Applications of Very Fast Inorganic Crystal Scintillators in Future HEP Experiments

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Abstract. Future HEP experiments at the energy and intensity frontiers require fast inorganic crystal scintillators with excellent radiation hardness to face the challenges of unprecedented event rate and severe radiation environment. This paper reports recent progress in application of fast inorganic scintillators in future HEP experiments, such as thin layer of LYSO crystals for a shashlik sampling calorimeter and a precision TOF detector proposed for the CMS upgrade at HL-LHC, undoped CsI crystals for the Mu2e experiment at Fermilab and yttrium doped BaF_2 crystals for Mu2e-II. Applications of very fast crystal scintillators for Gigahertz hard X-ray imaging for the proposed Marie project at LANL will also be discussed.

Keywords: Inorganic scintillators · Crystals · Radiation hardness

1 Introduction

Fast and radiation hard inorganic crystal scintillators are needed for future HEP experiments at the energy and intensity frontiers. For experiments to be operated at HL-LHC with 3000 fb^{-1}, for example, crystals should survive an environment with absorbed dose of 100 Mrad, charged hadron fluence of 6×10^{14} cm^{-2} and fast neutron fluence of 3×10^{15} cm^{-2}. For future HEP experiments at the intensity frontier, such as Mu2e-II, ultra-fast crystals are needed to face the challenge of unprecedented event rate as well as severe radiation.

Table 1 lists basic properties of crystals commonly used in HEP experiments, where experiment names in brackets were proposed but not constructed. Among the crystals listed in Table 1, bright, fast and radiation hard lutetium yttrium oxy-orthosilicate ($Lu_{2(1-x)}Y_{2x}SiO_5$:Ce or LYSO) crystals were proposed for a LYSO/W/Quartz capillary sampling calorimeter [1] and a precision time of flight (TOF) layer for the CMS upgrade for the HL-LHC [2]. Undoped CsI crystals are used to construct a calorimeter for the Mu2e experiment at Fermilab [3]. BaF_2 crystals have a unique fast scintillation light with sub-ns decay time, but also a slow scintillation light component with 600 ns decay time. Recently developed yttrium doped BaF_2 crystals with effective slow component suppression have a great potential for an extra fast calorimeter for Mu2e-II. They may also be used in the proposed MaRIE facility [4], where unprecedented X-ray fluxes requires ultra-fast X-ray imaging [5].

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Table 1. Inorganic crystals commonly used in HEP experiments

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (°C)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	26	650 0.9	300	40	30 10	?
Light Yield [b,c] (%)	100	165	4.7	36 4.1	21	85	0.3 0.1	?
d(LY)/dT [b] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES-III	KTeV S.BELLE Mu2e-I	(GEM) TAPS Mu2e-II?	L3 BELLE HHCAL?	COMET & CMS (Mu2e & SperB)	CMS ALICE PANDA	A4 g-2 HHCAL?

a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

2 Time Resolution of Crystal Scintillators

Crystal time resolution depends on the signal to noise ratio for the rise time measurement. While the intrinsic rising time of most crystals is as fast as a few tens ps [6], Fig. 1 shows the rising time measured for ten crystal samples of $1.5X_0$ size by using a Hamamatsu R2059 PMT.

The fast rise time of about 1.5 and 1.6 ns observed respectively for BaF_2 and LYSO is limited by the PMT rise time 1.3 ns (2500 V) and the rise time of 0.14 ns of the Agilent MSO9254A (2.5 GHz) DSO. The measured rise time is also faster for the same crystal with a black wrapping, where the light propagation in crystal is minimized [7].

Table 2 lists the figure of merit values on time resolution for various crystal detectors, which is defined as the light output in the 1st, or the 1st 0.1, ns [7]. It is clear that the best crystal scintillators for ultra-fast timing are BaF_2, LSO:Ca,Ce and LYSO:Ce. $LaBr_3$ is a material with high potential theoretically, but suffers from scattering centers in the crystal as well as its intrinsic hygroscopicity.

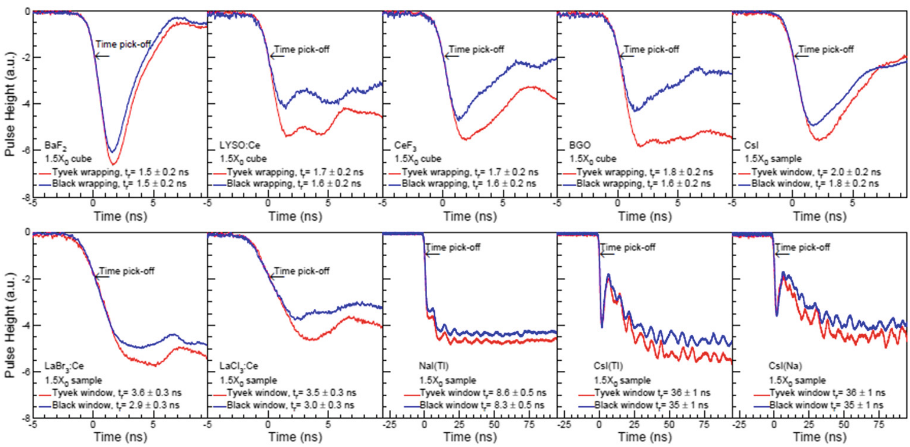

Fig. 1. Scintillation rising time measured for ten crystal samples of 1.5 X_0

Table 2. Figure of merit for time resolution for various crystal scintillators

Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF_3	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
$LaBr_3$:Ce	130	100	20			3810	185.8	19.0	229.9
$LaCl_3$:Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5

3 Quality of Preproduction CsI Crystals for Mu2e

The Mu2e experiment at Fermilab is constructing a fast calorimeter using undoped CsI crystals. 72 preproduction CsI crystals from three vendors were characterized.

Figure 2 compares data with the Mu2e specifications (red dashed lines), showing that most crystals meet the specifications on light output, FWHM energy resolution, light response uniformity, F/T (Fast/Total) ratio, γ-ray induced noise and radiation hardness. Some crystals failed specifications on F/T ratio and γ-ray induced noise because of significant slow scintillation component. Excellent correlations have been observed between the light output and the energy resolution, and the dark current, the γ-ray induced readout noise and the F/T ratio, confirming that they are of the same origin [8].

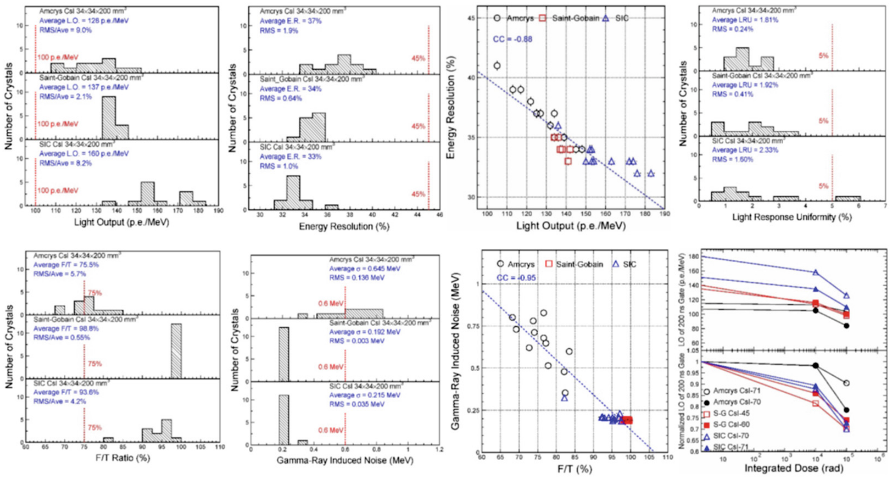

Fig. 2. Quality of preproduction undoped CsI crystals of 3.4 × 3.4 × 20 cm

4 Yttrium Doped BaF_2 Crystals

BaF_2 crystal has a very fast scintillation component peaked at 220 nm with sub-ns decay time, which provides a solid foundation for a very fast calorimetry. It, however, has also a slow scintillation component peaked at 300 nm with 600 ns decay time and a five times brightness of its fast component, which would cause pileup. Two approaches are used to reduce the pileup caused by slow component: selective doping with rare earth (La, Y, and Ce) in BaF_2 and selective readout with solar blind photodetector [9]. Figure 3 shows a set of yttrium doped BaF_2 crystal samples of Φ18 × 21 mm doped with yttrium from 0 to 7 mol% from BGRI. Also shown are their spectra of X-ray excited luminescence (XEL) and transmittance, light output as a function of integration time, light output in 50 and 2,500 ns gates, and the corresponding ratios as a function of the level of yttrium doping in mol%. It was found that the optimized yttrium doping in BaF_2 is about 5 mol%, which increases the F/s (Fast/Slow) ratio from 1/5 to 5/1 without selected readout while the amount of fast light is unchanged. The crystals of this nature is expected to find a broad application in future HEP experiments and GHz X-ray imaging.

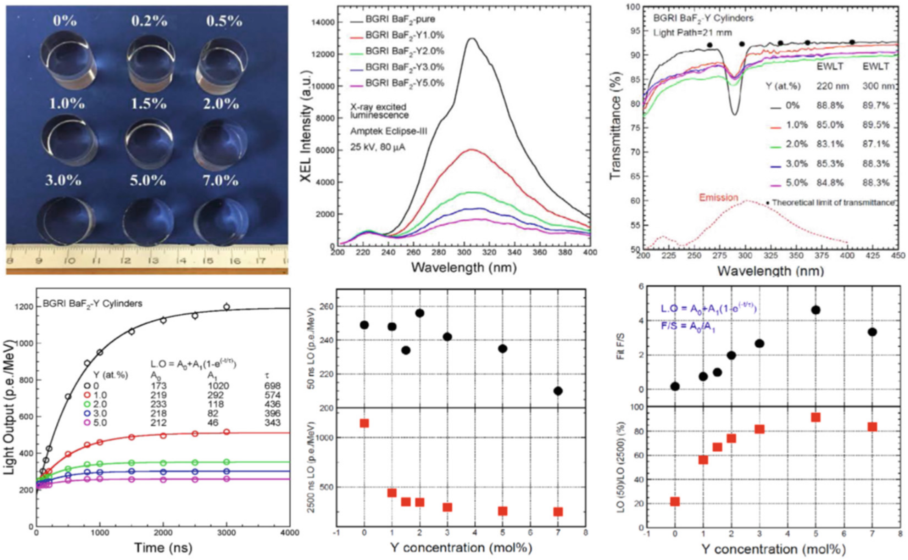

Fig. 3. Performance of Yttrium doped BaF_2 crystals of $\Phi 18 \times 21$ mm

5 Summary

LYSO is a robust scintillators against ionization dose as well as charged and neutral hadrons expected at the HL-LHC. Commercially available undoped CsI crystals satisfy the Mu2e requirements. Commercially available undoped BaF_2 crystals provide sufficient fast light with sub-ns decay time and excellent radiation hardness beyond 100 Mrad and 1×10^{15} p cm^{-2}. They promise a very fast and robust calorimeter in a severe radiation environment. Yttrium doping in BaF_2 crystals increases the F/S ratio from 1/5 to 5/1 without using a selected readout, while maintaining the amount of fast scintillation light. The slow contamination at this level is already much less than commercially available undoped CsI. The novel crystals of this nature is promising a very fast calorimetry for future HEP experiments and GHz X-ray imaging. Photodetector with DUV response, e.g. a Si or diamond based photodetector [10] and the radiation hardness of yttrium doped BaF_2 crystals need to be investigated.

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