New Materials for Calorimetry at EIC

Tanja Horn / Ian Pegg

THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab
Thomas Jefferson National Accelerator Facility

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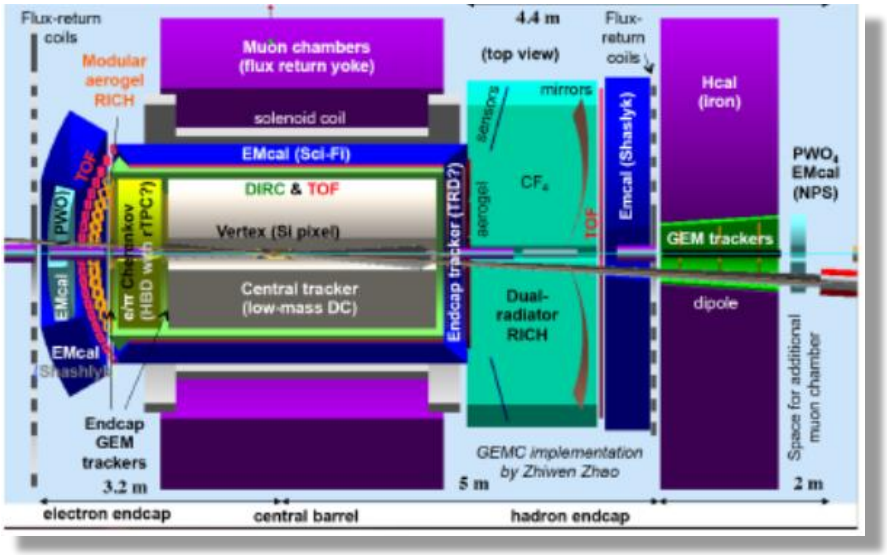
EIC Calorimeter Consortium Goals

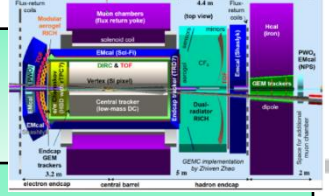
Develop calorimeters that meet the requirements of physics measurements at an EIC – including all regions of the detector

Systematic uncertainties are expected to be the main limiting factor in extracting the underlying physics

- ***Reduce systematic uncertainty*** on a broad range of physics measurements by employing ***different technologies***
- Broaden the spectrum to include ***new technologies*** that could potentially offer ***improved performance, lower cost, mitigate risk and broaden user involvement***

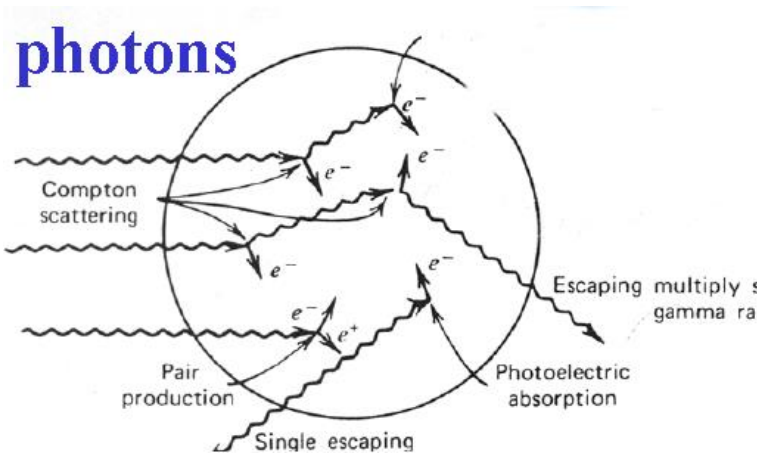
Backward **Barrel** **Forward**

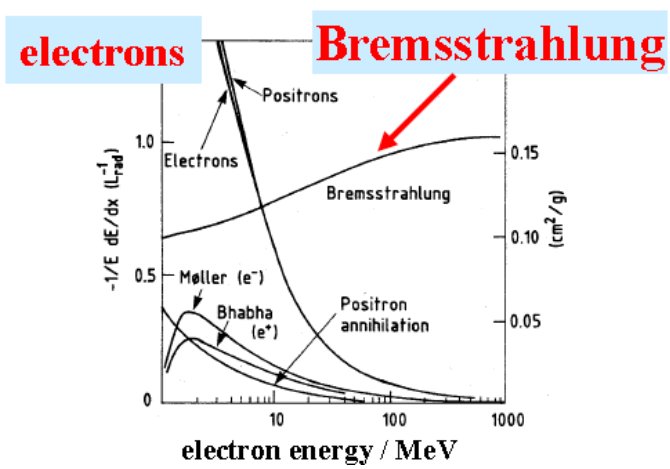




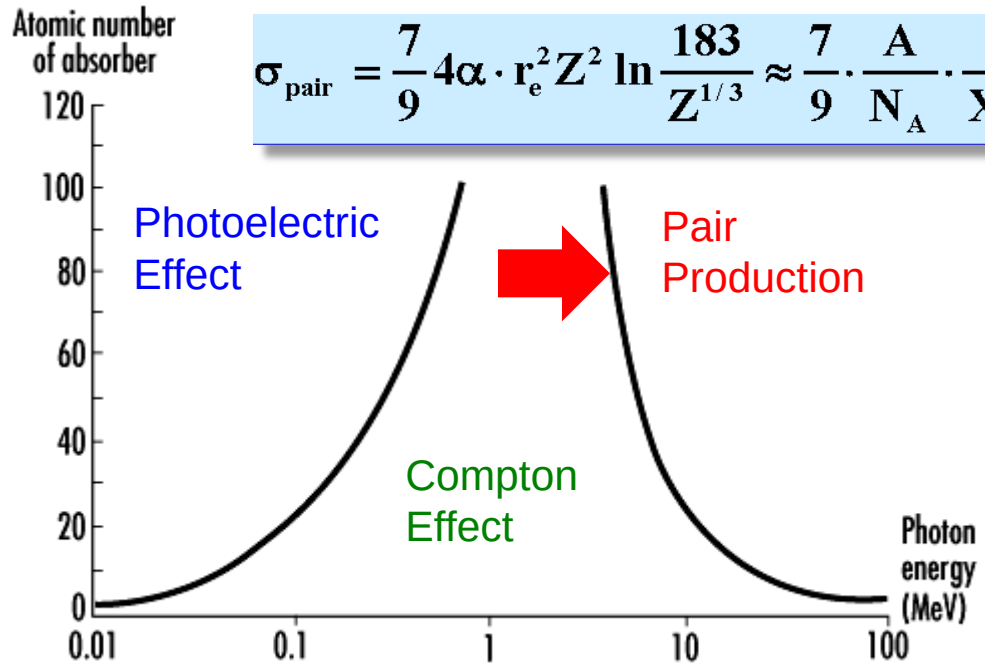
Regions and Physics Goals	Calorimeter Design
Lepton/backward: EM Cal ○ Resolution driven by need to determine (x, Q^2) kinematics from scattered electron measurement ○ Prefer 1.5%/√E + 0.5%	**Inner EM Cal for for η < -2:** ➢ Good resolution in angle to order 1 degree to distinguish between clusters ➢ 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. **Outer EM Cal for -2 < η < 1:** ➢ Energy resolution to 7%/√E ➢ Compact readout without degrading energy resolution ➢ Readout segmentation depending on angle
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	
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
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%/√E	**Hadron endcap:** ➢ Hadron energy resolution to order 40%/√E, ➢ EM energy resolution to < (2%/√E + 1%) ➢ Jet energy resolution < (50%/√E + 3%)

Electromagnetic Probes





$$\sigma_{pair} = \frac{7}{9} 4\alpha \cdot r_e^2 Z^2 \ln \frac{183}{Z^{1/3}} \approx \frac{7}{9} \cdot \frac{A}{N_A} \cdot \frac{1}{X_0}$$



$$-\frac{dE}{dx} = \frac{E}{X_0}$$

EM shower

radiation length $X_0 \sim \frac{1}{Z^2}$

Scintillator Basics – photons from scintillation

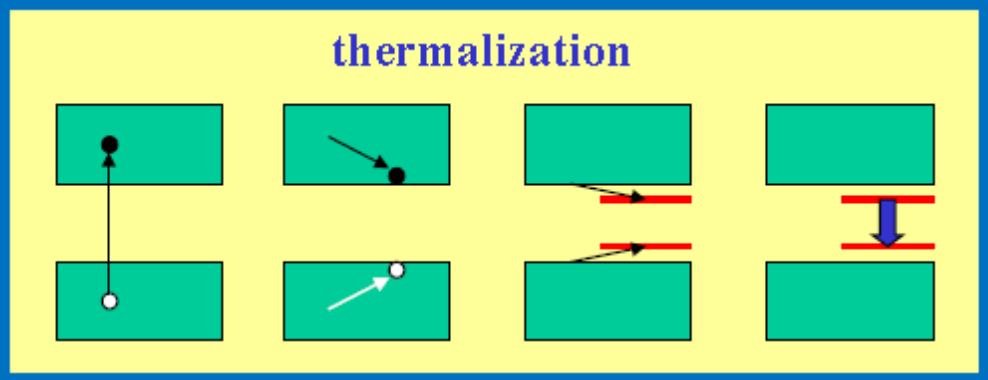
relative light output: $L_R = \frac{N_{ph}}{E_{dep}}$

energy to generate an e/h-pair:

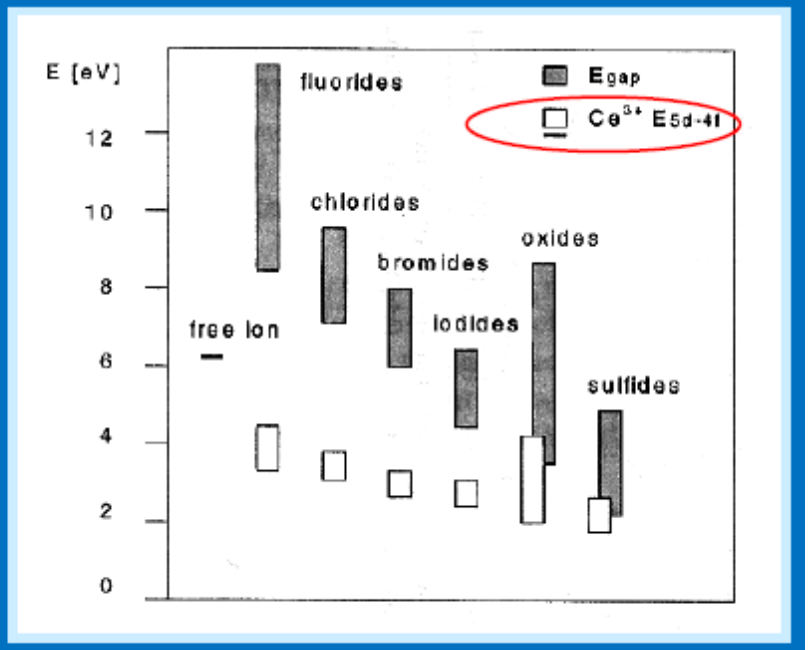
$\xi_{eh} = \beta \cdot E_g \quad E_g$: band – gap

$\beta = 1.5 - 2$: ionic crystals

$\beta = 3 - 4$: covalent binding



$$N_{ph} = \frac{E_\gamma}{\beta \cdot E_{gap}} \cdot S \cdot Q$$

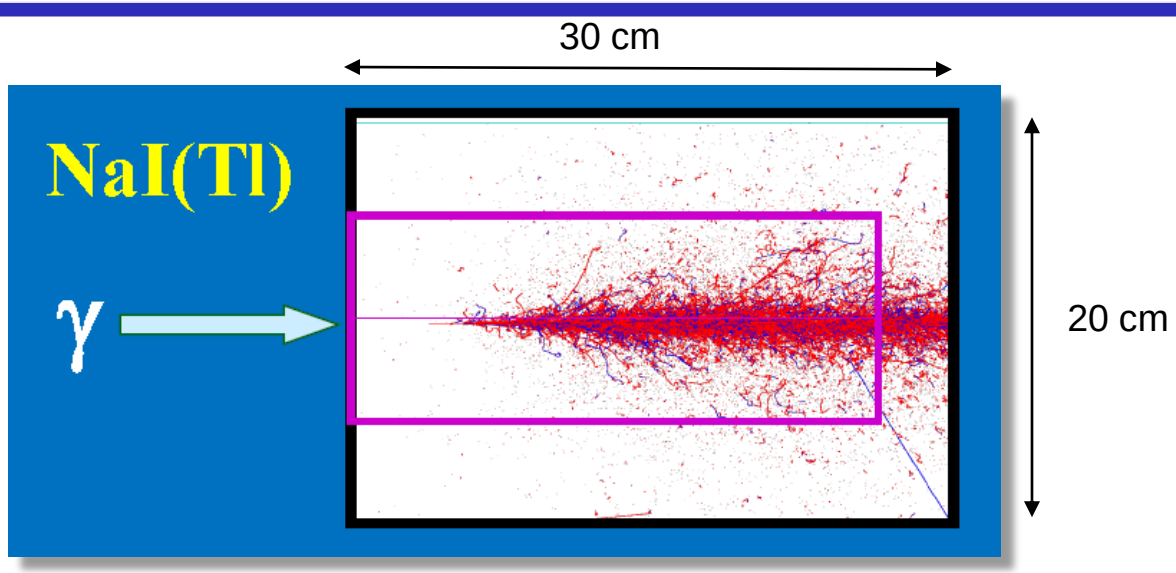


C.W.E. van Eijk, NIM A460 (2001) 1

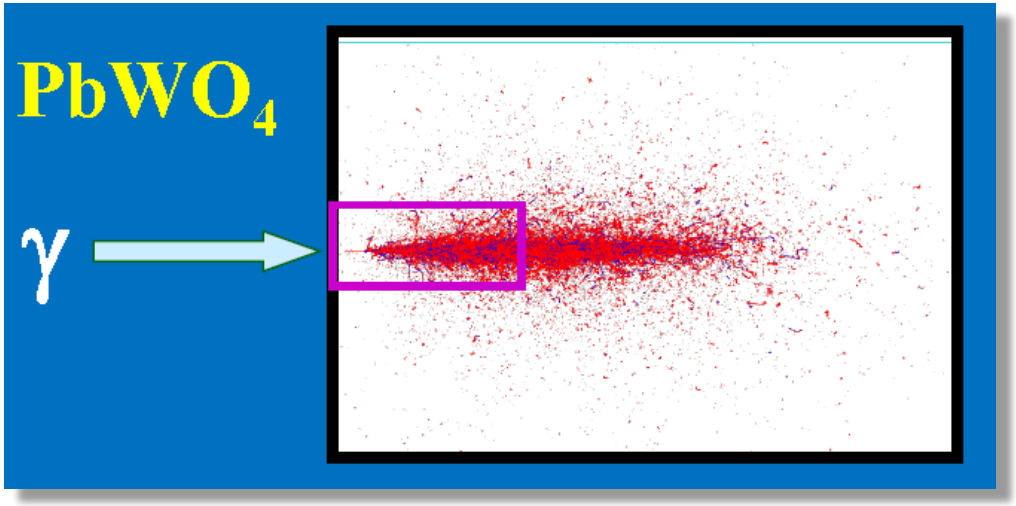
Requirements on calorimeter materials

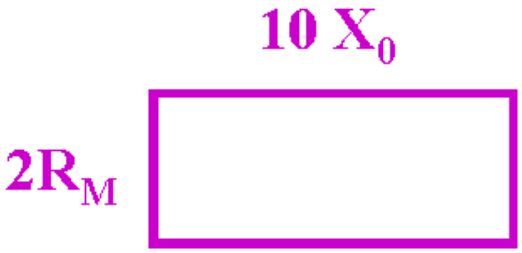
- Light Yield – Conversion of energy into visible light
- Attenuation Coefficient – Radiation length
- Scintillation Response – emission intensity
- Emission spectrum matching between scintillator and photo detector – emission peak
- Chemical stability and radiation resistance
- Linearity of light response with incident photon energy
- Moliere radius for lateral shower containment
- Temperature stability

Scintillator Basics – stopping power



Photon Energies:
50 MeV – 50 GeV





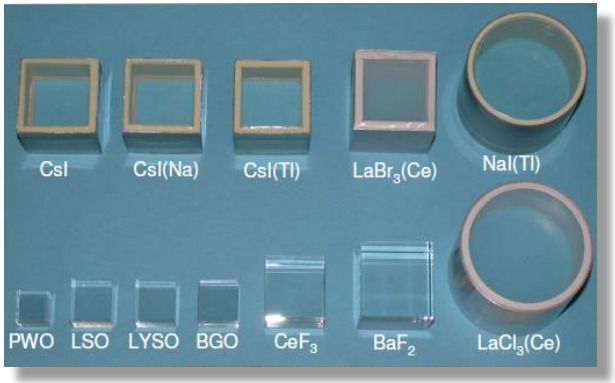
$$X_0 = \frac{716.4 \times A}{Z(Z+1)\ln(\frac{287}{\sqrt{Z}})}\frac{1}{\rho}$$

Small Moliere radius good to contain shower

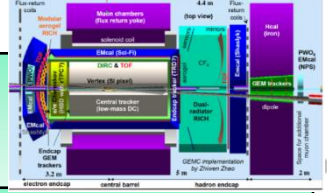
- Disadvantage: more sensitive to mismatches of tracking

Selection of Inorganic Scintillators

Material/ Parameter	Density (g/cm^3)	Melt. Point (°C)	Rad. Length (cm)	Moliere Radius (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (γ/MeV)	Rad. Hard. (krad)	Radiation type	Z_{Eff}
BaF_2	4.89	1280	2.03 2.06	3.10 3.40	1.50	300 220	650 0.9	16000 2000	>50	Scint.	52.7
CeF_3	6.16	1460	1.70 1.68	2.41 2.60	1.62 1.68	340 300	5 30	2800	>100	Scint.	50.8
(BGO)$Bi_4Ge_3O_{12}$	7.13	1050	1.12	2.23 2.30	2.15	480	300	8000 4000	>1000	.98 scint, .02 Č	83
(PWO)$PbWO_4$	8.30	1123	0.89 0.92	2.00	2.20	560 420	50 10	40 240	>1000	.90 scint. .10 Č	75.6
PbF_2	7.77	824	0.93	2.21	1.82	280 310	<30	2-6	50	Pure Č	77
(BSO):$CeBi_4Si_3O_{12}$	6.80	1030	1.85	≈5	2.06	470 505	≈100	1000 4000	>10	Scint.	75
(LSO):$CeLu_2SiO_5$	7.40	2050	1.14	2.07	1.82	420	40	30000	>1000	.98 sint ..02 Č	64.8
(LYSO):$Ce[LuY]_2SiO_5$	7.40	2050	1.14	2.07	1.82	420	40	30000	>1000	.98 scint. .02 Č	64.8



Identical Volume: X_0^3



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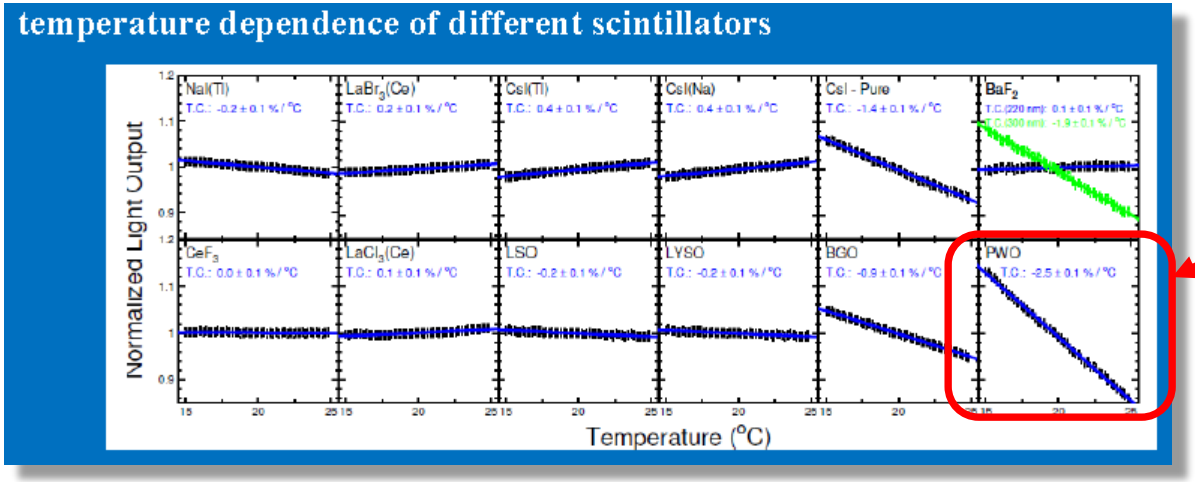
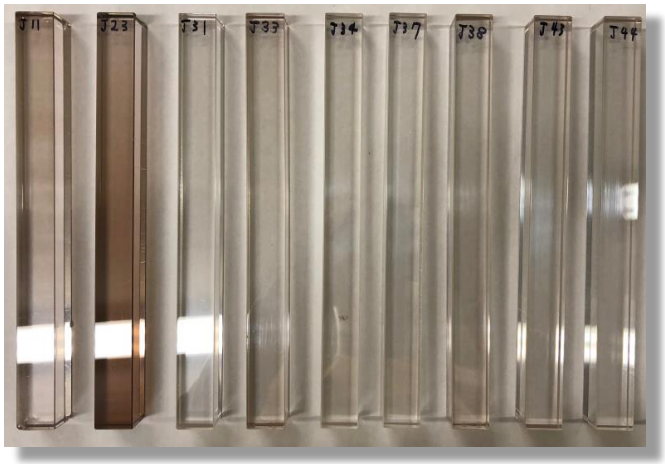
Backward/lepton <u>Inner</u> EM Cal – most demanding for high resolution

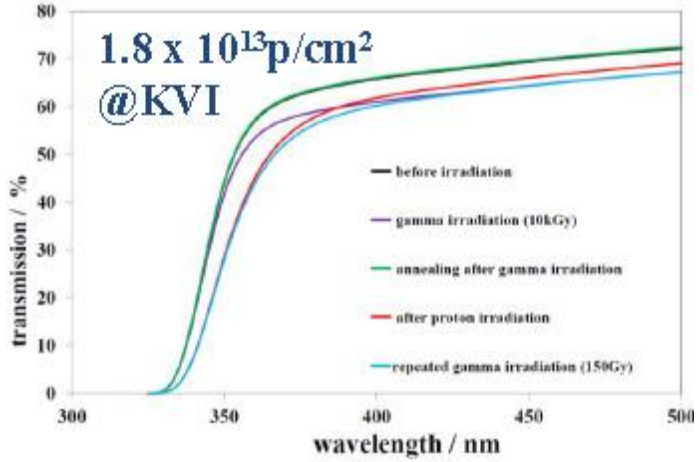
EIC EMCal Endcaps: $PbWO_4$

- $PbWO_4$ material of choice for EIC EMCal – stopping power, fast response, large and granular solid angle, etc., but also limitations, e.g. hadron radiation damage



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

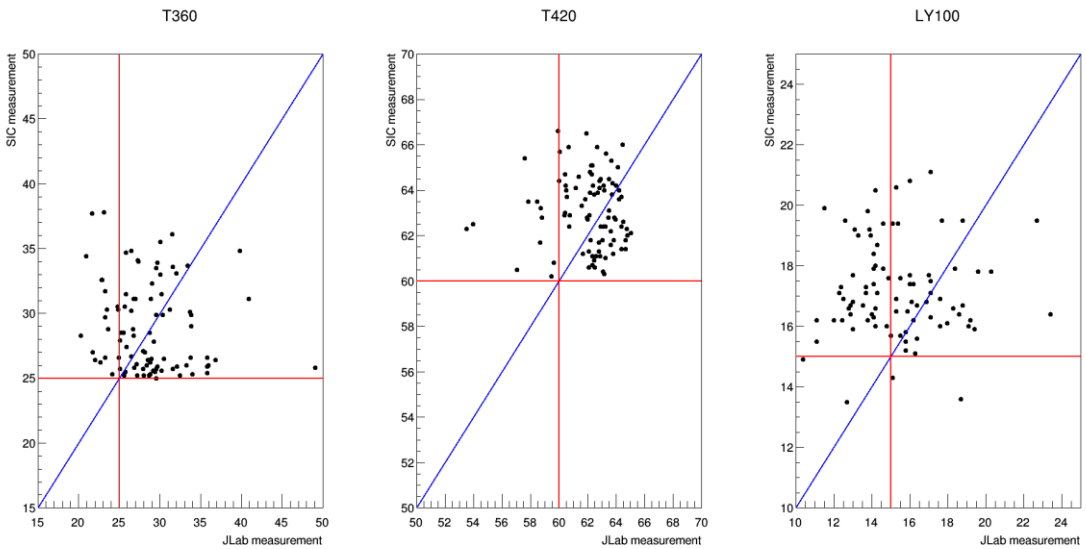


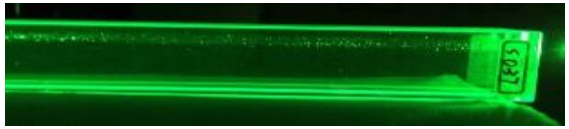


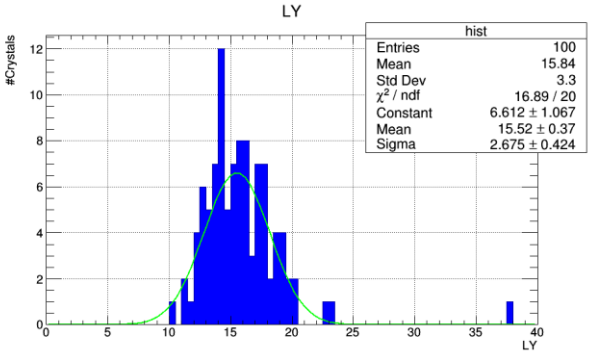
$PbWO_4$ radiation resistance

EIC EMCal Endcaps: $PbWO_4$

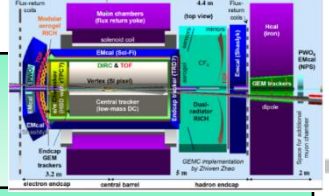
- Another consideration: expensive ($15-25/cm^3) and manufacturing uncertainty
  - Despite progress (work with SICCAS and now also CRYTUR) still a struggle to work with vendors to get reliable $PbWO_4$ crystals that would be compatible with EIC requirements at small angles in the forward and backward regions







- ~40% of SICCAS 2017 crystals fail specs, considerable delay in CRYTUR mass production



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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/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

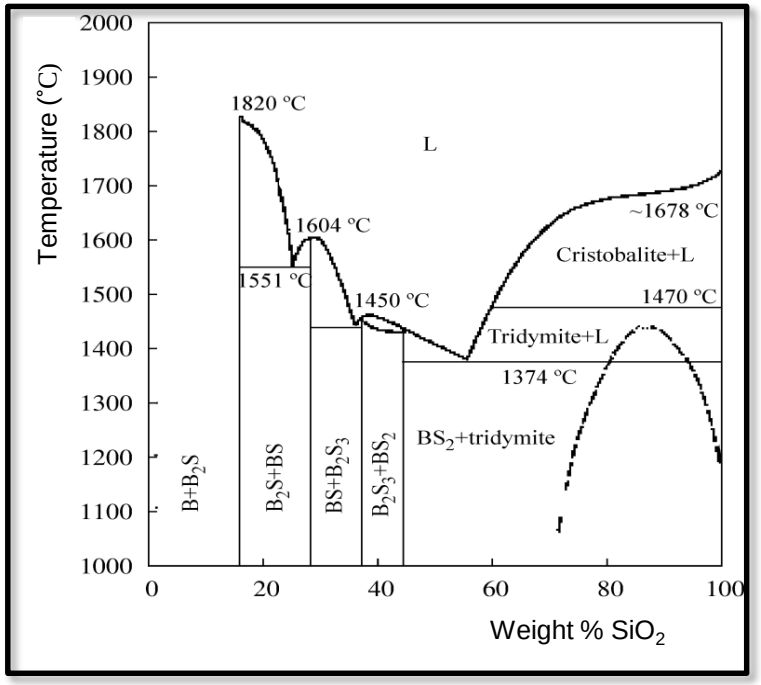
Shortcomings of earlier work:

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

Material Overview

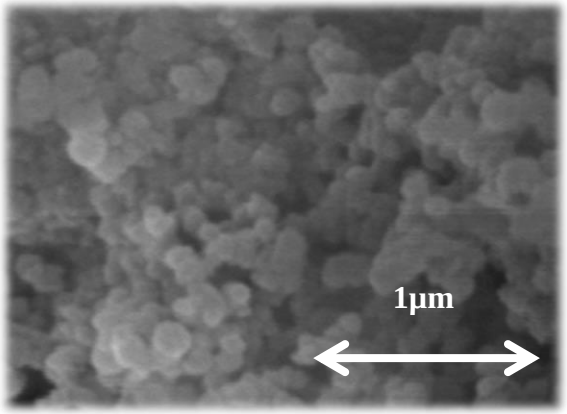
Technology: Glass production combined with successive thermal annealing (800 – 900°C)

Phase diagram of the $BaO*SiO_2$ system



Material	Density (g/cm³)	X_0 (cm)	Emission peak (nm)	Cutoff (nm)	Zeff
$(BaO*2SiO_2)$:Ce glass	3.7	3.6	440, 460	310	51
DSB:Ce	3.8	3.5	440, 460	310	51
$(BaO*2SiO_2)$:Ce glass loaded with Gd	4.7-5.4	2.2	440, 460	318	58

Study of New Glass and Glass Ceramics Scintillation Material (Novotny et al., 2016+)

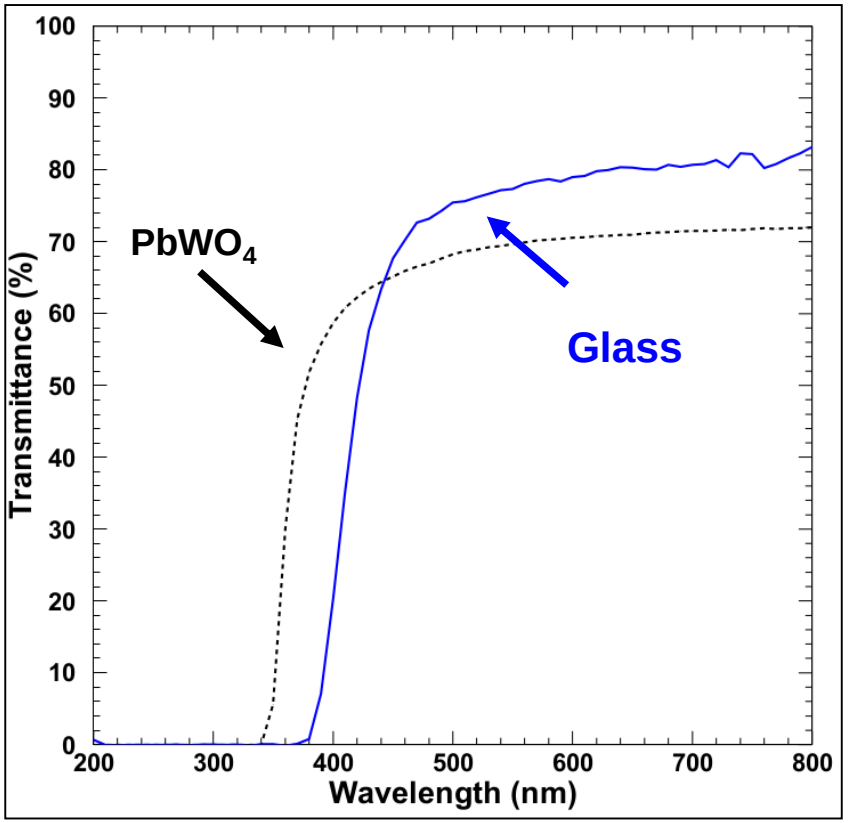


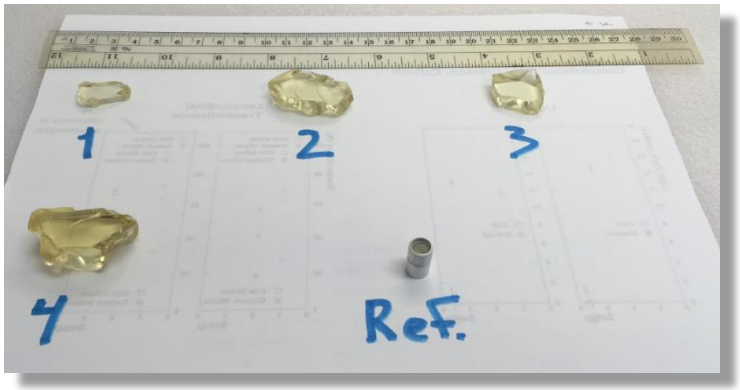
SEM image of recrystallized $BaO*2SiO_2$ at 950°C

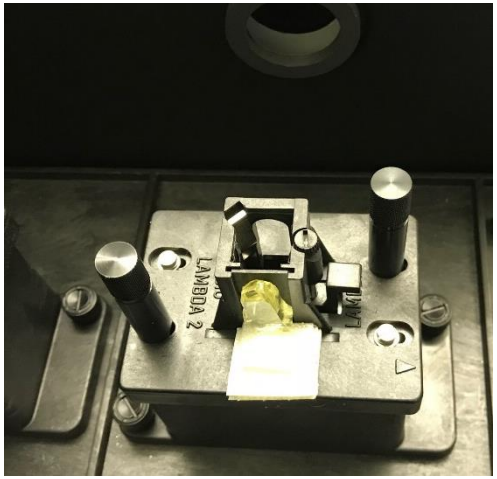
- Nano-sized particles of **$BaSi_2O_5$**
  - improve scintillation!
- Ba-Si system allows to incorporate trivalent ions: **Lu, Dy, Gd, Tb, Yb, Ce**

Status of New Glass/Ceramic Scintillator Material

- **Transmittance** of small samples comparable and sometime better than PbWO4

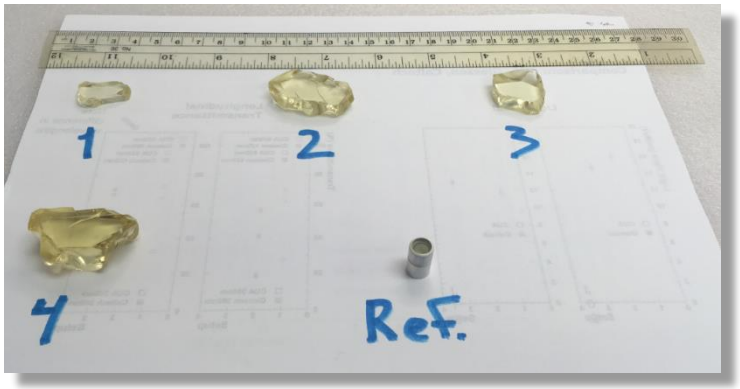


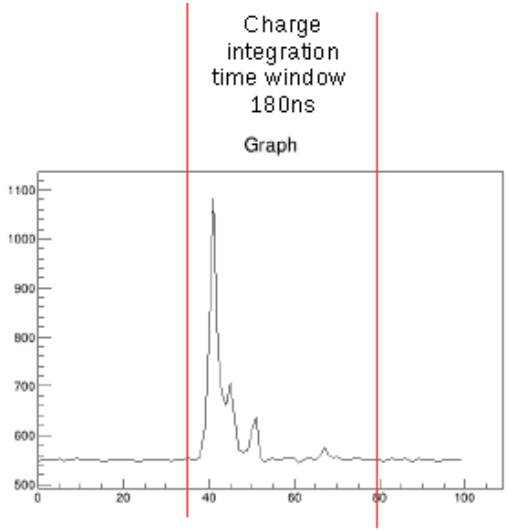


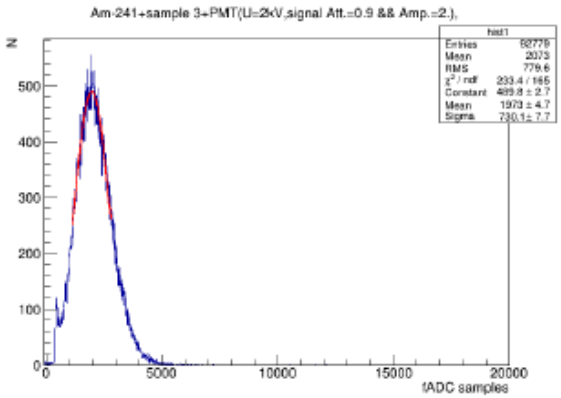


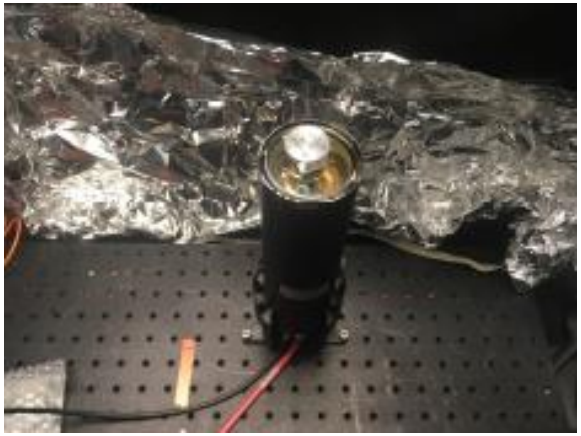
Status of New Glass/Ceramic Scintillator Material

- **Light yield** of small samples comparable and sometime better than PbWO4





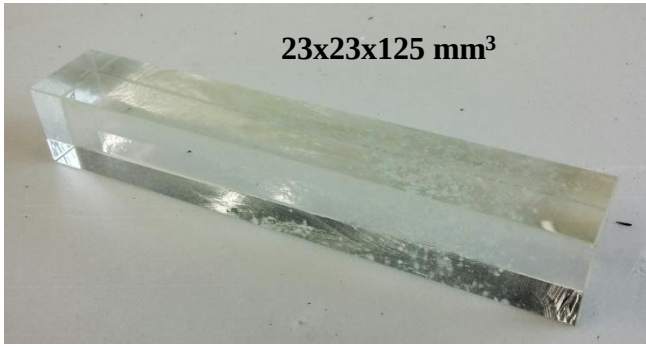


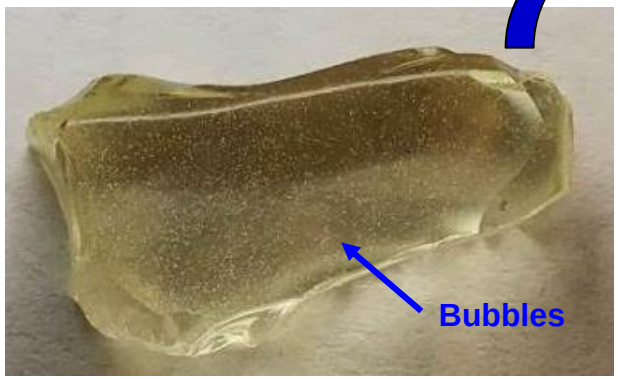


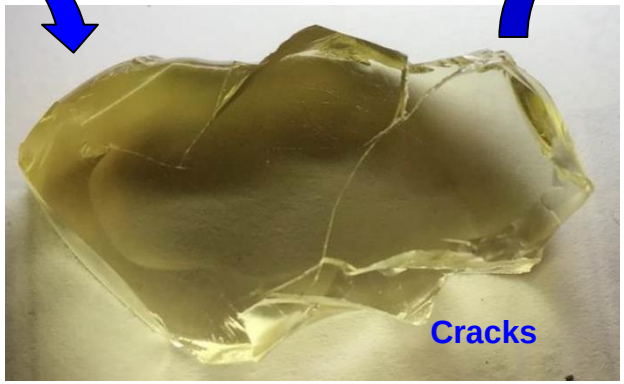
Material/ Parameter	$PbWO_4$	Sample 1	Sample 2	Sample 3	Sample 4
Luminescence (nm)	420	440	440	440	440
Relative light output (compared to $PbWO_4$)	1	35	16	23	11

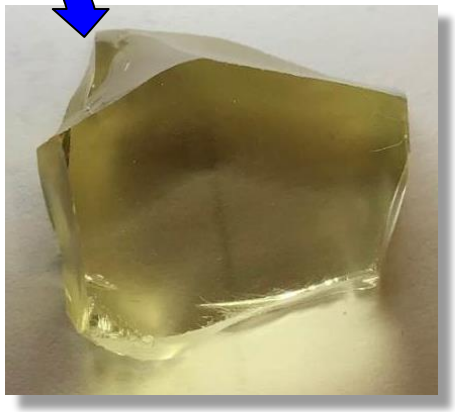
Status of New Glass/Ceramic Scintillator Material

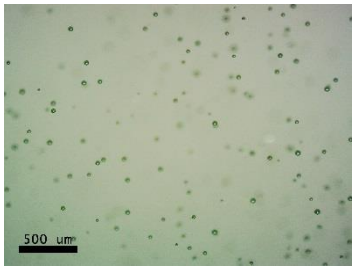
- Uniformity remains a concern – manufacturing process requires optimization – progress with new method at CUA/VSL



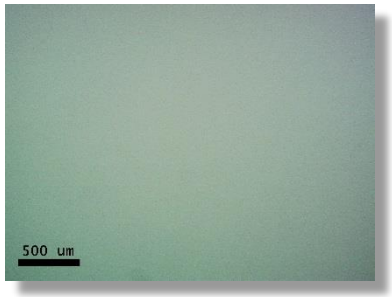








Sample made at CUA/VSL based on previous DSB:Ce work



Samples made at CUA/VSL with our new method

Summary and Outlook

- Resolution requirement different depending on EIC calorimeter regions
  - Lepton backward at small angles most demanding $PbWO_4$
- $PbWO_4$ crystals are ideal for EIC EMCal, but also have limitations – and are expensive
- Glass-based scintillators are cost-effective alternative to crystals, in particular in the outer endcaps and central EMCal regions
- Initial small samples produced at CUA/VSL have 35x light yield of PWO
  - New method also eliminates bubbles, a major problem in earlier work
- Next steps include: scale up and optimization of composition for sensitivity to EM probes