Generic Glass Scintillator R&D for EIC (EICGENR&D2023_03)

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EIC Generic Detector R&D Meeting

Online, October 31, 2023

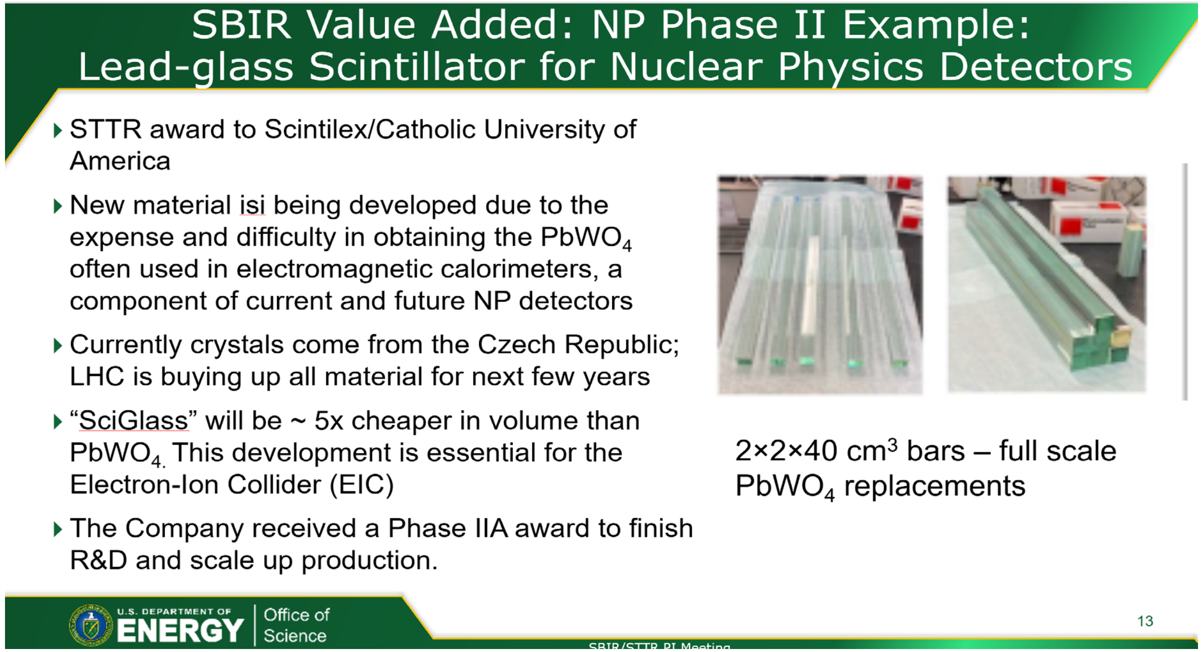
Introduction

Growing Interest in scintillating glass materials

- Increasing interest in these glasses in the global nuclear and also high-energy physics community.
  - EIC Detector R&D program - SBIR value added (Phase 2A awarded)
  - A proposal for R&D on scintillator materials for the ECFA DRD& calorimetry was submitted
  - Letters of interest to Snowmass organized by the American Physical Society Division of Particles and Fields

To capitalize on recent progress this generic R&D proposal on glass scintillator for EIC calorimeters was submitted:

- Goal: demonstrate scintillating glass with matched areal photosensor coverage and readout electronics over a large dynamic range as a viable cost-effective solution that can be used in the streaming readout DAQ.
- The results from areal photosensor coverage and readout electronics, as well as those for streaming readout, could also apply to the EPIC PWO EM calorimeter.



Slide from Dr. Timothy Hallman, Associate Director, Office of Science for Nuclear Physics, presentation at the 2023 Jefferson Lab User Group Meeting.

Report from the 2023 Detector Advisory Committee

Recommendation: continued study in the EIC Generic R&D program

Report of the

Detector Advisory Committee on

EIC Detector R&D Progress and

Proposals

Performed Remotely at Brookhaven National Laboratory

Upton, NY

August 28 and 31, 2023

- ❑ Further readout optimization is needed to understand the performance of the SciGlass
- ❑ Very interesting material that should be studied further

2.5 Proposal eRD105 – Scintillating Glass (SciGlass)

Findings:

We congratulate the SciGlass group on the successful production of large size SciGlass blocks (40cm). Light transmittance of the blocks has been studied along the length of blocks. Readout from the blocks using SiPM photosensors was successfully implemented. Beam tests using 3x3 and 5x5 arrays were performed at Jefferson Lab using electron test beam. Analysis of the data from the 3x3 array suggests transverse leakage of the shower. Results from the 5x5 array were less clear, and it is expected that further readout optimization is necessary in order to understand the performance of the SciGlass.

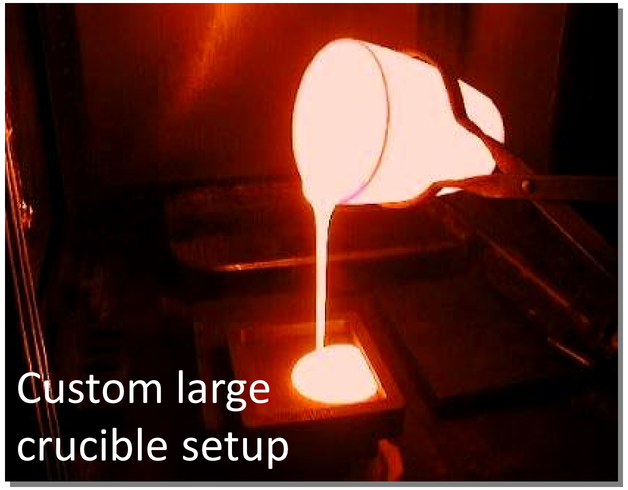
Comments:

Although no longer a baseline technology for the detector, the committee considers this is a very interesting material which should be studied further in order to understand intrinsic performance, details of light transmittance and effects of irradiation.

Recommendations:

1) The committee recommends proposing continued study in the EIC Generic R&D program.

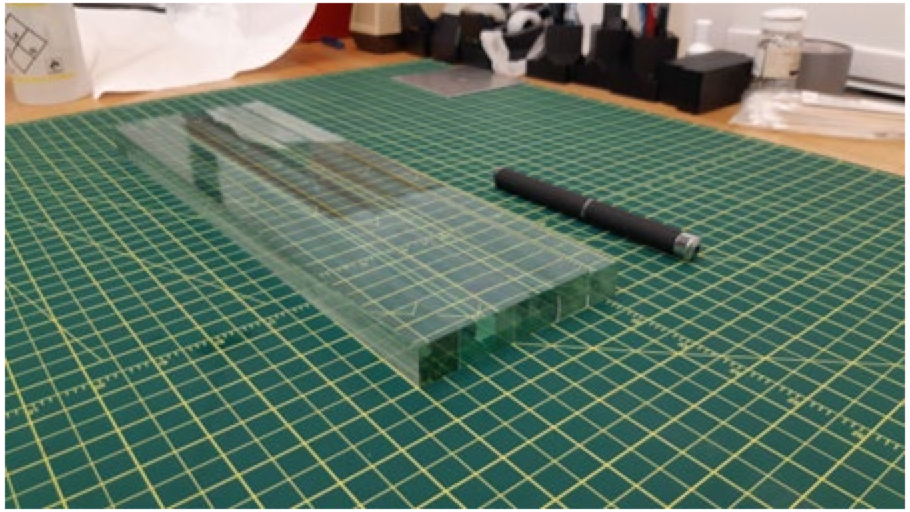
Status of Scintillating Glass R&D

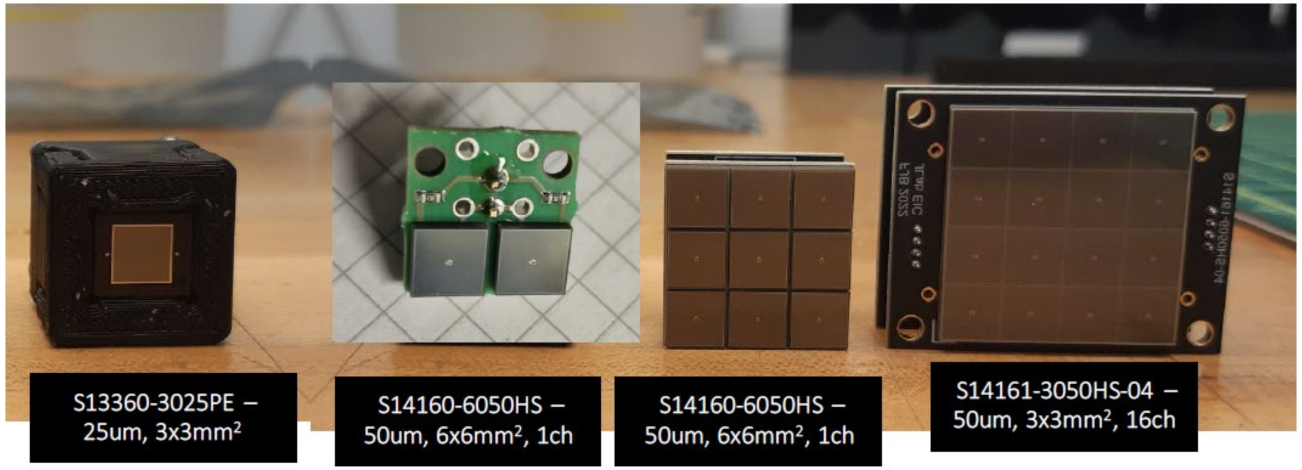


- **FY23: Scale-up to 40 cm complete**
  - ✓ Receive ~25 test samples
  - ✓ Beam test with 3x3 (5x5) prototype with 40+ cm. (CUA, AANL, JLab)
  - ✓ Develop and implement a SiPM-based readout (INFN-GE)
  - ✓ Design and test an optimized streaming RO chain (INFN-GE)
  - ✓ Sciglass blocks characterization, including Irradiation (IJCLab-Orsay, Kansas U.)

    → progress, cross-checks at Giessen U., beam test with hadrons, C/S response beam tests
  - Implement process for different geometries (CUA)

    → progress, to be completed with Phase 2A





Proposed program of EICGENR&D2023_03

- Quantify the properties of glass scintillator properties (attenuation, timing, scintillation vs. Cherenkov) and the readout electronics (areal coverage, selection, and tuning of electronics components), as well as the reflector choice through measurements on the test bench
- Demonstrate the optimized glass module over a suitable dynamic range prototype detector with beam tests.
- The proposed generic R&D plan for glass scintillators for EIC calorimeters builds on the results from the previous EIC glass scintillator research and focuses on the following topics:
  - Quantification of light attenuation
  - Quantification of timing properties
  - Quantify Cherenkov vs. Scintillation light
  - Quantify the impact of the reflector
  - Choice of electronics - verify the whole acquisition pipeline: blocks requires a large photosensor area; require linearity over a large dynamic range
  - Impact of SRO for homogeneous EM calorimeters
  - Demonstrate that the full glass module will work in different geometries:

FY24 Request	CUA	IJCLab-Orsay	INFN-GE	AANL	TOTAL
Student Support	14,000	8,000	8,000	5,000	35,000
Fringe	1,071	0	0	0	1,071
Materials	3,000	3,000	11000	3,000	20,000
Optimization of FEE boards (preamp/biasing: custom and commercial + LED or LASER system for SiPM tests) Mechanical supports, reflectors, optical components					
Travel	0	2,000	8,000	8,000	18,000
Indirect Cost	10,662	2,600	5,000	3,000	21,262
TOTAL	28,733	15,600	32,000	19,000	**95,333**

Table 1: FY24 request by institution

Funding Request, Budget, and Milestones

- **FY24**: Test bench measurements and initial validation with beam complete.
  - Receive ~25 test samples.
  - Measure transverse transmittance at selected points along the sample. (CUA, IJCLab)
  - Measure of scintillation time constant(s) and achievable time measurement. (AANL)
  - Measure light yield at selected points along the 40+cm sample. In addition, measure the light yield for different length samples, e.g., 1cm, 5cm, 20cm (CUA, INFN-GE, IJCLab).
  - Repeat the same measurement with different light reflectors/diffusers (CUA, IJCLab).
  - Measure light yield for different integration gates to investigate the impact of slow components on energy resolution. (AANL, CUA)
  - Measure separately Cherenkov and Scintillation light from the same glass sample using the signal waveforms. (CUA)
  - Measure radiation hardness of 40+cm samples (IJCLab)
  - Develop and implement a SiPM-based readout (INFN-CT)
  - Design and test an optimized streaming RO chain (INFN-GE)
  - Perform initial tests with cosmics (and beam if possible) to validate electronics and DAQ solutions for homogeneous calorimeters. (AANL, CUA)
- **FY25**: Prototype tests of full glass module (block+readout chain) complete
  - Beam test at JLab (and FNAL/CERN if high purity beams are available) with 3x3 (5x5) prototype with 40+ cm full glass module (optimized block+readout chain). (CUA, AANL, JLab, INFN-GE, INFN-CT)
    - HallD Jlab beam test logistics: installation, safety, DAQ, etc. (JLab)
    - Beam test preparation and data analysis (CUA, AANL, INFN-GE, INFN-CT)
    - Beam test preparation and SRO data analysis (INFN-GE, INFN-CT)
- **FY26**: Final test of different geometries
  - Receive a scintillating glass of different geometries for different EIC applications, e.g., tapered for barrel or tapered/hexagonal for cylindrical/hexagonal inserts
  - Validate optimized glass module parameters for different detector geometries

Item	Task	FY24			
		Q1	Q2	Q3	Q4
Glass characterization	Glass block sample procurement	■	■		
	Transmittance measurements	■	■		
	Light Scintillation Time	■	■		
	Light Yield measurement	■	■		
	Light Yield with different reflectors/diffusers	■	■		
	Effect of integration window on energy resolution	■			
	Radiation hardness tests		■	■	
	Scintillation vs. Cherenkov			■	■
SiPM readout + FEE characterization	Single SiPM RO performance assessment (baseline) with LED	■			
	2x matrix characterization with LED pulser	■			
	9x matrix characterization with LED pulser	■			
	Comparison of PMT-based readout	■			
	Repeat measurements with 1x glass block wih (1,2,9) SiPM RO and characterization of full channel	■	■		
SiPM SRO DAQ	Implementation of SRO DAQ using custom SRO-compatible digitizers	■	■		
	SRO DAQ test with cosmics		■	■	
Prototype	3x3 glass blocks prototype array		■	■	
	Deployment and test of (9+2) channels FEE and SRO DAQ			■	
	Tests of a 3x3 prototype array with cosmics or beam			■	■

Figure 4: *Estimated timeline for the proposed glass R&D project.*

Questions from the Review Committee

Can you describe the feedback loop between measurements and the glass suppliers?

>> Direct feedback is given through frequent meetings between physicists and glass suppliers

Contrary to the title, this proposal has a strong emphasis on photo-sensor arrangement and readout. Can you justify this?

>> The ultimate goal is to use the glass in a nuclear physics detector. To characterize the glass performance at scale therefore requires a fully optimized readout chain. This is particularly important for the SiPM readout envisioned for EIC that have thus far not been used extensively for homogeneous materials, and not at all for novel glass materials.

Can the differences in shape be simulated in ray tracing?

>> For for a new material, test bench and beam test campaigns - accessing different regions of the required dynamic range - to constrain simulation models and to validate results are essential. Nevertheless, it may be possible to consider ray tracing for full detector modeling. However, this will require feedback from the measurements and new material property data from the glass supplier.

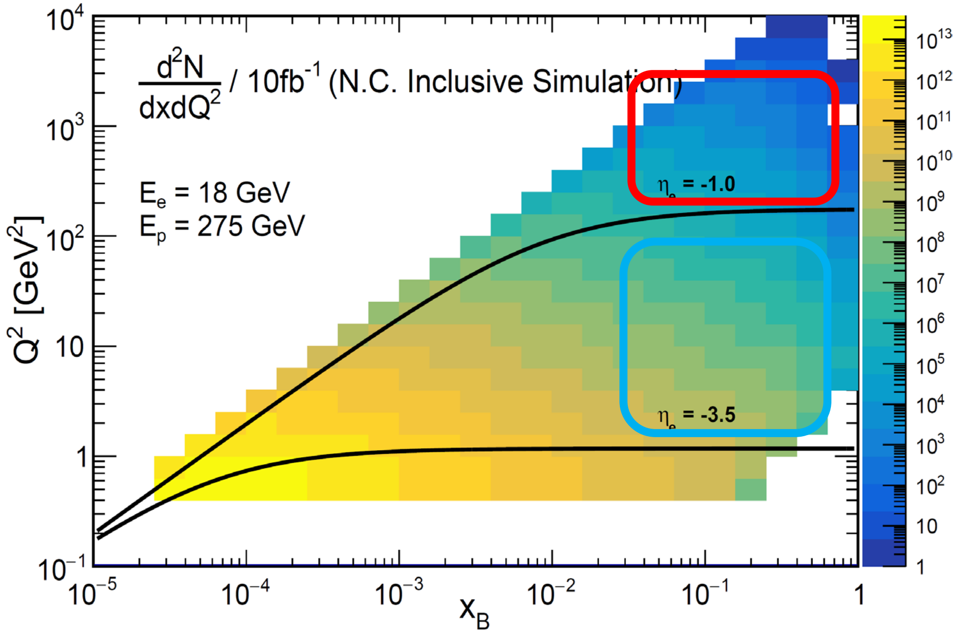
What is the size in terms of radiation length of the prototype 40cm blocks? What are the contingencies if the manufacturer cannot deliver?

>> The radiation length of one block is ~15X_0. The impact of the chosen manufacturer not delivering is a schedule contingency. However, based on our experience, the larger issue has been the scheduling of beam test campaigns, in particular because there are not many facilities available and there is a large demand.

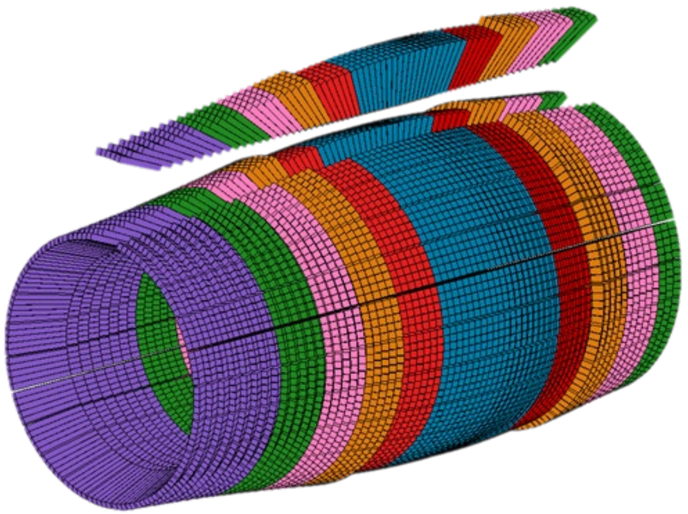
Context: Precision EM Calorimetry

Scattered electron kinematics measurement is essential at the EIC and will remain so for 2nd detector

- ❑ High precision, hermetic detection of the scattered electrons will be necessary over a broad range in η and over energy range from 0.1 to tens of GeV
  - In the very backward direction high precision is required for electron kinematics measurement
  - In backward and barrel region it is required for clean electron identification. In the barrel region, driven by high-x and high-Q^2 science drivers
- ❑ SciGlass (developed with DOE/STTR) supports excellent e/h separation due to its good energy resolution, matched to the backward region requirements while being more cost effective than crystal alternatives.



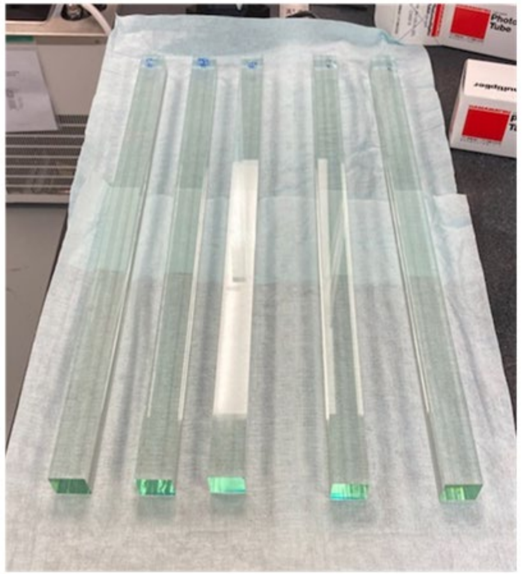
Scintillating glass could be incorporated into the second detector opening new perspectives for homogeneous EM/hadronic calorimetry where large volumes are required.

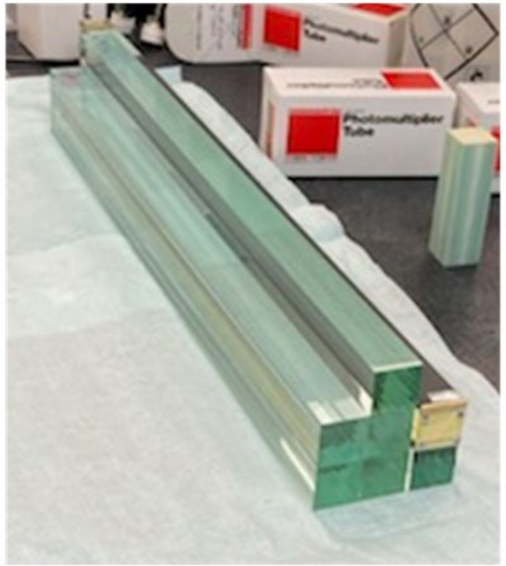


SciGlass optimization and production

SCINTILEX

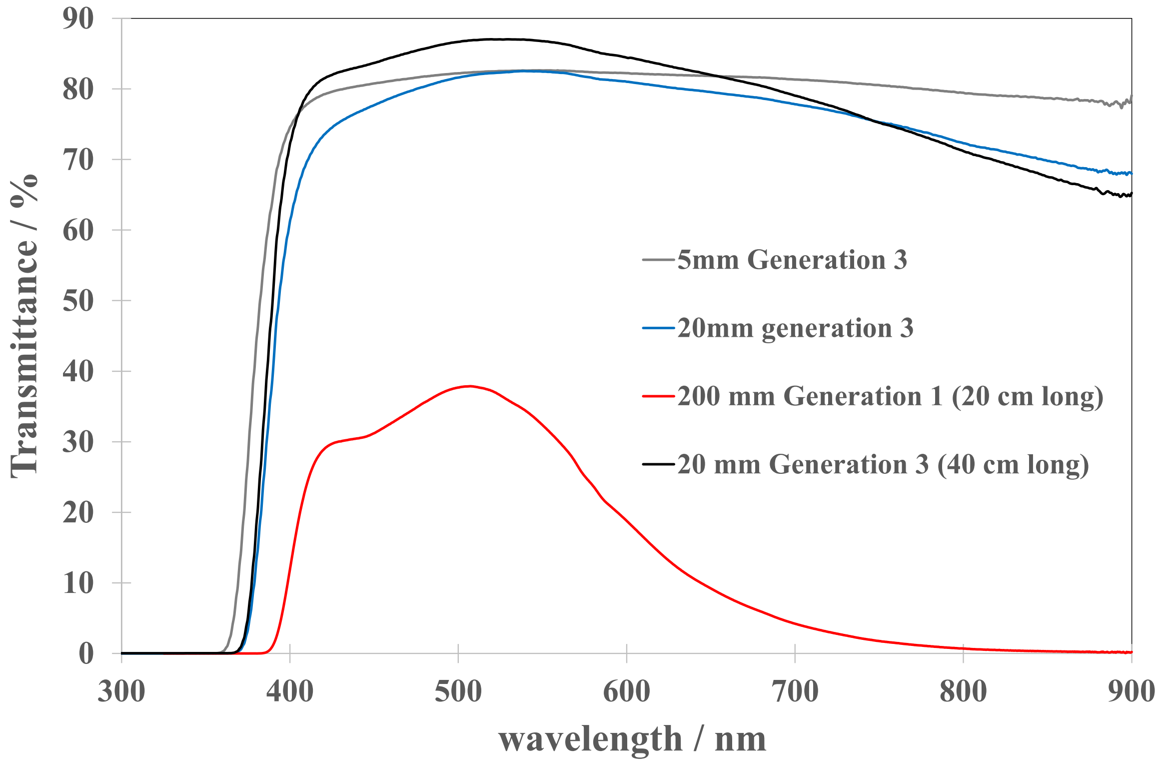
- SciGlass 20cm has been produced reliably and 40cm can now we produced routinely; We have an SBIR phase-II to start large-scale production of larger blocks (40+ cm, rectangular and projective shapes)
- A total of 42 SciGlass block test samples was produced over the last year - of these 27 SciGlass blocks were of dimensions 20mm x 20mm x 400mm and fabricated with an optimized formulation – better transmittance
- An issue in the fabrication method was identified. A new setup is being constructed that has the potential to even further improve the transmittance of long glass blocks.





SBIR/STTR DE-SC0020619

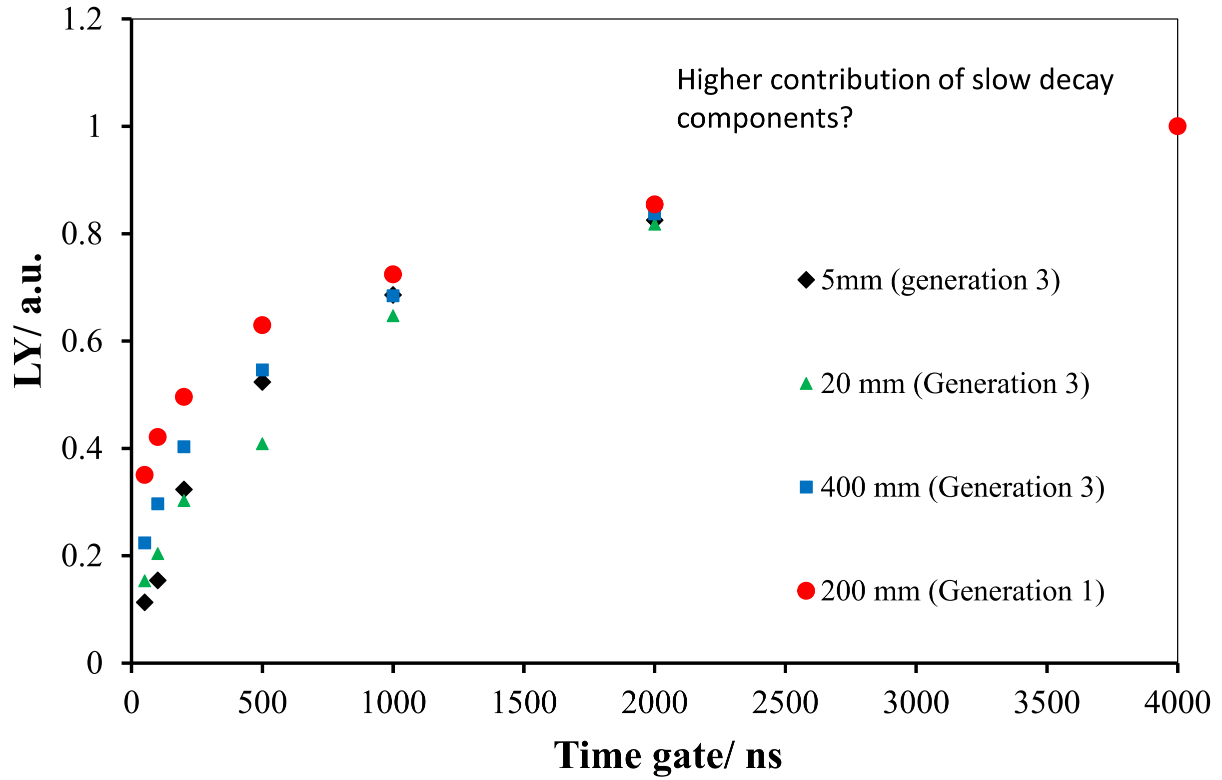
Transmittance of small/large samples



Quantification of light attenuation:

- Status: in glass characterization, over the last years a change in the shape of transmittance curves was observed when going from small to large radiation lengths. The focus has been on improving the transmittance in the region of interest
- Goals of this proposal: precisely determine light attenuation to understand the impact of glass bulk light transmittance and output. Iterate with supplier to optimize glass transmittance as needed

Light Yield of small/large samples



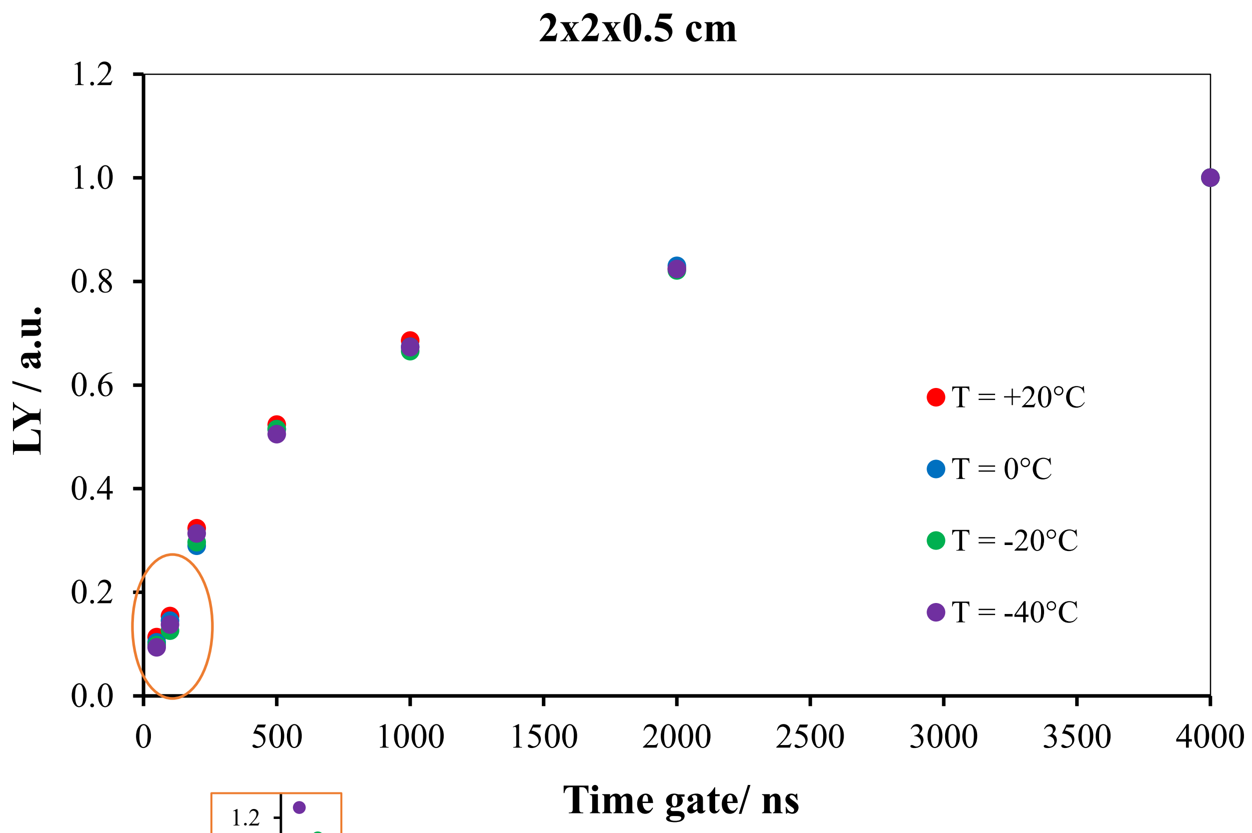
Quantification of timing properties:

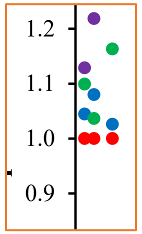
- ❑ Status: in previous measurements, a range of timing response was determined
- ❑ Goal of this proposal: investigate the contribution of slower components in detail. Determine the impact of slow components on energy resolution.

Quantify the impact of the reflector:

- ❑ Status: the present choice is based on PWO, but the best reflector for glass may be different. The choice of the reflector plays a large role in crystal/glass performance, e.g., it results in light yield variations along the length of the sample.
- ❑ Goal of this proposal: perform studies for optimal reflector selection

LY temperature dependence of small samples





Fluctuations at small integration gates (renormalized here for visual) not yet understood

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Temperature dependence:

- ❑ Status: measurements of the temperature dependence of the light yield were made. A strange behavior at small integration gates was observed
- ❑ Goal of this proposal: further investigate the temperature dependence at integration gates of few 100ns

Radiation hardness of small samples

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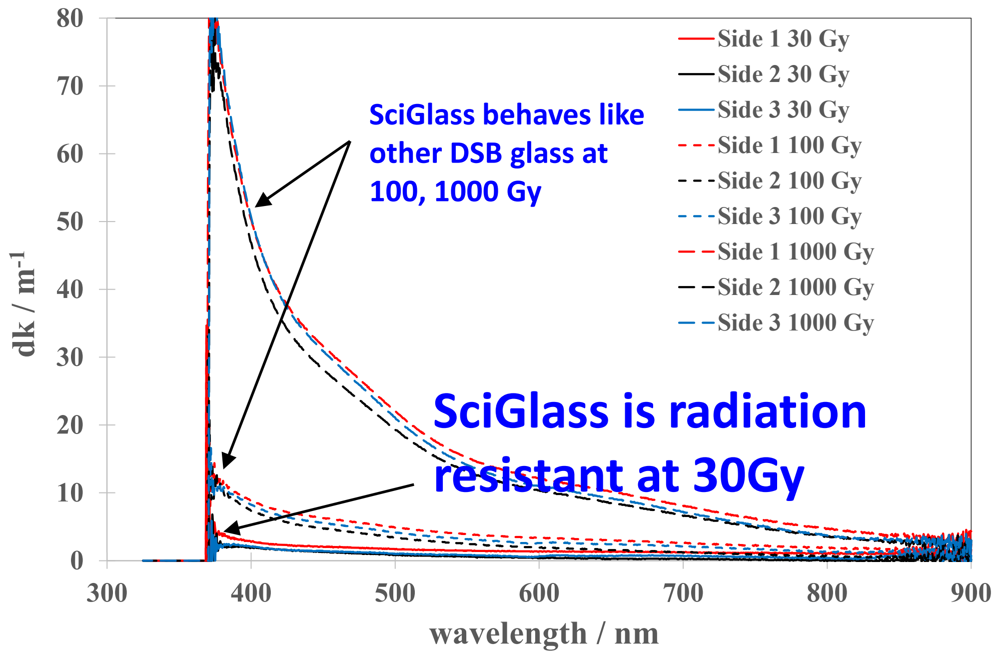
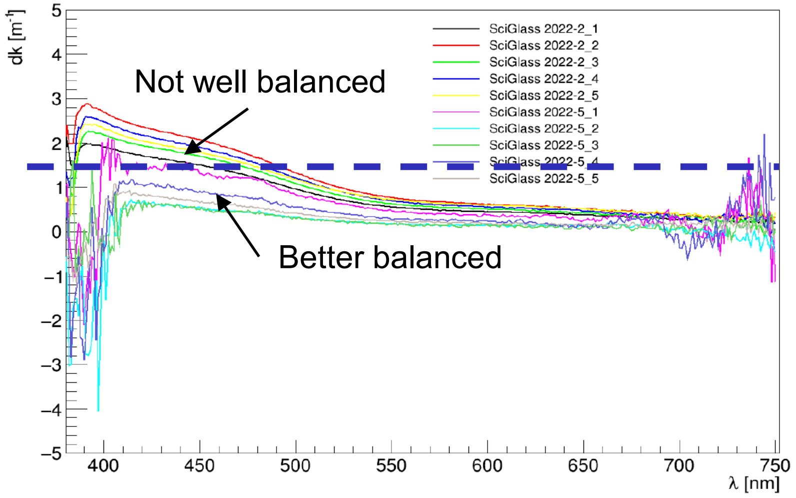
IJCLab-Orsay: Measured transmittance of 20-cm long glass samples (Gen 1 and Gen 3) before and after 30 Gy radiation at 1 Gy/min. Further tests are anticipated with 40cm blocks

Giessen U.: Irradiated a 2-cm long sample (Gen 3) at 30Gy, 100 Gy, and 1000 Gy with Co-60 source



SciGlass overall consistent with EIC specification

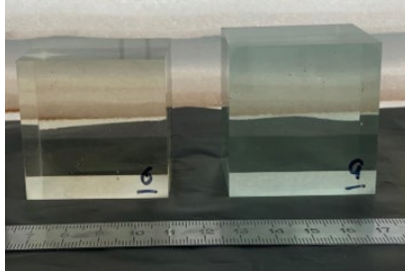


Radiation resistance:

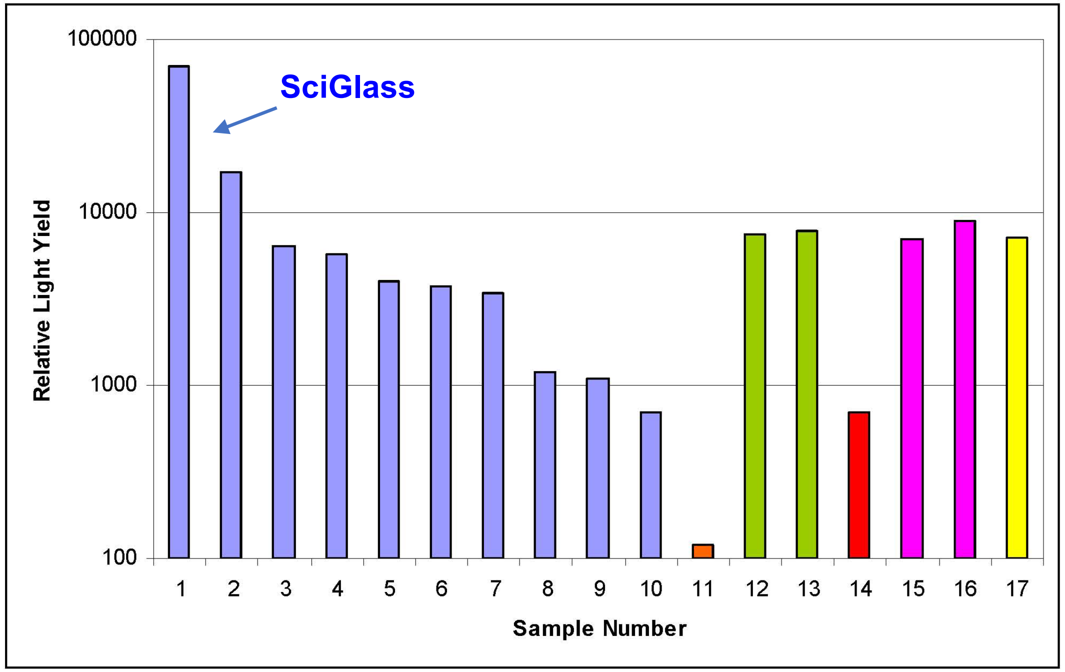
- ❑ Status: scintillating glass is radiation hard for EIC experiments (~30 Gy)
- ❑ Goal of this proposal: further investigate radiation hardness to higher dose rates

C/S Glass for Calorimetry

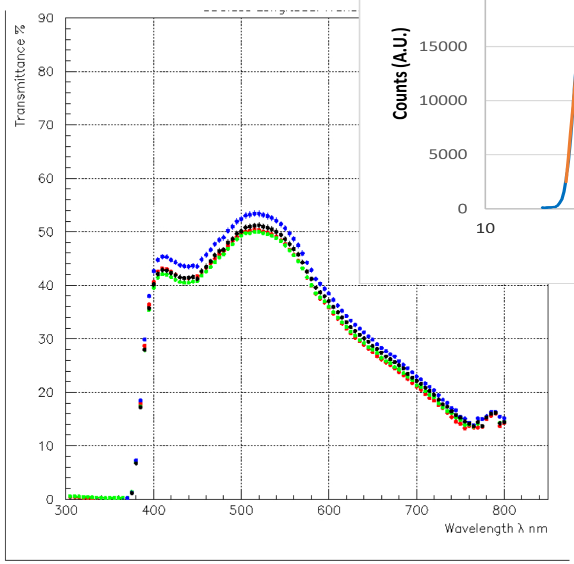
SCINTILEX **DE-SC0021459**

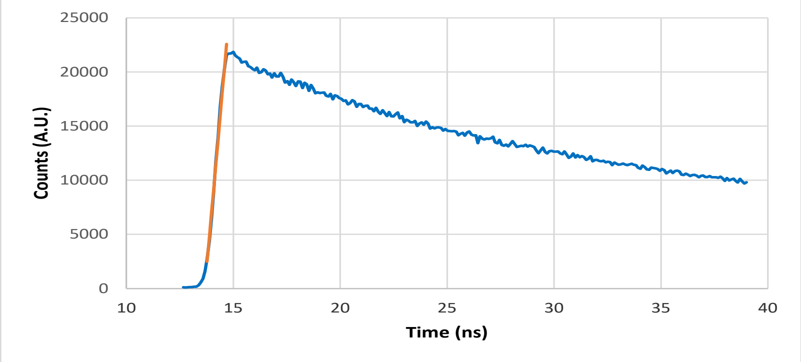


A family of scintillating glass with tuned C/S Ratio – C of interest for timing, DR, etc.



- ❑ Demonstrated a new formulation that further eliminates bubbles in the bulk, which is important for fabricating long or generally larger dimensions blocks
- ❑ So far produced rectangular shapes (20cm long) and larger lateral dimension blocks (5 x 5 x 5 cm3)





Samples made at CUA/VSL/Scintilex with different relative C/S light yield

Demonstrated control of relative C/S light yield and identified candidates for scale up

Separating Scintillation and Cherenkov Signals

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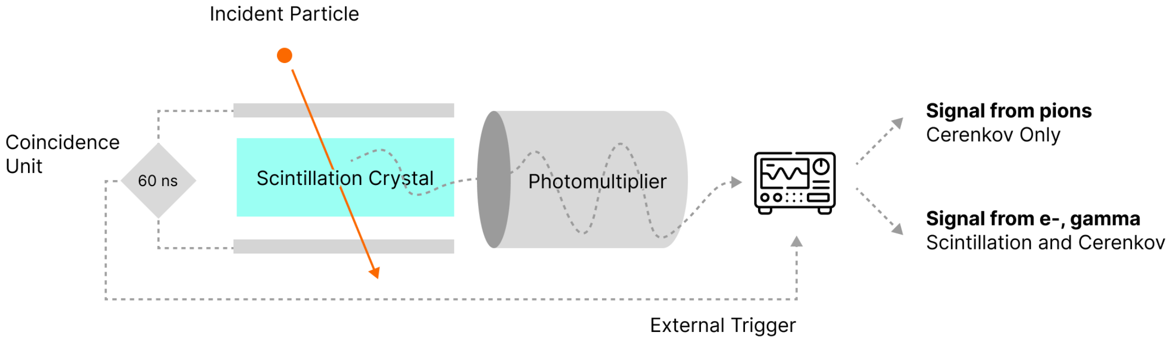
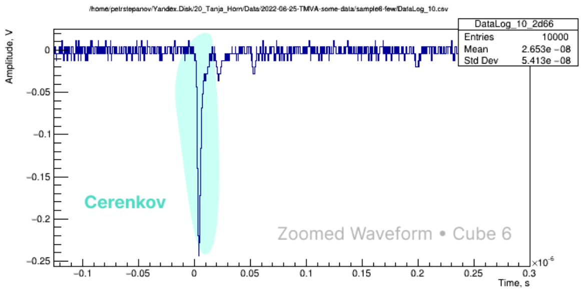
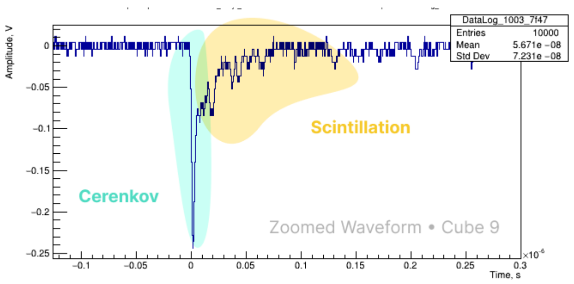
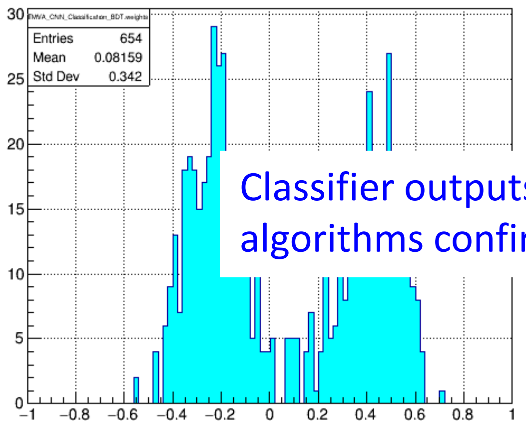




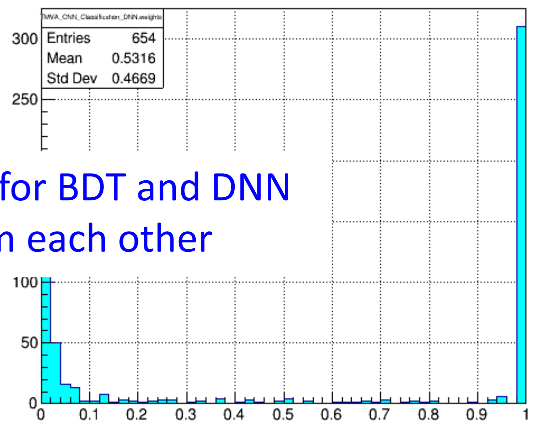


- ❑ Setup: Tektronix oscilloscope MDO4034C with external trigger using the PyVisa library. Acquire a few tens of thousand spectra for each Cher only and Cher+Scin
- ❑ Use ML techniques to perform classification of “unknown” experimental spectra – CERN ROOT TMVA framework with Binary Decision Trees (BDT) and Deep Neural Networks (DNN)

BDT Classifier Output



DNN Classifier Output



Classifier outputs for BDT and DNN algorithms confirm each other

Quantify Cherenkov vs. Scintillation light:

- ❑ Status: ML techniques can be used to separate C/S
- ❑ Goal of this proposal: further investigate the timing properties of scintillating glass, measure separately Cherenkov and Scintillation light from the same volume – beam tests planned

Prototype Beam Campaign to test performance at scale

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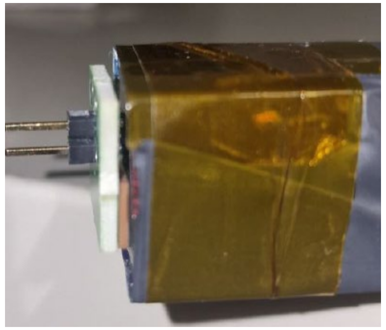
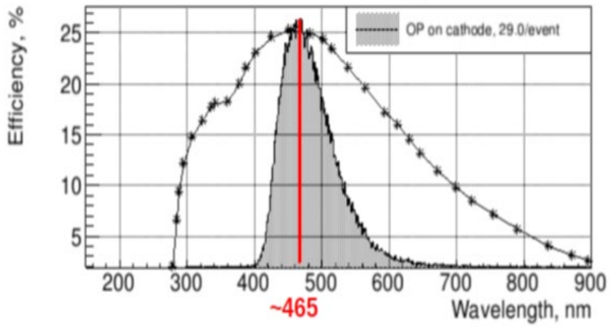
Preparations for beam tests ongoing

- Investigating alternative beam facilities for the test campaigns
  - Test at GeV scale with clean photon beam similar to the tests carried out for SciGlass – need to consider availability of facilities and any limitations on dimensions
  - Test at GeV scale with mixed electron/hadron beams – need to consider additional detectors for a clean measurement
  - Test at MeV scale with hadron beams – need to consider that one needs sufficient energy to have Cherenkov radiation
  - Few hundred MeV regime instead of GeV scale to validate fundamental glass properties, e.g., studies of the response to hadrons in general

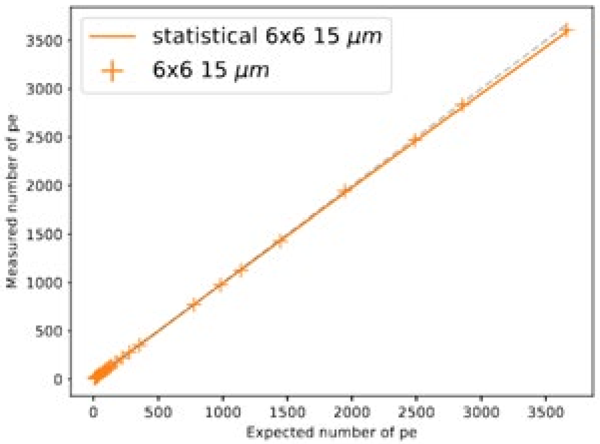


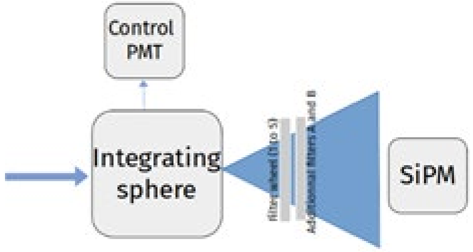


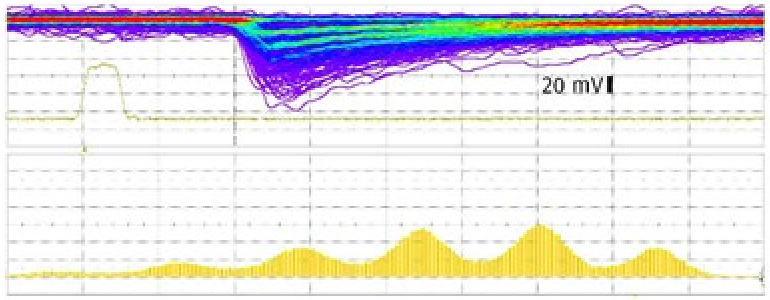
SiPM Test Bench Characterization

For coupling homogeneous material to electronics/RO and chain tests for precision calorimeters all elements of the chain have to be optimized

- **Calorimeters at EIC require photo-sensors with a very large dynamic range expanding more than 3 orders of magnitude.**
  - Both the Hamamatsu S14160-6015 and S14160-6010, high density, large array SiPMs were tested at IJCLab-Orsay and were shown to have linearity within 2% over 3 orders of magnitude and were within statistical expectations (figure on right).
    - Promising Candidates.
- **The SiPM must also detect at low energies**
  - Requires low dark current in order to trigger signals close to the single p.e. amplitude
  - These SiPM waveforms (figure on right) were measured using a low intensity LED and show a clear separation between the individual p.e. signals allowing for valid small signal identification







Preparations for the beam tests

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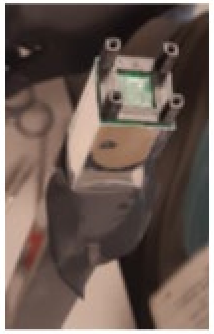
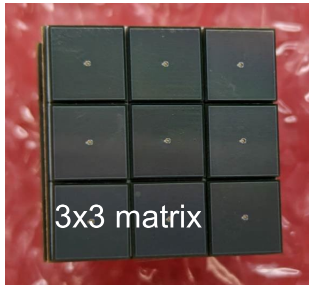
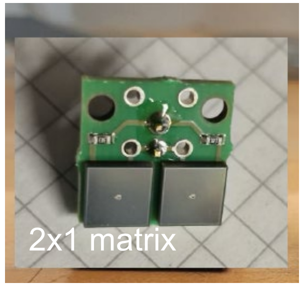
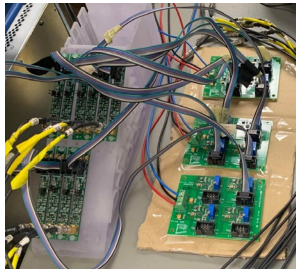
Prototype construction including the preparation of photosensors



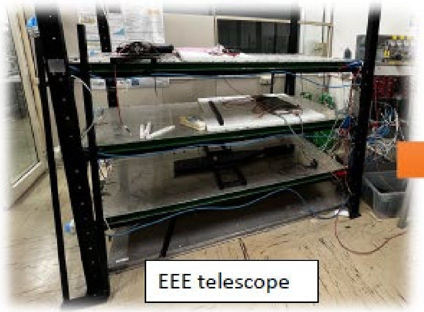


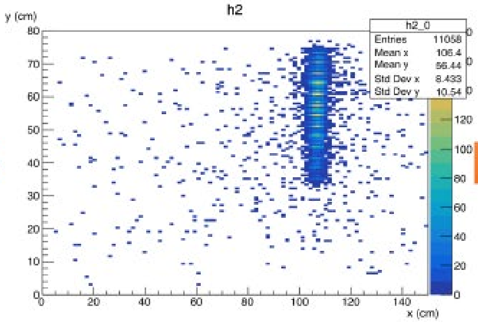


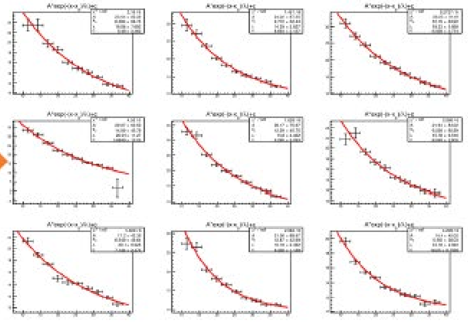


Prototype in Hall D at JLab

Measure properties of all blocks used to determine RO setup (gains, etc.)







Prototype Beam Test Campaigns at JLab

With SiPM coupled to homogeneous radiators

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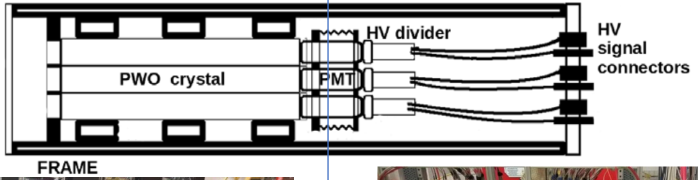
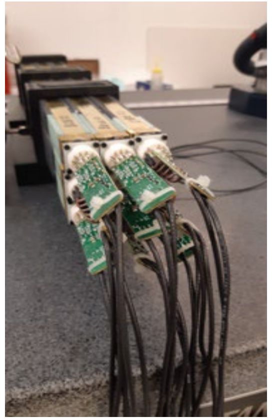
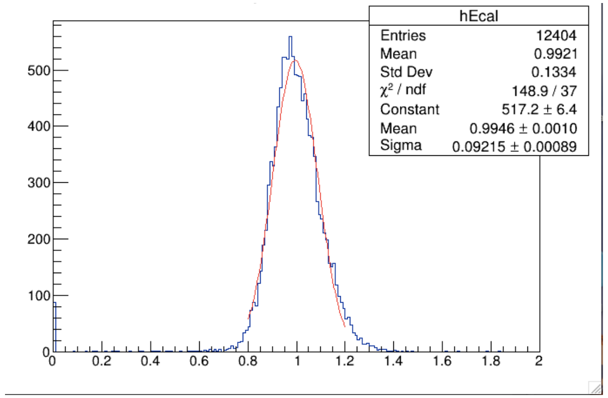
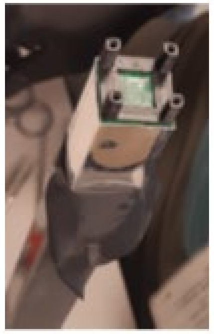
3x3 prototypes (2022) eRD105
9 scintillating glass blocks
1 x PMT (Hamamatsu R4125) baseline

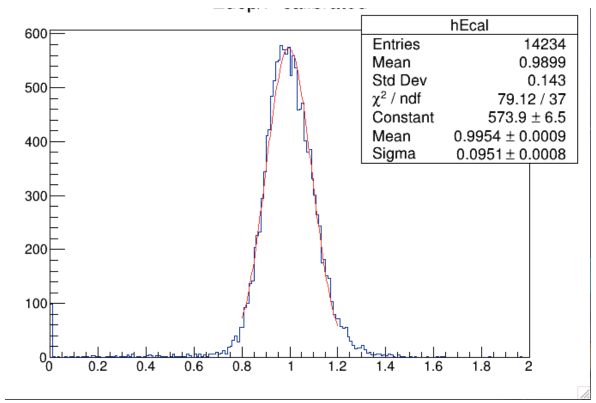




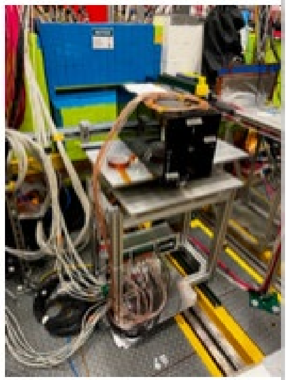


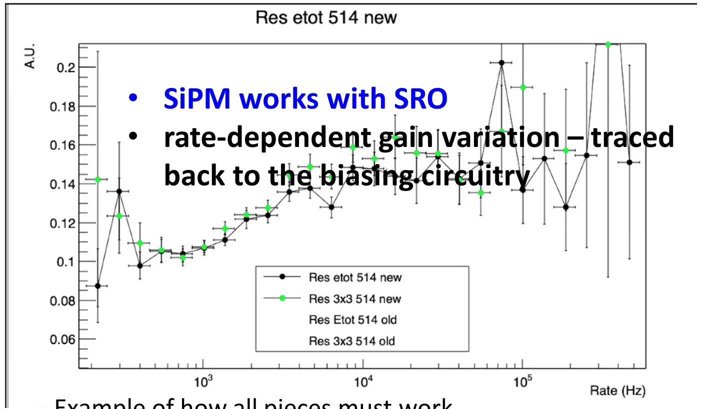
3x3 prototypes (2022) eRD105
9 scintillating glass blocks
1 x 6x6mm 50um Hamamatsu





5x5 prototypes (2023) eRD105
25 scintillating glass blocks
2 x 6x6mm2 50um Hamamatsu mounted on a PCB





- SiPM works with SRO
- rate-dependent gain variation – traced back to the biasing circuitry

Example of how all pieces must work together even when SiPMs are in hand

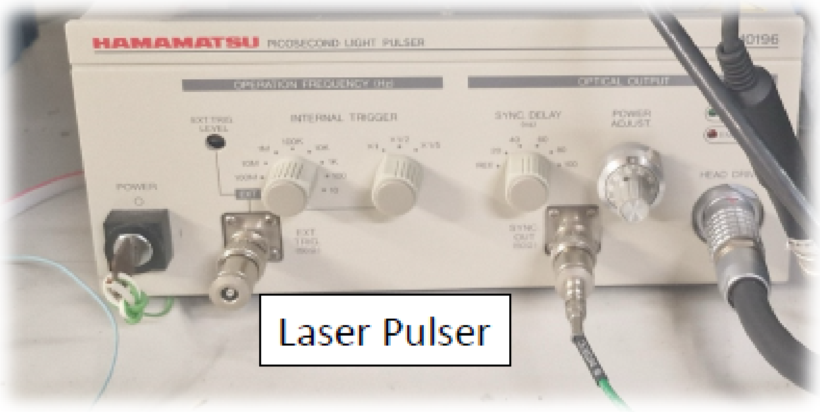
SiPM High Rate Response

SiPM response at different rate tested with pulsed light source at fixed-intensity (led, laser)

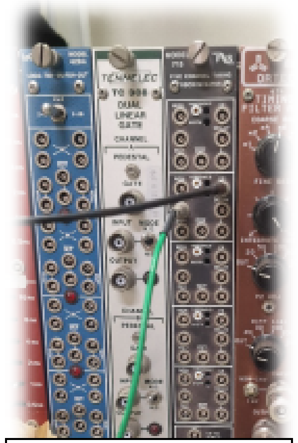
- Conducted test with fixed rate
- Test with stochastic signal (generated using SiPM dark noise passed through a discriminator)

→ Confirmed behavior observed in beam test

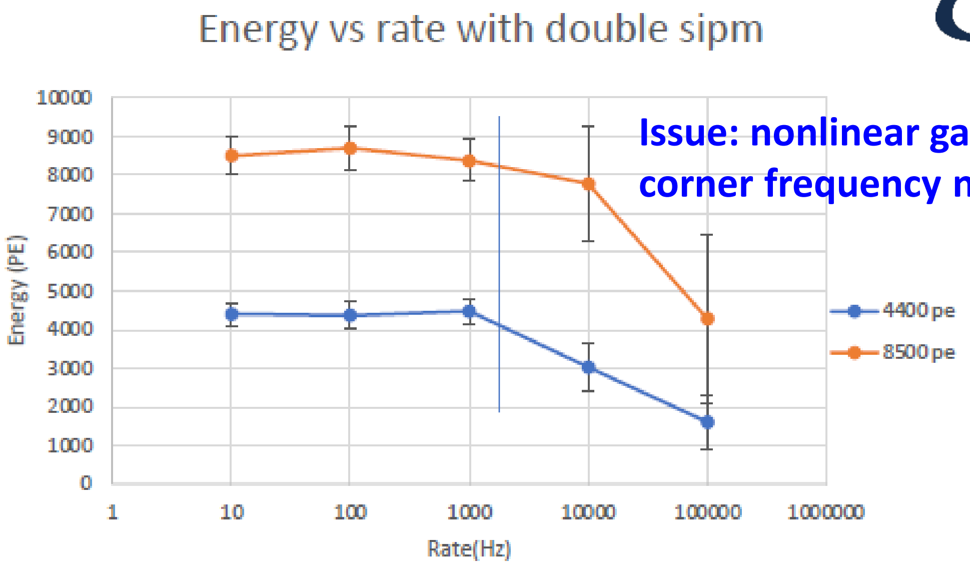
- Signal intensity depends on rate
- Resolution deteriorates at higher rates
- Critical rate lower for higher charge



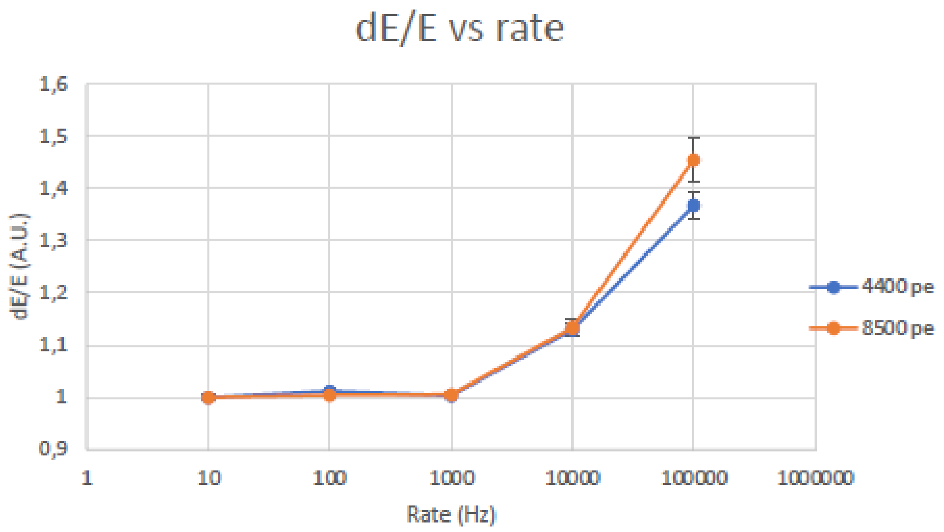
Laser Pulser



Discriminator



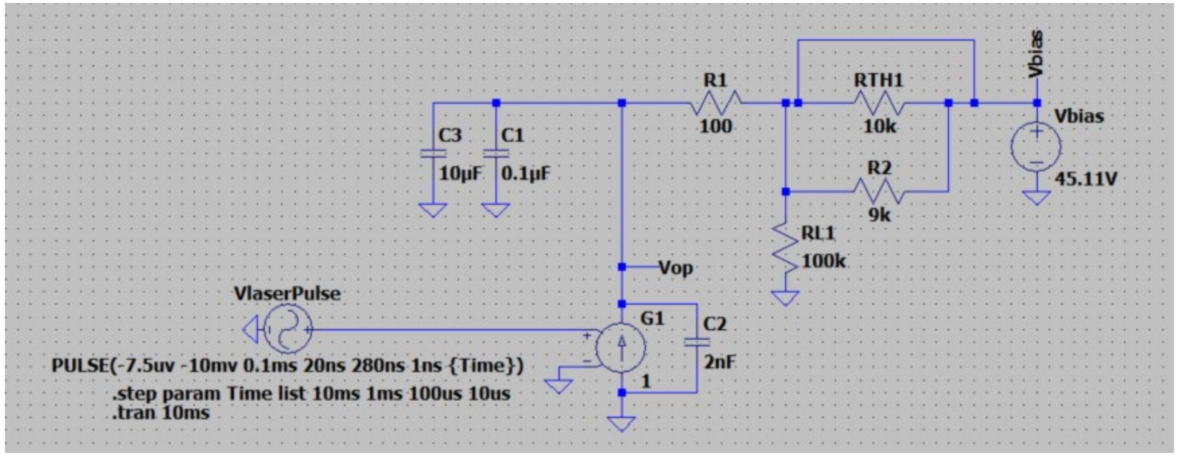
Issue: nonlinear gain – corner frequency near 1Khz



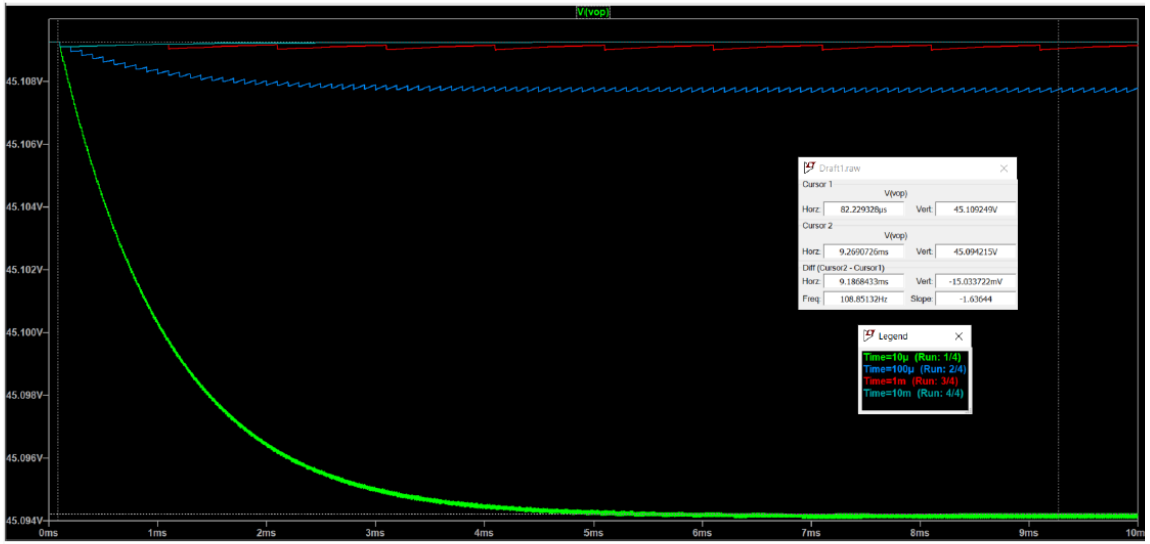
SiPM Gain Non-linearity Evaluation

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Slides adapted from
Steve Titus (JLab)

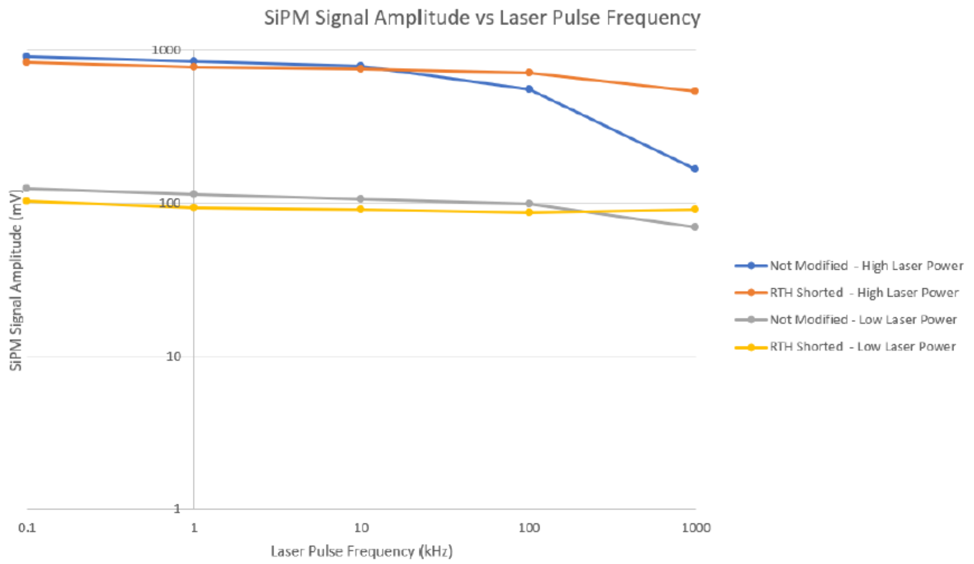


Simulation Results



- Original circuit: Vop drop of ~694mV at 100kHz
- Modified circuit: Vop drop of ~15mV at 100kHz

Experimental Results with S14160-6050HS (4x4 SiPM)



- Thermistor was removed from the circuit as in the simulation
- Higher capacitors were not available for testing due to voltage rating
- High power 58.5% laser power ~9600 pe
- Low power 58.5% laser power with N.D. filter with O.D. of 1.0

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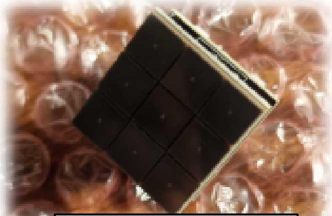
Jefferson Lab

- ❑ Status: a solution for the nonlinearity was identified
- ❑ Goal of this proposal: test this solution in the experimental setup at scale and further optimize as needed

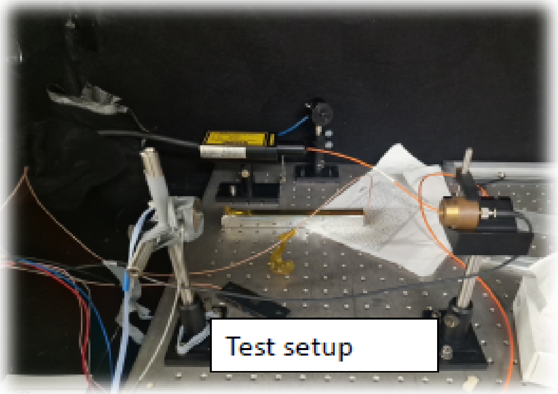
3x3 SiPM Matrix vs. Single SiPM

Custom 3x3 SiPM matrix tested:

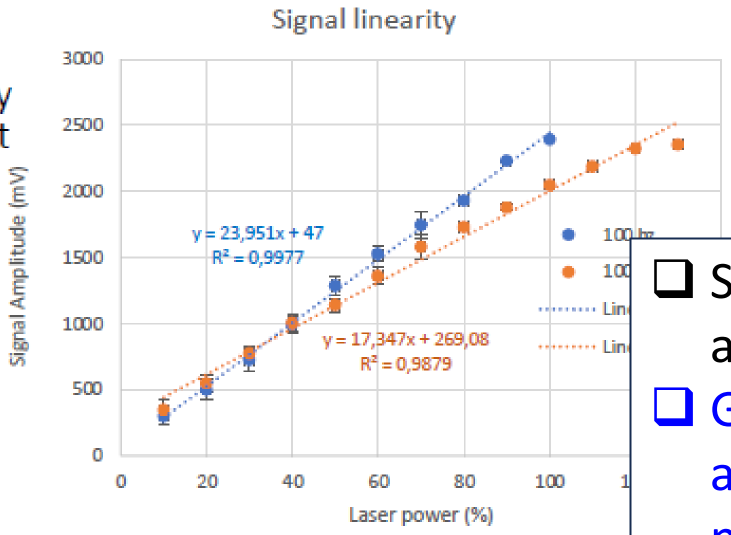
- 8x larger signal compared to single SiPM
- Linear response preserved for large signal
- No saturation up to few GeV
- Higher Dark Noise (single photoelectron measure not feasible)
- Similar energy/rate dependency as the 2 SiPM configuration, but with higher critical rate

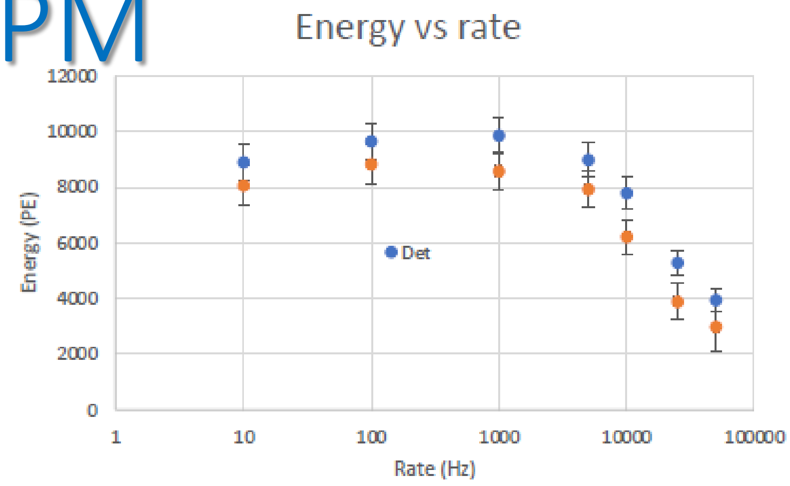


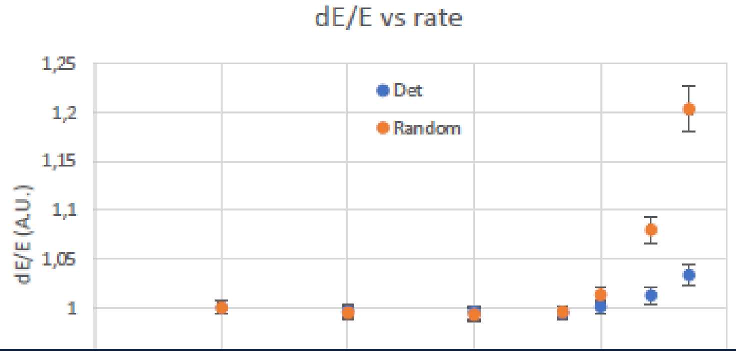
3x3 SiPM matrix



Test setup







- ❑ Status: have identified suitable candidates for the aereal coverage and RO/electronics
- ❑ Goal of this proposal: test the implementations in a realistic on-beam configuration with the real noise expected in an experimental hall. Test the full SRO to demonstrate that results are superior to conventional triggered solutions

Summary and Path Forward

- Much progress made with scintillating glass development for EIC and increasing global interest in scintillating glass technology
  - Scale up to 40cm complete and demonstrated reliable production
  - Recently completed beam tests demonstrate SiPM+SRO for SciGlass
  - STTR Phase 2A awarded
  - C/S Glass provides interesting characteristics for timing, DR for calorimeters (STTR Phase 2)
- To keep up the momentum, we submitted this FY24 Generic Detector R&D proposal that will build on the successful research of the last years
  - Goal: demonstrate scintillating glass with matched areal photosensor coverage and readout electronics over a large dynamic range as a viable cost-effective solution that can be used in the streaming readout DAQ.
  - The results from areal photosensor coverage and readout electronics, as well as those for streaming readout, could also apply to the EPIC PWO backward electromagnetic calorimeter.
  - Scintillating glasses could be incorporated into the second detector opening new perspectives for homogeneous EM/hadronic calorimetry where large volumes are required.