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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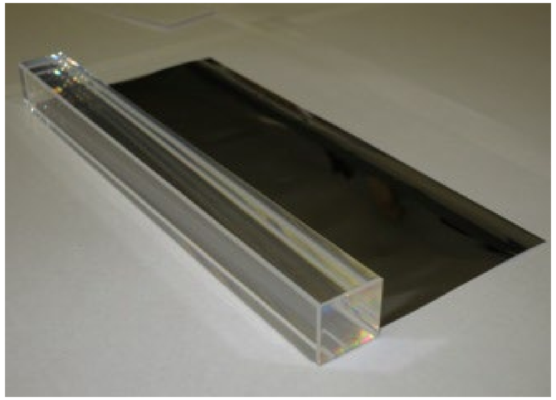
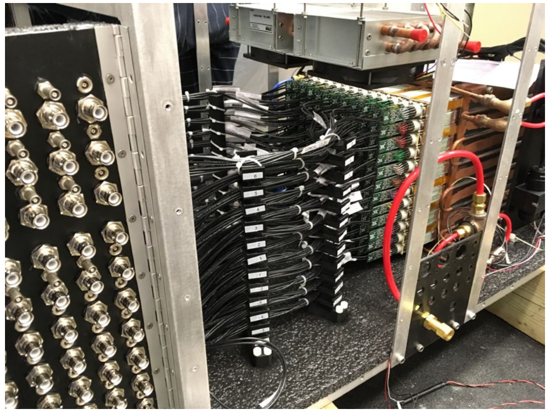
Scintilex Overview

- 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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Scintillation Detector Basics: Electromagnetic Showers

- Dominant processes at high energies (E > few MeV)

Photons: Pair Production

$$\sigma_{pair} \approx \frac{7}{9}\left(4\alpha r_e^2 Z^2 ln \frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

X_0 = radiation length in [cm] or [g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{pair} = \frac{7}{9}\frac{\rho}{X_0}$$

X_0 = radiation length in [g/cm^2]

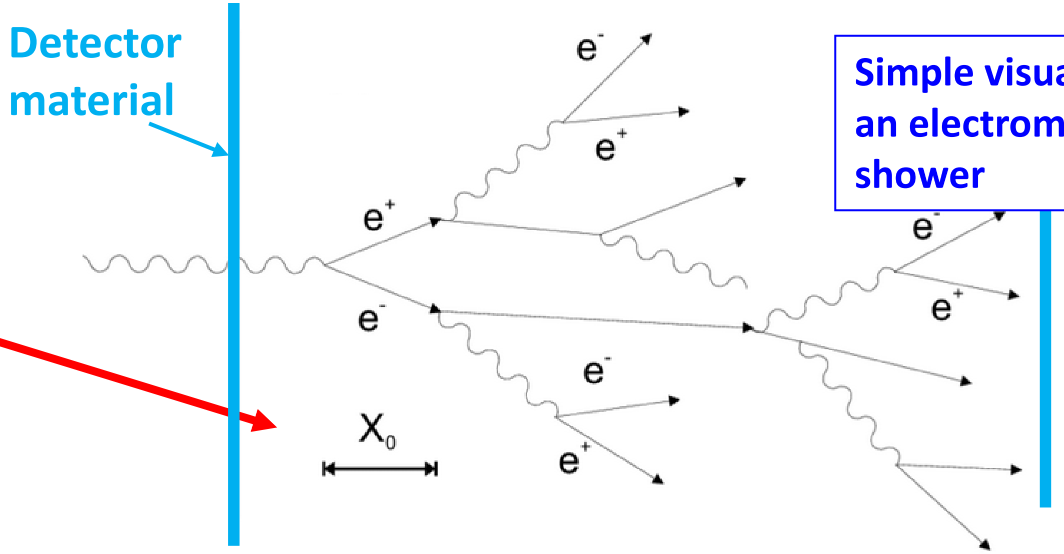
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 ln \frac{183}{Z^{1/3}}}$$

Electrons: Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E\ ln \frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow E = E_0 e^{-x/X_0}$$

After passage of one X_0, electron has only $(1/e)^{th}$ of its primary energy, i.e., 37%



Simple visualization of an electromagnetic shower

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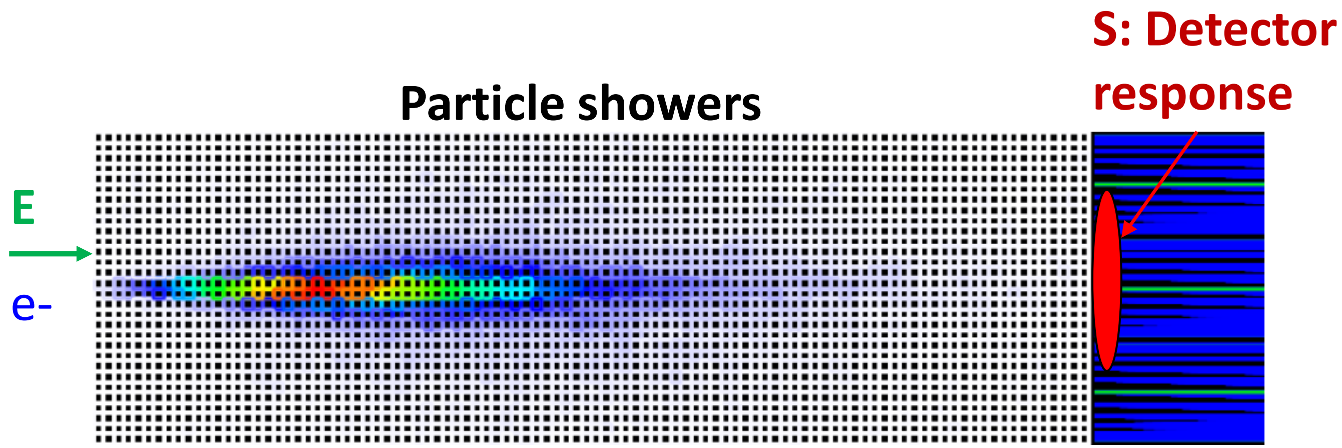
Electromagnetic Calorimeters in Nuclear physics

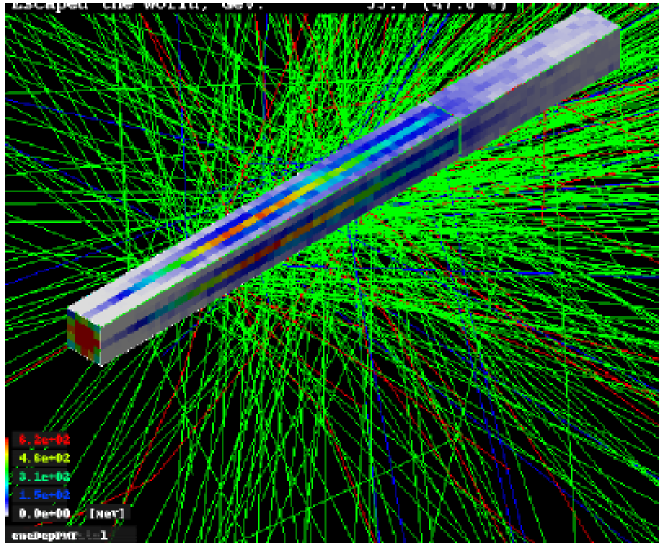
- In nuclear physics, calorimetry refers to the detection of particles, and measurements of their properties, through the total absorption in a block of matter, the calorimeter detector

- 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

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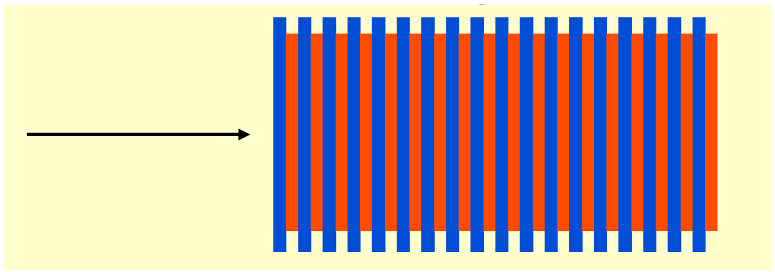
Types of Electromagnetic Calorimeters

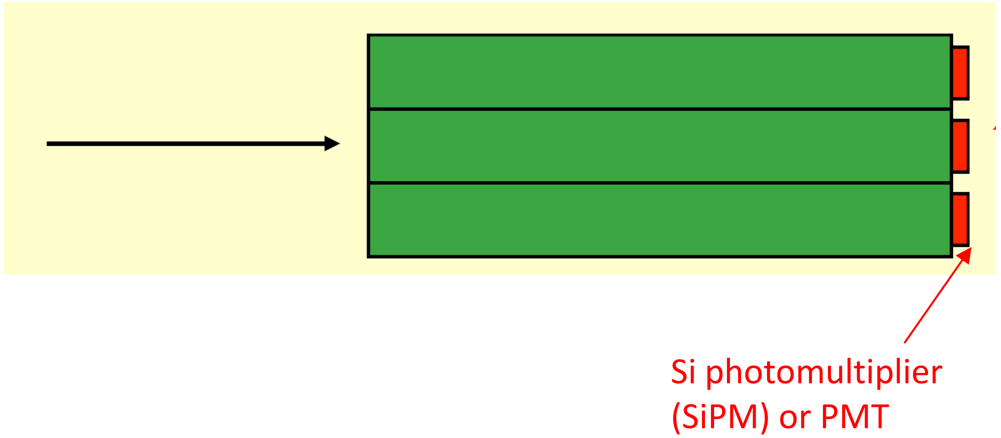
Two general classes of calorimeters

- ❑ 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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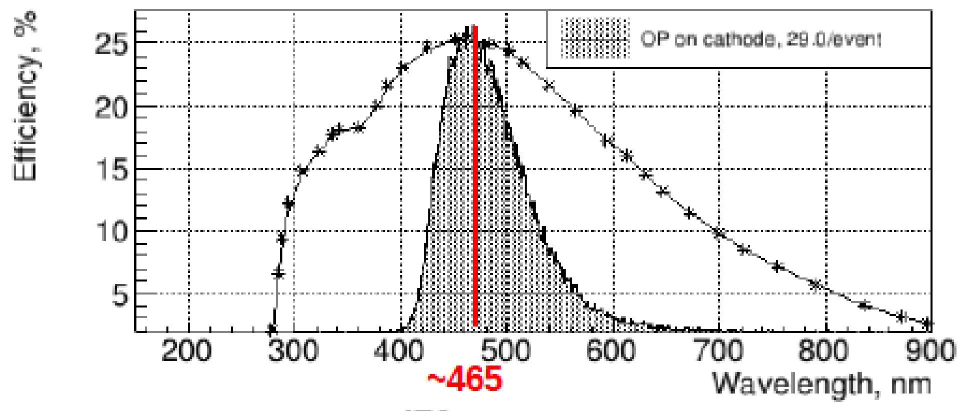
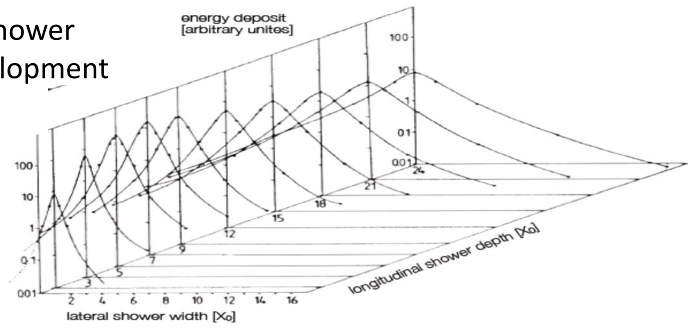
Requirements on scintillator materials

- ❑ 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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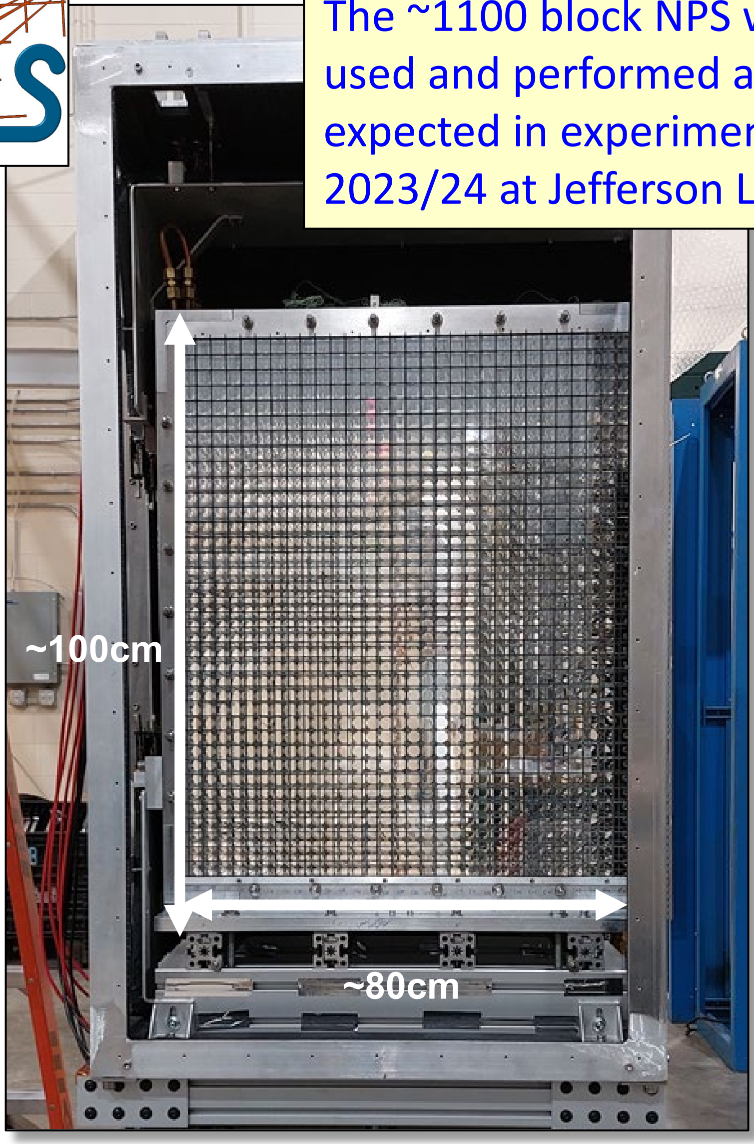
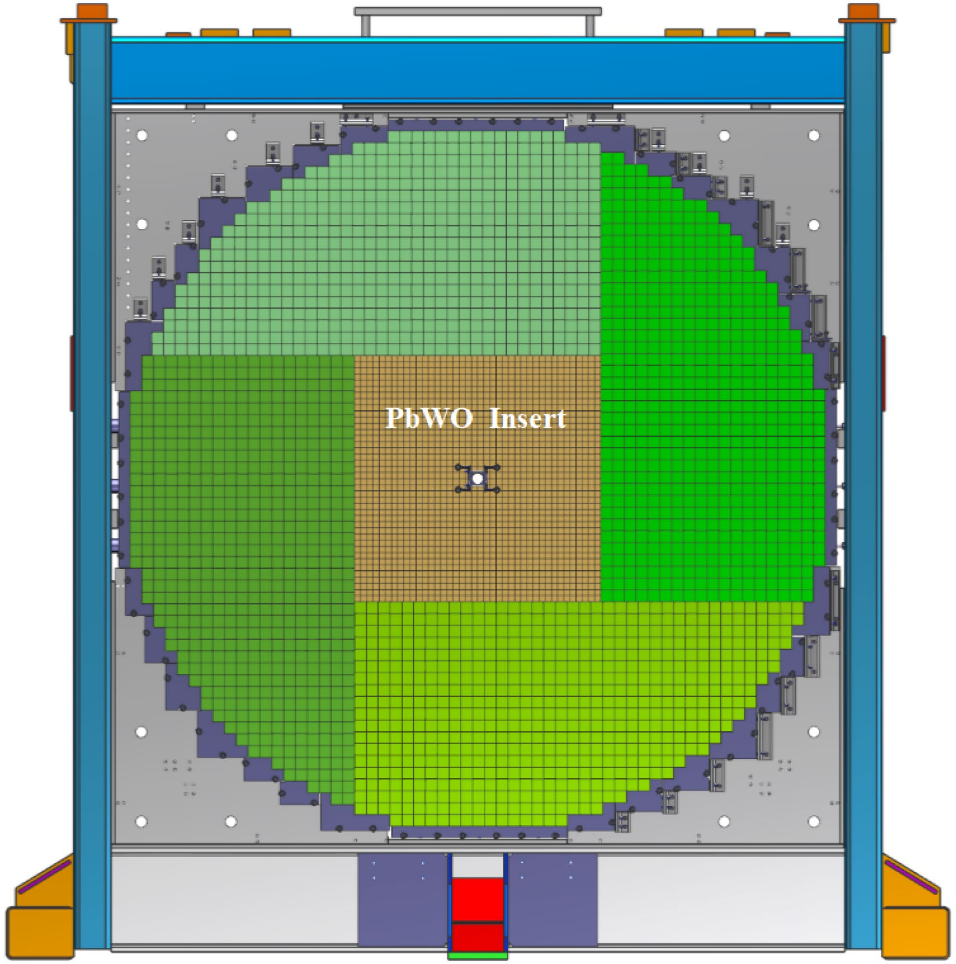
1. Examples of homogeneous EM Calorimeters at JLAB

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



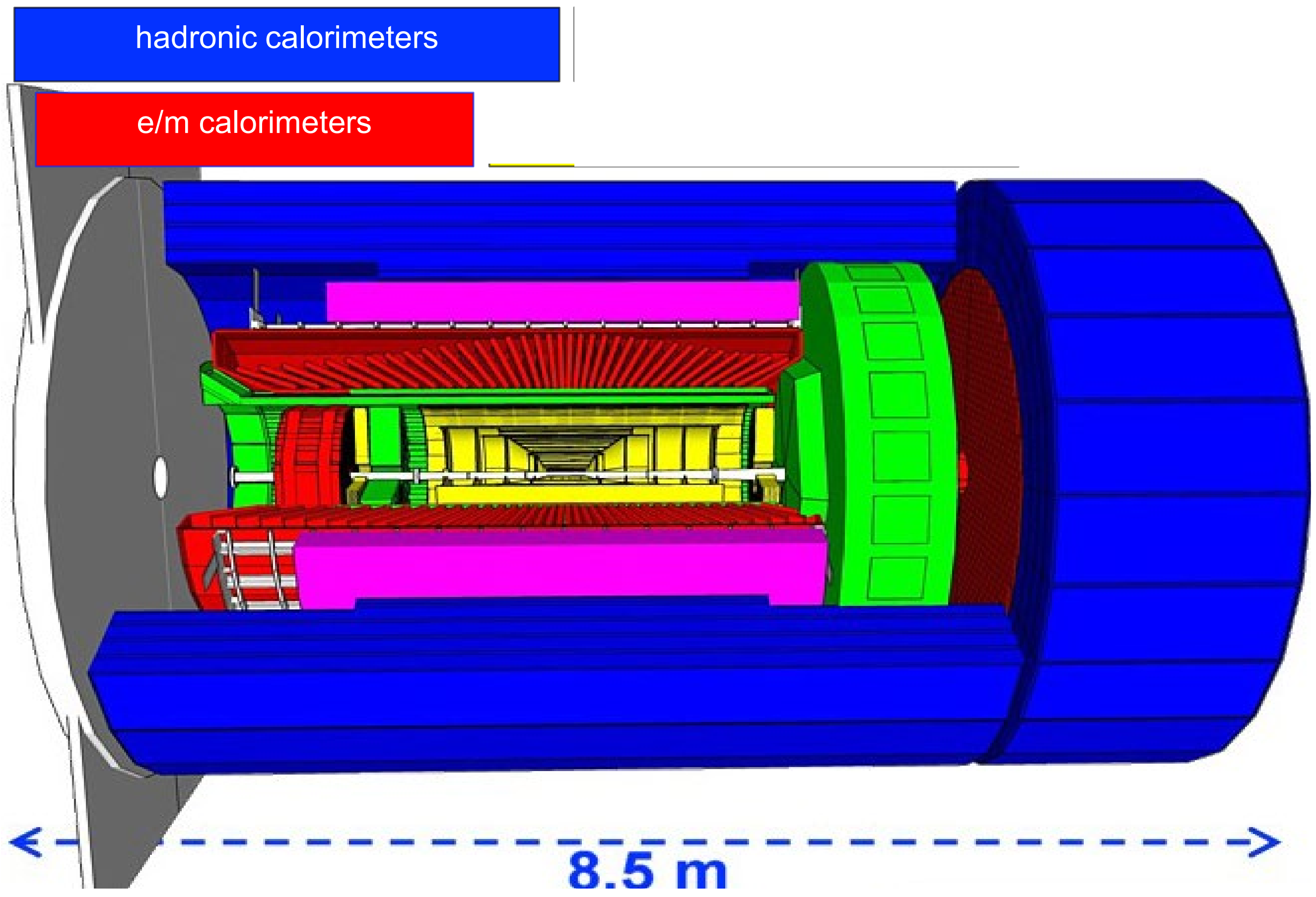
Neutral Particle Spectrometer (Hall A/C)



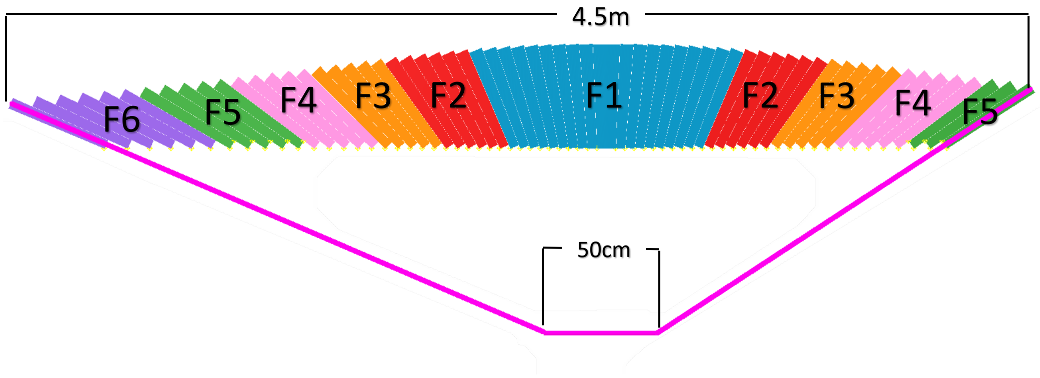
Forward CAL Insert (Hall D)

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

- **Crystals are expensive (\$15-25/cm^3)** – EIC barrel EMCal not affordable

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Glass-based Scintillators for Calorimeter Detectors

An alternative active calorimeter material that is more cost effective and easier to manufacture than, e.g. crystals

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

Shortcomings of earlier work:

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

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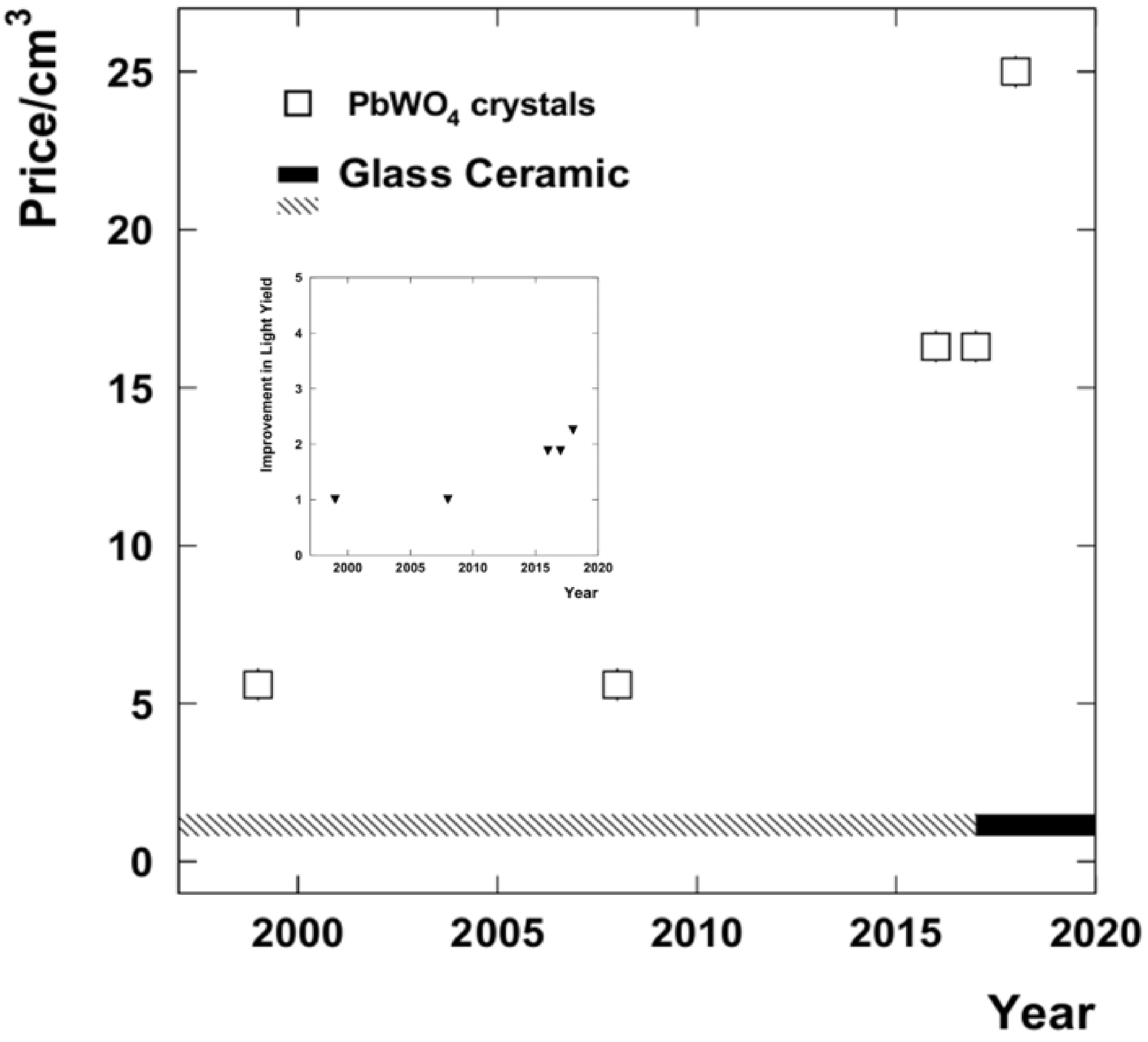
Scintilex STTR Concept



Glass fabrication is expected to be cheaper, faster, and more flexible than $PbWO_4$ crystals.

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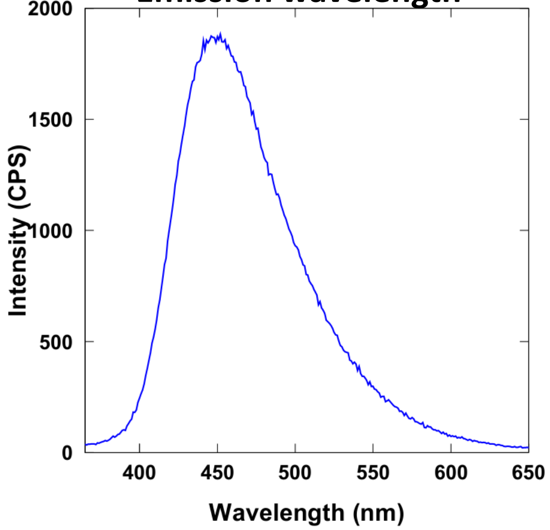
Glass Scintillator formulations

Two glass formulations for homogeneous calorimeter application

VSL-Scintilex-G4 (nominal)

VSL-Scintilex-T1

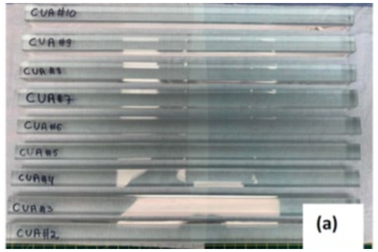
Emission wavelength



Scintillation light

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

SciGlass (this talk)

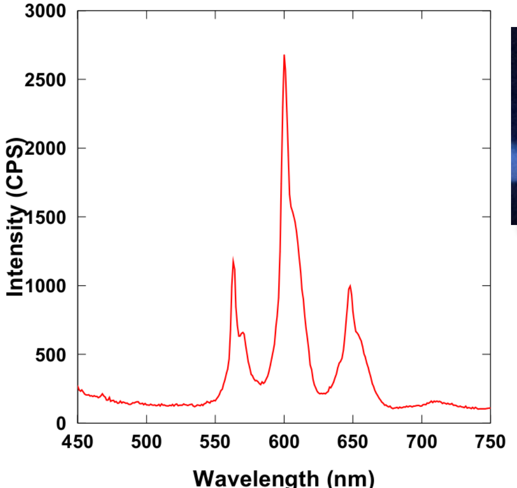


Formulations with initial emission wavelength tuning

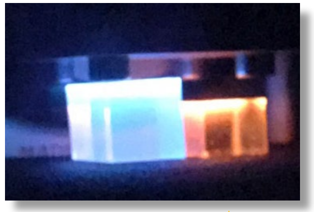
VSL-Scintilex-SC1

VSL-Scintilex-EC1

Emission wavelength

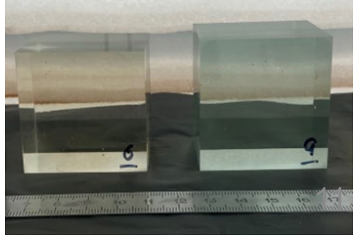


Scintillation light



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

CSGlass (for hadronic calorimeters)



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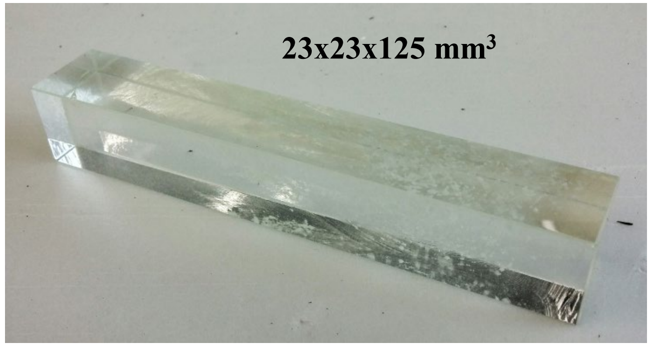
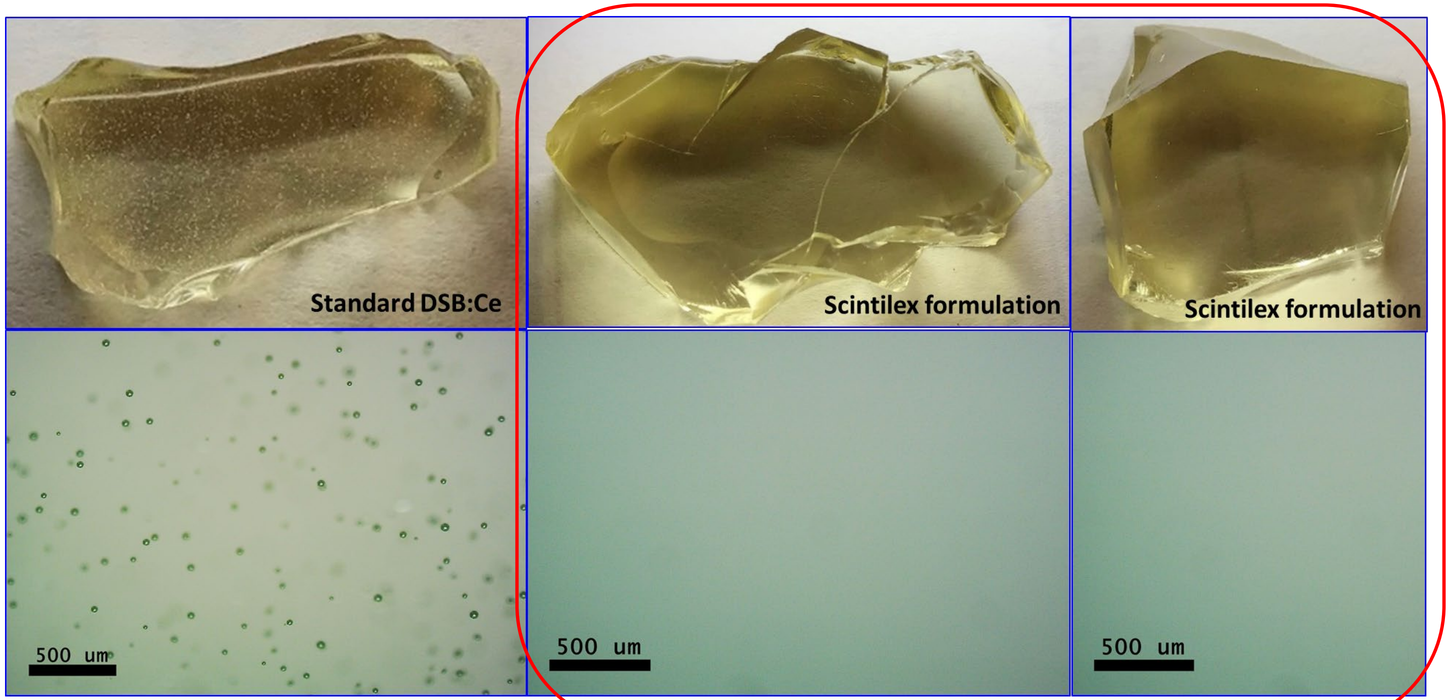
Phase 1: Process optimization to prevent non-uniformities

- ❑ 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

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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

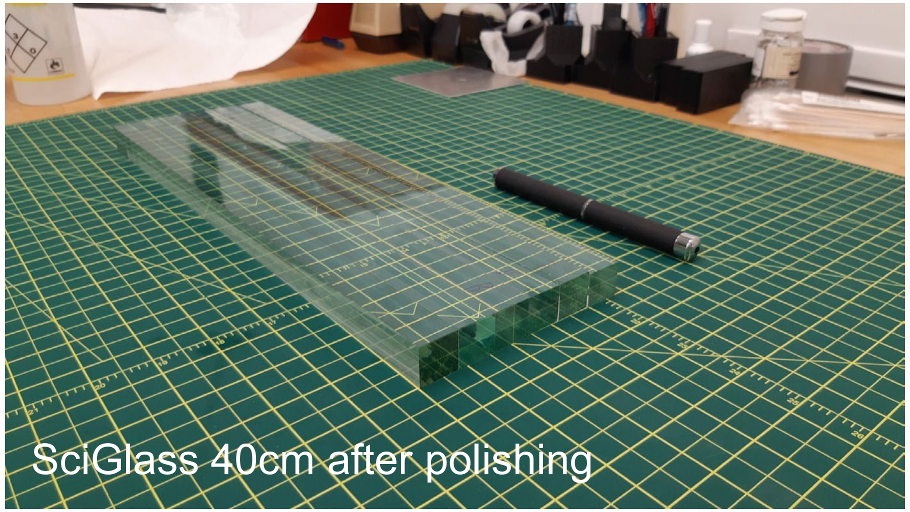
SciGlass of length 20cm can be produced reliably and 40cm blocks can now be produced routinely – lab size batches (10-25 blocks)

Glass pouring into the mold at Scintilex/VSL

SciGlass Scale-up production

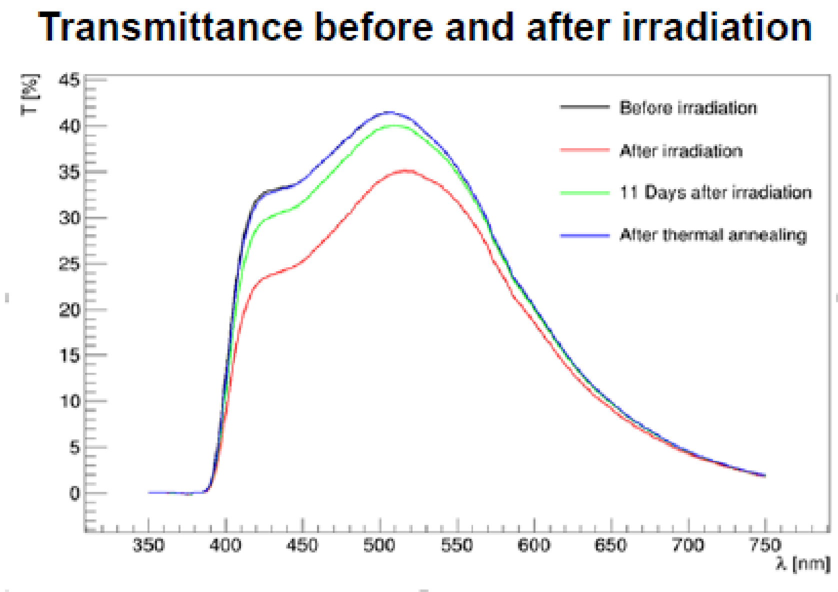
Custom fabrication setup for 40cm SciGlass

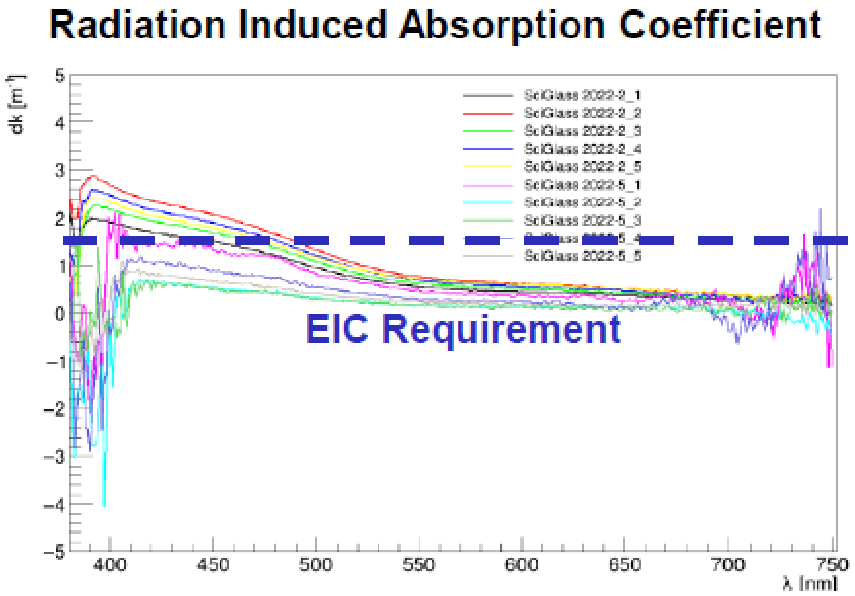
SciGlass 40cm before polishing



SciGlass 40cm after polishing

SciGlass Radiation Hardness





- ❑SciGlass blocks fulfill the radiation hardness requirements of the EIC
- ❑SciGlass has been shown to be radiation hard up to 1000 Gy (highest dose tested to date) EM radiation
  - Also radiation resistant up to 10^{15} n/cm^2 hadronic irradiation (not shown here)
- ❑Shown here are studies with 20cm blocks exposed to 30 Gy at a rate of 1 Gy/min

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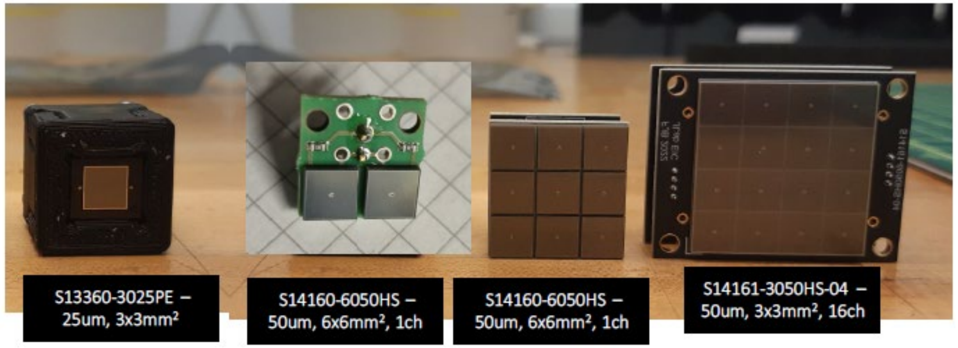
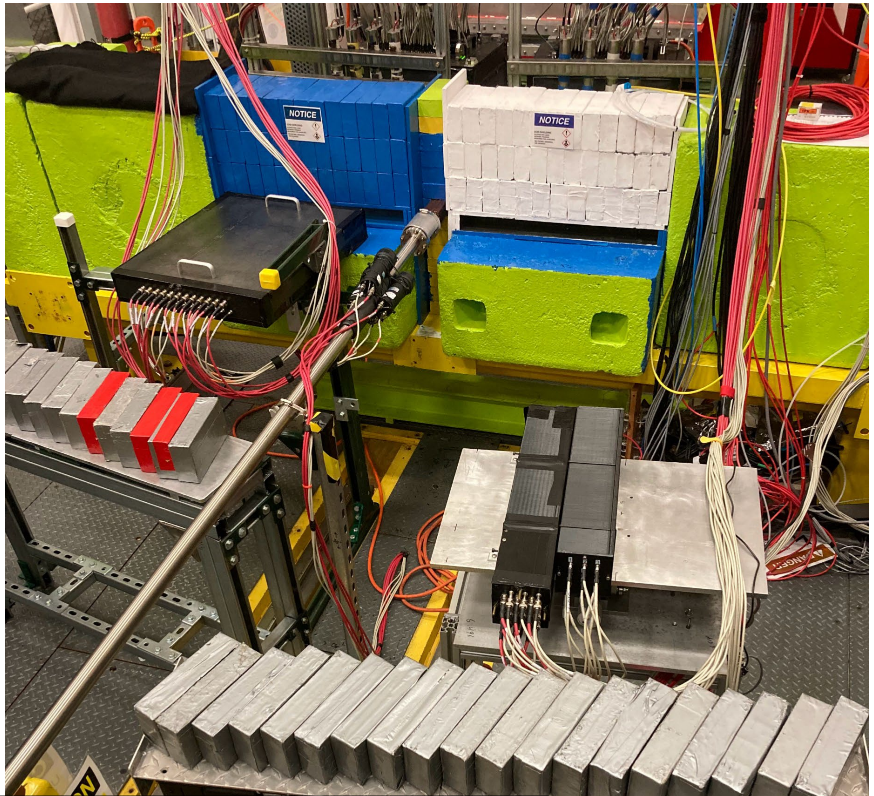
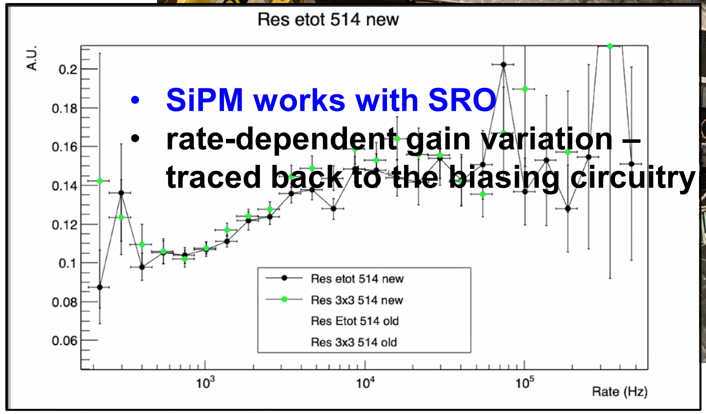
Phase 2A: SciGlass as Nuclear Physics Detector

- ❑Shortcoming of earlier work: tests not done at scale
- ✔ ❑Scintilex carried out preparations for a full beam test campaign
  - Initial chain test with glass+readout modules, 5x5 array
  - Global study of cerium-based scintillating glass
  - Glass matrix optimization – also expected to help when producing additional shapes







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

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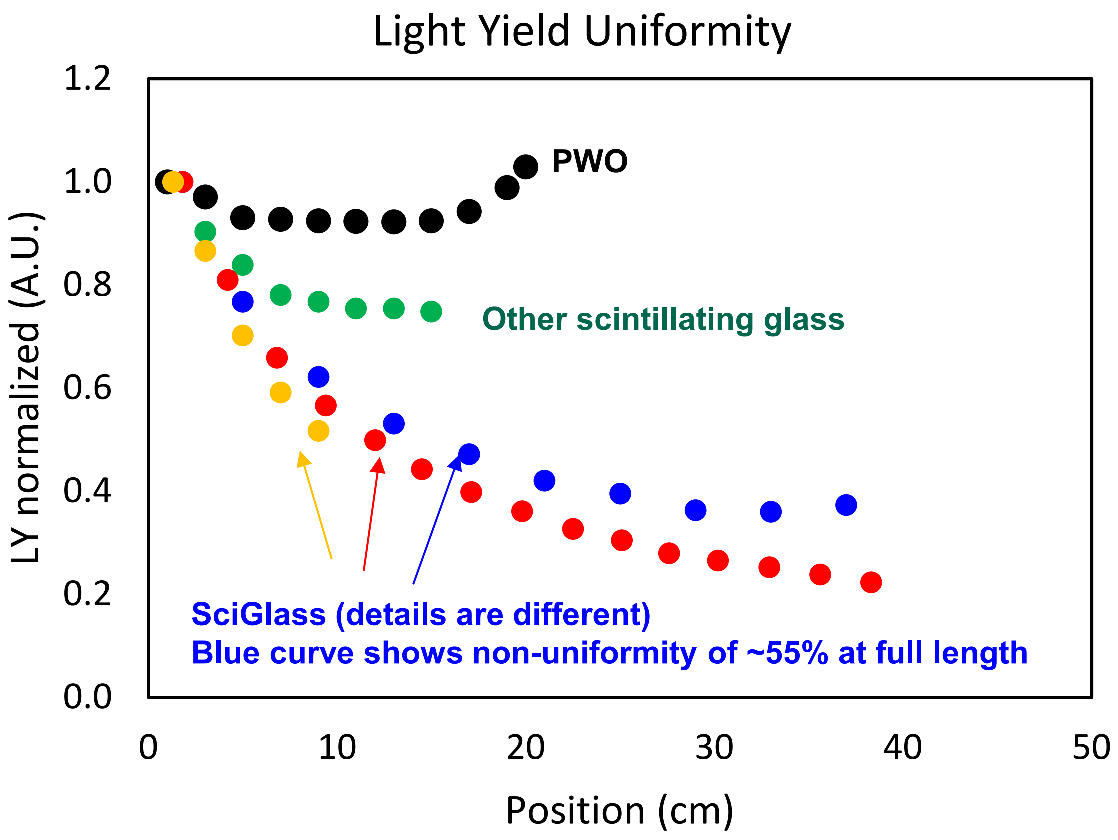
SciGlass Global Evaluation – primary optimization



Glass matrix optimizations are expected to improve the uniformity and absolute value of the light yield

- Maintaining optical properties is of the most significant challenges in scaling up scintillating glass. For example, variations in light yield as a function of length (non-uniformity) impacts the performance
  - Note: non-uniformity of the light yield along the long sample is not the light yield reduction due to length reduction(volume) of the sample. For example, for PWO it is well known that the light yield reduction is about a factor two when comparing a 1cm long sample and a 20cm long sample. For the latter the maximum light yield is on the level of 20pe/MeV and the non-uniformity is 10% for rectangular sample.
- All cerium-based scintillating glasses show a decrease in light yield as function of length. For SciGlass: down to about 80% at 5cm and ~60% at 10cm, with a further drop to ~45% at >20cm
- The dependence (non-uniformity) of the other scintillating glass is shallower (smaller) than SciGlass suggesting room for optimization to close the gap to PWO.

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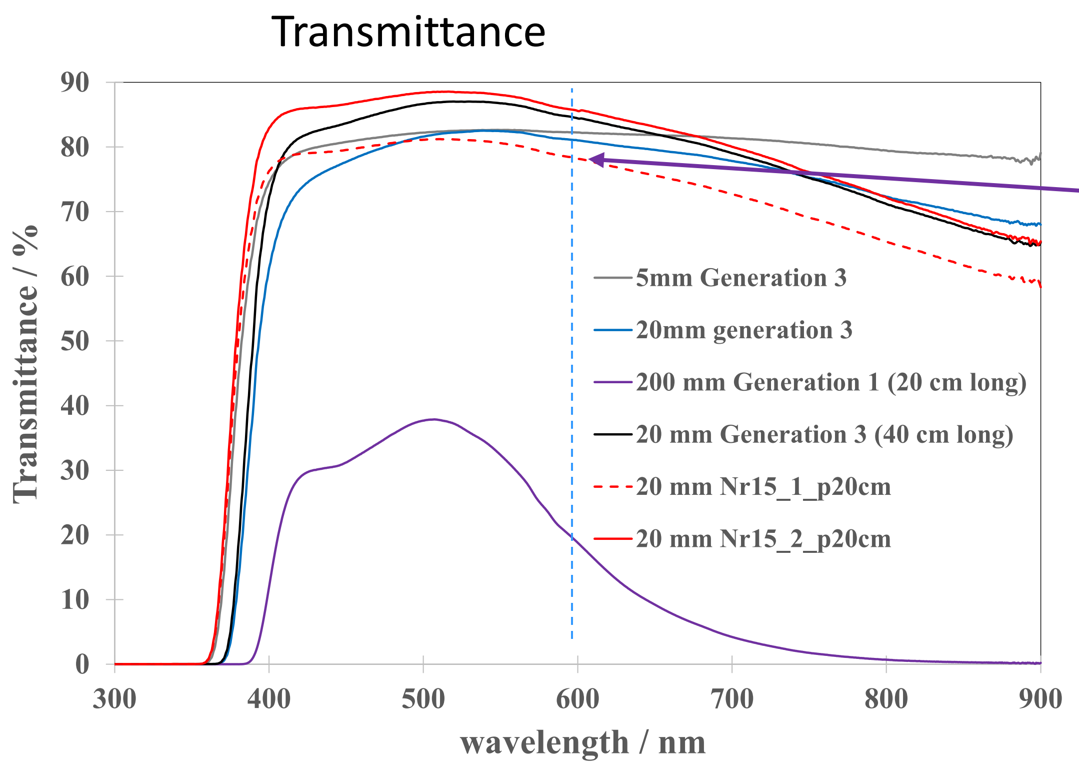
SciGlass Global Evaluation – primary optimization



- In our global analysis we found that other scintillating glasses of small thickness 0.5cm perform similarly to SciGlass. They do not show the observed turnover beyond 600nm, but their transmittance also significantly decreases in value as the thickness increases.
- Observations for SciGlass prior to matrix optimizations
  - The transmittance is flat for samples (any generation) of small thickness with a maximum value of about 80% for Gen3.
  - All longer samples show a characteristic turnover and decreasing transmittance beyond ~600nm.
  - The absolute max value depends on thickness and generation, e.g., close to 90% at ~500nm for the most recent SciGlass and ~80% for Gen3 and thickness 0.5-2cm and ~30% max at ~500nm for thickness 20cm.
  - For the long samples the transmittance goes to zero beyond wavelengths of 600nm.

Glass matrix optimizations are also expected to improve the transmittance

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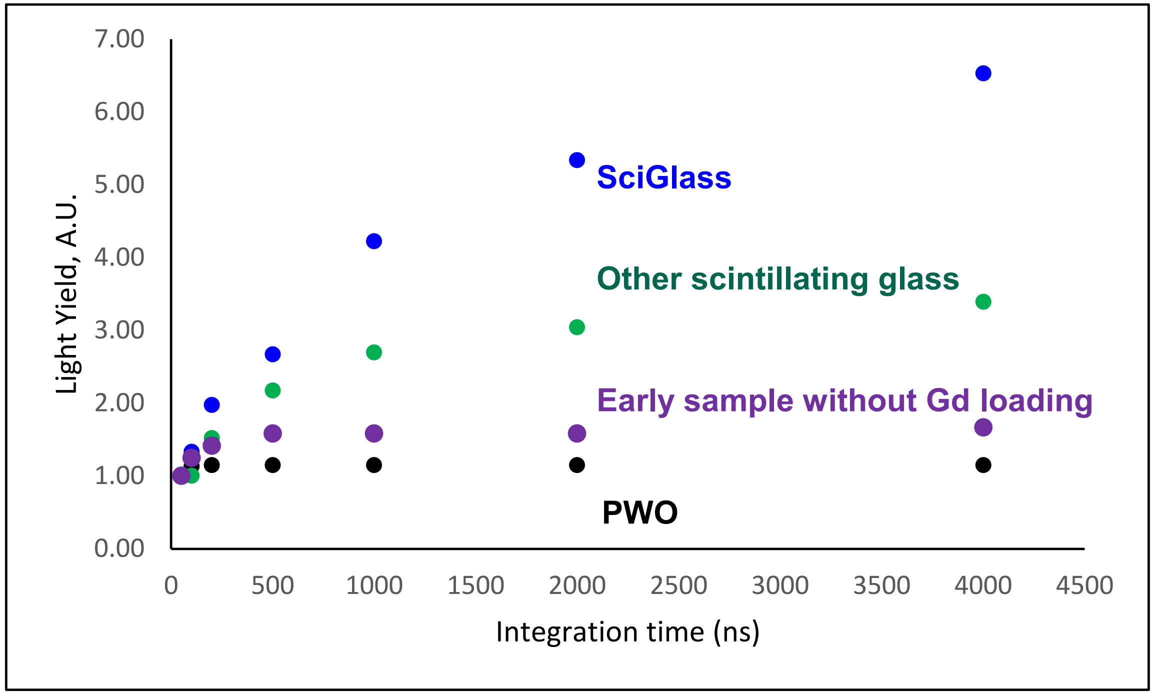
SciGlass Global Evaluation – secondary optimization

Normalized Integration Time



- New global studies include integration gates up to 5000 ns, whereas our previous studies had been limited to a few hundred nanoseconds integration time. The studies were carried out with 2cm thick samples.
- SciGlass and the other Ce-based scintillation glasses have contributions from slower components compared to PWO.
- 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.

Our second optimization path addresses the integration time - composition formula changes, Cerium doping control, raw material purity control, and optimizations of the production technology.

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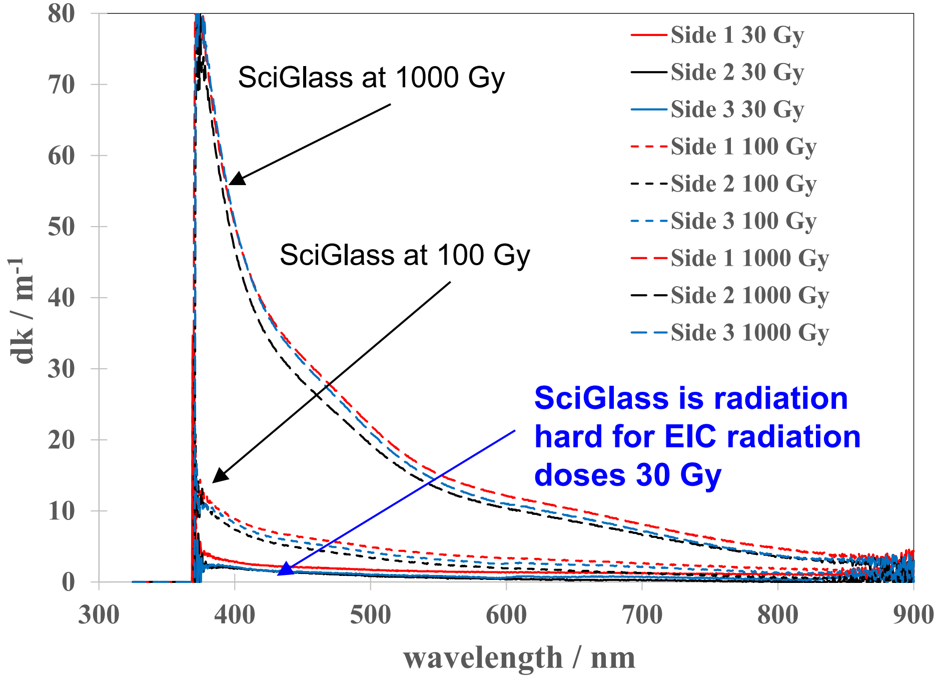
SciGlass Global Evaluation – future optimization

Radiation Resistance



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

- Our recent global radiation hardness studies were up to very high doses at lower dose rates compared to our previous studies.
- SciGlass is radiation hard at radiation doses expected at the EIC (30 Gy), shows signs of radiation damage at 100 Gy, and significant radiation damage at 1000 Gy.
- Based on our earlier studies the recovery mechanism of scintillating glass is like that of scintillating crystals, e.g., radiation damage can be cured by supplying energy (thermal or blue/UV light). The radiation resistance of SciGlass is comparable to that of other Ce-based scintillation glasses.

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

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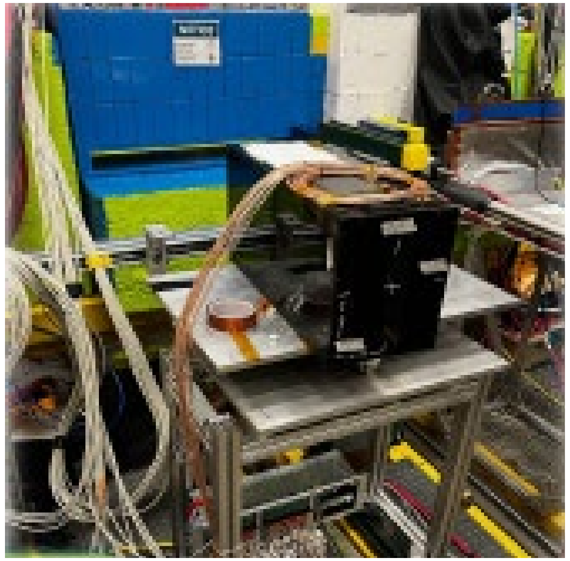
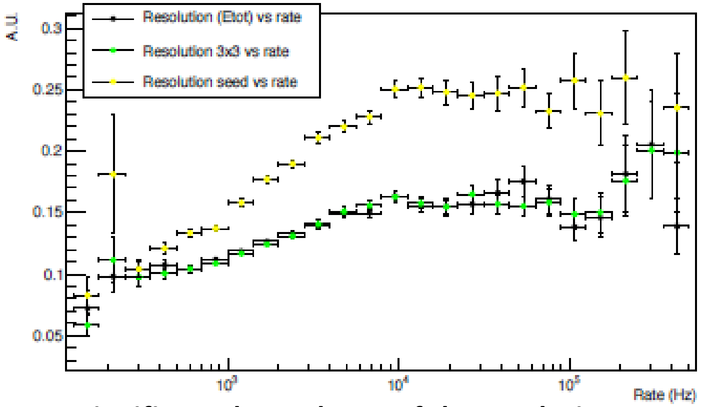
Full Prototype Beam Tests – 5x5 array with 40cm blocks

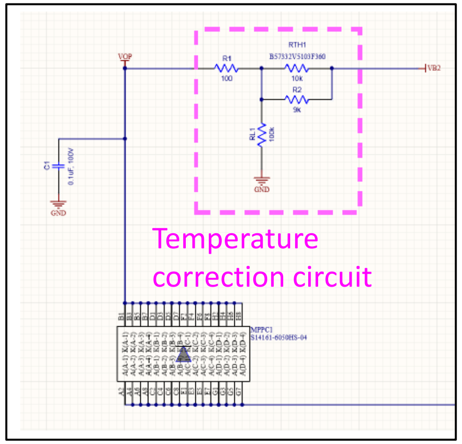


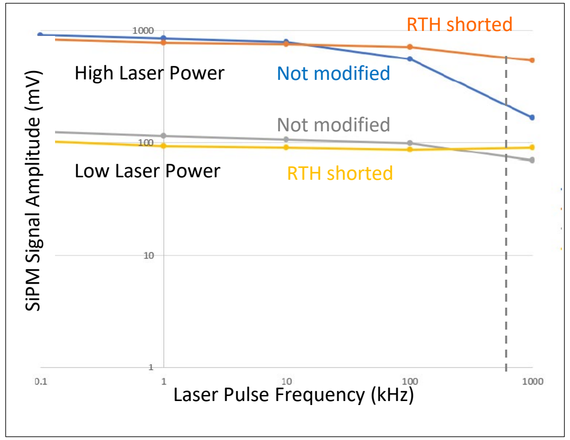
- The initial chain test was carried out with glass+readout modules in a 5x5 array configuration - 40cm long SciGlass and readout with a matrix of 2x1 Silicon PMs (the readout method of choice to be used at the EIC).
  - The chain test array detector was installed behind the pair spectrometer on Hall D.
  - Data were taken in two readout configurations: standard readout and streaming readout 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.



Significant dependence of the resolution on rate with the resolution deteriorating as the signal rate increases.

- Test bench of the SiPM response at different rate and with pulsed light at fixed intensity confirmed the chain test behavior
  - demonstrated that a 3x3 SiPM matrix has better performance compared to a 2x1 SiPM configuration - linear response for larger signals and did not saturate up to a few GeV.
  - However, shows similar energy/rate dependence for both with a higher corner frequency - observed to be around 1 kHz. The root cause of this behavior was traced back to high input impedance in the adapter board's temperature correction circuit. After minimizing the input impedance and increasing the bulk capacitance a linearized gain was obtained.





Based on these chain and test bench tests we plan to use the 3x3 SiPM matrix configuration for the beam test to assess the energy resolution performance of a SciGlass calorimeter detector.

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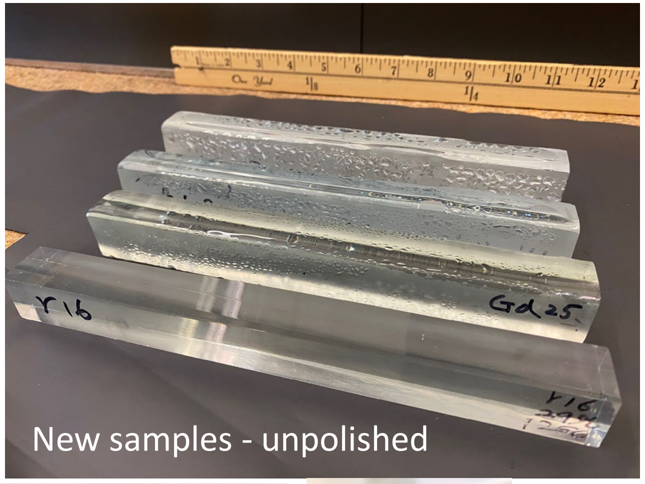
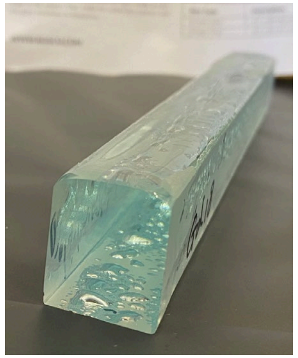
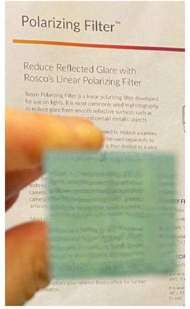
Glass Matrix Optimization Status



New samples - unpolished





View through 200mm

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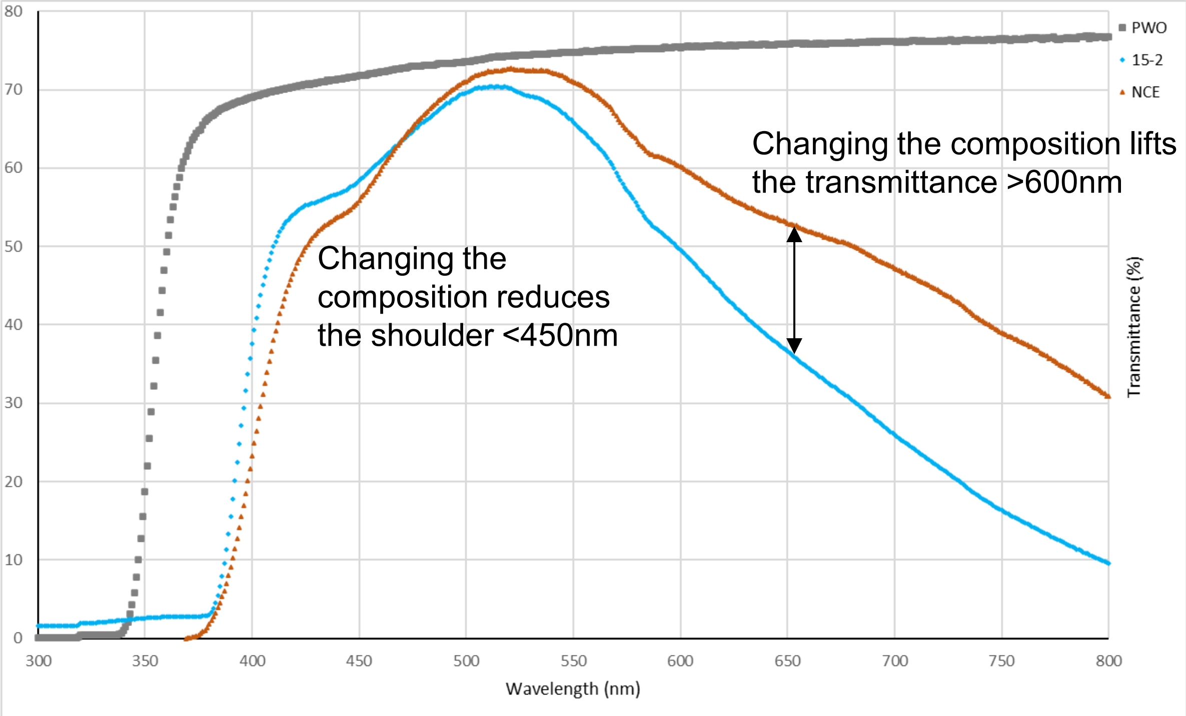
- ❑ New samples were made with new glass matrix and characteristics measured – provide the starting point of the optimization



The remaining Phase2A program can be divided into three periods:

- ❑ complete the glass formulation optimizations and initial preparations for the beam test, e.g., produce the readout boards; publish the results on SciGlass global studies
- ❑ produce and characterize the glass blocks needed for the beam test, which will also demonstrate our production capabilities. In parallel we will demonstrate the ability to produce bars of various shapes, which we have already started with different rectangular geometries.
- ❑ prepare and carry out the beam test and analyze the resulting data; prepare the final report

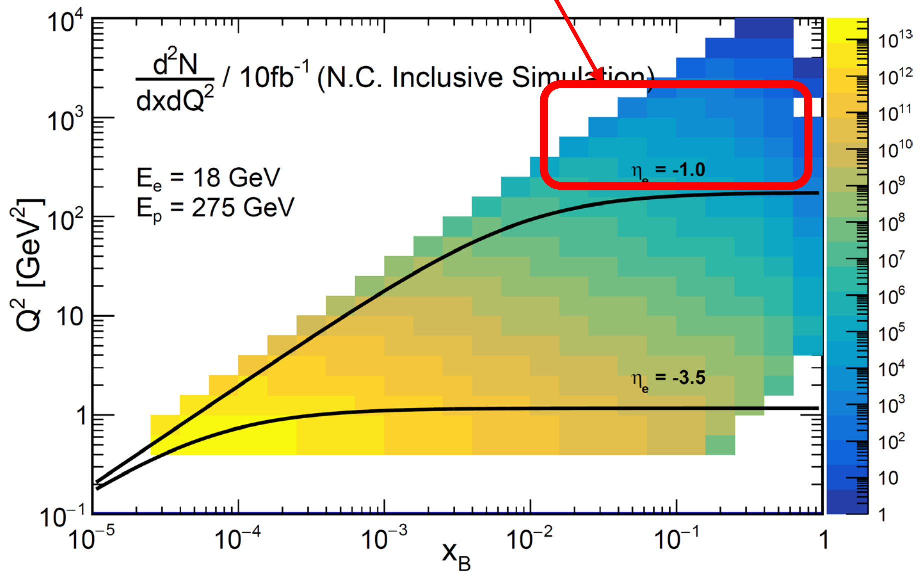
SciGlass at EIC

Scattered electron kinematics measurement is essential at the EIC

- High precision, hermetic detection of the scattered electron is required over a broad range in η and over energy range from 0.3 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
- Here, SciGlass is presented for the barrel EMCal as this provides excellent e/h separation due to its good energy resolution, matched to the backward region needs

η	Backward	Barrel
Material	$PbWO_4$	SciGlass
X_0 (mm)	8.9	24-28
R_M (mm)	19.6	35
Cell (mm)	20	40
X/X_0	22.5	17.5
Δz (mm)	60	56

Physics kinematic region enabled by the Barrel EMCal



Requirements (EIC Yellow Report)
- Good energy resolution
  - e.g., region -2 < η < -1 requires ~7%/√E
- e/h separation up to 10^{-4}

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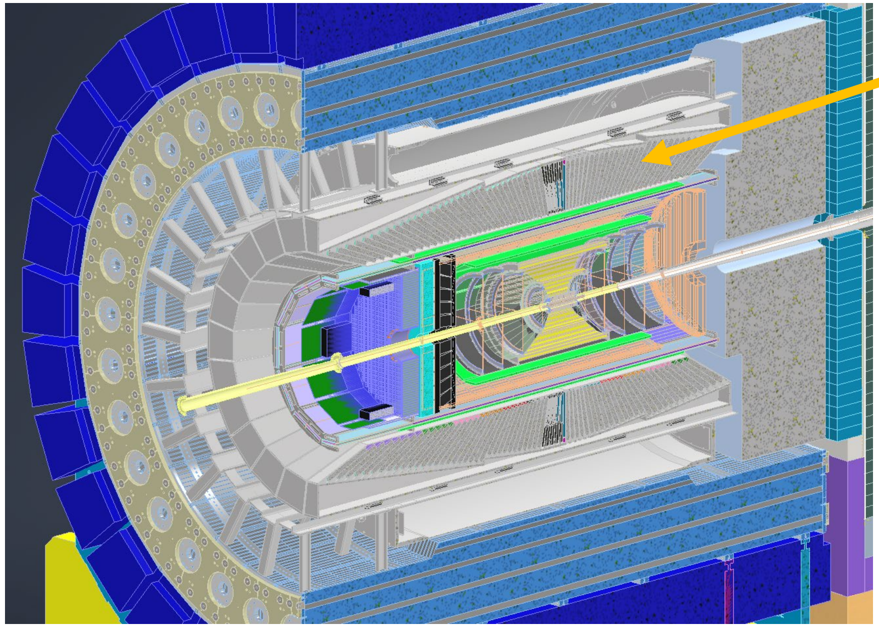
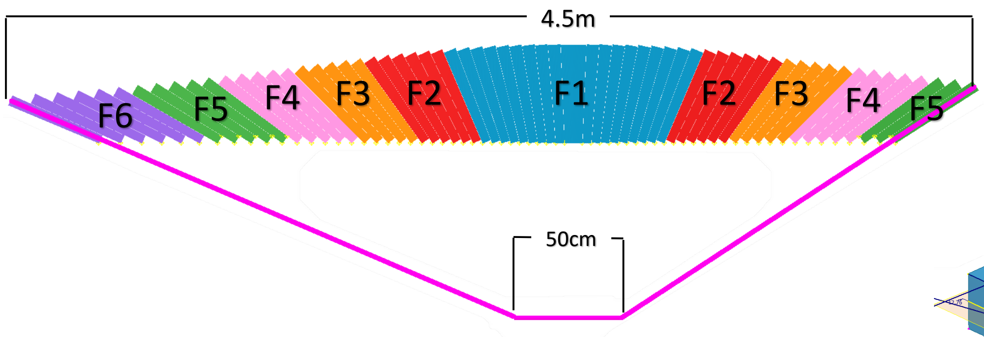
A SciGlass barrel EMCal in the EIC Detector

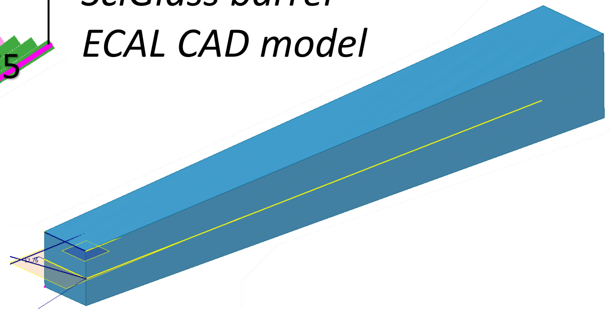


SciGlass ***Barrel ECAL in EIC detector model***

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

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

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SciGlass barrel EMCal Projected Performance

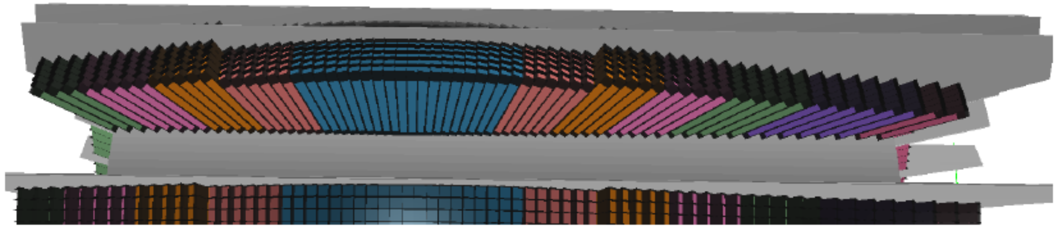
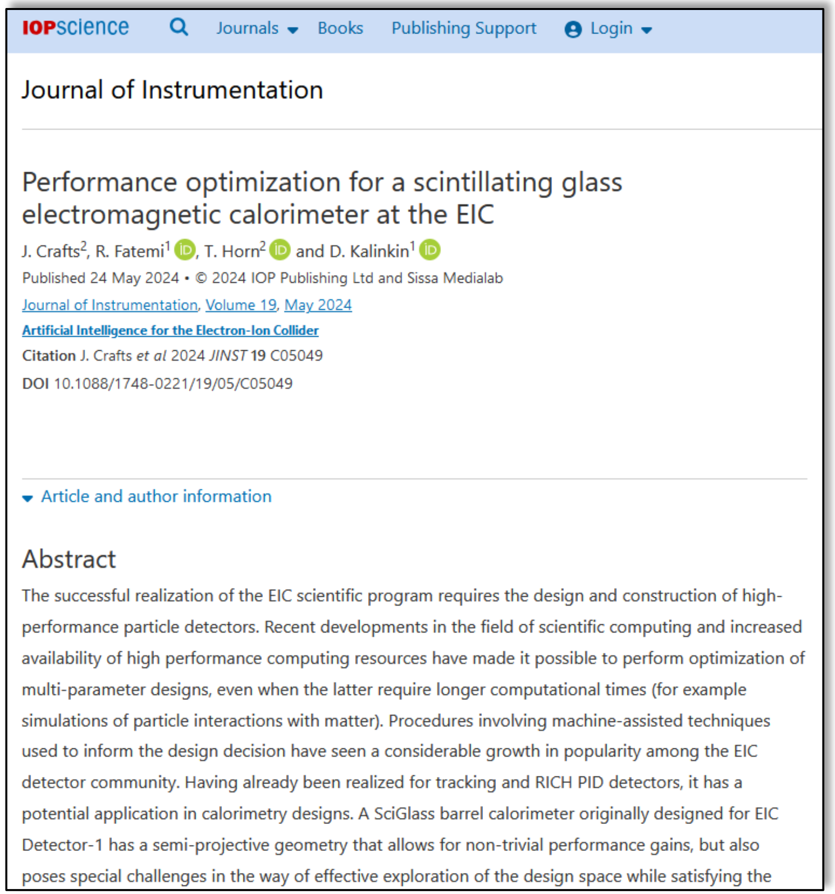


Figure 1: Top-down view of one of the 12 sectors of the SciGlass projective geometry for Detector-II at EIC, with the sector in front of it removed for visibility. Seven different cell colors mark seven assumed shapes. Black denotes carbon fiber supports, and grey represent wall of the wedge box surrounding each sector.

Analyze the performance using Multi-Objective Bayesian Optimization



Journal of Instrumentation

Performance optimization for a scintillating glass electromagnetic calorimeter at the EIC

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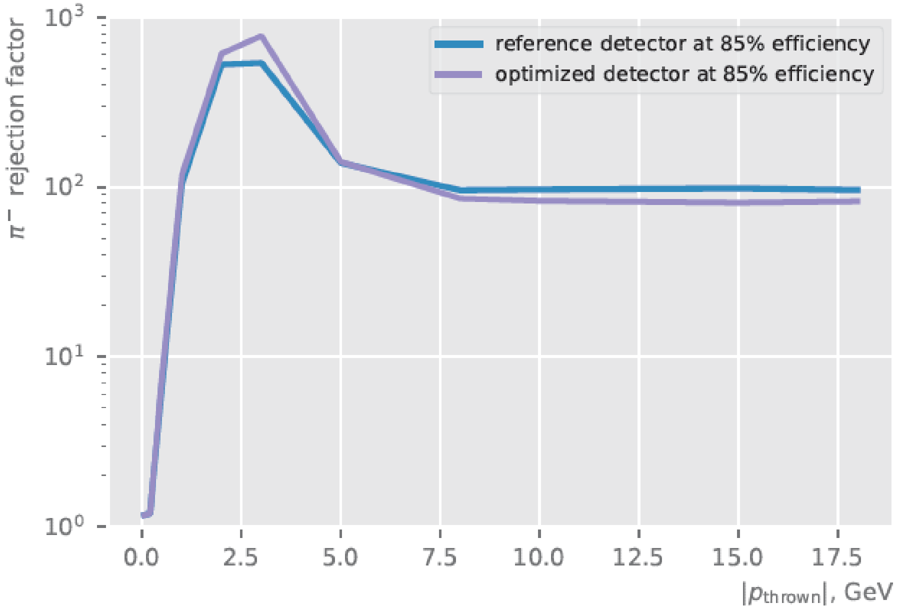
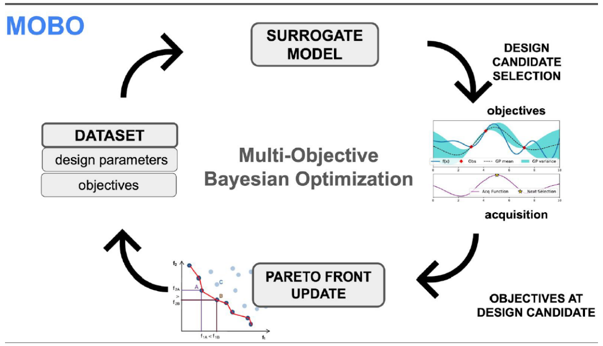
Article and author information

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 optimized detector outperforms the reference in terms of pion rejection

- The SciGlass detector has potential application as a prominent design mid-rapidity electron electron measurement device in EIC Detector-II
- The detector design can be further optimized using ML optimization techniques

SCINTILEX

Outlook

Acknowledgement: Award: DE-SC0020619

- ❑ Demonstrated a novel scintillating glass (SciGlass) as an 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)
- ❑ Performance validation carried out with prototype 3x3 SciGlass arrays (20cm and 40cm blocks) and suitable readout for NP experiments – energy resolution matches GEANT4 projections
- ❑ **Phase 2A:**
  - ❑ **produce sufficient SciGlass bars to complete testing with a larger, e.g., 5x5 detector prototype - supported by our characterization results, simulations, and community feedback, most recently from the EIC Detector Advisory Committee**
  - ❑ **further optimize the block size relative to the Moliere radius and complete the objective of demonstrating the ability to produce bars of various shapes**