EIC Project detector technical review
of the electromagnetic and hadronic calorimetry

December 6 – 8, 2022, Online (Zoom)
Organization: E.C. Aschenauer (BNL), R. Ent (JLab)

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Close-Out Report

General Remarks

We thank you very much for, the efficient organization of the review, the excellent presentations given by the team, and the open and fruitful discussions. We congratulate you for the great achievements documented in the presentations and the exciting phase your groundbreaking experiment is entering. We are happy to help you with your further progress.

Review Charge Questions

1. Are the technical performance requirements appropriately defined and complete for this stage of the project?
- *The detailed requirements are not fully clear for all systems. Design choices determine details how the systems will be built.*

2. Are the plans for achieving detector performance and construction sufficiently developed and documented for the present phase of the project?
- *Some steps are missing in the plans of new systems to ensure performance - see recommendations.*

3. Are the current designs and plans for detector and electronics readout likely to achieve the performance requirements with a low risk of cost increases, schedule delays, and technical problems?
- *At the current phase the risks are not yet fully assessed, in particular for new systems - see recommendations.*

4. Are the calorimeter fabrication and assembly plans consistent with the overall project and detector schedule?
- *Time schedules contain float and match the overall project, but risks of manufacturing for new systems are not yet assessed, and QC plans are at an early stage.*

5. Are the plans for detector integration in the EIC detector appropriately developed for the present phase of the project?
- *Detector integration is mostly based on placeholders, as designs are not yet fixed.*

6. Have ES&H and QA considerations been adequately incorporated into the designs at their present stage?

- *Some systems consider ES&H and QA appropriately and should serve as examples to other systems.*

General Findings

The shape of the overall layout and design of the calorimetry systems is good. There seems to be enough float in the project. We have seen two different Barrel ECal designs for which a decision is needed. Full detector simulations for physics performance studies using complete events are just now becoming available, but they are important for establishing a more direct relationship between physics performance and detector design choices. We heard reports from these projects:

- Backward em. calorimeter (EEMCAL)
- Backward hadron calorimeter
- Two Barrel Electromagnetic calorimeter designs
- Forward calorimeters (SciFi/W, LFHCAL)
- Electronics
- Integration

Backward ECal - EEMCAL

The backward em. calorimeter for detecting primarily photons and electrons with high resolution is based on close to 2900 PWO crystals of 20cm length and a cross section of 20x20mm^2. The rectangular crystals will be arranged as a circular wall with a central hole for the beam pipe. The individual crystals are optically separated by thin carbon sheets of ~ 0.5 mm thickness. The readout of the scintillation light is performed at the rear by a matrix of 16 SiPMs covering the complete end-face. The analog signals are digitized directly behind the sensors. It is foreseen to inject light via an optical fiber from the rear as well.
The scintillators will be operated at room temperature and can be cooled only from the circumference. It is expected to reach a temperature stabilization on the level of $\pm 0.5^o$C.

- **Findings**
  This sub-project is centrally crucial for the success of EIC Physics program, as it serves the detection of the scattered electron. PWO is an established technology and is the best choice for this sub-detector. The relevance of position resolution was not yet evaluated. Readout will be done with a matrix of SiPMs. The material budget in front of EEMCAL is still unclear. The e/pi suppression has still to improve by a factor 10 although this is not critical.

- **Comments/Concerns**
  Temperature stability is very crucial for long-term operation and must be verified. One should avoid direct **heating** of crystals due to front-end electronics. The effect might in addition be sensitive to the variation of the event rates or beam interruptions. Good thermal insulation has to be considered since a variance of 0.5°C already constitutes a change of light yield of 1.2% adding directly to the constant term of the energy resolution. The front-end electronics is still to be decided which is necessary for a full evaluation of the system.

Regarding mechanical integration one should avoid fixations with nuts in the forward part, as they would be inaccessible, and use fixed conical bolts that position the system when inserting it from the rear. Fixations can then be done solely at the rear.

The availability of PWO can be a major risk as currently there is only a single supplier of high-quality material with a limited production capability.

- **Recommendations**
  R1. Prepare a system test with close-to-final electronics to verify the achievable resolution and the level of the threshold of minimum detectable energy.

  R2. Assess impact on physics output due to temperature instabilities.

  R3. Procure PWO crystals as soon as possible as it is a long lead item. The supplier currently can provide approx. 700 crystals per year.

More Specific Comments to PWO based Backward EMCal (R.Novotny, U. Gießen)

There are several comments to be made which show the limitations of the presented concept.
The chosen geometry of rectangular crystals staged in a wall will limit the achievable position resolution of any electromagnetic shower at larger impact angles if deduced from the shower distribution.
In PWO it is well known that the scintillation light is thermally quenched with the consequence that the light yield changes at room temperature by 2.5%/^{o}C. As a consequence, PWO calorimeters like ECAL at CMS (CERN) or the EMC of PANDA are stabilizing the temperature below $\pm$0.1^{o}C. Due to the low thermal conductivity of PWO it will take a long time to cool or stabilize the temperature without a sophisticated concept. It makes no difference if the crystals are operated at room temperature (CERN) or at -25^{o}C (PANDA). In addition, the impact is independent of the energy range of detected probes.
In the present concept, there is an additional problem that the attached sensors including electronics will directly heat-up the end-part of the crystal and cause an additional temperature gradient. This effect will also depend on the grade of operation or interruption of the experiment. Both mentioned calorimeters monitor in addition directly the temperature with thin sensors between the crystals at different locations along the crystal length. Even the fact that the detector might be implemented in an environment of more or less constant temperature it will take a long time to reach asymptotically any stabile mode. Therefore, calibration will become a major problem. The foreseen light pulses injected in the rear part have **no sensitivity** on the effective luminosity. They can **only** control the readout electronics or monitor long-term changes of the optical transparency due to radiation damage. However, to be sensitive enough, it requires a very sophisticated and stabile light distribution system (see ECAL at CERN, provided by CALTECH). Concerning the monitoring of radiation damage, it would be more efficient to inject the light from the front part.
Radiation damage might be no problem at EIC but most of the damage will be caused by electromagnetic probes. As detailed studies at CERN and Giessen have shown, this contribution to the damage can be easily recovered by the injection of light (see papers on *Stimulated Recovery*). Only the hadronic damage requires dismounting the units and annealing at high temperatures.

The PANDA EMC considers the injection of additional light (LED) from the rear in order to recover the crystals periodically if necessary.
To underline, one always will have a temperature gradient within the crystal and even between neighboring crystals, but the temperature profile has to stay constant to achieve optimal resolution.
Concerning the simulations of the expected resolutions one should illuminate the whole crystal including the carbon plates at a fixed energy to reach a realistic value.
As a final comment, PWO allows even at a size of 20cm length a timing resolution in the range of 100ps and below. Therefore, it would be of advantage to deduce beside the energy measurement a fast-timing information. For example, this would help to exclude background events due to secondary reactions in the beam pipe, with the residual vacuum etc.

Backward HCal – Tail Catcher

The plan is to recycle scintillating plates from the STAR EEMC with embedded WLS fibers and SiPM readout. The original lead absorber will be replaced by steel. The full depth of the system will be only about 440mm. The purpose of the system is mainly to act as a tail catcher and see neutrons. High energy resolution is not needed. The acceptance $-4 < \eta < -1$.

- **Findings**
  The locations of the SiPM in the layout are not yet clear.
- **Comments/Concerns**
  The detector should be made easily removable to access Backward EMCal readout for maintenance.
- **Recommendations:** *None*

Barrel ECal

Two competing solutions were presented for the EM calorimeter in the barrel region. They both propose very different concepts and very interesting and innovative ideas. Therefore, it will be very difficult to come to a final decision within a short time.

Barrel ECal – SciGlass

- **Findings**
  The arrangement of the whole calorimeter is nearly identical to the concept at CMS and PANDA and has a lot of advantages for the assembly as well as implementation into the detector. The need for different shapes should be achievable at significantly lower costs than the machining of grown single crystals like PWO and profit from the technology available for glass. The advanced mechanical design is based on experience from CMS and PANDA.
  The new material SciGlass appears to be a more cost-effective material compared to other crystals like PWO. The system goal is a resolution term of $7\%/\sqrt{E}$ and e/h separation in the order of 10^{-4}. Tests were done with a 3x3 prototype matrix made from $2x2x40cm^3$ straight crystals, whereas the baseline design will consist of $4x4x40cm^3$ tapered crystals.

- **Comments/Concerns**
  Relevant parameters for the characterization of SciGlass have not been presented or are missing (light yield, time structure, …). The kinetics of the glasses is not understood, the duration of the scintillation signal is not known, in particular if there are slow components, which might limit the count rate capability.

  Also, an investigation and confirmation of the homogeneity of transmission and light yield along the 40cm will become very important, as e.g. bubbles can deteriorate the detector response and limit the shower reconstruction. The presented optical longitudinal transmission is not understood. It goes down at long wavelengths while it stays constant e.g. for ordinary lead glass.

  There are no data conclusive on radiation hardness (em- and hadronic probes), although it is expected that SciGlass shows good tolerance. One should measure the response to electromagnetic **and** hadronic showers.

- **Recommendations**
  R4. Determine all SciGlass properties relevant for a detailed simulation of light production and propagation. This must include the response to hadron showers.

More Specific Comments to SciGlass based Barrel ECal (R. Novotny, U. Gießen)

The concept of a homogeneous calorimeter based on scintillating glass is very attractive from the concept and probably can be achieved at lower cost. However, at the present status, in spite of the shown prototype blocks, there are many open questions partly due to the lack of given information.
Since a few years there are activities going on to recover the idea of scintillating glasses, which was carefully studied for LHC but without any breakthrough. Recent activities at Giessen, CERN and Minsk have concentrated on glasses loaded with Ba and/or Gd to reach higher density. The origin of the scintillation are nano-cells of Ce^{3+} delivering scintillation light at about 435nm. The already published parameters have shown light yields of about 500 photons/MeV but with additional slow components of decay times of a few hundreds of nanoseconds (R. W. Novotny et al., IOP Conf. Ser: J. of Physics 1162 (2019) 012023; V. Dormenev et al., Nucl. Inst. and Meth. in Phys. Res. A 1015 (2021) 165762). Recent publications of Gd-based glasses indicate significantly faster kinetics and light yield of up to 2500 photons/MeV (A. Amelina et al., J. of Non-Crystalline Solids 580 (2022) 121393). Major technical problems have been so far the homogeneity of the blocks primarily due to defects such as bubbles.
The presented glass samples show in spite of a nice optical transparency a very strange longitudinal optical transmission. There are no data shown on the scintillation characteristics, light output, homogeneity along the crystal length or radiation hardness. From the own experience with the glasses tested at Giessen and CERN, at least that material shows a good radiation resistance against electromagnetic as well as hadronic probes (up to 180 MeV protons and a fluence of 10^{13} (K.-T. Brinkmann et al., 2014 Conf. Rec. IEEE NSS Seattle WA, USA, N06-3; R. W. Novotny et al., 2017 IOP Conf. Ser. : J. of Physics 928 (2017) 012034) and the concept of stimulated recovery can be applied.
For a conclusive recommendation on the SciGlass development it will be much more convincing to deliver the missing parameters like the optical transmission perpendicular and at various positions and also measurements of the time components of the scintillation light.

Barrel ECal – Pb/SciFi+Imaging

- **Findings**
  The application of AstroPix MAPS ASICs as imaging part intereleaved with Pb/SciFi layers and followed by a larger Pb/SciFi absorbing the full energy of em. showers is planned. The AstroPix ASICs come as 500µm thick Silicon chips of 2x2 cm^2 with 500µm pixel size and are well adapted to the task.

  The imaging part offers the potential to provide proximity position information for the DIRC allowing to leave out the MPGD layer surrounding the DIRC for this purpose.

  In the Pb/SciFi long fibres are embedded in lead sheets in a similar fashion as done at GlueX. Currently no complete physics simulation is done. No prototypes or more detailed engineering test articles of the hybrid system are available.

- **Comments/Concerns**
  Integration and cooling of the system are unclear, especially for the imaging part. The installation and maintenance of a self-supporting barrel is difficult, as it would have to be extracted as a whole. Individual wedges would be more appropriate.

  One could consider having only Pb/SciFi as backup in case the imaging part requires more development time or reveals problems. For this aim one should simulate the achievable resolution of both scenarios.

- **Recommendations**
  R5. Do full physics simulation as soon as possible and demonstrate the added value of the imaging stage.
  R6. Move towards tests of prototypes or more detailed engineering test articles as soon as possible.

Barrel HCal

- **Findings**
  The ePIC Barrel HCal will reuse the existing system from sPHENIX consisting of iron layers acting as magnetic flux return and absorber interleaved by layers of scintillating tiles for the shower sampling. The existing tiles will be equipped with new SiPMs as readout. A detailed tile map exists from tests at MEPHI. It is considered to use the HGCROC ASIC in an emulated streaming mode as frontend electronics. The layers are arranged in tilted wedges to avoid showers passing through straight gaps.

- **Comments/Concerns**
  Control of inhomogeneities of the tiles is important to understand the calorimeter response. One should consider using one HGCROC channel per tile to have also longitudinal shower information, as this can be easily achieved with the highly integrated readout. This will allow to distinguish shower from MIP(µ). A concern is the possibly different systematics for positive and negative particles due to the chirality of setup with the inclined wedges.

- **Recommendations**
  R7. Re-map tiles to fully control inhomogeneities.

  R8. Exploit advantages of HGCROC to have longitudinal information (see comments).

R9. Once full physics simulations are available, study particle flow performance of ECAL-Coil-HCAL configuration for jets and muon ID.

Forward EMCal

- **Findings**
  In the forward endcap em. calorimetry will be done with a technology based on W powder and SciFi for sampling successfully developed and employed at sPHENIX. This will allow to reach a resolution term of 10%/√E and compensating behavior with e/h approximately 1. The detector system will be built by a group with members of the team that built the sPHENIX calorimeter.

- **Comments/Concerns**
  The inhomogeneity as a function of fiber arrangement should be validated in tests.
  A major concern is the readout on the front side: Light guides, sensors, electronics, cables, and cooling are all placed there. Thus, the electronics will be exposed to the forward flux of hadrons. This will lead to worsening of the elm. resolution. Alternatively consider the integration of the Forward EMCal in the bore of the barrel systems with its readout at the rear moving to the service position with the full barrel.

- **Recommendations**
  R10. Do full simulation with passive structures in front to study the effect on resolution.
  R11. Beam test of engineered structures including realistic upstream electronics shall be done as soon as possible.

Forward HCal

- **Findings**
  For ePIC the LFHCAL design was adopted following the concept of Projctile Spectator Detectors of other heavy ion experiments like CBM. The detector towers consist of steel and W tiles as absorbers sampled by scintillator tiles and WLS fibers read out by SiPMs. The dynamic range from 3MeV to 30GeV is quite large with a factor of 10,000. The readout is segmented in longitudinal direction to obtain shower profile information.

  No beam tests have been done yet. The Monte Carlo response was tuned with CALICE Data. The effective segmentation (fiber ganging) and dynamic range of front-end electronics are not yet optimized.

- **Comments/Concerns**
  Seeing the interplay between EMCal and LFHCAL we observe a shift of the LFHCAL towers to mount the EMCal. One should verify the EMCal integration if this is really the optimal solution.

  Regarding the manufacturing of the scintillator tiles, laser etching is labor intense, the presented alternative with molds is promising and a proven technique employed elsewhere. There are concerns that super-tiles break at groves if they are too deep. One should consider smaller super-tiles or single tiles with sliding guides to form larger assemblies.

  Carefully plan fiber bending to avoid breakage, as they run in one plane through the tile and then in an orthogonal plane towards the readout. It should be considered to mount

SiPMs directly on the tiles, connecting electronics with Kapton strips, possibly electrically ganged, which could be a robust alternative.

One should check crosstalk between tiles to see if cladding with Ti color or Tyvek are effective, and the grooves are sufficiently deep.

As an additional idea one could consider simulations/tests with W section in front instead of the steel sections and compare elm. response with and without W/SciFi calorimeter in front.

- **Recommendations**
  R12. Perform full simulations to optimize electronic segmentation and dynamic range to assess the benefit of measuring longitudinal shower profiles.

Detector Integration

- **Findings**
  For many systems placeholder volumes are still used. This is understandable at the current phase. The measurements of electrons and electromagnetic showers is crucial for scientific output.
- **Comments/Concerns**
  A structured design of supports and services shall be entered also in simulation as early as possible. One should do load checks and eventually FEM of static and dynamic cases (seismic events, moving detector, …). The early stage of cabling and detector design already shows some bottlenecks in cross sections.
- **Recommendations**
  R13. Define clear tolerances and keep-out volumes to facilitate integration of systems.

  R14. Follow design steps and hardware development with full simulation studies including mechanical structures to identify critical aspects of detector design for precision physics.

Electronics (General)

- **Findings**
  All calorimeters will use SiPMs to maximize synergies in the readout. There are different numbers of channels and different grouping levels according to the needs of the individual sub-systems. The data acquisition architecture is structured with FEBs, RDOs, and DAMs. A GTU determines the timing of the overall readout. Estimates state raw rates in the order of 100 Tbps, RDO rates in the order of 10 Tbps, and a data rate to storage of about 100 Gbps. These are well feasible values with the technology available by the year 2030. Standardization is aimed at wherever reasonably possible.
- **Comments/Concerns**
  A clock precision of 5ps is challenging, but reachable with a careful design of GTU and timing chain with dedicated FPGA clocks and/or jitter cleaners across the large system. One should consider employing the clock from the accelerator to structure the data to help online processing and event selection minimizing pile-up treatment.

  In the current design already one quarter of the required power goes lost in cables and creates an unnecessary heat load.

Many ASICs still under development are considered in the project, the existing HGCROC offers many features but is triggered and may not allow for optimal resolution with its built-in 10-bit ADC. For the SciFi/W system one should motivate the requirement of an ADC resolution of 12 or even 14 bits as it was presented and investigate if the ADC resolution of HGCROC would be sufficient as well.

- **Recommendations**:

  R15. Consider the use of DC/DC converters in the power supply scheme to reduce power losses and cables cross sections.

Electronics (FEMCal)

- **Findings**
  The baseline readout architecture is planned with discrete components, 50Msps ADCs and (flash-based) FPGAs. No streaming ASIC is ready yet. There are promising ongoing developments at Pacific Microchip, Alphacore, and at Sao Paolo with the SALSA chip (ALICE) that are in observation.
- **Comments/Concerns**
  One should motivate the ADC resolution requirement of 12 or even 14 bits. There is a lot of passive material due to electronics in front of that SciFi/W that may cause pile-up and failures. Single event upsets by radiation should be evaluated for this configuration. Even in radiation tolerant flash-based FPGAs logic can fail with SEU.

  The cooling of the electronics is not yet worked out yet. One could consider the use of an under-pressure cooling system to avoid the risk of damage due to leakage.
- **Recommendations**: *None*

Electronics (LFHCal) / HGCROC

- **Findings**
  Here the baseline is the HGCROCv3 ASIC, due to the large number of channels, featuring a 10-bit ADC and a 12 bit Time-over-Threshold for large signals. A trigger is generated locally via the RDO readout board with channel sum information for hit detection. Different topologies of grouping FEBs to RDOs are considered either locally (spider), linearly (snake) or with optical links.
- **Comments/Concerns**
  There will be high data rates due to missing on-chip hit-detection, as hit detection is only done on the RDO. There is the question if the ADC resolution of HGCROC is sufficient. One should check if the maximum trigger rate of HGCROC (960kHz) can cause deadtime in case of randomized peak rates exceeding this value. A possible option instead of HGCROC would be an analog transient recorder with on-chip ADC similar to the one developed recently at GSI (H. Flemming *et al* 2022, *JINST* **17** C07002, **DOI** 10.1088/1748-0221/17/07/C07002).
  As before one could consider the use of a subatmospheric-pressure cooling system.

- **Recommendations**
  R16. Give high priority to feasibility tests with HGCROC for all calorimeters. This must include dynamic range considerations, starting from calibration signals such as single photo-electrons or MIPs, to the largest expected physics signals, and could impact the three-dimensional calorimeter segmentation.

General Conclusions

- **Findings**
  The optimization for particle flow is still missing. Modern calorimetry aims to exploit this feature to maximize physics sensitivity. Most detector concepts inherently have the potential to employ this technique, some foresee it explicitly. Not all detailed technical requirements for the detector performance are clear but they are needed for the design of the systems.

- **Comments/Concerns**
  A unified scheme of readout electronics is helpful and is well in reach as the photon readout is based on SiPMs across all systems. Regarding the sensors, a careful choice of SiPM types is recommended regarding radiation hardness (they must be sufficiently insensitive against neutrons!), correct pixel size for the intended dynamic range of the measured particle energies and the appropriate front-end electronics, and geometrical acceptance as well as mechanical integration. One should characterize sensors before final procurement and establish a sample control of sensor deliveries (also regarding radiation hardness) as part of QA.

- **Recommendations**
  R17. Carry out more simulation and reconstruction studies regarding particle flow etc.

  R18. Construct comprehensive engineering test articles for the detectors where possible and validate simulations with beam tests.

  R19. Perform risk assessment for new designs.

  R20. Hold next review in person and schedule it sufficiently in advance.

Appendix 1: Agenda of Review Presentations in Open Session

December 6, 2022

14:30 → 15:00 **Welcome and Introduction to EIC Project** 30m
Speakers: E. C. Aschenauer (BNL), Rolf Ent (Jefferson Lab)
eca.CaloReview.pptx

15:00 → 15:30 **Electromagnetic Calorimetry Overview and Requirements** 30m
Speaker: Alexander Bazilevsky (BNL)
EMCal_Review_Dec...

15:30 → 16:00 **Hadronic Calorimetry Overview and Requirements** 30m
Speaker: Alexander Kiselev (BNL)
ayk-2022-12-06-hc...

16:00 → 16:30 **Overall Detector Integration Status and CAD Design** 30m
Speakers: Rahul Sharma (BNL), Roland Wimmer
Final_EIC_TR_EMC...

16:30 → 16:50 **Coffee Break** 20m

16:50 → 17:10 **Backward Hadron Calorimetry detector upgrade** 20m
Speaker: Leszek Kosarzewski (Czech Technical Univeristy in Prague)
FinalUpdated_nHC...

17:10 → 17:50 **Backward Electromagnetic Calorimetry detector and integration** 40m
Speakers: Carlos Munoz Camacho (IJCLab, CNRS/IN2P3), Julien Bettane (IJCLab)
Backward_ECAL_fi...

17:50 → 18:30 **SciGlass-Based Barrel Electromagnetic Calorimetry detector and integration** 40m
Speakers: Joshua Crafts (affiliate@jlab.org;member@jlab.org), Tanja Horn (Cath)
Final BEMCal DR Pr...

18:30 → 19:00 **Imaging-Calorimeter Barrel Electromagnetic Calorimetry alternate option** 30m
Speaker: Maria Zurek (Argonne National Laboratory)
Imaging-Calo-Zure...

December 7, 2022

14:00 → 14:30 **Barrel Hadronic Calorimetry detector and upgrades** 30m
Speaker: John Lajoie (Iowa State University)
FINAL Barrel Hadro...

14:30 → 15:10 **Forward Electromagnetic Calorimetry detector and integration** 40m
Speaker: oleg tsai (ucla)
EIC_fECal_final.pdf

15:10 → 15:50 **Forward Hadronic Calorimetry detector and integration** 40m
Speaker: Friederike Bock (ORNL)
LFHCAL_Status_N...

15:50 → 16:10 **Calorimetry Electronics Overview** 20m
Speaker: Fernando Barbosa (JLab)
Electronics Overvie...

16:10 → 16:25 **Forward Electromagnetic Calorimetry electronics** 15m
Speaker: Gerard Visser (Indiana University)
hadron_endcap_EC...

16:25 → 16:40 **Forward Hadronic Calorimetry electronics** 15m
Speaker: Norbert Novitzky (ORNL)
20221201CaloElec...

Appendix 2: List of Recommendations

Backward ECal - EEMCAL

R1. Prepare a system test with close-to-final electronics to verify the achievable resolution and the level of the threshold of minimum detectable energy.

R2. Assess impact on physics output due to temperature instabilities.

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R8. Exploit advantages of HGCROC to have longitudinal information (see comments).

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