Date: 3/5/21

EIC Detector R&D Progress Report

Project ID: eRD1
Project Name: EIC Calorimeter Development
Period Reported: from 8/1/20 to 2/28/21
Project Leaders: H.Huang and C.Woody
Contact Persons: T. Horn, O.Tsai, C.Woody

Collaborators

S.Boose, J.Haggerty, J.Huang, E.Kistenev, E.Mannel, C.Pinkenberg, P.Pisani, M. Purschke, S. Stoll and C. Woody
(sPHENIX Group, BNL Physics Department)

E. Aschenauer, A. Bazilevsky, S. Fazio, A.Kiselev, A.Ogawa
(Cold QCD Group, BNL Physics Department)

Y. Fisyak
(STAR HI Group, Physics Department)
Brookhaven National Laboratory

L. Zhang and R-Y. Zhu
California Institute of Technology

S. Ali, V. Berdnikov, J.Crafts, T. Horn, I.L. Pegg, P.Stepanov, R. Trotta
The Catholic University of America and
Thomas Jefferson National Accelerator Facility

M.Battaglieri, A. Somov
Thomas Jefferson National Accelerator Facility

W. Jacobs, G. Visser and S. Wissink
Indiana University

C. Riedl, T. Rinn, A. Romero, A. Sickles, X. Wang
University of Illinois at Urbana Champaign

M.Battaglieri, M.Bondi, A.Celentano, R. deVita
INFN Genova, Italy

J.Bettane, G. Hull, M. Josselin, C. Munoz-Camacho, H.S.Ko
IPN Orsay, France

H.Z. Huang, B. Chan, M. Sergeeva, D. Neff, S. Trentalange, O. Tsai, Z. Xu
University of California at Los Angeles

K. Barish, M. Arratia and R. Seto
University of California Riverside

C. Gagliardi, T. Lin
Texas A&M University

C. Fanelli, Z. Shi
Massachusetts Institute of Technology

S. Kuleshov, R.G. Silva, P. Ulloa, M.Liz
Universidad Andres Bello (UNAB), Santiago, Chile

A.Denisov, A.Durum,
Institute for High Energy Physics, Protvino, Russia

A.Brandin, A.Petrukhin, I.Yashin
MEPHI, Russia

H. Mkrtychyan, V. Tadevosyan, A. Asaturyan, H. Voskanyan
AANL, Armenia

Abstract & Summary

This report summarizes the activities of the eRD1 Calorimeter Consortium during the period from August 1, 2020 – February 28, 2021. These activites are divided into four Sub-Projects: Developments for Homogeneous Calorimetry for EIC using Crystals and Glasses (CUA/Orsay); Developments for a Tungsten Scintillating Fiber EMCAL and Iron Scintillator HCAL for EIC (UCLA); New Developments for Tungsten Scintillating Fiber Calorimetry for EIC (BNL); and R&D on a Tungsten Shashlik Calorimeter for EIC (BNL/UNAB).

The total report consists of four sections which includes a one page summary for each Sub-Project describing its accomplishments to date and an assessment of its technological readiness and the work remaining for a TDR, including a rough cost estimate and timeline. These summaries are included in a separate document. This report gives the normal detailed progress report covering the period from 8/1/2020 – 2/28/2021.

Sub Project 1: Homogeneous calorimeter development - crystals and glass
Sub Project Contact: Tanja Horn

Past

What was planned for this period?

Our main planned activities during the past funding period were to work closely with vendors towards ***cost-effective production of high-quality lead tungstate ($PbWO_4$) and glass scintillators for the EIC calorimeters. These R&D activities are well aligned with the EIC UG Yellow Report Calorimeter and R&D needs***. We expected to receive and characterize at least ~100 additional $PbWO_4$ crystals. We planned to produce SciGlass samples of ~$10X_0$ with adequate surface quality for physical, luminescence, and radiation hardness studies, and demonstrate the fabrication of a 15-$20X_0$ glass block. We also planned to explore high-dose rate radiation hardness studies, and, together with vendors, to prepare a small business funding proposal for new scintillator material (CSGlass) development that could be of interest for precision hadron calorimeters. In a synergistic activity with the Neutral Particle Spectrometer (NPS) project at Jefferson Lab, we planned to continue our test beam program with prototypes towards establishing the limiting energy and position resolution and uniformity of response. Beyond these plans, we note additional suggestions from the July 2019 and earlier EIC R&D Committee reports, which include following up with vendors on material control and purity, and crystal handling, as well as investigating sources of new raw material.

What was achieved?

1) Lead tungstate ($PbWO_4$) R&D

We characterized an additional 175 CRYTUR $PbWO_4$ crystals[1]. Our usual quality control has been limited to visual inspection. Based on that none of the newly arrived crystals have been rejected so far. We have started investigating $PbWO_4$ crystals fabricated with commercially available raw materials[2]. If successful, this approach may address the need for sources of new raw material for production of high-quality $PbWO_4$ crystals for EIC. *We expect to characterize these new crystals over the next months.*

2) SciGlass R&D

a. Fabrication and scale-up of glass samples

[1] The NPS project has received and characterized a total of ~927 Crytur and ~860 SICCAS crystals since 2015.
[2] The only source of raw material for Czochralski grown crystals is at present the limited amount leftover from BTCP operations. This raw material is expected to be exhausted with production for PANDA.

We have produced, in collaboration with the Vitreous State Laboratory (VSL) and Scintilex LLC, small batches of samples to optimize the formulation and to demonstrate the scale-up method. The scale-up process was divided into three stages as illustrated in Figure 1(left). The scale-up method has been established and several samples up to $10X_0$ can now be reliably produced. The first SciGlass block of 40cm length was produced in December

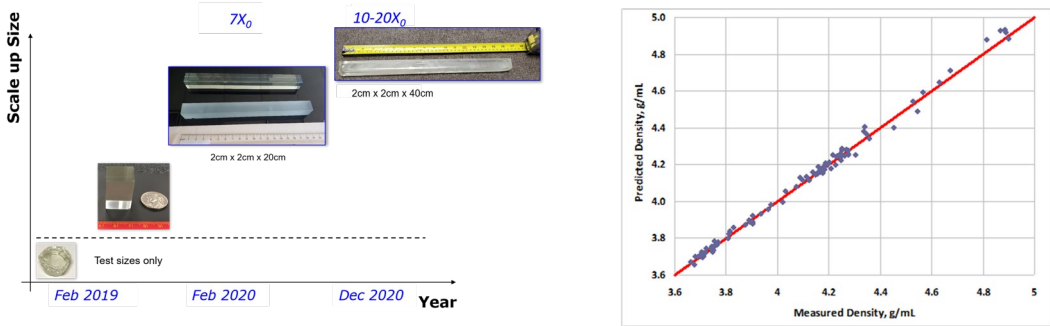

Figure 1: *(left)* Three stages of *SciGlass Scale-Up; (right) quality of the SciGlass model.*

2020. The quality of the glass composition model is illustrated in Figure 1(right). The vertical axis represents the calculated density from the SciGlass composition model. The horizontal axis represents the measured value of the density. The consistency between the projected and measured values demonstrates the high level of understanding and reproducibility of any SciGlass composition.

The optical properties of the blocks were measured in the wavelength range from 200 to 900 nm. The transmittance of light was measured by means of a Perkin-Elmer Lambda 950 double-beam spectrophotometer and an integrating sphere. The optical properties of SciGlass are shown in Figure 2 (left). The scintillation decay time was determined with a time-resolved

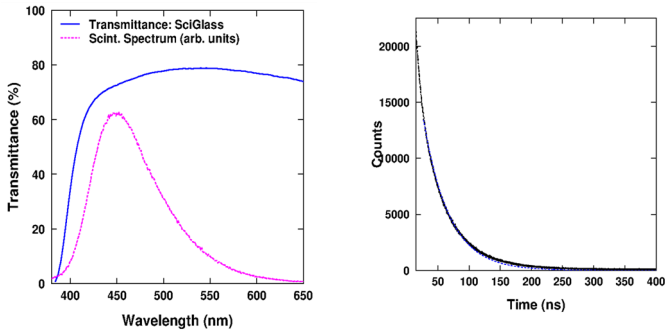

Figure 2: *(left) Scintillation spectrum (red curve) and transmittance (blue curve) of SciGlass; (right) scintillation decay time.*

photon counting/steady-state fluorescence spectrometer that allows for measurement of lifetimes down to the sub-nanosecond range as well as excitation/emission spectra. Figure 2 (right) shows the SciGlass scintillation decay time (right panel) with a fast component of 10-20ns and intermediate component of ~40ns. For comparison, the high-resolution EM calorimeters at the EIC require an interaction rate capability up to 0.5×10^6 Hz requiring reasonably fast scintillation kinetics.

As reported previously SciGlass is radiation hard up to integrated doses of 100 Gy at about 18 Gy/min. Our results thus far do not indicate any radiation damage to the glass and no impact of different photon irradiation rates. To test for possible hadron radiation damage, we irradiated two 2cm x 2cm glass samples with fluences of 4.3×10^{15} neq/cm^2 (2×10^{15} p/cm^2) and 2.3×10^{15} neq/cm^2 (1×10^{15} p/cm^2), respectively. No obvious discoloration, which may indicate radiation damage, was observed. For experiments at the EIC moderate radiation hardness up to ~3 krad/year (30 Gy/year) electromagnetic and 10^{10} n/cm^2 hadronic are expected in the EM calorimeters at the top luminosity. ***Current results suggest that SciGlass meets these specifications, but more detailed (and higher dose) tests are planned.***

b) Initial prototype beam tests

Despite Covid-19 challenges we were able to carry out initial performance tests of our crystal/glass prototypes using secondary electrons provided by the Hall D Pair Spectrometer (PS). Each detector arm covers a momentum range of $e^{\pm}$ between 3.0 GeV/c and 6.2 GeV/c. The energy resolution of the pair spectrometer is estimated to be better than 0.6%. The preliminary results are shown in Figure 3 along with the projections from the GEANT simulation discussed below. The observed energy resolution is ~15% for a 5.2 GeV particle energy. The slightly better performance observed in the experiment is due to the difference in composition/density of the SciGlass and the base composition implemented in the simulation. Energy leakage due to the limited length of the SciGlass blocks is clearly visible and expected from the shower development in relatively short SciGlass blocks. A visualization of the longitudinal and lateral shower development is shown in Figure 4. The shower is contained to ~92% in $PbWO_4$ blocks, which correspond to $23X_0$, while up to ~59% of the shower is contained in SciGlass blocks, which correspond to ~$7X_0$. To achieve the same high-resolution performance SciGlass thus requires a larger longitudinally dimension because of its larger radiation length compared to $PbWO_4$.

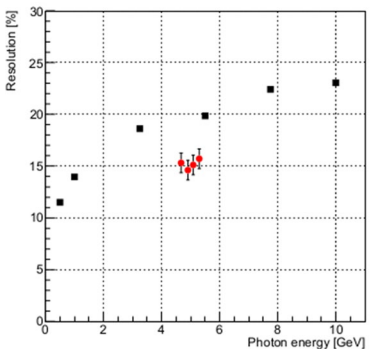

Figure 3: *Preliminary energy resolution from beam test (red circles) and simulation projections (black squares)*

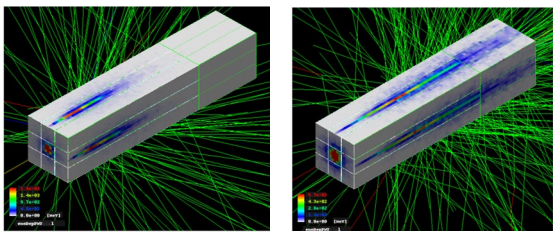

Figure 4: *Simulation of 3x3 matrix with $PbWO_4$ (left) and SciGlass (right), both of 20cm longitudinal length, which corresponds to $23X_0$ $PbWO_4$ and $7X_0$*

The optimal length for SciGlass was investigated with the GEANT4 simulation for particle energies 1-18 GeV, which corresponds to the energy reach of the EIC. Figure 5(left) illustrates the shower containment for 40cm long SciGlass for 18 GeV incident electrons in a 3x3 matrix of 2x2cm^2 blocks. The shower is contained to ~85%, with about 80% of the energy deposited in the central module. In general, the beam test results together with the simulation results in Figure 5(right) suggest that resolutions comparable to $PbWO_4$ can be achieved with SciGlass of length 40cm. ***To demonstrate the performance of such SciGlass we plan to produce modules with SciGlass length between 40-50cm and to evaluate their characteristics with test beam.***

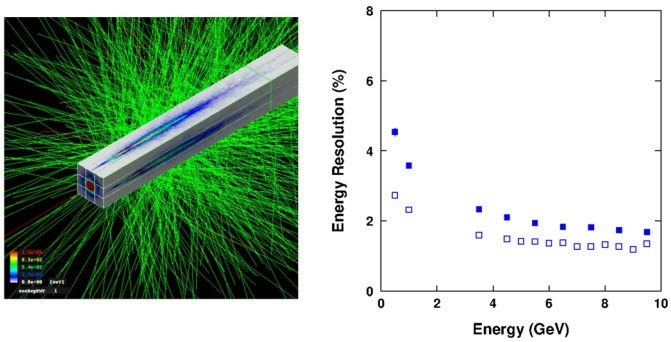

Figure 5: *Simulation results for energy resolution of 40cm SciGlass blocks of 40cm in 3x3 (5x5) arrays.*

3) EIC EMCal simulation studies

Simulation studies have been carried out to further optimize the scintillator material and to investigate its performance in the different regions of the EIC detector. The simulations consist of a GEANT4 simulation of the calorimeters and an Artificial Intelligence framework. ***The details of our ongoing and planned activities can be found in the "Future" section below.***

What was not achieved, why not, and what will be done to correct?

We have yet to complete the planned additional electromagnetic irradiation studies, which have been delayed due to COVID-19 (see below). We expect these to be resolved and irradiation completed as soon as possible. Due to COVID-19 we have also not yet carried out the planned glass/crystal characterizations and prototype beam tests for the eight production settings listed below, including those with SiPM (streaming) readout. However, we have gathered the needed expertise to commission hardware and configure software to carry out these tests as soon as possible.

How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

- Work with vendors on crystal/glass production: delays until laboratories/university return to normal operating mode with User Access
    - Crystals: delays of shipments from SICCAS; Crytur has been sending crystals, but we cannot characterize them until JLab returns to normal operations

    - Glass: polishing of produced samples cannot be completed and samples cannot be characterized until labs/university return to normal operating mode
- Produce larger numbers of ~$10X_0$ glass samples: delayed until labs/university return to normal operations
- Prototype test program: beam test delayed until restart of beam operations to the experimental halls. Also delayed is our ability to address the EIC R&D Committee's comments from the Jan 2020 Report: "*Near-term plans include measurement of light yield from cosmic-ray events, which is of great interest to the Committee. Having encouraging results would be a significant step forward towards further endorsement of this R&D effort. The Committee looks forward to the next reports.*"
- Additional radiation hardness tests: radiation facility available again, but delays in sending the glass samples
- SBIR/STTR Phase 2: Impact to be determined
- Extend evaluation of homogeneous calorimetry: Monte Carlo studies can proceed as planned; prototype tests delayed until laboratories return to normal operations

How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

We have not spent roughly 39% of our FY20 budget due to the pandemic related closing of facilities. We have spent FY20 funding mainly on getting started on materials and equipment purchases, while universities and laboratories are closed. We have not yet received our FY21 funding that was approved in July 2020. We were thus not able to spend any of these funds.

Do you have running costs that are needed even if R&D efforts have paused?

We do have running costs that are needed to keep our efforts going even if in-lab R&D efforts are paused. One example is equipment needed to keep remote work going, another is technical and student support, e.g., for Monte Carlo simulations of physics in preparation for prototype tests or modeling of calorimeter infrastructure and material production processes.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

Our main activities will be to continue R&D on $PbWO_4$ and glass scintillator production. These R&D activities are well aligned with the EIC UG Yellow Report Calorimeter and R&D needs. ***We plan to complete the SciGlass scale-up and larger scale production (Section 1) and evaluate working modules with a beam test program (Section 2). We plan to use simulations and the artificial intelligence framework to further optimize the material (Section 3).*** The simulations will also be

of interest for supporting the prototype tests and the configuration of the electron endcap calorimeter, e.g., coverage, reflector choices, impact of mechanical support structure on performance, light monitoring and cooling. Exploration of glass for the barrel EM calorimeter will be included as well. For SciGlass R&D the availability and carry-over of FY21 R&D funds will be important. ***Another major R&D activity is the development of CSGlass for possible improvement of hadron calorimeter resolution and, in particular, the evaluation of Cherenkov vs. Scintillation light output and small-scale beam tests (Section 4)***. This is a new component to our program and a moderate amount of R&D funding ($60k/year) is requested to carry out the CSGlass R&D. ***Long term goals and milestones of the $PbWO_4$/glass for EIC homogeneous calorimeters project are discussed in section 5.***

1) SciGlass Fabrication

Our early development work has focused on glass composition optimization and process modifications to improve uniformity and prevent the formation of bubbles and inclusions. With the process chemistry and material properties under control, we have moved progressively to emphasize scale up and factors of importance for large volume production. The basic production processes include batching, melting and high temperature processing, casting, annealing, grinding, and polishing. At present, we have demonstrated all of these steps at scales from a few centimetres up to 2 cm x 2 cm x 40 cm polished bars. Throughout the scale-up evolution, the objective is to maintain the uniformity demonstrated at the smaller scales.

Our longer-term plans will investigate the consistency of product quality over many repetitions of bar production in order to assess the statistical distributions of key properties. This will allow us to identify and understand the process parameters that affect these distributions and develop and implement process controls to ensure that the variations of these properties remain within acceptable ranges. This will include assessments of the effects of impurities in the raw materials and determination of the quality control specifications that will be required. In areas where the process is relatively insensitive to specific impurities, this will provide an opportunity to decrease costs. We will also optimize the required polishing quality since this is another factor that can affect overall costs if very high-quality polishes are needed.

As our focus moves more to large scale production, we will address the selection and optimization of process features that are best suited to the projected production rates (number of bars per day) that are likely to be required. This includes factors such as the selection of crucible types, materials, and volumes; melting furnace technology; and the use of a single production line versus multiple smaller production lines.

2) Prototype Beam Tests

A 3x3 $PbWO_4$/SciGlass prototype has been designed and is ready for data taking as soon as beam operations return and the necessary experts are allowed on site. Data remain to be taken for the eight planned production configurations listed below.

- PWO proto-PMT + fADC250+VTP
- PWO proto-PMT + WB
- PWO proto-SiPM+BIAS board/Preamp+fADC250+VTP
- PWO proto-SiPM+WB
- Glass proto-PMT + fADC250+VTP
- Glass proto-PMT + WB
- Glass proto-SiPM+BIAS board/Preamp+fADC250+VTP
- Glass proto-SiPM+WB

As part of the beam test program and also the simulation effort in Section 4 the impact of reflector choice on scintillator performance will be investigated. A mechanical structure holding the crystals/glass in place is advantageous for detector construction and maintenance. The impact of the material choice and dimensions for such a mechanical structure will be investigated.

3) Simulations to further optimize material and configuration

a. GEANT4 simulation development

We have been implementing the electron endcap EM Calorimeter (EEEMCal) in the EIC Geant4 simulation (G4E). This includes the geometry, readout digitization, and reconstruction algorithms in the eJANA framework. Analysis plugins have been developed for studies of the EEEMCal performance, e.g., energy resolution and effect of resolution on reconstructed quantities like Q^2 and x. An overview of the interplay between simulation and

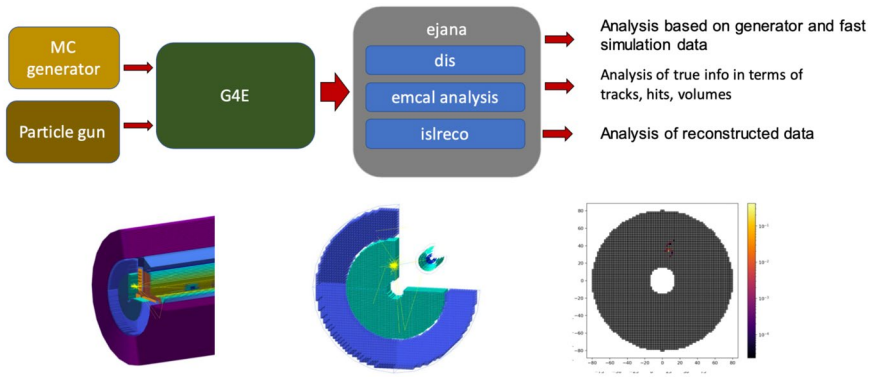

Figure 6: *A hit in the EEEMCal. Simulated with the g4e particle*

reconstruction is shown in Figure 6. The nominal geometry of the EEEMCal includes an inner part (R_{in}=15cm, R_{out}=49cm) of $PbWO_4$ crystals of size 20 x 20 x 200 mm^3 and an outer part (R_{in}=49cm, R_{out}=133cm) of SciGlass blocks of size 20 x 20 x 400mm^3. The response of the scintillator blocks coupled to SiPMs was implemented based on the CLAS12-FT[3] in Hall B and BDX experiment. The SiPMs have an area of 1.2cm x 1.2cm, pixel pitch of 25 um, and PDE of 0.22. The reconstruction algorithm implemented for the EEEMCal uses island clusterization combined with common reconstruction algorithms

[3] Nucl. Instr. Meth. A 959 (2020) 163475

and is based on that used in experiments like SELEX, PrimEx-II, and PrimEx-D. The EIC GEANT4 simulation includes other subdetectors of the central detector. We plan to carry out detailed studies of the impact of material in front of the calorimeter on the energy resolution. This is particularly important for high precision detection of the scattered electron and neutral final stated in the electron endcap.

b. Artificial Intelligence framework

To optimize the crystal/glass material selection in the shared rapidity EIC backward region and to explore feasibility of glass with suitable readout in the central region we have been setting up an Artificial Intelligence (A.I.)-optimized simulation of the EIC calorimeter[4]. An illustration of the electron endcap model is shown in Fig. 6. The cyan area represents PbWO4, the blue area SciGlass. The A.I. algorithm being developed interfaces with this

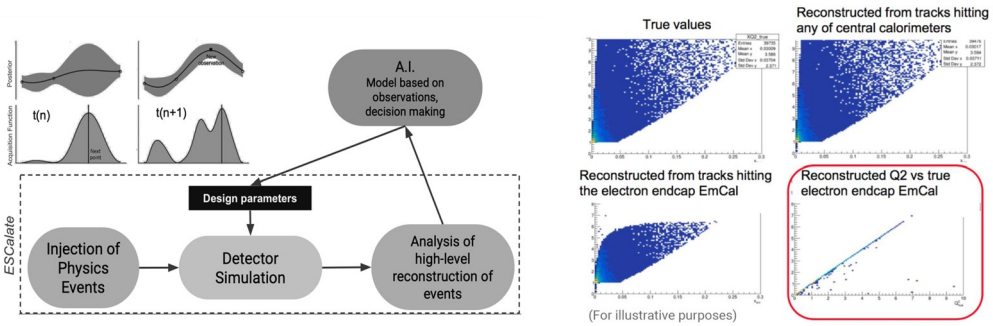

Figure 7: *(left) AI workflow to optimize the EEEMCal design; (right) illustration of the reconstructed quantities used in the design*

simulation and optimizes the input parameters for the figures of merit, see Fig.7 (left). The overall goal of the design optimization is to maintain the resolution needed by the physics processes, e.g., DIS, while minimizing the total crystal/glass cost (crystal being more expensive than glass), taking into account dynamically during the optimization process the constraints in the detector. The approach includes objective functions based on physics processes and hybrid calorimeter reconstruction algorithms as described above. Other reconstruction solutions like hierarchical clustering will also be investigated. The analysis will be based on the evaluation of the impact of EMCal resolution on the reconstructed quantities, of which a first illustration is shown in Figure 7 (right).

c. Initial Investigation of Support Structure for Crystal/Glass

The EEEMCal will require a support structure to hold the individual modules. We began investigating possible EEEMCal mechanical models, e.g., that of

[4] Compared to E. Cisbani et al., JINST 15 (2020) P05009, the A.I. algorithm for the EEEMCal is extended to a multi-dimensional objective space to optimize more figures of merit simultaneously.

the Hall C Neutral Particle Spectrometer (NPS) that was built by our team and the Hall D FCAL insert. These are shown in Figure 8. The NPS is a $PbWO_4$ crystal calorimeter consisting of ~1100 crystals. The FCAL insert is a hybrid calorimeter consisting of an inner part made of $PbWO_4$ crystals and an outer region made of lead glass. The FCAL hybrid design is similar to the design of the EEEMCal as detailed in the EIC Yellow Report. ***Since the support structure introduces a dead space between the scintillator modules the impact on the detector resolution has to be quantified.***

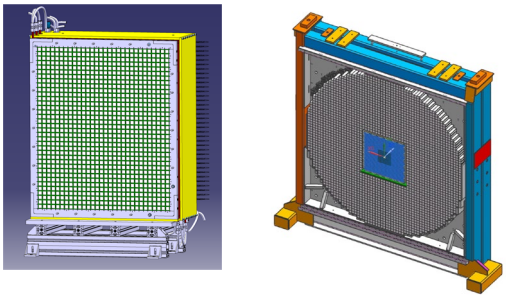

Figure 8: *(left) NPS and (right) FCAL mechanical model*

4) CSGlass R&D

One of the most promising methods to achieve better performance for hadronic calorimeters is dual readout. By comparing the signals produced by Scintillation light (S) and Cherenkov light (C) in the same detector, the EM shower fraction, whose fluctuations are the main culprit for problems encountered with hadronic calorimetry, can be determined for individual events. The validity of this principle has been demonstrated with the DREAM fiber calorimeter. However, two factors impacting hadronic resolution remain: sampling fluctuations and fluctuations in the Cherenkov light yield. Homogeneous materials such as crystals and glasses in which both S and C light are generated in the same optical volume have the potential to eliminate these two issues. ***The primary objective of this R&D activity is to produce novel CSGlass and to demonstrate that the glass has sufficient Scintillation and Cherenkov response.*** Samples of different shapes (e.g., rectangular, trapezoidal, fibers) and composition will be produced and their detection properties characterized. To determine the contribution of Cherenkov light, the ratio of Cherenkov vs. Scintillation light will be measured. ***Another objective is beam tests to show that signals can be separated into Scintillation and Cherenkov components that are measured simultaneously.***

5) Long-term goals and milestones

Our long-term goal is to align our R&D with the EIC critical decision process and to have reached a level for both crystals and glass to be considered as active material for EIC EM calorimeters. The FY21 milestones towards reaching this goal are:

- Fabricate additional ~$10X_0$ and ~$15\text{-}20X_0$ SciGlass bars
- Further develop and commission readout software and simulations
- Commission a SciGlass/$PbWO_4$ prototype and upgrade as needed
- Carry out a prototype beam test program
- Evaluate optimal reflector choice for the calorimeter

- Evaluate impact of mechanical structure, e.g., carbon fiber, on resolution
- Prepare for larger scale SciGlass production
- SBIR/STTR Phase 2 proposal

The estimated timeline for SciGlass is shown in Table 1. Receiving the SBIR/STTR Phase 2 funding is particularly important towards reaching this long-term goal. The estimated timeline for CSGlass is shown in Table 2. Receiving the SBIR/STTR Phase 2 funding is important for achieving this goal in about three years.

Item	Task	FY20				FY21				FY22				FY23		
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Fabrication	Composition optimization															
	Characterization															
	Scale up and demo 4x4x40cm^3															
	Show uniformity and reproducibility															
	Fabrication process optimization															
	Performance tests with prototype															
	Process design verification to scale up															
	Large scale production study															
Simulations	Prototype															
	Design options															
	Cost/performance optimization															
Prototype	Base version															
	Initial commissioning															
	Upgrade and commissioning															
Beam test	Beam test															
	Data analysis															

Table 1: *Estimated timeline for SciGlass development*

Another long-term goal is to construct the electron endcap EM calorimeter ($PbWO_4$/glass), EEEMCal. To achieve this goal, we have started discussions and assembling a team and submitted an Expression of Interest. The EEEMCal team consists of CUA, FIU, MIT, U. of Kentucky, Lehigh U., Charles U./Prague, and our collaborating institutions from Armenia (AANL) and France (IJCLab-Orsay) from this eRD1 project. This team brings experience with developing and building EM calorimeters at Jefferson Lab, e.g., the $PbWO_4$-based Neutral Particle Spectrometer, the PbGl calorimeters, the PbF2 DVCS calorimeter, and the STAR ECal at BNL, as well as expertise with and vendor presence for glass scintillators.

Item	Task	FY21				FY22				FY23				FY24				
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
CSGlass fabrication	Composition optimization																	
	Characterization																	
	Scale up and demo																	
	Show uniformity and																	
	Fabrication process																	
	Performance tests with																	
	Process design verification to																	
	Large scale production																	
Software	R&D Prototype																	
	Design options																	
	Cost/performance optimization																	
Prototype	R&D Base version																	
	Initial commissioning																	
	Upgrade and commissioning																	
Beam test	Beam test																	
	Data analysis																	

Table 2: *Estimated timeline for CSGlass development.*

What are critical issues?

For SciGlass R&D the main issues are scale-up, possible further formulation and fabrication optimization, and beam tests with suitable readout. Receiving the SBIR/STTR Phase 2 funding is critical to advance the scintillating glass development on a time scale to be considered as active material for the EIC EM calorimeters. Receiving and carrying over the FY21 funds will be essential for SciGlass and crystal characterization, e.g., the prototype tests for understanding and optimizing the actual performance for the EIC detector, as well as the simulation studies for further optimization of the material. This includes choice of reflector, light monitoring and cooling, mechanical structures to hold the blocks in place, as well as impact of materials in front of the calorimeter. For CSGlass, critical items are the formulation optimization and production of CSGlass test samples.

Additional information:

Manpower

IPN-Orsay: M. Josselin, J. Bettane, Ho San Ko (graduate student), G. Hull, C. Munoz-Camacho
CUA/Scintilex: V. Berdnikov (postdoc), J. Crafts, T. Horn, I.L. Pegg, P. Stepanov (postdoc), Richard Trotta (graduate student), Vitreous State Laboratory staff
Yerevan: H. Mkrtchyan, V. Tadevosyan, A. Asaturyan
BNL: C. Woody, S. Stoll, M. Purschke
INFN-GE: M. Battaglieri, M. Bondi, A. Celentano, R. deVita
MIT: C. Fanelli
JLAB: M. Battaglieri, A. Somov

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

- All of the FTEs required for working towards test setups and characterization are provided by CUA/VSL/IPN-Orsay/INFN-GE or external grants. The absence of labor costs makes this proposed R&D effort extremely cost effective.
- The 460 SIC crystals produced in 2017 and 211 CRYTUR crystals produced in 2018 and 2019, as well as the newly ordered SICCAS and CRYTUR crystals are provided through synergistic activities with independent research for the JLab Neutral Particle Spectrometer (NPS) project.
- The expertise and use of specialized instruments required for production, characterization, and chemical analysis are made possible through collaboration with the Vitreous State Laboratory (VSL) that is also collaborating on the NPS project.
- INFN is contributing in kind with part of the equipment of the testing lab at INFN-GE, as well as support for postdoctoral researcher Dr. Bondi.

Efforts related to production and characterization studies as described here were accomplished with external funds through synergistic activities with the NPS project at JLab. Additional funds and facilities for glass characterization were provided by the Vitreous State Laboratory at CUA. Salaries were provided by private external grants from the individual principal investigators, e.g., IPN-Orsay, INFN-GE, MIT, Yerevan, and the National Science Foundation.

Publications

Please provide a list of publications coming out of the R&D effort.

- *EIC Yellow Report, Volume III, Chapter 11 and Chapter 14, March 2021*
- *Electromagnetic Calorimeters based on the scintillating lead tungstate crystals for experiments at Jefferson Lab,* A. Asaturyan, V.Berdnikov, et al., to be submitted to NIMA (2021)
- *Scintillating crystals/glass for the Neutral Particle Spectrometer and EIC*, V. Berdnikov, T. Horn, C. Munoz-Camacho, I.L. Pegg, A. Somov, *et al*., Nucl. Inst. Meth. A**956** (2020) 163375
- *Expression of Interest (EOI) for the Electron-Endcap Electromagnetic Calorimeter (EEEmCal),* T. Horn, et al. (2020), available online: https://indico.bnl.gov/event/8552/contributions/43186/
- *Test of PWO calorimeter prototype using Hall D Pair Spectrometer*, V. Berdnikov et al., GlueX-doc-#3590-v1, May 2019
- *Performance of the PMT Active Base for CCAL (NPS Prototype)*, V. Berdnikov et al., GlueX-doc-#3998-v1, May 2019
- *Overview of calorimeter*, T. Horn et al., Detector Handbook and JLab documentation series (2018/19)

Sub Project 2: Progress on W/SciFi EMCAL and Fe/Sc HCAL Developments for EIC
Project Leader: H.Z. Huang and O. Tsai (UCLA)

What was planned for this period?

For the past six months we have been working intensively on the STAR forward calorimeter system, as planned in our previous report. Our highest priority was to construct STAR Forward Calorimeter System (FCS) at BNL. This STAR FCS is very similar to the Forward Hadron Endcap Calorimeter under consideration at EIC. The construction and operation of the STAR FCS will address many same questions for the EIC forward calorimeter system that we have planned for this period.

We have taken advantage of the synergy between the STAR FCS construction and the EIC calorimeter detector R&D project in the past several years. We would not be able to construct the STAR FCS in such a short period under the stress of the COVID-19 pandemic without the technology and experience that we have developed under the support of the R&D program. We expect that the operation and the performance of the STAR FCS will benefit the design and construction of the EIC calorimeter system in the coming years.

What was achieved?

The STAR FCS system was assembled efficiently at BNL during Oct. 2020 – Jan. 2021, and it is presently in commissioning. Physics data-taking with the FCS is expected to begin in the fall of 2021 with the p+p 500 GeV run. We will have a unique opportunity to operate a large-scale forward calorimeter system (STAR FCS) for jet physics measurement, similar to a calorimeter subsystem currently planned for the EIC reference detector, operating under conditions that would resemble those at the high luminosity EIC.

Figure 1. The STAR Forward Calorimeter System covers a pseudo-rapidity range of 2.5 to 4 and consists of 1496 channels of EMCal and 520 channels of HCal modules all with SiPMs readout.

A new very efficient construction technology was used for the Hadron Calorimeter of the STAR FCS. Despite considerable scheduling difficulties due to COVID19 restrictions and very tight space with limited access where the FCS is located at STAR, a 30 ton hadron calorimeter detector was assembled from parts in place in just 20 days. CAD technicians and STAR users (mostly students) had no difficulties to maintain an assembly rate of 26 HCal towers a day under these challenging conditions.

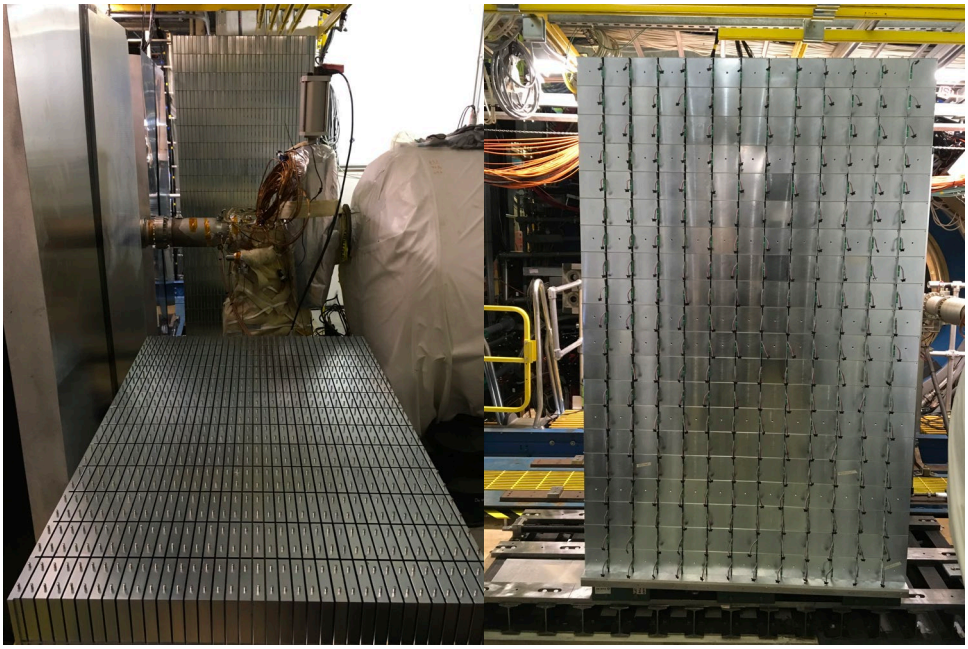

Figure 2. Construction photos of the STAR Forward Hadron Calorimeter. The LEGO type assembly technology was used to build the 30 ton HCal with 520 readout channels in place in 20 days. On the left, the North side of the HCal is being assembled. Behind the beam pipe is the fully assembled South Side of the HCal. On the right is the back side of the South HCal (13 x 20 matrix of towers with individual tower size of 10 cm x 10 cm).

The HCal section is a stack of layers of absorber and scintillation plates. The easiest way to describe the assembly process is to imagine building an entire HCal block from LEGO style parts layer-by-layer. Figure 2 shows the construction photos of HCal during assembly in place. Holes in the bottom base plate of the detector provide locations of the absorber plates. Each absorber plate has four holes for dowel pins, two at the bottom and two at the top. Steel dowel pins (5 mm in diameter) position absorber plates with respect to the bottom base and top steel master plates. A ~2 mm thick steel master plate in between HCal tower layers provides interlinks among all absorber plates within one tower, and among absorber plates of the adjacent row of towers. The entire structure of the HCal is very rigid and has excellent mechanical tolerances (better than 100 um for this assembly), which allows to keep clearance gaps to a minimum, mostly determined by the tolerances of the scintillation and WLS plates. That makes HCal relatively compact, with an effective interaction length of 20.16 cm. Very compact readout schemes with SiPMs were used for both EMCal and HCal section. The HCal readout electronics, LED monitoring system, cooling and cabling added just 5 cm at the back of the HCal towers. The compactness of the FCS was necessary in order to fit the system in STAR. The back cover of HCal detector almost touches the DX magnet behind the HCal in Figure 2. The EIC reference detector geometry will have similar constraints due to tight available space.

There are only five major components needed for HCal assembly. These are common parts relatively easy to produce at most machine shops from Universities or outside industry. That was an important factor leading to the timely completion of the FCS construction project as production of HCal parts took place during COVID19 pandemic. All participating Universities in STAR were affected by the COVID19 related lockout one way or another. Because of the very simple design of the FCS we were able to re-arrange production alternative shops to stay with the schedule.

The completion of the STAR FCS was an outcome jointly from STAR and EIC calorimeter R&D efforts over many years. Two designs for the Forward Calorimeter Systems were tested at FNAL. One is the compensated W/ScFi EMCal section followed by a Pb/Sc HCal section, and the other is non-compensated Pb/Sc Shashlyk EMCal and Fe/Sc HCal section. The current FCS is the later design, which was a compromise due to budget constraints. Accomplishments from these calorimeter studies include:

- Experimental proof of feasibility of W/ScFi technology for very compact sampling electromagnetic calorimeters with energy resolutions varying from (7%-12%)/sqrt(E) for stochastic and (1-2)% for constant term. Several designs of prototype calorimeter utilizing the W/ScFi technology were built and tested with beams at FNAL during 2012-2016 period.
- Demonstration of new effective construction technology for sampling hadron calorimeters with good energy resolution. Two prototypes were built and tested at FNAL in 2014, 2019. A 30 ton HCal for the STAR Forward Calorimeter System was constructed in 2020 using this innovative technology.
- Multi-year studies of SiPM characteristics in beam conditions close to those expected at high luminosity EIC. Notably, during Run 2017 at RHIC with 500 GeV pp data, our observation led to new understanding of mechanism responsible for the degradation of SiPMs responses after exposure to neutrons and ionization particles.
- Development of compact readout schemes using SiPMs for W/ScFi and Shashlyk type calorimeters (e.g., the STAR Forward Calorimeter System using SHASHLYK EMCal ~ 1500 channels instrumented in 2020) and WLS/SiPM for HCals (STAR Forward HCal 520 channels).

We will continue to investigate different configurations for a hadron endcap forward calorimeter system for EIC. In our previous reports we discussed some of the effects, which we believe are common for a combination of EMCal and HCal system. These effects include:

- Total depth;
- Instrumental effects (light collection unifromities);
- S/N for exposed SiPM sensors, vs light yield;
- Dead material between EM and Had sections;
- Sampling Frequency in HCal;
- Effect of tail catcher;
- Choice of detector technology for the EMCal section.

Presently we focus on EIC reference detector design, namely the EMCal section using the W/ScFi technology, followed by a Fe/Sc HCal section. Figure 3 shows effect of dead layers on energy resolution in the hadron endcap calorimeter system. No dead layer configuration for this plot refers to the geometry that the HCal structure starts with 2 cm thick Fe plate (nominal thickness of absorber block for HCal). There is a gradual degradation of energy resolution with increased thickness of dead layer between EMCal and HCal. After we finished this study, we realized that there is a simple mechanical solution of attaching EMCal to the HCal without placing additional support material between the two. Thus, we consider that this question is no longer relevant, and we present the results for our record. We expect no degradation of system performance because no dead material will be placed between two detectors.

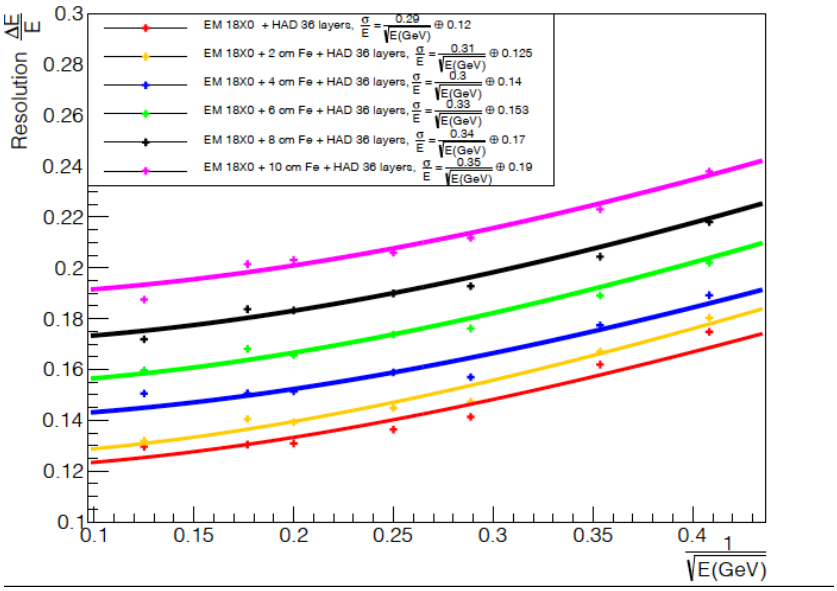

Figure 3. Effect of the thickness of the dead layer between W/ScFi EMCal and Fe/Sc HCal sections on energy resolution.

We also investigated if re-weighting technique of HCal towers [1] can be effectively used to improve energy resolution of the system. We also applied cut on tail catcher (explained in our previous report) for this analysis.

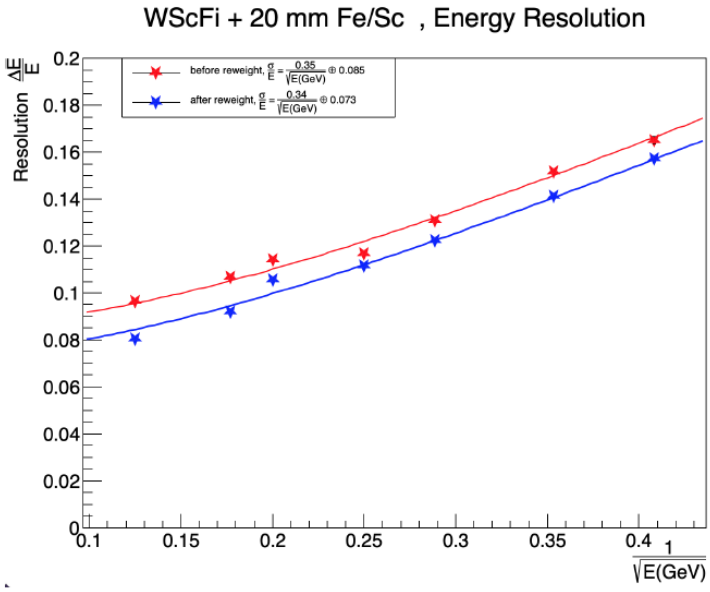

Figure 4. Energy resolution in W/ScFi + Fe/Sc system with using information from a tail catcher (red points) and with additional re-weighting technique for HCal towers (blue points).

There is a notable but not a dramatic improvement in energy resolution of the system with a re-weighting technique of HCal towers.

The energy of hadrons at EIC over a broad rapidity region is relatively low, usually below 10 GeV. Only in the very forward rapidity region > 2.5 it could go up to ~100 GeV or so [2]. The energy resolution of any hadron calorimeter system will probably deviate from square root dependence in the entire energy range presumably due to leakages from the back at high energy and particle-type dependence of detector response at low energy. The overall detector response gets more complicated with a combined EMCal and HCal system where the EMCal and the HCal may have different responses for different particles depending on the particle energy. The ZEUS experiment had very detailed measurements in this energy range [3].

We should note that fit results from simulations shown in our previous reports for hadronic calorimeters should be taken with a precaution. First, commonly used fit function for EMCal calorimeters dose not seem to work well for HCals. Second, the fit range should be restricted to the relevant energy range, i.e. at EIC the most relevant energy range is below ~10 GeV for most part of the detector, and only above pseudo rapidity 2.5 it is necessary to use the full broad energy range.

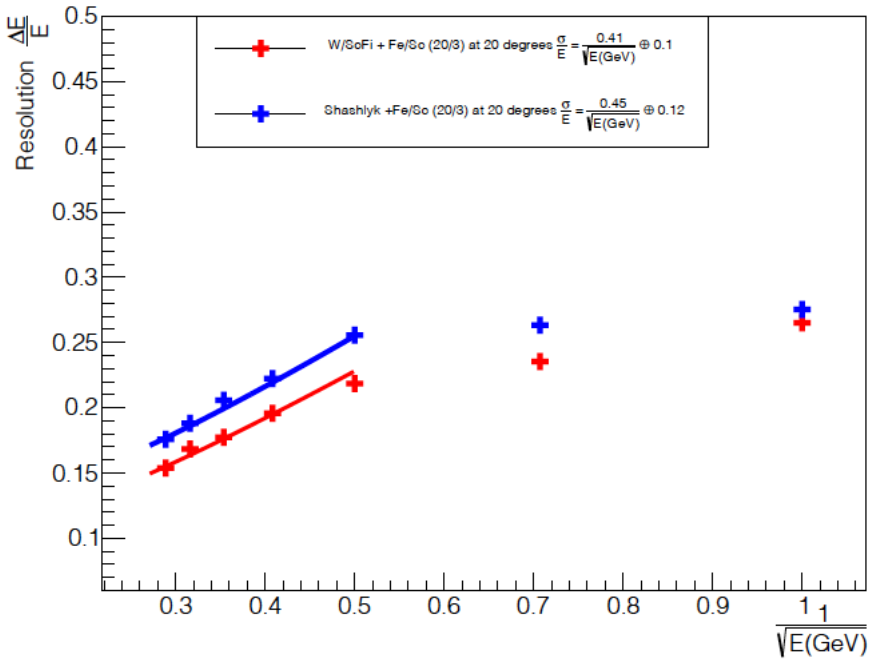

Figure 5. Comarison of energy resolution of W/ScFi and Shashlyk types of EMCals, followed by Fe/Sc HCal at low energy range.

Figure 5 shows comparison of energy resolution of two calorimeter systems utilizing two different EMCal sections (the Shashlyk is similar to the STAR FCS). The reference EIC calorimeter system has noticeably better performance. In both cases there is strong deviation from square root dependence at energies below ~ 4 GeV (fit range restricted to > 4 GeV) .

We are currently investigating if there are additional approaches to optimize the structure of the EMCal and the HCal (within given geometrical limitations at EIC) to improve energy resolution of the system. All results listed below are preliminary. One way to optimize the system is to tune the e/h response of the system to close to 1. In energy region below ~ 10 GeV e/h compensation was not demonstrated previously in otherwise compensated calorimetry system, i.e. the e/h compensation has been demonstrated to work only above ~10 GeV, for example [3]. To investigate the e/h compensation at the low energy region, we considered electron and hadron responses from different designs of EMCal and HCal calorimeter systems. In these cases, we made detector models large enough so that there are no leakages from the detectors. Figure 6 shows e/h responses of W/ScFi and Pb/Sc Shashlyk EMCals. The W/ScFi EMCal seems to work better at low energy range presumably because its e/h ratios are closer to 1 than these from the Pb/Sc Shashlyk EMCal.

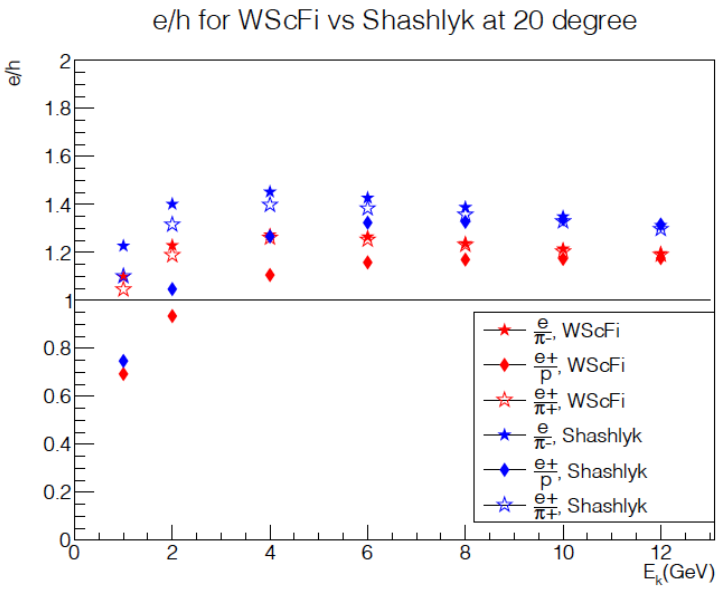

Figure 6. e/h responses with different EMCal options. Note the EMCal is made sufficiently large to avoid leakage.

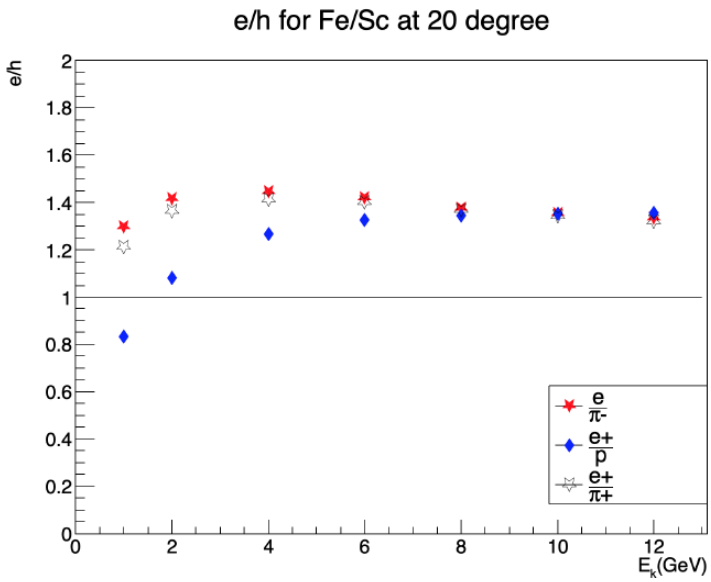

Figure 7. e/h ratios for Fe/Sc HCal

Figure 7 shows e/h ratios for the Fe/Sc HCal structure. It is different from both W/ScFi and Pb/Sc Shashlyk structures. There is very little room to improve e/h compensation for the Fe/Sc HCal structure as it will require to use very thin scintillation tiles, and/or very thick absorber Fe plates, which could make ether the effective light collection unfeasible or significant reduction of sampling fraction ruining the energy resolution.

Another approach for possible optimization is to vary the depth of the EMCal. In this case we keep the total length of the calorimeter system at 5 interaction length and vary the depth of the EMCal section from 0.5 to 1 interaction length. The main idea here is that the EMCal usually has much finer sampling frequency and at low energy a significant fraction of the hadron energy will be deposited in the EMCal section, thus in a longer EMCal configuration the hadron energy could be better measured. In the extreme limit, one could imagine to have a W/SiFi HCal, which did demonstrate

superior hadronic energy resolution. Figure 8 shows the variation of the energy depositions in the EMCal and HCal sections as we change the depth of the EMCal.

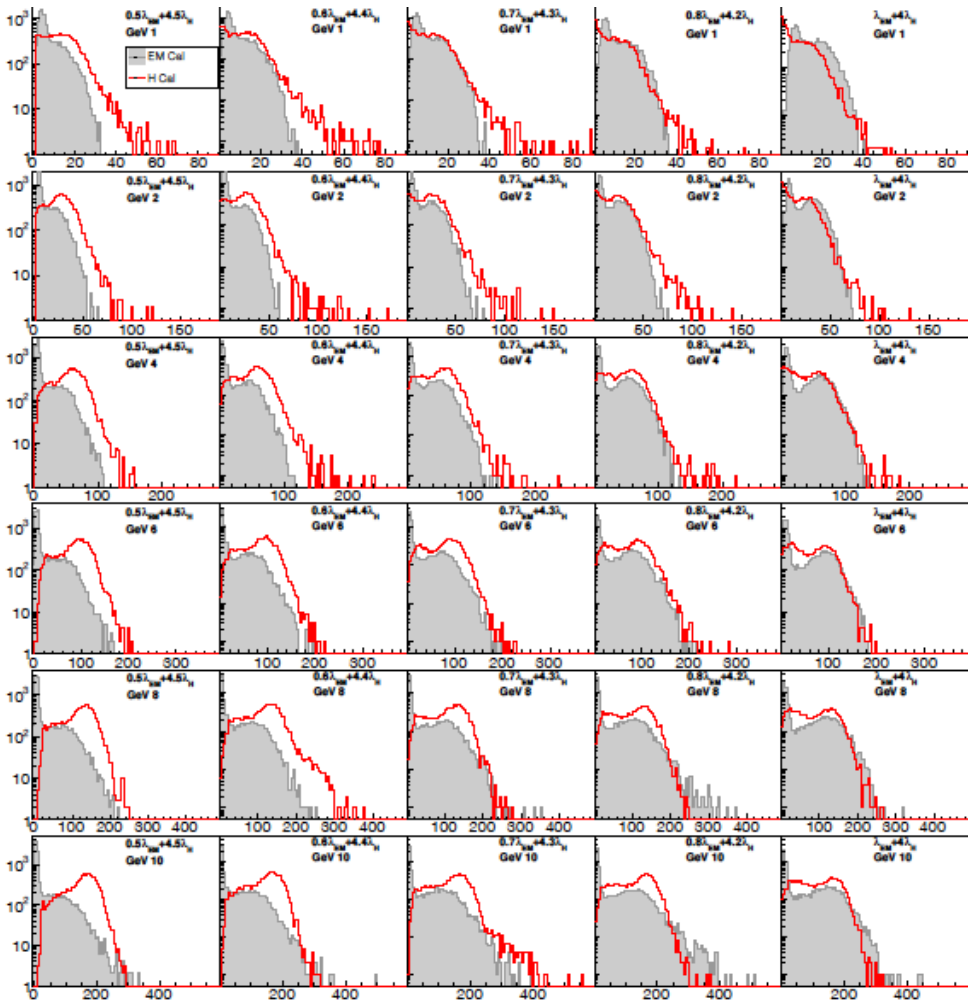

Figure 8. Fraction of energy carried by EMCal and HCal sections for different energies vs the depth of the EMCal.

Figure 9 shows the variation in energy resolution as a function of the EMCal depth. There is a modest improvement in the energy resolution of the system with increasing depth of the EMCal section. The improvements are not dramatic, and practical considerations will probably dominate at the end for the design of the calorimeter system.

To summarize this section, studies to optimize the performance of the W/ScFi EMCal + Fe/Sc HCal system incidate that an incremental improvements up to 20% in the energy resolutions are possible while maintaining the structure simplicity in the EMCal+HCal design of the system. Our simulations showed that the W/ScFi EMCal + Fe/Sc HCal system can meet or exceed the requirements specified in the EIC YR, except in the very forward region above the pseudo-rapidity of 2.5 which will require further investigations.

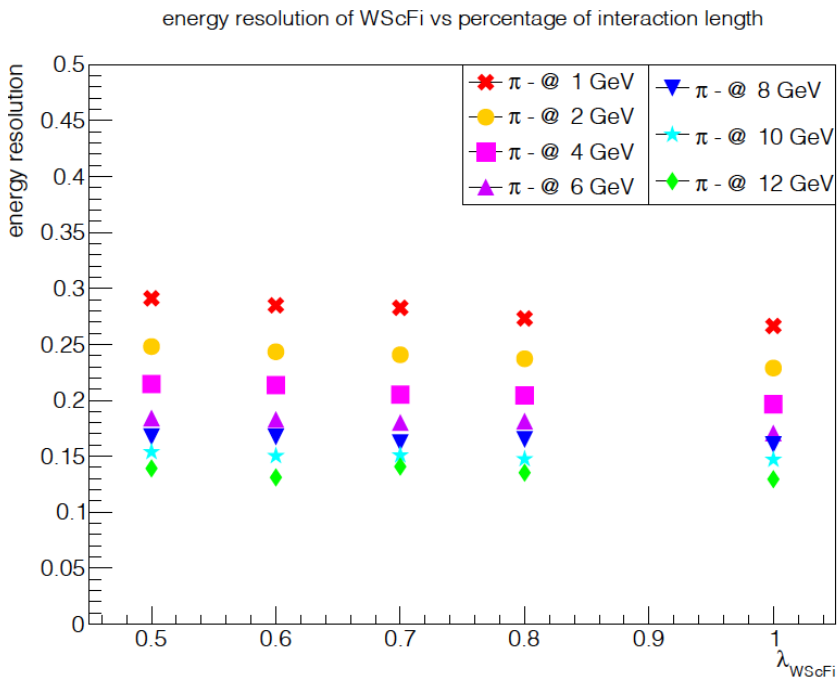

Figure 9. Energy resolution of the W/ScFi EMCal + Fe/Sc HCal system for different depth of the EMCal section.

What was not achieved.

For the past period we planned to study possible improvement of the Light Yield (LY) for the Fe/Sc HCal system with reference to the STAR FCS. The main consideration here is that the STAR FCS operates at a different energy scale from that of the EIC calorimeters. The LY for the EIC HCal needs to be optimized for the relevant EIC energies. We have not been able to carry out the studies in our lab due to lockout and reduction in allowed staff in the lab.

How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

Our lab at UCLA was closed in spring and early summer 2020 and was allowed to operate with one staff after August 2020. Our high priority was to complete the STAR FCS hardware project, which we did by the end of 2020. Our EIC detector R&D related hardware project was on hold. Our expectation is that the hardware project will resume in spring 2021. We expect to complete the hardware project in our FY21 plan in summer 2021.
We continued with the simulation of the EMCal+HCal configurations.

How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

Our graduate student Zhiwan Xu was supported by a UC pilot program for EIC simulations. We have $6k left in our FY20 budget and expect to use the fund to support student in the summer of 2021. We have not received our FY21 R&D fund yet.

Do you have running costs that are needed even if R&D efforts have paused?

No.

Future steps to optimize forward calorimeter structure.

In the coming months we will finish the optimization of the W/ScFi + Fe/Sc + Tail Catcher configuration. We plan to start the optimization of LY for the Fe/Sc HCal, and will investigate alternative vendors of SiPMs.

Moving past YR and towards more targeted R&D, we propose to construct a full scale W/ScFi + Fe/Sc prototype with a coverage of at least 0.6 m x 0.6 m. This would be a major step forward from our previous small scale prototype that was tested at FNAL where lateral leakages are major complications.
Important questions to be addressed with the full scale prototype include:

1. Construction technology – large W/ScFi block construction of 10 cm x 10 cm in transverse dimension, i.e. make a single block rather than glue it out of four units.
2. Evaluation of performance of such system at low energies relevant for EIC.

Our MC simulations used the latest GEANT4 physics list validated for LHC, which is a completely different energy domain from the EIC. For example, e/h ratios shown in Figure 6 are quite different compared to experimental results in [3]. Construction of such a prototype is expected to take 1.5 – 2 years and will require approximately a budget of $300K.

The other important subject that we want to bring to the DAC is that BNL should plan to revive the former A2 test beam line at the AGS. It had suitable energy range for EIC studies.

Manpower.

Four graduate students from UCLA continue to participate in these studies, M. Sergeeva, D. Neff, B. Chan and Z. Xu. supervised by H.Huang and O.Tsai. We will continue strong collaboration with BNL group (A. Kiselev, E. Aschenauer, A. Ogawa) related EIC and STAR Forward Upgrade, UCR group K. Barish, R. Seto related to the UC EIC consortium.

Our graduate student, Z. Xu, is funded by a UC Pilot program to support the UC EIC Consortium from the UCOP. The construction of the STAR FCS was funded by a NSF MIE project and the STAR collaboration. The STAR FCS design grew out of syngetic research activities supported by the EIC detector R&D program and the STAR collaboration.

Budget.

References:
[1] Abramowicz, H. , Groot, J. G. H. D. , Knobloch, J. , May, J. , Palazzi, P. , & Para, A. , et al. (1981). The response and resolution of an iron-scintillator calorimeter for hadronic and electromagnetic showers between 10 gev and 140 gev. Nuclear Instruments & Methods, 180(2-3), 429-439.
[2] http://www.eicug.org/web/sites/default/files/EIC_HANDBOOK_v1.2.pdf
[3] Andresen A. et al., Response of Uranium-Scintillator calorimeter to electrons, pions and protons in the momentum range 0.5-10 GeV/c. NIM A 290 (1990), 95-108

Sub Project 3: New Developments for Tungsten Scintillating Fiber Electromagnetic Calorimeters for EIC
Project Leader: C.Woody

What was planned for this period?

Our main activity planned for this period was to investigate new SiPM readouts for W/SciFi calorimeter blocks with large photocathode area coverage. We planned to do this using the sPHENIX calorimeter blocks in two different configurations. The first would be to utilize the standard sPHENIX light guides, which are currently read out with four 3x3 mm^2 SiPMs (which cover only 23% of the readout end of the light guide and only 6.4% of the total readout area of the block), and replace them with four 6x6 mm^2 SiPMs that would completely cover the readout end of the light guide, thus increasing the readout area by a factor of 4. The second configuration would be to eliminate the 1" long sPHENIX light guide and replace it with a shorter light guide and mixer covering the entire readout end of the block and couple this to a 6x6 array of 6x6 mm^2 SiPMs. This would give nearly complete photocathode coverage of the readout end of the block and eliminate the boundaries between the light guides. This configuration should not only give a much higher photoelectron yield, which would improve the stochastic term in the energy resolution, but also improve the uniformity of response across the block, and hence improve the constant term as well.

(Note that progress on the construction of the sPHENIX W/SciFi calorimeter is no longer included in this report at the committee's request.)

What was achieved?

Earlier in 2020 we purchased 120 Hamamatsu S13360-6050VE SiPMs which have an active area of 6x6 mm^2 and contain Through Silicon Vias (TSV) that allow a direct connection through the silicon from the photocathode to the back of the device where the external connections are made. This eliminates any wire bonds or edge connections and maximizes the useful photocathode area.

The Hamamatsu S13360-6050VEs have 50 μm pixels, which are not ideal for calorimetry due to their limited dynamic range but are well suited to study the improvements in the readout. It is expected that smaller pixel versions (25 μm pixels or smaller) will become available soon. The 6x6 mm^2 devices also have a rather high capacitance (~ 1300 pF), so the 6x6 array was divided into four 3x3 subarrays where one row of SiPMs are connected in series and then the three rows are connected in parallel, resulting in the same capacitance as a single device. Each 3x3 subarray is then read out as a single tower. For the 2x2 arrays, two devices are connected in series and then summed in parallel in order to achieve the same total capacitance for a single readout channel.

Two new PCBs were designed to accommodate the SiPMs in the two configurations described above. We have now produced and assembled several of these boards and carried out some preliminary tests with them which are described below.

2x2x4 arrays of 6x6 mm^2 SiPMs

Figure 2.1 shows a standard sPHENIX readout card with its four 2x2 arrays of 3x3 mm^2 SiPMs along with the new readout card with four 2x2 arrays of 6x6 mm^2 SiPMs. Both of these cards couple directly to the existing light guides used on the sPHENIX absorber blocks.

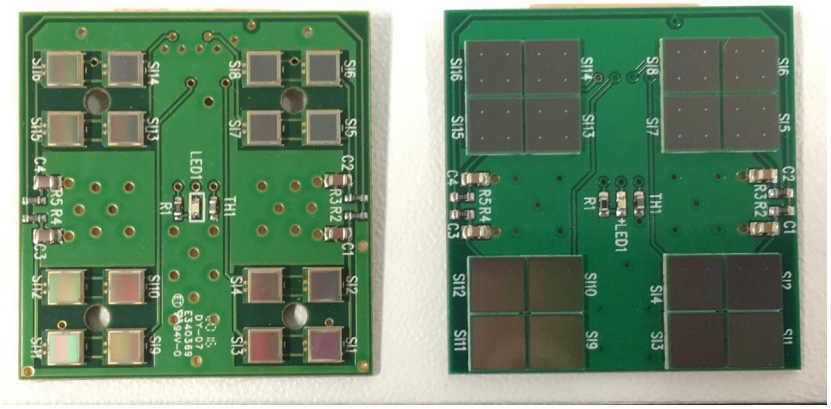

Fig. 2.1. Left: Standard sPHENIX readout card with four 2x2 arrays of 3x3 mm^2 SiPMs. Right: New readout card with four 2x2 arrays of 6x6 mm^2 SiPMs.

The readout cards were first scanned across the bare SiPMs with a 420 nm LED with no light guide attached to measure the response of the SiPMs alone. Figure 2.2 shows the result of this scan. The variation in amplitude for some of the 6x6 mm^2 SiPMs is due to the fact that the gains were not balanced. The white boxes are shown to indicate the areas that would be covered by the light guides.

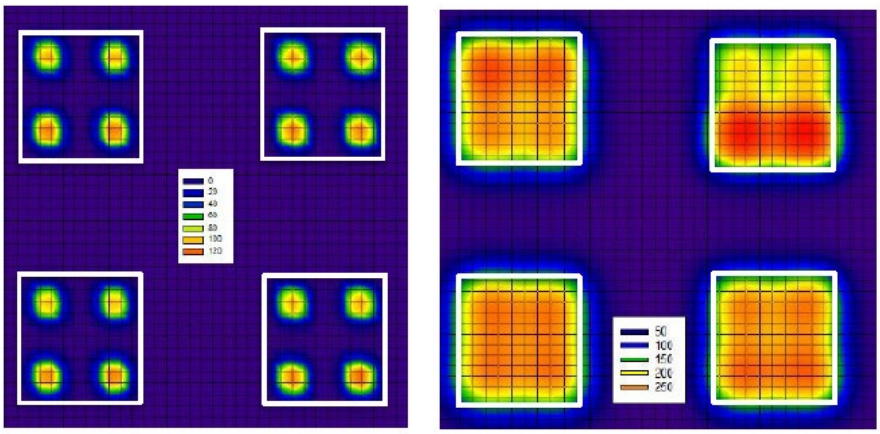

Fig. 2.2. Scan of SiPMs only (no light guides) with an LED. Left: Four 2x2 arrays of 3x3 mm^2 SiPMs currently used for the sPHENIX absorber blocks. Right: Four 2x2 arrays of 6x6 mm^2 SiPMs. The white boxes indicate the areas that would be covered by the light guides. Note that the gains of the 6x6 mm^2 SiPMs were not balanced.

In order to measure the response of the SiPMs to scintillation light from the fibers in the absorber block, the readout cards were coupled to the four light guides on the readout end of a block without a reflector on the opposite end. A 360 nm LED was then used to excite the fibers at the opposite end and was scanned across the block while measuring the signals from the SiPMs. Figure 2.3 shows the results of this scan for a standard sPHENIX block with four 3x3 mm^2 SiPMs compared with the new

readout cards with four 6x6 mm^2 SiPMs. While there is a noticeable improvement in the response near the edges of the 2x2 arrays with the 6x6 mm^2 SiPMs, the response is remarkably similar to the response with the standard readout cards with 3x3 mm^2 SiPMs. This indicates that the light collection efficiency with the smaller SiPMs is still rather uniform even given their smaller area. Note that the absolute amplitudes of the two measurements are not directly comparable, as the gains and LED amplitudes were adjusted to keep the signals within the dynamic range of the readout electronics.

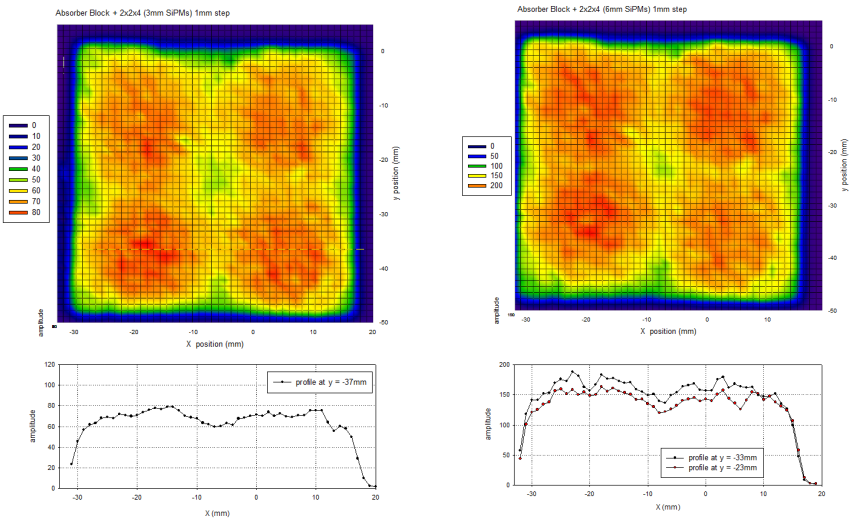

Fig. 2.3. Response of the four 2x2 arrays of SiPMs mounted to the light guides of an absorber with no reflector on the opposite end to a UV LED scanned across the opposite end to excite the fibers. Left: Standard sPHENIX readout card with 3x3 mm^2 SiPMs, Right: New readout card with 6x6 mm^2 SiPMs

6x6 Array of 6x6 mm^2 SiPMs

Figure 2.4 shows the new PCB with the 6x6 array of 6x6 mm^2 SiPMs. The 6x6 array is divided into four 3x3 subarrays which provide a separate readout for each tower and is designed to be mounted to a large area light guide and mixer that covers the entire readout end of the absorber block. The small gaps between the SiPMs are due to the fact that the area of the SiPMs does not exactly match the area of the readout end of the block and the SiPMs were distributed to evenly cover the block area.

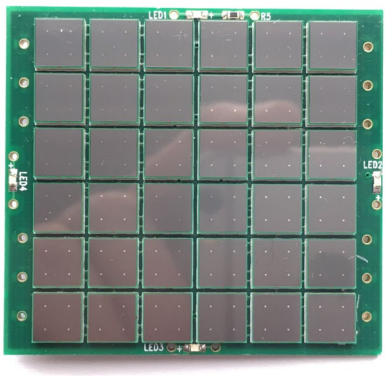

Fig. 2.4. New readout board with a 6x6 arrays of 6x6 mm^2 SiPMs. The readout is divided into four 3x3 subarrays corresponding to the four towers of the block.

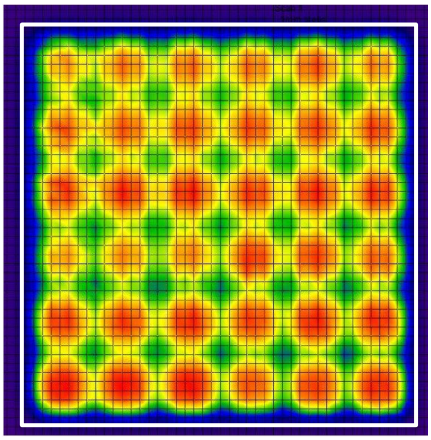

Fig. 2.5. LED scan across the 6x6 array of bare 6x6 mm^2 SiPMs. The white box indicates the readout area of the fiber ends of the absorber block.

Figure 2.5 shows a LED scan across the 6x6 array of bare 6x6 mm^2 SiPMs. The white box indicates the area of the readout end of the absorber block. There is again some variation in the amplitudes due to lack of gain balancing of the SiPMs but shows that all 36 SiPMs are working.

The PCB containing the 6x6 array of SiPMs was coupled to the readout end of an absorber block with a 4 mm thick lucite light guide as shown in Fig. 2.6 on the left. A UV LED was then scanned across opposite end of the block to excite the fibers and measure the response of the SiPMs. The result of this scan is shown in Fig. 2.6 on the right.

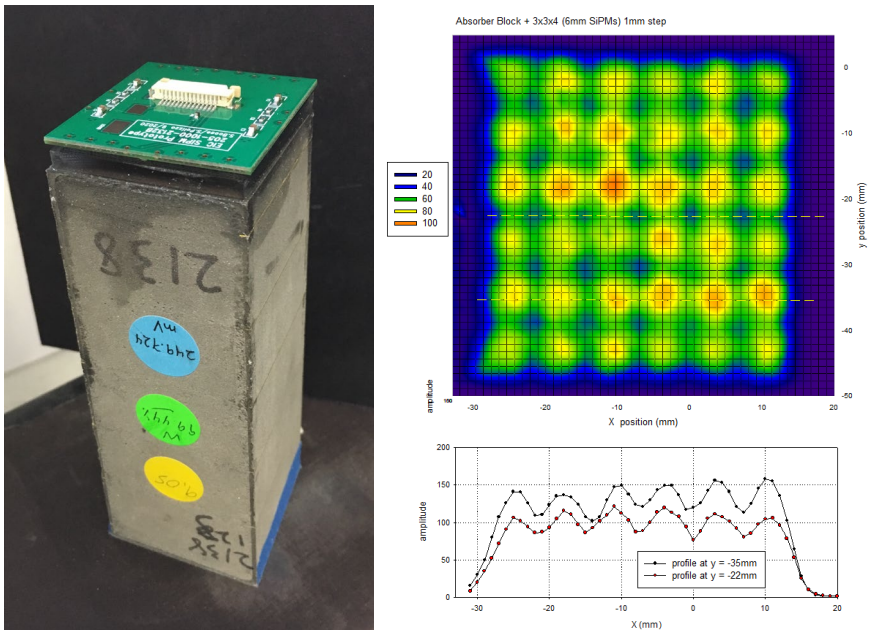

Fig. 2.6. Left: Absorber block with the 6x6 array PCB coupled to the readout end with a 4 mm thick lucite light guide/mixer. Right. Response of the 6x6 array of 6x6 mm^2 SiPMs to a UV LED scanned across the end opposite the readout to excite the fibers.

The scan shows that there are significant dips between the individual SiPMs which are due to the gaps in the way they were arranged on the PCB. We believe this is due to the fact that the light guide was too short to allow the light from the fibers to spread out over the full active area of the array. The length (4 mm) was chosen as the minimum distance required for the light to spread out from the fibers given their numerical aperture. However, this does account for the angular distribution of light within the exit cone from the fiber, which is strongly peaked at ~ 30°. Nevertheless, these first results demonstrate the concept and further studies will be done to optimize the light guide thickness.

However, these first results also suggest that it may be better to continue to consider each quadrant of the block as a single tower and couple it to a 3x3 subarray of SiPMs with an individual light guide. This would be much shorter than the 1" sPHENIX light guides and would have a much larger readout end corresponding to the area of the 3x3 array of 6x6 mm^2 SiPMs. This option will also be explored in future studies.

What was not achieved, why not, and what will be done to correct?

While we did manage to make the first initial measurements with the 6x6 mm^2 SiPMs, our progress was limited partly due to various restrictions due to COVID, but mainly due to the limited amount of manpower to devote to these studies because of other very pressing obligations for sPHENIX. This study is being carried out entirely by members of the sPHENIX EMCAL group, all of whom are extremely busy with the construction of the sPHENIX calorimeter. We hoped to bring a student on site to help with this work, but that was not possible due to travel restrictions and on site restrictions at BNL. However, we hope that starting in the spring or early summer of 2021, we will be able to have a student to help carry out this project.

How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

We had hoped to bring a student on site to help with this work, but that was not possible during the past 7 months due to travel restrictions and on site restrictions at BNL. However, we hope that starting in the spring or early summer of 2021, we will be able to have at least one student (Zhaozhong Shi, who is a graduate student from MIT) come to BNL to work with us on this project.

How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

We received $52K of funding in FY20 and spent $33.3K by the end of the FY. We were not able to spend some of our travel money to bring a student to BNL to help with this project due to restrictions related to COVID. However, we hope to be able to spend this money in FY21 and bring the student to BNL to work with us.

Do you have running costs that are needed even if R&D efforts have paused?

No. We are not supporting any personnel on our R&D funds that need to be paid during any work stoppage. However, we do pay for technician and designer support as needed when work on this project is being performed.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

We will continue with our measurements of the 6x6 mm^2 SiPM readout of the sPHENIX blocks with tests in the lab using LEDs, lasers and cosmic rays. Our goal is to map out the response of the blocks using the two SiPM configurations and compare them to the response of the standard sPHENIX readout using the 3x3 mm^2 SiPMs. We expect a significant improvement in both the photoelectron yield and the uniformity of response across the block with the larger area SiPMs.

We also want to simulate the light collection for the two SiPM configurations using a ray tracing program (TracePro). This turned out to be very useful in the design of the sPHENIX light guides and the agreement between measurements and simulations was very good. We hope that we can get a student to work on this.

What are critical issues?

The most critical issue during the next six months will be to add additional manpower, presumably a graduate student, to help with the measurements and simulations of the 6x6 mm^2 SiPM readout of the sPHENIX absorber blocks.

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.

All of the manpower for this project has so far come from the BNL sPHENIX EMCAL Group (with the exception of some paid services at BNL Instrumentation Division). However, due to the very demanding sPHENIX EMCAL construction schedule, only a very small fraction (~ few percent) of the total EMCAL manpower effort has been or can be devoted to this project.

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

All scientific and engineering manpower for this project (scientists, engineers and Physics Associates) are being supported by the sPHENIX EMCAL group. However, technical manpower, labor outside the BNL Physics Department, materials, and travel are supported by EIC R&D funds.

Publications

Please provide a list of publications coming out of the R&D effort.

Publications in Peer Reviewed Journals:

C.A.Aidala et.al., “Design and Beam Test Results for the 2-D Projective sPHENIX Electromagnetic Calorimeter Prototype”, IEEE Trans. Nucl. Sci. 68-2 (2021) 173-181.

C.A.Aidala et.al., “Design and Beam Test Results for the sPHENIX Electromagnetic and Hadronic Prototypes”, IEEE Trans. Nucl. Sci. 65-12 (2018) 2901-2919.

B.Biro et.al., “A Comparison of the Effects of Neutron and Gamma Radiation in Silicon Photomultipliers “, IEEE Trans. Nucl. Sci. 66 (2019) 1833-1839.

Sub Project 4: R&D on a Tungsten Shashlik Calorimeter for EIC
Project Leaders: S. Kuleshov, E. Kistenev and C.Woody

Past

What was planned for this period?

We had originally planned to begin the design and construction of a new larger prototype of a W/Cu shashlik calorimeter that is better optimized for EIC in order to study its energy resolution and uniformity, as well as to develop the tools and techniques needed to construct such a calorimeter. Compared to our existing prototype, which consists of a small array of 3x3 individual modules, each measuring 3.8 x 3.8 cm^2 and optimized for much higher energies, the new prototype would consist of four 12 x 12 cm^2 plates packaged in a single enclosure, which would significantly reduce the number of boundaries between modules and improve the uniformity. This prototype is described in our previous report from July 2020. However, we did not receive any funding for this project, so it has been deferred until a decision is made by the Committee whether or not to continue with it.

The Committee reiterated again in its July 2020 report that we should investigate the existing PHENIX Pb/Scintillator EM calorimeter modules before committing funding to a new W/Cu shashlik design. We agree that it would indeed be of interest to re-instrument a sufficient number of PHENIX EMCAL modules with SiPM readout to enable a meaningful study of its performance and then test in in the test beam, but this is a formidable task, and we cannot carry out this work without support for manpower, materials and testing.

The Committee also stated in its report from July 2020 that we needed to demonstrate the expected improvement of a W/Shashlik calorimeter relative to the existing PHENX Pb/Scintillator calorimeter. While we appreciate this request, we also wish to point out that even if the response of the two detectors were identical, the W/Shashlik would have the advantage of being more compact and therefore occupy less space inside an EIC detector, either in the barrel where radial space is at a premium in order to provide space for tracking and particle ID, as well as in the endcaps, where longitudinal space along the beam direction is limited. In addition, the Moliere radius of the PHENIX Pb/Shashlik is much larger than the proposed W/Shashlik calorimeter and it is not clear how well the concept of reading out individual WLS fibers will improved the ability to measure the shower position and shower shape in this detector. In the absence of being able to test this with the real detector, we have therefore undertaken a simulation study to compare the two shashlik calorimeters and report on some preliminary results below.

What was achieved?

We began a simulation study to compare the properties of a W/Cu/Scintillator shashlik calorimeter with a Pb/Scintillator calorimeter. For the Pb/Scintillator shashlik configuration, we started with a model of the PHENIX EMCAL modules which consist of 66 layers of 1.5 mm thick Pb plates and 4 mm thick scintillator tiles and have a total depth of 18 X0 and a total length of 37.5 cm. The modules have a

transverse dimension of 5.535 x 5.535 cm^2 and have an effective radiation length of ~ 2 cm and an effective Moliere radius of ~ 4 cm. In the PHENIX experiment, the calorimeter was located 5 m from the collision vertex in order to minimize its occupancy in heavy ion collisions.

The Monte Carlo used for these simulations was a modified version of the ePHENIX detector. This is a very powerful simulation and reconstruction tool that was developed for full EIC detector simulation and includes a complete digitization, calibration and clustering chain. It can be used to study the basic performance parameters of the calorimeter, such as energy and position resolution, as well as such things as the merging probability for pizeros using a clustering algorithm. However, it can also be used to study more complex physics processes such as jets, direct photons, electron/hadron separation, etc.

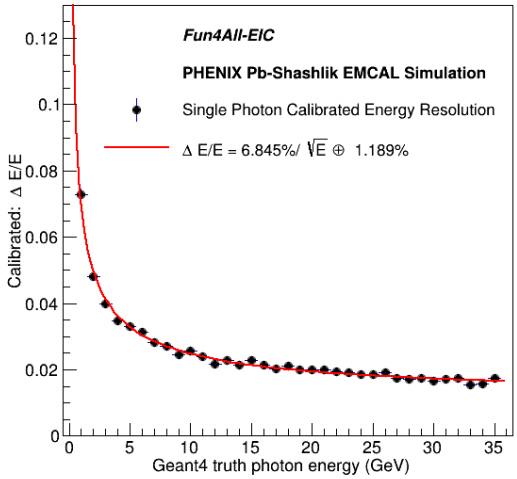

Figure 3.1. Energy resolution of the PHENIX shashlik for single photon clusters as a function of the true energy deposit in the calorimeter.

Our initial studies focused on studying the basic performance parameters of the PHENIX calorimeter. It was placed at a distance of 2.9 m from the collision vertex at the location of the Hadronic Endcap Calorimeter in ePHENIX and single photons and pizeros were generated at the vertex to study the ability to resolve single photons from pizeros as a function of momentum. In order to calibrate the energy scale, a calibration procedure was applied to obtain the reconstructed cluster energy and angle of single photons over an energy range from 1-35 GeV using a polynomial fit to the truth parameters generated in GEANT.

Figure 3.1 shows the energy resolution obtained for single photons using the calibrated photon cluster energy as a function of the GEANT truth energy. It gives a resolution of $6.8\%/\sqrt{E} \oplus 1.2\%$, which is slightly better than the published results for the PHENIX calorimeter ($8.1\%/\sqrt{E} \oplus 2.1\%$ as given in NIM A499 (2003) 521-536), due to the fact that many factors contributing to the measured resolution, such as photostatistics, non-uniformities, module to module variations, calibrations, etc, were not included in our simulation. Nevertheless, these results provide a good starting point for our studies.

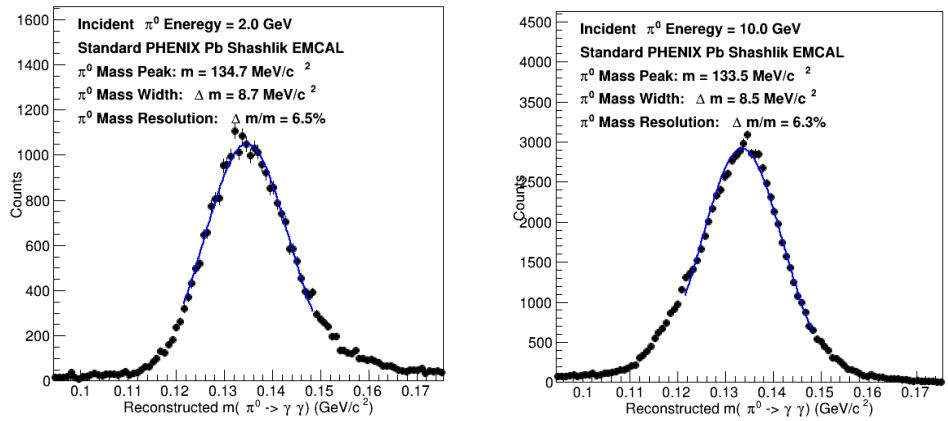

Figure 3.2. Pizero mass distributions for the PHENIX shashlik for 2.0 GeV and 10.0 GeV pizeros.

Pizeros were generated over an energy range from 1-45 GeV and used to study the merging probability for the two photons in the calorimeter. Figure 3.2 shows the pizero mass distribution for 2 GeV and 10 GeV pizeros. The mass is centered at approximately the right value and the width is consistent with the energy resolution for the two photons. Events were selected having two photons in the calorimeter and the clustering algorithm was used to determine their position and energies. The minimum cluster energy was set to 0.1 GeV. The merging probability was defined as the number of events with only a single cluster found in the detector divided by the total number of events.

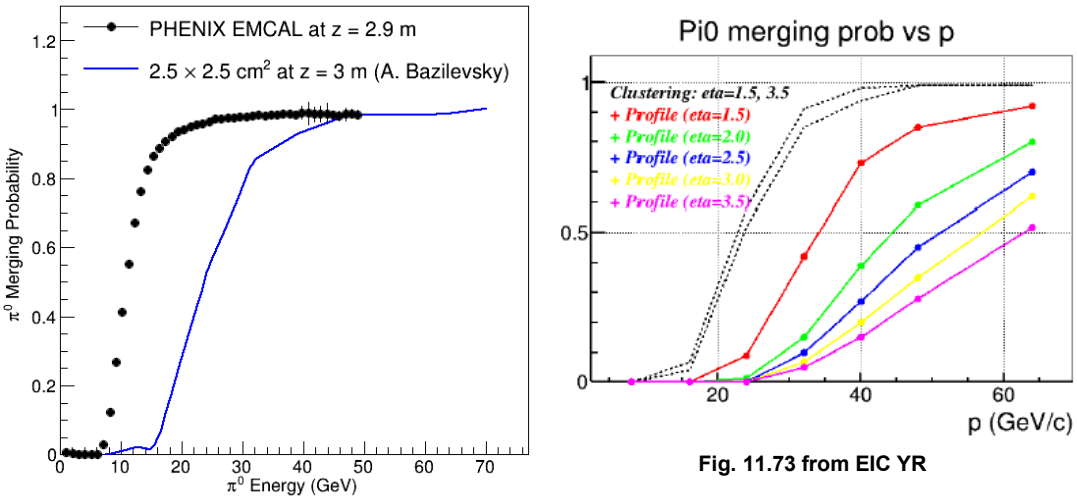

Fig. 3.3. Merging probability for two photons from pizero decays as a function of pizero energy or momentum. Left: The black points show the results of this simulation for the PHENIX Pb shashlik. The blue curve gives the merging probability for a presumed W absorber calorimeter with a segmentation of 2.5 x 2.5 cm^2 at η=3.5 from a simulation by A. Bazilevsky using only cluster information. Right: Fig. 11.73 from the EIC Yellow Report showing the extension in momentum range that can be achieved using shower profile information.

Figure 3.3 on the left shows the merging probability for the two photons from pizero decays as a function of pizero energy in the PHENIX shashlik calorimeter located in the Hadron Endcap at a distance of 2.9 m from the vertex. Due to the short distance from the decay vertex, the large Moliere radius and the large transverse segmentation, the two photon clusters start to merge at ~ 7 GeV and become totally unresolved at ~ 15 GeV. The blue curve shows the result of a simulation by A. Bazilevsky for a presumed W absorber calorimeter with a transverse segmentation of 2.5 x 2.5 cm^2 at η=3.5 and approximately the same distance from the vertex. The point of complete merging is pushed out to ~ 40 GeV in this configuration. Neither of these curves utilize information about the shower shape, which can extend the point of merging to much higher energies as shown in the figure on the right which is reproduced from Fig. 11.73 in the EIC Yellow Report. However, one can see that the starting point for applying this technique is much lower for the case of the Pb absorber, and it will be much more difficult to reach higher momenta in this case compared with the W absorber.

These results give only our initial preliminary studies comparing these two types of calorimeters. We intend to continue with these studies to investigate both configurations using the shower shape information to resolve the two photons, and then explore the advantages of effectively increasing the transverse segmentation by assuming that each WLS fiber of the shashlik is read out. This will require providing information about the light collection within the scintillating tiles and WLS fibers, which we plan to obtain from lab measurements of the tiles and fibers using a laser to scan the tiles and measure their response, and by simulations of the light collection using a ray tracing program (TracePro). This will allow us to study a variety of configurations with different WLS fiber spacings, tiles dimensions and module sizes. Finally, we wish to ultimately study the performance of both of these detectors with actually physics processes, which we can do within the framework of this simulation.

What was not achieved, why not, and what will be done to correct?

We were not able to make any progress on the design or construction of our larger W/Cu shashlik prototype due to lack of funding. We were also not able to make any progress on re-instrumenting the PHENIX calorimeters modules mainly due to lack of manpower. We have no available manpower to work on this at BNL due to our commitments on sPHENIX. There may be manpower available at UNAB but it is not possible for any personnel from UNAB to travel to BNL at this time. It would therefore require shipping an entire PHENIX supermodule to UNAB, disassembling it, re-instrumenting some significant fraction of it with individual SiPMs on each fiber or group of fibers, and shipping it back to BNL. However, the SiPMs would have to be purchased and we would need to obtain sufficient readout electronics to read them out as there is no sPHENIX electronics available for testing it. It would also require manpower at BNL to prepare the supermodule and make the arrangements to ship it to Chile, which is also currently unavailable. Should additional funding become available, we would hire a full time postdoc to work on this at BNL and hopefully bring personnel from UNAB to BNL to help with this effort.

How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

Because of the restrictions imposed by the pandemic, it was not possible to have personnel from UNAB come to BNL or for BNL personnel to travel to UNAB. This severely limited our ability to carry out any work on this project. We were also not able to have a student come to BNL to work on the small 3x3 module W shashlik prototype, and it was not possible to test this prototype at Fermilab due to the closure of the Fermilab Test Beam Facility.

How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

We received $52K of funding in FY20 and spent $33.3K by the end of the FY. We were not able to spend any of our travel money to bring UNAB personnel to BNL or for BNL personnel to travel to UNAB. We were also not able to bring a student to BNL to help with this project due to restrictions related to COVID.

Do you have running costs that are needed even if R&D efforts have paused?

No.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

Our main goal for the rest of this funding cycle is to continue with our simulations comparing various W/Cu and Pb shashlik calorimeter configurations, with our primary focus on the Pb shashlik being the PHENIX EMCAL design. In particular, we want to study the performance of the two detectors in an EIC environment. This will include simulations of both the W/Cu shashlik and Pb shashlik in the barrel and endcap regions with various assumption about segmentation. We also hope to make measurements of the light collection efficiency of the scintillating tiles and fibers as in the lab and to carry out ray tracing simulations to generate a light collection efficiency map which can be used as input to the MC.

This is significantly different than our original plan where we would be designing and building a new larger W/Cu prototype calorimeter during the current funding cycle and planning to test it in the beam during the next funding cycle. If additional funding and support becomes available, we will continue with this plan and resume this effort starting next FY.

With additional support, we could disassemble one of the PHENIX supermodules and re-instrument part of it with SiPMs on every fiber or small group of fibers. Ideally, this should be done at BNL since all the supermodules are currently there, but there is no manpower available at BNL to do this. It may be possible to send one supermodule to UNAB, perform the work there, and send it back, but this would also require additional support, both in terms of funding and manpower.

What are critical issues?

The main critical issue is lack of available manpower, particularly at BNL. The sPHENIX group is extremely busy with the construction of the sPHENIX EMCAL and HCAL and it is not possible for any of them to devote any substantial amount of time to this activity at the present time. We would therefore like to hire a full time postdoc to work on this project at BNL and to support the efforts of the group at UNAB.

Given that a shashlik calorimeter is one of the primary options for calorimetry at EIC (as stated in the Yellow Report), both in the central region as well as in both endcaps, we feel that not pursuing the development of a shashlik calorimeter for EIC would have a major impact on the future of the EIC detector development program.

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.

- All effort on this project stopped at UNAB during the current funding cycle due to lack of support from EIC funds. It could, however, be resumed if support were to be made available during the next cycle.
- All of the effort on this project at BNL has been carried out by the BNL sPHENIX Group.
- We have a graduate student (Zhaozhong Shi from MIT) who has been spending approximately 80% of his time performing simulations of W and Pb shashlik calorimeters. He is being supervised by C. Woody at BNL.

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

- All work done by the scientific staff at BNL on this project is supported by the sPHENIX Group or sPHENIX Project funds.
- Our graduate student performing the simulations is being supported by a DOE Office of Science Graduate Student Research Grant. He receives no support from EIC funds.

Publications

Please provide a list of publications coming out of the R&D effort.

There are currently no publications from this effort.