Applications of Very Fast Inorganic Crystal Scintillators in Future HEP Experiments

Ren-Yuan Zhu

California Institute of Technology

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Challenge for Inorganic Scintillators

- Fast and radiation hard scintillators for CMS ECAL Endcap at HL-LHC with 3000 fb^{-1} will face the following radiation:
  - Absorbed dose: up to 100 Mrad,
  - Charged hadron fluence: up to 6×10^{14} p/cm^2,
  - Fast neutron fluence: up to 3×10^{15} n/cm^2.
- Mu2e is building a undoped CsI calorimeter at Fermilab. Ultra-fast scintillators with radiation hardness better than CsI are needed to face the challenge of unprecedented event rate expected at Mu2e-II. In addition, GHz X-ray imaging for the proposed Marie project at LANL requires 3 ns frame rate. BaF_2 with sub-ns decay time and good radiation hardness is a promising candidate for both applications.
- Cost-effective scintillators are needed for a homogeneous hadronic calorimeter (HHCAL) detector concept to achieve excellent jet mass resolution at future high energy lepton colliders, such as CEPC, CLIC, FCC and ILC.

Bright & Fast Scintillators: LYSO & BaF_2

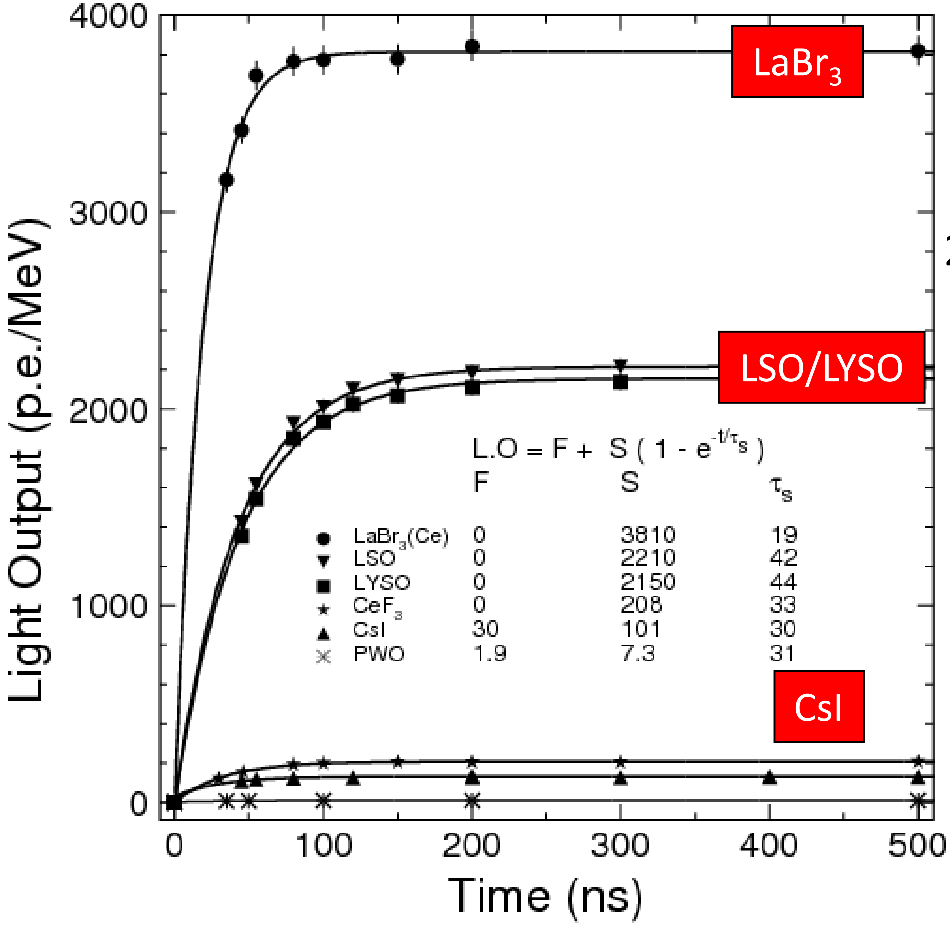
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (ºC)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction 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] (%/ ºC)	-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.

Light Output & Decay Kinetics

Measured with Philips XP2254B PMT (multi-alkali cathode)
p.e./MeV: LSO/LYSO is 6 & 230 times of BGO & PWO respectively

Fast Crystal Scintillators



Slow Crystal Scintillators

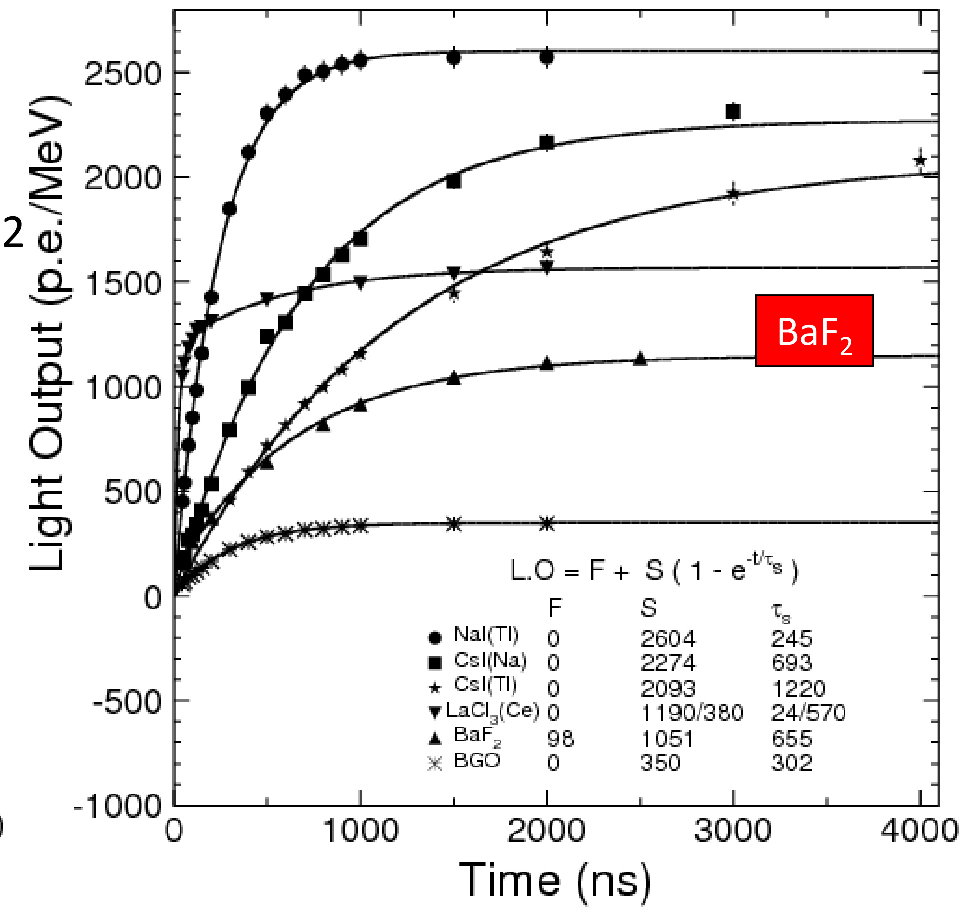


Figure of Merit for Timing

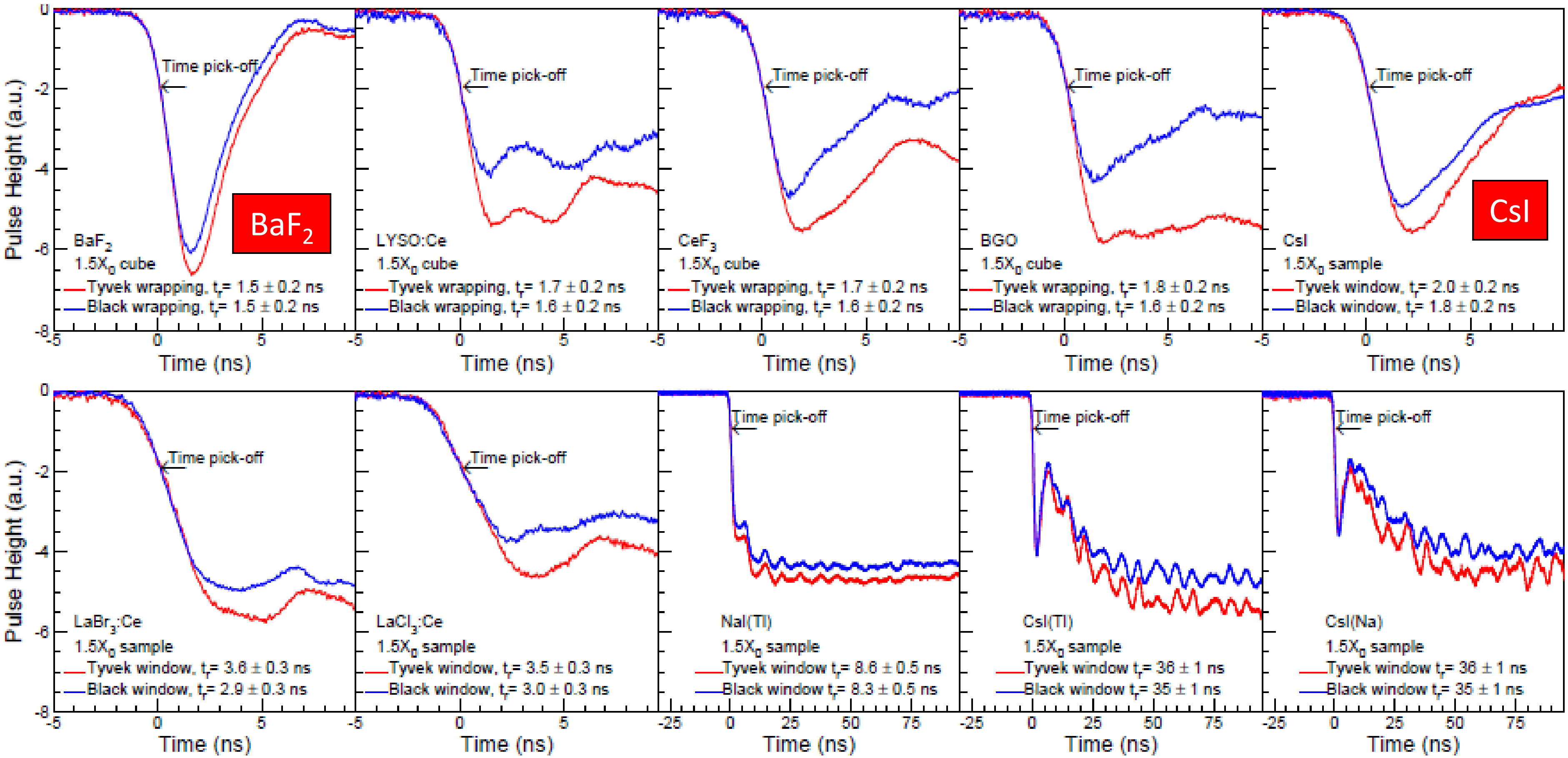
FoM is calculated as the LY in 1st ns obtained by using light output and decay time data measured for 1.5 X_0 crystal samples.

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

The best crystal scintillator for ultra-fast rate is BaF_2 and LSO(Ce/Ca) and LYSO(Ce). $LaBr_3$ is a material with high potential.

Fast Signals: 1.5 X_0 Samples

Hamamatsu R2059 PMT (2500 V)/Agilent MSO9254A (2.5 GHz) DSO with 1.3/0.14 ns rise time



The narrow width of BaF_2 pulse may be reduced by a faster photodetector
LYSO, $LaBr_3$ & $CeBr_3$ have tail, which would cause pile-up for GHz readout

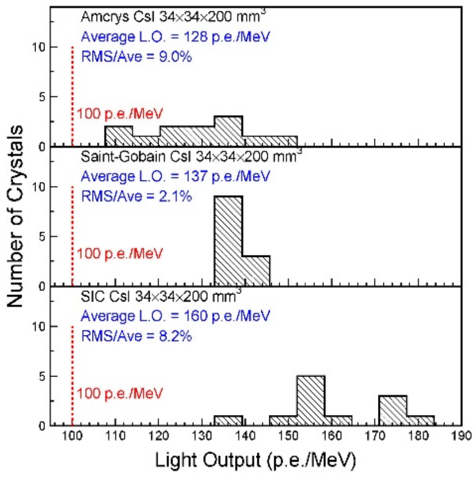
Mu2e Specifications for Undoped CsI

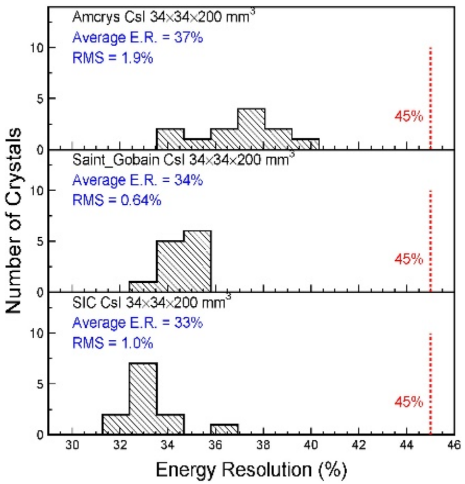
- Crystal lateral dimension: ±100 μ, length: ±100 μ.
- Scintillation properties at seven points along the crystal wrapped by two layers of Tyvek paper of 150 μm for alternative end coupled to a bi-alkali PMT with an air gap. Light output and FWHM resolution are the average of seven points with 200 ns integration time. The light response uniformity is the rms of seven points. F/T is measured at the point of 2.5 cm to the PMT.
  - Light output (LO): > **100 p.e./MeV** with 200 ns gate, will be compared to reference for cross-calibration;
  - FWHM Energy resolution: **< 45%** for Na-22 peak;
  - Light response uniformity (LRU, rms of seven points): **< 5%**;
  - Fast (200 ns)/Total (3000 ns) Ratio: **> 75%**.
- Radiation hardness:
  - Radiation Induced noise **@ 1.8 rad/h: < 0.6 MeV**;
  - Normalized LO **after 10/100 krad: > 85/60%.**

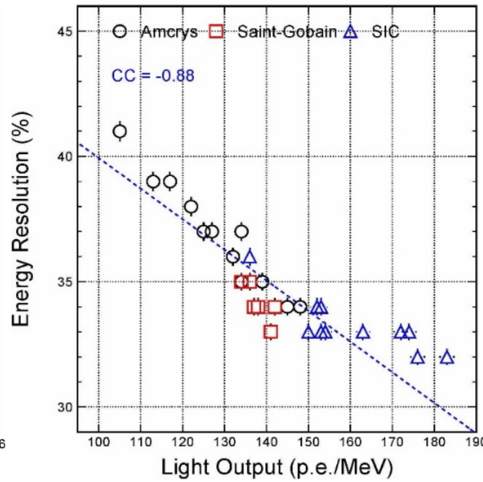
36 Preproduction Undoped CsI

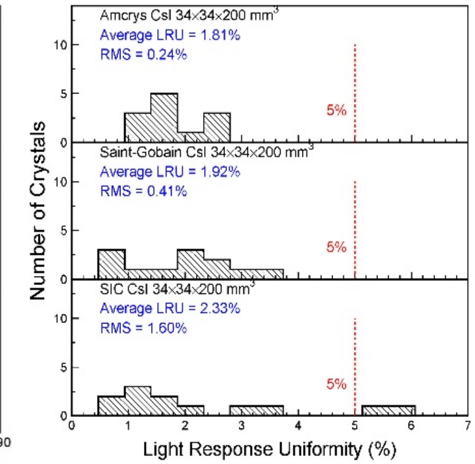
Arranged according to crystal ID in the Mu2e database

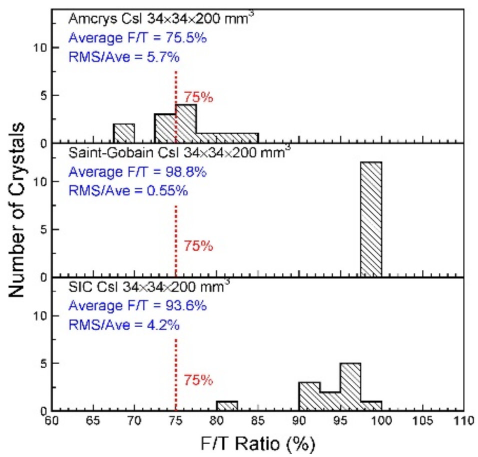
Quality of Pre-Production CsI

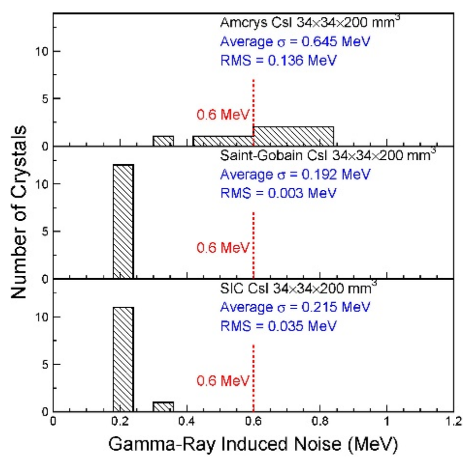


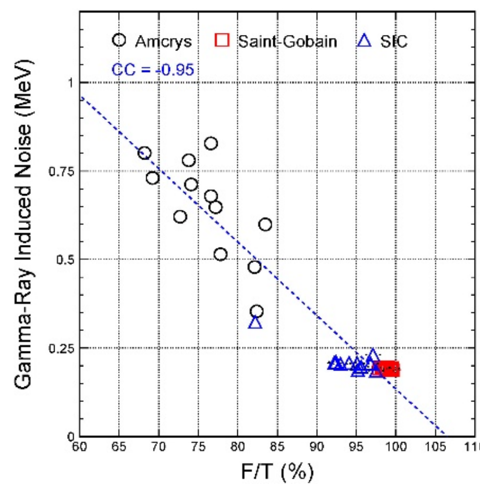


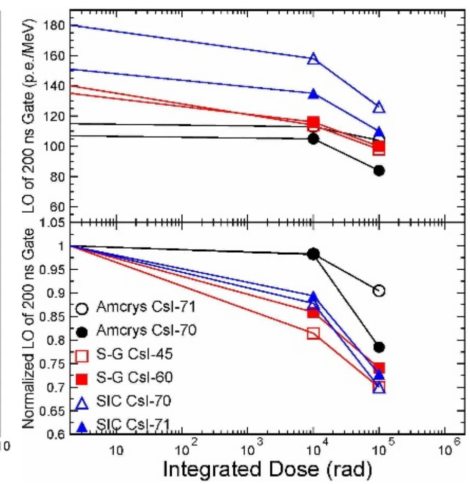






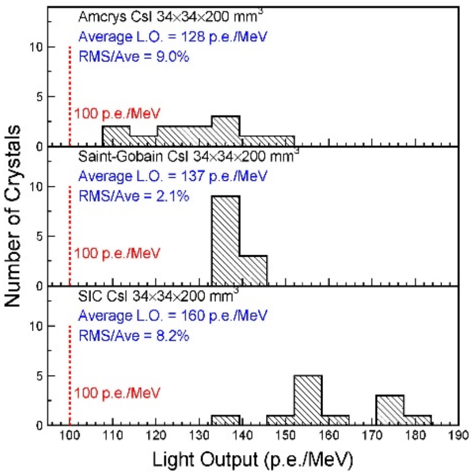


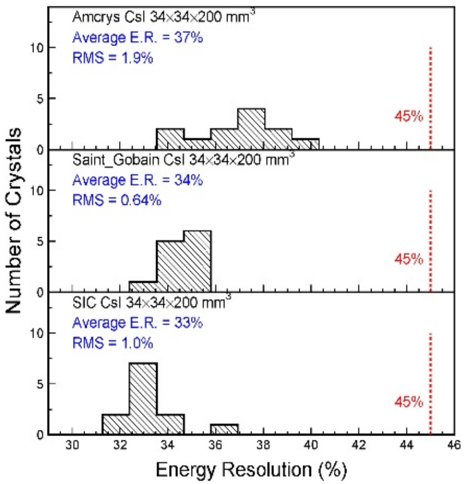


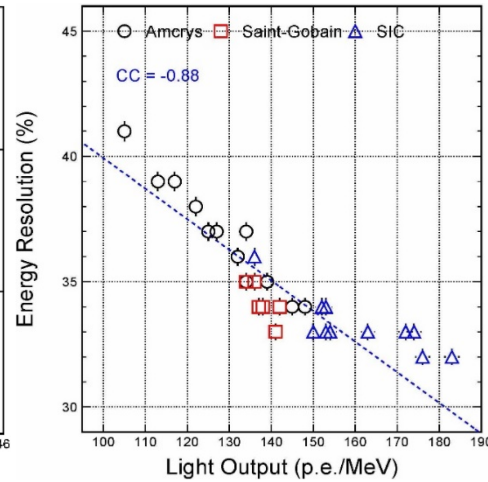


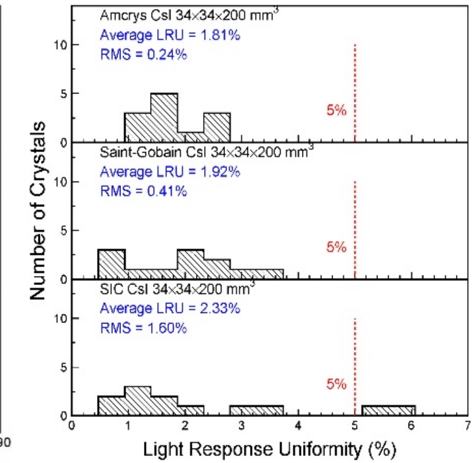
Most preproduction crystals satisfy specifications, except a few crystals from SICCAS fail the LRU spec and about half Amcrys crystals fail the F/T ratio and RIN

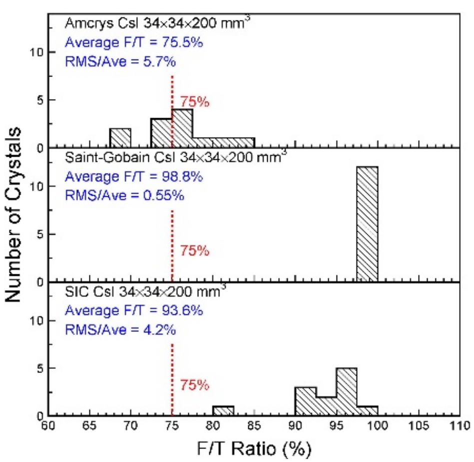
Quality of Pre-Production CsI

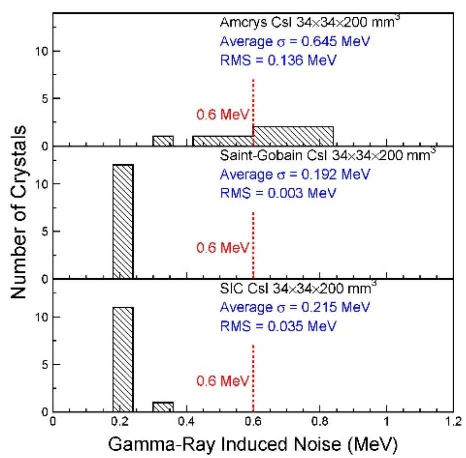


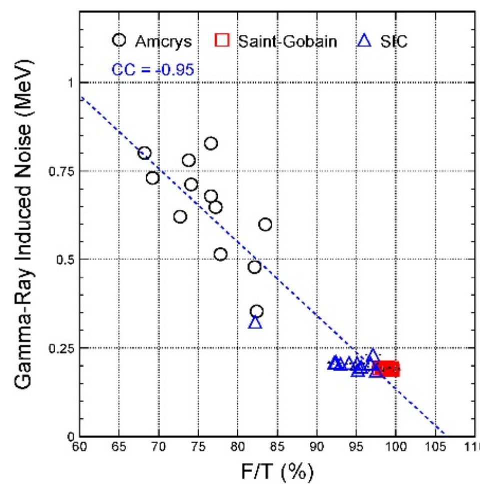


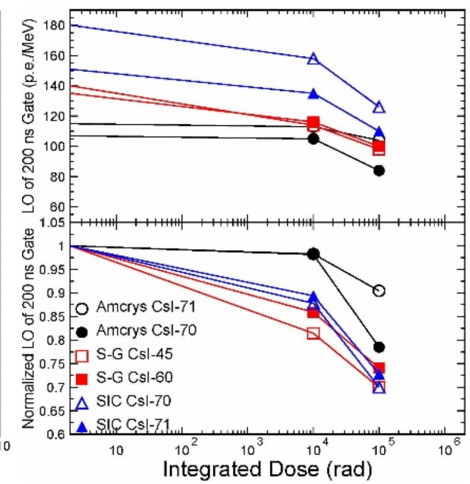












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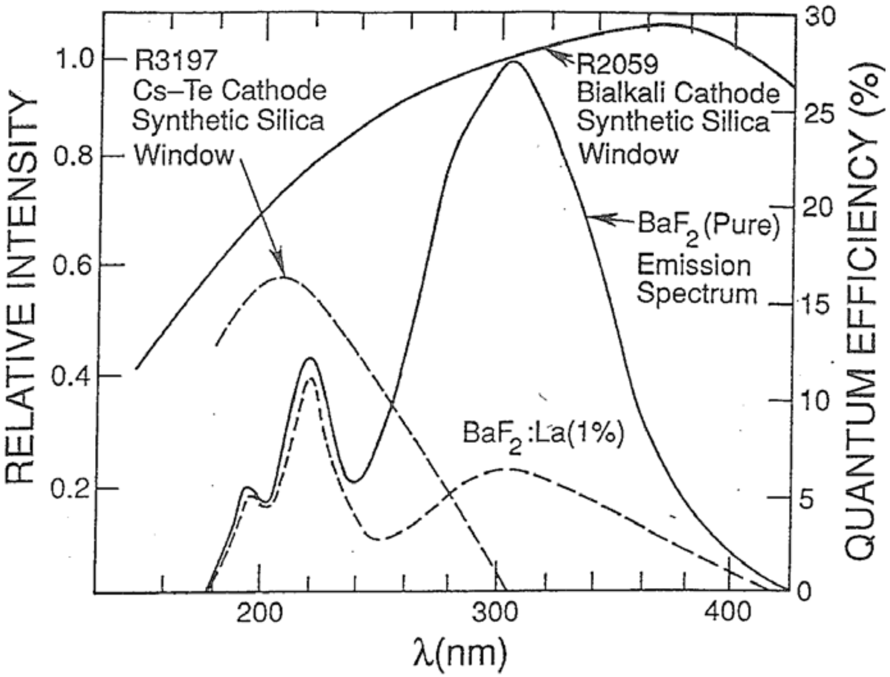
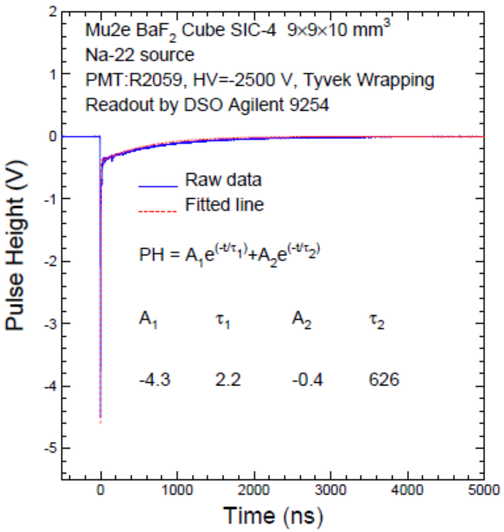
Fast and Slow Light from BaF_2

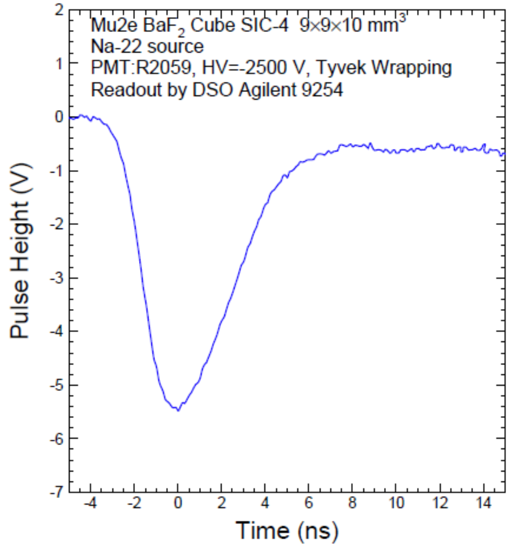
A radiation level exceeding 100 krad is expected at the proposed Mu2e-II, so BaF_2 is being considered.

The amount of light in the fast component of BaF_2 at 220 nm with sub-ns decay time is similar to CsI.

Spectroscopic selection of fast component may be realized by solar blind photocathode and/or selective doping.



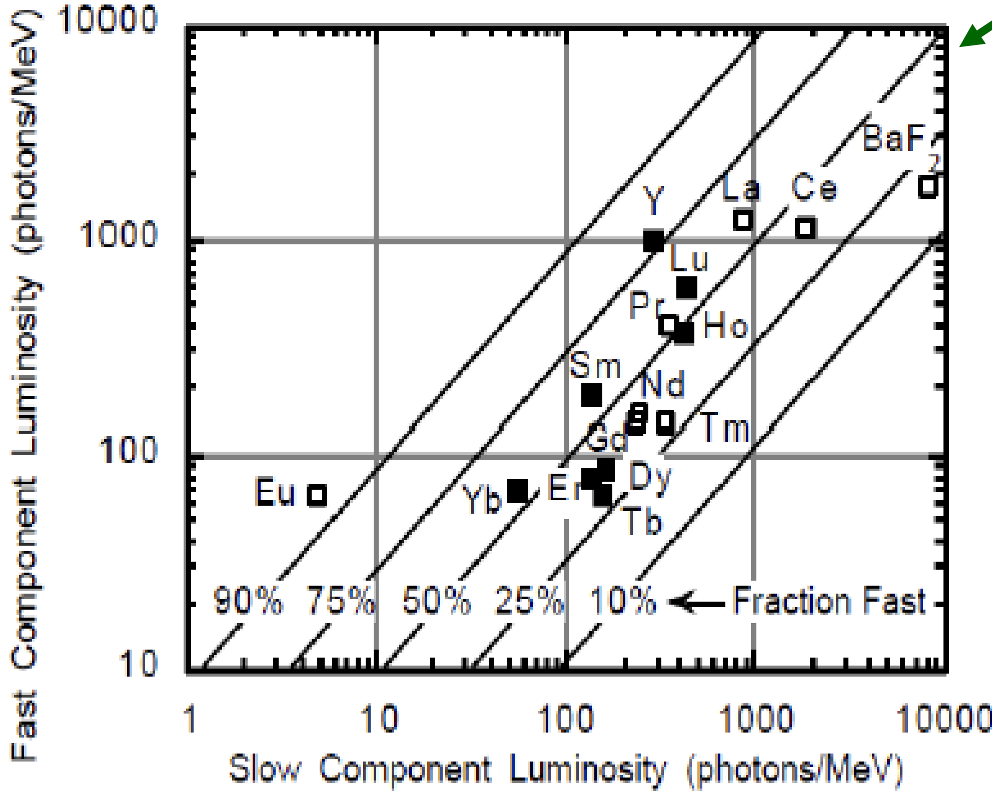


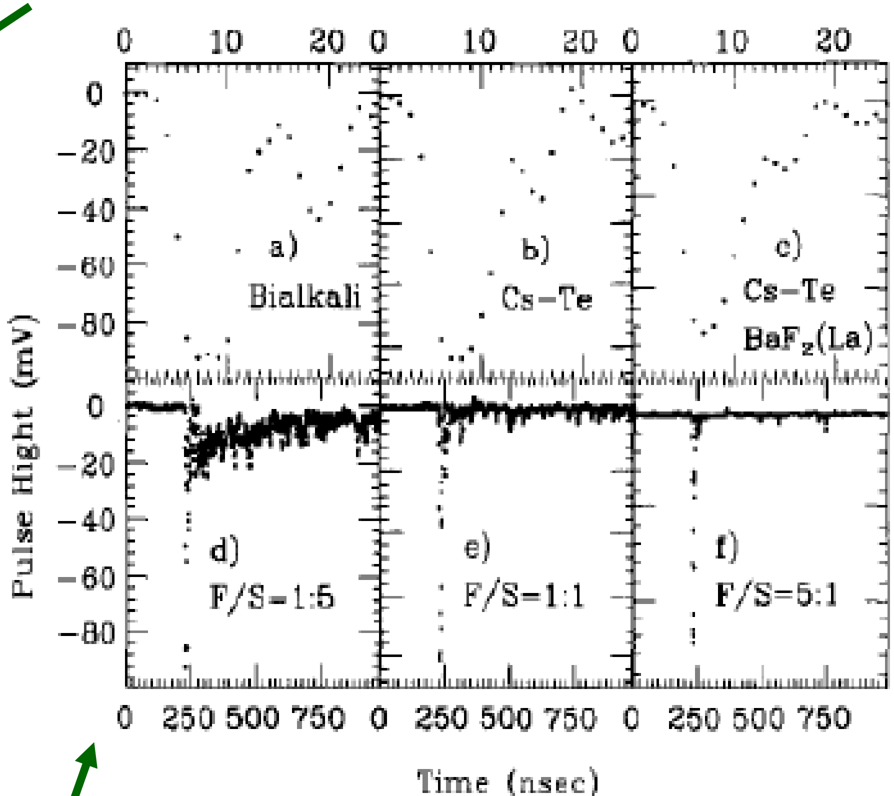


Slow Suppression: Doping & Readout

Slow component may be suppressed by RE doping: Y, La and Ce

B.P. SOBOLEV et al., "SUPPRESSION OF BaF2 SLOW COMPONENT OF X-RAY LUMINESCENCE IN NON-STOICHIOMETRIC Ba0.9R0.1F2 CRYSTALS (R=RARE EARTH ELEMENT)," *Proceedings of The Material Research Society: Scintillator and Phosphor Materials*, pp. 277-283, 1994.



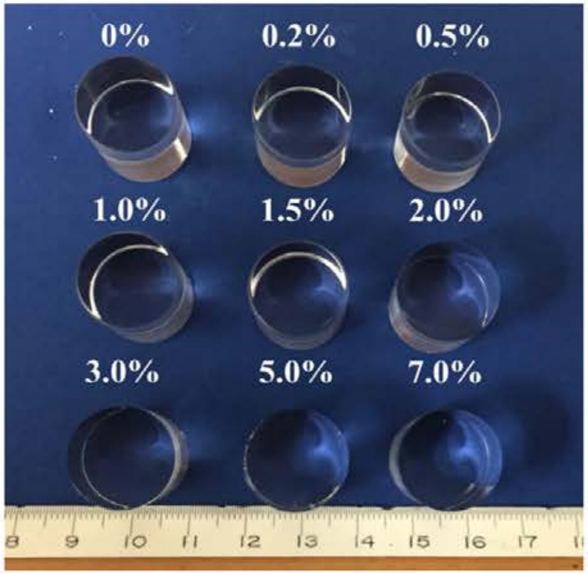


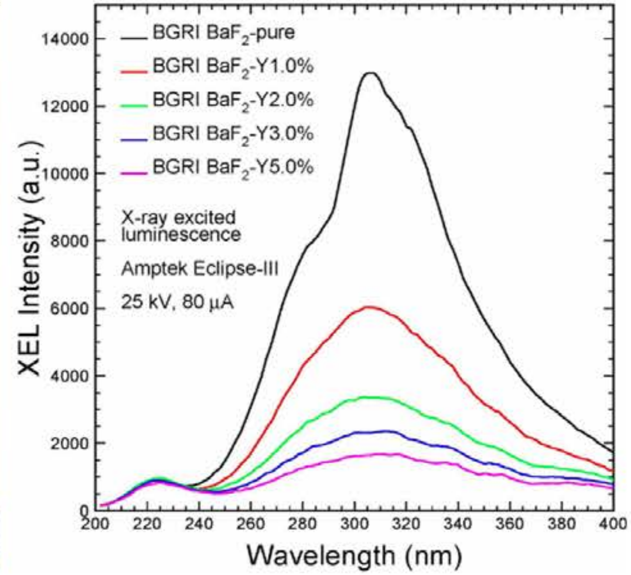
Solar-blind cathode (Cs-Te) + La doping achieved F/S = 5/1

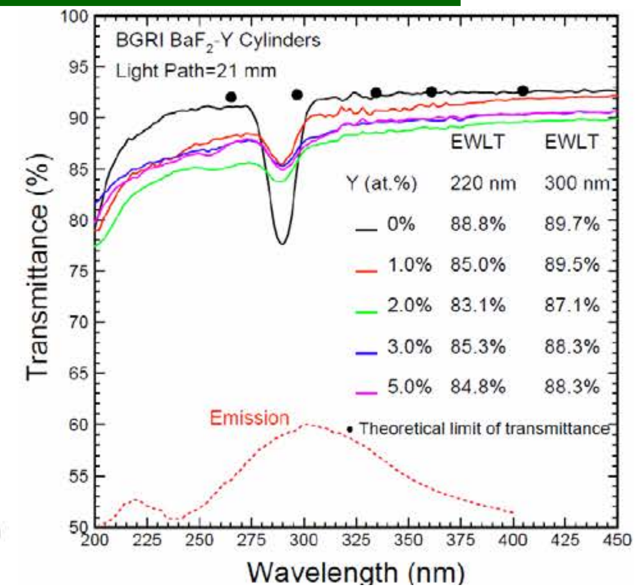
Z. Y. Wei, R. Y. Zhu, H. Newman, and Z. W. Yin, "Light Yield and Surface-Treatment of Barium Fluoride-Crystals," *Nucl Instrum Meth B*, vol. 61, pp. 61-66, Jul 1991.

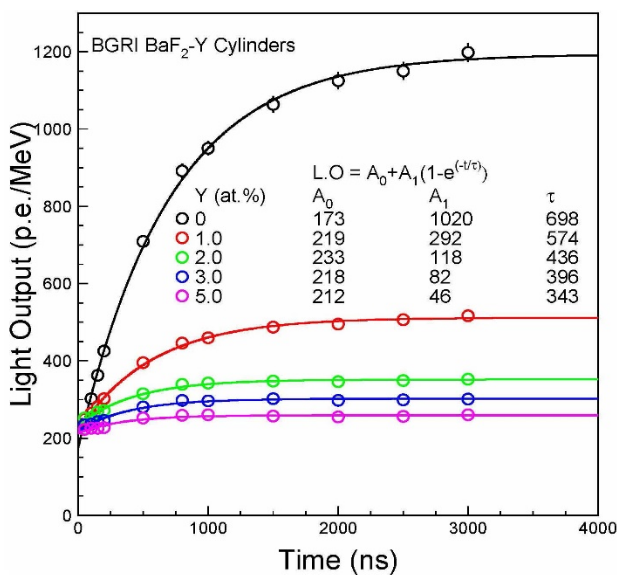
Yttrium Doped BaF_2

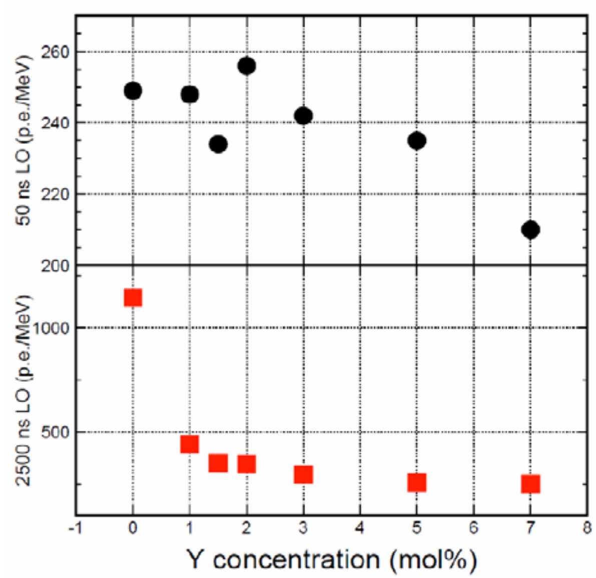
F/S ratio from 1/5 to 5/1: very effective slow suppression

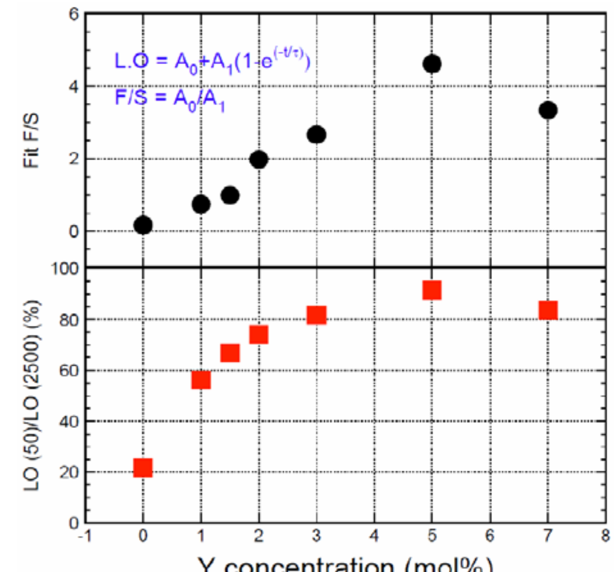










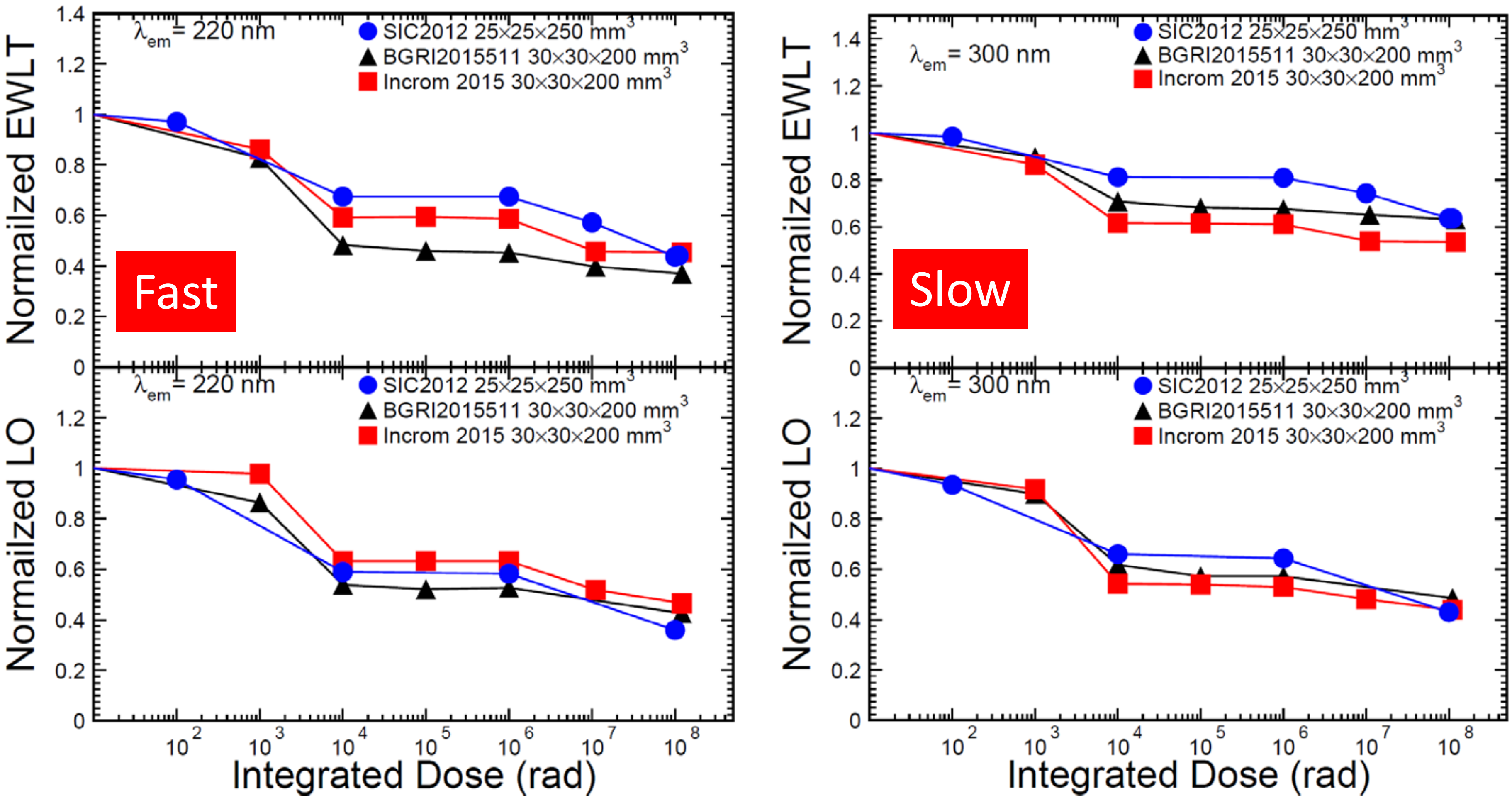


BGRI/Incrom/SIC BaF_2 Samples

ID	Vendor	Dimension (mm^3)	Polishing
SIC 1-20	SICCAS	30x30x250	Six faces
BGRI-2015 D, E, 511	BGRI	30x30x200	Six faces
Russo 2, 3	Incrom	30x30x200	Six faces

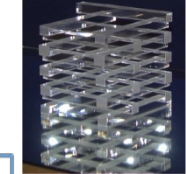
BaF_2: Normalized EWLT and LO

Consistent damage in crystals from three vendors

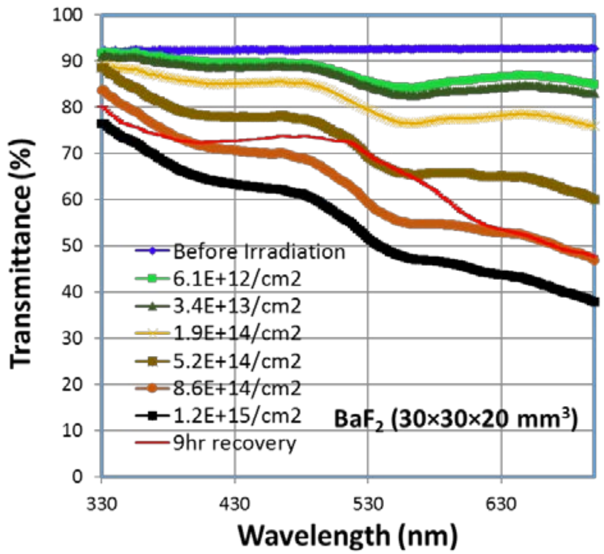


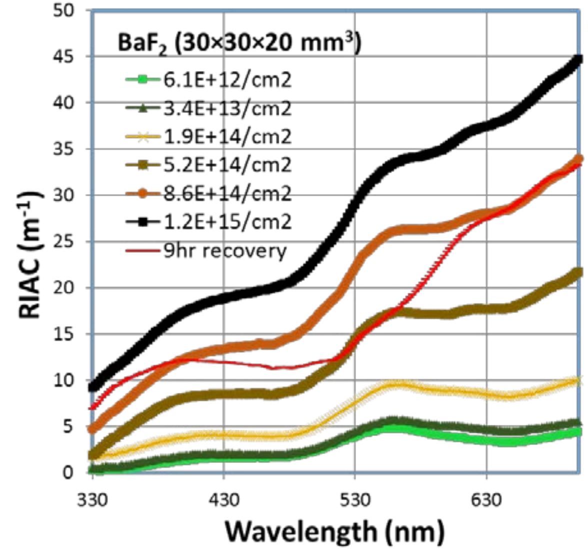
Remaining light output after 120 Mrad: 40%/45% for the fast/slow component

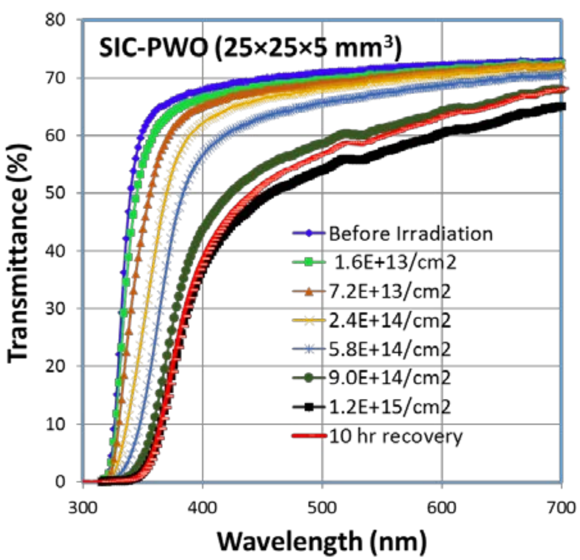
800 MeV Proton Damage in BaF_2 & PWO

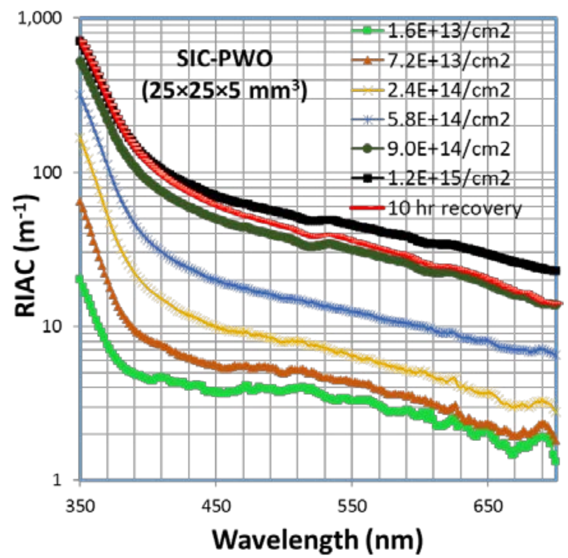


A Hellma BaF_2 of 2 cm was irradiated from 6.1×10^{12} to 1.2×10^{15} p/cm^2 in six steps with transmittance (330-650 nm) measured *in-situ*. The sample will be measured at Caltech for 200 – 650 nm.







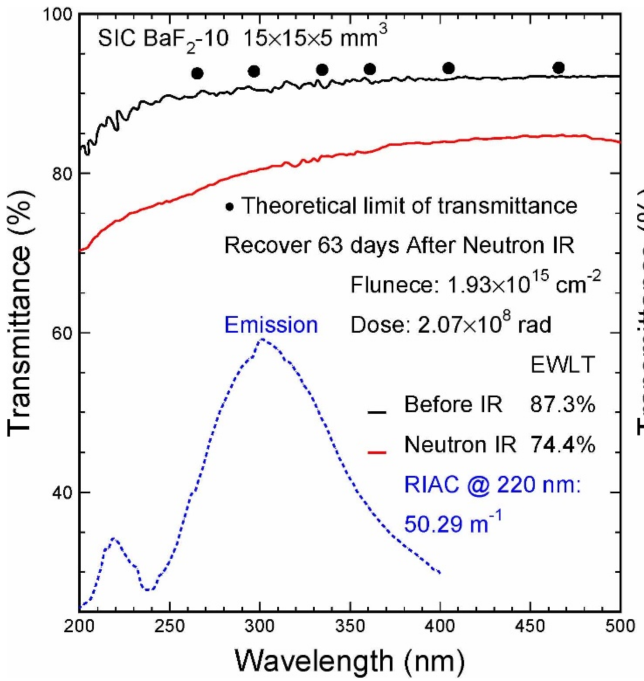


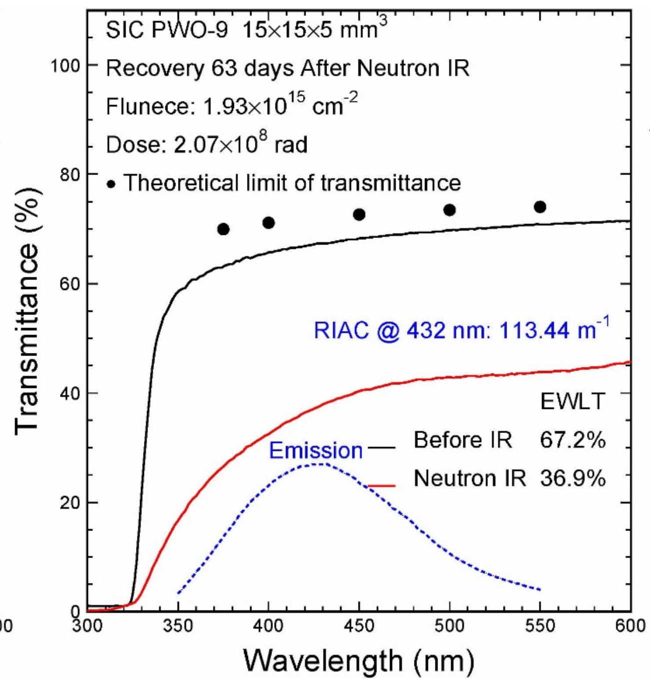
A 5 mm thick SIC PWO plate was irradiated from 1.6×10^{13} to 1.2×10^{15} p/cm^2 with transmittance (300-700 nm) measured *in-situ*. The RIAC at 420 nm was measured to be 13.1 / 92.2 cm^{-1} after 2.4×10^{14} / 1.2×10^{15} p/cm^2.

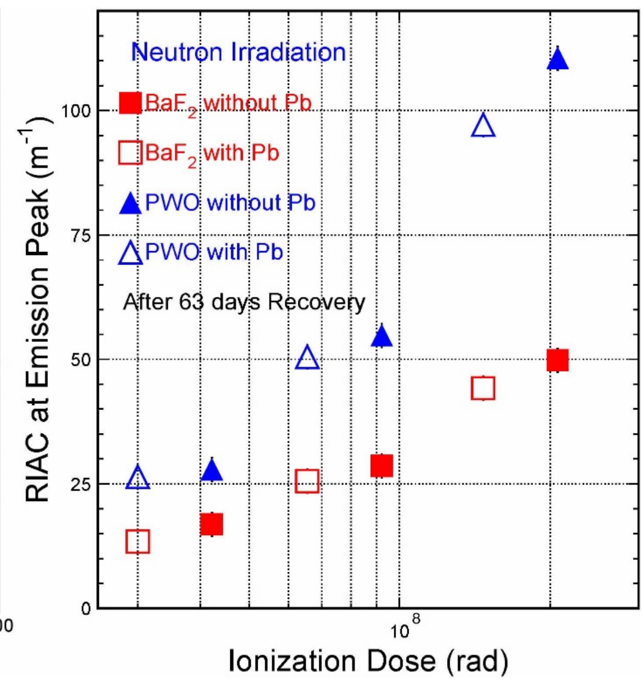
R.-Y. Zhu, "Preliminary Report on the Experiment 7324 with 800 MeV Protons at Los Alamos," http://www.hep.caltech.edu/~zhu/talks/ryz_1601207_LANL.pdf

Neutron + Ionization Dose in BaF_2 & PWO

Samples in three groups irradiated at the East Port of LANSCE







Results consist with ionization dose induced damage showing no neutron specific damage in BaF_2 and PWO

Summary

- LYSO is a robust crystal against ionization dose as well as charged and neutral hadrons.
- Commercially available undoped CsI crystals satisfy the Mu2e requirements.
- Commercially available BaF_2 crystals provide sufficient fast light with sub-ns decay time and excellent radiation hardness beyond 100 Mrad. They promise a very fast and robust calorimeter in a severe radiation environment.
- Work on yttrium doping in BaF_2 crystals has increased the F/S ratio from 1/5 to 5/1 without using selected readout. The slow contamination at this level is already less than commercially available undoped CsI.
- To be investigated are photodetector with DUV response, e.g. a Si or diamond based photodetector, and the radiation hardness of yttrium doped BaF_2 crystals.