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EIC Detector R&D Progress Report

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Project Name: EIC Calorimeter Development
Period Reported: from 7/1/19 to 12/31/19
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Abstract & Summary

This report summarizes the activities of the eRD1 Calorimeter Consortium during the period from July 1, 2019 – December 31, 2019. These activites are divided into four Sub-Projects: R&D on Forward Calorimetry (UCLA), Tungsten Scintillating Fiber Calorimeter Developments in sPHENIX (BNL), R&D on a Tungsten Shashlik Calorimeter for EIC (BNL/UTFSM), and R&D on Homogeneous Calorimeter Materials for EIC using Crystals and Glasses (CUA/Orsay).

The UCLA group focused its attention on forward calorimetry given their opportunity to develop a Forward Calorimeter System (FCS) for STAR which would be similar to a forward calorimeter system for EIC. The FCS project is now fuly funded and scheduled to be operational in 2021. Considerable effort was devoted to understanding their test beam data from the Spring of 2019 to try and understand why mesurements with their prototype calorimeter gave poorer resolution than expected in their simulations. A number of tests were performed on the scintillators and wavelength shifters in the lab to measure various possible sources of non-unifirmities, and in the end, it was found that the non-uniformities were due to different surface finishes of the scintillating plates they received from Eljen. There were also a number of discussions about the role of timing in the forward calorimeter system, and it is now believed that timing may not be of critical importance at the EIC if sufficient longitudinal segmentation is provided.

The sPHENIX project passed a major milestone in obtaining PD-2/3 approval and is now entering a construction phase with the goal of completing and commissioning the detector by the end of 2022 and to begin data taking in 2023. Procedures have now been developed for full scale production of W/SciFi blocks which are now under way at UIUC, and additional capabilities for block production is being developed in China. Sector production is also under way at BNL with the construction of more than a dozen pre-production prototypes.

Studies also continued on how to cope with the large expected increase in dark currents in the SiPMs after several years of running at RHIC. An extensive cooling system is being implemented in the sPHENIX EMCAL that will maintain and also lower the operating temperature of the SiPMs during operation. However, tests have shown that due to the difficulty in making good thermal contact with the internal silicon avalanche region of the SiPMs, additional cooling must be supplied to the external device in order to keep the gain constant in the presence of the high dark current due to radiation damage. Studies were also carried out to investigate covering a large portion of the readout area of W/SciFi blocks with large area SiPMs to increase the light collection efficiency and improved the uniformity of the readout

Progress on the W/Cu shashlik calorimeter continued with the construction of additional calorimeter modules at UTFSM (bringing the total to 9) and their shipment and delivery to BNL. The modules will now be tested at BNL and assembled into a 3x3 array for testing in the beam. However, this project suffers from lack of manpower and progress is expected to be limited until additional manpower is found.

R&D on homogeneous calorimeter materials focused on obaining and characterizing more PWO crystals from SICCAS and Crytur, which is being carried out in synergy with the NPS experiment at JLAB. Further R&D on scintillating glasses was carried out at CUA and VSL to produce larger blocks of the most promising materials and characterize them, including various radiation damage studies. Plans are under way to construct a prototype calorimeter using scintillating glass blocks and test it in the beam at JLAB some time in 2020.

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

What was planned for this period?

In the past six months we continued working on the forward calorimeter system, as planned in our July report. The priorities were altered to follow committee July's recommendation to focus on more specific R&D goals.

What was achieved?

We will have a unique opportunity to operate a sizeable forward calorimeter system (STAR FCS) similar in design to what we plan for a future EIC central detector. The RHIC environment conditions are very close to the high luminosity EIC environment. The STAR FCS is now fully funded and will be in operation in Run 22 at RHIC. For the next twelve months or so our highest priority is to construct and commission the FCS. The FCS project is progressing well according to our proposed schedule:

- A 1500 channel EMCal system, based on re-furbished PHENIX Shashlyk modules modified with SiPM readout, was installed in the STAR IP in October.
- Mechanical support structure for HCal section was installed during summer shutdown.
- About 10% of components for HCal have been produced. Production facilities and QA procedures were established at different collaborating Universities during the summer-fall pre-production cycle.
- The rest of HCal components and readout electronics were ordered (NSF funds become available on Sept.1st), and the first batches of these components started to arrive.

We continue to study instrumental effects on detector performance, in particular, the light collection non-uniformities. This was part of exercise to understand results from the April test run at FNAL. There were a few workshops last year and discussions at these workshops stimulated us to rethink our current priorities for our MC. In particular, the workshop for very forward instrumentation for EIC at SBU in 2019. There will be a LOI from interested groups as discussed during this workshop.

As we have reported previously, a prototype of the FCS tested at FNAL underperformed compare to ideal (no instrumental effects) MC calculations. We started to investigate which instrumental effects may be responsible. The first step was to include non-uniformities of light collection in the scintillation tiles. Figure 1 shows measurements of light collection efficiencies in scintillation tiles located at different depths inside the HCal tower. Non-uniformities resulted from two things. First, the WLS plates collect light only from one side of the tiles, which created a hot spot near the WLS plate. Second, the WLS plate has a taper, which is required to minimize the number of SiPMs and to make longitudinal light collection uniform within ~ 10% (an additional component to reach this uniformity goal is a variable reflectivity mask, which is located behind the WLS bar). We found a simple parameterization of the light collection efficiency across scintillation tile surface vs position of the tile in the HCal tower and implemented this in our model. We also considered three different method of collecting the light with the WLS. The first is the one similar to what was used at

FNAL; The second collected light from scintillation tiles at the opposite edges with a tapered WLS similar to one used at FNAL. For the third, the shape of WLS bars was made asymmetric (which we thought may help near the back side of the towers). Examples of the light collection efficiencies for all these cases are shown in Figure 2.

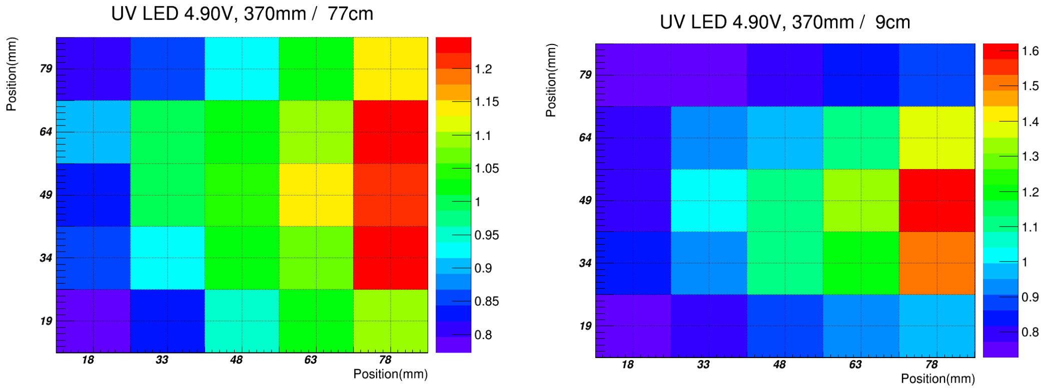


Figure 1. Measurements of light collection efficiency across the surface of scintillation tiles vs position of the tiles inside the tower.

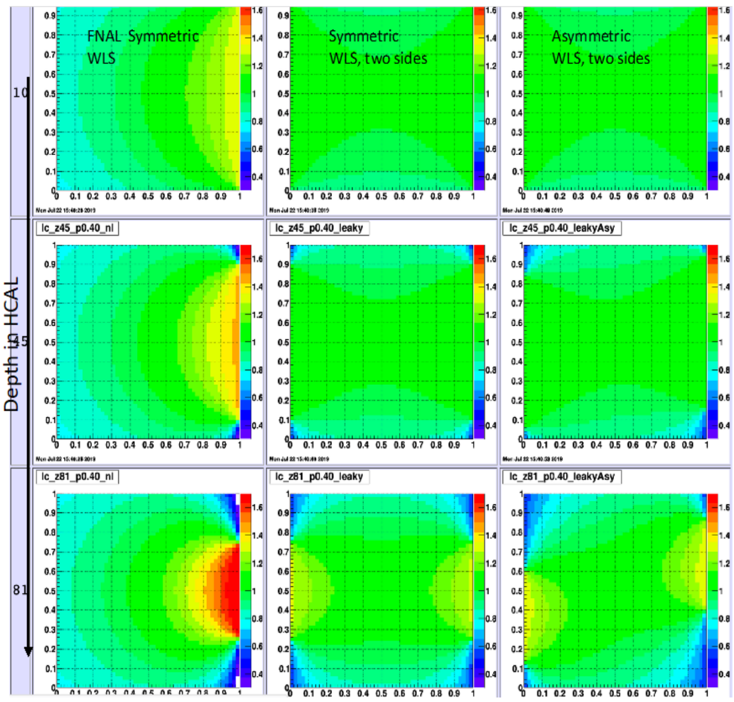


Figure 2. Uniformity of light collection, as implemented in MC model for three different arrangements of light collection. Rows shows uniformities maps for three different positions along the depth in HCAL tower.

An obvious observation is that collecting light from two opposite edges of scintillation tile makes it very uniform. However, the effect on energy resolution is very minor as shown in Figure 3, where we compare FNAL test run data vs the ideal MC and a MC with the three different types of light collections mentioned above. This was somewhat expected because in most cases, the hadronic showers are very wide and local non-uniformities are not as detrimental as it is the case of EM showers, which we discussed in our previous reports for W/ScFi developments. However, it was important to confirm this with the new MC. This has also led us to an interesting idea of what we can do to improve constant term, which we will discuss later.

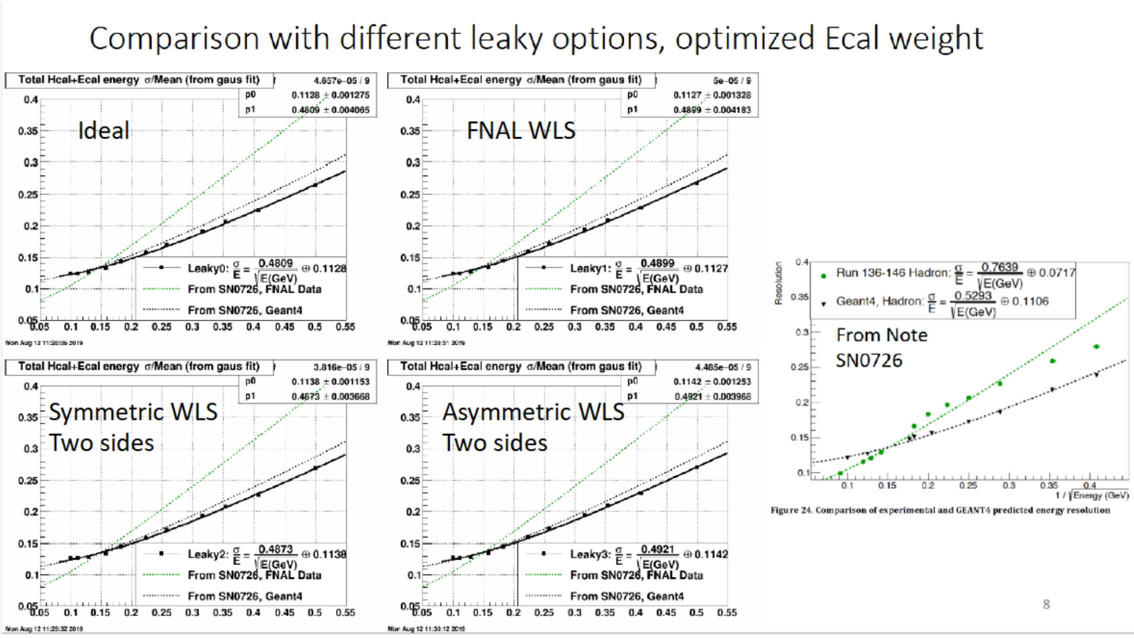


Figure 3. Energy resolution for FCS. Test run data compared vs MC for ideal case and three different types of light collection schemes.

The next things we investigated were the variation in the light collection efficiency we observed for different WLS bars. The situation is shown in Figure 4 where we plot the position of muon peak in the HCal towers measured at FNAL vs lab bench measurements of the response of WLS bars to a blue LED after the SiPM boards were calibrated and glued to them. The variation in efficiency by a factor of two was not understood at time of the test run at FNAL.

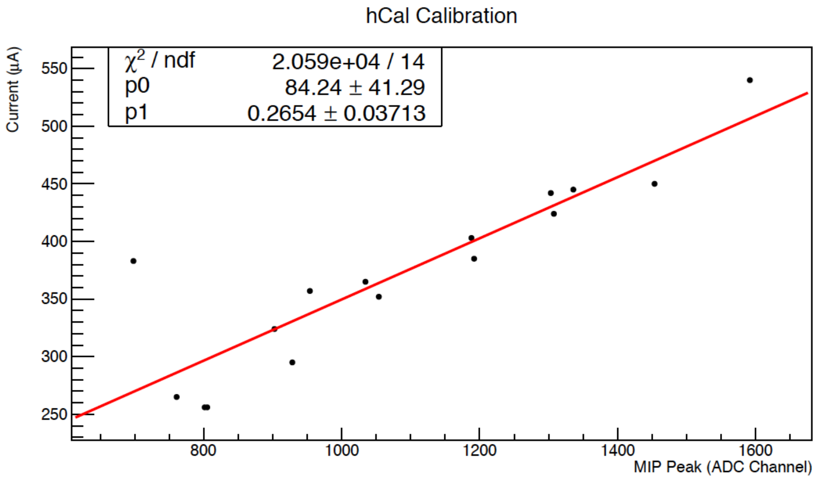


Figure 4. Muon peak position vs response to blue LED.

We discussed with Eljen (EJ) what the reason(s) for such variations could be, which we suspected may be due to variation of shifter concentration in the WLS bars. However, the reason turned out to be different. We were informed by EJ that in a batch of WLS plates we received, some of the bars had diamond milling on both sides of plates (to meet tolerances requirement), while others had it only on one side. Visually all plates look the same, and only upon careful examination could one distinguish the diamond machined side from the side which was formed during casting against a polished glass surface. We did measurements on two such WLS plates and, to our disbelieve, they had very different responses. In particular, the compensation scheme for one plate (both side diamond milled) worked as expected, while for plate which had one side 'polished' during casting it did not work. This is shown in Figure 5. We don't have a good explanation for this effect at this moment.

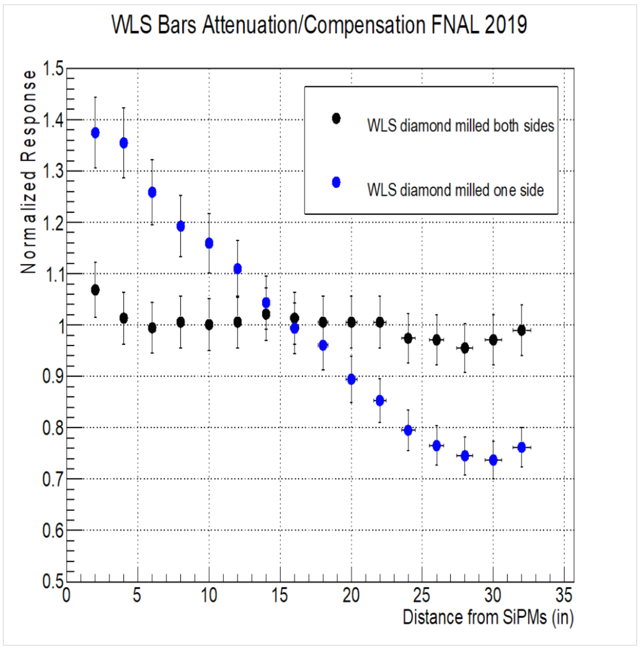


Figure 5. Variation of light collection efficiency vs length of WLS bars.

We now suspect that all WLS bars used at FNAL may have had different 'longitudinal' responses. They will be mapped in early January 2020, and we will update our MC model accordingly. We are also sending these WLS bars back to EJ so that they can inspect them. Per our discussion with EJ, it became clear that they probably had some problems with their tooling at the time of production for our batch of WLS bars. We have been assured that they have now fixed their tooling problems and will implement better QA methods before we order the full set of WLS plates for FCS, which will happen late January after we understand what caused observed variations in light collection efficiency.

Discussion.

As it was discussed during the closeout of previous the R&D meeting, the committee wanted us to focus on more targeted R&D as time is short and the EIC project is developing fast. We agree with the recommendation, although it is not completely clear how this will work prior to the formation of EIC collaborations. Discussions regarding the requirements for a forward calorimeter system and instrumentation required for the very forward region where a ZDC is generally needed led us to re-adjust our immediate R&D priorities. In particular, the requirements for the ZDC energy resolution may not be as strict as previously considered. This was discussed during the SBU workshop for ZDC instrumentation in the fall of 2019. We believe that a compensation technique for the ZDC may be sufficient, i.e. there may be no need for timing. For the central detector there were different numbers for the energy resolution shown at different recent meetings, ranging from about 60%/√ (E) to 40%/√(E) (as shown at December MIT kick off meeting for Yellow report). We believe that this will continue to iterate in the near future. However, one parameter for the forward calorimeter system is already well known. Space for such system would be very limited, which will lead to a longitudinally leaky calorimeter system. Thus, we want to investigate what methods we can develop to mitigate the effects of leakage, which, as shown in Figure 3, can contribute to both the constant and stochastic terms significantly at the highest energies expected at EIC. Our MC studies performed with asymmetric WLS bars lead us to a new idea in which we can use in the central detector to mitigate shower leakage. It seems to be very easy in practice to implement longitudinal segmentation of the HCAL readout by utilizing asymmetric WLS bars and an additional wedge shaped WLS bar in the same volume to readout ~ 30% of the scintillation tiles at the back side of the tower (so called tail catcher). In next six months we want to carry out MC simulations to understand how well that may work. In principle, one can consider a forward calorimeter system as a 4D device, and if timing will work, as a 5D system. Here we want to stress that this should not be confused with 5D calorimeter systems discussed for future HEP experiments (see, for example, the calorimeter summary shown at the DOE BRN Study Workshop on HEP Detector R&D, Dec. 11 2019). What we mean by a 4D system is (ECal + HCal + longitudinal separation in HCal readout), while a 5D system includes additional timing. However, our use of timing information is completely different than the one referred to in HEP, as we are interested to measure fluctuations of the f_{em} fraction in hadronic showers, rather than, for example, handling huge pileups. We therefore believe that timing will be most the difficult part of the calorimeter system, and that maybe 4D will be sufficient for the EIC forward calorimeter system for the central detector.

Finally, we want to discuss the funding situation and schedule. The last high-resolution hadronic calorimeter systems were built almost 30 years ago by the HEP community. In the foreseeable future, the HEP community will continue developing 5D calorimeters targeting specific HEP requirements, which has little in common with EIC. If the EIC physics goals truly require a central HCal with an energy resolution of ~40%/√(E), we request that the R&D funds for hadronic calorimeters be significantly increased in order to develop the expertise to meet the time schedule envisioned for EIC detector construction.

Sub Project 2: Tungsten Scintillating Fiber Calorimeter Developments in sPHENIX and future EIC Applications
Project Leader: C.Woody

What was planned for this period?

Our main activities planned for this period were:

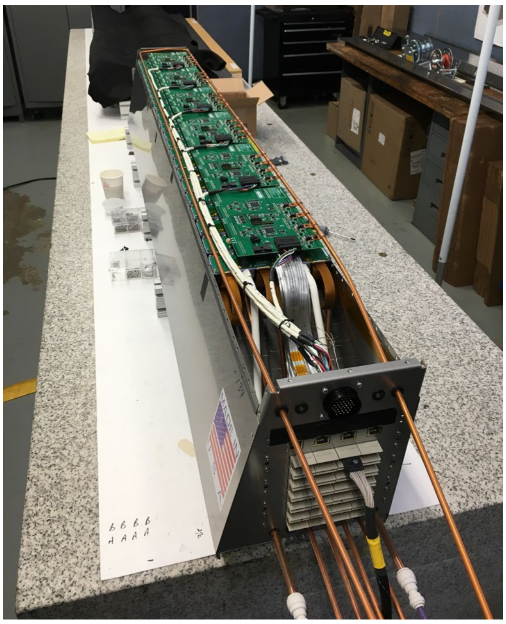
- Complete construction of the sPHENIX EMCAL Sector 0 prototype.
- Begin construction of sPHENIX EMCAL pre-production Sectors 1-12.
- Initiate studies on improving the performance of W/SciFi modules by increasing the photocathode area coverage using large area SiPMs.

What was achieved?

Progress on the sPHENIX W/SciFi EMCAL

sPHENIX successfully passed its PD-2/3 Review in May and received official PD-2/3 approval in September 2020. This now allows sPHENIX to proceed on a rapid path towards construction, installation and commissioning by the end of 2022 followed by the start of data taking in 2023. The first EMCAL preproduction sector (Sector 0) completed its first trial assembly in the fall of 2019. A number of changes and modifications were made to improve the sector design and assembly procedure and we are now in the process of completing its final assembly. In addition, we are proceeding with the construction of the first 12 preproduction sectors (Sectors 1-12) which are expected to be completed by the summer of 2020.

Figure 2.1 on the left shows Sector 0 during a trial assembly. All blocks, SiPMs and internal electronics have been installed, but only preliminary versions of the signal cables and the internal cooling were installed at this time. Figure 2.1 on the right shows a later installation of the final signal cables after adjusting their lengths. Figure 2.2 shows the blocks for Sector 1 being test fit onto their mounting support. We are currently waiting for the new versions of the internal electronics to be delivered that will be installed in all of the next pre-production sectors, which we hope will start arriving in January 2020.



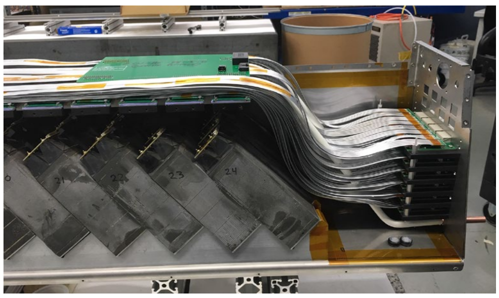


Fig. 2.1. Trial assembly of the sPHENIX EMCAL Sector 0 prototype. The photo on the left shows the sector assembled with all of its blocks, SiPMs and internal readout electronics, but with preliminary versions of the signal cables and internal cooling loops. The photo on the right shows a later installation of the final signal cables after adjusting their lengths.

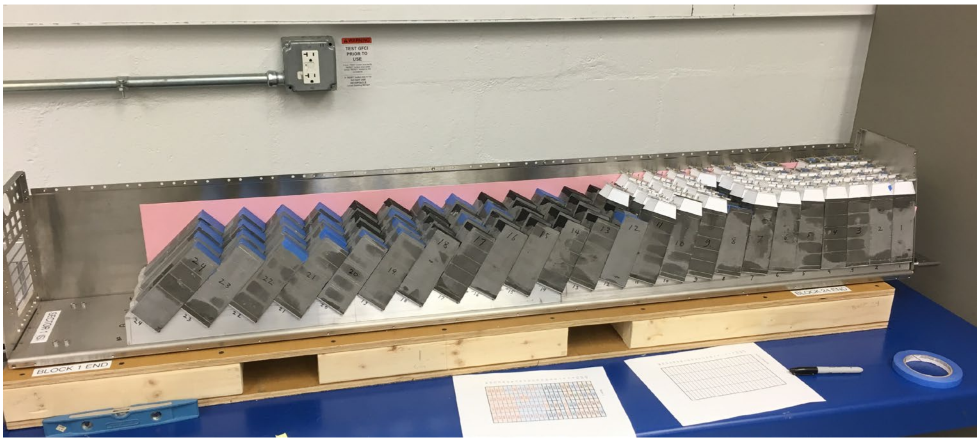


Fig. 2.2. Blocks for Sector 1 being test fit onto their support structure at BNL.

Each sector will have two internal cooling loops, one for the SiPMs and another independent loop for the preamps and other readout electronics. Due to the expected increase in dark current in the SiPMs after radiation damage, significant additional cooling capacity is being provided to cool the SiPMs after several years of running. Figure 2.3 shows the latest version of the SiPM cooling loop undergoing another trial assembly in Sector 0. It consists of two separate loops that are connected to cooling plates on the back of the SiPM daughter boards (each of which contain 16 SiPMs) using thermal braids. Thermal insulation will also be installed around the loops and other components to improve overall cooling efficiency. The cooling loops will remove the additional heat generated by the increased dark current in the SiPMs after radiation exposure and allow us to keep the temperature of the SiPMs at their nominal operating temperature (~ 20 °C), or go lower in temperature (~ 5 °C) if necessary.

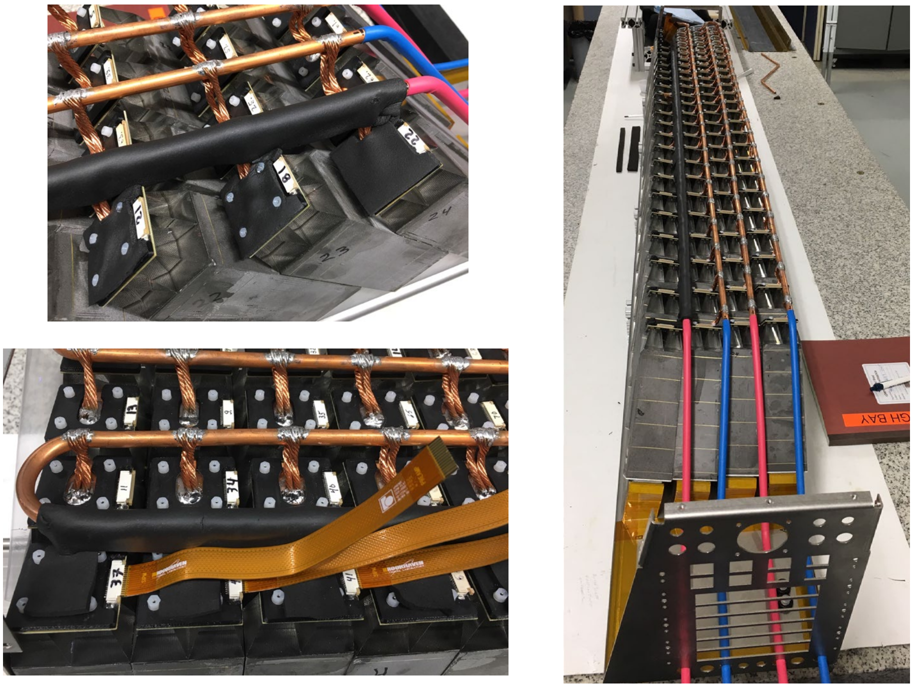


Fig. 2.3. Improved version of the SiPM cooling loops undergoing a trial assembly in Sector 0. The copper loops are connected to cooling plates on the back of the SiPM daughter boards using thermal braids. Insulation around the loops is also provided.

SiPM cooling and radiation damage

An important point should be noted about the current sPHENIX EMCAL design that could affect the use of the calorimeter at EIC, or any other calorimeter at EIC that would use SiPMs. After 3-5 years of running sPHENIX with heavy ion collisions at RHIC, one would likely want to change the SiPMs on the EMCAL, and perhaps even on the HCAL, before using these detectors for an EIC experiment The SiPMs used in the current sPHENIX calorimeters are an earlier version of the Hamamatsu 3x3 mm^2 15 μm pixel MPPCs (S12572-015P). A newer version of 3x3 mm^2 15 μm pixel devices is now available (S14160-3015PS) which has lower dark current, less cross talk and lower after pulsing than the earlier devices, and also operates at a lower bias voltage (~ 40 V vs ~ 70 V). Therefore, one would certainly want to replace the SiPMs with the new devices to refurbish the calorimeters for use at EIC, or use even more improved devices that may become available by that time. However, one would also want to improve the cooling of the new SiPMs as well. The S12572-015Ps are surface mounted devices that are mounted onto the SiPM daughter cards, which are cooled by copper cooling plates on the back of the PCBs. However, the thermal contact to the actual SiPM is mainly through the pads on the daughter cards, since the PCBs are poor thermal conductors, which then only contacts the internal silicon device itself through thin wire bonded leads. In order to keep the breakdown voltage the same with increasing current, one must cool the actual junction inside the device (see our previous report from January 2019), and therefore the cooling of this junction with the present scheme is rather inefficient.

We carried out a series of tests to study how external cooling of the SiPMs affect their gain stability after radiation damage. A group of Hamamatsu S12572-015Ps were irradiated to with neutrons at the reactor at the University of Lowell in Massachusetts for integrated fluences of 10^{10}, 10^{11} and 10^{12} n/cm^2. The gain of the unirradiated devices was measured using a LED inside a temperature controlled oven that was nominally used to determine the temperature of the SiPM. However, the temperature of the oven corresponded essentially to the temperature of the SiPM package and not the actual internal temperature of the device. In the case of the sPHENIX EMCAL, the temperature of the SiPMs is measured with a thermistor on the back of the daughter boards.

Figure 2.4 on the left shows how the gain of the SiPM changes after radiation damage when held at a constant temperature as determined by the temperature of the oven. After a dose of 10^{11} n/cm^2, the gain dropped by ~ 20% when the device (oven) temperature was held at a fixed at 23 °C. It was necessary to lower the temperature to ~ 13 °C in order to restore the full gain after radiation damage. This indicates that oven temperature (which should be very close to the temperature of the SiPM package) is not the same at the actual junction temperature inside the device, which is presumably much higher due to the high leakage current.

Figure 2.4 on the right shows the same effect measured in a different manner. It shows the current increasing due to the irradiation and the reduction in current as the measured temperature is reduced. However, lowering the temperature by even a large factor (from 23 °C to 5 °C) only lowers the current by a small amount (~ 30%).

Both these tests emphasize the need to provide extremely good thermal contact to the actual SiPM devices themselves in any future design. The design of the sPHENIX EMCAL needed to comply with numerous constraints on space, cost and schedule, and while this will always be true in any future design, it will be important to provide good thermal cooling for any detector using SiPMs at the EIC.

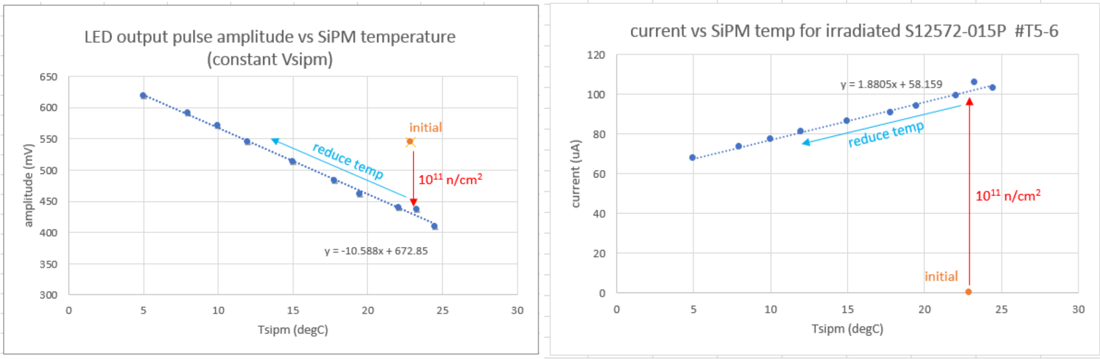


Fig. 2.4. Left: Dependence of the gain of a Hamamatsu S12572-015P before and after exposure to 10^{11} n/cm^2 as measured by the amplitude of a LED pulser as a function of the temperature of the SiPM as measured by the oven temperature. Right: Current of the same SiPM after irradiation as a function of the SiPM temperature as measured by the oven.

Further improvements may also become available with future developments in SiPM technologies for EIC. SiPMs are now available with Through Silicon Vias (TSVs) that provide much better thermal contact between the electrical pads on the device and the internal silicon inside. For example, the Hamamatsu S14160-3050HS is a 3x3 mm^2 device with TSVs, but it is currently only available in a 50 μm pixel version. However, smaller pixel devices may become available by the time they are needed for EIC. In addition, better packaging is being developed to provide better thermal contact as well. Hamamatsu has already developed such a package for the UV extended SiPMs for the Mu2e experiment at Fermilab which expects exposures up to 10^{12} n/cm^2 and will operate at 0° C.

Progress on block production in China

Our Chinese collaborators have been developing the capability to produce W/SciFi absorber blocks that will be used to instrument the large rapidity sections of the sPHENIX EMCAL. They have been working with UIUC to adopt the technology for producing blocks, testing them and carrying out QA evaluation on them. They have acquired scintillating fibers from Kuraray and have been investigating tungsten powder from several suppliers in China. They have found several suppliers that can provide powder with very similar properties as the Stack powder being used at UIUC, and at a lower cost. Figure 2.5 shows electron microscope photographs of the powder from one of the Chinese suppliers compared to the Starck powder. While there are some small differences in the distribution or particle sizes, the powders are very similar and have proven to produce blocks with very similar properties. Figure 2.6 shows some of the blocks produced at Fudan University that have been shown to meet the sPHENIX specs. Our Chinese collaborators will continue to develop their procedures for producing blocks and plan to be able to deliver the first production quality blocks by early next year.

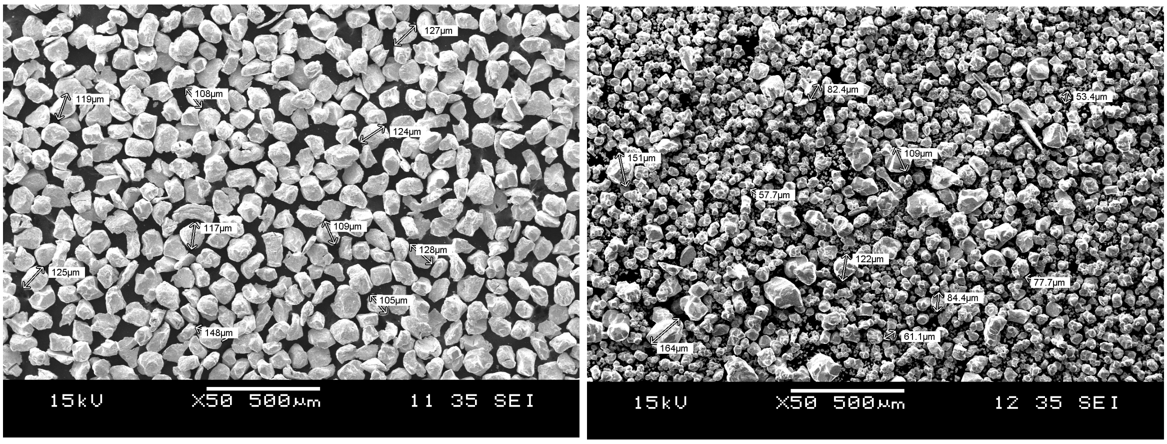


Fig. 2.5. Electron microscope photographs of Chinese tungsten powder (left) and Starck powder (right).

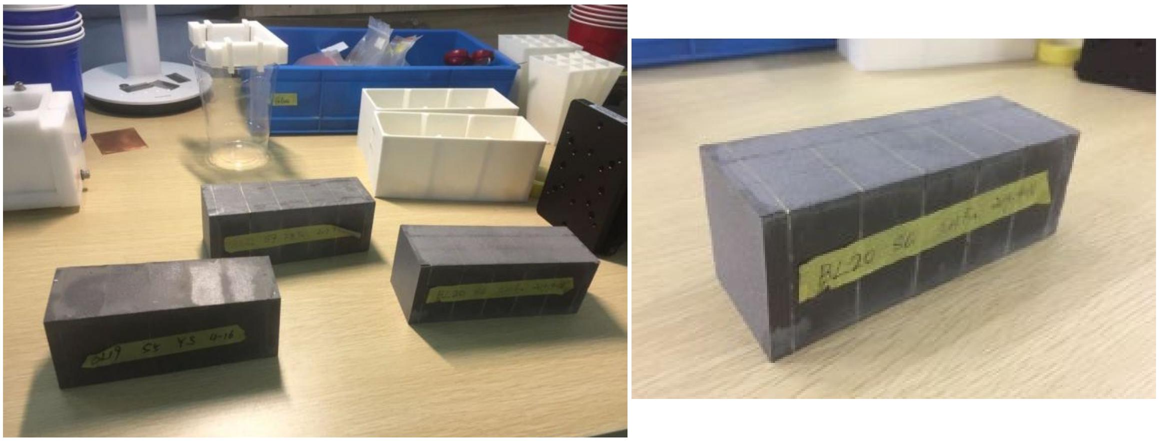


Fig. 2.6. Examples of W/SciFi absorber blocks produced at Fudan University in China.

Studies on increasing the photocathode coverage W/SciFi modules

As shown in several previous reports, W/SciFi calorimeter modules suffer from several inherent non-uniformities do to various practical considerations in their construction. While the uniformity of the array of fibers at the readout end of the block can be kept very uniform by controlling their position and using care in their fabrication, there are necessarily regions around the edges of the block that will have fewer fibers due to the tolerances of the mold and the need to machine the surfaces of the blocks without damaging the fibers. In addition, in the sPHENIX design, the blocks are read out using 4 light guides, each of which is read out with four 3x3 mm^2 SiPMs. This leads to non-uniformities at the boundaries of the light guides, as well as non-uniformities in light collection at the readout end of the light guide due to the fact that the 4 SiPMs cover only a small fraction of the readout area.

With the availability of new larger area SiPMs currently on the market, it should be possible to improve both the light collection efficiency and uniformity of light collection from the W/SciFi block by simply covering the readout end of the block with SiPMs. Note that this should essentially eliminate the effects of the light guide boundaries.

Figure 2.7 on the left shows one of the of 6x6 mm^2 SiPMs currently available from Hamamatsu. This device is the S13360-6025PE which is available in a 25 μm pixel version. It is a surface mounted device and has a small dead region on one side where the wire bonded signal leads are brought to the back of the device where the readout pads are located. However, another version of a 6x6 mm^2 SiPM is the S14160 series which uses TSVs to bring the contacts to the back and allows a so-called buttable configuration with virtually no dead areas between devices. The photo on the right in Fig. 2.7 right shows the S14161-6050HS-04, which is a pre-packaged 4x4 array of these devices. However, they can also be purchased as individual devices (S14161-6050HS) and assembled into a custom array.

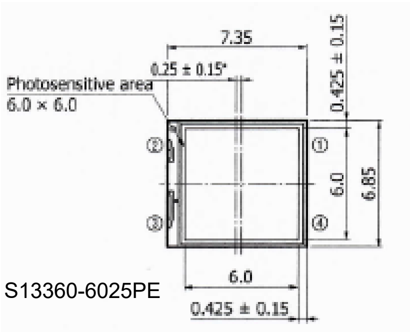
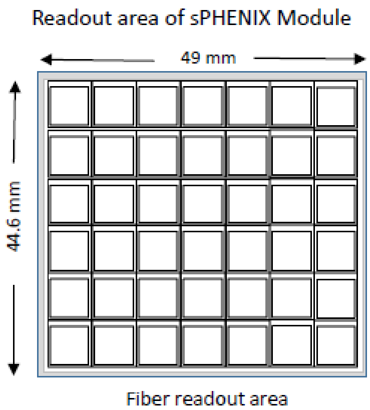


Fig. 2.7. Left: Hamamatsu S13360-6025PE 6x6 mm^2 SiPM with 25 μm pixels and wire bond connections to readout pads on the back. Right: S14161-6050HS-04 4x4 array of 6x6 mm^2 SiPMs with 50 μm pixels and TSV connections to the readout pads on the back of the array.

We investigated an initial design using the S13360-6025PEs to understand how the readout end of a sPHENIX absorber block could be covered with an array of these devices. The readout area of the block could in principle be covered with a 6x7 array as shown on the left in Fig. 2.8. However, one also wants to create 2x2 towers at the readout end, which suggests a more symmetric 6x6 array as shown in the PCB design on the right in Fig. 2.8. This would allow 3x3 devices to be summed together to form 4 individual equal sized towers.



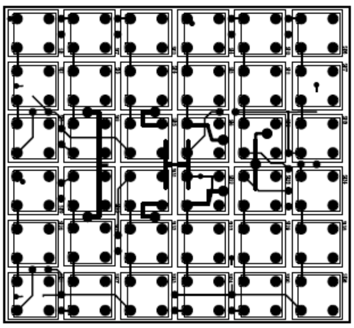


Fig. 2.8. Left: 6x7 array of S13360-6025PEs covering the readout end of a sPHENIX absorber block. Right: PCB design for a 6x6 array of S13360-6025PEs that allows reading out 2x2 towers of equal size and series/parallel connection of the devices.

There is also another issue when connecting multiple large area SiPMs together, which is the large resulting capacitance. Each S13360-6025PE has a capacitance of 1.28 nf. Therefore, the sum, when connected in parallel, would be 11.5 nf, which is quite large. However, one can also connect subsets of devices in series, which reduces the combined capacitance. This is done in with the SiPM readout in the Mu2e experiment where 3 SiPMs are connected in series and has been shown to work. Therefore, with a 3x3 array, one could connect 3 devices in a row in series and then connect the three rows in parallel with a resulting capacitance equal to that of a single device.

We are currently exploring this design and also exploring the possibility of using the S14161-6050HS TSV devices to obtain even better photocathode coverage. However, neither the S13360-6025PE (25 μm pixel) nor the S14161-6050HS (50 μm pixel) is currently available in a 15 μm pixel version (which would be highly desirable for calorimetry applications), but such devices are likely to become available in the future. In either case, for an initial test, the array of 6x6 mm2 SiPMs would be coupled to the readout end of the W/SciFi block with a short (~ 1.5 mm) light guide covering the entire readout area to allow mixing of the light from neighboring fibers, therefore eliminating any non-uniformities at the boundary of the light guides as in the sPHENIX design.

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

We believe we achieved all that we planned to do during the past six months. sPHENIX achieved its PD-2/3 approval and is now moving forward with construction. We completed the EMCAL Sector 0 preproduction prototype which refined the sector design and assembly procedure so that we can now begin construction of the next 12 preproduction sectors (Sectors 1-12). Fabrication of blocks for these sectors is currently under way at UIUC and the initial stages of assembly of Sector 1 has begun at BNL. Fabrication of blocks is also being carried out at Fudan University in China.

We also carried out further radiation damage tests on the SiPMs that will be used in the sPHENIX EMCAL and determined that additional cooling will be required in order to keep their gain constant as they experience radiation damage during operation at RHIC. We also learned that providing good thermal contact to the SiPMs will be very important in any future detector design using SiPMs at the EIC.

We started to investigate a design for reading out W/SciFi blocks with arrays of large area SiPMs to increase the photocathode coverage and reduce the non-uniformities associated with reading out the blocks. Several options are being explored, including standard devices with wire bond connections as well as newer devices with TSVs. We plan to decide on which options to pursue shortly after the first of the year, and then order the SiPMs and corresponding readout boards and test the concept.

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 construct the next 12 preproduction sectors for the sPHENIX EMCAL. The procedures for doing this will prepare us for the construction of the remaining sectors of the EMCAL which will begin in the summer of 2020. Our plan for constructing the EMCAL is fully described in the resource loaded schedule in Primavera P6.

For the large area SiPM readout, we will decide on which options to pursue (S13360-6025PE and/or S14161-6050HS) and then design and built the appropriate readout boards to read them out. We will then measure the uniformity of response of the sPHENIX EMCAL blocks with these readouts and compare the results with the current light guide/4 SiPM readout.

What are critical issues?

The most critical issues during the next six months will be to continue with the construction of the EMCAL sectors and to keep the project on schedule. Currently, the most critical aspect of this is the shortage of manpower to carry out many of the tasks involved, especially for the sector assembly and testing at BNL. There is also a shortage of manpower to carry out the large area SiPM tests as well.

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, the University of Michigan and Debrecen University in Hungary. The effort on the large area SiPM readout is done with personnel within the BNL sPHENIX Group whenever time is available.

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.

Publications in Peer Reviewed Journals:

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.

New since last report:

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

Sub Project 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 activity planned for this period was to complete the construction of the five additional prototype W/Cu shashlik calorimeter modules in order to give us a total of nine modules. The modules would first be tested at UTFSM and then sent to BNL for further testing where they would assembled into a 3x3 matrix of modules that could be tested in the test beam. We also planned to carry out further studies of the light collection within the shashlik modules using both a small stack of W/Cu and scintillator plates with WLS fibers as well as with simulations using a ray tracing program. We also planned to test some of the PHENIX Pb/Sc shashlik modules and compare them to the W/Cu shashlik modules.

What was achieved?

The remaining 5 modules were constructed and tested at UTFSM and send to BNL in mid December 2019. Figure 3.1 shows all nine modules that have now been received at BNL. Each is instrumented with 16 Hamamatsu S14160-3015PS SiPMs that are used to read out 16 individual WLS fibers running through the module. All modules were tested at UTFSM before shipment to BNL using the internal LED system and shown to be working. Figure 3.2 shows an example of the LED spectra for one of the modules measured at UTFSM.

Figure 3.1. Nine W/Cu shashlik modules that were constructed at UTFSM and are now at BNL.

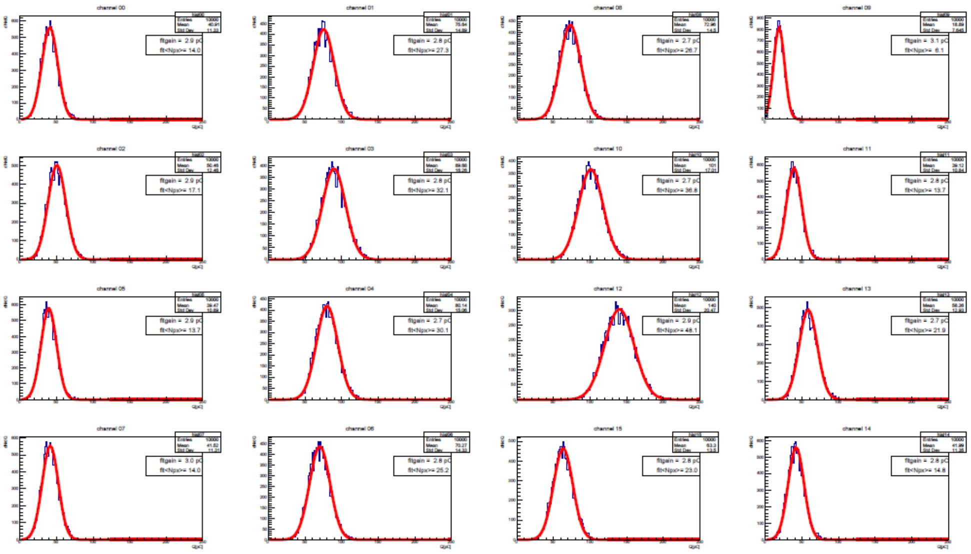


Figure 3.2. LED spectra of one of the shashlik modules measured at UTFSM.

Figure 3.3 shows the nine modules arranged into a 3x3 array as they will be tested in the test beam. Note, however, that a separate support structure and enclosure must be built in order to test them in the beam. In addition, the SiPMs will need to be connected to the sPHENIX calorimeter readout electronics, which will require making additional interface boards as shown in our previous report. The 3x3 array of modules will require 144 readout channels and will first need be tested with the sPHENIX readout electronics at BNL before doing any beam test. We plan to start these activities beginning in early January, although progress will be slow due to the limited availability of sPHENIX manpower. However, we hope to have an engineer from UTFSM come to BNL early next year to help with these activities, and the process of obtaining all the necessary approvals for this has been started.

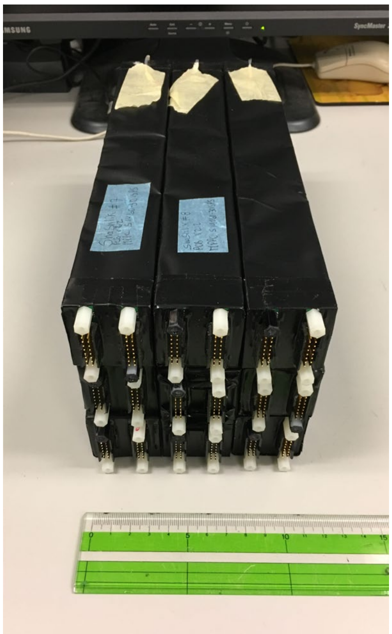


Fig. 3.3. Nine W/Cu shashlik modules arranged in a 3x3 array as they will be tested in the beam.

We also carried out simulations of the light collection within the shashlik modules using a ray tracing program (TracePro). These simulations were done by our SULI student last summer and some preliminary results were given in our last report and shown at the last Detector R&D meeting.

Figures 3.4, 3.5 and 3.6 give a summary of these results. Figure 3.4 shows the geometrical model of a scintillating tile and an example of some of the rays that were generated and traced through the tile using TracePro.

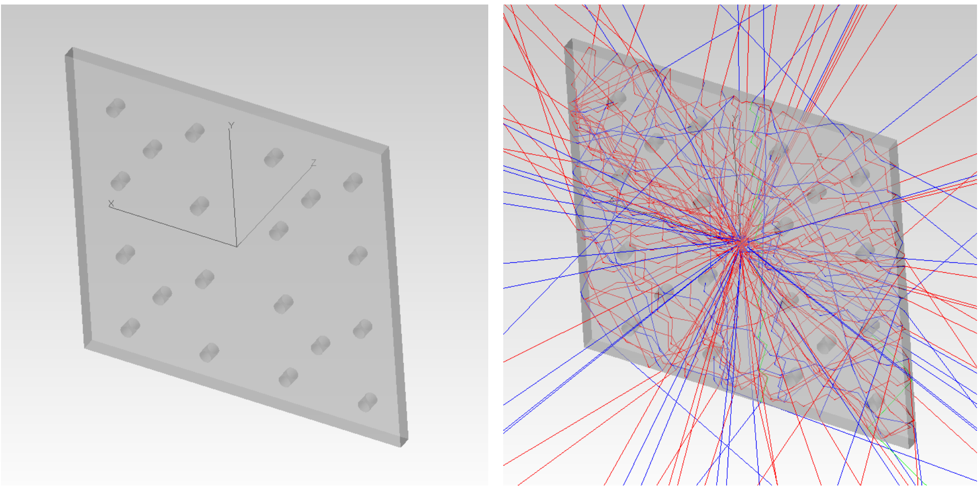


Fig. 3.4. Left: Geometrical model of a scintillating tile. Right: Example of rays traced inside the tile using TracePro.

The program modeled the light collected in each of the 16 readout fibers and was used to measure the uniformity of light collection as a point source of light was moved across the tile. Figure 3.5 shows how the collected light varies between two WLS fibers along with the sum for both fibers. The uniformity appears to be ~ ± 10 % except near the edges

Fig. 3.5. Light collected in two adjacent fibers in a scintillating tile as a function of the position of a point source of light generated in the tile, along with the sum of the light from the two fibers.

Tests were also done using the “Short Stack” of absorber plates and tiles described in our previous report. It was used to scan a fiber illuminated with a LED across the outermost tile to excite the scintillator and measure the light collected in each of the fibers. A weighted average of the position of the light source could then be calculated and compared with the known position of the excitation fiber. Figure 3.6 shows a comparison of the measured fiber position vs the known fiber position for both the MC simulation (orange curve) and the experimental data (blue curve). In the experimental data, due to the thin tile, a large fraction of the injected light is not absorbed in the tile and contributes to a large background which we tried to correct for using an assumed model. The overall dependence of the measured position vs the known position agrees, but the actual slopes do not agree very well, presumably due to various experimental effects that are not properly simulated in the Monte Carlo. Unfortunately, our SULI student left before these studies could be completed and no further progress has been made since that time.

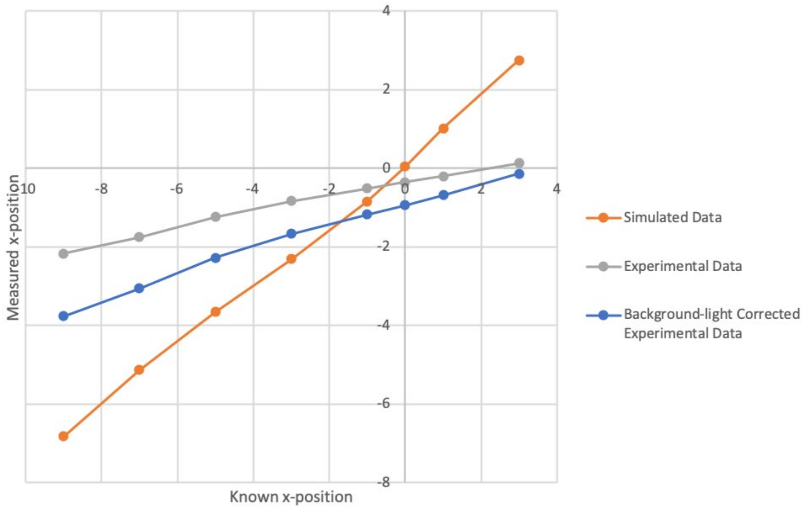


Fig. 3.6. Plot of the measured position vs the actual position of a point source of light scanned across a shashlik tile that is read out with 16 WLS fibers. The gray curve gives the raw experimental data and the blue curve gives the experimental data after a correction for the background of direct light injected into the tile from the excitation fiber.

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

We completed the construction of all 9 shashlik calorimeter modules and tested them at UTFSM, but they did not arrive at BNL until December and we therefore did not have time to test them in time for this report. Testing of these modules at BNL will begin starting in January, but a full test of the 3x3 array of modules will require fabricating additional interface boards to connect them to the sPHENIX calorimeter readout electronics.

We also completed the first preliminary studies of the light collection within the shashlik modules using both simulations and lab measurements, but we did not complete these studies due to the departure of our SULI student in early August 2019.

We also did not do any tests with the PHENIX Pb/Sc shashlik modules due to lack of manpower.

Future

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

Our main goal for the next funding cycle and beyond is to test the 3x3 matrix of shashlik modules and compare their performance in terms of energy resolution and uniformity with the W/SciFi modules from the sPHENIX calorimeter. Testing of all nine modules with the sPHENIX electronics will require a dedicated effort and we currently have no one at BNL who can spend the necessary time on this to get the system working do the testing. However, we have initiated the process of getting approval for an engineer from UTFSM to come to BNL to help with this, who we hope will arrive by February or March of 2020.

Assuming the modules and readout system can be put together and successfully tested by March or early April, we would take the modules to Fermilab where they would be tested in the test beam along with other sPHENIX calorimeter tests that are planned for the end of April.

We would also like to continue our studies of the light collection properties of the shashlik modules using both simulations as well as laboratory measurements. However, we again have no one at BNL who can spend time on this given our other commitments with sPHENIX.

Finally, we would also like to test the PHENIX Pb/Sc shashlik modules and compare them to the W/Cu modules but we have no manpower to devote to this effort.

What are critical issues?

The main critical issue is lack of available manpower, particularly at BNL. The sPHENIX group is extremely busy now with the construction of the sPHENIX EMCAL and it is extremely difficult for anyone to devote any substantial amount of time to this activity. We would therefore greatly benefit from a graduate student or post doc who could work on this project, and we intend to ask for this in our next funding request.

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.

- The technical work at UTSFM was carried out with approximately 10% of an FTE that was supported entirely from internal funding.
- All of the effort on this project at BNL has been carried out by the BNL sPHENIX Group.

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 manpower utilized at UTFSM on this project was paid for with internal funds.
- All work done by the scientific staff at BNL on this project is supported by sPHENIX Group or sPHENIX Project funds, while some technical and/or engineering work is being supported by eRD1 funds.

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. 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 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, e.g., glass resistance to hadron radiation, 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 new sources of raw material

What was achieved?

Over the last 6 months, we have been working closely with the vendors and through synergy with the NPS to characterize an additional 116 CRYTUR $PbWO_4$ crystals. None have been rejected so far. We also produced, in collaboration with the Vitreous State Laboratory (VSL) and vendors, five 2 x 2 x 2cm^3 and two 2 x 2 x 20cm^3 glass ceramic samples. Physical and luminescence characterization was carried out at CUA. EM irradiation tests have been performed at Orsay through collaboration with the Laboratoire de Chimie Physique with a panoramic irradiation facility based on 3000 Ci ^{60}Co sources. To test for possible hadron radiation damage, we irradiated two of the 2 x 2 x 2cm^3 glass samples at the MC40 Cyclotron, a high intensity irradiation line at the University of Birmingham. The first sample (VSL-Scintilex-G4-1) received a fluence of 4.3E15 neq/cm^2 (2E15 p/cm^2) and the second sample (VSL-Scintilex-SC1-1) received a fluence of 2.3E15 neq/cm^2 (1E15 p/cm^2). Figure 1 shows the two samples after the hadron irradiation was completed. No obvious discoloration, which

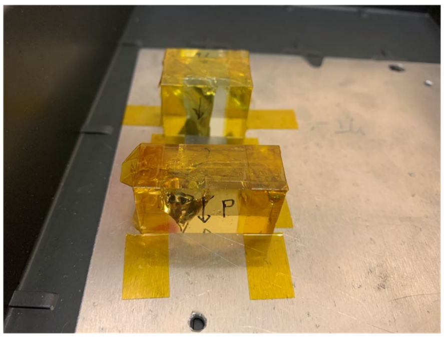


Fig 1: *Glass samples after hadron irradiation at the MC40 Cyclotron.*

may indicate radiation damage, was observed. The samples are currently stored in a temperature controlled dark box until activation is low enough for shipping them back. Measurements of optical characteristics will be performed when the samples have returned.

We have completed the optimization of glass formulations including heavy elements to increase sensitivity to EM probes and to meet the requirements of detector applications, and have started initial scale-up of our glass samples to larger ($2x2x20cm^3$) dimensions. This process is nontrivial as changes in properties related to glass melt batch size, such as surface area, can also change some of the high temperature reaction kinetics in the glass fabrication process. During the first scale-up attempts the glass sample bonded to the mold surface and could not be removed without breaking the glass. The mold was subsequently modified and three large samples were successfully produced. Figure 2 shows the first two samples of composition VSL-Scintilex-SC1. The sample shown at the front of is unpolished, the one at the back received some initial polishing. The bubbles visible in Figure 2 are located at the surface and can be removed in the polishing procedure.

Fig 2: *First $2x2x20cm^3$ glass samples*

Three main factors impact optical properties and light output, and therefore the overall scintillator performance: 1) Geometry, 2) Surface Quality, 3) Material Properties. Over the last six months we focused on the first two and started exploring optimizations for cutting and optical polishing the glass samples. Two polishing methods were explored. The first one uses standard glass polishing procedures, the second uses polishing methods for high precision optical components for laser scanning and imaging, airborne or space-borne sensors, optical flats, and molds for optical surfaces. Figure 3 shows two of the $2x2x2cm^3$ samples after polishing. The first polishing method was used for sample G4-23, the second for sample G4-22. The tolerance specifications are listed in Table 1. The flatness tolerance is the distance between two parallel planes, the roughness tolerance is a measure of surface irregularities. The specifications are based on those used for $PbWO_4$ crystals. Figure 4 shows measurements of the surface characteristics of two representative sides of sample G4-22 after polishing. A non-contact coherence scanning interferometer was

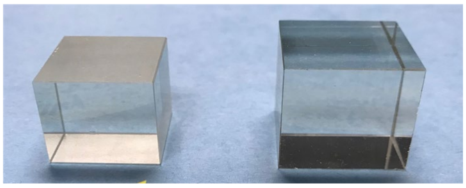


Fig 3: *G4-23 and G4-22 after polishing*

Sample	G4-23	G4-22
Flatness (mm)	0.01	0.02
Roughness (RA)		20
Parallelism (mm)		0.01
Perpendicularity	0.3-0.7	0.01

Table 1: *Surface Tolerances*

used to measure the optical profile of the surface simultaneously in all directions. This allowed for sampling the surface over a large area and averaging the frequency of irregularities. The results show that the surface quality is within and even better than the specifications listed in Table 1. The next step will be to evaluate the impact of the optimization of geometry and surface quality on optical and physics characteristics, as well as resolution.

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

Based on the BDX-MINI tests run at JLab in April 2019, INFNGE developed a version 2.0 of the WaveBoard digitiser used to read out photosensors (SiPMs). A new GPS system was bought and added to the test setup in Genova. A master thesis

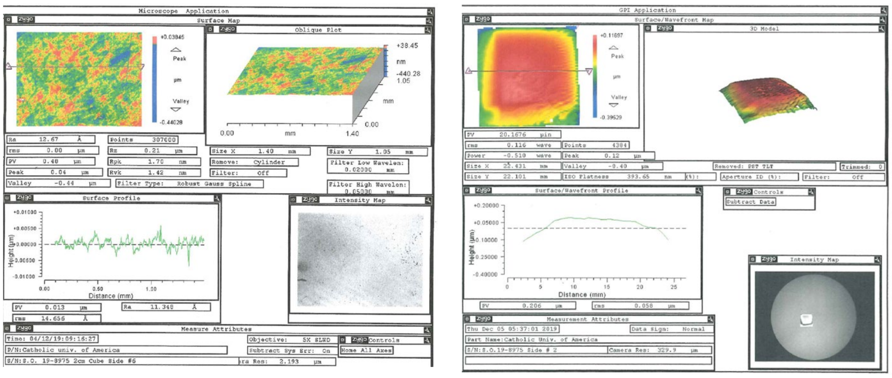


Fig 4: *Surface characteristics after polishing*

student (S.Vallarino) has been recruited and he is actively working on the test lab to synchronise the MRPC and crystals readout. The test facility will be used to characterize $PbWO_4$ and scintillating glass provided by CUA.

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

We have been analysing the 2018/19 data acquired with our 12x12 and 3x3 arrays of $PbWO_4$ crystals, but do not yet have additional results on energy and position resolution. We expect to conclude these studies over the next six months. We have yet to complete the planned additional electromagnetic irradiation studies, which have been delayed due to administrative procedures. We expect these to be resolved and the irradiation completed over the next six months. We have not yet carried out the glass/crystal prototype tests with SiPM (streaming) readout. However, we have gathered the needed expertise to install hardware and configure software to carry out these tests in Spring 2020.

In response to additional July 2019 and earlier R&D report recommendations, we started developing long-term goals and milestones for both crystals and glass scintillator development for EIC. We expect to complete an initial estimate of milestones and required resources in the next six months when additional information on crystal and glass production vendors, industry partnerships, and funding becomes available.

Future

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

Our main activities during the next 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. For crystals the main issues to address are quality control at SICCAS, development of production capacity with sustained crystal quality at CRYTUR, and continued availability of high purity raw material. We have had several encouraging discussions with the vendors and expect to continue these in the next six months.

Over the next six months we hope to have received at least ~240 additional CRYTUR and ~500 additional SICCAS crystals[1]. A total of 500 CRYTUR and 500 SICCAS crystals were ordered and are anticipated to be characterized. 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.

High quality crystals will remain expensive and the production process is slow compared to other materials. Our glass scintillator development effort thus plays an important role in large volume calorimetry. We plan to continue the production of larger glass samples with adequate surface quality for physical, luminescence, and radiation hardness studies. We are preparing for a prototype beam test program in spring 2020 to establish glass performance and iterate formulation/fabrication as needed. The prototype will be located behind the Hall D pair spectrometer (see Fig. 5) as for our 2018/19 NPS tests. We have assembled and are testing the crystal/glass-PMT-HV divider modules for this program. Some Front-End electronics used in Genova were moved to JLab to be used to readout crystals/glass. As soon as SiPMs will be available, a few channels will be instrumented and tested. For the next six months we will optimize the readout chain: SiPM, preamps, fADC and streaming DAQ system. We will first test the readout chain with crystals, then adapt it for scintillating glasses.

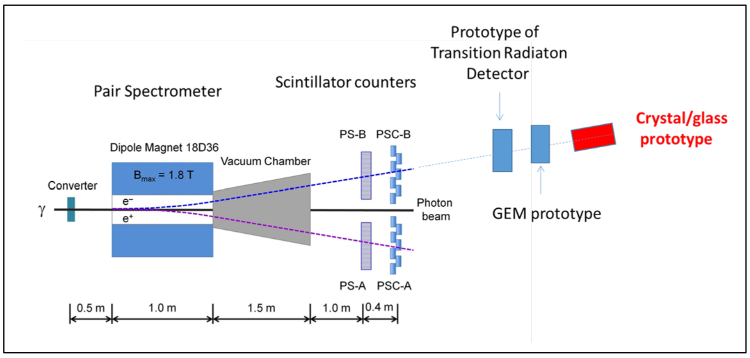


Fig 5: *Layout for fall 2020 prototype beam test with $PbWO_4$ and glass scintillator blocks.*

[1] 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.

We plan to extend our evaluation of glass scintillator as active material to additional regions, e.g., the barrel and hadron side. This will be important for a possible second detector with different technology to address systematic uncertainties in the physics measurements, but will also be of interest in its own right for the primary EIC detector. We have started setting up a Monte Carlo simulation for resolution studies and matching crystal and glass materials in the EMCal.

What are critical issues?

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

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, I.L. Pegg, Richard Trotta (graduate student), C. Walton (undergraduate student), Vitreous State Laboratory staff

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

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

INFN-GE
M. Battaglieri, A. Celentano, R. deVita, M. Bondi
JLAB
A. Somov

External Funding

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

- All of the FTEs required for working towards test setups and characterization are provided by CUA/VSL/IPN-Orsay/INFN-GE or external grants. The absence of labor costs makes this proposed R&D effort extremely cost effective.
- The 460 SIC crystals produced in 2017 and 211 CRYTUR crystals produced in 2018 and 2019, as well as the newly ordered 500 SICCAS and ~500 CRYUR crystals are provided through synergistic activities with independent research for the JLab Neutral Particle Spectrometer (NPS) project.
- The expertise and use of specialized instruments required for production, characterization, and chemical analysis are made possible through collaboration with the Vitreous State Laboratory (VSL) that is also collaborating on the NPS project.
- INFN is contributing in kind with part of the equipment of the testing lab at INFN-GE, as well as support for postdoctoral researcher Dr. Bondi.

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

Publications

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

- *Scintillating crystals for the Neutral Particle Spectrometer in Hall C at JLab*, V. Berdnikov, T. Horn, C. Munoz-Camacho, I.L. Pegg, A. Somov, *et al*., Nucl. Inst. Methods (2019) under review, arXiv:1911.11577
- *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)