Applications of Very Fast Inorganic Crystal Scintillators for Future HEP Experiments

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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 experiments at the energy and intensity frontiers.**
- **LYSO:Ce, BaF_2 and LuAG:Ce will survive the radiation environment expected at HL-LHC with 3000 fb^{-1}. LYSO is proposed for a precision timing layer 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 GHz X-ray imaging for the proposed Marie project at Los Alamos. Y:BaF_2 with sub-ns decay time and suppressed slow scintillation component is a leading candidate for both applications.**

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

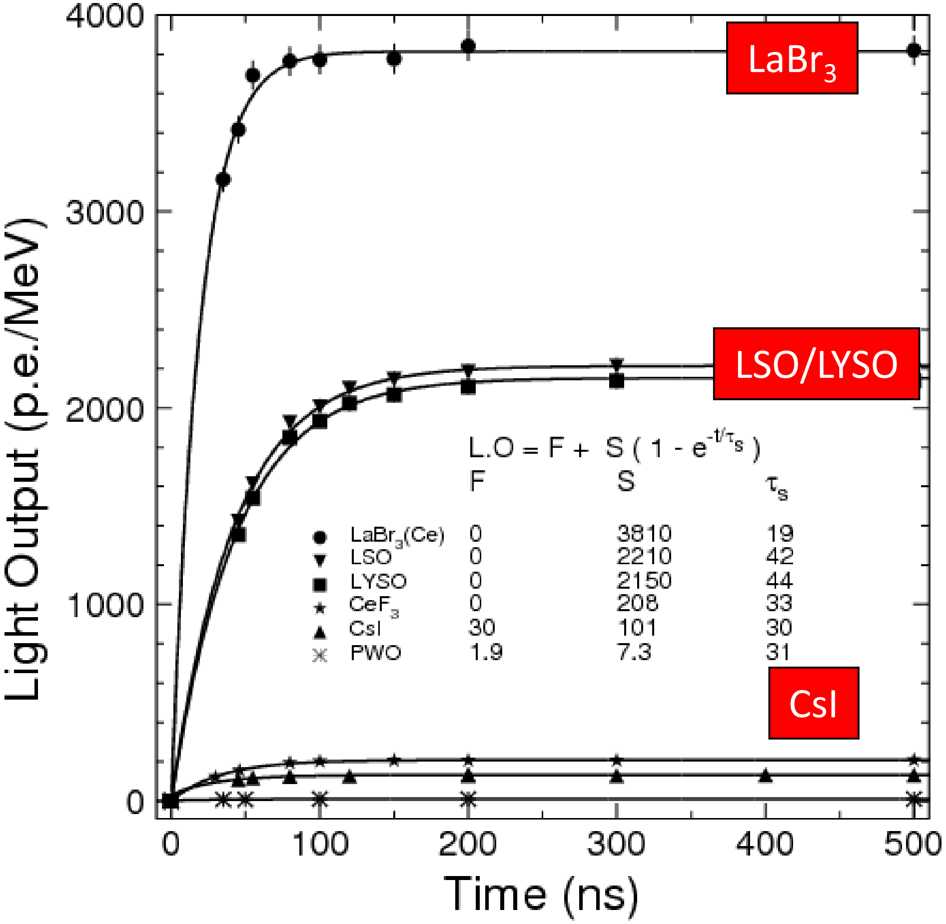
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

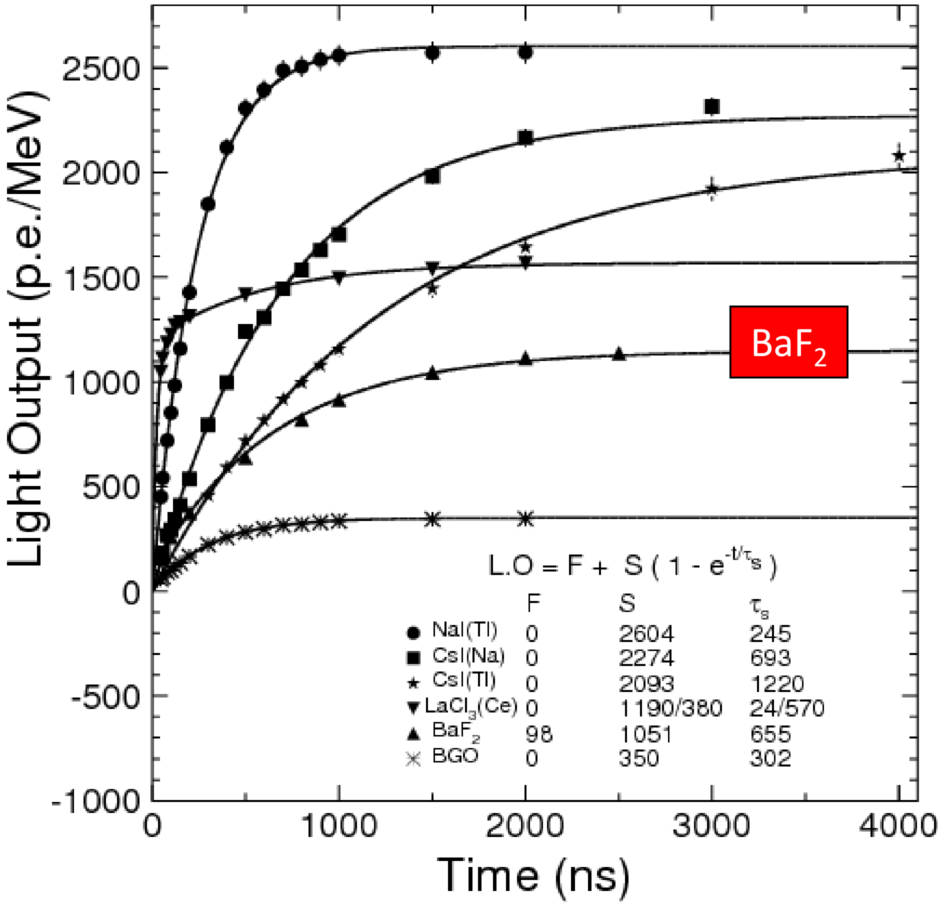
Light Output & Decay Kinetics

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

Fast Crystal Scintillators

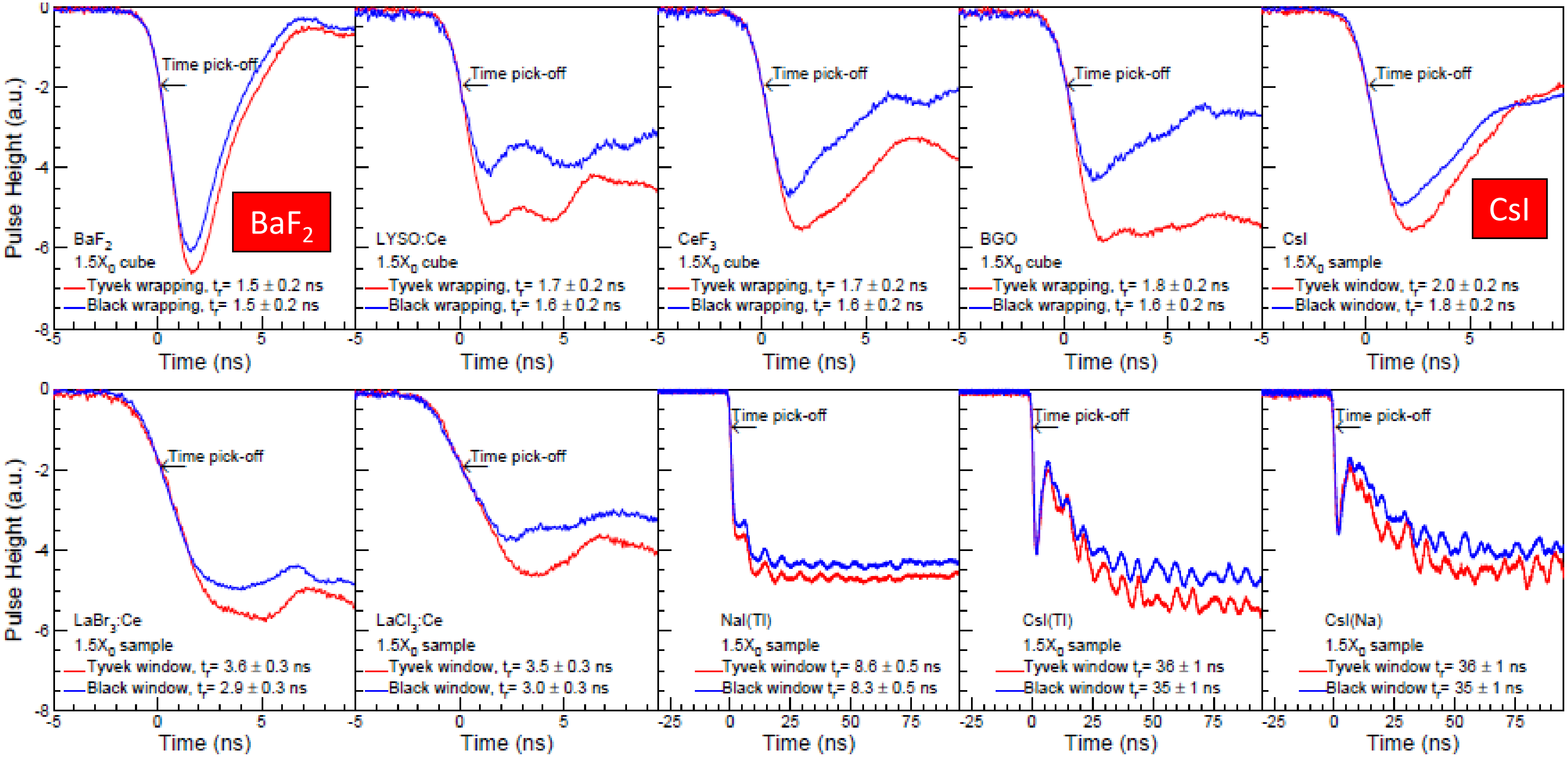
Slow Crystal Scintillators





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 3 ns width of BaF$_2$ pulse may be further reduced by faster photodetector
LYSO, LaBr$_3$ & CeBr$_3$ have tail, which would cause pile-up for GHz readout

Fast Inorganic Scintillators

	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 0.6	600 0.6	17	20
Light Yield in 1st 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

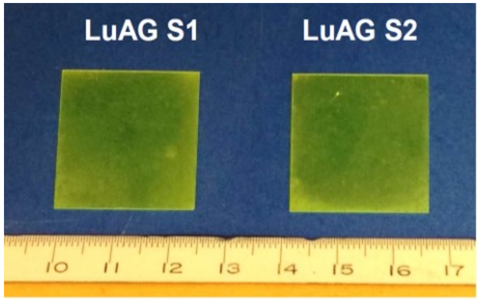
[4] Lucchini, et al., *NIM A* 2016, 816: 176-183

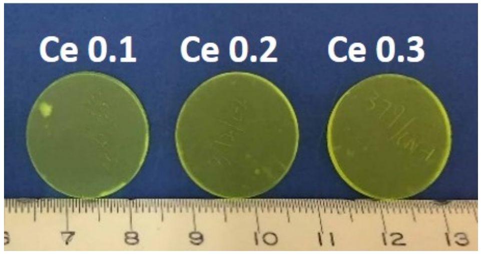
[5] Meng, et al., *Mat. Sci. Eng. B-Solid* 2015, 193: 20-26

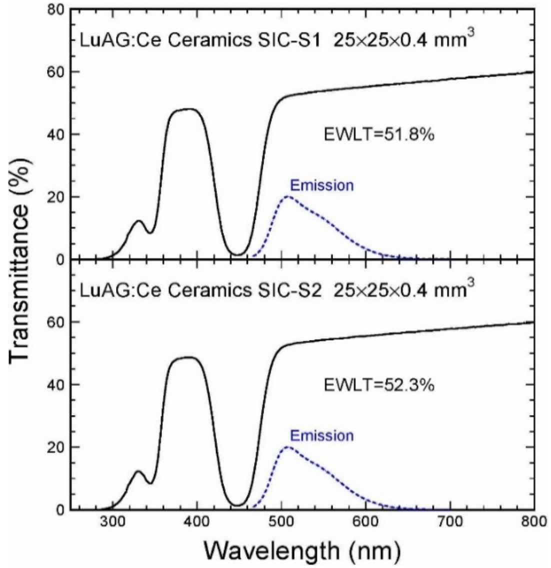
[6] Diehl, et al., *J. Phys. Conf. Ser* 2015, 587: 012044

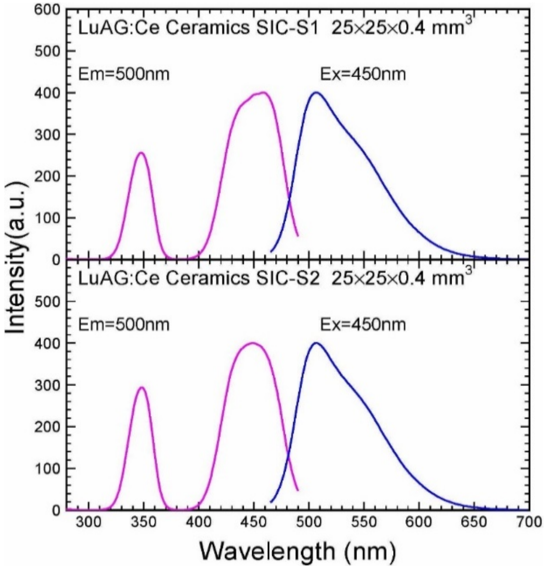
[7] Pustovarov, et al., Tech. Phys. Lett. 2012, 784-788

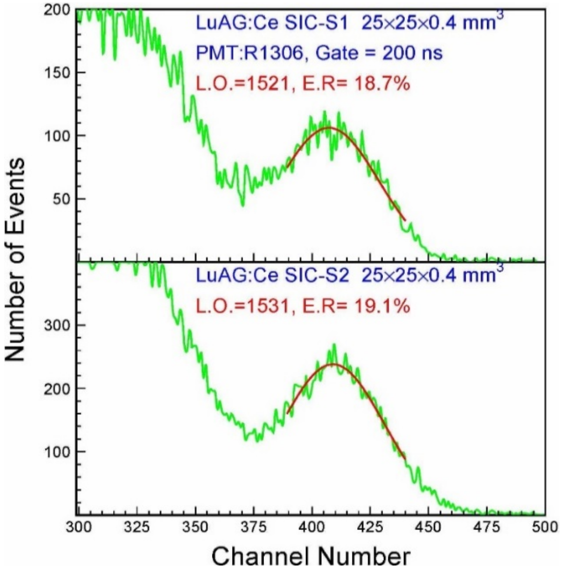
LuAG:Ce Ceramic Samples

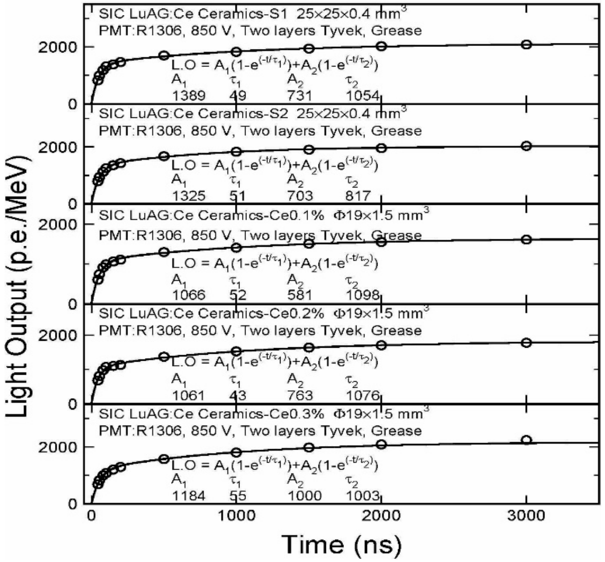


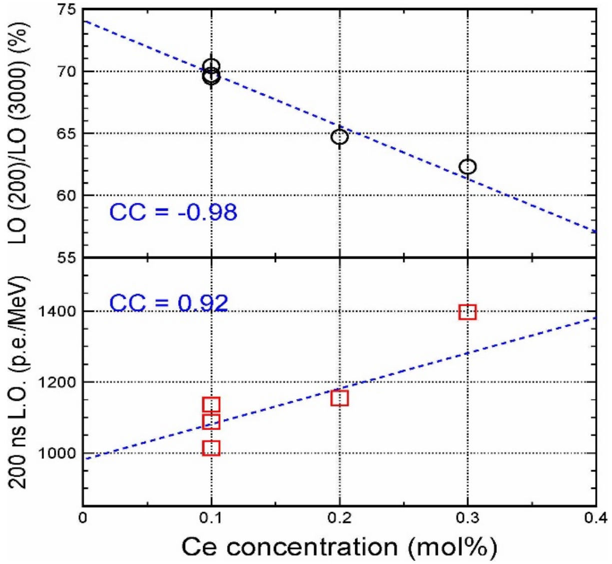






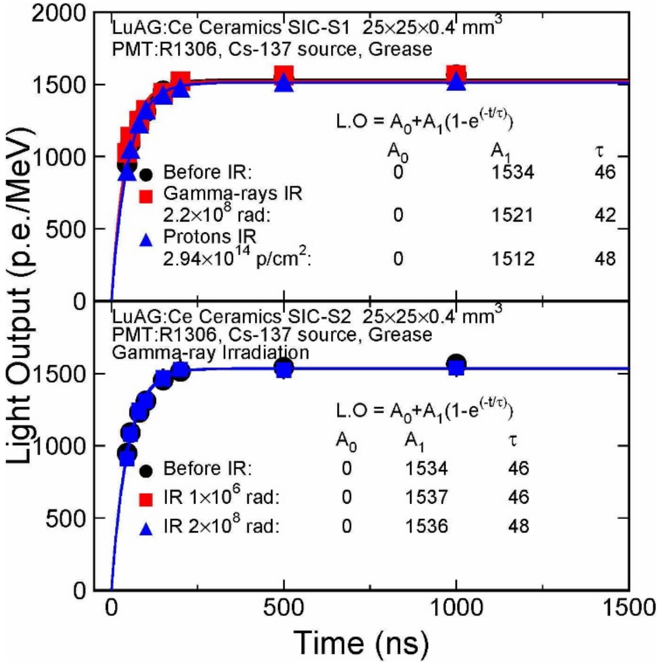


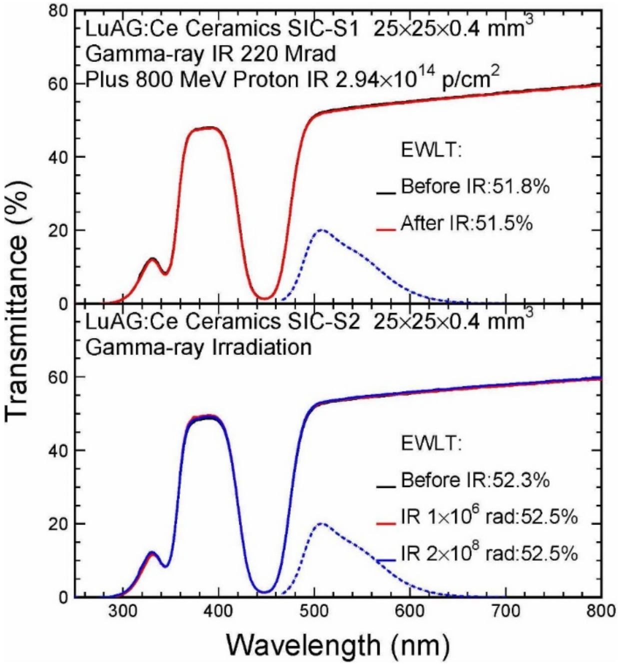


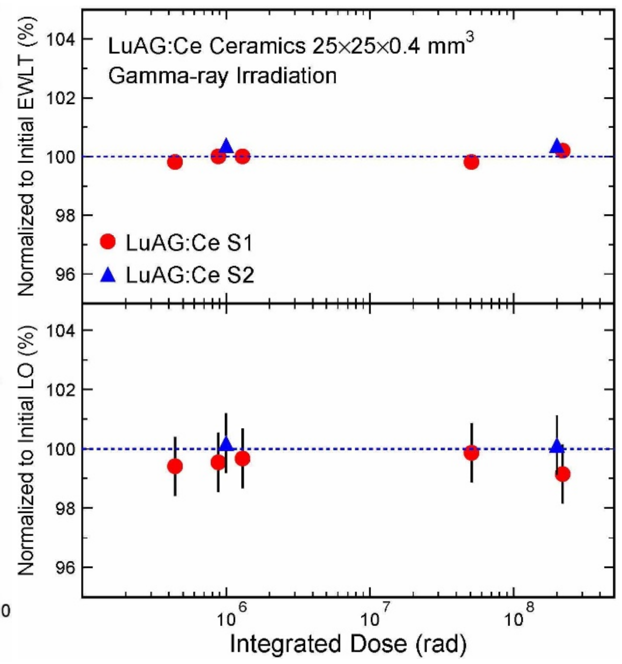


Excellent Radiation Hardness

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

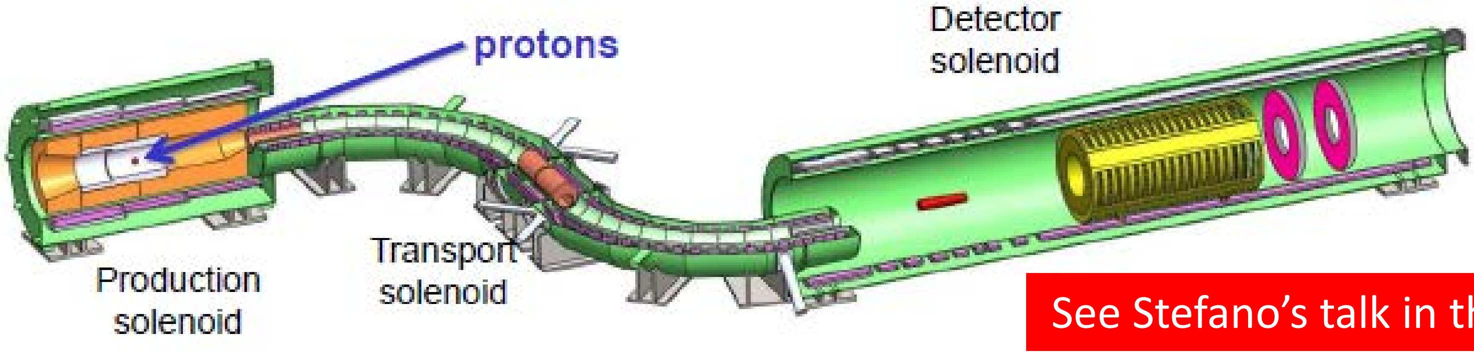






Very promising for a scintillating ceramics based calorimeter
Will be discussed in details in NSS2017 at Atlanta

Mu2e Specifications for Undoped CsI



See Stefano's talk in this session

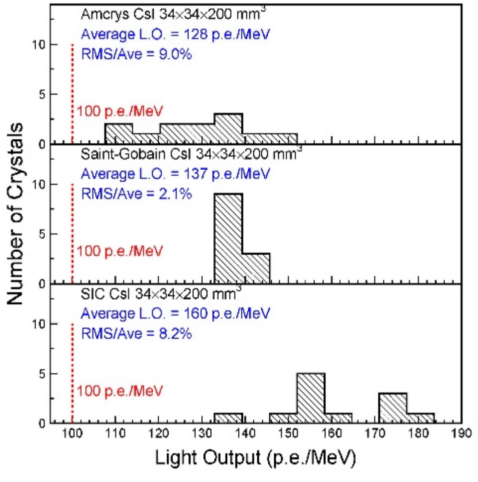
- Crystal lateral dimension: ±100 μ, length: ±100 μ.
- Scintillation properties at seven points along the crystal wrapped by two layers of Tyvek paper of 150 μm for alternative end coupled to a bi-alkali PMT with an air gap. Light output and FWHM resolution are the average of seven points with 200 ns 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**.

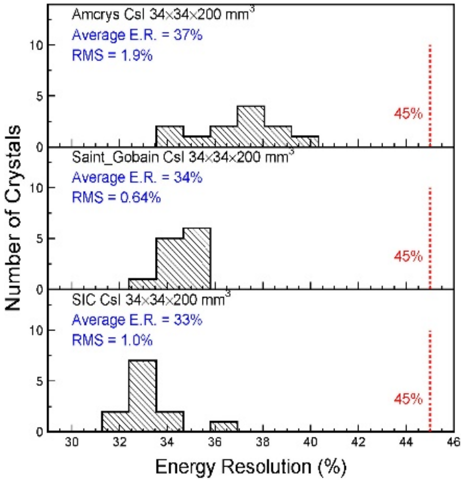
Mu2e Preproduction CsI

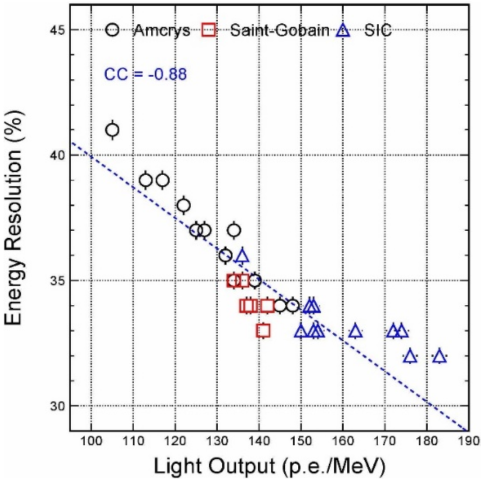
A total of 72 crystals from Amcrys, Saint-Gobain and SICCAS has been measured at Caltech and LNF

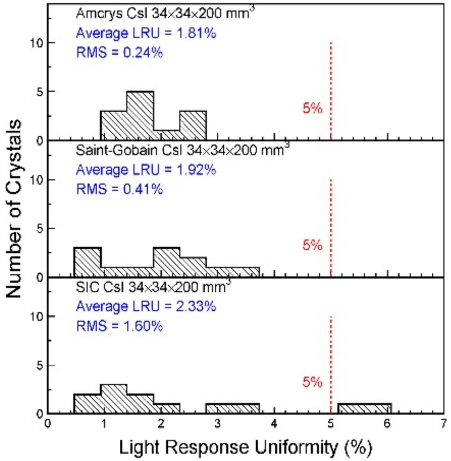
Quality of Pre-Production CsI

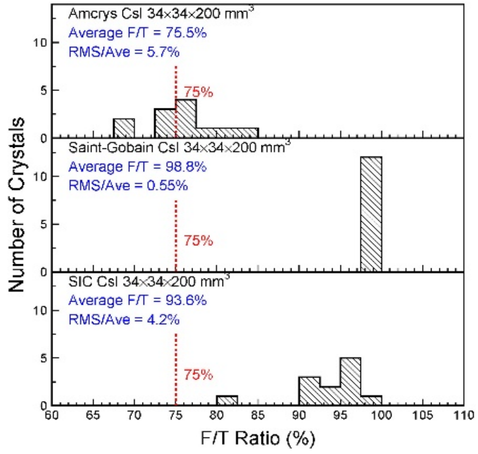
See paper P1-21 Tuesday morning

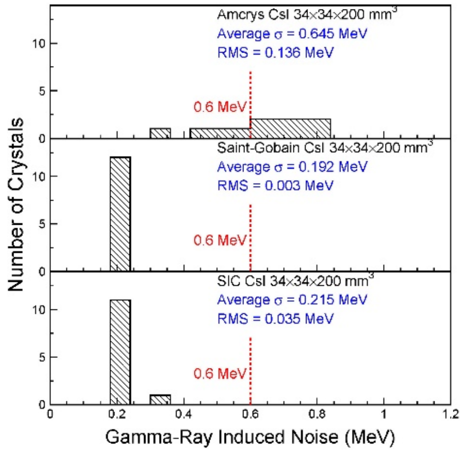


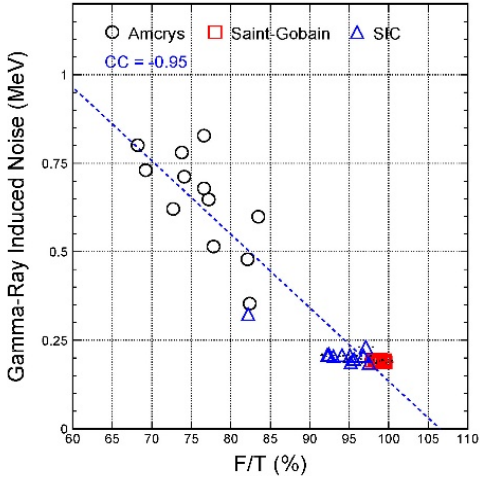


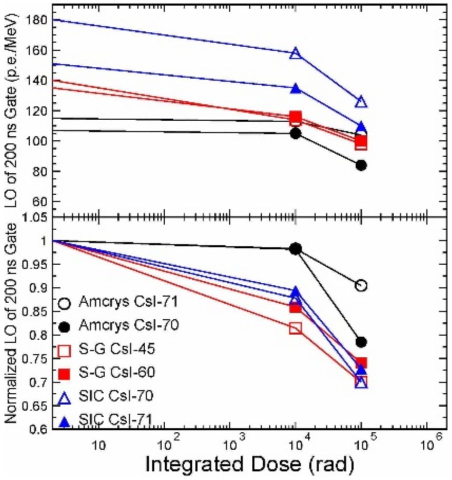












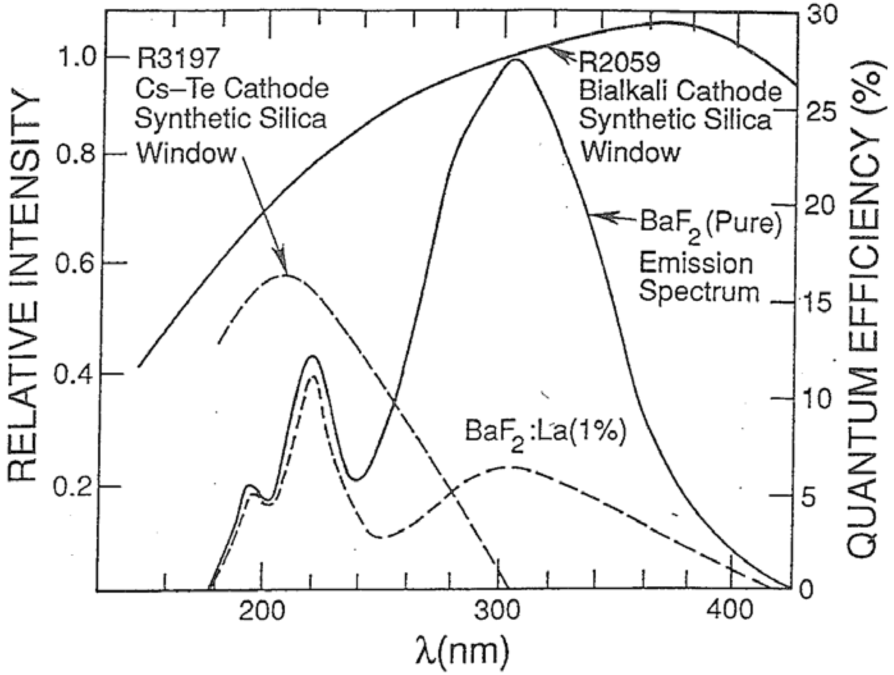
Most preproduction crystals satisfy specifications, except a few crystals from SICCAS fail the LRU spec and about half Amcrys crystals fail the F/T ratio and RIN

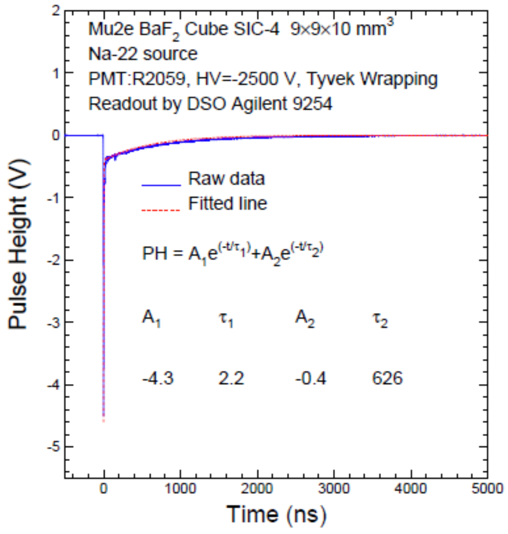
Fast and Slow Light from BaF_2

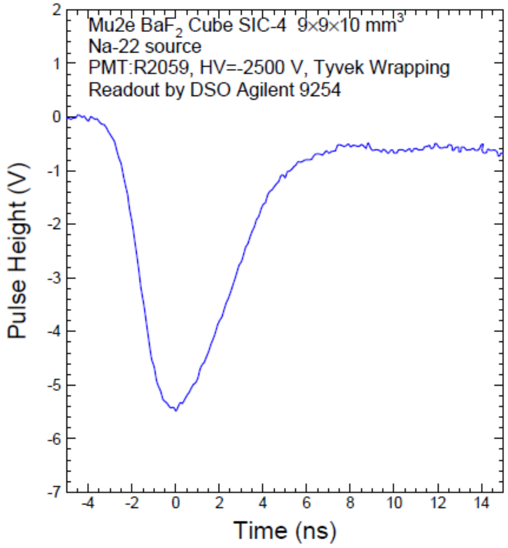
A radiation level exceeding 100 krad is expected at the proposed Mu2e-II, so BaF_2 is being considered.

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.



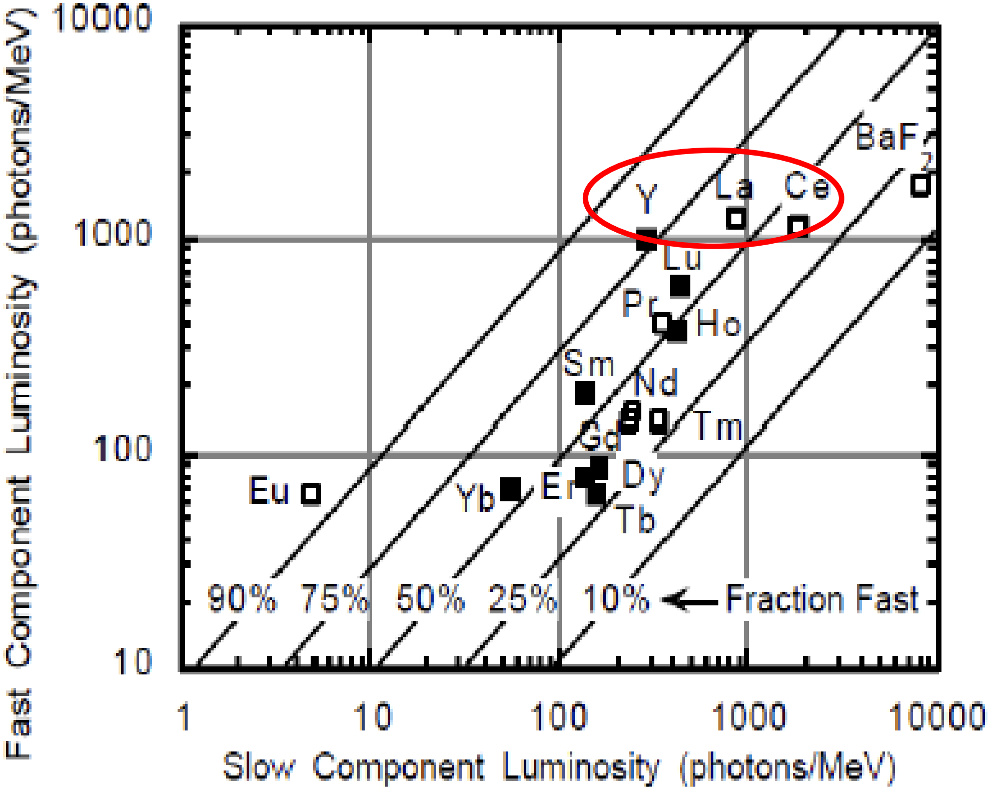


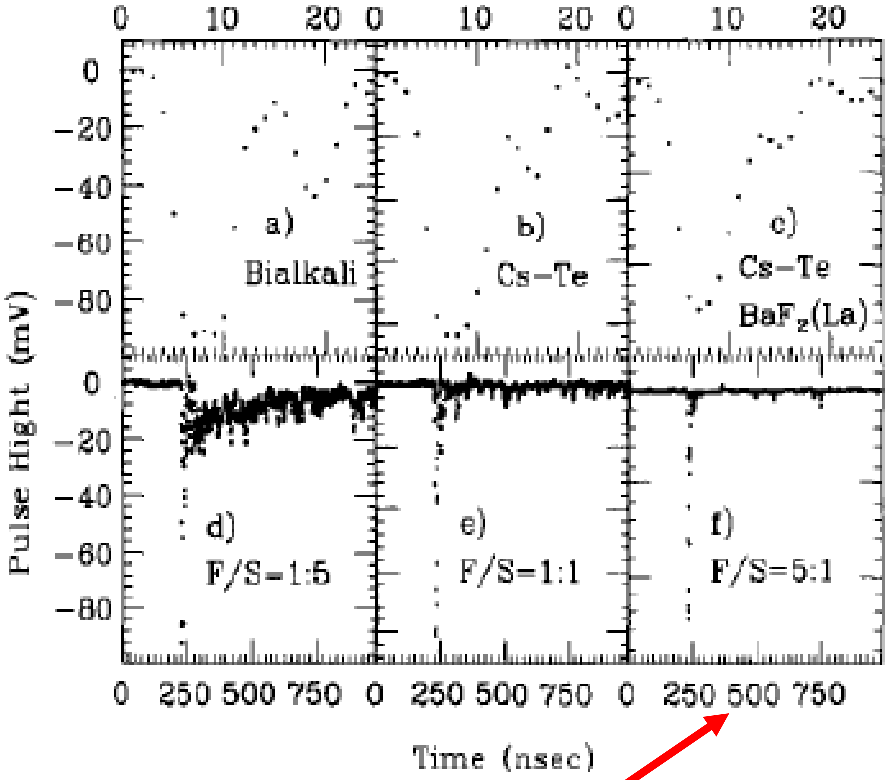


Slow Suppression: Doping & Readout

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.



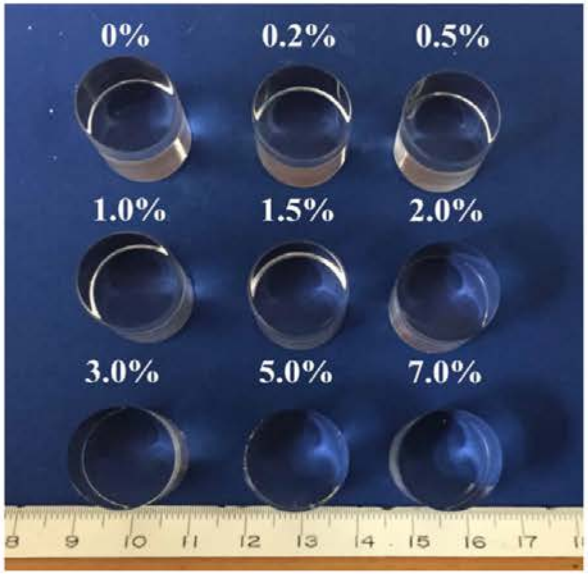


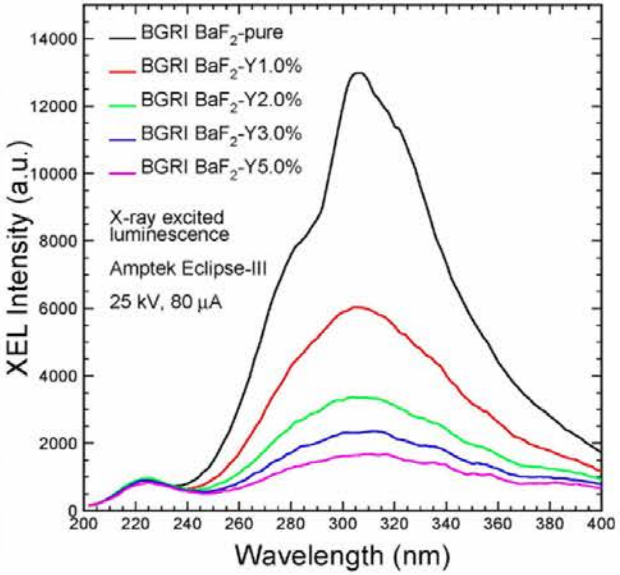
Solar-blind cathode (Cs-Te) + La doping achieved F/S = 5/1

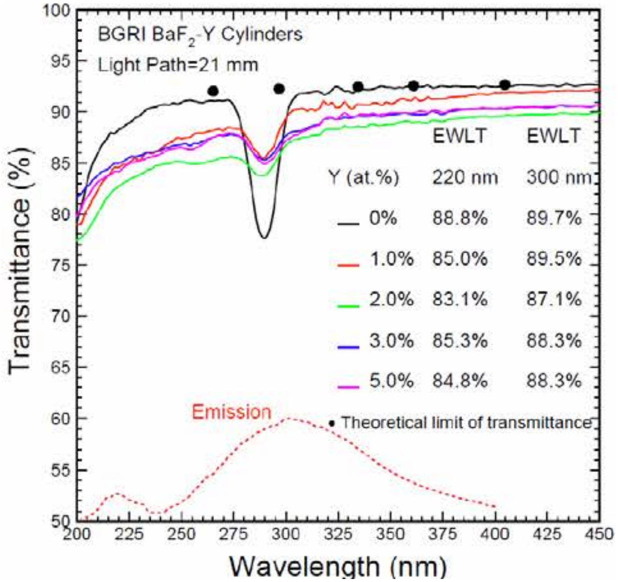
See J.F. Chen, paper P3-28 Thursday morning

Yttrium Doped BaF_2 for Mu2e-II

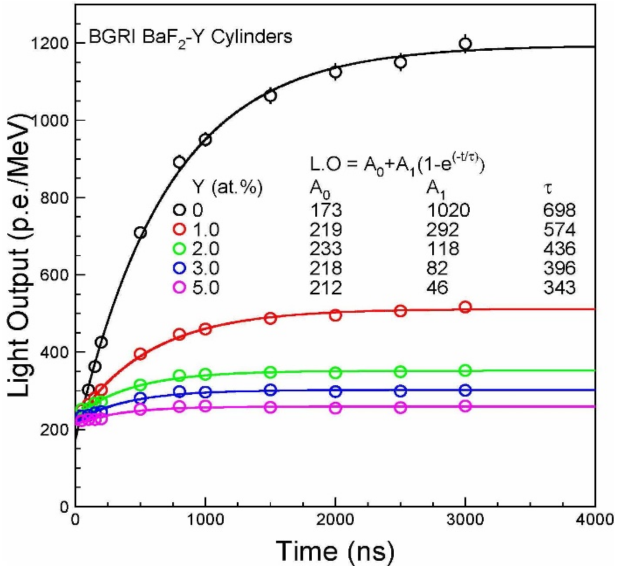
F/S ratio from 1/5 to 5/1: very effective slow suppression





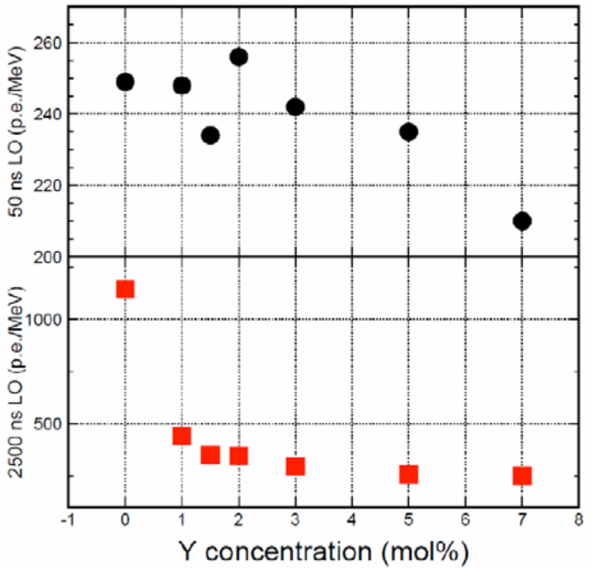


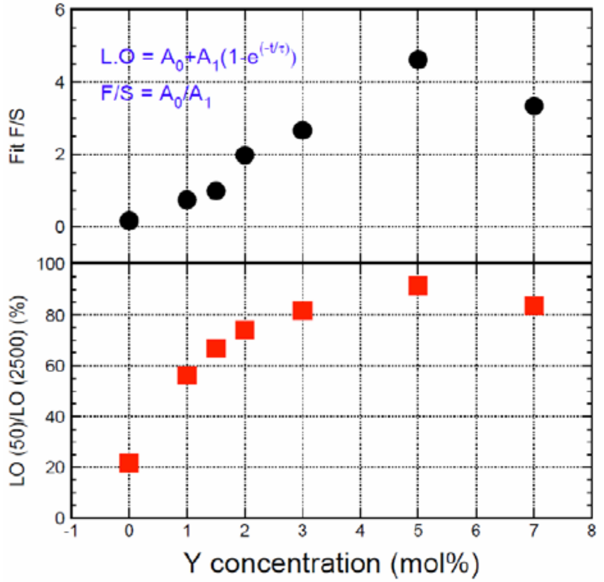
Y (at.%)	EWLT 220 nm	EWLT 300 nm
0%	88.8%	89.7%
1.0%	85.0%	89.5%
2.0%	83.1%	87.1%
3.0%	85.3%	88.3%
5.0%	84.8%	88.3%



$L.O = A_0 + A_1(1 - e^{(-t/\tau)})$

Y (at.%)	A_0	A_1	τ
○ 0	173	1020	698
○ 1.0	219	292	574
○ 2.0	233	118	436
○ 3.0	218	82	396
○ 5.0	212	46	343



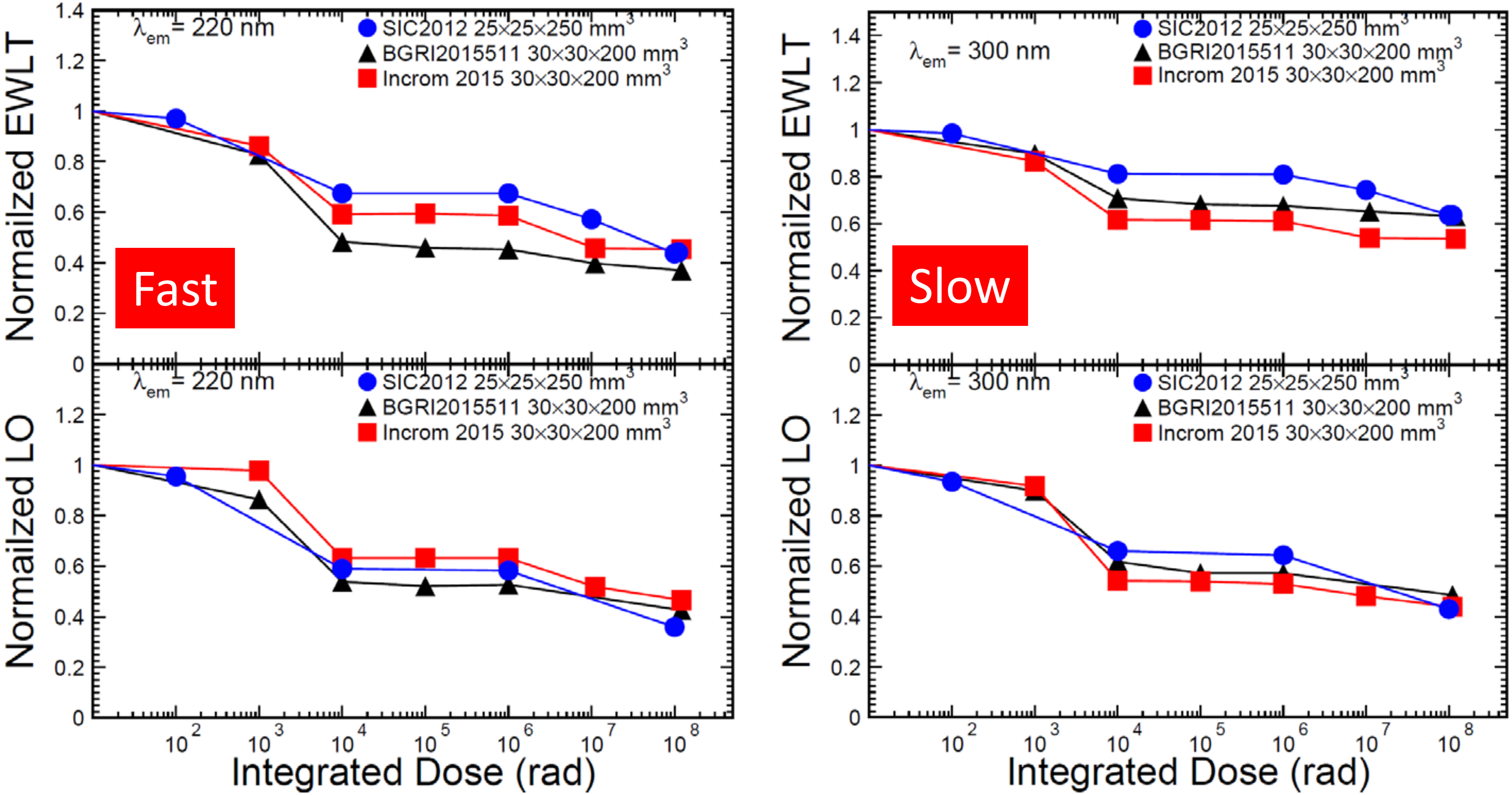


BGRI/Incrom/SIC BaF_2 Samples

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

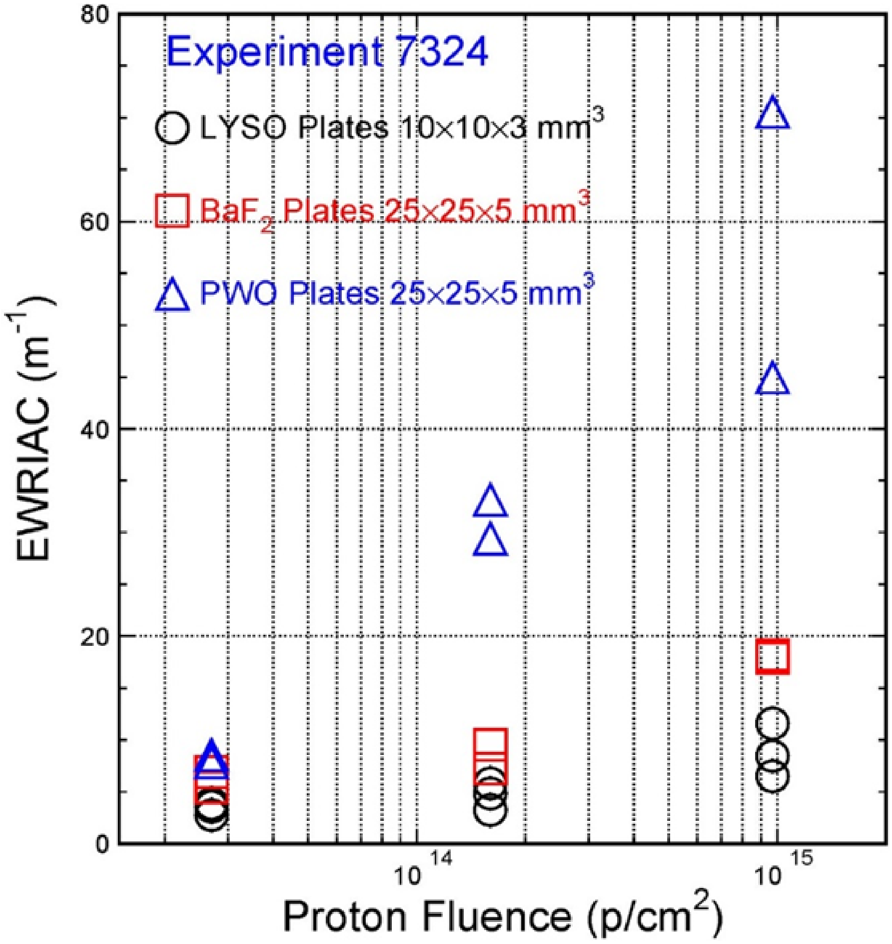
Consistent damage in crystals from three vendors

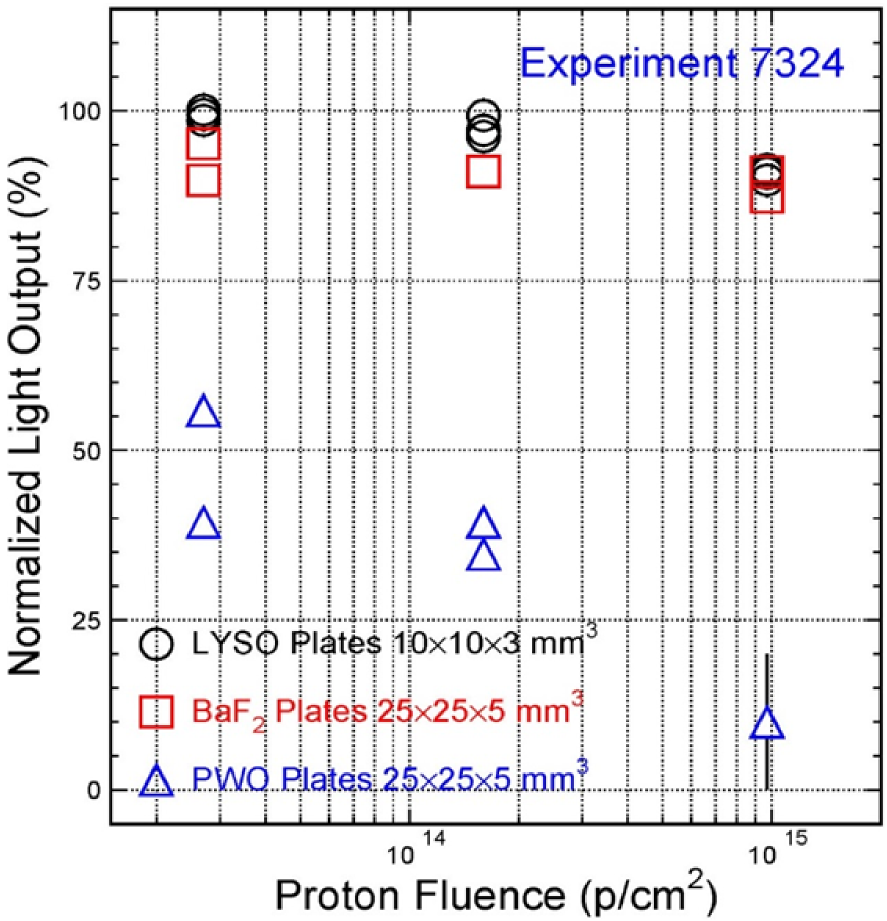


Remaining light output after 120 Mrad: 40%/45% for the fast/slow component

RIAC & LO Vs. Proton Fluence

Excellent radiation hardness of LYSO and BaF_2 up to 10^{15} p/cm^2

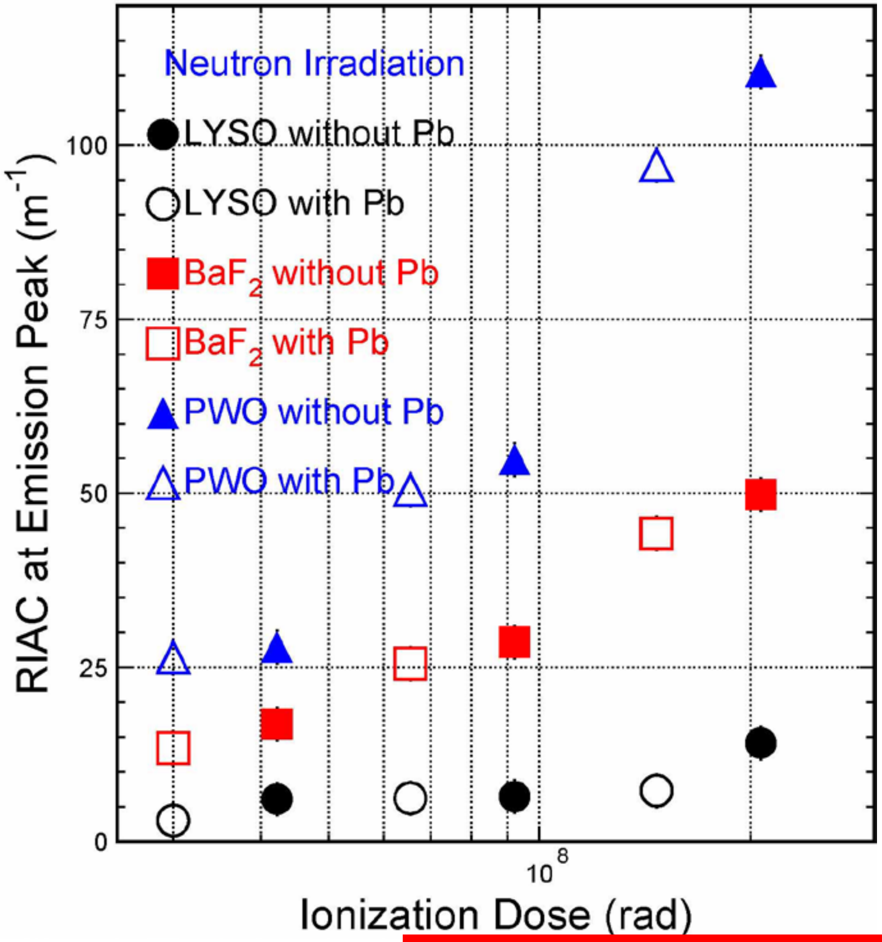


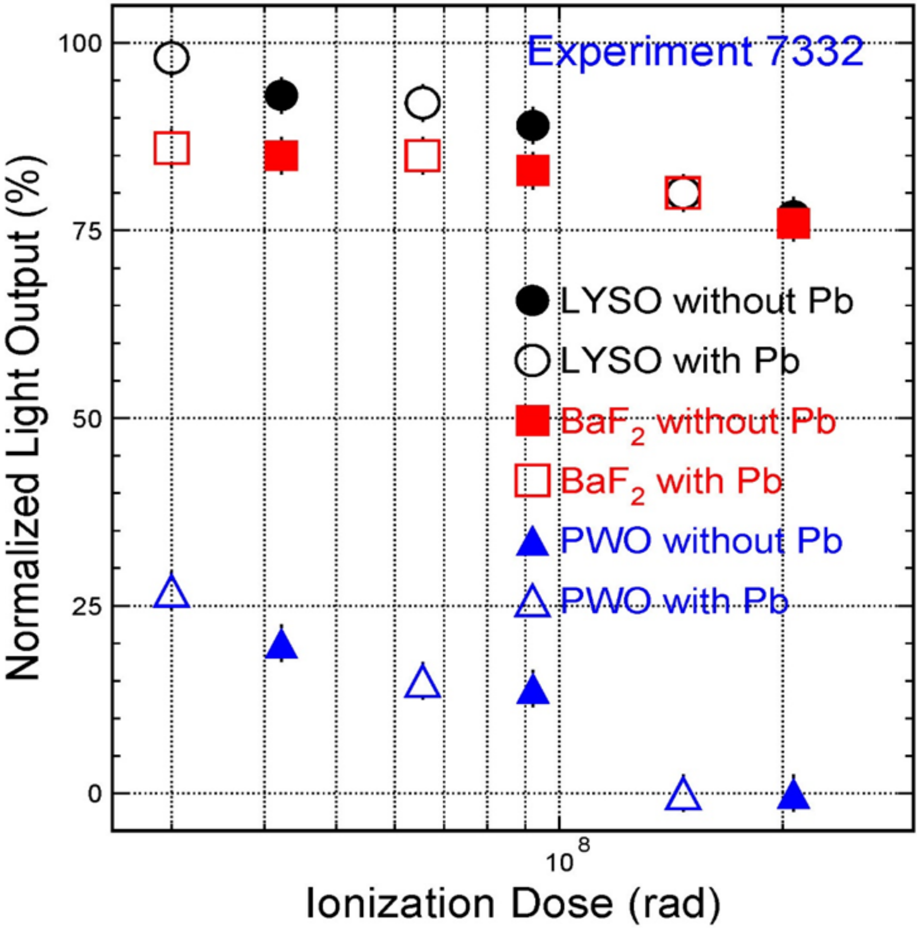


See L. Zhang, paper P2-34 Wednesday morning

RIAC & LO Vs. Ionization Dose

Excellent radiation hardness of LYSO and BaF_2 up to 2 x 10^{15} n/cm^2
No neutron specific damage in LYSO, BaF_2 & PWO

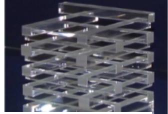




See L. Zhang, paper P2-35 Wednesday morning

Summary

- 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.
- 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 from 1/5 to 5/1 while maintaining the intensity of the sub-ns fast component. The slow contamination at this level is already less than commercially available undoped CsI, so is promising for Mu2e-II and GHz X-ray imaging. See talk Wednesday morning.
- Results of the experiments 6991 and 7332 at LANL show fast neutrons up to 2 x 10^{15} n/cm^2 do not damage LYSO, BaF_2 and PWO crystals, confirming early observation at Saclay reactor.
- Our plan is to investigate LYSO:Ce,Ca crystals, LuAG:Ce and LuAG:Pr ceramics, and radiation hardness of Y:BaF_2 crystals. Will also pay an attention to photodetector with DUV response: LAPPD, Si or diamond based solid state detectors.



GHz Hard X-Ray Imager

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: Talk Wednesday morning

Diamond Photodetector

In addition to SiPM with VUV response

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

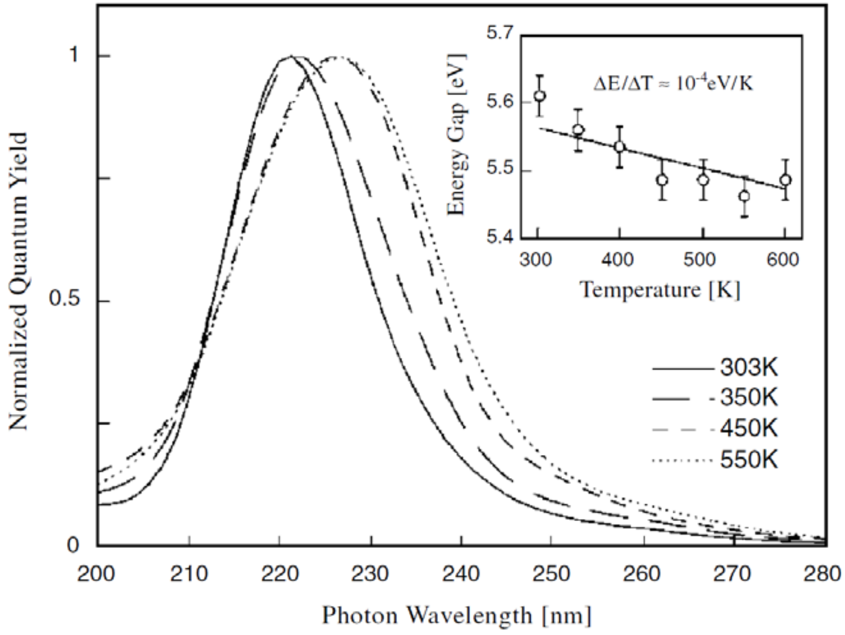


Figure 6. Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

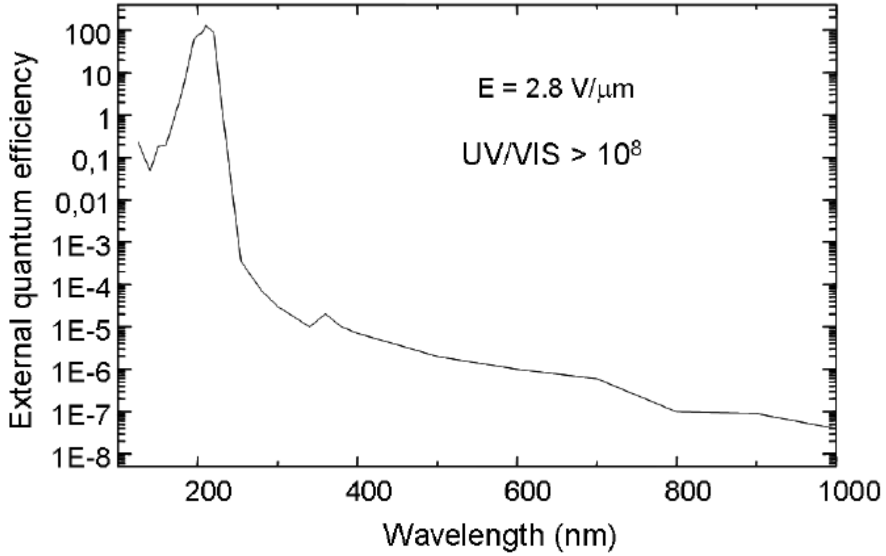


Fig. 4. External quantum efficiency extended to visible and near infrared wavelength regions. The

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