Date: 1/4/19

EIC Detector R&D Progress Report

Project ID: eRD1
Project Name: EIC Calorimeter Development
Period Reported: from 7/1/18 to 12/31/18
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Abstract & Summary

This report summarizes the activities of the eRD1 Calorimeter Consortium during the period from July 1, 2018 – December 31, 2018. These activites are divided into four Sub-Projects: R&D on Tungsten Powder Calorimetry at UCLA, Tungsten Scintillating Fiber Calorimeter Developments in sPHENIX, R&D on a Tungsten Shashlik Calorimeter for EIC and R&D on Homogeneous Calorimeter Development for EIC using Crystals and Glasses.

R&D on tungsten powder scintillating fiber calorimetry has been a part of the eRD1 program for many years. The design was originally developed at UCLA and has focused on the development of an electromagnetic calorimeter for the central and/or mid rapidity region at EIC. This technology was adopted for the sPHENIX central electromagnetic calorimeter and is currently in an advanced stage of preproduction prototying. We provide a status report to the Committee on the progress in sPHENIX related to building this detector, but we request no funding or support for this effort. In its last report, the Committee stated that while sPHENIX can accept a loss in resolution due to non-uniformities in the response of the calorimeter modules, a new EIC using this technology should not. Our response to this and other comments is given in the sPHENIX section of this report.

The Committee also requested that we provide a radiation map for a reference detector at EIC. Such a map was already provided to the Commitee in our report from January 2016 (see Fig. 1.4 in that report). This map gives the flux of neutrons for the BeAST detector for 20 x 250 ep collisions. Some preliminary results have also been obtained for the expected ionizing radiation dose and will be included in a future report.

The Committee also encouraged the Consortium to continue its studies on radiation damage in SiPMs. The report from the UCLA group includes important new results on this topic. We also submitted a paper on the comparion of radiation damage due to neutrons and gamma rays for publication which is now in its second stage of review and contains additional information on this subject.

The Committe also requested that the Consortium carry out a simulation to study the timing properties of showers produced in a hadronic calorimeter. These simulations have begun and are reported on in the first section of this report.

The Committee recommended that the Consortium pursue the development of a tungsten shashlik calorimeter for EIC. With the Committee's endorsement, this project has now moved forward at a much higher pace and progress on this effort is reported on in Section 3 of this report. It also recommended studying the currently decommissioned sPHENIX shashlik calorimeter modules to compare with the tungsten shashlik modules. This effort has not started yet but will be part of our future plans.

The Committee recommended that the Consortium have an active participation with the various vendors supplying crystals for our R&D effort on crystals. We believe we do have such an active involvement and participation, and these activities are reported on in Section 4 of this report. The Committee also recommended that a detailed chemical analysis be performed to try and understand the relationship between various impurities and the transmission and radiation hardness of the crystals. An analysis of the CRYTUR raw material was performed and the results are given in Section 4. Finally, the Committee asked for a plan for a beam test of a suitable sample of PWO crystals, and an actual beam test was performed using a set of 144 crystals obtained for the NPS experiment. These results are also reoprted on in Section 4.

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

What was planned for this period?

We planned to continue studies of effects of radiation damages of SiPMs and to investigate space-time evolution of hadron showers in a small prototype for the outgoing hadron endcap calorimeter through Monte Carlo simulations in anticipation of possible beam test run in the future.

What was achieved?

We have achieved a reasonably comprehensive understanding of effects of radiation damages of SiPMs observed during 500 GeV pp Run17 at RHIC at STAR IP. A localized heating of thin avalanche region of SiPMs associated with increased dark current due to exposure leads to shift in breakdown voltage, which in turn leads to decrease in response to incident light. These have been observed for all exposed sensors. Based on our observations, we know how to optimize operation settings for SiPMs for given experimental conditions and what parameters of sensors need to be improved by manufacturers to make them better suited for EIC calorimeters in future.

We started with large sample of fully characterised SiPMs, which was placed at STAR IP for exposure during isobar Run18. Unfortunately, exposure level was very low. Leakage current during exposure in Run 18 grow to ~5 uA, compare to ~ 100uA during previous 500 GeV pp Run 17. This sample of sensors was characterised again during summer 2018, no degradation in response was observed for such low levels of exposures, unlike previous high exposure results reported to the committee in Jan. 2018 meeting.

Two new undergraduate students supervised by one of our graduate student worked during summer 2018 to understand mechanism of degradation in response of SiPMs observed during Run 17. Although many groups have been looking at radiation hardness of SiPMs the cause of deterioration of response with exposure was not fully understood. We were unsuccessful to find explanation in literature. It is believed that at levels of exposure seen in Run 17 effects related to changes in dopants should be irrelevant. There were no indications that ~ 10% of individual pixels may be permanently damaged with exposure (no reports in literature on that). Also observation of successful annealing of defects at elevated temperatures and restoration of initial parameters of SiPMs suggests that individual pixels do not get damaged.

Given strong dependence of breakdown voltage (Vbd) on temperature, in particular, for HPK SiPMs used in Run 17 we argue that some sort of localized heating at elevated dark current might be a cause of shift in Vbd reported to committee in Jan. 2017.

To verify this hypothesis we tune our experimental setup/procedures for fast measurements of Vbd from I-V scans. Fit ranges to extract Vbd from I-V curves and experimental procedures were verified on un-exposed sensors with results for Vbd derived from I-V scans crosschecked against traditional single pixels response vs bias method as was reported earlier. Then, a method to test localized heating hypothesis was rather simple. A SiPM initially illuminated with constant LED source for five minutes (heating cycle), intensity of the LED during this cycle was set to mimic constant dark current seen in experiment. Then with a dimmed light source series of fifteen consecutive I-V scans were taken for five minutes, during this period initially heated avalanche region was being cooled down to ambient temperature. Knowing temperature dependence of Vbd (measured and reported earlier) one can directly measure changes of temperature of an avalanche region of a SiPM with time. The ambient temperature during experiment kept constant. To our knowledge, there are no direct method to measure temperature at avalanche region of SiPMs.

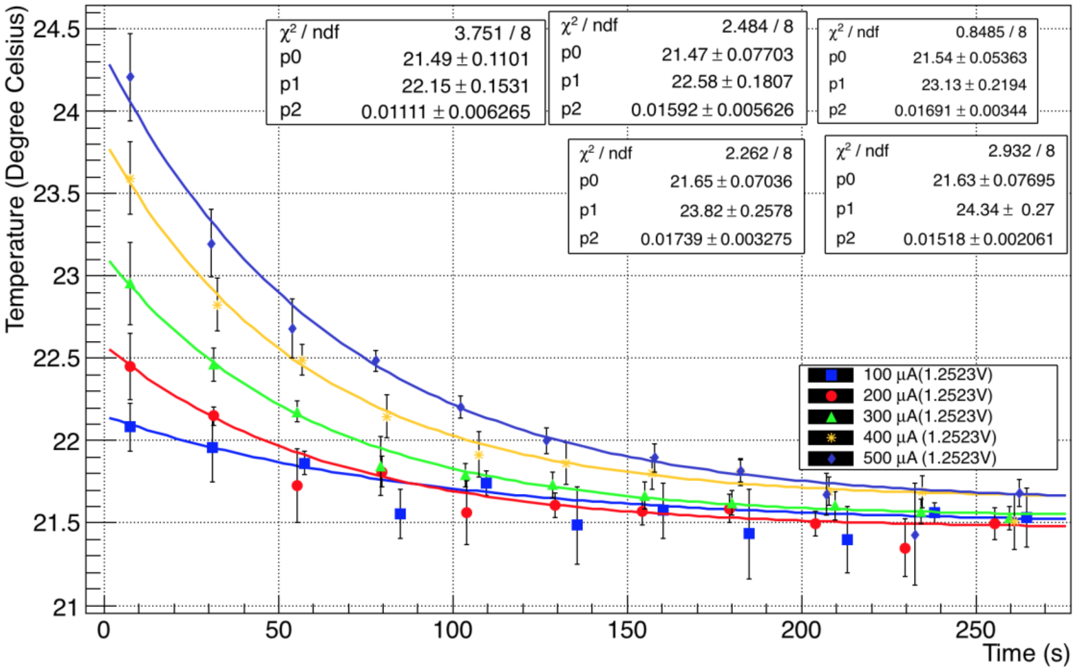

Figure-1. Temperature of avalanche layer of SiPM vs time for different initial conditions. Fitted with Newton's cooling law.

Figure 1 shows results of measurement of temperature of avalanche region of SiPM 'heated' by LED to a different initial conditions vs time of cool down. For Run 17 dark current reached ~ 100 uA during exposure at STAR IP. This corresponds to the lowest curve in Fig 1, which shows that temperature on junction is ~0.6 degrees C above ambient at t=0 (time when LED was dimmed for IV scans). The corresponding Vbd at that time was higher by about 40 mV, compere to Vbd at 21.6 degrees C (ambient temperature).

Another approach is to measure changes in response to dimmed laser light following by initial heating with LED. For this measurement, we used different set of equipment compare to the setup used for I-V scans mentioned above. Results are shown in Figure 2. As expected, in this case we see reverse dependence. As it was shown in our previous Jan 2018 report degradation of response was ~ 10% for exposed sensors having leakage current ~ 100 uA, which is in a good agreement with results shown in Figure 2 (blue markers, 10% drop at t=0, time when LED turned Off).

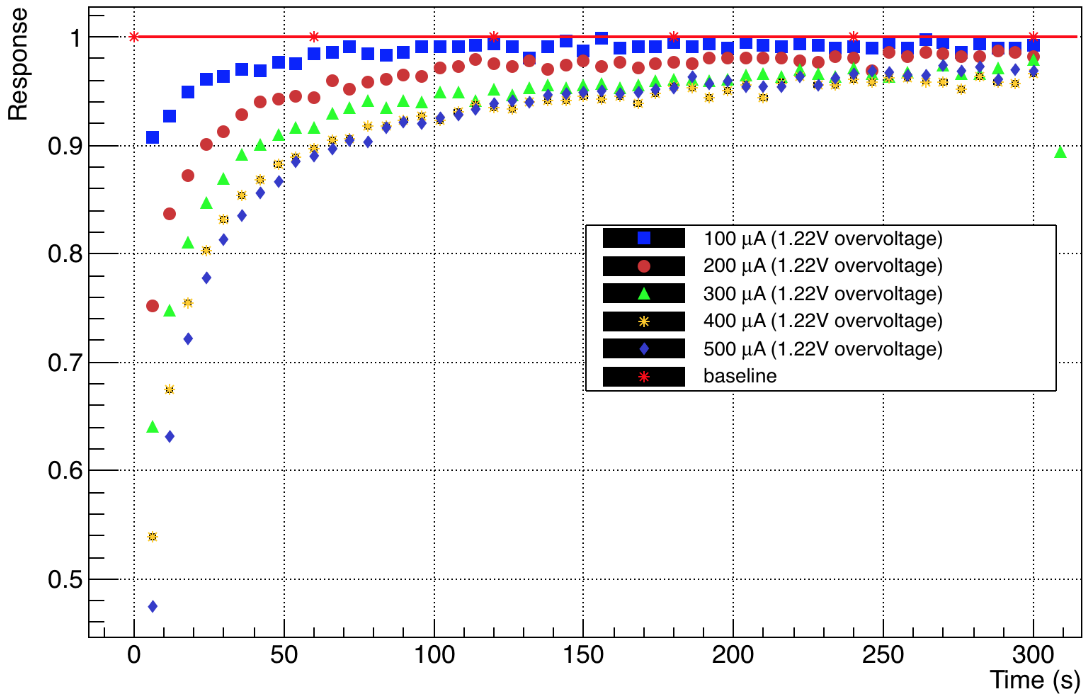

Figure -2. Response vs time of cool down for different initial conditions.

In the forward rapidity region (~ 2.5 < η < 4) SiPMs will degrade differently, due to differences in neutron fluxes, as predicted by MC, and observed during Run 17. Even at modest leakage currents of about ~ 18 uA, degradation will be approximately 1.5% as shown in Figure 3. These results again in very good agreement with measurement of exposed sensors we reported earlier.

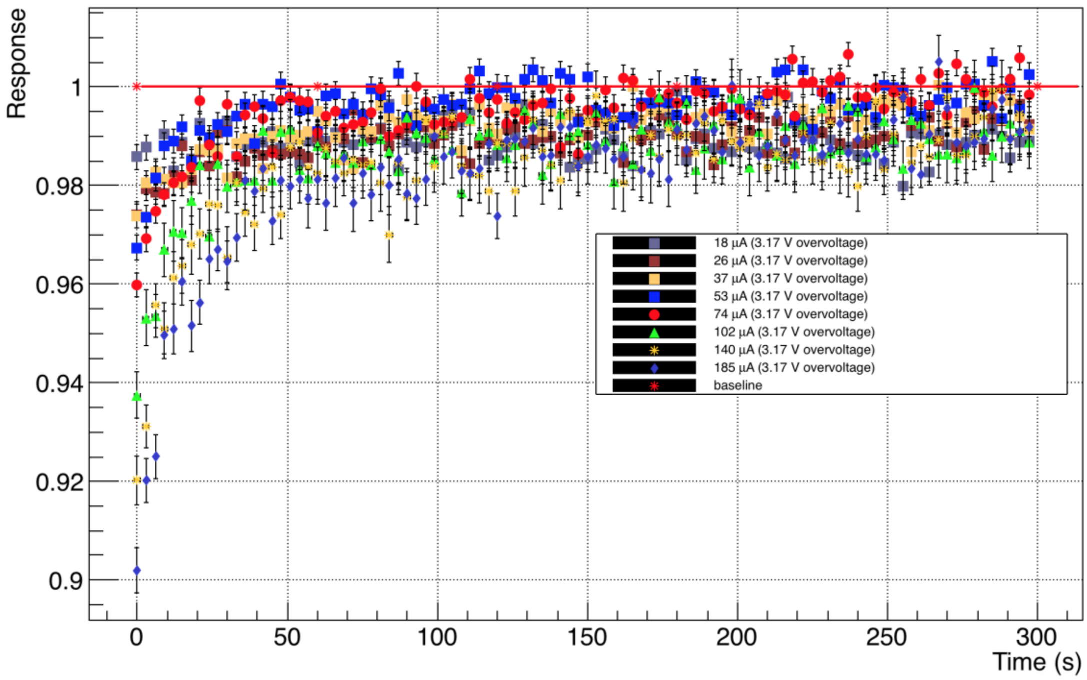

Figure -3. Range of degradation of S12572-025P SiPMs at forward rapidity at STAR (EIC).

A differential degradation of SiPMs (SiPMs located at same location, i.e. exposed to same level, but degraded differently), may be explained by different overvoltage (difference ~0.5V) required to achieve same response to incident light. GlueX, for example, measured this, with a large sample of SiPMs. Thus, amount of heat generated at avalanche region for different SiPMs having same leakage current will be different.

To summarize, localized heating of thin (~ 5um) avalanche region of SiPMs due to current flowing through junction leads to shift in Vbd and a drop in response to incident light. The effect depends on magnitude of the current. Thus, it is desirable to keep this current low. It can be achieved by active cooling of SiPMs, choosing SiPMs with lower gain, or sensors with small T dependence, which vary for different manufactures. The currently T dependence is in the range ~20-60 mV/C.

Two other things worth note, temperature compensation in SiPM bias circuitry, which is commonly implemented in many SiPM applications, is insensitive to variations of local temperature in avalanche region due to current flowing through SiPM. Monitoring of SiPM changes during experiment has to be done with the current flowing through SiPM similar to one during data taking (which may change from fill-to-fill and even during one fill due to drop in luminosity, as it is at RHIC now).

We obtain pre-production samples of new HPK SiPMs early summer and characterized these sensors. They have much lower operation voltage and better temperature dependence compare to HPK sensors we used in Run17 (~ 35mV/C compare to 60 mV/C). Sean S. and Craig W. helped us to irradiate these sensors to ~ $7x10^{11}$ n/cm^2 early fall. We characterized these sensors at UCLA after the irradiation and found that they possess much better tolerance of neutrons exposures compare to previous generation of sensors.

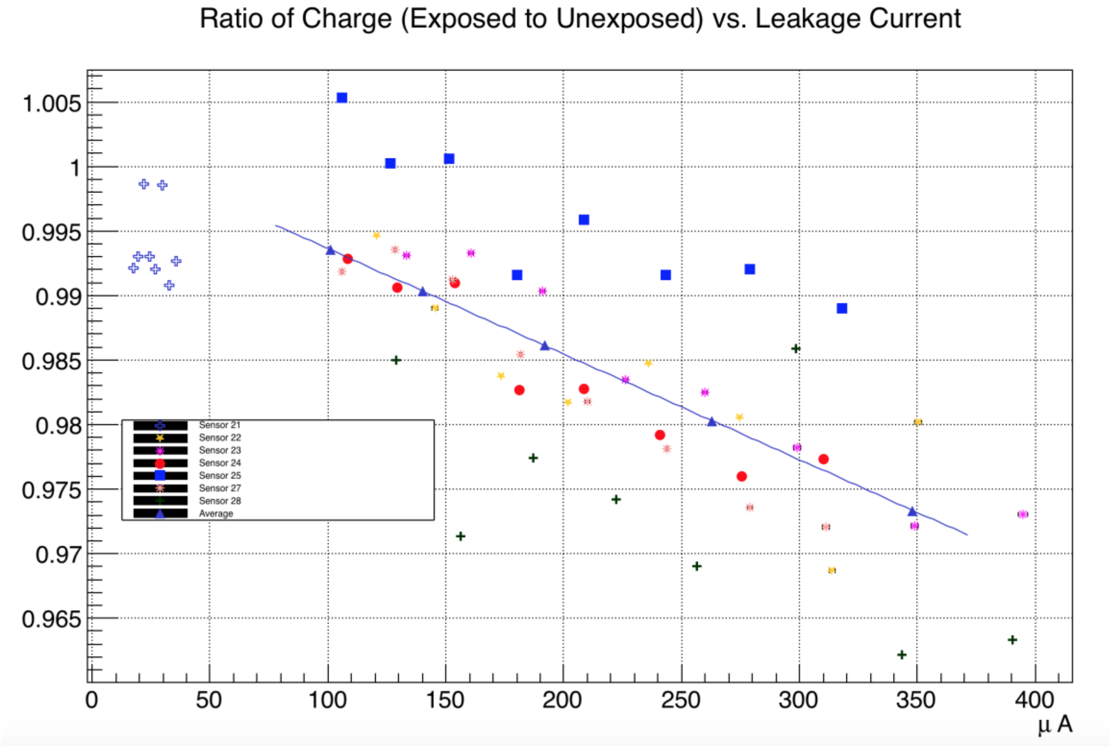

Figure -4 New HPK sensors, response degradation after exposure.

Compare to previous generation of sensors, response degradation at leakage current ~ 100 uA is about ten times smaller for new sensors (1% vs 10%), as shown in Fig 4. Essentially, the newly developed HPK sensors solved all problems we observed for older sensors in Run 17.

In addition, we performed same 'heating –cooling' measurements with unexposed new sensors, results shown in Figure 5 (new sensors – red markers, old – blue), note that current is about three times higher than what we plan to operate the SiPMs with in experiment.

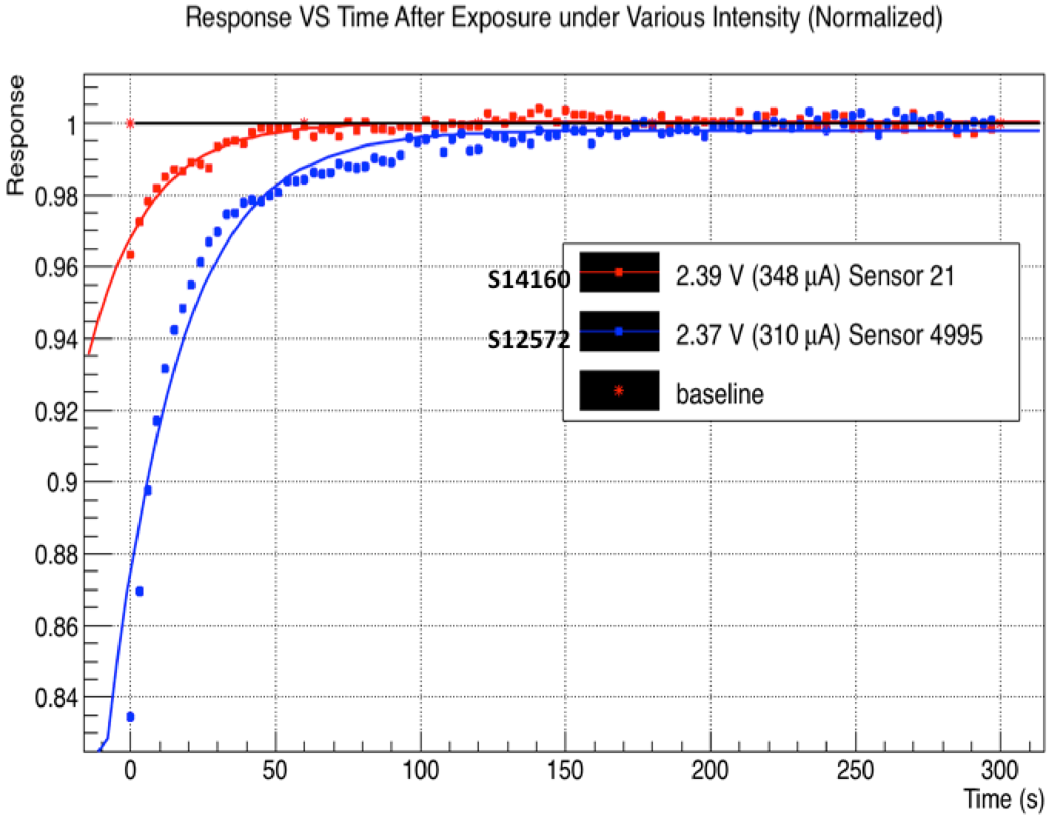

Figure -5 Comparison of S14160 vs S12572 type HPK SiPMs.

In October 2018, HPK released official data sheets for these new sensors, which confirmed results of our measurements during the summer 2018.

Other developments.

We started to investigate the space-time evolution of hadron showers in a small prototype geometry using Monte Carlo simulations for the outgoing hadron endcap calorimeter. These simulations will provide references for a possible future beam test run if validation of the simulations will be necessary. Committee recommended that we start from basic things such as leakages from possible test run prototypes and its effects on resolution of calorimeters. UCLA students started GEANT4 MC for sandwich type calorimeter consisting of three sections. The first section is EM (Shashlik type, 0.5λ int. long) followed by two independent HAD sandwich calorimeters (Fe/Sc) of 4.5λ int. long each). Our simulation goal is to compare response and energy resolutions for three cases; no leakages (EM + HAD + HAD), longitudinal leakage (EM + HAD), and longitudinal plus transverse leakages (EM + HAD, restricted to 0.4 m x 0.4 m in transverse dimensions, which is a reasonable test run configuration within our scope).

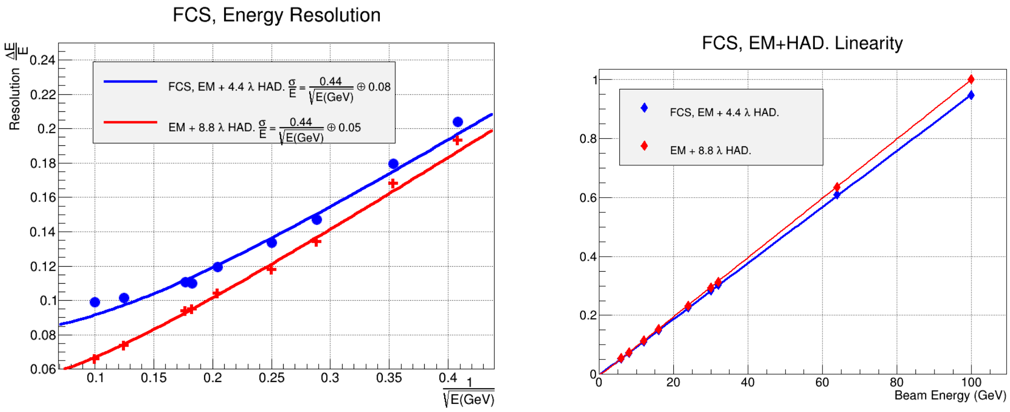

Figure -6 Energy resolution of 'ideal' vs longitudinally leaking calorimetry system.

As shown in Fig. 6 longitudinal leakage from ~5λ int. long calorimeter is about 6% at 100 GeV, which boosted the constant term in energy resolution from ~ 5% to 8%. As was expected at high energies effect of leakage may completely dominate in energy resolution. However, up to about 32 GeV situation is not that dire. We will continue this development and next step will be to look at third configuration and quantify contribution from recoil protons (delayed timing) to the overall signal.

Sub Project 2: 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:

- Complete the design and begin construction of the sPHENIX Sector 0 EMCAL prototype.
- Complete the analysis of the data run of the sPHENIX V2.1 EMCAL prototype from the 2018 test beam run.
- Submit the revised draft of our 2016 test beam results for the sPHENIX EMCAL and HCAL prototypes for publication.
- Submit our results on radiation damage in SiPMs for publication.

What was achieved?

Progress on the sPHENIX W/SciFi EMCAL

Fabrication of the blocks for the sPHENIX Sector 0 EMCAL prototype was started at UIUC and is proceeding well. Sector 0 is a full scale preproduction prototype that consists of 96 absorber blocks and is designed to cover the full rapidity acceptance of sPHENIX from $0 < \eta < 1.1$. The blocks come in 24 different shapes and the molds for all the blocks have been made. All of the fiber assemblies have also been filled and are ready for production. Thirty six blocks, representing 38% of the total, have been shipped to BNL and additional blocks are in various stages of production. Figure 2.1 shows a set of blocks at UIUC being prepared for shipment to BNL. We expect that all the remining blocks for Sector 0 will be delivered to BNL by the end of January 2019.

Figure 2.1. Blocks for Sector 0 at UIUC being prepared for shipment to BNL.

The blocks undergo a complete set of QA tests before leaving UIUC, which includes checks on block density, mechanical dimensions and tolerances, active fiber count and light output. The blocks are checked again for their dimensional tolerances when they arrive at BNL. Some blocks are also measured using a 3D scanning system as shown in Fig. 2.2a which provides a detailed check of all dimensions. After all QA checks are confirmed, reflectors are glued onto the back end of the block and the light guides are glued onto the front end of the block. Fig. 2.2b shows a set of blocks after gluing on the reflector plates and light guides.

Figure 2.2. a) (left): 3D scanner used to measure and check block dimensions at BNL. b) (right): Blocks for Sector 0 at BNL after gluing on reflector plates and light guides.

The mechanical design for Sector 0 is also complete, as well as the design for the readout electronics and cooling system. The readout electronics has been ordered and is scheduled for delivery in January 2019, after which the daughter cards containing the SiPMs will be mounted on the light guides. We expect that all the mechanical parts will be available by March 2019, after which the final assembly of the sector, along with the remaining readout electronics and cooling system, will begin.

Several of that Chinese collaborators that recently joined sPHENIX have also begun to produce calorimeter blocks. The groups from Fudan University in Shanghai and Peking University in Beijing plan to produce the blocks for the large η region of the sPHENIX EMCAL that was descoped due to budgetary constraints. Several Chinese collaborators visited UIUC in August of 2018 and learned the process for producing blocks. The then took this technology back to China and have now started producing blocks on their own. Figures 2.3 and 2.4 show some of the first prototype blocks that were produced which already look to be of very good quality.

Our Chinese collaborators are also looking into other vendors of tungsten powder in China that could potentially offer a cost savings over the tungsten powder vendors we have been currently been working with. They also plan to carry out additional tests of the powder and fibers, as well as help develop new and improved quality control techniques for producing blocks that will surely be beneficial to the overall production plan for producing blocks for sPHENIX, or any future calorimeter that would use this type of calorimeter design.

Figure 2.2. First prototype calorimeter block produced in China.

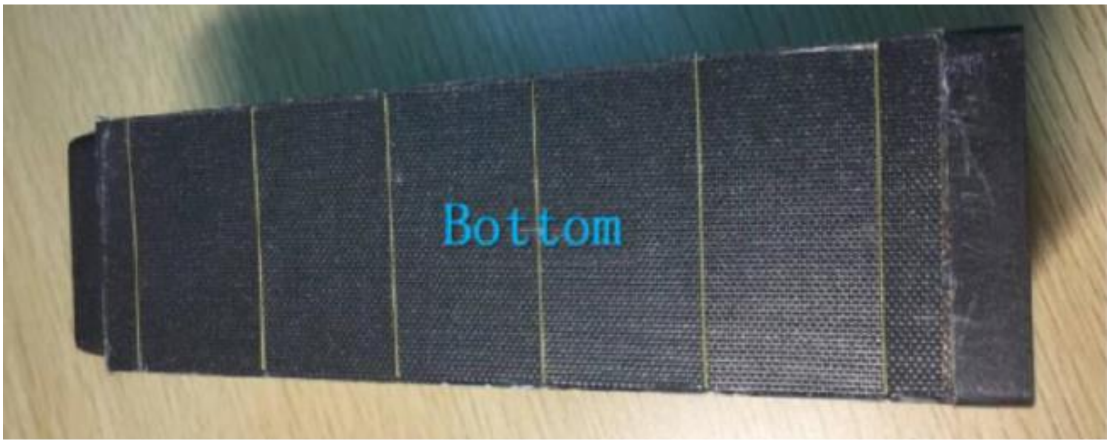

Figure 2.2. Another prototype calorimeter block produced in China after machining.

Analysis of the 2018 Test Beam Data

As mentioned in our previous report, the sPHENIX V2.1 EMCAL prototype was tested in the test beam at Fermilab last spring. The analysis of the data from that test has been ongoing and is not yet finalized, but the preliminary results look very good and show an improvement over our previous measurements. Figure 2.3 shows the resolution for the V2.1 prototype tested in 2018 compared with the V2.0 prototype tested in 2017. The data for the V2.1 was measured in two locations (towers 29 and 36) and is shown in the plot along with the average of the two. The data for the V2.0 prototype was also measured in two locations, one with blocks produced at UIUC and another with blocks produced at Tungsten Heavy Powder (THP). In both cases, the resolution is measured over a region of 2.5 x 2.5 cm^2 and includes boundary regions of different light guides and different blocks. After correcting for the position dependence of the shower position and unfolding the beam momentum spread of 2%, the average value for resolution measured for the V2.1 was $13.3\%/\sqrt{E} \oplus 3.5\%$, whereas the resolution for the V2 prototype was ~ $16\%/\sqrt{E} \oplus 2.9\%$. While it is difficult to unambiguously separate the contributions from the stochastic term and constant term, we believe there is a significant improvement, particularly at low energies, in the performance of the V2.1 prototype relative to the V2 prototype.

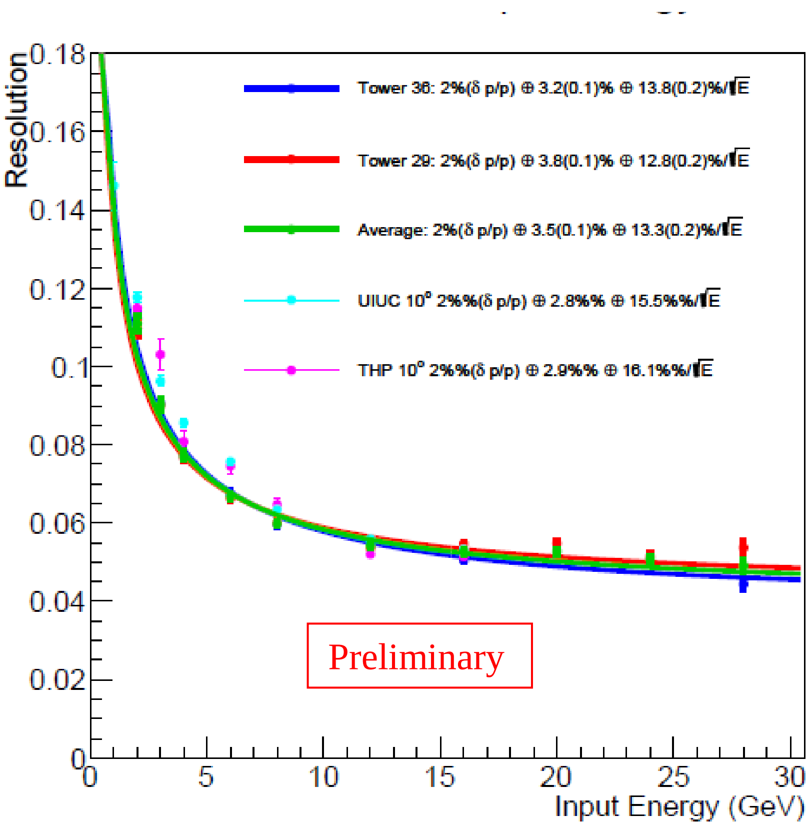

Figure 2.3. Energy resolution measured in the test beam for the sPHENIX V2.1 (2018) and V2.0 (2017) EMCAL prototypes. The V2.1 data is given for two towers (29 and 36) along with their average. The V2.0 data shows two regions of the calorimeter, one containing blocks produced at UIUC and another with blocks produced at THP.

Publications.

Our paper on the 2016 test beam results for the sPHENIX EMAL and HCAL prototypes has now been published. Our paper on radiation damage in SiPMs was submitted for publication, reviewed, revised and resubmitted. See publications list below.

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

We believe achieved all that we planned to do during the past six months. The production of blocks for Sector 0 is under way and essentially on schedule. The fabrication of the mechanical parts is slightly delayed, but we don't believe that this will affect the completion of Sector 0 by more than a month or so. We essentially completed the analysis of the 2018 test beam data which showed a significant improvement over our previous test beam results. We submitted the final version of our 2016 test beam results and those results are now published. We also submitted a first version of our paper on radiation damage in SiPMs and have just submitted a revised version for review. We therefore feel that we achieved all of our goals for this period.

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 laboratory. The schedule for this has been somewhat delayed due to the procurement of the mechanical parts, but we expect to complete the construction of the sector by spring of 2019. In parallel, we will start producing blocks for an additional 12 preproduction sectors for sPHENIX. Production of these blocks will be carried out at both UIUC, which will produce block types 1-18, and in China, which will produce block types 19-24. This differs from our original plan in that sPHENIX has only been budgeted by the DOE to construct the EMCAL out to a rapidity of 0.85 (which includes blocks 1-18). With the inclusion of our Chinese collaborators, who are providing their own internal funds to produce additional blocks, we will now be able to construct the sPHENIX EMCAL out to its full rapidity coverage of 1.1 as originally designed.

What are critical issues?

The most critical issues 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 start the production of blocks for the next 12 preproduction sectors, and to include the production of blocks in China in this plan so that when the assembly of these sectors begins, there will blocks available to instrument these sectors out to their full rapidity coverage.

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.

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.

The effort on the sPHENIX EMCAL is being supported entirely by external funds. There is no support for these activities from EIC R&D funds.

Publications

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

New since last report:

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

B.Biro et.al., “A Comparison of the Effects of Neutron and Gamma Radiation in Silicon Photomultipliers “, submitted to the IEEE Trans. Nucl. Sci. in September 2018. The first review was received in October 2018 and a new revised version was resubmitted January 2019. We are now waiting for the review of the revised version.

Response to the Committee’s Comments

In the Committe’s report from its last meeting, it made the point that while sPHENIX can accept a loss in resolution due to the inherent position dependence of the W/SciFi design, a new detector for EIC using this technique should not. The Committe also stated that it felt there was a need to improve the light collection uniformity via additional work on coupling of the readout devices to the tungsten fiber matrix, and to continue the study of the light guide geometry and the tradeoff between radial compactness and uniformity of response. While we fully agree that furher improvements in the uniformity of the calorimeter response are possible, we also wish to to point out that these issues were extensively studied in the development of the sPHENIX calorimeter, both to reduce the effects as much as possible given the constraints of the overall sPHENX design (and even going beyond those constraints in some cases), and to develop methods to correct for the remaining residual position dependence of the shower response using position dependent corrections. Many of these effects were also studied by the UCLA group, and all of this work has been reported to Committee in previous reports starting in 2015.

Regarding future work in this area, we feel that improving the light collection uniformity by either lengthening or redesigning the light guides (e.g., Winston cones or even more complicated designs) would offer at best only marginal improvements over the current sPHENIX design. This was studied in sPHENIX, both with measurements (including beam tests) and Monte Carlo, and there were only marginal differences given any reasonable constraints. Various types of compensating filters were also studied by the UCLA group, and while some improvement could be achieved in terms of uniformity, it resulted in significant losses in light collection efficiency. As this stage, we feel that the most promising possibility for improving the light collection uniformity without compromising the light collection efficiency would be to increase the photocathode area coverage of the fiber matrix. The Committee also notes this in their report and this is indeed a possible path forward in the future, especially given the possibility of obtaining larger area SiPMs at an affordable price. We have, in fact, already acquired samples of 6x6 mm^2 SiPMs and plan to study them as a future part of our EIC R&D program.

Sub Project 3: R&D on a Shashlik Calorimeter Using Tungsten Absorbers for EIC

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

Past

What was planned for this period?

The main planned activity for this period was to complete the construction of the first prototype shashlik calorimeter module using W/Cu absorber plates that will be used for testing as part of our EIC R&D program. The construction of this module has been under way for some time at UTFSM but was proceeding very slowly due to lack of resources and support. However, now that this project has received some support from the EIC R&D Committee, progress has greatly improved and we have now been able to complete the first module and its readout electronics, and also involve participation with our collaborators at BNL.

What was achieved?

Construction of the first prototype shashlik module to be used for EIC calorimeter R&D was completed at UTFSM. The module comprises seventy 38 x 38 x 1.5 mm W80Cu20 absorber plates with corresponding 1.5 mm thick scintillator plates sandwiched in between. Each module forms a 2x2 array of 19 x 19 mm towers that are each penetrated by 4 WLS fibers. Each fiber is read out individually with its own SiPM, which allows a measurement of the shower position within the tower. Figure 3.1 shows the stack of plates inside the module with the WLS fibers protruding from the readout end. Small clear plastic blocks, shown in Fig. 3.2, are mounted to the ends of the fibers which serve as mixers and for directing the light onto the SiPMs.

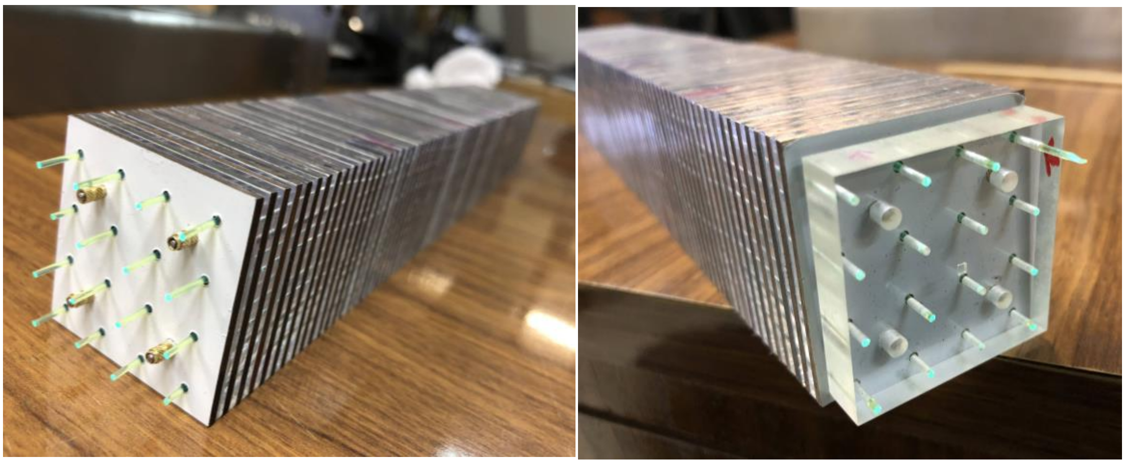

Fig. 3.1 Stack of W/Cu absorber plates and scintillator plates for the first prototype shashlik module with WLS fibers protruding from the readout end. Photo on the right shows the mounting plate used to align the fibers.

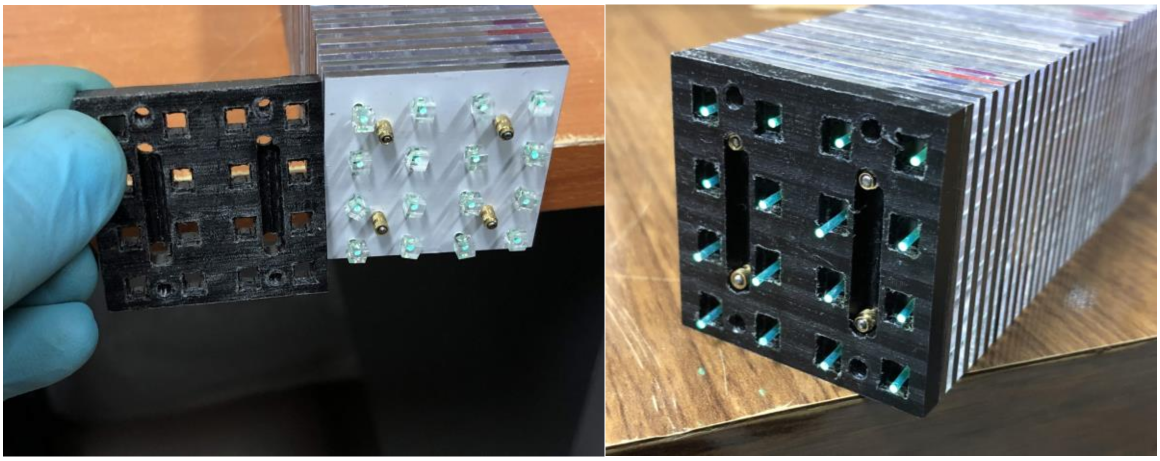

Fig. 3.2 Readout end of the stack with small clear plastic blocks attached to the WLS fibers that are used as mixers and for directing the light onto the SiPMs.

Figure 3.3 shows the readout board containing the SiPMs that is mounted onto the light guides and provides the connections to the readout cables. The photo on the right shows the readout end of the completed module wrapped in black tape in order to make it light tight and ready for testing at UTFSM.

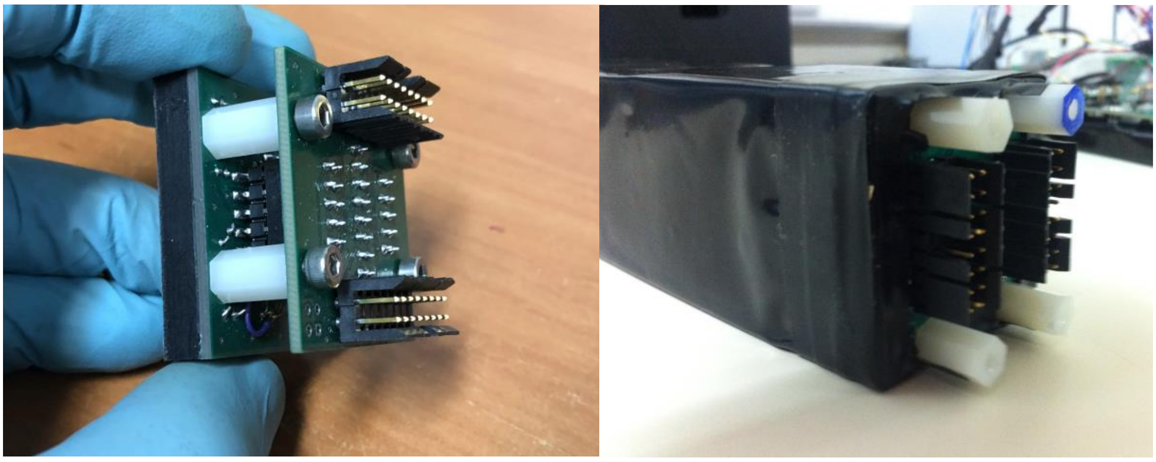

Fig. 3.3 First prototype shashlik module made with W/Cu absorber plates constructed at UTFSM for EIC R&D. The photo on the right shows the readout end with cable connectors for reading out the SiPMs.

Various components of calorimeter were also sent to BNL for testing. These consisted of a small stack of absorber and scintillator plates, a SiPM readout board, some short WLS fibers and some clear plastic light guides. These just arrived at BNL at the end of December and are shown in Fig. 3.4. We plan to use these components to study the light collection efficiency and uniformity of the scintillator tiles in various lab tests at BNL. The results of these tests will be combined with results of other tests at UTFSM using cosmic rays and LEDs in order to try and better understand the light collection and uniformity properties of the complete module

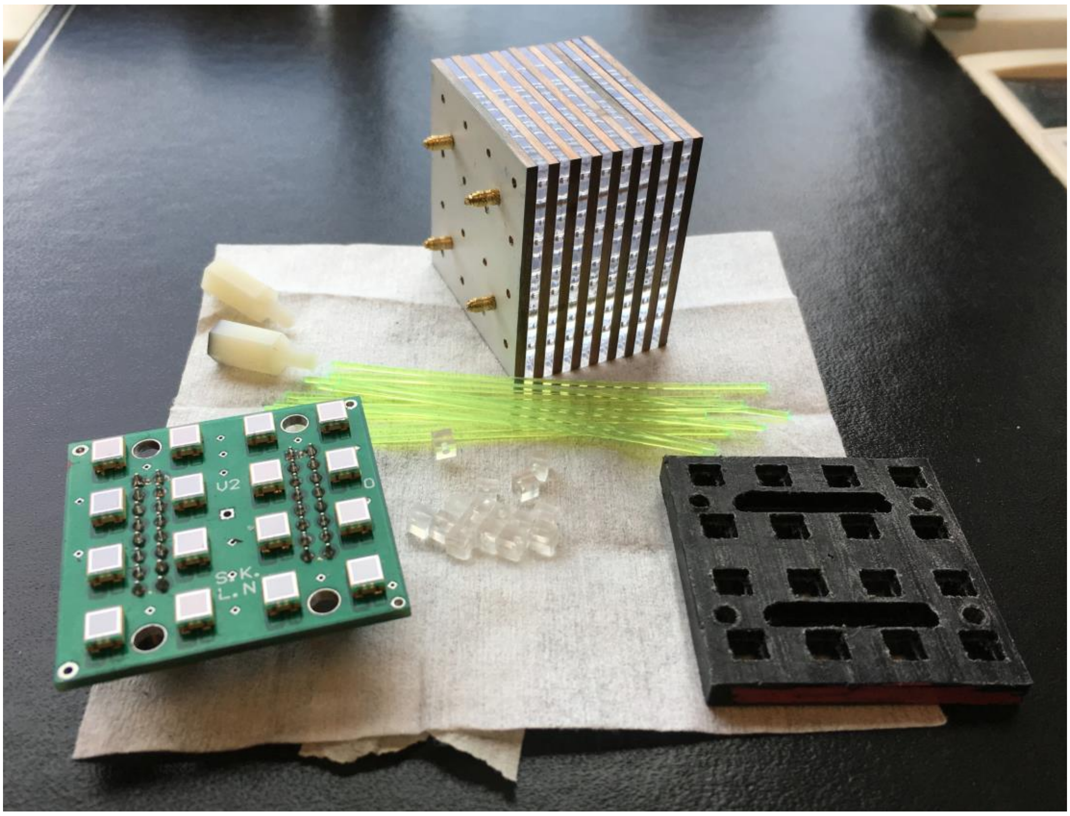

Fig. 3.4 Shashlik calorimeter sent from UTFSM to BNL for testing, consisting of of a small stack of absorber and scintillator plates, a SiPM readout board, some short WLS fibers and some clear plastic light guides.

A new scintillation hodoscope was also constructed at UTFSM that will be used to test the module with cosmic rays. It consists of 16 X and 16 Y layers of plastic scintillator counters read out with SiPMs as shown in Fig. 3.5. It will cover an area of 32 x 32 mm^2 and have a resolution of 1 mm in X and Y. Readout electronics and power supplies for both the calorimeter module and the hodoscope are also available at UTFSM.

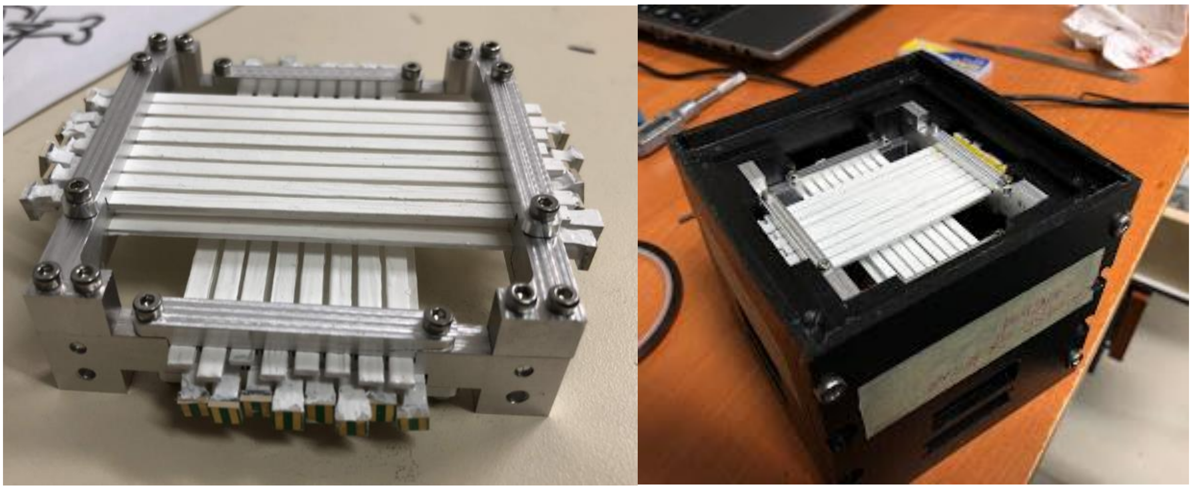

Fig. 3.5 Scintillation hodoscope constructed at UTFSM for testing the shashlik calorimeter module with cosmic rays.

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

The first prototype tungsten shashlik module was completed at UTFSM as planned and is now ready for testing. Available manpower at UTFSM is still rather limited so progress was slower than we had hoped, but the work was still completed within the prescribed time frame. We had also hoped that the calorimeter materials could have been sent to BNL sooner than when they actually arrived. The delay was caused partly by shipping problems which we feel have now been corrected and we hope that future shipments will not experience these problems.

Future

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

Our plan for the next six months is to test the first prototype module at UTFSM with LEDs and cosmic rays, and to begin construction of another five modules at UTFSM. The tests of the first module will include light output yields in terms of photoelectrons per MeV, an initial energy calibration that can be correlated with the LED response, initial results on uniformity of light collection and position resolution, and hopefully some initial results on timing. These tests will be done using the available readout electronics at UTFSM.

After the initial testing at UTFSM, the first prototype module will be sent to BNL for additional testing. Many of the initial tests will be repeated using the test setup at BNL in order to confirm and compare the results obtained at UTFSM. These tests will also be done using different electronics at BNL, which will utilize the readout system designed for the sPHENIX calorimeters. Initial preparations for these tests will begin before the module is shipped to BNL in order to provide an efficient transition to the new electronics when the module arrives. We also plan to use the sPHENIX readout electronics when we test this module, along with the other modules that will be produced, in the test beam at Fermilab.

We will also carry out separate light output and uniformity measurements at BNL using the individual calorimeter components. These tests will use radioactive sources, LEDs and lasers to study the light collection properties of the scintillating tiles and WLS fibers in the lab. We also plan to do tests with several new types of SiPMs at BNL which we have recently received from Hamamatsu and KETEK. We also hope to carry out simulations to study these light collection properties, but we currently do not have anyone who is able and available to do these calculations.

Finally, we plan to have collaborators from UTFSM visit BNL and collaborators from BNL visit UTFSM in order to exchange ideas and have more detailed discussions about the project. We feel that this is a very important aspect of our R&D program that should occur on a regular basis in order to ensure that the project moves forward in the right direction in the future.

We also plan to study the decommissioned sPHENIX shashlik calorimeter modules as part of this R&D effort on shashlik calorimetry. These modules are comprised of lead plates and will provide a comparison with the modules consisting of tungsten plate in terms of their uniformity of response and light collection. This study of these modules has not started yet but is part of our future plans.

What are critical issues?

The main critical issue is lack of available manpower, both at UTFSM and BNL, that have the skills and the time to work on this project. The most useful addition to our team would be either a graduate student or postdoc who could dedicate a significant fraction of his or her time to this effort.

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.

- 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.
- So far all of the effort on this project at BNL has been carried out by BNL staff supported from other sources. However, now that technical work is beginning at BNL, some of that work will be supported using EIC R&D funds.

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.

The major part of this effort, both at UTFSM and at BNL, is supported from internal sources. This includes support for the UTFSM Detector Laboratory by the University and support for the sPHENIX Group from the Physics Department at BNL.

Publications

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

There are currently no publications from this effort.

Sub Project 4: Homogeneous Calorimeter Development for EIC Using Crystals and Glasses
Project Leader: T. Horn

Past

What was planned for this period?

Our main activities during the past six-month period were to work closely with vendors towards cost-effective production of high-quality scintillator materials for the EIC EM calorimeters. 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 prototype consists of 144 scintillator blocks arranged in a 12 x 12 array. Each block is coupled to its own photomultiplier tube readout and a custom designed high voltage divider. Fig. 1 shows the prototype after assembly and installation of its components. The prototype was installed in Hall D at Jefferson Lab in fall 2018. 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, submit a small business funding proposal for new scintillator material development and production. Beyond these plans, we note the additional suggestions from the July 2018 and earlier EIC R&D Committee reports, which include possible investigation of reflective coating instead of reflector material wrapped around the blocks, analysis of raw materials used in block fabrication, and geometry of the block assembly.

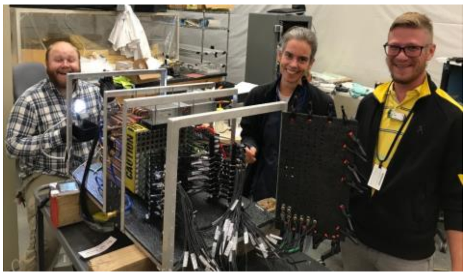
Fig 1: EMCal NPS 12x12 prototype assembly with student J. Crafts and postdoc V. Berdnikov

What was achieved?

We have been working closely with the vendors and through synergy with the NPS project characterized 460 SICCAS and 100 CRYTUR $PbWO_4$ crystals. We also produced and characterized, in collaboration with the Vitreous State Laboratory (VSL) and vendors, about 35 glass ceramic samples. Physical and luminescence characterization was carried out at CUA. 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 the glass ceramic 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 radiation damage to the glass and no impact of different photon irradiation rates. A representative result is shown in Fig. 2. $PbWO_4$ crystals were irradiated to 30 Gy at 1 Gy/min. Preliminary results indicate an average value of the radiation-induced absorption coefficient of 0.7 m^{-1} with values ranging from 0.4 to 1.1 m^{-1}. An example of the measured crystal-to-crystal uniformity and is shown in Figure 3. CRYTUR crystals have an average light yield of 16 with a variance of 0.6 photoelectrons/MeV, which is within the uncertainty of the measurement. SICCAS crystals have an average light yield of 17.4 with a variance of 3.8 photoelectrons/MeV. This large variation can be traced back to mechanical and chemical differences in crystals. For instance, 160 of the 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]. After negotiation and detailed discussion, as well as site visits by our collaboration, SICCAS agreed to replace the 160 rejected crystals. However, due to issues with the vendor's furnaces, the production of the replacement crystals has been delayed.

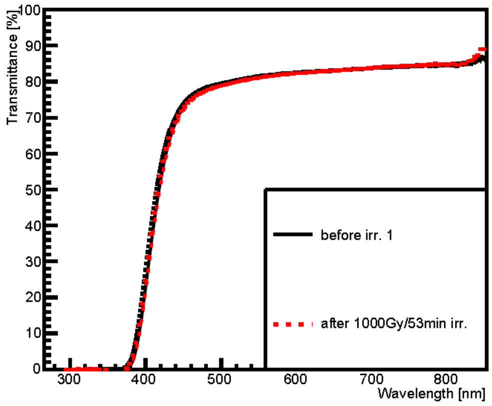

Fig 2: Glass radiation hardness

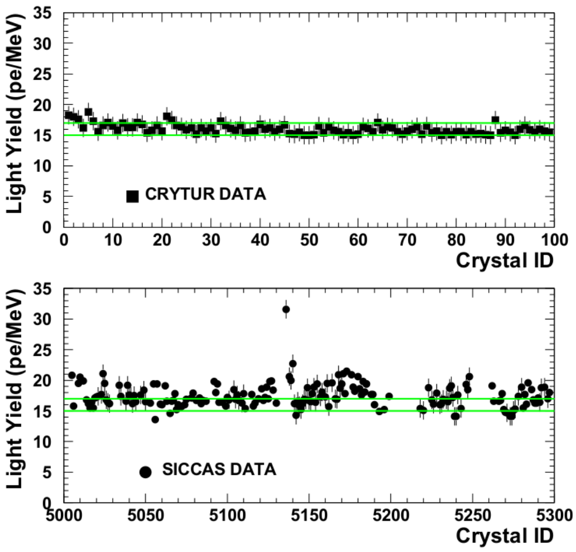

Fig 3: Crystal-to-crystal variation. A subset of 460 SICCAS crystals is shown

We have set up a strict quality control program at and with CRYTUR to meet specifications. 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 documented and provided the details of the methods used for testing and the results

[1] This project has more relaxed requirements on the crystals, in particular for radiation hardness

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

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 did not have to reject any of the 100 crystals received from CRYTUR in 2018. We also worked with CRYTUR on a method that could have potential to reduce production costs. It entails the use of a larger crucible to grow larger crystals, which can then be cut into two crystals of the required size.

Through our collaboration with the NPS project, we have obtained data from the chemical analysis of raw material used in the production of CRYTUR crystals. This raw material has been used in the production of BTCP crystals and was manufactured by NeoChem in Russia, specifically for Czochralski crystal growth. There is enough of this raw material available for the production of NPS and PANDA crystals, but not beyond. Through production of crystals for NPS and PANDA, CRYTUR has been learning about the composition of the raw material and hopes to be able to procure or produce it independently in the future. This is an important aspect that our collaboration will continue working on with the vendor. We were not successful in obtaining similar characteristics of the raw material used by SICCAS. Our purity specification to both vendors is <10ppm for the amount of Mo and <40 (100) ppm for La, Y, Nb, Lu contamination.

Element	Concentration [ppm wt]	Element	Concentration [ppm wt]
Li	0.15	Ag	3.5
Be	< 0.005	Cd	< 0.5
B	0.13	In	Binder
O	Matrix	Sn	< 0.05
F	< 0.02	Sb	0.55
Na	0.80	Te	< 0.05
Mg	0.03	I	< 0.05
Al	0.38	Cs	< 0.1
Si	1.8	Ba	< 0.005
P	0.06	La	< 0.01
S	5.0	Ce	< 0.01
Cl	1.1	Pr	< 0.01
K	0.80	Nd	< 0.01
Ca	0.61	Sm	< 0.01
Sc	< 0.05	Eu	< 0.05
Ti	0.02	Gd	< 0.005
V	< 0.005	Tb	< 0.005
Cr	0.75	Dy	< 0.005
Mn	< 0.01	Ho	< 0.005
Fe	0.29	Er	< 0.005
Co	0.04	Tm	< 0.01
Ni	0.09	Yb	< 0.005
Cu	2.0	Lu	< 0.005
Zn	< 0.01	Hf	< 0.01
Ga	< 0.05	Ta	< 1
Ge	< 0.1	W	Matrix
As	< 0.01	Re	< 0.5
Se	< 0.01	Os	< 0.05
Br	< 0.01	Ir	< 0.01
Rb	< 0.01	Pt	< 0.05
Sr	0.02	Au	< 0.5
Y	< 0.01	Hg	< 5
Zr	0.07	Tl	<= 1.8*
Nb	< 0.05	Pb	Matrix
Mo	0.17	Bi	< 0.5
Ru	< 0.005	Th	< 0.0005
Rh	< 0.05	U	< 0.001
Pd	< 0.05		

Fig 4: Composition analysis

Through synergy with the NPS project we submitted purchase orders for 300 additional CRYTUR crystals and initiated procurement of 400 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.

In anticipation of testing these new crystals and also new glass samples that we are producing, we identified methods for higher precision measurements. For instance, our waveform based analysis of the scintillation kinetics can be significantly improved through, e.g., the time-correlated single photon counting method, which provides a time-dependent intensity profile of the emitted light upon periodic excitation. The technique is well known, e.g., in scintillation decay times of liquid scintillators for neutrino experiments[3]. A drawback of our current luminescence measurement scheme based on diffraction gratings, an excitation light source and a

[3] E.g., Instruments and Experimental Techniques, 2013, No1, 34

PMT is that it does not take into account the PMT quantum efficiency. We thus started optimizing our equipment and through collaboration with the VSL purchased 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.

We designed, constructed, and commissioned a 12x12 prototype array. This included development of slow controls, calibration and analysis software. The geometry of the 12x12 prototype is representative of the NPS and EIC endcap EMCal geometry. It consists of a wall of 144 rectangular blocks of dimensions 2.05cm x 2.05cm x 20 cm. 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 prototype, 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 12x12 array detector box was monitored by thermocouples and LEDs, respectively. An example of the detector environment controls is shown in Fig. 5.

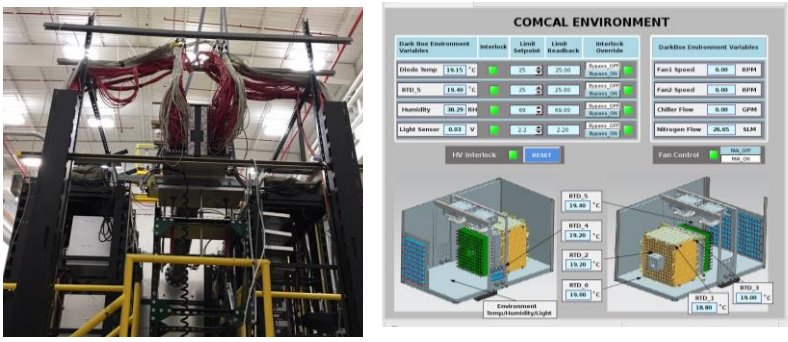

Fig 5: EMCal prototype in Hall D and environment monitoring.

We began prototype data taking in December 2018. Data were taken for beam photon energies ranging between 1 and 10 GeV. The energy was determined using the Hall D tagging detectors. Our preliminary results from the prototype beam tests show good energy linearity for photons of energies between 1 and 10 GeV/c. For 4.2 GeV photons, our preliminary results indicate an energy resolution of about 2%. The stability of this value was checked for different 5x5 regions in the detector and found to be stable to 0.3%. For 10 GeV photons our preliminary results indicate a typical energy resolution of 1.4-1.6 %. These results are anticipated to improve after a refined gain calibration. 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 $7\%/\sqrt{E}$.

We started work on the optimization of glass ceramic formulation to increase sensitivity to EM probes and to meet the requirements of detector application, e.g., density, light output, radiation hardness, timing. 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 over the next year. Our expertise and results to date have played a large role in the submission of Scintilex, LLC's STTR/SBIR proposal for the development of high performance glass ceramic scintillators. If funded, that award should further accelerate our progress in this area.

At INFN-GE we started setting up a test lab for crystal and glass sample readout. We loaned two scintillator paddles instrumented with WLS+SIPM readout to arrange a cosmic ray trigger test bench and a 250 MHz, 14 bit CAEN digitizer V17XX to sample the photodetector output. We also procured ½" and 1" PMTs and a dark box for sample characterization. Furthermore, we designed and constructed a thermalized LED light source to test the response of samples up to 15x15x250 mm^3.

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 delays in the delivery of the required larger crucible and quality assurance methods. CRYTUR hopes to test the new method as soon as all materials are available. A larger crucible is also required for larger glass ceramic block fabrication. Unfortunately, there have been delays in this delivery as well. The new equipment is expected to arrive early in the next six month period.

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 six months we hope to have at least 100 additional CRYTUR and ~200 additional SICCAS crystals.

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

We have carried out some additional work on 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. The results from our prototype tests will also be important in this step.

In response to additional July 2018 report recommendations, we started investigating the benefit of reflective coating instead of wrapping. For $PbWO_4$ crystals we performed a comparative GEANT4 simulation in which crystals were wrapped with a reflector plus an air gap or surrounded by a reflector without an air gap, representative of a reflective paint. Initial simulation results indicate no improvement of the light yield and possibly a negative impact when there is no air gap between crystal surface and reflector. This finding is consistent with prototype tests at Giessen U. $PbWO_4$ crystals for NPS and for PANDA were thus wrapped with VM-2000 reflector. For glass scintillators we are currently exploring the benefit of EJ-150, a TiO_2-based reflective paint, which we have been using in aerogel Cherenkov detectors in the past. However, wrapping also remains an option here too.

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 six months 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. Over the next six months we hope to have at least 100 additional CRYTUR and ~200 additional SICCAS crystals. A total of 300 CRYTUR and 400 SICCAS crystals were ordered. We will further develop and optimize our glass property models and property measurement evaluation. This entails procurement of equipment and rapid production of many small samples for evaluation of materials properties. We also plan to produce larger glass samples with adequate surface quality for physical, luminescence, and radiation hardness studies. For crystal and glass characterization, we will setup and take advantage of new instrumentation, e.g., for determination of scintillation decay time. We will also continue prototype data taking with crystals and glass and subsequent data analysis to determine actual performance parameters. We will explore the response of $PbWO_4$ crystals and glass scintillators to different photosensors (SiPM, APD, and PMT) readout. For the readout we plan to procure a set of different area (3x3 mm^2 and 6x6 mm^2) and pixel size (10 um, 25 um, 75 um and 100 um) SiPMs and Large Area APDs (1x1 cm^2). With these we plan to measure the response of $PbWO_4$ crystals of sizes 2x2x20 cm^3 and 1.5x1.5x20 cm^3 with SiPMs. Light yield and attenuation length over the longest side for ~16-20 MeV energy deposition by cosmic muons have been measured to test the procedure. We have started setting up a Monte Carlo simulation for resolution studies and matching crystal and glass materials in the EMCal. We expect to continue these studies over the next year. Over the next year we will also explore additional radiation hardness studies, e.g., at BNL or Caltech. Our planning is not different from the original plan.

What are critical issues?

The critical issues are to receive the components to continue production optimization and characterization at both vendors and universities. There are currently no major delays expected.

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

CALTECH
R-Y Zhu

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 100 CRYTUR crystals produced in 2018 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.

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.

Preparing documentation on crystal/glass characterization and prototype tests.