the Threshold KPPs. The management and organization of operations including installation and commissioning is outside the scope of the sPHENIX MIE project and will be summarized in the sPHENIX Transition to Operations Plan developed in support of the Project Closeout Review. The Transition to Operations plan will include a schedule for accomplishing the UPPs and will be tracked to completion.

The Transition to Operations Plan is included in the archival materials (and on the Indico sit

List of Tables:

List of Figures: