Proposal for a Comprehensive Study of 3D-Printed Scintillators and Light Guides

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Abstract

We propose here a comprehensive study of 3D-printed scintillators and light guides. Properties to be determined include their transparency, light yield (for scintillators), and mechanical properties and strength. The 3D-printed scintillator components can be widely used in EIC detectors from constructing shashlyk-type calorimeter modules to general-purpose scintillating detectors. 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. 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. The 3D-printing method will potentially open up a new venue for sampling-type calorimeter construction. If the test shows that the 3D-printed scintillator sheets meet the physical requirements of shashlyk calorimeter construction, we will proceed to prototyping shashlyk modules for the EIC's forward or backward calorimeter at the next funding cycle, with goals to simplify the construction procedure, to lower the overall cost, to produce projective-shape modules with ease, and to study the limitation on the energy resolution.

1 Overview of Calorimeter Technology in the Collider Era and the Proposed Study

Calorimeters provide measurement of particles' energy in modern 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 $12\%/\sqrt{E}$, while the resolution that can be achieved for Hcal is limited due to the nature of hadronic showers, and is typically in the order of $100\%/\sqrt{E}$. Other constraints on collider calorimetry include compactness, radiation hardness up to 10^6 rad, and sometimes a projective shape may be desired.

More specifically, for the EIC [1] – the next-generation collider in medium-energy nuclear physics focusing on detailed studies of the gluon sea of the nucleon, the QCD vacuum, and tests of the electroweak standard model – three calorimeters will be needed: A central Ecal, which needs to be very

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compact with a moderate $12\%/\sqrt{E}$ resolution; 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; and a backward (hadron direction) Ecal that requires a moderate $(12-15)\%/\sqrt{E}$ resolution. Among these three, none is required to have projective-shape modules. However if the EIC is to be built at RHIC then the central Ecal would be the currently planned barrel Ecal for sPHENIX [2], which must have a projective shape.

Many different technology have been developed for calorimetry in the past century. The commonly used options include lead-glass, NaI and CsI. The energy resolution varies from a moderate $5\%/\sqrt{E}$ for lead-glass 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 sampling detectors such as SPACAL or Shashlyk-type modules. They provide a reasonable energy resolution ($5\%/\sqrt{E}$ is achievable) with a moderate cost. In the following we will focus on shashlyk technology where the active component is made of scintillators.

Shashlyk-type calorimeter modules [3, 4, 5] 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 the complexity of the module parts and the module assembly process; the difficulty to make the modules in a projective shape due to the fixed size and shape of module parts produced from traditional methods (injection-molding for the scintillator layers and stamping for the absorber layers); 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.]

3D-printing is a new and fast-evolving technology. Currently, the material that can be 3D-printed include thermoplastics, thermoplastics mixed with metal powder, acrylic, ceramic, and pure metals such as aluminum, steel, and tungsten. The resolution of the 3D printing is typically 0.1 mm and can reach as low as 0.016 mm using higher-end industrial printers. Besides the high resolution, the main advantage of 3D printing is 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. 3D printing can be done simultaneously with a number of material, potentially producing end products in a single step and avoiding the assembling procedure compared to if different parts are produced separately.

We propose here a first attempt towards constructing shashlyk modules using 3D-printed scintillators. In the one-year period for which the funding is requested here, we will focus on a comprehensive study of the 3D-printed scintillator parts. The scintillators will be provided by the R&D department of Stratasys, a leading 3D-printing company [2]. 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 and will compare the results to existing modules made from three different types of scintillators produced from traditional methods. 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.

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

[2] www.stratasys.com

method. This will open up the possibility of 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.

2 Shashlyk-Type Calorimetry

As mentioned earlier, shashlyk calorimetry [3] 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. The energy resolution is determined to the first order by

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

where

$$N_s = \frac{E}{E_c}\frac{X_0}{\Delta t} \tag{2}$$

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. For shashlyk modules of $20X_0$ length constructed from 0.5-mm thick lead sheets, the simple calculation of Eqs.(1-2) gives an energy resolution of $\approx 3.5\%/\sqrt{E}$. The thickness of the scintillator would affect energy resolution to the second order, and detailed simulation for modules made of 0.5-mm lead and 1.5-mm scintillator sheets gives $5\%/\sqrt{E}$.

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 1 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

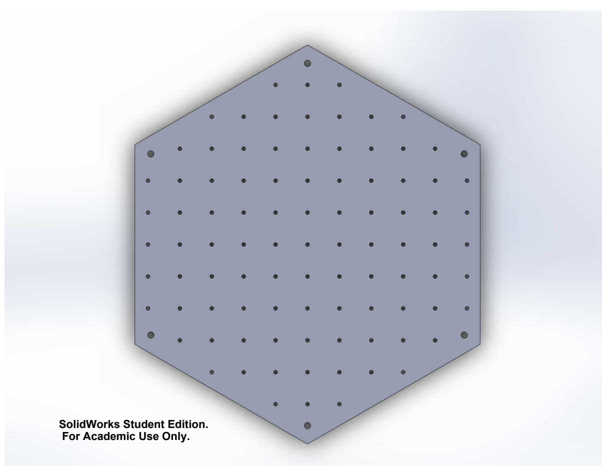

Figure 1: A typical shashlyk module layer design.

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. 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 finer adjustment 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 [6] 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 assemly 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 $\delta E/E$ that limits the overall resolution to $(3-5)\%/\sqrt{E}$ for EMcal. If the physics program requires better energy resolution, crystal Ecals must be used which costs one order of magnitude higher than the Shashlyk.

3 3D Printing Technology

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 3D printing is 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 (independ of the metal powder used) used mostly for medical radiation shielding. For parts that requires transparency, acrylic-based material or the so-called "t-glase" material exist at a higher cost. 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 pure metal or metal alloy, where metal powder is laid down to form 3D structures. The powder can be sintered before printing using an electron or a laser beam. Or it can be sintered using a "binder-jet" technique, where a binder material is printed on the metal powder, then loose powder is removed and the binder-powder mixture is sintered to form metal parts. The mechanical strength of the printed metal is nearly identical to that of the pure metal.

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 specificiations.

4 The Method and Potentials of 3D-Printing Scintillators

We propose here a comprehensive study of 3D-printed scintillators. 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. [7]), and we will be working with Stratasys (a leading company in 3D printing) to develope 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.

If the 3D-printed scintillator performance is comparable to those produced with traditional methods, we will proceed to constructing shashlyk prototype modules in the following years. We would also 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 printing the scintillator sheets, and absorber and reflective layers 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 multipling 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 hybrid 3D-printer that combines polyjet and metal-sintering. The metal-printing component can print both the absorber sheets and the reflective layers (possibly a single layer of aluminum). The layers can be aligned using alignment pins as described above. While projects that involving hybrid printers are beyond the proposed funding period, this is an attractive goal and we will keep it in mind when carrying out the proposed R&D.

5 Proposed Test Plan

5.1 Mechanical Properties

We propose to measure the following mechanical properties of both the Stratasys scintillator and the t-glase (a commercially available optical-quality 3D printing materal): 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). Samples of different shapes and sizes will be used depending on the quantity measured and the test setup. Samples of the scintillator will be provided by Stratasys, while we will 3D-print our own t-glase samples. 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. It is expected that we will need to iterate multiple times with Stratasys to improve the mechanical properties of the scintillator.

5.2 Transparency and Light Yield Test Using Rectangular Blocks

We will test the transparency of both t-glase 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.

5.3 Preshower Transparency and Light Yield Test

A common design for the Preshower module is a thick scintillator tile with WLS fiber embedded to guide out the light. We choose a specific preshower design (see Fig. 2) for which the the UVa group has already had extensive experience. We have already tested preshower prototypes of this design made of different scintillating base materials including polyvinyltoluene(PVT) (Eljen), polysterene (IHEP), and phenylethene (Chinese Kedi). All three prototypes gave ≈ 80 photoelectrons when two 1-mm diamter Kuraray Y11 fibers were used (each embedded in the groove 2.5 turns) and the fiber output was 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.

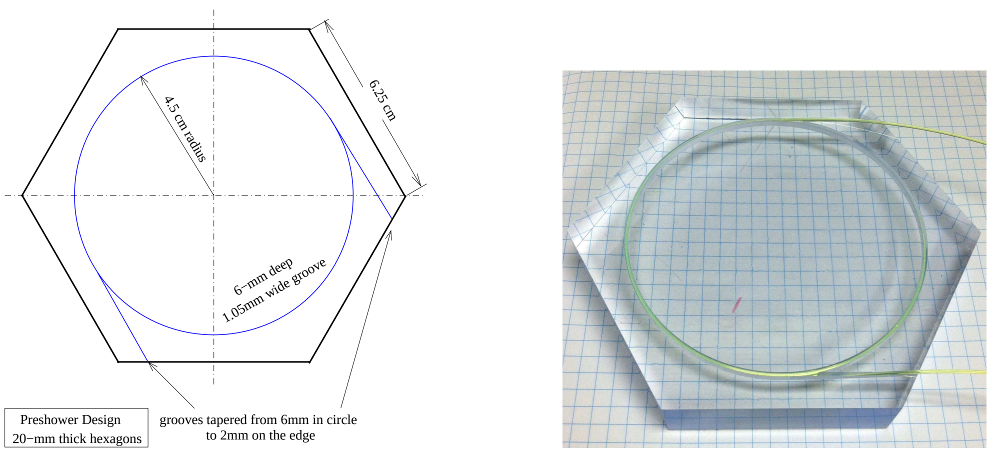

Figure 2: Proposed preshower module for testing. Left: schematic design for the preshower tile. The grooves are for embedding the WLS fibers; Right: a preshower tile produced by the Chinese Kedi company that we already tested.

5.4 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. 3. 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 EJ-200 sheets (Eljen) as the reference. 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.

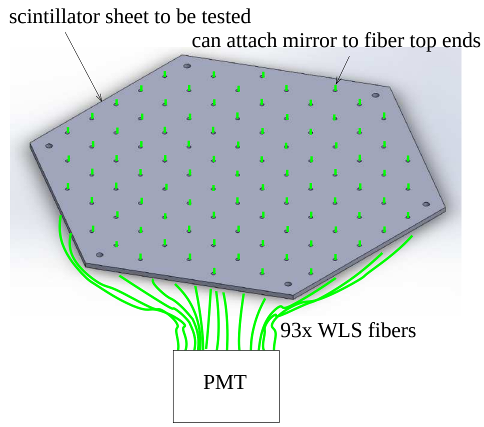

Figure 3: Hedgehog test to determine the cosmic light yield of individual shashlyk scintillator sheets.

6 Possible Use of the Shashlyk Calorimeter with 3D-Printed Scintillators for EIC

As described in the overview section, the detector package for the EIC will have three Ecals: the central compact Ecal with a $12\%/\sqrt{E}$ resolution, the electron-direction Ecal with a $(1-2)\%/\sqrt{E}$ or $5\%/\sqrt{E}$ resolution depending on the final tracking precision, and the hadron-direction ecal with a $(12-15)\%/\sqrt{E})$ resolution. The shashlyk calorimeter can be used for both the $5\%/\sqrt{E}$ electron-direction Ecal and the $(12-15)\%/\sqrt{E}$ hadron-direction Ecal straightforwardly. In addition, there is a possibility that the 3D-printing method can improve the energy resolution of shashlyk modules to better than $5\%/\sqrt{E}$, and the the flexibility of the method may also be proven useful for the central Ecal.

7 Budget Request

Table 1 shows the proposed budget. We request here funds for one half-time postdoc, material cost necessary for the proposed tests, and for traveling to BNL for result reporting. The multiple Shashlyk sheets from Eljen will serve as the references and will be used for both testing the mechanical strength and the light yield hedgehog test.

[The postdoc to be supported by the requested funding ... ...

]

Item	cost
Two scintillator bars (Eljen) for triggering the cosmic test	$1,400
Five EJ-200 shashlyk sheets (Eljen) as references	$1,570
Readout PMTs for the cosmic test (2 R11102)	$800
Other material and supply	$2,000
Travel	$1,000
Half-time postdoc support (incl. 28% F.B.)	$38,400
Total Request (direct only)	$45,170
Total Request (including 58% UVa F&A cost)	$71,369

Table 1: Funding request for the proposed research.

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