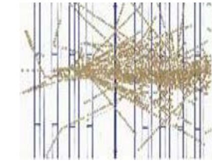


Ultrafast and Radiation Hard Inorganic Scintillators for Future HEP Experiments

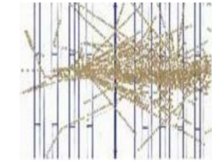
Ren-Yuan Zhu

California Institute of Technology

May 24, 2018

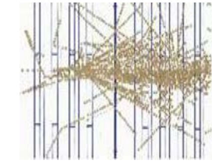
Talk in the XVIII International Conference on Calorimetry in Particle Physics, Eugene

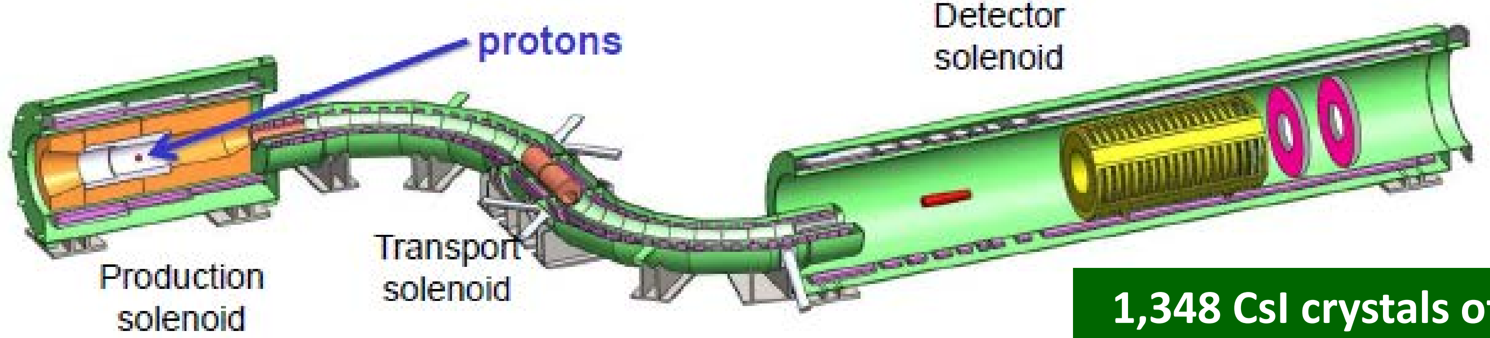
Why Ultrafast Crystals?



- Photons and electrons are fundamental particles. Precision e/γ measurements enhance physics discovery potential.
- Performance of crystal calorimeter in e/γ measurements is well understood:
  - The best possible energy resolution;
  - Good position resolution;
  - Good e/γ identification and reconstruction efficiency.
- Challenges at future HEP & other Applications:
  - Ultrafast and rad hard crystals at the energy frontier (HL-LHC);
  - Ultrafast crystals at the intensity frontier (Mu2e-II);
  - Ultrafast crystals for GHz hard X-ray imaging (Marie).

The Mu2e Undoped CsI Calorimeter





1,348 CsI crystals of 34 x 34 x 200 mm under production

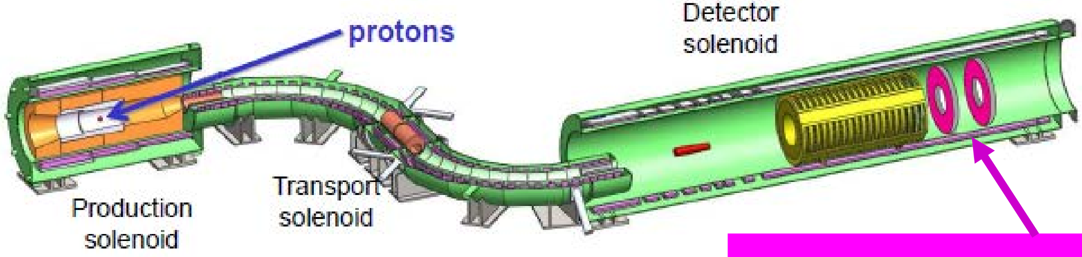
- Crystal lateral dimension: ±100 μ, length: ±100 μ.
- Scintillation properties at seven points along the crystal wrapped by two layers of Tyvek paper of 150 μm for alternative end coupled to a bi-alkali PMT with an air gap. Light output and FWHM resolution are the average of seven points with 200 ns 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 related spec::
  - Normalized LO **after 10/100 krad: > 85/60%;**
  - Radiation Induced noise **@ 1.8 rad/h: < 0.6 MeV**.

See also presentations by L. Morescalchi, R. Zhu, E. Diociaiuti & R. Donghia

Future Application of Ultrafast Crystals

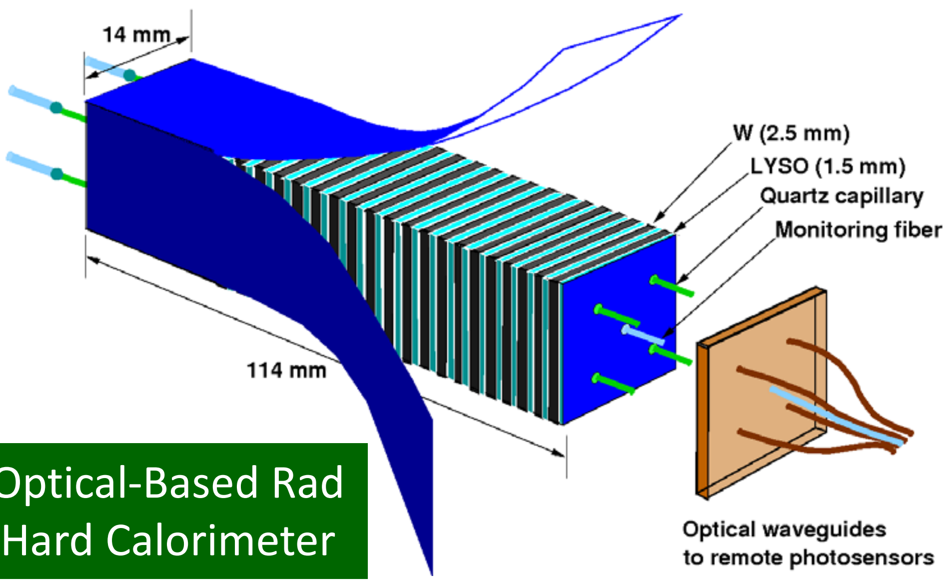
Ultrafast and radiation hard inorganic scintillators have broad applications

Mu2e-II: arXiv:1802.02599



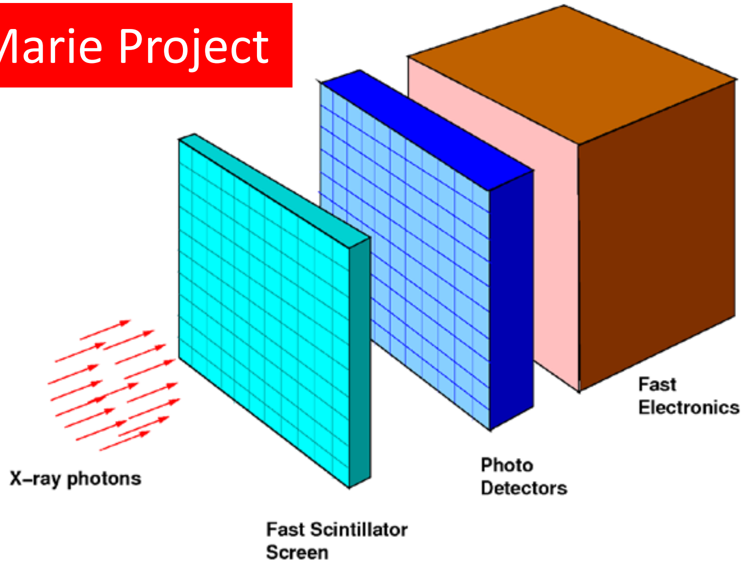
1,940 BaF_2:Y crystals
30 x 30 x 218 mm

BaF_2:Y, ZnO:Ga and others are attractive for an ultrafast front imager for the FEL based GHz hard x-ray imaging

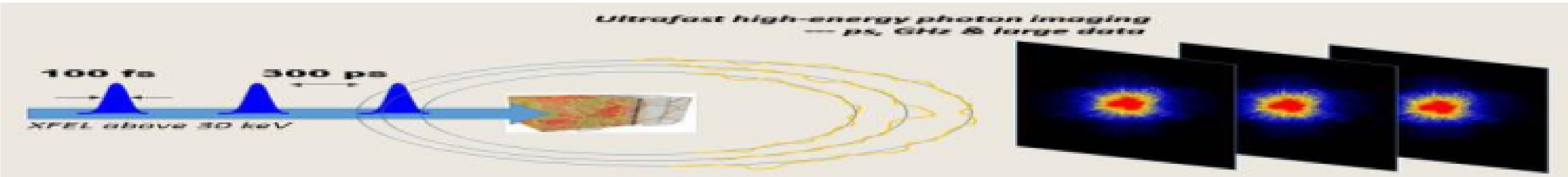


Optical-Based Rad Hard Calorimeter

Marie Project



Sensor for GHz Hard X-Ray Imaging



High-Energy and Ultrafast X-Ray Imaging Technologies and Applications

Organizers: Peter Denes, Sol Gruner, Michael Stevens & Zhehui (Jeff) Wang[1]
*(**Location/Time**: Santa Fe, NM, USA /Aug 2-3, 2016)*

The goals of this workshop are to gather the leading experts in the related fields, to prioritize tasks for ultrafast hard X-ray imaging detector technology development and applications in the next 5 to 10 years, see Table 1, and to establish the foundations for near-term R&D collaborations.

Table I. High-energy photon imagers for MaRIE XFEL

Performance	Type I imager	Type II imager
X-ray energy	30 keV	42-126 keV
Frame-rate/inter-frame time	0.5 GHz/2 ns	3 GHz / 300 ps
Number of frames	10	10 - 30
X-ray detection efficiency	above 50%	above 80%
Pixel size/pitch	≤ 300 μm	< 300 μm
Dynamic range	10^3 X-ray photons	≥ 10^4 X-ray photons
Pixel format	64 x 64 (scalable to 1 Mpix)	1 Mpix

2 ns and 300 ps inter-frame time requires very fast sensor

Fast & Radiation Hard Scintillators

- Supported by the DOE ADR program we are developing fast and radiation hard scintillators to face the challenge for future HEP and GHz hard x-ray applications.
- LYSO:Ce, BaF_2 and LuAG:Ce will survive the radiation environment expected at HL-LHC with 3000 fb^{-1}. LYSO will be used for a MIP Timing Detector (MTD) for CMS upgrade:
  - 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.
- Ultra-fast scintillators with excellent radiation hardness is also needed to face the challenge of unprecedented event rate expected at future HEP experiments at the intensity frontier, such as Mu2e-II and the proposed Marie project at Los Alamos. BaF_2:Y and other ultrafast crystals with sub-ns decay time and suppressed slow scintillation component is a leading candidate for all applications.

Inorganic Scintillators for HEP Calorimetry

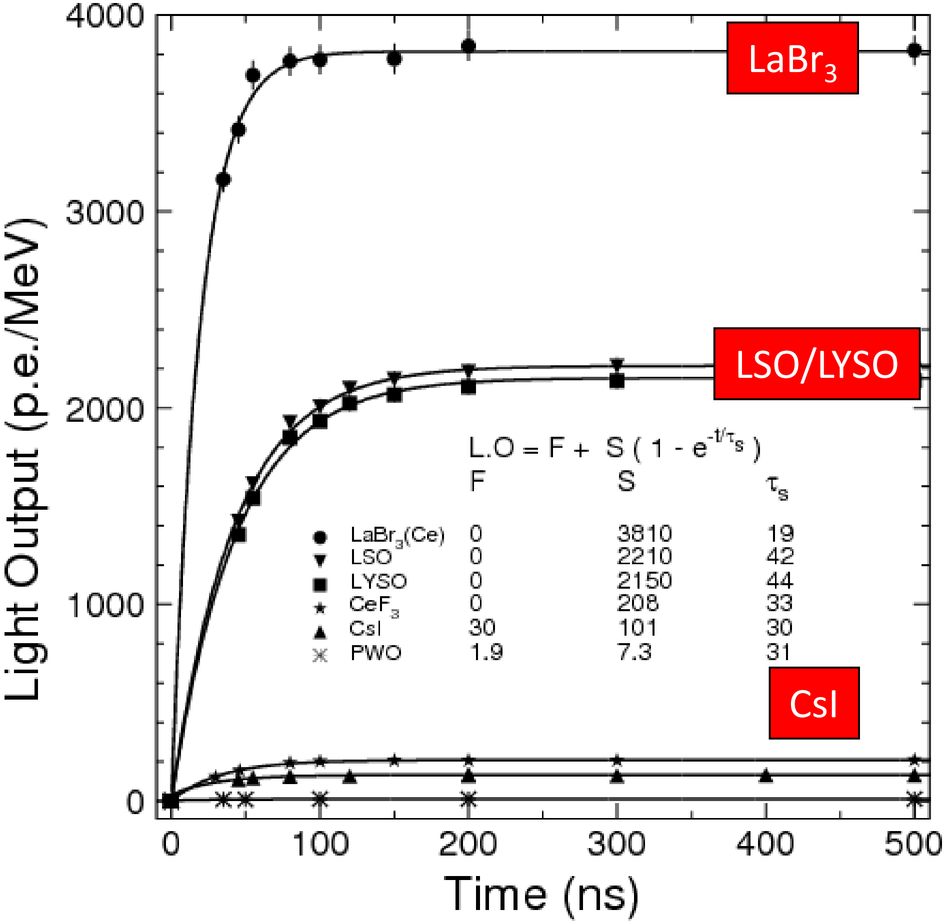
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm³)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (ºC)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction 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 0.5	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.

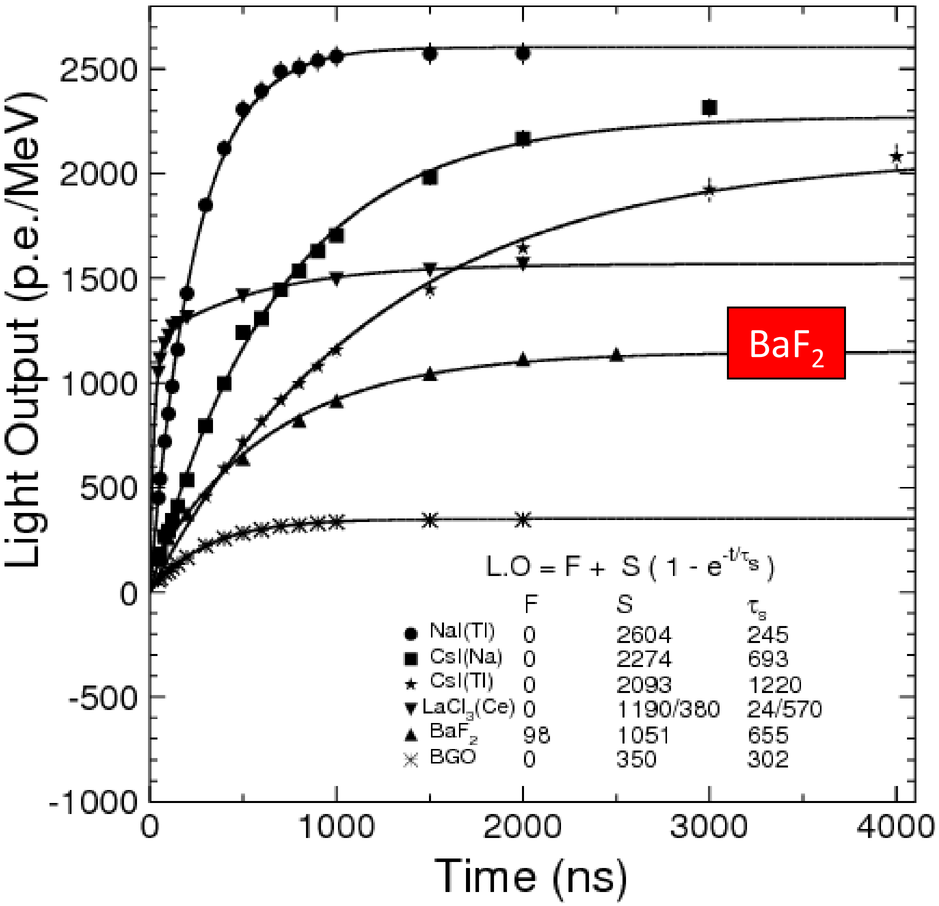
Light Output & Decay Kinetics

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

Fast Crystal Scintillators

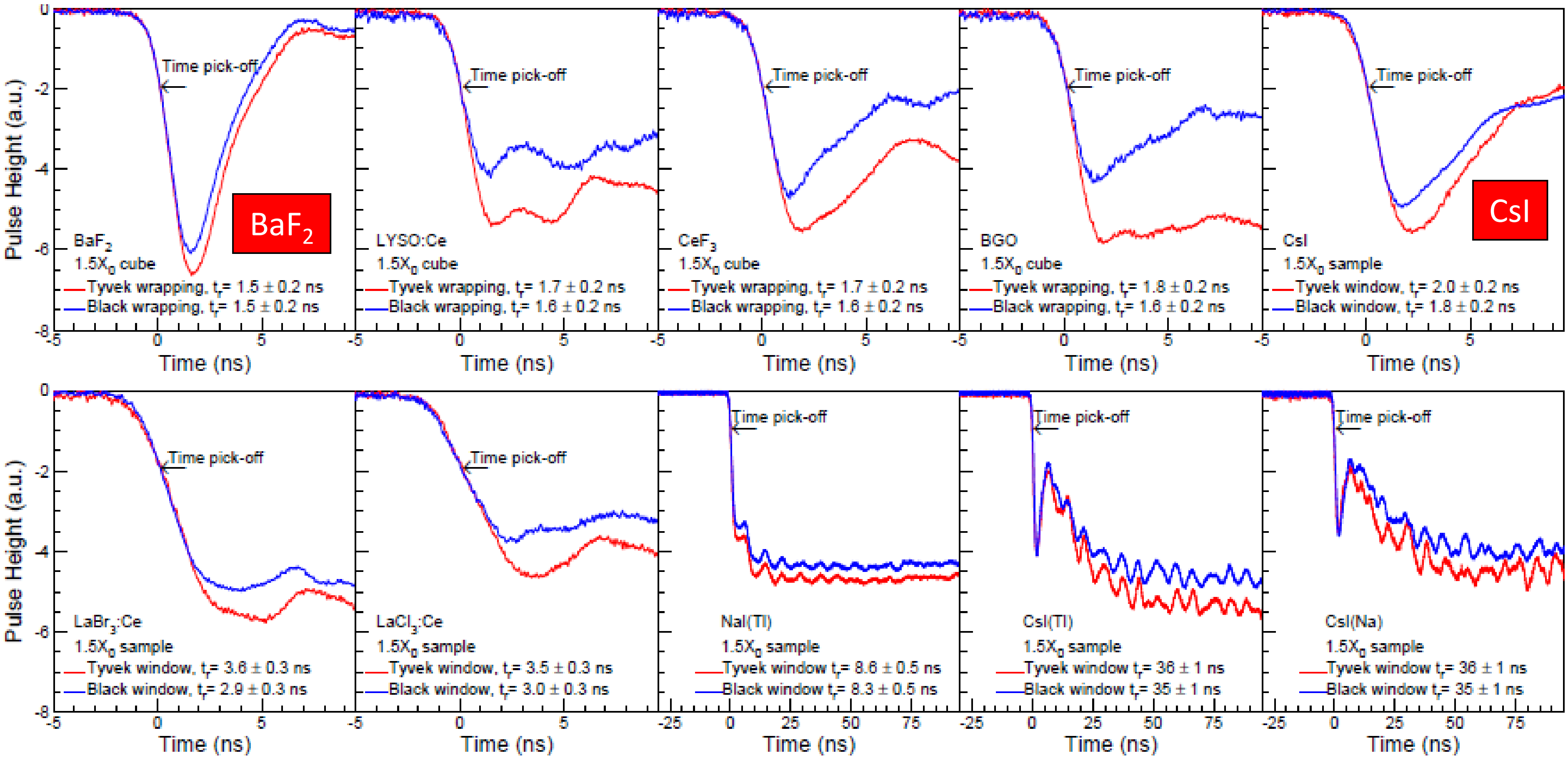


Slow Crystal Scintillators



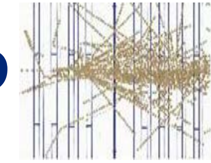
Fast Signals with 1.5 X_0 Samples

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



The 3 ns 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

Fast Inorganic Scintillators for HEP



	LYSO:Ce	LSO:Ce, Ca[1]	LuAG:Ce [2]	LuAG:Pr[3]	GGAG:Ce[4,5]	CsI	BaF_2[6]	BaF_2:Y	$CeBr_3$	$LaBr_3$:Ce[7]
Density (g/cm^3)	7.4	7.4	6.76	6.76	6.5	4.51	4.89	4.89	5.23	5.29
Melting points (°C)	2050	2050	2060	2060	1850[d]	621	1280	1280	722	783
X_0 (cm)	1.14	1.14	1.45	1.45	1.63	1.86	2.03	2.03	1.96	1.88
R_M (cm)	2.07	2.07	2.15	2.15	2.20	3.57	3.1	3.1	2.97	2.85
λ_I (cm)	20.9	20.9	20.6	20.6	21.5	39.3	30.7	30.7	31.5	30.4
Z_{eff}	64.8	64.8	60.3	60.3	51.8	54.0	51.6	51.6	45.6	45.6
dE/dX (MeV/cm)	9.55	9.55	9.22	9.22	8.96	5.56	6.52	6.52	6.65	6.90
λ_{peak}[a] (nm)	420	420	520	310	540	310	300 220	300 220	371	360
PL Emission Peak (nm)	402	402	500	308	540	310	300 220	300 220	350	360
PL Excitation Peak (nm)	358	358	450	275	445	256	<200	<200	330	295
Absorption Edge (nm)	170	170	160	160	190	200	140	140	n.r.	220
Refractive Index[b]	1.82	1.82	1.84	1.84	1.92	1.95	1.50	1.50	1.9	1.9
Normalized Light Yield[a,c]	100	116[e]	35[f] 48[f]	44 41	40 75	4.2 1.3	42 5.0	1.7 5.0	99	153
Total Light yield (ph/MeV)	30,000	34,800[e]	25,000[f]	25,800	34,700	1,700	13,000	2,100	30,000	46,000
Decay time[a] (ns)	40	31[e]	981[f] 64[f]	1208 26	319 101	30 6	600 0.5	600 05	17	20
Light Yield in 1[st] ns (photons/MeV)	740	950	240	520	260	100	1200	1200	1,700	2,200
Issues					neutron x-section	Slightly hygroscopic	Slow component	DUV PD	hygroscopic	

Fast Inorganic Scintillators (II)

a. Top line: slow component, bottom line: fast component;

b. At the wavelength of the emission maximum;

c. Excited by Gamma rays;

d. For $Gd_3Ga_3Al_2O_{12}$:Ce

e. For 0.4 at% Ca co-doping

f. Ceramic with 0.3 Mg at% co-doping

[1] Spurrier, et al., *IEEE T. Nucl. Sci.* 2008,55 (3): 1178-1182

[2] Liu, et al., *Adv. Opt. Mater.* 2016, 4(5): 731–739

[3] Hu, et al., *Phys. Rev. Applied* 2016, 6: 064026

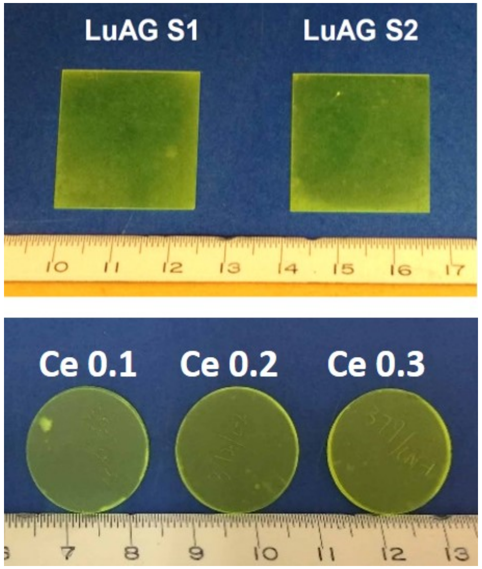
[4] Lucchini, et al., *NIM A* 2016, 816: 176-183

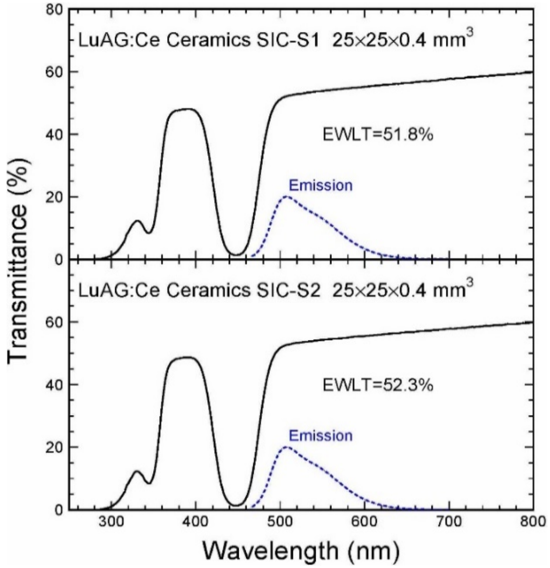
[5] Meng, et al., *Mat. Sci. Eng. B-Solid* 2015, 193: 20-26

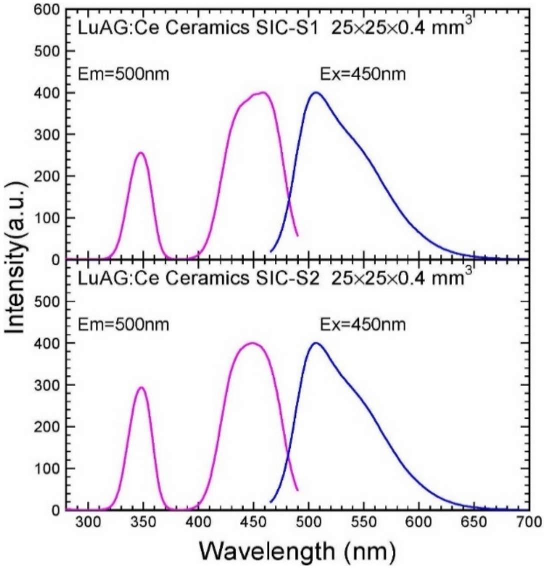
[6] Diehl, et al., *J. Phys. Conf. Ser* 2015, 587: 012044

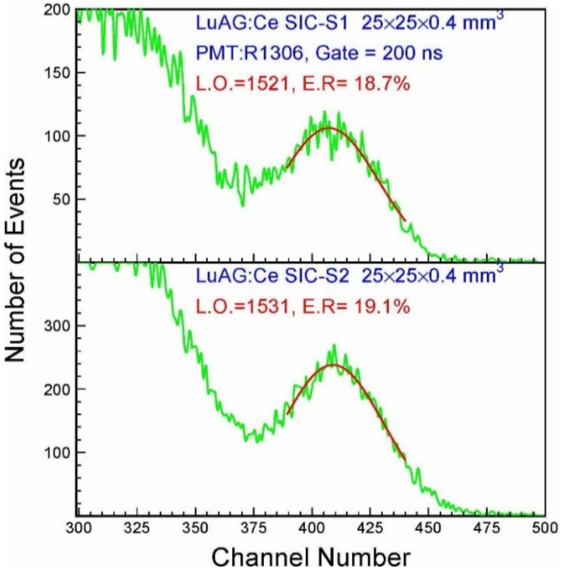
[7] Pustovarov, et al., Tech. Phys. Lett. 2012, 784-788

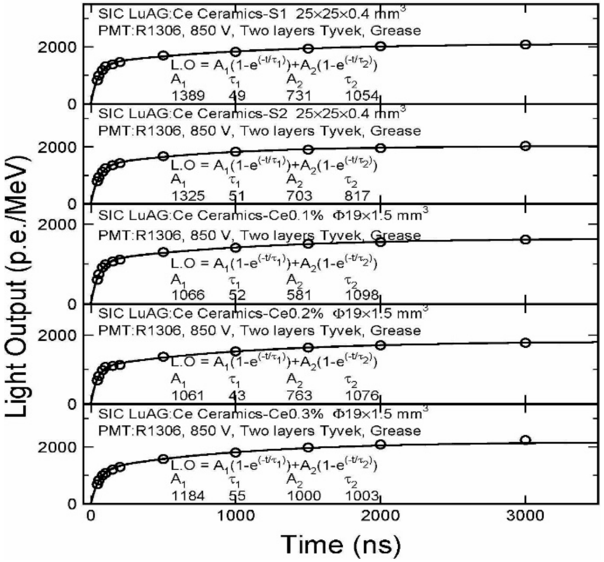
LuAG:Ce Ceramic Samples

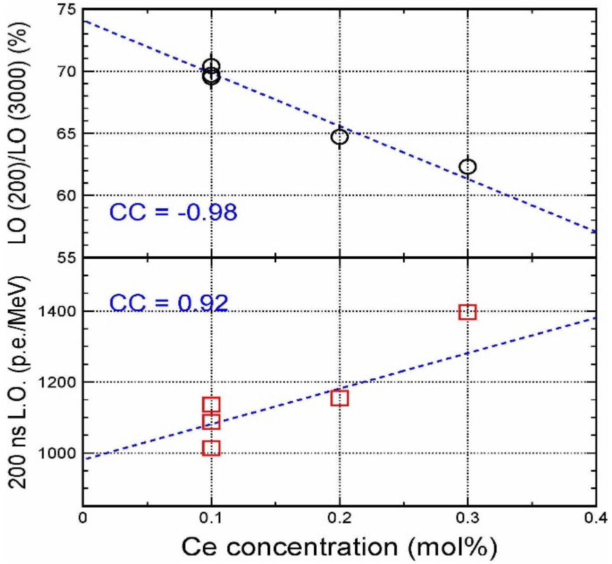








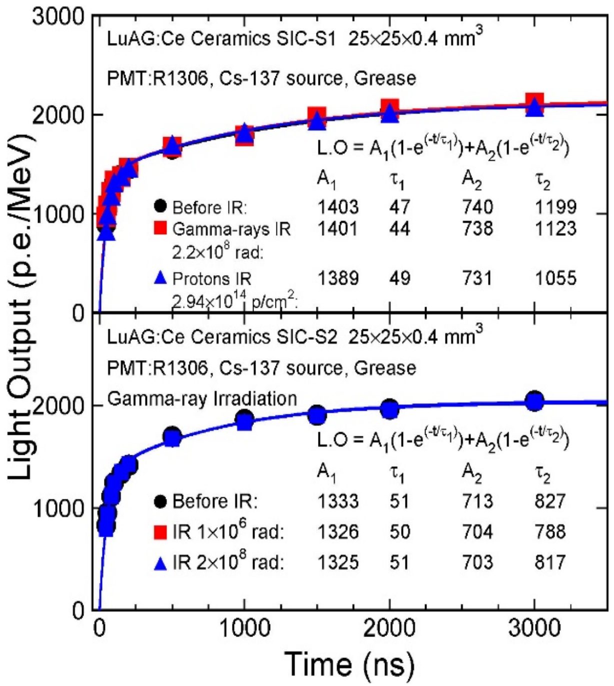


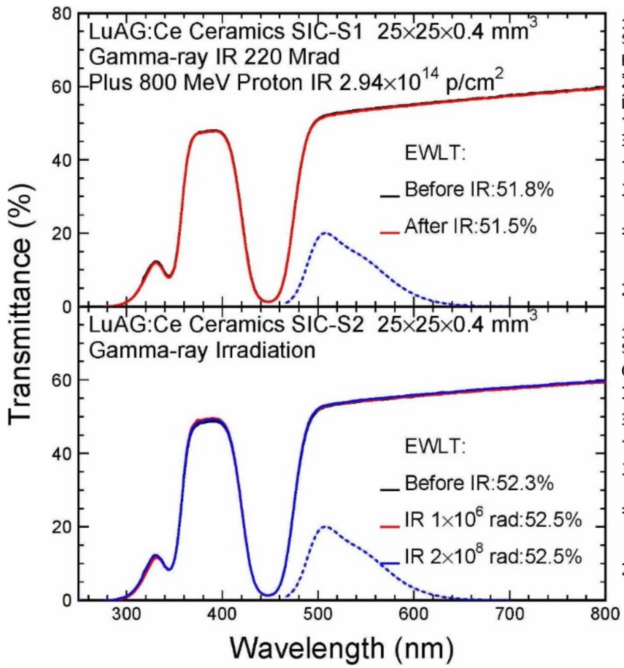


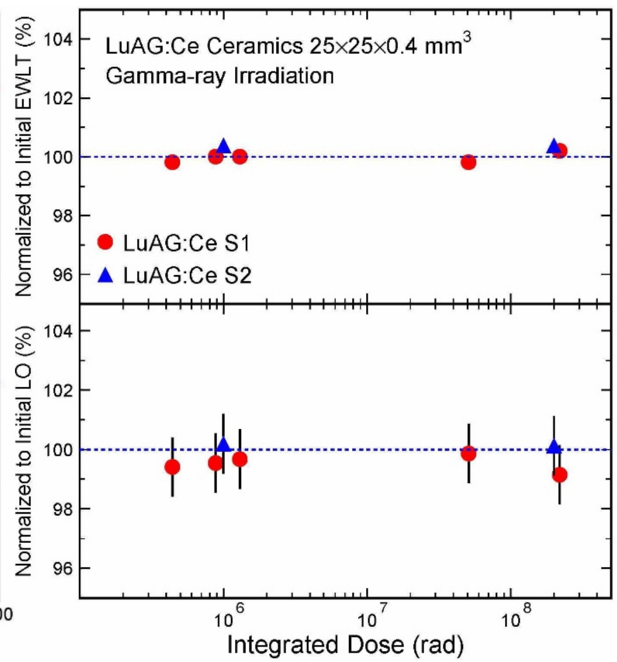
Excellent Radiation Hardness

No damage observed in both transmittance and light output after 220 Mrad ionization dose and 3×10^{14} p/cm^2 of 800 MeV

Very promising for optical-based radiation hard calorimeter





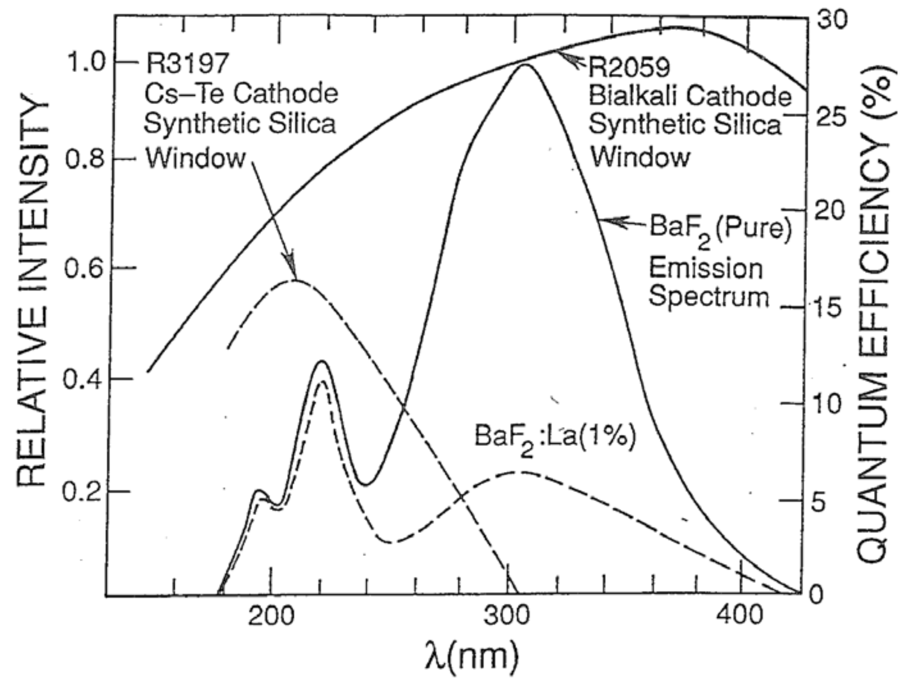


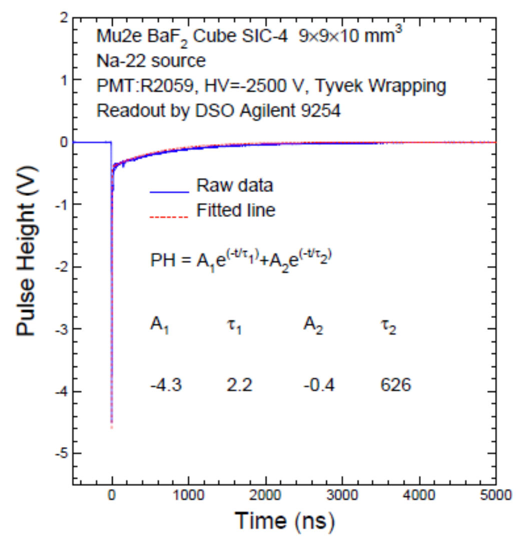
Key issue: slow scintillation component

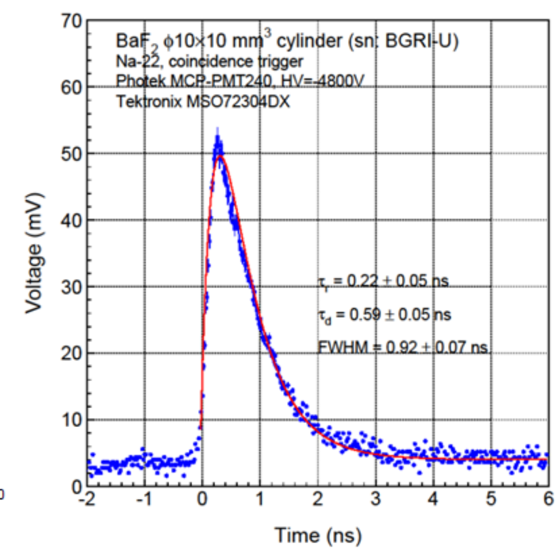
Fast and Slow Light from BaF_2

The fast component at 220 nm with 0.6 ns decay time has a similar LO as undoped CsI.

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



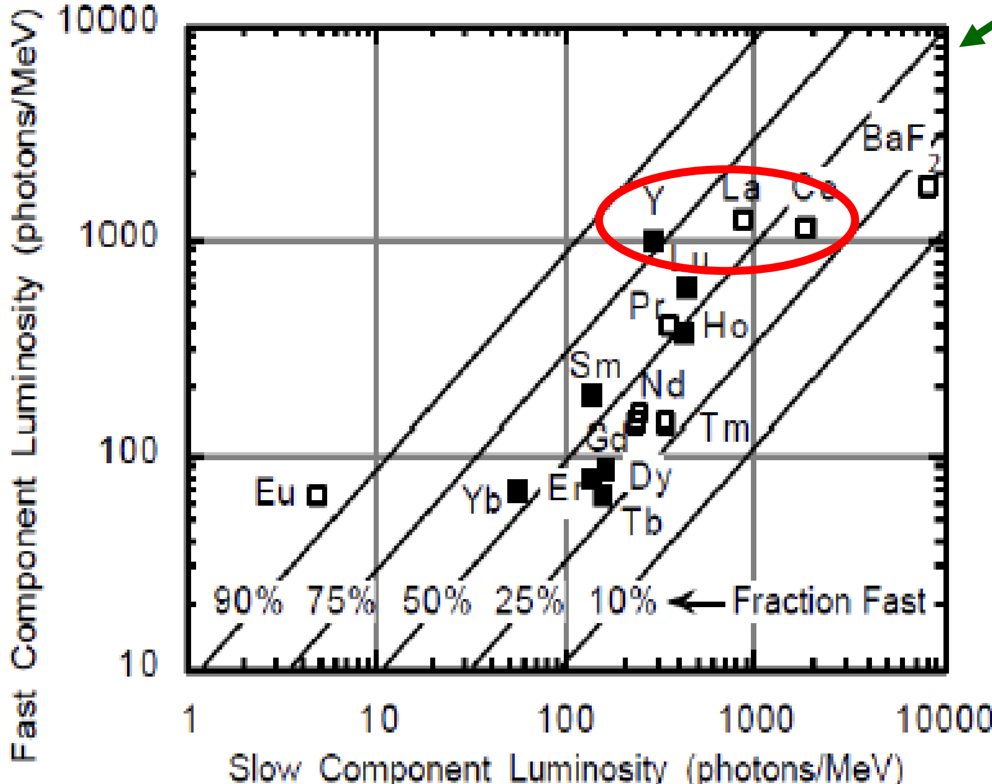


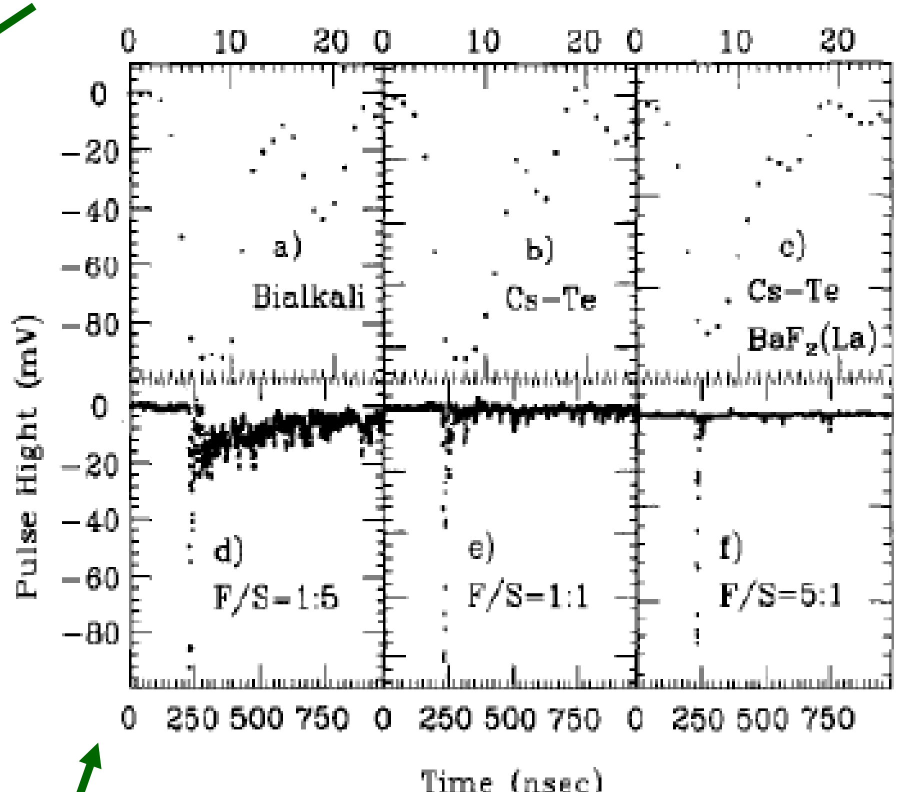


Slow Suppression: Doping & Readout

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.



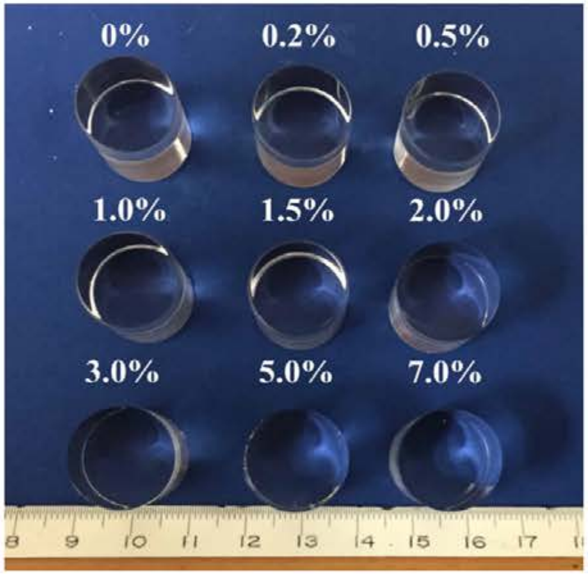


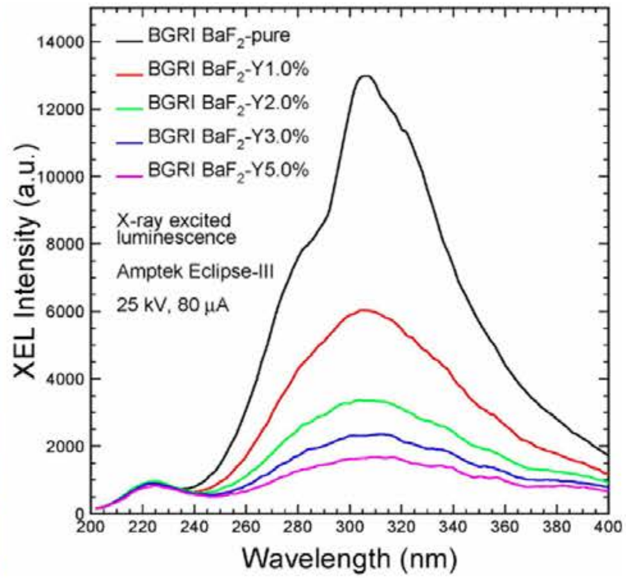
Solar-blind cathode (Cs-Te) + La doping achieved high F/S

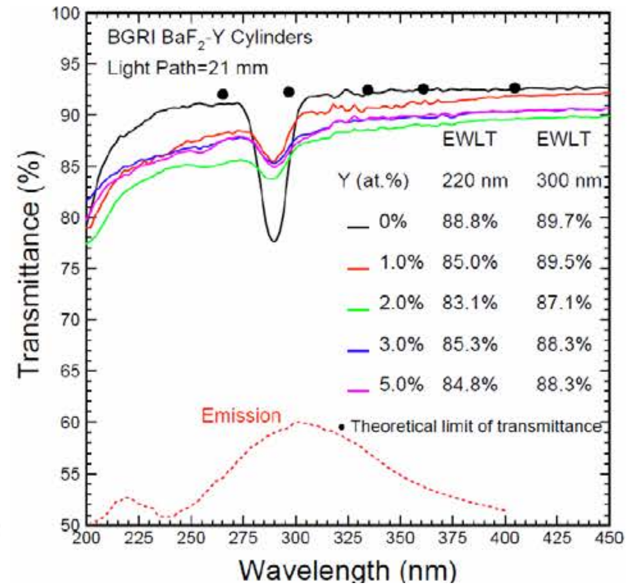
Z. Y. Wei, R. Y. Zhu, H. Newman, and Z. W. Yin, "Light Yield and Surface-Treatment of Barium Fluoride-Crystals," *Nucl Instrum Meth B*, vol. 61, pp. 61-66, Jul 1991.

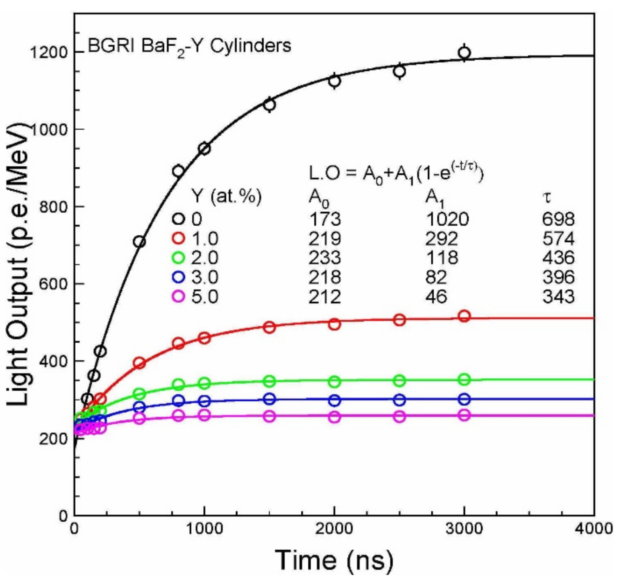
Yttrium Doping in BaF_2

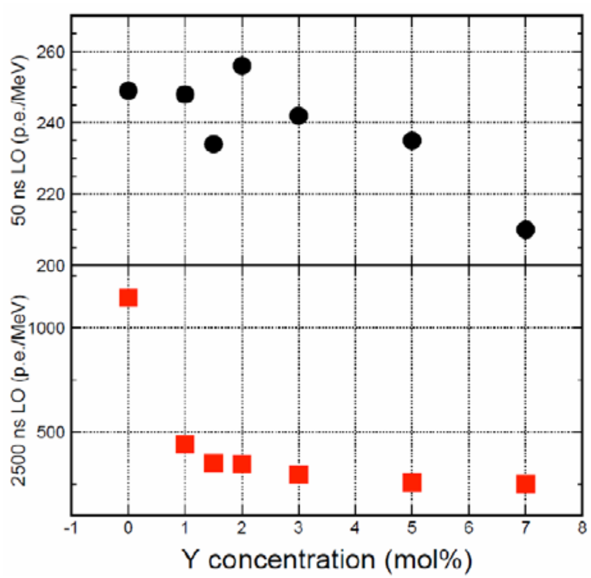
Significant increase in F/S ratio observed

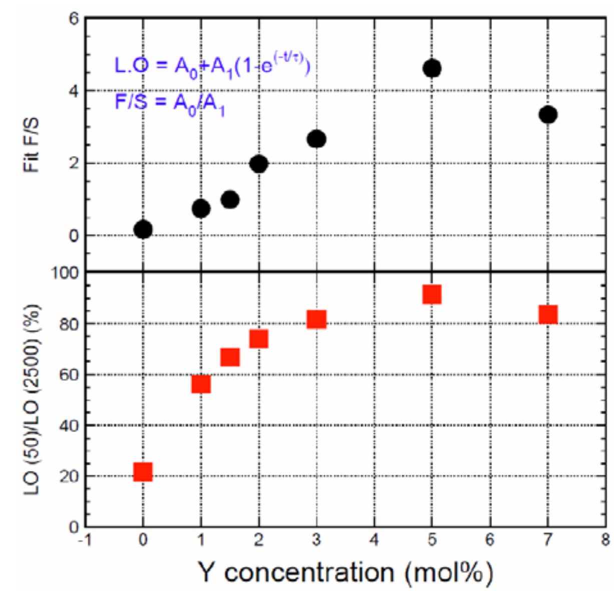








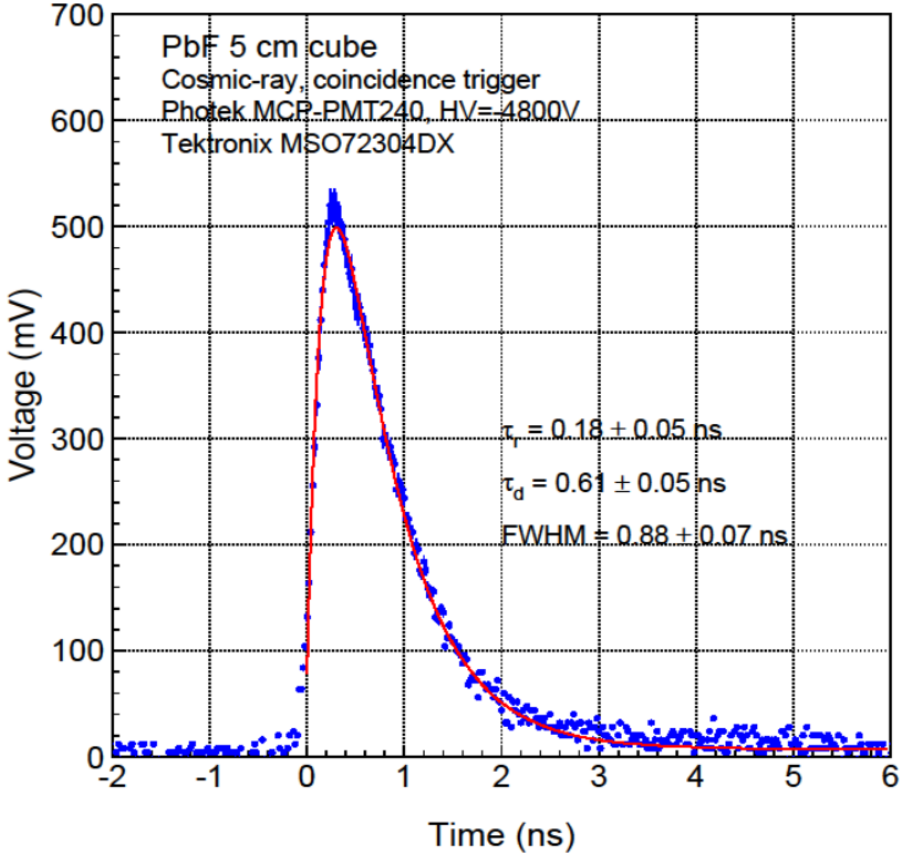




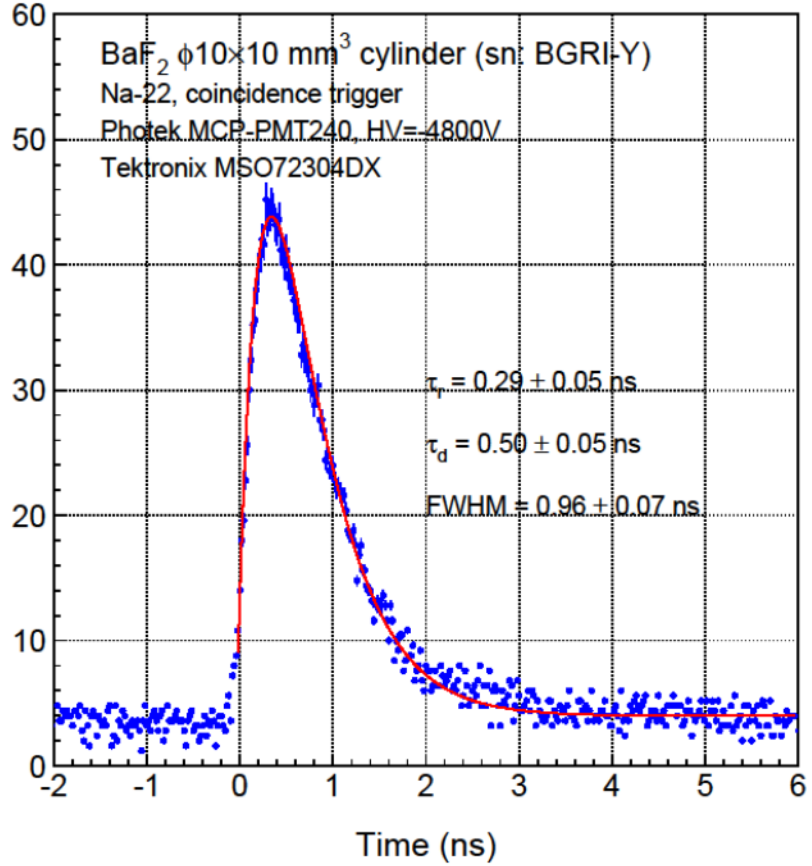
Pulse Shape: PbF_2 and BaF_2

BaF_2 cylinders of Φ10×10 cm^3 shows ɣ-ray response: 0.26/0.55/0.94 ns of rising/decay/FWHM width

PbF_2: Cosmic

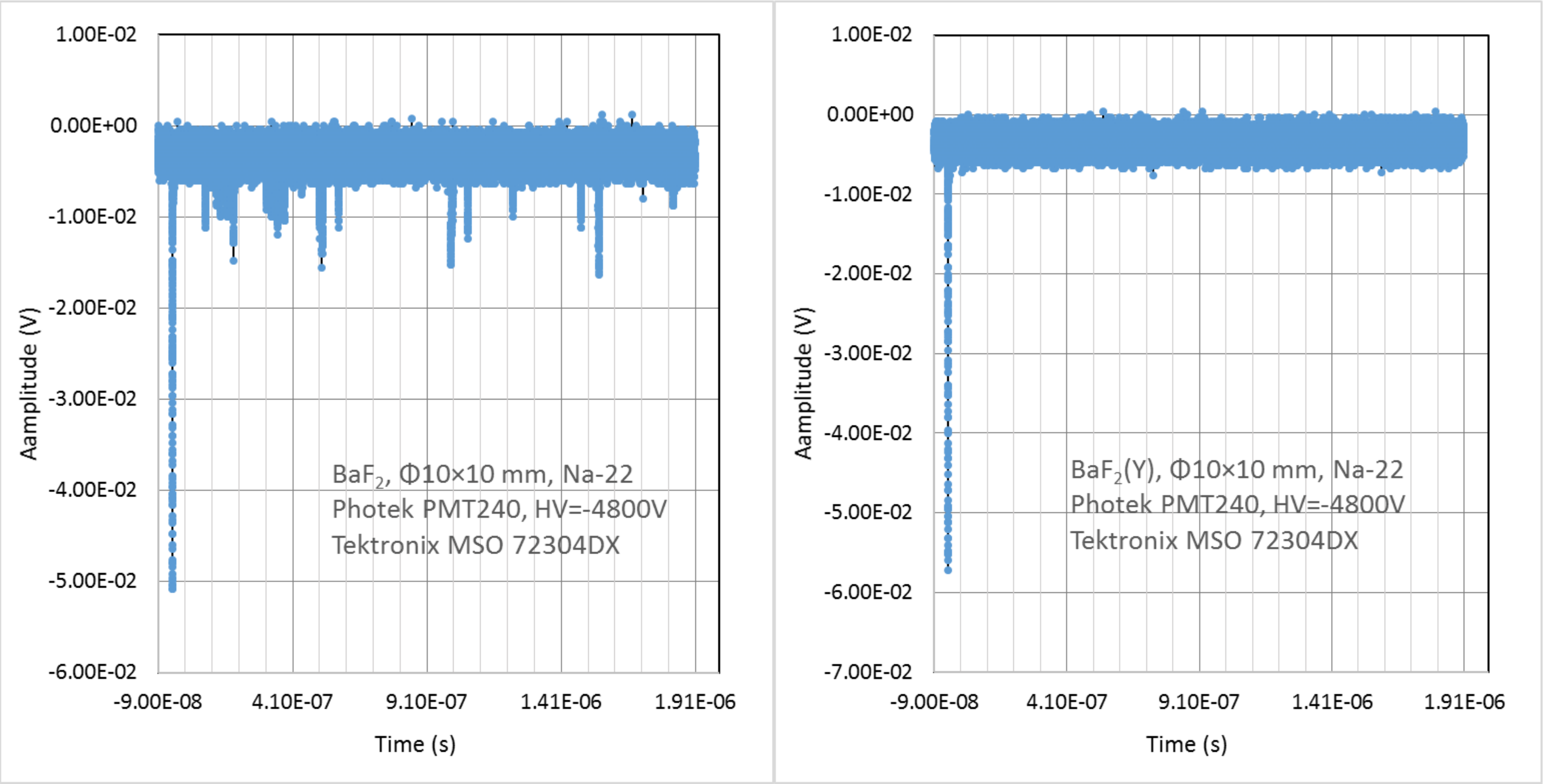


BaF_2:Y: Na-22



Tail Reduced in BaF_2:Y

Slow tail observed in BaF_2, much reduced in BaF_2:Y

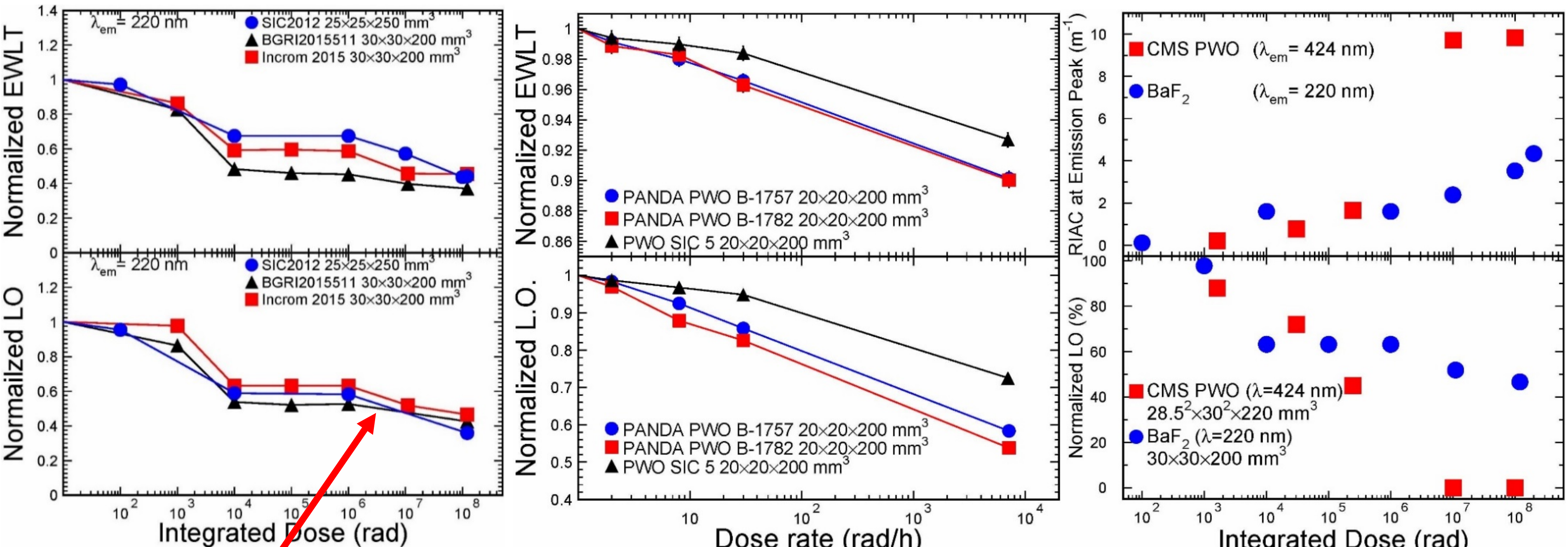


BGRI/Incrom/SIC BaF_2 Samples

ID	Vendor	Dimension (mm³)	Polishing
SIC 1-20	SICCAS	30x30x250	Six faces
BGRI-2015 D, E, 511	BGRI	30x30x200	Six faces
Russo 2, 3	Incrom	30x30x200	Six faces

Ionization Dose: BaF_2 and PWO

Dose rate dependent damage in PWO
Good radiation hardness in BaF_2 up to 100 Mrad

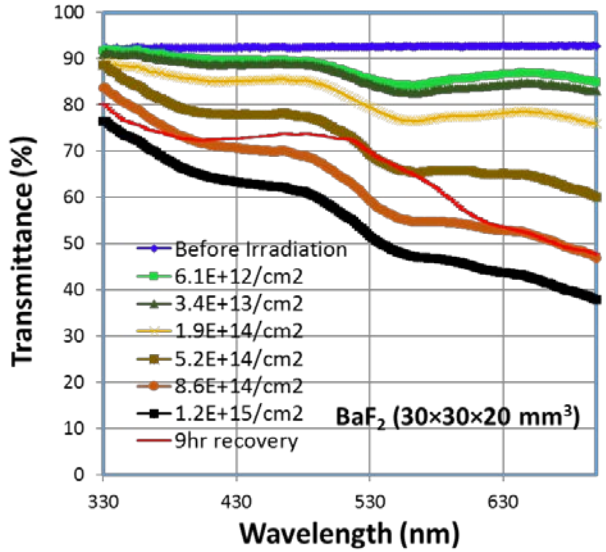


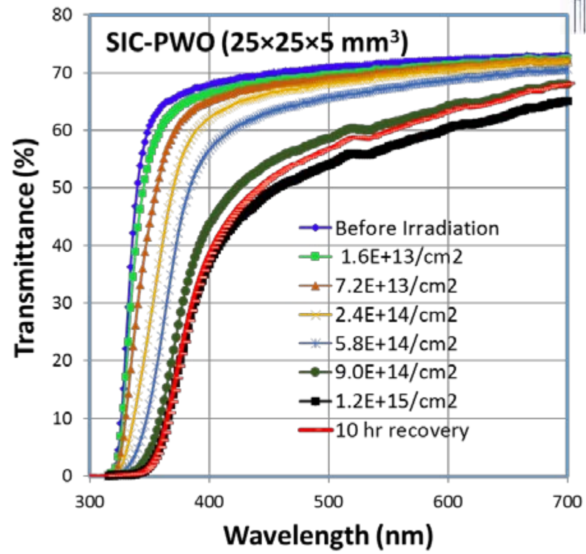
40% fast scintillation light remains after 120 Mrad ionization dose

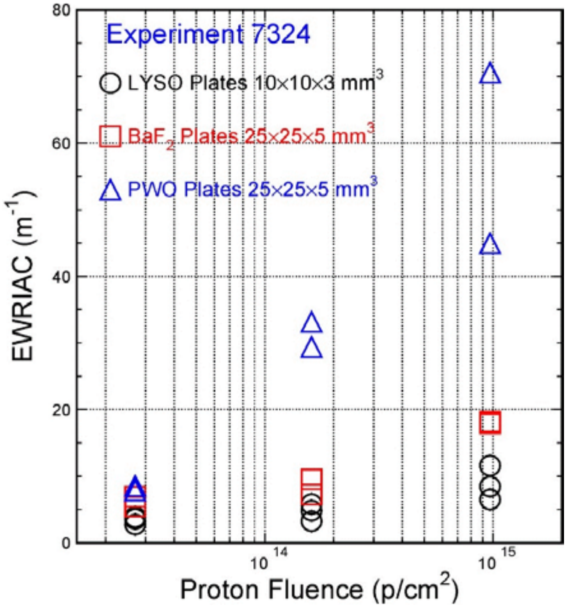
Fan Yang et al., IEEE TNS 64 (2017) 665-672

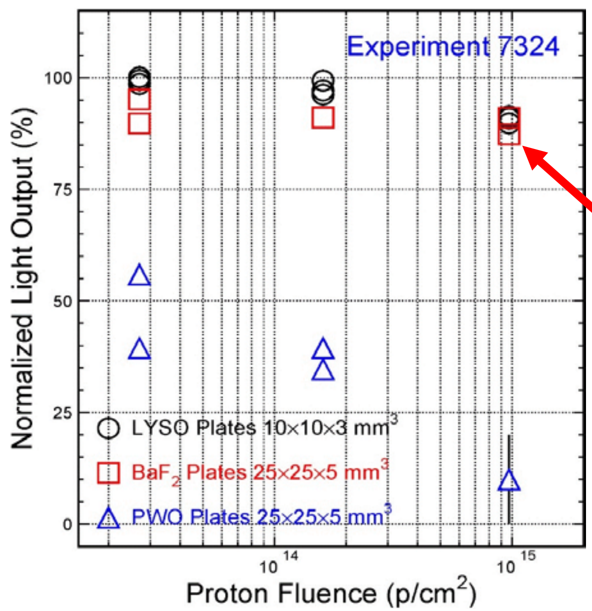
Protons: LYSO/BaF_2/PWO at LANSCE

A Hellma BaF_2 of 2 cm and a SIC PWO of 5 mm were irradiated up to 1.2×10^{15} p/cm^2 by 800 MeV protons at the blue room of LANSCE with transmittance measured *in-situ*.









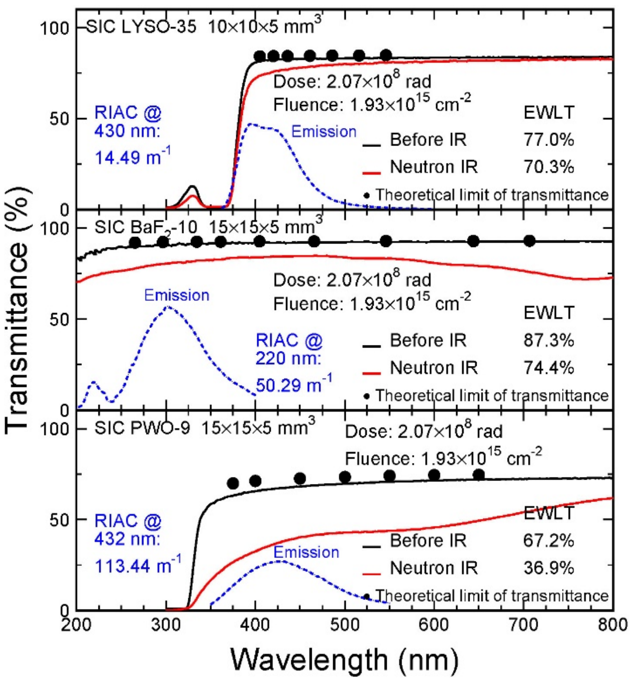
LYSO, BaF_2 and PWO plates of 3, 5 and 5 mm were also irradiated up to 1×10^{15} p/cm^2.

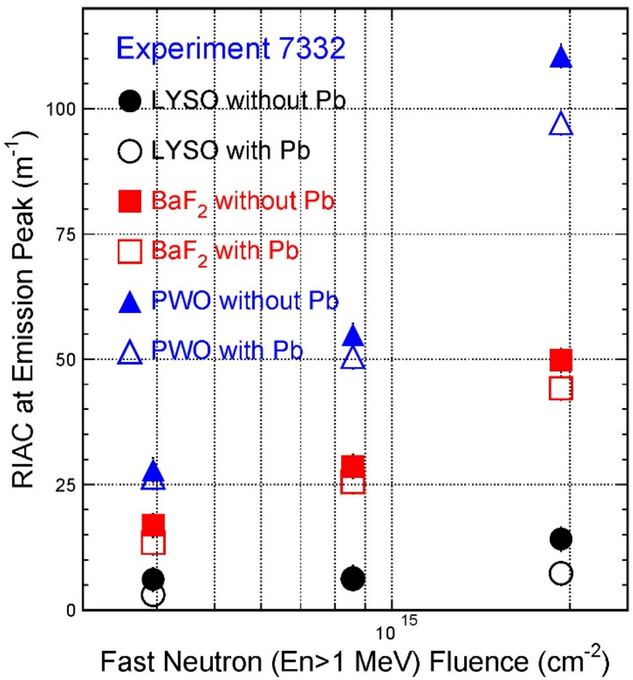
Excellent radiation hardness observed in LYSO and BaF_2, but not PWO.

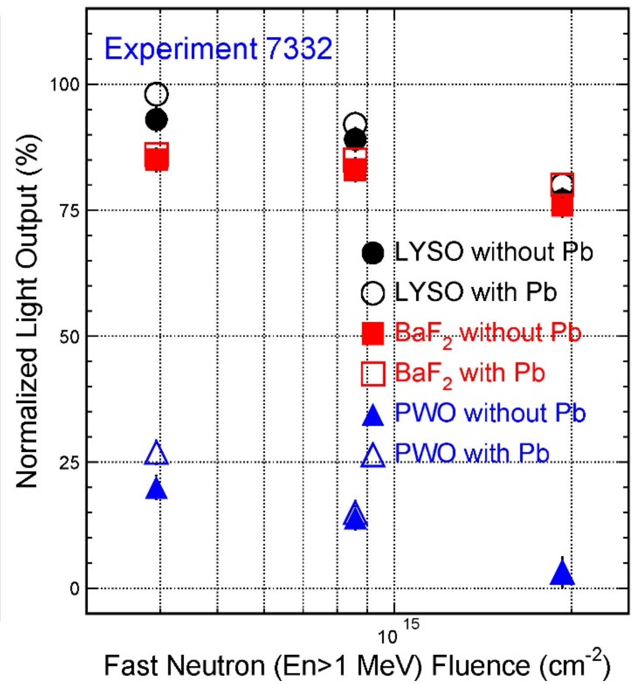
Proton-Induced Radiation Damage in BaF_2, LYSO and PWO Crystal Scintillators, IEEE TNS **65** (2018)
Digital Object Identifier 10.1109/TNS.2018.2808841

Neutrons: LYSO/BaF_2/PWO at LANSCE

LYSO, BaF_2 and PWO plates of 5 mm were irradiated up to 2×10^{15} n/cm^2 in three steps at the East Port of LANSCE



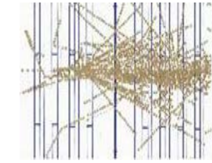




Excellent radiation hardness observed in LYSO and BaF_2, but not PWO

See talk by L. Zhang in this conference

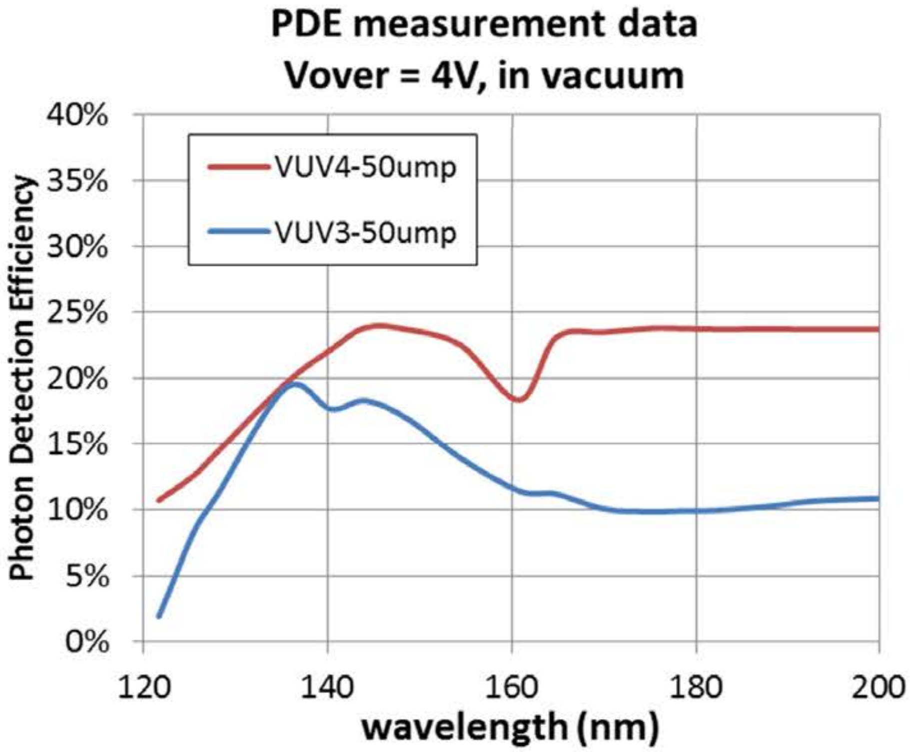
Summary: HEP Experiments

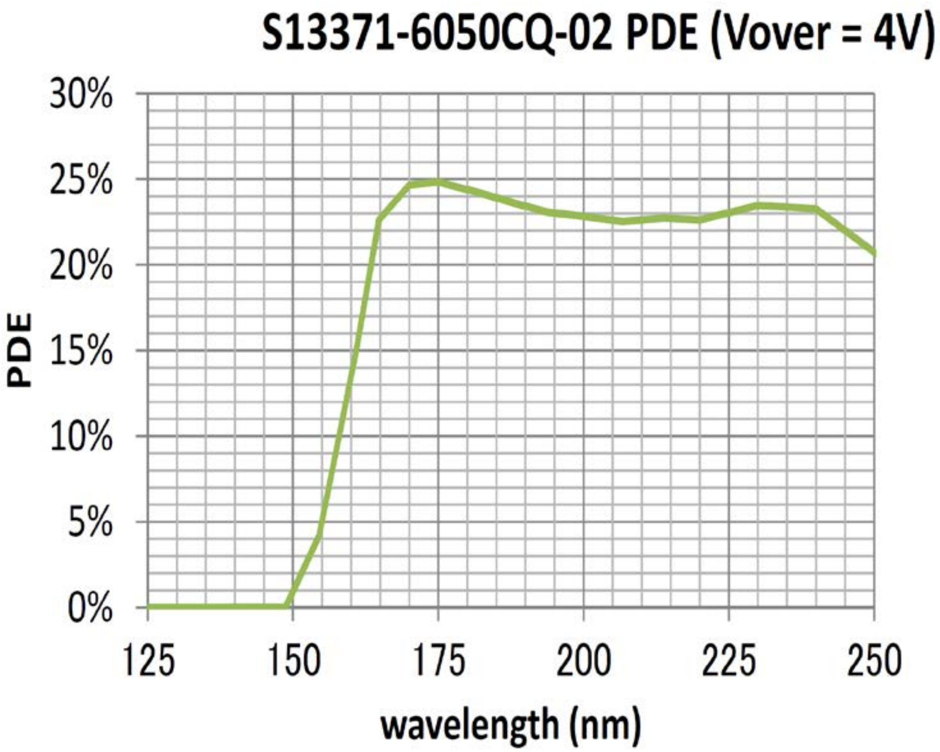


- LYSO, BaF_2 crystals and LuAG ceramics show excellent radiation hardness beyond 100 Mrad, 1 x 10^{15} p/cm^2 and 2 x 10^{15} n/cm^2. They promise a very fast and robust detector in a severe radiation environment, such as HL-LHC.
- Commercially available undoped BaF_2 crystals provide sufficient fast light with sub-ns decay time. Yttrium doping in BaF_2 crystals increases its F/S ratio significantly while maintaining the intensity of the sub-ns fast component. This material is promising for Mu2e-II and GHz X-ray imaging.
- Results of the LANL experiments 6991 and 7332 show fast neutrons up to 2 x 10^{15} n/cm^2 do not cause significant damage LYSO and BaF_2, qualitatively confirming early observation at the Saclay reactor.
- Our plan is to investigate novel ultrafast crystals and radiation hardness of BaF_2:Y crystals. Will also test TPBD WLS with R. Ruchiti *et al.* for BaF_2:Y, and pay an attention to photodetector with DUV response: LAPPD, Si or diamond etc.

Hamamatsu S13371-6050CQ-02

SiPM with VUV response is available: QE = 22% at 220 nm





Diamond Photodetector

E. Monroy, F. Omnes and F. Calle,"Wide-bandgap semiconductor ultraviolet photodetectors, IOPscience 2003 Semicond. Sci. Technol. 18 R33

E. Pace and A. De Sio, "Innovative diamond photo-detectors for UV astrophysics", Mem. S.A.It. Suppl. Vol. 14, 84 (2010)

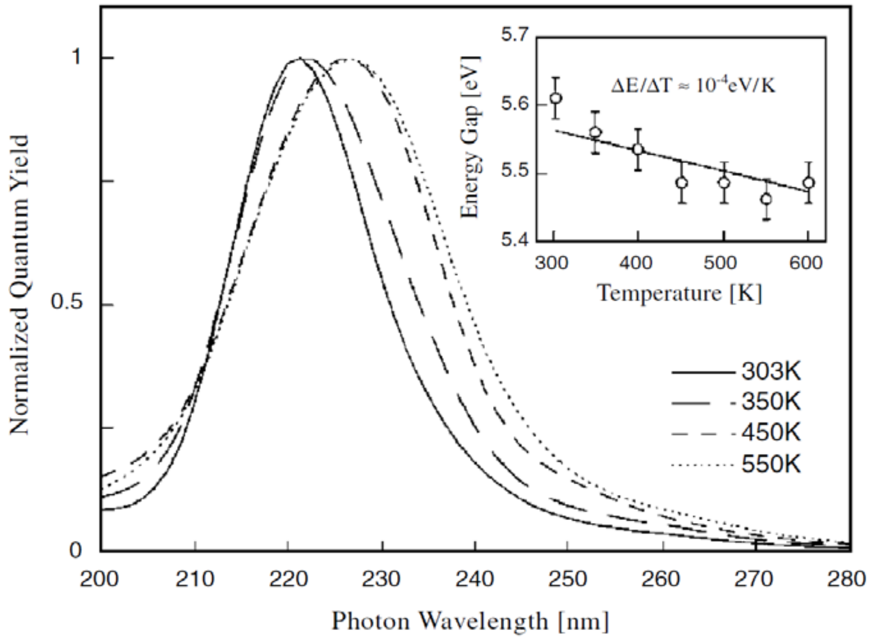


Figure 6. Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

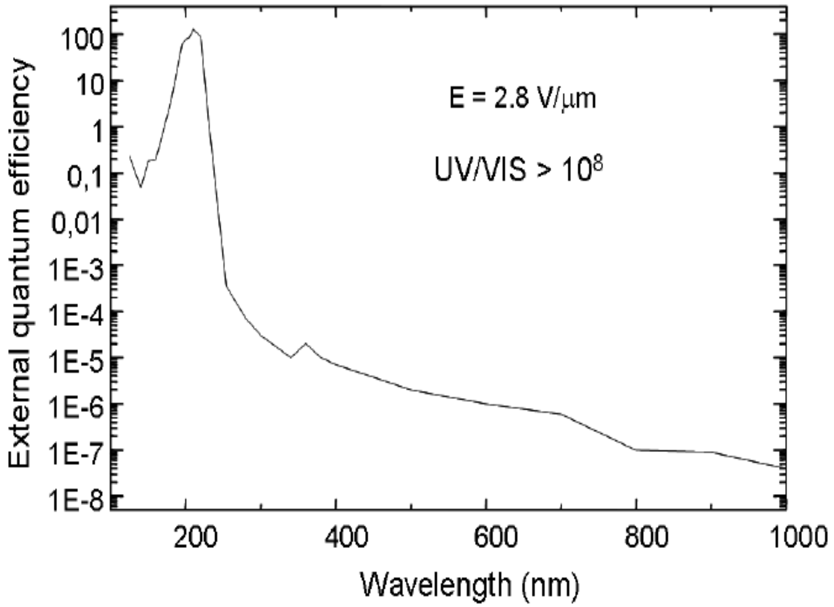


Fig. 4. External quantum efficiency extended to visible and near infrared wavelength regions. The