**Title of the Project:** Feasibility of Organic Glass Scintillators for EIC ZDC

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**Contact Person:** Gabriella Carini (carini@bnl.gov) and Elke Aschenauer, (elke@bnl.gov), BNL

**List of all proponents and institutions:**

Aleksey Bolotnikov, Erik Muller, James Kierstead, Ivan Kotov, Milind Diwan, Sean Stoll, and Craig Woody, BNL

## Introduction

The Zero Degree Calorimeter (ZDC) serves critical roles in a number of important physics topics at EIC. Its major goal is to detect primary neutrons and low-energy photons with high efficiency, which relies on the calorimeter's ability to accurately distinguish hadron and electromagnetic showers. The ZDC should provide excellent energy and position resolutions, large acceptance, and sufficient radiation hardness [1]. The calorimeter consists of alternating layers of tungsten absorbers and layers of Si and scintillation detectors. Several scintillation materials are being considered for the electromagnetic and hadronic sections of the ZDC: inorganic scintillator bars ($PbWO_4$, LYSO, GSO, LSO, SciGlas), plastics and quartz fibers to maximize both the energy and position resolution required for the neutron identification.   Special attention was paid to the novel SciGlas scintillators [2] that generate dual light signals (scintillation and Cherenkov light) used to improve the energy resolution of the hadron calorimetry. However, neither of these scintillators offers the pulse shape discrimination (PSD) capability that should be particularly helpful for directly distinguishing electromagnetic and hadron showers. Here, we propose to investigate the feasibility of novel PSD-capable OGS plastic blends for the EIC ZDC.

In many organic and some inorganic scintillators, the fraction of the light in the slow fluorescence component depends on the type of exiting radiation (rate of energy loss dE/dx). Using PSD this dependence can be measured and correlated with different ionizing particles. Several materials are particularly favorable for PSD because of the larger differences in intensities and durations of the slow components generated by different types of radiation, including neutrons and gamma rays. In contrast, conventional plastic scintillators—popular detector materials for nuclear physics experiments due to their low cost, fast decay, and scalability—are generally unsuitable for pulse shape discrimination.

Recently, a team at Sandia National Laboratories [3] developed a novel polymer-blend Organic Glass Scintillator (OGS) which is the next step in the development of plastic scintillators that can provide effective neutron detection, high light yield, and PSD capability, and compares to or in some energy ranges provides better performance than trans-stilbene organic crystals. Its emission spectrum matches most of the available photodetectors. The decay time of the fast component is less than 2 ns. However, the relatively long decay time of the second (slow) component, ~150 ns, could be challenging to satisfy time-response requirements.

To achieve efficient PSD scintillation signals should be measured (integrated) within a 100-200 ns window which, in the case of large-area scintillators, could be affected by pileups. To address this potential problem, we propose to make a high-granularity detector plane. For example, an array of small tiles or fibers can be inserted in several locations of the calorimeter. Specific dimensions of the scintillation cubes and the type of photodetectors will be optimized based on the studies proposed here.

We note that idea of using PSD-capable CsI(Tl) crystals was previously considered for distinguishing the hardon and electromagnetic showers in the Belle II calorimeter [4]. From this perspective, the polymer-blend OGS offers a similar capability to the EIC ZDC: adding layers of OGS plastic tiles or fibers to the proposed ZDC design will enhance its performance in distinguishing neutron and photon-generated cascades.

The goal of this proposal is to evaluate the characteristics of OGS plastics and assess the feasibility of using them in the EIC Zero-Degree Calorimeter for distinguishing the neutron and photon cascades. Samples of different shapes and compositions will be produced and characterized. We will evaluate the samples with the PMTs, SiPMs, and other photosensors.

A variety of proton accelerators are available at BNL. The BNL Tandem Van de Graaff accelerator is available as a user facility and can produce high-intensity, wide and focused beams of protons, neutrons, and other particles with energies up to 28 MeV. An alternative is to use the NASA Space Radiation Laboratory (NSRL) with protons, ranging in energy from 50 MeV to 2500 MeV. To demonstrate that the PSD approach works at high energies we propose to carry out a beam test at the GeV beam in Fermilab. The decision on using one or more test beams will be made later in the project subject to funding.

## Novel polymer-blend PSD-capable Organic Glass Scintillators (OGS)

Plastic scintillators are popular in high-energy calorimetry because of their low-cost, fast response, high efficiency for fast neutrons, and scalability. However, plastic scintillators suffer from low density (~1 g/cm$^3$) and low atomic number ($Z_{eff}$ ~ 4.5) giving them poor gamma-ray stopping efficiency and large nuclear interaction length. As a result, plastics are often used in combination with other absorbers in the sampling calorimeters. Conventional plastic scintillators cannot efficiently discriminate between different types of ionizing radiation—an essential tool for many nuclear physics experiments.

Polymer-bland OGS is a low-cost, high-light yield, fast scintillation material recently developed at SNL [3] to replace conventional plastics used for the detection of fast neutrons and gamma rays in different nuclear physics experiments. Among its advantages are a high light output, ~20,000 ph/MeV, an emission spectrum with the first and the second maxima at 431 and 463 nm matching the spectral sensitivity of the available photodetectors, and fast decays: 2 and 150 ns, respectively [5]. Table 1. summarizes the main characteristics of OGM scintillators produced by RMD, Inc.

| Scintillator | Emission (nm) | Light Yield (Ph/MeV) | Decay (ns) | PSD (FOM) |
|---|---|---|---|---|
| Stilbene | 390 | 17,000 | 2.4-4.5 | > 3 |
| EJ-200 | 425 | 10,000 | 2.1 | NO |
| EJ-232 | 370 | 8400 | 1.6 | NO |
| EJ-232Q-1% | 370 | 1700 | 0.7 | NO |
| EJ-276 | 425 | 8,600 | 13 | ~ 2 |
| Organic Glass Scintillators | 430 | 20,000 | 1.46 | > 3 |

The OGS is based on an amorphous host matrix that contains wavelength shifters and other enhancing additives. Its scintillation light output and pulse-shape discrimination properties and isotropic optical and mechanical properties are similar to plastic scintillators allowing for melt-casting into molds and complex shapes such as bars, cylinders, cubes, and pixelated arrays. Organic glass can also be blended with optical-grade plastics to create plastic scintillators with PSD. Polymer-blend OGS compositions are more suitable for the scale-up. Blends have higher oxidative and radiation stability required for scintillator materials and commercial plastic manufacturing, including melt-casting of high aspect ratio bars and injection-molding of thin tiles and sheets.

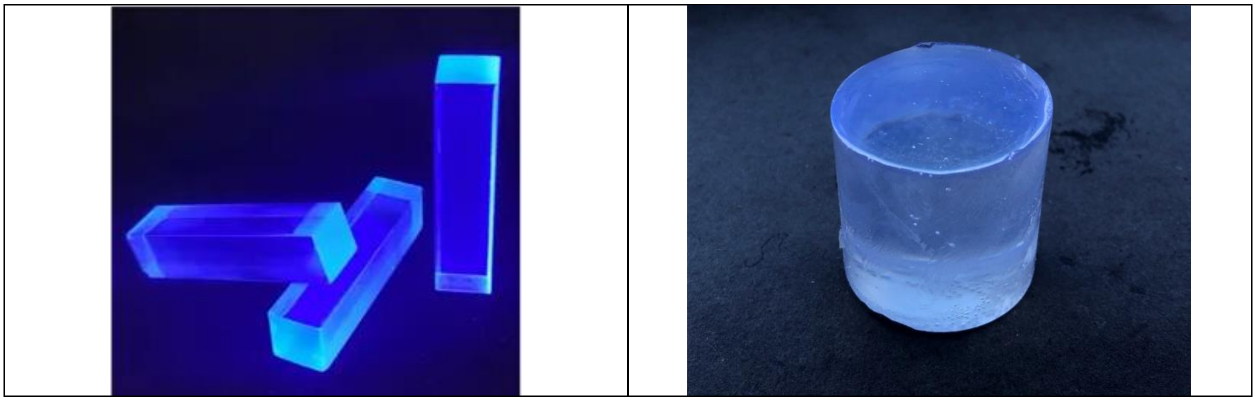

Fig. 1. Example of 20-cm long OGS blend plastic bars (left) and 38ID mm x38 mm RMD OGS plastic cylinder (right) (blueshiftoptics.com/org-glass-scintillator and rmdinc.com/product-category/organic-glass-scintillator)

An important feature of OGS is the pulse discrimination capability. In many organic and some inorganic scintillators, the fraction of the light in the slow fluorescence component depends on the type of exiting radiation or rate of energy loss dE/dx. This dependence can be used to differentiate between different ionizing particles. and good PSD. For example, in the case of gamma and neutron events separation, the typical PSD Figure of Merit (FOM) was found to be ~3.0 with a 1.0 MeV cut of energy. The high light yields of OGS allow for lower energy thresholds in PSD measurements. So far, there is no data on Cherenkov light generated in OGS plastics which is expected to be similar to the Cherenkov light measured in quartz since refractive indices are nearly the same for both materials. We note that strong Cherenkov light signals generated by 2.7 MeV electrons were recently measured from PMMA plates [6]. We propose to investigate this.  Fig. 2. shows normalized light pulse shapes (left) and PSD (right) recorded with PuBe sources (right) obtained for fast neutrons and γ-rays recorded with an OGS detector [5]

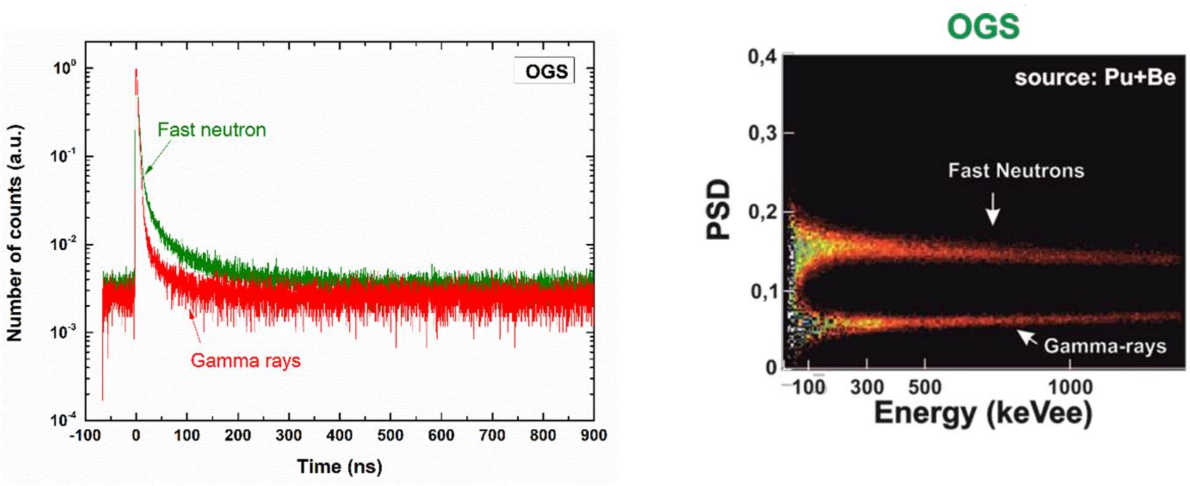

Fig. 2. Normalized light pulse shapes obtained for fast neutrons and γ-rays recorded with OGS detector (left), PSD versus energy recorded with PuBe sources (right) [7].

The effects of long-term irradiation effects on the light output and particle-discriminating capabilities of OGS have been recently tested. No light output reduction was observed after gamma-ray irradiation up to 50 kRad and 17% reduction was determined up to 100 kRad. No changes in PSD capability were observed. Damage due to neutrons was not observed up to 2.5x $10^{11}$ n/cm$^2$. For experiments at the EIC, moderate radiation hardness up to ~3 krad/year (30 Gy/year) electromagnetic and $10^{10}$ n/cm$^2$ hadronic are expected at the top luminosity [8]. Current results reported in the literature suggest that OGS should be able to meet this specification [9].

Two vendors: RMD, Inc, and Blueshift Optics, LLC can supply OGS plastics scintillators.

## Proposed Research Plan

Our goal is to investigate the properties of the novel OGS plastic blend scintillators and evaluate the feasibility of using them as active materials in the EIC ZDC. The mechanical and physical properties of this material are similar to the conventional plastic scintillators commonly used in high-energy calorimetry, but their performance as scintillators has several advantageous features:

- Higher than conventional plastic scintillators’ light output (20,000 ph/MeV)
- Fast response (3 and 150 ns decay times of the fast and slow components)
- Pulse shape discrimination (PSD) capability for particle identification (demonstrated for fast neutrons and gammas)
- Better radiation hardness (no degradation was observed up to 50 kRad gamma-ray exposure)
- Using commercial plastic manufacturing technologies including injection molding of thin tiles and sheets
- Available from two vendors (RMD, Inc. and Blueshift Optics, LLC)

We will verify the performance parameter of OGS available in the literature. We will test OGS samples of different shapes acquired from two vendors using different formulations and fabricated by different methods. We will investigate PSD and evaluate its applicability for particle identification. We will evaluate the responses of OGS scintillators of different shapes (blocks, bars, rods, these tiles) using different photodetectors (PMTs, SiPMs). We also investigate if the OGS blend plastic can be used as a Cherenkov detector. If the Cherenkov light exists, can it be practically detected from the total scintillation flash? After addressing these topics, we will be able to propose possible techniques and detector configurations to be implemented in EIC ZDC to enhance its capability to distinguish the cascades generated by neutrons and photons.

**Task 1: Acquiring OGS plastic scintillators with different dimensions (blocks, bars, and tiles)**

**Task 2: ORG sample characterization**

***Subtask 2.1: Optical transmittance*** will be measured in the 300 - 600 nm range, along several directions to check the homogeneity of the samples, and the longitudinal measurements for checking the absorption length. Provide feedback to the vendors with potential formulation refining.

***Subtask 2.2: Light yield*** will be measured with radioactive sources and cosmic rays using different types of photodetectors, including PMTs and SiPMs. The sources will be moved along the scintillator for the response uniformity test. In addition, we will investigate wrapping materials for OGS scintillators and optical coupling. A spectrophotometer will be used to measure absorption and light output along the length of the scintillator bars.

***Subtask 2.3: Decay times*** of the scintillation light will be measured for different samples using a pulsed laser fluorescence spectrometer and time-correlated single photon counting.

***Subtask 2.4: PSD*** will be measured with radioactive sources in the lab using the standard radioactive sources. We will use electrons, protons, and alpha particles. We will investigate the optimal integration time windows for high-energy neutrons and gammas.

***Subtask 2.5: Cherenkov and scintillation*** light will be measured with radioactive sources and using particle beams at BNL.

***Subtask 2.6: Radiation hardness*** to gammas will be measured with the BNL at $^{60}$Co facility using 300 Ci $^{60}$Cosource.

**Task 3: Measurements at NSRL**

***Subtask 3.1: Light yield and PSD*** will be measured at NSRL using 100 and 1000 MeV protons.

***Subtask 3.2: Radiation hardness*** to protons will be measured at BNL NSRL: The OGS samples were irradiated with integrated doses ranging from 500 Gy to 1000 Gy. To test for possible hadron radiation damage, several samples will be irradiated by 100 MeV protons at NSRL with a fluence of $1x10^{15}$ p/cm$^2$ and $2x10^{15}$ p/cm$^2$.

**Task 4: Prototype testing**

***Subtask 4.1: A prototype*** will be designed and integrated after completing the characterizations and testing in Tasks 1 and 2. To address a relatively slow OGS response, 100-200 ns, we propose to design a thin, <0.5 cm, high-granularity detector plane made up of small-area tiles, bars, or fibers. Specific dimensions of the tiles and the type of photodetectors will be optimized based on the studies proposed here.

***Subtask 4.2: Testing the prototype*** at the Fermilab test beam. This task will depend on the results obtained during FY2024.

***Table 2:*** *Estimated timeline for OGS plastics testing.*

| Item | Task | FY2024 | | | | FY2025 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Characterizations at the lab | OGS samples procurement | 🟩 | | | | | | | |
| | Optical characterization | | 🟩 | 🟩 | | | | | |
| | Light Yields | | 🟩 | 🟩 | | | | | |
| | Decay times | | | 🟩 | 🟩 | | | | |
| | PSD | | | 🟩 | 🟩 | | | | |
| | Cherenkov Light | | | 🟩 | 🟩 | | | | |
| | Radiation hardness, Co-60 | | | | 🟩 | | | | |
| Characterizations using protons at NSRL | Light Yields | | | | | 🟩 | 🟩 | | |
| | Decay times | | | | | 🟩 | 🟩 | | |
| | PSD | | | | | 🟩 | 🟩 | | |
| | Cherenkov Light | | | | | 🟩 | 🟩 | | |
| | Radiation damage | | | | | 🟩 | 🟩 | | |
| Testing array prototype | Array integration | | | | | | 🟩 | 🟩 | 🟩 |
| | Testing at the Fermilab test beam | | | | | | 🟩 | 🟩 | 🟩 |
| | | | | | | | | | |

**Funding Request, Budget, and Milestones**

The funding request is shown in Table 2. We request support for laboratory scientists, technicians, and students to carry out the characterization tasks. We request support for purchasing the OGS samples from RMD, Inc., developing the techniques and software, and for carrying out the testbench measurements. We will design and construct a detector prototype including a suitable readout. We plan to carry out measurements at NSRL beams. We plan to test the detector prototype at the Fermilab test beam.

| FY2024 Nominal (baseline) budget | | | | |
|---|---|---|---|---|
| Task 1 | Task 2 | Task 3 | Task 4 | Total |

| | | | | |
|---|---|---|---|---|
| $250k | $150K | | | $300 |
| | | | | |
| FY2025 | | | | |
| | | $100K | $150k | $250k |

**Reduced Funding Scenarios**

In the case of a 20 % reduction in the granted budget, we can still carry out most of the tasks described above, however at greater risk on each individual step and less available contingency. With a smaller number of samples, we continue with testing and characterizations, however, we might have to reduce the overall scope. In the −20 % scenario, the proposed NSRL time and the number of samples will be reduced. travel would be canceled as well. In the case of a 40 % reduction in the granted budget, the scope of the whole project would have to be reduced to testing fewer samples, we skip the measurements at NSRL but keep the beam tests at Fermilab. The beam test campaign would be reduced accordingly. In the case of a 40% cut, priority would be given to ***Task 1*** and ***Task 2*** without or reduced ***Subtask 2.6***. Details are summarized in the attached budget sheets.

**Plan for FY2026**

The research plan for potential follow-up funding periods entirely depends on the results obtained from this initial proposal.

**Diversity, Equity, and Inclusion**

This proposal has two female scientists as contact persons. Funding this proposal will give us the opportunity to engage minority students and postdocs in cutting-edge R&D collaborating with the world's experts on radiation detectors. Proposed R&D projects are suitable for engaging undergraduate students through summer programs like SULI, and research for undergraduates during the academic year. We are committed to recruiting underrepresented minorities to participate in our activities. Our IO team is composed of scientists with diverse backgrounds and expertise. We have research scientists, students, engineers, and technical staff, who have expertise in hardware, simulation, electronics, and data analysis.

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