High Performance Glass Scintillators for Nuclear Physics Experiments

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

SCINTILEX

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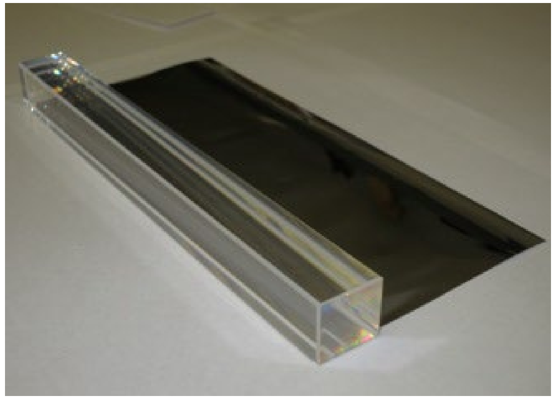
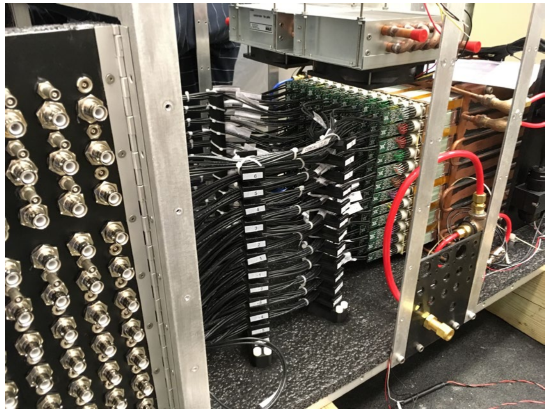
Business Official: Ian L. Pegg

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
  - ➢ 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





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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/cm²]

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/cm²]

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

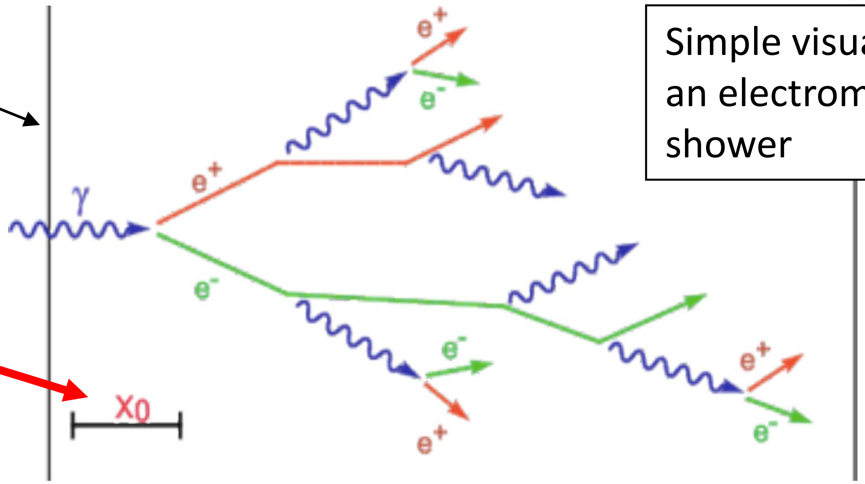
Electrons : Bremsstrahlung

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

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

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

Detector material

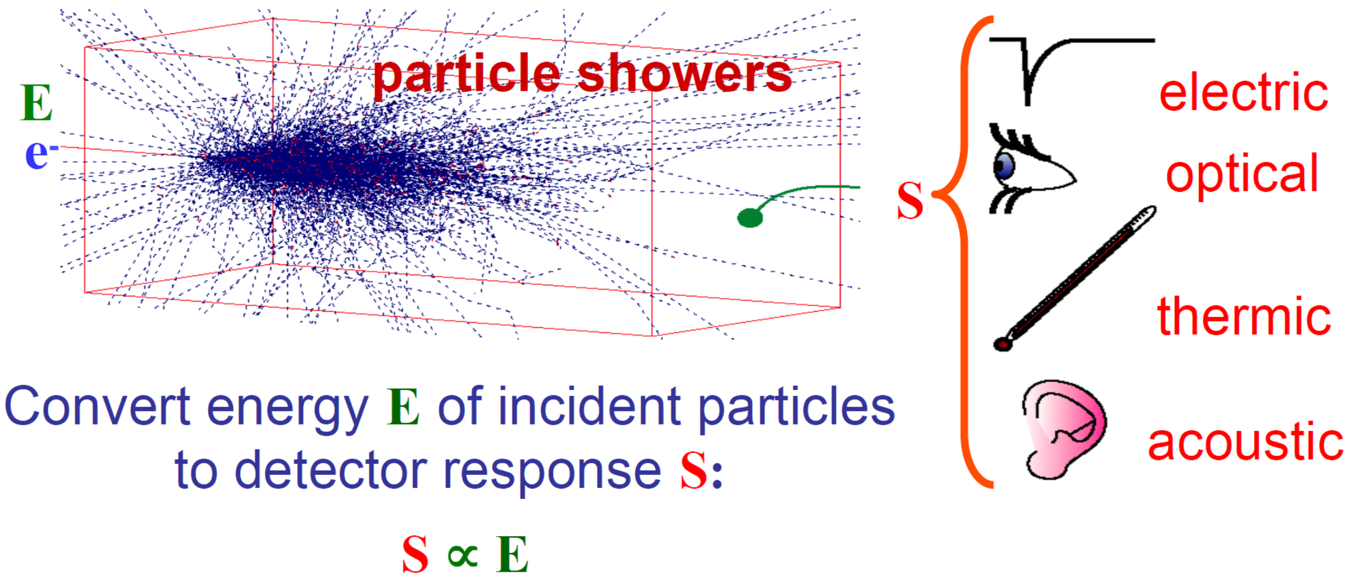


Simple visualization of an electromagnetic shower

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

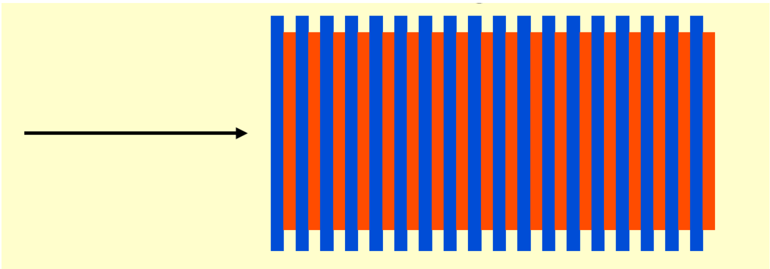
- Calorimeters make use of various detection mechanisms, e.g.,
    - **Scintillation**
    - Cherenkov radiation
    - Ionization



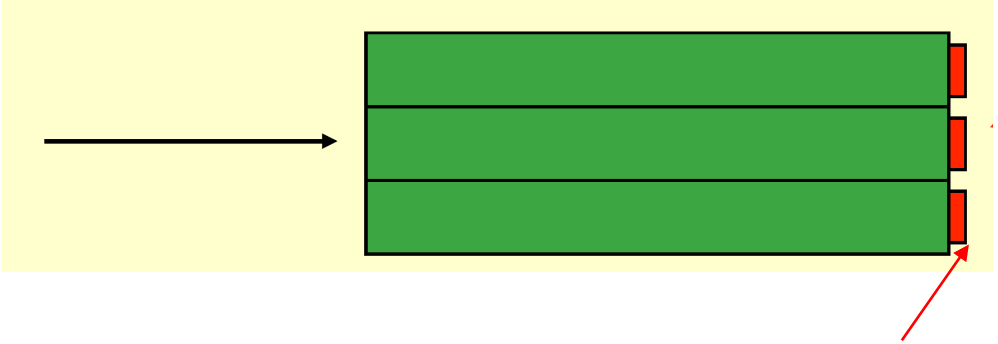
Types of Electromagnetic Calorimeters

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, PbWO4, …) or glass scintillators



Si photodiode
or PMT

Precision measurements in nuclear physics experiments require homogeneous calorimeters

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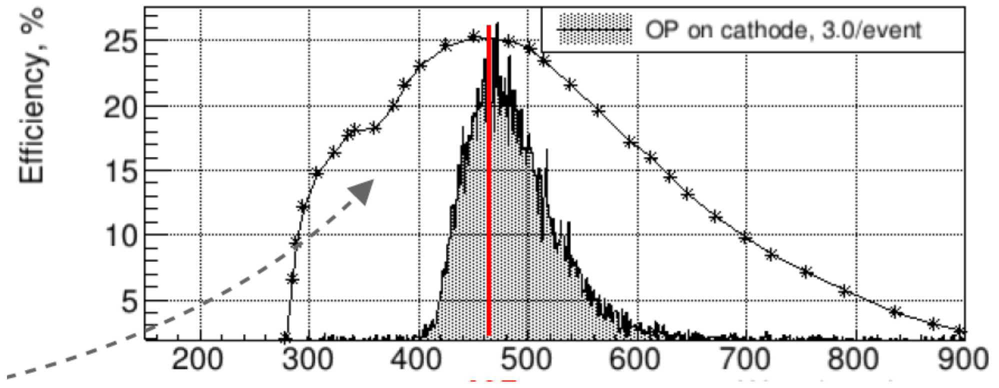
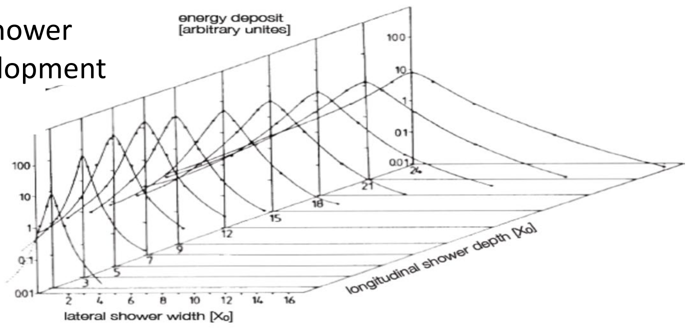
Requirements on scintillator materials

- ❑ 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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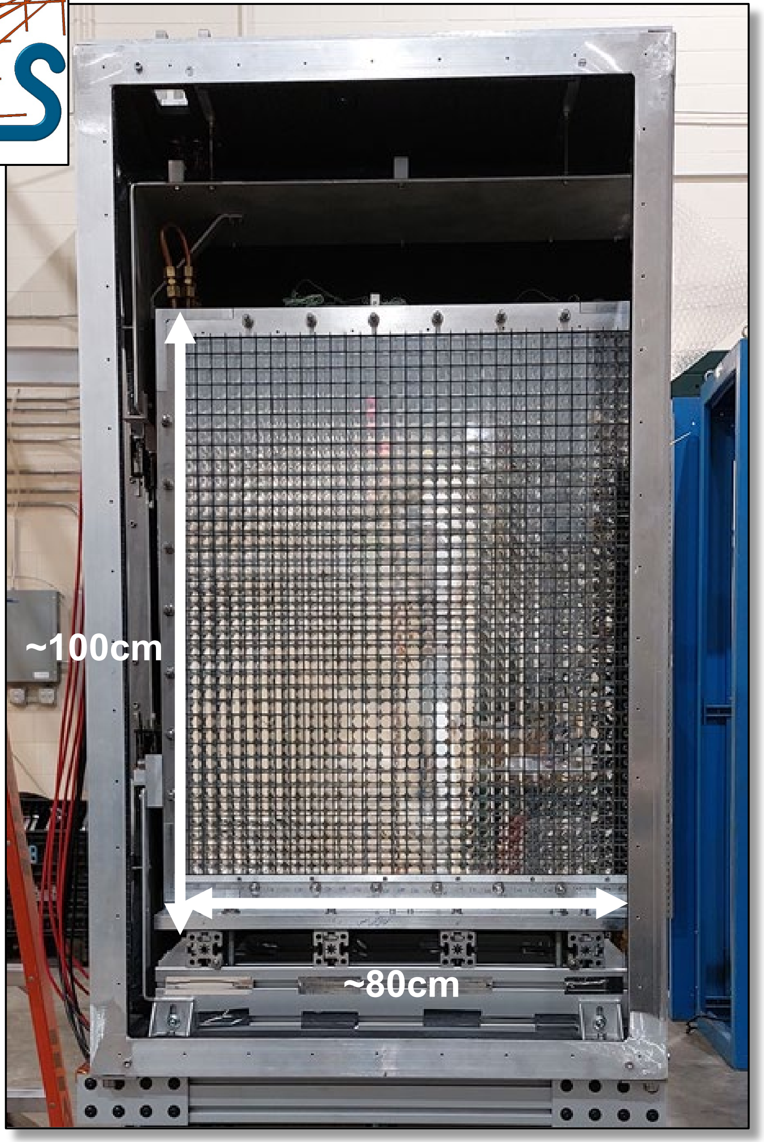
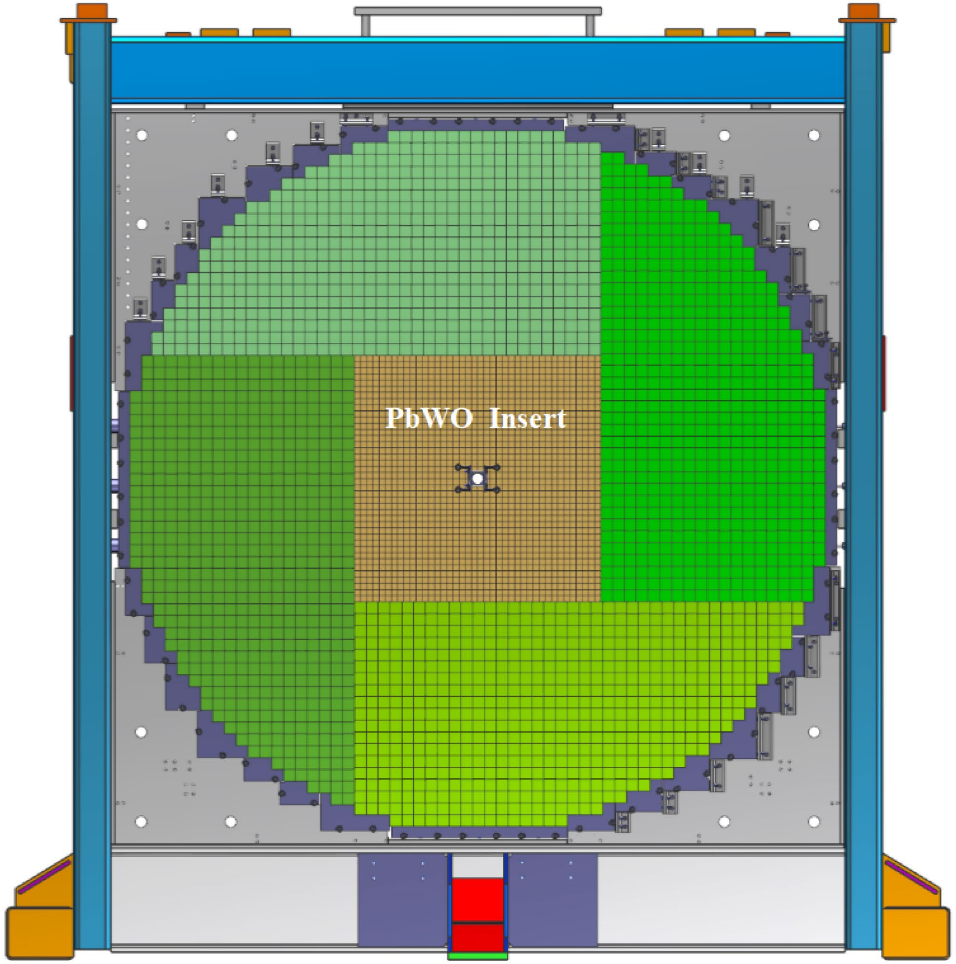
1. Examples of homogeneous EM Calorimeters at JLAB



Neutral Particle Spectrometer (Hall A/C)



Forward CAL Insert (Hall D)

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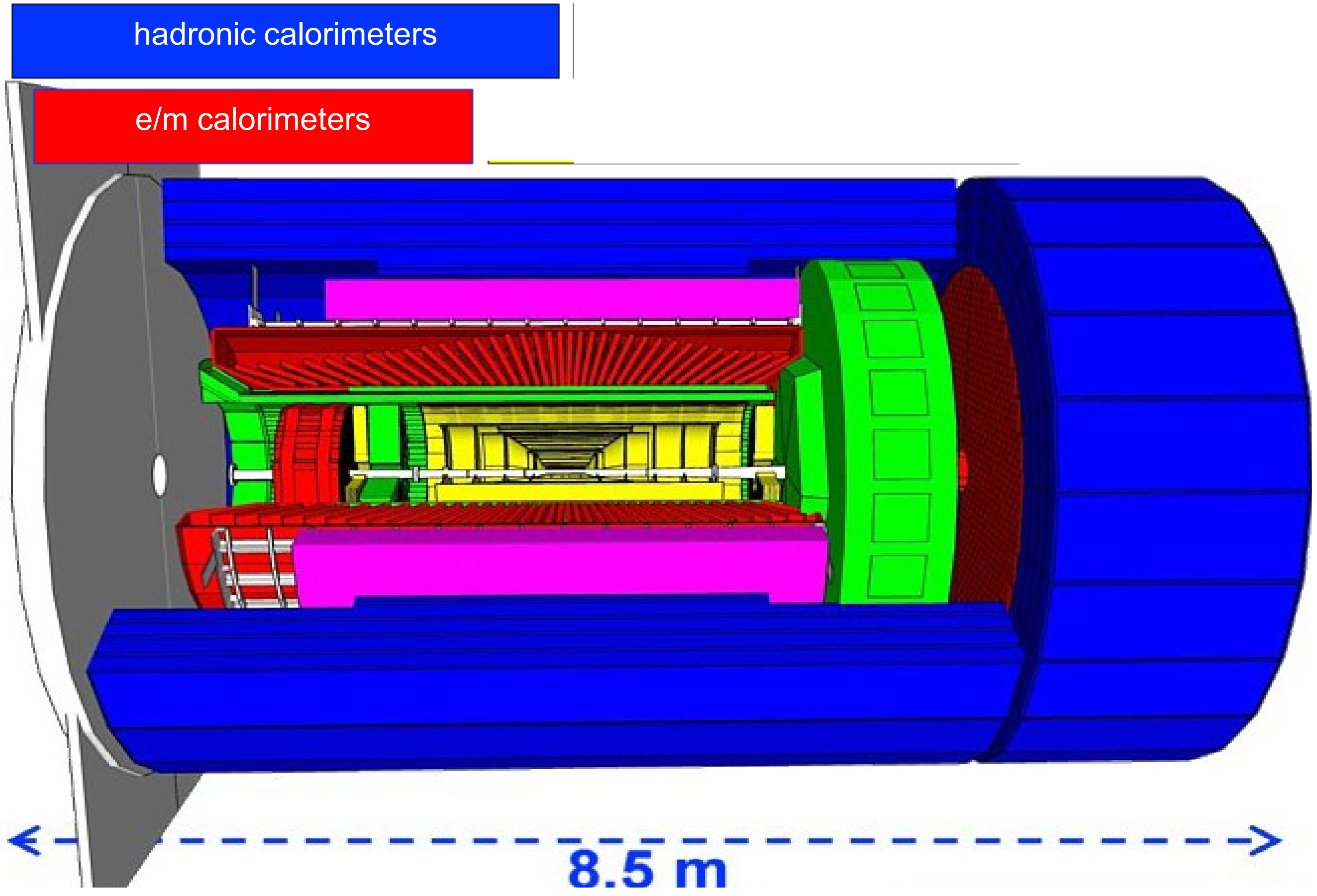
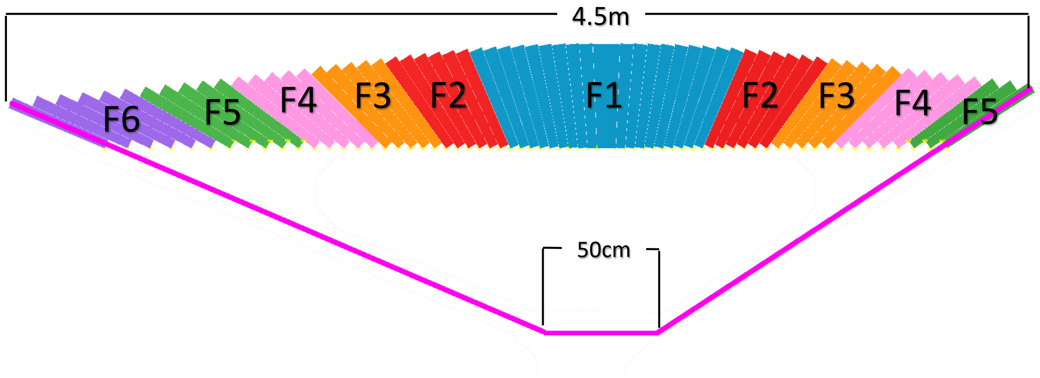
2. Homogeneous Electromagnetic Calorimetry at EIC

- ❑ EIC EMCal: central and auxiliary detectors



Auxiliary detectors not shown



- ❑ Large-volume detectors requiring large numbers of homogeneous scintillator blocks and custom shapes

- ❑ **Crystals are expensive (\$15-25/cm³)** – 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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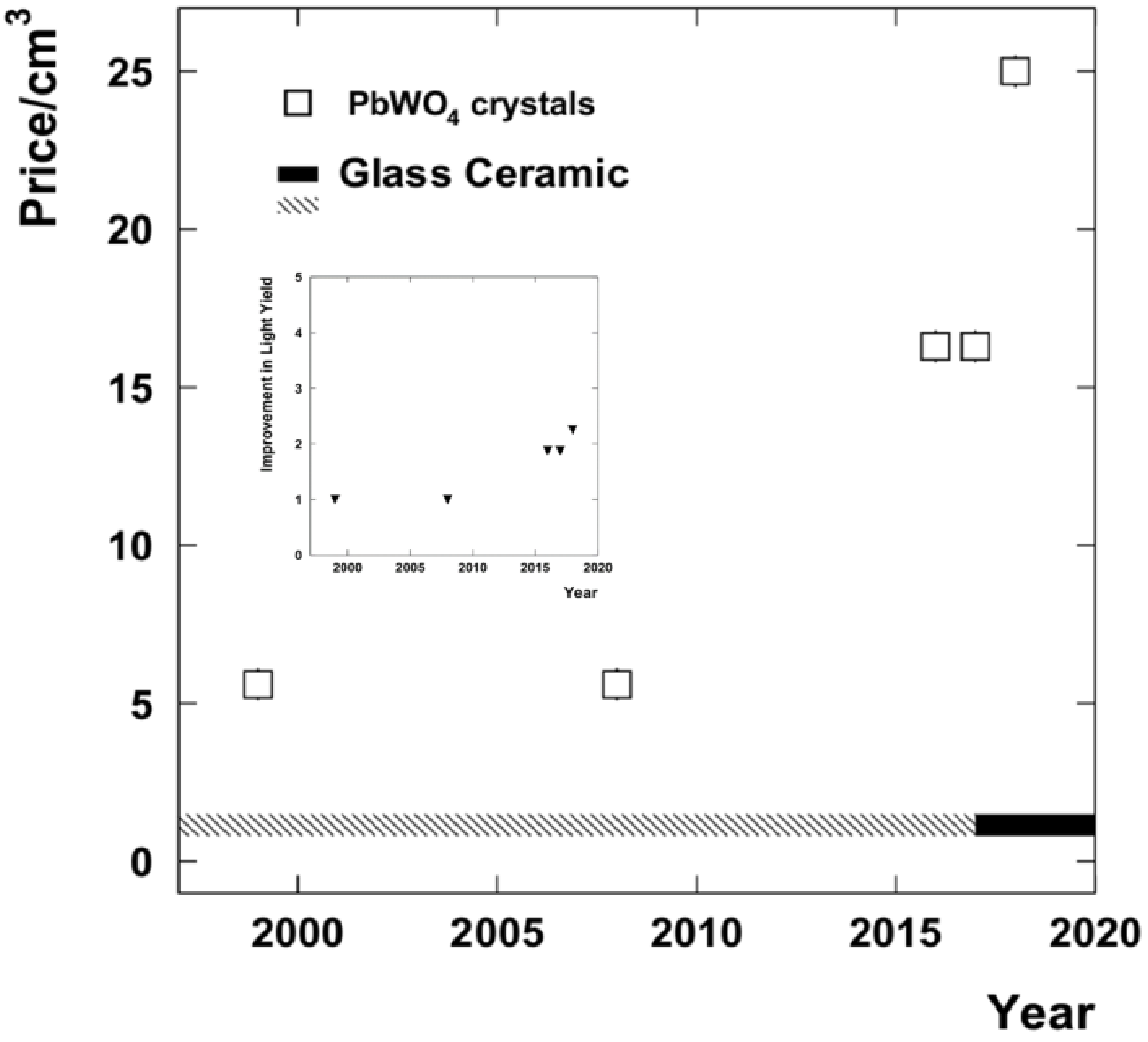
Scintilex STTR Concept



Glass fabrication is expected to be cheaper, faster, and more flexible than PbWO4 crystals.

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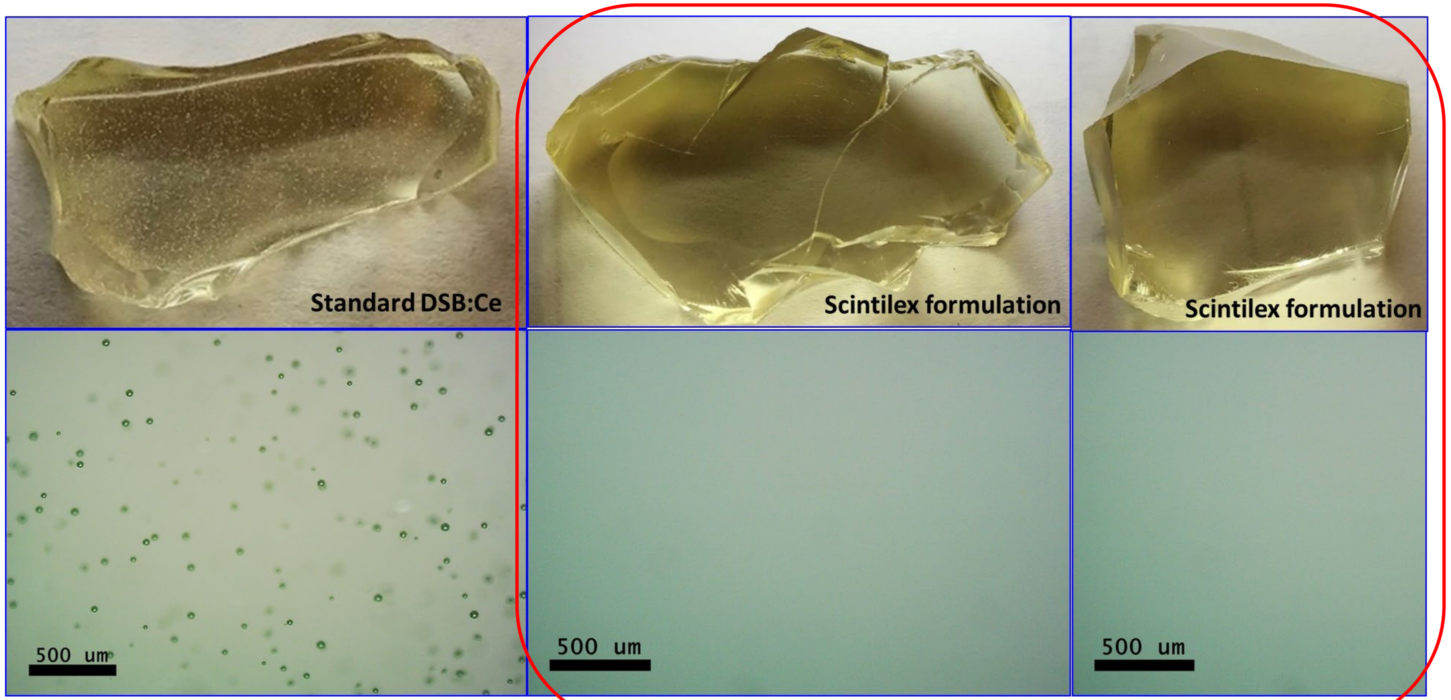
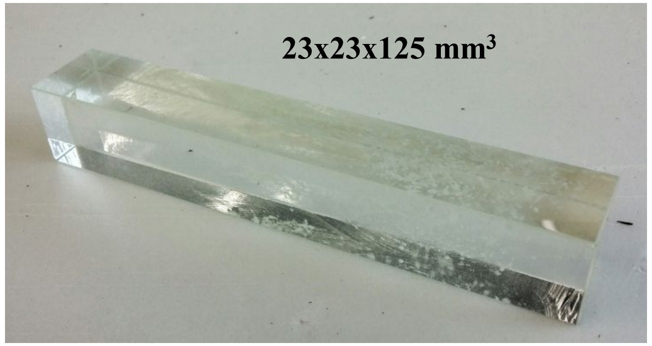
Process optimization to prevent non-uniformities

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



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

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



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

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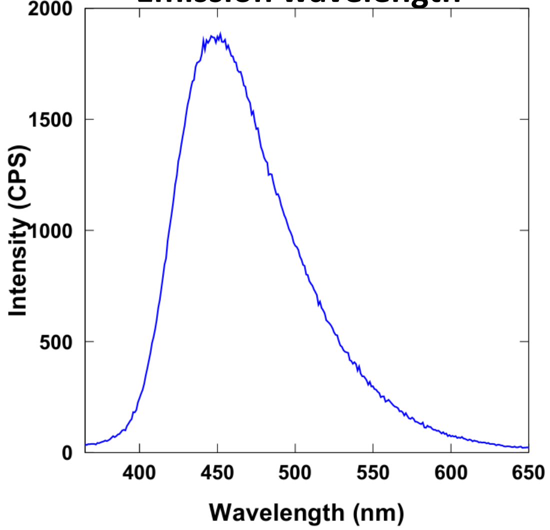
Glass Scintillator formulation optimization

Two glass formulations for homogeneous calorimeter application

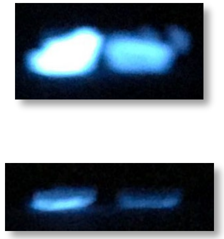
VSL-Scintilex-G4 (nominal)

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

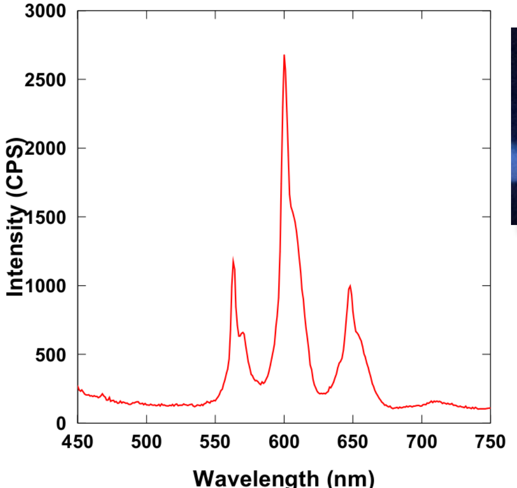
SciGlass (this talk)

Formulations with initial emission wavelength tuning

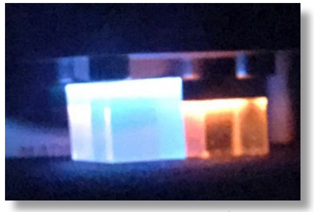
VSL-Scintilex-SC1

VSL-Scintilex-EC1

Emission wavelength

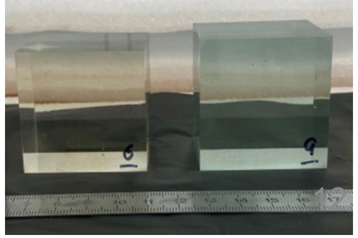


Scintillation light



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

CSGlass (for hadronic calorimeters)



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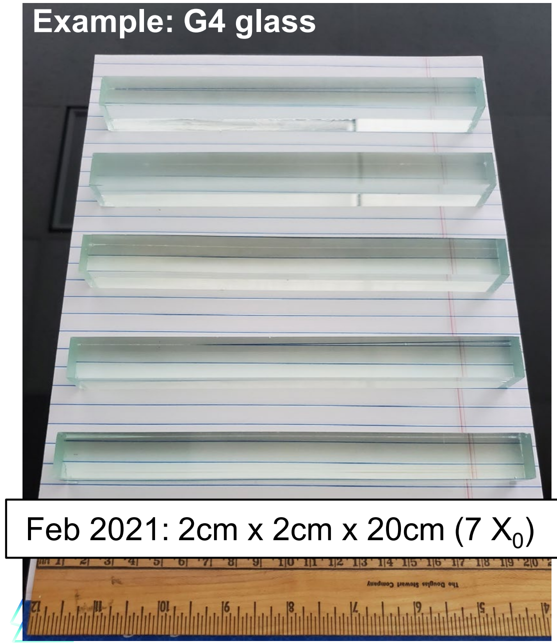
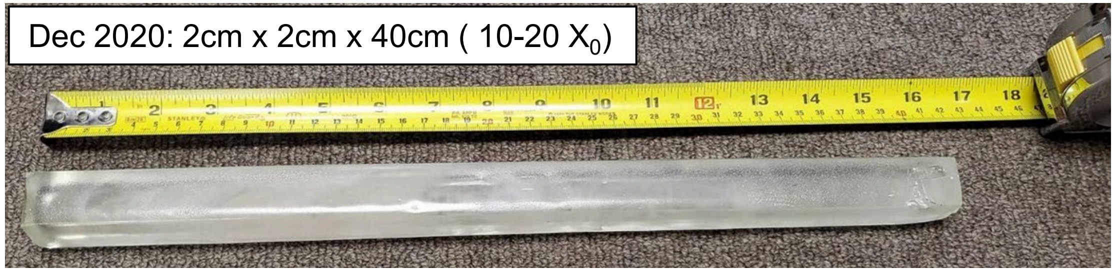
Scale-up and larger scale production

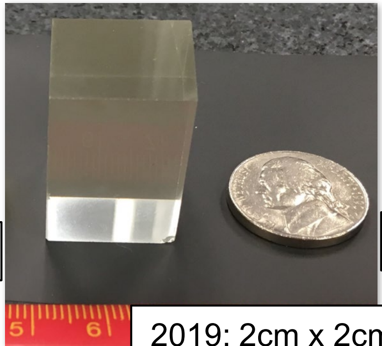
- SciGlass 20cm has been produced reliably; We tested a 3x3 20 cm SciGlass prototype detector in beam and measured its performance
- **Measured performance for 20cm SciGlass ($7X_0$) as per GEANT simulation**
- Phase 2 started large-scale production or larger blocks (40+ cm, rectangular and projective shapes)
- The first polished 40 cm SciGlass ($15X_0$) produced in late 2021, the first detector prototypes produced in summer 2022



Feb 2021: 2cm x 2cm x 20cm (7 X_0)



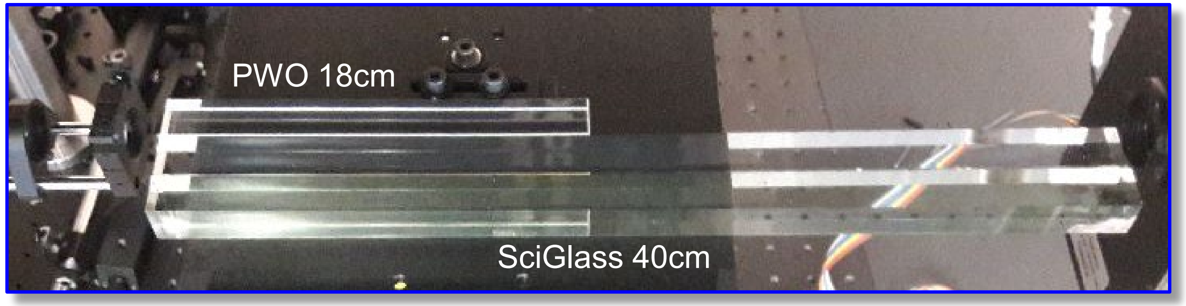
Dec 2020: 2cm x 2cm x 40cm (10-20 X_0)



2019: 2cm x 2cm x 4cm

2018: 1cm x 1cm x 1cm

Summer 2022: 2cm x 2cm x 40cm (10-20 X_0) first detector prototypes



Radiation Hardness of SciGlass

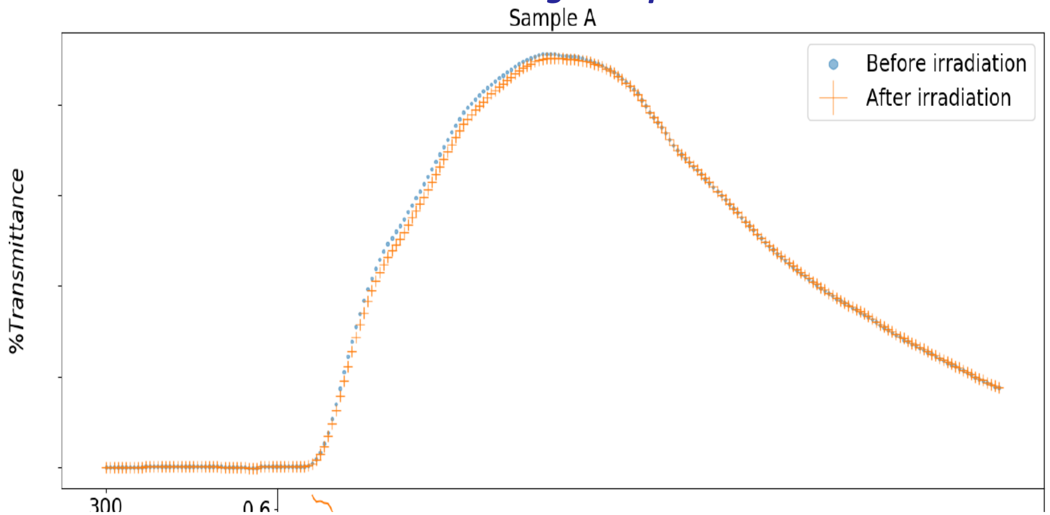
- ❑ SciGlass blocks of 20 cm length were irradiated with a strong Co-60 source
- ❑ Irradiation to a dose of 30 Gy (estimated dose for 1 year running at EIC) at a rate of 1 Gy/min

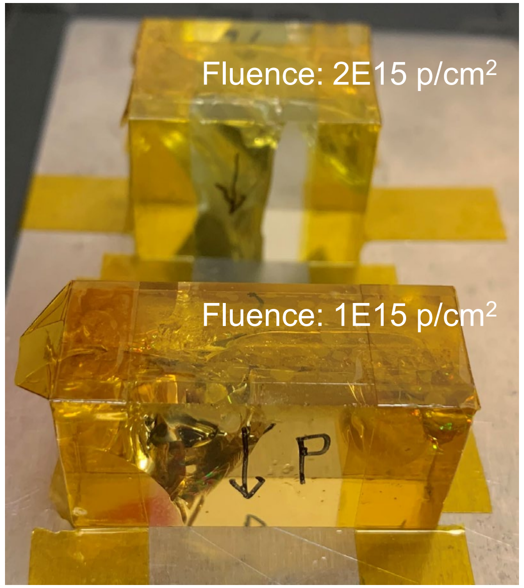
✔ → ***Samples are EM radiation hard***

- ❑ SciGlass blocks were exposed to hadron radiation with 40 MeV protons with fluences 10^{15} p/cm^2

✔ ***Samples are hadron radiation hard***

Radiation hardness – electromagnetic probes





Photograph taken immediately after irradiation. No visual evidence of radiation damage

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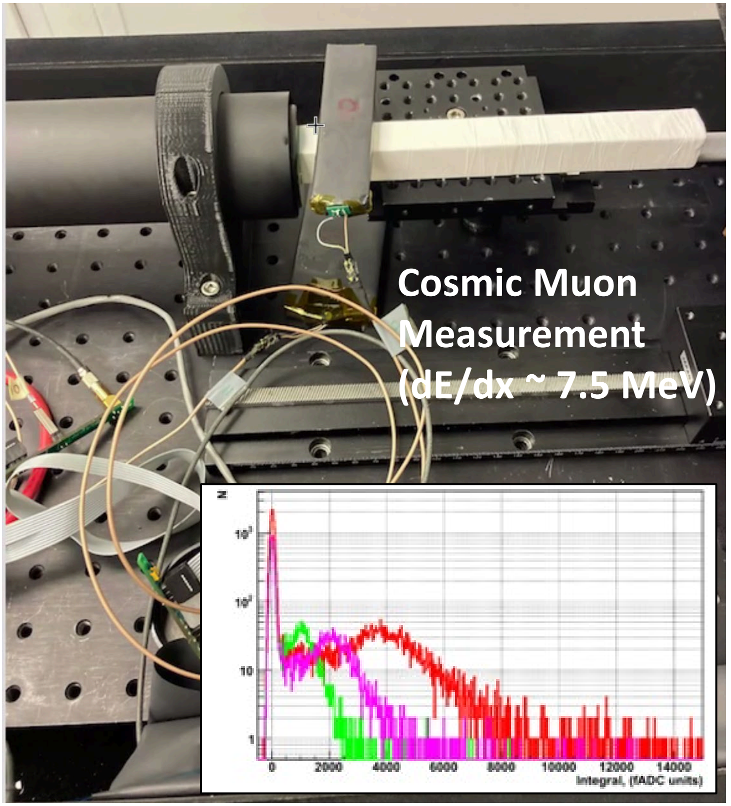
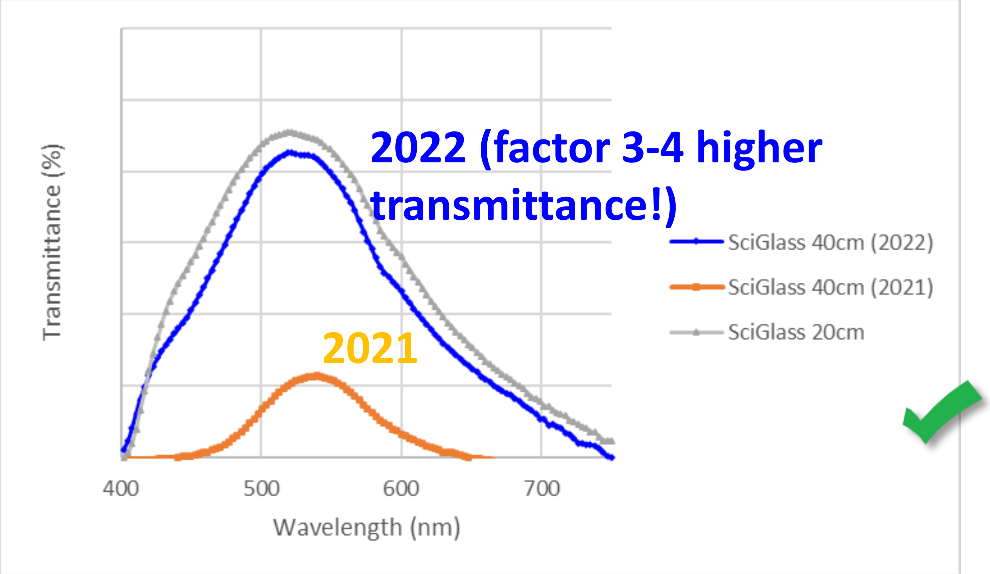
Testbench and Scale up optimization

- Maintaining and optimizing optical properties is one of the biggest challenges in scale-up of scintillating glass for nuclear physics experiments
- Testbench: optical characterization and response to cosmics and radioactive sources to benchmark against specific experiment requirements and to prepare for detector prototype beam tests

✔ **Testbench set up for rapid feedback loop on SciGlass**





✔ **Significant improvements made in 40cm SciGlass performance within one year**

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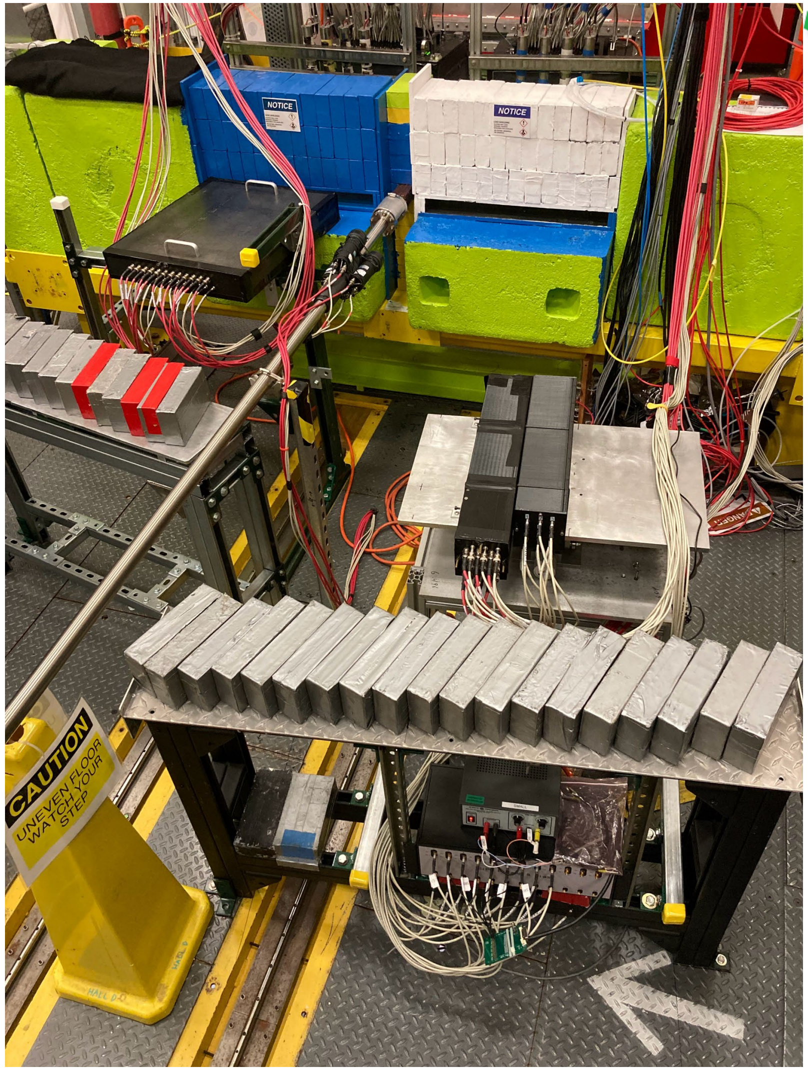
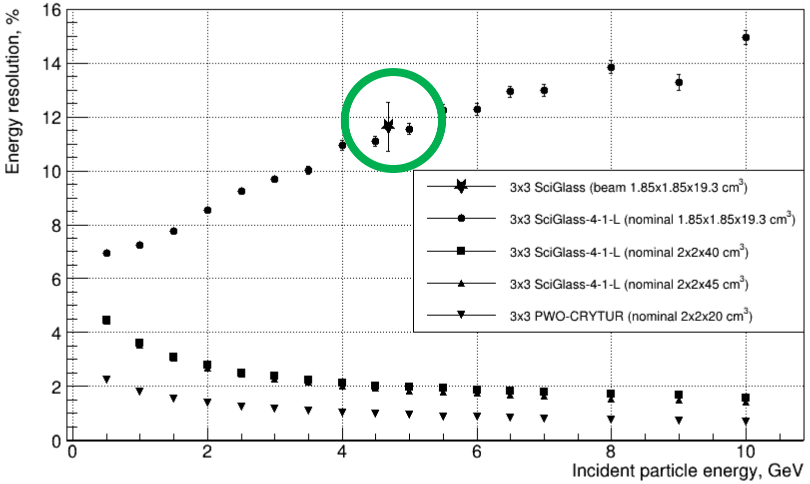
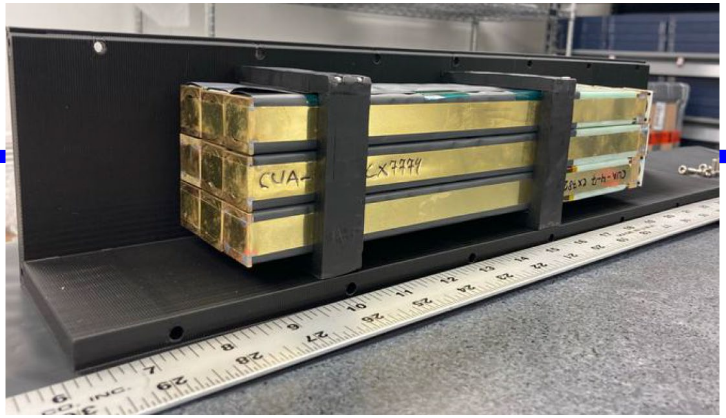
Detector Prototype Beam Tests



- ✔ Prototype 3x3 array installed and tested – energy resolution measured for three different beam energies
- ✔ **Results for ~7 X_0 blocks – matches with Geant4**
- **Plans for 2022: Test with ~15X_0 (40cm) long blocks**





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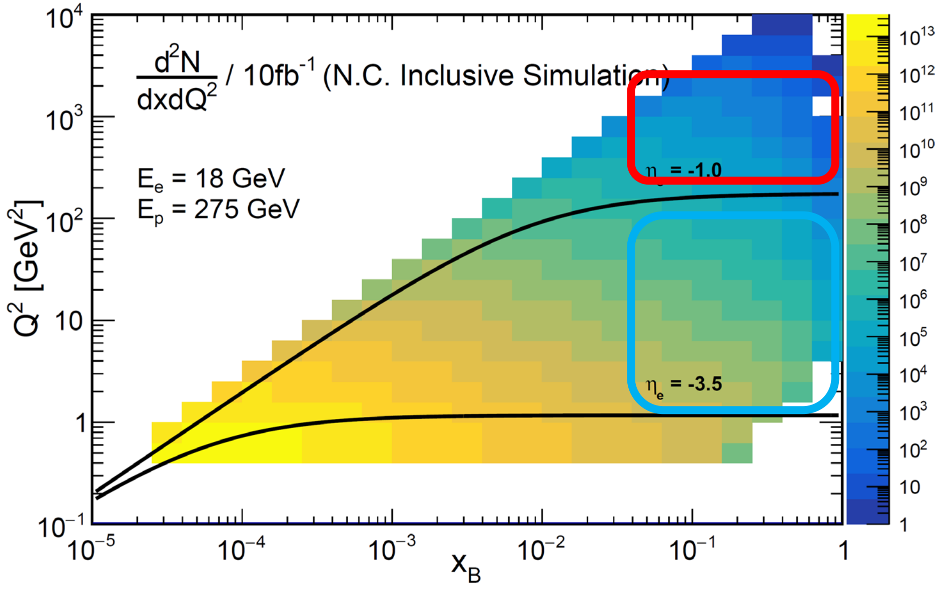
SciGlass at EIC

Scattered electron kinematics measurement is essential at the EIC

- High precision, hermetic detection of the scattered electron is required over a broad range in h 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
- In ECCE SciGlass was chosen in the barrel as this provides excellent e/h separation due to its good energy resolution, matched to the backward region need, and its cost effectiveness

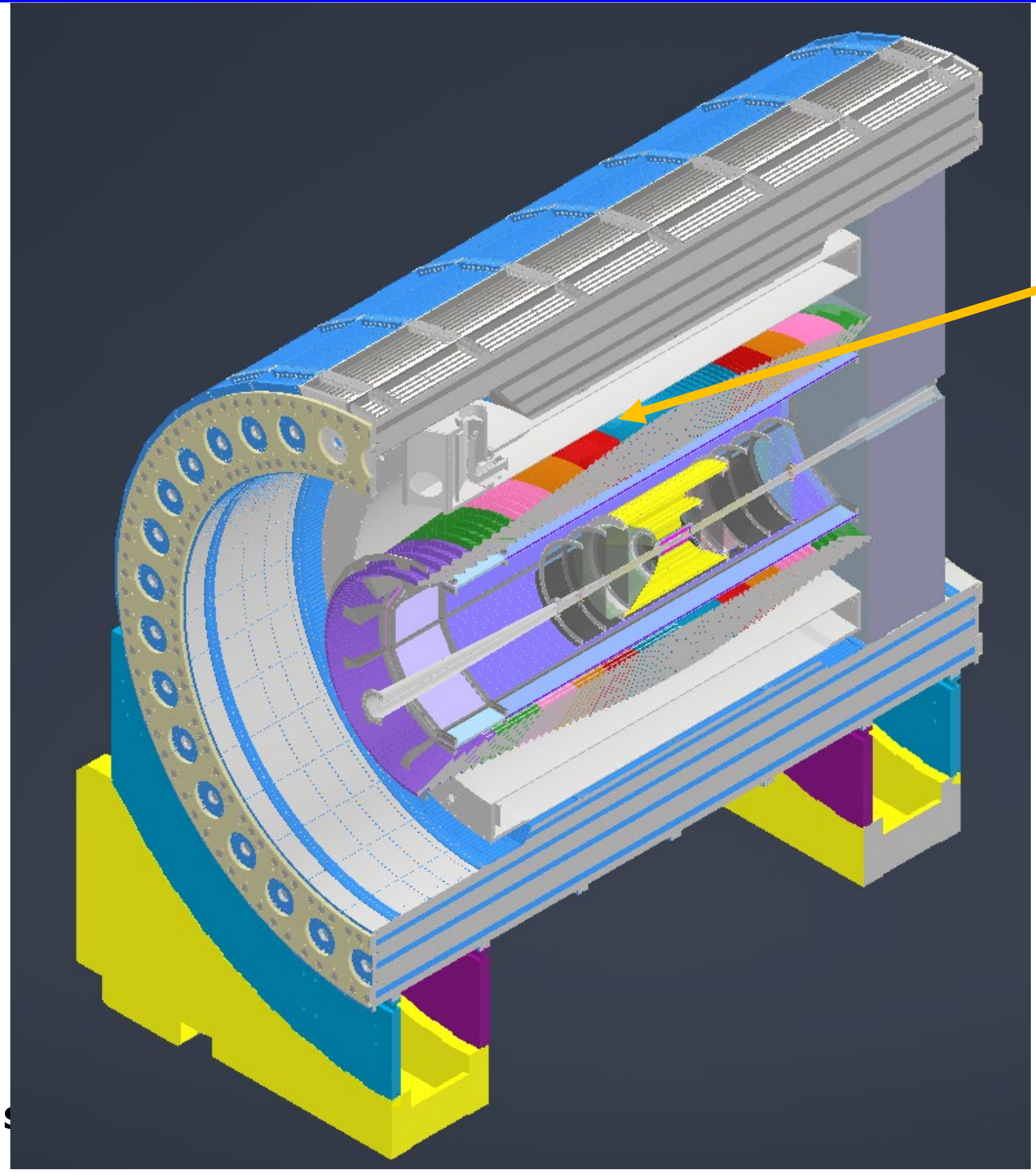


η	[-4 .. -1.75]	[-1.75 .. 1.3]	[1.3 .. 4]
Material	$PbWO_4$	SciGlass	Pb/Sc
X_0 (mm)	8.9	24-28	16.4
R_M (mm)	19.6	35	35
Cell (mm)	20	40	40
X/X_0	22.5	17.5	19
D_z (mm)	60	56	48

Requirements

- Good energy resolution
  - e.g., region $-2 < \eta < -1$ requires $\sim 7\%/\sqrt{E}$
- e/h separation up to 10^{-4}

SciGlass barrel EMCal in the EIC Reference Detector

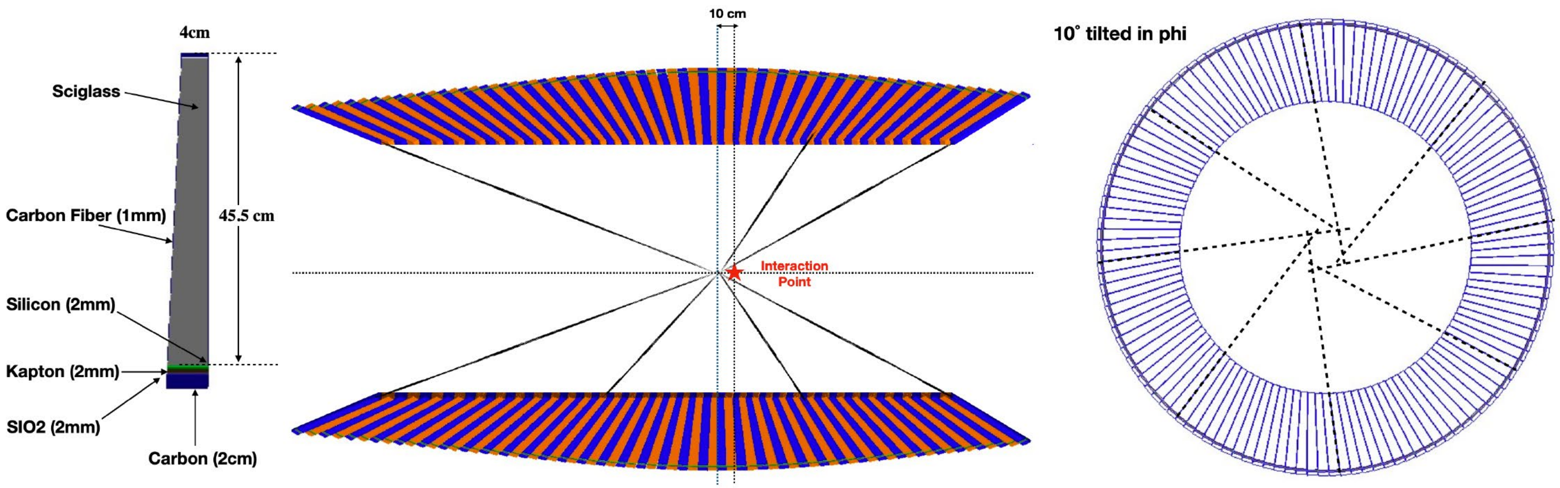


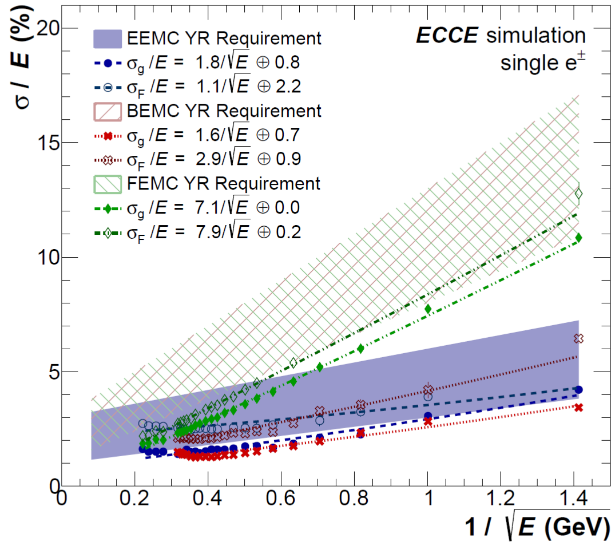
Barrel ECAL(BEMC)

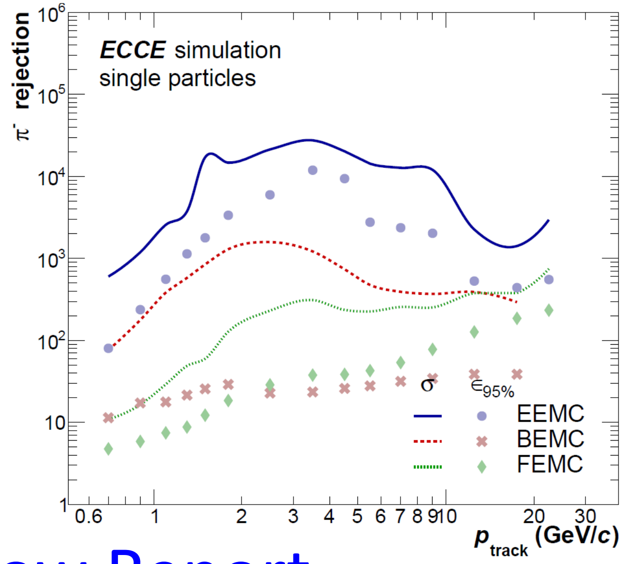
Homogeneous, projective calorimeter based on SciGlass, cost-effective alternative to crystals

- The barrel is one of the largest sub-detectors with 8000 homogeneous scintillator blocks of 45.5cm length (and ~10cm radial readout space)
- It is extended in the negative rapidity direction (with η coverage from -1.75 to +1.3) to provide hermeticity with the backward ECal.
- In the backward direction hermeticity is provided by the combination of barrel, backward ECals, and mRICH complements (3σ e/h up to 2 GeV) . Readout and supply lines are included.
- In the forward direction the barrel EMCal faces much higher range of particle rates across the acceptance of the forward endcap

SciGlass barrel EMCal Projected Performance







- Assumes 45.5cm long blocks ($17X_0$) – close to 40cm 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.)

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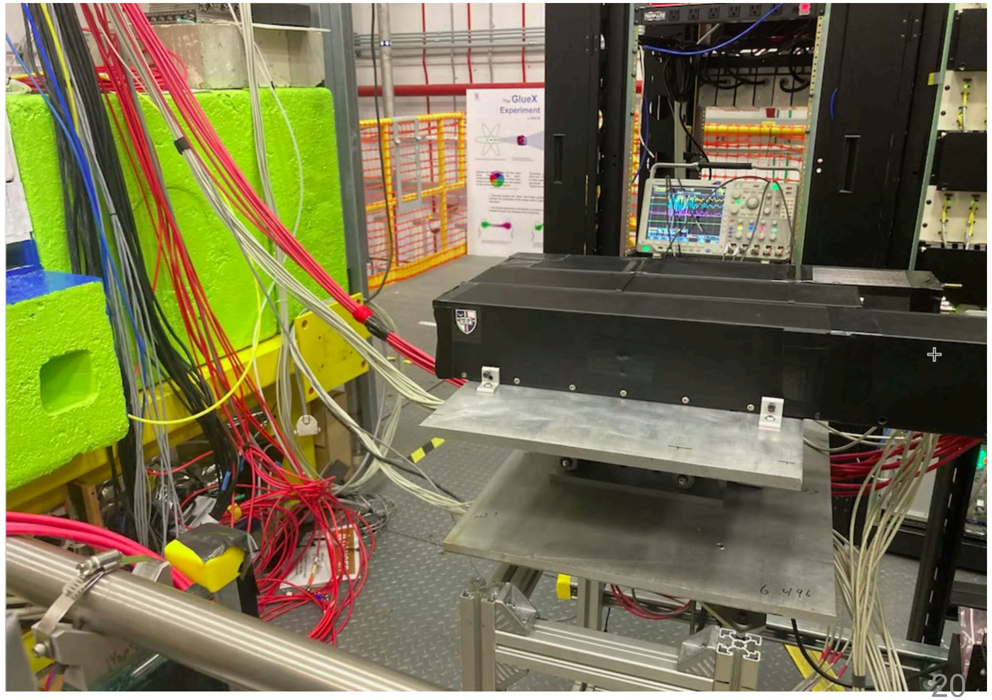
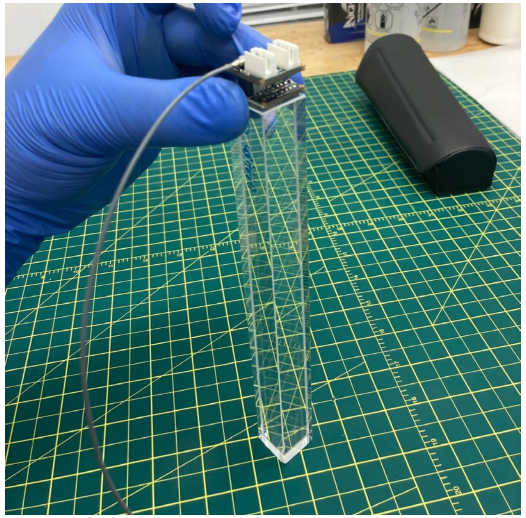
✔ Exceeds requirements from EIC Yellow Report

Outlook

- 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 20cm has been produced reliably; started large-scale production or larger blocks (40+ cm, rectangular and projective shapes)
- Constructed and commissioned methods to characterize SciGlass. Performance validation with prototype 3x3 SciGlass array – energy resolution measured for three different beam energies
- **Results for ~7 X_0 blocks – matches with Geant4**
- **Plans for 2022: Test with ~15X_0 (40cm) long blocks**





Acknowledgement:
Award: DE-SC0020619

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