December 2013 Status Report and Proposal For EIC Calorimeter Development

The EIC Calorimeter R&D Consortium

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Overview

Within the EIC calorimeter consortium, there are four major R&D efforts to develop calorimeter technology: 1) the RD1 (2011) effort to develop a W-powder/Scintillating Fiber-based compact SPACal-type electromagnetic calorimeter (UCLA/IU/TAMU/PSU/BNL); 2) the development of a Tungsten plate-based EMC(BNL); 3) the R&D project on crystal calorimeter development based on BSO and PWO crystals(USTC); and 4) Monte Carlo simulations for both detector design and physics to develop detector requirement specifications and physics capabilities for a comprehensive detector at EIC(BNL).

The UCLA/IU/TAMU/PSU/BNL team has constructed three prototypes, two EMC for barrel and for forward region, and one HCal, for beam testing planned in Feb.-Mar. 2014 at FNAL. Samples of SiPMs from Hamamatsu have been tested and characterized in laboratory using a laser. The beam testing will focus on light yields, light collection and SiPM performance and front-end electronics. The team requests $115.1k to continue the R&D project in FY2014.

The BNL (PHENIX) team has been building a prototype module and much effort also went into investigating light collection scheme and SiPM characterization. A beam testing in Feb. at FNAL will be a key milestone for the R&D project to evaluate the detector construction technology. The team requests $135k to continue the R&D project in FY2014.

The USTC crystal R&D team has completed quality test on a sample of 9 BSO crystals and the recent effort has been centered on simulations. A high quality electron beam is needed to test the crystals and to compare with simulation results. The team is investigating options of possible beam test early next year or joining the SLAC beam testing with the rest of the consortium in the fall 2014.

The Monte Carlo simulation project by the BNL team aims at the development of tracking and calorimeter requirements for an EIC detector. A separate report covering both the tracking and calorimeter related simulations will be submitted by the BNL group.

We note that we have regular meetings among the tracking and calorimeter consortia. The BNL-PHENIX and the RD1 team have been working very closely on all aspects of the calorimeter R&D including the prototype module construction technology, light collection scheme, SiPM characterization and front-end electronics. We continue to improve our approaches with the understanding that we will collaborate to design an EIC calorimeter system with the best technology combining from all groups. This has been very productive and enjoyable collaboration for all involved. We also recognize that we need more research groups if we are to build the EIC calorimeter system. We hope to reach out to more groups and expand our R&D activities in the coming year.

EIC Detector R&D Project RD1 Progress Report
Reporting Period: From 05/01/2013 to 12/12/2013

Project Name: Development of a New Technology for Fiber Sampling Calorimeters for EIC

Project Leader: Huan Z. Huang

Date: 12/12/2013

1. Overview.

Over the past two years, the RD1(UCLA/IU/TAMU/PSU/BNL) group has been working towards development of a technology to build compact calorimeters utilizing W powder and scintillation fibers. Several prototypes were constructed and two of them were characterized in test beams at FNAL in 2012 in order to demonstrate the proof of principle. During the past year, we have continued to improve our construction techniques. The technology has been extended to build non-projective barrel calorimeters with wedge-shaped towers, as well as calorimeters for the forward region (this effort was funded from STAR R&D in 2013 and are considered a continuation of EIC R&D from 2012). Two new EM calorimeter matrices (16 towers for the forward calorimeter) and 18 wedge-type towers for a barrel EM calorimeter prototype were constructed during the summer/fall of 2013 at UCLA and are presently in the final stages of preparation for a test run at FNAL scheduled in Feb-March 2014. The parallel R&D for the STAR forward upgrade led to construction of a compensated hadronic calorimeter prototype consisting of 16 towers (4 interaction lengths deep, each tower 10 x 10 cm^2). This same technology is under consideration for hadronic calorimeters in the forward region as part of a dedicated EIC detector system. All three calorimeter prototypes will be equipped with compact readout systems utilizing silicon photomultipliers, which was a goal we set for R&D in 2013. For the EM section, each tower will be read out with four Hamamatsu 3 mm x 3 mm sensors. Each HAD tower will be readout with eight such sensors. Funding for development of the front end electronics for this compact readout has been provided somewhat late and mostly from STAR. EIC R&D funds covered only preliminary design efforts.

We completed analysis of the thermal neutron flux measurements in the STAR experimental hall during RHIC Run 13. The full analysis was presented in an article [1] submitted to NIM.

Undergraduate students have been participating in our effort to measure characterization of Hamamatsu SiPMs and have performed optimization of the optical light collection scheme for the hadronic calorimeter. They are also helping us with the construction of prototypes. Two of our students presented their research results at the fall 2013 DNP meeting (poster session for CEU program).

2. W Powder ScFi: New Developments.

Construction of wedge-shaped towers for scintillation fiber calorimeters has always been a challenging and extremely labor-intensive task mostly because of strict requirements for mechanical tolerances and homogeneity of towers. With our technique, the simplicity of construction for rectangular towers is preserved for tapered towers as well. The desired taper is achieved by inclination of the meshes along the tower length as shown in Fig. 1.1. We found that two types of mesh, with the same pattern of holes and different diameters to allow

for inclination, are sufficient to build a barrel EM prototype. This is the only difference in the construction technique. All other steps in building towers are essentially the same for the two types of geometries.

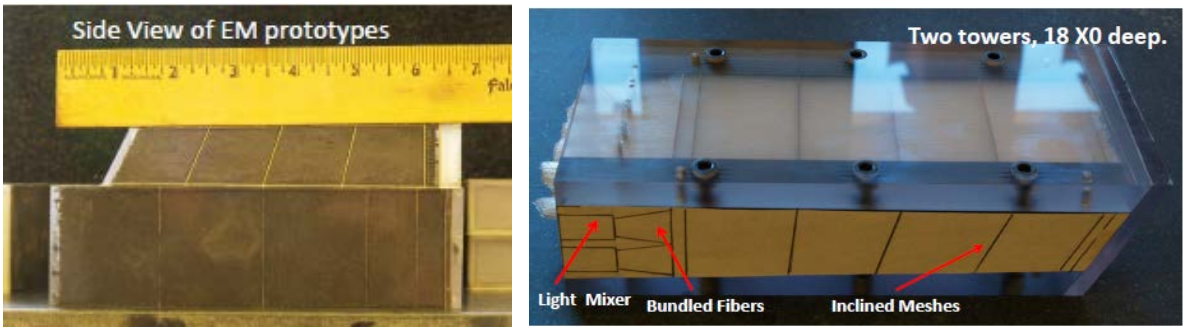


Figure 1.1: A side view of new EM prototypes. (Top) Molding form with fiber assembly, prior to filling with W powder and epoxy. (Bottom) Tapered 18 X_0 deep barrel prototype on top of a 23 X_0 deep forward EM prototype.

As was discussed in our previous proposal, the requirements on light collection for barrel EM prototype is 500 p.e./GeV in order to keep the contribution from photo-statistics on energy resolution at a negligibly low level. To meet this requirement, the original idea for light collection was to bunch fibers as shown in Fig. 1.2.

Figure 1.2: A possible scheme for light collection from a tapered Barrel EM prototype.

This scheme was prototyped before we performed characterization of the SiPMs. However, final design of the light collection scheme will depend on results from the upcoming test run

at FNAL. With this scheme, and with single-clad fibers and the SiPM sensors already in hand, our goal for light collection was reachable, based on our previous test results, as described in last year's proposal.

The reason to try another light collection scheme is that the light is not well-mixed in different parts of a single tower and that the photo-detection efficiency can potentially change for different SiPMs differently with changing temperature, which will lead to degradation of the energy resolution. Instead of four independent small light mixers, we decided to proceed with a single, traditional trapezoidal light mixer of about 1 inch long. The view of both EM matrixes from the sensor side (prior to gluing the light guides) is shown in Fig. 1.3.

Figure 1.3: View of new EM matrixes from photo-detector side. The separation between towers was achieved by pre-bunching of fibers. For the Barrel EM prototype, the fibers were bunched more tightly, compared to the forward EM prototype, which can be seen as an increased separation gap between towers. The last meshes facing the light guides have a mirror coating on them for integration of the monitoring scheme and potentially better efficiency of light collection.

For barrel EM prototypes we used multi-clad scintillation KURARAY fibers to boost light yield (for forward EM section where light yield requirements are relaxed, we used single-clad fibers). Depending on results of the test run at FNAL, the light collection scheme may be modified. If the required light yield is not reached, then we have to make improvements on the light collection scheme, mostly likely in the sensors. The present sensors we bought for the test run have photo-detection efficiency for blue light of about 20%, which is a factor of two lower than many other new sensors coming on the market this year.

The technique for building rectangular towers has also been improved. The entire supermodule consists of four towers built at once, while in 2012 they were glued from two subassemblies. This reduces production time and also improves uniformity between the towers. We switched to Epotek 301-1 epoxy which has lower viscosity compare to the Bicron BC600 epoxy used previously. The injection time for epoxy into a 2 inch depth of W powder is approximately 10 minutes. The size of the supermodule can probably be extended a bit more, but one should consider potential damage to fibers during packing of W powder for heavier modules. We believe that at present stage of development, this technology is close to be final, with perhaps only minor adjustments. For example, we have found that the close tolerances on the diameter of holes for new meshes actually can create problems with bunching of fibers at the end of the module and that additional treatment of the edges of the holes in the last mesh is desirable in this case. A similar treatment will be needed for tapered

towers as well. Small improvements in technology can be made with a few more iterations, and then this technology will be ready for mass production.

3. Brief Description of HAD Prototype.

The HAD prototype is funded by STAR R&D and is based on a design being considered for a dedicated EIC detector. Data which will be obtained in the test run will be very important to tune MC simulations for realistic EIC detector performance. At present, not a single physics list in GEANT3 or GEANT4 can reliably describe the performance of compensated hadronic calorimeters. In Fig. 1.4, for example, we give the e/h ratio for different lists of physics for simulations..

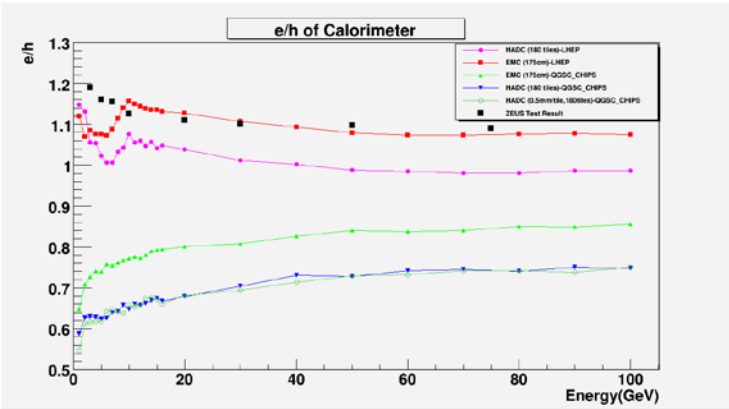


Figure 1.4: e/h ratio for EM and HAD sections with experimental results from ZEUS Pb/Sc prototype. Both sections have the same compositions as the proposed EM and HAD sections of the FCS, but the dimensions of both sections were kept sufficiently large for complete containment of showers. The LHEP physics list provides the best description above 10 GeV.

The design of this detector is modeled from the ZEUS Pb/Sc prototype [2], with the sampling fraction and thickness of absorber and scintillation plates to keep it compensated. However, the construction technique and mechanical design of the calorimeter is quite different, as it is aimed for detector to be built in place. Fig. 1.5 shows one tower of the HAD prototype with the EM matrix in front of it. The combined detector is 5 interaction lengths deep.

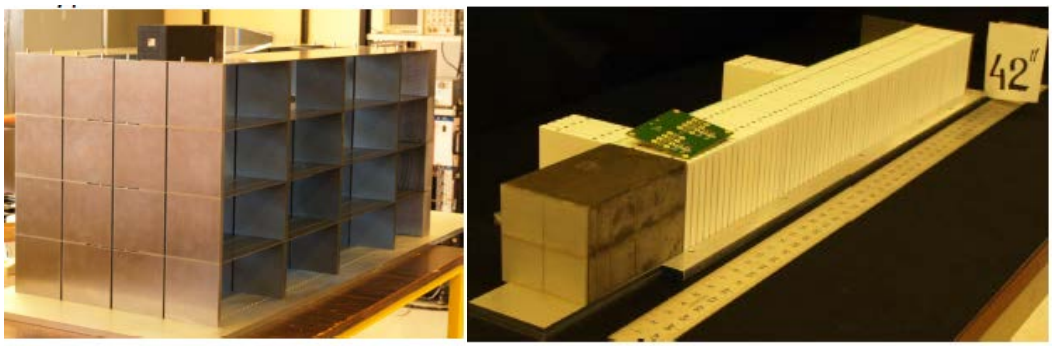


Figure 1.5: (Left) HAD prototype; size is 0.4 m x 0.4 m. A single hadronic tower consist of 65 absorber plates of 10 mm thick painted with white diffuse reflective paint and 64 scintillation tiles of 2.5 mm thickness which were inserted in the gaps between absorber plates. A single WLS bar along the side of the tower collects light from scintillation plates. SiPM readout module (green card on top of the HAD tower) attached to the end of the WLS bar.

One of our undergraduate students measured the parameters and optimized the light collection scheme for the hadronic calorimeter. The results of bench test measurements were fed to a GEANT4 MC to evaluate effects of optical chain on energy resolution. It was found that the major effect which needs to be taken into account is the rapid change of light collection efficiency as a function of position of the scintillation tile along the tower. All other effects (variation of tile thickness, variation of air gap thickness between Sc tiles and WLS tiles etc.) are not significant. The best reflector arrangement was similar to that used in the ZEUS design, with white diffuser at the far end of the WLS bar and aluminized Mylar behind this bar. The results of some of these measurements are shown in Fig. 1.6. Compensation of light collection was achieved with a simple filter printed on Mylar film which was inserted between scintillation tiles and WLS bars. With such a filter, light collection is uniform to within 10%. The effect of non-compensated light collection on energy resolution is very strong, without proper compensation the energy resolution degraded by a factor of two, as shown on the left side of Fig. 1.6. One HAD tower was placed vertically and the response was measured with cosmic muons to extract absolute light yield. We measured 110 p.e. (most probable value) from cosmic muons. Relying on ZEUS measurements of e/muon and e/h [2], we found that we will be detecting about 80 p.e./GeV with readout based on SiPM (see section on FEE developments).

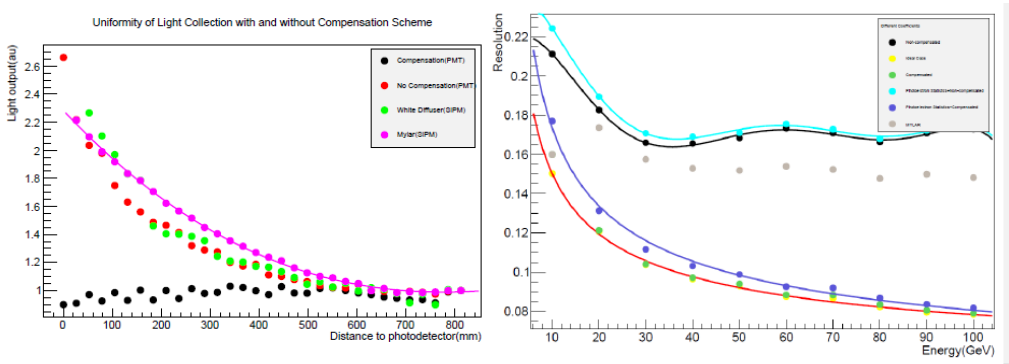


Figure 1.6: (Left) Light collection efficiency as a function of a distance between scintillation tile and photo-detector for different combination of reflective materials. (Right) Expected hadronic energy resolution, according to GEANT4, of combined (EM+HAD) calorimeter with and without optical compensation (red line -ideal case, blue -expected including photo-statistics and optimized light collection scheme. Black and cyan curves -energy resolution without proper filtering of scintillation light).

According to GEANT4, for the forward calorimeter system we should expect an energy resolution for hadrons close to 43%/√E + 3.8%, when instrumental effects are taken into account.

4. SiPM Characterization in the Lab.

Sensors for compact readout for this test run were bought from Hamamatsu. These sensors from last year are MPPC S1093-025p (3 mm x 3 mm, 25 um cell size). Two undergraduate students measured characterization of samples of these sensors in the lab at UCLA. All major parameters: gain vs bias, breakdown voltage, relative PDE, excess noise factor, temperature dependences etc. were studied during summer/fall in the lab.

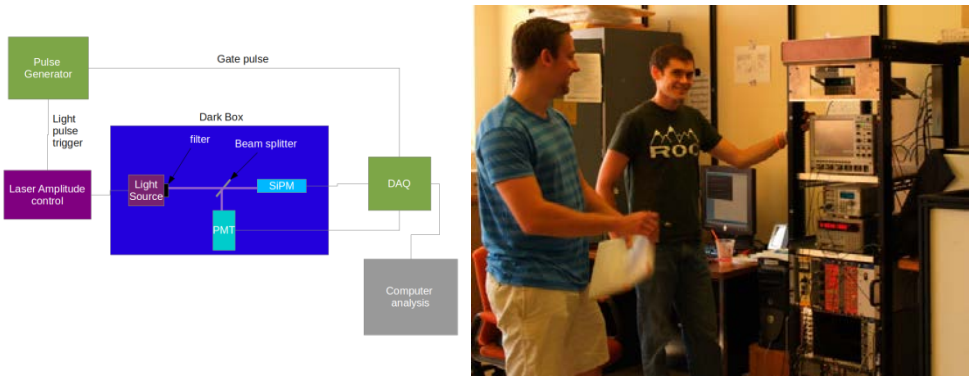


Figure 1.7: Basic schematic of the experimental setup to measure parameters of the SiPMs.

A diagram of the testing setup is shown in Fig. 1.7. We used different homemade preamplifiers for different types of measurements. Only a few results will be discussed for illustration purposes. Fig. 1.8 shows excellent single pixel resolution with our setup which was required to measure essentially any parameters of SiPMs.

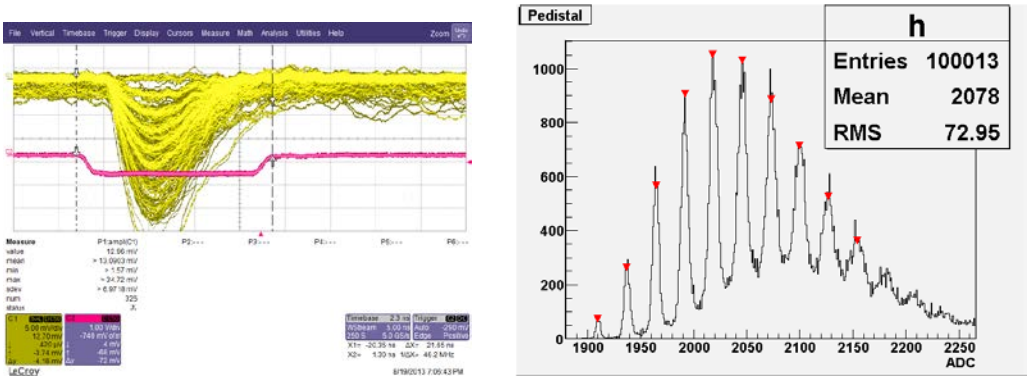


Figure 1.8: Oscilloscope traces and ADC spectra from Hamamatsu SiPMs.

Relative PDE was measured as a function of bias voltage and temperature. To extract relative PDE numbers we used different procedures: one used by GLUEX [3], where both optical cross talk and PDE were taken into account and the other method by directly accounting for the noise contribution under the pedestal peak to correctly calculate probability of firing zero pixels. Both methods give similar results as shown in Fig. 1.9 (labeled by students as the GlueX Calculation and Adjusted Poisson Calculation, respectively).

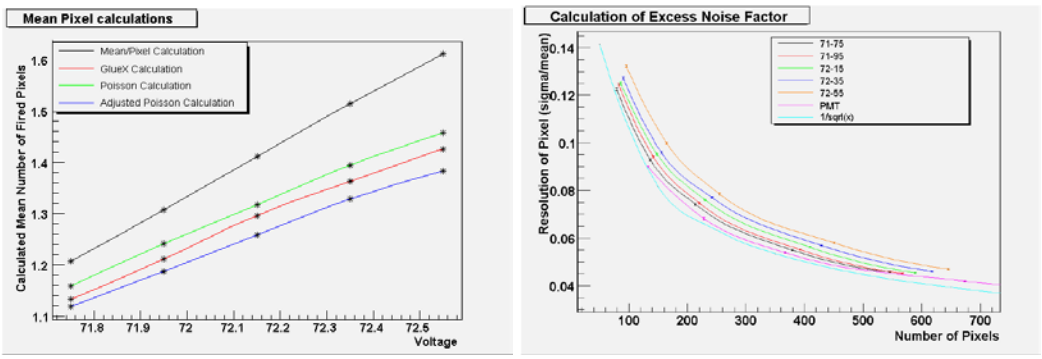


Figure 1.9: (Left) Excess noise factor for different bias voltages. (Right) Relative PDE vs bias voltage.

The probability to create an avalanche strongly depends on bias voltage, as is obvious from Fig. 1.9. That is an unfortunate property of SiPMs. Complications will arise once one wants to compensate the response of the system with changing temperature by changing the bias voltage, because not only will the gain change, but also the PDE. Depending on the light collection scheme, this may or may not be critical. For example, for the HAD calorimeter, all light detected by the SiPMs are perfectly mixed by the WLS bar, so that with a single temperature compensation slope for all eight sensors attached to that WLS bar, one can, in principle, achieve perfect correction of detector response with changing temperature. Even imperfect compensation will not introduce significant additional factors influencing the energy resolution. That is not the case for the light collection scheme shown in Fig. 1.2. For such scheme, a single temperature compensation slope may cause degradation of energy resolution. An excess noise is rising with increased overvoltage as shown on the top panel of Fig. 1.9. In principle, optimal setting of the overvoltage should be a compromise between the left and right panels of the Fig. 1.9. However, without direct beam measurements of light yield from the detector, such optimization is not realistic. We wish to accomplish this task during the next round of R&D after data from the test run at FNAL is analyzed.

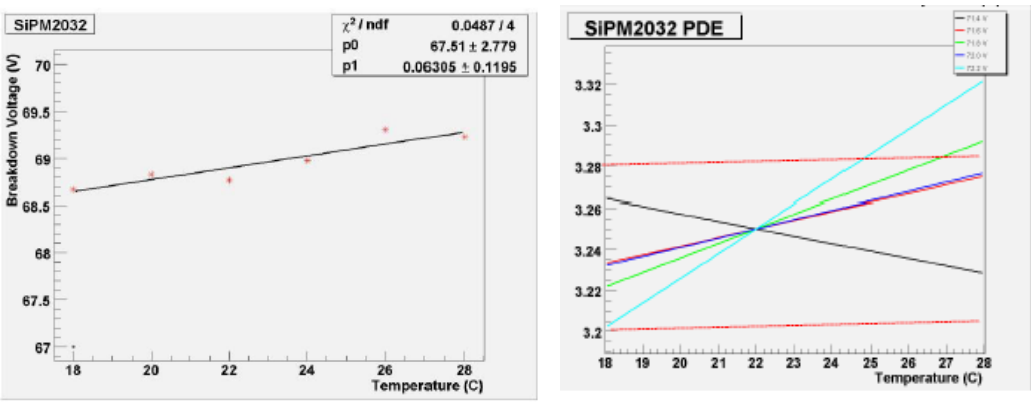


Figure 1.10: (Left) Breakdown voltage as a function of temperature. (Right) Relative PDE vs temperature for different bias voltages. Red horizontal lines define a window of +- 1%.

Temperature dependence of sensors was measured using an environmental chamber with temperature control. Fig. 1.10 shows the dependence of breakdown voltage and PDE as a function of temperature. We will continue these studies in the future. Expectation was that both gain and PDE would drop with increasing temperature at a given bias voltage. The gain indeed changes smoothly with a slope of about 1.5% per degree C. The PDE on sensors we measured so far seems to be changing much less (or even may be considered as flat) in the temperature range from 18-28 degrees C.

5. Development of FEE for the Test Run.

The development of front end electronics to readout multiple SiPMs was carried out by the IUCF group. The requirements for this electronics can be summarized as follows; provide independently adjustable bias for every SiPM, provide independently adjustable T compensation for every SiPM, amplify/sum signals from four SiPMs, bridge front end electronics with existing DAQ (differential output/receiver for cables up to 100 ft. long). The dynamic range must match the desired energy range of test beam at FNAL, however, it should

be noted that at the time design was implemented, the dynamic range was not well known, primarily because of an unknown efficiency of light collection from prototypes. This work was supported mostly from STAR R&D funds. The HAD front end readout board is shown on Fig. 1.11.

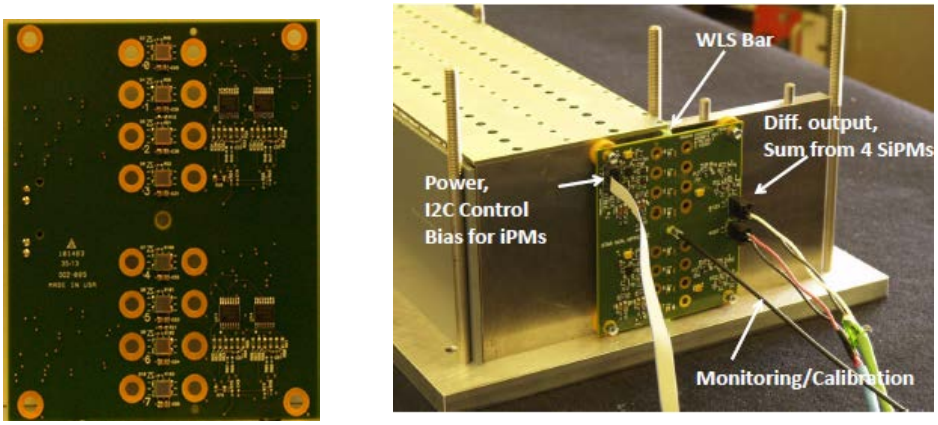


Figure 1.11: First HAD board with eight SiPMs installed on the left. HAD readout front end board at the end of the HAD calorimeter tower during bench test measurements.

The design is very flexible and probably overcomplicated, but for the test run we decided to cover all possible scenarios. Control software using the I2C protocol was written by a UCLA postdoc. The performance of this board was carefully tested at UCLA. To correctly set bias on every SiPM it is required to first calibrate every DAC channel. Response from every sensor can be equalized within the stability of the light injection system, which was 1%. The board was tested in a temperature controlled chamber in the same range as a single SiPM sensor (18-28 degrees C). With temperature compensation settings recommended by Hamamatsu, response of this board is stable within 1% in this temperature range (1% is stability of our laser). Response of this board to low levels of light is shown in Fig. 1.12.

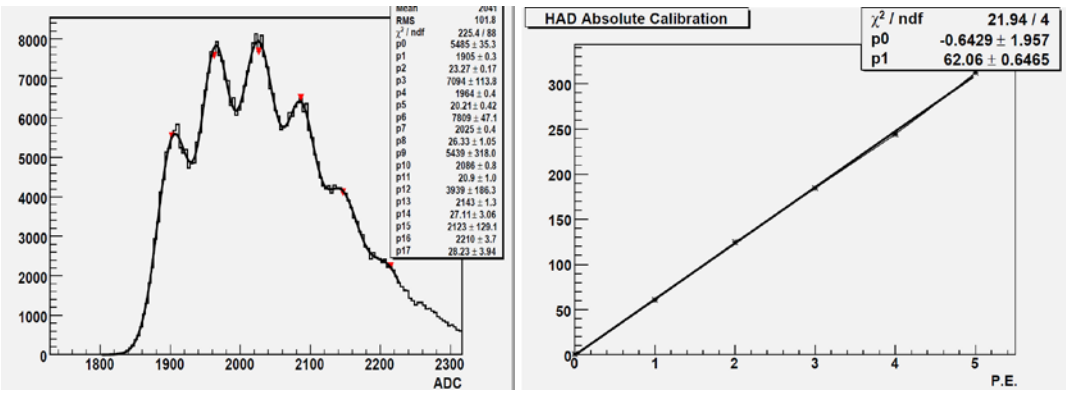


Figure 1.12: (Left) Response of summed/amplified signal from four SiPMs in HAD board to low level of light. (Right) Calibration curve. An absolute calibration of 1% appears to be possible (note that for this test we used temporary version of the receiver board).

With this board we measured the absolute light yield from comsic muons in our HAD calorimeter, as described in Section 1.3.

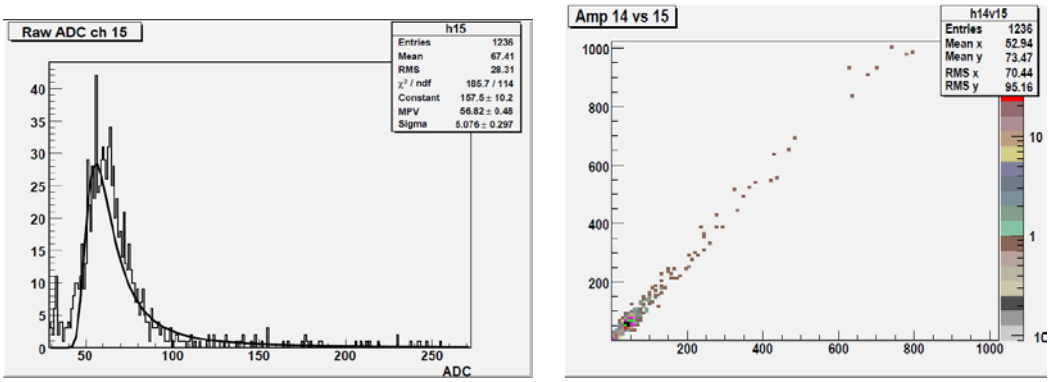


Figure 1.13:(Left) Cosmic muons in the HAD calorimeter (sum from4 SiPMs). (Right) Correlation between two groups of sums of four SiPMs during cosmic muon measurements.

The same design was intended for use in the EM section of the calorimeters. However, the footprint of the board is sufficiently smaller and the new board layout (or sandwich of two boards) is required to fit the EM prototypes as well. With the delay of the FEE development, this part of the project is currently on the critical path for the planned beam test in Feb. 2014..

6. Neutron Flux Measurement at STAR Experimental Hall in Run 13.

The data obtained during Run 13 were analyzed. Our conclusion is that we can estimate neutron background for STAR detector with good precision. The results of the measurements and simulation are presented with absolute values and their ratios in Table 1 [1]. The comparison is good (within 30%) for the West, East and Far Away locations. However, for the South, North and Bottom locations the simulation overestimated the flux by a factor of ~3. Interestingly, a similar conclusion was made in studies for the ATLAS experiment[4]. The mismatch between the measurements and simulations may be due to inaccurate descriptions of geometry and material in the experimantal hall, which would affect the neutron dissipation from the interaction region. The deviation could also be related to the neutron transport parameters.

7. Discussion for Goals for Next Year.

Development of the compact readout will continue to be the focus of our R&D effort. We will utilize data from the test run to determine the absolute light yields and uniformity of light collection from EM prototypes as necessary information for future developments. In part, this information can be investigated in the laboratory. However, beam measurements with a finely-segmented tracking detector in front of the calorimeters will be required. We anticipate that some iteration of the light collection scheme and front end electronics will be required next year. To carry out these tasks we will need to have support for undergraduate students who will carry out the analysis of test run data and do measurements in the lab with modified light collection schemes. At the same time we will need support for an electrical engineer to do iteration of the front end electronics for our prototypes. We would like to utilize the prototypes we constructed this year as much as possible, however if we find out that light collection scheme has to be modified in the way shown in Fig. 1.2, we will have to build a new prototype for the barrel EM calorimeter. We will also need to build a new scintillation hodoscope with better spatial resolution to carry out test beam measurements. We plan to carry out a test run at SLAC in the fall of 2014 with refined EM prototypes, which is also part of our requested budget.

SiPM technology is developing rapidly. As an example, the sensors we will be using for the test run at FNAL in 2014 are already considered obsolete. We want to continue to investigate new sensors for applications in calorimetry. Instead of concentrating on HPK sensors alone, we propose to investigate several sensors from other vendors as well. For example, sensors from KETEK and SENSL with different technology than HPK have characteristics as good as HPK. In some cases they are better as they have order of magnitude higher gain and seemingly smaller temperature dependences. We would like to establish better communication with these companies and investigate new sensors from all these vendors in next year. Samples of sensors will be first fully characterized in the lab. For that we will need support for summer students and some support for the electronics shop and an electrical engineer, since the bias range for HPK is quite different from SENSL and KETEK and we will not be able to use front end electronics build this year for these sensors.

The second step of characterization of these sensors will take place at BNL. With established procedures to monitor neutron fluxes at RHIC and with an upcoming pA/pp run in 2015, we want to place all sensors characterized in the lab in front of the forward meson spectrometer at STAR, along with neutron counters and a laser monitoring system and perform continuous monitoring of performance of these sensors during Run 15. We are considering additional counters for neutron flux measurements to carry out these tests. Potentially, we will need to duplicate our laser system, which will require additional funds.

We have developed the technology of building W powder ScFi calorimeters and the technology is mature enough that we need to start considering QA and outsouring mass production. There are a few approaches under consideration at this moment. One is to try to transfer this technology to Heavy Tungsten Powder Co., (the company PHENIX was working with in the past). Second, which is preferred, is to invite additional institutions into the EIC calorimeter consortium. These additional institutions must have ‘industrial capabilities’ to pick up this technology, and at the same time strong interest in EIC physics program. We want to investigate these capabilities in Russia (IHEP, Protvino) and in China. We will need additional support for travel.

8. Budget Request

Sensors (HPK, SENSL, KETEK)	$15k
Materials and Supplies	$10k
Machine and Electronics Shop	$10k
Upgrades for optical system and additional neutron counter.	$15k
Undergrad students labor (includes 26% overhead)	$12.6k
Electronics Engineer (includes 56% overhead)	$27.3k
Travel for test beam, EIC meetings and Recruit new groups for mass production (includes 26% overhead)	$25.2k
Total direct cost	$97.5k
Total indirect cost	$17.6k
Total	$115.1k

References:

1. Y. Fisyak, O. Tsai, Z. Xu. Thermal neutron flux measurements in STAR experimental hall. arXiv:1310.2495v1
2. E. Bernardi et al., Performance of a compensated lead-scintillator hadronic calorimeter. NIM A262 (1987) 229-242
3. O. Soto et al., Characterization of novel Hamamatsu Multi Pixel Photon Counter (MPPC) arrays for the GlueX experiment. NIM A(2013) http:/dx.doi.org/10.1016/j.nima.2013.06.071
   M. Campbell et al., "Analysis of the Radiation Filed in the ATLAS Using 2008-20011 Data from the ATLAS-MPX Network," ATL-GEN-PUB-2013-001 http://cds.cern.ch/record/1544435/files/ATL-GEN_PUB-2013-001.pdf

EIC Detector R&D Report

Reporting Period: From 05/01/2013 To 12/12/2013

Project Name: EIC Calorimeter R&D at BNL

Project Leader: Craig Woody

Date: 12/12/2013

Past

What was planned for this half year?

The main goal for the second half of this year was to design and build a new prototype calorimeter with 1 mm tungsten plates and 1 mm scintillating fibers. In the first half of this year, we built a small prototype module that consisted of 2.6-3.4 mm tapered accordion shaped tungsten plates with 1 mm fibers. In the process of building that module we learned that the company that supplied the plates could not maintain adequate tolerances on them in terms of thickness and shape. In addition, we learned from our Monte Carlo studies that for a given sampling fraction, the energy resolution is poorer when the fibers are oriented longitudinally along the incoming particle direction compared to when they are oriented perpendicular. Since our calorimeter design has the plates almost longitudinally, we decided to build a new prototype module consisting of 1 mm tungsten plates with 1 mm fibers in order to achieve better energy resolution. We also decided to use two layers of 0.5 mm flat tungsten plates to achieve the 1 mm absorber thickness, which were cheaper to produce and made the assembly with the scintillating fibers easier.

We planned to build this prototype module and test it in the test beam at Fermilab in February of 2014. This will include measuring the light output from the module, determining its energy resolution, testing the SiPM readout and readout electronics, and a test of a calibration system to control, measure and monitor the gain of the SiPMs with time and temperature.

What was achieved?

The new prototype module is currently in the final stages of assembly and should be ready for the beam test at Fermilab in February. The absorber stack consists of seven tower modules, each with seven individual light collecting cavities, that form an array of 7x7 towers. Figure 2.1 shows the assembly of a tower module. The first step was to produce “sandwiches” consisting of a layer of 1 mm fibers that was glued between two 0.5 mm flat tungsten plates. A set of thin spacers were inserted at one end of the sandwich to achieve an overall tapered shape. Twelve sandwiches were then glued together to form a tower module. On the readout end of the module, the ends of the fibers were potted with a white reflecting epoxy containing $BaSO_4$ to improve reflectivity. The fibers on the other end of the module were potted with clear epoxy and then covered with a specular reflector.

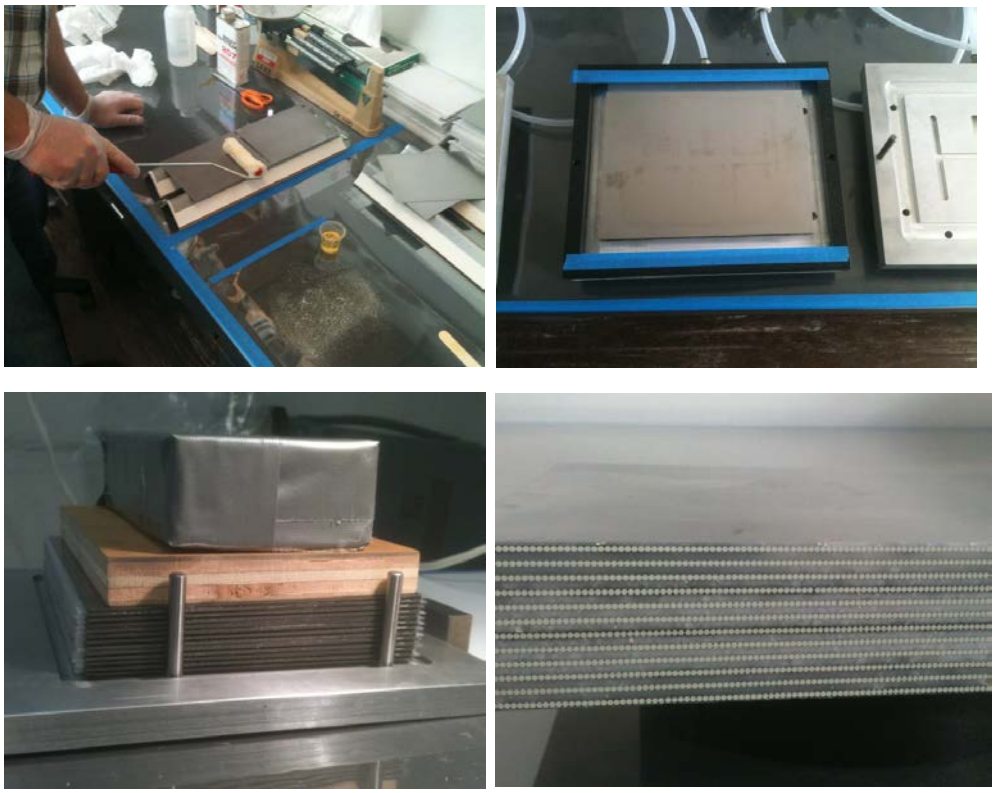


Fig. 2.1. Assembly of a tower module: a) Glue is applied to two 0.5 mm flat tungsten plates; b) Scintillating fiber layer is glued between tungsten plates under vacuum; c) Stack of 12 sandwiches is glued together under pressure; d) Readout end of fibers is potted with white reflecting epoxy.

Figure 2.2 shows the entire absorber stack consisting of seven tower modules in a trial configuration before the final assembly. The stack will be held together in an aluminium frame and the light collecting cavities will be attached to the readout end along with the readout electronics.

Fig. 2.2. Absorber stack consisting of seven tower modules in a trial configuration before final assembly. As shown in the photo on the right,the stack is slightly tapered from to back.

Fig.2.3. Light collection cavities used to study the light collection efficiency and uniformity and the placement of the SiPMs.

Figure 2.3 shows several versions of the light collecting cavities that were used to study their light collection efficiency. One row of seven cavities fits on to the readout end of a tower module to form the individual calorimeter towers. The cavities were produced using 3D printing and the inside was coated with a white reflecting paint (Labsphere 6080) to achieve good efficiency and uniformity of light collection. Fig 2.4 shows the measured uniformity of one of the cavities for an SiPM placed on the top portion of the dome. The average efficiency was 4.7% and the maximum variation in the efficiency across the cavity was a factor of 1.7.

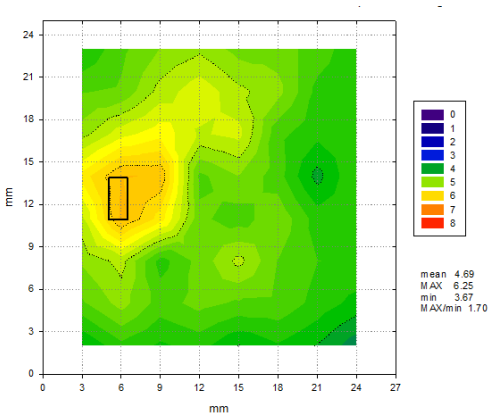


Fig. 2.4. Measured efficiency and light uniformity of a light collection cavity with the SiPM placed at ~ 20° along the dome.

Fig. 2.5. Connection of SiPMs to the readout board.

Fig 2.5 show a row of SiPMs mounted to the cavities and the connection to the readout board. The readout board consists of an 8x8 array of preamps of which we use 7x7=49 channels. The design of the preamps was described in a previous report and the total number of preamps required for the beam test has now been produced. We have also acquired all of the SiPMs (Hamamatsu S10931-025P) required for the beam test and are in the process of testing them. In addition, we have acquired a set of new SiPMs (Hamamatsu S12572-025P) that have many improved characteristics over the previous ones (lower noise, less cross talk and afterpulsing, higher Photon Detection Efficiency and larger dynamic range). We have enough of these devices to equip the central part of our detector and hope to be able to carry out several tests with them during the beam test.

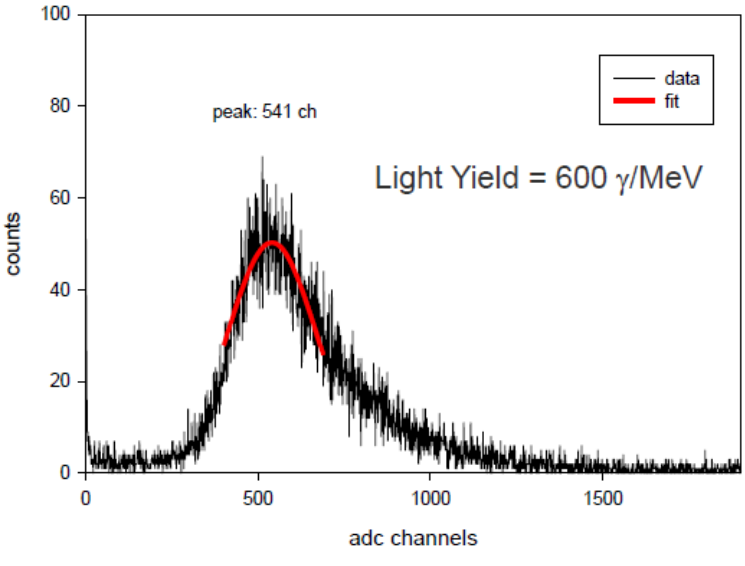


Fig. 2.6. Pulse height spectrum for cosmic rays from one tower module read out with a standard PMT coupled directly onto the readout end of the fibers. Light yield was measured to be 600 γ/MeV of energy deposited in the scintillator.

Fig 2.6 shows a pulse height spectrum from one of the tower modules with a standard photomultiplier tube (not an SiPM) coupled directly to the fibers. This measurement was done in order to determine the actual light output from the module, which was measured to be approximately 600 photons per MeV of energy deposited in the scintillator. Given the sampling fraction of our calorimeter (~ 6%), and assuming a light collection efficiency of 4.7% from the cavities and a PDE of 25% for the SiPMs, we expect a signal corresponding to ~ 450 photoelectrons per GeV from the calorimeter. The PDE of the new SiPMs is higher (approximately 35%), which should produce a corresponding increase in the photoelectron yield.

Fig. 2.7 shows a block diagram of the preamp and readout circuit for the SiPMs, which also contains a feedback circuit for measuring the temperature of the SiPMs and adjusting their bias voltage for any temperature variation. Fig 2.7b shows results from a test of the feedback system, which shows that the gain can be stabilized to a level of better than 1% over a temperature range of 25 degrees.

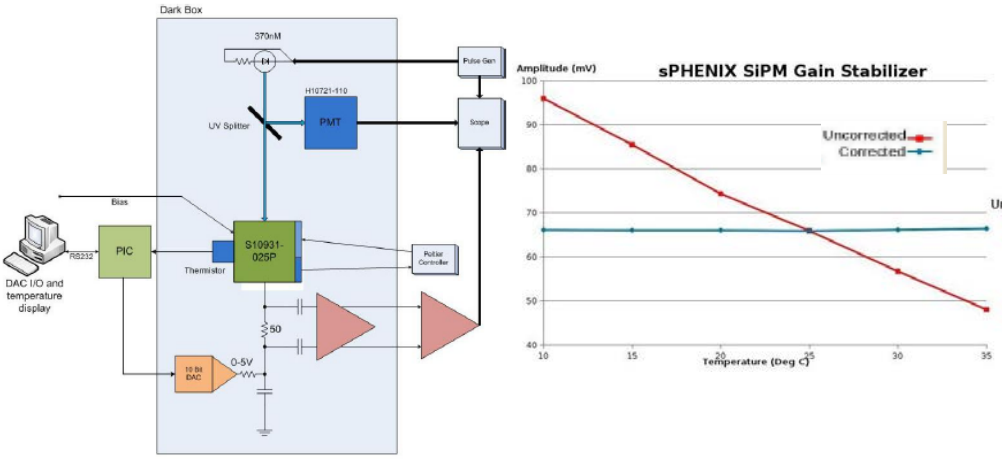
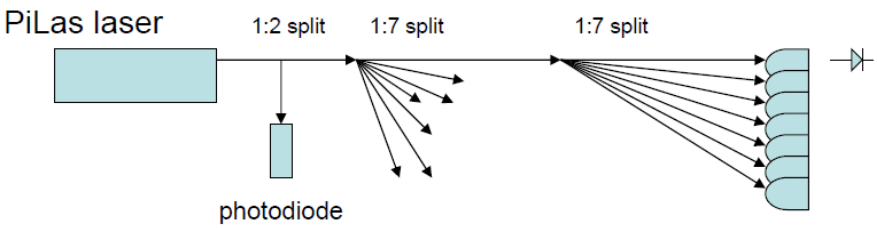


Fig. 2.7a. Block diagram of the SiPM readout circuit containing the preamp, bias voltage adjustment and temperature compensation circuit, b) SiPM gain variation before and after temperature compensation.

In addition to the gain stabilization system, a separate calibration system will also be used to measure and monitor any gain variation of the SiPMs with temperature. Fig 2.8 shows a proposed calibration system. It consists of a diode laser (PiLas EIG2000DX), which produces light at 420 nm, and a series of beam splitters to deliver a calibrated light pulse to each individual cavity/tower. The light output from the laser is monitored with a photodiode and the light is delivered to the cavities though a series of 1:7 splitters. We are currently investigating the light output from this system to determine if it is sufficient to provide a suitable calibration pulse for calibrating and monitoring all of the towers in the prototype. If not, it is also possible to use LEDs to inject light into each of the fiber splitters that go directly to the cavities, which should provide sufficient light at the expense of having more than one light source to monitor.



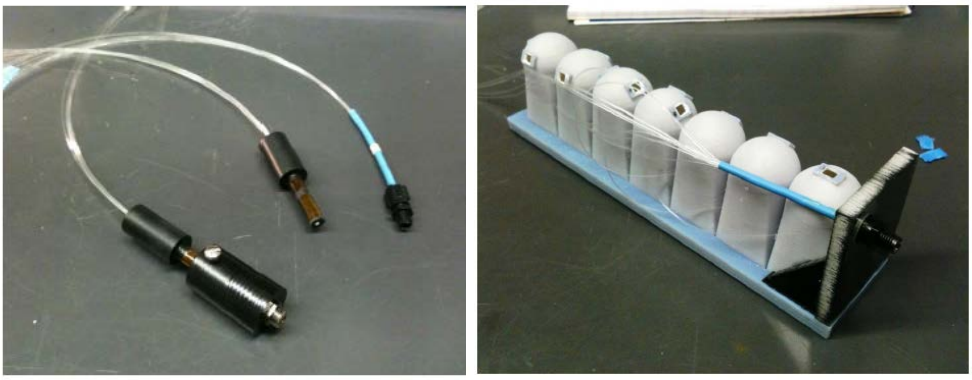


Fig. 2.8. a) Schematic layout of the laser calibration system based on a diode laser and series of beam splitters, b) Fiber splitters, c) Fibers connected to the light collection cavities.

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

We have not yet completed the final assembly of the second prototype calorimeter, although we expect to have it completed by the end of the year, which will allow sufficient time for preliminary testing before the beam test at Fermilab. We have also not completed the calibration system, and the final design and implementation of that will depend on the amount of light that can be injected into each cavity. However, we do expect that this will also be completed and tested in time for the beam test.

We did not pursue further development of the accordion shaped tungsten plates with Tungsten Heavy Powder (THP) at this time, since we felt that it was important to have a working prototype in time for the beam test in February. However, we do still intend to pursue this design with them, which will be a subject for future R&D next year.

Finally, we did not complete our Monte Carlo studies of the prototype calorimeter, nor for the full calorimeter as it would be implemented at EIC. This is a subject of ongoing R&D and will incorporate input from the beam test.

Future

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

The main activity for the next six months will be to carry out the beam test at Fermilab. This will occur in February of 2014 and will be done in conjunction with a test of a prototype hadron calorimeter for PHENIX that will be tested at the same time. The STAR group is also planning to test their EMCAL prototype and a prototype HCAL in the same test beam immediately following our test. We have been

working closely with them to plan these tests together so that we can obtain the greatest amount of information for an EIC calorimeter from these combined set of measurements.

We expect that the maximum useful energy of electron beam at Fermilab will be about 8 GeV. It is limited by both the rate for electrons and also the energy resolution at higher energies (for energies above 8 GeV, the beam momentum resolution is comparable to the expected calorimeter energy resolution). We therefore plan to test our prototype EM calorimeter, along with the UCLA prototype calorimeter, in the test beam at SLAC at some time during the coming year. The maximum beam energy there is ~ 15 GeV and the momentum resolution is ~ 1%, which will provide a better measure of the constant term for the calorimeter at higher energies. However, the exact dates of this test and what all will be tested will depend on the results obtained in the Fermilab test.

We also plan to pursue the development of thin, accordion shaped tungsten plates with Tungsten Heavy Powder. It would be very beneficial for the overall calorimeter design to make these plates in an accordion shape, as it would allow reducing or even eliminating the need to tilt the plates in the final calorimeter. This would not only simplify the design, but it would also keep the light from the towers more along the radial direction, thus making the showers more compact. There was not enough time to develop an viable, cost effective method of producing accordion shaped plates for this prototype in time for the beam test in February, but based on the experience we now have in building modules with flat tungsten plates, we feel it possible to produce thin accordion shaped plates by a number of different methods. We also plan to have THP produce larger plates (~ 1m or more in length), both flat and accordion shaped. This will allow us to determine what tolerances can be achieved on such plates, both in terms of thickness and in shape, which will be very important to know in order to build larger calorimeter modules for an actual EIC calorimeter.

What are critical issues?

Carry out a successful beam test of the prototype EMCAL module and measure its light yield and energy resolution. Measure the energy resolution as a function of the tilt angle, and in conjunction with the hadron calorimeter.

Carry out an additional beam test of the EMCAL prototype that provides a better measure of the constant term of the energy resolution at higher energies.

Obtain experience in setting, stabilizing and monitoring the gain of the SiPMs a function of temperature.

Produce large, thin flat tungsten plates and determine what tolerances can be achieved on flatness and thickness.

Determine whether thin, accordion shaped tungsten plates (also up to large sizes) can be produced with the require tolerances in a cost effective manner.

Carry out further measurements and simulations to optimizing the light collection efficiency and uniformity of the reflecting cavities.

Test new SiPMs from Hamamatsu and compare with previous devices,

Carry out more detailed simulations of the prototype calorimeter as well as the final EIC calorimeter.

Additional information:

We are requesting additional funding to extend the R&D on this calorimeter deign for an additional year. The budget request is listed below. We also expect that this R&D will continue beyond this one additional year of funding in order to develop a complete design of an EIC calorimeter

Budget request for an additional year of funding for a tungsten plate scintillating fiber electromagnetic calorimeter for EIC.

Item	Year 3
Materials and supplies	10
Additional SiPMs	5
Readout electronics development	10
Technical support and designer	10
R&D on W plates with THP	40
Test beam (SLAC)	15
Total Direct	**90**
Overhead (50%)	45
Total (including overhead)	**135**

EIC Detector R&D Progress Report
Reporting Period: From 05/01/2013 To 12/12/2013

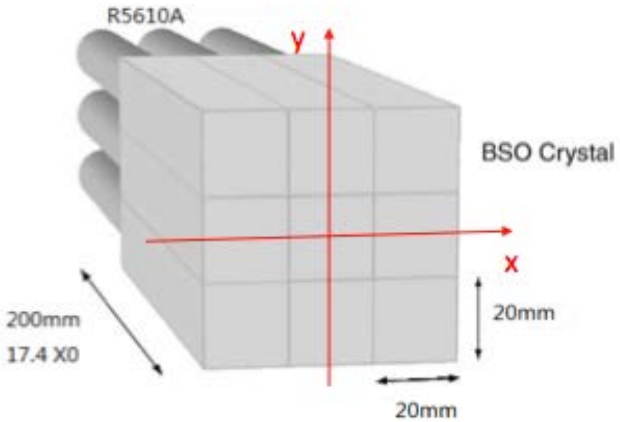
Project Name: Crystal R&D for a Forward Calorimeter at EIC

Project Leader: Yifei Zhang

Date: 12/12/2013

The planned work and the progress for the report period:

1) Continue simulation on BSO calorimeter and the performance study.
An ideal geometry of 3×3 BSO calorimeter was designed in GEANT4, with the size of 20×20×200 mm for each crystal. Fig.3.1 shows an event *that* the electron beam interacts with the crystals.



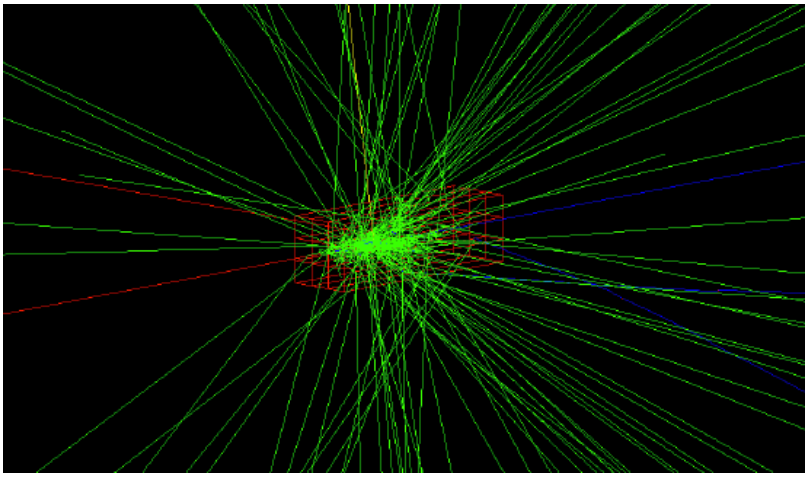


Figure 3.1: 3×3 BSO calorimeter design and geometry in an electron beam.

The incident electron energies were scanned from 0.5 – 3.5 GeV. Fig. 3.2 shows the deposit energy distribution in the crystals and the energy resolution versus incident electron energy.

The energy resolution was extracted as:

$$\frac{\sigma_E}{E} = (0.021 \pm \frac{0.000098}{\sqrt{E}})^2 + (0.013 \pm 0.000081)^2$$

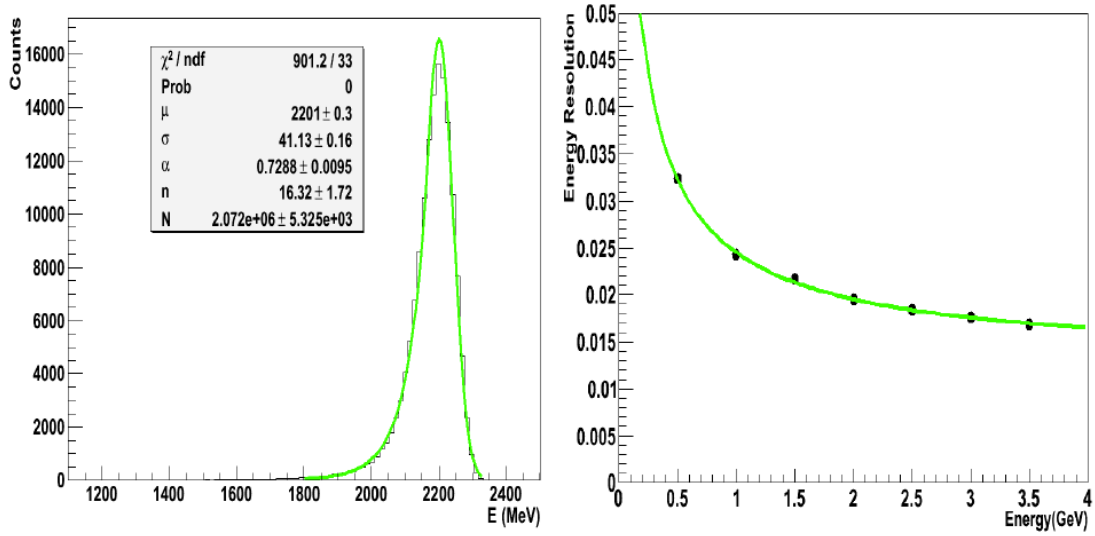


Figure 3.2: Left: The deposit energy distribution in the crystals. Right: The energy resolution versus incident electron energy.

A center of gravity method was used to study position resolution. The center of gravity X_{CG} for the incident position is calculated with measured energy deposits as:

$$X_{CG} = \frac{\sum_{i=1}^{9} E_i x_i}{\sum_{i=1}^{9} E_i}$$

x_i and E_i are the center position and the energy deposit of the i-th crystal, respectively. Fig. 3.3 shows the scatter plot of X_{CG} and Y_{CG} with an incident 3 GeV electron beam. Fig. 3.4 shows the position resolution versus incident electron energy.

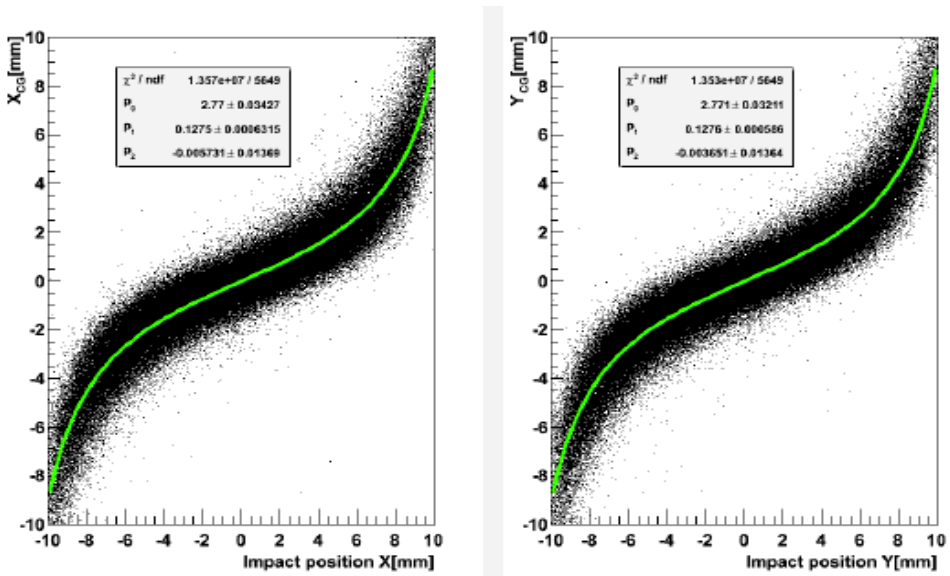


Figure 3.3: X_{CG} and Y_{CG} distributions with an incident 3 GeV electron beam.

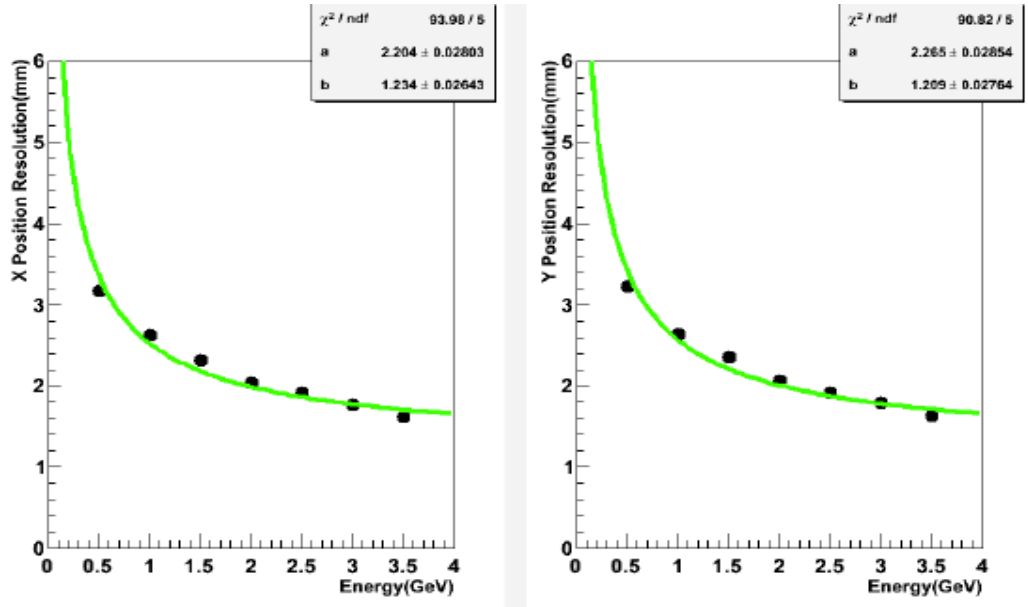


Figure 3.4: Energy resolutions versus incident electron energy.

The position resolution is better than 5mm for incident electron energy > 0.5 GeV and is better than 2mm for energy > 3 GeV.

The efficiencies of energy deposit in the crystals are shown in Fig. 3.5. The non-linearity of the energy response is less than 2% in the scanned incident electron energy region.

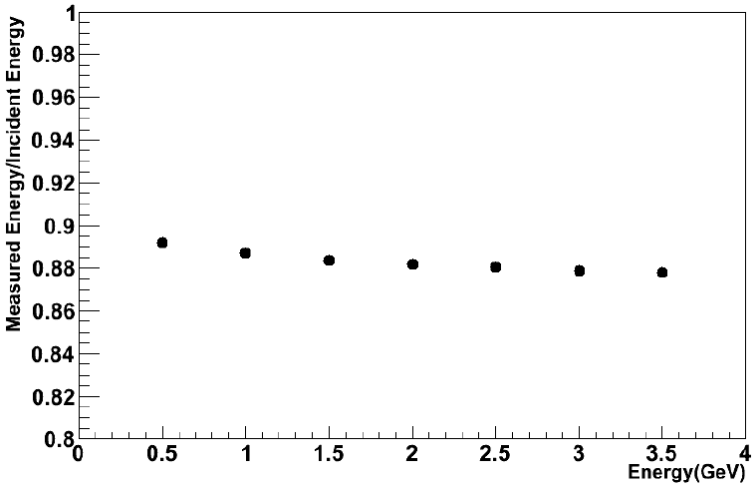


Figure 3.5: Efficiency of energy deposit versus incident electron energy.

To further study the particle identification capability of the BSO calorimeter, a 5×5 geometry was used in GEANT4. The input particles were generated in PYTHIA with e+p at 5+250 GeV collisions. The energy transfer Q^2 was required larger than 1. Fig. 3.6 (3.7) shows the phase space of the input electrons (pions and protons) generated from PYTHIA.

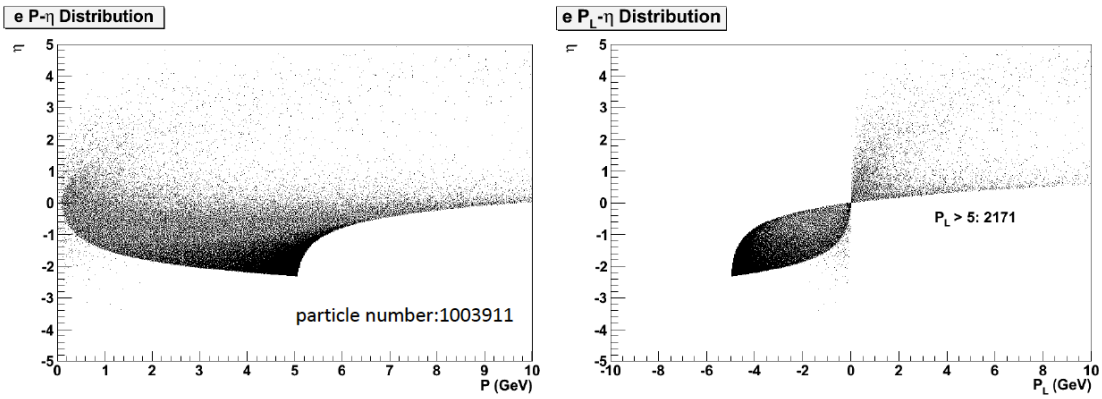


Figure 3.6: The phase space of the electrons generated from PYTHIA.

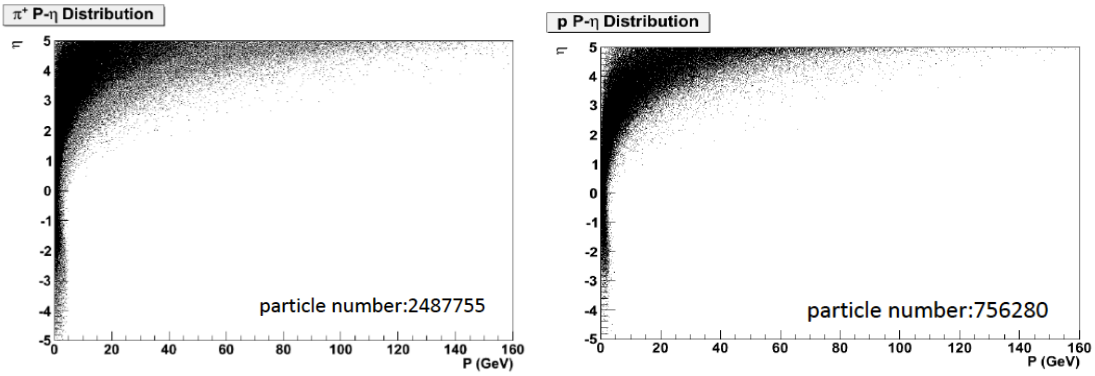


Figure 3.7: The phase space of the pions (left) and protons (right) generated from PYTHIA.

Most of the hadrons are going to the positive eta direction. The hadrons scattered to the electron direction are with small energy. This is helpful to separate electrons and hadrons with BSO crystal calorimeter. We further require $\eta < -2$ for very forward particles, where the expected BSO calorimeter covers.

Figure 3.8 shows the measured energy deposits in BSO crystals as a function of particle momentum for electrons (black), pions (red) and protons (blue). The performance is clearly seen that electrons are well separated from those hadrons with a feature of higher energy deposit. Figure 3.9 implies how the hadrons are simply rejected by the energy cuts while electrons are survived.

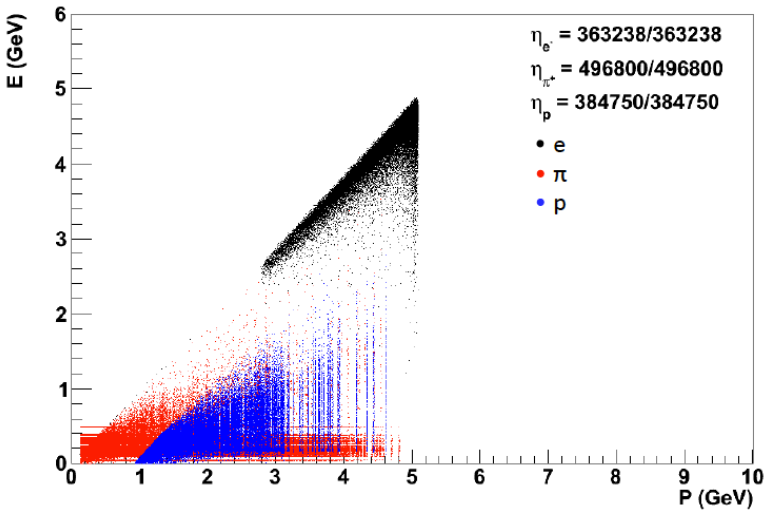


Figure 3.8: Energy deposits of electron and hadrons versus momentum.

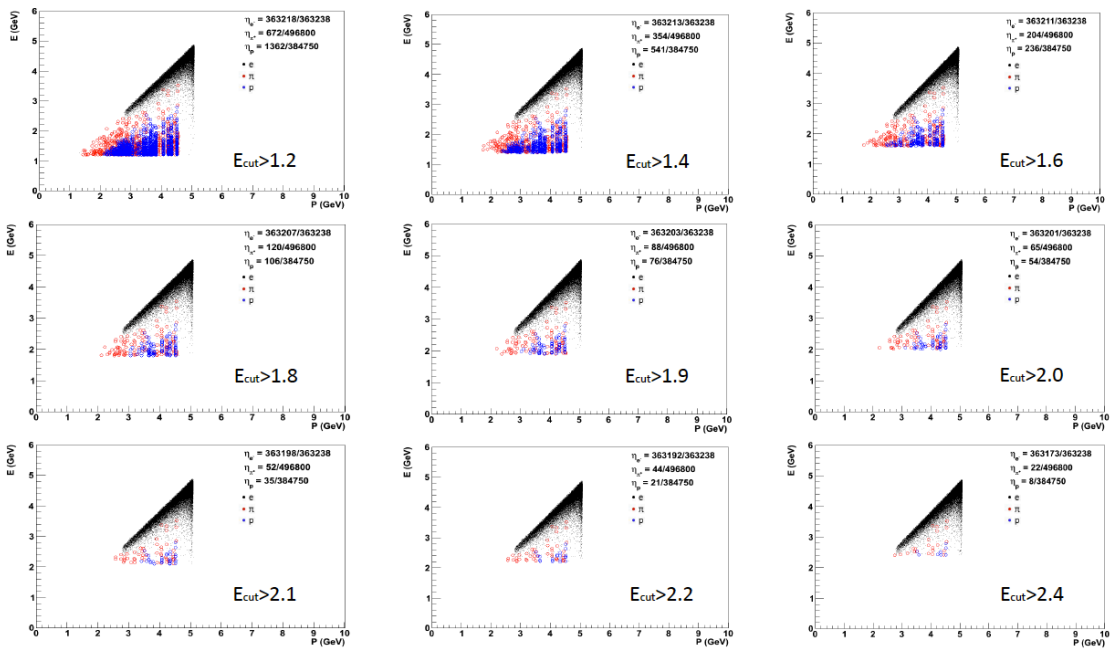


Figure 3.9: Energy deposits of particles under different energy cuts.

Figure 3.10 shows the electron identification efficiency and hadron rejection powers (hadron efficiencies and contamination rates) as a function of the deposit energy cut. An example of E_{cut} > 2.6 GeV keeps over 99.9% electrons and with very little hadron contamination (~10^{-5}). Over 99.9% hadrons were rejected.

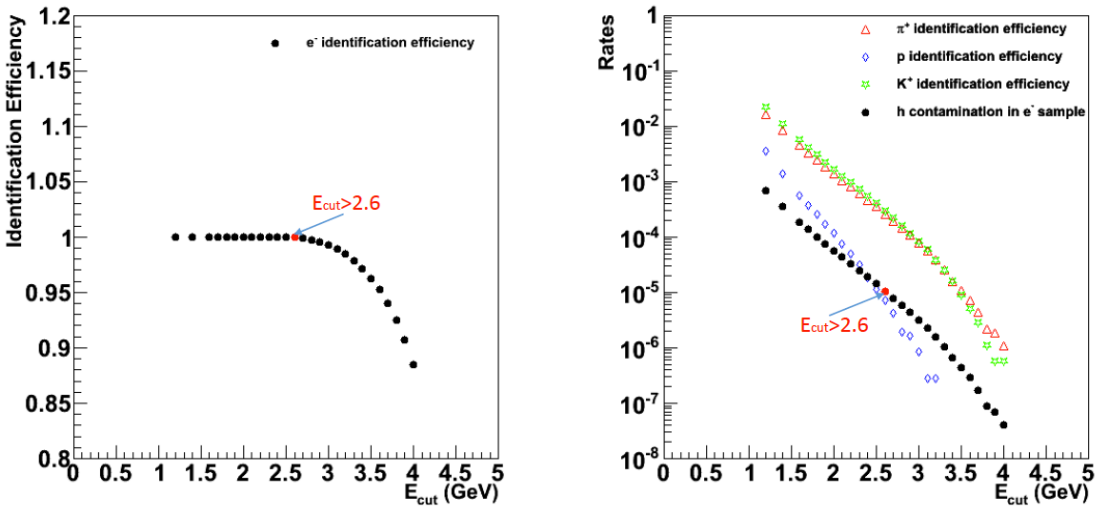


Figure 3.10: Left: Electron identification efficiency as a function of E_{cut}. Right: Hadron efficiencies and contamination as a function of E_{cut}.

To further study the particle interaction characters with the crystals, we simulated the transverse showers of the energy deposits. This part of simulation is still ongoing. Limited with only one layer of the crystal, the image of shower shapes is not very accurate. The electron energy shower image is shown in Fig. 3.11 (gamma is very similar).

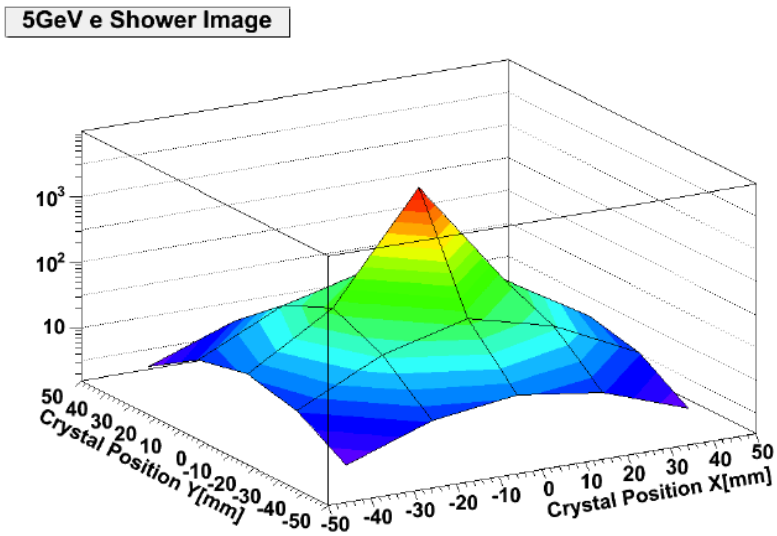


Figure 3.11: Energy shower image of 5 GeV incident electrons.

2) Possible beam test for the BSO prototype.
This work was planned to perform in Feb. next year, but since the beam resolution of Fermilab is not suitable for crystal calorimeter, we cancelled the plan and we are looking into other options. We contacted with BEPC-BES where the electron beam intensity is too high to be suitable. We are now looking for a possible beam test elsewhere (e.g. KEK, CERN or SLAC test beam next September).

Future

1) Continue simulations for design optimization of a crystal calorimeter in an EIC detector.

2) Beam test for the BSO prototype.