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

Principal Investigator: Tanja Horn

Business Official: Ian L. Pegg

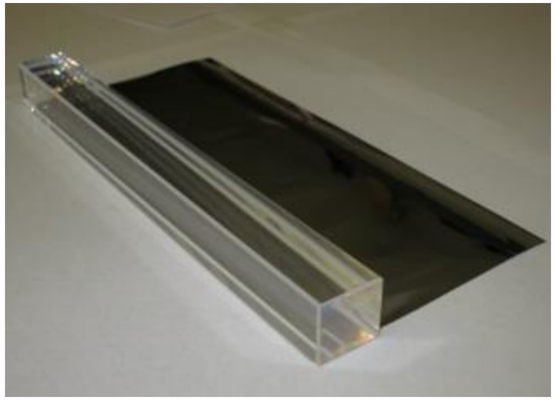
Award: DE-SC0020619

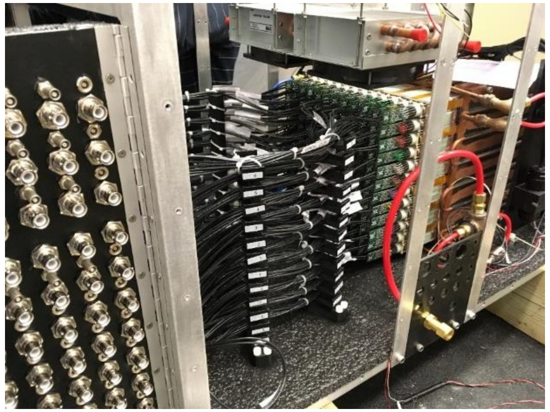
Scintilex Overview

- 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
  - 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): eRD1, eRD105, EPIC Detector
  - PANDA EMCal test runs





SCINTILEX

Scintillation Detector Basics: Electromagnetic Showers

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

Photons : Pair production

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

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

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

Absorption coefficient:

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

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

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

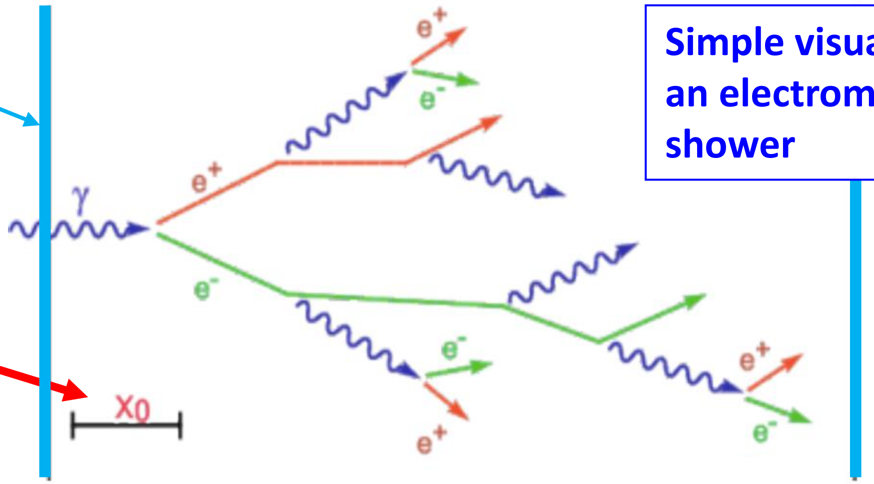
Electrons : Bremsstrahlung

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

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

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

Detector material

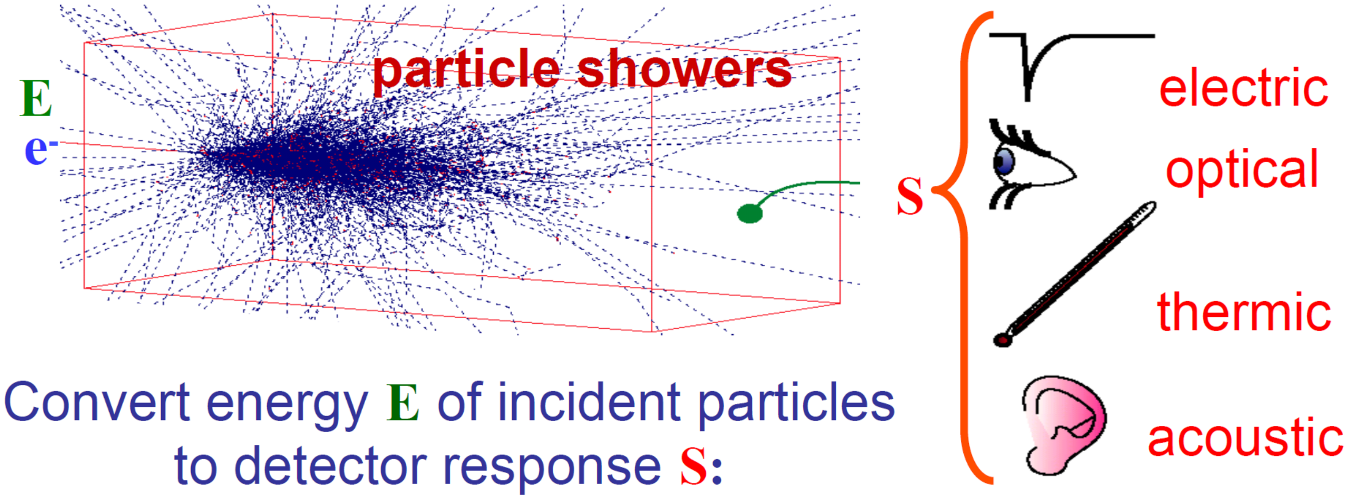


Simple visualization of an electromagnetic shower

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



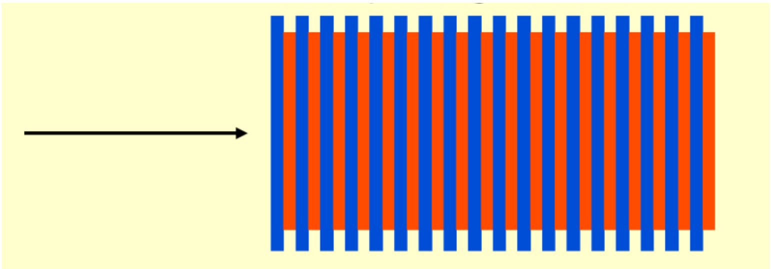
Convert energy **E** of incident particles to detector response **S**:

$S \propto E$

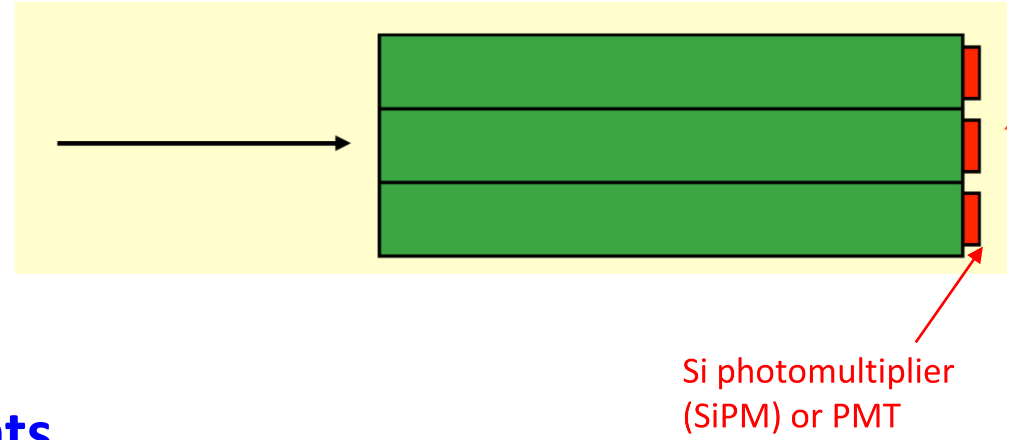
Types of Electromagnetic Calorimeters

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.



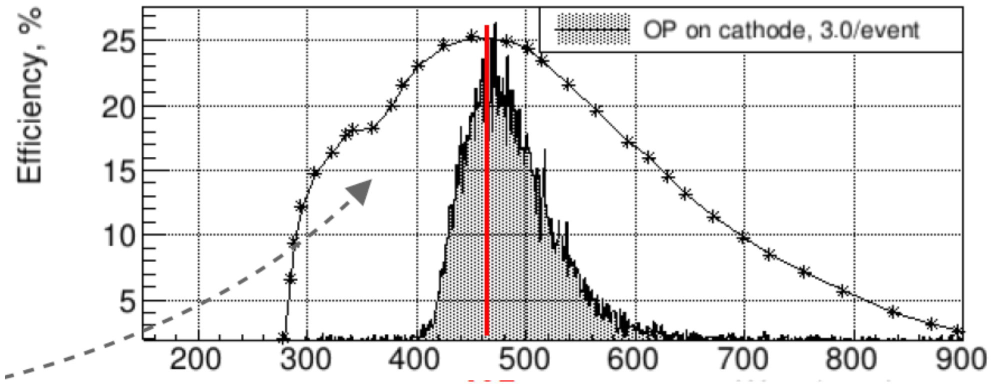
- ❑ Homogeneous Calorimeters: A single medium serves as both absorber and detector, e.g., crystals (BGO, $PbWO_4$, …) or glass scintillators



Precision measurements in nuclear physics experiments require homogeneous calorimeters

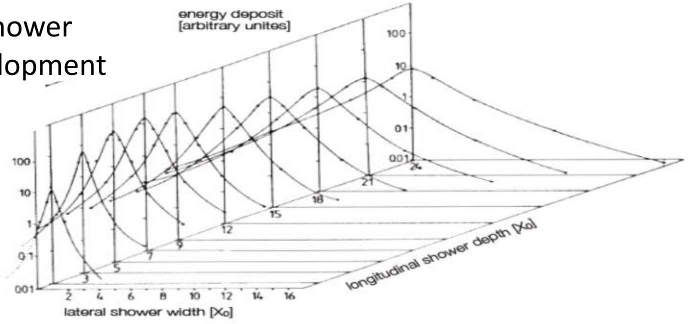
Requirements on Scintillator Materials

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



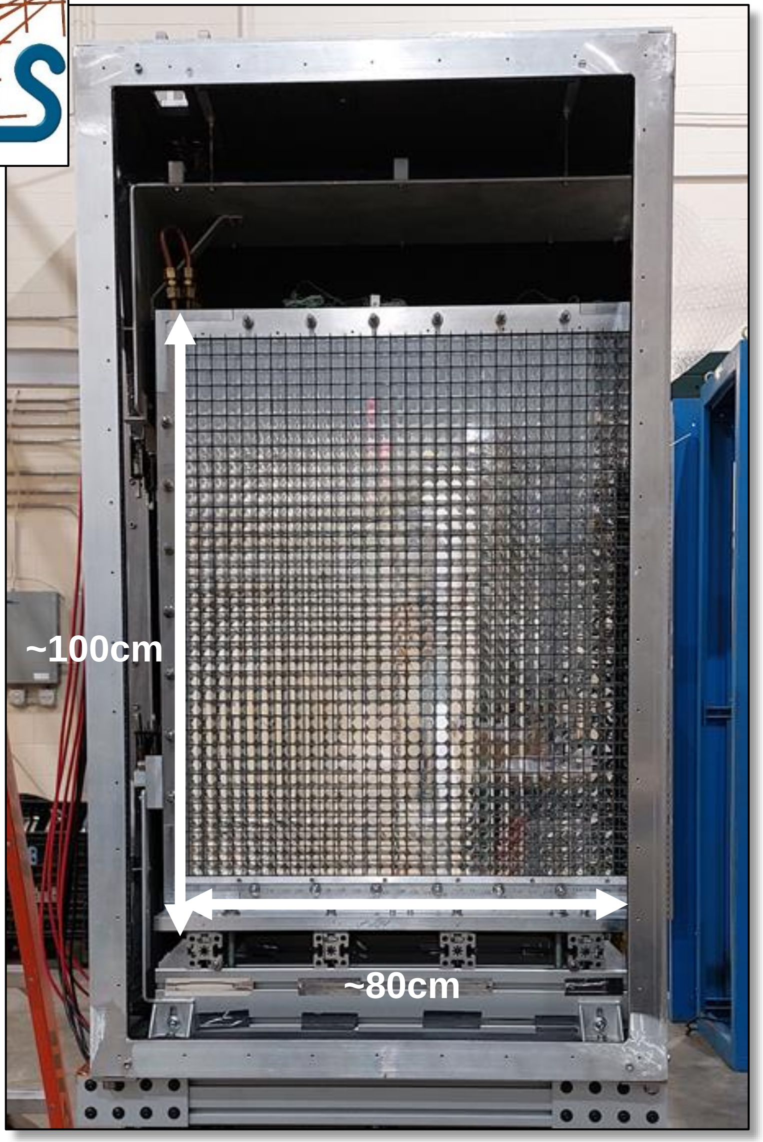
- ❑ Emission spectrum matching between scintillator and photo detector – emission peak
- ❑ Chemical stability and radiation resistance – induced absorption coefficient
- ❑ Linearity of light response with incident photon energy – LY(100μs)/LY(10ms)
- ❑ Moliere radius for lateral shower containment
-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

3D shower development

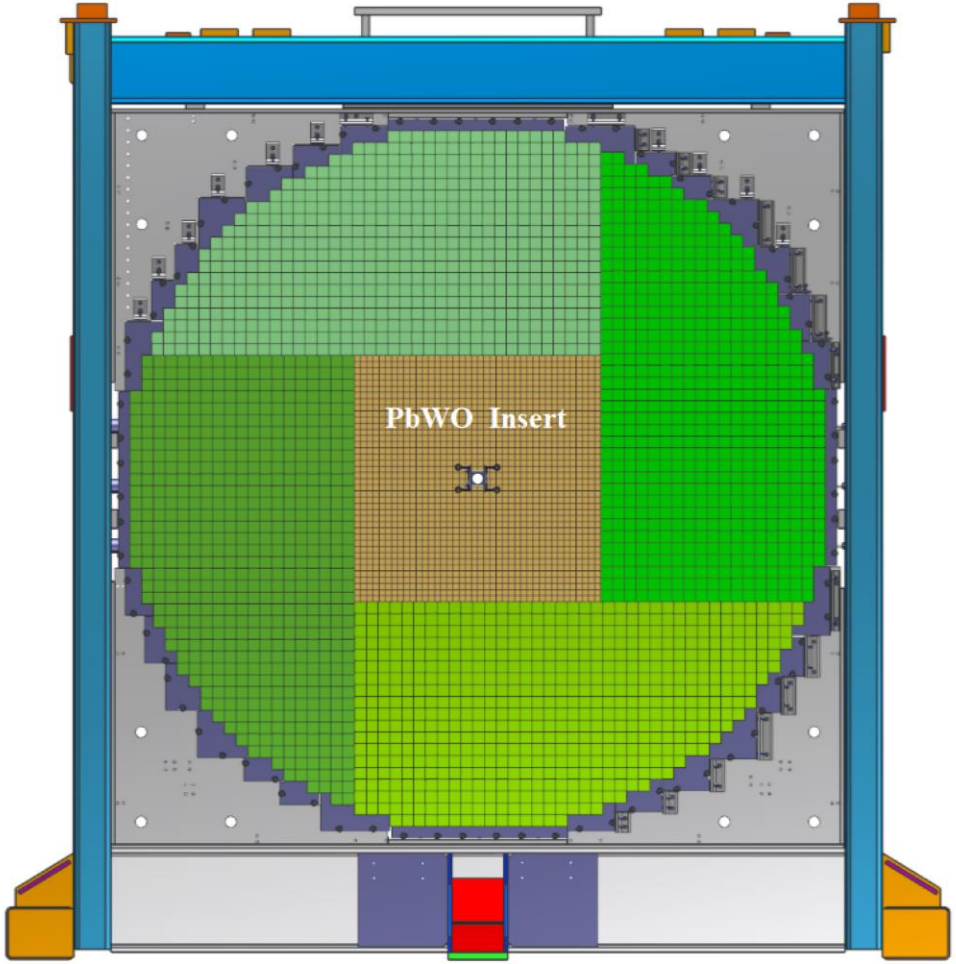


SCINTILEX

1. Examples of Homogeneous EM Calorimeters at JLAB



Neutral Particle Spectrometer (Hall A/C)

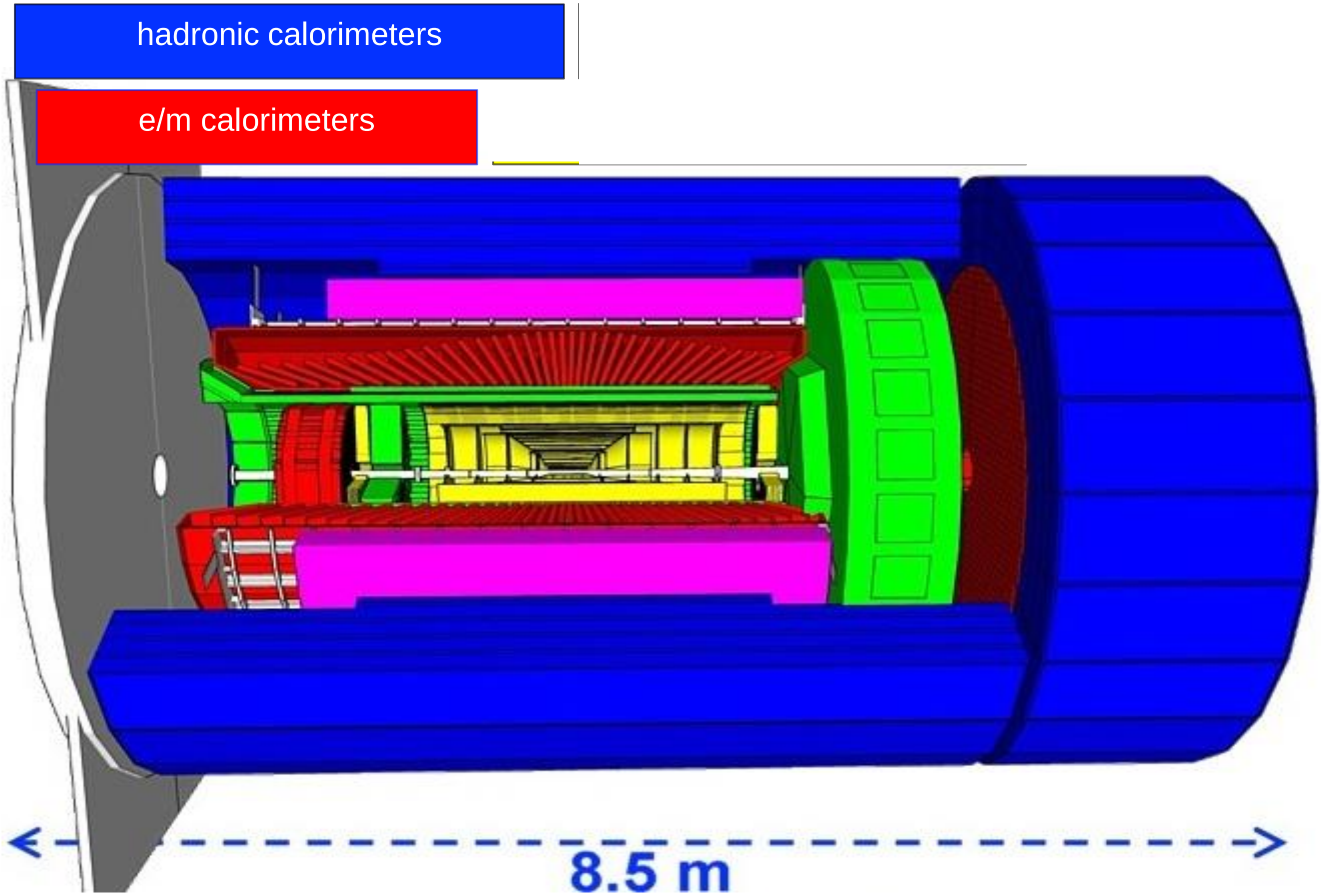


Forward CAL Insert (Hall D)

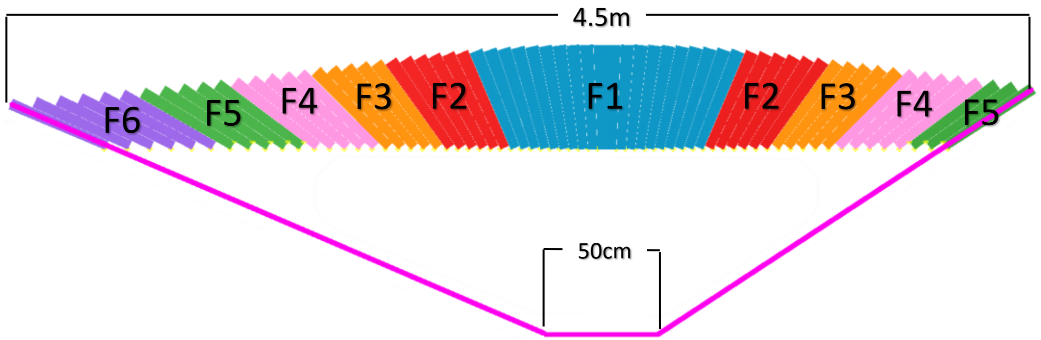
SCINTILEX

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

- **Glass** is simpler and cheaper to produce

SCINTILEX

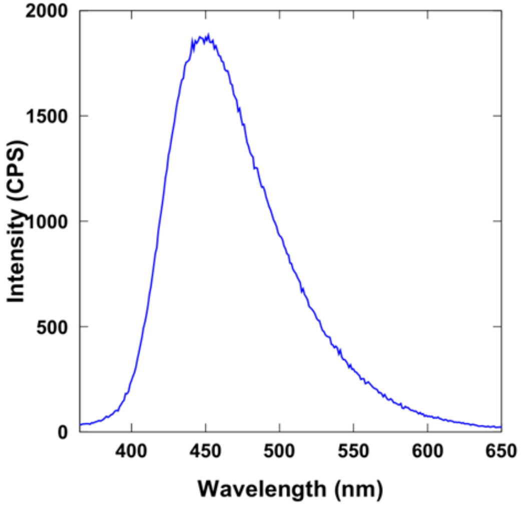
Glass Scintillator Formulations

✓ Two glass formulations for homogeneous calorimeter application

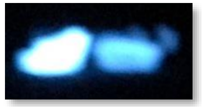
VSL-Scintilex-G4 (nominal)

VSL-Scintilex-T1

Emission wavelength

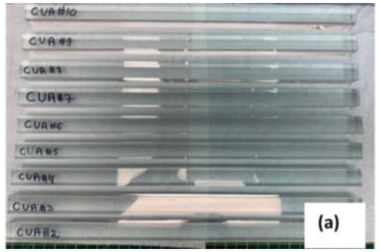


Scintillation light



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

SciGlass (this talk)

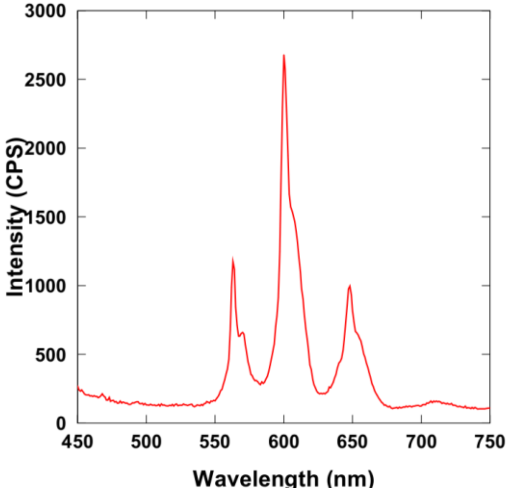


✓ Formulations with initial emission wavelength tuning

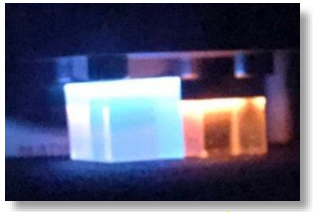
VSL-Scintilex-SC1

VSL-Scintilex-EC1

Emission wavelength

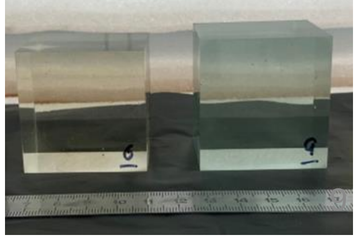


Scintillation light



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

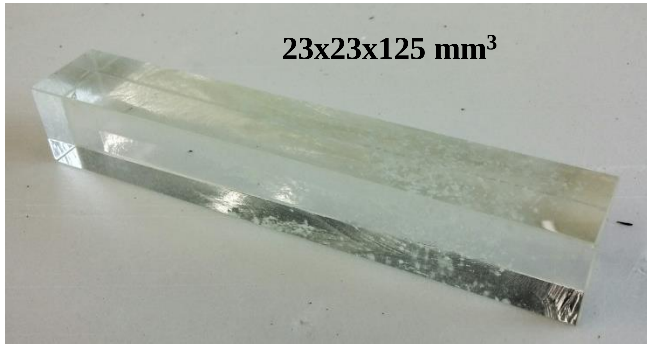
CSGlass (for hadronic calorimeters)



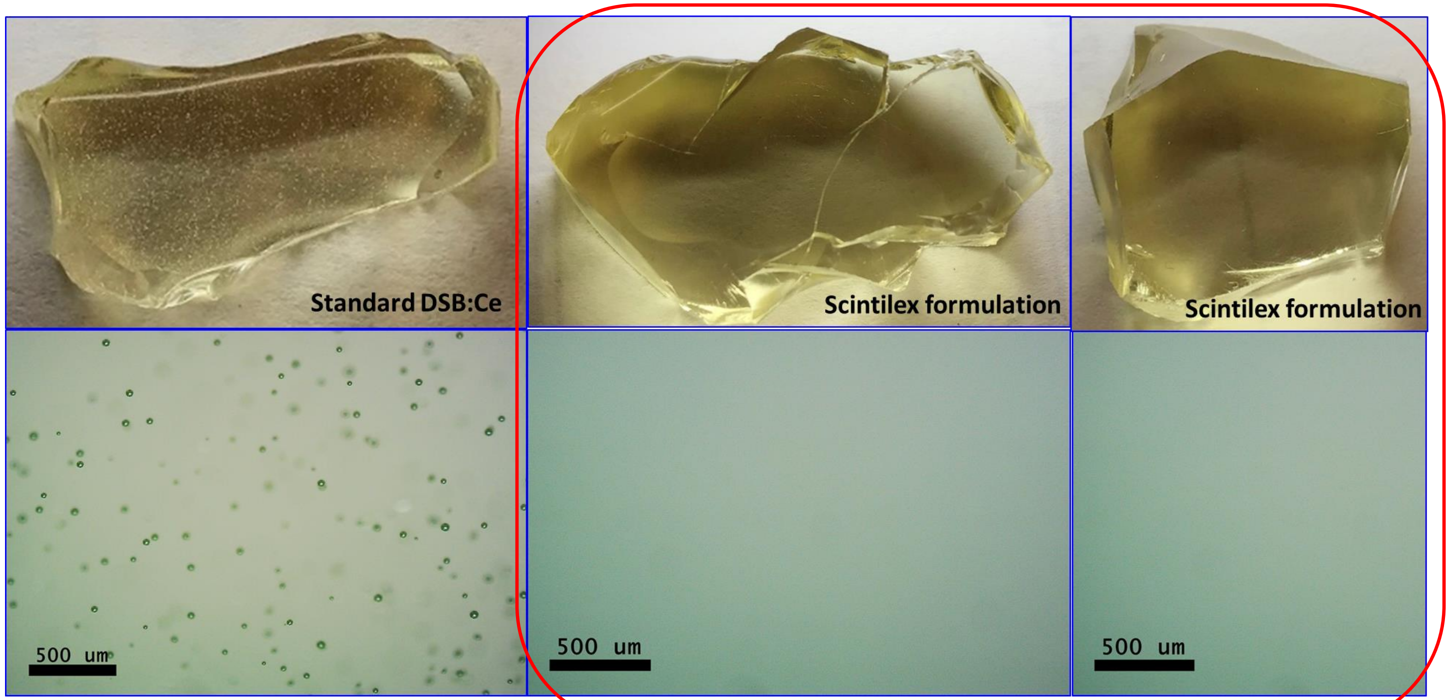
SCINT

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

Scintilex formulations and production method eliminate imperfections, even for larger-dimension blocks

SCINTILEX

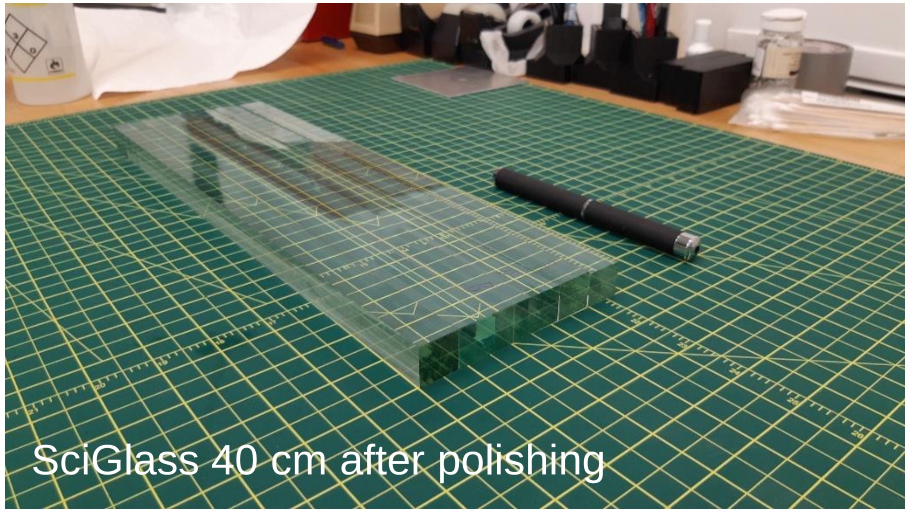
Phase 2: Scale-up and Larger Scale Production

- ❑Scintilex in collaboration with the VSL at CUA has made much progress with the development and fabrication of SciGlass over the last 2 years
- ❑SciGlass of length 20 cm, and now 40 cm blocks, can now be produced routinely – most recently 25 blocks of 40 cm length. Additional batches are planned for prototype tests, including different shapes, under Phase 2A

Glass pouring into the mold at Scintilex/VSL

Custom fabrication setup for 40cm SciGlass

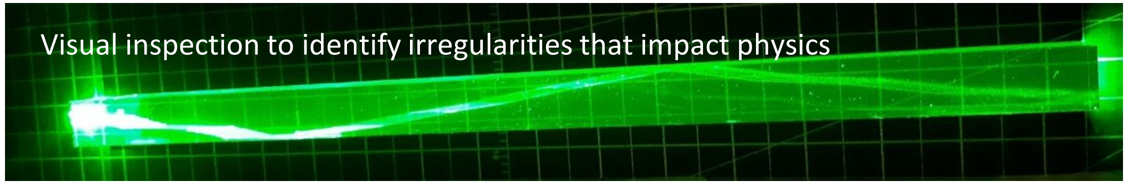
SciGlass 40cm before polishing



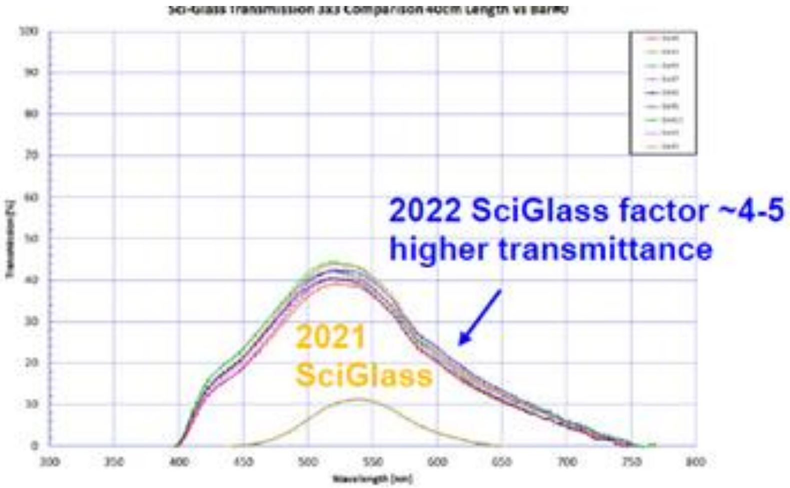
SciGlass 40 cm after polishing

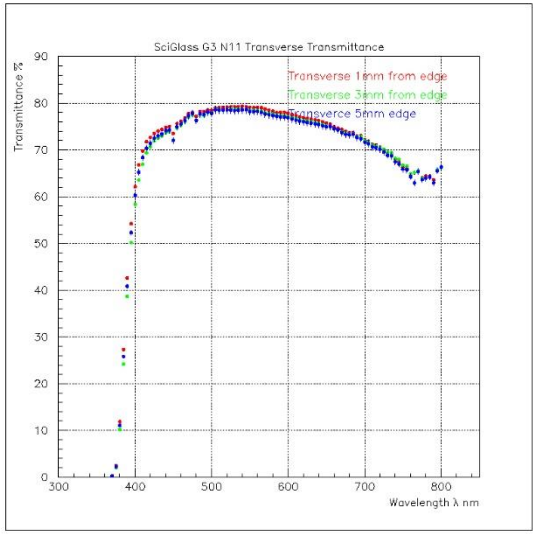
SCINTILEX

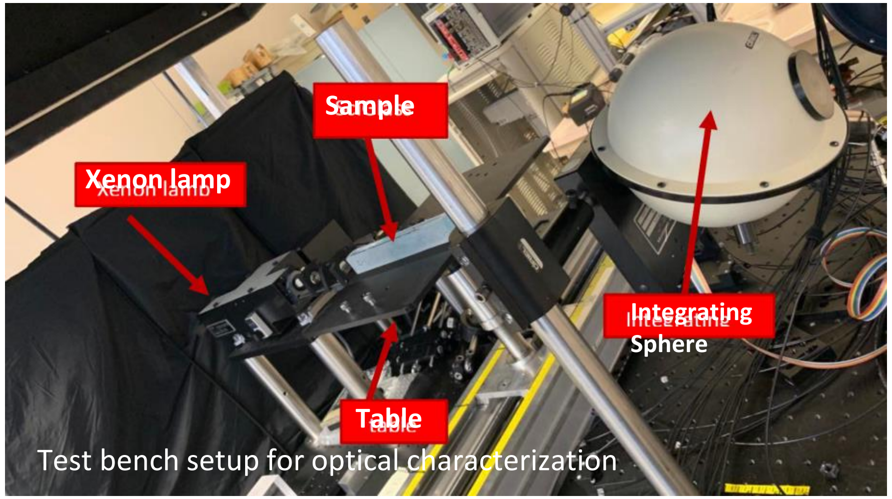
SciGlass Characterization



Longitudinal and transverse transmittance of 40 cm glass blocks

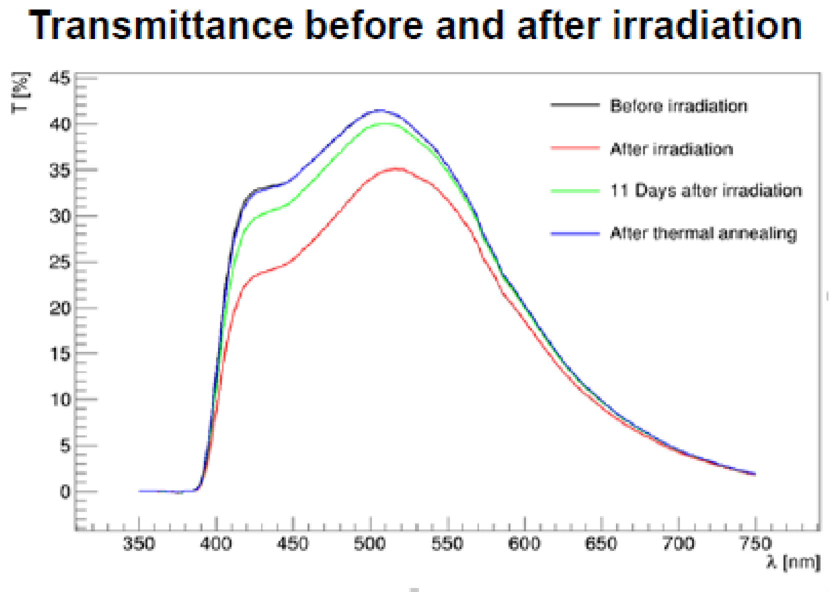


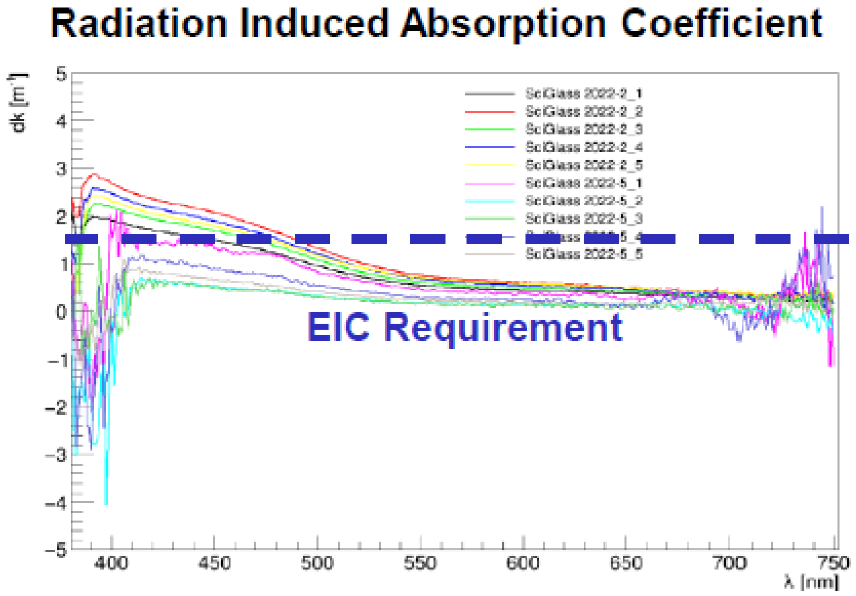




- ❑ Maintaining optical properties is of the most significant challenges in scaling up scintillating glass for nuclear physics. Our fabrication process focuses on optimizing transmittance
  - ➢ Visual inspection, geometrical dimensions and optical characterization and response to cosmics and radioactive sources allows for rapid feedback and optimization of glass production
- ❑ Significant improvements made in 40 cm Sci-Glass performance over the last year – now reaching ~45% (longitudinal) and ~80% (transverse) at 500 nm - wavelengths well matched to the photon detection of typical SiPMs.
- ❑ Further improvements in transmittance anticipated after new glass production method is implemented

SciGlass Radiation Hardness

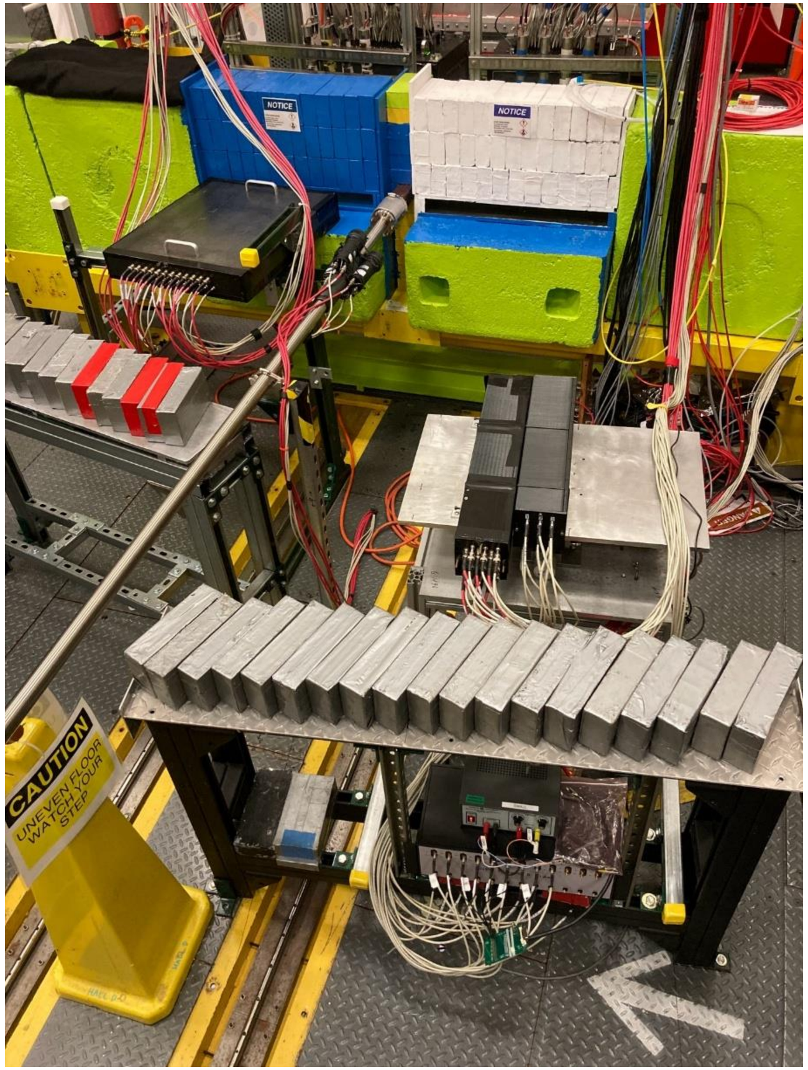




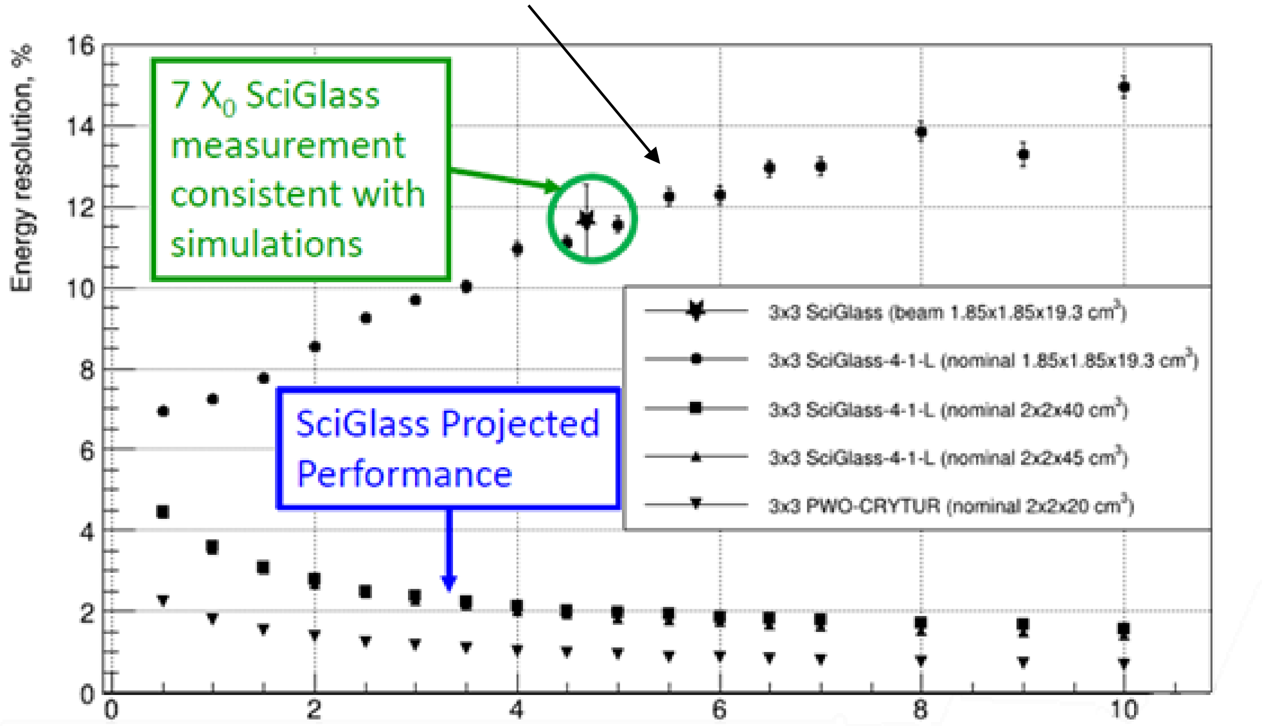
- ❑ SciGlass blocks meet the radiation hardness requirements of the EIC
- ❑ SciGlass has been shown to be radiation hard up to 1000 Gy (highest dose tested to date) EM radiation
  - ○ Also radiation resistant up to 10^{15} n/cm^2 hadronic irradiation
- ❑ Shown here are studies with 20 cm blocks exposed to 30 Gy at a rate of 1 Gy/min
- ❑ Further tests will be conducted with 40 cm long samples

SCINTILEX

Prototype Beam Tests – 3x3 Array with 20 cm Blocks

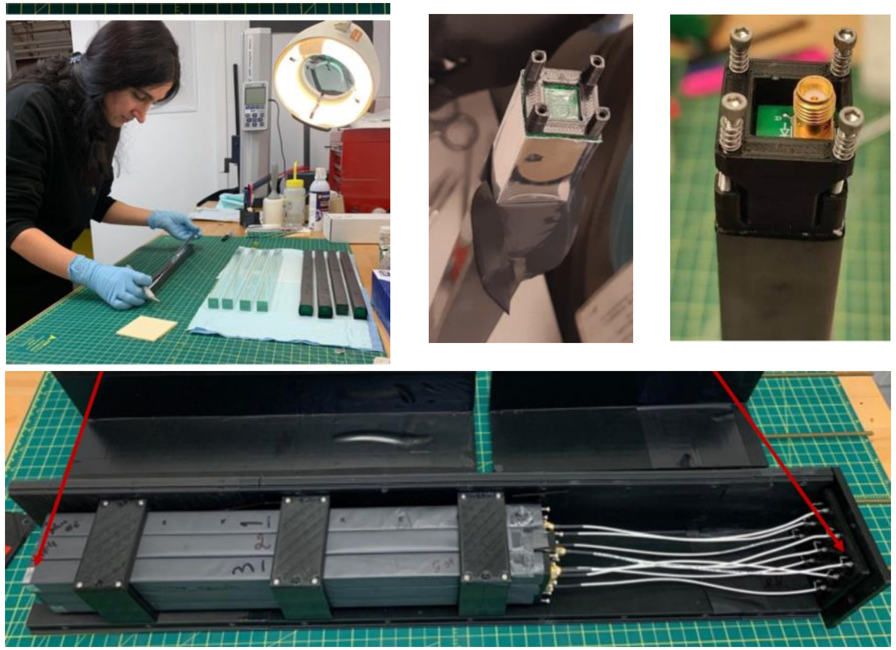


- ❑ Prototype 3x3 array installed and tested – energy resolution measured for three different beam energies
- ❑ **Results for ~7 X_0 blocks – matches with Geant4**
- ❑ **Test with ~15X_0 (40 cm) long blocks to address the longitudinal shower leakage**

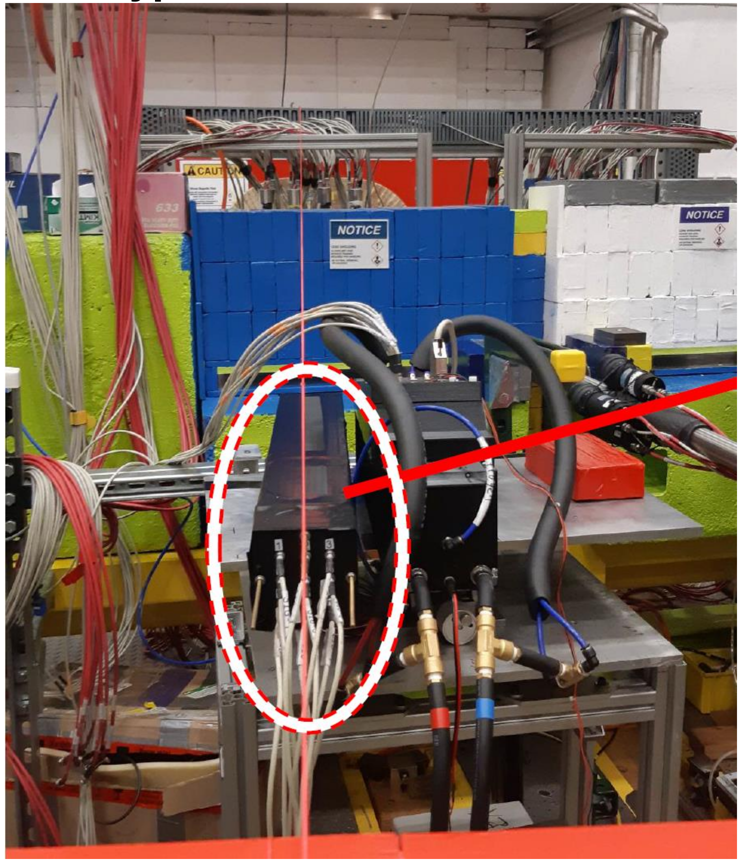


Prototype Beam Tests – 3x3 Array with 40 cm Blocks

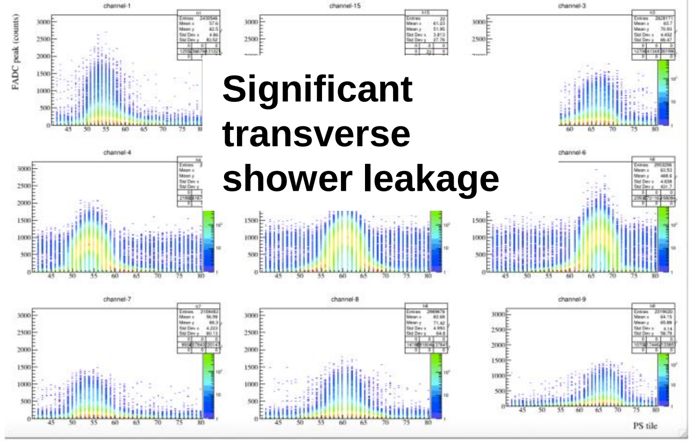
Prototype construction

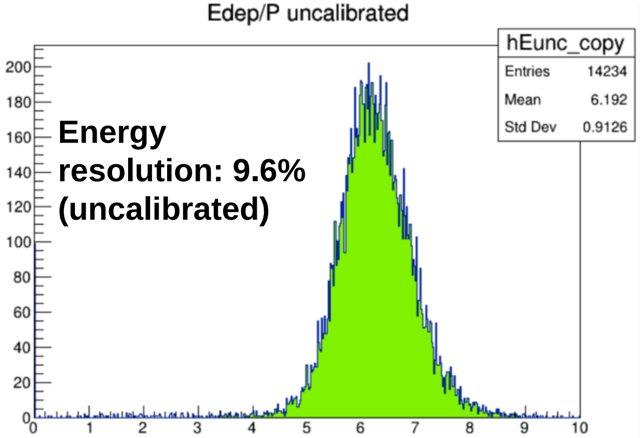


Prototype in Hall D at JLab



Results from data analysis





- ❑ 3x3 array prototype with SiPM readout, envisioned for EIC and other NP experiments
- ❑ Custom matrix of 50 micron pixel pitch, devices –> compact readout size: longitudinal dimensions ~2 cm without cables and services

The longitudinal shower is now largely contained in the 40 cm block – in comparison with our earlier tests with 20 cm long blocks – but there is a significant transverse shower leakage that increases the energy resolution → need larger array of 40 cm long blocks

SCINTILEX

Prototype Beam Tests – 5x5 Array with 40 cm Blocks

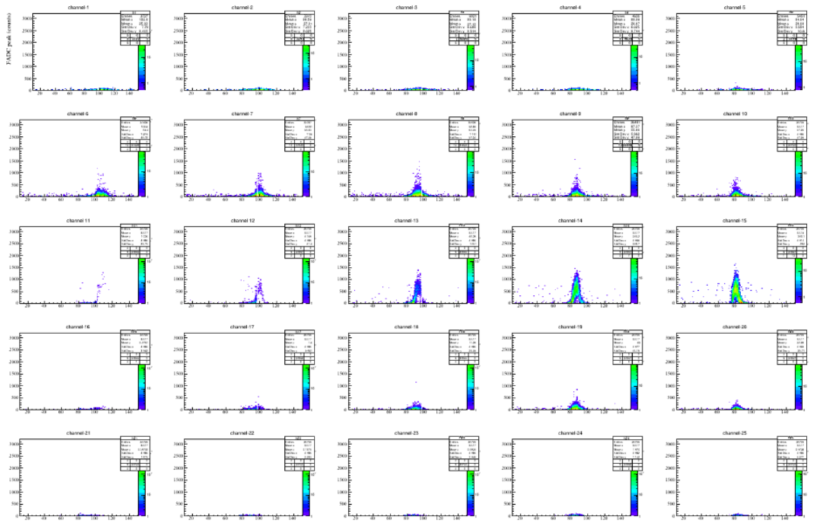
Initial test with a 5x5 prototype

Beam test impacted by COVID19

- ❑ 25 glass blocks of dimensions 2x2x40 cm^3 and Hamamatsu SiPMs (S13360-6075) – two per block
- ❑ Sensors were powered with custom biasing circuitry based on JLab detectors. The SiPM signal was processed with a custom trans-impedance amplifier.
- ❑ Signals were acquired using two branches: streaming (SRO) and triggered DAQ (standard method), both using fADCs

Preliminary Results

- ❑ Demonstrated SiPMs and SRO (envisioned for EIC) for SciGlass – both streaming and triggered DAQ provide similar results
- ❑ The EM shower was reconstructed correctly, but a rate-dependent gain variation – traced back to the biasing circuitry - plus a too-narrow pre-set signal integration window on the fADCs increased the energy resolution



➢ **Next: complete the beam test program with larger, e.g. 5x5 detector prototype. Also further optimize block size relative to Moliere radius.**

SCINTILEX

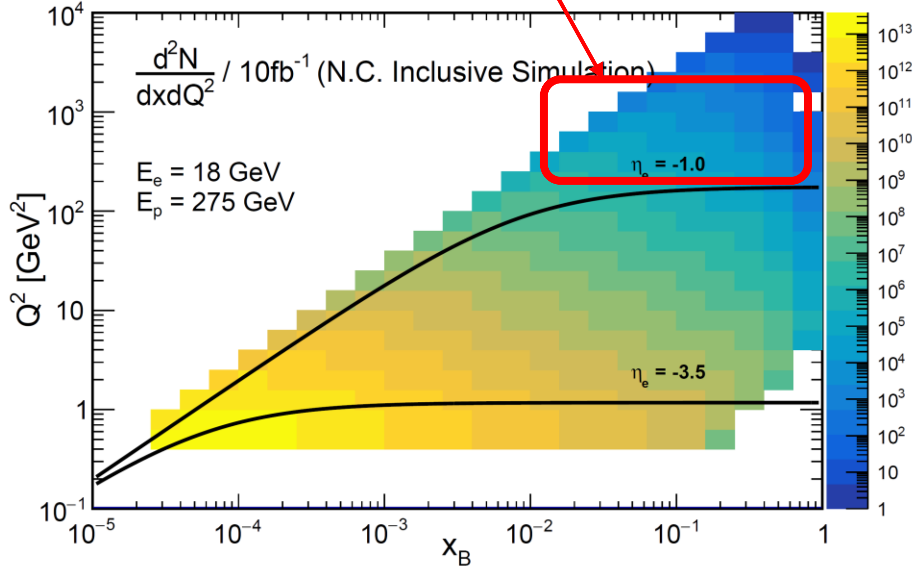
SciGlass at EIC

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

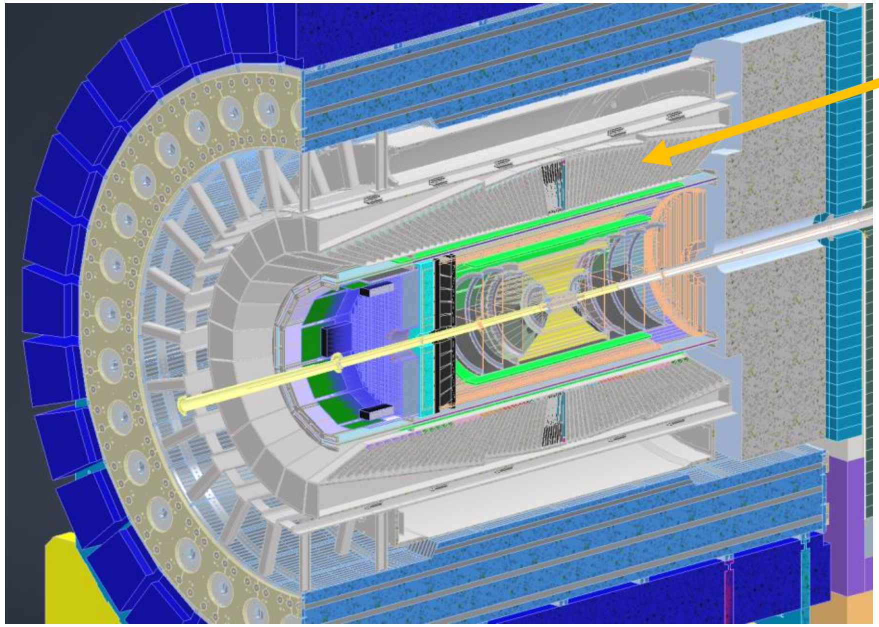


Requirements (EIC Yellow Report)

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

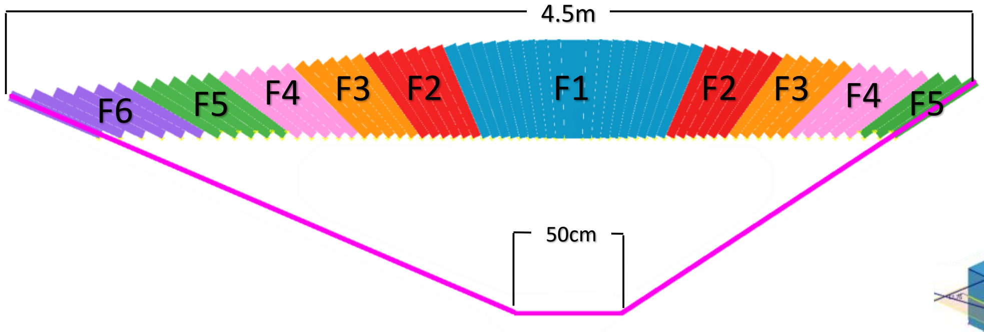
SCINTILEX

A SciGlass Barrel EMCal in the EIC Detector

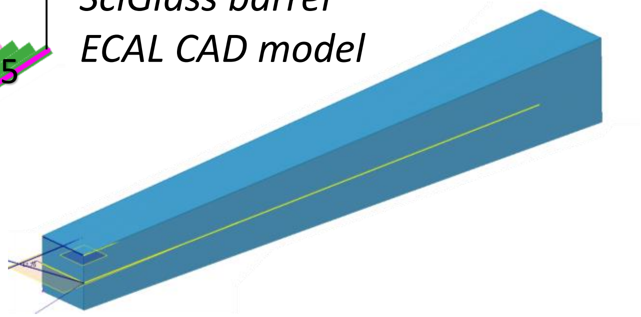


SciGlass ***Barrel ECAL in EIC detector model***

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



SciGlass barrel ECAL CAD model

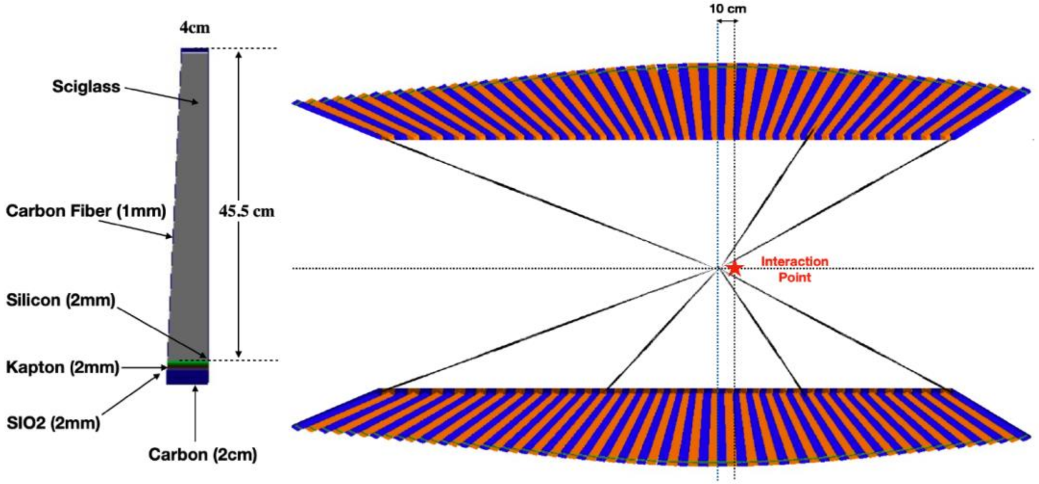


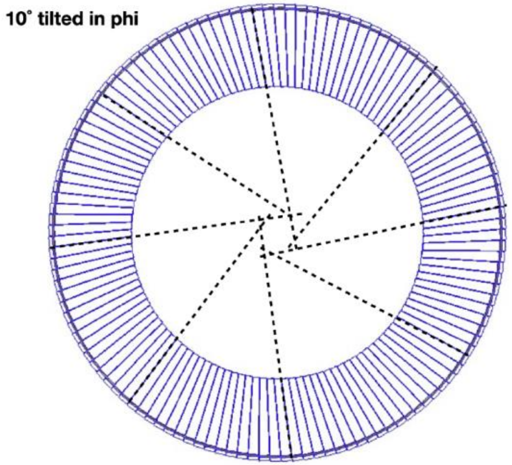
- ❑ For an EIC the geometry requires 68 SciGlass blocks per slice with 6 family variations
- ❑ Slices combined into groups of 5 separated by 2.811° radially to produce a wedge
- ❑ 120 slices combined to create 24 wedges separated by 15° radially.
- ❑ Central region of 50 cm considered due to non-fixed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

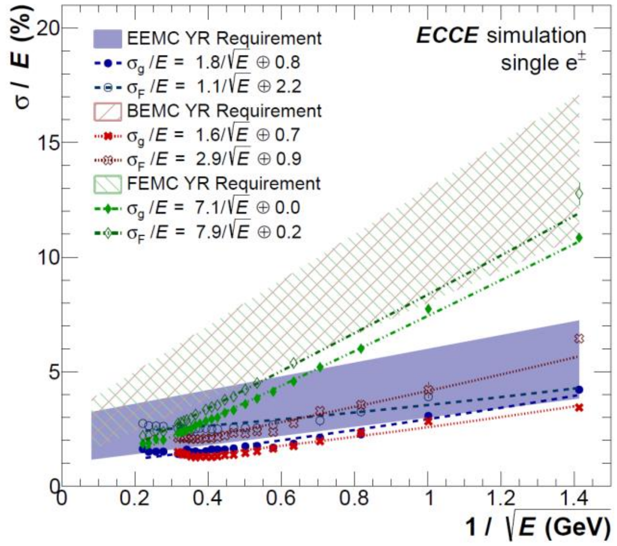
➢ **Goal: produce and characterize different block geometries needed for a barrel EMCal**

SCINTILEX

SciGlass Barrel EMCal Projected Performance

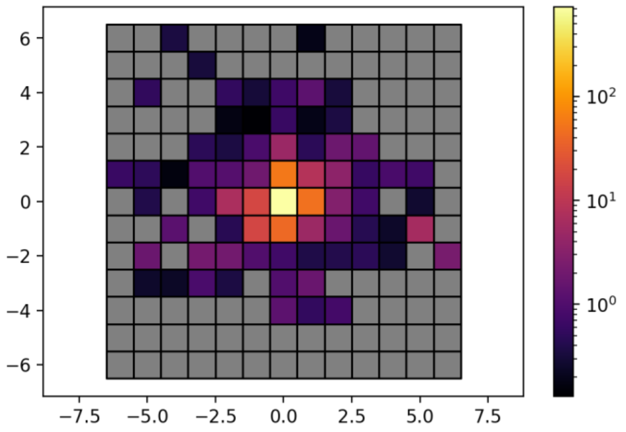




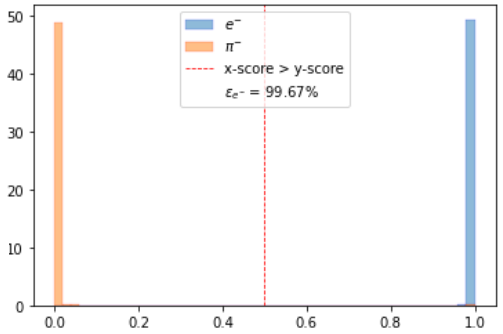


- Assumes 45.5 cm long blocks ($17X_0$) – close to 40 cm prototype
- Implemented with the active components and support structures
- Also important to consider materials in front of the EM calorimeter as it impacts performance (resolution, rejection, etc.)

Projected resolution exceeds EIC Yellow Report requirement



Convolutional Variational Auto Encoder Backbone



Use of AI methods improves pion rejection to nearly 100%

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 40 cm long blocks have been produced routinely in lab size batches (10-25 blocks)
- Performance validation carried out with prototype 3x3 SciGlass arrays (20 cm and 40 cm blocks) and suitable readout for NP experiments – energy resolution matches GEANT4 projections
- **Plans for 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**