Date: 6/26/20

EIC Detector R&D Progress Report

Project ID: eRD1
Project Name: EIC Calorimeter Development
Period Reported: from 1/1/20 to 6/30/20
Project Coordinators: H.Z. Huang and C. Woody
Contact Persons: T. Horn, O. Tsai, C. Woody

EIC Calorimeter R&D Consortium

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

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

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

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

S. Ali, V.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. de Vita
INFN Genova, Italy

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

C. Fanelli, Z. Shi
Massachusetts Institute of Technology

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

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

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

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

The eRD1 Calorimeter Consortium currently has three funded subprojects: 1) development of tungsten powder/scintillating fiber (W/SiFi) EMCal technology and development of a Forward Jet Calorimeter System by the UCLA team; 2) development of homogeneous crystal and glass calorimeters by the CUA/Orsay team; and 3) development of a Tungsten Shashlik EMCal by the BNL/UNAB team. Here we summarize the activities and progress from January 1 to June 30, 2020 and outline our proposal for our R&D plan for FY21. The selection of BNL as the site for the EIC facility has ushered in a new era of detector development. In anticipation of a transition from the current detector R&D program to an EIC detector project soon beyond FY21, our focus in FY21 will be to bring our calorimeter R&D activities in the past years to a mature stage so that we will be ready for detector CDR/TDR preparation in the EIC detector project phase.

Subproject 1 by the UCLA team developed a synergy with the STAR upgrade project of the Forward Calorimeter System (FCS). The team is building the FCS consisting of an EMCal of PHENIX Shashlik calorimeter modules and a new Fe/Sc plate sampling HCal for jet measurements in the forward rapidity region in STAR. The FCS project is currently under construction with funding from both DOE and NSF, and is scheduled to be ready for the RHIC 2022 run despite delays due to the COVID-19 shutdown. From the EIC R&D program, this subproject is funded for a simulation effort to evaluate possible endcap calorimeter configurations of a Shashlik EMCal+Fe/Sc HCal and a W/SiFi EMCal+Fe/Sc HCal for EIC forward jet measurements in the hadron direction. The FY21 R&D plan will focus on completion of the simulations to prepare a forward calorimeter design for jet measurements, optimize detector parameters for the HCal readout using WLS bars, and measure the characteristic performance of SiPMs from various vendors to ensure the quality of the supply of SiPMs when EIC detector construction commences. The team will submit an Expression of Interest for an Endcap EMCal+HCal system in the hadron direction to measure jets by November 2020.

Subproject 2 by the CUA/Orsay team focuses on developing glass scintillators for the EIC EM calorimeters, material characterization, and a prototype beam test program to establish glass performance and iterate formulations/fabrication with vendors as needed. Simulations are being developed as part of this effort and for optimizing the configuration of the electron endcap EM 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 and for possible improvement of resolution of hadron calorimeters are included as well. Due to COVID-19 planned beam tests could not be carried out and are thus a goal of the FY21 activities. The long-term goal of this R&D is to align 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. Receiving SBIR/STTR Phase 2 funding is particularly important towards reaching this long-term goal. Another long-term goal is to construct the electron endcap EM calorimeter (crystal/glass). To achieve this goal, we have started discussions and assembling a team to submit an Expression of Interest. The team would consist of CUA, MIT, U. of Kentucky, Lehigh U., and, pending final negotiations with our collaborating institutions from Armenia, France, and Italy 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 EMCal at BNL, as well as expertise and vendor presence for glass scintillators.

Subproject 3 by the BNL/UNAB (previously UTFSM) team continues on the development of a W Shashlik EMCal with SiPM readout. A compact shashlik calorimeter is one of the technologies being considered for the two endcap regions at intermediate rapidities and as a possible candidate for the barrel EMCAL for EIC. In FY21 the team focused on the construction of a first prototype of this design. An array of 3x3 modules based on a previous design for NA64 at CERN were delivered to BNL and was being tested before being interupted by the lockdown of the BNL due to COVID-19. The priority for FY21 will be to design and construct several new W/Shashlik modules that are better optimized for EIC applications. The plan is to complete the tests of the first 3x3 prototype detector in the lab using cosmic rays and then take it to Fermilab where it will be tested in the beam. In parallel, the design of the new calorimeter modules will proceed by carrying out simulations and performing lab tests of detector components. It is hoped that some number of modules will be completed by the time of the beam test and can be tested along with the other prototype. Simulations will also be done to study the relavent physics performance parameters of the shashlik design for EIC. The team plans to submit an EOI to continue these activities beyond FY21 with the goal of developing a suite of working detectors that would be suitable for its various EIC applications.

The eRD1 consortium has developed several calorimeter technologies to cover the full EIC detector acceptance including Crystal and Glass homogeneous detectors for the electron endcap calorimeter, W/SiFi or Shashlik EMCal for the central barrel, and an EMCal (W/SiFi or Shashlik) + Fe/Sc HCal for the hadron endcap calorimeter. We look forward to carry forward these technologies arising from this R&D program to the construction of an EIC detector in the coming years.

Sub Project 1: Tungsten Powder Calorimeter R&D at UCLA
Project Leader: H.Z. Huang and O. Tsai

What was planned for this period?

For past six months, we continued working on the STAR forward calorimeter system including both EMCal and HCal for jet physics measurements, as planned in our previous report. We have adjusted our priorities to emphasize specific R&D aspects related to EIC hadron-side calorimeters for jet physics in anticipation of the future EIC detector project according to recommendations by the Committee.

What was achieved?

We will have a unique opportunity to operate a sizable-scale forward calorimeter system (STAR FCS) with a structure similar to what is envisioned for EIC detector, in experimental conditions that will be close to high luminosity EIC running. STAR FCS project was moving well on schedule for installation at BNL starting in Aug. 20202 before the complete shutdown of activities due to COVID19 at national labs and Universities. However, major components from industrial vendors such as absorber blocks, scintillator and WLS bars followed closely the initial production schedule and they are on path to finish tasks on time or already completed production. A shutdown related to COVID19 delayed all University tasks by approximately three months. Currently Universities started gradually to open up for research but many University shops will remain closed or at very low level for possibly the entire summer. A lot of jobs, which supposed to be carried out at Universities shops, are being outsourced now. Revised milestones for FY20 now is to finish instrumentation of ECal and have at least 50% of HCal installed and instrumented. There was an unexpected complication with Hamamatsu SiPMs supply as well. The newer version of SiPMs intended for STAR FCS had experienced production problems. As a result, we had to switch back to older version of SiPMs. At present, we have received all SiPMs and production of sensor boards is ongoing. The response from Hamamatsu on the SiPM order was a major concern.

It is important for the EIC calorimetry consortium to evaluate the SiPMs from various manufacturers before the commencement of the EIC detector project. It is important that the evaluation of SiPM characteristics will be carried out in a beam environment similar to what we expect for EIC. RHIC Run 22 will be optimal opportunity where environmental conditions at forward rapidity with the STAR FCS will be very close to these at future EIC.

Due to COVID-19 we have expressed some slowdown in our plan. One of our graduate students Zhiwan Xu was not able to return to UCLA from China since Dec. 2019. Zhiwan was supposed to work closely with a senior graduate student, Maria Sergeeva, and take over the responsibility of GEANT simulation task related to calorimeter system in our EIC R&D project. After an initial slow start, Zhiwan has been able to carry out simulations remotely in China. She will continue her work through the summer. Zhiwan and Masha will be able to finish most simulation tasks outline in our last year's R&D plan by the end of summer. One major goal of our simulation task is to maintain the synergy between the STAR FCS upgrade project and the EIC R&D towards a hadron-side jet calorimeter system. It is important to crosscheck the simulation results when there is very limited or no test-beam data on the HCal prototype design under consideration.

In particular, in our last report we showed that finite non-uniformities of light collection across scintillation tiles has very little effect on energy resolution. Surprisingly, measured non-uniformities along the towers due to problems with WLS bars has little effect as well, confirmed both in gSTAR and GEANT4. This is quite different conclusion from our earlier studies with compensated Pb/Sc calorimeter where such non-uniformities lead to significant increase in a constant term. Our hypothesis is that HCal design with Fe/Sc plate structure is less prone to local fluctuation due to, for example, charge exchange process when a large amount of energy can be deposited at a large range of length along the hadronic tower, which is different from the case for Pb/Sc type structures. We are still uncertain about this hypothesis and we want to investigate further. If this insensitivity to local fluctuations can be shown to be true, we can establish additional advantages of a Fe/Sc HCal design over the Pb/Sc HCal. This is especially important for a large-scale system such as the EIC hadron endcap calorimeter.

We show below simulation results of energy resolution of a combined EM+Had system as a function of

- Total depth;
- Dead material between EM and Had sections;
- Sampling Frequency in HCal;
- Effect of tile catcher;
- Choice of technology for EM section.

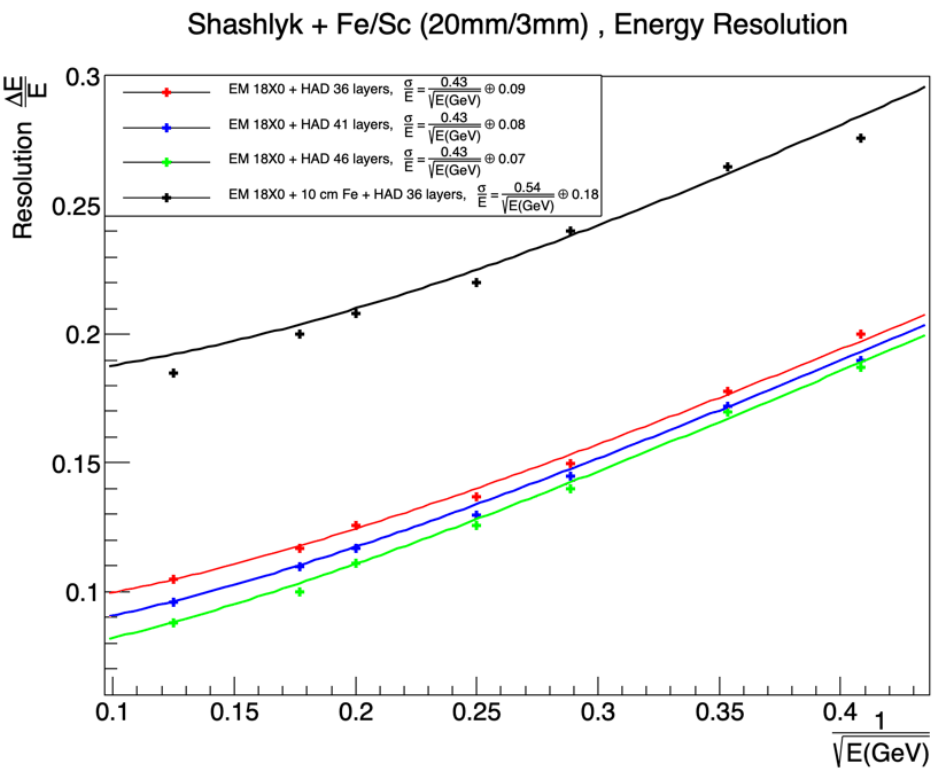

Figure 1. Effects of total depth and dead material on energy resolution of Hadron EndCap.

One major challenge for an EIC central detector is to fit all subsystem in a very limited space. According to an estimate of integration volume for a possible EIC detector, an endcap calorimeter system should fit in about 1.2 meter of space, which is very challenging. With steel absorber and reasonable sampling frequency, it will result in a depth of about 5 interaction length leading to considerable longitudinal leakages. Figure 1 shows that indeed by increasing the number of layers in HCal from 36 to 46 the constant term for energy resolution will go down from 9% to 7%. Increasing in cost by ~25% (proportional to number of layers to first order) can lead to improvement of energy resolution at 64 GeV by ~ 25%, with very little improvements at low energy region (most of particles in jets will have energy below 10 GeV, i.e. very soft). Given space restrictions, the 46-layer HCal configuration is probably out of question in any case. As we will show later, utilizing a design with tail catcher may be a more effective approach. The black points in Fig.1 shows the effect on energy resolution when a passive steel layer of 10 cm is placed between EM and Hadron calorimeter sections. The combined weight of hadron endcap is about 200 tonnes and the EMCal will require additional support structure. A steel of 10 cm thickness is a hypothetical example (the sPHENIX return flux is 10 cm thick in endcap). Our simulation indicated that placing Fe plates between EMCal and HCal sections, which will effectively have dead materials, approximately at position of shower maximum, will have very strong degrading effect and should be avoided, i.e. preferentially HCal should serve as support structure for EMCal. There are possibly other limitations due to magnet design itself, which may require additional compensation coils between EMCal and HCal and other associated support structure.

As indicated in multiple recent studies, particles from jets spanning barrel and endcap region are very soft. To improve energy resolution for low energy hadrons one needs to increase sampling frequency.

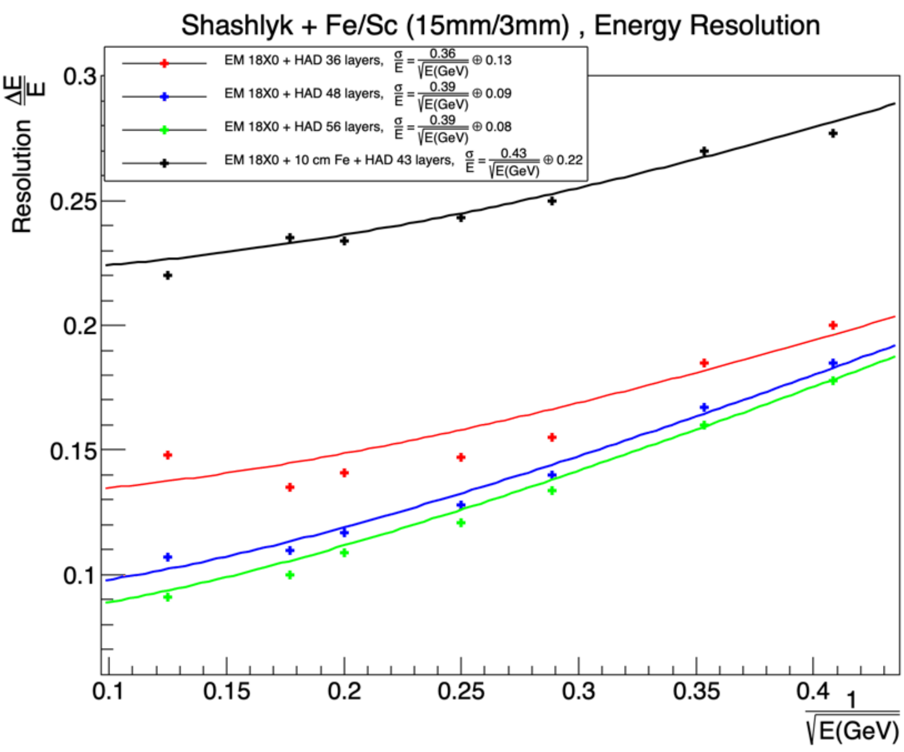

Figure 2. Energy resolution vs number of layers for 15/3 mm Fe/Sc HCal plate design.

Figure 2 shows how energy resolution for hadron endcap will change with increased sampling frequency. There are improvements for low energy hadrons as expected. The high energy region is dominated by leakages as it was in the previous case. Figure 3 shows direct comparison of two configurations, with approximately fixed total depth, i.e. 36 layers for 20/3 and 48 layers for 15/3 (Fe/Sc) configurations.

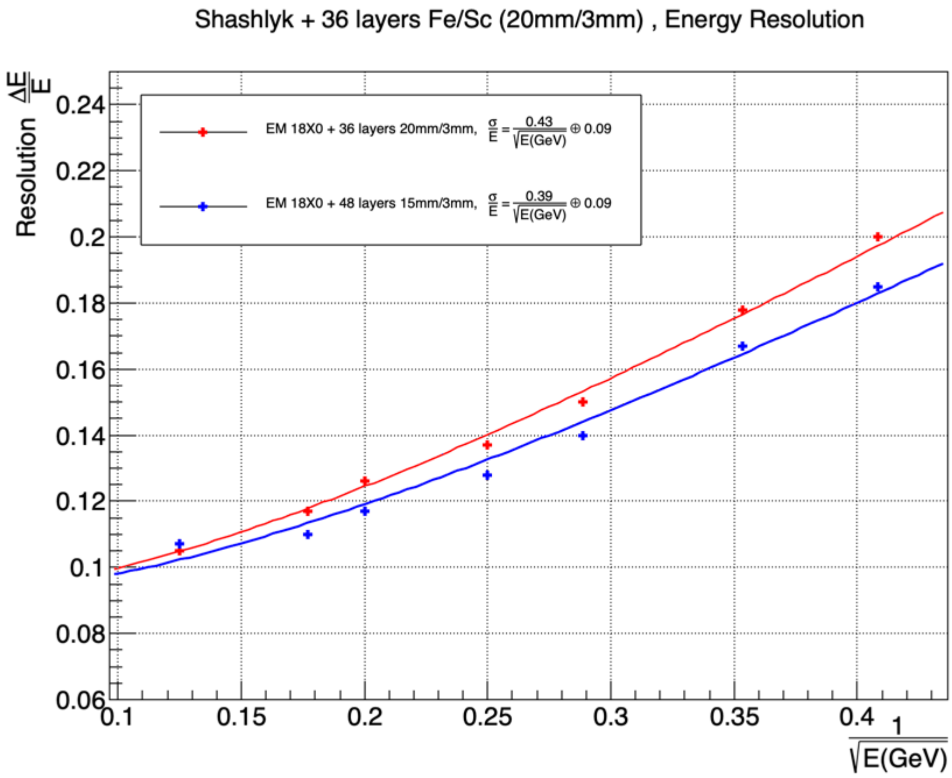

Figure 3. Comparison of 20mm/3mm to 15mm/3mm (Fe/Sc) HCals corresponding to approximately the same total length.

The simulation showed an improvement of about 10% in energy resolution at low energy with the more sampling configuration, but the number of layers from 36 to 48 corresponds to approximate cost increase of 25% and complications due to calorimeter mechanical structure, which will have to be taken into account.

With high granularity EMCal+HCal system one has access to spatial development of showers, i.e. by applying different cuts on multiplicity or ratio between EMCal/HCal energy depositions it is possible to select particles with longitudinally late shower developments with likely leakages. We note that with current scheme of light collection it would be straightforward to implement a tail catcher where a few last tiles in the HCal tower may be readout using both with WLS bar and WLS fibers. Then we can achieve simultaneous measurements of total energy and energy in the tail catcher. This readout scheme is illustrated in Figure 4 for 64 GeV pions.
With various schemes to suppress particles with leakage in the HCal, the low energy tail in the measured energy spectra can be reduced significantly. A simple scheme to use three last layers as a tail catcher has some advantages in both performance and implementation.

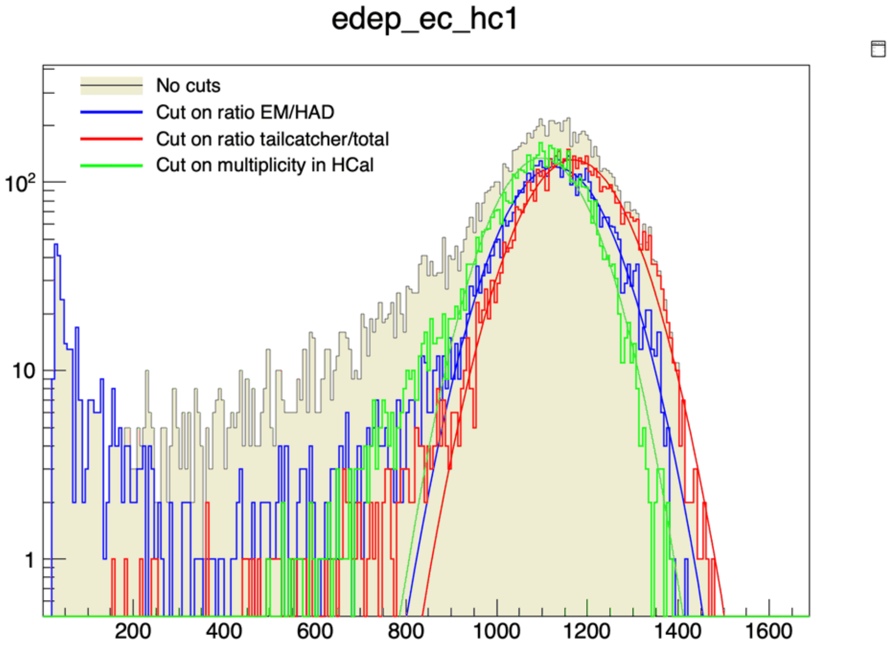

Figure 4. Methods to select longitudinally late showering particles using multiplicity, ratio between EM and HAD section, and by using information from tail catcher for 64 GeV incident pions.

The tail catcher scheme has significant advantages compared to traditional longitudinal segmentation method, in particular with respect to calibration of the system. With these readout methods we can identify particles with leakages. We also studied whether we can use the measured tail catcher energy to recover the total energy through a correction method. Our initial study showed that, unfortunately, there is little hope to do e-by-e corrections for any of these methods. The number of tiles in tail catcher varied from 3 to 10 with little improvements on final result. Although granularity of HCal is high, multiplicity method will not work well at EIC due to relatively low energies of most hadrons.

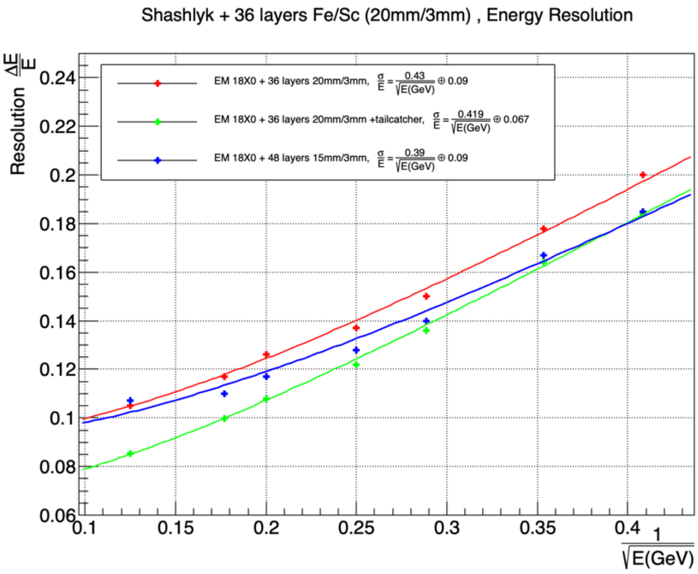

Figure 5. Comparison of different schemes for hadron endcap.

Without event-by-even correction, we can take an efficiency hit to remove particles with leakages and maintain good energy resolution for the remaining particles. Figure 5 shows that 36 layers (20/3) Fe/Sc HCal with three-layer tail catcher works as well as finer sampled (15/3) Fe/Sc HCal at low energy scale, and also improves the constant term at the expense of rejecting 50% of events at 64 GeV and 10% of events at 6 GeV. Not all measurements at EIC are statistics limited and such approach may be valid and useful for internal crosschecks in any case (like understanding biases due to leakages). This will be a subject for physics simulation studies that we hope to clarify in the coming years.

We also started to investigate W/ScFi EMCal + Fe/Sc HCal performance. Our preliminary results indicated that the performance of such system is somewhat better than the SHASHLYK+Fe/Sc combination. W/ScFi is more compact and was the subject of eRD1 project for several years. We have developed the technology. Several groups are capable of producing the W/ScFi calorimeter. Currently we consider this configuration as a preferred option than utilizing old existing PHENIX EMCal as an EM section for hadron endcap system. These studies will continue during the summer of 2020.

COVID-19 Impact and FY20 Budget Situation

Due to COVID-19, our lab at UCLA was shutdown in March 2020. Our lab received permission to open partially in the middle of June 2020 and Oleg Tsai resumed working on the STAR FCS upgrade project. For the EIC R&D project, our focus was on the simulations of various HCal design and EMCal and HCal combinations for optimal jet measurements on the hadron-side of the EIC. By the end of summer 2020, we expect to complete most of our planned work.

Two of our graduate students, Zhiwan Xu and Maria Sergeeva, have been working on the simulation task. Zhiwan is supported by a UC EIC Consortium project funded by UC President’s office. Our FY2020 budget will have a carry-over around $8k by the end of summer 2020 mostly from travel allocation. We planned to attend a Calorimeter conference to report our R&D results and a few EIC workshops. Since all meetings are either cancelled or virtual, we have not spent much of the travel budget. We propose to keep the travel budget for students to travel to EIC workshops next year.

Future Plan towards an EIC Calorimeter System for Jet Measurement

Our team has developed the W/ScFi EMCal detector technology and the W/ScFi EMCal block production technology is mature and can be adapted to variations of design details. The selection of BNL as the EIC site ushered in a transition from detector R&D phase to a new phase of EIC detector design construction. Our team intends to express a strong interest in the EMCal and HCal calorimeter system for jet measurements on the hadron-side of an EIC detector. Our R&D goal next year is to determine the most optimal configuration for the EMCal and HCal combination in terms of energy resolution, practical constraint due to limited integration volume and construction technology. We will also evaluate the characteristic performance of SiPMs from different vendors so that we will have viable options available in construction project.

Our high priority is to complete detailed simulations with W/ScFi + Fe/Sc + Tail Catcher configuration to have direct comparison with previous SHASHLYK + Fe/Sc results shown in Figure 5. W/ScFi EMCal has significantly different e/h ratio from that of SHASHLYK. In particular, W/ScFi configuration with 0.47 mm diameter scintillating fibers placed 1 mm apart in the W/epoxy compound gives e/h close to 1, which should help improve energy resolution of combined system. The next step in investigation of this configuration is implementation of gaps and passive structural materials in HCAL design instead of working with simplified ideal geometry. We want to see how results shown in Figure 5 will change when a realistic detector geometry is implemented. Optimization of gaps can affect efficiency of light collection and degradation of SiPMs in experiment. We may optimize, with respect to energy resolution, the thickness of WLS plates to be used (gap width). We will need to study the efficiency of light collection for WLS plates with different thickness and potentially different concentration of dopants. We need to order some WLS plates from EJ for the study. However, optimization of just energy resolution may not be sufficient, as it becomes clear during YR discussions that detection threshold may be important as well. In this case, one needs to optimize LY to keep desired S/N ratio (due to increased noise in SiPMs with exposure). The other aspect of such optimization is to consider using thicker scintillation tiles in HCal. However, there are some indications that such HCal becomes undercompensated and we will have to demonstrate that tails on the right side of amplitude spectrum can be suppressed with re-weighting technique and that this will not lead to a significant degradation in energy resolution.

In addition to the hadron endcap EMCal and HCal optimization, we want to investigate SiPMs from different vendors, other than the two type of SiPMs we have in hand from Hamamatsu. We would like to characterize sufficient number of SiPMs from at least two additional manufacturers, KETEK and SENSL. We want to address these questions: what efficiencies of light collection with these sensors are before and after irradiation, how S/N ratio changes with more radiation dosage, what type of cooling will be required to keep desired S/N ratio for different types of SiPMs. The proposed R&D on SiPM measurements will provide needed guidance for the development of the EIC detector design.

Manpower

Four graduate students from UCLA continue to participate in these studies, M. Sergeeva, D. Neff, B. Chan and Z. Xu under the Supervision of H. Huang and O. Tsai. Graduate student Z. Xu will be supported by a UC EIC consortium project until the end of 2020. We will continue our strong collaboration with the BNL medium energy group (A. Kiselev, E. Aschenauer and A. Ogawa) on EIC and STAR Forward Upgrade, and with the UCR group (K. Barish, M. Arratia and R. Seto) on the development of an EIC research plan via UC EIC consortium.

Budget

Budget Scenario	100%	20% cut	40% cut
UCLA support for students (26% overhead included)	$18.6k	$18.6k	$18.6k
Travel (26 % overhead included)	$9.6k	$7.6k	$7.6k
EJ WLS Plates	$4.5k	$4k	$0k
SiPMs	$4k	$0k	$2k
Machine Shop, Electronics shop (26% overhead included)	$6k	$5k	$0k
Materials and supplies	$5k	$3k	$0k
Total	**$47.7k**	**$38.2k**	**$28.2k**

In case of a 20% budget cut a partial study on light collection can be carried out. In case of a 40% cut only MC studies will be performed. Our travel budget takes into account a FY20 $8k carryover expected.

Sub Project 2: Homogeneous calorimeter development - crystals and glass
Project Leader: 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 scintillator materials for the EIC EM calorimeters. We expected to receive and characterize at least ~100 additional CRYTUR and ~200 additional SICCAS $PbWO_4$ crystals. We planned to produce larger glass samples of ~10X_0 with adequate surface quality for physical, luminescence, and radiation hardness studies. We also planned to start developing long-term goals and milestones for material development, to explore additional radiation hardness studies, and, together with vendors, to prepare a small business funding proposal for new scintillator material development and production. In a synergistic activity with the Neutral Particle Spectrometer (NPS) project at Jefferson Lab, we planned to continue our test beam program with an EMCal prototype 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 SICCAS on material control and purity, and crystal handling, as well as with CRYTUR on investigating sources of new raw material.

What was achieved?

1) **Characterization of crystal samples**

We have been working closely with the vendors and through synergy with the NPS project we characterized, over the last six months, an additional 152 CRYTUR and 192 SICCAS $PbWO_4$ 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.

2) **Fabrication and scale-up of glass samples**

We have produced, in collaboration with the Vitreous State Laboratory (VSL) and Scintilex LLC, five ~10X_0 glass scintillator samples. After successfully completing this initial scale-up we can now reliably produce several glass samples of transverse dimensions 2 cm x 2 cm and ~10X_0 length per week. Fig. 1 shows our progress with scaling up the glass bar dimensions over the last year. Scintilex has developed the scale-up manufacturing process and can now, within less than one year, fabricate 20-cm long glass bars with further scale-up optimization ongoing. The goal is to demonstrate a 40-cm long scintillating glass bar by the end of the year. Our expertise and results to date have played a large role in the submission of Scintilex,

[1] The NPS project has received and characterized a total of ~600 Crytur and ~860 SICCAS crystals since 2015.

LLC's STTR/SBIR proposal for the development of high-performance glass scintillators. The proposal was approved and the Phase 1 award was made in March 2020.

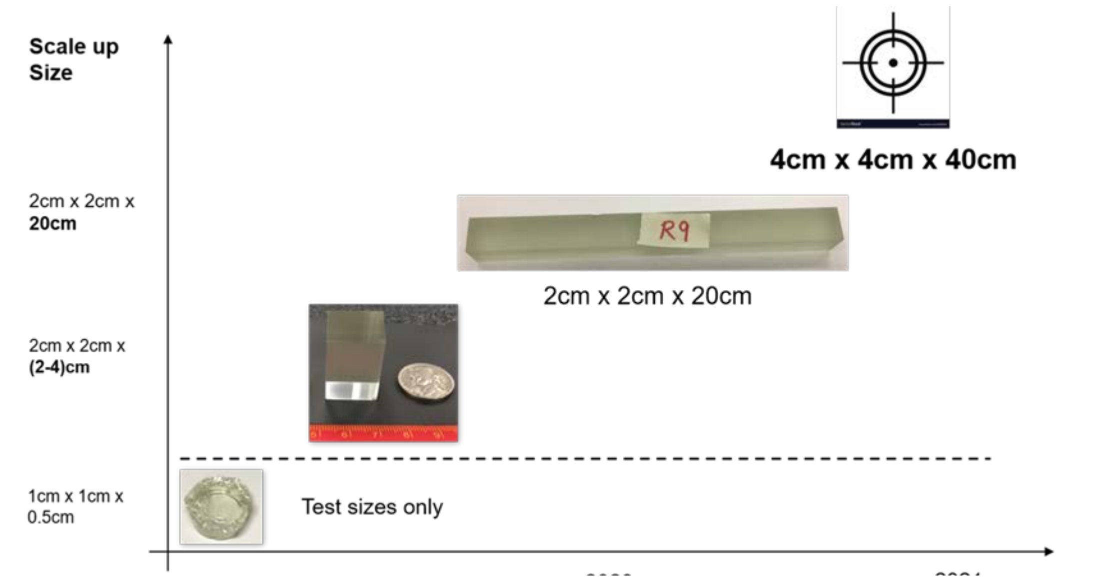

Fig. 1: *Illustration of glass scintillator scale-up progress. Several bars of ~10X_0 can be produced per week. The goal is to reach ~20X_0 by November 2021.*

3) EIC EMCal crystal/glass prototype beam tests

a. Prototype construction

We have prepared for our planned prototype beam test program. Before the Jlab shut-down we instrumented two 3x3 prototypes, one with SiPM and one with PMT to test and optimize the glass/crystal scintillator material and the readout chain. An illustration of the SiPM-based prototype is shown in Fig. 2. The housing is 3D printed and includes a custom 2-piece SiPM holder developed for this application. Silicone based glue is used for the frame, but SiPMs are not glued to the scintillator bar. SiPMs are soldered to the circuit board with SMA connectors. LEMO output is used at the detector patch panel. The SiPMs are Hamamatsu S13660 Multi-Pixel Photon Counters with effective photosensitive area of 6x6mm^2 and pixel pitch 25μm (57600 pixels) and 75μm (6400 pixels). Their performance was tested in the lab with cosmics and LED using bias and preamp boards, fADC250, and forming coincidences between two plastic scintillator pads. The results show clearly separated multi-photoelectron peaks with LED and a clear signal from cosmic muons. Initial results from cosmics data suggest ~50 photoelectrons for ~15 MeV energy deposit, or ~3.3 PE/MeV. Further studies are

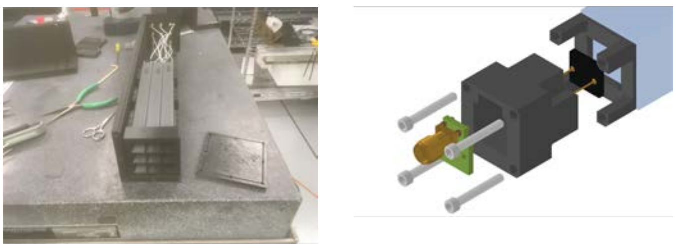

Fig. 2: *(left) SiPM-based prototype, (right) SiPM custom 2-piece holder concept.*

planned and will be performed when possible. The 3x3 prototypes are assembled and ready for beam tests.

b. Prototype streaming readout tests in the lab

We have tested the full prototype readout chain with streaming readout and Analyzer in the lab. For this the prototype was moved to the Jefferson Lab Facility for Innovation in Nuclear Data Readout and Analysis (INDRA) and connected to the INFN Waveboard (see Fig.3). The parameters (HV, gain, thresholds, etc.) were set to perform measurements with cosmic muons. In first quick tests, data were streamed to the host machine equipped with the TRIDAS software and data were successfully analyzed via the JANA-2+SRO plugin. These tests demonstrated that the streaming readout is mature for beam tests with the 3x3 prototype.

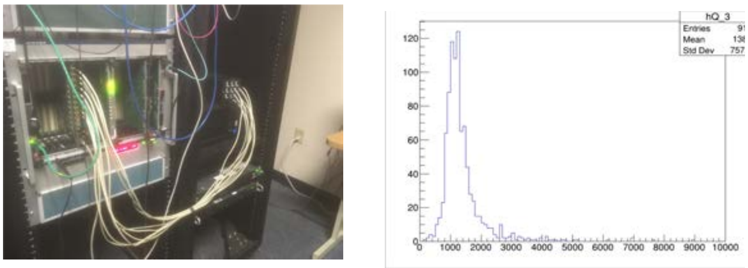

Fig.3: *(left) 3x3 prototype in the INDRA facility, (right) first signal from the full readout chain*

c. Prototype initial commissioning

The baseline performance with regular PMT readout was established with the PWO prototype before the lab shut down. The prototype was installed, as for our earlier tests, behind the Pair Spectrometer in Hall D at JLab, and was surveyed and aligned in place (see Fig. 4). The readout was accomplished in parasitic mode with the GlueX data stream. After standard calibrations an energy resolution of ~1.9% for ~4 GeV electrons was obtained for the baseline, consistent with our 2019 results of $\frac{\sigma_E}{E} \sim \frac{2.23\%}{\sqrt{E}} + 0.73\%$. Data remain to be the taken for the eight planned production configurations listed below.

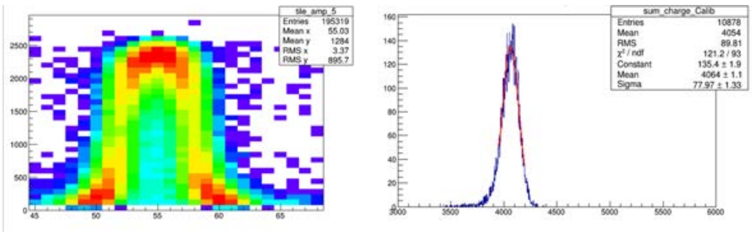

Fig. 4: *EMCal EIC prototype installed in Hall D*

4) EIC EMCal simulation studies

a. Resolution projections for glass bar length optimization

In synergy with the NPS project we performed energy resolution simulation studies for the prototype to understand energy leakage and optimize glass bar dimensions. The results are shown in Fig. 5. The simulation suggests an energy resolution of $\frac{\sigma_E}{E} = \frac{2.5\%}{\sqrt{E}} \oplus \frac{2.7\%}{E} \oplus 1.5\%$ comparable to $PbWO_4$. This projection for matching the high resolution of $PbWO_4$ assumes that 40-cm long glass bars with these properties will be available. For regions where the resolution requirements are less stringent shorter glass bars, e.g. ~25-30-cm long may be sufficient, which could be attractive for compact detector geometries.

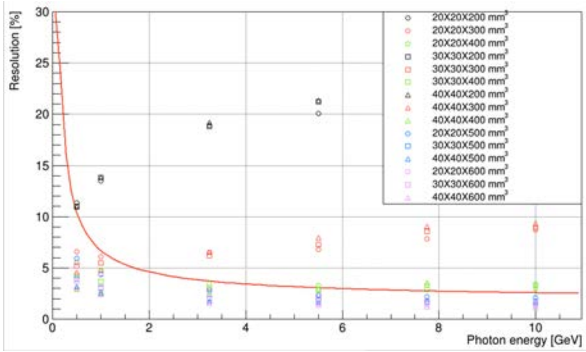

Fig. 5: projected *energy resolution of the EIC EMCal 3x3 prototype*

b. Optimization of crystal/glass configuration in electron endcap

To investigate the optimal configuration of crystal and glass in the electron endcap 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[2]. An illustration of the electron endcap model is shown in Fig. 6(left). The cyan area represents $PbWO_4$, the blue area the glass scintillator. In the detector simulation, the energy deposited in the crystals/glass by the incident particles is transformed into the corresponding signal in the following way: 1) In the sensitive detector volume a hit is defined by the energy deposited, time, and position; 2) The response of the active volume (crystal/glass) is determined in terms of number of photoelectrons; and 3) A root tree is filled and the figure of merit, the number of photoelectrons vs. incoming particle energy, is plotted. To obtain the energy resolution of the endcap a clustering algorithm based on that used for the Hall D BDX and Hall B forward tagger was implemented. Fig. 6(right) shows the results for an initial test configuration with incident electrons at angle 160˚, energies ranging from 0.1 to 15 GeV, threshold energy of 10 MeV, and SiPM readout with active area $1.2 \times 1.2 cm^2$ neglecting saturation effects. The energy resolution curve is consistent

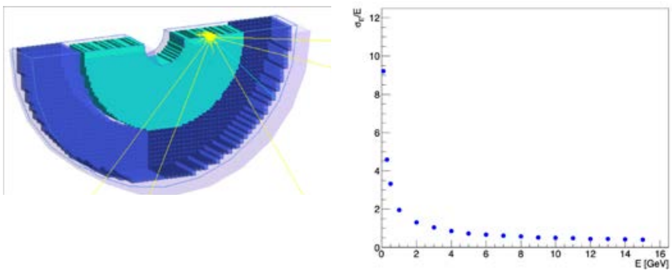

Fig. 6: *(l.) electron endcap EMCal with crystal (green) inner and glass (blue) outer part; (r.) first look at energy resolution for particles at fixed angle*

[2] The A.I. algorithm is based on that in Ref. E. Cisbani et al., JINST 15 (2020) P05009

with literature values. The A.I. algorithm being developed interfaces with this simulation and optimizes the input parameters for the figure of merit.

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 can't 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 ~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: delayed until radiation facility available again.
- 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 65% of our FY20 budget due to the pandemic related closing of facilities. We have spent FY20 funding mainly on getting started materials and equipment purchases, while universities and laboratories are closed.

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 working with vendors on crystal and glass production and to explore with Monte Carlo simulations the optimal configuration of glass and crystal scintillator in the electron endcap. The main focus for the FY21 EIC R&D will be on crystal/glass characterization and a prototype beam test program to establish glass performance and iterate formulation/fabrication as needed. A second focus will be on simulations in support of 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 and for possible improvement of resolution of the hadron calorimeter will be included as well.

1) **Long-term goals and milestones**
    a. **Glass/crystal for EIC EM calorimeters**

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 glass bars
- Further develop and commission readout software and simulations
- Commission a 3x3 glass/crystal 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 fibre on resolution
- Demonstrate a ~20X_0 glass bar and prepare for larger scale production (see section 2 for details)
- Submit the SBIR/STTR Phase 2 proposal in December 2020

The estimated timeline is shown in Table 1. Receiving the SBIR/STTR Phase 2 funding is particularly important towards reaching this long-term goal.

Table 1: *Estimated timeline for glass development*

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														■	
Software	Prototype	■	■	■	■	■	■									
	Design options				■	■	■	■	■							
	Cost/performance optimization					■	■	■	■	■	■	■	■			
Prototype	Base version	■														
	Initial commissioning		■	■	■	■										
	Upgrade and commissioning							■	■	■						
Beam test	Beam test		■		■		■				■	■				
	Data analysis	■	■	■	■	■	■	■	■	■	■	■	■	■	■	

b. Expression of Interest to construct the Electron Endcap calorimeter

Another long-term goal is to construct the electron endcap EM calorimeter (crystal/glass). To achieve this goal, we have started discussions and assembling a team to submit an Expression of Interest. The team would consist of CUA, MIT, U. of Kentucky, Lehigh U., and pending final negotiations our collaborating institutions from Armenia, France, and Italy 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. The milestones towards reaching this long-term goal are:

- submit the Expression of Interest by November 2020
- explore options for research instrumentation funding, e.g. NSF MSRI
- submit an EIC detector proposal following the EoI in 2021.

2) Fabrication of glass scintillator bars ~10-20 X_0

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 centimeters up to 2 cm x

2 cm x 20 cm polished bars. We plan to extend this to (2-4) cm x (2-4) cm x 40 cm bars. Throughout this 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.

3) Prototype Beam Test

The 3x3 baseline prototype instrumented with 9 $PbWO_4$ crystals and PMT readout is presently still installed and aligned in Hall D, and could take data 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.

4) Optimization of crystal/glass configuration in endcaps and barrel

As discussed in the section above, we have started setting up a Monte Carlo simulation for resolution studies and matching crystal and glass materials in the electron endcap EMCal. Next steps will include further simulation development including optimization studies for physics processes of interest and developing a custom AI-framework which allows to distribute multiple simulations and combine them with bayesian optimization and machine/deep learning for the regression part. This highly parallelized AI-driven approach is able to build a model from the exploration of the calorimeter parameter space and determine the global optimum design.

We plan to extend our evaluation of glass scintillator as active material to additional regions, e.g., the barrel and hadron side. For the barrel region, segmentation and possible readout, e.g. through fibres, will be investigated. For the hadron side, an optimized glass scintillator that might provide improved jet energy resolution will be investigated. The jet energy in the combined EMCal+HCal calorimeter could have contributions from components of EM, charged hadrons and neutral particles like neutrons/K_L etc. The electromagnetic shower component in the HCAL section could be due to charge exchange of $\pi^+ n \rightarrow \pi^0 p$, for example. Fluctuations in the fractions of these components are the major concern for jet energy resolution. Balances of detector responses for these components can help optimize the jet energy resolution. A direct measurement of the electromagnetic fluctuations on an event-by-event basis has the potential to do that. Scintillating glass with good EM energy resolution and a well-tuned scintillation/Cherenkov ratio has advantages to provide this measurement. In collaboration with Scintilex, LLC we plan to develop an optimized glass composition and to submit an SBIR/STTR Phase 1 proposal.

5) Crystal characterization

Over the next six months we hope to have received at least ~180 additional CRYTUR and ~400 additional SICCAS crystals[3]. A total of 900 CRYTUR and ~1300 SICCAS crystals are anticipated to be characterized by the end of FY21. To establish adequate quality assurance, in particular at SICCAS, we plan to continue to have frequent meetings with the vendors and provide feedback based on our measurements.

What are critical issues?

For glass scintillator fabrication the main issues are scale-up, possible further formulation/fabrication optimization, and evaluation of glass in different configurations with suitable readout, and different regions of the detector. 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. Prototype tests for both crystals and glass scintillator are essential for understanding and optimizing the actual performance for the EIC detector. 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.

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[3] CRYTUR's nominal production rate is 30 blocks/month, but the vendor expects to be able to deliver 40 blocks/month for most of calendar year 2020.

Additional information:

Budget

The request for FY 21 and carry-over from FY20 are shown in Table 2. Some of the categories, e.g. materials and equipment for CUA and travel for CUA and IPN-Orsay, can be funded from FY20 carry-over and no additional funds are requested. However, due to a 30-40% cut in the FY20 budget additional funds are required to carry out the FY21 prototype beam tests. The FY21 request thus includes technical support and some additional material and equipment for the prototype beam tests and glass characterization, e.g. the facilities at IPN-Orsay, as well as technical and student support for the glass characterization and EIC EM calorimeter simulation studies to optimize crystal/glass configurations, investigate reflector choices, and the impact of mechanical structure to hold the glass/crystal blocks in place on resolution and optical properties. The impact of material in front of the EM calorimeters on resolution could be addressed as well.

	Full FY21 Request	**20% cut**	**40% cut**	**FY20 Carryover**
CUA/VSL/Scintilex	**27,413**	**21,930**	**16,448**	**36,430**
Technical Support for glass prototype	15,000	12,000	9,000	4,237
Fringe	3,563	2,850	2,138	2,312
Materials	0	0	0	8,675
Equipment	0	0	0	11,524
Travel	0	0	0	4,292
IDC	8,850	7,080	5,310	5,389
IPN-Orsay	**20,000**	**16,000**	**12,000**	**4,400**
Student Support	7,000	3,600	0	0
Materials	1,000	1,000	1,200	300
Equipment	9,000	9,000	9,000	1,500
Travel	0	0	0	2,000
IDC	3,000	2,400	1,800	600
INFN-GE	**20,000**	**16,000**	**12,000**	**6,766**
Materials	2,000	1,600	1,200	
Equipment	7,000	5,600	4,200	45
Travel	9,000	7,200	5,400	4,227
IDC	2,000	1,600	1,200	2,494
MIT	**7,200**	**5,760**	**4,320**	**0**
Materials	7,200	5,760	4,320	0
TOTAL	**74,613**	**59,690**	**44,768**	**47,596**

Table 2: *Budget request*

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.

Manpower

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

CUA/Scintilex: S. Ali (graduate student), V. Berdnikov (postdoc), J. Crafts, T. Horn, 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, 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, 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*., Nucl. Inst. Meth. A**956** (2020) 163375

Sub Project 3: 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?

Our main objective for the past 6 months was to test the first set of prototype W/Shashlik modules that were built at UTFSM and sent to BNL at the end of last year. A total of 9 modules were sent to BNL, that last of which arrived in December 2019. In January, the modules were assembled into a 3x3 array as shown in Fig. 1 on the left, and an enclosure was constructed to support the modules and readout electronics which is shown on the right. Together they form a complete prototype detector assembly that can be tested in the beam.

Fig. 1. Left: 3x3 array of W/Cu shashlik constructed in UTFSM and sent to BNL for testing. Right: Enclosure for module array and front end readout electronics for testing the modules in the beam.

Our plan was to test the prototype detector in the lab during February and March and then take it to the test beam at Fermilab at the end of April. Unfortunately, BNL was shut down due to COVID-19 on March 23rd and we were not able to continue these tests. In addition, Fermilab was also shut down at around the same time and all test beams scheduled for this fiscal year were cancelled. There has therefore been no further work on the prototype detector since the middle of March.

We also planned to continue our studies on the light collection within the tiles using the TracePro ray tracing program, and to do simulations of the overall shashlik design using GEANT.

What was achieved?

The nine modules were assembled into a 3x3 array and mounted inside the enclosure along with the front end readout electronics. The front end electronics is a reconfiguration of the sPHENIX calorimeter electronics which is then connected to the sPHENIX calorimeter digitizer system. Figure 2 on the left shows the LED spectra for the nine modules using the internal LED pulser system. The plot on the right shows the pulse height spectra for cosmic rays passing transversely through the modules which exhibit clear Landau peaks corresponding to an energy deposit of E_{dep} ~ 40 MeV.

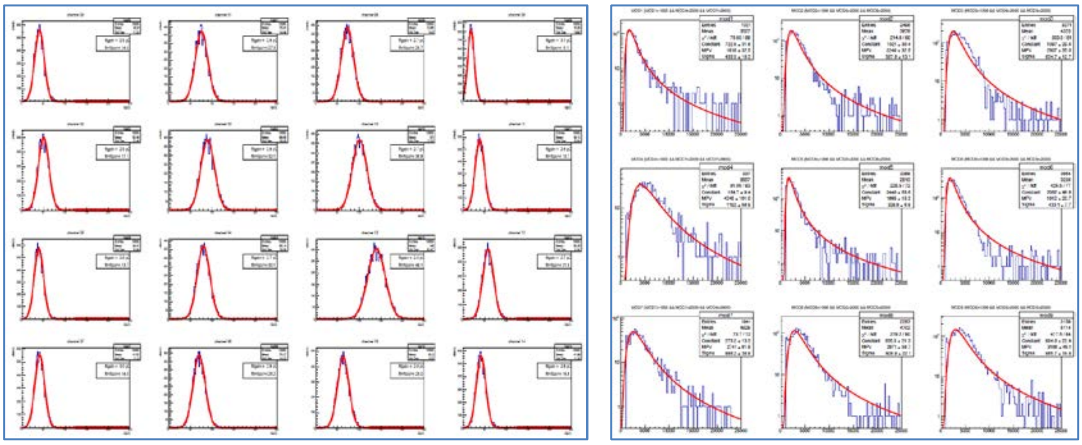

Fig. 2. Left: LED spectra from the internal LED pulser system. Right: Cosmic ray spectra for particles passing transversely through the nine modules (3.8 cm path length, E_{dep} ~ 40 MeV).

It should be noted that the modules that were constructed at UTFSM were originally designed to be tested for use in NA64 at CERN. They consist of 1.5 mm 80W/20Cu absorber plates and 1.63 mm injection molded plastic scintillator tiles with 1 mm wavelength shifting fibers passing down the length. Each module has 80 absorber plates and 79 scintillating tiles and has a total length of 27 cm (29.5 X0). This gives a sampling of ~ 0.37 X0 per layer and should give an energy resolution ~ 8-10%/√E. This is in the range of what would be required for EIC, but the modules contained other features that were not optimized for EIC applications. The WLS fibers form a spiral pattern as they pass through the module, which was a feature that was designed especially for NA64 to minimize shower leakage down the holes for the fibers but would not be necessary at EIC. The blocks were also individually wrapped with a black wrapping material, which optically isolated each module and made them easier to test individually, but the wrapping would increase the effect of the boundaries between the modules when studying the uniformity of response of the detector as a whole. Our plan was to unwrap all the modules mount them together in a close packed arrangement in order to minimize these gaps, but we were not able to complete this assembly due to the COVID-19 shutdown.

In mid February, just before the COVID-19 shutdown, one of us (C.Woody) visited Santiago and had a meeting with our Chilean collaborators. The meeting was held at Andres Bello University in Santiago were most of the team from UTFSM has now relocated. We discussed our plans for testing the 3x3 module prototype detector as well as future plans for designing and building a new prototype that would be better optimized to study the performance of a W/Shashlik detector at EIC.

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

We were not able to do any further testing of the 3x3 module prototype detector after BNL was shut down on March 23rd. However, the tests done prior to that time were very encouraging with each module showing nice cosmic ray spectra with well resolved Landau peaks. The next step would have been to unwrap all the modules and reassemble the array in a close packed arrangement with minimum gaps between the modules and repeat the cosmic ray tests. We would have then taken the detector to the test beam at Fermilab and measured its energy response to electrons and hadrons. We would have also attempted to measure the position dependence of the energy response across the detector. However, since the transverse size of each module is 3.8 cm x 3.8 cm and the Moliere radius is ~ 2.5 cm, and it is only a 3x3 array, our ability to study the position dependence within such a small detector would have been a very limited due to the effects of side leakage.

Assuming Fermilab reopens its test beam facility in 2021, we plan to reschedule our test of the 3x3 module array in the spring of next year. However, we also appreciate the limitations of what we can learn from this test in terms of measuring the uniformity of the shashlik configuration. We therefore plan to design and build a new, larger shashlik prototype in 2021 which will not only have larger dimensions and therefore better containment of the showers, but will also be better optimized to match the requirements of a future EIC detector. The design and construction of this larger prototype detector specifically designed for EIC will be the main focus of our future activities as described below.

We did not make any progress on our simulations, neither with GEANT for the overall shashlik detector, nor with TracePro for the light collection, due to lack of manpower. However, we have now identified a senior graduate student from MIT (Zhaozhong Shi) who has just started working with us on the GEANT simulation and plans to continue with these studies during the coming year. He also plans to come to BNL as soon as the lab will allow visitors again (hopefully sometime in the early fall) and spend the remainder of his time at BNL working on simulations as well as working with the hardware. He would also participate in the beam test at Fermilab in the spring of next year. A portion of our funding request for next year will include some support for him while he is at BNL and for him to participate in the test beam.

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

As described above, all testing of our 3x3 prototype detector stopped in mid March of 2020 due to the closure of BNL. We were also not able to carry out the beam test of the prototype we had planned in 2020 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 $52,500 in new funding in FY20 for R&D on the shashlik calorimeter. As of June 1st we have spent a total of $29,729 (including overhead) in FY20 on expenses which included travel (attendance of the SCINT 2019 conference to give a talk on calorimetry for EIC), purchase of materials, equipment and software licenses. This also included ~$7K for new 6x6 mm^2 SiPMs to study increasing the photocathode area coverage of the sPHENIX W/SciFi modules. The remainder of approximately $23K (~ $15K after overhead) would have been spent on the beam test at Fermilab and should be available to be carried over into FY21.

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

No. At this time we are not supporting any personnel on our R&D funds that need to be paid during the 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?

For the next funding cycle, we plan to continue testing our 3x3 prototype module in the lab and study it using cosmic rays and the internal LED pulser system. We will then unwrap the modules and reassemble them in a close packed arrangement in order to minimize the gaps between them. We will take the reassembled prototype to Fermilab and test it in the beam with electrons and hardons over an energy range from ~ 1 GeV - 20 GeV. We will also perform a limited study on the position dependence of the energy response of the 9 modules in the 3x3 array. All of these studies have been in our original plan.

As mentioned above, the nine modules we currently have were originally designed for NA64 and are not optimized for EIC applications, nor is the 3x3 array large enough to do a systematic study of the uniformity of the energy response. We have therefore started to design a new larger prototype detector that will be more optimized to study the performance of a shashlik calorimeter at EIC. This is a new activity that was not in our original plan, but it will advance the conceptual design of a shashlik calorimeter for EIC for the next phase of R&D that will focus more on specific detector applications. As has been discussed in the preparation of the EIC Yellow Report, a shashik calorimeter with an energy resolution ~ 10-12%/√E is being considered for the barrel and forward endcap detectors, and a shashlik with an energy resolution ~ 7-8%/√E is being considered for the intermediate rapidity region of the backward endcap detector.

The new prototype would have overall dimensions of approximately 24 cm x 24 cm and an overall length ~ 20 X0. Mechanically, it would consist of four individual modules that would be made up of a stack of 12 cm x 12 cm absorber plates and scintillating tiles. The larger module size would reduce the number of boundaries between the modules compared with the current prototype and also reduce the time and labor required for assembly. Since each WLS fiber is read out individually, there are no physical “towers” in this configuration, but one can think of each module as effectively having 4 x 4 towers that are 3 cm x 3 cm each (which is slightly larger than the Moliere radius of ~ 2.5 cm). Note that this would be a factor of 4 larger in terms of towers than the sPHENIX W/SciFi modules which have 2 x 2 towers each.

The four larger modules would be arranged in a close packed configuration next to one another in order to minimize the gaps. This would then form a detector with effectively 8 x 8 towers which would be sufficient to map out the uniformity of response over several module boundaries without significant effects of side leakage.

For the absorber plates, we are considering using either 80W/20Cu as in our current prototype, or possibly tungsten carbide (WC). In either case, they would have a thickness ~ 1.5 – 2.0 mm (~0.4 X0). Based on preliminary inquiries from several vendors, both types of plates are available in the size and thickness we require and both can be supplied with or without holes. We are also investigating the cost and availability of new scintillating tiles that would be produced in Russia by the same supplier (Uniplast) that supplied the tiles for our current prototype. These tiles would likely be produced by extrusion and would have a thickness ~ 2 mm. We would use the same type of WLS fibers as in our current prototype and arrange them in pattern that would optimize the uniformity of light collection within a module. With an effective tower size of 3x3 cm^2 this would result in ~ 7.5 mm grid spacing. However, we plan to study the light collection and optimize the spacing of the WLS fibers using TracePro along with measurements performed in the lab. Each WLS fibers would be read out with small SiPMs (e.g., Hamamastu S14160-1315s, which are 1.3 x 1.3 mm^2 and have 15 μm pixels) which would reduce the cost of the photosensors but still provide sufficient photocathode area and number of pixels for good linearity. An initial cost estimate for the new prototype is given in our budget request.

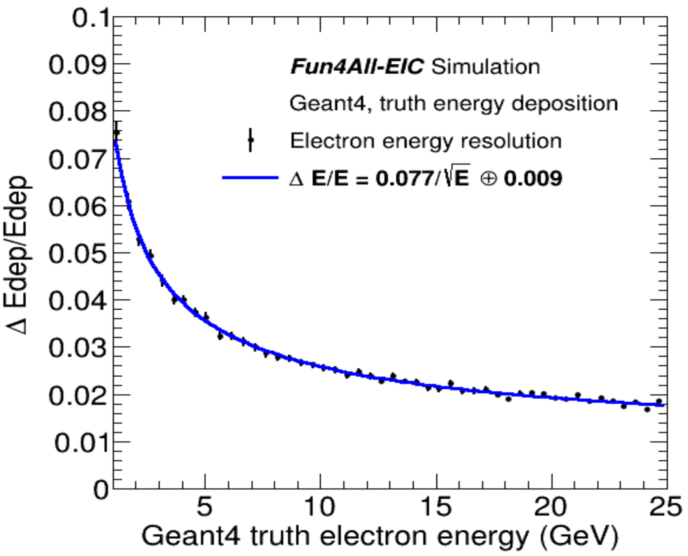

Fig. 3. GEANT simulation of a W/Shashlik calorimeter with 80W/20Cu absorber plates with the same fraction and sampling frequency as our current 3x3 prototype.

We have also started to carry out simulations of the new prototype design using GEANT. These studies have just begun using some of the simulation framework for the upgrade of the sPHENIX detector for EIC. Figure 3 shows a simulation of a W/Scintillator shashlik calorimeter with 80W/20Cu absorber plates that has the same sampling fraction and sampling frequency as our current 3x3 prototype (0.37 X0 per layer). It does not include any effects due to light collection or module boundaries, but it shows that based on the deposited energy, the expected resolution should be ~ 8%/√E. Using this simulation framework, we will be able to simulate various other shashlik configurations, as well as look at a number of physics parameters such as electron/hadron rejection, gamma/pizero separation etc.

We plan to design and build this new prototype detector in FY21. However, given the current slowdown, we believe that it may take until sometime in the early fall to complete the design and order all the materials. Therefore, it may not be possible to begin the construction of the new prototype until late 2020. We hope that we can then complete the construction in early 2021 and have it ready for the beam test in the spring. However, this will depend on when personnel can get back into the lab at BNL and the availability of manpower for the construction of the new prototype and preliminary testing of both the new and old prototypes.

What are the critical issues ?

Our most critical issue at the present time is to be able to resume our R&D activities on site at BNL. The current shutdown has prevented making any further progress on testing our existing prototype or carrying out any other tests in our lab. We hope to be allowed to have some access to the BNL site starting in July or August, and hopefully full access by early fall.

Our second most critical issue is still the lack of manpower. We have gotten excellent support from UTFSM group in terms of building the current prototype modules and from the sPHENIX group in terms of providing the readout electronics and test facilities at BNL, but we have no dedicated personnel working on this project at BNL at the present time. All of the sPHENIX physicists, engineers and technicians are now extremely busy with the construction of the actual sPHENIX detectors and we expect that they will be under even more pressure to make up lost time in the construction schedule once BNL is reopened and work on the EMCAL and HCAL can resume. We also note that we do not have the manpower or sufficient funds to carry out a beam test at Fermilab on our own. Any test we do would have to be coordinated with other tests at the FTFB (such as with other groups testing detectors for EIC) which would provide all the necessary infrastructure (readout electronics, DAQ, etc) in order for us to carry out our tests of the shashlik prototype(s).

However, on a positive note, we have identified a graduate student who has now started to work on this project as part of his Ph.D. thesis and we hope that he can continue on this during the next year. He is currently starting to do the GEANT simulations for the new prototype design, which we expect will continue over the summer months, after which he will come to BNL and begin to also work on the hardware. We feel that this will be an extremely important addition and huge benefit to our overall effort on this project.

Additional information:

As stated in our previous report, we are studying ways to improve the light collection of the sPHENIX W/SciFi modules in order to improve the calorimeter's energy resolution (both in the statistical term as well as the constant term). This is partly because we expect that the SiPMs for the sPHENIX EMCAL will need to be replaced after 3 years of running with heavy ions, and that it would be advantageous to try and improve the calorimeter's performance at that time in order that it can continue to be used at EIC. However, this study is also relevant for any future new W/SciFi calorimeter that may be built for EIC.

As presented at the last Detector R&D Committee Meeting, we are investigating two ways to improve the light collection for the sPHENIX W/SciFi modules, both of which involve increasing the photocathode area coverage of the readout end of the absorber blocks. The first would be to remove the SiPM daughter cards from the existing modules which contain a 2x2 array of 3x3 mm^2 SiPMs and replace them with four 6x6 mm^2 SiPMs. This would require no modification of the existing light guides and could easily be accomplished without the risk of damaging the modules. The second approach would be to cut down the existing light guides, leaving only a short (~ 2 mm long) piece that would remain attached to the module, and then cover the entire exposed area with a 6x6 array of 6x6 mm^2 SiPMs. This would provide much more photocathode area coverage (and hence more photostatistics) as well as better uniformity of light collection. However, this would require cutting down the light guides while they are attached to the modules inside the sectors. Preliminary discussions with our senior technician (Bill Lenz) indicate that this may be possible using a special wire cutting tool, but we would need to investigate this further and conduct further tests to determine if this would actually be possible.

In order to investigate both possibilities, we ordered 120 6x6 mm^2 SiPMs from Hamamatsu (S13360-6050VE) which will allow us to test both options. These SiPMs are the new state of the art SiPMs from Hamamatsu, which uses through-silicon via (TSV) technology that will provide the greatest amount of photocathode coverage with minimal dead areas. These SiPMs were delivered to BNL in mid March and we are now waiting to be able to return to the lab in order to carry out these tests.

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 group that was formerly at UTFSM in Valpariso, Chile has now moved to Andres Bello University in Santiago Chile. It consists of the Group Leader (Prof. Sergey Kuleshov), an Assistant Professor (Pablo Ulloa) and a mechanical engineer (Matias Liz Vargaz).

- Technical work at UTSFM was carried out with approximately 10% of an FTE. The total amount of effort was limited by internal funding at UTSFM.
- Further work at Andres Bello will be continued by the group mentioned above at approximately the same level (~ 10% of an FTE).
- There technical effort on this project at BNL is approximately 10% of an FTE. The group includes several scientists, one Electronic Engineer, one Physics Associate and several technicians, all of which spend only a very limited amount of time on this project due to their commitments on sPHENIX.

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 effort on this project at UTSFM was provided by internal funding at UTFSM
- All effort on this project at Andres Bello is being provided by internal funding at Andres Bello and is not supported through any of these R&D funds.
- 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.

Publications

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

"A Comparison of the Effects of Neutron and Gamma Radiation in Silicon Photomultipliers", B.Biro et.al., paper accepted for publication in the IEEE Trans. Nucl. Sci. (published May 2019)

Budget

Our main funding request for FY21 is for the construction of the new larger W/Shashlik prototype and for the support of a new graduate student to work on this project. Funds for the beam test at Fermilab are carried over from last year. However, these funds are not sufficient to carry out a stand alone test of one or both prototypes. Our beam test will have to be coordinated with other groups testing EIC detectors a Fermilab in order to share various infrastructure and costs.

The table below gives Money Matrix for full funding, a 20% reduction and 40% reduction in the amount requested for FY21.

Budget Request

eRD1 BNL Funding Request (FY21) - Amounts shown in $K				
	Full Funding	**20% Cut**	**40% cut**	**Carryover from FY20 funding**
New Prototype Shashlik Calorimeter (Four 12 x 12 cm^2 modules)				
Absorber plates with holes (60 per module)	26	26	26	
Scintillating tiles with holes (60 per module)	2	2	2	
WLS fibers (64 per module)	2	2	2	
SiPMs (64 per module)	5	5	5	
Mechanics	5	5		
Technical support at BNL (technicians, designer)	10	2	1	
Support for graduate student	10	6		
Test Beam (in collaboration with other EIC detector tests)				15
Total	**60**	**48**	**36**	**15**
Overhead	30	24	18	7.5
Total with Overhead	**90**	**72**	**54**	**22.5**