New Materials for EIC Calorimeters

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and the EIC Homogeneous Calorimetry eRD1 Consortium

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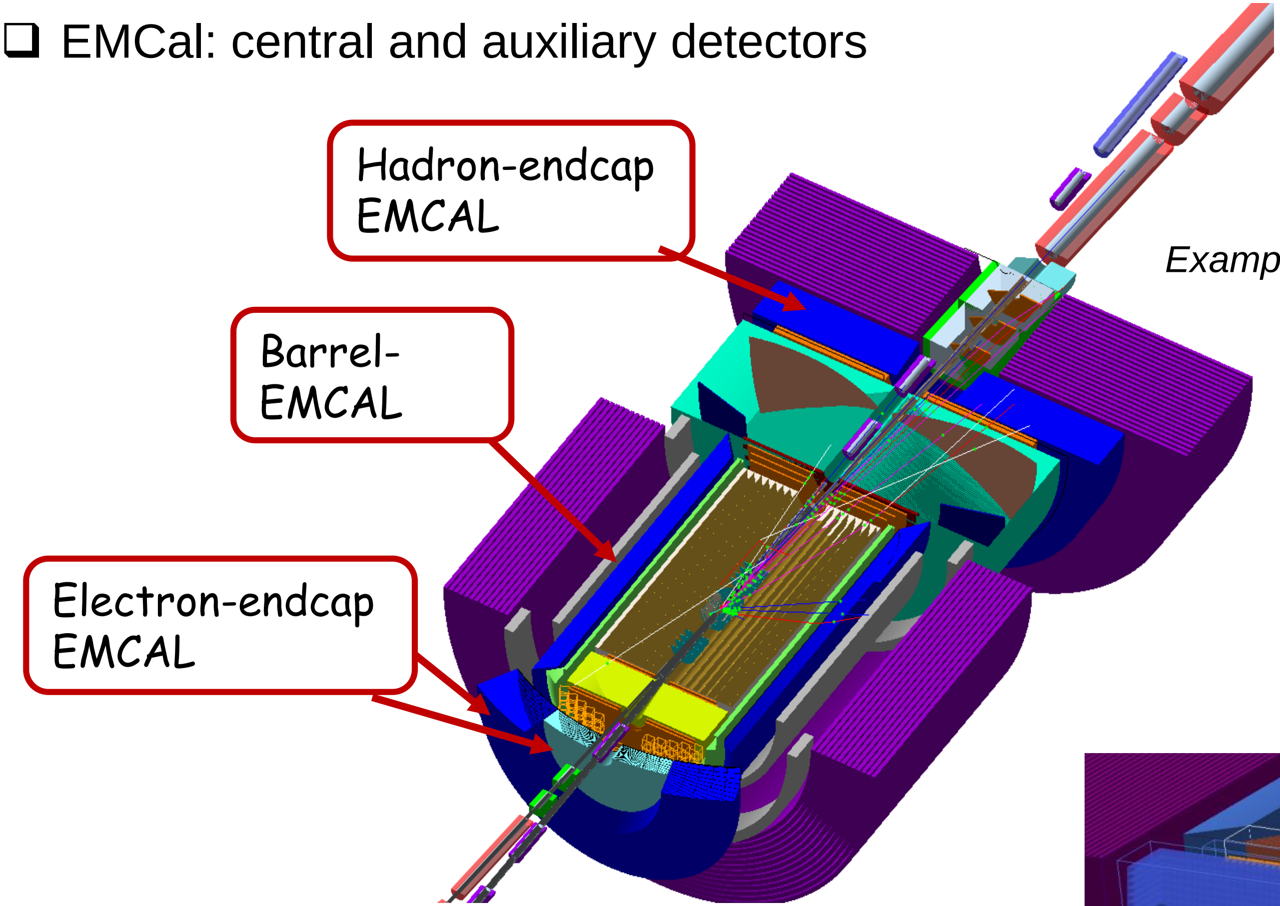
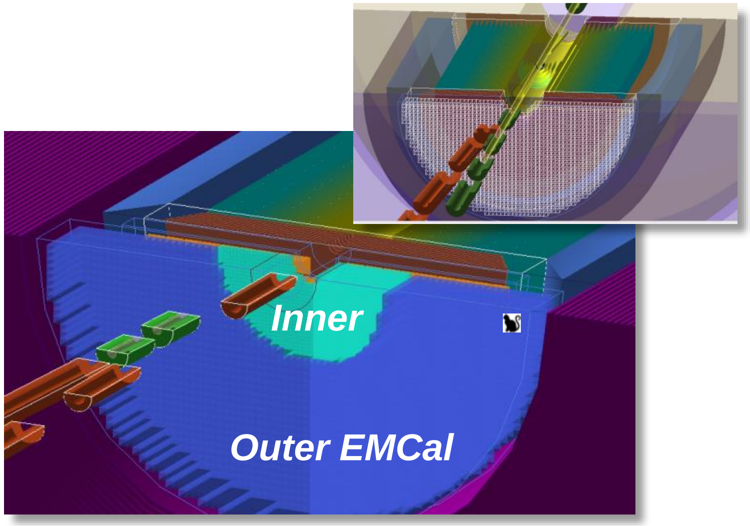
EIC EM Calorimetry

- EMCal: central and auxiliary detectors



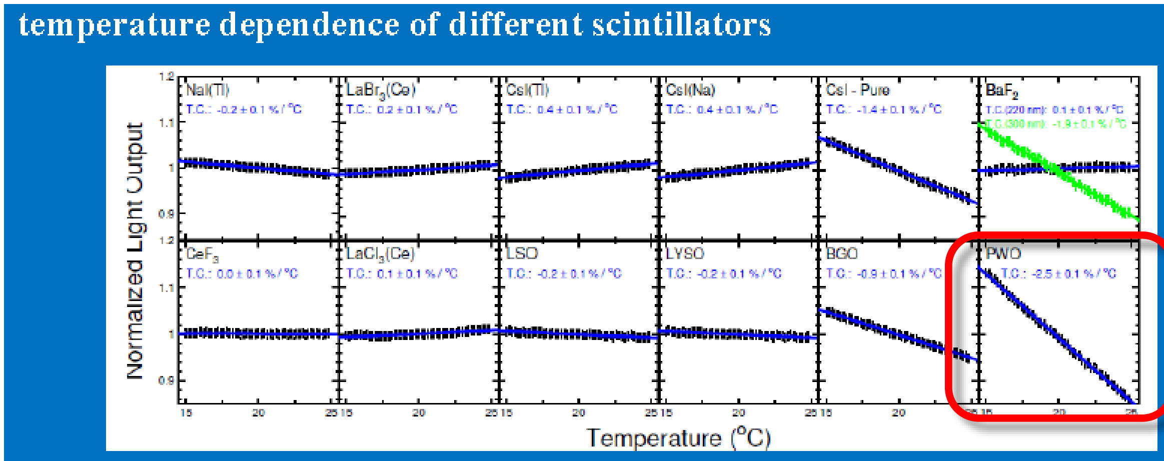
Example: JLEIC detector



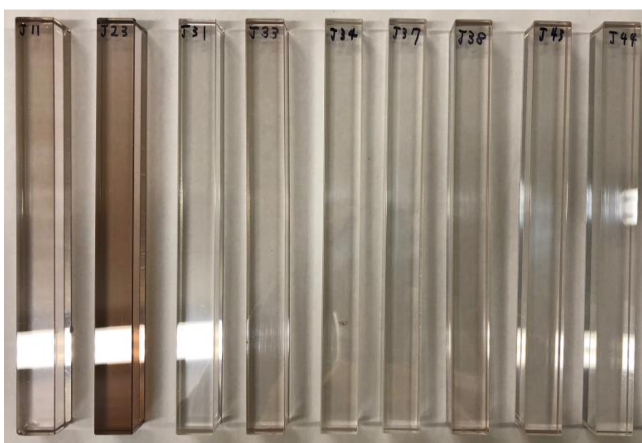
<table>
<tr><th>Regions and Physics Goals</th><th>Calorimeter Design</th></tr>
<tr><td>Lepton/backward: EM Cal
○ Resolution driven by need to determine (x, Q^2) kinematics from scattered electron measurement
○ Prefer $1.5\%/\sqrt{E} + 0.5\%$</td>
<td rowspan="2">Inner EM Cal for for $\eta < -2$:
➢ Good resolution in angle to order 1 degree to distinguish between clusters
➢ Energy resolution to order ($1.0\text{-}1.5\%/\sqrt{E}+0.5\%$) for measurements of the cluster energy
➢ Ability to withstand radiation down to at least 2-3 degree with respect to the beam line.
Outer EM Cal for $-2 < \eta < 1$:
➢ Energy resolution to $7\%/\sqrt{E}$
➢ Compact readout without degrading energy resolution
➢ Readout segmentation depending on angle</td></tr>
<tr><td>Ion/forward: EM Cal
○ Resolution driven by deep exclusive measurement energy resolution with photon and neutral pion
○ Need to separate single-photon from two-photon events
○ Prefer $6\text{-}7\%/\sqrt{E}$ and position resolution < 3 mm</td></tr>
<tr><td>Barrel/mid: EM Cal
○ Resolution driven by need to measure photons from SIDIS and DES in range 0.5-5 GeV
○ To ensure reconstruction of neutral pion mass need: $8\%/\sqrt{E} + 1.5\%$ (prefer 1%)</td>
<td>Barrel, EM calorimetry
➢ Compact design as space is limited
➢ Energy resolution of order $8\%/\sqrt{E} + 1.5\%$, and likely better</td></tr>
<tr><td>Ion/Forward: Hadron Cal
○ Driven by need for x-resolution in high-x measurements
○ Need Δx resolution better than 0.05
○ For diffractive with ~50 GeV hadron energy, this means $40\%/\sqrt{E}$</td>
<td>Hadron endcap:
➢ Hadron energy resolution to order $40\%/\sqrt{E}$,
➢ EM energy resolution to $< (2\%/\sqrt{E} + 1\%)$
➢ Jet energy resolution $< (50\%/\sqrt{E} + 3\%)$</td></tr>
</table>

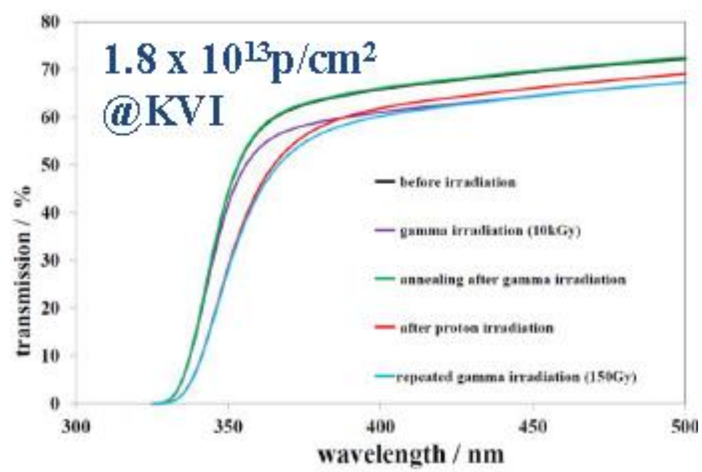
Crystals in EMCal: $PbWO_4$

$PbWO_4$ optimal for EMCal, e.g. CMS, PANDA detectors – stopping power, fast response, etc., but also limitations, e.g. hadron radiation damage, low Light Yield



$PbWO_4$ light yield temperature dependence: **2%/°C**





$PbWO_4$ radiation damage

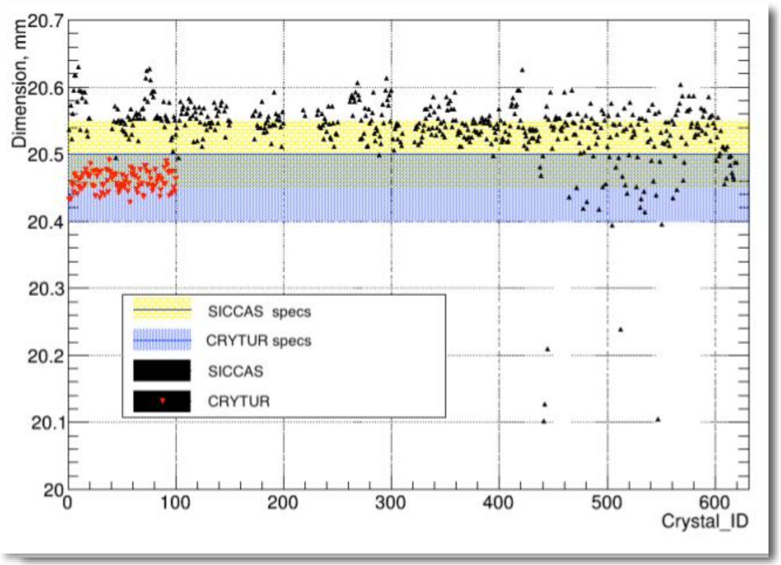
Crystals in EMCal: $PbWO_4$

- ❑ **Expensive (\$15-25/cm³)** – barrel EMCal not affordable
- ❑ Another consideration: manufacturing uncertainty

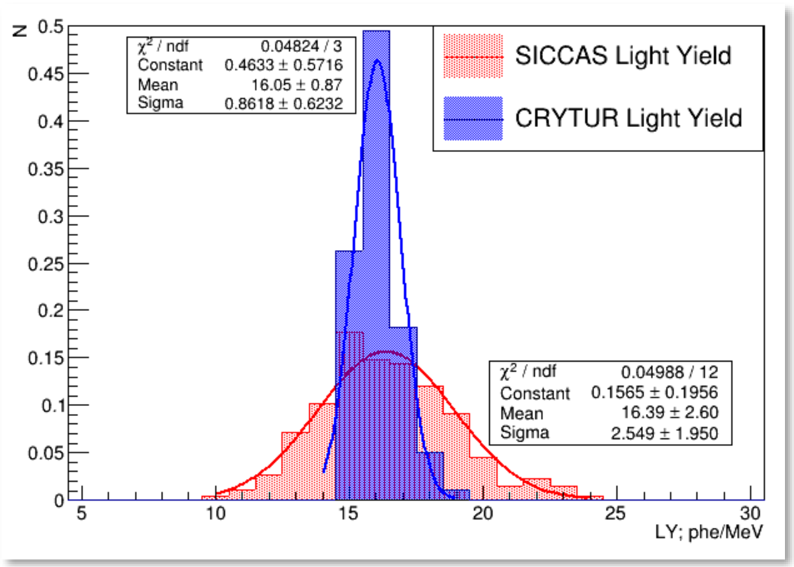
➢ SICCAS: failure rate ~35% for crystals received 2017-19 due to major mechanical defects – an additional 15% are questionable

➢ CRYTUR: Strict quality control procedures – so far 100% of crystals accepted, but limited raw material

Quality analysis:



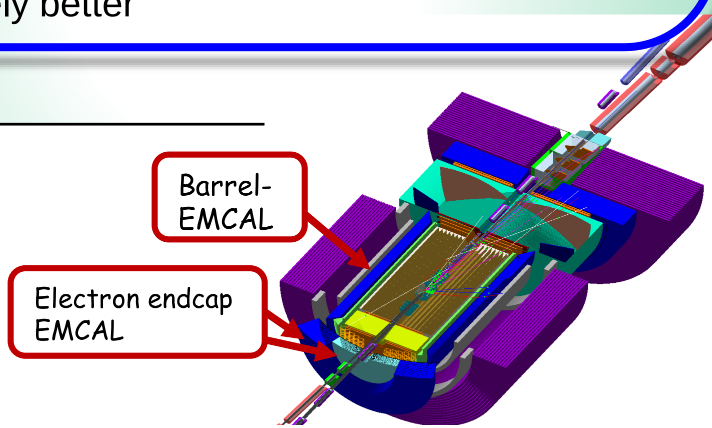
Dimensions



Light yield

Regions and Physics Goals	Calorimeter Design
Lepton/backward: EM Cal ○ Resolution driven by need to determine (x, Q^2) kinematics from scattered electron measurement ○ Prefer 1.5%/√E + 0.5%	**Inner EM Cal for for η < -2:** ➢ Good resolution in angle to order 1 degree to distinguish between clusters ➢ Energy resolution to order (1.0-1.5 %/√E+0.5%) for measurements of the cluster energy ➢ Ability to withstand radiation down to at least 2-3 degree with respect to the beam line.
Ion/forward: EM Cal ○ Resolution driven by deep exclusive measurement energy resolution with photon and neutral pion ○ Need to separate single-photon from two-photon events ○ Prefer 6-7%/√E and position resolution < 3 mm	**Outer EM Cal for -2 < η < 1:** ➢ Energy resolution to 7%/√E ➢ Compact readout without degrading energy resolution ➢ Readout segmentation depending on angle
Barrel/mid: EM Cal ○ Resolution driven by need to measure photons from SIDIS and DES in range 0.5-5 GeV ○ To ensure reconstruction of neutral pion mass need: 8%/√E +1.5% (prefer 1%)	**Barrel, EM calorimetry** ➢ Compact design as space is limited ➢ Energy resolution of order 8%/√E +1.5%, and likely better

Backward/lepton <u>Outer</u> EM Cal and barrel region – more relaxed on resolution requirements



Glass-based Scintillators for Detector Applications

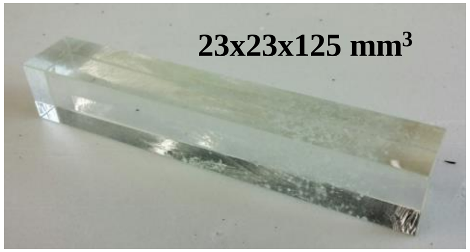
An alternative active calorimeter material that is more cost effective and easier to manufacture than, e.g. crystals

Material/ Parameter	Density (g/cm³)	Rad. Length (cm)	Moliere Radius (cm)	Interact Length (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (pe/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	450, 540	10 20-200 ~500	17-22	10	.90 scint. .10 Č	75.6
($BaO*2SiO_2$):Ce glass	3.7	3.6	2-3	~20		440, 460	22 72 450	>100	>2000 *(no tests >2Mrad yet)*	Scint.	51
($BaO*2SiO_2$):Ce glass w/ Gd	4.7-5.4	2.2		~20		440, 460	50 86-120 330-400	>100	>2000 *(no tests >2Mrad 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



The Vitreous State Laboratory – unique expertise

Premier materials science facility with unique capabilities and expertise in glass R&D

- Current R&D program includes
  - Nuclear and hazardous waste stabilization
  - Glass and ceramic materials development
    - Formulation optimization
    - Characterization
    - Property-composition models
  - Materials corrosion and characterization
  - Off-gas treatment
  - Water treatment, ion exchange
  - Cements, flyash
  - Geopolymers
  - Biophysics
  - Nano-materials
  - Thermoelectrics
  - Spintronics
  - Scintillation detectors

The Vitreous State Laboratory – unique facility

- Designing, constructing and testing large glass production systems
  - VSL Joule Heated Ceramic Melter (JHCM) Systems:
    - The largest array of JHCM test systems in the US
    - The largest JHCM test platform in the US

PILOT SYSTEM SCALE-UP

DM10 and DM100 JHCM Systems at VSL

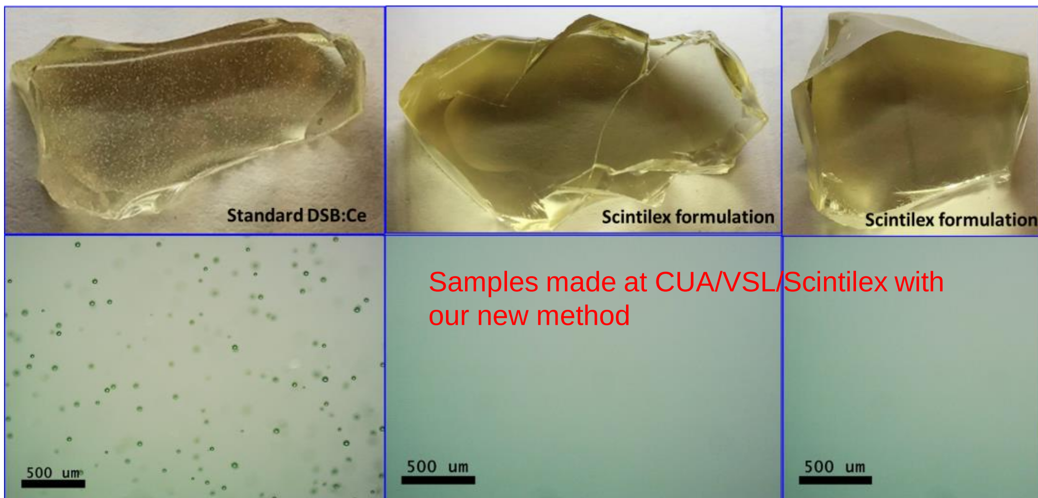
VSL DM1200 HLW Pilot Melter System

About 400,000 kg glass made from about 1 million kg feed

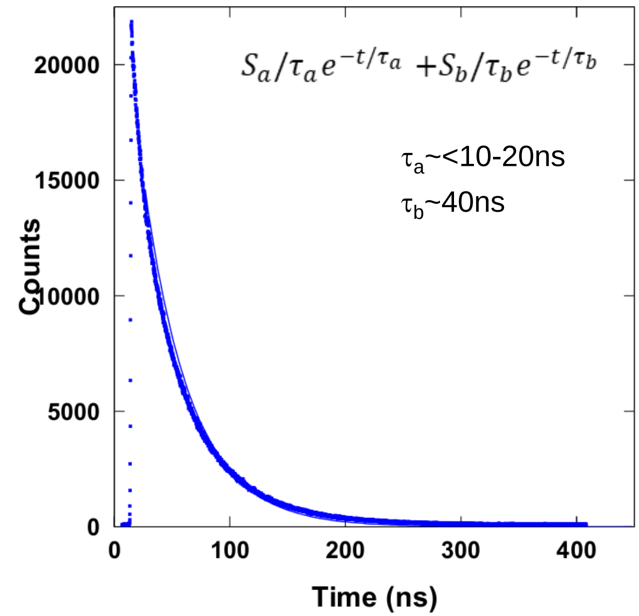
New Glass Scintillator Material

- Glass scintillators being developed at *VSL/CUA/Scintilex*

Progress with new method to eliminate defects



Scintillation decay time



Decay time measured with single photon counting

Optical properties comparable or better than $PbWO_4$

Light Yield

Material/ Parameter	$PbWO_4$	Sample 1	Sample 2	Sample 3	Sample 4
Luminescence (nm)	420	440	440	440	440
Relative light output (compared to $PbWO_4$)	1	35	16	23	11

Glass Scintillator – formulation optimization

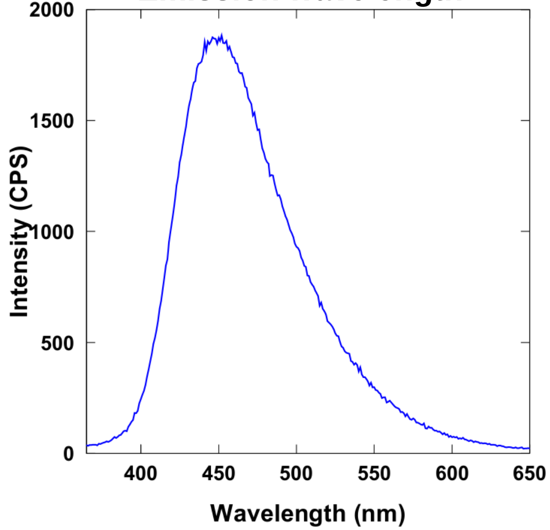
SCINTILEX

❑ Two glass formulations for calorimeter application

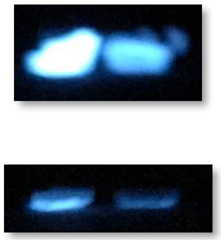
VSL-Scintilex-G4 (nominal)

VSL-Scintilex-T1

Emission wavelength



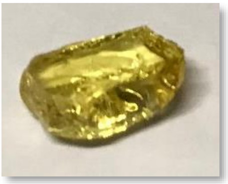
Scintillation light



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

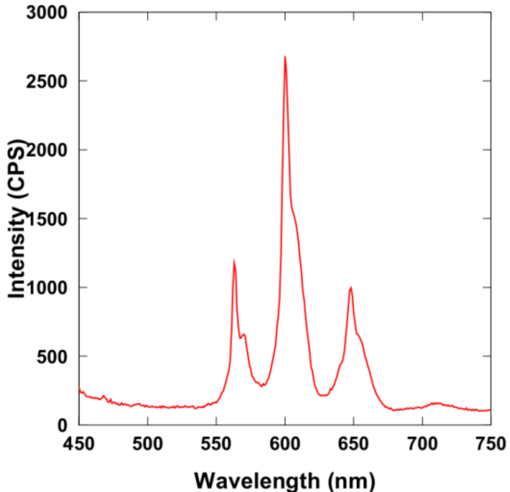
❑ Formulations with initial emission wavelength tuning

VSL-Scintilex-SC1

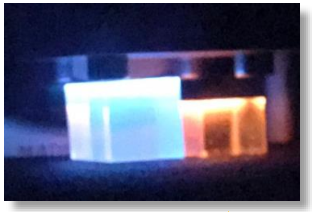


VSL-Scintilex-EC1

Emission wavelength



Scintillation light



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

Glass Scintillator – Radiation Hardness

SCINTILEX

- ❑ High dose radiation tests – progress with new method at CUA/VSL/Scintilex

VSL-Scintilex-S1 | **VSL-Scintilex-S2** | **VSL-Scintilex-G4 (nominal)**



Before irradiation



After 2min 160KeV
Xray at >3k Gy/min


After curing

- ❑ T, SC, EC series are EM radiation hard with new method too
- ❑ Hadron irradiation test planned

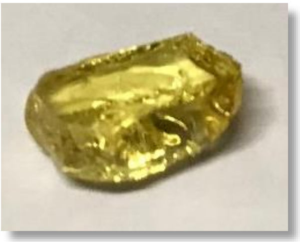
Glass Scintillator – Initial Scale-Up

SCINTILEX

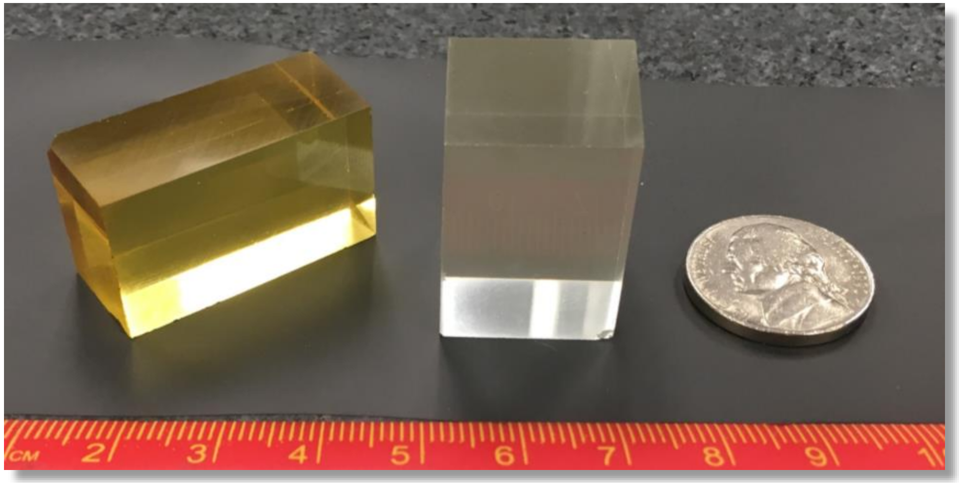
- Progress with scale-up – medium-size samples produced, issues associated with further scale-up identified, solutions are being implemented and tested

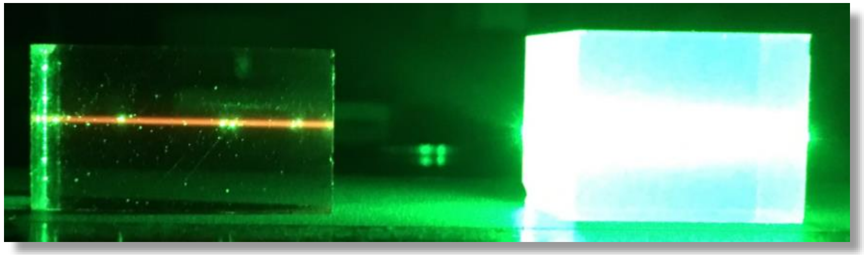
Example: G4 (nominal), SC1 glass

1cm x 1cm x 0.5cm (test size)

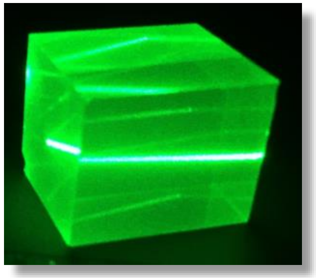


2cm x 2cm x ~3cm (medium size)



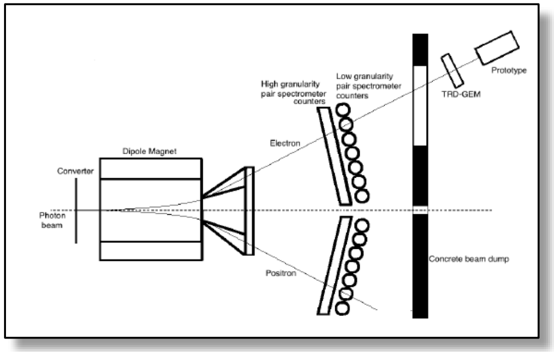


Outlook



- ❑ **Produce larger glass samples** with adequate surface quality for physical, luminescence, and radiation hardness tests

- ❑ **Prototype beam test program** – quantify performance and response of glass to different photosensors and streaming readout



- ❑ **Extend evaluation of glass calorimetry** – develop MC for resolution studies and matching crystal/glass, increase efforts to other regions

- ❑ **Additional radiation hardness studies** – evaluate resistance to hadron radiation (MC40 synchrotron) and higher EM radiation doses (IPNO)

- ❑ **SBIR/STTR proposal** – glass scintillator development

SCINTILEX

Summary

- $PbWO_4$ crystals are ideal for precision EMCal, but also have limitations and are expensive – large volume detectors are unaffordable

- Glass-based scintillators are cost-effective alternative to crystals, in particular EMCal regions with relaxed resolution requirements

  - Small samples produced at CUA/VSL/Scintilex have a factor of ten or higher light yield compared to $PbWO_4$

  - Initial scale-up successful – medium-size samples produced without defects

  - Ongoing optimization

  - Beam test program expected to start this fall