Title of the Project: CSGlass for hadron calorimetry at the EIC
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Abstract:

A particular focus at high-energy colliding beam accelerators over the next decade is on improving the energy resolution for hadronic particles like protons or pions. The hadron calorimeter concept with dual readout is one of the most promising paths towards high-resolution hadron calorimetry. Because of the large volume of these detectors key features of the scintillator include small interaction length and low cost. Slow and >500 nm scintillators with UV transparency, as well as radiation resistance are key for particle identification in the momentum range from a few hundred MeV to ~50 GeV where other techniques cannot be used or have markedly poorer performance. Based on the EIC Yellow Report effort, high-resolution hadron calorimetry in the hadron endcap and the barrel demand inexpensive high-quality scintillators for hadronic jets measurements. Auxiliary detectors like the EIC Zero-Degree Calorimeter (ZDC) may also benefit from radiation-hard, inexpensive scintillator material.

CSGlass is optimized for the dual readout approach, where one compares the signals produced by Cherenkov and Scintillation light in the same detector. This approach has been a promising method to achieve better performance for hadron calorimeters. CSGlass is derived from SciGlass and expected to be similarly resistant to EM and hadron irradiation up to 100 Gy and 10^{15} n/cm^2, the highest doses tested so far. The CSGlass interaction length is comparable to crystals and should allow for small tower size. The anticipated space for the homogeneous calorimeter configuration could be similar to a binary system and may provide better resolution. The areas of needed R&D for CSGlass include the demonstration of CSGlass with sufficient UV transparency for Cherenkov light collection, clear separation of Cherenkov and Scintillation light of sufficient intensity (slow scintillation, > 500 nm beneficial), low cost, and characterization of CSGlass in the lab and with test beam R&D prototypes. The most critical items are the formulation optimization and production of CSGlass test samples. The approximate timeline for completing the CSGlass R&D is around three years assuming R&D funds are available. CSGlass could be ready for future detector upgrades.

Introduction

Calorimeters are ubiquitous in modern nuclear physics experiments, providing particle identification as well as measurements of energy and momentum of electromagnetic (EM) particles and hadrons. Achieving high-quality science at nuclear physics facilities requires the measurement of particle energy with excellent calorimeter energy resolution. Particles that produce EM showers can be detected with high precision. However, there is a need to improve the energy resolution of hadron calorimetry. As an example, the desired resolution in the EIC forward (hadron) endcap is 35%/sqrtE, which exceeds the anticipated resolution with presently available technologies as documented in the EIC Yellow Report.

One of the most promising methods to achieve better performance for hadronic calorimeters is dual readout [1]. By comparing the signals produced by Scintillation light (S) and Cherenkov light (C) in the same detector, the EM shower fraction, whose fluctuations are the main culprit for problems encountered with hadronic calorimetry, can be determined for individual events. The validity of this principle has been demonstrated with the DREAM fiber calorimeter. However, two factors impacting hadronic resolution remain: sampling fluctuations and fluctuations in the Cherenkov light yield. Homogeneous materials such as crystals and glasses in which both S and C light are generated in the same optical volume have the potential to eliminate these two issues.

Studies of crystals such as BGO and $PbWO_4$ outfitted with optical filters to extract sufficiently pure Cherenkov signals have shown that the use of optical filters results in unacceptable losses of Cherenkov photons and the crystal absorption characteristics result in strong attenuation of the Cherenkov signals [2]. Crystals are also prone to radiation damage, time consuming to manufacture, and relatively expensive. In comparison, radiation-hard glasses can be tuned for favorable C/S signal ratio, eliminating the need for optical filters, and thus offer great potential for both precision hadron calorimetry and significant cost reductions if competitive performance parameters can be achieved. Furthermore, glass compositions can be optimized for neutron detection, which may further improve hadron performance. ***The primary objective of this proposal is to characterize and prototype novel C/S glass for the EIC.*** Major development objectives for C/S glass for hadronic calorimeters with dual readout include:

- Good UV transmittance with UV cutoff < 350 nm
- Scintillation light output that is not too bright, slow, and at around 500-600 nm for clear C/S discrimination
- Large block dimensions, free of macro defects
- Low cost, less than ~\$2/cm^3, compared to, e.g., $PbWO_4$ (\$15-25/cm^3)

These requirements are driven by the need to improve hadron calorimeter resolution for high-precision measurements of hadrons and hadron jets in nuclear and particle physics, e.g., at the Electron-Ion Collider (EIC) [3-5] and future high-energy lepton colliders. Due to the large volume of hadronic calorimeters, the glass material should be dense to reduce volume, UV transparent to effectively collect the Cherenkov light, and allow a clear discrimination of Cherenkov and scintillation light. High-density C/S glass has the potential to meet these requirements.

The primary objectives of this R&D activity are to demonstrate that novel CSGlass has sufficient Scintillation and Cherenkov response to be used for duel readout at EIC and that signals can be separated into Scintillation and Cherenkov components that are measured simultaneously. Samples of different shapes (e.g., rectangular, fibers) and composition will be analysed and their detection properties characterized. To determine the contribution of Cherenkov light, the ratio of Cherenkov vs. Scintillation light will be measured. Specific attention will be paid to evaluating the samples with the SiPMs that are envisioned for the EIC readout method of choice. A longer-term objective is to prepare and carry out a beam test campaign to evaluate C/SGlass at the GeV scale.

Background on CSGlass

Small batches of CSGlass were produced by Scintilex and an initial evaluation of CSGlass with R&D prototypes was performed on the test bench. The ratio of Scintillation and Cherenkov signals was initially determined without the use of optical filters[1]. A cosmic ray setup was constructed and triggered by a pair of plastic scintillators in coincidence. The Cherenkov and scintillation light pulses generated by the cosmic rays were measured simultaneously by two PMTs. The anode signals were directly digitized using a charge sensitive analog-to-digital converter (fADC250). The fADC250 is a VME64x 16-channel direct conversion ADC module conforming to the VITA-41 switch serial standard (VXS). The contribution of Cherenkov vs. Scintillation light or a non-optimized glass formulation is illustrated in Fig. 5. The Cherenkov contribution is highest up to energies of about 1 GeV and stays relatively constant afterwards. The time of arrival of Scintillation vs. Cherenkov light was also analyzed using a simple analysis of the pulse rise time and a representative waveform. The measurements suggests that Scintillation and Cherenkov light can be separated by time of arrival and analysis of the recorded waveform. A more detailed analysis of the scintillation and Cherenkov waveforms could be enabled with AI algorithms to determine pulse types and the overall ratio and will be part of the proposed R&D.

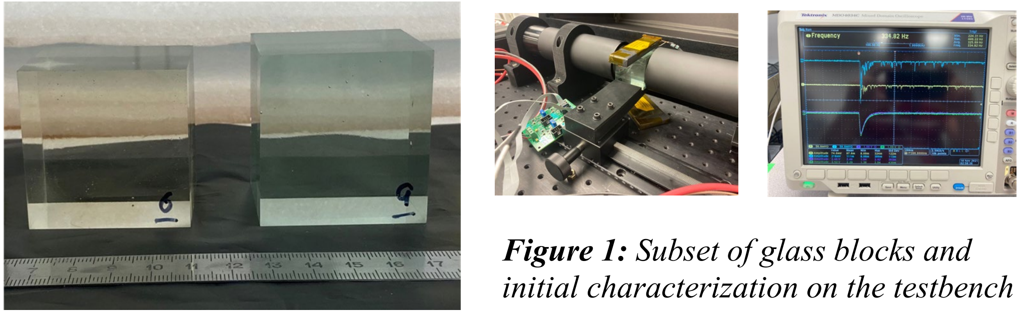

Figure 1: *Subset of glass blocks and initial characterization on the testbench*

The radiation hardness to electromagnetic probes was measured with 160 keV X-Rays and ^{60}Co sources. The glass samples were irradiated with integrated doses ranging from 500 Gy to 1000 Gy at about 18 Gy/min. Our results thus far do not indicate any

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[1] For validation a measurement was also performed with optical filters the UV pass filter UG5 to select Cherenkov and the low-pass band filter GG435 with cut-off at 400 nm to select scintillation light.

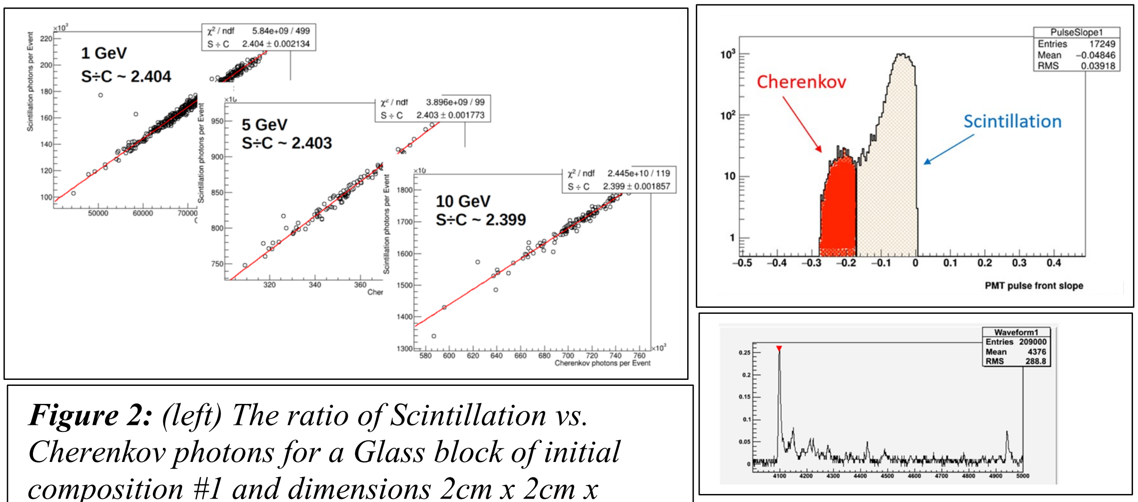

Figure 2: *(left) The ratio of Scintillation vs. Cherenkov photons for a Glass block of initial composition #1 and dimensions 2cm x 2cm x 20cm; (right) measured time of arrival of Scintillation vs. Cherenkov light.*

radiation damage to the glass and no impact of different photon irradiation rates. To test for possible hadron radiation damage, we irradiated two 2cm x 2 cm glass samples with a fluence of 4.3x10^{15} neq/cm^2 (2x10^{15} p/cm^2) and 2.3x10^{15} neq/cm^2 (1x10^{15} p/cm^2), respectively. No obvious discoloration, which may indicate radiation damage, was observed. 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 in the EM calorimeters at the top luminosity. Current results suggest that CSGlass meets these specifications.

Proposed Research Program

Our long-term goal is to align our R&D with the EIC critical decision process and to have reached a level for CSglass to be considered as active material for EIC EM calorimeters.

Our initial results with the first Glass glass blocks suggest that it is possible to separate Cherenkov and Cherenkov+Scintillation light. A machine learning algorithm would enable a more detailed study and its development is part of the proposed R&D. New glass formulations, e.g., with emission shifted to higher wavelength that cuts out Cherenkov would allow for more detailed measurements. A suitable readout system for CSglass blocks that is commensurate with the EIC will need to be evaluated. SiPMs are envisioned as the method of choice at the EIC, but the response of large-surface CSglass blocks has not yet been studied. Our proposed R&D will address these topics.

The estimated timeline for CSGlass is shown in Table 1. The proposed work benefits from an ongoing Phase 2 SBIR/STTR that is focused on glass fabrication and scale up production. Our program has three major tasks consisting of: 1) the fabrication of suitable glass blocks and their characterization for immediate feedback to the vendor, 2) the detailed study of the simultaneous detection of Scintillation and Cherenkov light, including the development of the necessary R&D prototypes and software algorithms, and 3) the preparation and execution of a beam test campaign with detector prototypes.

Task 1: Fabrication of glass blocks and characterization

Subtask 1.1: Optical transmittance will be measured in the 300 - 900 nm range, both along the crystal longitudinal and lateral dimension. The transverse transmission measurements will allow for checking the homogeneity of the sample, the longitudinal measurements for checking the absorption length. Based on the results, the glass formulations will be refined and iterated. A Perkin-Elmer Lambda 950 spectrophotometer equipped with an integrating sphere will be used.

Subtask 1.2: Light yield will be measured with radioactive sources (^{22}Na, ^{137}Cs, or ^{241}Am) and cosmic rays. Signals from the PMT will be digitized. For the cosmic ray tests, the data acquisition system will be triggered using a coincidence of two plastic scintillators positioned above and below the glass sample. To determine the uniformity, the sources will be moved along the scintillator length. Another goal of this task is to determine the optimal wrapping material for glass scintillator, such as Tyvek, ESR VM-2000, or EJ-140 (a TiO_2 based reflective paint), as well as the optical coupling.

Subtask 1.3: Decay time of the scintillation light and its dependence on composition can be determined with a pulsed laser fluorescence spectrometer. Additional measurements can be done with time correlated single photon counting. The measurement consists of the acquisition of the time interval between the signals produced by a start detector and the glass. The time difference of the two PMT hits reproduces the scintillation light emission probability per unit of time of the glass scintillator. The decay time will be calculated from an exponential fit function.

Task 2: Simultaneous detection of Cherenkov and Scintillation light:

The goal of this task is to design and construct the R&D prototypes based on actual detector geometries and develop algorithms and control and data analysis software. For tests of energy resolution, the calorimeters will be the combination of a matrix to hold up to 5x5 blocks, each attached to a PMT (or SiPM). The housing of the matrix will be designed to allow for testing different block and readout configurations. The samples will be stacked with optional carbon fiber dividers. This increases mechanical stability and ensures good positioning but also increases the space between blocks, which affects resolution. We will develop software algorithms for a detailed analysis of the scintillation and Cherenkov waveforms assisted by Artificial Intelligence methods to determine pulse types and the overall ratio. This portion of the work builds on our work in which we demonstrated that Machine Learning techniques can be successfully applied to perform the binary classification of unknown experimental waveform spectra[2].

Task 3: Detector Prototypes and Beam Test Campaign:

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[2] https://github.com/petrstepanov/dual-readout-tmva

Subtask 3.1: Detector prototypes. For the beam test program, detector prototypes will have to be constructed. Detector prototypes will be constructed taking into account any findings from Tasks 1 and 2, e.g., on optimal layout and/or readout. A monitoring system will be designed to be installed on either the front or back depending on the actual detector geometry. Optional cooling and radiation curing systems will be designed as well. To interpret the data, a simulation will be developed, e.g., using the GEANT4 toolkit. As part of this task, we will compare the performance of different light systems for CSGlass and determine whether the whole detection system can meet nuclear physics experiment requirements. The performance of different light readout systems: 1) PMT (the nominal choice) and 2) SiPM will be evaluated. SiPMs offer several advantages, e.g., a high gain and a medium photodetection efficiency of about 20%. The drawbacks are small surface, noise, susceptibility to radiation, in particular to neutron/proton radiation, sensitivity to temperature, a small dynamic range, and the performance degrades with the current flow. For the same amount of light, a SiPM can fire a number of pixels comparable to a PMT photoelectron count. However, a fraction of the pixels fire due to the cross talk, not improving the statistical fluctuations. While a SiPM readout is natural for fiber technologies, it has to be demonstrated for a large-surface CSGlass.

Subtask 3.2: The CSGlass produced and characterized and the calorimeter detectors constructed will be installed at a particle beam facility and commissioned. This could be done at the Jefferson Lab. Other possible facilities that have test beams suitable

Item	Task	FY23				FY24				FY25			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
CSGlass fabrication	Composition optimization	■	■										
	Characterization		■	■		■	■	■		■	■	■	
	Scale up and demo			■	■								
	Show uniformity and reproducibility				■	■	■	■	■				
	Fabrication process optimization				■	■	■	■	■				
	Performance tests with prototype					■	■	■	■	■	■		
	Process design verification to scale up								■	■	■	■	
	Large scale production study												■
Software	R&D Prototype		■	■									
	Design options				■	■	■						
	Cost/performance optimization						■	■	■	■	■		
Prototype	R&D Base version		■	■	■	■							
	Initial commissioning				■	■							
	Upgrade and commissioning						■	■	■		■	■	
Beam test	Beam test					■			■			■	

***Table 1:** Estimated timeline for CSGlass development.*

for this task include Fermilab, DESY, or CERN. intrinsic nonlinearity. In FY23 a suitable beam test plan will be developed.

Funding Request, Budget, and Milestones

The funding request is shown in Table 2. We request support for a laboratory technician or student to carry out the CSGlass characterization of Task 1. The laboratory technician or student will be stationed at CUA to provide fast feedback to the Vitreous State Laboratory on the CUA campus where the CSGlass samples will be fabricated. The laboratory technician or student will be supervised by Dr. Tanja Horn as part of her group. For Task 2 and Task 3 we request travel support for two members of the AANL team for a 6-month visit to Jefferson Lab to develop the methods and carry out the testbench measurements to separate Cherenkov and Scintillation light and to design and construct a detector prototype including suitable readout. A plan for a beam test campaign in FY24 would also be prepared. The AANL team has a long-standing track record of detector design, construction, and maintenance at Jefferson Lab including lead-glass and lead-tungstate based calorimeters. The travel support cost is estimated based on the recent travel costs of two AANL members to Jefferson Lab for the assembly of the Hall C Neutral Particle Spectrometer as well as to carry out their experiments. For the software development of Task 2 we request support for a student at William & Mary that would be supervised by Dr. Cristiano Fanelli. Dr. Fanelli is an expert in the field of AI/ML in Nuclear Physics, and EIC specifically. He is Convener of the EICUG AI Working Group and also convened the ECCE AI Working Group during the EIC Detector Proposal process.

In the case of a 20% cut, all three Tasks could still proceed. The funds would cover an ~4-month visit of two members of the AANL team. The detector prototypes for the beam test campaign would be completed during the next visit of the AANL team, assuming R&D funding

FY23 Nominal (Baseline) Budget				
	Task 1	**Task 2**	**Task 3**	**Subtotal**
AANL		31120	31120	62240
CUA	29000			29000
W&M		6000		6000
TOTAL	29000	37120	31120	**97240**
FY23 Nominal Minus 20% Budget				
	Task 1	**Task 2**	**Task 3**	**Subtotal**
AANL		21500	21500	43000
CUA	29000			29000
W&M		6000		6000
TOTAL	29000	27500	21500	**78000**
				0.80
FY23 Nominal Minus 40% Budget				
	Task 1	**Task 2**	**Task 3**	**Subtotal**
AANL		29000		29000
CUA	29000			29000
W&M				0
TOTAL	29000	29000	0	**58000**
				0.60

Table 2: *Budget scenarios*

is available, and the beam test campaign would be delayed accordingly.

In the case of a 40% cut, priority would be given to Task 1 and Task 2. We would not be able to design/construct the detector prototypes and would not be able to do the software development. A beam test campaign would be deferred.

External Funding

The expertise and use of specialized instruments required for production, characterization, and chemical analysis are made possible through collaboration with the Vitreous State Laboratory (VSL). Additional funds and facilities for glass characterization are provided by the Vitreous State Laboratory at CUA.

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