Joint Proposal to Develop Calorimeters for EIC

E. Kistenev, S. Stoll, A. Sukhanov and C. Woody

PHENIX Group, Physics Department

E. Aschenauer and S. Fazio

Spin and EIC Group, Physics Department

Brookhaven National Laboratory

S. Heppelmann

Pennsylvania State University

C. Gagliardi

Texas A&M University

L. Dunkelberger, H. Z. Huang, G. Igo, K. Landry, S. Trentalange, O. Tsai and Q. Zhang
University of California at Los Angeles

Y. Zhang, H. Chen, C. Li and Z. Tang

University of Science and Technology of China

The Calorimeter R&D Consortium – Contact Persons: H.Z. Huang huang@physics.ucla.edu and C. Woody woody@bnl.gov

Table of Content

1. Introduction to the Calorimeter R&D Consortium

2. Year 2 Renewal of RD1 Proposal for W Powder Fiber Sampling Calorimeter

    2.1 Summary of Year 1: Results from RD1

    2.2 Proposed Scope of Work for Year 2

    2.3 Budget Breakdown

3. Development of Accordion Shape Tungsten Plate and Scintillating Fiber Sampling Calorimeters for EIC

    3.1 PHENIX R&D Effort

    3.2 Readout Considerations

    3.3 Proposed R&D Plan

    3.4 Budget Breakdown

4. Physics Simulations and EMC Requirements

5. Future Perspectives of the Calorimeter R&D Consortium

1. Introduction to the Calorimeter R&D Consortium

We propose to form a calorimeter R&D consortium to develop calorimeters for EIC applications. Key physics measurements currently under consideration for EIC scientific program require the detection of photons, electrons and jets. Calorimeters, in particular Electro-Magnetic Calorimeters (EMC), are expected to be an essential part of the future EIC detector configuration. For example, in a solenoidal magnetic field detector configuration a barrel EMC would be required for photon and jet measurements. In the forward direction a fine resolution EMC, possibly a crystal detector, may be needed to measure the scattered electrons. Our goals are to develop the best detector technology in terms of performance and cost for these calorimeters, and to define technical requirements on these calorimeters through simulations of physical processes that are critical to the EIC scientific program.

The current members of the consortium are from the STAR and PHENIX collaboration with extensive experiences on calorimeters. The UCLA/TAMU/PSU team is currently working on the RD1 project to develop construction technique for W-Powder and scintillating fiber based calorimeter. A suitable construction technique has been developed and prototype EMC modules have been tested at a FNAL test beam run in Jan. 2012. Test result shows that the detector performance is consistent with Monte Carlo simulations and is promising for a future EIC detector. The RD1 team proposes to continue the R&D project to develop compact readout scheme using APD and/or SiPMT technology and to explore further construction technique for wedge shape EMC modules.

The BNL PHENIX group has a long history in working on calorimeters in high energy physics. The group has been working on R&D project to develop a tungsten plate and scintillating fiber accordion shape calorimeter. The proposed R&D activity in next year centers on building fine sampling accordion shape EMC prototype modules and investigate the read-out scheme.

The STAR USTC group has over a decade of experience in testing crystal detectors. The group is currently working on an EIC R&D project to test BSO and PWO crystals produced by SICCAS. SICCAS has produced many high quality crystals for high energy particle and nuclear physics experiments in the past. The price of the SICCAS crystals is very competitive. The BSO crystal has a performance close to the BGO crystal, but significantly less expensive. The PWO crystal has a relatively low light yield. There is a R&D effort at SICCAS to increase the PWO light yield by proper doping. The first goal of the EIC crystal R&D project is to work with SICCAS to produce a high performance crystal at a reasonable price that is suitable for a large crystal detector array at EIC.

We recognize and also as noted by the EIC Detector R&D Review Committee that we need to work closely with physics simulations to better define the calorimeter performance

requirements in the framework of measurements for key physical processes at EIC. To this end the BNL Spin/EIC group led by Elke Aschenauer has agreed to join this consortium. This will significantly boost the simulation effort needed for physics considerations of an EIC detector and provides guidance to the calorimeter detector development in the coming years.

By forming a calorimeter R&D consortium we plan to work closely among all groups and share the knowledge and expertise about the detector construction, readout tests and future planned electronics development. We expect that the development of suitable calorimeter detector technology for EIC detectors will take many years. In this proposal we will only focus on our R&D effort in the coming year. In sections 2 and 3 we will describe the proposed R&D projects from the RD1 team and the PHENIX group, respectively. In section 4 status from simulation effort on using EM calorimetry for the measurement of selected physical processes at EIC will be reported. In section 5 we will give brief perspectives of our R&D plan for the near future.

2. Year 2 Renewal of RD1 Proposal for W Powder Fiber Sampling Calorimeter

L. Dunkelberger, H. Z. Huang, G. Igo, K. Landry, S. Trentalange, O. Tsai and Q. Zhang
University of California at Los Angeles

C. Gagliardi

Texas A&M University

S. Heppelmann

Pennsylvania State University

Executive Summary

We have successfully completed the proposed work in the RD1 proposal to demonstrate a "proof-of-principle" for a new calorimeter construction technique using W powder and Scintillating Fibers. Three prototype sampling calorimeters of different designs were built and operated in a test beam run at FNAL in January of 2012. We identified the SPACAL type design as the best choice for this new detector technology. The measured energy resolution is very close to calculations from MonteCarlo and the light yield of the detector is close to 2000 photoelectrons/GeV. We propose to continue the R&D program in year 2 as outlined in our initial proposal. We will concentrate on the development of a compact readout scheme for the selected calorimeter detector, investigate mechanical properties of the detector modules, and extend this detector technology for possible application as a barrel electromagnetic calorimeter. We expect to continue the R&D project in year 3. Depending on the result of our readout design we plan to build a complete EMC prototype module which is optimized for EIC physics measurements. We will also start an R&D effort on digitizing and trigger electronics in year 3.

2.1 RD1 Activities and Results from Year 1

In the first year we built three different detectors. They are (in order of construction):

Spaccordion (a matrix of 16 towers; each tower of about 30mm x 30mm made of four subassemblies; 0.33 mm BCF12 scintillation fibers spaced by 0.8 mm, fibers undulate along the tower). This prototype was a straight-forward extension of the design proposed in 2004.

SPACAL (a matrix of 16 towers, tower of approximately 26 x 26 mm; doublets of towers were built at one time, 0.47mm KURARAY SCSF78 fibers, spaced by 1 mm, fibers straight). The construction technique was significantly simplified. We used precision screens produced by FotoFab which allowed us to easily feed more than 3000 fibers thru a set of twelve screens. Because the fibers were straight, there was no need to build a single tower from multiple subassemblies. Assembly of tower doublets into a super-module was significantly simplified, compared to the Spaccordion design.

Fine sampling: Two cells were constructed with very fine sampling (0.33 mm fibers BCF20, spacing 0.53 mm). One of these cells was infused with Liquid Scintillator.

The motivation for this R&D was to develop new detector technology that will allow us to build **compact** sampling calorimeters that are **simple to construct** and **cost effective**. After building three different prototype detectors we concluded that the SPACAL type prototype meets all three requirements and is our best choice for future development. The two other prototype constructions were found to be more labor intensive. We also found that building large modules will be challenging because of the weight of the assemblies. The heavier the assembly, the more difficult it will be to control uniformity within the modules. We decided to postpone the development of construction techniques for hadronic calorimeters with tungsten powder, due to their larger size, and concentrate only on electromagnetic calorimeters for the time being.

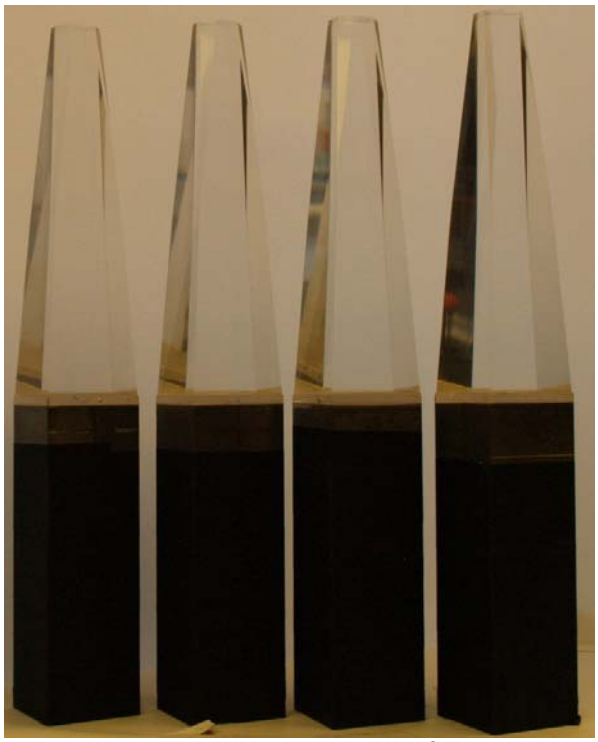
The test run results revealed another important consideration. The light attenuation length in the scintillation fibers is an important factor that determines calorimeter performance. In particular, we conclude that using fibers with a diameter smaller than ~0.5 mm is not advisable, because smaller diameter fibers have significantly shorter attenuation lengths (this was one of the reasons why the energy resolution of the SPACCORDION prototype is slightly worse than the SPACAL energy resolution measured in the test run). Thus, just increasing sampling frequency in calorimeter design is not enough to achieve a good energy resolution. Some boost in sampling fraction will also be required. This we believe will be the most obvious future direction in the development of this technique for EIC electromagnetic calorimeters. The energy resolution for SPACAL super-modules measured in the test run is already close to the desired ~10%/sqrt(E) energy resolution for EIC. There is no strict requirement of superior hadronic resolution for an EIC calorimeter detector at this moment, so strict compensation (that was required in our design for the prototypes last year) can be relaxed and the sampling fraction can be increased slightly.

In year one of the R&D we have achieved our goal to prove the principle for the proposed tungsten powder and scintillating fiber calorimeter construction technology. We have identified the best detector configuration (SPACAL) to proceed for future development. We propose to continue our R&D in year 2 to address some of the remaining issues for applications of tungsten powder detector technology in an EIC experiment.

2.2 Proposed Scope of Work for Year 2

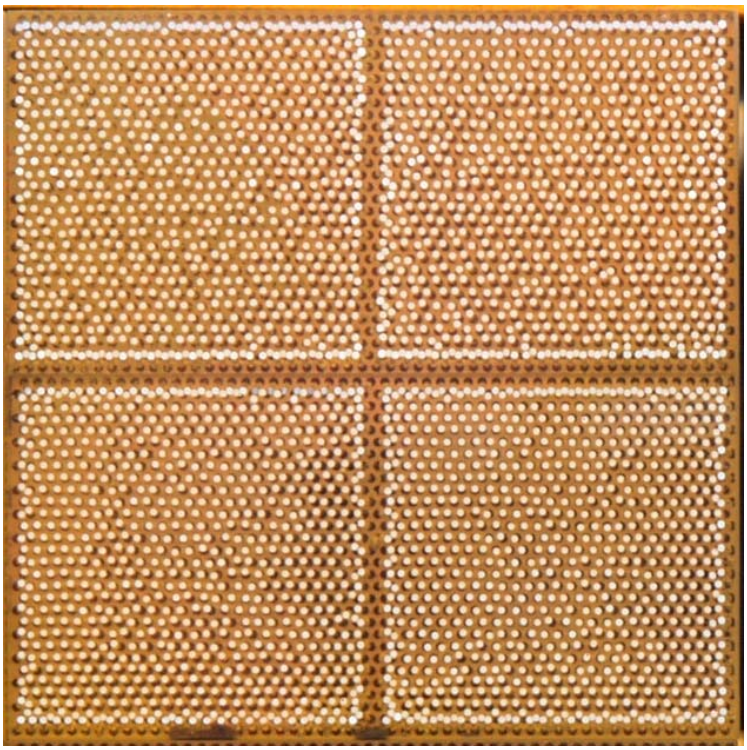
In the second year of this R&D we will concentrate on the development of a **compact readout** scheme for the SPACAL type detector and investigate the **mechanical and optical properties** of our detectors in detail. We also propose to extend our construction technique to explore **wedge modules** which can be used in a barrel calorimeter configuration.

Compact Readout



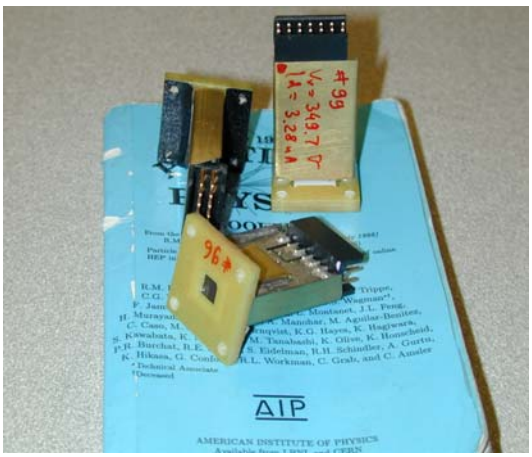
A SPACAL tower is very compact, with a density of ~10.3 g/cm^3, a radiation length of ~7 mm, and a Moliere radius of 2.3 cm. To test this detector with the beam at FNAL last January we did not attempt to optimize the light collection geometry, the coupling to photodetector, etc. Instead, we proceeded with a very conservative approach to collect light using a very long acrylic light guide glued to each supermodule, mirror pipe, and PMT coupled using optical grease to the light guide. This, as indicated by our test results, allowed us to collect and efficiently mix almost all light from the fibers. The light yield is a key parameter which determines possible schemes for light collection and suitable choice of photodetector for the development of a compact readout. The light yield from the SPACAL prototype that we have measured in the test run is ~2000 phe/GeV. This light yield is sufficiently large to allow for different possible schemes of light collection/mixing and choices of various photodetectors. A light collection scheme with WLS plates or short light guides could be developed to achieve the desired energy resolution based on initial estimates. Both APD and SiPMTs are viable choices as possible photodetectors.

Light Collection Design



In the present design we have already included provisional integration gaps between the towers. This picture shows the end cross section of a SPACAL supermodule consisting of four ~ 2.6 cm x 2.6 cm towers. The gaps provide separation between the towers and will simplify gluing of light guides for a single tower. The shape of the light guide will need to be optimized for uniform and efficient light collection. The alternative and more economical way to collect and mix light is to use WLS plates instead of light guides. In this scheme, we will replace the last brass mesh seen in this photograph with a mesh which has been electrically polished and plated with silver or other similar highly reflective coating. Then the last mesh will also serve as a mirror to collect light from a WLS plate. There are number of parameters which need to be optimized in both schemes to achive efficient and uniform light collection. Both MC and test measurements in the lab to verify absolute light collection efficiency and uniformity of light collection wll be required. We have all test equipment required to carry out such measurements . We plan to use undergraduate and graduate students to perform these measurments in the lab. One of the original SPACAL supermodules will be used to determine the absolute light intensity of the light source. We plan to build at least one additional supermodule with the mirrored mesh at the end to perform these tests.

Photodetectors



We plan to investigate both APD and SiPMT options. For the choice of APD we will use the S8664-1010 which was developed for PANDA. This is a larger version of the S8664-55, developed for the CMS electromagnetic calorimeter. In the past we have used the S8664-55 to read out a few channels of our very first prototype during the test run at SLAC

(shown in the picture on the left). We did not find a significant performance difference in comparison to PMT readout at that time. The most important question we need to answer is the number of photoelectrons we will achieve with a new compact readout. This number will determine what we may expect from the nuclear counting effect (NCE) in terms of equivavlent energy deposition in the calorimeter. For example, if we assume the same 2000 phe/GeV collected with a new compact readout, this number will correspond to ~ 300 MeV equivalent energy deposition in the detector due to the NCE. There are several uncertainties at this moment. The QE of APDs will be a factor of three higher than the SiPMT, but the light losses in the compact readout have not been determined yet – that has to be established through a combination of MC and measurements on the bench. Our work on the APD performance and characteristics is expected to benefit greatly from the recent extensive R&D results from PANDA and experience from the LHC experiments.

SiPMTs presumably should be free from the NCE. If there is a considerable loss in light collection from a compact design, then SiPMTs would be more favorable as a photodetector. Here we would like to learn as much as possible from the JLAB group which carried out a R&D project on SiPMT for the GLUEX experiment. Both the Hamamatsu MPPC and Zecotek MAPD-3N will be investigated. SENSL detectors will also be considered and their performance will be compared to those from Hamamatsu and Zecotek.

We request funds to purchase APDs and SiPMTs and will build simple preamplifiers and mechanical structures to adapt these detectors for our compact readout. We plan to use undegraduate and graduate students to perform many of the proposed measurements. Most of the needed equipment already exists in our laboratory. A small amount of funds is requested for test with APDs.

Mechanical Properties

One of the highest priority tasks that we must address before we construct large scale prototype detectors is to determine the mechanical properties of the W-Powder based calorimeter super-modules. To perform a static stress analysis, both the Young's modulus and the shear modulus need to be measured. Once stresses in the stack are understood we plan to use one of the existing SPACAL modules to study light yield as a function of stress on the module and carry out a long term stability test (monitoring the light yield under pressure for long period of time). To carry out tasks related to mechanical analyses we plan to sub-contract a mechanical engineer in the Infra-Red Instrumentation Group from the UCLA Department of Physics and Astronomy for about two months. We had a preliminary discussion with the mechanical engineer and the P.I. of the astronomy group about the scope of work and schedule. We expect that most of the work can be accomplish in the summer or early fall of 2012. We plan to use UCLA undergraduate and graduate students to perform most of the work

needed for the long term stability tests. Mechanical fixtures with load cells etc. will need to be designed and produced. We request funds to support student's labor and machine shop costs.

In our year 1 R&D budget we planned to construct a large calorimeter module to investigate the feasibility of our construction technique for hadron calorimeters. We decided to postpone the construction of the large calorimeter until after the mechanical properties have been measured. We request to re-direct the $25K fund from the year 1 construction towards the sub-contract for the mechanical engineer.

Feasibility for Wedge Modules

For a barrel calorimeter design a cylindrical geometry is required for the detector. We propose to study the feasibility of wedge-shape electro-magnetic calorimeter towers by adapting the detector construction technique that we have developed for the SPACAL type detector. Using wedge-shaped super-modules, a non-projective, hermetic barrel calorimeter can be build. Machining wedge-shaped towers from blocks similar to our SPACAL prototype super-modules is possible, but it will not be feasible for two reasons. One is light yield -- once machined there will be no easy solution to add mirror at the end of the fiber opposite to the photodetector; this mirror adds at least 70% more light at the photodetector as measured in the test run. Without this mirror the compact readout design may not be able to achieve the desired energy resolution. The other reason is the cost effectiveness since expensive materials will be wasted. We propose to investigate new ways of building wedge shaped towers by preserving the simplicity of construction that we have achieved with the SPACAL calorimeter. We plan to use different meshes along the tower depth. Namely, all meshes will have exactly the same hole pattern (this will preserve the simplicity of stuffing set of meshes with fibers), but all meshes will have slightly different hole diameters. Meshes close to the mirror end will have holes with large diameters. That will allow us to incline meshes along the fibers to form a desired wedge type block. This fiber arrangement will introduce variable sampling fraction and frequency along the depth of the tower. The effect due to the increase in sampling fraction and frequency at the front end of the tower will be partially cancelled out by the light attenuation in fibers. The expected resolution and linearity of the detector with such a wedge structure will require detailed MC simulations including all other physical effects. The simulation results will provide useful guidance for the construction of a wedge-shape super-module and optimization of the geometry. We request the necessary funds to acquire the special meshes for the construction. We plan to use the scintillation fibers and W powder materials remaining from the first year of R&D. Our requested budget includes the support of a visiting post-doc on simulation efforts, machine shop time to produce new molds, additional meshes, and some materials.

2.3 Budget Breakdown

Photodetectors (APD, MPPC, MAPD-3N)	$15k
Machine Shop	$13k
Students Labor (includes 26% overhead and fees)	$25k
Visiting Post Doc	$16k
Test equipment	$5k
Supplies	$5k
Oleg Tsai*(50%)	$45k
Total direct cost	$124k
Total indirect cost (26%)	$30k
Total Year 2 Request	$154k
Mechanical Engineer (includes 26% overhead)	$25k (carry-over from year 1, re-direct)

*previously supported by the UCLA intermediate energy grant from DOE, which is under the DOE review now.

3. Development of Accordion-Shaped Tungsten Plate and Scintillating Fiber Sampling Calorimeters for EIC

E.Kistenev, S.Stoll, A.Sukhanov and C. Woody
PHENIX Group, Physics Department
Brookhaven National Lab

3.1 PHENIX R&D Effort

For the past two years, the PHENIX collaboration has been developing a plan for a major upgrade of the PHENIX experiment called sPHENIX which will incorporate two new electromagnetic and hadronic calorimeters that will enable a systematic study of jets in heavy ion collisions, as well as provide enhanced physics capabilities for nucleon-nucleus interactions, spin physics, and eventually electron-nucleus collisions at EIC. The electromagnetic calorimeter proposed for sPHENIX is a compact tungsten scintillating fiber accordion calorimeter, and is very similar to the design being pursued by the UCLA/TAMU/PSU team. It will use scintillating fibers sandwiched between two tungsten metal plates and formed into an accordion shape. The accordion design has the advantage of preventing channeling of particles through the calorimeter (channeling is a phenomenon that can occur when particles incident on the calorimeter at certain angles traverse the entire depth of the calorimeter interacting only with the scintillator). In the PHENIX design, which incorporates layers of pure tungsten metal and tungsten powder saturated epoxy as a filler and bonder, it is possible to achieve a higher overall density than having a matrix of only tungsten powder and epoxy. Also, the technique for fabricating the layers of tungsten sheets and scintillating fibers embedded in the tungsten epoxy matrix is different than the one used by the RD1 team and may more easily permit the construction of larger calorimeter modules in a single section.

Both PHENIX and UCLA have been working with the company Tungsten Heavy Powder (THP) [1] to obtain tungsten powder and other tungsten materials, and to work together with them on the design and fabrication of actual calorimeter components. Tungsten Heavy Powder has also recently received a Phase I SBIR grant to study and develop materials and components for compact tungsten based calorimeters for nuclear physics applications. Members of the PHENIX group at BNL and Stony Brook University are also working with them on this SBIR grant. While this SBIR has only recently received funding, it has already produced some interesting and encouraging results. Figure 3-1 shows a set of tungsten plates with an accordion shape that were produced by sintering high density tungsten powder in a mold at high temperature. The final density of these plates is ~ 17.5 g/cm^3, which is very close to pure tungsten that has a density of 19.3 g/cm^3.

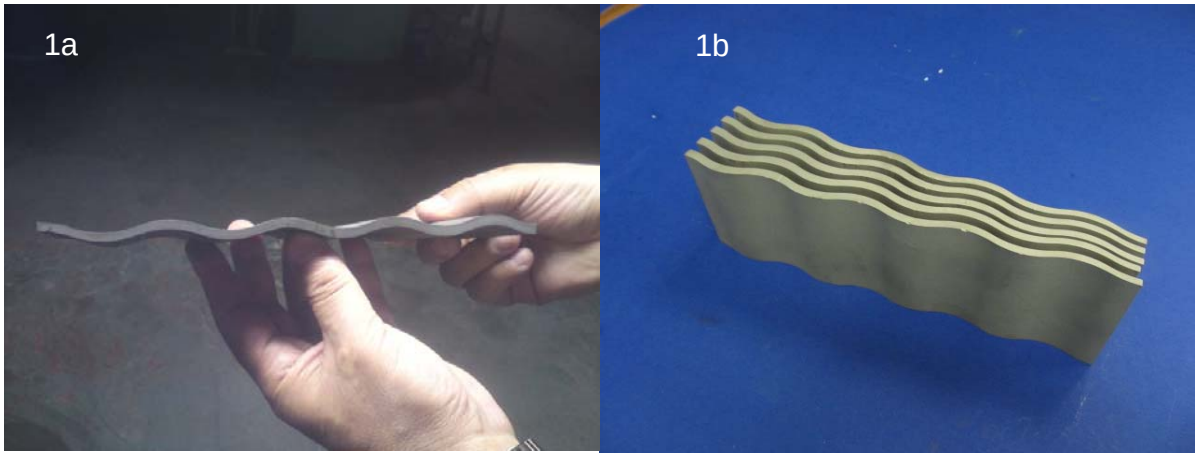


Figure 3-1. Sintered tungsten plates with an accordion shape (density ~ 17.5 g/cm^3)

These were some of the first accordion shaped plates produced by THP, and demonstrated that accordion shaped plates could be formed out of high density tungsten materials. However, while the sintered plates have a very high density, they undergo a certain degree of distortion during the sintering process, and require further treatment after sintering to restore them to their precise shape. This treatment process was successful, as shown in Fig. 3-1b, and resulted in plates that could be stacked together with scintillator in between to form a calorimeter module with minimal dead space. However, the size of the sintered plates is limited to ~ 20 cm by the process used to produce them, and the post sintering treatment adds to the fabrication cost.

A different technique is now being investigated that incorporates a tungsten powder and epoxy composite with embedded scintillating fibers sandwiched between two pure tungsten metal sheets. This arrangement is shown schematically in Figure 3-2. It is possible to bend pure tungsten sheets into an accordion shape, provided that their thickness does not exceed 1.0-1.5 mm. However, due to the deformation properties of tungsten, they also incur some “spring back” after being bent and do not precisely retain their accordion shape unless supported by an additional structure. Therefore, a separate block is formed by gluing scintillating fibers together in a mixture of tungsten powder and epoxy to form an accordion shaped piece with the desired shape for the module. A first sample layer of such a block produced by THP using this technique is shown in Figure 3-3. The pre-bent tungsten sheets, which already have nearly the correct shape, are then glued onto the top and bottom of this block to form one layer of the module. Additional layers are then glued together to form the entire module. The final module can have a rather large size, as it is only limited by the size of the plates and the tungsten powder epoxy mold.

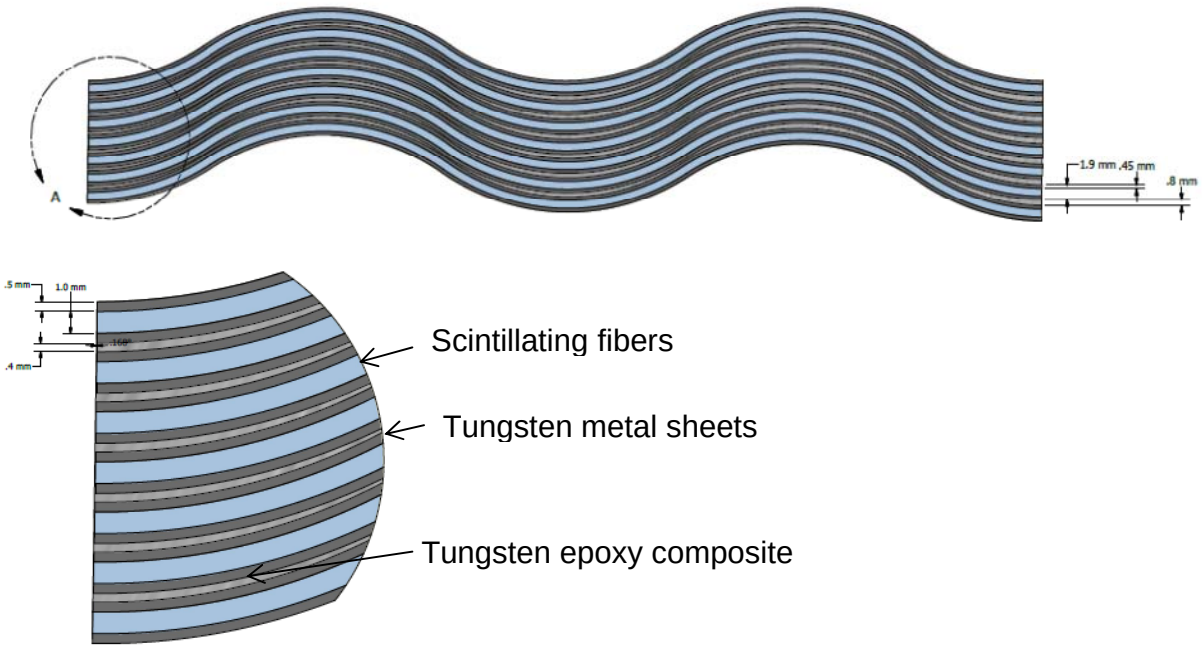


Figure 3-2. Tungsten accordion structure consisting of tungsten metal sheets (dark gray) with scintillating fibers (blue) and tungsten epoxy composite in between (light gray).

Figure 3-2 also illustrates another feature of the accordion design. One of the important design requirements for the calorimeter is that it be projective, both in the azimuthal direction, and, at least approximately, along the beam direction (precise projectivity is not required due to the spread of interaction points along the beam direction). Given that the calorimeter volume increases with radius, it is necessary in a layered structure such as this, that some layered components increase in thickness towards the back of the calorimeter, or the amplitude of the oscillations must increase, or both. It is not desirable to have large oscillations due to the fact that one does not want to have a small bending radius for the fibers. In addition, some variation in thickness is necessary at the crests and troughs of the oscillations due to the difference between the inner and outer radii of curvature. One would therefore like to keep the amplitude of the oscillations small, which are only required to be slightly larger than the fiber diameter to avoid channeling. Also, while it is in principle possible to fabricate tungsten sheets with variable thickness, it is more expensive and more difficult to form them into an accordion shape. Since scintillating fibers come with a fixed diameter or cross section, we use the tungsten epoxy layer to fill in the gaps between the tungsten sheets and fibers, which can then have the shape of a tapered accordion that is thicker towards the back. This tapering has the effect of slightly changing the sampling fraction as a function of depth in the calorimeter, but since the total thickness of a calorimeter with a depth of 18-20 X_0 is only ~ 10 cm, this effect is quite small.

Figure 3-3. Scintillating fibers embedded into a tungsten powder and epoxy composite and formed into an accordion shape (top). Tungsten metal sheets would then be glued to this structure.

It is also possible to make the calorimeter approximately projective along the beam direction using this technique. Figure 3-4 gives an example from the proposed sPHENIX EM calorimeter of how the fibers can be fanned out radially in groups that point approximately to a distribution of vertices along the beam direction.

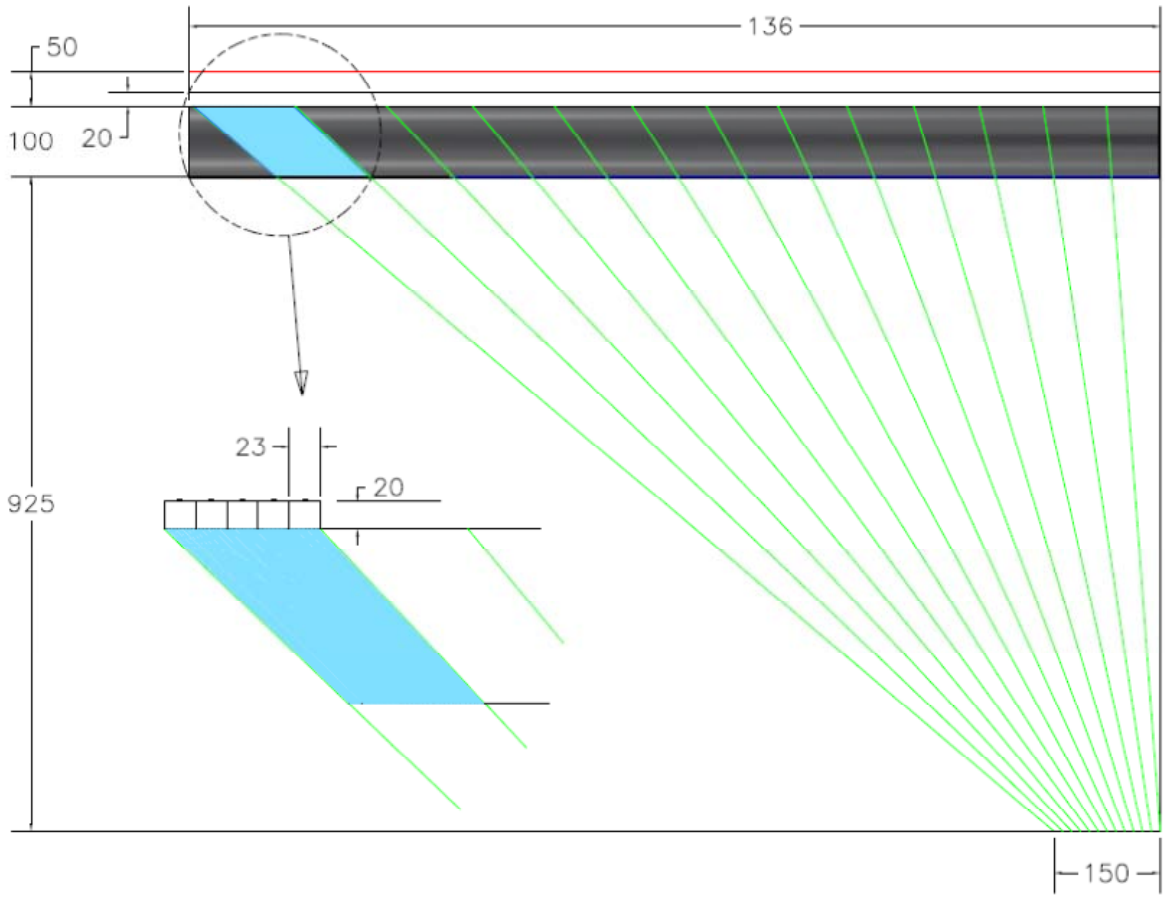


Figure 3-4. Fiber layout for an accordion calorimeter that is approximately projective along the beam direction.

3.2 Readout Considerations

In the beam test conducted by the UCLA/TAMU/PSU team, their prototype calorimeter module was read out using conventional photomultiplier tubes. The light yield was determined to be ~ 2000 photoelectrons/GeV. With this light yield, the photostatistics contribution to the calorimeter resolution is negligible (~ 2%/√E) compared with the overall measured resolution of ~12%/√E. It is therefore possible to consider other forms of readout which may reduce the number of detected photoelectrons, but may provide other advantages, such as the ability to work inside a magnetic field, have lower cost, or provide more flexibility in terms of readout geometries. The UCLA/TAMU/PSU team has included the study of readouts using silicon photomultipliers (SiPMs) and avalanche photodiodes (APDs) as a part of their R&D project, and the PHENIX group is also investigating these devices as part of their R&D program for sPHENIX.

The PHENIX group has already begun to carry out tests with some of these devices to explore the possibility of using them with a fiber calorimeter. Figure 3-5a shows the light yield measured for a group of nine BCF60 1 mm square scintillating fibers arranged into a 3x3 mm^2

bundle at one end and read out using a 3x3 mm^2 Hamamatsu S10362-33-25C Multi Pixel Photon Counter (the MPPC is Hamamatsu's version of the SiPM). The measurement was made using a Sr-90 beta source with the setup shown in Fig 3-5b in which the beta can deposit a maximum of 200 keV in a single fiber. This gave a lower limit on the light yield of 16.1 photoelectrons/0.2 MeV, or ~ 80 p.e./MeV of energy deposited per fiber. However, the true average light yield is certainly higher than this (most likely > 100 p.e./MeV), since the average energy deposited by the betas is less than 200 MeV.

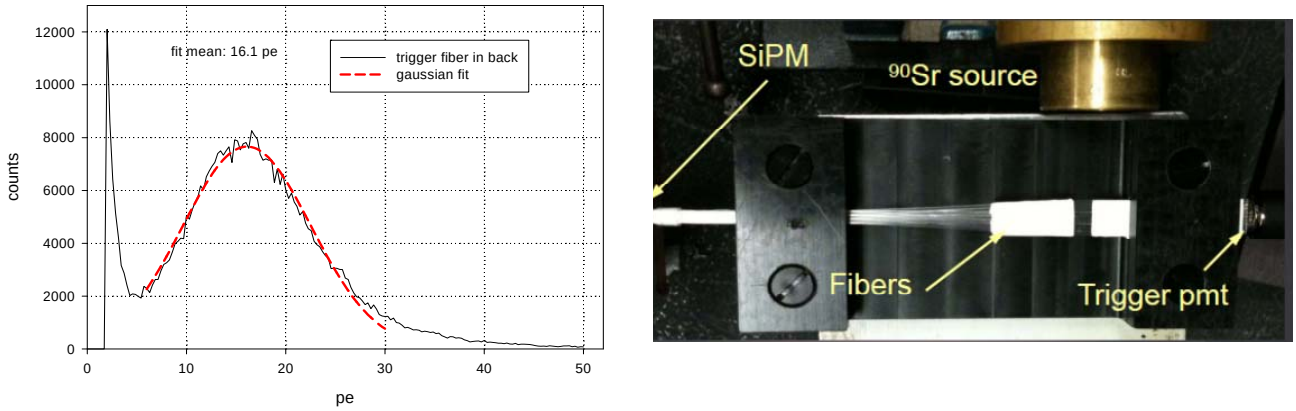


Figure 3-5. (a) Light yield for scintillating fibers read out using a Hamamatsu S10362-33-25C MPPC (SiPM). The peak value of 16.1 photoelectrons corresponds to a maximum energy deposit of 200 keV for a beta particle traversing a single fiber, or a minimum of ~ 80 p.e./MeV. The true average light yield is higher than this value. (b) Setup for measuring the light yield from the fibers using the MPPC and Sr-90 beta source.

The measurements conducted so far have certainly not determined what the actual light yield would be for a real fiber calorimeter, but it does illustrate an important point. Any fiber calorimeter that would be used at EIC will have a large number of fibers to be read out, and the amount of photocathode area coverage required to accomplish this with any form of direct readout is also large. In addition, the number of readout channels will also be large if one wants to have high segmentation in order to deal with high multiplicities or measure the shower shape. One could imagine covering such a large area with conventional photomultipliers, but one then has the limitations and costs associated with phototubes. It is possible to cover a modest readout area using SiPMs, such as is done for the GlueX calorimeter at JLAB [2], but the total number of readout channels in their calorimeter is rather low (3840). For a larger calorimeter with higher segmentation, more readout channels would be required, which are expensive not only in terms of the photodetector, but also because of the readout electronics. It would therefore be very useful to study various types of readout methods that could be used to reduce the number of readout devices and readout channels by gathering the light from many fibers at the back of the calorimeter, and focusing or collecting that light onto a limited number of small area readout devices, such as SiPMs or APDs. Ideally, one would like to have one readout device per tower or segment of the calorimeter, which contains many more fibers

than can be read out directly with a small device with a photocathode area of only a few square millimeters.

We would therefore like to explore a number of these readout options as part of this R&D program to develop a compact calorimeter for EIC. This study would fit very naturally into the overall R&D plans for this consortium, as well as for the PHENIX group that is looking at similar forms of readout for the sPHENIX calorimeter. The goal would be to develop an efficient, compact form of readout that would allow a given tower or segment of the calorimeter to be read out with a single small area, solid state readout device (either a SiPM or APD) with sufficient light yield so as not to degrade the overall calorimeter resolution. These could include various possibilities such as short light guides, reflecting cavities (similar to an integrating sphere), wavelength shifters, etc.

The study of various readout options is already in the plans for the UCLA/TAMU/PSU team, and is similar to what is being studied for the sPHENIX calorimeter, although the requirements would be different for an EIC calorimeter. The requirement for the energy resolution of the sPHENIX calorimeter is ~15%/√E, while for EIC, one would hope to achieve much better resolution. Hence the requirements on the light output would be different, as well as the possible segmentation. In addition, the range of energies of interest at EIC is also different than for the primary jet measurements in sPHENIX, and the kinematic range over which to measure the scattered electron is also unique to EIC. Therefore, while the investigation of various readout methods for sPHENIX and EIC are similar, the specific requirements and goals are very different, and we feel they deserve their own separate studies.

We also propose to optimize the design of the calorimeter itself for the physics at EIC. For measuring the scattered electron, it is desirable to have as good an energy resolution as possible, consistent with other capabilities and limitations on the entire EIC detector, as well as having an affordable cost. The sPHENIX calorimeter will most likely use 1 mm fibers, and it would certainly be an advantage to have finer sampling in an EIC calorimeter by using smaller fibers, as has been studied by the UCLA/TAMU/PSU team in their prototype. It is also worth noting that another group has also constructed and tested a fine sampling tungsten-scintillating fiber calorimeter using conventional tungsten plates [3], which may not be practical for a large, projective calorimeter, but they were able to obtain an energy resolution ~12%/√E with their prototype.

3.3. Proposed R&D plan

We propose to combine the ongoing efforts by the RD1 team and the PHENIX Collaboration to study tungsten scintillating fiber calorimeters into a common effort to design a compact, tungsten scintillating fiber calorimeter for EIC. This would ***not*** combine ***all*** aspects of these two presently independent studies which are part of the ongoing STAR and PHENIX upgrade projects. It would combine only those parts that are common to the design of a calorimeter that would be optimized for EIC, and which may have very different requirements than for

PHENIX or STAR. However, there are many aspects that are of common interest, and it would be advantageous to both groups to share information, resources and combine various activities such as beam tests. The focus of this combined effort would be to design and test various types of tungsten-scintillating fiber prototype calorimeters, built using different construction techniques, and determine which methods would produce a calorimeter for EIC with the best energy resolution, uniformity, light yield, etc, and which could be built in the most cost effective way.

Our plan for the first year of this combined R&D would be to build, in collaboration with Tungsten Heavy Powder, several fine sampling versions of our tungsten scintillating fiber tungsten powder epoxy modules. These would be used to investigate the problems associated with constructing a module with small diameter fibers and fine sampling using our design, and to measure the light output from these modules. We would also investigate various light collection schemes for gathering and collecting the light onto either a single or limited number of photodetectors, either SiPMs or APDs. This is closely coupled with the design of the front end electronics to read out these devices, both of which must be optimized for each specific application in order to achieve the maximum possible dynamic range and best overall linearity for the energy range of interest. There is also an interest in the PHENIX Collaboration to develop readout electronics for SiPMs or APDs for the sPHENIX calorimeter, and we plan to utilize parts of that design to develop a readout system that can be used for testing the various calorimeter prototype modules produced in course of this R&D.

In the second year, we would build a full scale prototype module (~ 20x20 cm^2 x 10 cm deep) using the best methods determined in Year 1, and test this module in the test beam along with other prototype modules from other groups in the consortium. These prototype modules would be divided into a sufficient number of individual readout towers that various properties such as shower shape and uniformity, as well as energy resolution, time resolution and light output, could be studied.

The PHENIX Collaboration has also developed a number of detailed simulation tools (mostly based on GEANT4) that can be used to study various calorimeter configurations. We plan to utilize these tools to study and understand the properties of the different calorimeter configurations, to help improve their design, and to eventually compare the simulation results with real data from prototype modules obtained in the test beam.

3.4. Budget Breakdown

The table below lists the budget request for an initial two year R&D program for the development of a fine sampling, high resolution tungsten plate and scintillating fiber electromagnetic calorimeter for EIC. Much of the work related to this R&D is supported by other funds (the ongoing effort within the PHENIX collaboration to develop a similar calorimeter and the Phase I SBIR with Tungsten Heavy Powder). Therefore, this budget request is only for those items not specifically supported by these other funds. We also plan to work closely with the UCLA group to combine our efforts and resources wherever possible, such as for beam tests and for the development of new materials at Tungsten Heavy Powder. We envision that after these first two years of R&D, we would be able to select the best technology choice from the various approaches being studied and focus on a single optimized design that would eventually lead to full scale calorimeter for EIC.

Item	Year 1	Year 2
Materials and supplies for testing fine sampling modules	10	
Materials and supplies light output studies	10	
Development of readout electronics and DAQ	5	10
Technical support and designer	5	10
Construction of full scale high resolution prototype module		40
Test beam activities		15
Total Direct	**30**	**75**
Overhead (50%)	15	37.5
Total (including overhead)	**45**	**112.5**

3.5. References

[1] Tungsten Heavy Powder, Inc., 7430 Trade St, San Diego, CA, 92121 (http://www.tungstenheavypowder.com)

[2] Performance of the prototype module of the GlueX electromagnetic barrel calorimeter, B.D.Leverington et.al., Nucl. Inst. Meth. A596 (2008) 327-337.

[3] A Tungsten/scintillating fiber electromagnetic calorimeter prototype for a high rate muon (g-2) experiment, R.McNabb et.al., Nucl. Inst. Meth. A606 (2009) 396-204

4. Physics Simulations and EMC Requirements

One of the main goals of an EIC will be a precise determination of the Generalized Parton Distribution functions (GPDs), which lead to a three-dimensional imaging of the protons/nuclei in the impact parameter space. GPDs are functions describing the distribution of quarks and gluons in the nucleon with respect to both position and momentum. The concept of GPDs has revolutionized the way scientists think about the structure of the nucleon, leading to completely new methods of "spatial imaging" of the nucleon in the form of genuine 3-dimensional images. Moreover, GPDs allow us to study how the orbital motion of quarks in the nucleon contributes to the nucleon spin - a question of crucial importance for nucleon structure.

It is universally believed that the golden measurement toward the determination of the whole set of GPDs is Deeply Virtual Compton Scattering (DVCS), which is the exclusive production of a real photon. This process is sensitive to both quarks and gluons and, unlikely the exclusive production on Vector Mesons, it is not affected by the uncertainty on the VM wave-function. Furthermore it shows a very clean experimental signature consisting of two clusters in the calorimeter with a track matching one of the clusters and a leading proton eventually measured in the forward detectors (Roman Pot spectrometer).

The important observables sensitive to the GPDs are the differential cross section as a function of the four-momentum transfer at the proton vertex |t| and the charge- and spin-asymmetries.

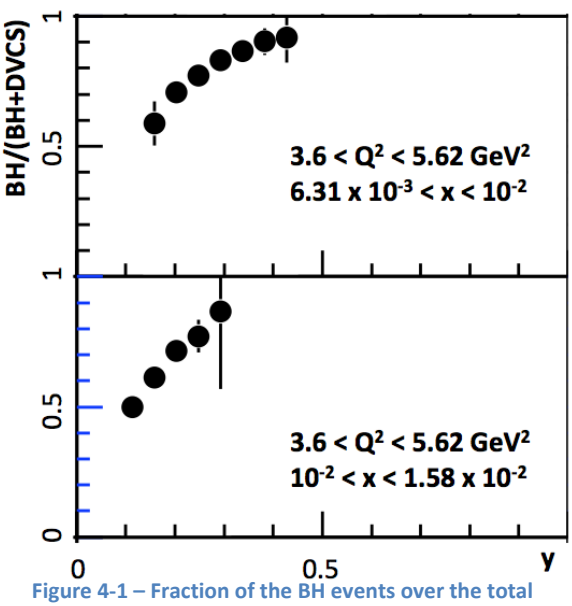


Figure 4-1 – Fraction of the BH events over the total sample as a function of y.

For the cross section measurement it is important to remove from the signal the background coming from the Bethe-Heithler (BH) events. This is essentially a QED process with the same final state of DVCS and can be subtracted from the signal by the means of MC technique. Nevertheless, even if its cross section is well known, there is still an uncertainty of at minimum ~3% coming from the uncertainty on the proton form factor. Thus, especially for an EIC where systematics will dominate the measurements, it is important to minimize the BH contribution, particularly at low energy configurations where BH tends to dominate over the DVCS.

The fraction of BH events has been estimated using an MC sample containing both DVCS and BH processes. The BH contamination has been investigated for each Q^2, x_{Bj} , |t| bin as a function of y. After all BH suppression criteria have been applied it was found that for high energy configurations the BH contamination grows from negligible (at low-y) to about 70% at y < 0.6, whereas for low energy configurations it grows faster with y and can be dominant at large y depending on the bin as shown in Fig. 4-1, nevertheless most of the statistics at this low center-of-mass energy is contained in the safe region y < 0.3. It is then crucial to have a detector, which makes the experimentalists fully capable to apply all the selection criteria required for a BH suppression.

To minimize the BH contribution, a very effective criterion is to look at the sign of the angular difference between the electron and the photon clusters. In fact we can have two possible final states: one as in Fig.4-2a, where the scattered lepton goes closer to the beam pipe than the produced real photon leading to a positive sign in the angular difference between the clusters and the other as in Fig. 4-2b where the photon ends closer to the beam-pipe than the scattered lepton.

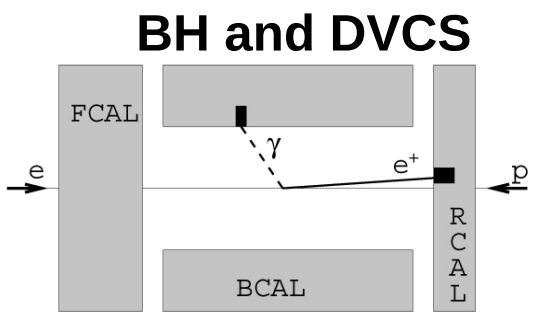


Figure 4-2a - topology typical of DVCS and BH events

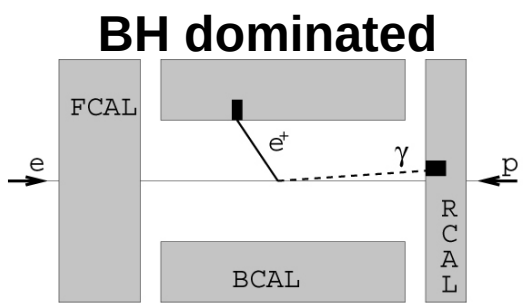


Figure 4-2b – topology typical of only BH events

The first signature contains both DVCS and BH processes whereas the latter mainly contains BH.

In Fig. 4-3 the distribution of the difference in azimuthal angle between the lepton and the photon is plotted for DVCS and BH separately for high and low beam-energy configurations. It is clear that requiring θ_{el}-$\theta\gamma$ > 0 one can reject most of the BH background without affecting the DVCS signal significantly. The problem arises when the electron and the photon cluster get very close that they basically overlap. Conventionally we call "FORWARD" the direction of the outgoing proton beam and "REAR" the direction of the outgoing electron beam. Fig. 4-4 shows that for a DVCS event the electron cluster is always seen in the REAR endcap and the photon cluster, at lower center of mass energies can be produced close to the electron in the REAR

endcap, in the barrel or even in the FORWARD endcap, whereas at larger center of mass energies the photon is always produced backwards in the REAR endcap, very close to the electron cluster.

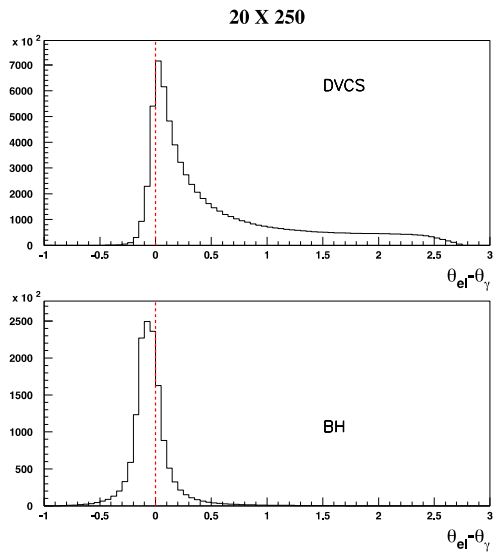


Figure 4-3a – distribution of the difference in azimuthal angle between the electron and the photon clusters for the 20x250 configuration configura

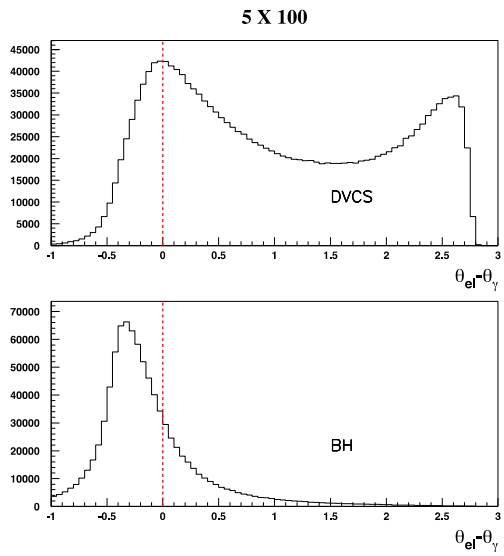


Figure 4-3b - distribution of the difference in azimuthal angle between the electron and the photon clusters for the 5x100 configuration

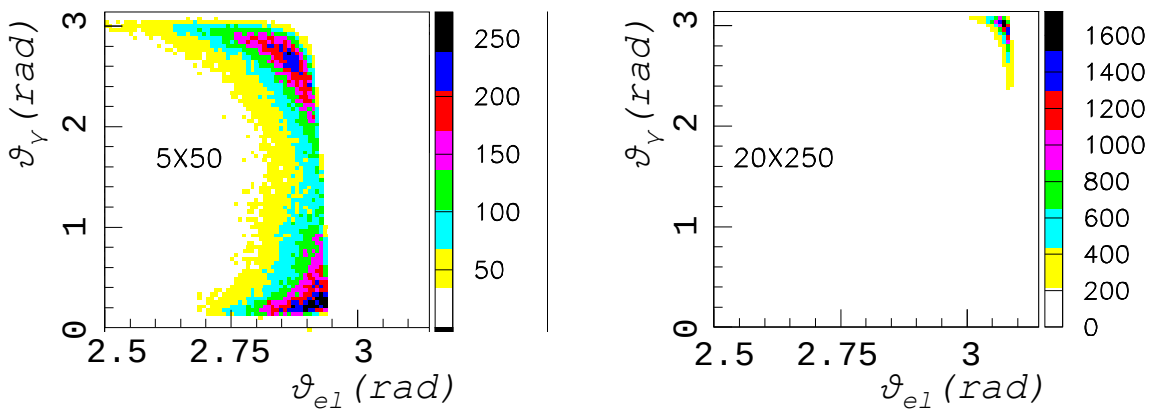


Figure 4-4 – distribution of the photon angle vs the electron angle for the 5x50 GeV (left) and 20x250 GeV (right) beam energy configurations.

Nevertheless there is always a limit in the discriminative power between the electron and the photon clusters, which comes from the spatial resolution of the EM calorimeter and which

limits how hard one can cut on the minimum difference in the azimuthal angles between the photon and the electron. However this cut cannot be too soft since it impacts not only the statistics of the measurement but also the reconstruction of the azimuthal angle, ϕ, between the production and the scattering planes in the proton rest frame, whose dependence of the asymmetries is of a crucial importance towards the determination of the GPDs. According to simulations, a requests of $|\theta_{el}-\theta\gamma|> 1$ deg will not significantly impact the ϕ-angle reconstruction. Therefore it is very important for the EM calorimeter in the REAR endcap to have a granularity fine enough to be able to discriminate two clusters down to an azimuthal angular difference of 1 degree.

Another effective way to reduce the BH background is to look at the energy of the electromagnetic clusters. Fig. 4-5 shows the electron and photon energies for DVCS as well as BH events. One can easily realize that requiring the electron cluster to have the energy > 1 GeV rejects much of the BH contribution without significantly affect the DVCS signal; nevertheless imposing a cut above 1 GeV could affect DVCS too. Thus, it is important for the electromagnetic calorimeter in the REAR region (the region where the electron is always scattered) to be able to accurately measure the electron energy down to 1 GeV.

Another critical role an EM calorimeter at EIC will play in addition to measure photons is to identify the scattered lepton (e-PID). This will require a good resolution in E/P to allow the suppression of charged hadron. As shown in Fig. 4-6, the suppression factor needed changes with center of mass energy and rapidity. But suppression factors of 100 are required at a minimum.

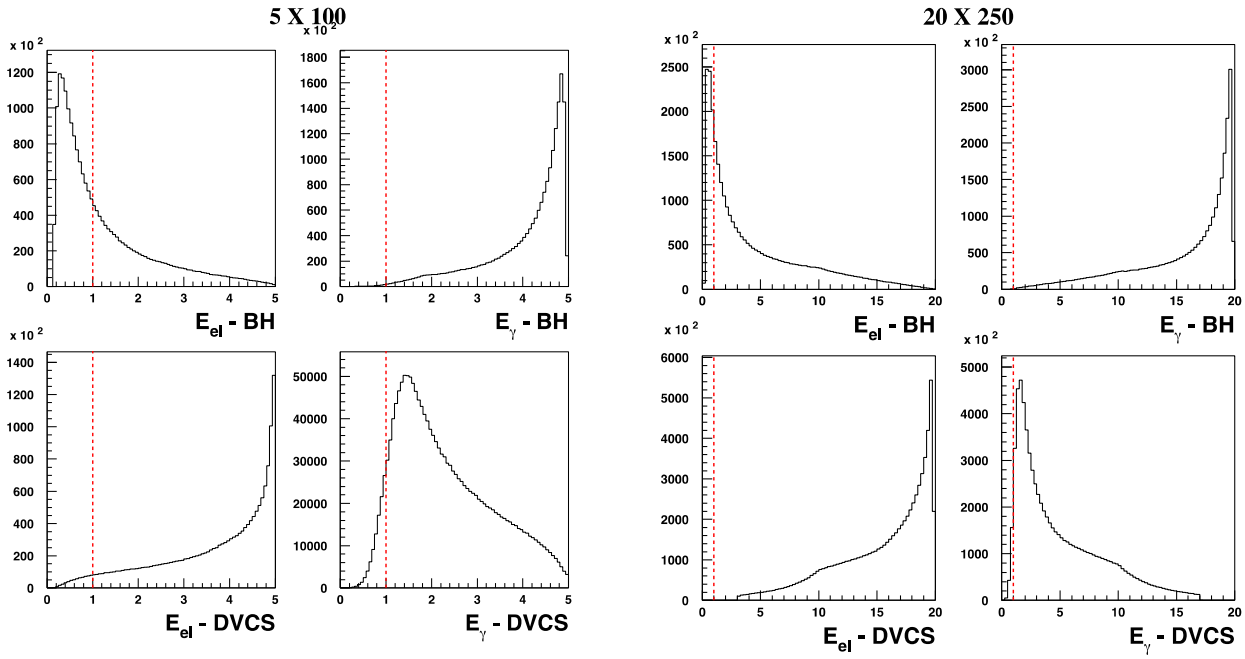


Figure 4-5 – distribution of the electron and photo cluster energy for the DVCS and the BH processes for the 5x100 GeV (left) and 20x250 (right) beam-energy configurations.

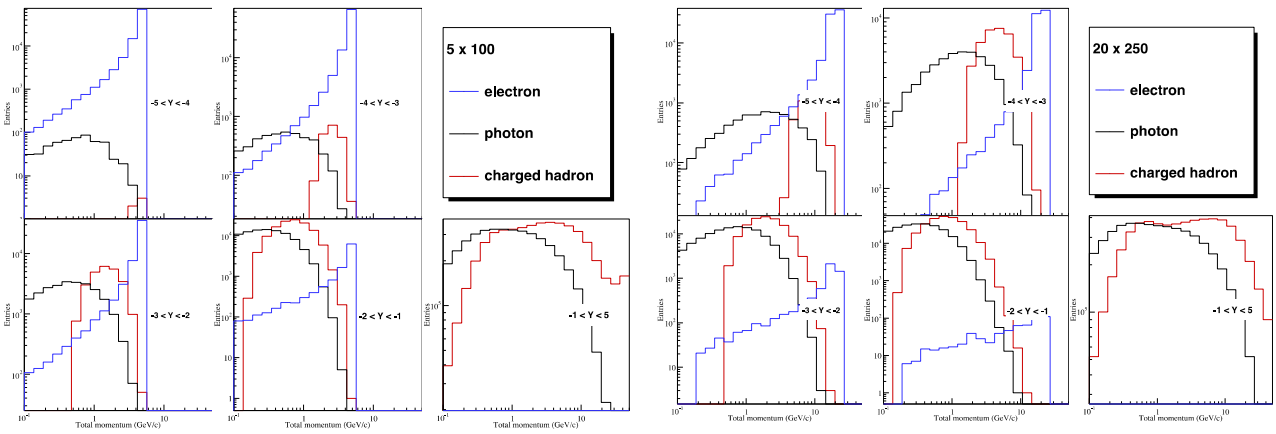


Figure 4-6 – distribution of the total momentum for electrons, photons and hadrons as a function of the detector rapidity for 5x100 GeV (left) and 20x250 GeV (right) beam-energy configurations

Preliminary Requirements on EMC

The EM calorimetry will be one of the crucial detectors for an EIC detector, especially for the measurement of exclusive processes such as the production of vector mesons and real photons, of a great importance towards the determination of GPDs. Here we used the DVCS process to drive the requirement for the calorimeter, since it is the most important measurement for

GPDs and it relies heavily on electromagnetic calorimetry. After an initial study based on MC simulations preliminary requirements for EM calorimeter performance for an EIC detector should include the following properties:

- Granularity fine enough to be able to discriminate close clusters down to an azimuthal angular difference: $\Delta\theta$= 1 deg
- Noise levels and resolution good enough to measure clusters with energy down to E= 1GeV
- Good E/P to discriminate electrons and photons over the charged hadrons and give an excellent electron PID.

This consortium plans to have people from the experimental R&D teams and the simulation team to work closely to search for viable detector technologies covering a broad kinematic region with optimizations for both physics and costs.

5. Future Perspectives of the Calorimeter R&D Consortium

We are committed to develop calorimeter technologies for EIC applications in the future. It is important to note that we are still in the early phase of the EIC planning and we need to explore many viable technology choices at this stage. We will share our knowledge and technical expertise so that we can bring all potential technology choices to a mature stage, preferably with beam testing results, so that we will be ready to select the best detector choice for an EIC experiments.

The R&D on readout schemes is an important step which will benefit all detector choices under consideration. For example, the crystal detector R&D project could use what we will learn about APD and SiPMT readout performances and tailor a new design for crystal calorimeter readout. We expect that the readout for a crystal detector may be more restrict due to the higher energy resolution for crystals.

We should also mention that calorimeter R&D consortium is an open collaboration. In order to develop and eventually build full scale calorimeter detectors more research groups and resources will be needed. We will actively recruit more groups to join our effort. In particular, we expect that the next phase of R&D development will involve many mechanical structure and stability studies, readout and trigger electronics. These will be our future R&D focuses in the coming years.

We expect that simulation efforts will play an important role in our R&D projects. This includes both the Geant Monte Carlo simulations for detector design and the physics simulations to better define the detector requirements. Comparison between Geant detector simulation and the test beam results indicate that the Geant simulation can be used as guidance for future optimization of detector design. We have a visiting post-doc from China (Q. Zhang) and a graduate student (L. Dunkelberger) working on the Geant detector simulations. For the physics evaluation it is necessary to combine barrel EMC and tracking detectors together to study physical processes that we intend to measure at EIC. The BNL EIC group is uniquely positioned to take upon this challenge task and a good progress has already been made in that direction.

In summary, we note the report by the EIC Detector R&D Review Committee stated "Calorimetry is a critical component of EIC detectors. Fiber sampling calorimetry has attractive features. The technique allows, in principle, the construction of versatile compact and fine-grained sampling electromagnetic and harmonic calorimeters with good energy resolution, hermeticity, timing and position resolution. It is appropriate to explore this in the context of the EIC R&D program". Our consortium is on our way to achieve these goals.