Date: 1/6/17

EIC Detector R&D Progress Report

Project ID: eRD1
Project Name: EIC Calorimeter Development
Period Reported: from 7/1/16 to 12/31/16
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Abstract

The efforts of the eRD1 Calorimeter Consortium are essentially divided into four Sub-Projects. These are: Tungsten Calorimeter R&D at UCLA, Tungsten Calorimeter R&D at BNL (sPHENIX), R&D on Crystal Calorimeters for EIC and Simulations. For this period, the R&D carried out at UCLA focused mainly on improving the light collection uniformity for the EIC Backward Electromagnetic Calorimeter (BEMC). This involved simulations of various components of the BEMC detector and studying how they a ffected the light colection uniformity of the SiPM readout. The group also built a new version of a BEMC module with a modified fiber configuration that was designed to provide a more uniform light path from all the fibers in the absorber block to the SiPMs. This module will be installed in the STAR experimental hall during RHIC Run 17 where tests will be done with longer light guides and multiple types of readout. The operation of the SiPM readout in the RHIC beam environment for a substantial period of running time will provide essential data for our next phase of the R&D project.

The BNL group focused its effort on analysing the data from the last beam test of their sPHENIX prototype calorimeter and building a new prototype calorimeter consisting of 2D projective blocks that will be tested at Fermilab in early 2017. We are also investigating ways of improving the light collection uniformity from the absorber blocks and exploring ways of manufacturing large numbers of light guides in a cost effective way.While the sPHENIX effort is not officially part of the EIC R&D program, the EMCAL they are building is same type of calorimeter that is being proposed for EIC and much of the R&D effort is therefore very relevant for a future EIC calorimeter. It is also planned that the sPHENIX calorimeter will be available to do EIC physics as a Day 1 detector at eRHIC, so we feel that the EIC R&D Committee should be kept informed as to its progress. The BNL group also continued to carry out studies of radiation damage in SiPMs by comparing the effects damage caused by neutrons and gammas.

R&D on a crystal calorimeter for EIC consisted of studies of PWO crystals from two different producers (Crytur and SIC) and simulations on the performace of a crystal calorimeter in the forward electron going direction at EIC. Due to limited funding, the crystal characterization effort focused mainly on setting up infrastructure at CUA and Orsay in order to be able to measure crystals at these two institutions in the future. However, we are also working closely with the PANDA Collaboration in order to follow the development of PWO crytsals for their endcap calorimeter. The simulation effort was focused mainly on studying the effect of the energy resolution and constant term of a crystal calorimeter on DIS kinematic event reconstruction.

Our greatest concern as a Consortium is the continued decrease and lack of funding for what we feel are critical or important issues. We have experienced significant funding cuts below our requests for the past several funding cycles and we feel that the level of support we are now receiving is sub-critical and does not allow us to proceed with many of our R&D programs. This has also had a detrimental effect of losing interest and participation by many of our collaborators, and we feel that both of these issues need to be addressed in the next funding cycle.

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

Past

What was planned for this period?

- Modify BEMC (Backward EMCal—non-projective) and old HR (High Resolution) prototypes for tests during RHIC Run17.
- Produce new sets of FEEs and SiPM boards for tests at BNL.
- Perform systematic studies of light collection schemes for BEMC.

What was achieved?

We achieved most of the goals we planned for the past 6 months. Both BEMC and HR prototypes were modified for future tests at BNL. The BEMC was equipped with a long light guide with a PMT readout and the old HR detector was equipped with 16 light guides with SiPM readout. We produced enough SiPM readout boards to instrument the BEMC with a triple readout (a PMT on one end, a set of SiPMs detecting scintillation light and another set of SiPMs detecting 'primary' ionization) plus spare boards. However, due to lack of funding, only the BEMC will be instrumented for tests at RHIC during Run17. All readout channels were calibrated at UCLA. The test setup was shipped to BNL in early December and will be installed at the East side of STAR in December 2016.

A new UCLA undergraduate student joined our effort to perform systematic studies of compact light collection schemes for the BEMC and this study is now in progress. We started this investigation by studying different coupling media between the SiPMs and light guides. We found that there is significant improvement in uniformity and absolute efficiency using a higher refractive index coupling between the SiPMs and light guides and that the coupling configuration between the SiPMs and light guides used in our previous prototypes can be significantly improved. The silicone compound (Sylgard 184) we used in the past has refractive index of about 1.4, and we used a rather thick (3 mm) layer of this silicone between the SiPM and the light guide in order to relieve stress caused by pressing the SiPM boards onto the light guide. This was necessary because a single SiPMs may have a 'point like' stress due to the slightly uneven height of the individual SiPMs mounted on the sensor board. However, there is about 10% light loss in this silicone layer. A mismatch of the refractive indexes of the SiPM window and the silicone cookies is possibly responsible for the additional degradation of the light collection efficiency from the corners of the towers. The new SiPM boards produced in the UCLA electronics shop have a different method of mounting the SiPMs to insure good flatness of the four sensors. Thus, a very thin layer of optical coupling can be used between the SiPMs and the light guide without the risk of mechanical stress on the individual sensor due to mounting (the SiPM boards are also held in place by a small screw which is attached to the light guide).

We obtained a sample of a new high refractive index silicone (Lumisil 591) released by Waker Silicones in 2016 for encapsulation of high power LEDs. Long term degradation studies performed by Waker indicate that it has good stability, and we also plan to make a few samples and irradiate them in the STAR IR during Run17.

Modification of the SiPM/light guide coupling has already improved the uniformity of light collection for our old prototypes, but it still will require a compensation filter between the end of the fibers and the light guide to make it uniform.

As we discussed in our previous report, we also wanted to investigate alternate schemes to improve the light collection uniformity which would not require a compensation filter. The basic idea in our approach is to make similar light paths to the SiPMs from the fibers in the corners of the towers and from the fibers located in the center of the tower.

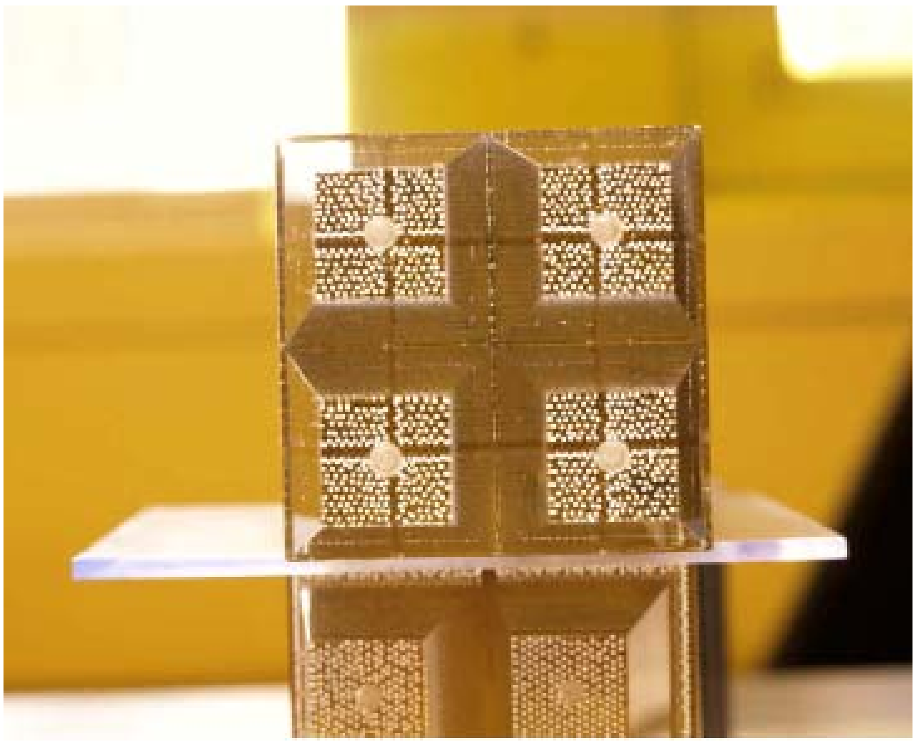

Figure 1.1. New BEMC superblock with 'homogenized' arrangement of fibers**.**

So far, we have performed a series of scans with a ‘standard’ configuration used in the FNAL test beam runs in 2014/2015 and compared them with a newly produced BEMC block which has a new arrangement of scintillation fibers at the photodetector end. In this block, shown in Fig. 1.1, the fibers in the center of the tower were bent away from the axis of the tower so that some fraction of light from these fibers undergo secondary reflections from the sides of the light guides, similar to the fibers located in the corners, which were bent toward to center of the tower to decrease fraction of light having secondary reflections from the sides of the light guide. This is seen in Fig 1.1 as a cross in the new (top) BEMC block, compared with standard block at the bottom where the fibers are spaced uniformly. This new arrangement of fibers at the end of the block significantly improved the light collection uniformity. With a UV LED (which emulates the intensity profile of an e.m. shower), we measured a uniformity of response of 1.6% (r.m.s.), which is comparable with our resent scans for the HR prototypes from the test bean run at FNAL in 2016, as shown in Figure 1.2 and 1.3.

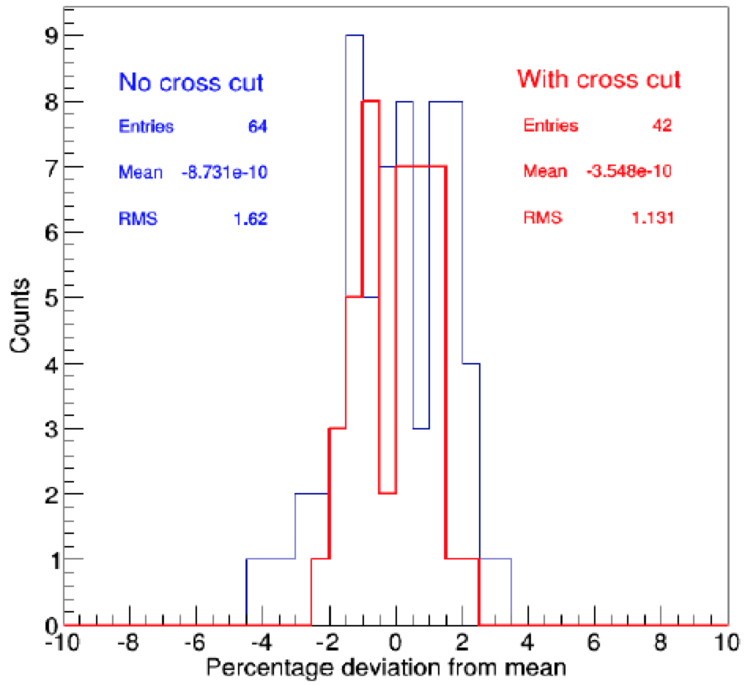

Figure 1.2. Uniformity of response, non-projective orientation of the crack.

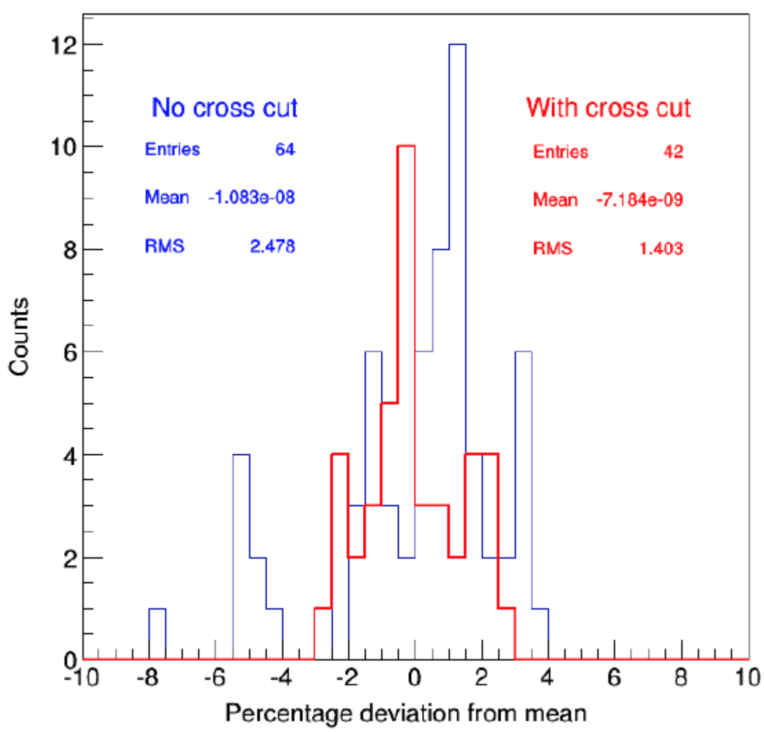

Figure 1.3. Uniformity of response, projective orientation of the crack.

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

Originally, we planned to install two detectors in the STAR IR for testing during RHIC Run 17. However, due to lack of funding, only one is instrumented and will be tested in Run 17.

Future

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

During the next six months we will be taking and analysing data with the BEMC prototype installed in the East side of STAR. To complete the optimization of light collection scheme for the BEMC, we will perform additional uniformity scans with longer light guides. Until now, we used one inch long light guides as in all of our previous test runs. The UCLA machine shop produced two additional sets of 1.25" and 1.5" long light guides which will be glued to the latest BEMC block that we used in our recent scans. We plan to finish the optimization of light collection scheme for the BEMC sometime during the spring 2017.

The plan beyond the current funding period is being developed. Measurements with the BEMC during Run 17 are necessary to finalize the choice of readout sensors for backward hadron calorimeter. Once we make the decision of the readout sensors, we want to use RHIC Run18 to test at least one HCAL tower with the new version of readout under realistic collider conditions.

A high-resolution hadron calorimeter will be required for very forward spectator tagging at EIC. However, it is not clear how and when to approach this with the current EIC R&D budget. Any device targeting the required energy resolution at the level of $30\%/\sqrt{E}$ will be quite expensive, simply because of its size to contain the hadronic shower. We will continue to investigate possible approaches to start this R&D program at some time in the future.

Additional information.

From the final 2016 EIC R&D committee report, it was stated:
"The Committee would like to see energy resolution plotted vs $1/\sqrt{E}$ in the next report to better understand the various observed constant terms; a histogram of measured non-uniformity in response would also be instructive."

In response to this request, Figure 6 (left panel from our previous report with a minimal set of cuts) for the 'S' prototype, is redrawn in Figure 1.4 as requested.

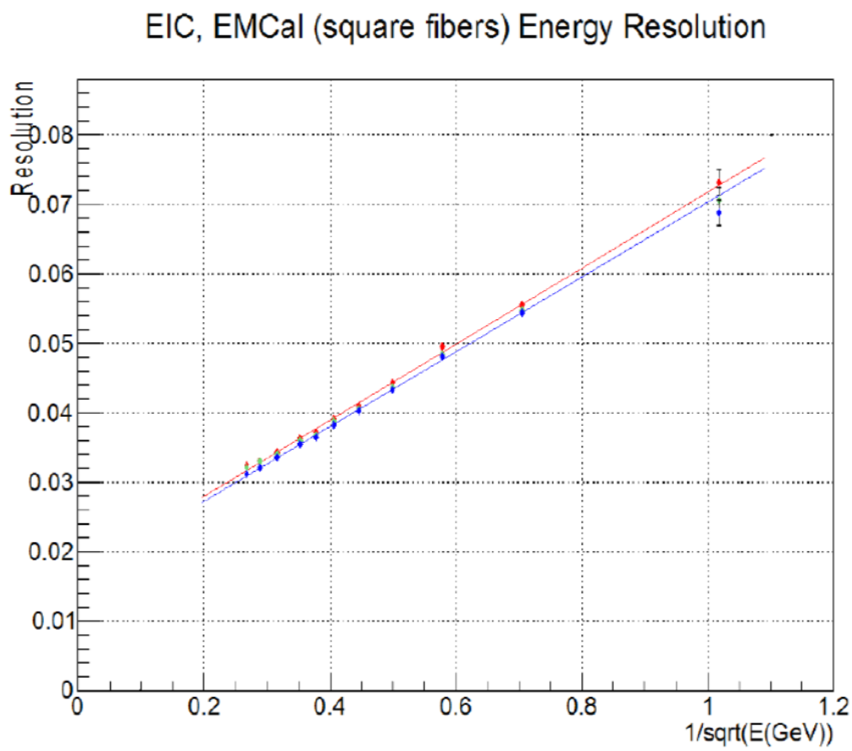

Figure 1.4. Energy resolution of S type prototype with minimal set of cuts. Red: raw data. Blue: requiring Cherenkov hit, single hit in the hodoscope and no signal in the PbGl located behind the EMCAL prototype (to suppress bremsstrahlung).

Manpower

We have the usual rotation of students involved in EIC R&D at UCLA. Two new graduated students (Dylan Neff and Brian Chan) worked on data analysis of the dual readout BEMC tested during Run16 at RHIC, and a new undergraduate student, Mark Warner, is working on optimization of light collection schemes for the BEMC

External Funding

There is no other direct external funding supporting this effort.

Publications

No updates in the past six months

Sub Project 2: Progress on Tungsten Powder Calorimeter R&D at BNL
Project Leader: C.Woody

Past

What was planned for this period?

Our main activities for this period were:

- Complete the analysis of our test beam data from our prototype EMCAL that was tested at Fermilab in April 2016.
- Construct new 2D projective W/SciFi blocks and build a new prototype calorimeter using these blocks that will be tested at Fermilab in early 2017.
- Investigate ways of improving the light collection uniformity of the light guides used for the calorimeter and fabricating them in a cost effective way.
- Continue our investigation of radiation damage in SiPMs

What was achieved?

Analysis of April 2016 test beam data

The analysis of the data from the April 2016 beam test of our prototype W/SciFi ENCAL is essentially complete. This analysis was performed by the sPHENIX Collaboration and results were presented at the 2016 IEEE Nuclear Science Symposium (NSS) in Strasbourg, France. A manuscript is currently in the final stages of preparation and will be submitted for publication in the IEEE Transactions on Nuclear Science (TNS) in early 2017.

The prototype calorimeter consisted of an array of 8x8 towers that were formed from 1x2 tower absorber blocks that were based on the original 1D projective UCLA design. Half of the blocks were produced by Tungsten Heavy Powder (THP), which is the company that has supplied the raw tungsten powder for all the calorimeter blocks, and half were produced at the University of Illinois at Urbana Champaign (UIUC). Further details about the construction of the absorber blocks, the prototype calorimeter and the beam test are described in our previous report from June 2016. The following is a brief summary of the results from the final analysis of the test beam data.

Figure 2.1 shows the linearity and energy resolution of electron showers in the calorimeter for blocks produced at THP and UIUC. Data was taken with the beam at incident angles of 10° and 45° and was selected to be in a 10 x 5 mm^2 area centered on a tower using a small scintillation hodoscope. The hodoscope (which was provided by UCLA) consisted of eight vertical and eight horizontal 5 mm wide fingers. For the UIUC blocks at 10°, the fit to the data gives a resolution of $12.7\%/\sqrt{E} \oplus 1.6\%$, where the beam momentum spread of 2% $\delta p/p$ has been factored out separately. This is in reasonably good agreement with our simulations, which gave $11.4\%/\sqrt{E} \oplus 1.5\%$, and also with previous tests of these types of modules by the UCLA group, which gave $10.8\%/\sqrt{E} + 1.1\%$ for the beam centered on a tower (see our previous report from July 2014). Note that the deviation from linearity at 45° is due to the fact that the energy calibration was done for the 10° configuration, and the sampling fraction is effectively greater for the calorimeter at 45°.

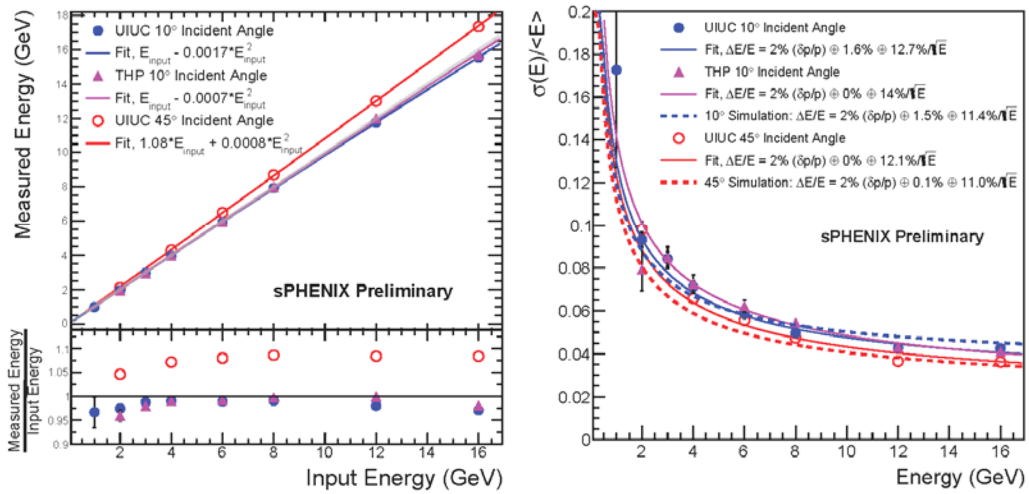

Figure 2.1. Linearity and energy resolution of electron showers in the EMCAL prototype for absorber blocks produced at THP and UIUC. Beam was incident at an angle of 10° or 45° and was selected to be in a 10 x 5 mm^2 area centered on a tower. The beam momentum spread of 2% δp/p is factored out separately.

By measuring the beam position as it entered the calorimeter using the hodoscope, we found that there was a significant dependence of the observed cluster energy on the position of the shower within a given tower. This is shown on the left hand side in Fig. 2.2 where the distance between the two dips is equivalent to one tower width. This is the same effect seen by the UCLA group, which we believe to be due to the non-uniform light collection efficiency from the fibers in the tower onto the 4 SiPMs. We further believe this effect is due to the short light guide that was used, which for this prototype calorimeter was a 1” long trapezoid, similar to that which was used by UCLA. However, we were able to correct for position dependence using the hodoscope in 5x5 mm^2 bins. The plot on the right in Fig. 2.2 shows the position dependence of the cluster energy after this correction.

Before correcting for the position dependence, the energy resolution for the UIUC blocks for an incident angle of 10° was ~ 18.6%/√E ⊕ 7.5% without unfolding the beam momentum spread. Figure 2.3 shows the linearity and energy resolution after correction for the position dependence, which gives 15.5%/√E ⊕ 2.8% after unfolding the beam momentum spread of 2% δp/p. As discussed above and again below, we believe this can be substantially improved by improving the uniformity of light collection from the fibers within the absorber blocks.

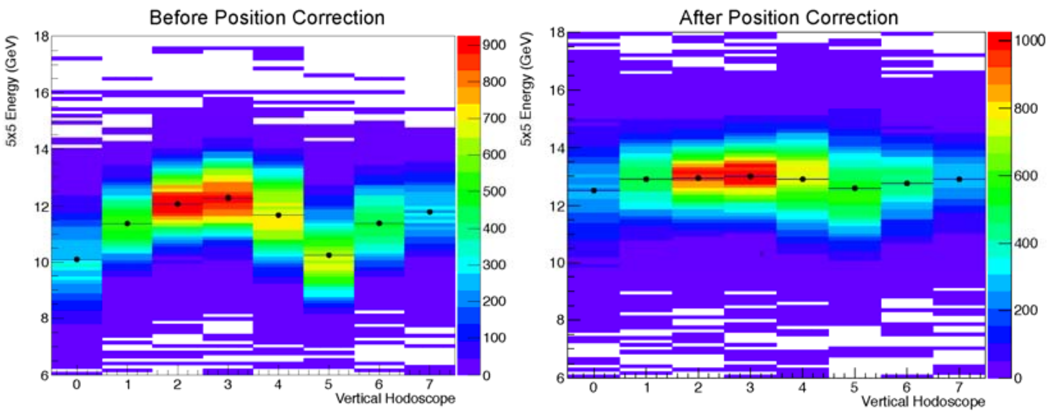

Figure 2.2. Left: Position dependence of the cluster energy across a tower measured using the hodoscope with 5 mm wide horizontal and vertical fingers. Right: Position dependence of the cluster energy after position correction using the hodoscope. Electron beam energy is 6 GeV and entered the detector at an angle of 10°.

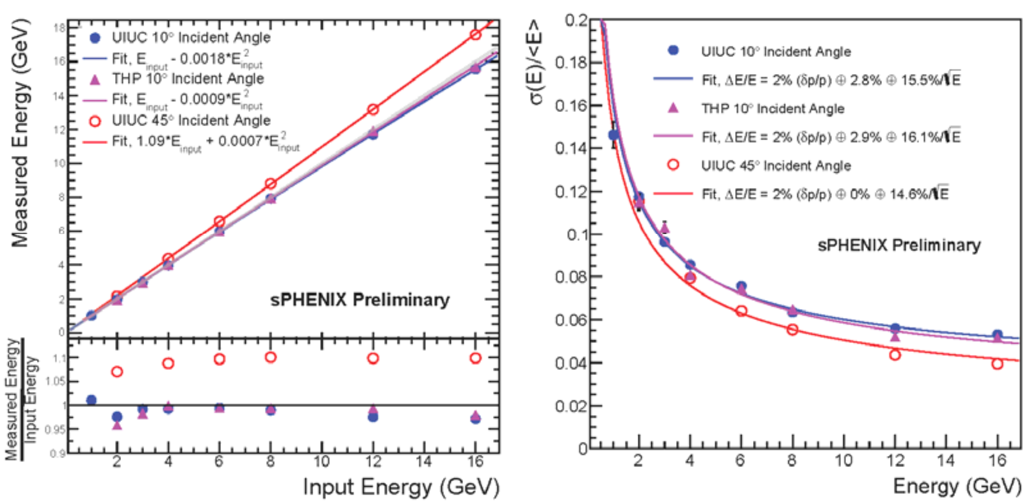

Figure 2.3. Linearity and energy resolution of electron showers in the EMCAL where the beam was selected to be in a 25 x 25 mm^2 area covering a full tower, after position correction in 5x5 mm^2 bins using the hodoscope. The beam momentum spread of 2% δp/p is factored out separately.

Construction of 2D projective modules and a large η prototype

We have made substantial progress in learning how to build 2D projective absorber blocks and are building a new prototype calorimeter using these blocks that we will test at Fermilab in early 2017. This prototype will represent a central barrel calorimeter at large rapidity (η~1). The procedure for producing these blocks was developed at UIUC and was done with the aim of mass production for a full size calorimeter. The blocks consist of 2x2 towers that are produced using a "bath tub" mold where the fiber assemblies are placed inside a mold that has the double tapered shape. The mold is then filled with tungsten powder and compacted by vibration and then infused with epoxy. The molds are produced using an inexpensive 3D printing process and can be made in any shape. Figure 2.4 shows a block inside the mold along with 16 blocks produced at UIUC that will go into the large η prototype calorimeter. The 16 blocks will form an 8x8 array of towers that will be tested at Fermilab along with a large η version of the sPHENIX hadron calorimeter.

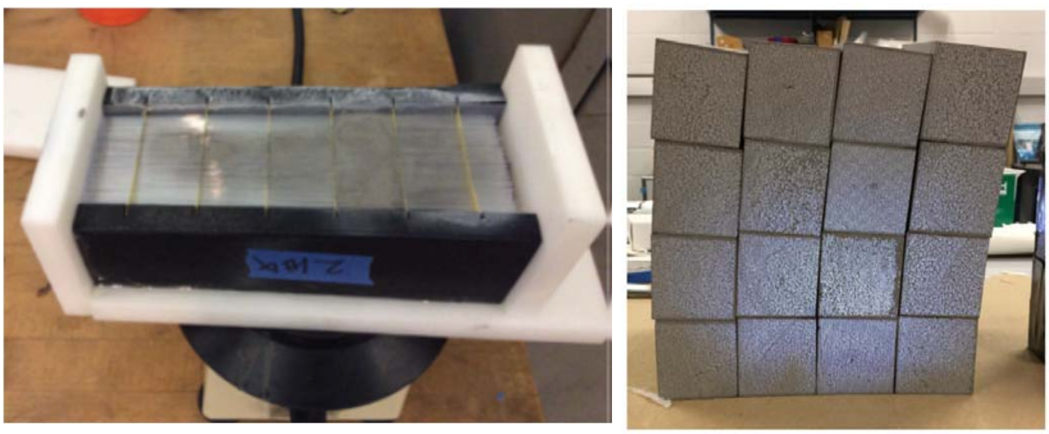

Figure 2.4. Left: 2D projective block in a double tapered mold. The tapered sides (black) are produced by 3D printing. Right: Sixteen 2D projective blocks produced at UIUC that will be used for the new large η prototype calorimeter.

Light guides and improving light collection uniformity

The basic problem in trying to build a compact calorimeter using W/SciFi absorber blocks, which have dimensions on the order of the Moliere radius (~ 2.3 x 2.3 cm^2), and reading them out with SiPMs, which have dimensions ~ 3 x 3 mm^2, is collecting the light output from the fibers in a short distance. This requires some form of focusing element, but since the light exiting the fibers is not parallel and is distributed over a large area, it is not possible to use a standard optical lens to accomplish this. We therefore rely on a light guide to collect the light, and also to mix the light from all the fibers such that it uniformly illuminates the SiPMs. However, it is very difficult to achieve both of these requirements in a short distance.

We have studied the light collection uniformity of the 1" trapezoidal light guides that were used in our first prototype using a single fiber that is excited with an LED and mounted on a movable stage that allows mapping the light collection efficiency as a function of position within the light guide. Figure 2.5 shows a scan across the middle of the light guide (blue dots) and shows that the light collection efficiency drops off near the edges by about 20% compared to the middle.

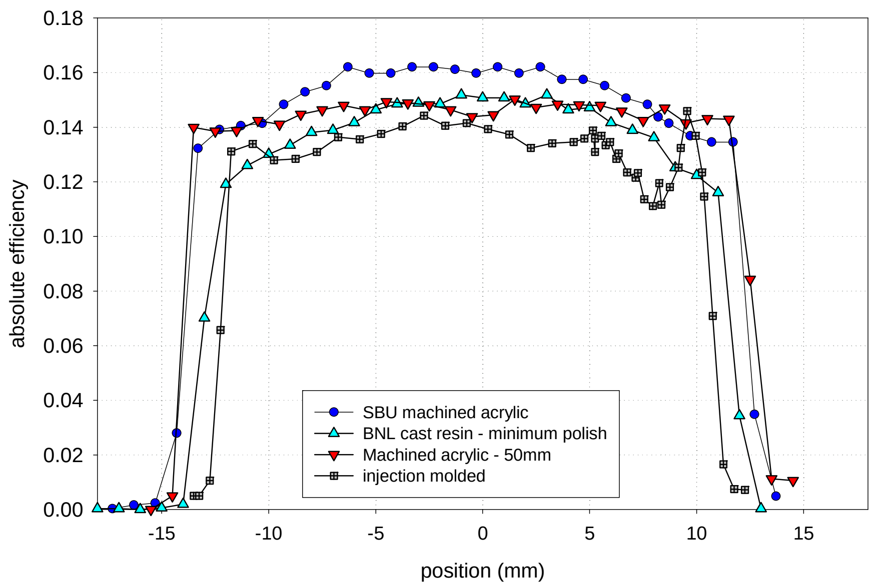

Figure 2.5. Light collection efficiency as a function of position for various types of light guides. Measurements were performed with a single fiber scanned across the middle of the light guide.

The red points in Fig. 2.5 show a similar scan for a 2” long trapezoidal light guide and shows that the uniformity is much better out to the edges. Both of these light guides were individually machined and polished in the Stony Brook machine shop are as high a quality as one could ever hope to achieve. However, the cost of producing many such light guides this way (e.g., for the ~ 25K light guides needed for sPHENIX) is prohibitive. We have therefore explored other options for producing light guides in a more cost effective way. After contacting many companies, there seems to be no precedence with either scintillation counter manufacturers or the plastics industry for doing this. The most cost effective method seems to be injection molding, but this is not typically used to produce optical quality parts. We had a batch of light guides made by a rapid prototyping injection molding company to explore this option and the results were disappointing. There were many distortions and imperfections in the parts that came back and the yield for acceptable quality parts was only ~ 20%. The grey points in Fig. 2.5 shows a scan of one of the acceptable parts which shows a loss of ~ 12% in overall efficiency compared with the machined light guide along with some distortion at one edge. The problem with injection molding seems to be quality of the mold and the process of cooling the part after it is formed. We now discussing ways of circumventing these problems with another injection molding company that has some prior experience making optical parts and we are hopeful that this will lead to a solution.

A second alternative for producing the light guides is by casting. In this process, the polymers that form the acrylic are mixed together and poured into a mold and allowed to set at room temperature. We tried making several light guides this way and the results are shown by the turquoise point on Fig. 2.5. It shows an overall loss in efficiency of ~ 6% compared to the machined light guide and a drop of ~ 20% at the edges. The problem in this case was very likely the quality of the mold that was used. However, we have found a company in the UK that has experience in casting acrylic optical parts and plan to pursue ways of casting light guides with them.

We plan to test the effect of longer light guides in our upcoming beam test of the large η prototype calorimeter at Fermilab. The calorimeter will consist of an 8x8 array of towers, and half of the towers will be equipped with 1” long trapezoidal light guides produced by injection molding (where each part actually consists of 4 light guides for the entire block), and the other half will be equipped with 2” long machined and polished light guides. While we know that it is not possible to use individually machined and polished light guides on a large calorimeter, we hope that the improved light collection uniformity of these light guides will demonstrate that good energy resolution can be achieved once the position dependence has been eliminated or significantly reduced. We expect that the injection molded light guides will give a similar position dependence to what was observed with our previous prototype along with a slightly reduced overall light collection efficiency. However, this will tell us what the expected performance of the calorimeter would be if we were forced to use such light guides.

We will also explore other ways of improving the light collection uniformity, such as those discussed by the UCLA group. Another way to improve the uniformity is to simply cover more of the readout area with SiPMs. However, while this is rather straightforward, it does add significantly to the cost. We nevertheless also plan to investigate this option as well.

Radiation Damage in SiPMs

We continued our study of radiation damage in SiPMs by carrying out a series of measurements with several different types of devices exposed to neutrons and gammas. Different types of radiation are expected to cause different effects due to damage, since neutrons with energies ~ few MeV can cause displacement damage in the silicon leading to clusters of defects, whereas gammas are more likely to cause more localized point defects.

Figure 2.6 shows two different SiPMs with 25 μm and 50 μm pixels (Hamamatsu S12572-025P and S12572-050P) exposed to increasing doses of ^{60}Co gamma rays. One observes a large increase in dark current during irradiation which is presumably due to direct Compton interactions in the silicon that mostly goes away immediately after exposure. However, there is a steady increase in the background current with increasing dose. The dark current increases by a factor ~ 40 (80) for the 25 μm (50 μm) devices respectively for a maximum dose of 1 Mrad (which is much higher than expected at EIC).

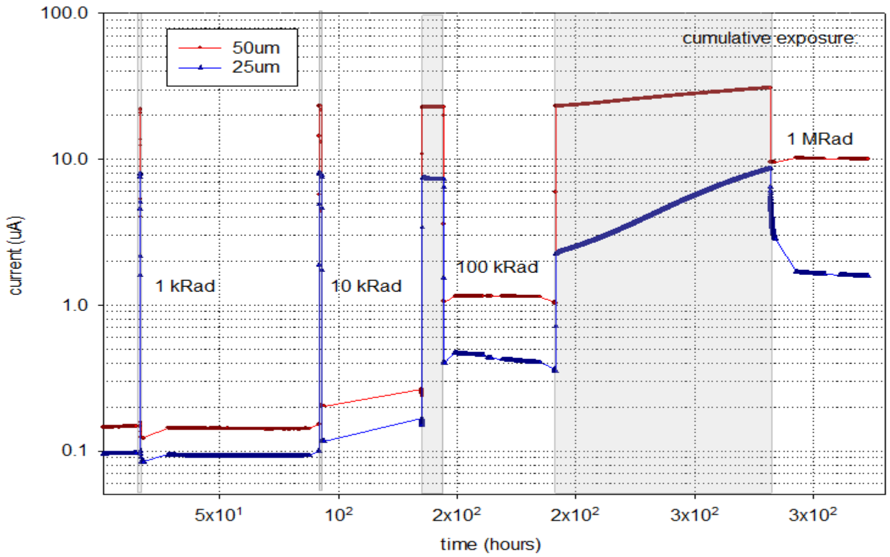

Figure 2.6. Increase in dark current from exposure of 25 µm and 50 µm pixel SiPMs (Hamamatsu S12572-025P and -050P) to increasing doses of ^{60}Co gamma rays.

Figure 2.7 show a similar set of curves for 15 µm, 25 µm and 50 µm pixel devices (Hamamatsu S12572-015P, -025P and -050P resp.) exposed to 14 MeV neutrons. In this case, there is a steady increase in current during irradiation, followed by some small recovery immediately after the exposure, but most of the large increase in dark current remains. This is the type of effect that one would expect from either high energy charged particle or neutron damage. The factors of increase in current for the maximum dose (10^{10} n/cm^2, which one may well achieve at EIC) are much larger than for gammas (factors of 900, 1100 and 2100 for the 15 µm, 25 µm and 50 µm pixel devices resp.).

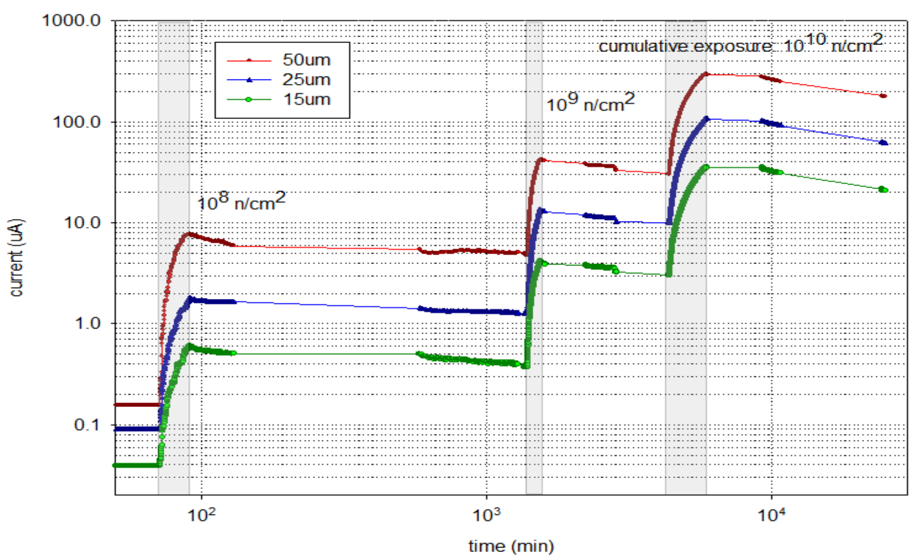

Figure 2.7. Increase in dark current from exposure of 15 µm, 25 µm and 50 µm pixel (Hamamatsu 12572-015P, -025P and -050P) SiPMs to increasing doses of neutrons (E_n = 14 MeV).

As part of this study, our collaborators on sPHENIX from the Debrecen University in Hungary also measured radiation damage in some of the same types of devices that we measured and obtained very similar results. In addition, they measured the breakdown voltage in several devices before, during and after irradiation and found that there was no significant change in breakdown voltage up to several x 10^{11} n/cm^2. This is an important result, since if the breakdown voltage were to change either during or as a result of irradiation, it would make maintaining a constant gain during the operation of any detector using SiPMs very difficult.

We also studied the effect of neutrons and gammas on various types of optical window materials used in SiPMs. We obtained special samples of epoxy and silicone used for molding and potting SiPMs from Hamamatsu that were prepared in thin films on thin quartz windows that allowed us to measure their transmission before and after irradiation. We exposed them to gamma rays up to 1 Mrad and neutrons up to 10^{10} n/cm^2. For gamma irradiation, we observed a slight increase in absorbance near the band edge for the epoxy samples, and less of an increase for the silicone samples. However, in both cases, the absorbance at the emission peak for most scintillators (~ 400-450 nm), there was no observable effect. For neutrons, there was virtually no change in the transmission of any of the samples up to the highest dose. The conclusion from this study is that there should be no degradation in the performance of the SiPMs (such as loss of PDE) due to radiation damage to the optical window from either gammas or neutrons. These results and the results from our other radiation damage studies with gammas and neutrons were presented at the 2016 IEEE NSS conference and will later be submitted for publication in the IEEE TNS.

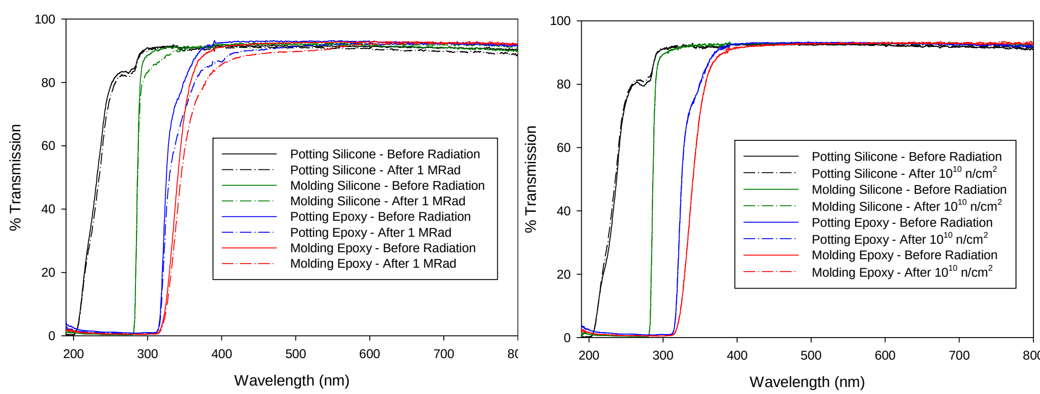

Figure 2.8. Transmission of various materials used for entrance windows of SiPMs for gammas and neutrons. Left: ^{60}Co gamma rays, Right: 14 MeV neutrons.

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

We basically achieved all that we planned to do during the past six months. The schedule for preparing the large η prototype calorimeter for the beam test at Fermilab is very tight, but we feel it will be ready in time for the test which is scheduled to begin on Jan. 18th. We hope that this test will tell us how the 2D projective blocks perform under real beam conditions and provide a measurement of their energy resolution, linearity and other important parameters. The main item that remains unsettled at this time is how to achieve better light collection uniformity from the light guides and how to fabricate high quality light guides in large numbers at an affordable cost. As discussed above, we have several paths we are following to try and achieve this, but we do not have solution at the present time.

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 carry out the beam test of the large η prototype calorimeter and to analyse the test beam data. At the same time, we will be continuing to develop mass production techniques for producing 2D blocks at UIUC and preparing to build a half sector prototype of the sPHENIX EMCAL at BNL. We will also be pursuing a solution for improving the light collection uniformity of the light guides and exploring ways for mass producing them.

What are critical issues?

The most critical issues during the next six months will be to measure the performance of the large η prototype calorimeter and to find a cost effective solution for improving the light collection uniformity.

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 PHENIX Group and the group at UIUC. However, there has also been some participation by the University of Michigan and Debrecen University in Hungary.

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. There is also some support on radiation damage studies in SiPMs from a joint LDRD between the BNL Physics Department and BNLs Instrumentation Division.

Publications

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

There have been no new publications since the last report.

Sub Project 3: Crystal Calorimeter Development for EIC based on $PbWO_4$
Project Leader: T. Horn

Past

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 to 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 a 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* FY17 budget some of us started receiving in December 2016 was 43% of the requested budget.

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 were:

- 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 in SIC and Crytur crystals
- Tested two methods of crystal chemical analysis and obtained initial results
- Developing non-destructive sampling methods for chemical analysis
- Work towards growing scintillating crystals at VSL
- Preliminary measurement of light output of one PWO crystal with photodiodes at CUA

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

- We made good progress on initial characterization of a subset of SICCAS 2014 crystals and understanding systematic uncertainties due to the setup. In anticipation of the next phase of crystal testing and with support from the VSL and JLab, we procured some components for a crystal testing facility at CUA. Similarly, IPNO procured components and setup space for crystal testing at Orsay. We are planning to work within the constraints of the approved budget for FY17 to complete our crystal testing setup to address systematic uncertainties and to perform chemical analysis of crystals.

- IPN-Orsay procured three full-size crystals from Crytur and made initial measurements in collaboration with Giessen University through the JLab NPS collaboration. Though the results are encouraging, an evaluation of Crytur crystal-to-crystal variation with a set of three crystals was not possible. Based on our experience this is not sufficient to draw a final conclusion. With the budget constraints for FY17 we will not have a reasonable batch of crystals to evaluate the crystal-to-crystal variation. We are planning to explore if information from tests at Giessen U. albeit on a different crystal geometry can provide any information.

- We did not make progress on the prototype studies as we did not obtain funding for FY17 for this activity. We anticipate making some progress in design optimization based on the smaller 3x3 prototype for the NPS at JLab.

Future

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

- For this funding cycle we plan to complete our goals from the previous FY16 cycle (see our report from June 2016 for reasons why these have not yet been completed) and also try to make progress beyond that as budget constraints allow. We will work towards finalizing the crystal testing facilities at CUA and IPN-Orsay. In anticipation of the next crystal testing phase and with support from the universities and laboratories, both CUA and IPN-Orsay have been actively procuring components and allocating space. This will allow us to perform chemical analysis and test the optical properties and the homogeneity of crystals produced at SICCAS and procured through synergy with the VSL and 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 a few full-sized crystals from Crytur. 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 extent 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 VSL and the NPS project, as well as the impact of systematic uncertainties between measurements. 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:

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
R. Trotta
A. Vargas
R. Uniyal
A. Mkrtchyan, postdoc
T. Horn
Vitreous State Laboratory

Yerevan
H. Mkrtchyan
V. Tadevosyan

BNL

C. Woody
S. Stoll

Caltech
R-Y Zhu

External Funding

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

- All of the FTEs required for working towards 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 here were accomplished with external funds through synergistic activities with the NPS project at JLab. 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

No new publications during this period.

Sub Project 4: Simulations for a Crystal Calorimeter at EIC
Project Leader: A. Kiselev

Past

What was planned for this period?

The main goal of the first round of Monte-Carlo simulations was to establish a basic set of the realistic design parameters (in particular the energy resolution), which should be met during the on-going hardware R&D prototyping work.

What was achieved?

As a starting point of the respective Monte-Carlo simulation work we concentrated on the kinematic parameter smearing effects in the inclusive deep-inelastic scattering (DIS) process at the highest anticipated EIC beam energies (20 GeV electrons on 250 GeV protons). The quality of the physics measurement in this process is determined to a large extent by the level of bin-to-bin migration in the 2D $\{x_{bj}, Q^2\}$ kinematic plane. Past experience, in particular the HERMES Collaboration data analysis, indicates that acceptable the "bin survival" level (the probability to register the event in the same kinematic bin where it originally occurred), which effectively determines the kinematic reach, should be of on the order of at least 0.6-0.7, spanning from the maximum values of *y* down to the region of $y \sim 0.01$ (where *y* is the DIS variable, describing a fraction of the beam electron energy carried by the virtual photon). A significant fraction of the "small *y*" kinematic domain is characterized by small electron scattering angles and large energy. Tracker momentum resolution, which is typically used for the scattered electron track parameter determination, degrades rapidly under these circumstances because of the vanishing effective B*dl integral of the central part of the solenoid field (see figure 4.1). A crystal calorimeter with the sufficiently high energy resolution in the electron-going direction end-cap can potentially circumvent this problem. Namely, the scattered electron momentum can be taken as a weighted mean of the momentum measured by the tracker system and the energy measured by such a calorimeter.

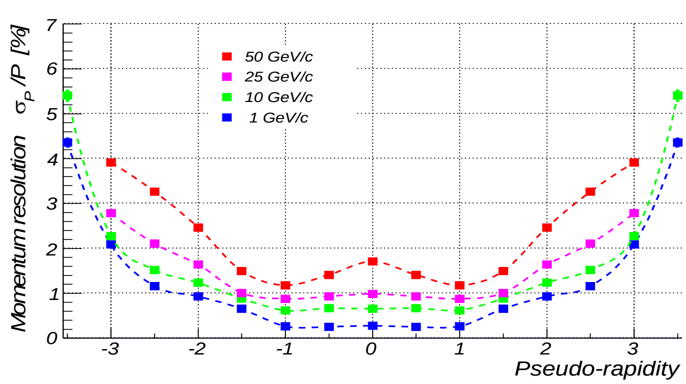

Figure 4.1. BeAST (Brookhaven eA Solenoidal Tracker) momentum resolution in the pseudo-rapidity range $-3.5 < \eta < 3.5$. Momentum resolution is determined by the composition of tracking detectors (TPC, Silicon, GEMs) contributing at a given pseudo-rapidity, their spatial resolutions, material budget and effective B*dl integral

of the solenoid field transverse component along the secondary track direction. It rapidly degrades at the edges of the shown η range because scattered tracks are getting more and more aligned with the magnetic field lines and therefore bending becomes too small.

We originally considered the case when a crystal calorimeter with an energy resolution of ~2%/√E (and no constant term) was installed in the pseudo-rapidity range $\eta < -2$, as shown in the right panel of Fig. 4.2 (this was also shown at the recent DIS 2016 conference and the Argonne EIC R&D Committee meeting in July 2016). In order to disentangle various instrumentation effects and to emphasize the pure impact of a high resolution EmCal on the quality of this physics measurement, all the external bremsstrahlung effects are turned off in this particular round of simulations.

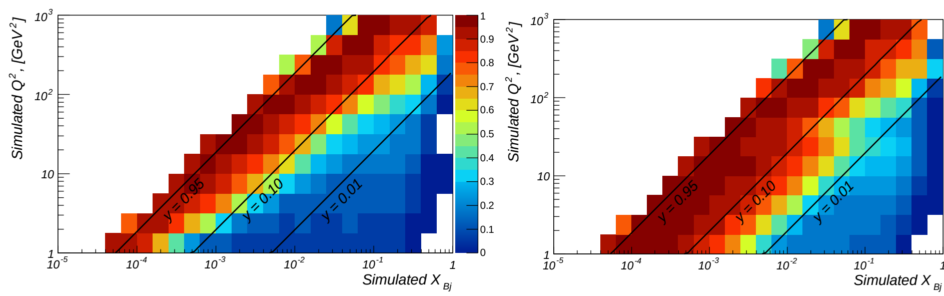

Figure 4.2. Inclusive DIS event parameter migration in the $\{x_{bj}, Q^2\}$ kinematic plane. Pythia 20x250GeV events with external bremsstrahlung turned off. Only the area with survival probability >0.6-0.7 is suitable for a conclusive analysis. Left panel: only the tracker information is used to calculate scattered electron momentum. Right panel: same events, but a weighted mean of the tracker momentum and the crystal calorimeter energy is used. Calorimeter resolution is taken to be $\sigma_E/E \sim 2.0\%/\sqrt{E}$ for pseudo-rapidities below -2.0 and ~ 7.0%/√E for the rest of the acceptance.

Figure 4.3 (left panel) shows the same simulation with a more realistic energy resolution, taken from the JLAB Hall B PrimEx calorimeter parameterization: $\sigma_E/E \sim 1.75\%/\sqrt{E} + 1.15\%$. A comparison of Fig. 4.3 (left panel) with Fig. 4.2 (right panel) seems to indicate that part of the improvement gained with high-resolution calorimetry – access to a larger range of y for high “bin survival” - is partially reduced due to the influence of the constant term in the energy resolution. The impact of the constant term may be a larger factor for the highest anticipated electron beam energy, 20 GeV, which was chosen for this simulation. At the same time one should bear in mind, that at smaller beam (and therefore scattered lepton) energies, not only does the tracker provide higher momentum resolution at the same values of pseudo-rapidity (see Fig. 4.1), but also the scattered DIS electrons are boosted more towards central rapidities (see Fig. 4.4), where the tracker is performing better in general, and therefore the positive impact of a high resolution calorimeter would be getting less pronounced.

Nevertheless, the present study illustrates the desire to reduce the constant term to below 1%. For comparison, the right panel of Fig. 4.3 shows simulation results for an “ideal” calorimeter with energy resolution parameterized as $\sigma_E/E \sim 1.0\%/\sqrt{E} + 0.5\%$, where one can see a clear improvement in performance (a noticeable extension of *y* range with sufficiently high bin survival probability).

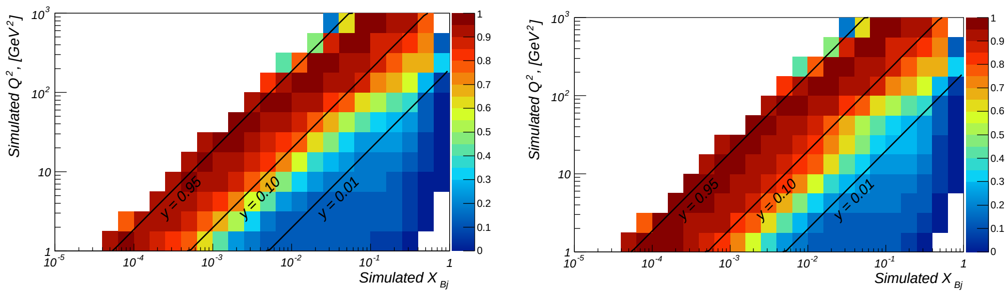

Figure 4.3. Same set of events as in Fig. 4.2. A weighted mean of the tracker momentum and the crystal calorimeter energy is used. Left panel: calorimeter resolution is taken to be $\sigma_E/E \sim 1.75\%/\sqrt{E} + 1.15\%$ (PrimEx PWO calorimeter at JLAB) for pseudo-rapidities below -2.0 and $\sim 7.0\%/\sqrt{E}$ for the rest of the acceptance. Right panel: simulations for a hypothetical "ideal" calorimeter resolution $\sigma_E/E \sim 1.0\%/\sqrt{E} + 0.5\%$ for $\eta<-2$.

The preliminary conclusion of this simulation study is that in order to make a clear positive impact on the scattered electron kinematics determination, especially when one deals with the highest EIC electron beam energies, a crystal calorimeter in the electron-going end-cap direction should be pushed towards a constant term of ~0.5%.

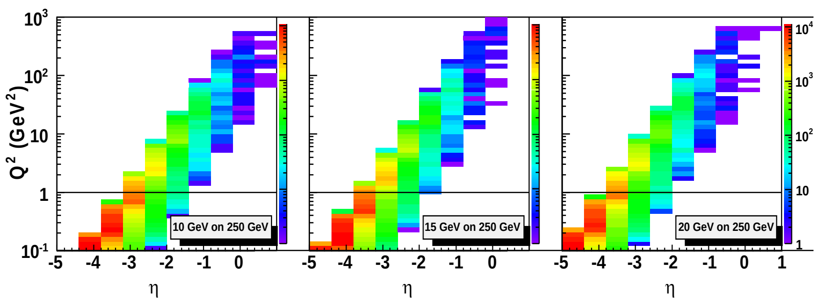

Figure 4.4. $\{\eta, Q^2\}$ distribution of scattered electrons at various lepton beam energies. With decreasing beam energy the DIS electrons with $Q^2 > 1$ are boosted more towards central pseudo-rapidity values.

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

The demonstrated results adequately represent the original set of goals, which were planned as a first stage of the Monte-Carlo simulation work to justify the high-resolution crystal inset in the electron-going direction end-cap EmCal setup. The impact of the constant term with differing EIC electron energies and on lepton identification should still be checked.

Future

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

The next steps will be to perform the simulation in a more realistic environment (account for the bremsstrahlung tails and perform detailed calorimeter digitization), to quantify the crystal granularity requirements needed for spatial resolution (in particular for the photon-induced clusters, where the tracker cannot contribute), take into account fiducial volume restrictions close to the beam pipe, as well as perhaps further optimize the tracker system and the solenoid magnetic field configuration in the electron-going direction. We are also planning to consider different physics benchmark processes, in particular registration of high-energy photons from DVCS process. It is also planned to verify via detailed Monte-Carlo simulation that a calorimeter with high enough energy resolution should greatly improve lepton identification via selection based on the E/P ratio.

What are critical issues?

The critical issue is to establish a coherent set of realistic requirements for the combined tracker plus calorimeter setup, which on one hand can be met in hardware, and on the other hand would allow the anticipated end-cap crystal calorimeter system to make a clear positive impact on the physics measurement in a selected set of the relevant benchmark processes.

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.

These calorimeter simulations were carried out by A.Kiselev from the RHIC Spin 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.

Support for all personnel involved in this sub-project is provided by the BNL Physics Department.

Publications

There were no publications resulting from these simulations during this period.