High Performance Glass Scintillators for Nuclear Physics Experiments

- ❑ Scintilex
- ❑ Electromagnetic Calorimeter projects
  - ➢ Examples of homogeneous calorimeters
- ❑ Experiment Requirements and STTR goals
- ❑ Project Overview and results
- ❑ Outlook

SCINTILEX

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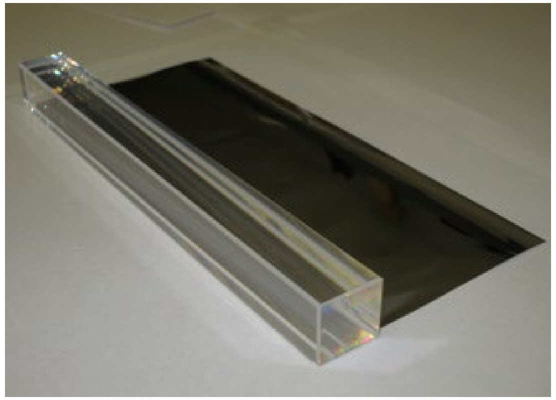
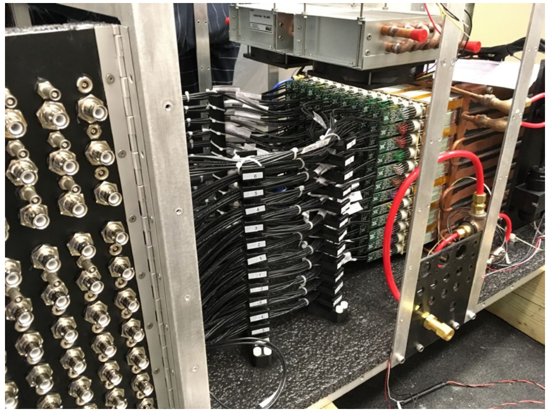
Business Official: Ian L. Pegg

Award: DE-SC0020619

Scintilex Overview

- ❑ Main focus: design and construction of instrumentation based on Cherenkov and scintillation light using novel materials
  - ➢ Applications: particle detection in nuclear physics experiments and homeland security; also medical
- ❑ Activities and expertise
  - ➢ R&D new detector materials
  - ➢ Pilot testing and scale up; hardware
  - ➢ Algorithm/software development and DAQ systems
- ❑ Activities related to scintillator material
  - ➢ Jefferson Lab (JLab): EM calorimeters detectors: TCS@NPS, Hy(F)CAL …
  - ➢ Electron-Ion Collider (EIC): EPIC Detector, *EIC 2nd detector*
  - ➢ Possibly CERN future colliders, e.g., FCC





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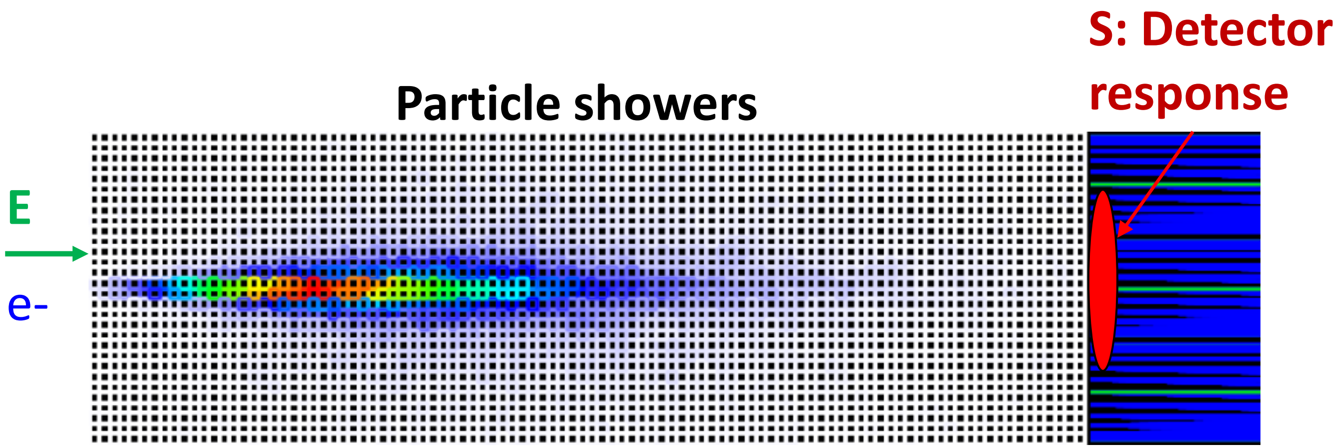
Context: Electromagnetic Calorimeters in Nuclear Physics

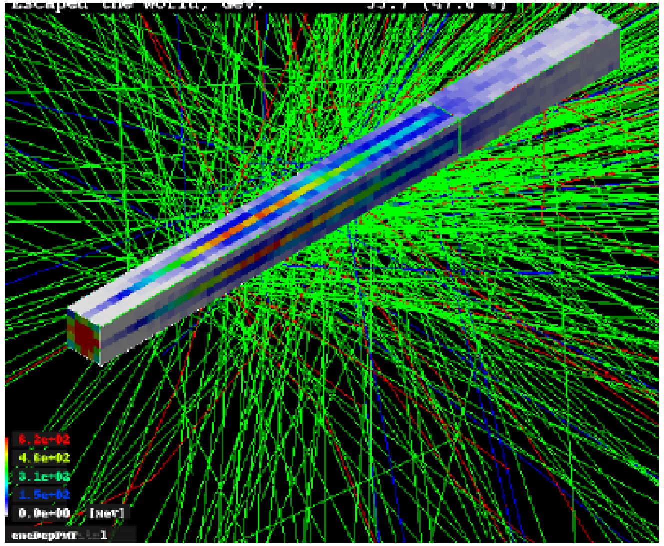
- In nuclear physics, calorimetry refers to the detection of particles, and measurements of their properties, through the total absorption in a block of matter, the calorimeter detector

- Calorimeters make use of various detection mechanisms, e.g.,
  - **Scintillation**
  - Cherenkov radiation
  - Ionization



Convert Energy E of incident particles to detector response S:

$$S \propto E$$



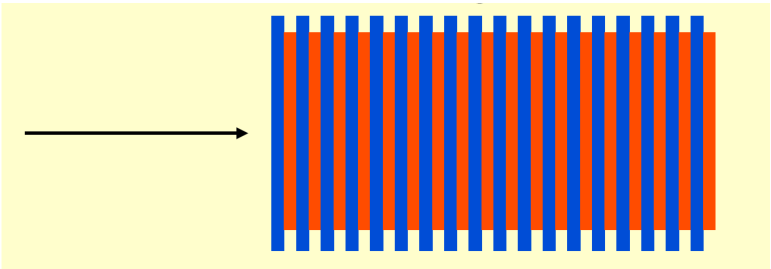
Scintilex MC simulations of shower development in scintillating blocks

Types of Electromagnetic Calorimeters

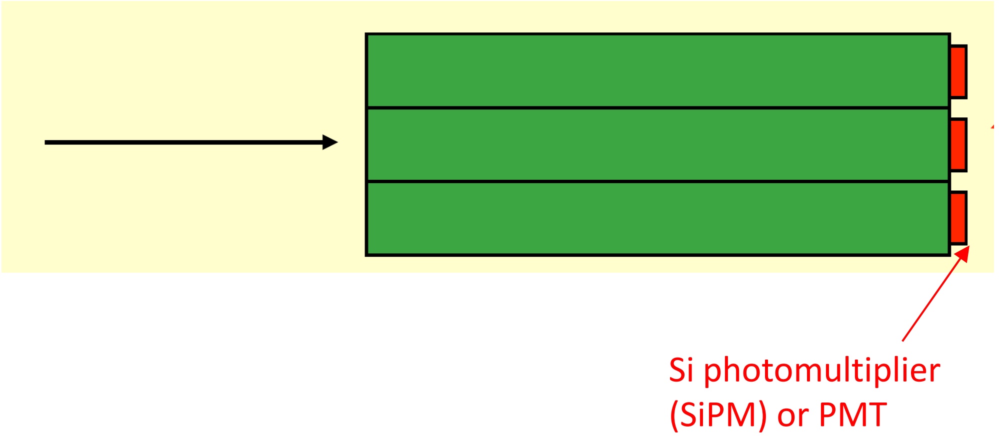
Two general classes of calorimeters

- ❑ Sampling Calorimeters: Layers of passive absorber (such as Pb or Cu) alternate with active detector layers such as Si, scintillator, liquid argon etc.
- ❑ Homogeneous Calorimeters: A single medium serves as both absorber and detector, e.g., crystals (BGO, $PbWO_4$, …) or glass scintillators.
  - ➢ Good resolution because all shower particles seen
  - ➢ Uniform response → linearity

Typical energy resolution: $\sigma_E/E \sim 10\%/\sqrt{E}$



Typical energy resolution: $\sigma_E/E \sim 1\%/\sqrt{E}$



Precision measurements in nuclear physics experiments require homogeneous calorimeters

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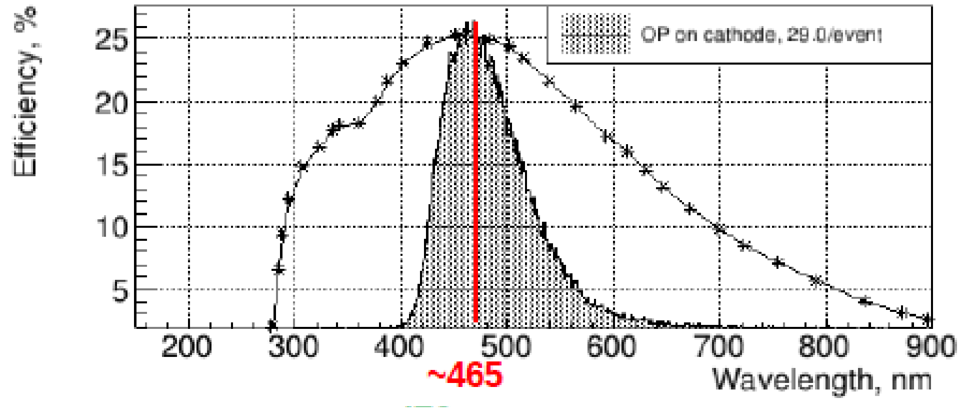
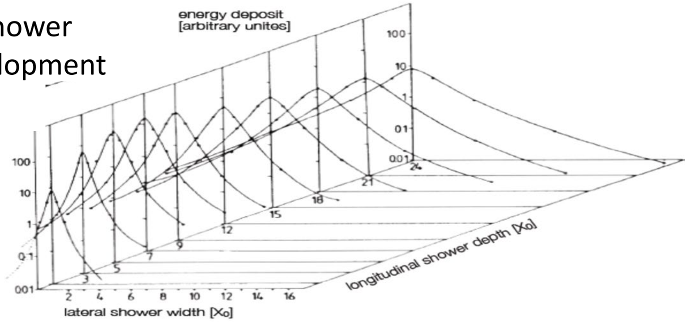
Requirements on scintillator materials

- ❑ Conversion of energy into visible light – Light Yield
- ❑ Attenuation Coefficient – Radiation length
- ❑ Scintillation Response – emission intensity, decay kinetics



- ❑ Emission spectrum matching between scintillator and photo detector – emission peak
- ❑ Chemical stability and radiation resistance – induced absorption coefficient
- ❑ Linearity of light response with incident photon energy – LY(100μs)/LY(10ms)
- ❑ Moliere radius for lateral shower containment
- ❑ Temperature stability

3D shower development



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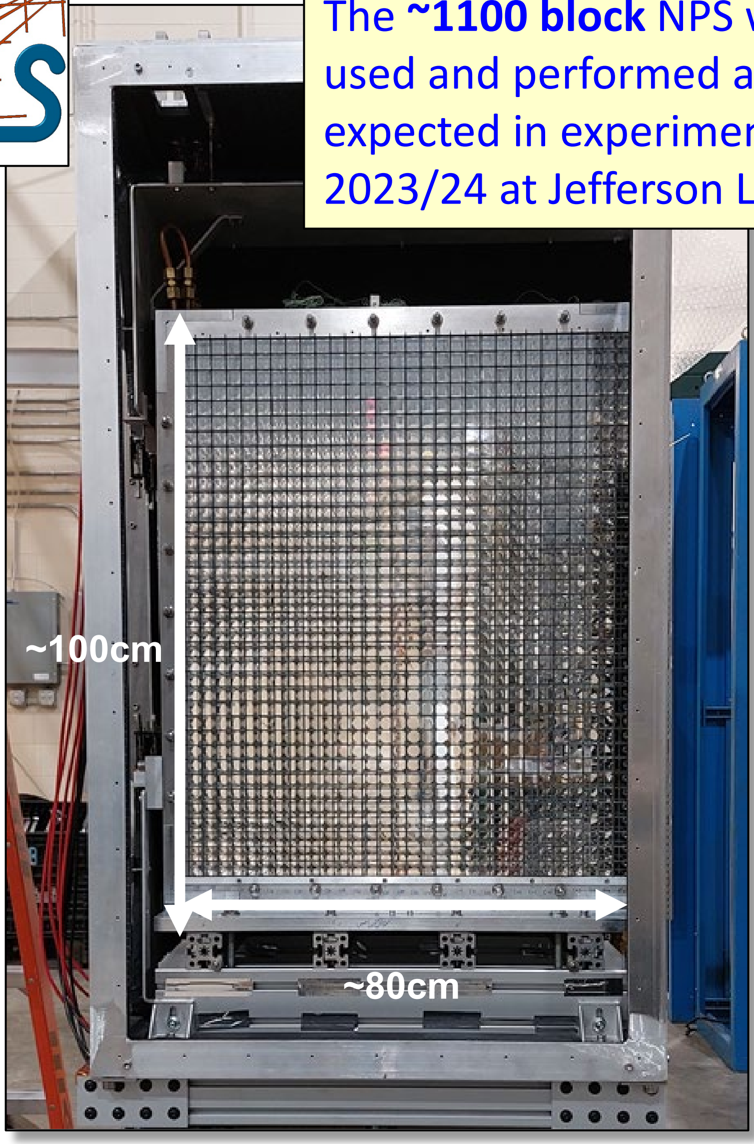
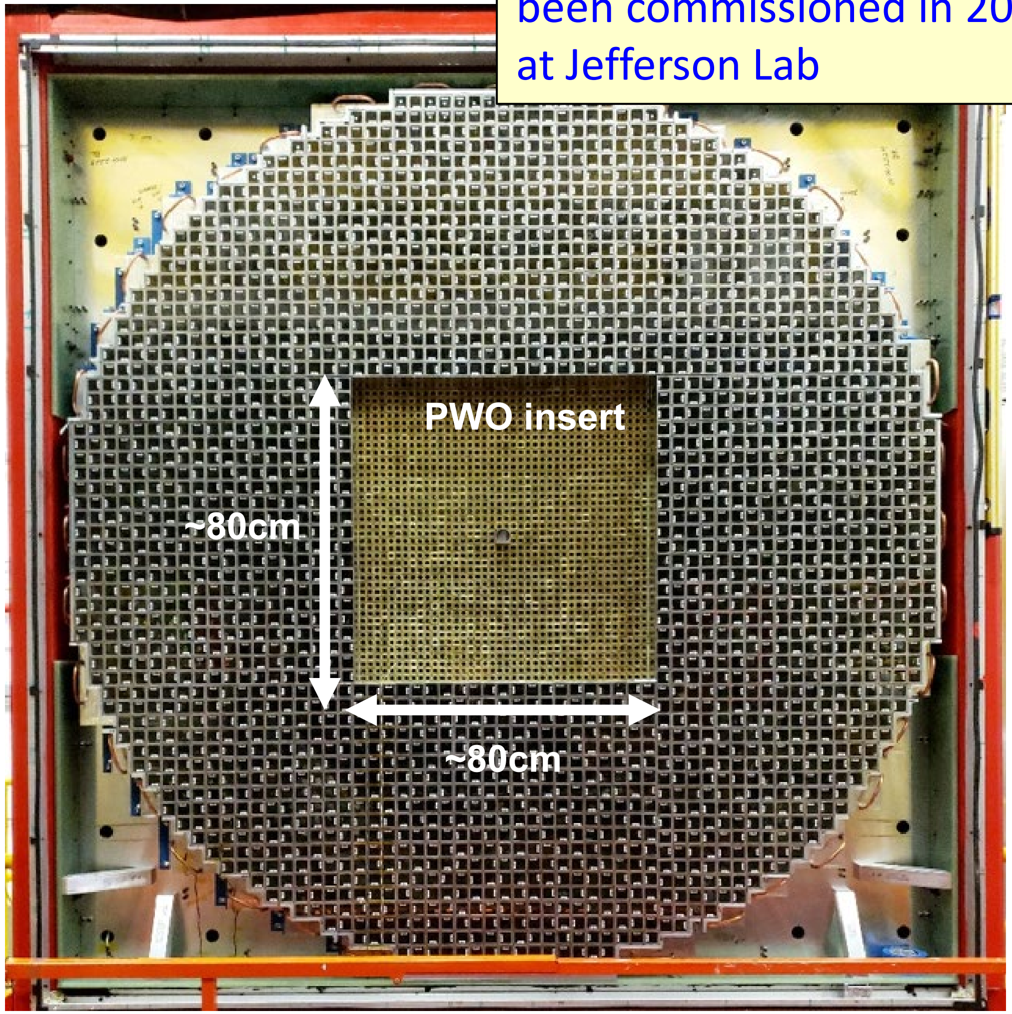
1. Examples of homogeneous EM Calorimeters at **JLAB**



The **~1100 block** NPS was used and performed as expected in experiments in 2023/24 at Jefferson Lab

Neutral Particle Spectrometer (Hall A/C)



The **~1600** block FCAL has been commissioned in 2025 at Jefferson Lab

Forward CAL Insert (Hall D)

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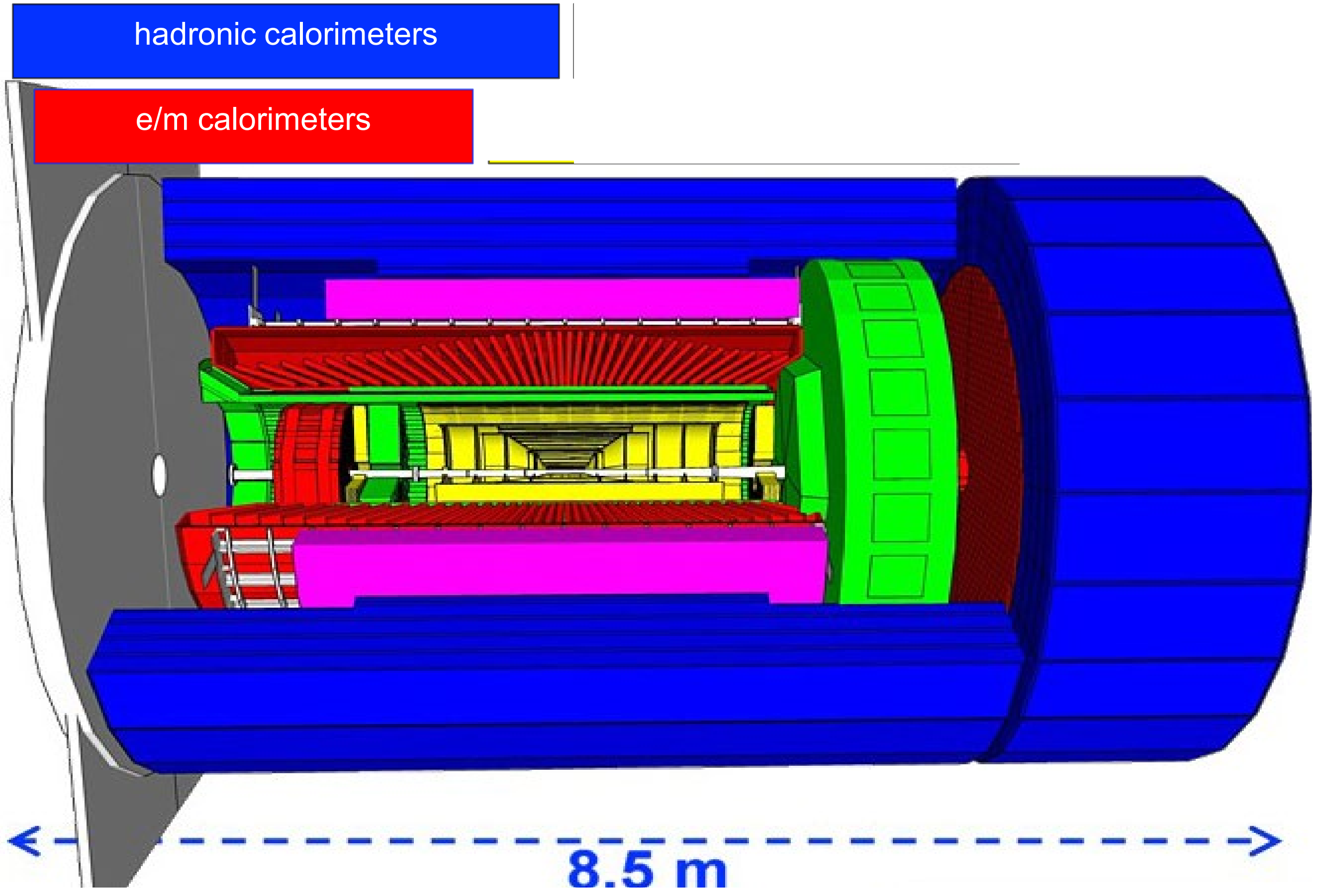
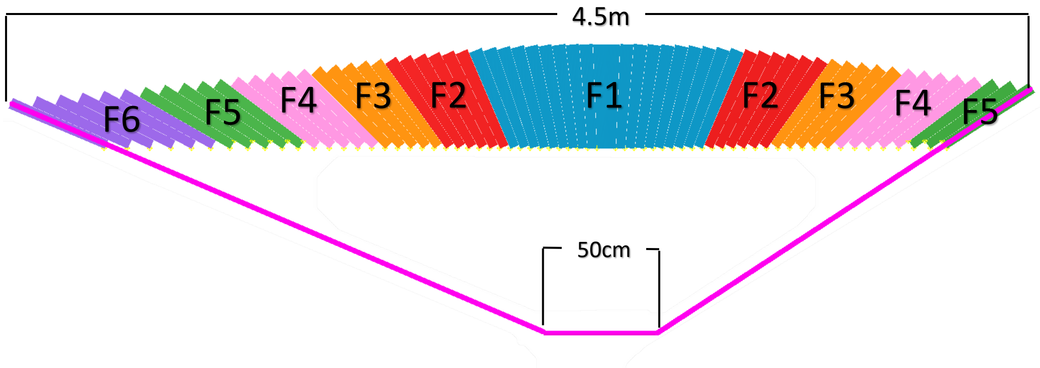
2. Homogeneous Electromagnetic Calorimetry at **EIC**

- EIC EMCal: central and auxiliary detectors



Auxiliary detectors not shown



- Large-volume detectors requiring large numbers of homogeneous scintillator blocks and custom shapes
  - For reference: endcap requires ~3000 PWO crystals for precision electron detection; barrel would require more than twice that
- **Crystals are expensive (\$35-40/cm^3)** – EIC barrel EMCal not affordable
- ➢ Need an **alternative active calorimeter material** that is more cost effective and easier to manufacture: **Scintillating Glass**

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Scintillating Glass Development - Overview

- A lot of recent activity and interest in glass scintillators! Note that many efforts are limited to small samples only.

- All-Inorganic Glass Scintillators: Scintillation Mechanism, Materials, and Applications 2024 https://onlinelibrary.wiley.com/doi/abs/10.1002/lpor.202300006
- Balancing high density and scintillation light yield in Ce3+-doped gadolinium borosilicate glass https://www.sciencedirect.com/science/article/pii/S027288422403534X
- SCINT2024 DSB glass Dormenev 2025 https://ieeexplore.ieee.org/document/10890911
- Multipurpose Ce-doped Ba-Gd silica glass scintillator for radiation measurements https://www.sciencedirect.com/science/article/pii/S0168900221007476
- Scintillating Glass for Future HEP Calorimetry https://ieeexplore.ieee.org/document/10656903
- Fundamentals of inorganic glasses (Varshneya, Mauro)
- Hodoscope multiphoton spectrometer GAMS2000 https://www-sciencedirect-com.proxy-um.researchport.umd.edu/science/article/pii/0168900286905012
- Sub-10 ps time tagging of electromagnetic showers with scintillating glasses and SiPMs https://www.sciencedirect.com/science/article/pii/S0168900223002048
- Optical and physical characteristics of HBLAN fluoride glasses containing cerium https://www.sciencedirect.com/science/article/pii/S0022309399000204
- The development of dense scintillating hafnium fluoride glasses for the construction of homogeneous calorimeters in particle physics https://www.sciencedirect.com/science/article/pii/S0022309396006643
- Cerium doped heavy metal fluoride glasses, a possible alternative for electromagnetic calorimetry https://cds.cern.ch/record/300042/

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The European Physical Journal A

Regular Article - Experimental Physics

Scintillating glass for precision calorimetry in nuclear physics

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- Recent publication on Scintilex glass performance
  - Also includes initial beam test campaign results

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Scintillating Glass Development - Overview

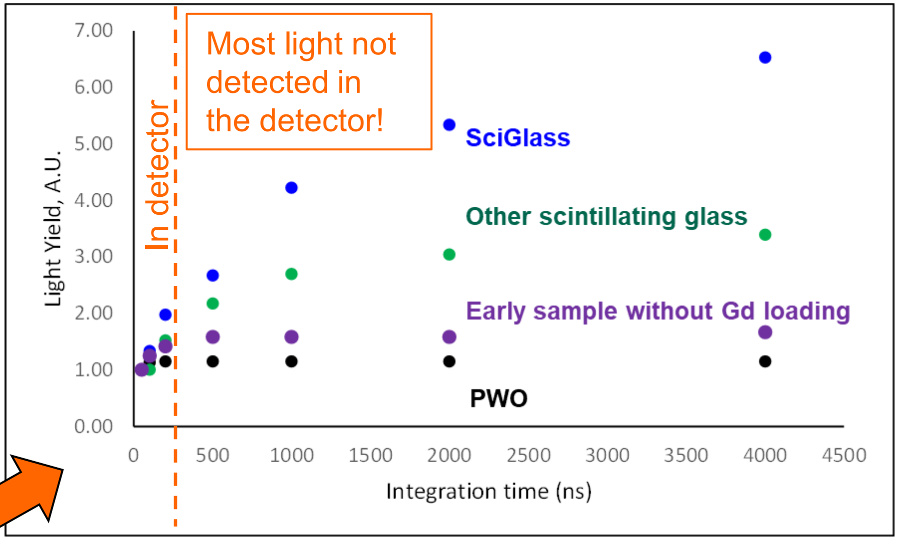
- Many ongoing activities on developing scintillating glass for subatomic particle detectors and many talks summarizing the literature
- However, there is often confusion about what is the “leading” scintillating glass - it really depends on the specific nuclear physics experiment detector requirements, e.g.,
  - Sen Qian in China makes Ce^{3+} doped gadolinium borosilicate glass, but no samples longer than 10cm exist → problem for large-volume homogeneous calorimeter performance at GeV scale (energy leakage)
  - Schott/Germany and Preciosa/Czech Republic have been producing Ce^{3+} doped gadolinium barium di-silicate glasses (DSB), but production of longer samples has been plagued by inclusions and bubbles → can be a problem for detector calibration and performance
  - **Scintilex** has developed the methods to routinely produce long (>10cm) glass samples of densities up to 4.3 g/cc and evaluated thoroughly the impact of increasing density on other quantities like optical properties and radiation hardness – properties overall suitable for EIC and JLab, but need further validation with beam test

Overview Glass (Scintillator) formulations

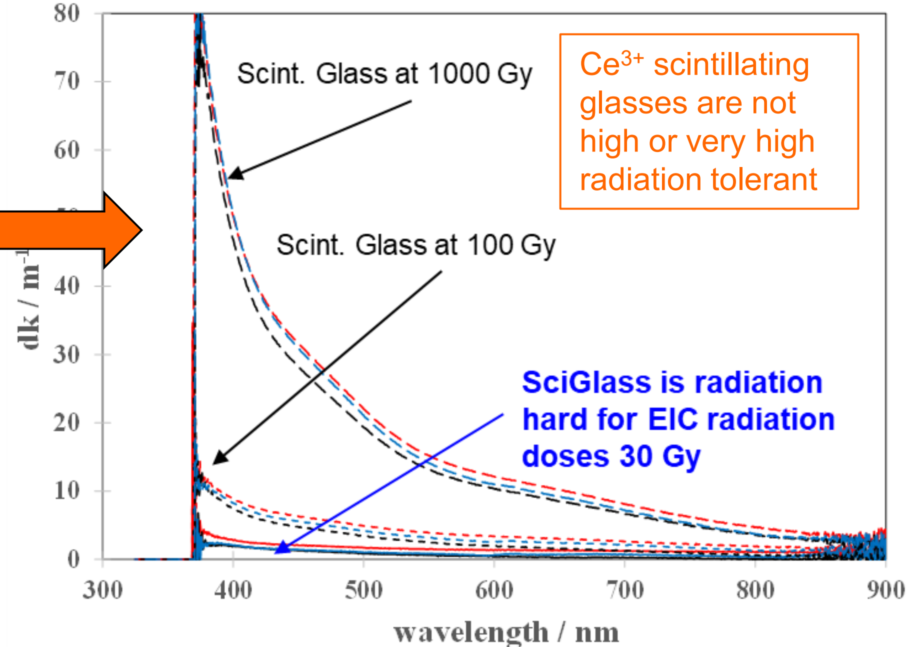
- ❑ In the literature there are standard procedures for producing glass (Springer Handbook of Glass or Fundamentals of Inorganic Glass), but in practice making scintillating glass for experiments is not so straightforward. ***For example,***

- ➢ Nuclear physics experiments have been using **Lead glass**, but it is a Cherenkov radiator (low light output), and it is not very dense – tradeoff between heavy element weight and fitting them in the glass matrix.
- ➢ **Glass Density:**
  - ❑ Barium and Phosphorous make rel. heavy glasses with densities ~4 g/cc.
  - ❑ Germanium also makes heavier glasses, but light yield is reduced significantly.
  - ❑ Including **Gadolinium** is better as it increases density and keeps light yield, but glasses have a much-reduced decay time.
  - ❑ Lanthanum and Lutetium have been used, but both have presented challenges for physics performance.
- ➢ **Glass Scintillation:**
  - ❑ Rare-Earth metals have been used to make glass scintillate. Most efforts concentrate on **Ce^{3+}**, but glasses show light yield nonuniformity and limitations in radiation hardness.
  - ❑ Sm and Eu^{3+} have been used - the emission of these glasses are shifted towards longer wavelengths (not desirable for typical particle detectors)

Normalized Integration Time



Radiation Resistance



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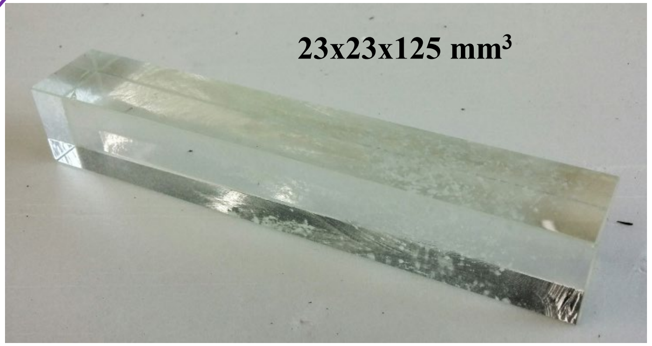
Scintilex Base Formulation for Scintillating Glass

Start from gadolinium barium di-silicate glass (DSB) base formulation

Material/ Parameter	Density (g/cm^3)	Rad. Length (cm)	Moliere Radius (cm)	Interact Length (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (γ/MeV)	Rad. Hard. (krad)	Radiation type	Z_{Eff}
(PWO)$PbWO_4$	8.30	0.89 0.92	2.00	20.7 18.0	2.20	560 420	50 10	40 240	>1000	.90 scint. .10 Č	75.6
($BaO*2SiO_2$):Ce glass	3.7	3.6	2-3	~20		440, 460	22 72 450	>100	10 *(no tests >10krad yet)*	Scint.	51
($BaO*2SiO_2$):Ce glass loaded with Gd	4.7-5.4	2.2		~20		440, 460	50 86-120 330-400	>100	10 *(no tests >10krad yet)*	Scint.	58

Also: ($BaO*2SiO_2$):Ce shows no temperature dependence



DSB:Ce glass block manufactured in Europe for Nuclear Physics Experiments - macro defects not under control and become increasingly acute on scale-up. → **not acceptable for homogenous calorimeters**

Shortcomings of earlier work:

- Macro defects, which can become increasingly acute on scale up
- Sensitivity to electromagnetic probes

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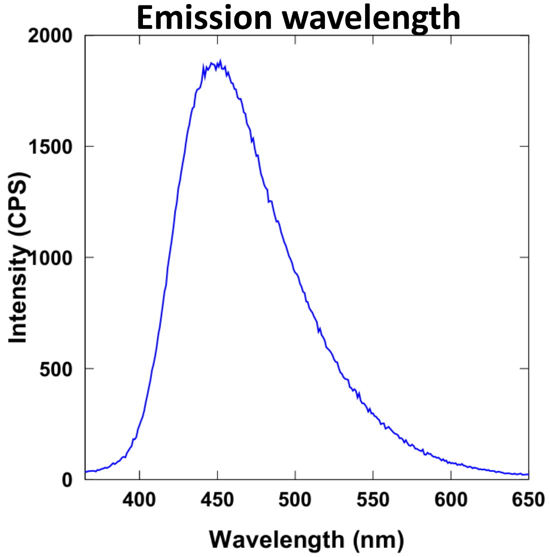
Glass Scintillator formulations

Two glass formulations for homogeneous calorimeter application

VSL-Scintilex-G4 (nominal)

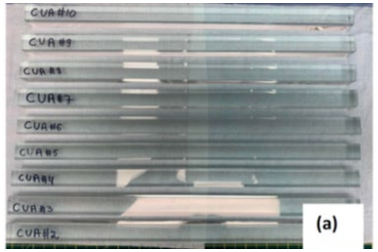
VSL-Scintilex-T1



Scintillation light

- Nominal: optimized LY, timing, radiation hardness, etc.
- Increased density compared to nominal, lower LY, but still higher than PWO

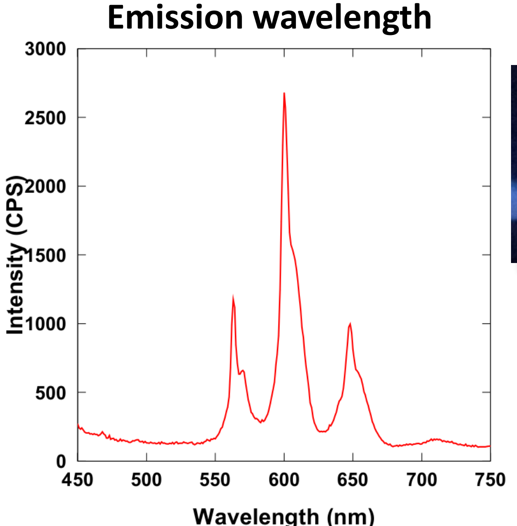
→ **SciGlass (this talk)**



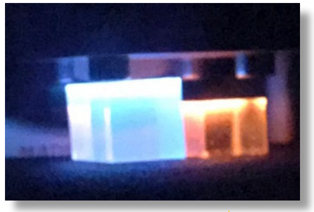
Formulations with initial emission wavelength tuning

VSL-Scintilex-SC1

VSL-Scintilex-EC1



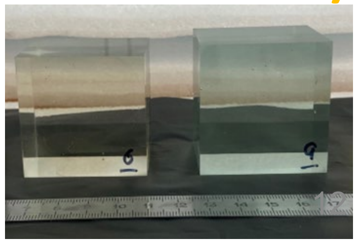
Scintillation light



Doping with Sm

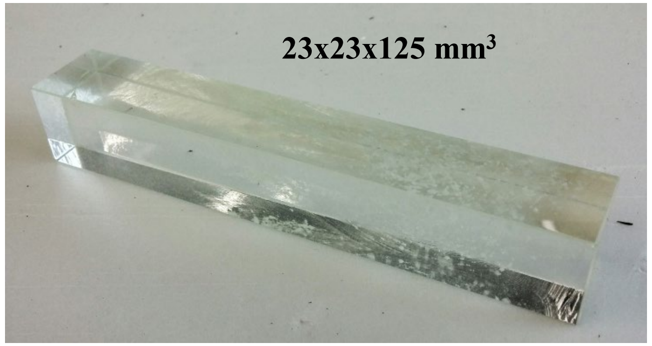
- Can have higher density compared to nominal, emits at >550nm, good LY

→ **CSGlass (for hadronic calorimeters)**

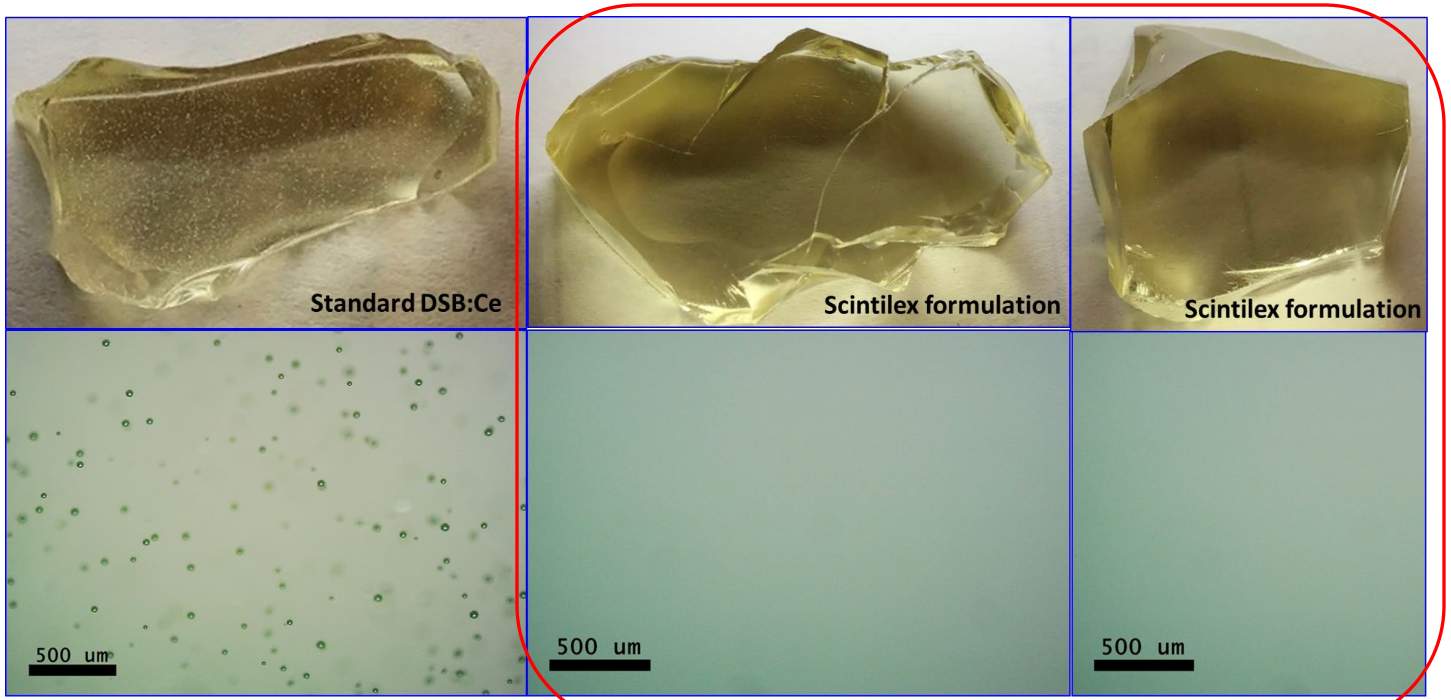


Phase 1: Process optimization to prevent non-uniformities

- ❑ Shortcoming of earlier work: macro defects that can become increasingly acute on scale up
- ✔ Developed new processing method at CUA/VSL/Scintilex



DSB:Ce glass block manufactured in Europe for Nuclear Physics Experiments - macro defects not under control and become increasingly acute on scale-up. → not acceptable for homogenous calorimeters



Sample made at CUA/VSL based on previous DSB:Ce work

Samples made at CUA/VSL/Scintilex with our new method

Our method eliminates bubbles in the bulk, which is important for fabricating longer or generally larger dimensions blocks

Phase 2: Scale-up and larger scale production

- ❑Shortcoming of earlier work: no scale up to long blocks sizes
- ✔ ❑Scintilex developed a method to scale up while maintaining reasonable optical properties

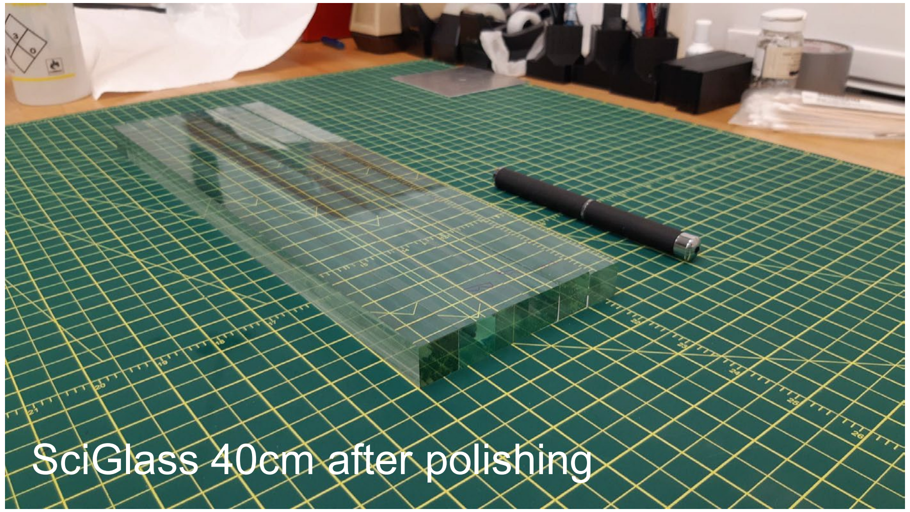
SciGlass of length 20cm can be produced reliably and 40cm blocks can now be produced routinely – lab size batches (10-25 blocks)


Glass pouring into the mold at Scintilex/VSL


SciGlass Scale-up production

Custom fabrication setup for 40cm SciGlass

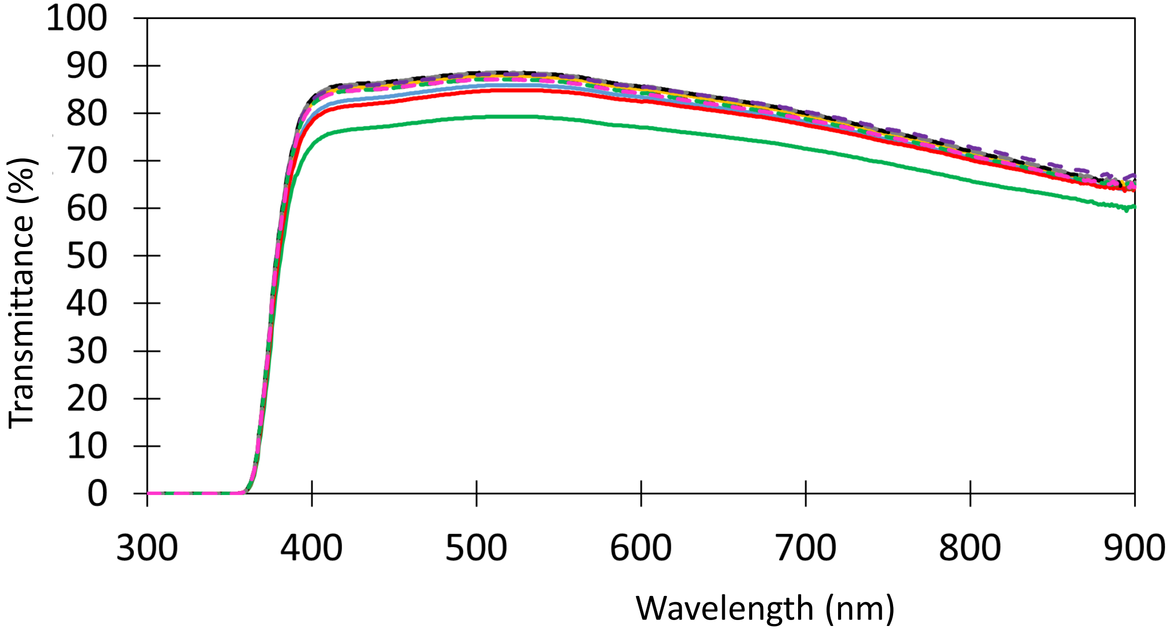

SciGlass 40cm before polishing


SciGlass 40cm after polishing

Phase 2A: SciGlass Global Evaluation – primary optimization

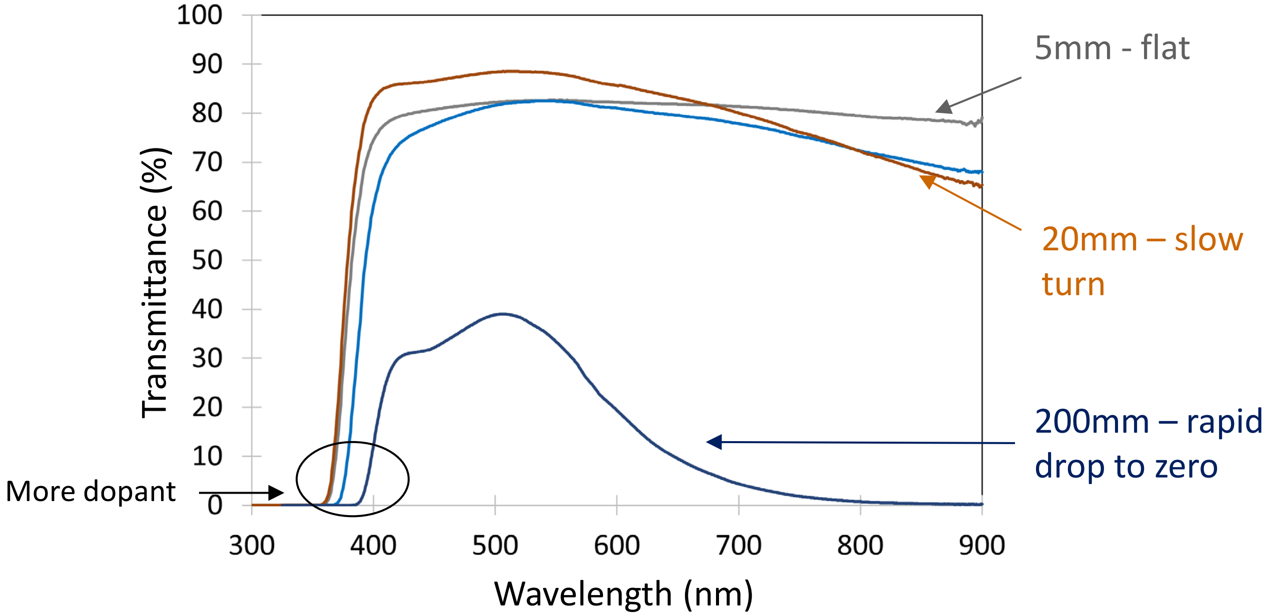
Transverse Transmittance

- ✔ Overall shape consistent for all points along the length → **no macro defects**
- ✔ Variations at 10% level → understood: non-ideal polishing



Longitudinal Transmittance for different sample lengths

- ✔ small shift in the absorption edge as the length is increased → understood: more dopant in the light path
- ➡ drop in transmittance >550nm with length → defects which seem to impact light yield uniformity and so the detector performance (next slides)



All Ce^{3+} scintillating glasses have such issues upon scale up - in some cases preventing production of large samples

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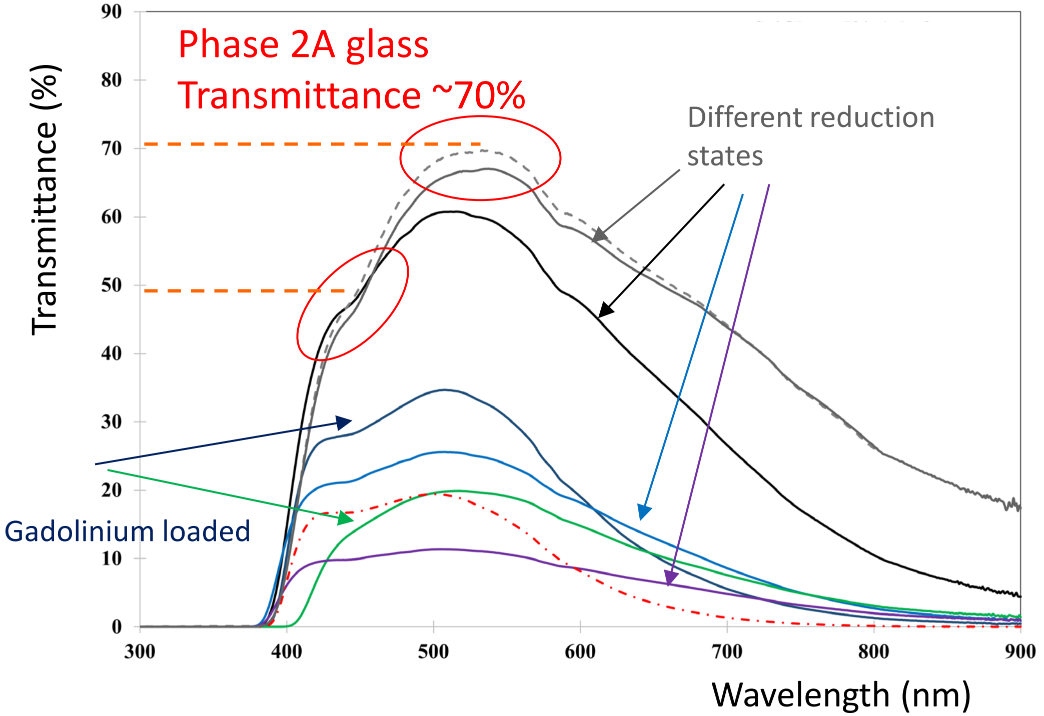
Phase 2A: Transmittance Optimization Results

Longitudinal transmittance – 20cm samples



- **Gd loading** though relevant for the glass density did not result in significant increase in transmittance
- **Different reduction states**: the highest reduction states (less Ce^{4+}) have the highest transmittance, comparable to PWO at 500nm and 50% at ~400nm - also show less rapid drop off in the transmittance above 600nm

Assuming that suitable photosensors (MPPCs) and modern advanced computing methods are available, the **optimized transmittance would be acceptable for the experiment** ✔

Physics Label	Length (cm)	Year tested
L20.G4 (0%-1)	20	2024
L20.G4 (Gd-25)	20	2024
L20.G4 (Gd-18)	20	2024
L20.G4 (15%-3)	20	2024
L20.G4 (10%-1)	20	2024
L20.G4 (5%-1)	20	2024
L40.G3 #28	40	2023
L40.G3 #2	40	2023
L40.G3 #3	40	2023
L40.G3 #1	40	2022
L40.G3 #2	40	2022
L40.G3 #3	40	2022
L40.G3 #4	40	2022
L40.G3 #5	40	2022
L40.G3 #6	40	2022
L40.G3 #7	40	2022
L40.G3 #8	40	2022
L40.G3 #9	40	2022
L40.G3 #1	40	2022
L40.G3 #1	40	2023
L40.G3 #1	40	2023
L40.G3 #1	40	2023
L40.G3 #1	40	2023
L40.G3 #1	40	2023
L40.G3 #1	40	2023
L40.G3 #1	40	2023
L40.G3 #1	40	2023
L40.G3 #1	40	2023

Samples used in the optimization study

L40.G3 #20	40	2023
L40.G3 #21	40	2023
L40.G3 #22	40	2023
L40.G3 #23	40	2023
L40.G3 #24	40	2023
L40.G3 #25	40	2023
L40.G3 #26	40	2023
L40.G3 #27	40	2024
L20.G2	20	2022
L20.G3	20	2022

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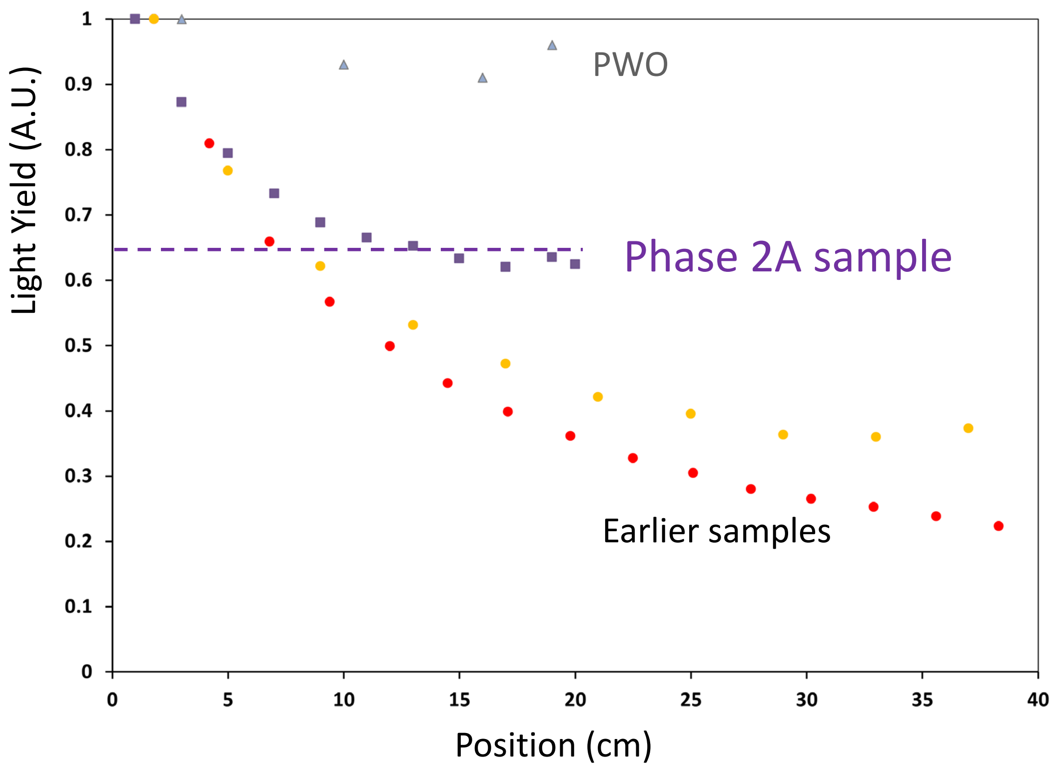
Phase 2A: Transmittance Optimization Results

Light Yield Uniformity



Notes:
- Focus is on non-uniformity of the light yield along the long sample and not the light yield reduction due to length reduction (volume) of the sample.
- For detector calibrations and performance variations should be minimal

- ❑ The dependence (non-uniformity) of the new sample is shallower than for the earlier blocks
- ❑ The new sample light yield uniformity stabilizes at ~65% for lengths above 10cm.
- ❑ The earlier samples LY drops to ~60% at 10cm, with a further significant drop to ~40%@20cm.

With the advent of AI/ML methods may expect that non-uniformity could be at least partially compensated → uniformity acceptable for the experiment ✔

Physics Label	Length (cm)	Year tested
L20.G4 (0%-1)-2	20	2024
L20.G4 (Gd-25)	20	2024
L20.G4 (Gd-18)	20	2024
L20.G4 (15%-3)	20	2024
L20.G4 (10%-1)	20	2024
L20.G4 (5%-1)	20	2024
L40.G3 #28	40	2023
L40.G3 #2!	40	2023
L40.G3 #3(	40	2023
L40.G3 #1	40	2022
L40.G3 #2	40	2022
L40.G3 #3	40	2022
L40.G3 #4	40	2022
L40.G3 #5	40	2022
L40.G3 #6	40	2022
L40.G3 #7	40	2022
L40.G3 #8	40	2022
L40.G3 #9	40	2022
L40.G3 #1(	40	2022
L40.G3 #1	40	2023
L40.G3 #1	40	2023
L40.G3 #1:	40	2023
L40.G3 #1	40	2023
L40.G3 #1:	40	2023
L40.G3 #1(	40	2023
L40.G3 #1	40	2023
L40.G3 #1	40	2023
L40.G3 #1!	40	2023

L40.G3 #20	40	2023
L40.G3 #21	40	2023
L40.G3 #22	40	2023
L40.G3 #23	40	2023
L40.G3 #24	40	2023
L40.G3 #25	40	2023
L40.G3 #26	40	2023
L40.G3 #27	40	2024
L20.G2	20	2022
L20.G3	20	2022

Highest Transmittance sample selected for this study

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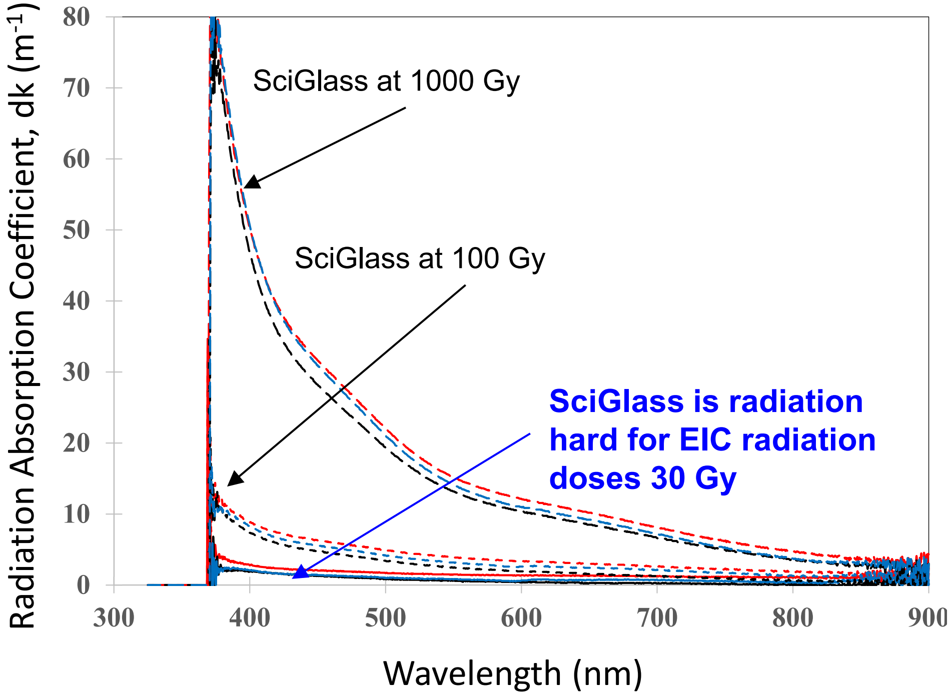
SciGlass Global Evaluation – future optimization

Radiation Resistance

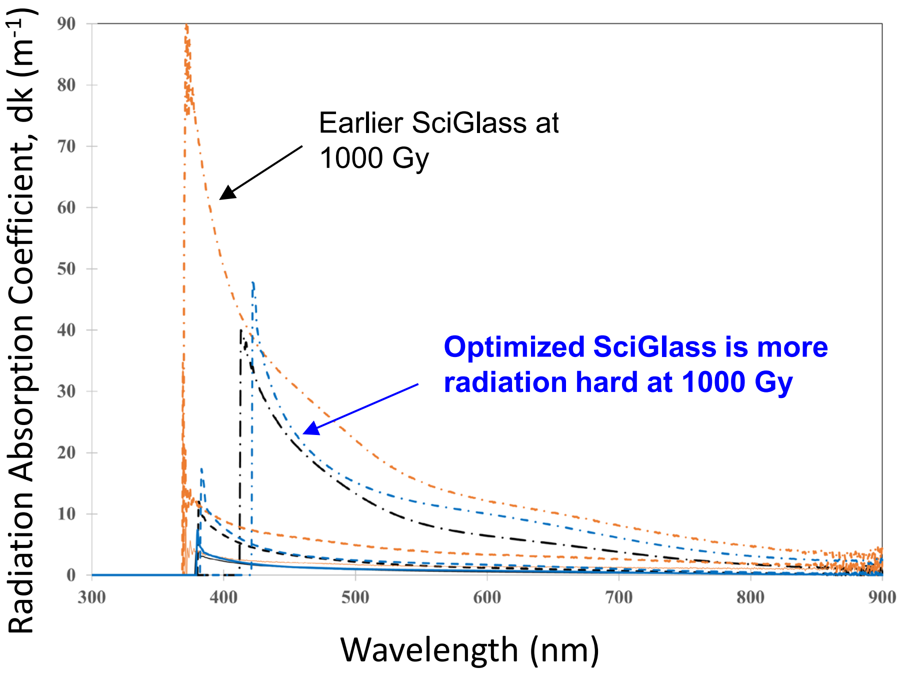
SciGlass is radiation hard for EIC radiation doses 30 Gy ✔

Earlier SciGlass samples



Radiation resistance is expressed through the radiation absorption coefficient, dk. For EIC the requirement is $dk < 1\ m^{-1}$

Optimized Samples (highest Transmittance)



Curves shifted horizontally for better visualization

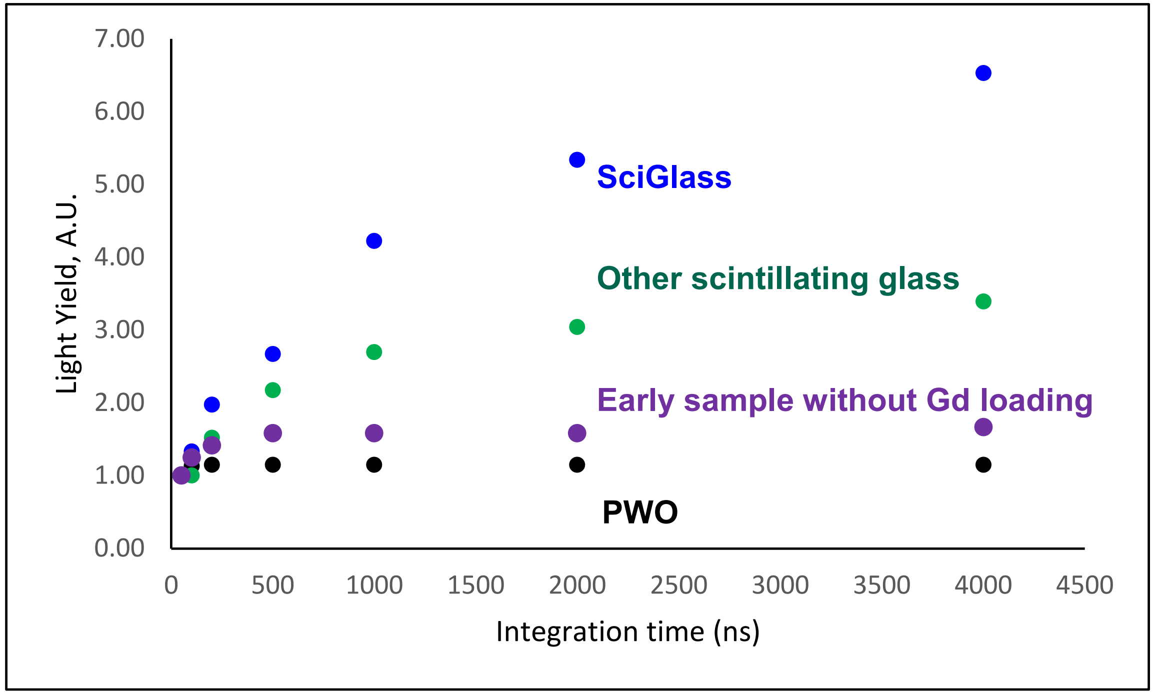
Physics Label	Length (cm)	Year tested
L20.G4 (0%-CO-2	20	2024
L20.G4 (Gd-25)	20	2024
L20.G4 (Gd-18)	20	2024
L20.G4 (15%-3)	20	2024
L20.G4 (10%-1)	20	2024
L20.G4 (5%-1)	20	2024
L40.G3 #28	40	2023
L40.G3 #29	40	2023
L40.G3 #30	40	2023
L40.G3 #1	40	2022
L40.G3 #2	40	2022
L40.G3 #3	40	2022
L40.G3 #4	40	2022
L40.G3 #5	40	2022
L40.G3 #6	40	2022
L40.G3 #7	40	2022
L40.G3 #8	40	2022
L40.G3 #9	40	2022
L40.G3 #10	40	2022
L40.G3 #11	40	2023
L40.G3 #12	40	2023
L40.G3 #13	40	2023
L40.G3 #14	40	2023
L40.G3 #15	40	2023
L40.G3 #16	40	2023
L40.G3 #17	40	2023
L40.G3 #18	40	2023
L40.G3 #19	40	2023

While not important for the present project goals, we may in the future investigate higher radiation resistant scintillating glass and recovery from high radiation dose damage.

SCINTILEX

SciGlass Global Evaluation – future optimization

Normalized Integration Time



Future optimization may address the integration time - composition formula changes, Cerium doping control, raw material purity control, and optimizations of the production technology.

- SciGlass and the other Ce-based scintillation glasses have contributions from slower components compared to PWO.
- Have been able to detect SciGlass signals in initial detector prototype tests and measure energy resolutions consistent with expectation – timing seems suitable, but needs further validation
- It has been shown that one can optimize the kinetics parameters through the fractional contributions of the heavy cation compositions.
  - For example, an early sample without Gd loading – the (purple curve) has kinetics parameters comparable to PWO.
  - To keep the glass density on the level of 4.0-4.5 g/cm^3 it may be preferable to include Gd, but choose an optimized cation ratio with Ba, another heavy element.

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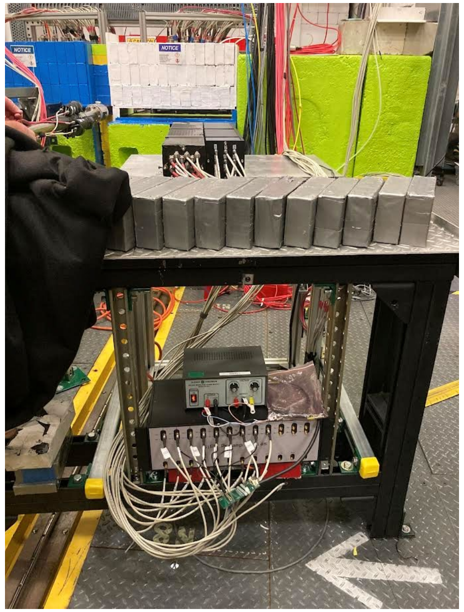
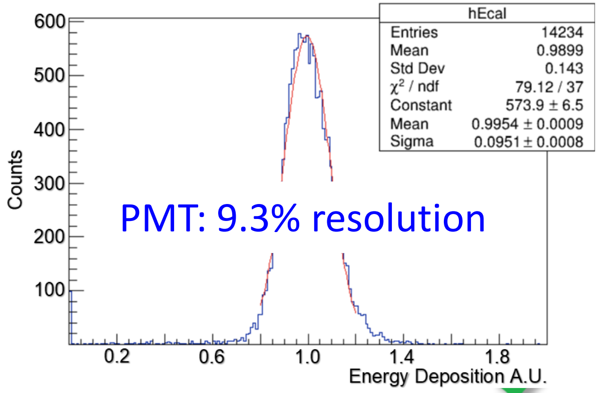
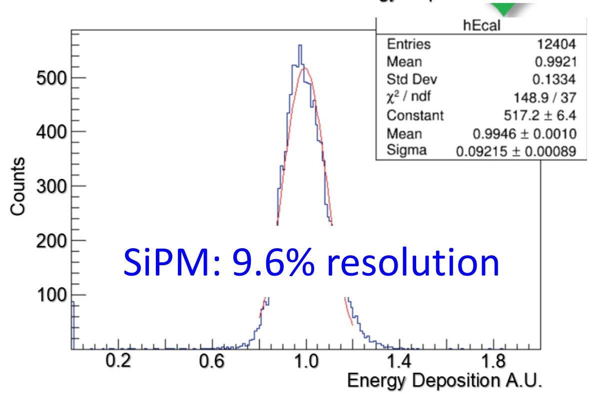
Phase 2A: SciGlass as Nuclear Physics Detector at Scale

Shortcoming of earlier work: tests not done at scale

- ❑ Direct Comparison of PMT and SiPM readout: using glass+readout in 3x3 array
  - ❑ Two detector prototypes: one with standard PMT, one with SiPM (the method of choice for EIC)

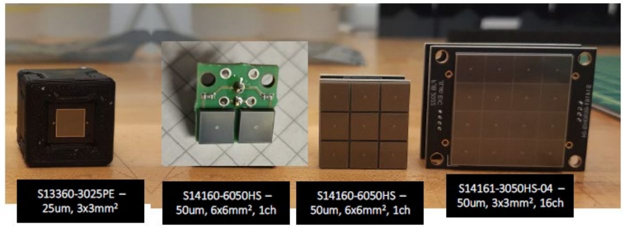


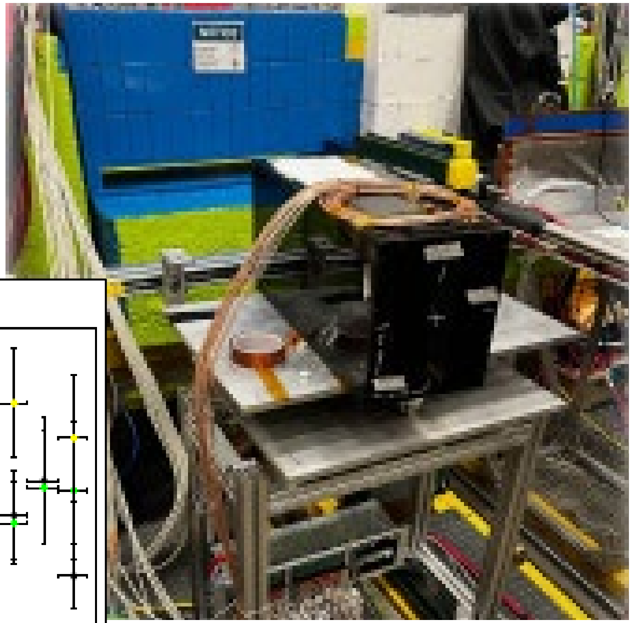




- ❑ Similar energy resolution with PMT and SiPM
- ❑ Already in range of EIC requirements in central region

- ❑ Readout Chain Test with Streaming Readout (SRO) with glass+readout in a 5x5 array
  - ❑ Data were taken in two readout configurations: standard readout and streaming readout(SRO) as envisioned for the EIC. The results are shown in terms of the resolution vs rate as a function of the number of blocks used in the clustering.

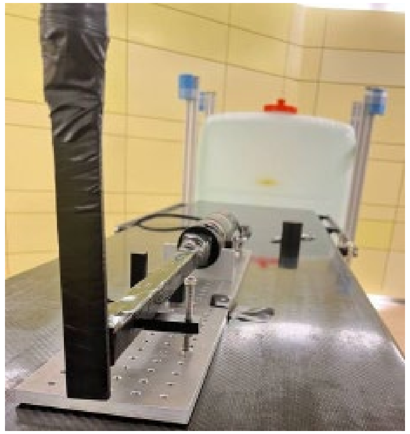


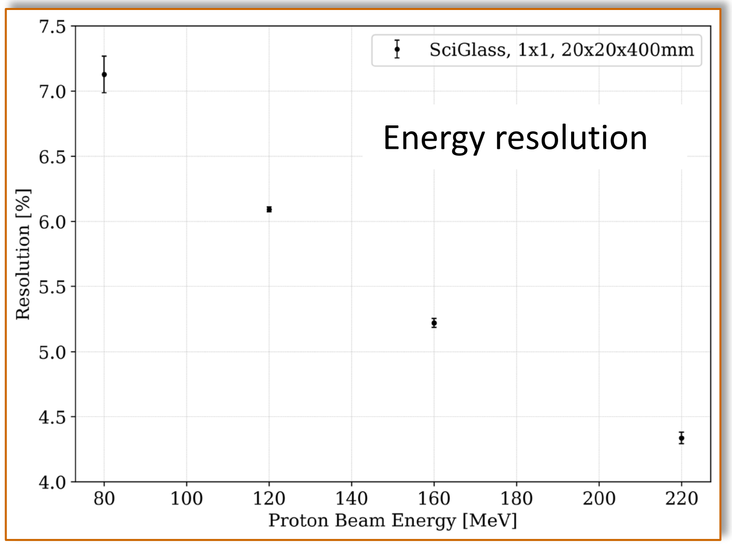


- ❑ Glass+SiPM works with SRO
- ❑ 3x3 SiPM matrix identified for full test

Phase 2A: Hadron Beam Test and other Beam Test Data

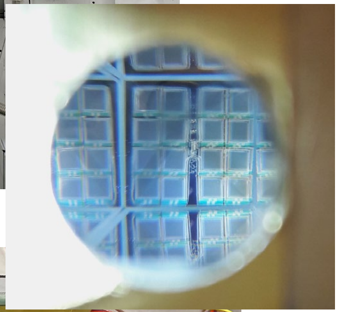
- MIT2024: observe the response of SciGlass to hadrons
  - One 40cm long block was subjected to proton beam with energies 90, 120, 160, 220 MeV with beam spot sizes 19.6mm, 13.3mm, 10.6mm, 8.1mm





- Results are the first data with hadron beam for SciGlass
  - allows for further characterization of the material
  - May give an indication of Cherenkov contribution to light yield – may be of interest to hadron calorimeters

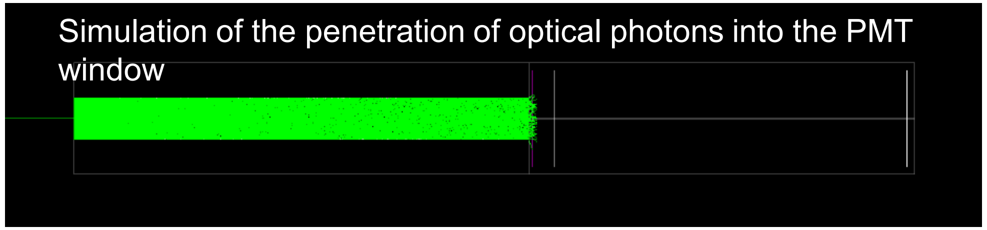
- DESY2025: two SciGlass blocks with ePIC SiPM MPPC readout scheme inside a 5x5 array (EEEMCAL PWO prototype)
  - Lepton beam of energy 1-5 GeV
  - **See signal!** Further analysis ongoing

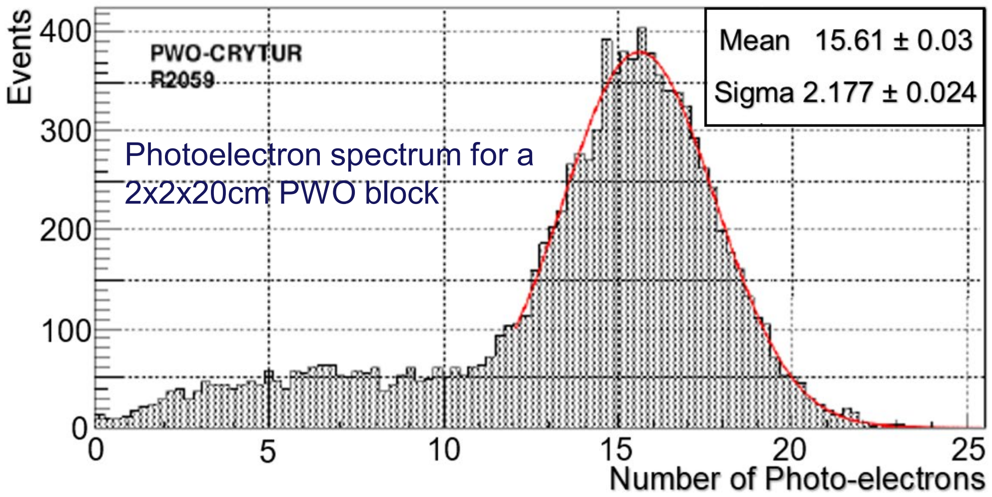


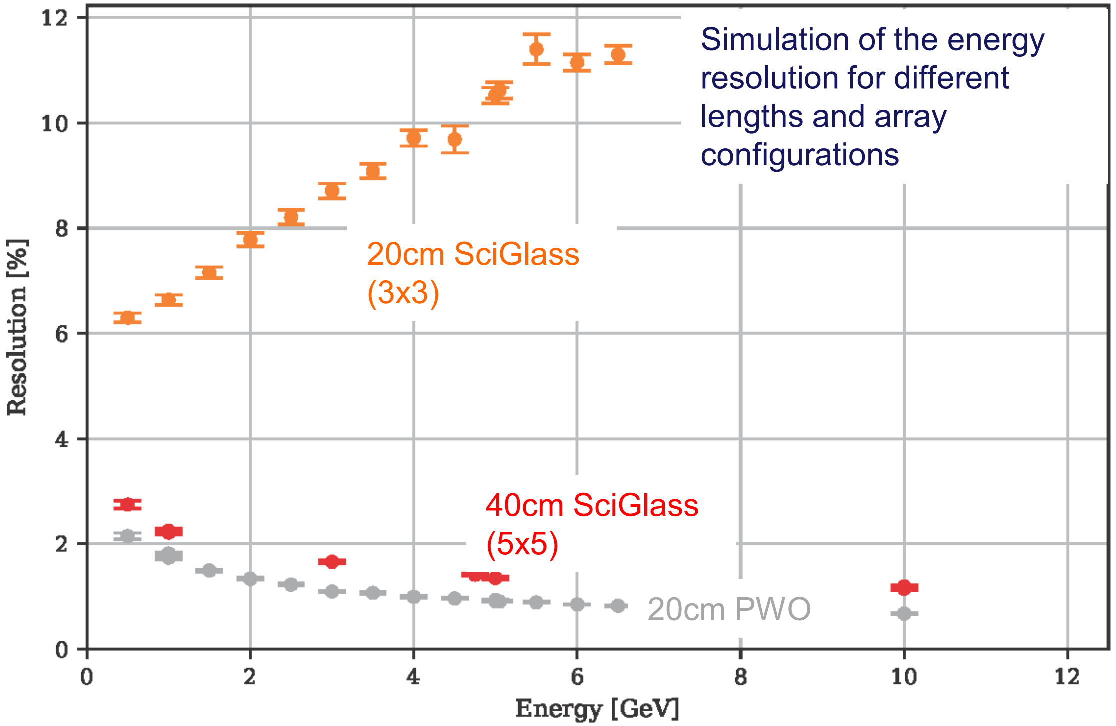
SCINTILEX

Supporting High Fidelity Simulations

- Goal: estimate the energy resolution, optical resolution, visualize shower profiles, etc. to support the beam tests
- Developed a program using the Geant4 framework
  - Includes the physical parameters and optical properties of SciGlass
  - To reflect the experimental setup reflector wrapping material was included
  - Each block included either PMT or SiPM photosensors as used in the beam tests
  - To calibrate the light yield against that measured on the test bench included a simulation with optical photons

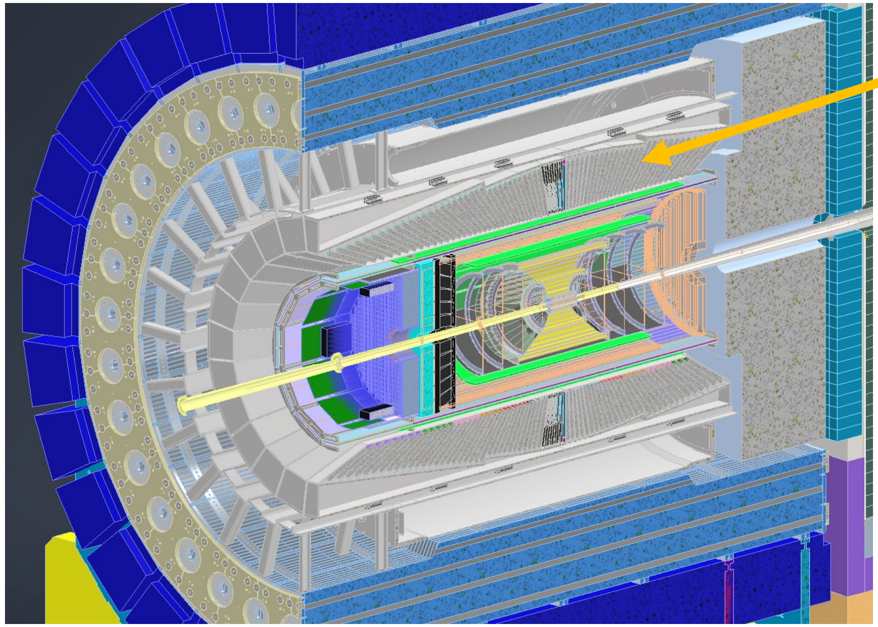






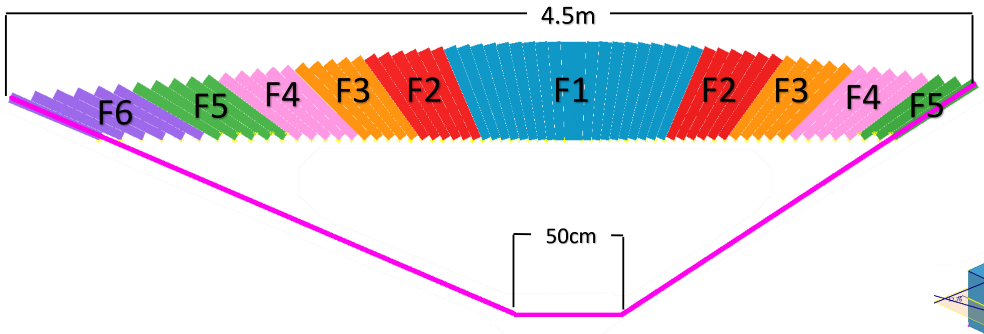
- The simulated energy resolution for 20cm SciGlass in a 3×3 array at about 5 GeV is 10%, which is consistent with the measured energy resolutions.
- The apparent increase in energy resolution with energy is due to shower leakage in longitudinal and transverse direction

A SciGlass barrel EMCal in the EIC Detector

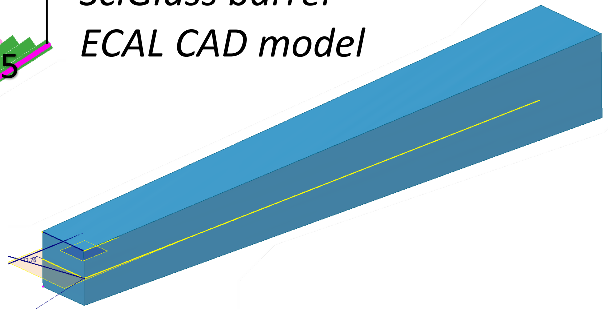


***SciGlass* Barrel ECAL in EIC detector model**

Homogeneous, projective calorimeter based on SciGlass, cost-effective alternative to crystals



SciGlass barrel ECAL CAD model

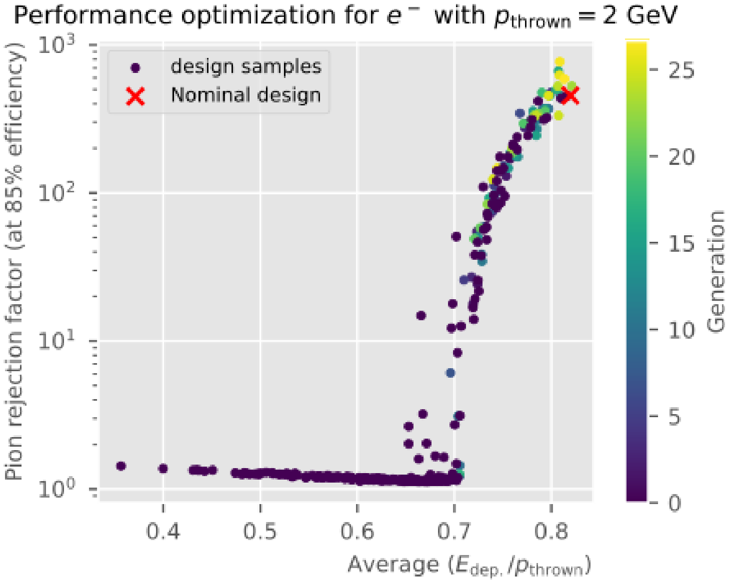


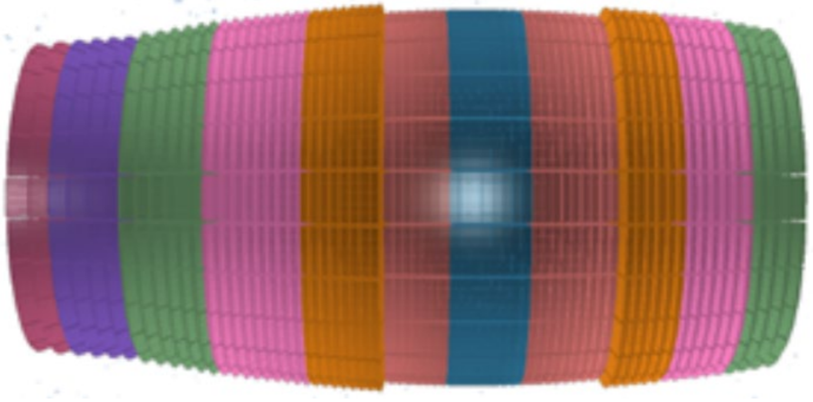
- ❑For an EIC the geometry requires 68 SciGlass blocks per slice with 6 family variations
- ❑Slices combined into groups of 5 separated by 2.811° radially to produce a wedge
- ❑120 slices combined to create 24 wedges separated by 15° radially (see next page).
- ❑Central region of 50 cm considered due to non-fixed target.
- ❑Currently ~8,000 towers to complete the barrel

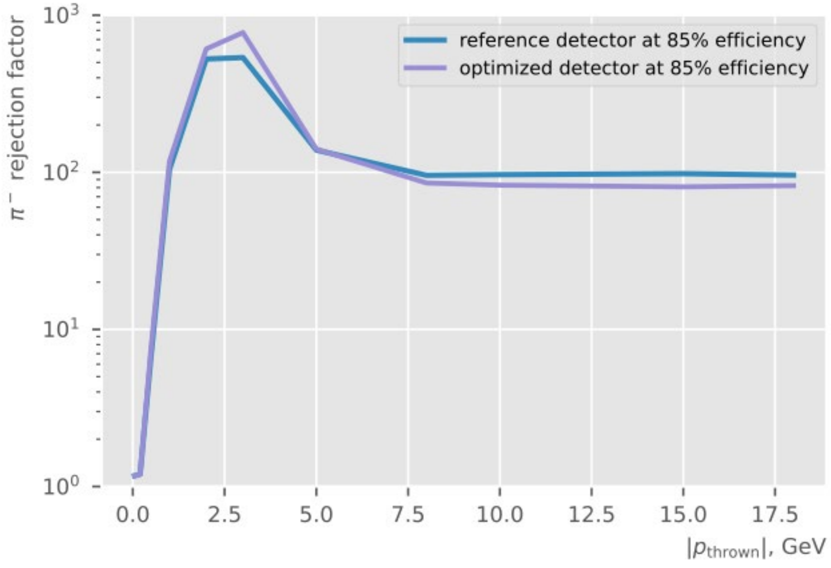
➤ **Ultimate Goal: produce and characterize different block geometries needed for a barrel EMCal**

SCINTILEX

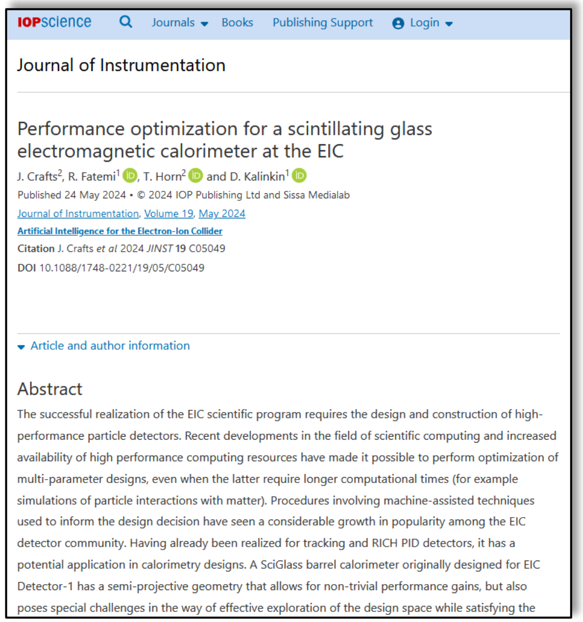
AI for Detector Design: optimize SciGlass EM Calorimeter for EIC Detector 2







The optimized detector outperforms the reference in terms of pion rejection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Journal of Instrumentation

Performance optimization for a scintillating glass electromagnetic calorimeter at the EIC

J. Crafts[2], R. Fatemi[1], T. Horn[2] and D. Kalinkin[1]

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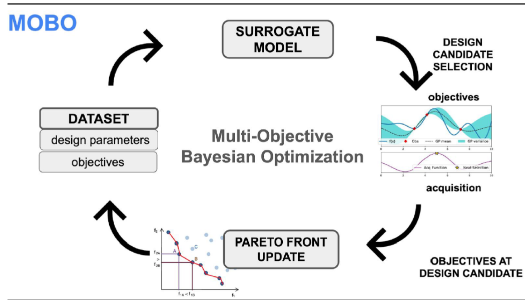
Article and author information

Abstract

The successful realization of the EIC scientific program requires the design and construction of high-performance particle detectors. Recent developments in the field of scientific computing and increased availability of high performance computing resources have made it possible to perform optimization of multi-parameter designs, even when the latter require longer computational times (for example simulations of particle interactions with matter). Procedures involving machine-assisted techniques used to inform the design decision have seen a considerable growth in popularity among the EIC detector community. Having already been realized for tracking and RICH PID detectors, it has a potential application in calorimetry designs. A SciGlass barrel calorimeter originally designed for EIC Detector-1 has a semi-projective geometry that allows for non-trivial performance gains, but also poses special challenges in the way of effective exploration of the design space while satisfying the



- The SciGlass detector has potential application as mid-rapidity electron measurement device in EIC Detector-2
- Optimization beyond pure geometrical
- 2-objectives (multi-objective) optimization
- Genetic algorithms and Bayesian optimization

Outlook

Acknowledgement: Award: DE-SC0020619

- ❑ Demonstrated a novel scintillating glass (SciGlass) as a cost-effective alternative to scintillating crystals for precision electromagnetic calorimeters in nuclear physics experiments, e.g., at the EIC
- ❑ SciGlass 40cm long blocks have been produced routinely in lab size batches (10-25 blocks)
- ❑ Global optimization improved shortcomings observed during a global glass study
- ❑ Performance validation at scale carried out with prototype 3x3 SciGlass arrays (20cm and 40cm blocks) and suitable readout for NP experiments; also measured response to hadrons with proton beam
- ❑ High-fidelity supporting simulations developed - energy resolution from 3x3 at scale beam test matches the simulated projections
- ❑ AI-assisted design optimization shows that a SciGlass detector has potential application as mid-rapidity electron measurement device in EIC Detector-2
- ❑ **Future work towards a SciGlass detector at EIC or JLab**
  - **Perform beam test with a larger detector prototype and matched to EIC preferred readout**
  - **Further develop AI/ML assisted methods to optimize the detectors and material**