Date: 6/20/19

EIC Calorimeter R&D Proposal and Progress Report

Project ID: eRD1
Project Name: Development of EIC Calorimeter Technology
Period Reported: from 1/1/19 to 06/30/19
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Abstract

We summarize R&D activities from the eRD1 Calorimeter Consortium from the period of Janury 1, 2019 to June 30, 2019. The consortium is pursuing four major directions of calorimeter technologies for future EIC detector. The sub-project one centers on the Forward Calorimeter System development including both EMCal and HCal sections aiming at energy resolution improvement for jet measurement in the forward direction of the hadron side. The sub-project two focuses on the development of crystal and glass calorimeter development for electron side measurement with superior energy resolution. The sub-project three aims at developing Shashlyk EMCal technology with W-Cu plate and SiPM readout. The sub-project four includes construction of the sPHENX Tungstern-powder/SiFi EMCal.

The Sub-Project one team (UCLA et al) tested a STAR Forward Calorimeter System (FCS) prototype at FNAL in spring 2019. Data are being finalized. The measured timing information for longitudinal shower in the HCal is not sufficient to improve significantly on the HCal sector resolution in the current configuration. The STAR FCS received NSF MIE support and started construction. A UC Consortium was also formed and included EIC calorimeter simulation as a major task. We propose to continue the optimization for an EIC FCS design and carry out a beam test at FNAL in 2020. More simulations of the HCal design will be carried out.

The Sub-Project two team (CUA/Jlab et al) continues to work with CRYTUR and SICCAS on PWO crystals. Much work has been done to charaterize the crystal performance. Many issues with the SICCAS crystals have been identified and the acceptance rate is low while the CRYTUR crystals generally showed superior performance. Prototype crystal arrays were tested at Jlab Hall D and we obtained promising results. About 40 glass ceramic samples have been received and under testing. We propose to continue working with the vendors on crystal/glass QA and improve acceptance rate from SICCAS for quality crystals. More prototype beam testing is planned for fall 2019.

The Sub-Project three team (UTSFM/BNL et al) constructed 6 Shashlyk EMCal modules and these modules are under testing. We propose to complete the planned additional module production and start extensive testings at BNL to evaluate the performance of the EMCal design.

The Sub-Project four team (BNL/UIUC et al) focuses on the sPHENIX EMCal production now. The production procedure and the QA process continue to be improvised in this initial phase of the construction. This project is entirely funded by the sPHENIX experiment.

The eRD1 Consortium covers essential calorimeter technologies for both forward directions of hadron and electron sides and for the barrel region. We request support from the EIC detector R&D program to continue our progresses towards a full converage calorimeter system in an EIC detector in the comin years.

The budget request from the eRD1 Consortium:

Budget Scenario	100%	20% cut	40% cut
Sub-Project One (UCLA team)	51.2 k	40.2 k	28.2 k
Sub-Project Two (CUA/JLab team)	120 k	96 k	72k
Sub-Project Three (UTSFM/BNL team)	75 k	60 k	45 k
Total	246.2 k	196.2 k	145.2 k

Budget for Sub-Project One

Budget Scenario	100%	20% cut	40% cut
UCLA support for students (26% overhead included)	$12.6k	$12.6k	$12.6k
Travel (26 % overhead included)	$15.6k	$15.6k	$15.6k
ZDC WLS	$12k	$12k	$0k
ZDC Mechanical Components	$4k	$0k	$0k
ZDC Machine Shop (26% overhead included)	$4k	$0k	$0k
Shipping, supplies	$3k	$0k	$0k
Total	**$51.2k**	**$40.2k**	**$28.2k**

Budget for Sub-Project Two

Item	Full budget ($k)	20% cut ($k)	40% cut ($k)
CUA/VSL/Scintilex	**80**	**64**	**48**
Technical support for glass prototype	11	8.8	6.6
Student support - glass/crystal characterization and simulation	30	24	18
Equipment	5	4	3
Travel	5	4	3
Overhead	29	23.2	17.4
IPN-Orsay	**20**	**16**	**12**
Equipment	9	9	9
Materials	1	1	1
Travel	2	1.5	0
Student Support	5	2	0
Overhead	3	2.4	1.8
INFN-GE	**20**	**16**	**12**
Equipment (front-end electronic boards for light sensor readout, additional photo-sensors)	7	5.5	3
Materials (cables, mechanical supports...)	2	1.5	1
Travel	9	8	7
Overhead	2	1.5	1
TOTAL	**120**	**96**	**72**

Budget for Sub-Project Three

eRD1 BNL Funding Request (FY20)			
	Full Funding	**20% Cut**	**40% cut**
Large Area SiPMs	15	7.5	
Additional sPHENIX interface boards and readout boards for large area SiPMs	5	5	5
Technical support at BNL (technician, designer) including a visit by someone from UTFSM	5	5	5
Test Beam (in collaboration with sPHENIX, STAR or other EIC calorimeter beam tests)	15	15	15
Travel (includes support for UTFSM and BNL)	10	7.5	5
Total	**50**	**40**	**30**
Overhead	25	20	15
Total with Overhead	**75**	**60**	**45**

Sub Project 1: Progress on Forward Calorimeter System R&D at UCLA
Project Leader: H.Z. Huang and O. Tsai

What was planned for this period?

We continue to pursue validation of space-time evolution of hadron showers for the outgoing endcap hadron calorimeter through beam test at FNAL and Monte Carlo simulations of hadronic shower characteristics.

What was achieved?

First, we would like to share with the committee a few important recent developments, which will influence our plan of future R&D efforts, in particular, those related to the forward calorimeter system for EIC. They are:

- The formation of a UC EIC Consortium led by Professor Barbara Jacek from Berkeley/LBNL and UC is funding the Consortium to work on simulation and development effort on EIC. Major tasks under development include tracking and calorimeter for EIC. The UCLA and the UCR groups will work on the calorimeter project.
- Endorsement by BNL and DOE of the STAR Forward Upgrade proposal; the major science driver is for spin physics at RHIC and a polarized p+p run 22 at 500 GeV beam Center-of-Mass energy has been presented to BNL RHIC PAC in June 2019.
- The MRI application to NSF for the construction of STAR Forward Calorimeter System (FCS) has received favourable response from NSF and is likely to be funded.

The importance of 500 GeV pp runs at RHIC for future EIC was discussed in our previous reports. In particular, conditions for the proposed Forward Calorimeter Systems in terms of neutron fluences during 500 GeV pp run at RHIC is very close to the expected conditions for high luminosity EIC. This gives unique opportunity to study performance of calorimeter systems at RHIC well ahead of EIC. We used such opportunity during RHIC Run 17 to study characteristics of a large sample of SiPMs in such environment. These studies lead to very good understanding of mechanisms of degradation of performance of SiPMs in such conditions and its effects on calorimeter performance, which we have reported in previous reports. Experience, which we expect to gain with the proposed STAR FCS in Run22 and beyond (physics observables in many cases similar to one at EIC) will be very important for the development of a forward calorimeter system (outgoing hadrons side) at EIC.

In April 2019 STAR collaborators with help from RIKEN colleagues conducted a test run at FNAL. We tested forward calorimeter system consisted of EM section (EMCal) (refurbished PHENIX shashlyk EMCal) followed by a hadronic calorimeter (HCal) made of Fe/Sc plates. Both calorimeters were readout using 15 um HPK SiPMs with an updated version of FEEs developed for STAR forward upgrade. Additional tests were performed with passive layers of steel (1 cm and 10 cm thick) in between the EMCal and the HCal to investigate experimental consequence of passive absorber (un-instrumented sPHENIX Inner HCal). This was a joint program for cold QCD physics developed by STAR and sPHENIX a few years ago, which we hope to achieve with the STAR forward upgrade and mid rapidity measurements at both STAR and sPHENIX.

At present, a large-scale prototype FCS consisting of 64 channel EMCal (refurbished PHENIX Shashlyk), 16 channel HCAL and a Preshower detector has been installed and is under commissioning at STAR IP. These calorimeters are equipped with newly developed digitizers and LED monitoring system.

The FNAL test run in spring 2019 served two purposes for our EIC R&D effort: First, we carried out the test run with newly formed UC EIC consortium including graduate students from both UCLA and UCR groups, shown in Fig. 1. Second, we modified readout of the Fe/Sc HCal to make measurements of timing information of hadronic shower in longitudinal development. For the timing measurement, the SiPM readout used for FCS was replaced with fast PMT readout and gated integrators were replaced with fast (1 GHz) waveform digitizers. The goal of this exercise was to understand if present light collection scheme (Sc/WLS) is suitable for such measurements, i.e. whether timing information of shower development can be preserved.

Figure 1. Participants of April FCS Test Run at FNAL.

Preserving timing information is just one of the requirements for a dual readout scheme to work. A second requirement is sufficiently strong signal from recoil protons to allow for e-by-e correction of invisible energy (analogous to number of Cherenkov photons in DREAM method). This requires high Z absorber (production of spallation neutrons) and sufficiently high fraction of scintillator in calorimeter structure. In that respect, the FCS was not optimized at all. The current FCS design was instead optimize in performance/cost, with very strict requirements on available space and cost, resulted in a rather crude sampling structure of Fe/Sc (20 mm/ 3mm). Nevertheless, we attempted to answer the first question regarding timing preservation.

The first method we employed was to look at T_0 differences from central and side channels of the HCal when the beam bombarded at the centre of HCal stack. In this case, the central channels always have fast component of the shower, while signal in the peripheral channels of the HCal in general should have delayed signals due to at least the time of flight from shower particles originated in the core of the shower. Figure 2 shows difference in nanoseconds of the central towers T_0 and peripheral towers T_0. To improve accuracy T_0 determination was made from signals in four central towers. A left panel in Fig.2 shows distribution of $T_0^{AvgCent} - T_0^{Outer}$, and right panel in Fig.2 shows difference between average T_0 in central and peripheral towers. In both cases, this difference is about 2 ns, which is consistent with time of flight of shower particles. The distribution on the left panel is Gaussian without tails at large negative values, which indicates that delayed signals from recoiled protons are weak.

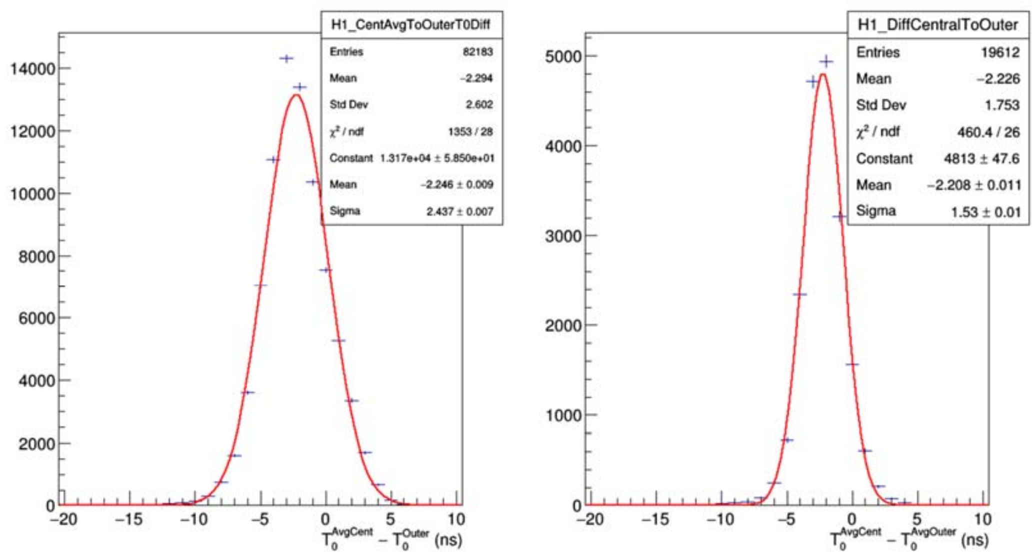

Figure 2. Difference in T_0 in central and peripheral towers of HCAl.

The second approach is to make direct comparison of shapes of the signals from EM showers and pion showers, for this analysis we used 20 GeV mixed FTBF beam with electrons identified by a Cherenkov counter.

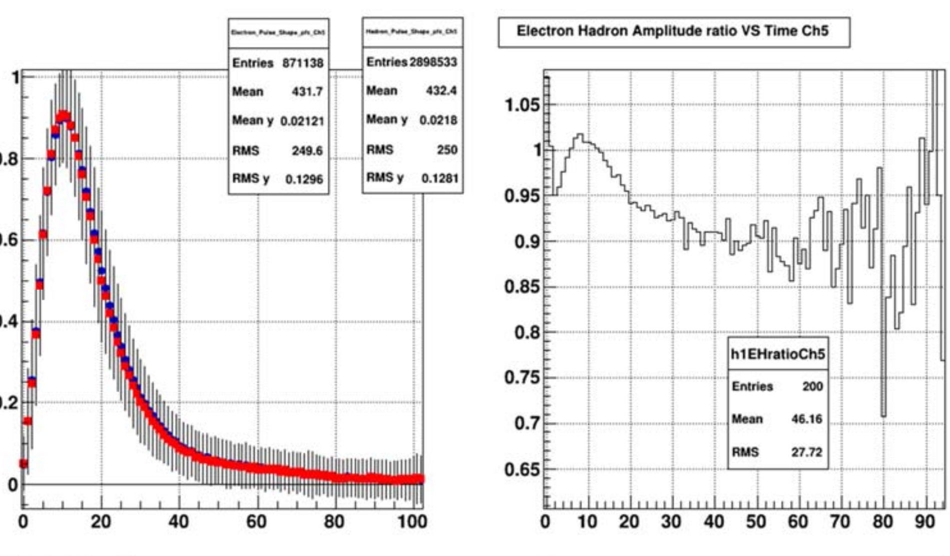

Figure 3. Shape of signals for 20 GeV electrons and pions. X axis bin size 1 ns.

Figure 3 left panel shows average shape of the signal in central HCal tower for showers initiated by electrons (red) and hadrons (blue), the bin size is 1 ns. A bin-by-bin ratio of two signal shapes (e/h) is shown in the right panel. Excess in the tails (> 10 ns) of pion signals vs electron signals is signature of recoil protons in hadronic showers. This is qualitatively similar to results of ZEUS e/h signal ratios for different gate width, shown in Fig. 4 (right panel).

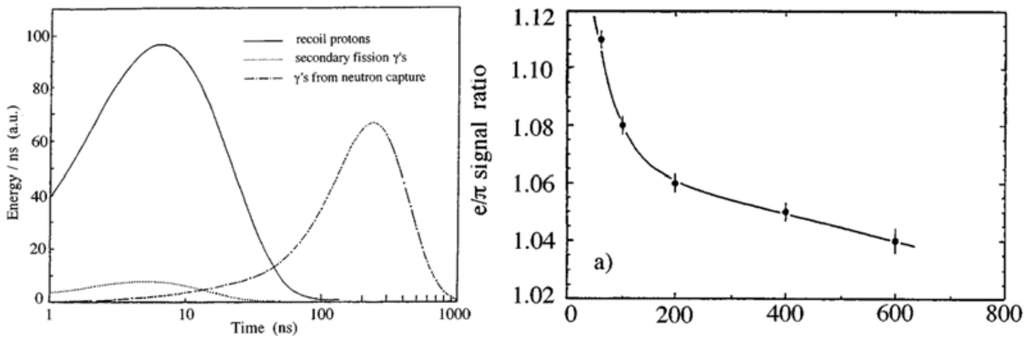

Figure 4. Contribution from different processes to ZEUS HCal signal (left panel). Ratio of e/h signal vs gate width for ZEUS HCal (right).

We did look at possible correlation between total energy detected in HCal vs ratio of fraction of signal integrated in the first 10 ns and signal integrated from 10 – 100 ns, i.e. fast predominantly EM component vs slow recoil protons signal and found none.

The test run data was not completely analysed at this moment, but conclusions below are not expected to change significantly with detailed analysis:

- Current WLS/Sc light collection scheme sufficiently fast to preserve timing information about showers development.
- Signal from recoil protons for FCS type structure is too weak to make e-by-e corrections of invisible energies necessary for further improving the resolution.

Monte-Carlo Simulations

GEANT4 10.05.p01 was used for modelling. The HCal setup of the 2019 test run was described precisely in essential details, which should determine the light collection properties and timing characteristics. In particular, the material composition, tower geometry, optical parameters of the scintillator plate and the WLS bulk material plastic and surface boundaries, timing constants for the light emission of the scintillator, as well as absorption and re-emission by WLS, were taken into account and described in the GEANT simulation. A single HCal tower, hit by a high energetic electron, is shown in Fig. 5.

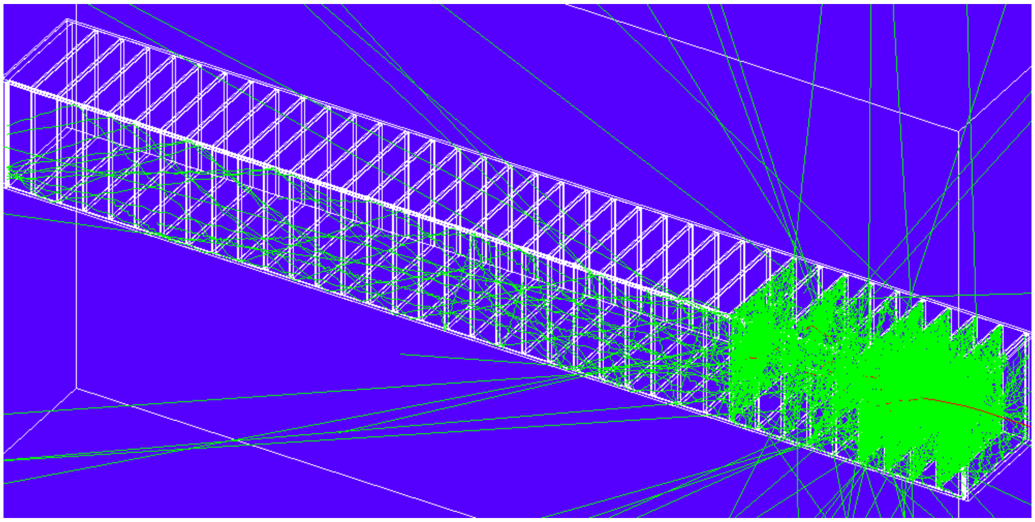

Figure 5. GEANT4 display of the electromagnetic shower produced by a 1 GeV electron in a single HCal tower. Electron is coming from the right, along the tower axis. Tracks of the optical photons created in the first several scintillator plates are seen, as well as a few photons, which were absorbed and re-emitted in the WLS bar installed along the front tower side, and travelled all the way down to the rear tower side, where photon detectors were installed.

To this moment several effects, which can distort the original timing picture of the hadronic shower development, were evaluated. The key question here is by how much the signal from the large prompt "core" of the hadronic shower (developing on a time scale of <1 ns) will be smeared in time and dilute the weak late neutron tail with a typical exponential decay time constant of ~10-20 ns.

In all subsequent plots the time of optical photons escaping the rear end of the WLS bar and entering a fake photon detector volume through a thin air gap is shown. Plots are accumulated over several events, and *t=0* corresponds to the time, when a relativistic particle, producing the shower, would reach the rear calorimeter end if physics interactions were turned off. The additional timing spectrum broadening caused by a particular photon detector and the readout electronics choice is not shown in the plots. In other words to this moment the study is focused on optimizing the internal structure of the calorimeter towers.

Some of the effects (see Fig. 6) appeared to be relatively modest on the time scale of several dozens of nanoseconds, where late neutron signature should manifest itself. This is in particular true for all of the distortions, related to the optical photon flight path variation in both the scintillator and the WLS. It should be noted, that the spectrum in Fig. 6a becomes somewhat wider if a proper optical coupling is used between the WLS bar rear end and the photon detector (photons from a wider angular cone make it through, rather than bounce back due to the total internal reflection), but the additional broadening is still relatively small compared to all other contributions.

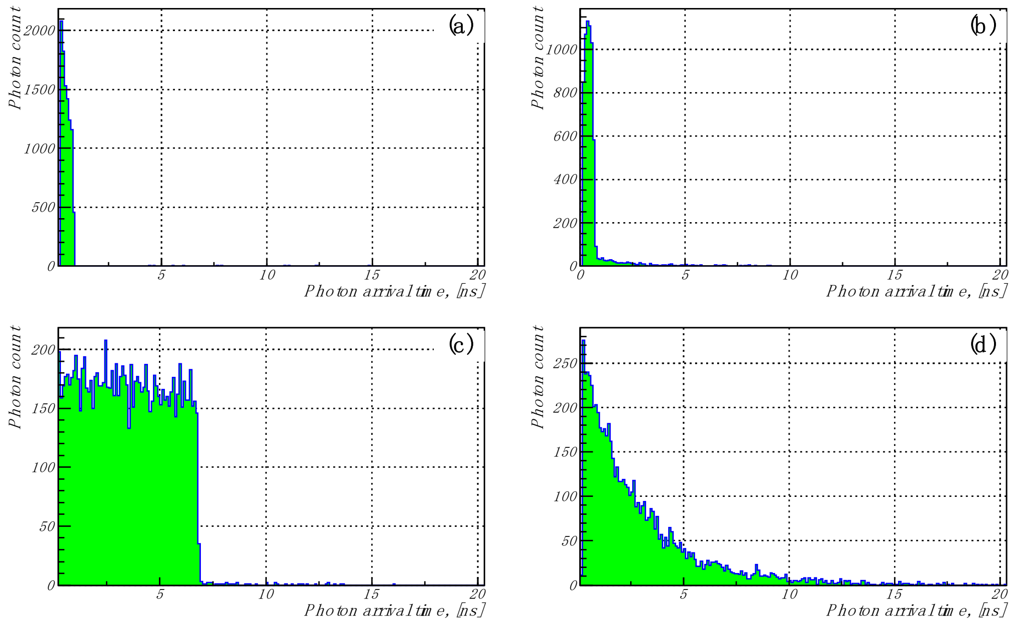

Figure 6. Minor timing distortions, disentangled into separate groups: (a) photon propagation time spread in WLS for a fixed longitudinal coordinate along the bar (bar center case is shown in the plot); (b) photon propagation time spread in a given scintillator plate, (c) difference between the relativistic primary particle time of flight and photon moving along the WLS parallel to the beam direction (shown for the full HCal tower length of ~850mm); (d) exponential decay time of ~2.4ns in the EJ-212 scintillator.

As expected, the biggest distortion comes from the very large (~8.5 ns) decay constant of the EJ-280 WLS, see Fig. 7a. Being effectively added to the ~2.4 ns decay constant of the EJ-212 scintillator, and taken together with all other effects considered so far, this contribution is expected to smear the instant shower core signal by several dozens of nanoseconds. Its tails will critically overlap with the range of ~15-50 ns, where one can expect to observe a detectable late neutron signal (see Fig. 7b for a comparison).

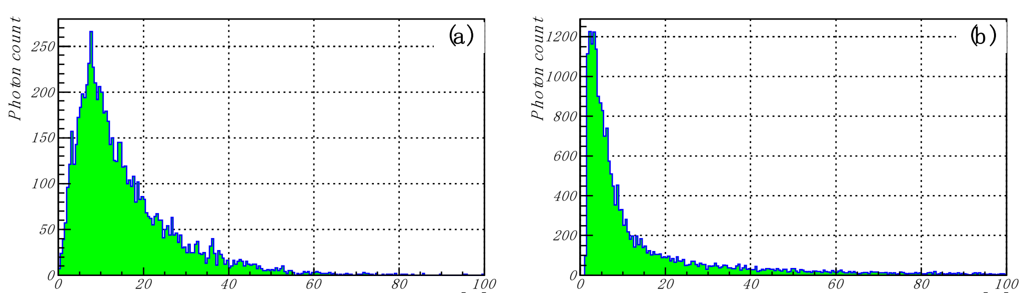

Figure 7. (a) All timing distortions taken together, including the ~8.5ns exponential decay time of the LJ-280 WLS, which dominates the tails, (b) timing signals produced by 5 MeV neutrons, generated in the 4x4 tower HCal geometric center (accumulated over several events).

As the detailed simulations of the full chain of hadronic shower development, from the primary cascade to the re-emission and propagation of secondary photons in the WLS, are still in progress, what is now shown in Fig. 7b is a simple case of a timing signal, expected from a 5 MeV neutron, generated in the 4x4 tower calorimeter center. The plot is accumulated over several events. Birk's correction is taken into account. One can clearly see an exponential decay time spectrum, where the characteristic constant is determined by the tower geometry and the relative fraction of hydrogen-containing materials (plastic) in the calorimeter chemical composition.

By using faster WLS, like EJ-282 with the decay time constant of ~1.9ns, (and potentially a faster scintillator plastic, like EJ-230 with the constant of ~1.3ns) one should be able to drastically improve the discouraging timing picture displayed in Fig. 7a. This is exactly what we are proposing to try out in the next round of our R&D. See Fig. 8, which shows the expected level of timing distortions. The tails of the smeared shower core signal do not extend beyond ~20ns past *t0*. This means that the late neutron signature in a sufficiently wide time window of a couple of dozens of nanoseconds (see Fig. 3 as measured in the April 2019 test run) must be visible with almost no "background", which should give us a practical opportunity to use it for the hadron energy correction on event-per-event basis.

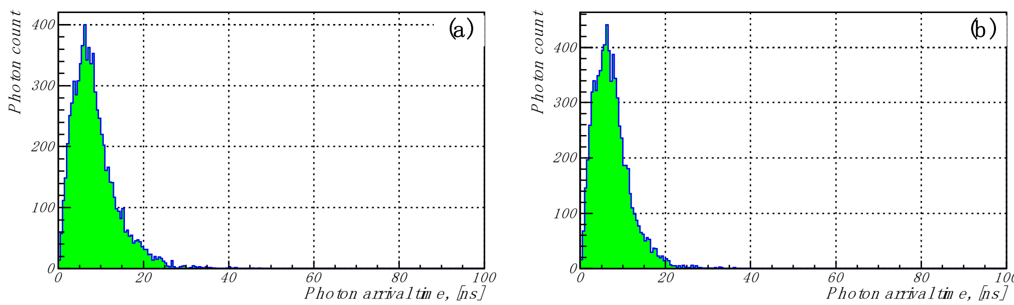

Figure 8. (a) Same as Fig. 7a, but for the fast EJ-282 WLS; (b) Same as Fig. 8a, but also EJ-212 scintillator is replaced by the fast EJ-230.

Discussions

Dual readout technique is interesting but very challenging technically. One of the main obstacles is the weak signal on which corrections for invisible energy are based. This was an issue in the early developments of DREAM with small number of Cherenkov photons detected. For timing-based approach, the signal from recoil protons can be increased by using high Z absorber (generating more spallation neutrons) and by increasing amount of scintillator (increase sampling fraction for recoil protons) in the detector volume. However, practical limitations, in particular, for central detector of EIC, most likely, will be prohibitive to move in either of these two directions. Situation can be different for ZDC where both high Z absorber and a large sampling fraction can be utilized. These approaches could potentially improve the energy resolution of ZDC with a simple detector structure.

One of the lessons learned during the FCS test run at FNAL is that the transverse non-uniformity in light collection must be improved for both STAR Forward and future EIC calorimeter design. The origin of the non-uniformities is the tapered WLS bar, required for efficient and longitudinally uniform light collection with limited number of SiPMs (six per WLS bar). The tapered shape, however, introduces quite large non-uniformities in light collection from a single scintillation tile, i.e. strong dependence on hit position across the scintillation tile surface. It was believed that due to wide shape for hadronic shower deep inside tower, where WLS start to taper, this will not affect resolution much. However, measured energy resolution of FCS for hadrons at FNAL is about 20% lower than GEANT4 predictions. We tested too different WLS schemes and both underperformed. This was not observed in 2014 tests. Crude sampling fraction in the FCS probably contributed to the worsening resolution as well.

Future

With results obtained in April 2019 test run, we identified two directions for future developments of hadron calorimeters for EIC. For central detector we want to concentrate on optimization of W/ScFi + Fe/Sc structure. Optimization means finding parameters for hadronic section giving best performance with the fixed length of the overall system. As we reported many times, compactness of the system is one of the critical parameter. The W/ScFi EMCal structure in this analysis will be kept the same as in our previous studies performed in 2014. Parameters for HCal including sampling structure, i.e. number of layers and thickness, can be optimized. As we learned, it is important to include in these studies instrumental effects, i.e. realistic light collection discussed above. Graduate student from UCLA Z. Xu (partially supported from UC EIC consortium funds) will carry out these studies with help from our senior graduate student M. Sergeeva.

For ZDC, we propose to check if new Pb/Sc structure with increased sampling fraction will allow viable timing information to improve the energy resolution. We propose to have one weeklong test run at FNAL. To keep cost of the prototype reasonable we plan to borrow scintillation tiles from STAR forward upgrade. It is anticipated, that by spring 2020 we will be able to borrow about 2k scintillation tiles for these studies from STAR (this has to be done before FCS assembly starts later in the 2020). Pb absorber plates from our 2014 prototype are still located at FNAL FTBF. To build the new HCal structure, we will need new WLS bars, new base and assembly plates. We plan to use fast PMTs used in 2019 test run for readout.

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. At least two students from UCR (members of UC EIC Consortium) D. Kapukchyan and D. Chen will be involved in these activities as well, supervised by K. Barish, R. Seto and O. Tsai. We will continue our collaboration with the BNL medium energy group (A. Kiselev, E. Aschenauer). Our graduate student Z. Xu may spend significant time at BNL working with A. Kiselev on detailed MC.

Budget

Budget Scenario	100%	20% cut	40% cut
UCLA support for students (26% overhead included)	$12.6k	$12.6k	$12.6k
Travel (26 % overhead included)	$15.6k	$15.6k	$15.6k
ZDC WLS	$12k	$12k	$0k
ZDC Mechanical Components	$4k	$0k	$0k
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Shipping, supplies	$3k	$0k	$0k
Total	**$51.2k**	**$40.2k**	**$28.2k**

Sub Project 2: Homogeneous Calorimeter Development - Crystals and Glass
Project Leader: Tanja Horn

Past

What was planned for this period?

Our main activities during the past 12-month period were to work closely with vendors towards cost-effective production of high-quality scintillator materials for the EIC EM calorimeters. We also planned to start developing long-term goals and milestones for material development. Our activities have been focused on developing the crystal and glass scintillator formulations and production processes and optimization of quality assurance/quality control procedures. This includes purchase and setup of additional equipment needed for the evaluation of scintillator materials and providing feedback to the vendors. In a synergistic activity with the Neutral Particle Spectrometer (NPS) project at Jefferson Lab, we planned to start a test beam program with an EMCal prototype towards establishing the limiting energy and position resolution and uniformity of response. The prototypes consist of 144 (9) scintillator blocks arranged in a 12 x 12 (3 x 3) array. Each block is coupled to its own photomultiplier tube and a custom designed high voltage divider. The 12x12 prototype was installed in Hall D at Jefferson Lab in fall 2018. The 3x3 prototype was installed in spring 2019. We also planned to start setting up a test bench for testing different readout options, a synergistic activity with the streaming readout consortium, and, together with vendors, prepare a small business funding proposal for new scintillator material development and production. Beyond these plans, we note additional suggestions from the January 2019 and earlier EIC R&D Committee reports, which include following up with SICCAS on material control and purity, and crystal handling, as well as with CRYTUR on investigating sources of new raw material.

What was achieved?

We have been working closely with the vendors and through synergy with the NPS project characterized, over the last six months, an additional 160 SICCAS and 111 CRYTUR $PbWO_4$ crystals. We also produced and characterized, in collaboration with the Vitreous State Laboratory (VSL) and vendors, about 40 glass ceramic samples. Physical and luminescence characterization was carried out at CUA. EM irradiation tests were performed at Orsay through collaboration with the Laboratoire de Chimie Physique with a panoramic irradiation facility based on 3000 Ci ^{60}Co sources. We irradiated crystals and the glass samples that we produced with integrated doses ranging from 500 Gy to 1000 Gy at about 18 Gy/min. The facility at Orsay can, in principle, provide even higher doses, up to 5000 Gy. Our results thus far do not indicate any EM radiation damage to the glass and no impact of different photon irradiation rates. To test for possible hadron radiation damage, we have applied for AIDA-2020 beam time at the MC40 Cyclotron. This is a high intensity irradiation line designed for fluences above 1E14 1MeV neq/cm^2. Tests are expected to commence in summer 2019.

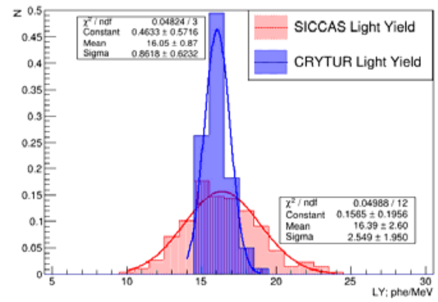


Fig 1: *Light yield of $PbWO_4$ crystals from vendors SICCAS (red) and CRYTUR (blue).*

Fig. 1 shows a representative comparison of the light yield from SICCAS and CRYTUR crystals including those analysed over the last six months. The mean light yields are 16.1 ± 0.9 and 16.4 ± 2.6 photoelectrons/MeV for CRYTUR and SICCAS crystals respectively. The large variation in SICCAS crystals can be traced back to mechanical and chemical differences in crystals. As summarized in Fig. 2, 160 of 460 SICCAS crystals had to be rejected due to major mechanical defects, e.g., unknown chemical substance on all surfaces, old label traces, large cracks, chips, and/or bubbles. An additional 52 SICCAS crystals failed NPS (and EIC) specifications for light yield, transmittance, or radiation hardness, but were accepted because their quality was acceptable for another project at JLab[1]. SICCAS replaced the 160 rejected crystals, but the acceptance rate for the new crystals remained low. In addition to 39 (24%) crystals falling into the categories of visual defects listed above, 34 (21%) of the 160 replacement crystals had to be rejected because dimensions were outside NPS tolerance (> ±50 μm from mean 20.5mm). To improve the crystal acceptance rate, we had additional meetings with SICCAS, the most recent one with group leader Dr. Hui Yuan on April 15, 2019. Detailed specifications and requests for quality assurance procedures were discussed. We grouped our specifications into visual properties, geometry, optical properties, and radiation hardness, and described and documented step-by-step quality assurance tests, some of which would be performed at the vendor, some at CUA or JLab. This procedure is similar to the one we use for our interactions with CRYTUR discussed below. To provide local guidance and feedback to SICCAS we are furthermore trying to establish quality assurance methods with the home institution of our active JLab collaborators (University of Beijing). Additional discussions are planned during the HADRON2019 conference in China.

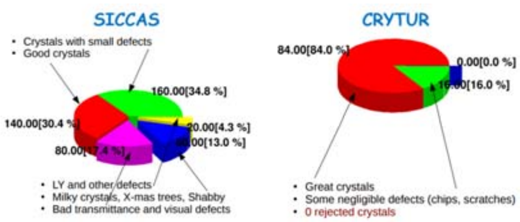


Fig 2: *Crystal evaluation status overview*

[1] This project (CCAL/FCAL) has more relaxed requirements on the crystals, in particular for radiation hardness

Our strict quality control program at and with CRYTUR to meet specifications continues to work well. Quality control procedures include visual inspection[2] and measurements of crystal properties including dimensions, transmittance, light yield and non-uniformity of the light yield, and absorption coefficient. Quality of polishing and final packaging methods were also included in the procedures. The vendor documents and provides the details of the methods used for testing and the results for each crystal, which are then verified by our collaboration. The agreement between measurements thus far has been within 10%, which can be attributed to differences in the measurement setups. Overall, this protocol has been successful and we have so far not rejected any of the 211 crystals received from CRYTUR in 2018 and 2019. However, we did notice an increase in mechanical defects in crystals produced after March 2019 when CRYTUR started speeding up the production process. Maintaining good crystal quality with increased production capacity is currently being discussed with the vendor. We also continue to work with CRYTUR on a method that could have potential to reduce production costs and increase mass production capability. It entails the use of a larger crucible to grow larger crystals, which can then be cut into multiple crystals of the required size. The status of this method is the subject of a meeting scheduled for June 2019.

Through synergy with the NPS and FCAL projects we submitted purchase orders for 500 additional CRYTUR crystals and initiated procurement of 500 additional SICCAS crystals. The current cost for $PbWO_4$ crystals with NPS (and EIC) specifications is \$15-25/cm^3. Both vendors, SICCAS and CRYTUR, are subject to new, strict rules for handling of lead. A significant decrease in crystal price is thus not anticipated. This has been motivation for our ongoing R&D on glass scintillators, which could be produced more cost effectively.

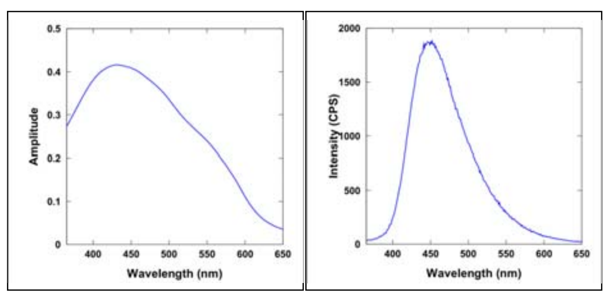


Fig 3: *Emission spectra for $PbWO_4$ (left) and glass scintillator (right).*

To test these crystals and new glass samples that we are producing, we commissioned methods for higher precision measurements. We constructed a new modular dark box that can accommodate measurements of light yield and time-dependent intensity profile of the emitted light upon periodic excitation. To address a drawback of our previous luminescence measurement scheme we procured and commissioned through collaboration with the VSL new instruments, including a time-resolved photon counting/steady-state fluorescence spectrometer that will allow measurement of lifetimes down to the sub-nanosecond range as well as excitation/emission spectra. Representative emission spectra of $PbWO_4$ and glass are shown in Fig. 3.

[2] Visual inspection includes the control of macro-defects inside the scintillation elements and defects on the element’s polished surfaces and chamfers

We continued data taking with the 3x3 (12x12) prototype arrays that we constructed and commissioned in 2018. The prototypes are representative of the NPS and EIC endcap EMCal geometry. They consist of a wall of 9 (144) rectangular blocks of dimensions 2.05cm x 2.05cm x 20 cm[3]. Due to this relatively straightforward geometry, rectangular crystals are the most suitable shape. Trapezoidal crystal shapes are another option. These have higher light yield, but also larger nonuniformity caused by the interplay of absorption and focusing effects influencing the amount of scintillation light reaching the readout end-face. The origin and characterization of light collection nonuniformities has to be carefully investigated through geometrical calculations, simulations, and dedicated experimental setups. However, if a simple geometry is sufficient, as for NPS and EIC endcaps, it is not beneficial to turn to trapezoidal shapes. In our prototypes, each block is attached to a 19-mm diameter photomultiplier tube (R4125) with custom HV base and active divider, which was developed for the NPS. The environment and light in the detector box were monitored by thermocouples and an LED-based light monitoring system, respectively. Photographs of the two prototypes in the experimental hall are shown in Fig. 4.

Fig 4: *3x3 and 12x12 EMCal prototypes in Hall D and environment monitoring.*

We began prototype data taking in December 2018. Data were taken using the Hall D tagging detectors. The 3x3 prototype was installed behind the Hall D Pair Spectrometer and used the secondary electrons provided. Electron-positron pairs are produced by beam photons in a 750 µm beryllium converter. The produced leptons are deflected in a 1.5 T dipole magnet and detected using two layers of scintillation counters positioned symmetrically around the photon beam line. Each arm consists of 8 coarse counters and 145 high-granularity counters. The high-granularity hodoscope is used to measure the lepton momentum; the position of each counter corresponds to the specific energy. Each detector arm covers a range in lepton momentum of 3 GeV/c to 6.2 GeV/c. The energy resolution is estimated to be better than 0.6%. For these tests additional detectors placed in front of the 3x3 prototype did not allow us to use the whole energy range of the pair spectrometer. Fig. 5 shows the

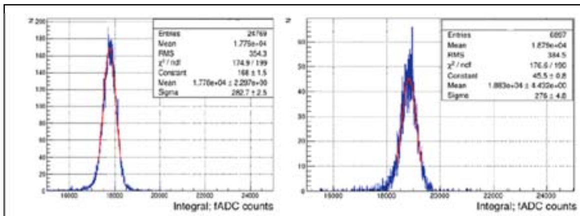


Fig. 5 *Total energy reconstructed in the 3x3 prototype for 4.7 GeV electrons incident on the central module for CRYTUR (left) and SICCAS (right) crystals.*

[3] We have taken data with both CRYTUR and SICCAS crystals separately for comparison of crystal performance and resolution.

reconstructed energy in the 3x3 prototype for 4.7 GeV electrons incident on the middle of the central module. The prototype was instrumented with 9 Crytur crystals and in a later test with 9 SICCAS crystals. The high voltage was about 1 kV with the divider amplifiers bypassed. The preliminary result for the energy resolution is 1.5-1.6%. Additional analysis and beam tests will allow for quick configuration tests, estimations of energy resolution, and further comparison of crystal properties. With our 12x12 prototype we were able to take data over a larger energy range and also study linearity, e.g., of the high voltage divider and amplifier. Our preliminary analysis of data focused on a 3x3 cluster of the 12x12 prototype and resulted in an energy resolution of $\sigma(E)/E=0.7+2.2/\sqrt{E}+2.8/E$ (see Fig. 6)[4]. Results are anticipated to further improve when extending to larger cluster sizes. Another improvement might be expected from eliminating nonlinearities that were traced back to the custom high voltage amplifier performance. Based on our data, we found and tested a solution, which will be tuned over summer 2019. Additional prototype tests are scheduled for fall 2019. For comparison, the required EIC resolutions for 10 GeV/c particles at a critical angle (rapidity), $\eta\sim-2$, should be $(1.0\text{-}1.5\%)/\sqrt{E} + 0.5\%$. At larger angles the requirements of energy resolution may be relaxed to $7\%/\sqrt{E}$.

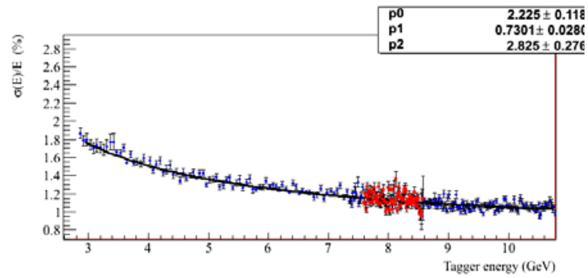


Fig 6: *Preliminary energy resolution for a selected 3x3 cluster within the 12x12 prototype*

We have completed the optimization of glass formulations including heavy elements to increase sensitivity to EM probes and to meet the requirements of detector applications, and have started initial wavelength tuning to match the readout. Our approach includes a systematic glass property measurement and modelling evaluation. The derived models allow us to use the glass composition to predict several important properties including density, effective atomic number, radiation length, and Moliere radius. This provides a valuable tool for refinement of the glass composition to optimize these properties. In other cases, such as light yield, radiation hardness, etc., we have to rely on direct measurement. However, the objective is to include all relationships between glass composition and observed properties through an iterative combination of measurement and statistical analysis to organize all phenomena. At present, we have created and verified, with measurements on the glass samples that we have produced, an initial set of models that allow us to go from observation to interpretation with much higher confidence. These models will be further optimized as we acquire data, e.g., from planned prototype tests (see section "Future"). We have started initial scale-up of our glass samples to medium $2x2x(5\text{-}10)cm^3$ and larger ($2x2x20cm^3$) dimensions. This process is nontrivial as changes in properties related to glass melt batch size, such as surface area, can also change some of the high temperature reaction kinetics in the glass fabrication process. Our expertise and

[4] The readout threshold is set to 5-7 fADC counts above the baseline, which corresponds to energy threshold of 11-15 MeV (for maximum energy range of 7.6 GeV).

results to date have played a large role in the (re)submission of Scintilex, LLC's STTR/SBIR proposal for the development of high-performance glass scintillators.

At INFN-GE we started setting up a test lab (see Fig. 7) for crystal and glass sample readout. We assembled three MRPCs (the same technology used for LHC-ALICE TOFs) to make a telescope and measure cosmic rays over a large area. This will allow to map out the crystal/components response over a large area in a very short time (the chambers are 80x160 cm each). The information is recorded in a data stream labeled with the absolute (UTC) time stamp with up to few nanosecond precision. We are using the streaming readout boards we developed at INFN (Wave Board) for the EIC streaming RO studies to readout signals from the detectors under test. The time stamp provided by the board will allow us to correlate the hit with the chambers. In this way we will be able to measure energy deposition and efficiency. We also assembled two plastic scintillator bars read on each side by a PMT. The same arrangement has been used some time ago to characterize the CLAS12-CND detector and the CLAS12-FT_Cal. We were able to reach ~100 ps time resolution for a precise determination of the detector response. To complete the setup, we are in the process of procuring a GPS system to be used in conjunction with the Wave Board.

Fig 7: *INFN-GE test lab setup.*

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

We have not yet procured crystals from CRYTUR cut from a large-volume crystal. This is due to continued delays in the commissioning of a larger crucible and quality assurance methods. CRYTUR hopes to test the new method as soon as all materials are available. The status and path forward are the subject of a meeting scheduled for June 2019. The fabrication of larger glass blocks is making good progress. We have produced the first samples of medium size, but none of large dimensions yet. This is not unexpected due to intrinsic challenges of any scale-up process. We have identified the issues and are in the process of implementing and testing solutions. In the meantime, our medium size samples can already provide important feedback and guide further optimizations of the formulation and fabrication.

We have encountered delays in the procurement of additional SICCAS and CRYTUR crystals, which were due to equipment malfunction at SICCAS and capacity limits at CRYTUR. Over the next funding period we hope to have characterized a total of ~700 CRYTUR and ~1000 SICCAS crystals.

We have not yet analysed all data needed to study the performance of the prototypes. We expect that this will be done over the next six months.

We have carried out additional work on simulations of glass, crystal, and combined calorimeters in the endcaps, as well as the constant term characterization in resolution, in particular as it pertains to the NPS construction. Further work for EIC is expected to be done over the next year also extending our studies to the outer and central region of the detector. The results from our prototype tests will also be important in this step.

In response to additional January 2019 report recommendations, we started developing long-term goals and milestones for both crystals and glass scintillator development for EIC. A general aim is to have identified all EIC detector regions benefitting from homogeneous calorimetry, specified requirements, and have available suitable crystal/glass scintillator material production capability with the start of detector construction. For crystals the major items include development and implementation of quality assurance, test and optimization of new raw materials and production methods to increase capacity, and prototype tests and optimization of different calorimeter configurations including readout. For glass scintillators the major items include optimization of base formulation, initial scale-up and test of medium and large glass blocks, formulation wavelength tuning, additional scale up and testing of larger glass blocks, as well as extension of our studies to additional regions of the EIC detector, prototyping additional glass shapes, e.g., fibers. We expect to complete an initial estimate of milestones and required resources in the next funding period when additional information on crystal and glass production vendors, industry partnerships, and funding becomes available.

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 during the next funding period will be to continue working with vendors on crystal and glass production and optimization, as well as to continue characterizing crystals and glass to provide feedback. For crystals the main issues to address are quality control at SICCAS, development of production capacity with sustained crystal quality at CRYTUR, and continued availability of high purity raw material.

Over the next six months we hope to have received at least ~100 additional CRYTUR and ~200 additional SICCAS crystals[5]. A total of 500 CRYTUR and 500 SICCAS crystals were ordered and are anticipated to be characterized. EIC R&D funding is requested for FY20 to help with this process, e.g., graduate student support at both CUA and IPN-Orsay. To establish adequate quality assurance, in particular at SICCAS, we plan to have frequent meetings with the vendors and provide feedback based on our measurements. We will also work to establish local crystal characterization guidance and feedback for SICCAS.

[5] CRYTUR's nominal production rate is 15-20 blocks/month, but the vendor expects to be able to deliver 40 blocks/month for the last three months of calendar year 2019.

High quality crystals will remain expensive and the production process is slow compared to other materials. Our glass scintillator development effort thus plays an important role in large volume calorimetry. We plan to produce larger glass samples with adequate surface quality for physical, luminescence, and radiation hardness studies. We are preparing for a prototype beam test program in fall 2019 to establish glass performance and iterate formulation/fabrication as needed. We plan to resubmit an STTR proposal in collaboration with a small business, which if funded could help to speed up glass production. The requested EIC R&D funding in FY20 for a graduate student at CUA would help with the glass characterization.

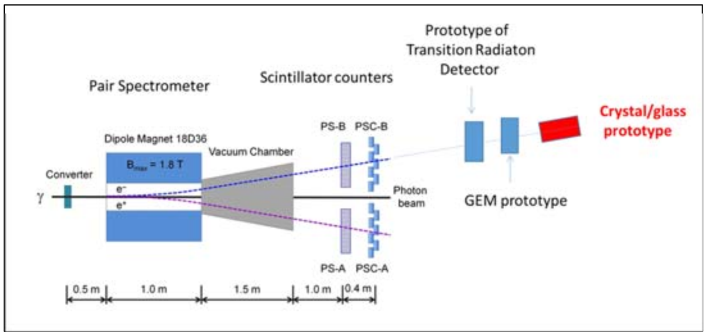


Fig 8: *Layout for fall 2019 prototype beam test with $PbWO_4$ and glass scintillator blocks.*

We have discussed and received confirmation of availability of beam time and location for our prototype detector. The prototype will be located behind the Hall D pair spectrometer (see Fig. 8) as for our 2018/19 NPS tests. Over the summer/early fall 2019 we will assemble and test the crystal/glass-PMT-HV divider modules, which will benefit from our experience with the 3x3 and 12x12 NPS prototypes. We will also evaluate the installation and testing of both PMT and SiPM based (streaming) readout schemes for the fall 2019 prototype tests. This will be done in collaboration with the NPS project and streaming readout consortium. EIC R&D funding is requested for FY20 to help with this preparation, e.g., graduate student support at both CUA and IPN-Orsay. The requested travel support will be important for our groups to participate in assembly and/or data taking during the beam tests.

We plan to extend our evaluation of glass scintillator as active material to additional regions, e.g., the barrel and hadron side. These studies will also include the light transport, e.g., through glass fibers, to readout outside the barrel acceptance. This will be important for a possible second detector with different technology to address systematic uncertainties in the physics measurements, but will also be of interest in its own right for the primary EIC detector. We have started setting up a Monte Carlo simulation for resolution studies and matching crystal and glass materials in the EMCal. We expect to be able to increase these efforts to other regions of the detector over the next year with contributions from postdoctoral fellow Dr. Mariangela Bondi from INFN-CT. She has submitted an internal INFN proposal to support these activities.

Over the next year we will also explore additional radiation hardness studies, e.g., glass resistance to hadron radiation. Initial tests are planned for this summer at the MC40 Synchrotron beamline.

What are critical issues?

For crystals the main issues to address are quality control at SICCAS, development of production capacity with sustained crystal quality at CRYTUR, and continued availability of high purity raw material. For glass scintillators the main issues are scale-up, possible additional formulation/fabrication optimization, and evaluation of glass in different configurations with suitable readout, and different regions of the detector. Prototype tests for both crystals and glass scintillator are essential for understanding and optimizing the actual performance for the EIC detector.

Funding Request and Budget

Table 1. Funding by Institution

Item	Full budget ($k)	20% cut ($k)	40% cut ($k)
CUA/VSL/Scintilex	**80**	**64**	**48**
Technical support for glass prototype	11	8.8	6.6
Student support - glass/crystal characterization and simulation	30	24	18
Equipment	5	4	3
Travel	5	4	3
Overhead	29	23.2	17.4
IPN-Orsay	**20**	**16**	**12**
Equipment	9	9	9
Materials	1	1	1
Travel	2	1.5	0
Student Support	5	2	0
Overhead	3	2.4	1.8
INFN-GE	**20**	**16**	**12**
Equipment (front-end electronic boards for light sensor readout, additional photo-sensors)	7	5.5	3
Materials (cables, mechanical supports...)	2	1.5	1
Travel	9	8	7
Overhead	2	1.5	1
TOTAL	**120**	**96**	**72**

Budget scenarios and impact statement: Our main goal over the next year is to produce crystal and glass scintillators and to investigate their performance. Prototype beam tests are essential for understanding and optimizing the actual performance for the EIC detector calorimeters including the readout. The results will also be required to iterate with vendors on formulations and fabrication methods to further optimize the material. Prototype tests require the testing of components (physical and optical properties, radiation hardness), assembly of modules and testing, and integration of detector with readout and analysis hardware and software. Simulations will allow to identify additional regions of the EIC detector benefitting from homogeneous calorimetry and will be guided by prototype beam test results.

In the case of a 20% cut, we would be able to produce and test subsets of crystal and glass scintillators and perform investigation and optimization of the manufacturing process. However, we would have to delay a prototype test beam program, which would impact our ability to determine the real limits of position and energy resolution of the material for application in EIC calorimeters.

In the case of a 40% cut, we would not be able to carry out a prototype test beam program to determine the real limits of resolution for EIC. Our focus would mainly shift towards the NPS project, which would be the funding source for our activities, and we may only provide information relevant specifically for EIC, as possible.

Additional information:

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.

IPN-Orsay
M. Josselin, J. Bettane, Ho San (graduate student), R. Wang (postdoc), G. Hull, C. Munoz-Camacho

CUA/Scintilex
S. Ali (graduate student), V. Berdnikov (postdoc), T. Horn, M. Muhoza (graduate student), I.L. Pegg, Richard Trotta (graduate student), C. Walton (undergraduate student), Vitreous State Laboratory staff

Yerevan
H. Mkrtchyan, V. Tadevosyan, A. Asaturyan

BNL
C. Woody, S. Stoll, M. Purschke

INFN-GE
M. Battaglieri, A. Celentano, R. deVita

INFN-CT
M. Bondi

JLAB
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 500 SICCAS and ~500 CRYUR 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, Yerevan, and the National Science Foundation.

Publications

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

- *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)
- *Scintillating crystals/glass for the Neutral Particle Spectrometer and EIC*, V. Berdnikov, T. Horn, C. Munoz-Camacho, I.L. Pegg, A. Somov, *et al*., in preparation

Sub Project 3: Progress on the Development of a Shashlik Electromagnetic Calorimeter with Improved Energy, Position and Timing Resolution for EIC

Project Leaders: S. Kuleshov, E. Kistenev and C.Woody

Past

What was planned for this period?

At UTSFM, we planned to test the first prototype W/Shashlik module using cosmic rays and LEDs and construct several additional prototype modules. These modules would be tested using existing readout electronics at UTFSM and would provide an initial calibration for future study. We then planned to send one or more of these modules to BNL where they would be tested again using BNL readout electronics, which would include a standalone CAEN readout system as well as with the sPHENIX readout electronics. The sPHENIX readout electronics would eventually be the system that we would use for a beam test of these modules in the test beam at Fermilab.

At BNL, we planned to test the calorimeter components that we received just prior to the last report and start to measure some of the fundamental performance parameters of the shashlik design. These include the total light output and the response of each of the SiPMs used to read out each fiber, as well as the uniformity of the response across the tiles. This would be done using a UV LED or laser to inject light into a fiber that would be used to excite one of the tiles and then move it across its area. These measurements would then be compared with ray tracing simulations of the light production and light collection in order to provide a better understanding of the intrinsic of the light collection properties and uniformity of response of the shashlik configuration.

We also planned to have someone from UTFSM visit BNL and participate in the tests that were being carried out there, and for several people from BNL to visit UTFSM to see their setup and discuss future collaboration plans with them.

We also planned to refurbish several original PHENIX shashlik modules with individual SiPM readouts on each fiber and compare its performance to the W shashlik.

What was achieved?

Six shashlik modules were constructed at UTFSM and preliminary tests were carried out using LEDs. Figure 1 on the left shows five completed modules and one before completion showing the interior stack of W/Cu plates and scintillating tiles, and on the right, one of the modules under test. The modules were tested using a blue 480 nm LED to excite one of the tiles and all 16 SiPMs from the module were read out using a CAEN DT5740 digitizer with 16 ns sampling. Three of the modules were equipped with Hamamatsu S12752-010P SiPMs, which are the 10 μm pixel version of the same S12572-015P 15 μm pixel SiPMs that are used in the sPHENIX calorimeters, and three were equipped with Hamamatsu S14160-3015PS SiPMs which are the new, lower noise, lower cross talk and lower after pulsing devices that replaced the S12572 series. It can be seen that all channels are working, although there is some variation from channel to channel due to the light distribution inside the tile. We will later make use of this difference to try to determine the position of where the light is produced in the tiles using a small fiber to illuminate the tiles.

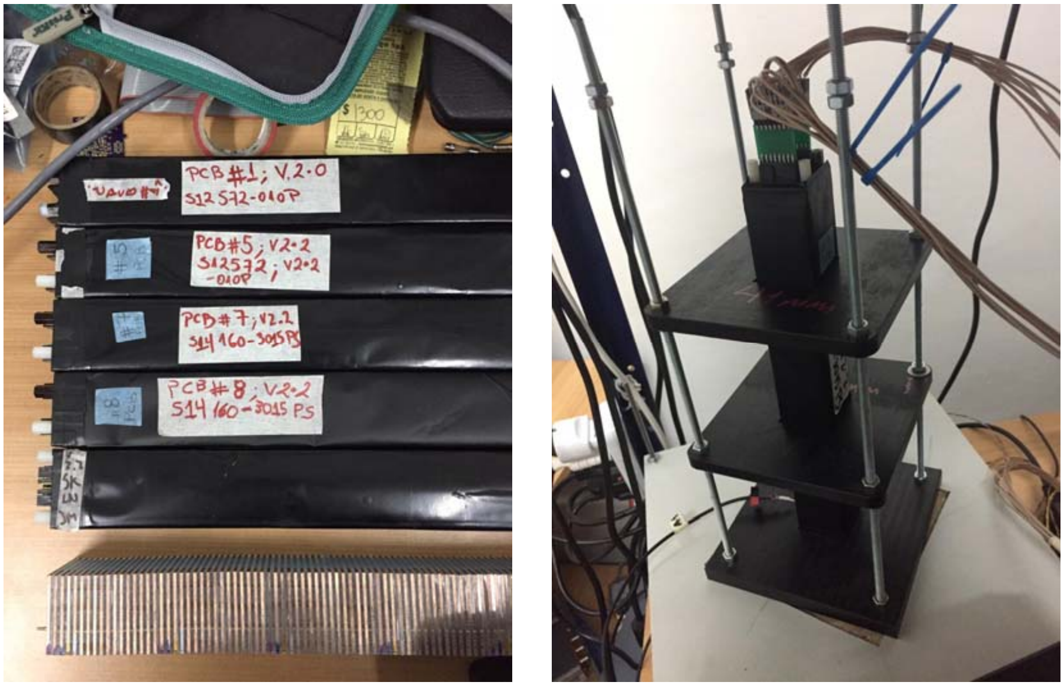
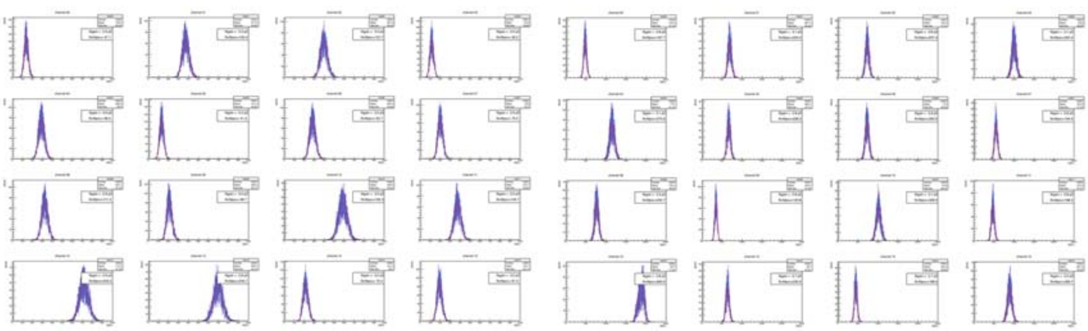


Fig. 1. Left: Five completed W/Cu shashlik modules and a sixth module before completion showing the interior stack of W/Cu plates and scintillating tiles. Right: One of the modules under test.



SHA2 (S12572-010P) SHA6 (S14160-3015PS)

Fig. 2. Left: LED spectra for module SHA2 read out with S12573-010P 10 μm pixel SiPMs. Right: LED spectra for module SHA6 read out with S14160-3015PS 15 μm pixel SiPMs.

Figure 2 shows two of the LED spectra obtained. These first LED tests look very encouraging. We intend to follow up on these measurements using the fiber illumination and also compare them to simulation results using a ray tracing program. However, time did not permit us yet to carry out cosmic ray tests with any of the modules in order to determine the absolute light output of the modules (i.e., number of photoelectrons produced per MeV of energy deposit). This will be done next at UTFSM and then modules will be sent to BNL for further testing.

At BNL we focused on testing the calorimeter components that comprise the module in order to study in detail the light collection properties and uniformity of light response within the tiles. Figure 3 shows the “short stack” of absorber plates and scintillating tiles that will be used in this study. It consists of a similar configuration of 16 SiPMs that are each read out with individual SiPMs.

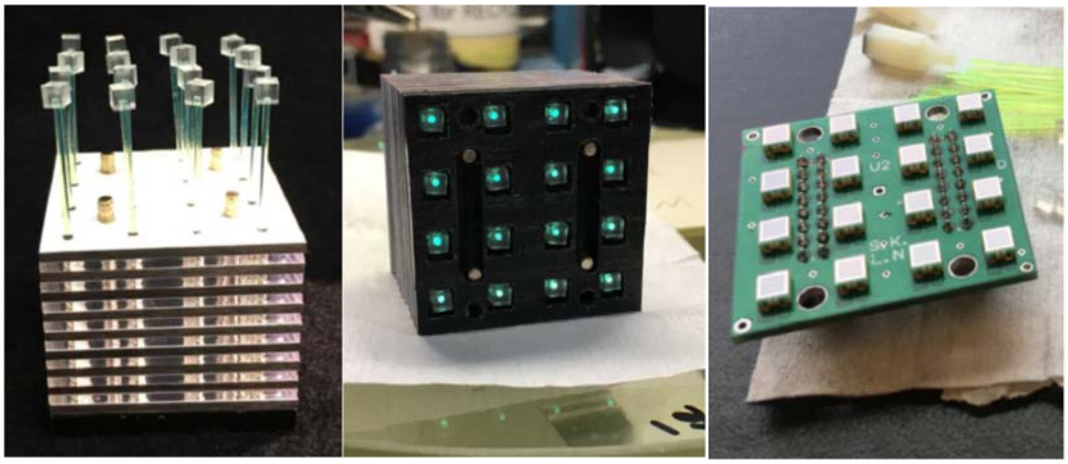


Fig. 3. Short stack of W/Shashlik calorimeter components for measuring light output and uniformity.

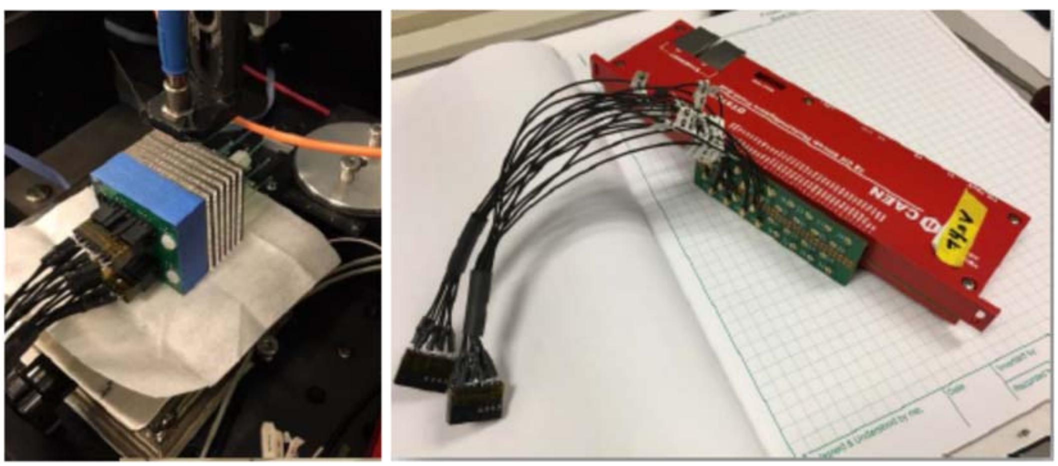


Fig. 4. Short calorimeter stack read and CAEN SiPM readout electronics.

Figure 4 shows the short stack in a setup using a CAEN DT5702 digitizer that is in principle designed to bias and read out SiPMs. However, we found that while we can indeed measure SiPM signals with this unit, the noise was too high to allow us to see the single photoelectron spectrum from the SiPMs. We initially thought that this might be due to noisy conditions in our test setup, but we learned later that other groups have also had difficulty seeing the single photoelectron spectra with this unit.

We therefore devoted more effort to reading out the short stack with the sPHENIX readout electronics. This required designing and building an interface board that connected the output of the SiPMs on the module to the input of the sPHENIX digitizers.

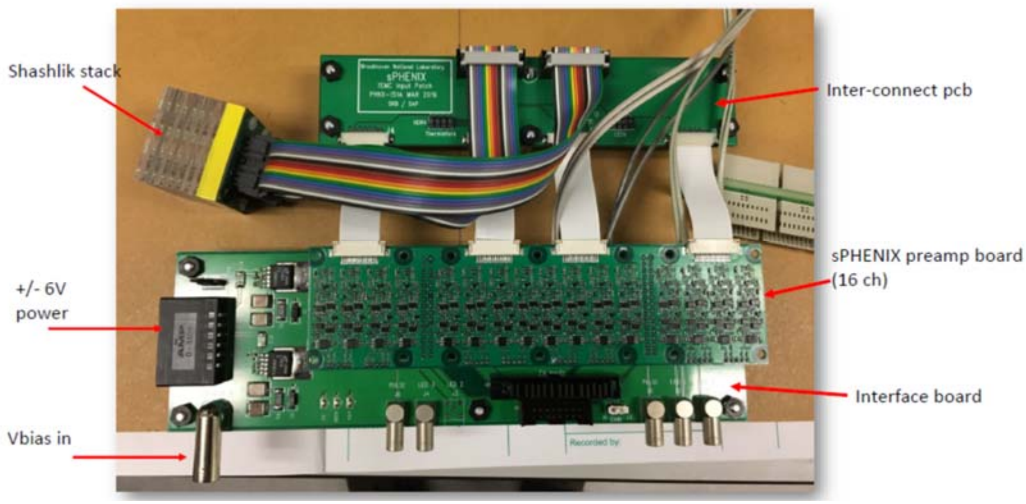


Fig. 5. Interface electronics for reading out W/Shashlik prototype modules with the sPHENIX readout electronics.

Figure 5 shows the readout interface board that was designed and built for this purpose. It uses the sPHENIX EMCAL preamp board with an interconnecting PCB to the SiPM readout board on the short stack, and also provides the bias for the SiPMs. This setup worked much better in terms of noise and allowed us to see the single photoelectron spectrum in each SiPM.

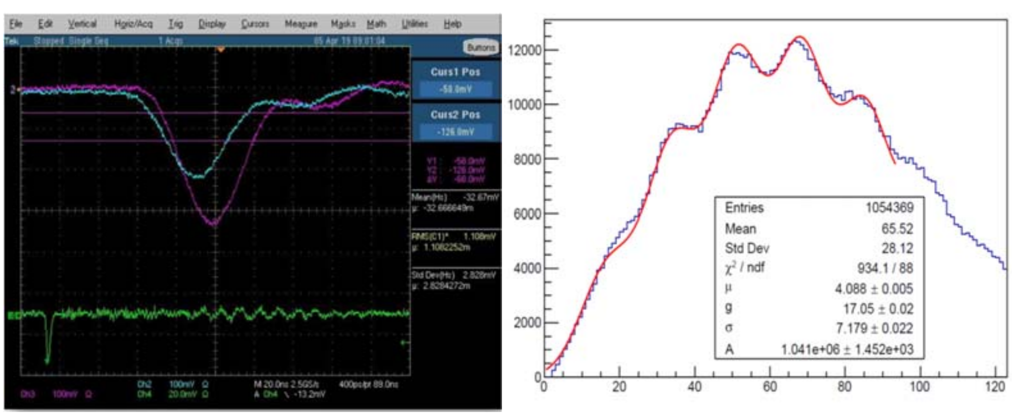


Fig. 6. Left: Pulses from a W/Shashlik SiPM (Hamamatsu S14160-3015SP) with the sPHENIX EMCAL preamp; Right- Single photoelectron spectrum from one of the SiPMs from the short stack using a LED with a low light level output giving an average of ~ 4 p.e.

Figure 6 gives an example of one of these spectra along with an example of the pulse from the SiPM as measured on the scope. While there is still a fair amount of noise at the single photoelectron level (as expected), the single photoelectron peaks are clearly resolved when the light level of the LED is adjusted to give a few photoelectrons on average. This will allow us to determine the absolute gain of the SiPMs in terms of ADC counts, which can then be used to determine the absolute photoelectron yield of the module using cosmic rays.

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

We did not test any of the modules using cosmic rays as we had hoped to do during this period. As a result, none of the completed modules were sent to BNL and will remain at UTFSM until these tests have been completed. However, six modules were constructed and tested with LEDs and the results from those tests look very encouraging. We will carry out the cosmic ray tests at UTSFM in the near future and then send the modules to BNL. We also plan to have a postdoc from UTFSM visit BNL after the modules arrive who will help with the testing.

We also hoped to carry out some initial studies on the light output using the short stack, but initial problems with the CAEN readout unit delayed this. However, in parallel, we developed the interface board to connect the short stack to the sPHENIX readout electronics and see the single photoelectron spectrum. This will allow us to proceed with the cosmic rays tests at BNL when the modules arrive, and also prepare for a beam test of the modules at Fermilab.

We had also hoped to carry out simulations of the light collection in the modules using our ray tracing program (TracePro) but we were not able to accomplish this during the last period due to lack of manpower. However, we currently have a summer student who is working on this and hope to have some results on this simulation by the end of the summer.

We also planned for several people from BNL to visit UTSFM during the last period, but this did not occur due to other pressing commitments. However, we hope that this visit will take place in the fall of this year.

Finally, we hoped to refurbish and study one or more of the original PHENIX Pb/Scintillator shashlik modules in order to compare them to the W/Scintillator shashlik. However, lack of resources (mainly time and manpower) prevented making any progress on this part of the effort.

Future

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

We plan to finish the testing of the six calorimeter modules at UTFSM using LEDs and cosmic rays and then send these modules to BNL. It is also planned to build 3 more modules for a total of 9. This will also require fabricating more interface boards to read out all 9 modules with the sPHENIX readout electronics. All of these modules wiIl first be tested at BNL using the sPHENIX readout electronics using cosmic rays and LEDs to cross check the tests and calibrations done at UTFSM. They will then be assembled into an array and tested in the test beam at Fermilab. Depending on the test beam schedule, we hope to carry out this test in the winter or spring of next year, hopefully in combination with other calorimeter beam tests (e.g., sPHENIX, STAR or other eRD1 efforts). This is somewhat later than we had originally planned due to other commitments in sPHENIX and CERN that prevented devoting more manpower to this effort during the last cycle, but we feel much progress was made.

We also plan to continue our light output studies, both with simulations and measurements, to try and better understand the light output and uniformity of the absorber tile stack. These studies are now under way with the help of our summer student and we hope to find the manpower to continue these studies after he leaves (perhaps with a UTFSM student).

We also feel that it is important to increase the interaction between UTFSM and BNL and hope to have exchange visits by both institutions by the end of this year.

The current EIC R&D plan would then be as follows:

- Construct 3 additional shashlik modules at UTFSM and test all 9 modules at UTFSM with LEDs and cosmic rays.
- Send these modules to BNL for subsequent testing with LEDs and cosmic rays using the sPHENIX readout electronics. This requires constructing additional interface boards to read out all the modules. This would also include having a UTFSM postdoc visit BNL to help with these tests.
- Assemble the 9 modules into an array and test it at Fermilab. These tests would include measuring the energy resolution, linearity and light response uniformity of the module array.
- Compare the resolution and uniformity of the shashlik module array to the W/SciFi modules that were measured in sPHENIX.
- Carry out measurements and simulation studies of the shashlik modules in the lab to try and understand the light output and uniformity of response of the stack.
- If additional manpower can be found, refurbish several PHENIX Pb/Sc shashlik EM calorimeter modules at BNL with individual SiPM readout on each fiber and measure light collection efficiency and uniformity. This would give a direct comparison between the very compact high density W/Cu/Sci shashlik modules and the larger, lower density Pb/Sci shashlik modules.
- Have several people from BNL visit UTFSM to see their facility and discuss future R&D plans.

What are critical issues?

The most critical issue is to finish constructing all 9 shashlik calorimeter modules and complete the tests of these modules with LEDs and cosmic rays. We also need to carry out the laboratory tests and simulation studies of the shashlik configuration. However, we are currently limited by manpower on this effort after our summer student leaves. Hopefully we will find another student who can continue these studies. We also cannot carry out the planned beam test with only the resources provided by e RD1. We therefore hope to collaborate on this beam test with other test beam activities from sPHENIX, STAR or eRD1.

Finally, we feel that this effort is extremely important for the design of a future EIC calorimeter in that one wants to develop a calorimeter design that will have better resolution than was obtained with the sPHENIX W/SciFi calorimeter, which was limited mainly by intrinsic non-uniformities. This technology offers the hope of achieving this if the details of the light collection and other performance parameters can be understood. This is therefore the primary goal of this effort.

Additional information:

In addition to continue to studying the W/Shashlik design in order to improve the uniformity of response of the calorimeter, we would also like to explore the option of increasing the photocathode coverage of the W/SciFi design, which we know was a major contributor to the non-uniformities observed in the sPHENIX design. This is now possible using larger area SiPMs that are now available from Hamamatsu. The Committee specifically requested proposals to do this in their last recommendations and we would like to respond to this request.

Hamamatsu now makes a 6x6 mm^2 SiPM (S13360-6025PE) which has 4 times the area coverage of the 3x3 mm^2 SiPMs. These devices are produced using the same technology as the new 3x3 mm SiPMs (S14160-015PS) that we are testing with the shashlik and come in a 25 mm pixel version. We have several of these devices in our lab and have done some initial studies with them and they seem to perform quite well.

We would like to equip several of the sPHENIX calorimeter modules with a number of these devices to increase the photocathode area coverage of the readout end. This would greatly increase the total light output (therefore increasing the Npe/MeV) and also improved the uniformity. We could essentially eliminate the 1" light guides used in the sPHENIX modules and install a simple light mixer block over the 49.0 x 44.6 mm^2 readout area of the module. Due to the physical dimensions of the S13360-6025PE, we could install a 5x5 array of these devices over the readout area. This would provide 41% of the active area coverage as opposed to only 6.5% that is covered by the 4 light guides with the 4 SiPMs each in the current sPHENIX design. We would also expect that this would improve the uniformity of light collection since the light guides do not capture the light very uniformly over the readout area.

Figure 7 show some measurements and simulations of the light collection efficiency and uniformity that we carried out during the design of the sPHENIX calorimeter. It shows that with complete photocathode coverage with a PMT, the light collection efficiency is close to 90% and fairly uniform over the readout area (dropping of slightly towards the edges). However, with the 4 SiPM and light guide readout, the light collection efficiency is only ~ 15%, and while the lab measurements did not show a significant variation across the readout area, beam tests showed that the light guide boundaries do cause non-uniformities that worsen the energy resolution. We therefore expect that the large area, multiple SiPM readout will greatly improve the light collection efficiency and uniformity of the readout of the block.

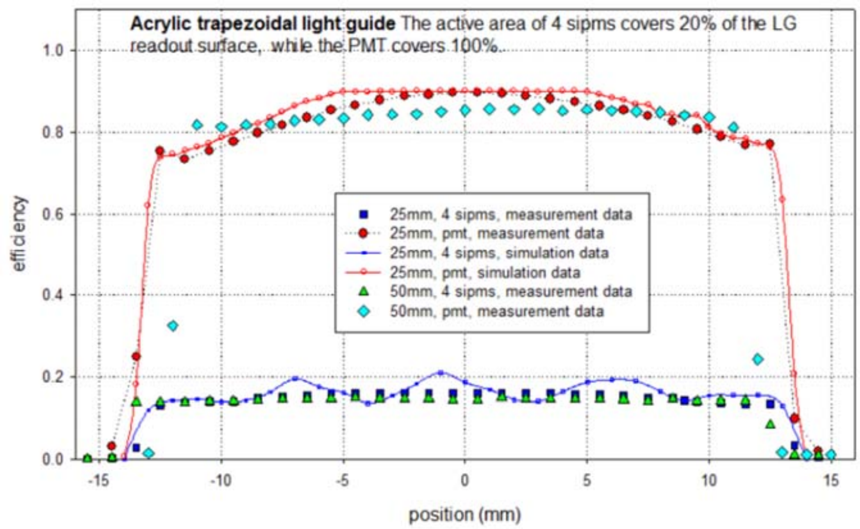


Fig. 7. Efficiency and uniformity of light collection for a sPHENIX calorimeter module using a PMT covering the entire readout end and with 4 light guides having 4 SiPMs each as is used in the sPHENIX design. A comparison with ray tracing simulations is also shown.

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.

- Technical work at UTSFM is currently being carried out with approximately 10% of an FTE. This effort is currently limited by internal funding at UTSFM.
- There technical effort on this project at BNL is approximately 10% of an FTE, including one Physics Associate and one technician, along with discussions among scientists.

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 manpower at UTSFM is currently being provided by internal funding.
- All scientific manpower at BNL is provided by internal funding from sPHENIX. However, technician and designer labor needs to be supported through EIC R&D funds.

Budget

Funds are requested from EIC E&D to support the completion of the 9 prototype modules and to test them at UTFSM and BNL. We are also requesting funds to produce additional sPHENIX electronics readout boards for these modules and to test the modules at Fermilab. Support for travel and partial support for the beam test are also requested. We are also requesting funds to purchase additional large are (6x6 mm^2) SiPMs to study the W/SciFi modules with increased photocathode coverage.

The table below gives Money Matrix" for full funding, a 20% reduction and 40% reduction.

Budget Request

eRD1 BNL Funding Request (FY20)			
	Full Funding	**20% Cut**	**40% cut**
Large Area SiPMs	15	7.5	
Additional sPHENIX interface boards and readout boards for large area SiPMs	5	5	5
Technical support at BNL (technician, designer) including a visit by someone from UTFSM	5	5	5
Test Beam (in collaboration with sPHENIX, STAR or other EIC calorimeter beam tests)	15	15	15
Travel (includes support for UTFSM and BNL)	10	7.5	5
Total	**50**	**40**	**30**
Overhead	25	20	15
Total with Overhead	**75**	**60**	**45**

Sub Project 4: Tungsten Scintillating Fiber Calorimeter Developments in sPHENIX
Project Leader: C.Woody

Past

What was planned for this period?

Our main activities for this period were:

- Continue with the construction of the sPHENIX EMCAL Sector 0 preproduction prototype.
- Begin fabrication of blocks for sPHENIX EMCAL preproduction Sectors 1-12
- Obtain PD-2/3 approval of the sPHENIX project and proceed towards construction of the sPHENIX EMCAL
- Continue to develop the capability to produce absorber blocks in China so that the large rapidity blocks can eventually be produced there.
- Complete the analysis of the data for the sPHENIX V2.1 EMCAL prototype from the 2018 test beam run.
- Resubmit our revised paper on radiation damage in SiPMs for publication in IEEE TNS.

What was achieved?

All of the blocks for the sPHENIX EMCAL Sector 0 prototype were completed and tested at UIUC and sent to BNL for installation into the sector. They were first test fit onto the sawteeth support structures inside the sector to see how the blocks all fit together and to determine the nature of any gaps between the blocks. Most of the blocks fit together very well and there were only one or two places where the gaps were deemed to be unacceptable. These were believed to be caused by problems with casting and machining several of the blocks and an incorrect mold for one of the block types, both of which can be corrected. The blocks were finally glued in place at the end of May completing the first phase of the construction of Sector 0. Figure 1 shows the sector with all of the blocks installed.

The final design for Sector 0 was completed and all of the mechanical parts for assembly have been delivered to BNL. Figure 2 shows the 3D model of the sector which contains all of the internal electronics, cables, cooing system etc. Sector 0, which is a preproduction sector and not intended to be installed in the actual experiment, will be used to perform an initial assembly of all the internal components and study any problems that occur during the assembly. Any adjustments or modifications that need to be made will be incorporated into the sector design and implemented into the first 12 preproduction sectors (Sectors 1-12) and the remaining production sectors (Sectors 13-64). All of these sectors will be fully functional sectors installed into the sPHENIX detector.

Figure 2.1. Sector 0 with all blocks installed and glued into place on the sawtooth supports.

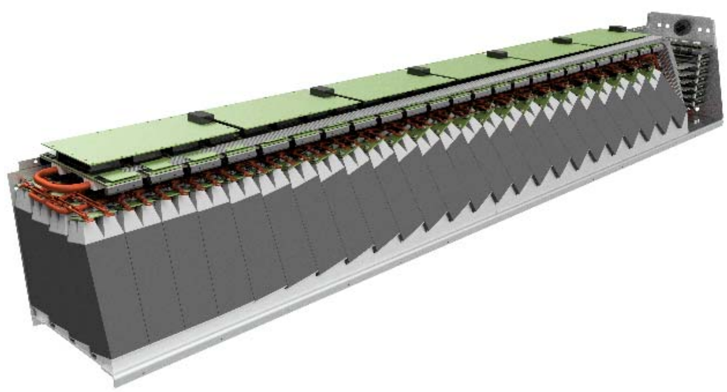


Figure 2.2. Final design of a complete sector with all blocks, readout electronics, cables and cooling inside.

Block production also continued at UIUC with the production of blocks for Sector 1. While Sector 0 was produced with mostly powder supplied by Tungsten Heavy Powder (THP), Sector 1 will be produced with powder supplied by Stark. Initial studies showed that the powders are very similar but it turned out that the process for casting the blocks was somewhat different for the different powders. It took some time to understand these differences, which mainly had to do with how to infuse the epoxy into the block. This issue was resolved by adding some additional ethyl alcohol to the epoxy mixture, allowing it to flow more easily, and the casting of the blocks has now greatly improved. Production of the Sector 1 blocks is now continuing, and as of the middle of June, 34 blocks have been produced and were in the process of going through their QA procedures.

The most significant event for the sPHENIX EMCAL during the last period was that sPHENIX underwent its PD-2/3 Review. This was a 3 day review that took place from May 28th-30th that was conducted by an outside committee of experts on the physics, technology, project management, budget and ES&H aspects of the sPHENIX project. The committee concluded that sPHENIX was ready for PD-2/3 approval contingent on addressing a few remaining issues. The main issues had to do with the demonstrating that the required operating conditions of the TPC and its readout could be achieved, but there were no major issues for the EMCAL. The only recommendation for the EMCAL was that we re-evaluate our cost contingency for the tungsten powder given the current uncertainty in the market price of tungsten and the threat of tariffs on goods from China.

Progress on block production in China also continued. The plan is to produce all of the large rapidity blocks for the EMCAL in China at facilities at Fudan and Peking University. These blocks will be produced with powder supplied by a different vendor in China and using fibers supplied by Kuraray. We have tested blocks produce with Kuraray fibers and found them to be essentially indistinguishable from those produced with Saint-Gobain fibers. However, the powder could require a different process for casting the blocks than that which was used for the THP powder, just as we found for the Starck Powder. This is now being investigated at Fudan and the results look very encouraging. Figure 2.3 shows an example of a recently produced block at Fudan which, except for some minor issues with missing fibers that can easily be corrected, the resulting block looks very good.

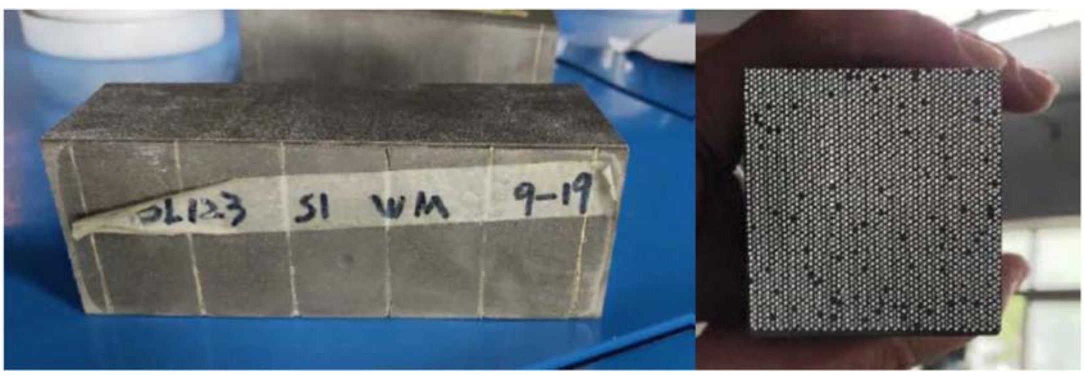


Figure 2.3. Absorber block produced at Fudan University using Chinese powder and Kuraray fibers.

The analysis of the 2018 V2.1 test beam data was completed during the last period and the results are now written up in an sPHENIX analysis note. We are still waiting for the analysis of the HCAL prototype data to be completed for this run, but once it is, we intend to submit another paper to IEEE TNS with the complete analysis results of the 2018 beam test. Finally, our paper on radiation damage in SiPMs was revised and resubmitted to TNS and has now been accepted for publication.

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

The assembly of Sector 0 was not completed due to delays caused by the extra effort required to test fit the blocks and having to wait for the delivery and certification of the sawteeth support structures. Both of these issues have now been resolved and the assembly of the sector is continuing with the installation of the internal electronics, cables and cooling system.

The production of blocks for Sector 1 was delayed due to problems encountered with casting the blocks with the Starck powder, but this issue has now also been resolved and block production for Sector 1 is continuing at UIUC.

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 activity during the next six months will be to finish the construction of Sector 0 and test it in the lab. The schedule for this has been somewhat delayed due to the late delivery of the mechanical parts but all of these parts are now in hand and the assembly of the sector can now proceed. The production of the blocks for Sector 1 was also somewhat delayed due to the problems we encountered with casting the blocks but this problem has now been solved and block production is continuing.

What are critical issues?

The most critical issue during the next six months will be to complete the construction of Sector 0 and to test it to see that it meets the performance specs for sPHENIX. It will also be important to continue with the production of blocks for Sector 1 at UIUC and to continue to develop the ability to produce block in China at Fudan and Peking University. One of the most critical issues there will be to certify the powder that will be used to produce the Chinese 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.

The effort on the sPHENIX EMCAL is being carried out mainly by the BNL sPHENIX Group, UIUC, Fudan University, Peking University, the University of Michigan and Debrecen University in Hungary, but also with participation by other sPHENIX collaborators.