A Comprehensive Study of 3D-Printed Scintillators and Light Guides for Constructing Shashlyk-Type Electromagnetic Calorimeters for the Electron-Ion Collider

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Abstract

Electromagnetic calorimeters (Ecal) consist an important part of the detector package for the Electron-Ion Collider (EIC). The shashlyk-design is a type of sampling calorimeter that provides a reasonable energy resolution and a high radiation resistance, and at a lower cost than crystal calorimeters. We propose here a first step towards an R&D study for building shashlyk calorimeters for the EIC. For the first year, we will conduct preparation work such as testing the optical and mechanical properties of the scintillator and absorber components of the calorimeter, with a focus to explore possible new technology which will allow us to efficiently carry out the prototyping process and to push beyond the existing shashlyk module construction methods. We will also carry out preliminary simulation work to establish the basic design for possible shashlyk calorimeters for the EIC.

The new technology we choose is 3D-printing. We will start from a comprehensive study of 3D-printed scintillators and light guides and compare results with those made from traditional methods. Properties to be determined include their transparency, light yield (for scintillators), mechanical properties and strength, and radiation hardness. The 3D-printed scintillator components will at the least allow a fast turn-around time in prototyping the shashlyk calorimeter at low cost, and will allow easy construction of projective-shape modules. The 3D-printed light guides will provide an alternative to the conventional machining method at a potentially lower cost and are particularly suited for applications where complicated shapes are required. Meanwhile we will also investigate the possibility and the cost of 3D-printing absorber parts. Generally speaking, the 3D-printing method will potentially open up a new venue for sampling-type calorimeter construction in the near future.

The requested funding period is for one year and the funds will be used to cover the necessary test setup, material and supplies, and the manpower needed to conduct this R&D research. If the test shows that the 3D-printed scintillator parts meet the physical requirements of shashlyk calorimeter construction, we will proceed to prototyping shashlyk modules for the EIC's calorimeters at the next funding cycle, with goals to simplify the construction procedure, to lower the overall cost, to produce projective-shape modules, and to study the limitation on the energy resolution.

1 Calorimeter Needs for the EIC and the Proposed Study

Calorimeters provide measurements of particles' energy in medium- and high-energy experiments. They often also provide triggering and moderate tracking information. For collider experiments such as those being carried out at the large hadron collider (LHC) and being planned for the electron-ion collider (EIC) [1], both hadron and electromagnetic calorimeters are needed. Typical energy resolutions required for Ecal varies between $(1-2)\%/\sqrt{E}$ to $12\%/\sqrt{E}$ with E in unit GeV/c, while the resolution that can be achieved for Hcal is much larger, in the order of $100\%/\sqrt{E}$. Other constraints on collider calorimetry include compactness, radiation hardness, and sometimes a projective shape may be desired.

1.1 Shashlyk-Type Calorimetry

Many different technologies have been developed for calorimetry in the past century. The commonly used options include lead-glass, NaI and CsI. The energy resolution is moderate, varying from $5\%/\sqrt{E}$ to $(1.5-2.0)\%/\sqrt{E}$ for NaI and CsI. However these are not radiation hard and cannot be used under the harsh environment at colliders. Crystal calorimeters such as LSO, $PbWO_4$ or PbF_2 are radiation hard and with excellent energy resolution, however their cost is often too high for collider experiments where large volumes of calorimeter are needed. A relatively new technology is based on samplings of electromagnetic showers developed by the particle, such as SPACAL or Shashlyk-type calorimeters. They provide a reasonable energy resolution ($5\%/\sqrt{E}$ is achievable) with a moderate cost. In the following we will focus on the shashlyk sampling technology.

Shashlyk-type calorimeter modules [2, 3, 4] are made of alternating layers of an absorber and scintillator. Scintillating light is guided out from the module by wavelength-shifting (WLS) fibers that penetrate through all layers and is detected in PMTs or SiPMs. The shashlyk technique has been used successfully in recent LHC experiments. It is a cost-efficient alternative to crystal calorimeters while providing a comparable radiation resistance in the order of 10^6 rad. On the other hand, the drawbacks of the shashlyk method include high costs of prototyping due to the traditional methods used for producing the module parts (injection-molding for the scintillator layers and stamping for the absorber layers); the complexity of the module assembly process; the difficulty to make the modules in projective shapes due to the fixed size and shape of module parts; and the limitation on the energy resolution due to non-uniformity of both absorber and scintillator sheets (to provide a $5\%/\sqrt{E}$ resolution, the absorber layers are as thin as (0.3-0.5) mm and the scintillator layers are 1.5 mm. Thinner layers are hard to manufacture and the thickness uniformity is usually limited to 0.025 mm.)

1.2 Shashlyk EM Calorimeters for EIC

Figure 1 shows the conceptual design for the interaction region of both ePHENIX at RHIC [6] and MEIC at JLab [7, 8]. In the following we will describe the general requirement of Ecals for both cases.

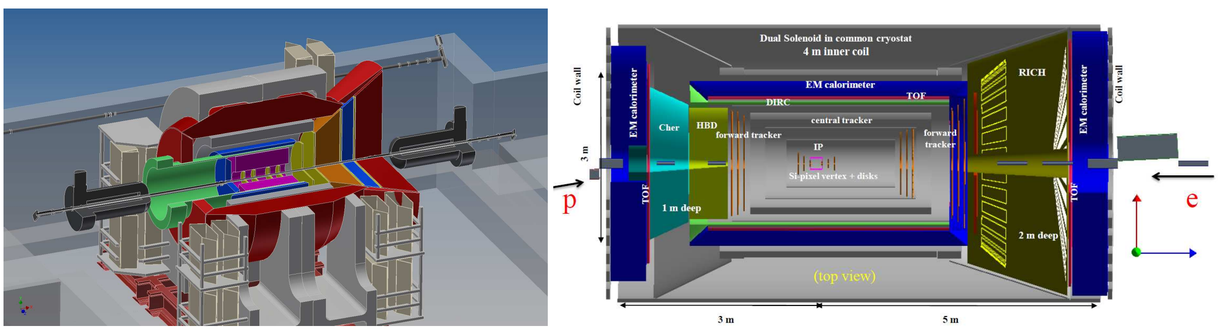


Figure 1: Detector package for ePHENIX (left) [6] and MEIC (right) [7, 8].

For ePHENIX, we will need:

- A central Ecal, needs to be very compact radially with a moderate $12\%/\sqrt{E}$ resolution. Currently the top choice is the tungsten sci-fi design [9], but a shashlyk type design is not out of the question;
- A forward (electron direction) Ecal that requires a $(1-2)\%/\sqrt{E}$ resolution or a $(5-6)\%/\sqrt{E}$ resolution if good tracking information is available. Currently the top choice is crystal Ecals [10], but a shashlyk design is possible and maybe budgetarily desired if the energy resolution needed is only $(5-6)\%/\sqrt{E}$.
- A backward (hadron direction) Ecal that requires a moderate $(12-15)\%/\sqrt{E}$ resolution. A shashlyk design may be the best choice.

Among these three, none is required to have projective-shape modules. However since it is envisioned that the central Ecal will be the currently planned barrel Ecal for sPHENIX [6], the central Ecal must have a projective design.

For MEIC, we will need:

- A central (barrel) Ecal, which currently is designed to be a lead sci-fi type calorimeter and is the same as the JLab Hall D Ecal.
- An electron-direction endcap Ecal. It will consist of a crystal (lead-tungstate) inner layer plus an outer layer. The requirement on the energy resolution of the outer layer is moderate and a shashlyk design is possible.
- A hadron-direction endcap Ecal. The energy resolution required is $(5-6)/\%$ and a shashlyk design is possible.

Similar to ePHENIX, none of the Ecals for MEIC needs to be projective. However, a projective design will certainly improve the energy resolution compared to a non-projective design.

As one can see from above, Shashlyk calorimeter can potentially be used for at least two of the three Ecals for the EIC. On the other hand, the expertise in shashlyk calorimeter construction lies mostly in Russia (IHEP and ITEP). Only a couple of university groups in the US currently have experience constructing shashlyk modules, but they are all outside the nuclear physics community. It is urgent to gain experience and obtain expertise in shashlyk module construction within the EIC community.

1.3 The Proposed Study

We propose here a first step in the R&D of shashlyk calorimeter design and construction for the EIC. On the design R&D, we will carry out preliminary simulations to determine the basic parameters of EIC shashlyk Ecals. On the construction R&D, we will start from testing the optical and mechanical properties of the scintillator parts for shashlyk modules. In order to push beyond the limit of existing shashlyk construction methods, we choose to focus on a comprehensive study of both 3D-printed scintillators and scintillators produced from traditional methods. The most appealing advantages of 3D-printing are the fast turn-around time, the possibility of in-house prototyping and production, and the ease of changing the product shape and size during production which is needed for producing projective-shape shashlyk modules. In the longer term, 3D-printing could provide better control over layer uniformity (layer thickness of 3D printing can be in the micron level) which is crucial for reducing the energy resolution of the shashlyk calorimeter. Depending on the printer used and possible modifications that can be made to the commercially-available printer, one could also simplify the module assembly process.

The scintillators produced with traditional methods will be provided by the Chinese Beijing High-Energy Kedi company [2] and Eljen Technology [3]. The 3D-printed scintillators will be provided also by two parties: 1) made in-house at the College of William and Mary; and 2) the R&D department of Stratasys, a leading 3D-printing company [4]. We will start from the general transparency, light yield, and mechanical strength and properties of simple-shape samples. Then we will proceed to testing preshower modules which are made of a single piece of 20mm-thick scintillator with WLS-fiber embedding, for which we already have data on three different prototypes produced with traditional methods, including prototypes from Beijing HE-Kedi and Russian IHEP. As a third step, we will test the light yield, transparency, and the mechanical strength of thin scintillator sheets needed for constructing shashlyk modules. Related to 3D-printed scintillators, we will also explore the optical clarity and light transmission of 3D-printed light guides made from commercially available optical-quality materials ("veroclear" and "tglase").

Within the proposed one-year funding period, we hope to show that scintillators produced using the 3D-printing method can provide comparable performance as those produced from the traditional method. This will open up the possibility of fast and in-house prototyping, producing projective-shape shashlyk modules with ease, and possibly pushing the energy resolution to a couple of $\%/\sqrt{E}$ using thinner 3D-printed layers in the near future. Even if the 3D-printed scintillators do not perform well enough, we will have gained experience and data testing scintillator parts produced from traditional methods, which is a crucial step in constructing shashlyk modules for the EIC's calorimeters.

2 Shashlyk-Type Calorimetry – Current Status and Limitations

As mentioned earlier, shashlyk calorimetry [2] is a type of sampling detectors that provide a cost-effective alternative to radiation-hard crystal calorimeters. Shashlyk-type calorimeter modules are

[2]http://www.gaonengkedi.com/
[3]http://www.eljentechnology.com/
[4]www.stratasys.com

made of alternating layers of an absorber (such as lead or tungsten) and a scintillator. Particles are efficiently slowed down and stopped by the absorber layers, and the scintillator layers sample the amount of showers produced. Scintillating light is guided out by wavelength-shifting (WLS) fibers penetrating through all layers of the module. In a simple model where we assume the shower particles share the energy evenly, the energy resolution is determined to the first order by [11, 12]

$$\left(\frac{dE}{E}\right)_{shashlyk} = \frac{1}{\sqrt{N_s}} \quad (1)$$

where

$$N_s = F(\xi)\cos\theta_{\mathrm{MS}}\frac{E}{E_c}\frac{X_0}{\Delta t} \quad (2)$$

with E the particle energy, E_c the critical energy ($E_c \approx 550$ MeV$/Z$ for electrons), X_0 and Δt the radiation length and the layer thickness of the absorber. In Eq. (2), E/E_c is the total number of shower produced by the particle and $X_0/\Delta t$ represents how often the shower maximum (within one radiation length) is being sampled by the absorber/active layers, θ_{MS} is the multiple-scattering angle, and $F(\xi)$ is a function depending on the detection threshold. If the threshold energy is small and at the MeV level or below, $F(\xi) \approx (0.7-1.0)$. For electrons of $(1-10)$ GeV initial energy, the shower maximum develops at $(7-10)X_0$, and an additional $(7-9)X_0$ is needed to absorb $> 95\%$ of energy carried by all photons that are originated at the shower maximum. This means a total absorption Ecal need to be at least $(14-16)X_0$ thick. For shashlyk modules constructed from 0.5-mm thick lead sheets, using $E_c \approx 8$ MeV and $X_0 \approx 0.54$ cm for lead, the simple calculation of Eqs.(1-2), ignoring terms $F(\xi)$ and $\cos\theta_{\mathrm{MS}}$, gives an energy resolution of $\approx 3.3\%/\sqrt{E}$. The thickness of the scintillator would affect energy resolution to the second order. In reality, the actual energy sharing between shower particles is not even and the number of showers is smaller than Eqs.(1-2). Detailed simulation for modules made of 0.5-mm lead and 1.5-mm scintillator sheets gives $\approx 5\%/\sqrt{E}$.

Shashlyk-type calorimeter has been widely used in experiments at the LHC, including ATLAS, ALICE and LHCb. On the other hand, the construction of Ecal modules is labor-intensive and prototyping is expensive due to the complexity of parts. Figure 2 shows a possible design of the absorber and the scintillator sheets for a hexagon-shape shashlyk module. The lateral size is 100 cm^2 with

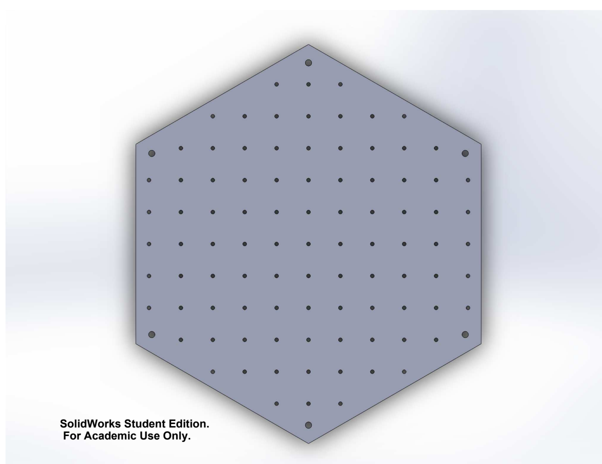


Figure 2: A typical shashlyk module layer design.

93 holes spaced uniformly across the surface to accommodate the WLS fibers. Because of the large amount of holes, scintillator sheets are usually produced by injection-molding, for which the expertise resides almost solely in Russia (Beijing HE-Kedi does do injection molding but we do not know

of any shashlyk calorimeter constructed using scintillators from this company, and the following discussions apply to all injection-molding-based productions). Each mold typically cost $30k which makes up the bulk part of the prototyping cost. Although for mass production the mold cost is not as significant, the high cost of prototyping makes fine adjustments to the design difficult. A second difficulty common to shashlyk module design and construction is that the size of the scintillator sheet is determined by the mold. The fixed size of the mold makes it nearly impossible to construct shashlyk modules of projective shape. (For example to construct the LHC/ALICE modules [5] which are semi-projective, scintillator sheets of a fixed size were produced using injection molding and then cut down to 76 different sizes individually.) Both difficulties also apply to the lead (absorber) sheets which are produced by stamping for large quantities. Although the stamping technique is available in the US and the stamping tool can be made of fixed hole positions with variable outer shape and size, the position and the size of the holes cannot be changed and each stamping tool can cost as much as $15k, again making prototyping cost very high.

Once all sheets are manufactured, they are assembled on a specially-designed assembly stand. Intensive care is spent on designing the assembling stand such that all holes are aligned. The assembling process itself is highly-technical, tedious, and labor-consuming. For example the LHC/ALICE Ecal construction of 16,000 modules (4,000 "assemblies") took about 3 years by ten full-time technicians and students.

Performance-wise, because of the production technique of the sheets, there is a limit on how thin the sheets can be manufactured and how uniform the thickness is. Typically, lead sheets as thin as 0.3 mm can be manufactured with a tolerance of $\pm$0.025mm. The tolerance of scintillating sheets can only reach a fraction of mm. For thinner sheets, non-uniformity in the thickness gives rise to a constant term in dE/E that limits the overall resolution to $(3-5)\%/\sqrt{E}$ regardless of the design layer thickness. If the physics program requires better energy resolution, crystal Ecals must be used which costs one order of magnitude higher than the Shashlyk design.

3 The Method and the Potentials of 3D-Printing

Three-dimensional printing, also known as additive manufacturing (AM), is a process in which successive layers of material are laid down under computer control. These objects can be of almost any shape or geometry (hollow structure can be printed with a secondary supporting material that can be dissolved away after printing). The control can be provided from a 3D model or other electronic data source such as CAD drawings. Earlier AM equipment and materials were developed in the 1980s, but have only progressed rapidly in the past 5-10 years. Currently it is being used in a wide area of applications such as industrial prototyping, providing low-cost prototypes with fast turn-around time; high-tech development such as printing high-density lithium-ion batteries; printing medical shielding with highly-customized size and shape; in-home project construction by amateurs; and even educational projects in public schools, allowing teenage children to learn 3D construction and modeling and thus provide an interface for them to participate in higher-end research projects long before they enter college.

There are currently three kinds of 3D printing methods. The first is Fused Deposition Modeling (FDM), in which spools of plastic filament is melted when it approaches the tip of the printer and is printed on a supporting material. The supporting material is dissolved away after printing. The filament is typically made of thermoplastics such as acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA), but can also be made of thermoplastics mixed with metal powder, providing a density up to 4 g/cm^3 [5] used mostly for medical radiation shielding. For parts that requires transparency, acrylic-based material ("veroclear") or the so-called "t-glase" material exist at a higher cost. In addition to commercially available filaments, one could extrude filaments in-house using custom extruders. Some people use in-house extruders to reduce the material cost of 3D-printing and to recycle plastics. We think it is also possible to experiment mixing plastic powder with metal powder and make our own high-density filaments. The second 3D printing technique is called poly-jet, in which

[5]This density is independent of the metal powder used. We do not know why higher density filaments are not available commercially.

liquid "ink" is printed from an inkjet-like printer head and then is UV-cured to the solid state. The third is for printing ceramic, pure metal or metal alloy. To print pure metal, metal powder is sintered (heated to just below melting point) either before or after printing. To sinter the metal powder before printing, an electron or a laser beam is typically used and the sintered powder is laid down in the desired 3D structure. To sinter the metal powder after printing, a binding material is printed on the powder by the printer, then lose powder is swept away and the bound powder is sintered in a furnace. This is called the "binder-jet" method.

For all three printing technique, the resolution varies from 0.1 mm for typical industrial-use printers, to slightly coarser ones for home and school uses, to 16 μm for more higher-end models. The most commonly used 3D printers are the FDM type, with costs ranging from a few hundreds of US dollars to tens of thousands. Poly-jets and metal printers typically cost one and two orders of magnitudes more, respectively, than FDM printers of comparable specifications.

To 3D-print scintillators, one must formulate a 3D-printer compound from a plastic base with scintillating components. This technique is new and highly non-trivial (for an original study see Ref. [13]), and we will be working with Stratasys (a leading company in 3D printing) to develop scintillating compounds to use in polyjet printers. Their current formula produces scintillator pieces with similar light yield to EJ-204 (Eljen), and they are in the process of improving the mechanical strength of the product. The compound is only at the R&D stage and is not for sale, thus we will be obtaining only samples from Stratasys for the proposed study, at least in the first year.

We would like to point out two possibilities where the 3D-printing method can be particularly interesting for calorimeter construction. The first is a potentially simpler assembly procedure. Alignment pins can be printed using a different material at the same time as the scintillator sheets, and absorber layers (made from conventional methods) can be added by pausing the printer after each scintillator layer is printed. This procedure could be made automatic, and the only remaining steps of module assembly would be to compress the layers, to add endcaps, and to thread the WLS fibers. The second possibility is higher energy resolution. With the precision of 3D-printing and the fact that the cost is only proportional to the volume of the material and not the number of layers, one might expect construction of shashlyk modules made of ultra-thin layers without multiplying the cost. We would like to see how high energy resolution can be achieved.

With the advancement in 3D-printing one might also envision a final stage where the full shashlyk module can be printed on a 3D-printer. While it is unlikely that one can combine polyjets with metal-sintering, one could explore the possibility of mixing tungsten powder with thermoplastic or a liquid compound that reaches a density high enough to be used as the absorber. In this case, the full shashlyk module could be printed on a hybrid printer that combines FDM with poly-jet (although we still need to figure out how to add the reflective layers, if not manually). The layers can be aligned using alignment pins as described above. While this is certainly beyond the proposed funding period, it is an attractive goal and we will keep it in mind when carrying out the proposed R&D.

4 Proposed Test Plan and Simulation Study

4.1 Mechanical Properties

We propose to measure the following mechanical properties of both the scintillator and the light guide: compressive strength, tensile strength, shear strength, and Young's modulus and shear modules. The focus will be on the compression strength because shashlyk modules from LHC ALICE and LHCb experiments were all made by compressing the scintillator and the lead sheets with a 500 kg force. This requires a 5×10^5 N/m^2 compression strength on the scintillator (no safety factor included). 3D-printed samples of different shapes and sizes, from both Statasys and made in-house at William and Mary, will be used depending on the quantity measured and the test setup, and results will be compared to traditionally made scintillators for which data are available online. Depending on the initial results, we may need to iterate multiple times with Stratasys on the scintillator production.

After the initial tests using simple-shaped samples, we will test the compressive strength of 3D-printed shashlyk scintillator sheets as shown in Fig. 2. Then we will sandwich the scintillator sheets with lead or tungsten sheets to test the combined strength. Note that the requirement on the scintillator strength may defer between different absorbers, as lead is significantly softer than tungsten.

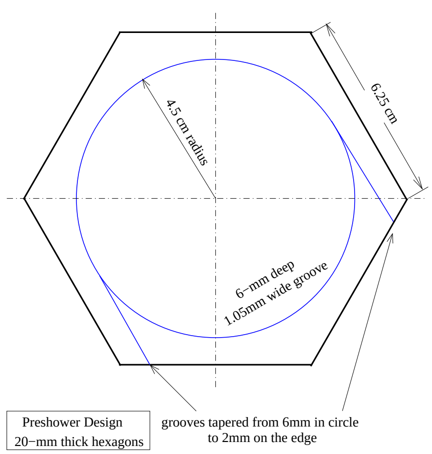
We hope to find all necessary equipment in the physics and the engineering departments at the University of Virginia. But we will include a $2k in the budget to cover material and supply.

4.2 Transparency and Light Yield Test Using Rectangular Blocks

We will test the transparency of both the light guide and the scintillator using samples of simple rectangular shape, blue LEDs, and a spectrophotometer from the UVa/physics demo lab. For the light yield test, we will optically couple the sample directly to a PMT and measure the MIP response using cosmic rays. 3D-printed samples of the scintillator will be provided by Stratasys or made in-house at William and Mary, while we will 3D-print our own light guide samples for the light guide study. The light guide material and a FDM 3D-printer will be procured using Prof. Zheng's other funds.

4.3 Preshower Transparency and Light Yield Test

A common design for the Preshower module is a scintillator tile with WLS fiber embedded to guide out the light. We choose a specific preshower design (see Fig. 3) because the UVa group has already had extensive experience with this particular module. We have already tested preshower prototypes of this design made of different scintillating base materials including polyvinyltoluene(PVT) (Eljen), polysterene (IHEP), and phenylethene (Beijing HE-Kedi). All three prototypes gave ≈ 80 photoelectrons when two 1-mm diameter Kuraray Y11 fibers are used (each embedded in the groove 2.5 turns) and read out using a Hamamatsu R11102 PMT. We will carry out the transparency test using blue LED lights and a spectrophotometer from the UVa/physics demo lab, and then the light yield test by both coupling a PMT directly to the side of the prototype, and by WLS-fiber embedding. We will compare results from the 3D-printed sample with all other three existing prototypes. The cosmic test of the 3D-printed Preshower module will provide the first characterization of detector performance using 3D-printed scintillating material.



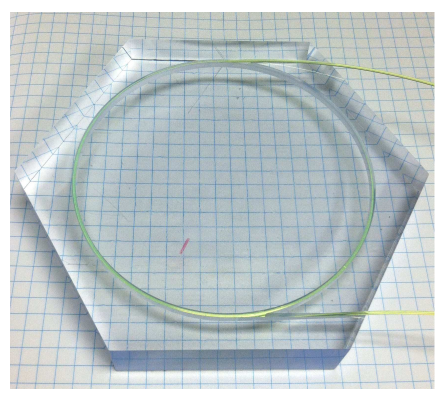


Figure 3: Proposed preshower module for testing. Left: schematic design for the preshower tile. The grooves are for embedding the WLS fibers; Right: a preshower tile produced by Beijing HE-Kedi company that we already tested.

4.4 Shashlyk Sheet Light Yield Test ("Hedgehog" Test)

To examine the quality of the 1.5-mm thick scintillator sheets for shashlyk module construction, we plan to set up a "hedgehog" test where 93 WLS fibers are inserted into the holes of the scintillator sheet, see Fig. 4. The inserted fiber ends should be just above the holes. To increase light yield, a single mirror may be attached to the scintillator's top surface. The other fiber ends are grouped and coupled to a 2-in dia PMT. Response to cosmic rays will be measured. Since we don't have any scintillator sheets with known light yield on hand, we plan to procure 5 each from Beijing HE-Kedi and Eljen as the reference. 3D-printed samples of the scintillator will be provided by Stratasys or made in-house at William and Mary. If the 3D-printed material has a comparable light yield as the polysterene-based ones (which we will know from the preshower test), we expect the MIP response to be about 12 photoelectrons which should be straightforward to measure. Measurement of light yield below 2 photoelectrons will be difficult, but in that case the light yield of the 3D-printed scintillator will be too low to be useful for detector construction.

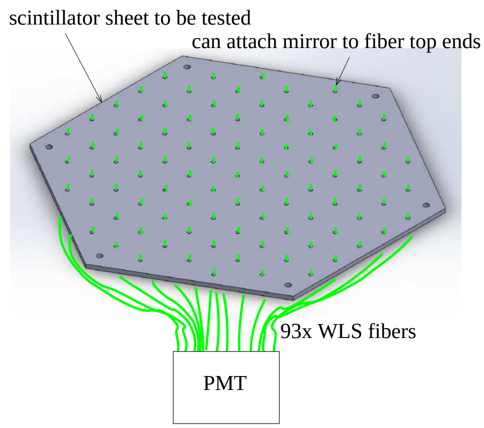


Figure 4: Hedgehog test to determine the cosmic light yield of individual shashlyk scintillator sheets.

4.5 Simulation for the EIC Shashlyk ECal

We would like to conduct preliminary simulation for the EIC shashlyk Ecal. We will start from the required energy and spatial resolution and the available space to determine the absorber material, layer thickness, and transverse segmentation of the two endcap Ecals as well as the central Ecal.

5 Budget Request

We request here funds for one quarter of a postdoc, one-half academic year graduate student stipend, material and supply necessary for the proposed tests, and for possible travel to BNL.

While most of the tests can be conducted by the graduate student, the radiation hardness test and the GEANT-4 simulation will require the expertise at a postdoctoral level. The postdoc to be supported partially by the requested funding here [... ...]

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Item	cost
5 Eljen EJ-205 shashlyk sheets	$1,570
5 Beijing HE-Kedi shashlyk sheets	???
10 lead layers (Kolgashield) for the combined mechanical test	$800
Two scintillator bars (Eljen) for triggering the cosmic test	$1,400
Readout PMTs for the cosmic test (2 R11102)	$800
Other material and supply	$2,000
Travel	$1,000
One quarter postdoc support (incl. 28% F.B.)	$17,910
Graduate student, one-half A.Y. stipend	$19,158/2=$9,579
Total Request (direct only)	$35,059
Total Request (including 58% UVa F&A cost)	$55,393

Table 1: Funding request for the proposed research. Note the graduate student's health insurance and tuition will come from Prof. Zheng's research funds. Some of the hardware and parts needed for the test, such as a FDM 3D-printer and t-glase for printing the light guide, will come from Prof. Zheng's other resources. For the absorber sheets needed for the combined mechanical tests, we only included costs for the lead sheets because we have not found a vendor to produce the needed tungsten sheets.

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