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Simulation and Construction of Shashlyk-Type Electromagnetic Calorimeters for the Electron-Ion Collider

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Abstract

Electromagnetic calorimeters (Ecal) constitute 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 the R&D study for building shashlyk calorimeters for the EIC. For the first year, we will carry out preliminary simulations to determine a basic design of shashlyk calorimeters for the EIC's outer electron and hadron endcap calorimeters, and to study the feasibility of using shashlyk for the barrel calorimeter. We will also conduct preparation work towards shashlyk module construction, focusing on testing the optical and mechanical properties and the radiation hardness of the scintillator and absorber components of the module. In addition to using scintillators produced with traditional methods, we will incorporate a possibly innovative method which is 3D-printed scintillators. 3D-printed scintillator parts will allow us to efficiently carry out the prototyping process and to directly produce projective-shape modules, the latter may be important for the EIC. The proposed project will work for both eRHIC and MEIC.

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. Once we have determined the design and have obtained the basic data on properties of the scintillator and the absorber components, we will proceed to prototype construction at the next funding cycle, focusing on the two endcap calorimeters and the possibility of producing projective-shape modules.

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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 particle identification, 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 WLS fiber ends that are opposite to the readout are typically coated with a reflective layer using aluminum sputtering to improve the light yield and the longitudinal uniformity. 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.

1.2 Shashlyk EM Calorimeters for EIC

Figures 1 and 2 show respectively 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.

For ePHENIX, we will need:

- A central/barrel Ecal, needs to be compact radially with a moderate $12\%/\sqrt{E}$ resolution. Because ePHENIX will be built upon the upgrade sPHENIX, the central Ecal needs to be projective with fine lateral segmentation [6]. Currently the top choice is the tungsten sci-fi design with 2.5cm×2.5cm segmentation and occupies about 25 cm of radial space including 13 cm of the detector itself and 12 cm of readouts [9]. However, the radial space constraint is ultimately determined by the coil size, which extends beyond 25 cm. A shashlyk design is therefore possible from the space point of view, provided it can be projective. A careful study is needed to develop the shashlyk design and compare to the existing tungsten sci-fi design in both cost and performance.
- A forward (electron direction) Ecal that requires a $(1-2)\%/\sqrt{E}$ resolution for the small angle region and a $(5-6)\%/\sqrt{E}$ for the large angle region. The different requirement is due to the angle dependence of tracking. For small angles, the precision in tracking will be poor and one

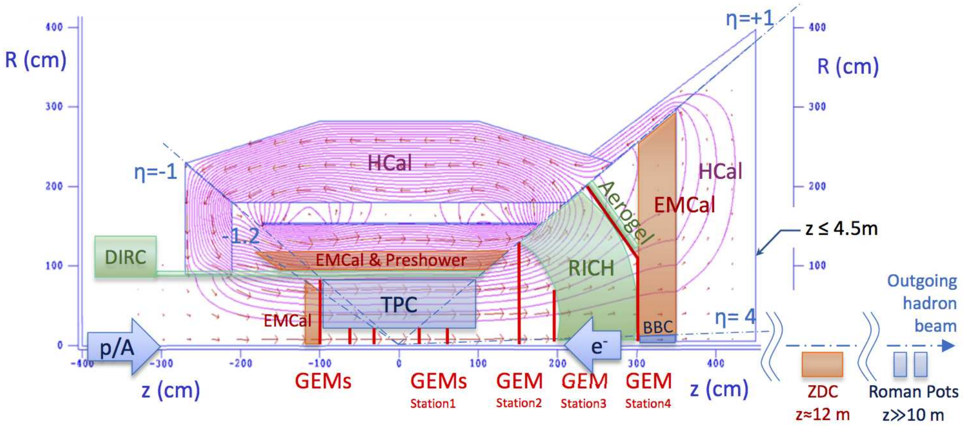

Figure 1: Detector package for ePHENIX [6]. The three EM calorimeters are shown in red.

needs Ecal to provide both PID and the absolute energy information of the particle. For large angles, the precision in tracking is significantly better and the Ecal is needed only for PID, for which a moderate energy resolution will be sufficient. For the inner Ecal the choice would be crystal (lead-tungstate) [10]. But for the outer Ecal a shashlyk design may be the best choice.

- A backward (hadron direction) Ecal that requires a moderate $(12-15)\%/\sqrt{E}$ resolution. A shashlyk design may be the best choice.

The electron and the hadron Ecals do not need to have projective-shape modules but a projective design will help with PID and energy resolution compare to a non-projective one.

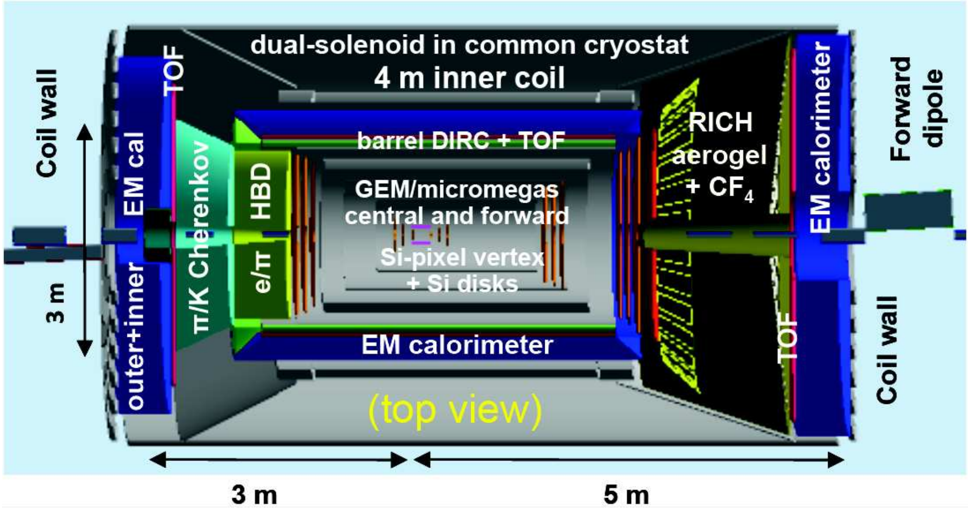

Figure 2: Detector package for MEIC's interaction point [7, 8]. The three EM calorimeters are shown in blue.

For MEIC, we will need:

- A central (barrel) Ecal, needs to be compact radially with a moderate $12\%/\sqrt{E}$ resolution. Currently a 25-cm radial space is reserved for the Ecal including readout. This constraint is directly from the location of the magnet coil and is therefore more stringent than for ePHENIX.

The tungsten sci-fi design for ePHENIX will work here, although one does not need the fine lateral segmentation. Another possible choice is to use a lead sci-fi design which is identical to the JLab Hall D/GlueX Ecal. However, a shashlyk design is not yet out of the question. A careful study is needed for the feasibility of a shashlyk design that fits into the tight radial space, and to compare cost with the other two choices.

- An electron-direction endcap Ecal. Similar to the ePHENIX case, it will consists of an inner(-radius) crystal (lead-tungstate) Ecal plus an outer(-radius) Ecal. Again 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.

Unlike sPHENIX's barrel Ecal, the MEIC barrel Ecal does not need to be projective. Overall 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 be used for both the hadron Ecal and the outer-radius electron Ecal for the EIC. It can also possibly be used for the barrel Ecal although a more careful study is needed to study its feasibility. On the other hand, no simulation has been done to establish the basic design parameters for EIC's shashlyk Ecals and to estimate their costs, and to investigate if shashlyk modules from other projects (either existing or planned) can be used. In addition, 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's hadron and outer-electron endcap Ecals, and will study the feasibility of using shashlyk for the barrel Ecal. On the construction R&D, we will start from testing the optical and mechanical properties and radiation hardness of the scintillator parts for shashlyk modules. In addition to using scintillator parts produced from traditional methods, we would like to incorporate studies of 3D-printed scintillators which is now available from some industrial R&D programs as well as from universities.

Although 3D-printed scintillators are only a component of the proposed study, it is a relatively new technique and is not well known. Therefore we will describe it here briefly and its status and potential in detail in Appendix A. 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 at 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

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[2] http://www.gaonengkedi.com/

[3] http://www.eljentechnology.com/

[4] www.stratasys.com

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 towards shashlyk module construction, we will test the light yield, transparency, and the mechanical strength of thin scintillator sheets needed for constructing shashlyk modules. If all goes well, we will place the samples in a high radiation area and then repeat the light yield test to obtain data on their radiation hardness. Related to 3D-printed scintillators, we will explore the optical clarity and light transmission of 3D-printed light guides made from commercially available optical-quality materials ("veroclear" and "t-glase"). We will also experiment with aluminum-sputtering which has been used to attach reflective mirrors to WLS fiber ends.

Within the proposed one-year funding period, we hope to achieve a conceptual design of shashlyk calorimeters for the EIC. In terms of hardware work, we hope to show that the scintillator parts from both traditional methods and from 3D-printing have the mechanical strength and the light yield required for shashlyk module construction. These initial tests will also provide hands-on experience on working with thin scintillators and absorber (lead) parts, which are valuable by themselves and will allow us to design the shashlyk modules and the assembling process more realistically. If 3D-printed scintillators work, it may open up the possibility of fast and in-house prototyping, and producing projective-shape shashlyk modules with ease.

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 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]

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

where

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

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 3 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

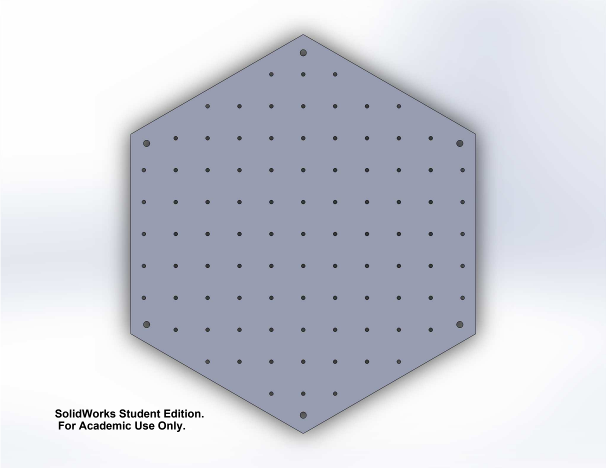

Figure 3: A typical shashlyk module layer design.

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 ±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.

While the focus of this R&D proposal is to establish the shashlyk Ecal design for the EIC and to gain experience towards shashlyk module construction, the 3D-printed scintillator study will potentially help to address the limitations of existing construction method described above. For details please see Appendix A.

3 Proposed Simulation and Test Plan

3.1 Simulation for the EIC Shashlyk ECal

We would like to conduct preliminary simulation for the EIC shashlyk Ecal(s). We will start from the hadron and the outer-electron endcap Ecals. We will determine the basic longitudinal design to reach respectively a $(10-12)\%/\sqrt{E}$ resolution for the ePHENIX hadron Ecal and a $5\%/\sqrt{E}$ resolution for the MEIC hadron Ecal and the outer-electron Ecal for both ePHENIX and MEIC. For MEIC both endcap Ecals also have a thickness constraint. Meanwhile we will study the feasibility of using shashlyk design for the barrel Ecal. As one can see from the previous section, if a 0.5-mm Pb/1.5-mm scintillator layer design can provide a $(5-6)\%/\sqrt{E}$ resolution, simple scaling of the lead layers tells us that $(10-12)\%/\sqrt{E}$ resolution may be achieved using a 2.0-mm Pb/1.5-mm scintillator design and a $18X_0$ Ecal will be 17.5 cm in thickness (50 layers each). This is smaller than the 25-cm radial spatial constraint and leaves room for readouts. Of course, a thorough study is needed to fully understand the energy resolution and to estimate the cost. And for ePHENIX case, ultimately whether we can use a shashlyk design for the barrel Ecal will depend on if we can produce projective-shape modules, which in turn may depend on whether 3D-printed scintillators can be used. In addition to the longitudinal design, we need to also determine the transverse segmentation (module lateral size) which will be a determining factor in the cost estimate. However, the module lateral size can simply be about one Moliere radius since for the luminosity of EIC there is no strong constraint on the module size for suppressing the background.

3.2 Mechanical Properties of Scintillator Parts

We propose to measure the following mechanical properties of the scintillators: compressive strength, shear strength, and possibly also tensile strength, Young's modulus and shear modulus. The focus will be on the compressive 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 compressive strength on the scintillator (no safety factor included). Shear strength will be important if modules are stacked together. Scintillator samples of different shapes and sizes will be used depending on the quantity measured and the test setup. For scintillators made from traditional methods, we will carry out this measurement only for samples without public data (that is, we will focus on scintillators from Beijing HE-Kedi). For 3D-printed scintillators, we may need to iterate multiple times with Stratasys to improve the mechanical properties.

After the initial tests using simple-shaped samples, we will test the compressive strength of shashlyk scintillator sheets as shown in Fig. 3 using samples produced from both traditional methods and 3D-printing. 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.

3.3 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. Samples of scintillators and light guides produced from traditional methods will be measured as well to provide the baseline.

3.4 Preshower Transparency and Light Yield Test

A longitudinal segmentation of Ecal into a preshower and a shower portion will significantly help with particle identification. Although it is not clear if we will need preshowers for the EIC (this will be one of the simulation goals), we include tests of preshower samples here because the UVa group has already had extensive experience testing its light yield using prototypes from different vendors, and thus it is straightforward to test new samples and compare with existing data. The preshower design to be used is shown in Fig. 4, which is a 20-mm thick scintillator tile with WLS fiber embedded on the surface to guide out the light. 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 typical PMTs. We will carry out 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. This cosmic test of the 3D-printed Preshower module will provide the first characterization of detector performance using 3D-printed scintillating material.

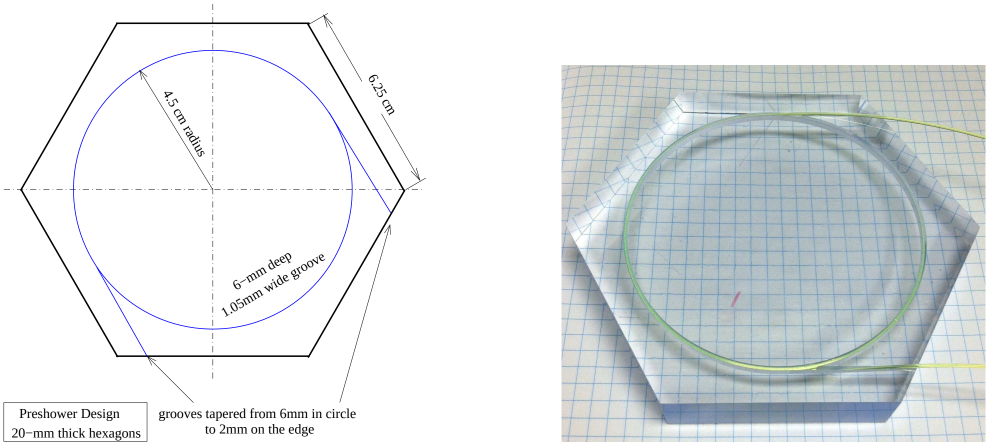

Figure 4: Proposed preshower module for testing. Left: schematic design for the preshower tile. The grooves are for embedding the WLS fibers; Right: a preshower tile produced by Beijing HE-Kedi company that we already tested.

3.5 Shashlyk Sheet Light Yield Test (“Hedgehog” Test)

To examine the light-yield 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. 5. 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. For scintillators produced with traditional methods, we plan to procure 5 each from Beijing HE-Kedi and Eljen. 3D-printed samples of the scintillator will be provided by Stratasys or made in-house at William and Mary. If the new samples 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 new sample will be too low to be useful for detector construction. Similar tests have been used by LHC collaborations to screen the scintillator parts in their shashlyk Ecal construction, and we expect this test to be part of the construction for EIC’s shashlyk Ecals as well.

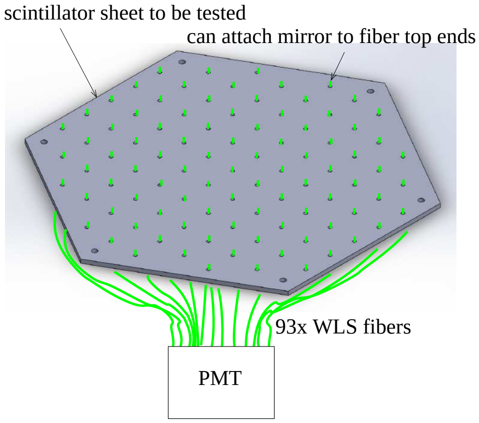

Figure 5: Hedgehog test to determine the cosmic light yield of individual shashlyk scintillator sheets.

3.6 Radiation Hardness Test

Once we have established the initial data on the mechanical properties and the light yield of the scintillator samples, we will place the samples in a high radiation area at Jefferson Lab. Then we will conduct the tests again to study the radiation hardness of the samples.

4 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.

Item	cost
5 Eljen EJ-205 shashlyk sheets	\$1,570
5 Beijing HE-Kedi shashlyk sheets	\$1,000*
10 lead layers (Kolgashield) for the combined mechanical test	\$800
Simple-shape scintillators as references (Eljen)	\$1,000*
Light guides as references (Eljen)	\$1,000*
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)	\$38,059
Total Request (including 58% UVa F&A cost)	\$60,133

Table 1: Funding request for the proposed research. Numbers with the * sign are rough estimates (without quotes). 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.

While most of the tests can be conducted by graduate students, the GEANT-4 simulation and the radiation hardness test will require the expertise at a postdoctoral level. The postdoc to be supported partially by the requested funding here is Dr. Vincent Sulkosky. Dr. Sulkosky is currently supported half-time by Prof. Zheng's DoE grant and he has extensive experience working with scintillators and detectors in general, including the preshower prototype tests mentioned in previous sections. Therefore the part-time postdoc support requested here can be integrated perfectly with Prof. Zheng's existing research funding. In the case that the test results for the proposed one-year period are promising, Dr. Sulkosky may allocate more of his time to work on the EIC shashlyk calorimeter R&D at the next funding cycle. The graduate student involved will be Jie Liu, a 5th-year graduate student. Jie Liu will be supervised by Prof. Zheng and Dr. Sulkosky. The proposed work will be carried out in the Physics department at the University of Virginia.

A The Method and the Potential of 3D-Printing

Because 3D printing is a relatively new technology and is not well known, we will describe in this section how 3D printing works in detail, and how it may be applied to shashlyk module construction.

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 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

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

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.

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