Date: 12/31/15

EIC Detector R&D Progress Report

Project ID: eRD1
Project Name: EIC Calorimeter Development
Period Reported: from 7/1/15 to 12/31/15
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Overview

During the past six months, the eRD1 Calorimeter Consortium continued to develop new technologies for many calorimeter applications at EIC. These included technologies for a central barrel calorimeter, as well as forward calorimetry in both the electron going and hadron going directions. This R&D is being carried out by various groups, each with somewhat different emphasis on future applications. The BNL group, along with their collaborators at the University of Illinois at Urbana Champaign (UIUC), are focusing mainly on the central barrel calorimeter, adapting the technology for the tungsten scintillating fiber SPACAL that was originally developed at UCLA for a central barrel calorimeter for sPHENIX, which would also serve as a Day 1 detector for eRHIC. Considerable progress was made in learning how to produce W/Scifi modules in a simpler, more cost effective way that would eventually lead to being able to mass produce enough blocks for a larger central calorimeter. The UCLA group is also further developing this technology, with more of an emphasis on its application in the forward and backward rapidity directions, although many of the developments and improvements in this technology could also be applied to the central region. In the electron going direction at large rapidity, a high resolution version of the SPACAL would be required, and techniques are being developed that could achieve a resolution ~ 6-7%/√E. We are also investigating the use of crystal calorimetry in the electron going direction, particulary using lead tungstate, which would provide even better resolution at the level of 2%/√E. This effort is being lead by the groups at Catholic University/JLAB and IPN Orsay, with participation from the BNL and Caltech groups. In the hadron going direction at large rapidities, where we expect the radiation levels at EIC to be the highest, the UCLA group is investigating the use of APDs as an alternative readout for a SPACAL calorimeter in this region.

We have also carried out a new calculation that estimates expected neutron fluences at EIC. This was done using the simulation code that was developed to estimate the fluence levels in STAR and was adapted to model the BeAST detector at eRHIC. The simulation predicts fluences ~ 5×10^{10} n/cm^2 per run in the region of the forward calorimeter. Along with this, we have also carried out additional measurement on radiation damage in SiPMs, both with neutrons and with gamma rays.

All of the current work is ongoing and additional tests are planned for 2016, including beam tests of a prototype of the central barrel calorimeter for sPHENIX and a prototype of the high resolution SPACAL. Additional tests are also planned in both the PHENIX and STAR halls during the 2016 RHIC run to study radiation damage in SiPM and to compare SiPM versus APD readouts in the large rapidity region under actual running conditions.

Status of the Calorimeter Consortium

The Calorimeter Consortium of the EIC Detector R&D Program was formed in May of 2012 and has been carrying out a diversified program of R&D on calorimetry for EIC since that time. We feel this has been an extremely successful program. It has included R&D on compact sampling calorimeters, investigating both an accordion tungsten plate design as well as a tungsten powder scintillating fiber design that is currently being expanded. Based on this R&D, the sPHENIX collaboration has adopted the tungsten powder design for its central barrel electromagnetic calorimeter for sPHENIX, which may someday become a Day 1 detector for EIC. This design is now being extended to include possible applications in the forward and backward rapidity directions, which also includes improving the energy resolution that can be achieved with this technology. At the last meeting, we also proposed to study a new design for a shashlik sampling calorimeter that could lead to a new, cost effective method for implementing this technology at EIC.

Our collaboration also carries out R&D on scintillating crystals and has done detailed studies on BSO and PWO. Our work on PWO has also benefitted the physics program at JLAB which plans to use PWO on a shorter time scale than EIC, and has helped grow our collaboration and form alliances with other groups developing scintillating crystals for nuclear physics such as PANDA.

We are also developing new readout systems for calorimeters at EIC, many of which include the use of silicon photomultipliers. We have carried out numerous studies of radiation damage in these devices in order to understand their performance and operation under actual operating conditions in various radiation environments. These studies will also help understand the benefits and limitations of the use of these devices for many other applications.

Our collaboration has published four publications on the results of our R&D and many of our collaboration members have given talks at various conferences and workshops. We feel that efforts of the Calorimeter Consortium have served the EIC Community very well and that this effort should not only be continued but expanded in the future.

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

Past

What was planned for this period?

1. Backward EMC (BEMC) (electron-direction), Central EMC (CEMC), and Forward EMC (FEMC) (hadron direction) - Boost Light Yield (LY) with compensation from the back end of the calorimeter. The BEMC design aims at high energy resolution for electron measurement.
2. BEMC -- existing prototype re-work at UIUC, and change to a single PMT readout.
3. BEMC – build a new prototype with thicker fibers, single W absorber, optimized with MC, i.e. goal to have minimal complication in the design so that the test run data can be evaluated for viability of the technology.
4. BEMC -- test run at FNAL, determine limit on intrinsic resolution, and evaluate if this technology is viable for High Resolution ('HR') type EMC.
5. FEMC -- build a prototype detector with Kuraray radiation hard 3HF fibers, optimized for APDs (rad hardness next to the beam pipe, i.e. similar to PWO at back side, possible option for 'HR' readout).
6. Quantify rate of anomalous signals for SiPM and APD based readout.

What was achieved?

We have made progress in all six areas of interest.

We started detailed studies of light collection scheme for W/ScFi type calorimeters. We have built two single tower full-length detectors without filling them with tungsten powder. Tips of this detector had different finishes, which we think are technologically feasible for a mass scale production. One detector has essentially the same finish we had in the past, i.e. clear epoxy and fibers, the other one has TiO2 impregnated finish, as shown in Fig.1.1 At the beginning both ends of these detectors were diamond milled and then hand polished.

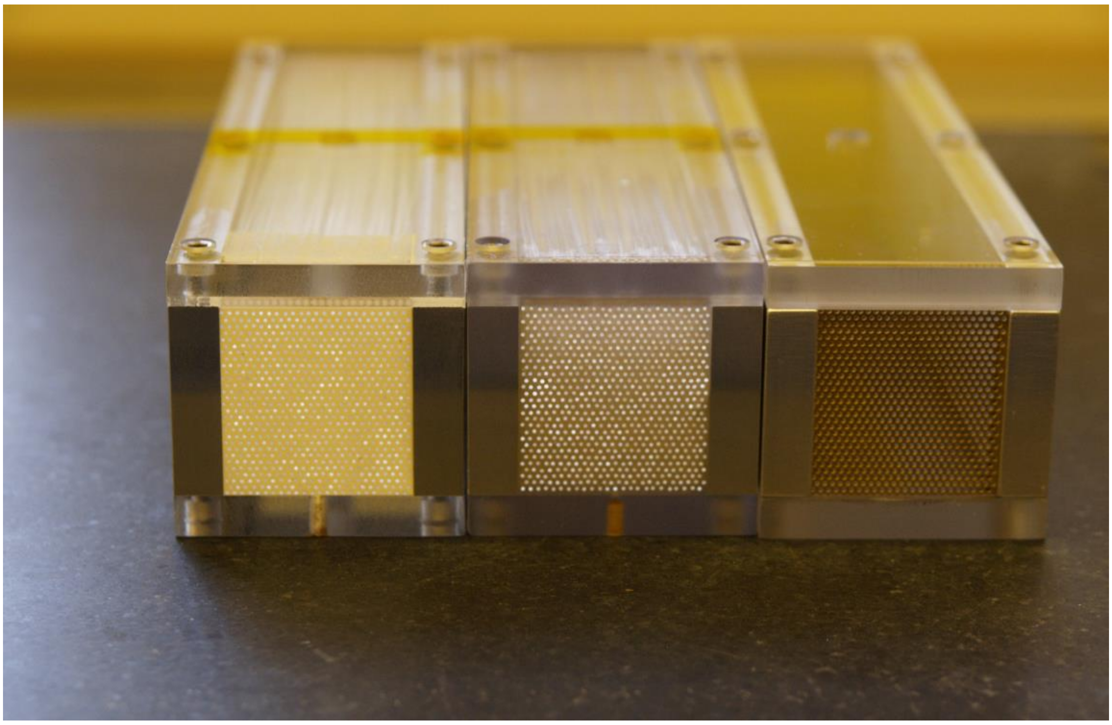


Figure 1.1 Two towers prepared for LY measurements.

Four (one on each side) 370 nm UV LEDs are used to excite scintillation fibers at the middle of the tower as shown in Fig. 1.2. Both ends of the assembly were filled with silicone to suppress cladding light. We used the same SiPM readout and light guides we had in the last test run. One of the SiPM boards was modified (the surface of the PCB were painted with TiO2). This setup allows to measure LY with different treatments of the ends of the module (polished, rough ends, glued reflectors etc.) at the far end of the fiber opposite of the photo detector. The first set of measurements was performed with polished far end. We used two types of mirrors and white diffusive reflector. An ESR mirror gives about 70% more light (same result we obtained in the test run 2012), cheap front face acrylic mirror gives about 65% more light, white diffuser 22%. The last result is a bit puzzling as expectation was about 12%. Possibly not all cladding light was suppressed in the set up. This set of measurements emulates sputtering mirrors or painting of the polished end of fibers, which we don’t favour, because of concerns of long term stability, protection and handling of modules built this way.

For a second set of measurements the surface of the fibers was abraded (following procedures recommended by Epotek for gluing) and again a set of materials was used as reflectors with a thin optical coupling (emulation epoxy). Acrylic mirror adds about 45%, white diffuser 15% and aluminium (cold pressed, not polished) 35%, compared to black film. At present, aluminium surface glued to the far end of the module seems to be the most robust option for BEMC and CEMC. The increase in LY is sufficient to perform equalization of light collection with SiPMs. For FEMC that may not be sufficient. We will continue developments in these directions and final summary of our measurements will be presented at the next (summer) EIC meeting.

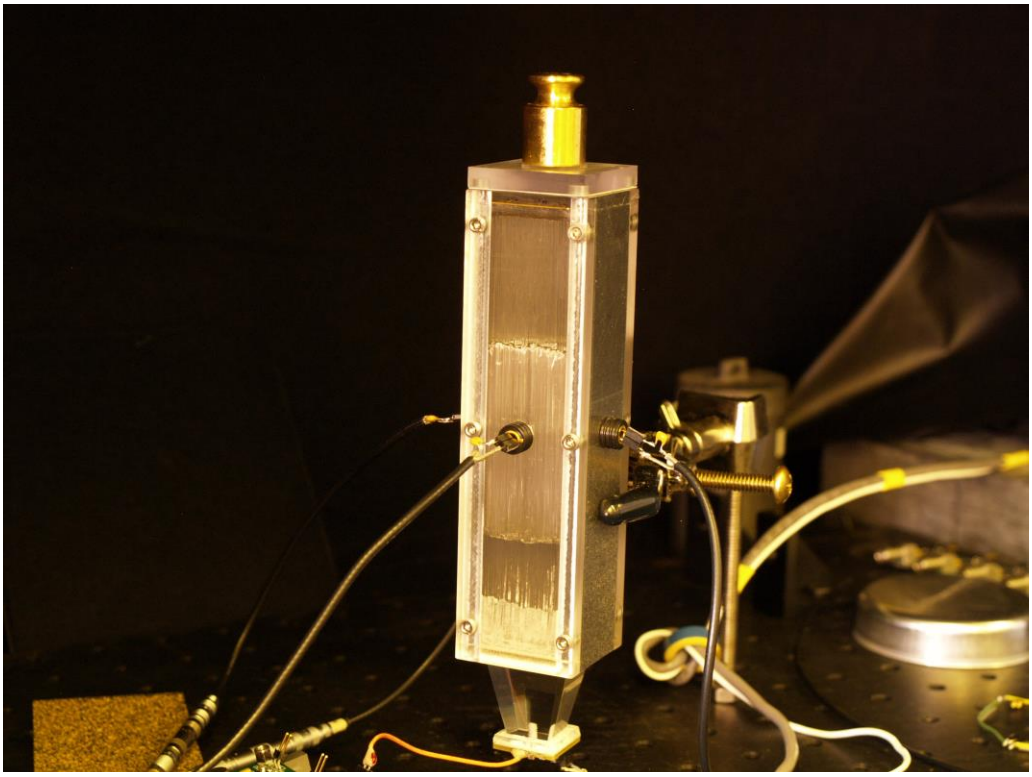


Figure 1.2. Setup to measure Light Yields

2. The BEMC prototype tested at FNAL in 2015 was re-worked at UIUC, both ends were diamond milled there. However, to achieve good optical finish at both ends we still had to hand polish them. The resulting finish is much better compared to what we had prior to the last test run. We will decide how to couple a large area PMT to this detector using either a long mirror pipe or a single long acrylic light guide.

3. Development of a new BEMC prototype with thicker fibers, single W absorber, optimized with MC, i.e. goal to have minimal complication in design so that interpretation of the test run data will be straightforward. We performed optimization of this new prototype, which required a series of Monte Carlo calculations (performed by A. Kiselev) and communications with both KURARAY and FOTOFAB to achieve required tolerances on components. At the end we decided to use square 0.6 mm SCSF78 fibers. Comparing to previous year prototype this new detector will have lesser frequency of sampling but increased sampling fraction and a single W powder absorber vs composite (W/Sn). The targeted energy resolution is shown in Fig. 1.3. Required meshes for construction of this detector were already produced, fibers from KURARAY were ordered with expected delivery in early March 2016. That will give us about two months prior to the scheduled test run at FNAL in May 2016 to build this detector.

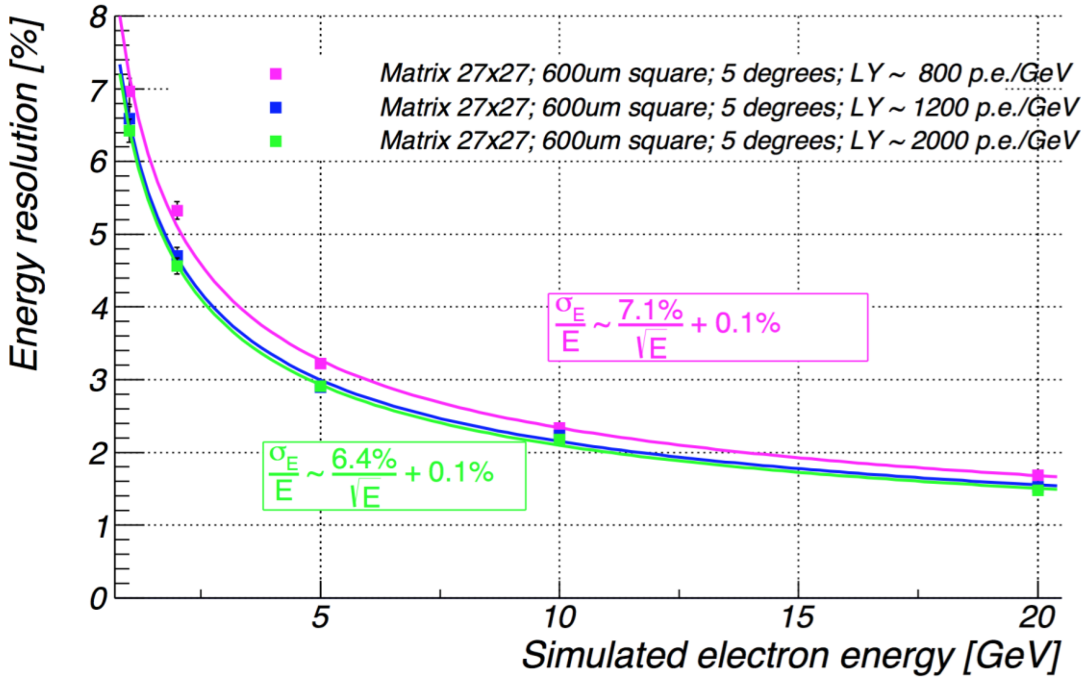


Figure 1.3. Expected energy resolution of new BEMC

4. A test run at FNAL has been scheduled for May 4- May 10, 2016.

5. We stopped the development of BEMC using radiation hard 3HF fibers due to reduced budget and technical issues with 3HF fibers. We measured light yield of 3HF fibers and found that it is only 22% of the standard SCSF78 fiber. That precludes using this type of fibers for any central calorimeters at EIC.

6. Quantify rates of anomalous signals for SiPM and APD based readout.

A. Kiselev calculated neutron fluxes for BeAST setup using EICRoot framework. As a sanity check, he first compared his calculation based on EICRoot with calculations done by Y. Fisyak for the STAR configuration 2014 (pp 200 GeV). A good agreement was found. Then he used BeAST detector model and STAR experimental hall, but without beam line elements. The resulted neutron fluxes for ep 20 x 250 GeV are shown in Fig. 1.4. Assuming designed EIC luminosity, in one year of running (100 days) the highest integrated fluence is about 5 x 10^{10} n/cm^2 at the FEMC locations. Neutron fluences at the BEMC and CEMC are expected to be about two orders of magnitude lower, which indicates that these detector areas are probably very safe for SiPM applications.

The biggest concern is the expected exposure at the FEMC location, which is similar to what we have at RHIC now. For calorimeters at this location we are investigating both SiPM and APD based readouts.

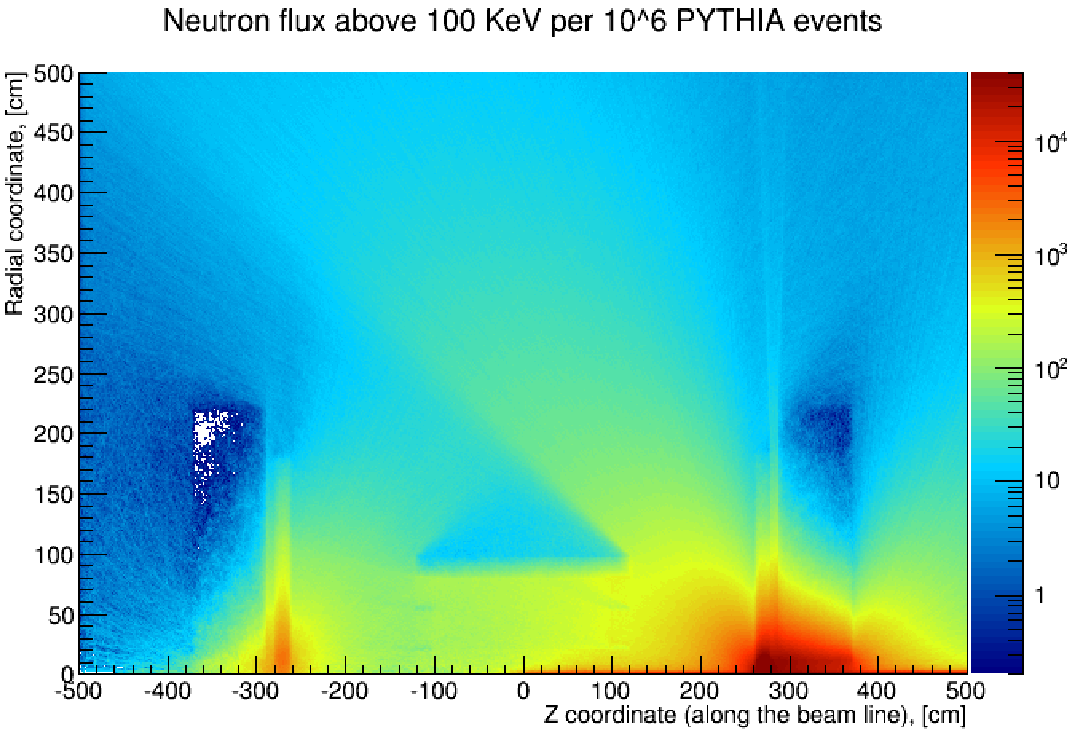


Figure 1.4 Neutron fluxes at BeAST, ep 20 x 250 GeV

We plan to have a testing set-up at the STAR experimental hall during the coming run in 2016. We equipped our existing BEMC prototype with a dual readout (SiPM at one end and a single large area PMT at the other end) as shown in Fig. 1.5. The side of the detector opposite to SiPM was diamond milled and hand polished. A large area PMT is coupled via mirror pipe. The setup is equipped with a LED monitoring system.

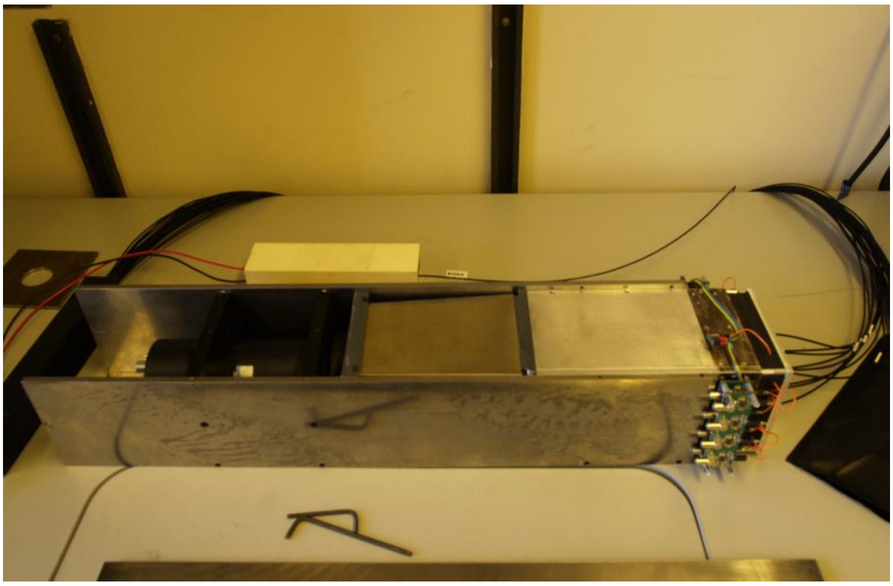


Figure 1.5. BEMC with dual readout.

This detector and associated data acquisition system were delivered at BNL. We set up this testing experiment at the East side of the STAR detector.

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

We stopped development on item (5) due to reduced budget and low LY of 3HF fibers. We compared light yield of different fibers against standard composition SCSF78 (Sr90 source, bundle of fibers attached to a PMT, current measurements). 3HF fibers have LY of only 22% of standard SCSF78. That precludes using this type of fiber for any central calorimeters at EIC.

Future

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

We are moving forward according to our plan outlined 6 months ago. The decisive test of HR prototypes (BEMC) at FNAL will be carried out in time. We have enough time to build new detector with square fibers for this test. The old prototype was re-worked and is almost ready for this test.

The first measurement with FEMC at RHIC during Run16 to investigate potential problems with anomalous signals with high tower trigger is under preparation. A similar test with APD readout is on tight schedule (we have sensors in hand, but not preamps). Early January 2016 we'll attempt to make at least four channels to be 'easily' swappable with SiPM readout at FEMC.

For longer term planning, we believe that RHIC will provide unique opportunity to test EIC calorimeters in environment close to what will be at EIC. MC calculations performed by A. Kiselev for BeAST setup confirmed our expectation. We think that it will be important to build a sufficiently large scale FEMC prototype, to install it at one of the RHIC IP and use it for future developments. This full scale prototype will be used for tests of not only front end but the whole readout chain (digitizers, trigger, slow control, daq) in an environment close to what is expected at EIC.

What are critical issues?

Timely delivery of square fibers from Kuraray is critical (in the past they always meet our schedule). This is tied to an open question of filling square fibers in meshes we produce at FOTOFAB. The tolerances are a bit tight. Current design of meshes is a compromise between our requirement and what FOTOFAB was willing to produce. The issue is thickness of brass (which required for assembly) and minimal width of walls between holes (spacing of fibers). Unfortunately, KURARAY can't guarantee specs on the radius in the corners of the fibers due to production technique. So, without fibers in hand we will not know if assembly is possible. If the first set of screens (which we already produced) will not work we still have time to modify and produce a new set of screens.

Development of front-end electronics for APD tests with FEMC.

Manpower

No updates in past six months

External Funding

No updates in past six months

We expect to seek additional funding from EIC Detector R&D funds at a level of approximately $100k to continue our outlined R&D effort at the next review meeting in June/July 2016.

Publications

No updates in past six months

Sub Project: Progress on Tungsten Powder Calorimeter R&D at BNL
Project Leader: C.Woody

Past

What was planned for this period?

We planned to continue our development of single tapered (1D projective) SPACAL modules at UIUC and THP with the aim of producing enough modules to construct an 8x8 tower prototype detector that we will test in the test beam at Fermilab in the spring of 2016. In addition, we planned to continue our development of producing double tapered (2D projective) modules that could be used in a doubly projective (in η and ϕ) central barrel calorimeter for sPHENIX, which would eventually also serve as the central EM calorimeter at eRHIC.

We also planned to continue our study of radiation damage in SiPMs. These included tests of SiPMs with various pixel sizes that were exposed to neutrons at the LANSCE Facility at Los Alamos and studies with gamma irradiations at the BNL Gamma Ray Irradiation Facility.

Further development was also planned on the control circuit that will be used to stabilize the gain of the SiPMs with temperature and increasing dark current due to radiation damage, along with the associated readout and calibration system.

What was achieved?

1D Projective Modules

Considerable progress was made on producing 1D projective SPACAL modules at both THP and UIUC. THP has been focusing on developing a process that could be used for cost effective mass production of these types of modules for a large scale calorimeter. They produced a number of samples during the past six months that have achieved most of the technical specifications that we require for the prototype we plan to test at Fermilab next spring. Figure 2.1 shows a recent module produced at THP in November 2015.

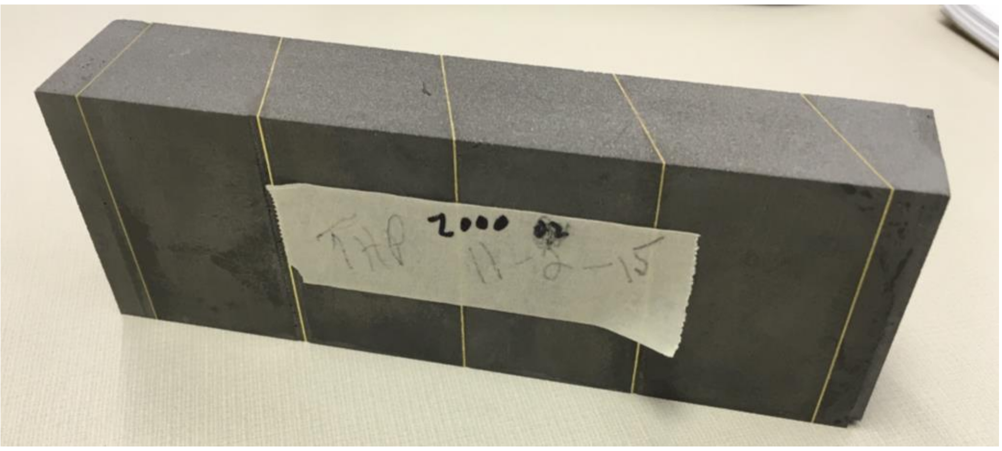


Figure 2.1. 1D projective module produced at Tungsten Heavy Powder (THP) in November 2015

The modules produced at THP have achieved a density in excess of 10 g/cm^3, which is our desired spec for the density. They achieve this by using a centrifuging method to compact the mixture of tungsten powder and epoxy that fills the mold containing the fiber assemblies. We also studied the variation in density within a module by cutting it up into a number of pieces and measuring the density variation along the length, width and depth of the module. We found that the average variation from top to bottom (which would correspond to the compacting direction during centrifuging) was < 0.5%, and the variation from end to end and side to side was ~ 1%. These values are all within our spec of 1% density variation across the module.

The 1D projective modules that we require for our prototype differ from the original modules produced at UCLA in that we plan to read them out from the front (narrow end), whereas the UCLA module were read out from the back (wide end). This required extending the narrow end of the module beyond the last tilted screen, as indicated by the dashed line in Fig. 2.2.

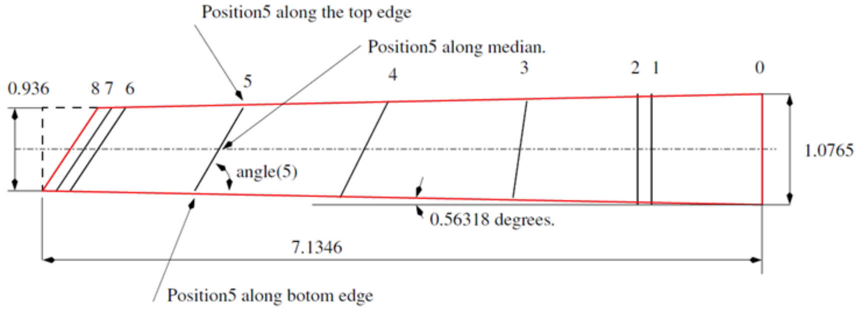
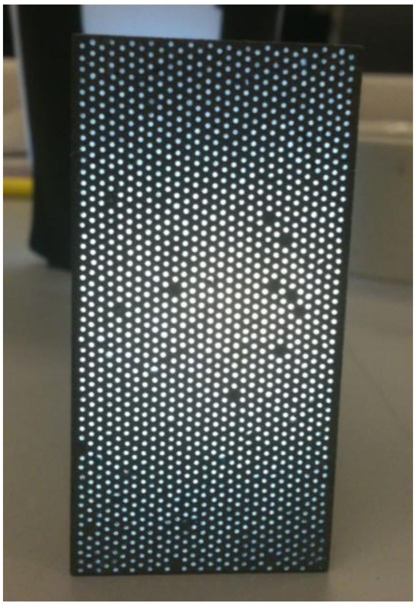


Figure 2.2. Design drawing for the 1D projective module with the narrow end extended beyond the last tilted screen to allow readout from this end.



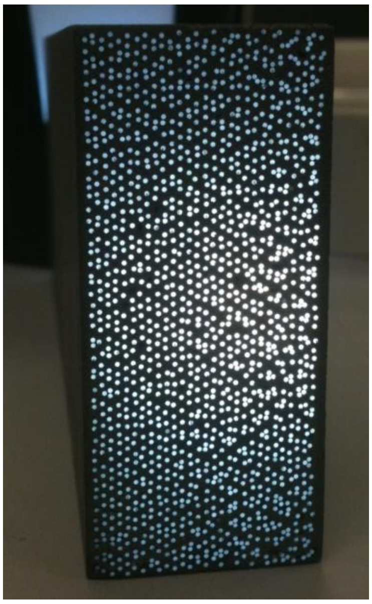


Figure 2.3. Comparison of fiber positions at the wide end (left) and narrow end (right) of a finished module. The fibers at the narrow end were not fully supported across the width of the module during the compacting step which allowed some movement.

One minor problem occurred when extending the block past the last tilted screen. The fibers were not well constrained at this end, which led to some movement of the fiber ends during the compacting step. This is shown in Fig. 2.3. The wide end on the left has good registration of the fiber positions but the narrow end on the right shows poorer registration. It is not clear that this is really a problem in terms of its effect on the final energy resolution or uniformity, but it is relatively easy to fix by adding an additional screen to the mold to support the fibers past the narrow end of the finished module while fiber assembly is still in the mold and being compacted. While it is straight forward to implement this into the production process, it would require modifying the mold and has not yet been done for the all of the modules that have been produced so far in order to meet our delivery schedule.

A number of modules for the prototype have also been produced at UIUC. A total of 18 modules have been produced so far, some of which are shown in Figure 2.4. The production method at UIUC is somewhat different than at THP. They use a vibration method to compact the tungsten powder and epoxy, which so far has achieved a slightly lower average density than the THP modules (~ 9.3 gm/cm^3). While this is ~ 7 % lower than our design spec, it is not clear that this will have a significant effect on the energy resolution. We are therefore planning to use these modules for our prototype, while at the same time develop ways of improving the module density using this method.

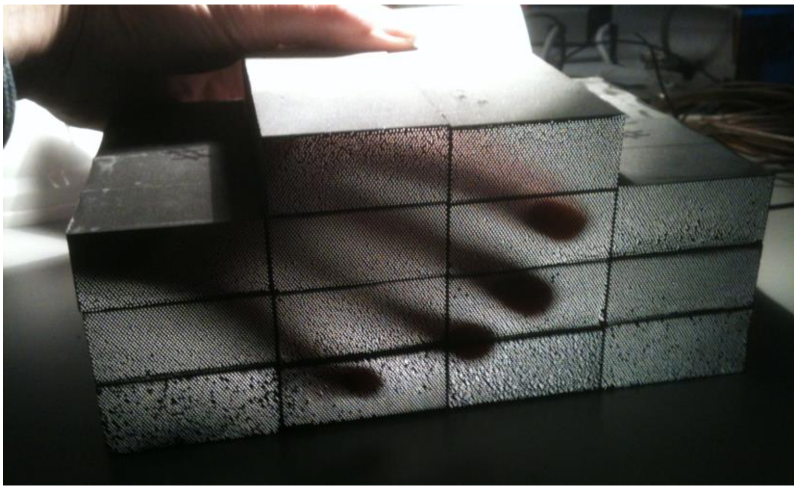


Figure 2.4. Modules produced at UIUC for the 8x8 tower prototype

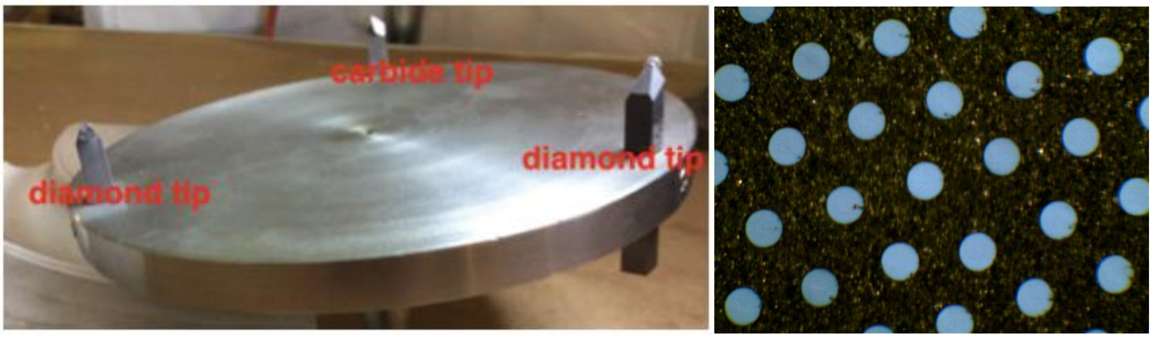


Figure 2.5. Left: Fly cutting tool used at UIUC to finish the ends of the fibers. Right: Fibers ends after fly cutting step.

UIUC also developed a method for finishing the ends of the modules without the need for additional polishing after machining. They use a diamond fly cutting tool, shown in Fig. 2.5, to finish the ends of the fibers during the final machining step. The photo on the right in Fig 2.5 shows the end of the fibers after the fly cutting step, which appears to be sufficient to achieve good light output, as discussed below.

We have currently received 15 modules from UIUC that we plan to use for our 8x8 tower prototype calorimeter. We have several modules from THP that we could in principle also use, but we expect to receive additional improved modules from them during the month of January 2016 which should be improved over the ones we currently have. We have started to assemble the modules we have from UIUC into 1x8 tower arrays that will be used in the prototype. Figure 2.6 shows an example of a single 1x2 tower module with its light guides attached along with a 1x8 array of towers and its electronic readout board. The SiPMs (4 per tower) are mounted on the underside of the board where they are coupled to the light guides.

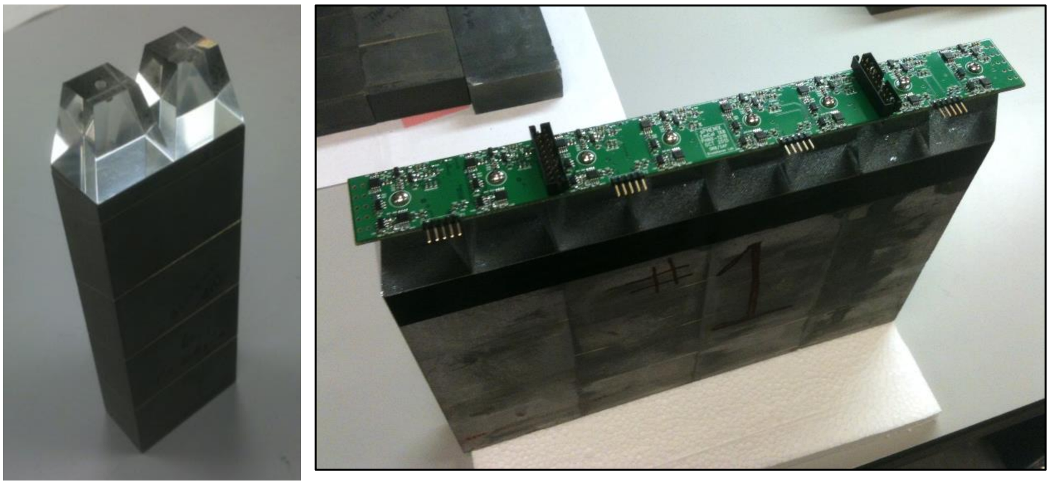


Figure 2.6: Left: Single 1x2 tower block with light guides attached. Right 1x8 tower array with readout electronics board.

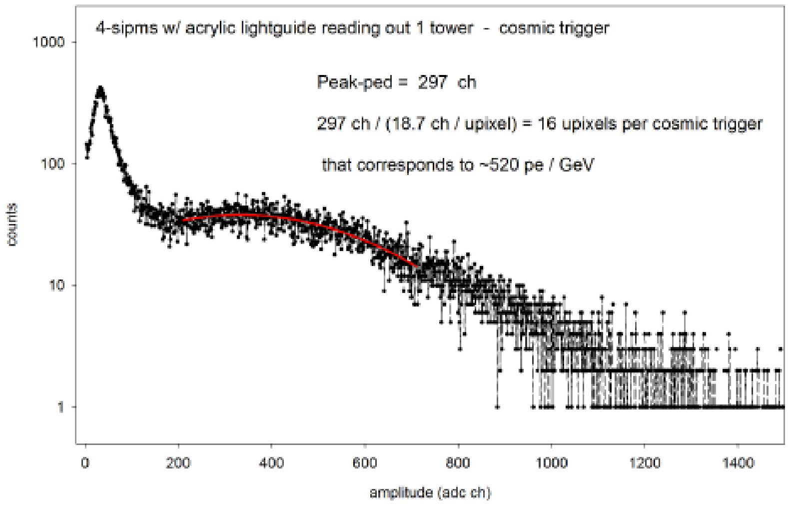


Figure 2.7: Light yield for one of the THP modules measured with cosmic rays and read out using 4 SiPMs with an acrylic light guide.

We also measured the light output of some of the modules that have been produced. Figure 2.7 shows the spectrum of one of the THP modules measured with cosmic rays traversing the module in the transverse direction, corresponding to an energy deposit ~ 30 MeV. The module was read out using 4 SiPMs and an acrylic light guide, similar to the way it would be read out in the calorimeter. The light yield was measured to be ~ 520 p.e./GeV, which is very consistent with the light yield measured for the UCLA modules in their 2014 beam test.

2D projective modules

Considerable progress was also made on developing a process to produce 2D projective modules. The main difference between producing 1D and 2D projective modules is the “trick” of tilting the screens along the length of the module to produce the taper cannot be used in two dimensions independently. To produce a different taper in two dimensions requires tilting the screens at a compound angle. Also, since the hole spacing changes by ~ 10% over the length of the module, it is not possible to fill the fiber assemblies in the same way as is done for the 1D modules.

We have developed two methods for producing 2D tapered modules which overcome this difficulty. The first uses screens with different hole spacings that change along the length of the length of the module. These screens also have conical shaped holes, which make the fibers assemblies easier to fill. The screens are first separated by only a small amount, which provides clearance through the holes, and then the fibers are dropped through the holes. We have found this procedure works quite well and takes little extra time beyond the procedure that is used for the 1D modules. Figure 2.8 shows an example of the fibers filling the tapered screens and then being separated along the length of the module to form the fiber assembly. This method also has the advantage that it produces the desired fiber spacing at each position within the module, therefore assuring better spacing uniformity.

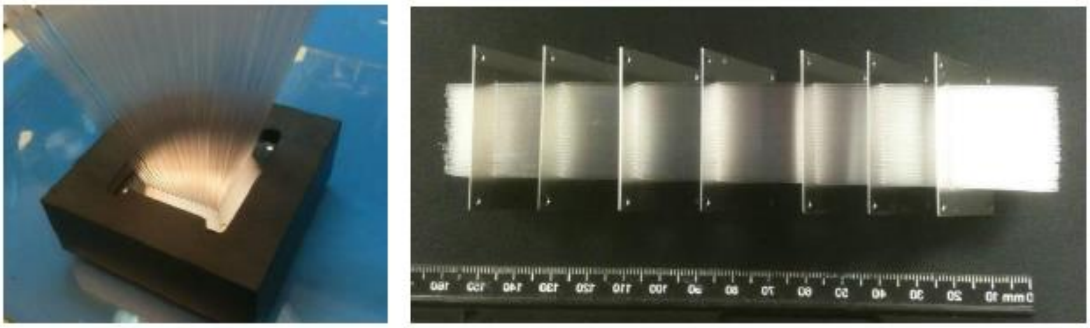


Figure 2.8: Left: Fibers filling a stack of tapered hold meshes which are separated by only a small amount to enable filling. Right: Fiber assembly after fully separating the meshes in preparation for insertion in the mold.

The second method we developed for producing 2D modules uses pairs of small wire frames to position the fibers. Each frame supports the fibers in only one direction, but positioning the two screens at different angles achieves the 2D taper, while at the same time allowing for filling the fiber assemblies when the wire frames are stacked close together. Figure 2.9 shows examples of several fiber assemblies using these sets of wire frames. Note the compound angle of the inner screens. This procedure also allows for a “bow tie” design, in which two modules can be made simultaneously by making two modules end to end.

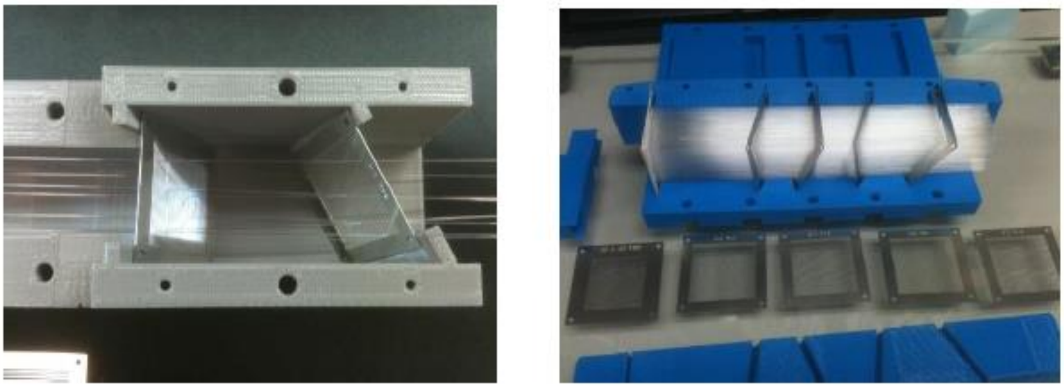


Figure 2.9: Left: Fibers inserted through two angled wire frames in a prototype mold. Right: Completed fiber assembly with tilted screens positioned in an actual mold in preparation for filling with tungsten powder and epoxy.

We have produced a number of 2D tapered modules at BNL using these two methods, some of which are shown in Fig. 2.10 below. All of the modules produced so far have been single tower modules, as opposed to the two tower 1D modules. However, it should be noted that once the fiber assemblies are filled using one of the two methods described above, the remaining steps in the construction of the modules is essentially the same as for the 1D modules. We feel that the procedures developed would not add significant time or cost to the fabrication of the modules and could be adapted for mass production in very much the same way as the 1D modules. However, additional work is required to develop these procedures, which we plan to do in the coming year.

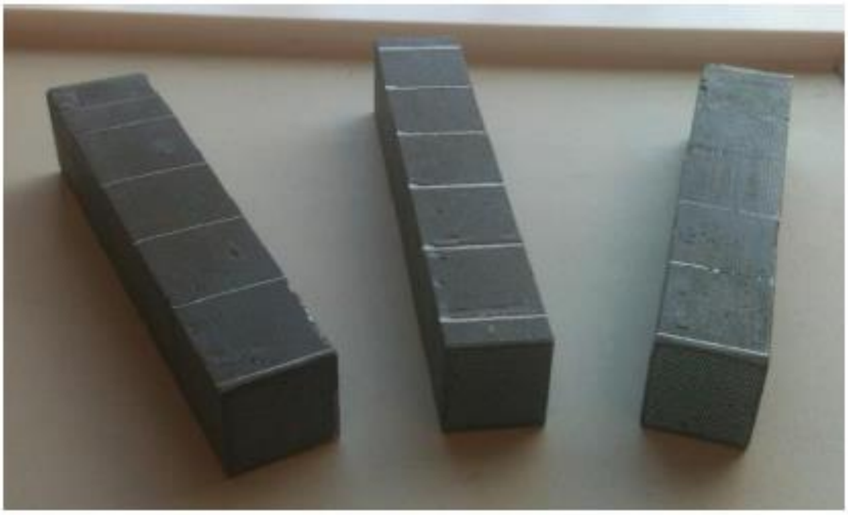


Figure 2.10: 2D tapered single tower SPACAL modules produced at BNL

Radiation Damage in SiPMs

We continued our study of radiation damage in SiPMs by exposing a number of different devices to both neutron and gamma ray irradiations. Additional neutron irradiations were done at the LANSCE Facility at Los Alamos and new gamma ray irradiations were done at the BNL Gamma Ray Irradiation Facility at BNL using ^{60}Co gamma rays.

Three different types of devices with 10 μm, 15 μm and 25 μm pixel sizes (Hamamatsu S12572-010P, -015P and -025P) were exposed to neutrons with an energy greater than 10 MeV up to a dose of 7.2 x 10^{10} n/cm^2, which corresponds to a 1 MeV equivalent dose ~ 2 x 10^{11} n/cm^2. Figure 2.11 shows the relative change in dark current with bias voltage for the three different devices before and after exposure. The 10 μm pixel device showed the smallest relative increase in current while the 25 μm pixel device showed the largest. However, given that the PDE of the 15 mm device is ~ 25% versus ~ 10% for the 10 μm device, the 15 μm device may be a better choice for use in a calorimeter at EIC, depending on the level of dose expected.

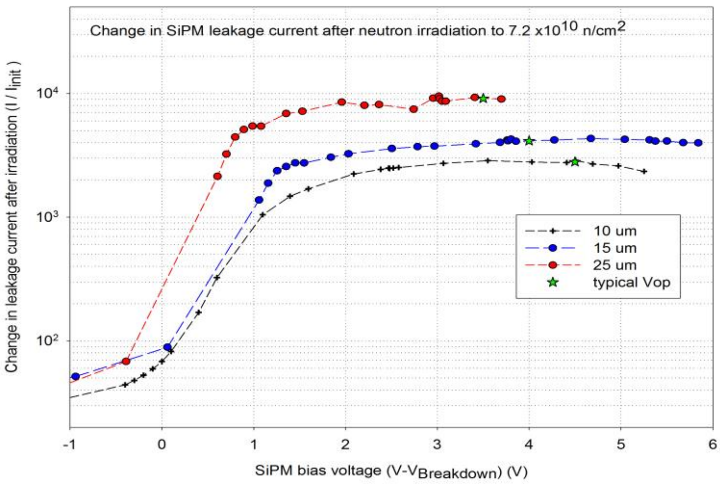


Figure 2.11: Relative increase in dark current with bias voltage for three different pixel size devices after exposure to 7.2 x 10^{10} n/cm^2 at LANSCE.

A group of Hamamatsu S12572-015P 15 μm pixel devices were exposed to ^{60}Co gamma rays with increasing dose from 1 krad to 1.15 Mrad at a dose rate of 10 krad/hr. The leakage current and a pulse height spectrum from an LED were measured before and after exposure. Figure 2.12 shows the increase in dark current for increasing levels of exposure. A significant increase in dark current was observed. However, even at the highest dose of more than 1 Mrad (which is much higher than one would expect at EIC), the current only reached a level ~ 1 μA, which is much less than the expected level of dark current from neutrons at dose level of ~ 10^9 - 10^{10} n/cm^2. A slight reduction (~10%) in the average LED pulse height distribution was observed at the maximum dose. The single photoelectron resolution was also significantly decreased at the highest dose due to the increased noise, similar to the effect seen in exposures to neutrons.

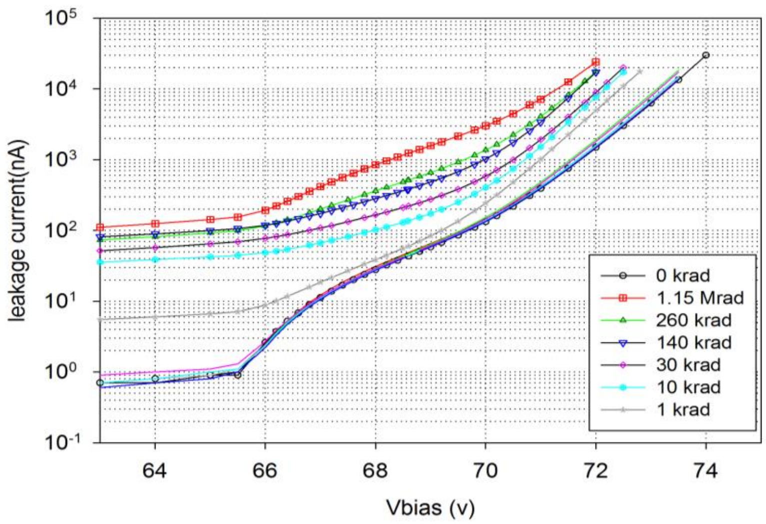


Figure 2.12: Change in dark current for Hamamatsu S12572-015P 15 μm pixel SiPMs for increased exposures to ^{60}Co gamma rays at the Gamma Ray Irradiation Facility at BNL.

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

A number of 1D projective modules were produced at UIUC and THP. We plan to use some of these modules in our 8x8 tower prototype calorimeter that we will test in at the Fermilab Test Beam Facility in the spring of next year. The modules produced at UIUC did not achieve the desired density of 10 g/cm^3, having an average density of only ~ 9.3 g/cm^3, but we believe these modules are still suitable for using in our prototype and that the energy resolution will not be significantly affected. The UIUC group already managed to increase the density from 9.2 g/cm^3 for the first modules they produced to 9.4 g/cm3 for the later modules by increasing the time used for compacting the tungsten powder by vibration, and they believe they can continue to increase it further by additional improvements in their process. THP produced a number of modules that were very close to meeting all of our specs, and they could have also produced a number of modules that would be suitable for our prototype. However, they believe with several additional small changes they will be able to meet all of our specs. We agreed to let them do this and they now plan to deliver a complete set new of modules for use in our prototype in January 2016. However, certain improvements, such as adding an additional screen beyond the narrow end of the module during the fabrication process to improve the fiber alignment, will not be done for either the UIUC or THP modules at this time in order that we may complete the prototype in time for our test at Fermilab.

We made excellent progress on developing a technique for fabricating 2D projective modules. In fact, we developed two methods that we think will work. However, we have only demonstrated that it is possible to produce the 2D modules, and we have not developed either technique far enough yet that it could be used for mass production. We do not expect to be able to work on this much during the next several months since we will be quite busy preparing and testing our 1D prototype, but we hope to continue with this development after our beam test at Fermilab.

We carried out a number of radiation damage studies of SiPMs with neutrons and gamma rays, but we believe more investigation is still needed in order to understand how to use these devices in an actual experiment with significant levels of neutron and gamma ray exposure. In particular, we want to test the bias control circuit that will stabilize the gain with temperature and with increasing dark current due to radiation damage, and to determine the cooling requirements that would be needed to keep a detector using these devices operating for an extended period of time. We plan to study some of these effects in a test in the PHENIX hall during Run 16 at RHIC.

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 complete the construction of our 8x8 tower 1D prototype calorimeter and test it at Fermilab in April 2016. This will be done in conjunction with a test of a prototype HCAL for sPHENIX. Both detectors will be tested individually and as a combined system. We plan to measure the main important parameters such as energy resolution, linearity, uniformity of response, e/h ratio and the e/h rejection factor. For this test, both the EMCAL and HCAL prototypes will be configured to represent the central region in rapidity for a central barrel calorimeter. We plan to do another test later next year where the two calorimeters will be reconfigured to represent a larger region ($\eta \sim 0.7$) in rapidity.

After the April beam test, we plan to go back to developing our technique for producing 2D projective modules. The aim will be to come up with a procedure that is very similar to producing 1D modules such that they can be produced in a cost effective way in terms of mass production. This work will mainly be done at BNL, but we hope that the method that is developed can be transferred to either UIUC or THP (or both) in order that they can then produce many more such modules.

We plan to continue our tests of radiation damage in SiPMs with additional measurements in the PHENIX IR. These will include installing scintillation counters with SiPM readout that are read out, controlled and calibrated using a readout system that is very similar to what we plan to use in our final calorimeter. This will allow us to study our ability to maintain a constant gain for the SiPMs and a constant signal amplitude for the scintillation counters in situ in an actual radiation environment. We also plan to do additional radiation tests of SiPMs with neutrons and gammas at various other radiation facilities.

What are critical issues?

The main critical issue for the next six months is to demonstrate that we can produce 1D projective SPACAL modules and obtain the same performance in terms of energy resolution, linearity, light yield, etc. that was achieved with the modules that were produced and tested by UCLA in 2014. We plan to do this with our beam test at Fermilab in April 2016. We also need to show that our gain stabilization system will maintain a constant gain for the SiPMs, which we will do during our Fermilab beam test and with our test in the PHENIX IR during Run 16.

Another critical issue is the performance of the final calorimeter at larger rapidities. Monte Carlo calculations performed by the PHENIX group have shown that the e/h separation at larger rapidties is improved with a 2D projective design, especially in heavy ion collisions. The need for a 2D projective central barrel calorimeter is not a requirement for the barrel EMCAL at EIC, although it would certainly improve its e/h rejection capabilities. However, recent calculations for the sPHENIX barrel seem to indicate that a 1D projective design may suffice for measuring the Y over the full ±1 range in η, even in heavy ion collisions, although with little margin of safety. A critical decision will need to be made in the next approximately six months to decide whether the sPHENIX EMCAL will be 1D or 2D projective. This will then clearly have an impact on its use as a future calorimeter for EIC. Additional simulation work is also needed to assess the effects that variation in fiber positioning, module density and dead regions within the module have on the measured energy resolution and uniformity of response of the calorimeter.

Another critical issue is how the SiPMs will perform and survive in the radiation environment at EIC. The recent calculations by the STAR and BNL EIC groups seem to indicate that the neutron radiation levels may be much lower at EIC than in either STAR or PHENIX, as discussed earlier in this report. However, the SiPMs for the sPHENIX barrel must first survive many years of running at RHIC, and it is therefore important to know whether they will still be usable for EIC in the future.

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.

Since the last report, the group at UIUC was added to this effort through their work on the sPHENIX calorimeter. This includes Prof. Anne Sickles (0.2 FTE), Dr. Vera Loggins (Postdoc, 0.75FTE) and Eric Thorsland (Technician, 0.2 FTE). All of these personnel are paid entirely out of UIUC or sPHENIX 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 R&D on the projective calorimeter modules, including the construction of the 1D prototype calorimeter that will be tested at Fermilab next spring, is supported mainly from PHENIX R&D funds. The work on studying radiation damage in SiPMs is partly funded by PHENIX, in that we use the PHENIX IR and its infrastructure to carry out some of our tests. However, tests done outside of PHENIX are not funded by PHENIX R&D. We also obtained a BNL LDRD that will fund some additional R&D on radiation damage in SiPMs. This will mainly be used to pay salary for some of the personnel involved, and additional operating funds may be required from EIC during the next funding cycle. We also submitted an SBIR with THP to help fund their development of mass production techniques for calorimeter modules. This SBIR was submitted in October 2015 and we expect to hear about the decision regarding funding in January 2016.

Publications

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

No new publications since the last report.

Sub Project: Crystal Calorimeter Development for EIC based on PbWO4
Project Leader: T. Horn

Past

The critical aspect for crystal quality, and thus resolution performance of the EIC calorimeter, is the combination of high light output and radiation hardness, which depend strongly on the manufacturing process. Our previous studies have shown that there is significant crystal-to-crystal variation for crystals manufactured by SICCAS. Our results are consistent with observations of crystal-to-crystal variation at PANDA. *Evaluation of the variation from crystal to crystal and possibly determining the origin of it is thus one of the main goals of this R&D project.* In the end, this information will be important for what is acceptable for the EIC inner endcap calorimeter. Based on our studies a reasonable batch for such studies consists of at least 10 crystals. Our previous studies also showed significant differences in crystal characterization results at different institutions. *Understanding the effect of such systematic effects is thus important for the interpretation of crystal quality and the setup of crystal specifications for EIC, which would be used by a vendor.*

What was planned for this period?

- We had planned to finalize setting up the infrastructure for crystal testing, e.g., at IPN-Orsay and CUA, and understand systematic effects in the characterization of 2014 and 2015 SICCAS produced crystals.

- We had planned to procure a reasonable batch of full-sized crystals from Crytur and evaluate their crystal-to-crystal variation.

- We had planned to construct a prototype to study the crystals from either SICCAS or Crytur in test beam and measure the actual energy and position resolution that we could achieve with them. Further, the prototype would have allowed us to test a SiPM-based readout system for the EIC crystal inner calorimeter.

What was achieved?

The *actual* FY16 budget received was 21% of the requested budget.

With these constraints our activities were:

- procurement of *three* full-sized crystals from Crytur

- Work towards finalizing the infrastructure for crystal testing at CUA and IPN-Orsay, and initial studies towards understanding crystal-to-crystal variations and systematic effects

- Additional studies of radiation damage of a subset of the 2014 SIC produced crystals we reported on in our last update at Caltech.

- Preliminary measurement of light output of one PWO crystal with SiPMs

With commitment of internal university and laboratory funds and through synergy with the NPS project at JLab we managed to partially setup crystal testing infrastructure at CUA and IPN-Orsay. Our activities related to crystal characterization were:

- Progress in developing a crystal testing facility at CUA including optical properties and their homogeneity. This is an essential aspect required to quantify the crystal-to-crystal variation of crystals produced at SIC, and thus would provide a measure of the quality that can be achieved by that vendor. As part of the NPS project at JLab a subset of crystals has been characterized at CUA and an additional set of 2015 SIC produced crystals is waiting to be characterized. The CUA crystal testing facility benefits from being located in close proximity to Jefferson Lab. This proximity will also be essential for making progress on understanding systematic effects between different laboratories.

- Collaboration with the Vitreous State Laboratory (VSL) for crystal characterization was formed. The VSL is one of the Nation's premier research facility on nuclear waste vitrification and renowned for their expertise in glasses and crystals. Established in 1968, VSL has a staff of ~70 and a wide array of facilities for materials development, fabrication, and characterization. Research on processes for nuclear waste immobilization, and particularly vitrification, supports major programs in the USA, Japan, and the UK. A general research theme is the interplay between composition and structure and materials properties and the design and optimization of new material compositions. The VSL operates a fully equipped facility for crystal characterization including:
    - X-ray irradiators and a wide spectrum of radioactive materials licenses
    - Wide array of temperature-programmable furnaces (room temperature to 1600 °C)
    - X-ray diffraction
    - X-ray fluorescence spectroscopy, optical-UV absorption spectroscopy

  - Scanning electron microscopy with energy dispersive x-ray spectroscopy and wavelength dispersive x-ray spectroscopy
  - Transmission electron microscopy with energy dispersive x-ray spectroscopy and wavelength dispersive x-ray spectroscopy
  - Numerous optical microscopes
  - Raman microscope with multiple excitation wavelength
  - Thermogravimetric analysis, differential scanning calorimetry, differential thermal analysis, thermal conductivity, heat capacity/Density
  - Crystal cutting and polishing facilities, vacuum coating facilities
  - Extensive chemical analysis (ICP-MS, ICP-ES, DCP-ES, MS, GC, IC, XRF, FT-IR)

  The collaboration with the VSL enables detailed characterization of crystals including chemical analysis at CUA, which will be important to understand PbWO4 crystal-to-crystal variations.

- Since our last report we also made progress with developing a crystal testing facility at IPN Orsay. This facility is located close to Giessen University and also to the crystal vendor Crytur in the Czech Republic. We have acquired a portable fiber-based spectrometer in order to measure optical transmission longitudinally and transversally to the block axis. This will allow measuring these properties as soon as the crystals are irradiated in the different facilities. The stability of the fiber-based spectrometer has been measured to be better than 0.1% over a 24h period. A mechanical support to hold the fibers and place the block in a reproducible way has been designed and built by the engineering group of IPN-Orsay. Block position and alignment is repeatable to ~0.1 mm. Measurements are underway using old BTCP blocks borrowed from the PANDA collaboration, waiting for a delivery of new PbWO4 crystals from Crytur in January 2016.

PbWO4 crystal characterization and initial studies of systematic effects

At CUA, both longitudinal and transverse transmittance were measured using a PerkinElmer Lambda 750 UV/Vis spectrophotometer with double beam, double monochromator, and a large sample compartment. The spectrometer allows for measurements of the transmittance and absorption between wavelengths of 200 to 900 nm with 1 nm resolution. However, the spectrometer compartment is optimized for characterizing 1-cm long liquid glass and had to be modified for testing 20-cm long crystal samples. The modified compartment is equipped with a horizontal positioning slide and a programmable stepper motor. The systematic uncertainty in reproducibility of the transmittance measurements is on the order of 0.2%. The light yield was measured with a Photonis XP2262 PMT with a bi-alkali lime glass window. For the light yield measurements a collimated Na-22 source was used to excite the samples. The light yield was measured at a constant temperature of 18°C controlled to better than 1°C. Options for calibrating the PMT for inter-laboratory comparisons are being explored. The systematic uncertainty due to temperature control is better than a few %/°C.

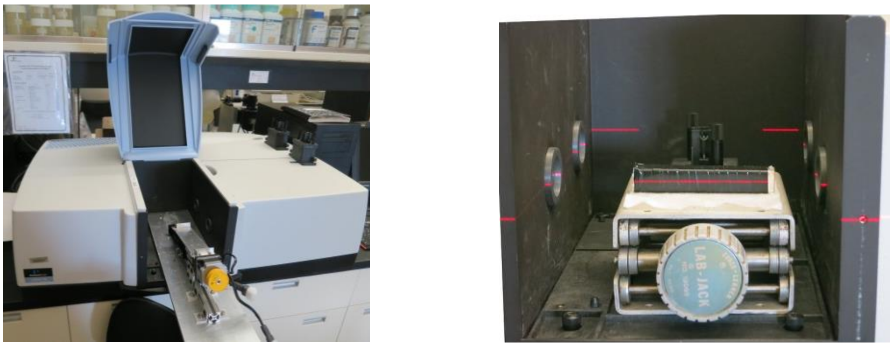


Figure 1. Illustration of an optical transmittance measurement setup at CUA and IPN-Orsay showing the general setup for transverse (a) and longitudinal (b) transmittance measurements.

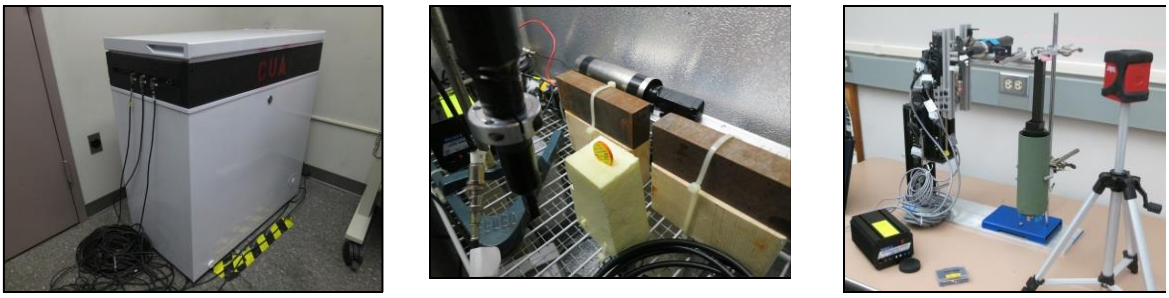


Figure 2. Illustration of a light yield measurement setup constructed at CUA and IPN-Orsay. Temperature-controlled dark box (left), horizontal (middle) and vertical (right) setup for light yield measurements. The vertical setup was found to be optimal for the bond between the crystal and the PMT.

Fig. 3 shows longitudinal and transverse transmittance spectra for a group of rectangular PbWO4 crystals manufactured by SICCAS in 2014 and 2015 and measured at CUA. Crystals #17 and higher were manufactured in 2015 while crystal #2 was manufactured in 2014. Also shown is the transmittance for a 10-cm long CRYTUR crystal produced in 2015 and a 5-cm long reference sample manufactured at BTCP. Although the lengths of crystals are different, the longitudinal transmittance of the Crytur sample is significantly better than that of the SICCAS samples and consistent with that of the BTCP sample. Sample #17 has a significant number of internal scattering centers and lower transmittance than the other samples. Overall, the longitudinal transmittance of the SICCAS crystals produced in 2015 and measured at CUA is lower than that of the majority of crystals produced in 2014 and measured at

JLAB, as shown in our earlier reports, and would not pass our requirements. The transmittance along the crystal, shown here for sample #2, is relatively uniform. Fig. 4 shows the light yield of the CRYTUR crystal compared to that of crystals produced by SICCAS in 2014 and BTCP. The light yield of the 10 cm long Crytur sample is ~21 pe/MeV and is higher than both of the 20 cm long SICCAS and BTCP samples. The next step in these studies will be a detailed analysis of crystal-to-crystal variations in transmittance and light yield for both full-size SICCAS and Crytur produced crystals, as well as a study of possible systematic differences between the various sets of measurements. Fig 5 shows the decay kinetics of the Crytur crystal.

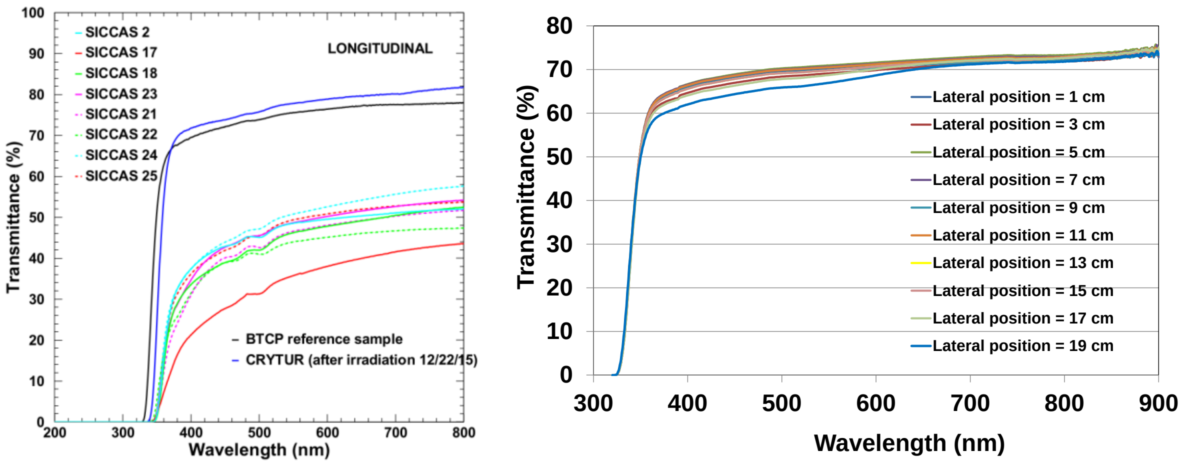


Figure 3. (a) The longitudinal transmittance of a subset of eight 20-cm long PbWO4 samples produced by SICCAS in 2014 and 2015. Also shown is the transmittance of a 10-cm long PbWO4 crystal sample produced by Crytur in 2015 and that of a 5-cm long crystal sample from BTCP. (b) The transverse transmittance along the crystal for sample #2 produced in 2014 by SICCAS.

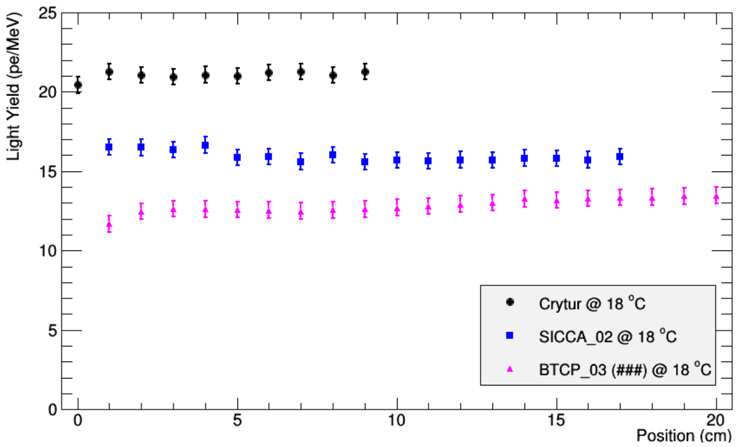


Figure 4. The light output of a 10-cm long PbWO4 crystal sample produced by Crytur in 2015 compared to that of 20-cm long PbWO4 crystals produced by SICCAS in 2014 and BTCP. The measurement was carried out at 18 °C.

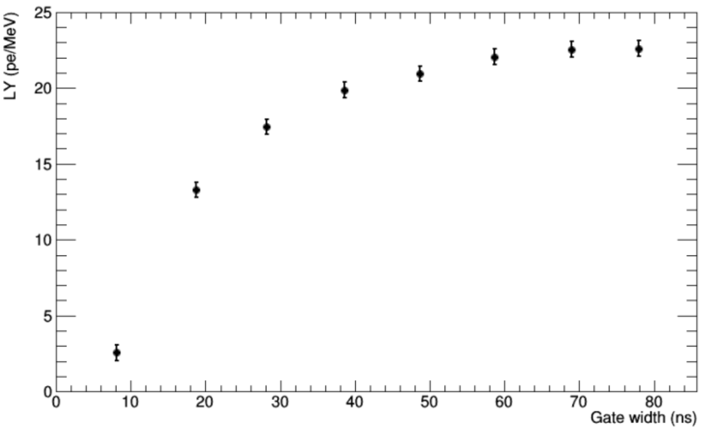


Figure 5. The light output as a function of integration gate of a 10-cm long PbWO4 crystal sample produced by Crytur in 2015. The measurement was carried out at 10 °C.

At IPN-Orsay a setup to measure optical transmittance (both longitudinal and transverse) and a setup to measure crystal light yield and timing were commissioned successfully.

Another requirement on crystal quality is their performance in a radiation environment. Characterizing the radiation damage on the PbWO4 crystals is thus another important aspect of this R&D effort. At CUA crystal irradiation options are available through the VSL. These include radioactive sources and an X-ray irradiation system. An initial setup for crystal testing has been constructed and a subset of the 2014 produced SIC crystals and one 2015 Crytur crystal have been tested. This subset of crystals seems to be radiation hard, which is also consistent with our results from Idaho. The rest of the 2014 SICCAS produced crystals and those from 2015 will be tested next once the irradiation setup is complete. Tests of the 2014 SICCAS crystals will be important for understanding differences in crystal characterization results at different institutions. Tests of the 2015 SICCAS and additional Crytur crystals will be essential for understanding crystal-to-crystal variations. At IPN-Orsay through collaboration with the Laboratoire de Chimie Physique at Orsay the group has access to a panoramic irradiation facility based on 3000 Cu Co-60 sources. This facility can provide dose rates ranging from 6 to 5000 Gy/h. Thus, high total doses can be accumulated in a short period of time and the effect of different photon irradiation rates can also be studied. In addition, IPN-Orsay houses several beam facilities that can be used to further study the effects of radiation on PbWO4 blocks. Firstly, a 50 MeV electron facility (ALTO) can provide up to 1 microA of electrons that can complement the irradiation tests made with photon sources. Secondly, a proton (and several ions) accelerator of the “Van de Graaf” type (Tandem) can provide proton energies in the range of tenths of MeV. This facility is also readily available and will provide information on the crystal damage induced by hadrons, important for the future EIC.

Figure 6. Illustration of irradiation setups with radioactive sources and a cabinet X-ray irradiator available at the CUA and INP-Orsay, and a crystal during and after irradiation.

At Caltech, four samples (#5, #7, #11 and #15) from the JLab NPS crystal set produced by SICCAS in 2014 were irradiated. The results were compared to the average performance of PWO used at CMS and PWO-II developed for PANDA as shown in Fig 7. Good radiation hardness was found for sample #5 and samples #7 and #11 are compatible with the average of CMS $PbWO_4$ crystals while sample #15 was significantly worse. These results are consistent with our earlier irradiation studies in Idaho with electron beam (see our July 2015 report for details).

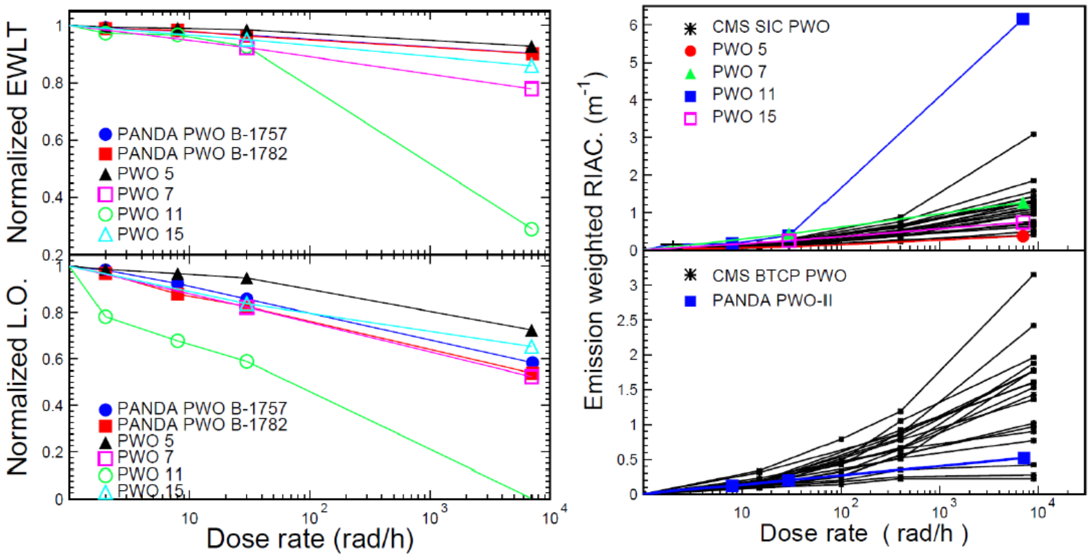


Figure 7. Comparison of four SICCAS crystals measured at Caltech with similar crystals from CMS and PANDA. Left: Normalized Emission Weighted Light Transmission and Normalized Light output as a function of dose rate. Right: Emission Weighted Radiation Induced Absorption Coefficient as a function of dose rate.

In summary, the test results of SICCAS crystals produced in 2014 and 2015 are promising. The recent Caltech measurements confirm that crystals produced in 2014 are radiation hard. ***The next step and key in this R&D effort is to understand the crystal-to-crystal variations and possibly determining their origin. Another important aspect is to understand the differences in crystal characterization results*** e.g., between measurements carried out at JLab, Giessen and Caltech. This is important for the interpretation of crystal quality and the setup of crystal specifications for EIC. Data from CUA and IPN-Orsay on the same crystals and calibrated to JLab and Giessen Univ. will help to further understand these systematic effects in the crystal characterization.

Material characterization

To understand variations in PbWO4 characteristics like transmittance, light yield, decay times and radiation hardness material characterizations are being carried out at CUA. These include determination of trace element impurities, defects, oxygen vacancies and structural analysis. These studies are being carried out by and in collaboration with the VSL and use a combination of different instruments, e.g., XRF, TEM and SEM, as well as Raman spectroscopy. In particular, XRF analysis is used to identify the crystals' elemental composition. Non-optimal Pb/W ratios have been shown to be related to poor radiation hardness. The trace element Mo is an impurity in PbWO4 crystals and can generally be related to slow components. Initial tests of the chemical methods were carried out with a 2-cm long crystal sample produced at SICCAS and a 5-cm long sample from BTCP. The former has a lower optical transmittance than expected even after stimulated and thermal annealing. Chemical analysis showed that the sample consists of two phases and the observed low optical transmittance seems to be due to surface oxidation. Characterization of selected full-size PbWO4 samples produced by SICCAS in 2014 and 2015 and by Crytur is ongoing.

CRYTUR production and crystal-to-crystal variation

As of June 2015 Crytur has been able to demonstrate that the company can grow crystals that conform to the strict requirements of PANDA. Since then the company has been focusing on setting up for production, e.g., commissioning new furnaces and polishing machines (see Fig. 8(a) and (c)), and optimizing their capabilities for cutting and polishing crystals. A picture of a mechanical holder for cutting of regular prisms that was designed, made and tested is shown in Fig. 8(b). It enables cutting of all sides and small changes of its design also enables cutting of crystal ends. The company was able to reduce the addition for grinding and polishing from 1 to 0.5 mm. The company has also been investing time in the search for new raw materials.

At CUA, we have been characterizing a 10-cm long crystal sample manufactured by Crytur in early 2015. Initial results are shown in Figs. 3-5. To characterize the crystal-to-crystal variation we have ordered a batch of full-length $PbWO_4$ crystals. Due to limited funding the batch size was limited to three such crystals. The crystals will be first characterized by IPN-Orsay once they arrive in early 2016.

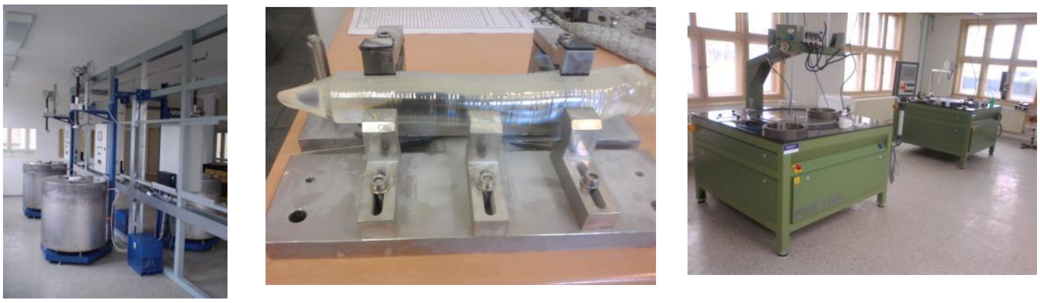


Figure 8. Crytur facilities: (a) Three new crystal growth furnaces have been commissioned, (b) Custom-built mechanical holders facilitate crystal cutting and polishing, (c) Lapping and polishing machines.

Measurement of light output of PWO crystals with SiPMs

The light output of SIC crystal #5 was measured using a PMT and with four SiPMs in order to compare the number of photoelectrons detected in both cases. The PMT provided full photocathode coverage of the readout end of the crystal and gave a measure of the total light output. The SiPMs used were Hamamatsu S-12572-015Ps, which are 3x3 mm2 devices with 40K 15 μm pixels each. The SiPMs were coupled to the crystal using a 1’’ long acrylic light guide which provided ~ 35% light collection efficiency for the 4 SiPMs. The crystal was wrapped in Tyvek paper to improve reflectivity and the light output was measured using cosmic rays traversing the crystal along the 2 cm direction, which gave an energy deposit ~ 20 MeV.

Figure 9 show the pulse height spectrum measured using the PMT. The peak corresponds to ~ 238 photoelectrons and a photoelectron yield of 11.8 p.e//MeV. Figure 10 show the pulse height spectrum measured with the four SiPMs. The peak corresponds to ~ 54 pixels and a photoelectron yield of 2.7 p.e./MeV, which agrees reasonably well with the expected number from the PMT and the light collection efficiency of the light guide. ***While this is the first preliminary measurement of the light yield of PWO with SiPMs, and we expect that it can be significantly improved, this level of light yield is sufficient to provide better than 2%/√E in terms of energy resolution.***

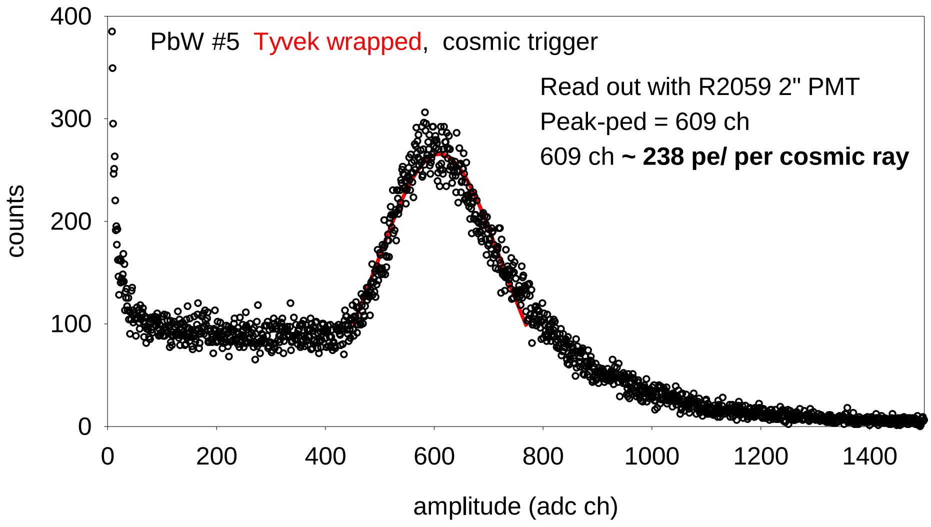


Figure 9. Pulse height spectrum for SIC crystal #5 measured with a PMT with full photocathode coverage of the readout end of the crystal.

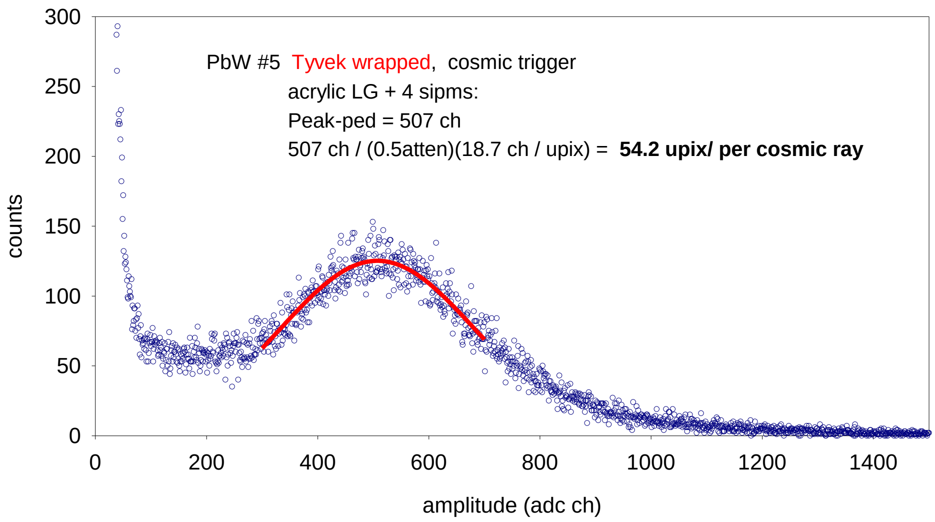


Figure 10. Pulse height spectrum for SIC crystal #5 measured with cosmic rays using 4 Hamamatsu S-12572-015P SiPMs and a 1" acrylic light guide.

Meetings in 2015

To take full advantage of the expertise of all collaborators on this project and also the Giessen group (building the EMC for PANDA), a number of meetings were arranged to exchange knowledge. With the limited budget we received for FY16 we again used internal funds from universities and laboratories to make this possible. Carlos Munoz-Camacho, Gabriel Charles and Tanja Horn visited Giessen University in October 2015 to discuss a strategy to understand the systematic uncertainties between measurements at different facilities.

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

- With the significantly reduced budget we were not able to finalize the crystal testing setups at CUA and IPN-Orsay. Good progress was made regardless on initial characterization of a subset of SICCAS 2014 crystals and understanding systematic uncertainties due to the setup. There are still open questions on disagreements between measurements of crystal properties at different institutions that have to be addressed. Assuming that our budget for FY17 will be approved we will complete our crystal testing setup to address the systematic uncertainties between institutions.

- The first Crytur crystal was characterized at CUA. The results are in good agreement with those from Giessen University of the same crystal. We will attempt to evaluate the Crytur crystal-to-crystal variation over the next six months, but our studies will be limited to three crystals. Based on our experience this is not sufficient to draw a final conclusion about crystal-to-crystal variations. Assuming that our budget for FY17 will be approved we are planning to obtain a reasonable batch of crystals to evaluate the crystal-to-crystal variation.

- We did not make progress on the prototype studies as we did not obtain funding for FY16 for this activity. Some progress was made in design optimization based on the smaller 3x3 prototype for the NPS at JLab. We also made some progress on exploring prototypes for cooling designs through collaboration with Giessen University. Assuming that our FY17 budget will be approved, we are planning to construct a 5x5 prototype to study the actual energy resolution of the crystals in beam.

Future

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

- For the next funding cycle we plan to complete our goals from the FY16 cycle and also try to make progress beyond that. In particular, assuming that we will be approved for funding we will finalize the crystal testing facilities at CUA and IPN-Orsay. This will allow us to test the optical properties and the homogeneity of crystals produced at SICCAS and procured through synergy with the NPS project at JLab. The results are an essential aspect required to quantify crystal-to-crystal variations and possibly understand their origin, and would thus provide a measure of the quality that can be achieved by that vendor.

- We also plan to procure 10 full-sized crystals from Crytur. This would allow us to do a reliable evaluation of their crystal-to-crystal variation. These crystals could also be tested in the prototype we are planning to build.

- Assuming that our FY16 crystal quality tests are completed successfully and one or two vendors capable of producing such crystals have been identified, the crystal calorimeter R&D will focus in subsequent years on the optimization of geometry, cooling and choices of readout system of the endcap inner crystal calorimeter. Cooling and choice of temperature are important aspects for crystal calorimetry. The choice of temperature balances light output and radiation recovery. Cooling techniques have been explored for the NPS project based on PANDA and CMS. The type of cooling and avoiding condensation depend to some extend on environmental factors. Our planned future R&D will explore how cooling could be achieved for the inner endcap calorimeter for EIC. Another reason for cooling is the reduction of noise in the readout system. Our initial studies with a SiPM-based readout have shown significant effects of noise at room temperature emphasizing the need for cooling. Our future R&D activities will also explore if cooling is the optimal choice to reduce readout noise and if it is how to implement such a system.

What are critical issues?

At this stage, the most critical issues are to complete the FY16 activities. These will address fundamental questions about the crystal-to-crystal variation of crystals procured from SICCAS through synergy with the NPS project, as well as the impact of systematic uncertainties between measurements at different institutions. These also include the evaluation of crystal-to-crystal variation in full-size crystals from SICCAS and Crytur. Further, the construction of a prototype would allow us to study the crystals in test beam and measure the actual energy and position resolution that we could achieve with them. These measurements would provide essential information on crystal specifications and their impact on EIC detector performance.

Additional information:

The planned timeline and funds requested for our second (third) year R&D in FY16 (FY17) can be found in Section 6 of our July 2015 proposal.

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.

A list of existing manpower is shown below. All of the participants are supported by external funds and not through the EIC R&D program.

IPN-Orsay
G. Charles, postdoc
F. Georges
G. Hull
C. Munoz-Camacho

CUA
M. Carmignotto
S. Ali
A. Mkrtchyan, postdoc
T. Horn
Vitreous State Laboratory

Yerevan
H. Mkrtchyan

BNL
C. Woody
S. Stoll

Caltech
R-Y Zhu
L. Zhang
F.Yang

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 finalizing the crystal test setup and crystal characterization are provided by CUA/IPN-Orsay or external grants. The absence of any labor costs makes this proposed R&D effort extremely cost effective.

- The 2014 and 2015 SIC crystals are provided through synergistic activities with independent research for the Neutral Particle Spectrometer (NPS) project at JLab.

- The expertise and use of specialized instruments required for crystal characterization and their chemical analysis, as well as additional crystals samples are made possible through collaboration with the Vitreous State Laboratory (VSL) at CUA that is also collaborating on the NPS project. The VSL has trained and experienced staff and procedures already in place requiring no additional setup overhead beyond what is required for finalizing the crystal test setup, prototype construction, and procuring crystals.

Efforts related to crystal studies as described in the proposal were accomplished with external funds through synergistic activities with the NPS project at JLab. EIC R&D funds were used to procure three Crytur crystals and to complete the crystal characterization setup at IPN-Orsay and CUA. Additional funds and facilities for crystal characterization were provided by the Vitreous State Laboratory at CUA. Salaries and wages were provided by private external grants from the individual principal investigators, e.g., IPN-Orsay, Yerevan, and the National Science Foundation.

Publications

Through synergy with the NPS project at JLab:

T. Horn et al., J.Phys. Conf. Ser. **587** (2015) 1, 012048 "*A PbWO4-based Neutral Particle Spectrometer in Hall C at 12 GeV JLab*"

T. Horn et al. "*Physics Opportunities with the Neutral Particle Spectrometer in Hall C*", presentation at the APS DNP 2015 Fall meeting, Santa Fe, NM