Recent Progress on Fast Inorganic 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

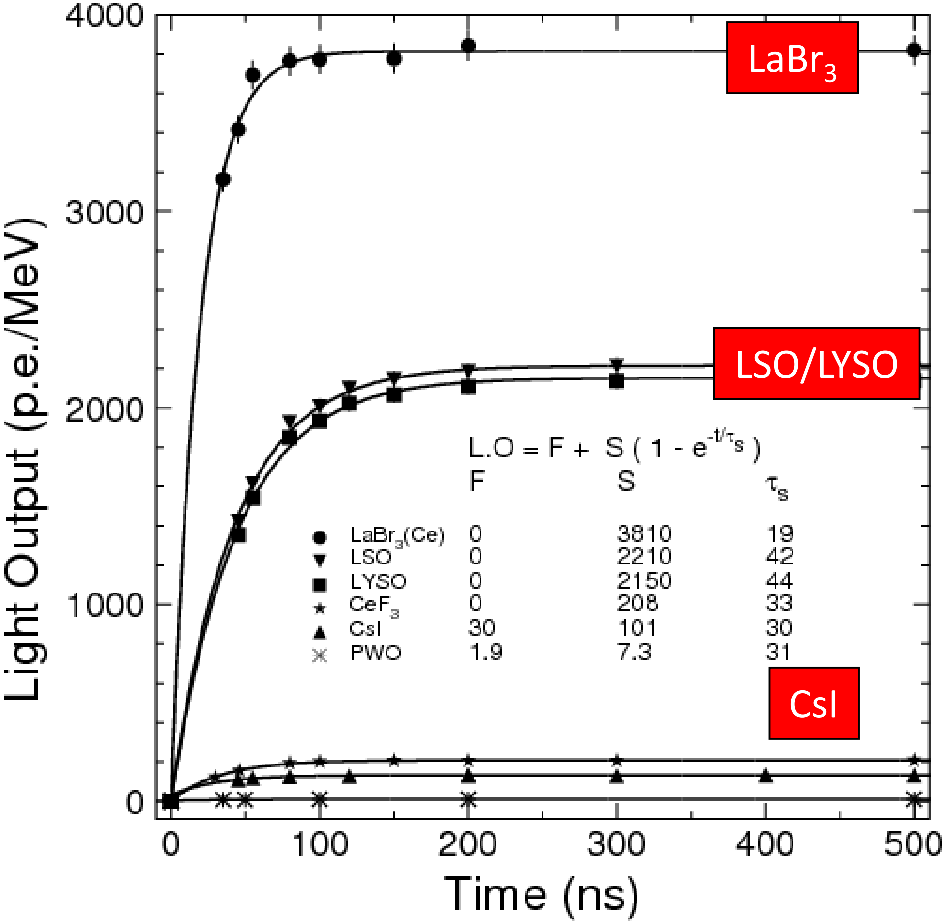
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm³)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (ºC)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction 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 0.9	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.

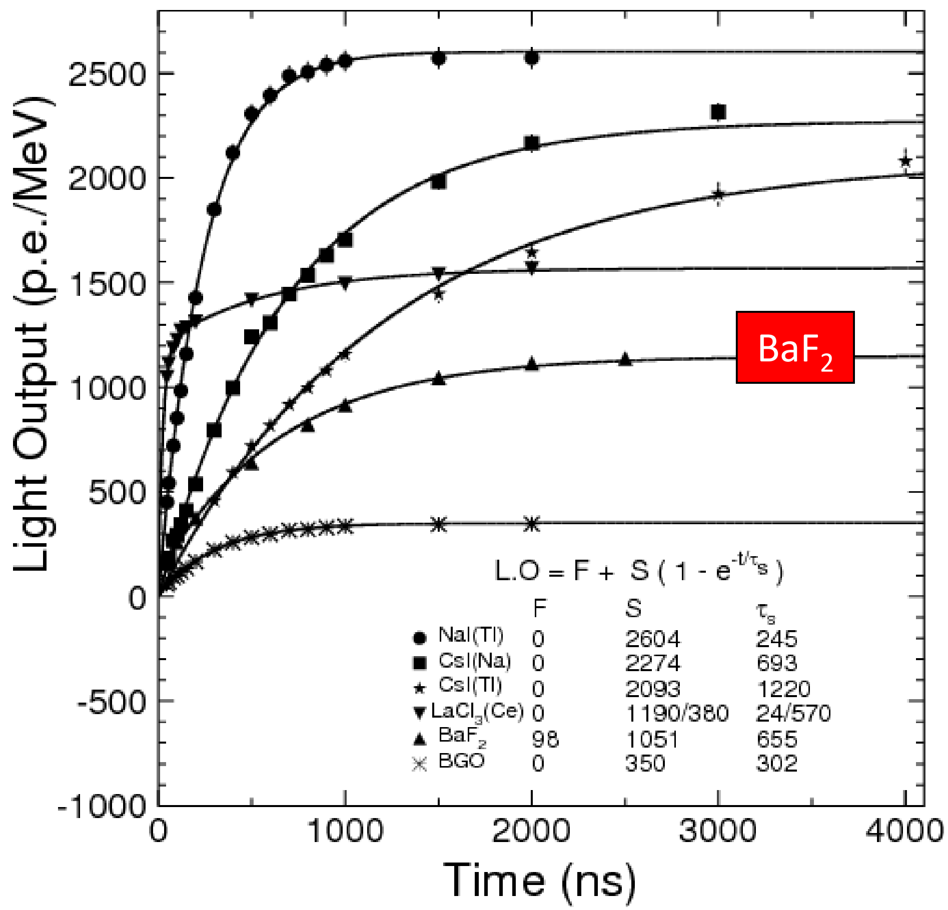
Light Output & Decay Kinetics

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

Fast Crystal Scintillators

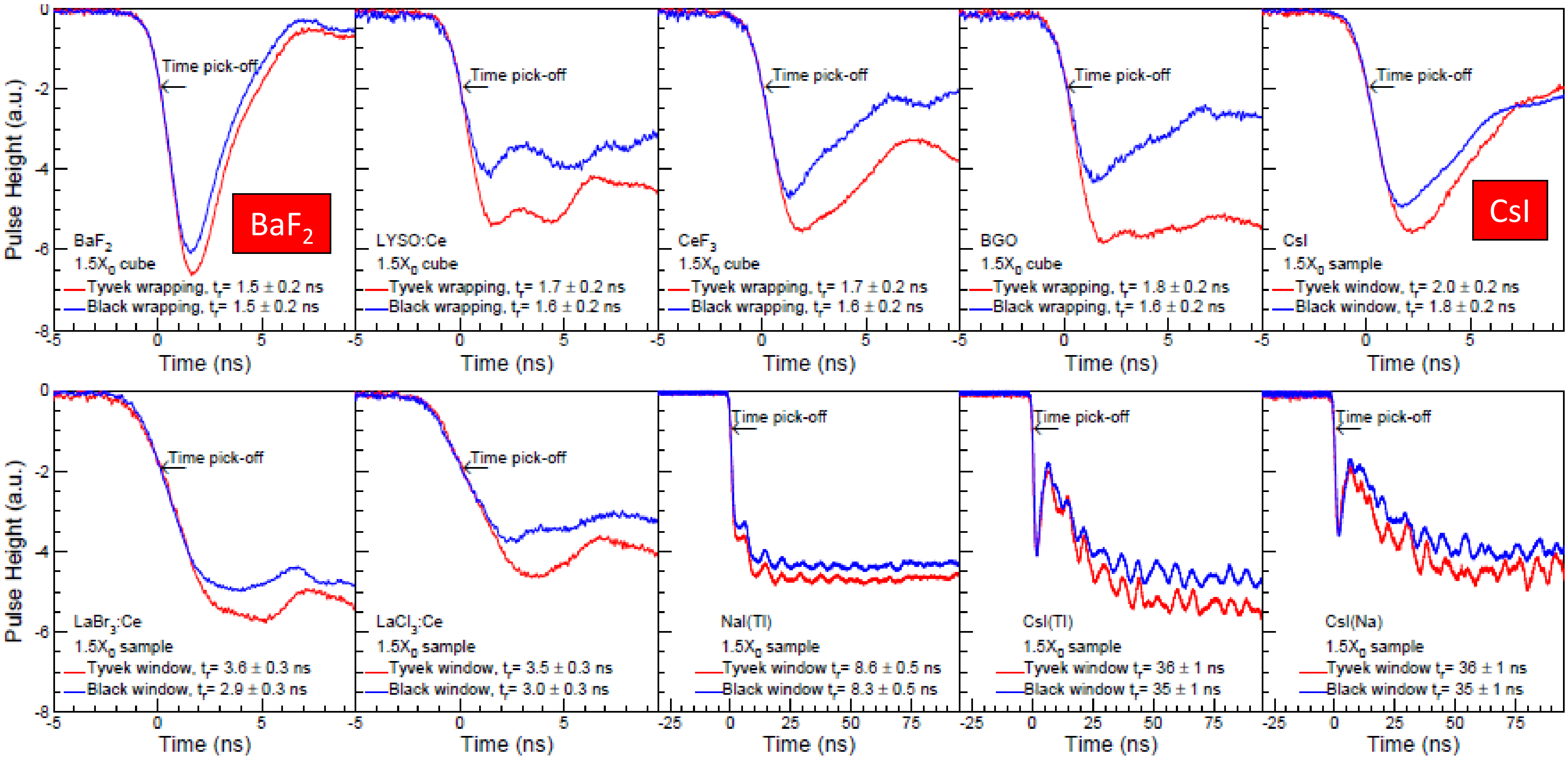


Slow Crystal Scintillators



Fast Signals 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 further reduced by 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/cm³)	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

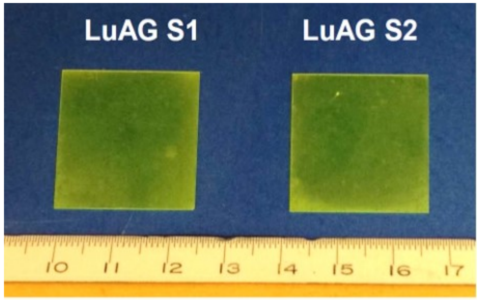
[4] Lucchini, et al., *NIM A* 2016, 816: 176-183

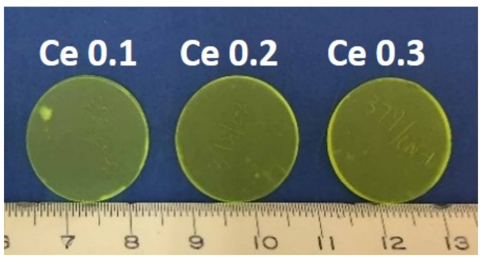
[5] Meng, et al., *Mat. Sci. Eng. B-Solid* 2015, 193: 20-26

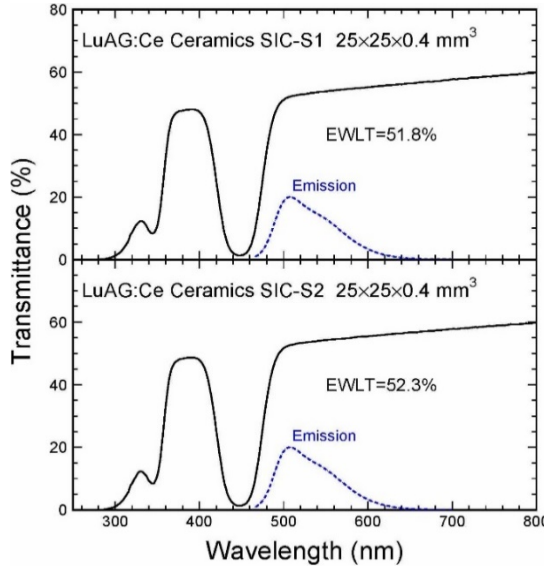
[6] Diehl, et al., *J. Phys. Conf. Ser* 2015, 587: 012044

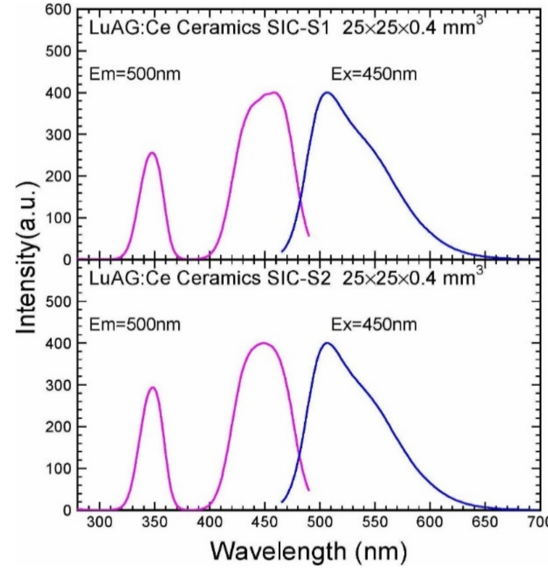
[7] Pustovarov, et al., Tech. Phys. Lett. 2012, 784-788

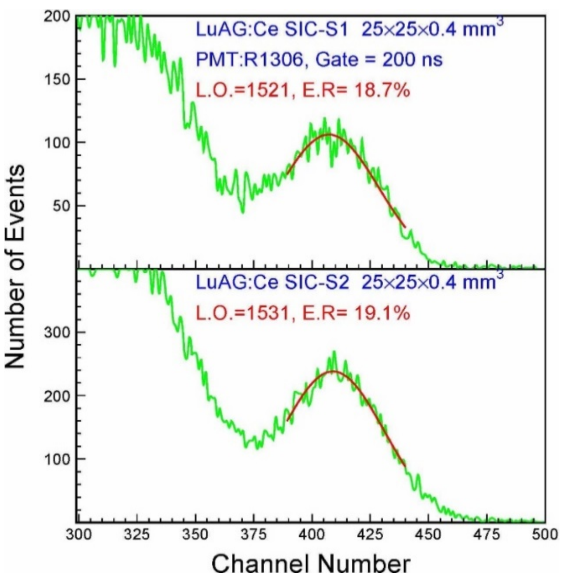
LuAG:Ce Ceramic Samples

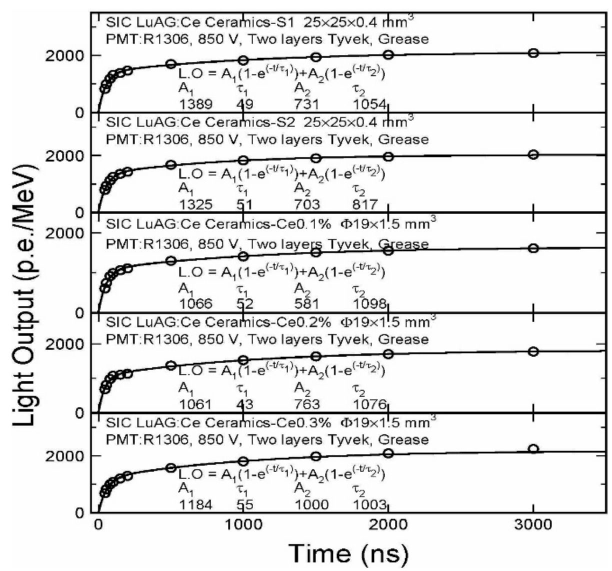


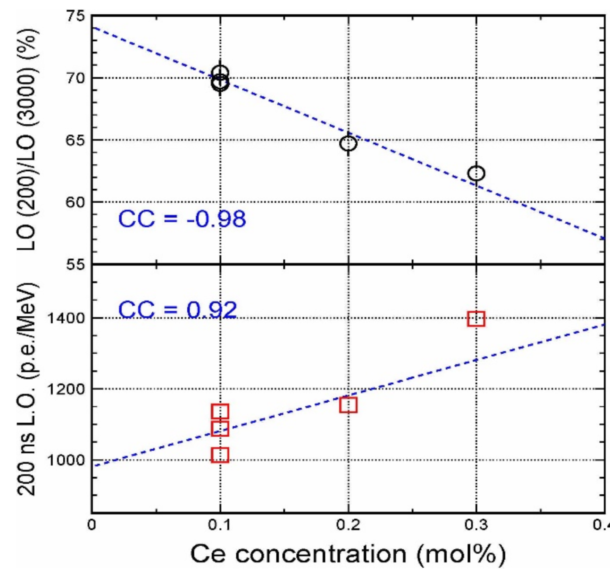






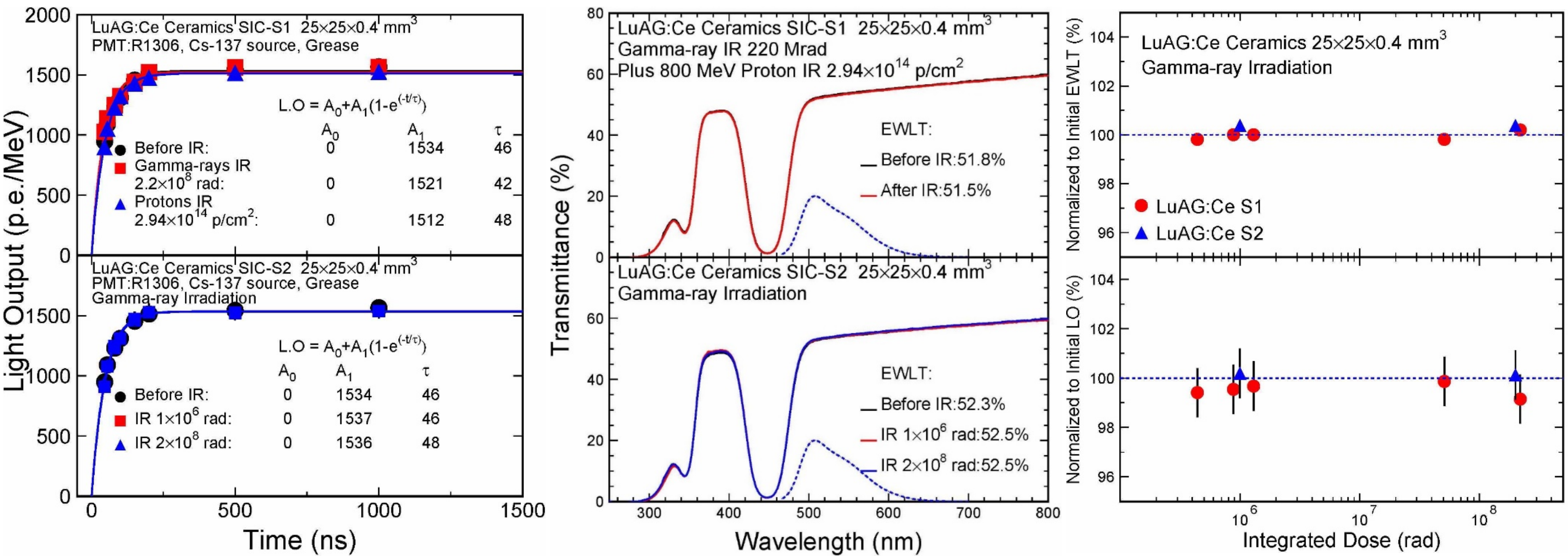






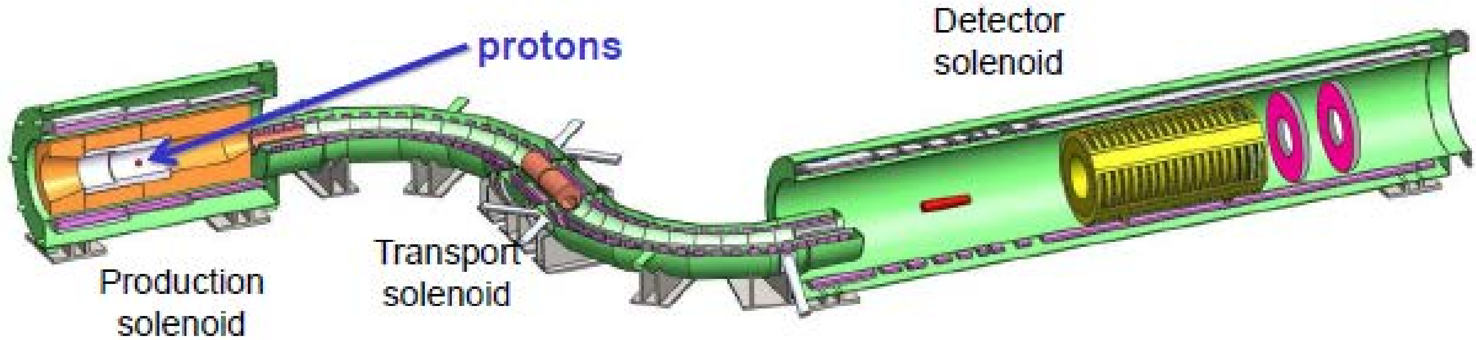
Excellent Radiation Hardness

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



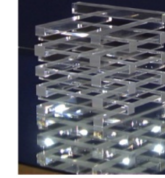
Very promising for a scintillating ceramics based calorimeter
Will be presented in NSS2017 at Atlanta

Mu2e Specifications for Undoped CsI



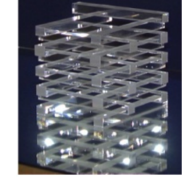
- Crystal lateral dimension: ±100 μ, length: ±100 μ.
- Scintillation properties at seven points along the crystal wrapped by two layers of Tyvek paper of 150 μm for alternative end coupled to a bi-alkali PMT with an air gap. Light output and FWHM resolution are the average of seven points with 200 ns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

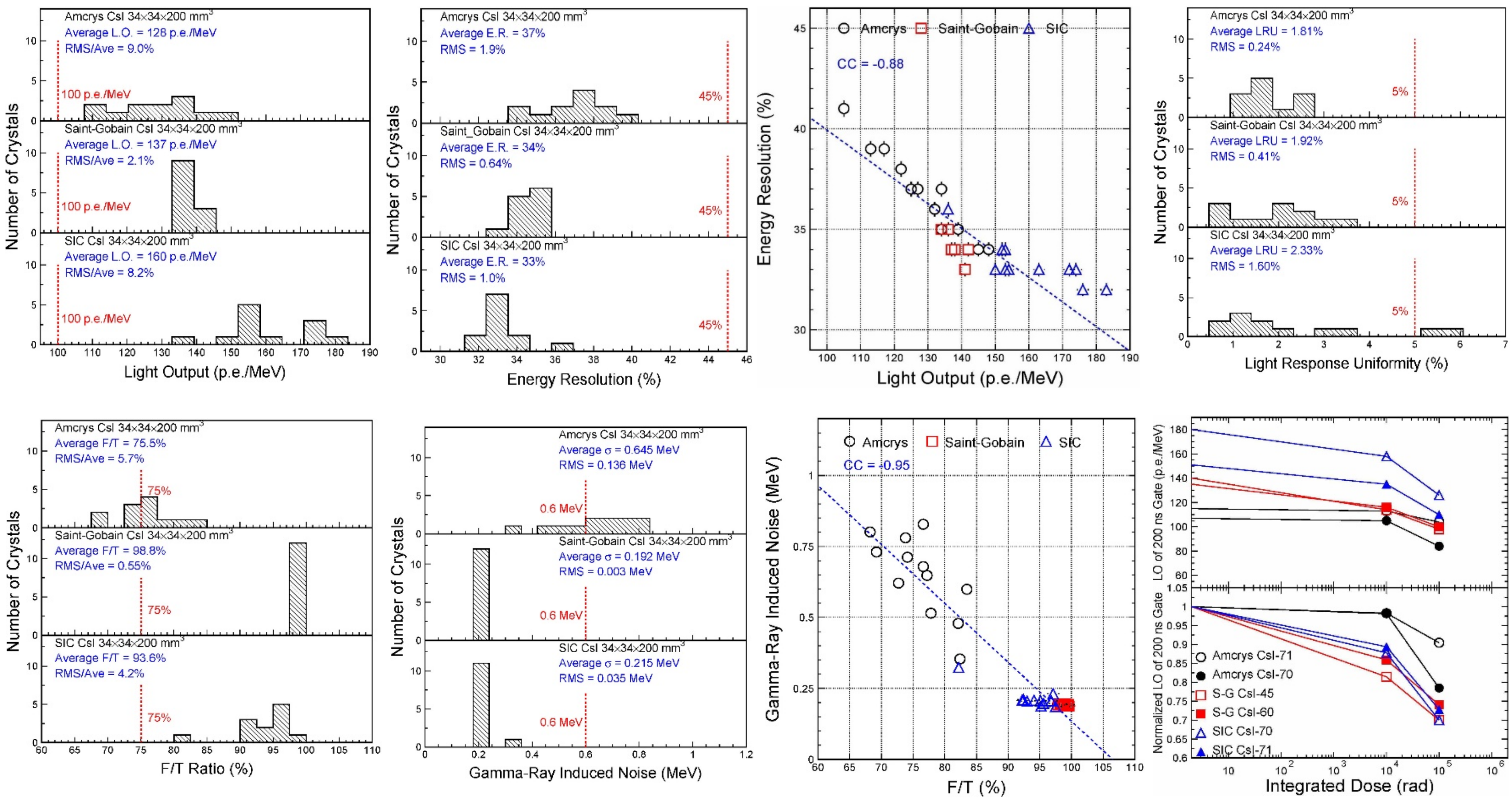
Mu2e Preproduction CsI



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

Quality of Pre-Production CsI





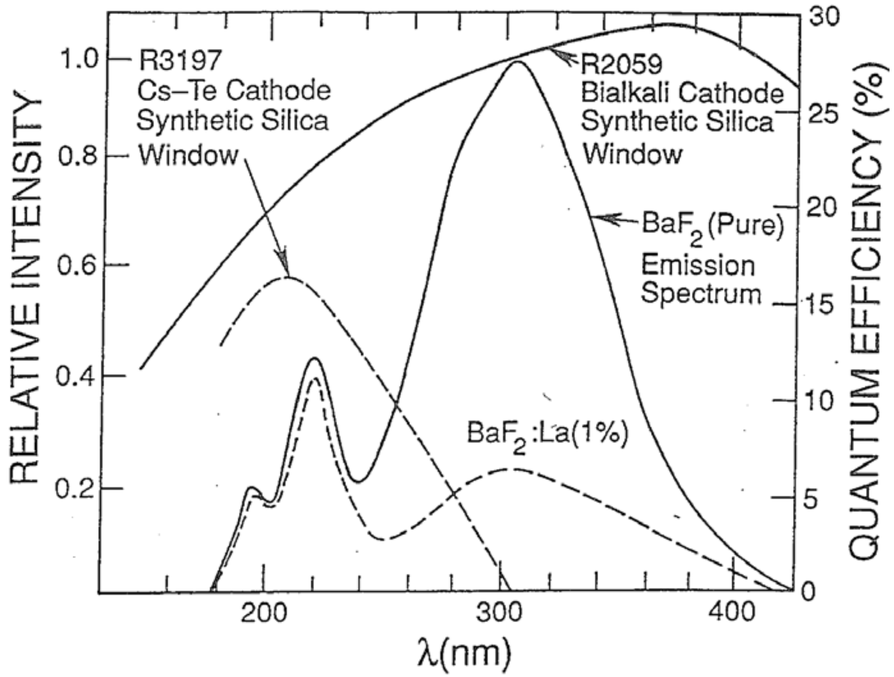
Most preproduction crystals satisfy specifications, except a few crystals from SICCAS fail the LRU spec and about half Amcrys crystals fail the F/T ratio and RIN

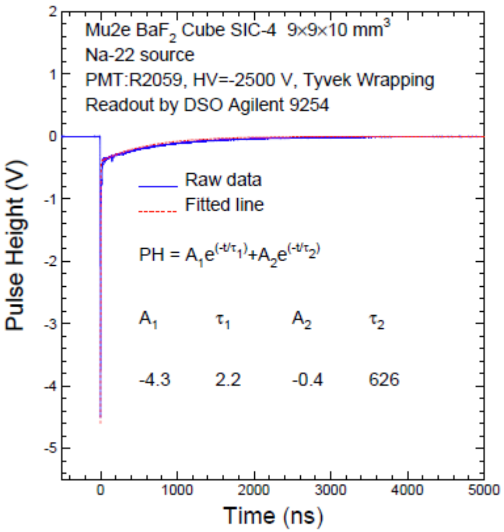
Fast and Slow Light from BaF_2

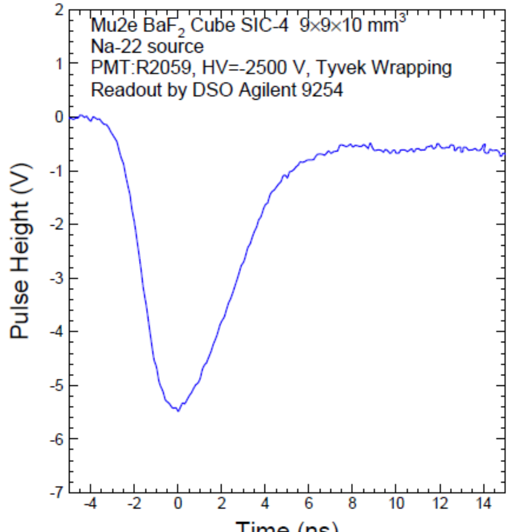
A radiation level exceeding 100 krad is expected at the proposed Mu2e-II, so BaF_2 is being considered.

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

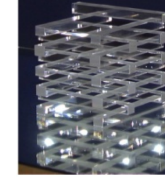
Spectroscopic selection of fast component may be realized by solar blind photocathode and/or selective doping.





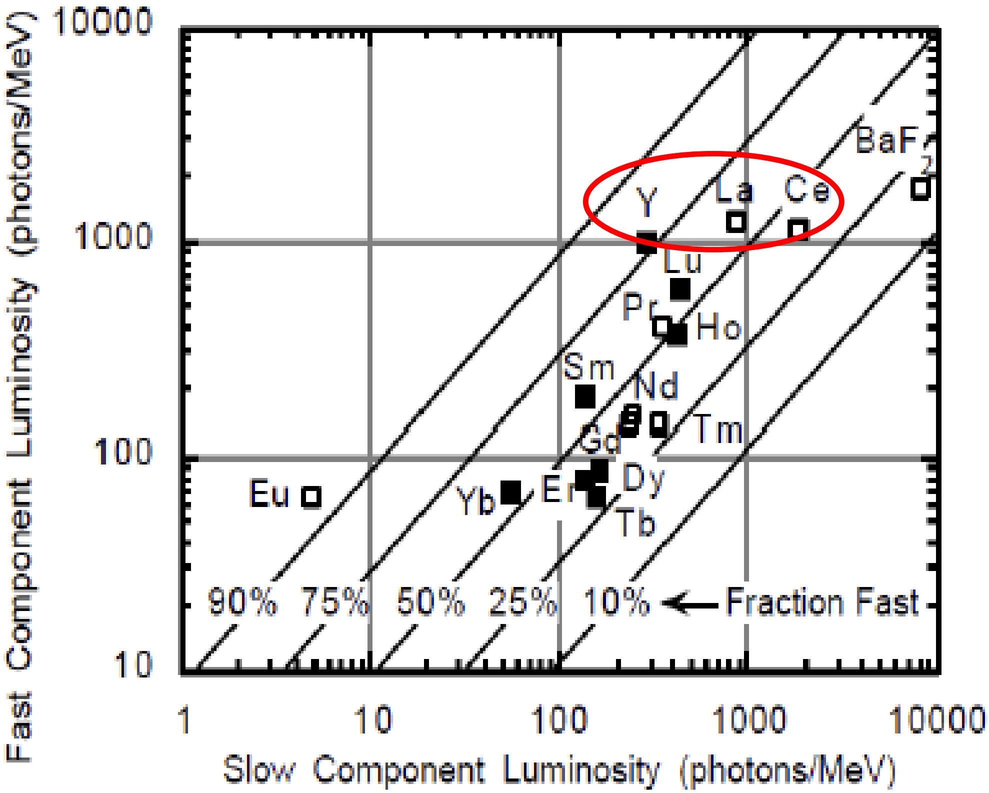


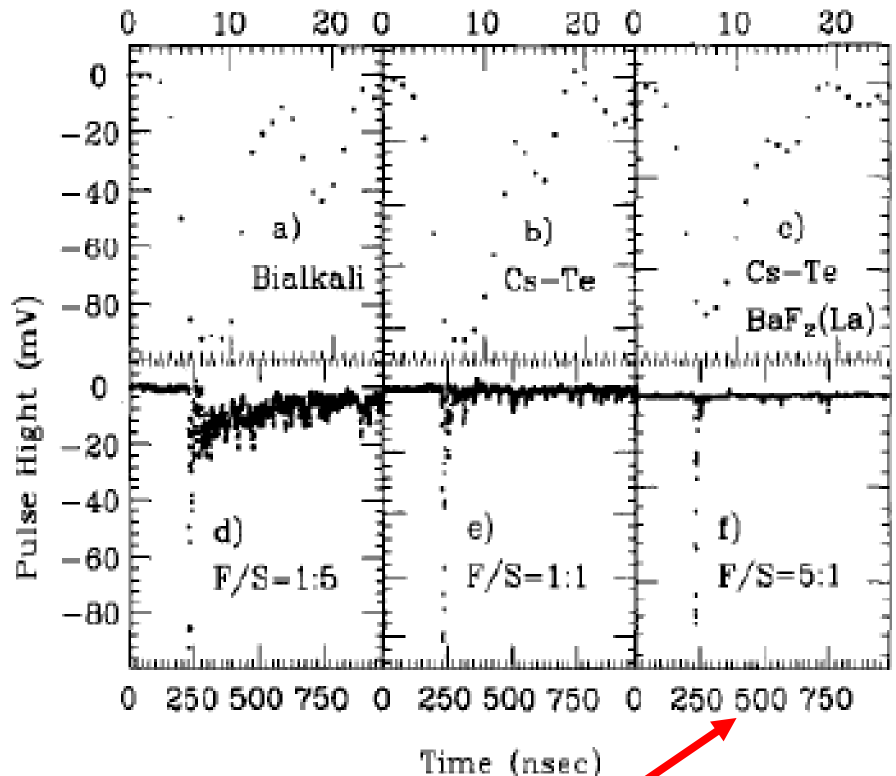
Slow Suppression: Doping & Readout



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.

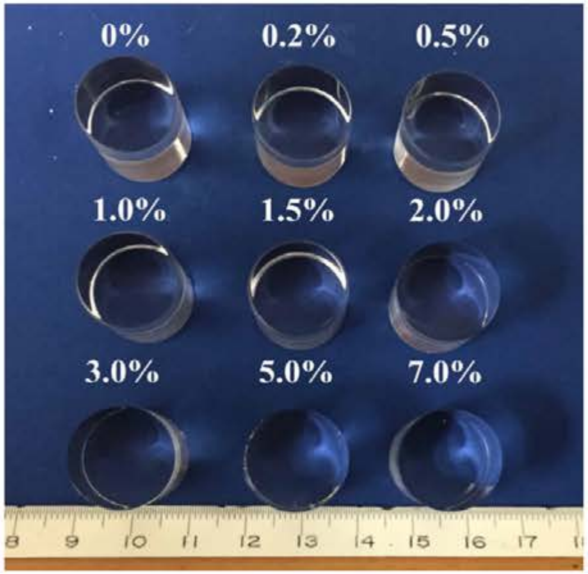


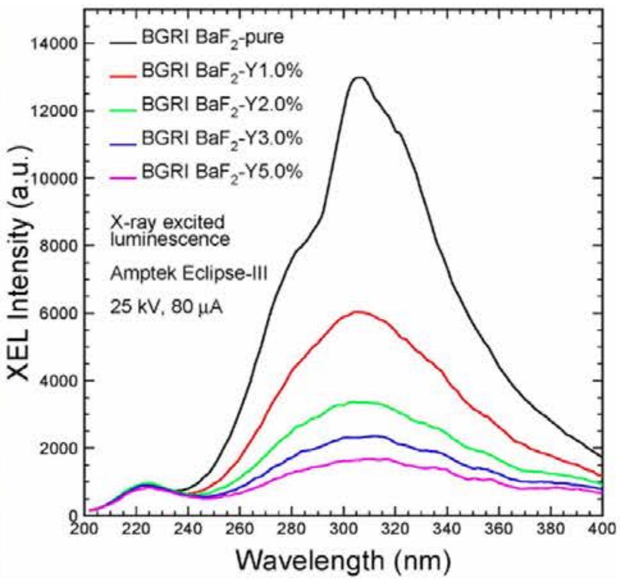


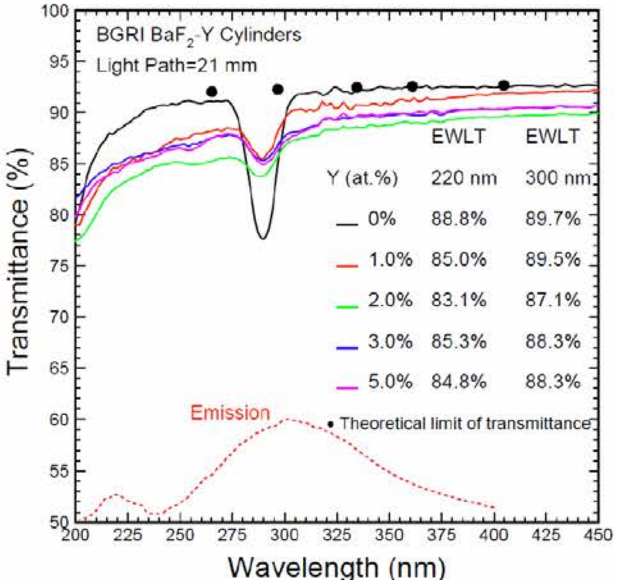
Solar-blind cathode (Cs-Te) + La doping achieved F/S = 5/1

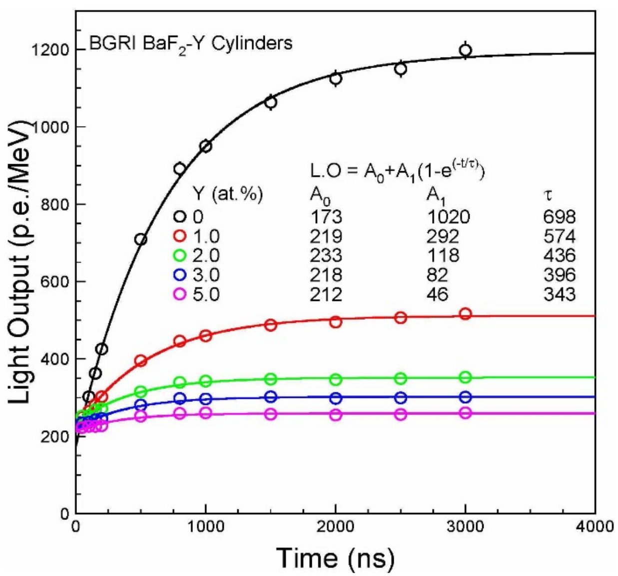
Yttrium Doped BaF_2 for Mu2e-II

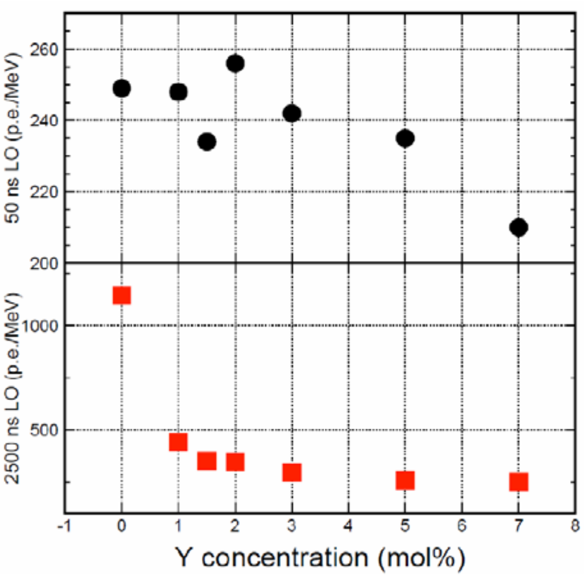
F/S ratio from 1/5 to 5/1 , presented in TIPP 2017 Beijing

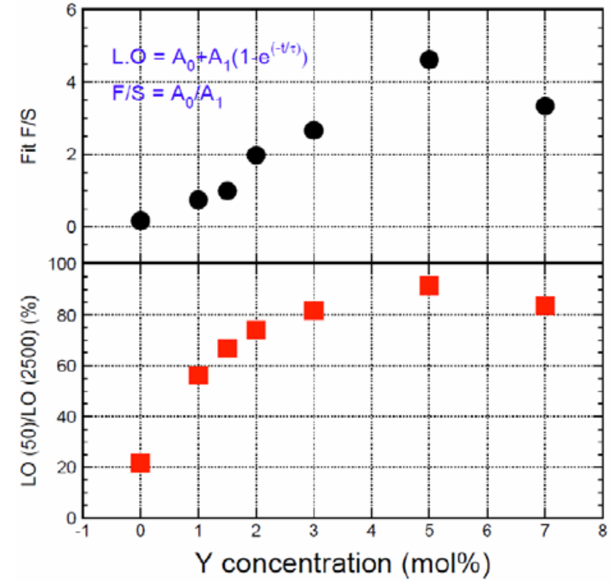






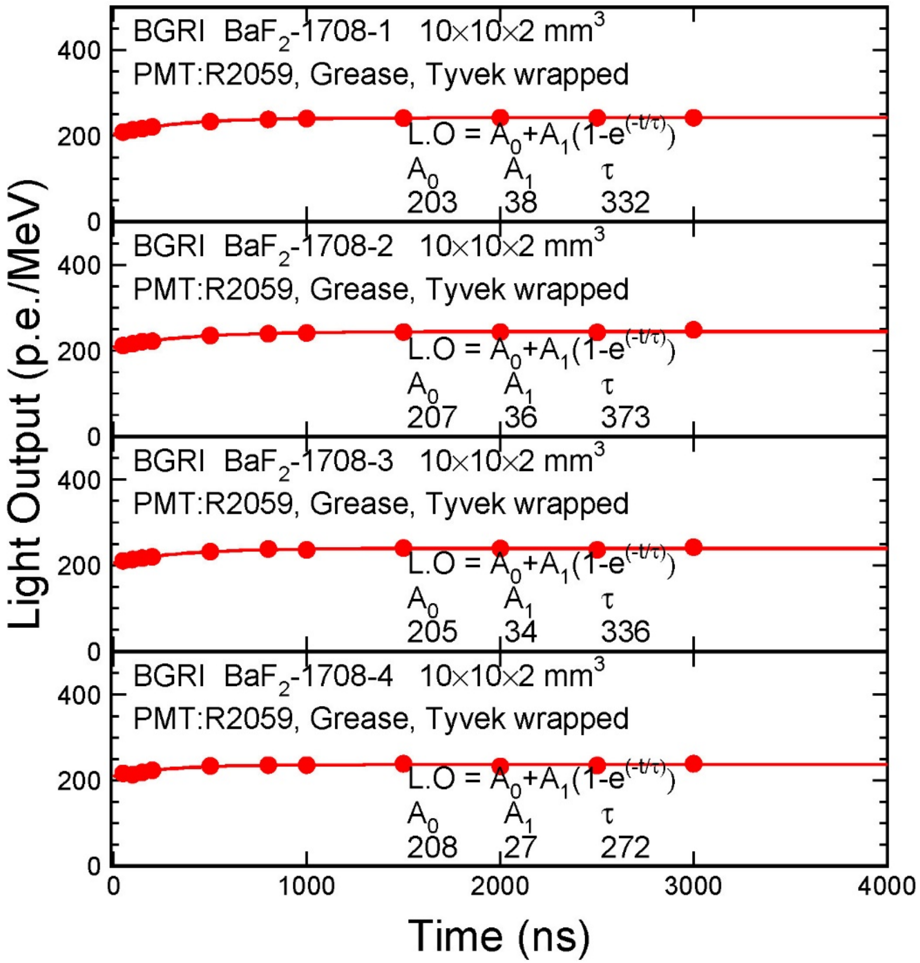


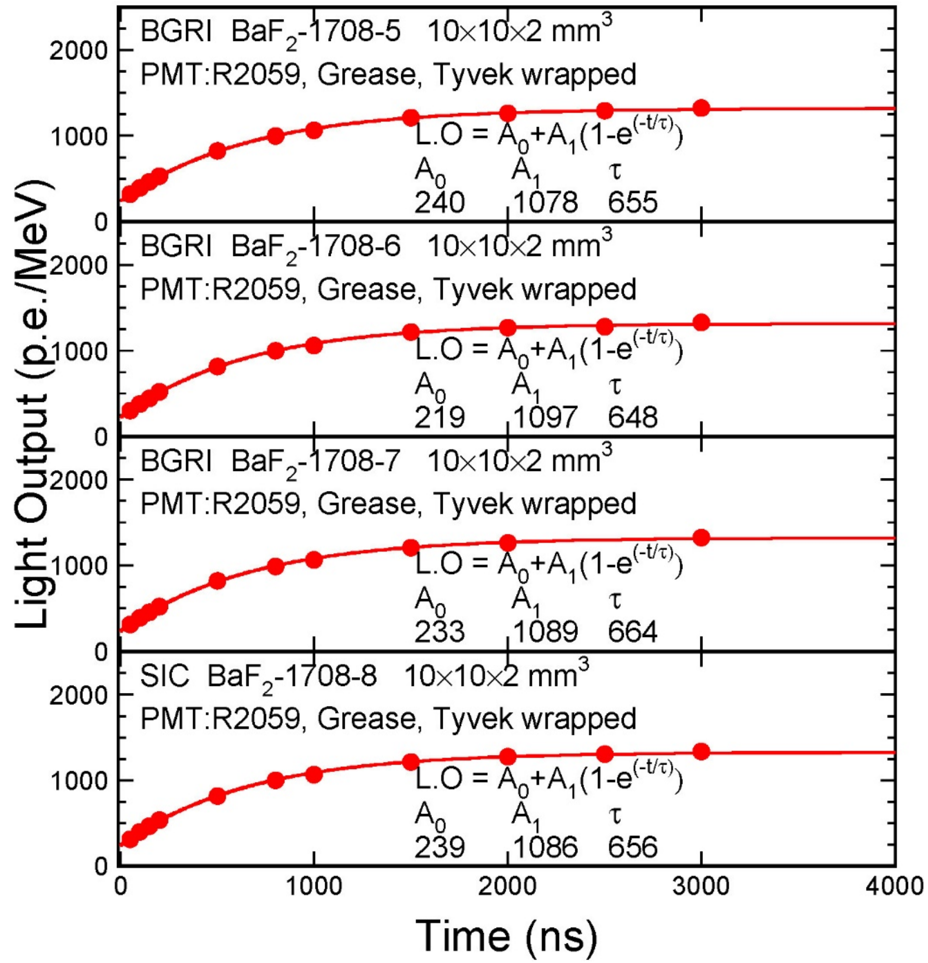




BGRI Y:BaF_2 and BaF_2

F/S ratio increased from 0.21 to 6 .2



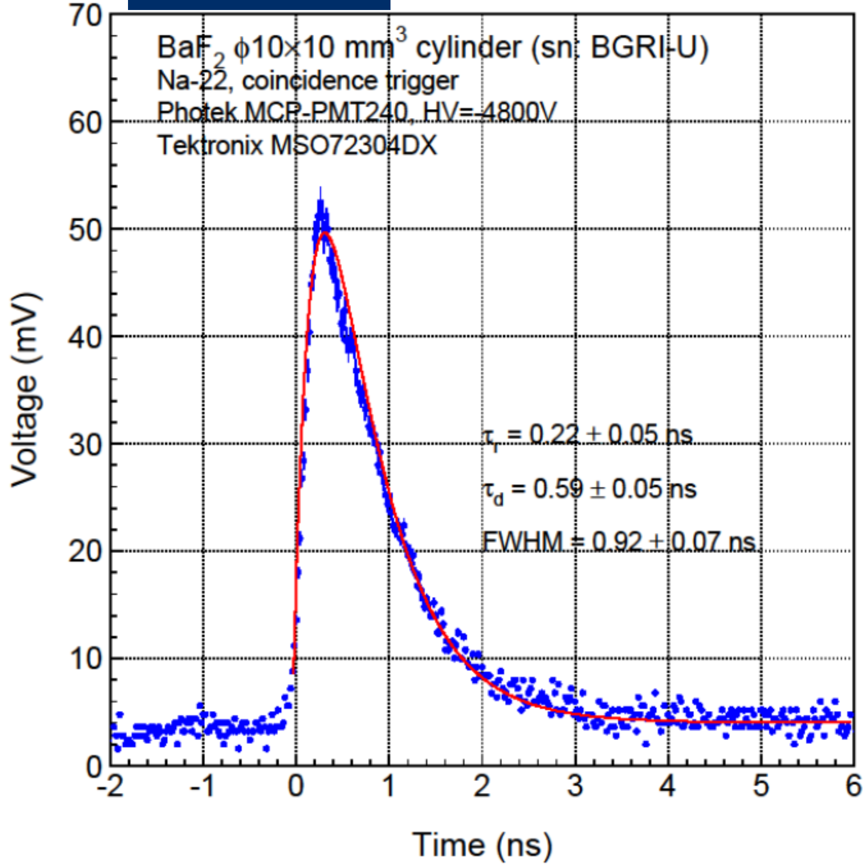


Being irradiation up to 200 Mrad and $2x10^{15}$ n/cm^2 at the East Port of LANSCE

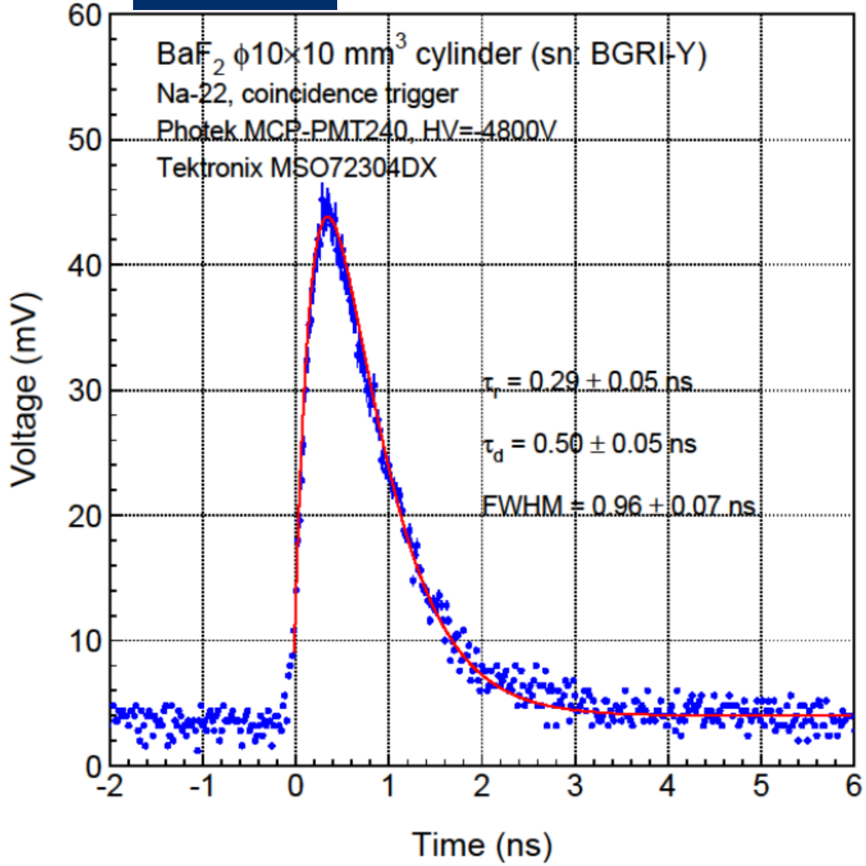
Pulse Shape: BaF_2 Cylinders

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

Non-doped

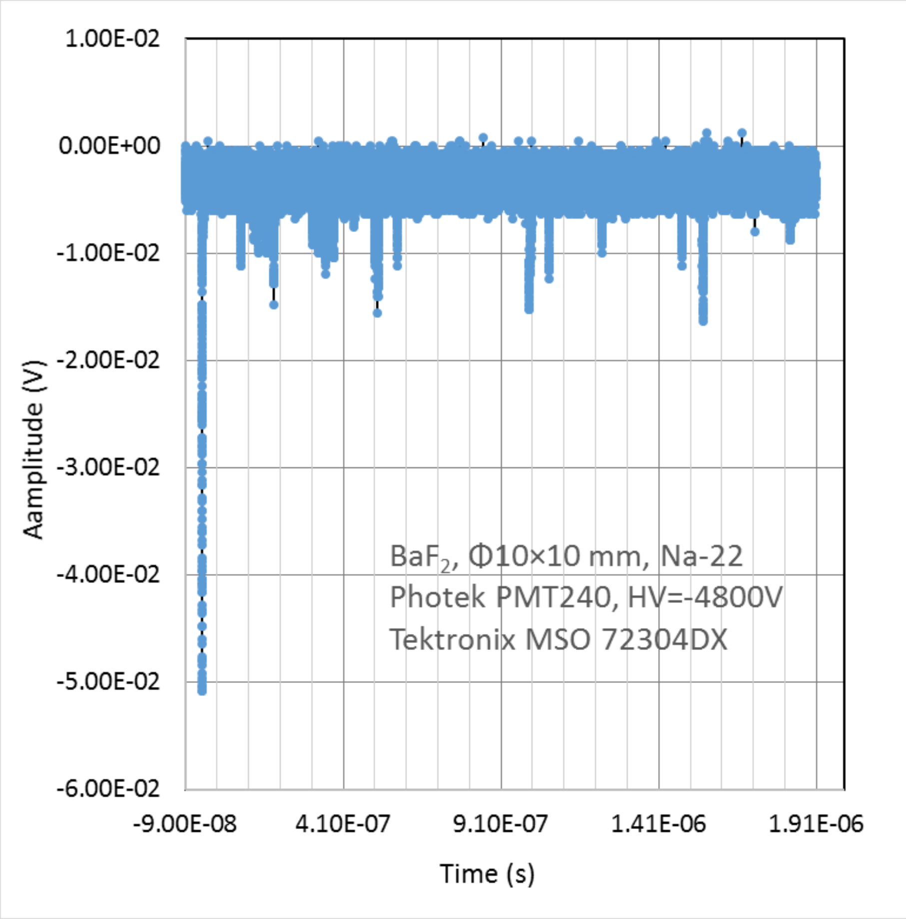


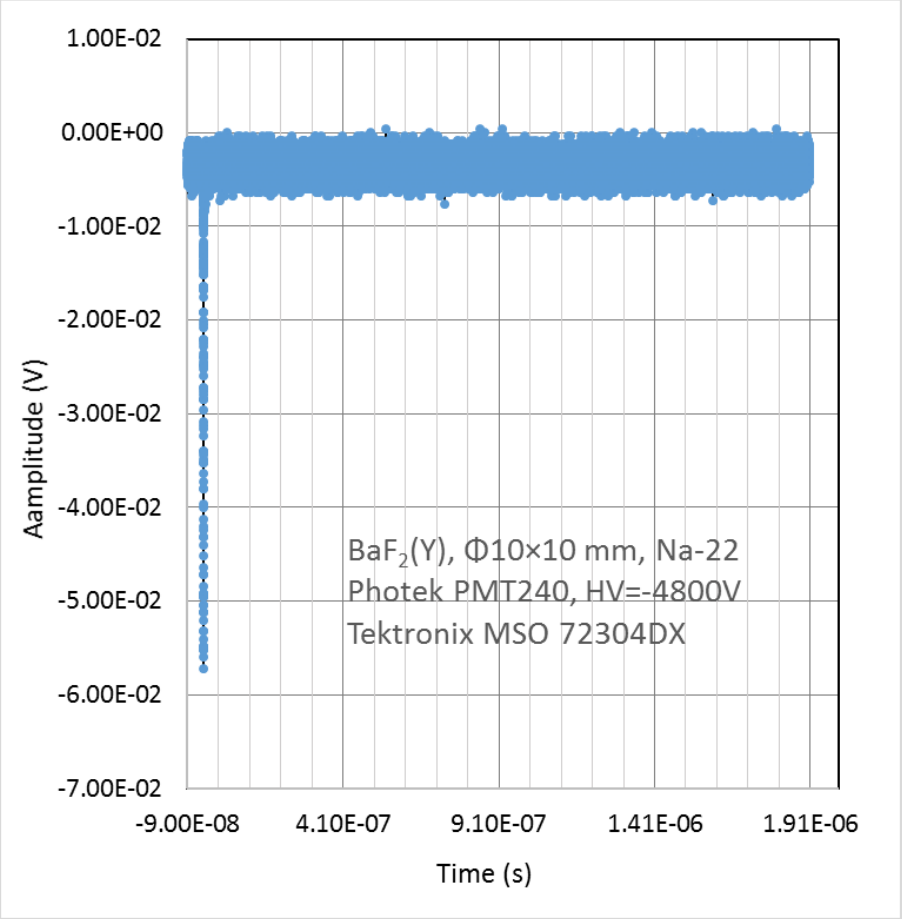
Y-doped



Tail Reduced in BGRI BaF_2:Y

Slow component tail observed in 2 μs in BaF2, not BaF2:Y





Summary of BaF_2 Cylinders

Consistent pulse shape observed between PbF_2 and BaF_2, indicating that the decay time of the fast component in BaF_2 less than 0.6 ns, faster than literature

Samples	Dimensions	Excitation	Rise time (ns)	Decay time (ns)	FWHM (ns)
MCP-PMT240*	Φ40 mm	Laser pulse	0.185	N/A	1.36
PbF	50×50×50 mm^3	Cosmic-ray	0.18±0.05	0.61±0.05	0.88±0.07
SIC-U	Φ10×10 mm^3	Cosmic-ray	0.26±0.05	0.52±0.05	0.92±0.07
SIC-Y	Φ10×10 mm^3	Cosmic-ray	0.26±0.05	0.57±0.05	0.98±0.07
BGRI-U	Φ10×10 mm^3	Na-22 (511KeV)	0.22±0.05	0.59±0.05	0.92±0.07
BGRI-Y	Φ10×10 mm^3	Na-22 (511KeV)	0.29±0.05	0.50±0.05	0.96±0.07

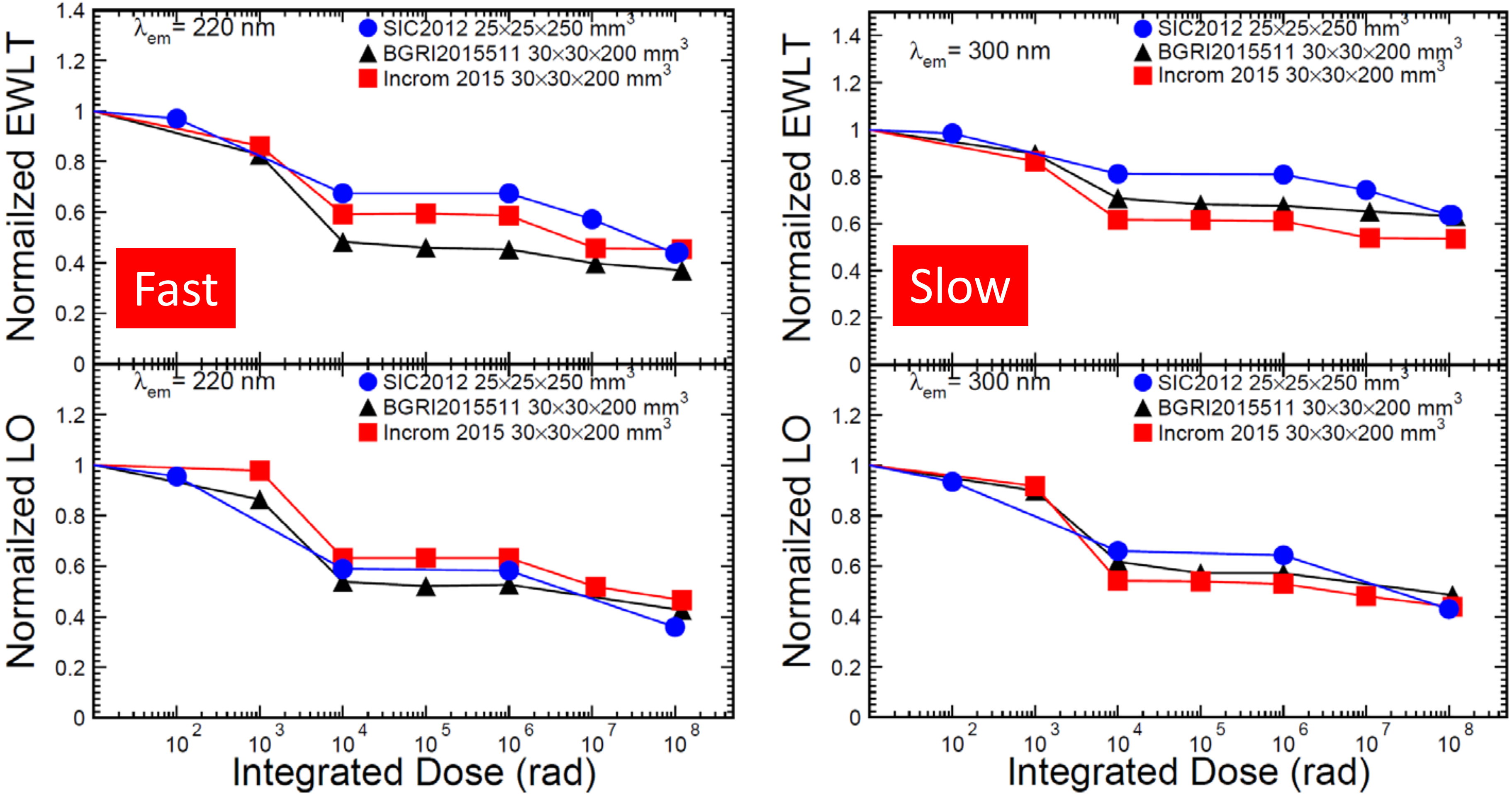
*From test report of the Photek PMT240 MCPT.

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

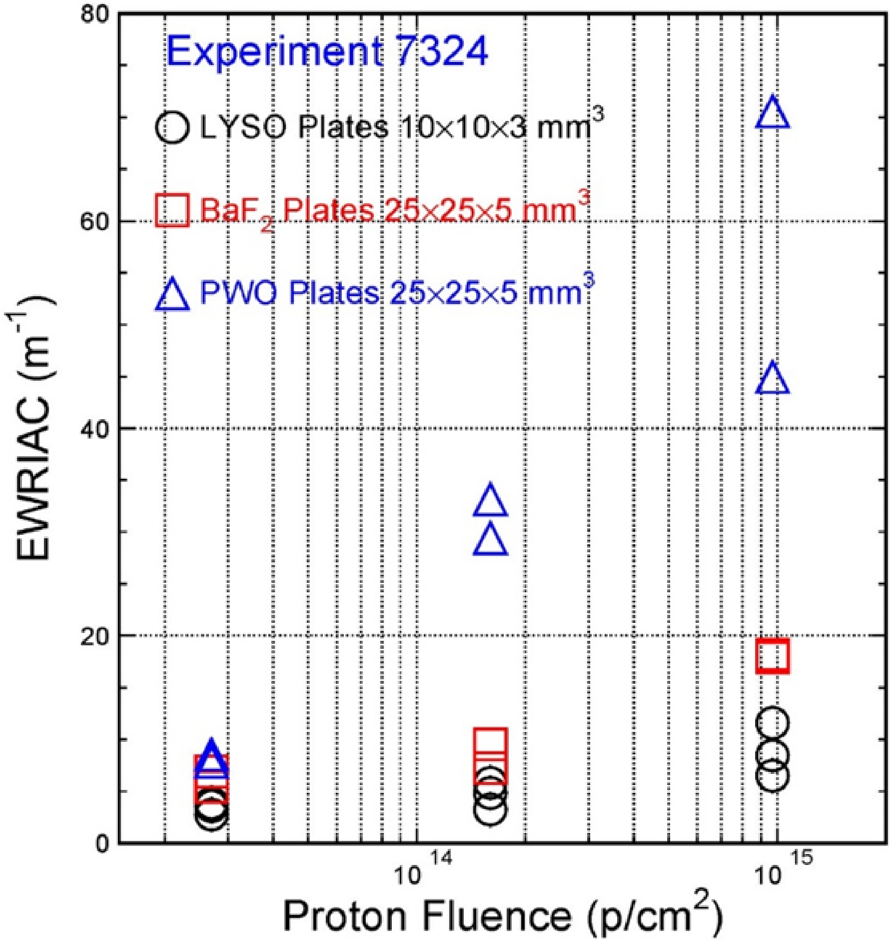
Consistent damage in crystals from three vendors

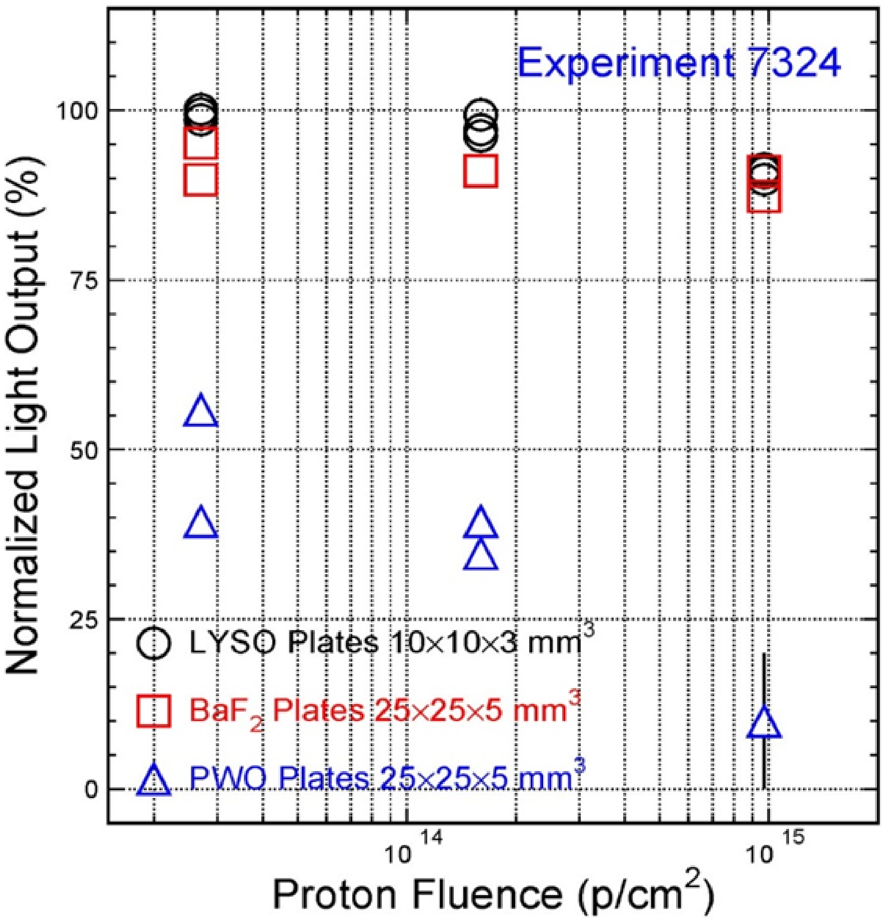


Remaining light output after 120 Mrad: 40%/45% for the fast/slow component

RIAC & LO Vs. Proton Fluence

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

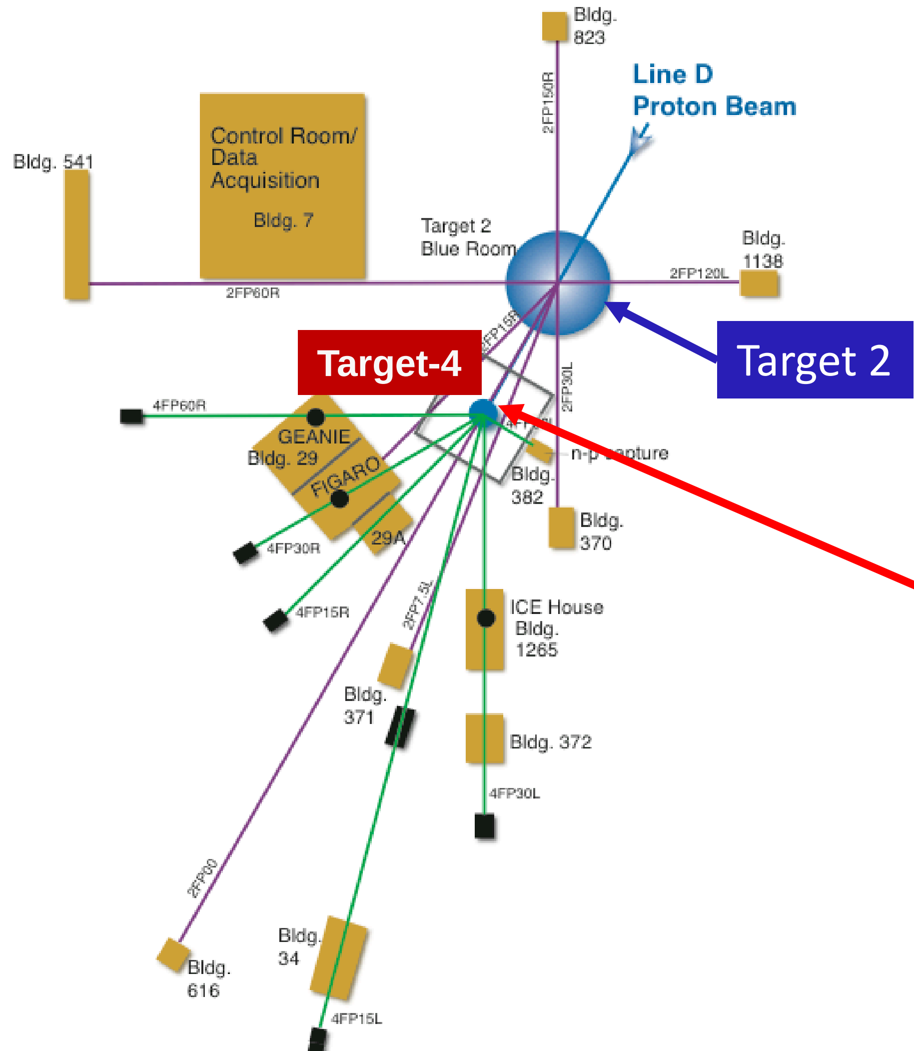




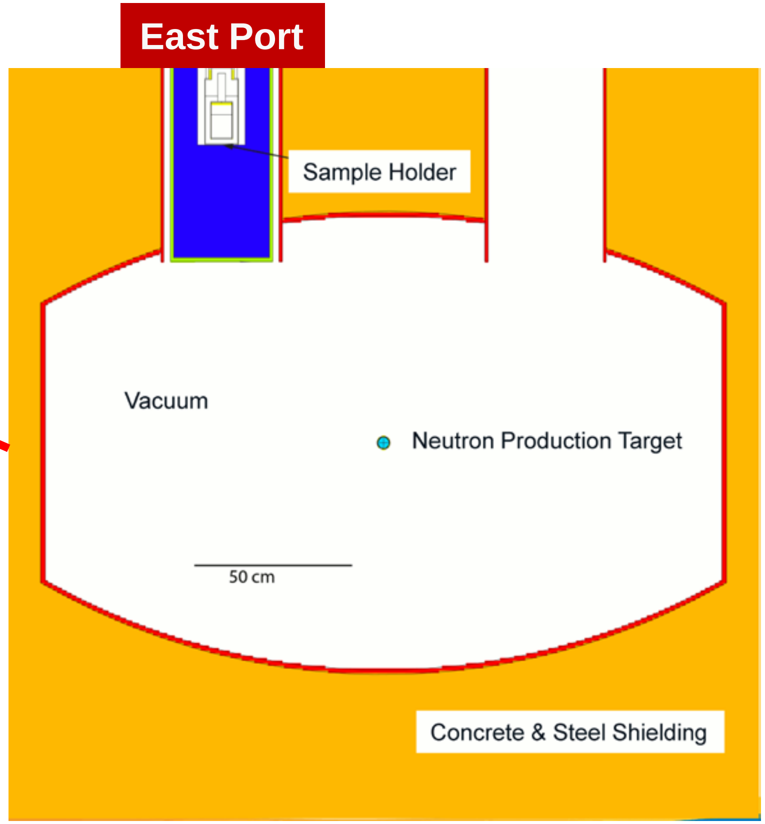
Presented by L.Y. Zhang in SCINT 2017

Neutron Irradiation Test at LANL

Los Alamos Neutron Science Center (LANSCE)

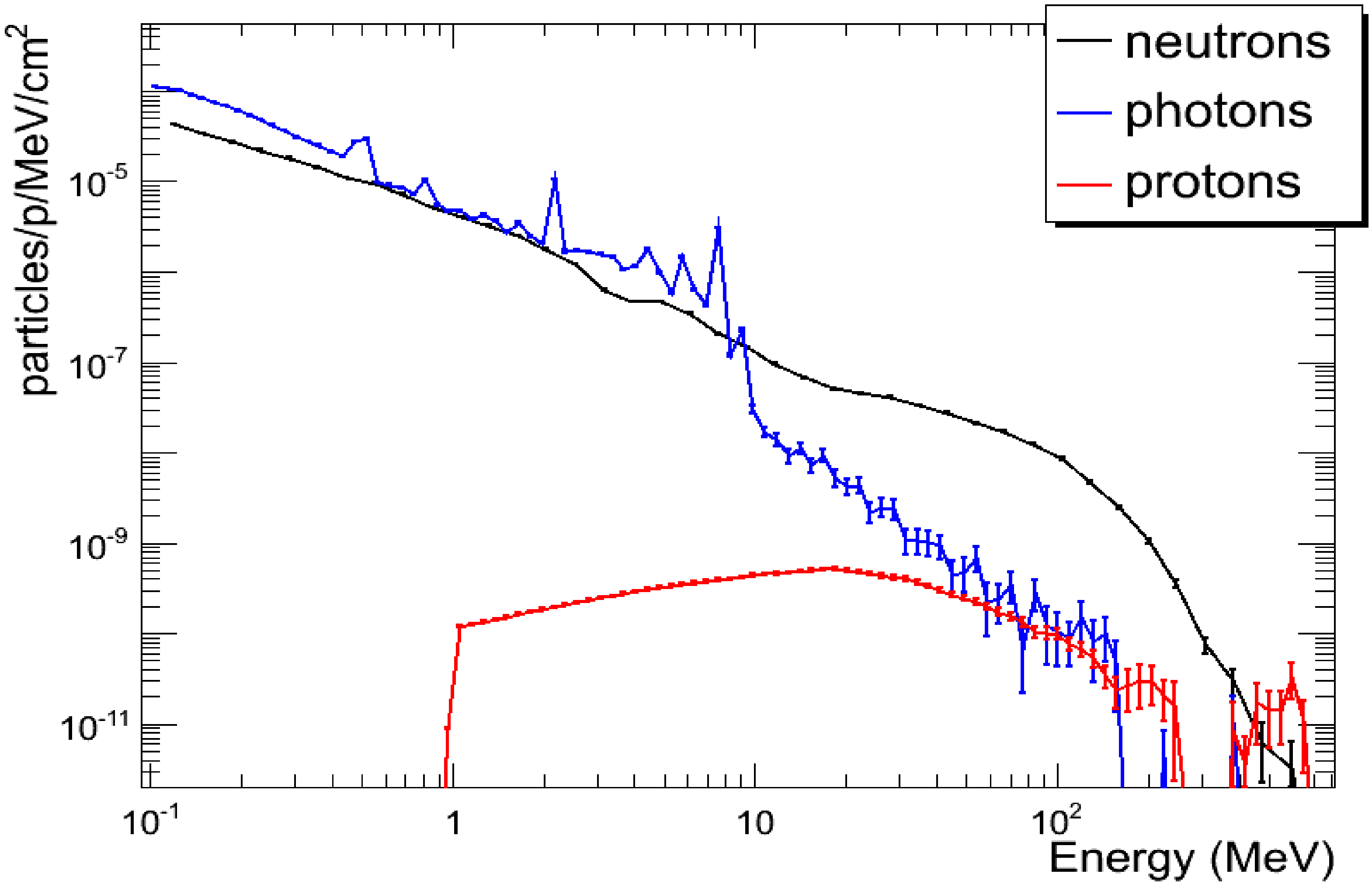


Samples are placed at the Target-4 East Port, about 1.2 m away from the neutron production target.



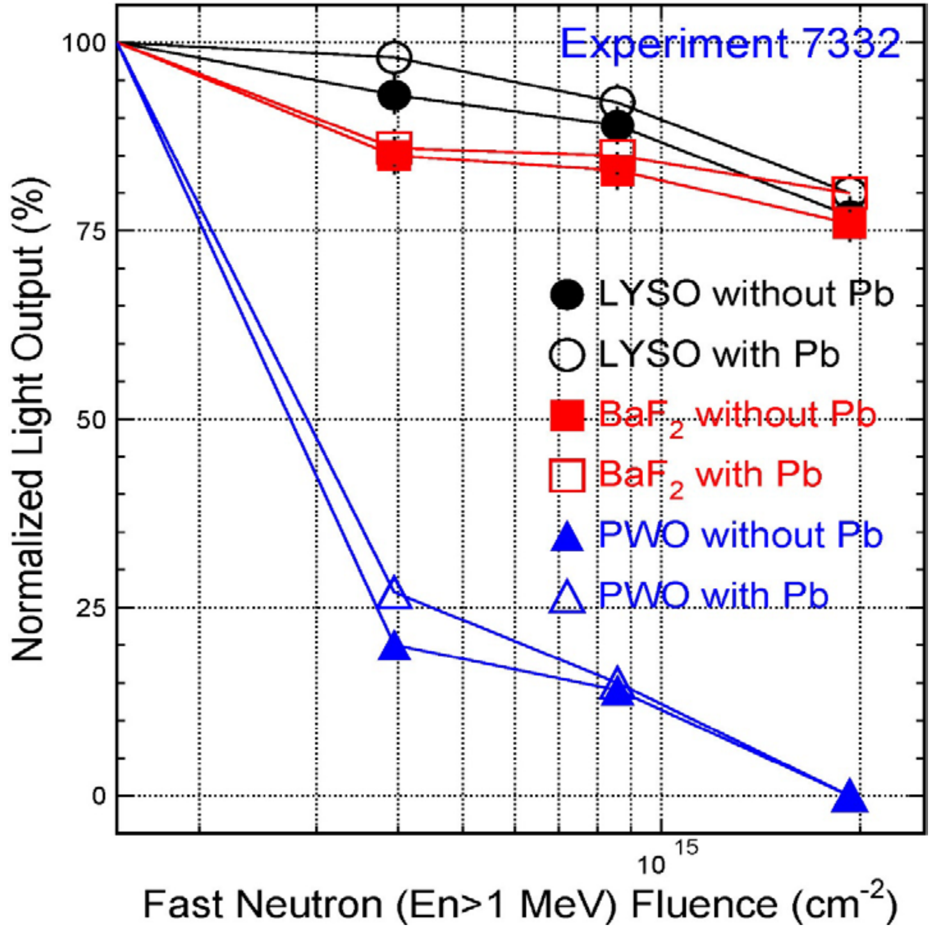
Neutrons/Photons/Protons Fluxes

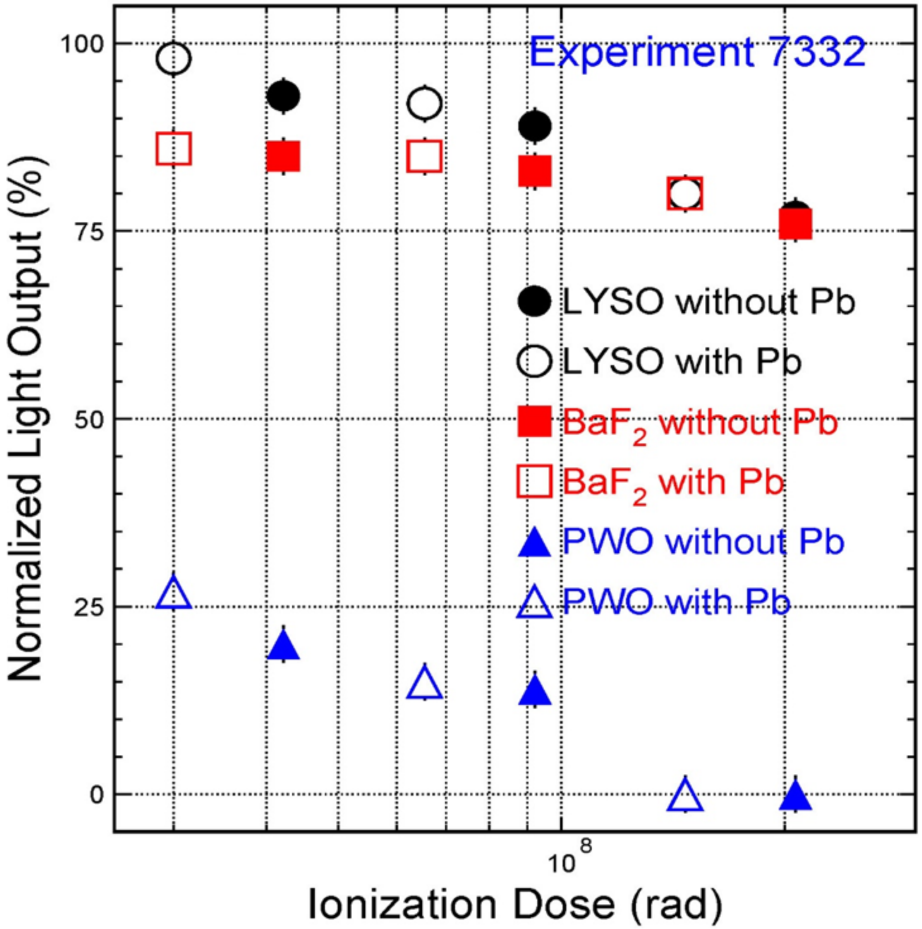
Neutrons/Photons/Protons fluxes are calculated by using MCNPX (Monte Carlo N-Particle eXtended). Plotted spectra are tallied in the largest sample volume (averaging)



LO Vs. Fast Neutron Fluence And Ionization Dose from γ-Rays

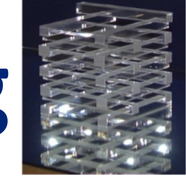
Robust LYSO and BaF_2: up to 200 Mrad and 2 x 10^{15} n/cm^2
No neutron specific damage in LYSO, BaF_2 & PWO

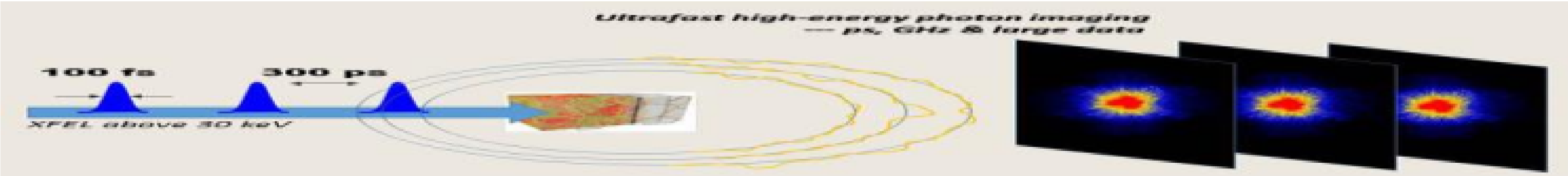




Will be presented in IEEE NSS 2017 at Atlanta

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.

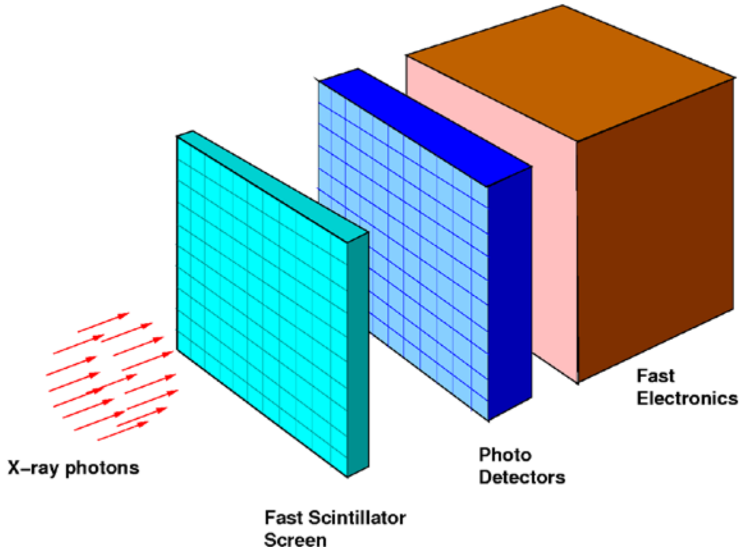
Table I. High-energy photon imagers for MaRIE XFEL

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

Why Crystal Scintillator?

- Detection efficiency for hard X-ray requires bulk detector.
- Scintillation light provides fast signal.
- Pixelized crystal detector is a standard for medical industry.
- A detector concept:
  - Pixelized fast scintillator screen;
  - Pixelized fast photodetector;
  - Fast electronics readout.

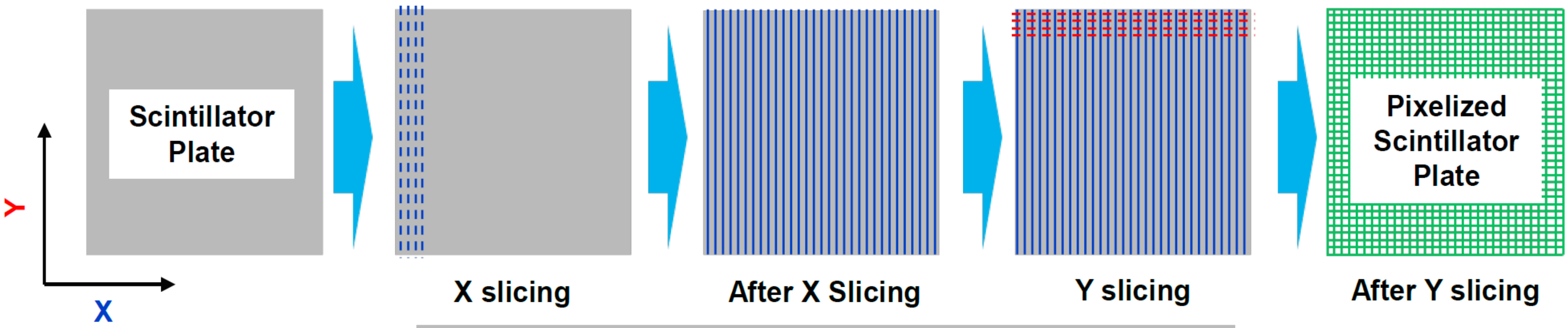


- Challenges:

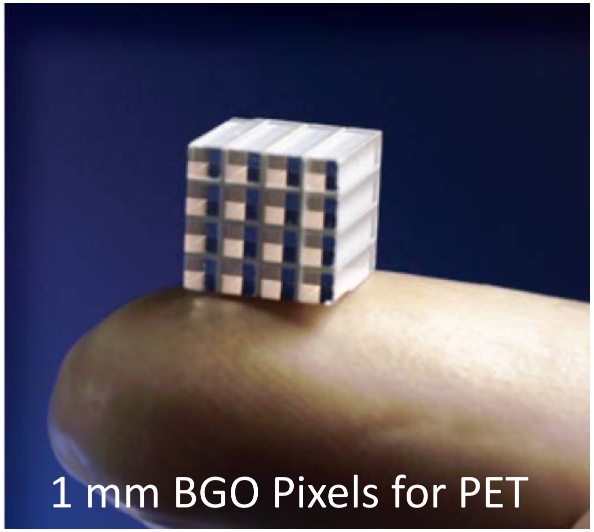
  Ultra-fast crystals, photodetectors and readout.

Pixelized Crystal Detectors

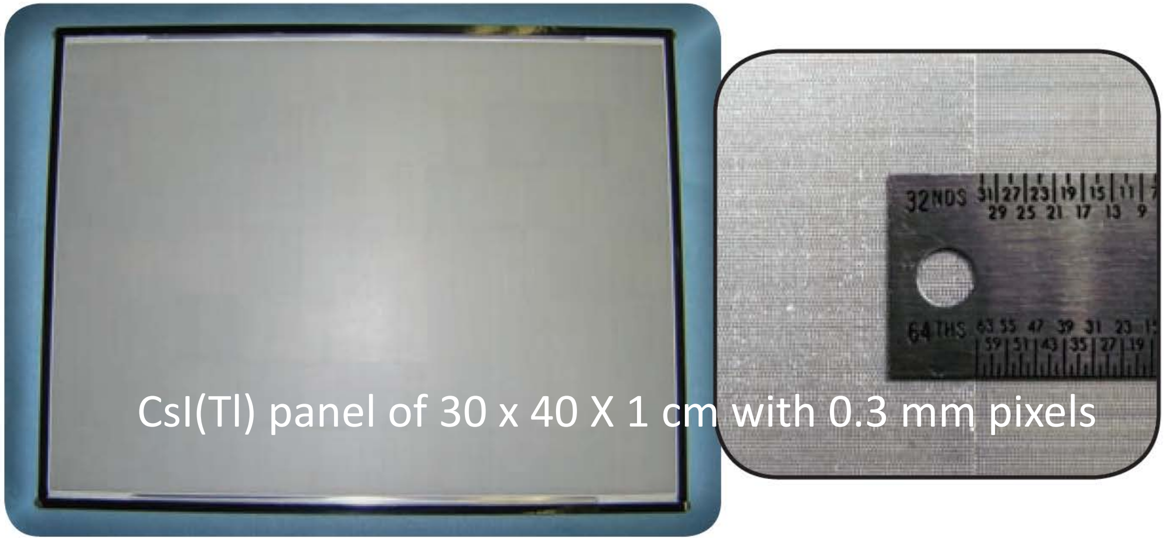
Crystal panels of 300 µ pitch may be fabricated by classical mechanical processing



A Schematic showing pixelized scintillator plate processing



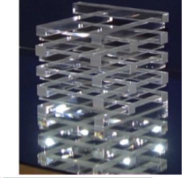
1 mm BGO Pixels for PET



CsI(Tl) panel of 30 x 40 X 1 cm with 0.3 mm pixels

Laser slicing, micropore or not pixelized provide better coverage

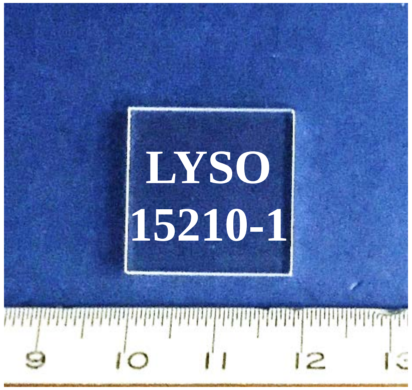
Candidate Scintillators for Marie

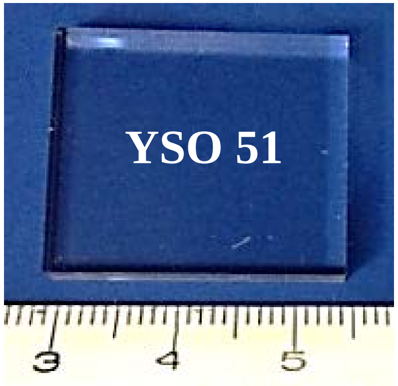


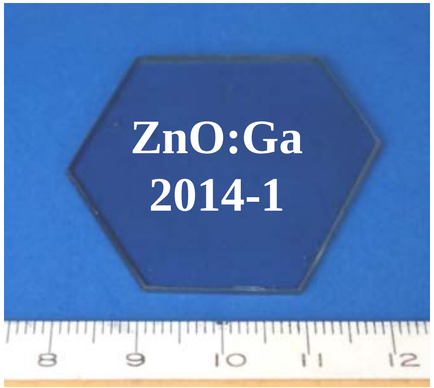
	LYSO (:Ce)	YSO:Ce	ZnO:Ga	BaF_2	BaF_2:Y	YAP:Ce	YAP:Yb	YAG:Yb	LuAG:Ce	$LaBr_3$ (:Ce)
Density (g/cm^3)	7.4	4.44	5.67	4.89	4.89	5.35	5.35	4.56	6.76	5.29
Melting points (°C)	2050	2070	1975	1280	1280	1870	1870	1940	2060	783
X_0 (cm)	1.14	3.10	2.51	2.03	2.03	2.77	2.77	3.53	1.45	1.88
R_M (cm)	2.07	2.93	2.28	3.1	3.1	2.4	2.4	2.76	2.15	2.85
λ_I (cm)	20.9	27.8	22.2	30.7	30.7	22.4	22.4	25.2	20.6	30.4
Z_{eff}	64.8	33.3	27.7	51.6	51.6	31.9	31.9	30	60.3	45.6
dE/dX (MeV/cm)	9.55	6.57	8.42	6.52	6.52	8.05	8.05	7.01	9.22	6.90
λ_{peak}[a] (nm)	420	420	389	300 220	300 220	370	350	350	520	360
Refractive Index[b]	1.82	1.78	2.1	1.50	1.50	1.96	1.96	1.87	1.84	1.9
Normalized Light Yield[a,c]	100	80	6.6[e]	42 4.8	1.7 4.8	9 32	0.19[e]	0.36[e]	35[f] 48[f]	153
Total Light yield (ph/MeV)	30,000	24,000	2,000[e]	13,000	2,000	12,000	57[e]	110[e]	25,000[f]	46,000
Decay time[a] (ns)	40	75	<1	600 0.6	600 0.6	191 25	1.5	4	981[f] 64[f]	20
Light Yield in 1st ns (photons/MeV)	740	318	610[e]	1200	1200	391	28[e]	24[e]	240	2,200
40 keV Att. Length (1/e, mm)	0.185	0.334	0.407	0.106	0.106	0.314	0.314	0.439	0.251	0.131

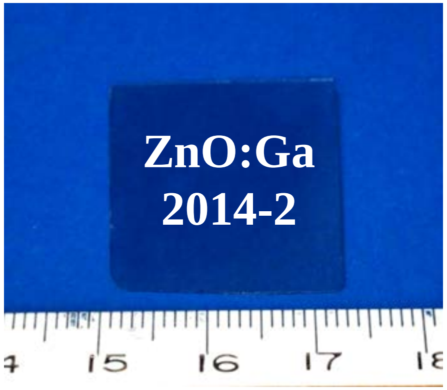
[1] Spurrier, et al., *IEEE T. Nucl. Sci.* 2008,55 (3): 1178-1182.
a. Top line: slow component, bottom line: fast component;
b. At the wavelength of the emission maximum;
c. Excited by Gamma rays;
d. For 0.4 at% Ca co-doping;
e. Excited by Alpha particles.
f. Ceramic with 0.3 Mg at% co-doping

LYSO and ZnO:Ga Samples









Crystal	Vendor	ID	Dimension (mm^3)
LYSO:Ce	SIC	150210-1	19x19×2
YSO:Ce	SIC	51	25×25×5
ZnO:Ga	FJIRSM	2014-1	33×30×2
ZnO:Ga	FJIRSM	2014-2	22×22×0.3

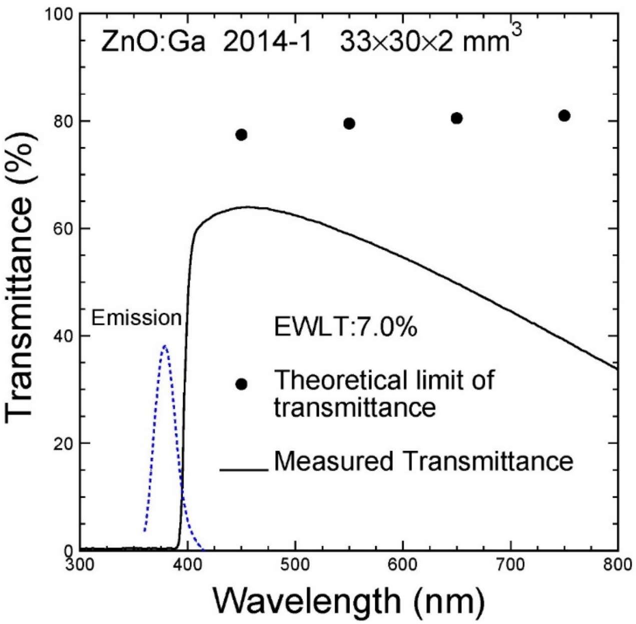
Experiments

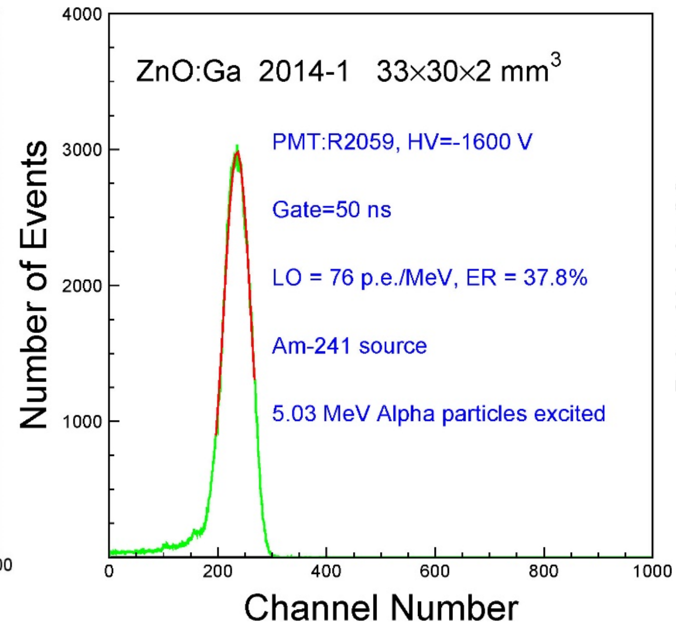
- Properties measured at room temperature : PL & Decay, Transmittance, PHS, LO & Decay kinetics

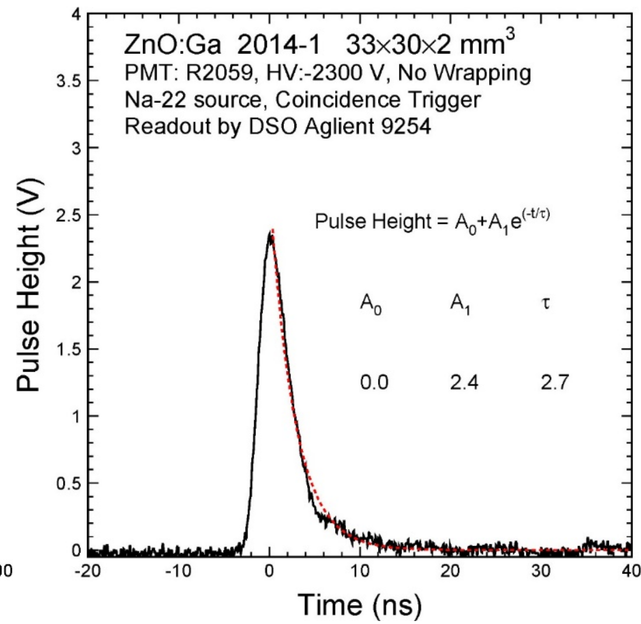
FJIRSM 2mm ZnO:Ga-2014-1

✓ Very short decay time

× Low EWLT and LO due to severe self absorption

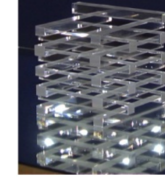




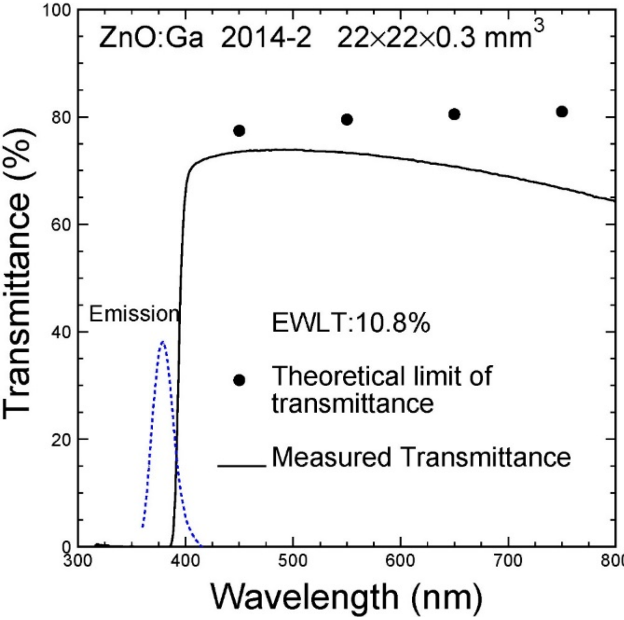


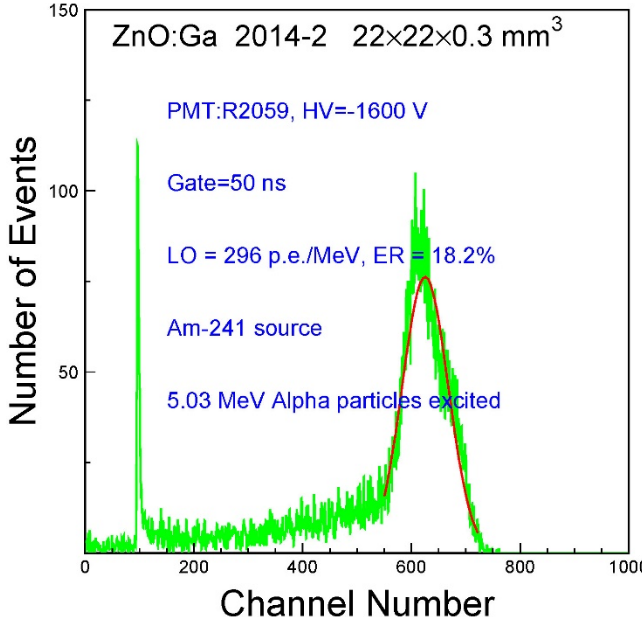
ID	Dimension	EWLT (%)	ER (%)	50 ns LO (p.e./MeV)	Primary Decay Time (ns)
FJIRSM ZnO:Ga-2014-1	33×30×2	7.0	37.8	76 (α)	2.7

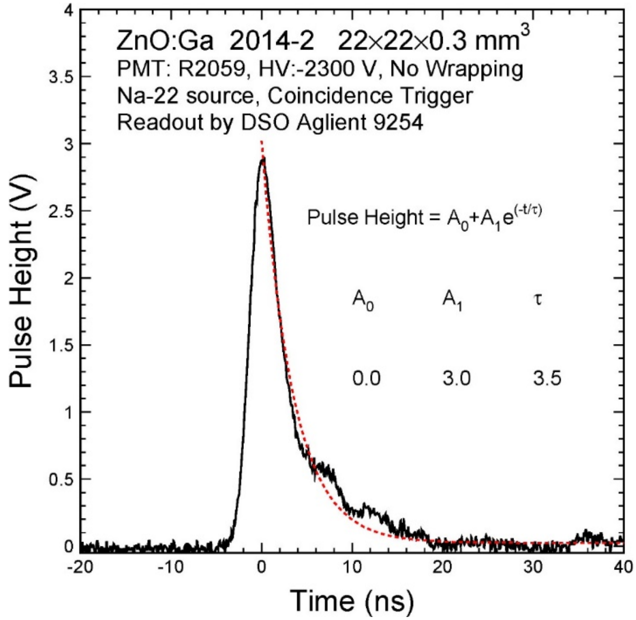
FJIRSM 0.3 mm ZnO:Ga-2014-2



- Reduced self absorption due to 0.3 mm thickness
- May pursue QD, NP or thin film based solution





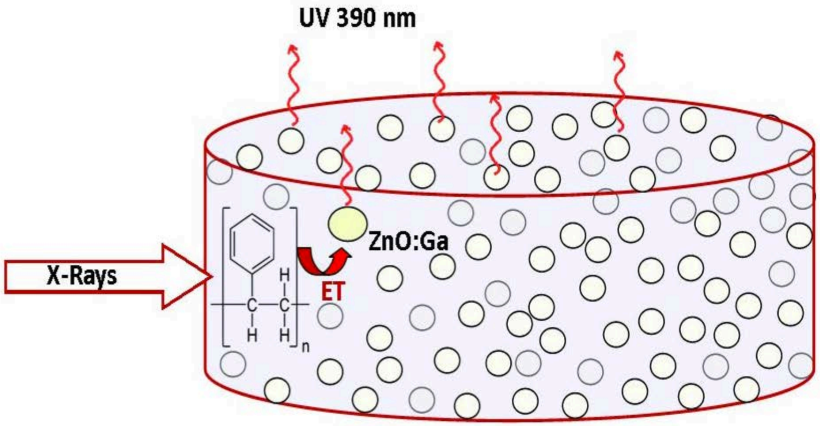


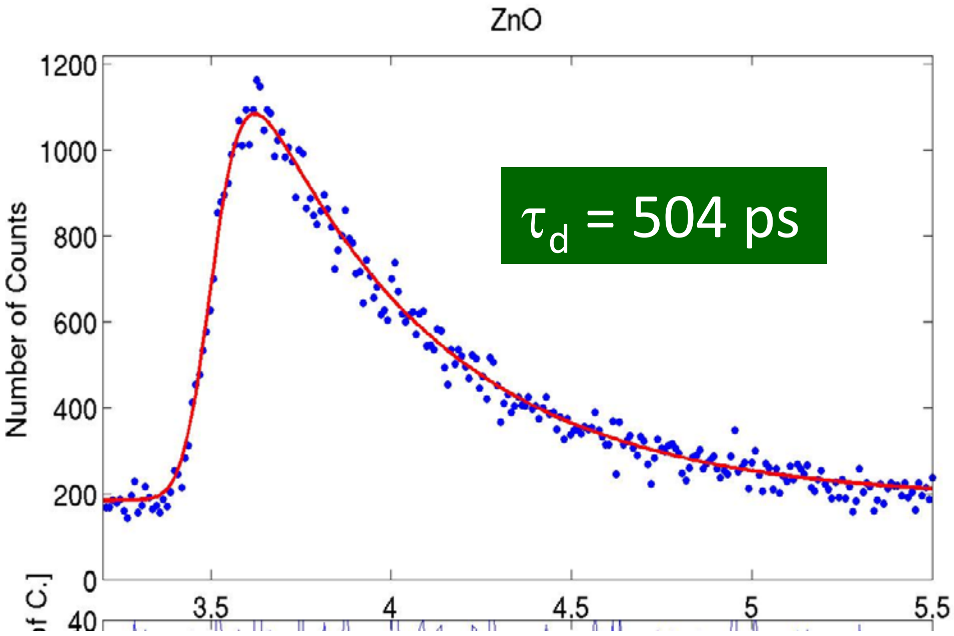
ID	Dimension	EWLT (%)	ER (%)	50 ns LO (p.e./MeV)	Primary Decay Time (ns)
FJIRSM ZnO:Ga-2014-2	22×22×0.3	10.8	18.2	296 (α)	3.5

ZnO:Ga Polystyrene Composite Scintillator

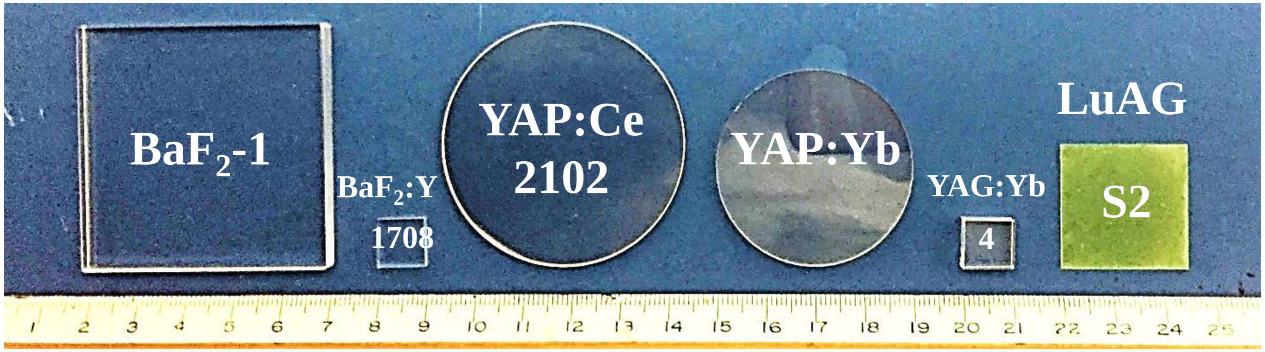
P. Lecoq, Talk in the Picosecond workshop, Kansas City, 15-18 September, 2016

- Highly luminescent ZnO:Ga nano crystals 80-100nm
  - Prepared by a photochemical method
  - Embedded in a polystyrene sheet 10%weigth





BaF_2 and Other Samples



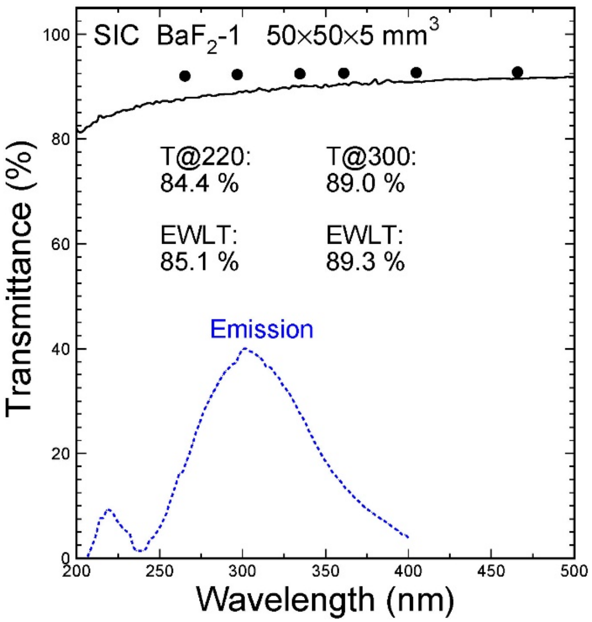
Crystal	Vendor	ID	Dimension (mm^3)
BaF_2	SIC	1	50×50×5
BaF_2:Y	BGRI	1708	10×10×2
YAP:Ce	Dongjun	2102	Φ50×2
YAP:Yb	Dongjun	2-2	Φ40×2
YAG:Yb	Dongjun	4	10×10×5
LuAG:Ce	SIC	S2	25×25×0.4

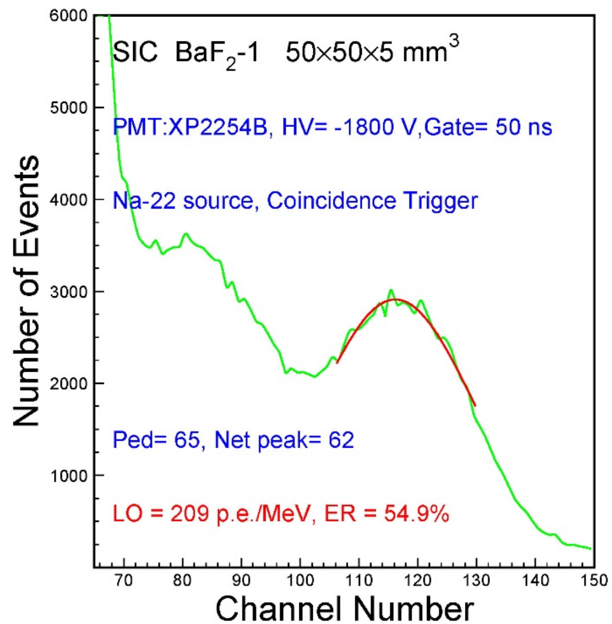
Experiments

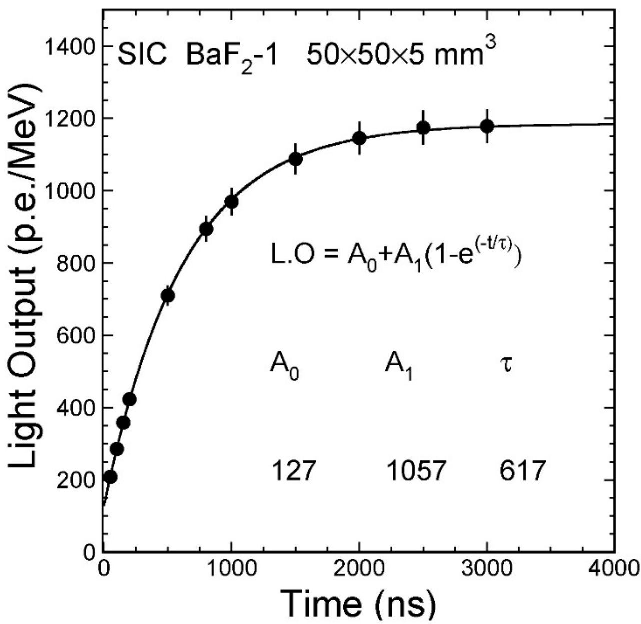
- Properties measured at room temperature : PL & Decay, Transmittance, PHS, LO & Decay kinetics

SIC BaF_2-1

- ✓ The highest LY in 1st ns among all non-hygroscopic scintillators
- × ~600 ns slow component may be suppressed by Y doping







ID	Dimension	EWLT (%)	ER (%)	50 ns LO (p.e./MeV)	Primary Decay Time (ns)
SIC BaF_2-1	50×50×5	85.1	54.9	209	0.6

Use Thin Layer Scintillators

Proc. of SPIE Vol. 9504 95040N

A multilayer high QE photocathode coated thin fast scintillators concept was proposed for GHz hard X-ray imaging:

- Spatial resolution determined layer thickness,
- Overall efficiency defined layer number,
- Maximized conversion of scintillation photon to p.e.,
- Magnetic field extraction of p.e. and image preserving,
- Off-beam p.e. multiplication,
- On-board charge storages.

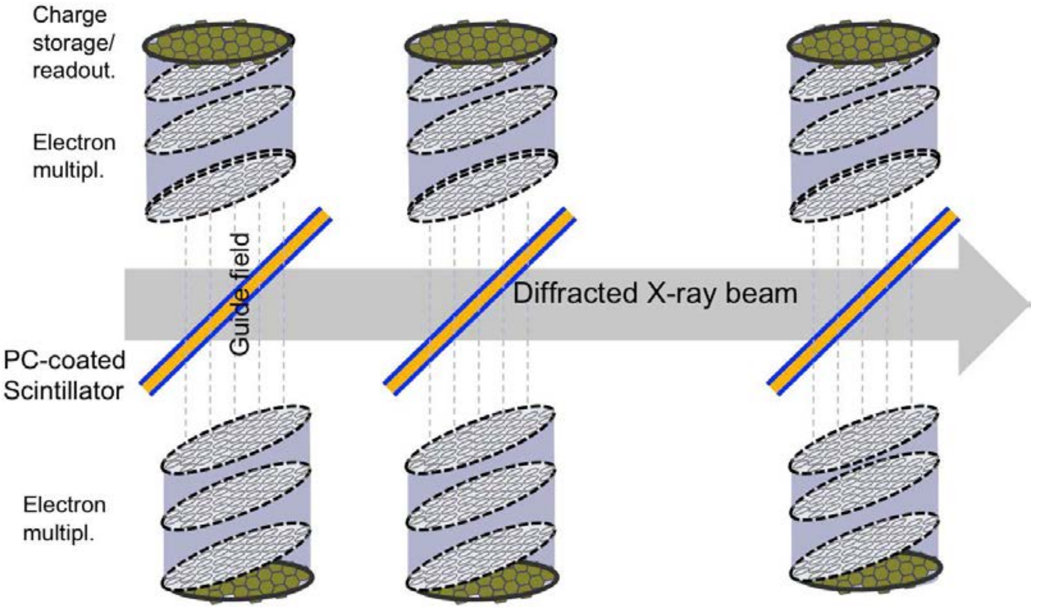


Figure 6. A multi-layer detector architecture for efficient and fast imaging of diffracted X rays. A guide magnetic field perpendicular to the X-ray direction guide the photoelectrons to amplification and storage. The magnetic field also preserves the image contrast due to X-ray absorption at the scintillator location.

Ag/Au-ZnO Core-Shell Nano Particles

Nature Scientific **Reports** | 5:14004 | DOI: 10.1038/srep14004

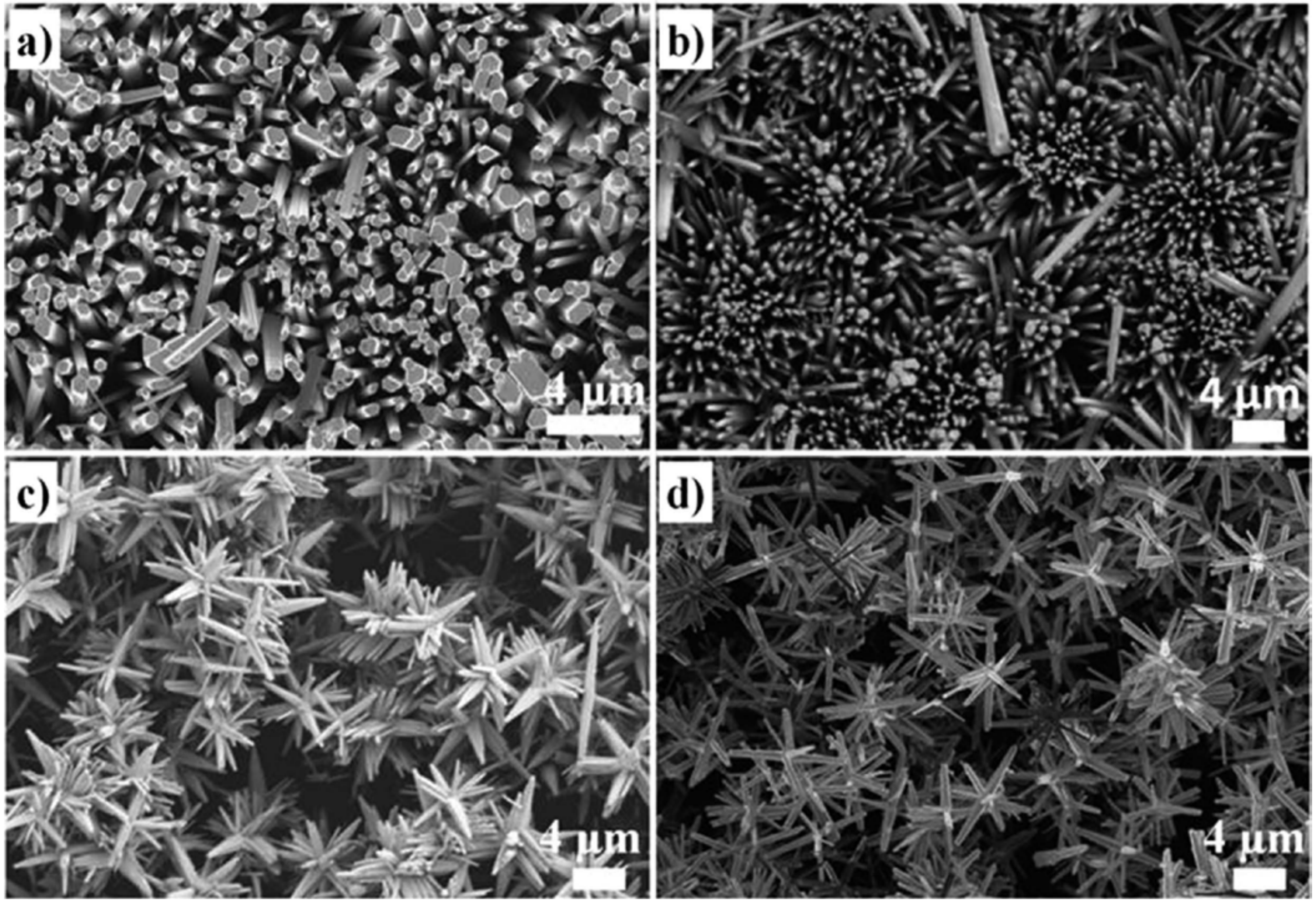
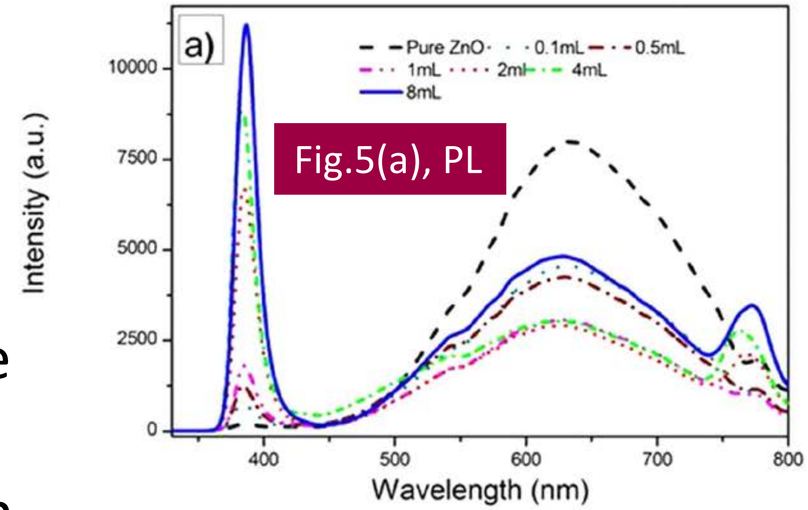


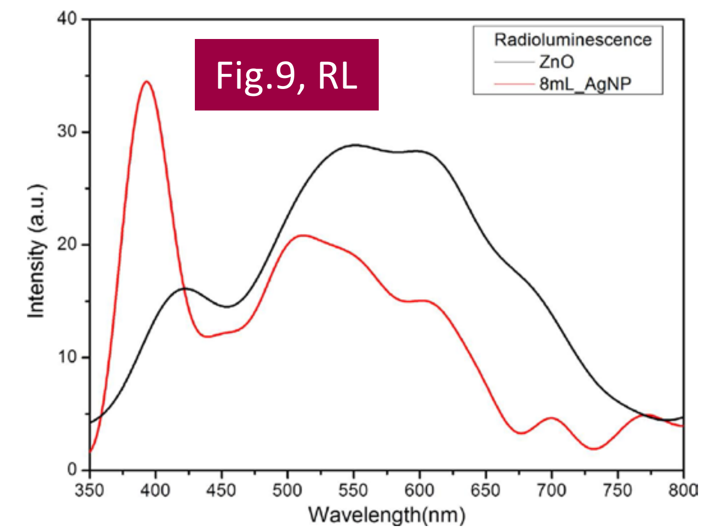
Figure 2. SEM images for ZnO samples without nanoparticles (**a**), with 2 mL_AgNP (**b**), 8 mL_AgNP (**c**), and 8 mL_AuNP (**d**) illustrating the change in shape of the particles. The particles in the lower two micrographs are referred to as "star" or "thistle" shaped in the text.

Enhanced UV Emission in Ag/Au-ZnO

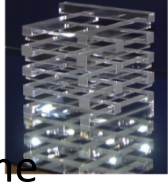
Nature Scientific **Reports** | 5:14004 | DOI: 10.1038/srep14004

- Enhancement of ZnO near-band-edge (UV) emission centered at 385 nm was reported in PL and RL of Ag/Au-ZnO core shell nanoparticles.
- The enhanced luminescence and the decreased free exciton lifetime suggest a plasmon-coupled-emission mechanism.
- This suggests that plasmon-coupled luminescence can be employed for the development of improved scintillators.





Purcell effect for enhancing ZnO luminescence (Theoretical framework)



Total field :

$$\langle \hat{\boldsymbol{E}}_m(\boldsymbol{r}) \rangle = \boldsymbol{E}_m^L(\boldsymbol{r}) + \frac{\omega^2}{\epsilon_0 c^2} \overleftrightarrow{\boldsymbol{G}}(\boldsymbol{r}, \boldsymbol{r}_0; \omega) \cdot \boldsymbol{\mu} \langle S \rangle$$

(a) (b) (c)

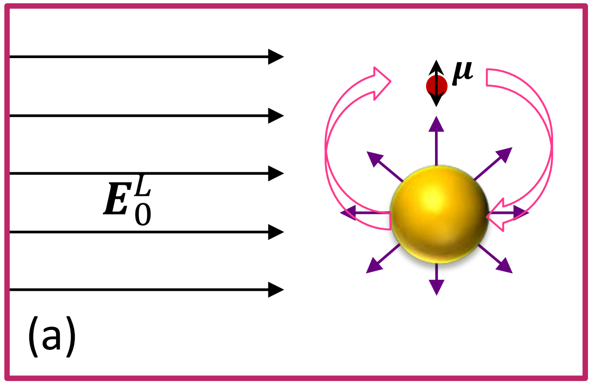
Dipole moment: $\langle \hat{S} \rangle = \frac{-\Omega[2\Delta - i\gamma_m]}{4\Delta^2 + 2|\Omega|^2 + \gamma_m^2}$

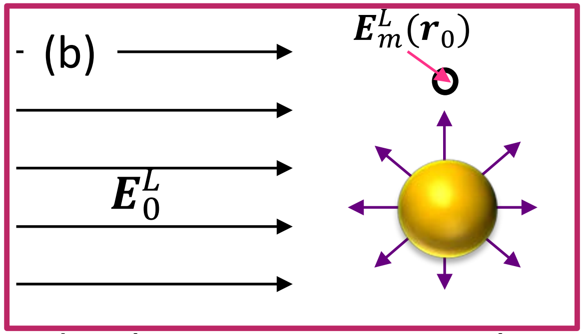
Rabi frequency: $\Omega = 2\boldsymbol{\mu} \cdot \boldsymbol{E}_m^L(\boldsymbol{r}_0)$

Δ is detuning

$\overleftrightarrow{\boldsymbol{G}}(\boldsymbol{r}, \boldsymbol{r}_0; \omega)$ is Dyadic Green's function

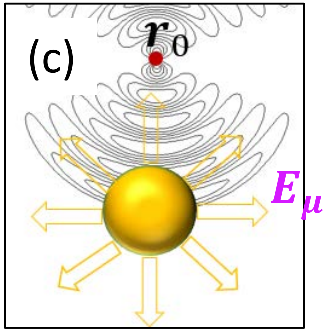
Hybrid system as experimental frame





No dipole: Mie scattering theory

NOTE: dipole is considered as a point in theory. In experiment, ZnO is the dipole.



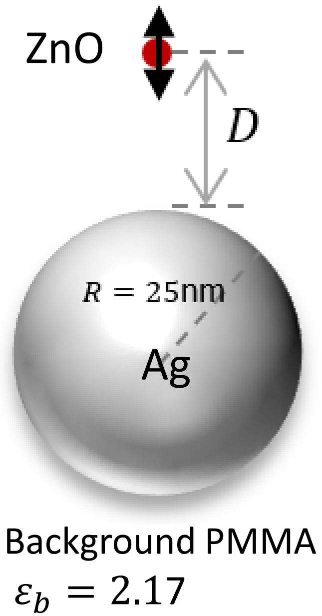
Dipole vs. Nanostructure: dyadic Green's function

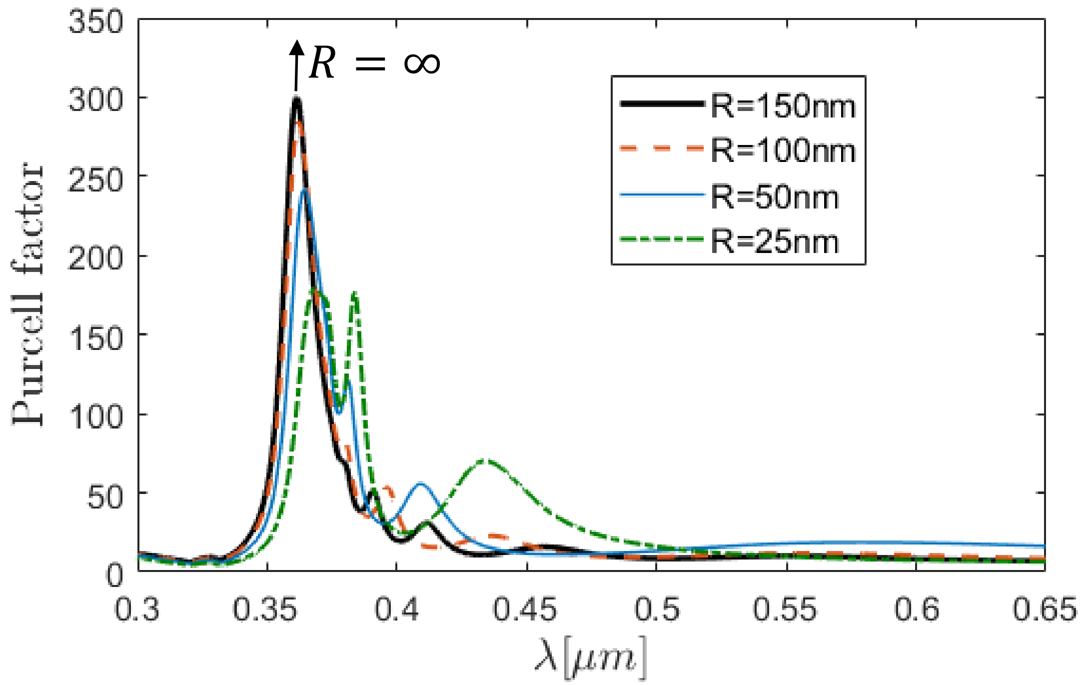
In numerical calculation, the dyadic Green's function is the kernel.

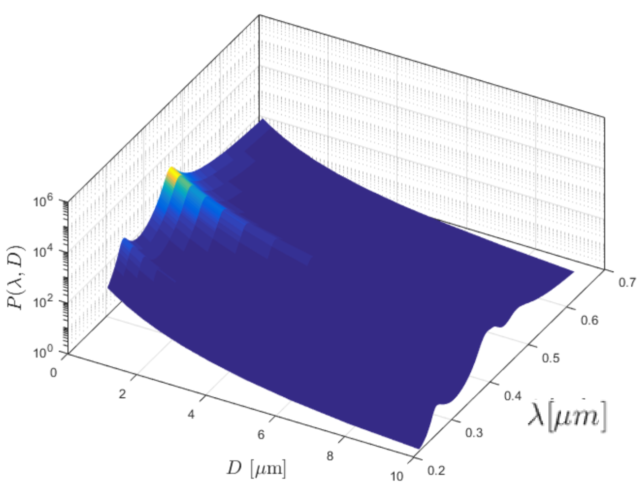
$$\gamma_m = 2\mathrm{Im}[\boldsymbol{\mu} \cdot \boldsymbol{E}_\mu(\boldsymbol{r}_0)] = 2Im[\boldsymbol{\mu} \cdot \overleftrightarrow{\boldsymbol{G}}(\boldsymbol{r}, \boldsymbol{r}_0; \omega) \cdot \boldsymbol{\mu}]$$

γ_m / γ_0 is Purcell enhancement factor

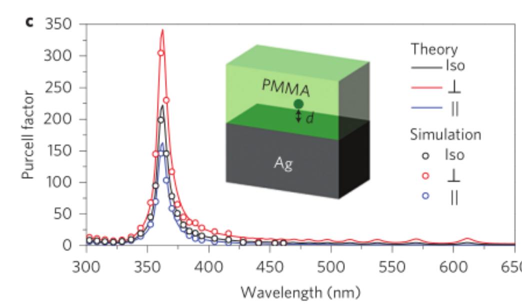
Purcell Factor for Ag Particles





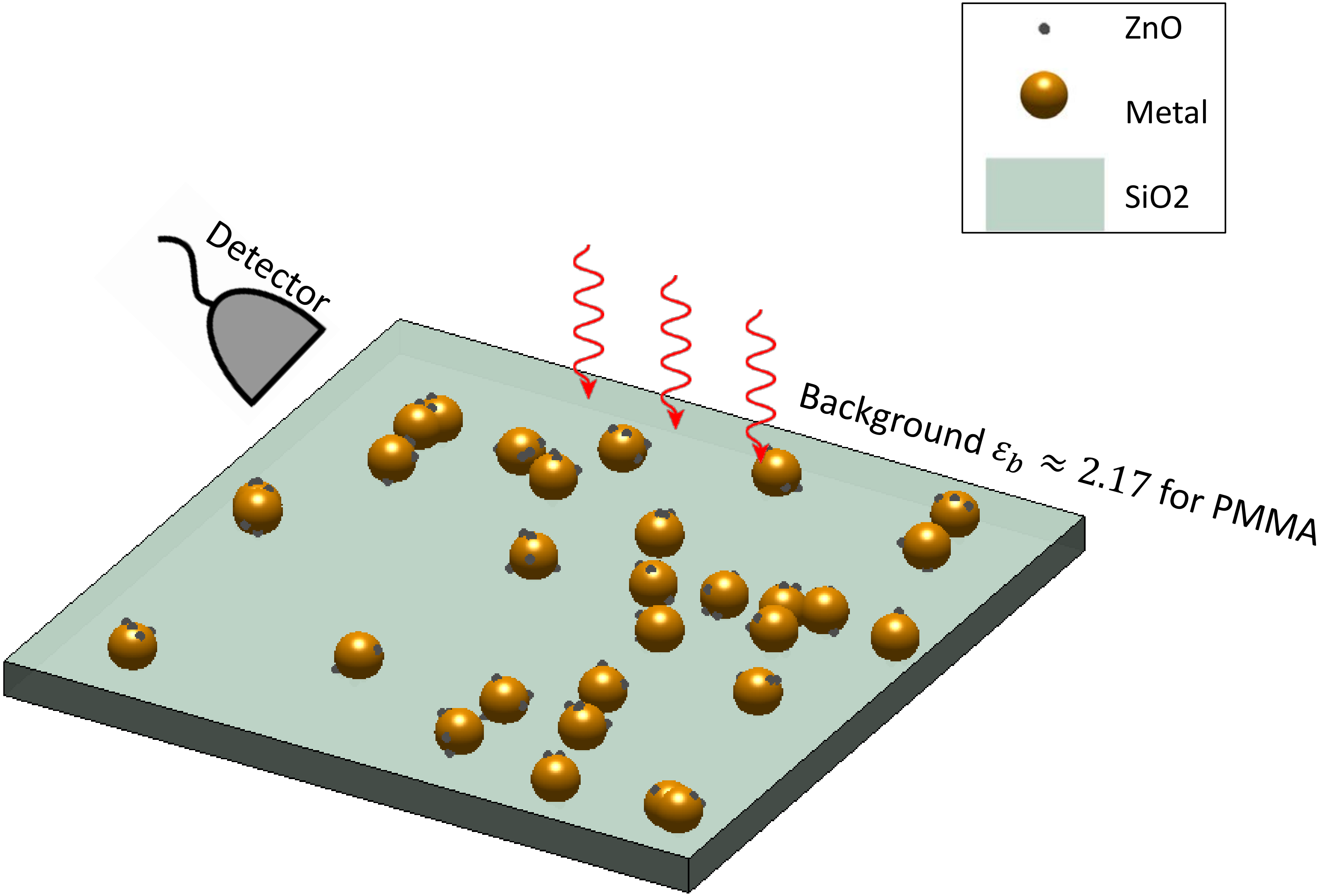


$R = \infty$ is equivalent to a infinite layer. Our simulation is greatly agree with experiments (red circles) as right figure. Agreement includes the peak value, wavelength and bandwidth.



-Lu, Dylan, et al. "Enhancing spontaneous emission rates of molecules using Nano patterned multilayer hyperbolic metamaterials." *Nature nanotechnology* 9.1 (2014): 48.

Experimental Proposal



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 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.
- 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 the 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.

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

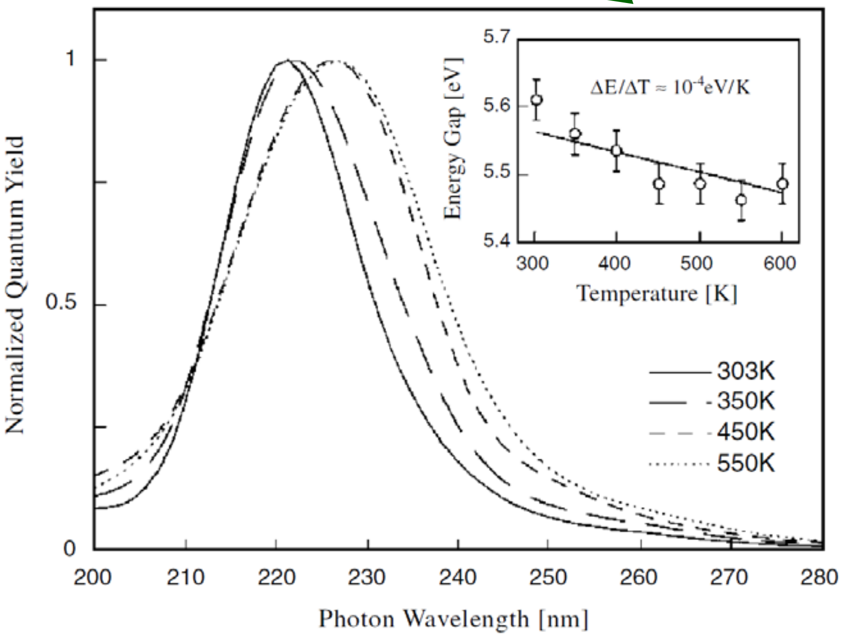


Figure 6. Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

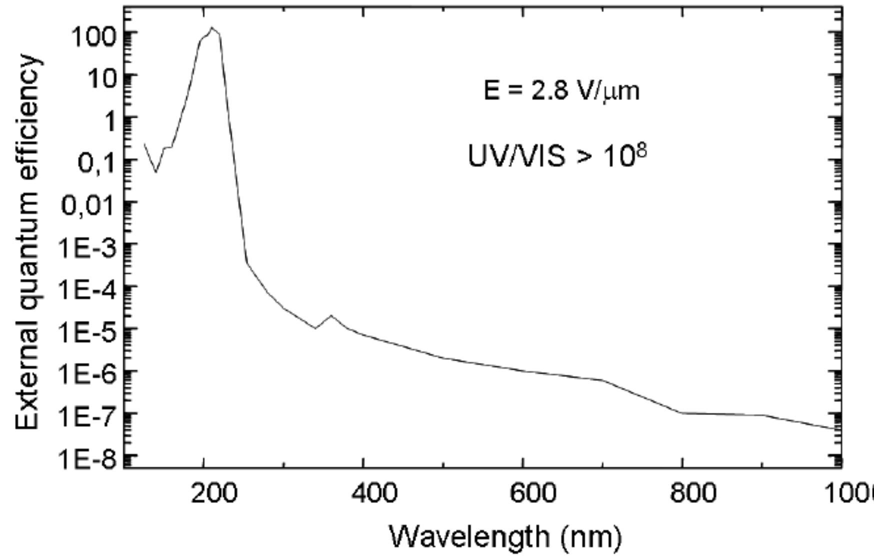


Fig. 4. External quantum efficiency extended to visible and near infrared wavelength regions. The

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

Summary: GHz Imaging

- GHz hard X-ray imaging for the proposed Marie project presents an unprecedented challenge to the speed and radiation hardness of the inorganic scintillators.
- BaF_2 crystals provide sufficient fast light with sub-ns decay time and excellent radiation hardness beyond 100 Mrad and 1 x 10^{15} h/cm^2. With its slow component effectively suppressed by yttrium doping Y:BaF_2 promises a fast and robust front imager.
- Bulk ZnO:Ga crystals suffer from serious self-absorption. Enhanced UV emission observed in Ag/Au ZnO core-shell nano particles hints a thin film based approach.
- Our plan is to investigate along both lines: Y:BaF_2 crystals, and ZnO QD/NP based thin film for the Marie project with a close collaboration between the NP, HEP and material science community.