Materials for the EIC EM Calorimeters

The EIC high-resolution EM Calorimeters have the following basic requirements:

- Interaction rate capability up to $0.5x10^6$ Hz requiring reasonably fast scintillation kinetics
- Sufficient energy resolution and efficiency over a large dynamic range of photon energies, typically from order 50 MeV to 50 GeV
- Adapted geometrical dimensions to contain the major part of the EM shower
- Moderate radiation hardness up to ~3 krad/year (30 Gy/year) electromagnetic and 10^{10} n/cm^2 hadronic at the top luminosity.

This rules out most of the well-known scintillator materials. Finally, even a compact geometrical design requires, due to a minimum granularity, a large quantity of crystal modules, which rely on existing technology for mass production to guarantee the necessary homogeneity of the whole calorimeter.

For hadron physics measurements with electromagnetic reactions, such as at multiple setups at Jefferson Lab and also at PANDA/GSI, the most common precision calorimeter of choice has been lead tungstate, $PbWO_4$ (PWO). This is mostly driven by the requirement of good energy resolution and high granularity to detect and identify electrons, photons and pions. Good energy resolution aids in electron-pion separation and to determine the electron scattering kinematics, compactness and high granularity is driven by need for position resolution and separation of single-photons from neutral-pion decays. PWO meets the requirements of an extremely fast, compact, and radiation hard scintillator material providing sufficient luminescence yield to achieve good energy resolution. PWO is available from two commercial vendors with established mass production capability.

Crystalline scintillators like NaI(Tl), CsI(Tl), and CsI used in detectors at electron-positron colliders like Crystal Ball at SPEAR, Babar at PEPII, or BELLE at KEK have high light output, but cannot provide the required granularity and have relatively slow decay time. These materials also have a relatively low radiation resistance, which makes them not suitable for the EIC operating at top luminosity. BaF_2 used at Crystal Barrel/TAPS experiment at ELSA has similar limitations for the granularity and scintillation kinetics. Although BaF_2 has a very fast component its separation from the slow component is nontrivial. BGO and CeF_3 are the closest candidate crystalline scintillators to PWO. Their properties and drawbacks are discussed in an Appendix.

A bridge between PWO and less stringent resolution requirements could be provided by SciGlass. SciGlass has a larger radiation length than PWO, but can have a Moliere radius close to those of PWO, BGO and CeF_3. Due to its larger radiation length, it requires roughly twice the longitudinal length as PWO, for similar energy resolution, but can achieve similar granularity due to the similar Moliere radius. It also has a small interaction length (twice smaller than those for CsI and NaI) and high light yield, similar as BGO and CeF_3. Advantages are its lack of temperature dependence and high radiation hardness (>1000 kRad and >10^{15} n/cm^2).

Parameter ======= Material	Density (g/cm^3)	Rad. Length (cm)	Moliere Radius (cm)	Decay time (ns)	Light Yield (γ/MeV)	dLY/dT (%/°C)	Rad. Hard. (krad)
NaI(Tl)	3.67	2.59	4.13	245	41000	-0.2	1--2
CsI(Tl)	4.51	1.86	3.57	1220	60000	0.4	1
CsI	4.51	1.86	3.57	35 6	1600 400	-0.6 -1.4	1
BaF_2	4.89	2.03	3.1	650 0.9	16000 2000	-1.9 0.1	>50
CeF_3	6.16	1.70	2.41	30	2800	~0.1	>100
(BGO) $Bi_4Ge_3O_{12}$	7.13	1.12	2.23	300	8000 4000	-0.9 -1.6	>1000 (recovery
(PWO) $PbWO_4$	**8.3**	**0.89**	**2**	**30 10**	**40 240**	**-2.5**	**>1000**
SciGlass	3.7-4.5	2.2-2.8	2--3	20-50	500-2000	None	>1000

In general, for high-precision electromagnetic calorimetry, the following are of relevance:

- Smaller Moliere radius allowing higher granularity
- Smaller radiation length allowing smaller longitudinal size
- Better energy resolution.
- Smaller constant term contribution to energy resolution, mainly due to non-uniformity and gaps, to readout and noise. Note that to achieve convergence to good energy resolution one often needs 20 radiation lengths (like for PbWO4 or SciGlass) and sometimes more (like for CsI).
- Smaller decay time
- Higher light yield
- No or minimal temperature dependence to light yield
- Higher radiation hardness (EM and/or hadron fluences)

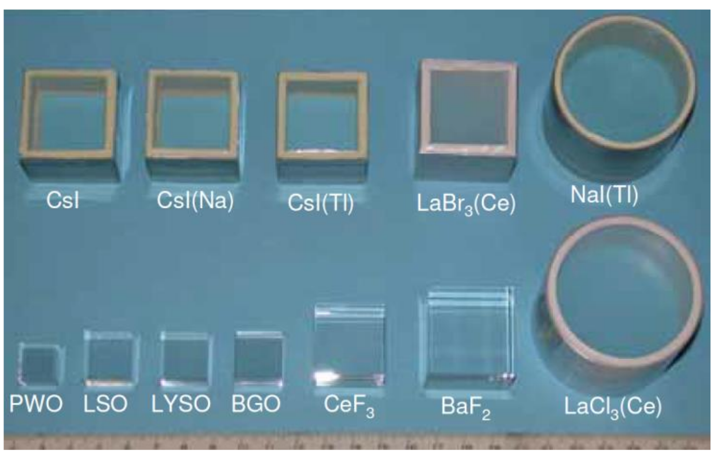
EIC EM Calorimeter Technical Requirements

- Interaction rate capability up to 0.5×10^6 Hz requiring reasonably fast scintillation kinetics
- Sufficient energy resolution and efficiency over a large dynamic range of photon energies
  - In backward region, $\eta < -2$ or -2.5, energy resolution of order $2.5\%/\sqrt{E}$ to achieve required 10^4 π/e rejection (for E > 2 GeV). Or, in other words, to achieve clean electron identification making use of tracking information to determine E/p. For $-2 < \eta < -1$, an energy resolution of $7\%/\sqrt{E}$ suffices to achieve clean electron identification for E > 2.5-3 GeV. For $|\eta| < 1$, $12\%/\sqrt{E}$ suffices.
  - In backward and especially far-backward region a small constant term, 1% or less, to aid in determination of electron scattering kinematics. Note that to achieve convergence to good energy resolution including constant term typically requires 20 or more radiation lengths (X_0). For PbWO4, this is $22X_0$ (20 cm), for CsI 27 X_0 (50 cm).
  - Electron energy range from order 1 GeV to order 20 GeV for $\eta < -1$, and up to ~40 GeV for $|\eta| < 1$.
  - Photon energy range from order 20 MeV to order several tens of GeV.
- Geometrical dimensions to contain the major part of the EM shower and cleanly identify scattering process
  - Sufficient granularity (0.02-0.03) to separate single photons from π^0 decays
    - In the forward region, at a distance of 5 meters, if only done with the EMcal requires granularity < 2 cm to identify for momenta up to 50 GeV/c.
    - In the barrel region, need less than 2-3 cm granularity.
  - In the backward region, at a distance of about 3 meters, need position resolution of order 2-3 mm to pinpoint electron scattering kinematics, and granularity of order 2 cm.
- Moderate radiation hardness up ~3 krad/year electromagnetic and 10^{10} n/cm^2 hadronic at the top luminosity.

Appendix – considerations for other radiation-hard crystal materials

Bismuth Germanate ($Bi_4Ge_3O_{12}$, BGO) has been a well-known scintillator material for many decades. It has been used in experiments like L3 at CERN or GRAAL at Grenoble, providing well performing electromagnetic calorimeters. However, presently it is only used in large quantities of small samples for medical applications such as Positron Electron-Tomography (PET) scanners. The properties of BGO, listed in Table 1, allow for the design of a very compact calorimeter. The light yield is comparable to cooled PWO crystals. The emission wavelength is well suited for an efficient readout with photo- or avalanche diodes. The moderate decay time could be suitable for the rate capability for the envisaged interaction rate at EIC. However, it excludes in general any option for the generation of fast timing information on the level of <1–2 ns or even below for higher energies. Concerning the radiation hardness, which has not been a major issue for the earlier applications, controversial results are reported in the literature. Some authors report recovery times in the order of days or online recovery by exposure to intense light from fluorescent lamps at short wavelengths. Since most of these studies are rather old, an update with new studies using full size scintillation crystals produced recently would become necessary.

CeF_3 has been identified as a fast scintillator with maximum emission wavelength between 310-340 nm. The luminescence process is dominated by radiative transitions of Ce^{3+} ions, resulting in a fast decay time of ~30 ns and insensitivity to temperature changes. The luminescence yield is comparable or even higher than the fast component of BaF_2, corresponding to approximately 5% of NaI(Tl). Since the crystal matrix is extremely radiation hard, it was considered for the CMS calorimeter during a long period of R&D, supported by the short radiation length and Moliere radius, respectively. However, homogeneous crystal samples beyond $10X_0$ length, grown by the Bridgeman method, have never been produced with adequate quality. Detailed studies of the response function to low energy protons and high energy photons have documented excellent time and energy resolutions, which are limited only in case of the reconstruction of the electromagnetic shower energy by the inhomogeneity of the available crystals. Further improvement relies on a significant optimization of the manufacturing process.



In the last two decades cerium doped silicate based heavy crystal scintillators have been developed for medical applications, which require high light output for low energy gamma-ray detection and high density to allow for small crystal units. Mass production of small crystals of Gd2SiO5 (GSO), Lu2SiO5 (LSO) and Lu2(1-X)Y2XSiO5 (LYSO) has been established in the meantime. Because of the high stopping power and fast and bright luminescence, the latter material has also attracted interest in calorimetry. However, the need for large homogeneous samples and the presently high costs, partly justified by the high melting point, are retarding the R&D. LYSO, which has almost identical physical and scintillation properties as LSO and shows identical emission, excitation and optical transmittance spectra, has been produced in samples up to 20 cm length. The light output of small samples can reach values 8 times of BGO but with decay time shorter by one order of magnitude, determined by the Ce-activation. Aiming at applications for the next generation of homogeneous calorimeters, detailed studies of full-size crystals with respect to homogeneity, scintillation processes and radiation hardness have been part of a research program promoted by a group at Caltech.