Ultrafast Radiation Hard Inorganic Scintillators for Future HEP and NP Experiments

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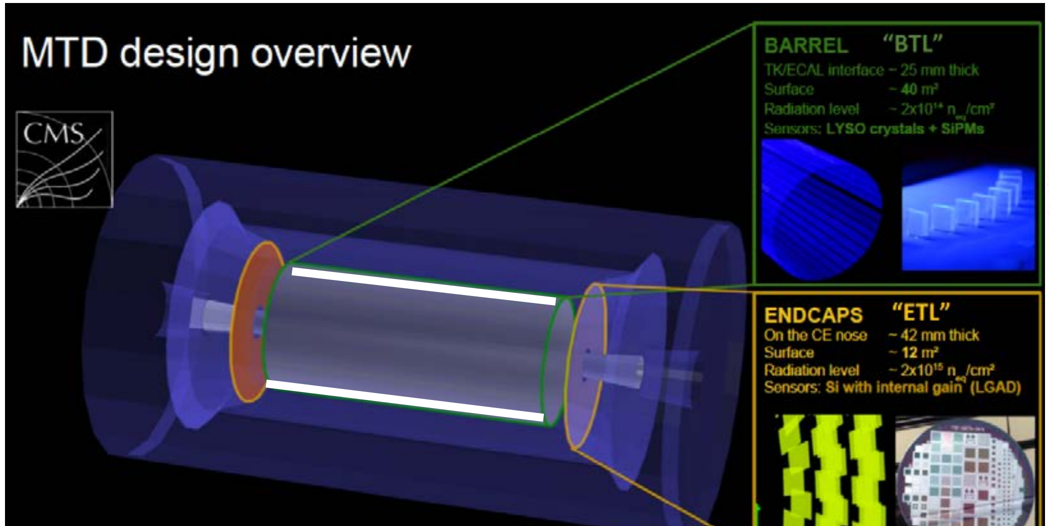
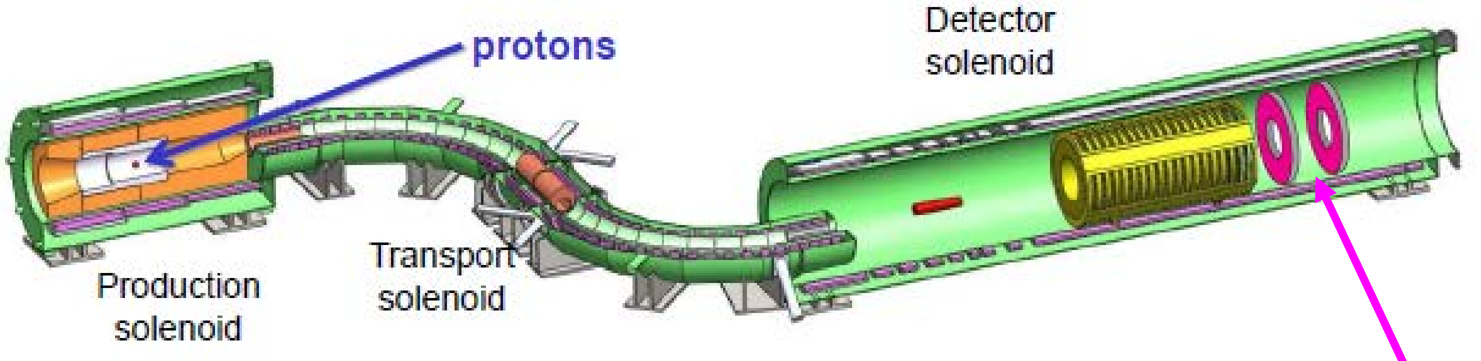
Why Ultrafast Crystals?

- **Precision photons and electrons measurements enhance physics discovery potential in HEP experiments.**
- **Performance of crystal calorimeter is well understood for e/γ, and is investigated for jets measurements :**
  - **The best possible energy resolution and position resolution;**
  - **Good e/γ identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout (CEPC?).**
- **Ultrafast and rad hard crystals for HEP & NP experiments:**
  - **At the energy frontier (LYSO BTL & Shashlik Cal for CMS at HL-LHC);**
  - **At the intensity frontier (BaF_2:Y calorimeter for Mu2e-II);**
  - **For GHz hard X-ray imaging (Ultrafast front imager for MaRIE at LANL).**

Application of Ultrafast Crystals

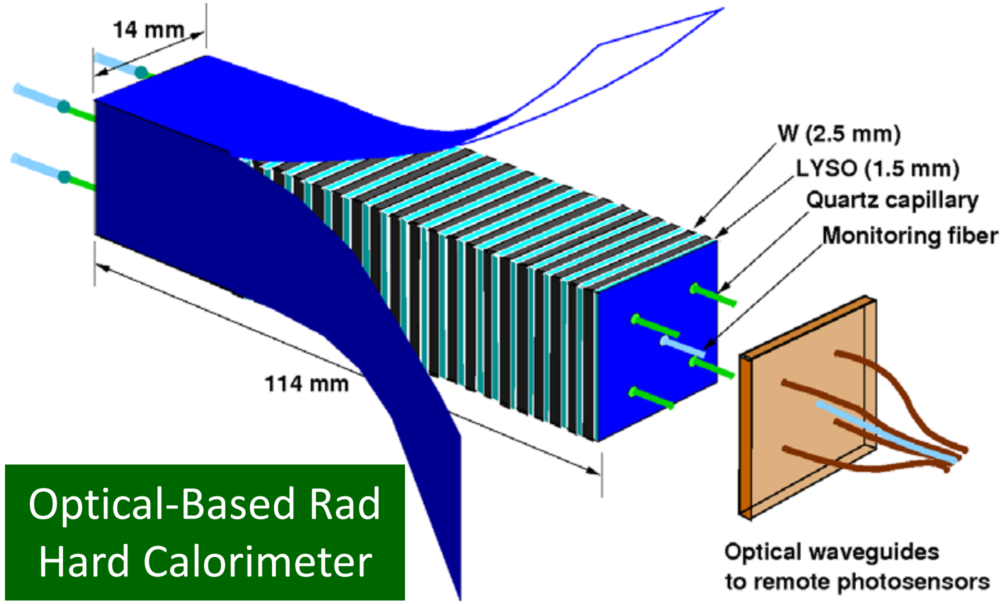


CMS BTL: An LYSO + SiPM Layer



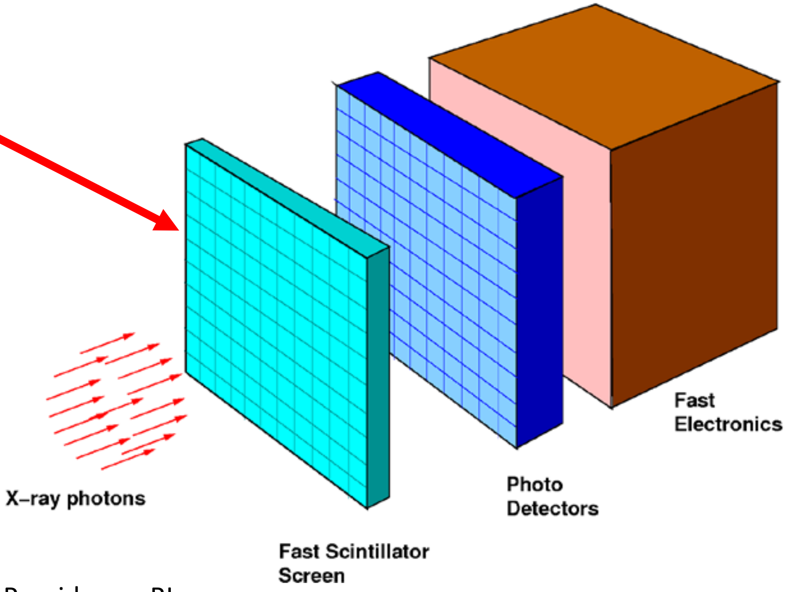
Mu2e-II: arXiv:1802.02599

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm
Mu2e-II: 1,940 BaF_2:Y of 30 x 30 x 218 mm

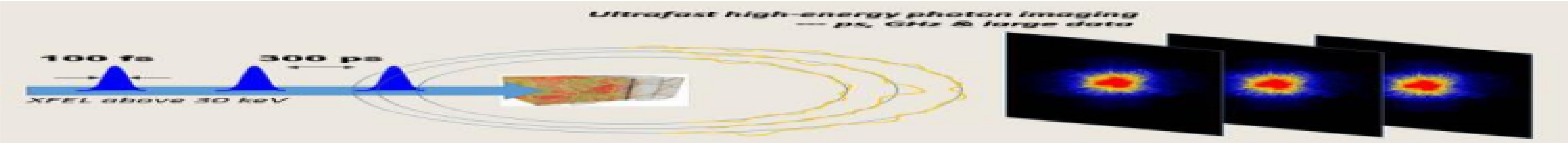


Optical-Based Rad Hard Calorimeter

An ultrafast scintillator based ultrafast front imager was proposed for GHz hard X-ray imaging for the proposed MaRIE project in the 2016 workshop at Santa Fe



MaRIE: 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

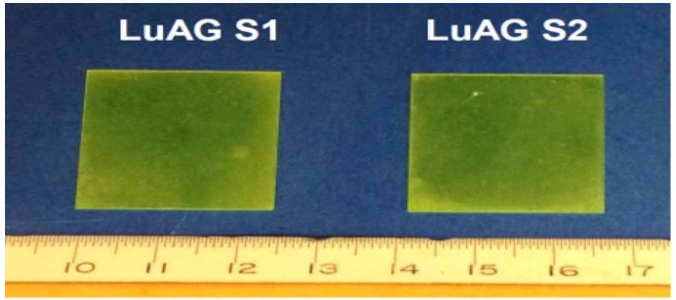
Performance	Type I imager	Type II imager
X-ray energy	30 keV	42-126 keV
Frame-rate/inter-frame time	0.5 GHz/2 ns	3 GHz / 300 ps
Number of frames	10	10 - 30
X-ray detection efficiency	above 50%	above 80%
Pixel size/pitch	≤ 300 μm	< 300 μm
Dynamic range	10^3 X-ray photons	≥ 10^4 X-ray photons
Pixel format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

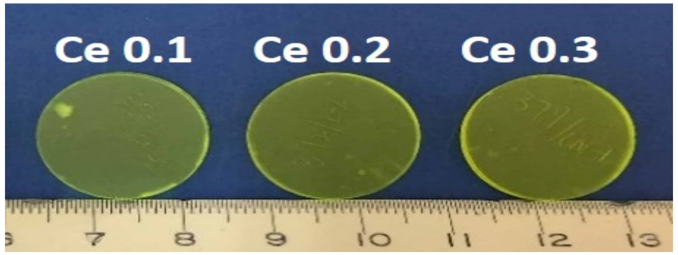
2 ns and 300 ps inter-frame time requires very fast sensor. Will crystal work?

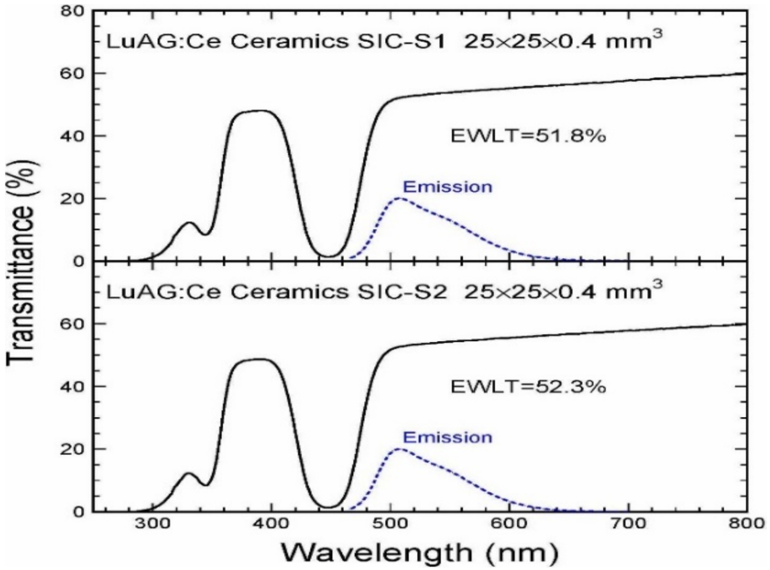
Fast and Ultrafast Inorganic Scintillators

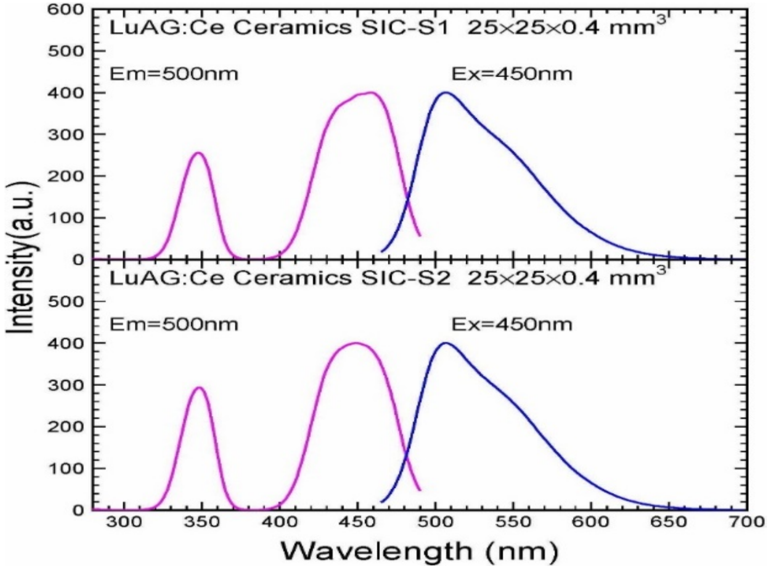
	BaF_2	BaF_2:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (^oC)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	2.4	2.76	2.20	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	22.4	25.2	20.9	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	31.9	30	28.1	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	8.05	7.01	8.82	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak} [a] (nm)	300 220	300 220	380	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	1.96	1.87	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	6.6[d]	0.19[d]	0.36[d]	6.5 0.5	100	35[e] 48[e]	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000[d]	57[d]	110[d]	2,100	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 0.6	600 0.6	<1	1.5	4	148 6	40	820 50	191 25	53	1485 36	75
LY in 1^{st} ns (photons/MeV)	1200	1200	610[d]	28[d]	24[d]	43	740	240	391	640	125	318
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

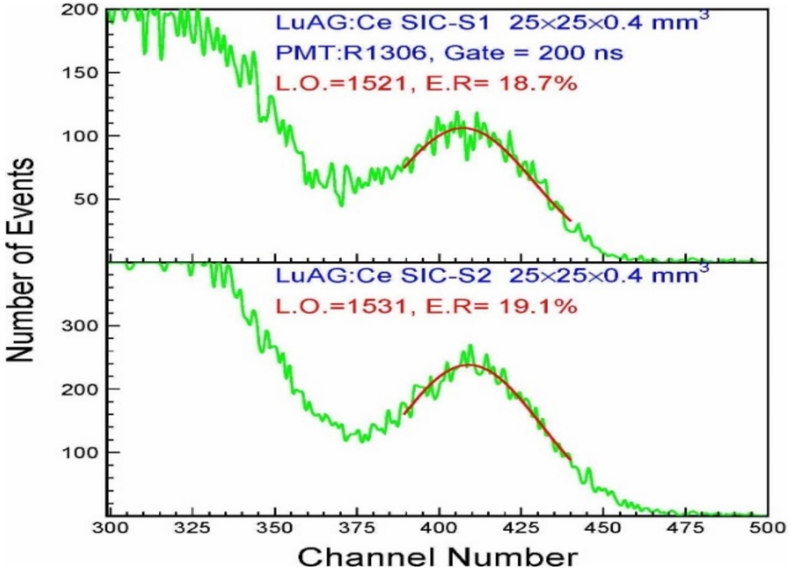
LuAG:Ce Ceramic Samples

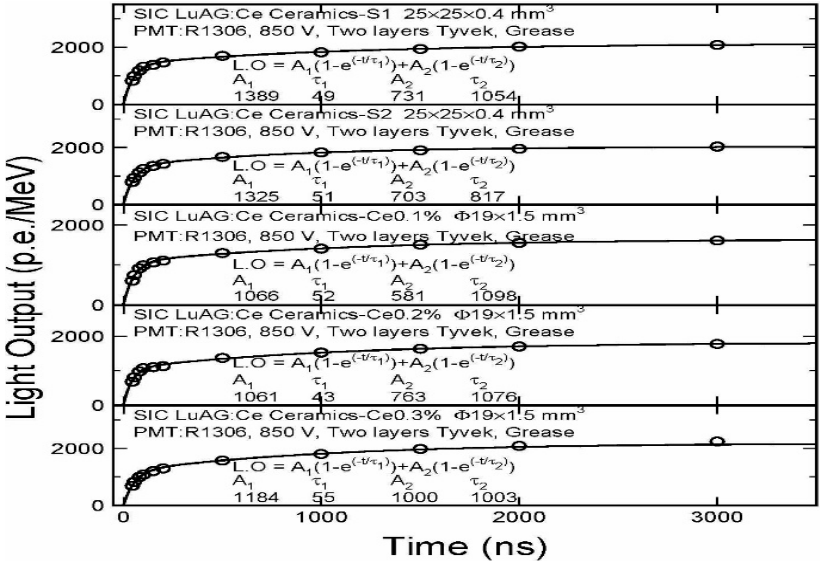


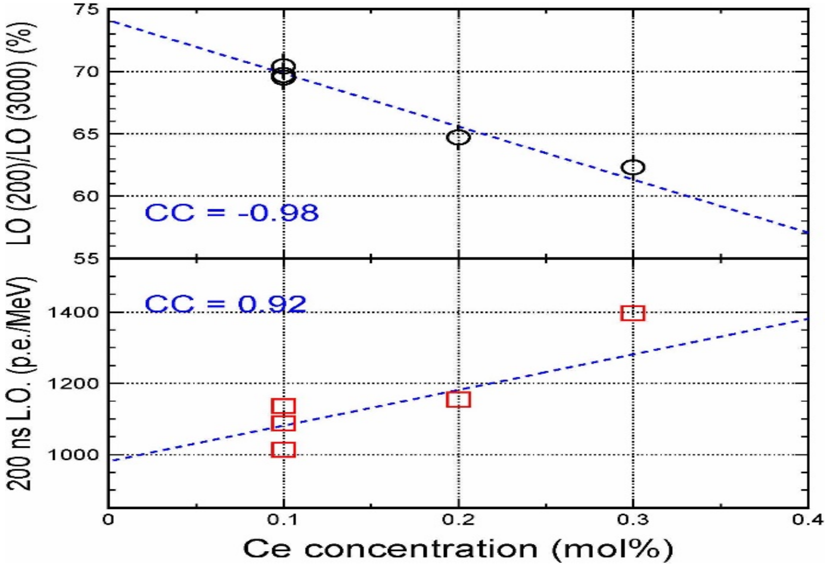






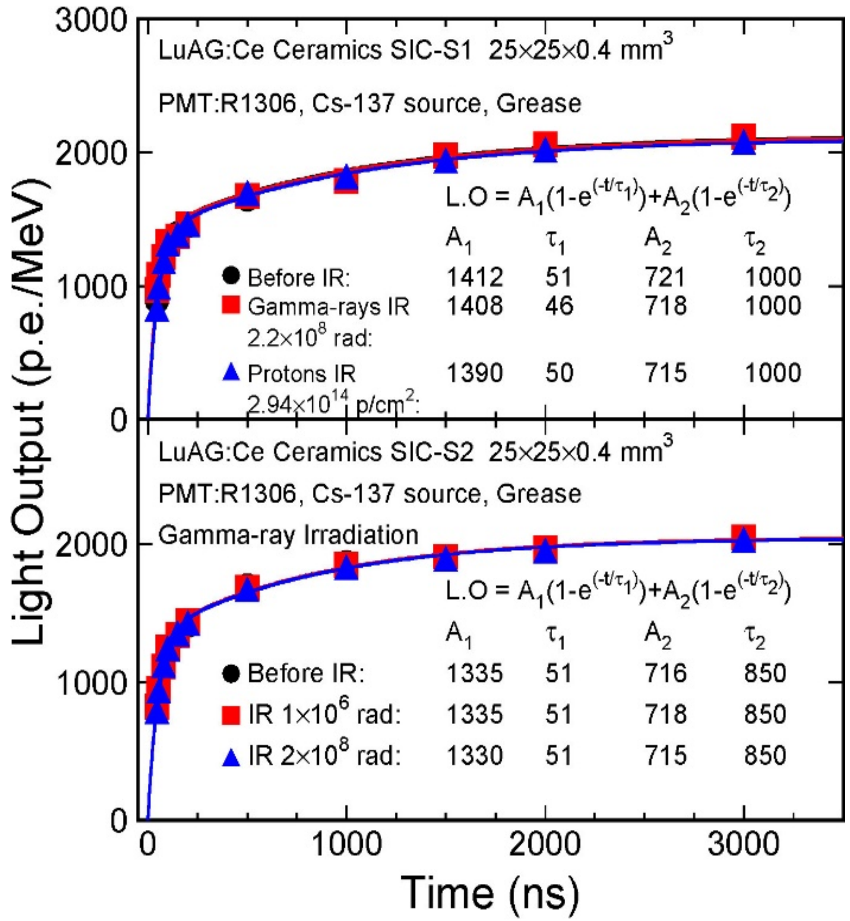


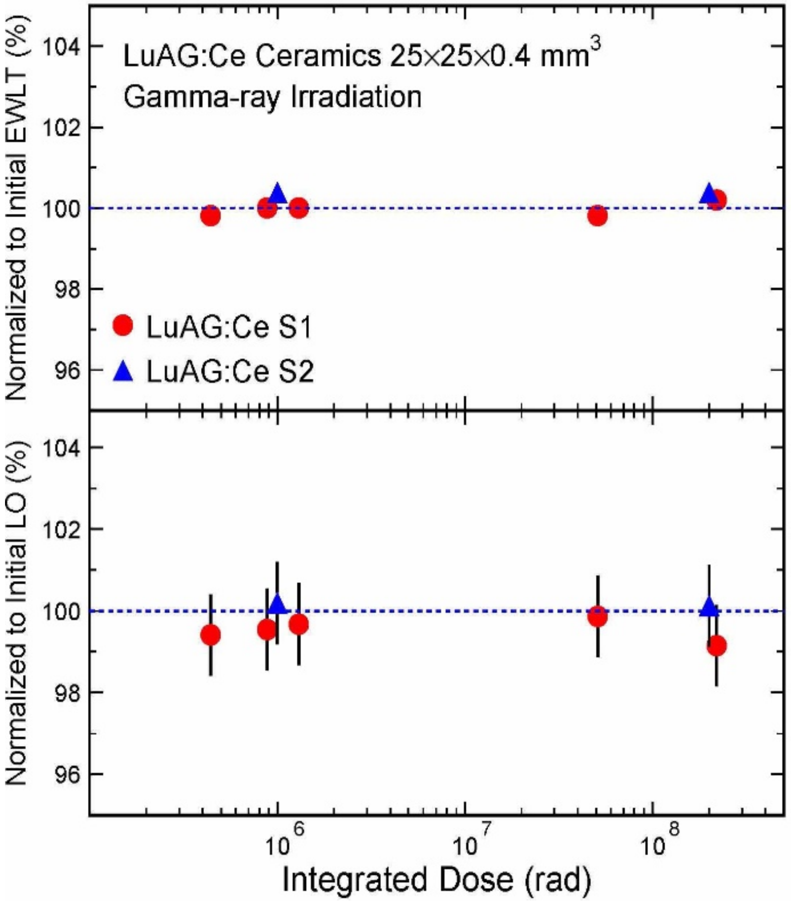


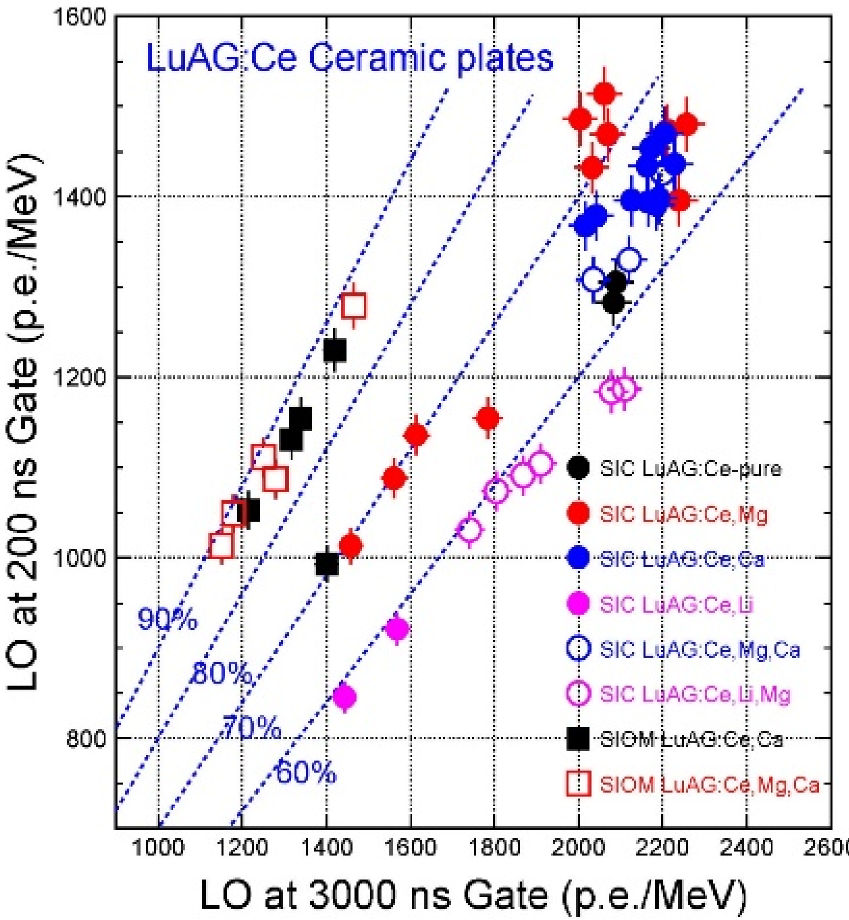


Radiation Hard LuAG:Ce Ceramics

Investigated at LANSCE up to 3×10^{14} p/cm^2 of 800 MeV, and at Sadia up to 220 Mrad







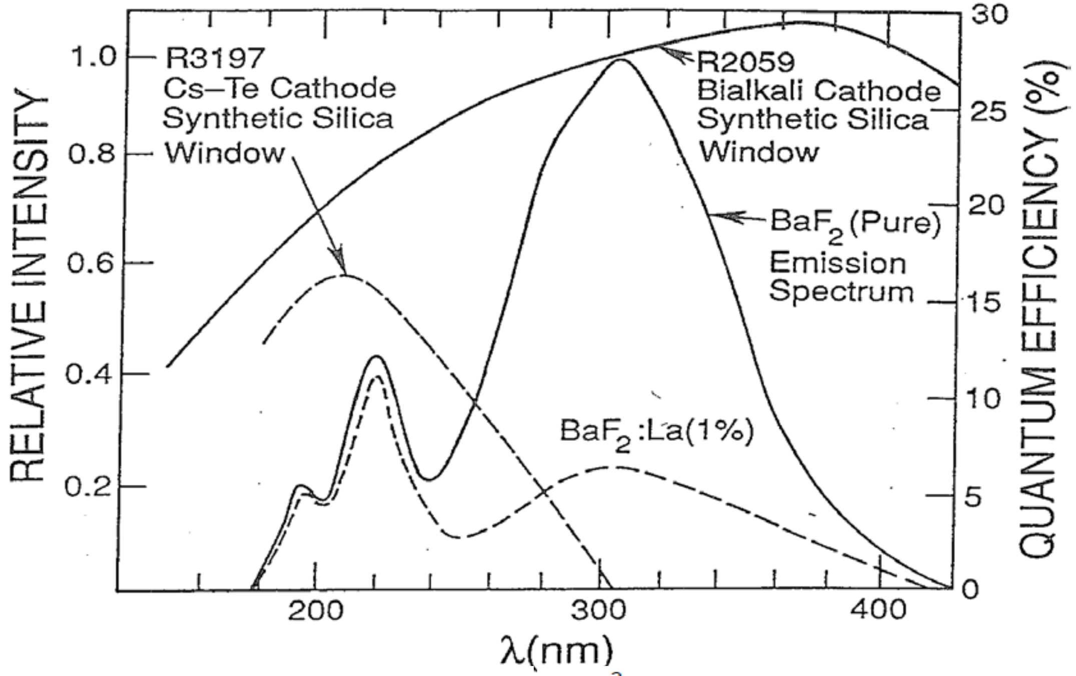
On-going R&D to suppress μs slow component by Pr doping or co-doping

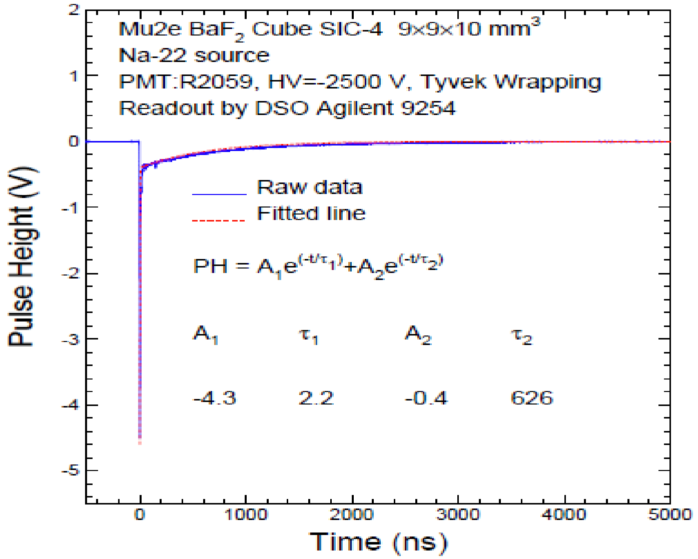
Ultrafast and Slow Light from BaF_2

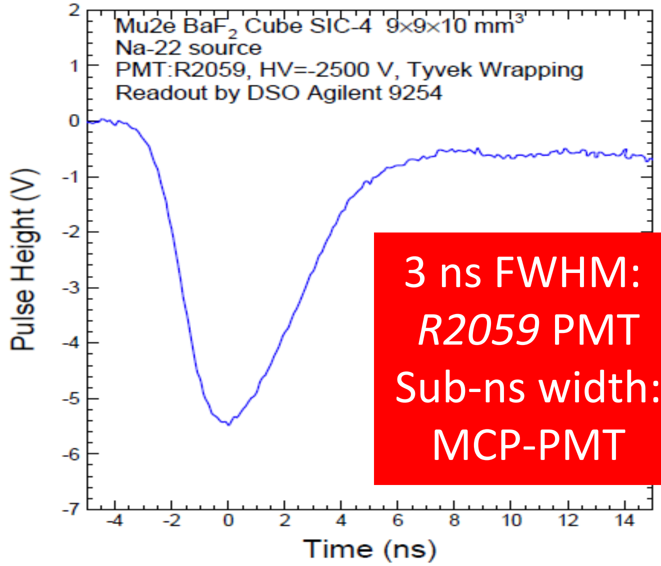
BaF_2 has an ultrafast scintillation component with sub-ns decay, and a 600 ns slow component.

The amount of the fast light is similar to undoped CsI, and is 1/5 of the slow component.

Selective readout of the ultrafast component may be realized by (1) selective doping in crystals or (2) selective readout with solar blind photodetector.





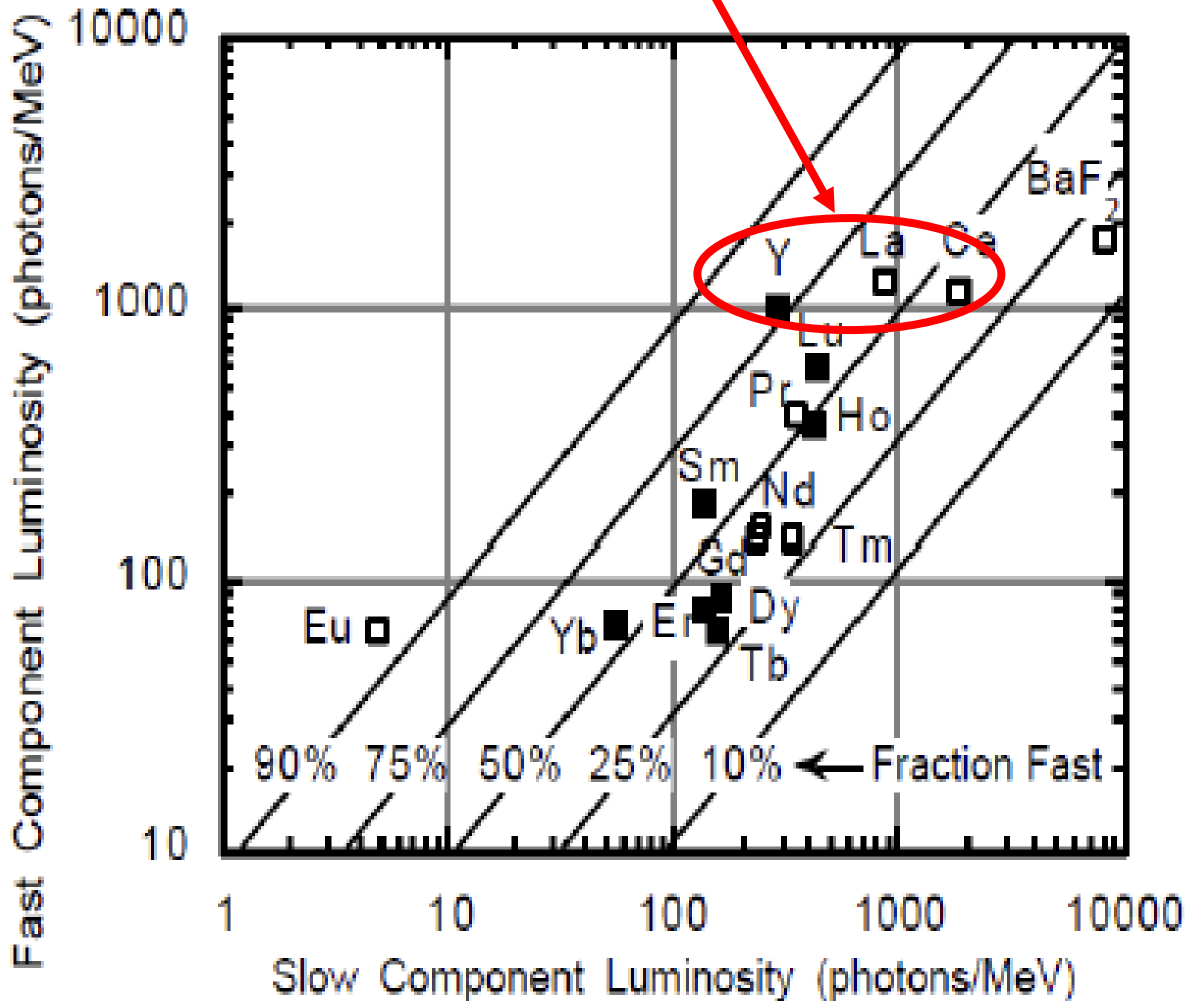


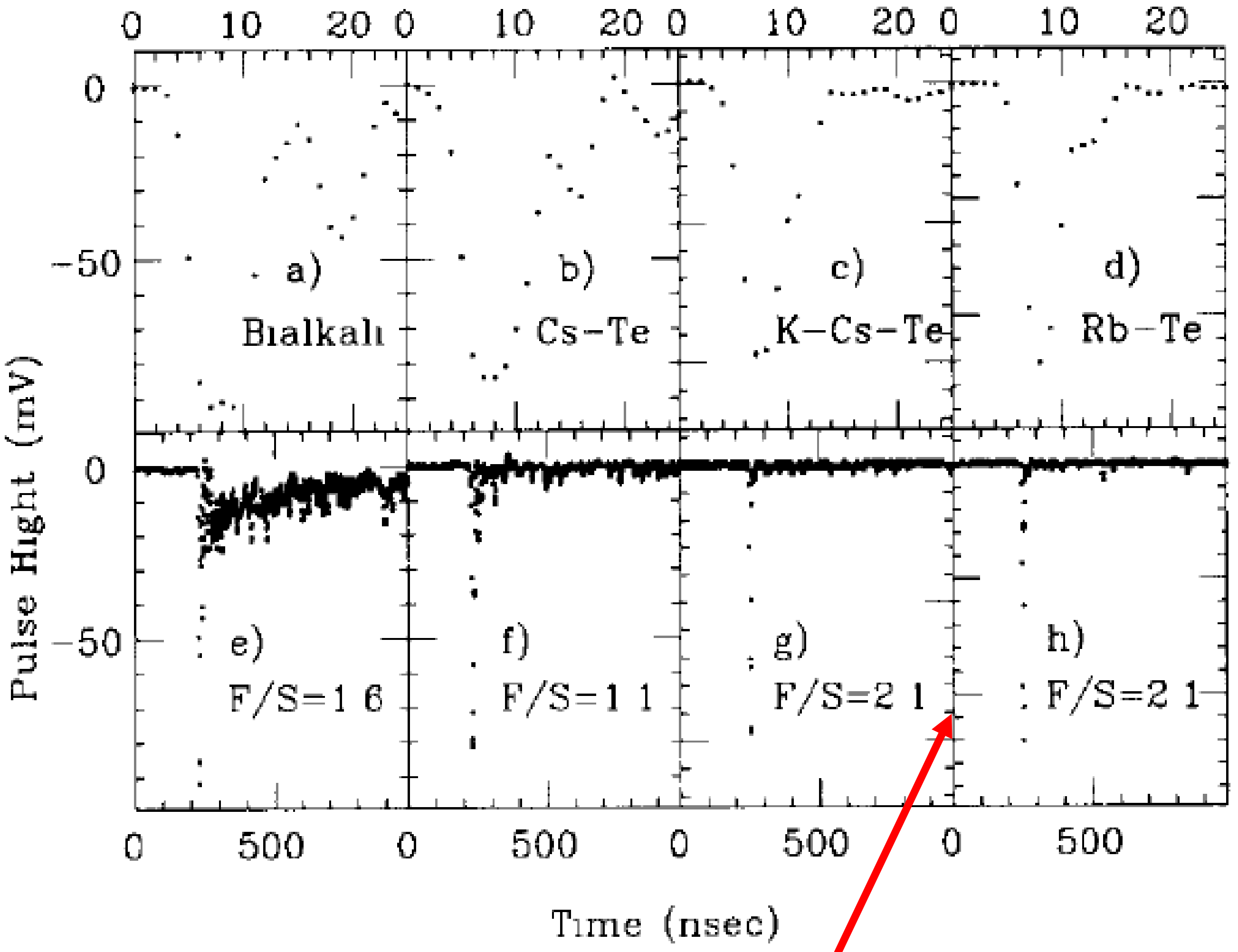
3 ns FWHM: *R2059* PMT

Sub-ns width: MCP-PMT

Slow Suppression in the Nineties

MRS Proceedings (1994) 277: Slow suppression by RE doping

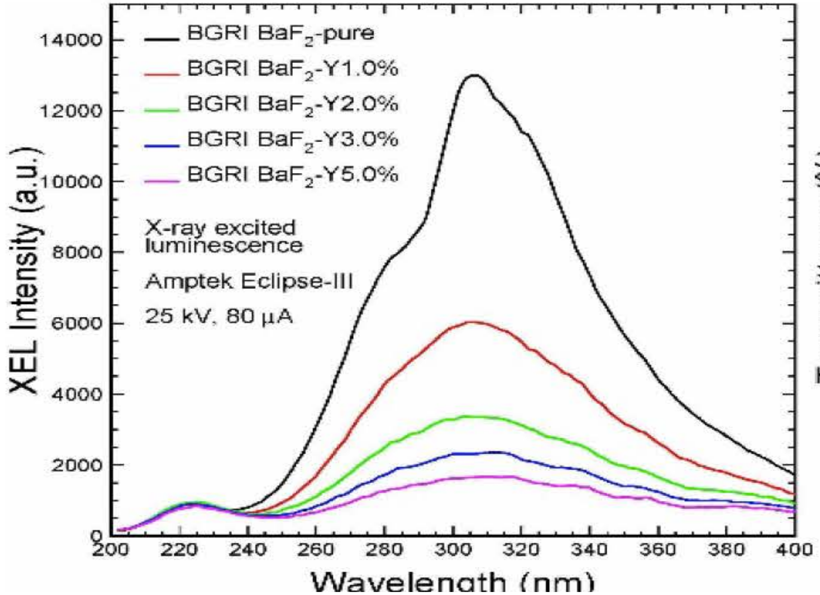


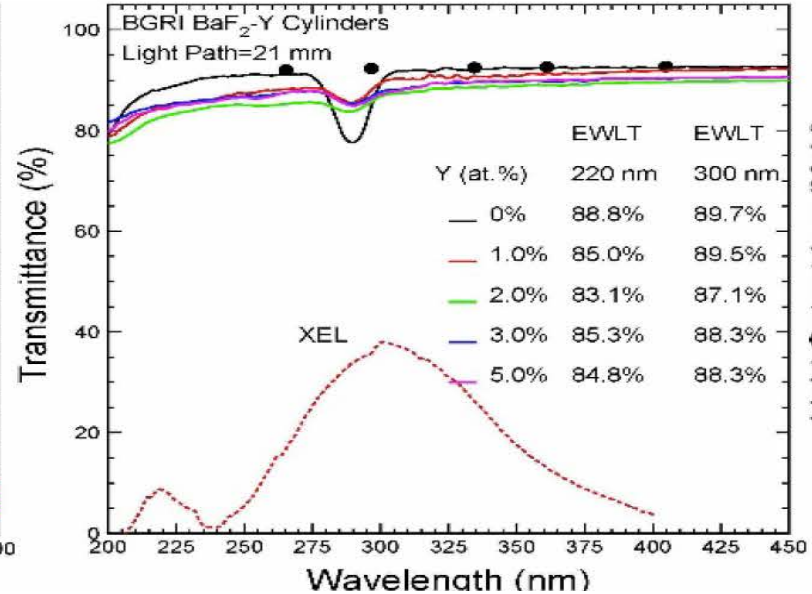


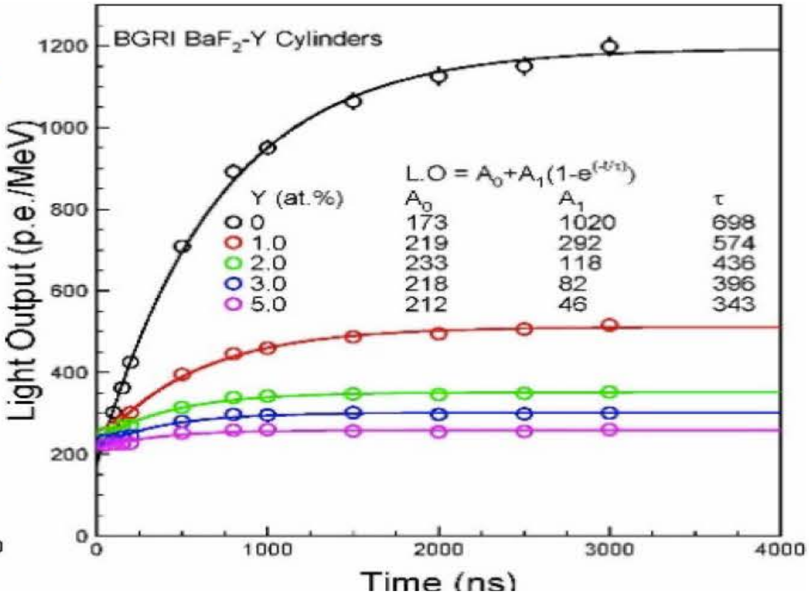
NIM 240 (1994) 442: Cs-Te, K-Cs-Te and Rb-Te cathode achieved F/S = 2/1

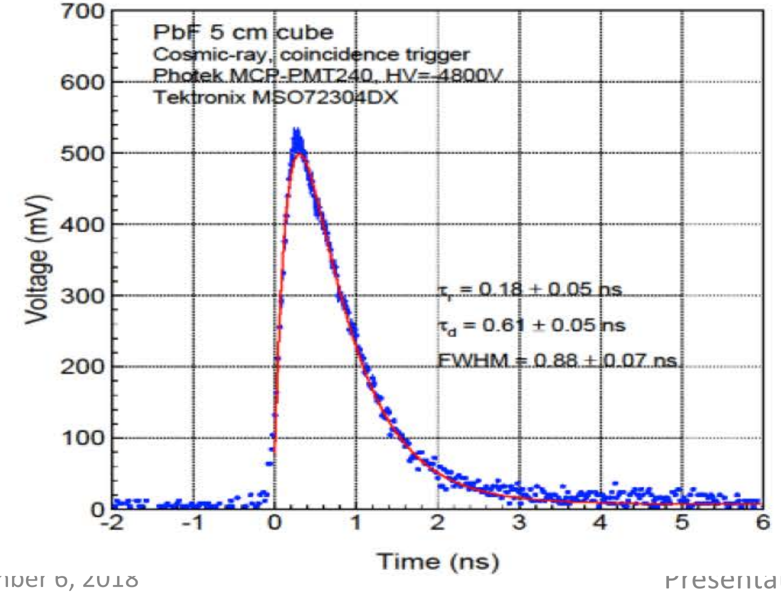
Yttrium Doped Barium Fluoride: BaF_2:Y

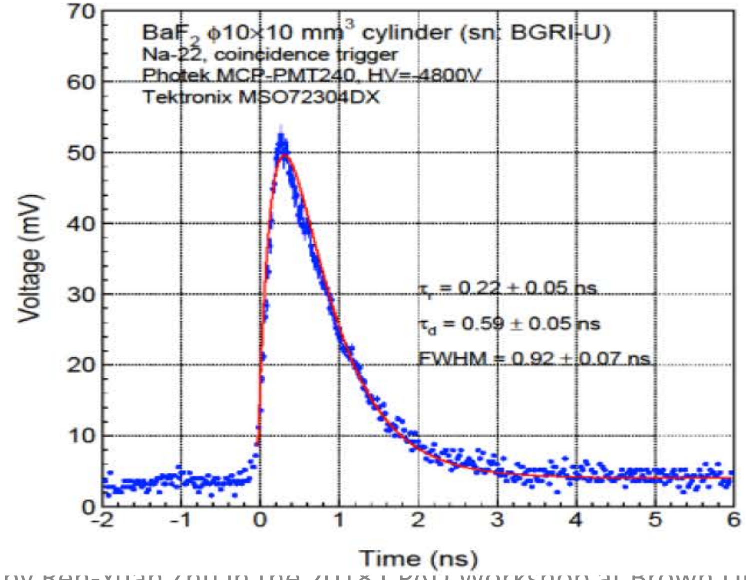
Significant increased F/S ratio in BaF_2:Y; Sub-ns FWHM by MCP-PMT

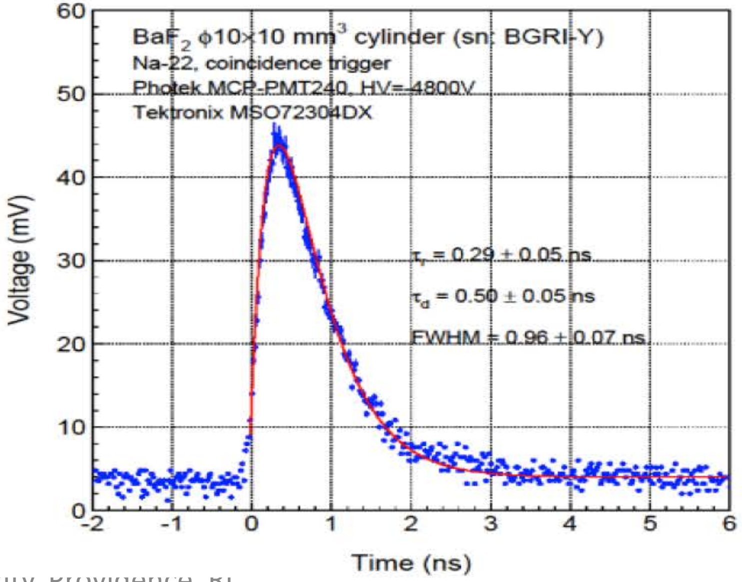




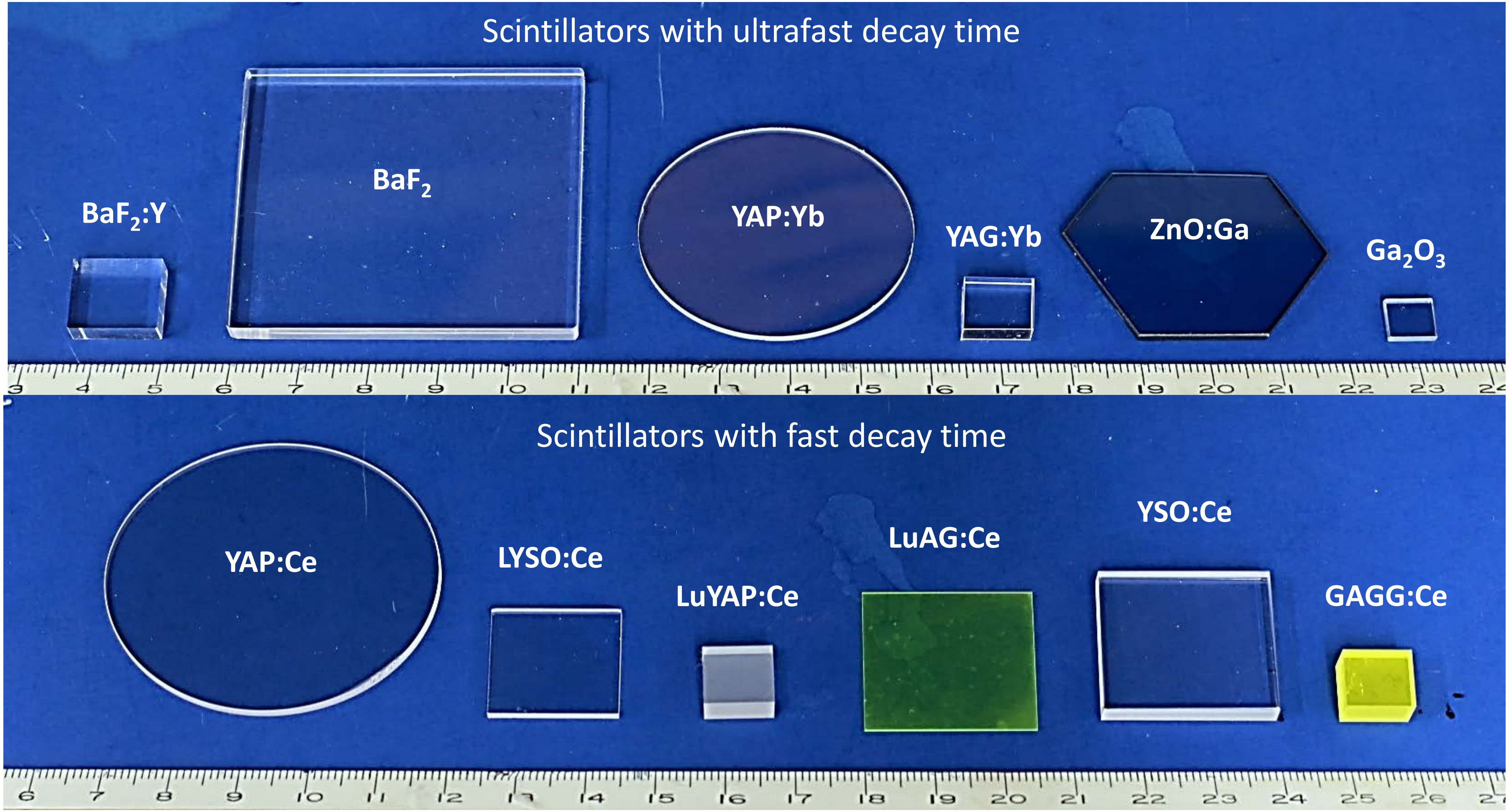








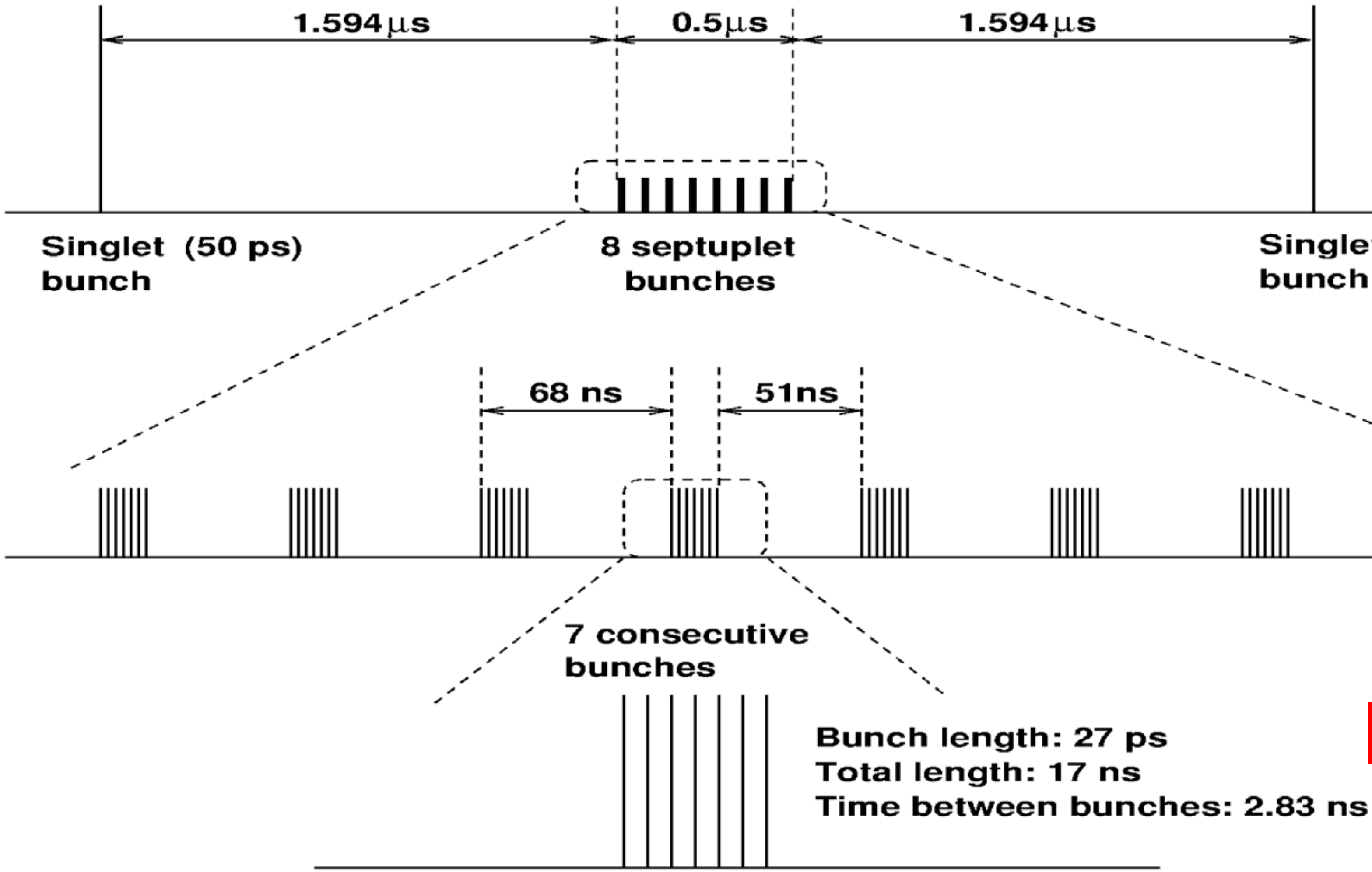
Temporal Response Measured at APS



APS 30 keV X-Ray Hybrid Beam

Singlet (16 mA, 50 ps) isolated from 8 septuplets (88 mA) with 1.594 µs gap; 8 septuplets (88 mA) with a 68 ns period and a 51 ns gap; Each septuplet of 17 ns consists of 7 bunches (27 ps) and 2.83 ns apart; Total beam current: 102 mA, rate: 270 kHz, period: 3.7 µs.

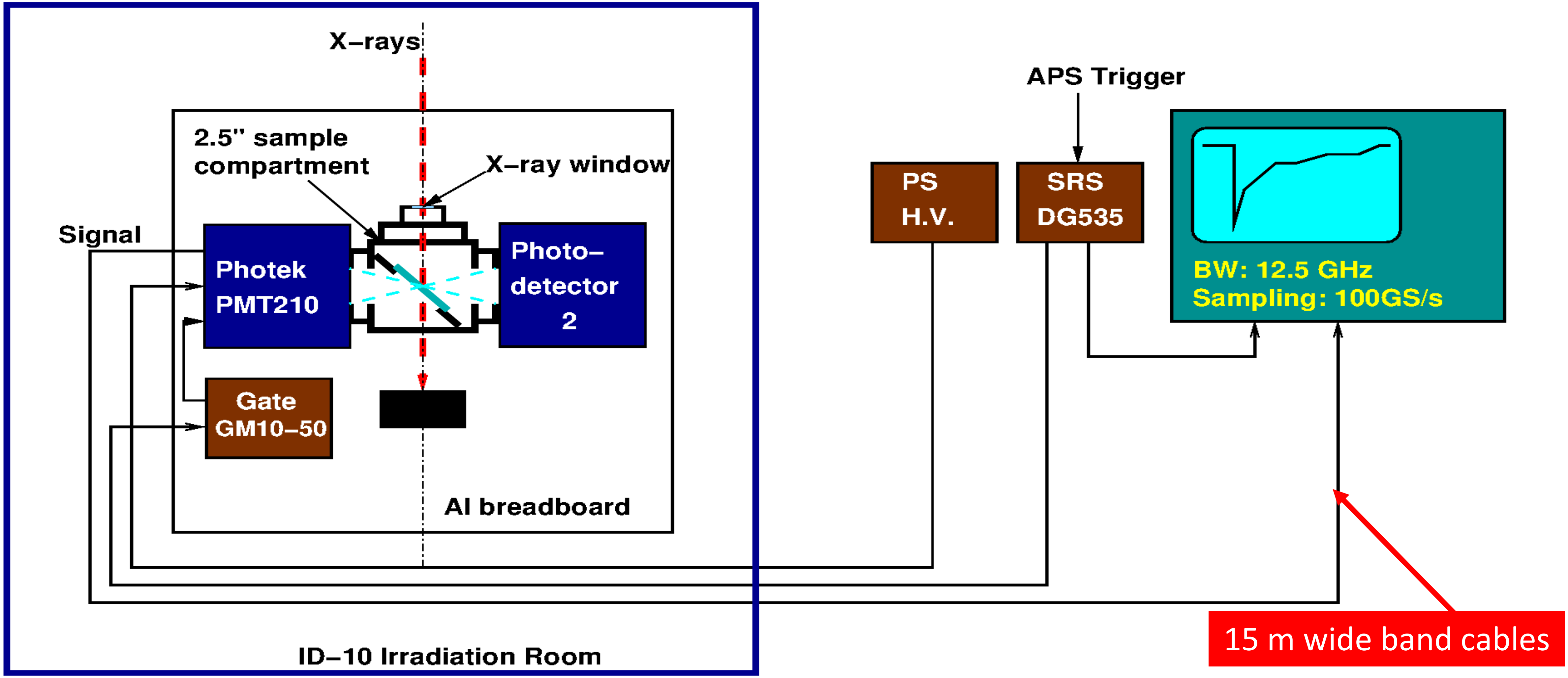
https://ops.aps.anl.gov/SRparameters/node5.html



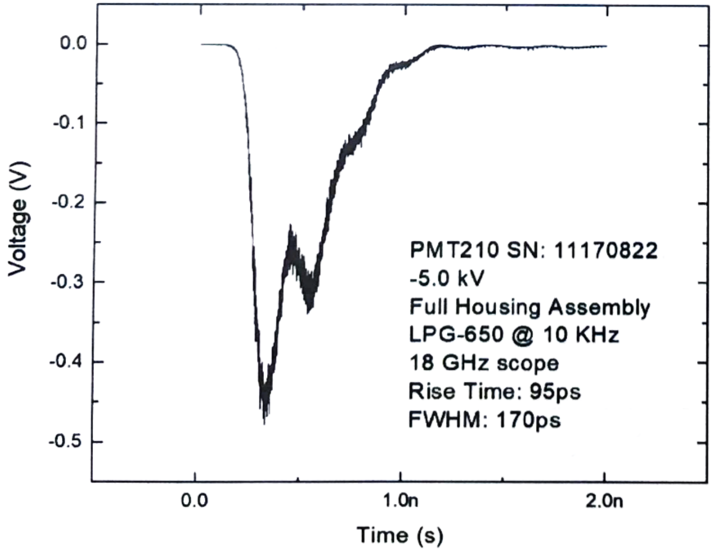
Tested with 2.83 ns x-ray bunches at APS of ANL

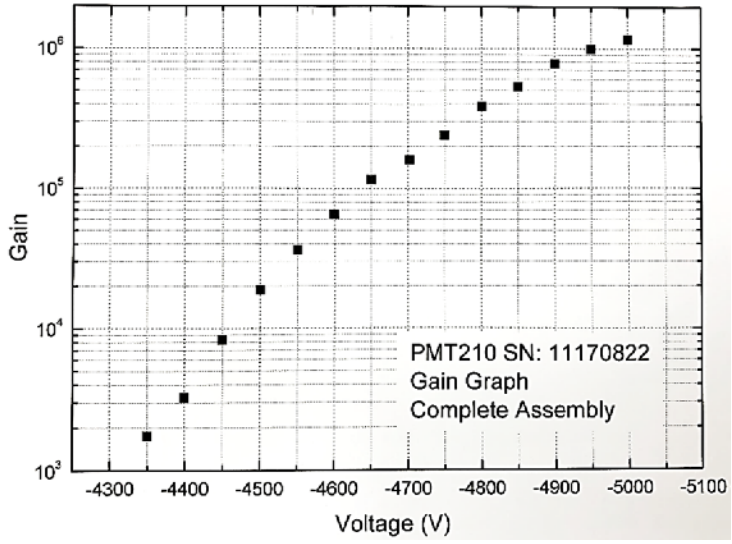
Test Setup at APS Beam Test

Crystals, MCP-PMT and gate unit were in the hutch of the APS 10-ID site; DPO, delay generator and HV power supplier were in the control room; MCP-PMT signal went through a 15 m wideband SMA cable to DPO

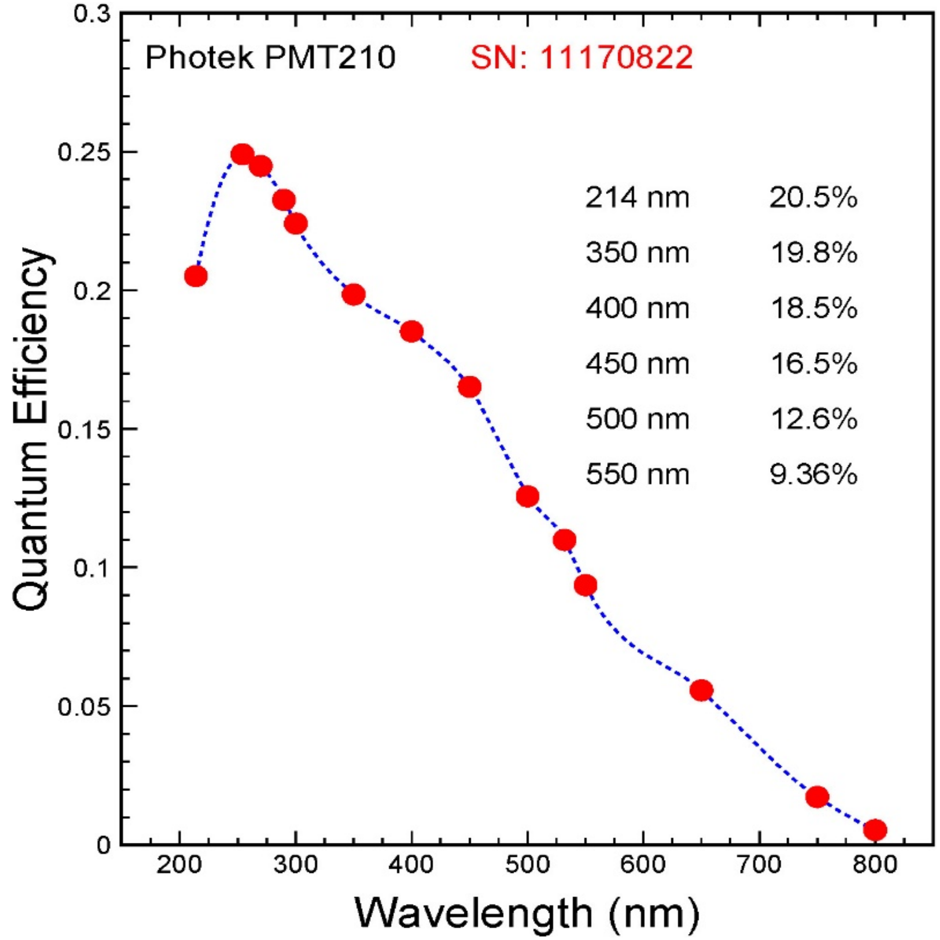


Ultrafast Photek MCP-PMT



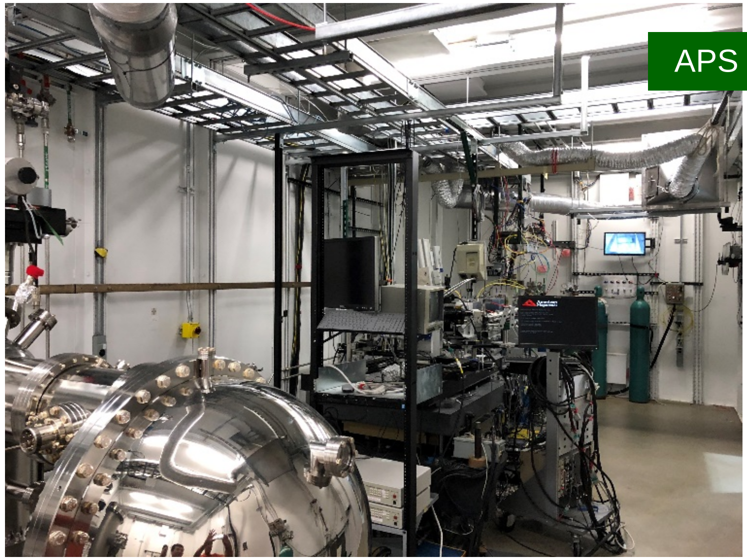


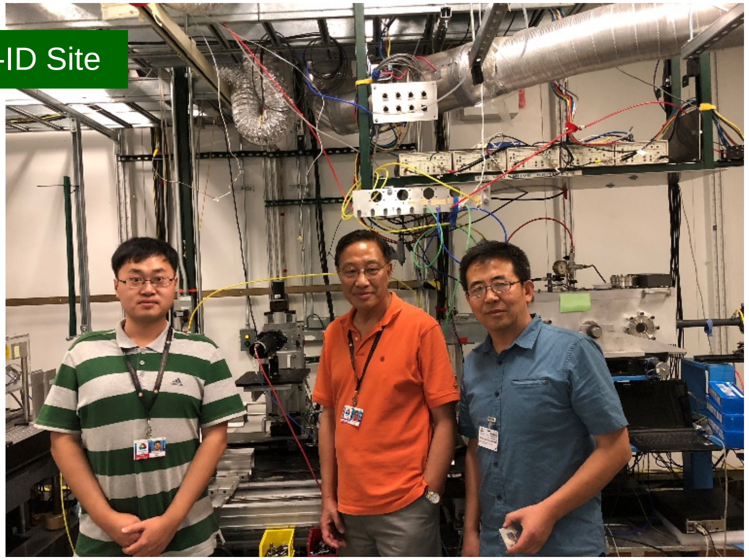
Solar blind cathode needed for BaF2:Y

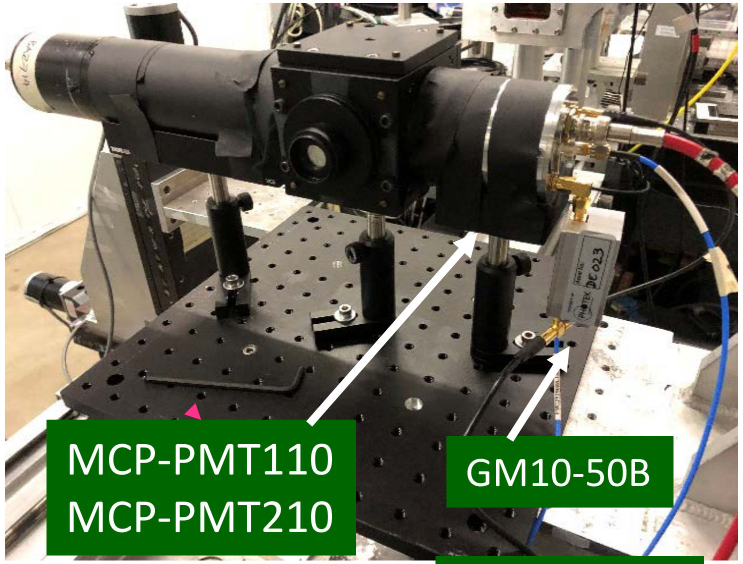


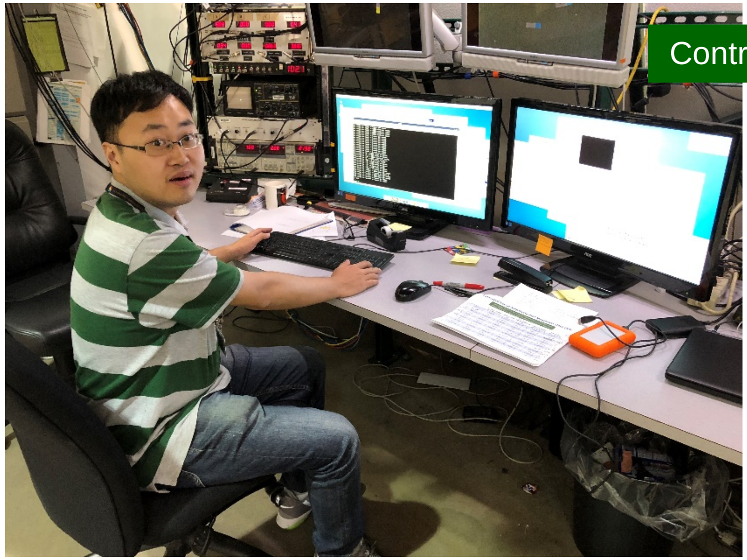
PD	Active area (mm^2)	Spectral range (nm)	Peak sensitivity (nm)	Gain	Rise time (ns)	FWHM (ns)
Hamamatsu PMT R2059	Φ46	160-650	450	2×10^7	1.3	3
Photek MCP PMT110	Φ10	160-850	280-450	1×10^4	**0.065**	**0.11**
Photek MCP PMT210	Φ10	160-850	280-450	1×10^6	**0.095**	**0.17**
Photek MCP PMT240	Φ40	160-850	280-450	1×10^6	**0.18**	**0.85**

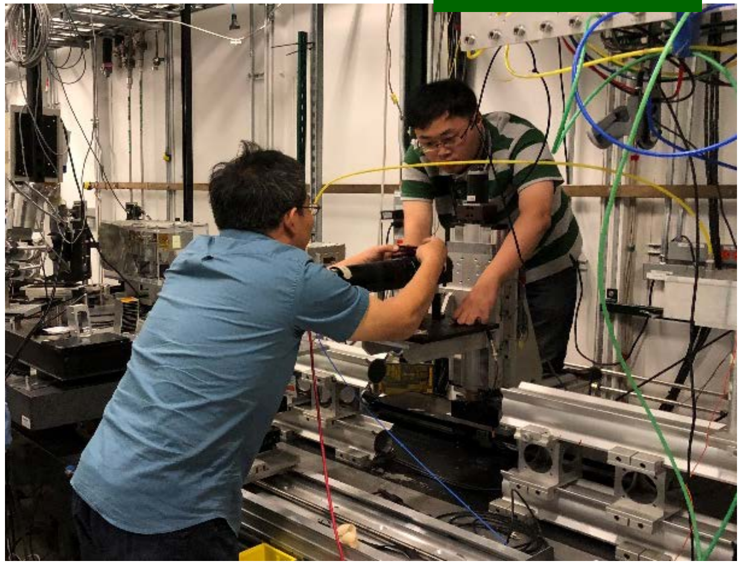
Caltech Team at APS of ANL (July 2 -3, 2018)







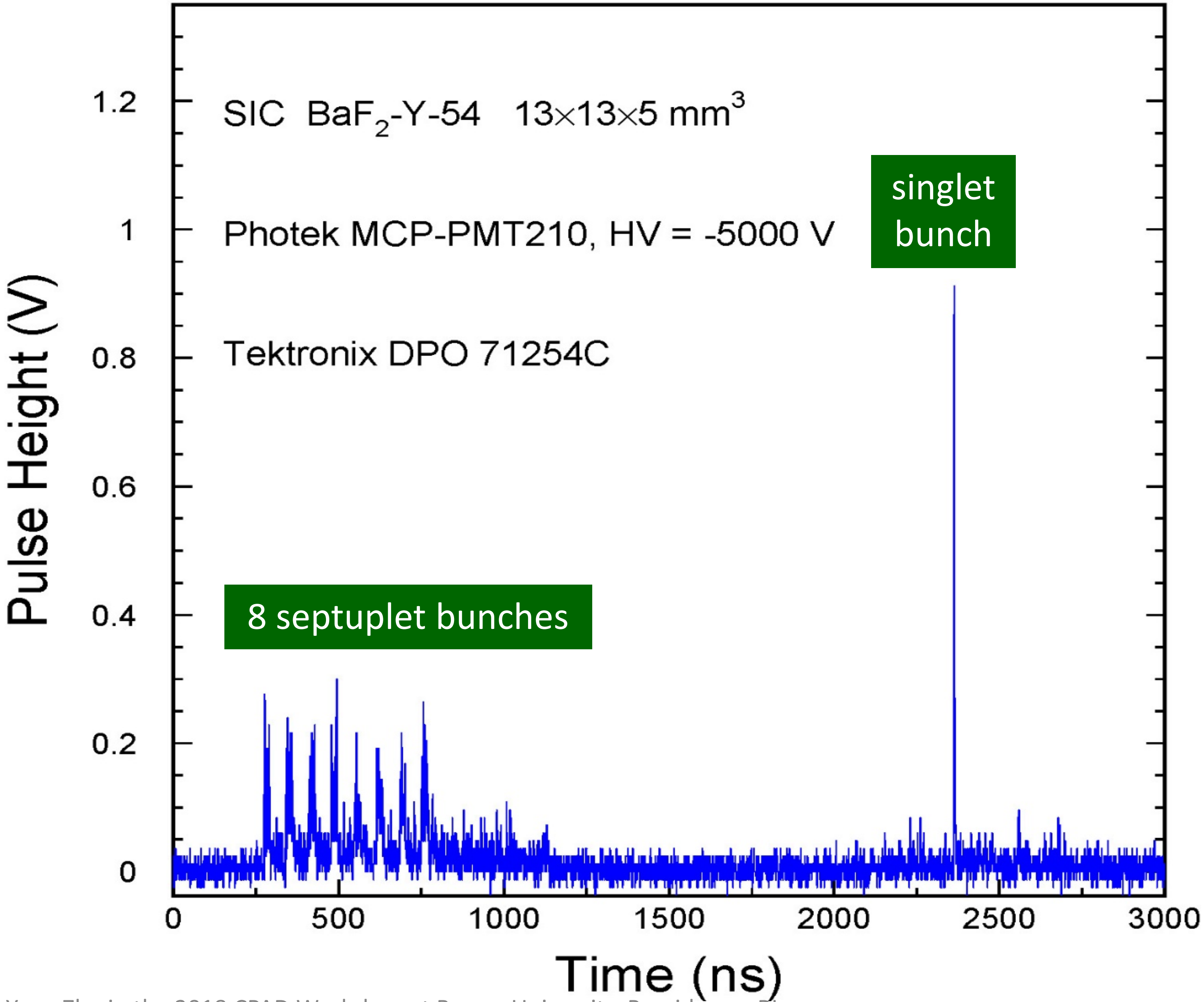




BaF_2:Y Response to Hybrid Beam

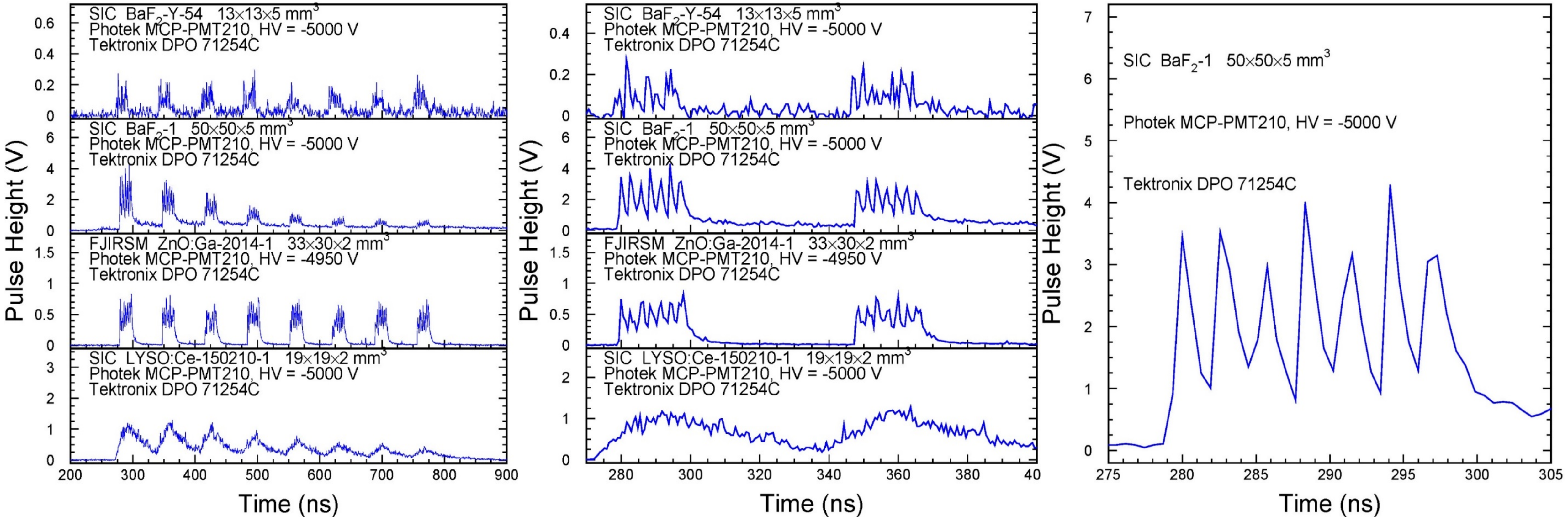
Data taken with ultrafast Photek PMT & gate unit for septuplet bunches show BaF_2:Y's capability for 30 keV X-ray imaging with 2.83 ns bunch spacing. No pile-up for 8 septuplets

Data were also taken for singlet bunches to show various crystal's temporal response.



Septuplets: BaF_2:Y, BaF_2, ZnO:Ga & LYSO

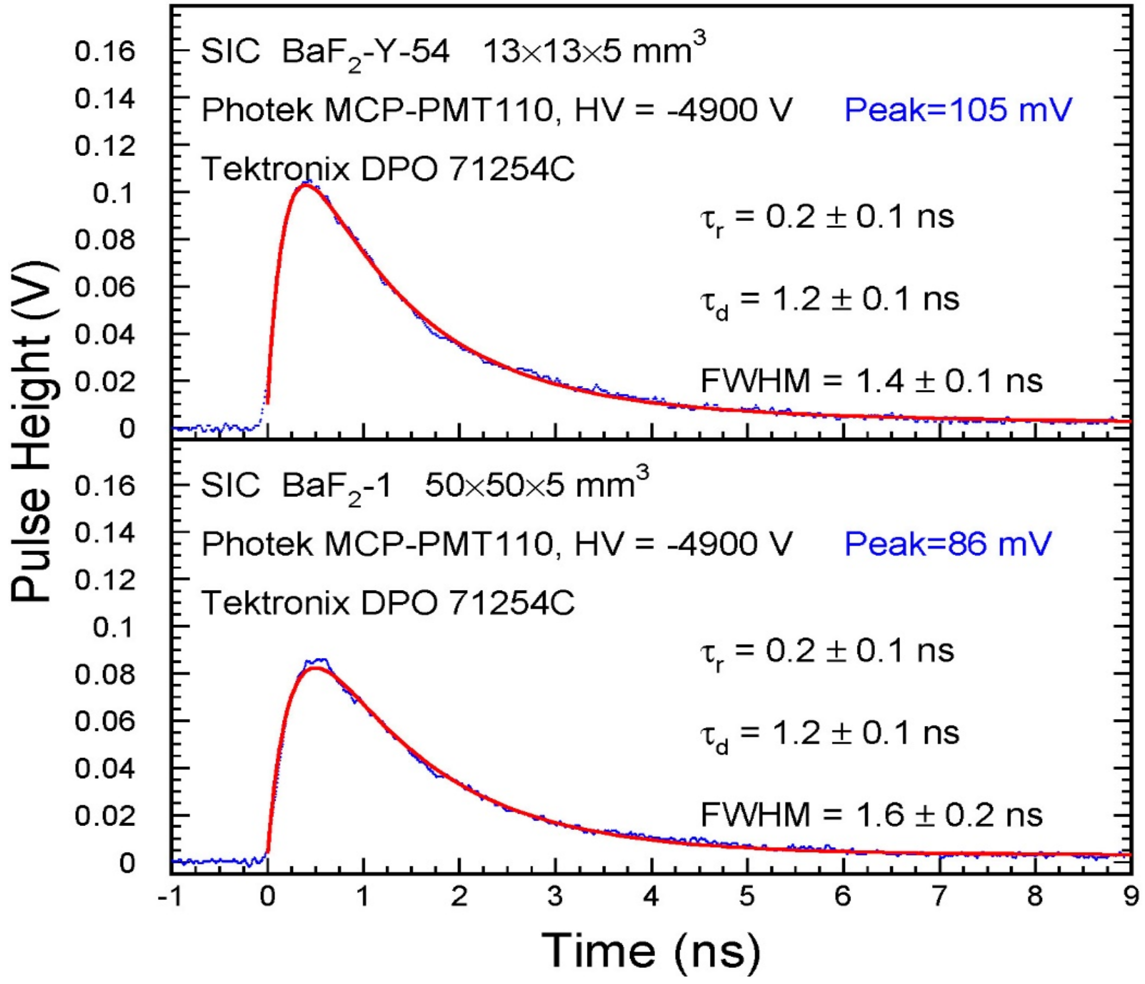
X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals, showing a proof-of-principle for the type –I imager

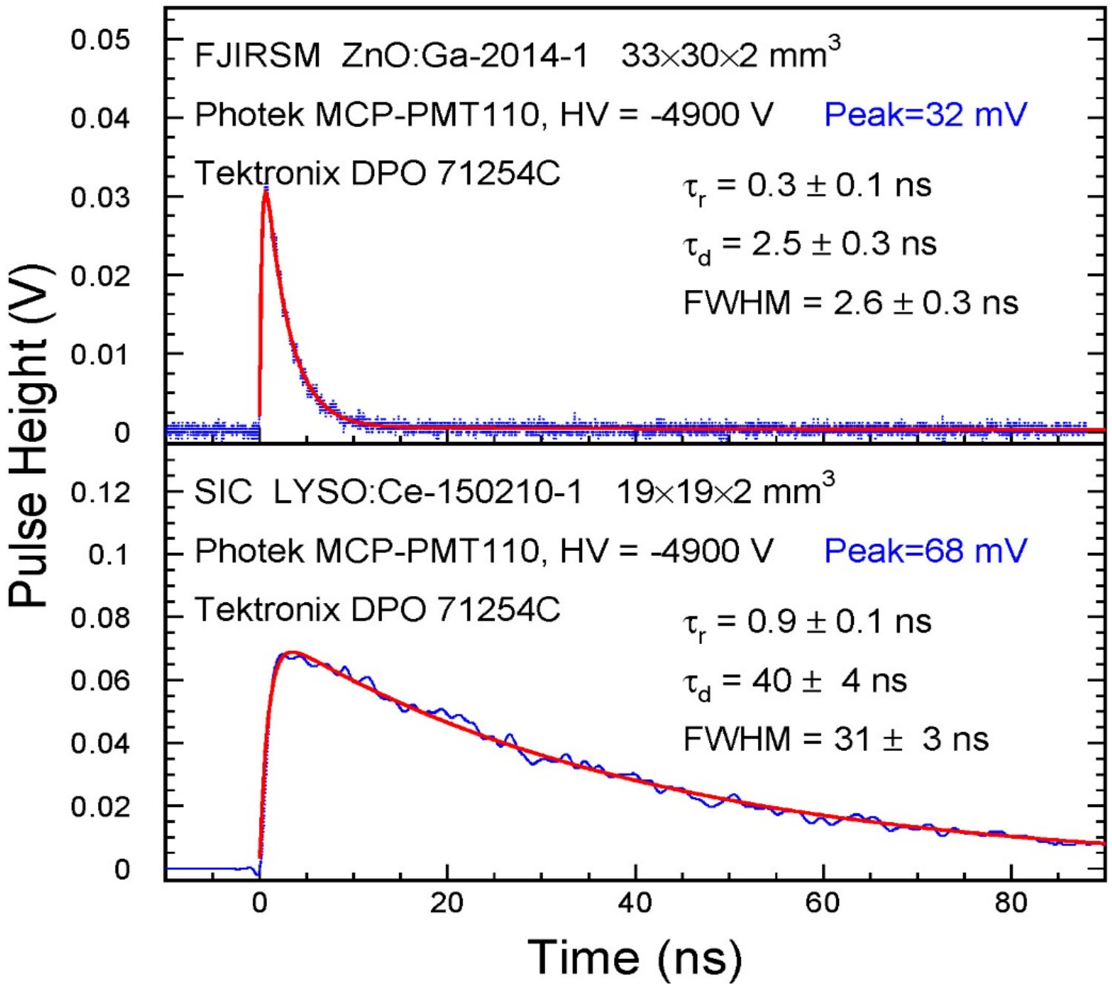


Amplitude reduction in BaF_2 and LYSO due to space charge in PMT from slow scintillation, but not in BaF_2:Y
Reducing the 15 m cable length will reduce BaF_2 pulse width to sub-ns for a much better bunch separation

Singlet: BaF_2:Y, BaF_2, ZnO & LYSO

Amplitude of BaF_2:Y and BaF_2 higher than LYSO and ZnO:Ga, expected as light output in the 1st ns

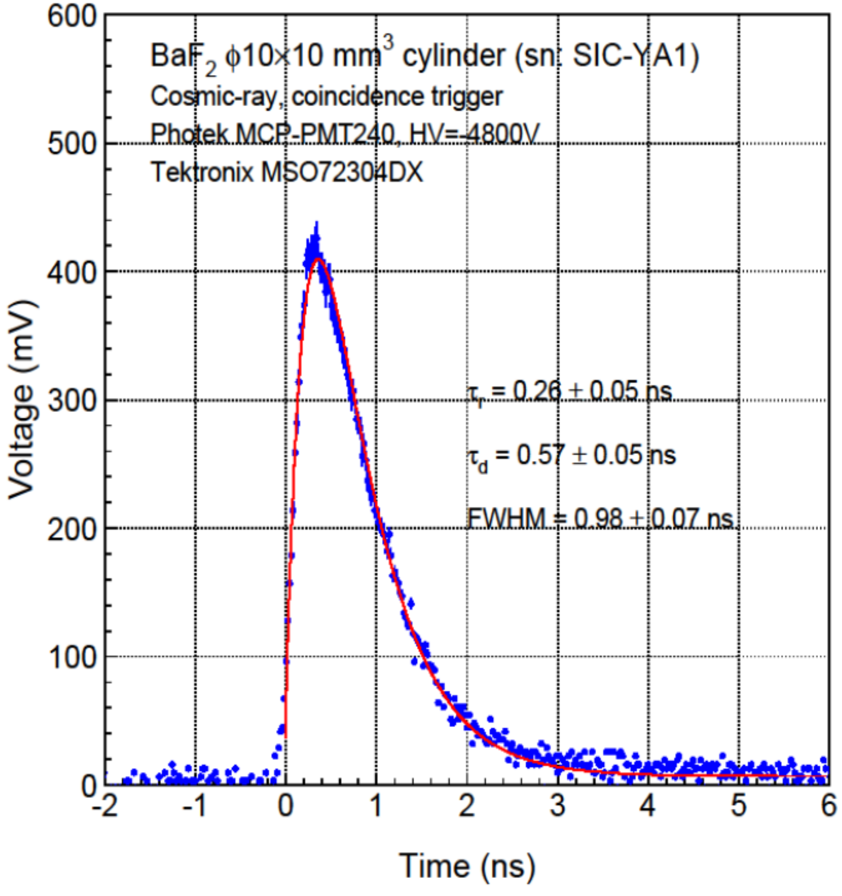


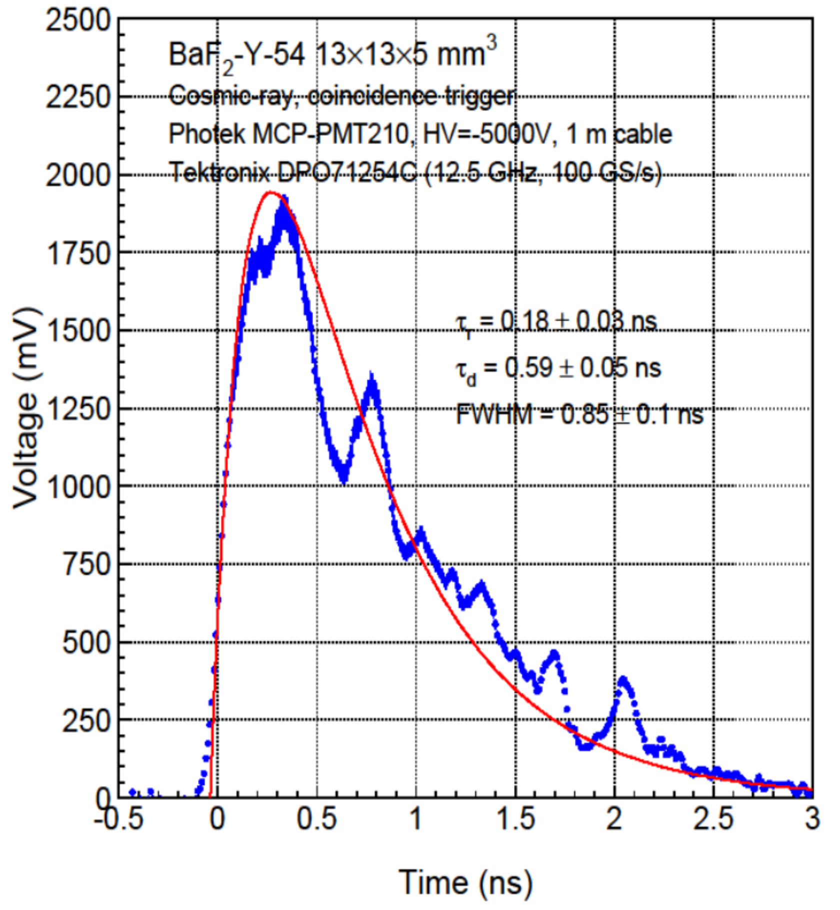


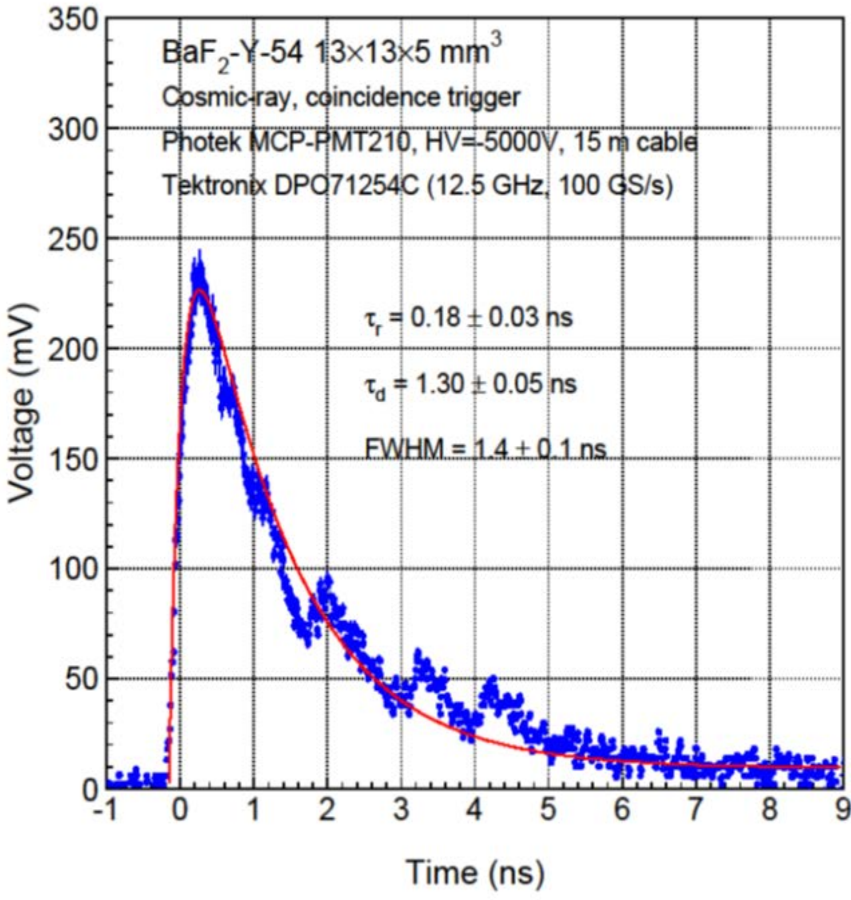
Decay of BaF_2:Y and BaF_2 shorter than ZnO:Ga, but longer than ɣ-ray data due to the 15 m cable

Temporal Response of BaF_2:Y

Significantly slower responses observed at APS with a 15 m cable as compared to pulses measured with a 1 m cable at Caltech

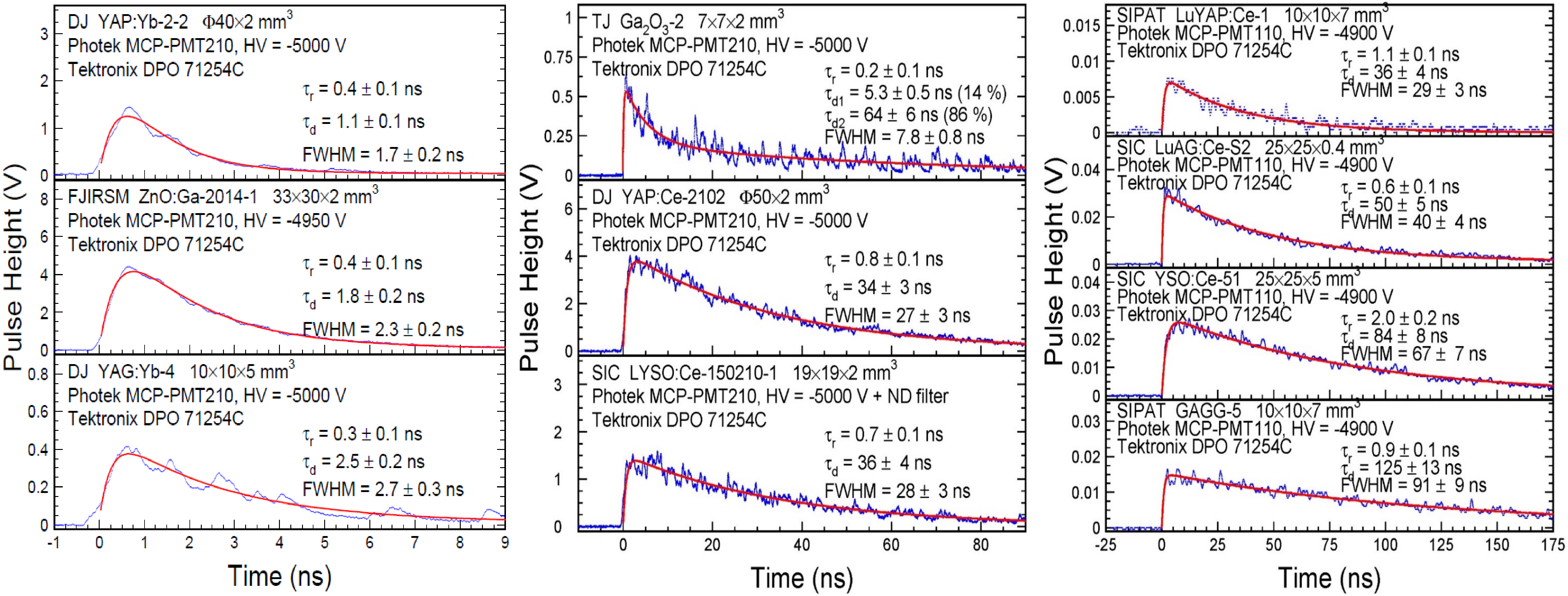






Singlet: Temporal Response

YAP:Yb, ZnO:Ga, YAG:Yb and GaO have pulse width less than 10 ns



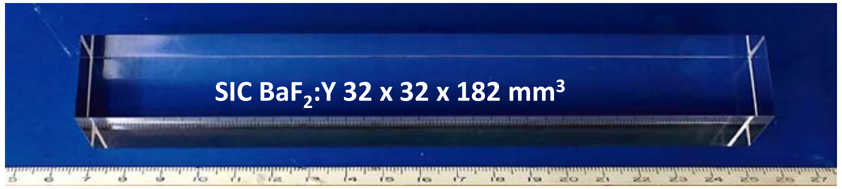
Decay time consists with our Lab data measured with γ-ray source

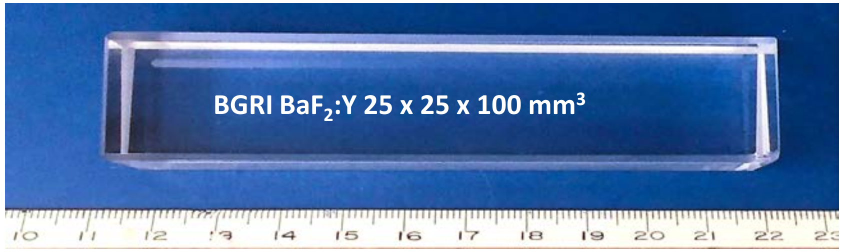
Summary: Temporal Response

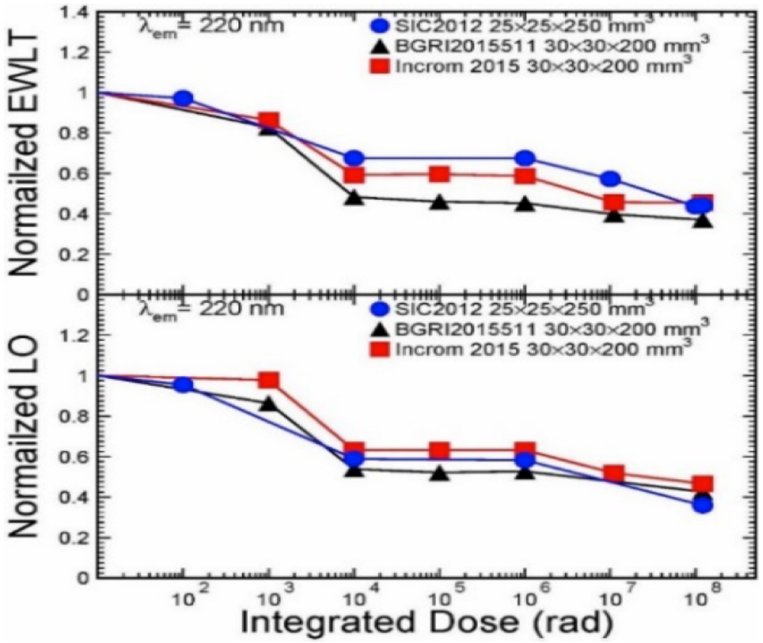
Crystal	Vendor	ID	Dimension (mm³)	Emission Peak (nm)	EWLT (%)	LO (p.e./MeV)	Light Yield in 1st ns (ph/MeV)	Rising Time (ns)	Decay Time (ns)	FWHM (ns)
BaF_2:Y	SIC	4	10×10×5	220	89.1	258	1200	**0.2**	**1.2**	**1.4**
BaF_2	SIC	1	50×50×5	220	85.1	209	1200	**0.2**	**1.2**	**1.6**
YAP:Yb	Dongjun	2-2	Φ40×2	350	77.7	9.1*	28	**0.4**	**1.1**	**1.7**
ZnO:Ga	FJIRSM	2014-1	33×30×2	380	7	76*	157	**0.4**	**1.8**	**2.3**
YAG:Yb	Dongjun	4	10×10×5	350	83.1	28.4*	24	**0.3**	**2.5**	**2.7**
Ga_2O_3	Tongji	2	7x7x2	380	73.8	259	43	**0.2**	**5.3**	**7.8**
YAP:Ce	Dongjun	2102	Φ50×2	370	54.7	1605	391	**0.8**	**34**	**27**
LYSO:Ce	SIC	150210-1	19x19×2	420	80.1	4841	740	**0.7**	**36**	**28**
LuYAP:Ce	SIPAT	1	10×10×7	385	\	1178	125	**1.1**	**36**	**29**
LuAG:Ce Ceramic	SIC	S2	25×25×0.4	520	52.3	1531	240	**0.6**	**50**	**40**
YSO:Ce	SIC	51	25×25×5	420	72.6	3906	318	**2.0**	**84**	**67**
GAGG:Ce	SIPAT	5	10×10×7	540	\	3212	239	**0.9**	**125**	**91**

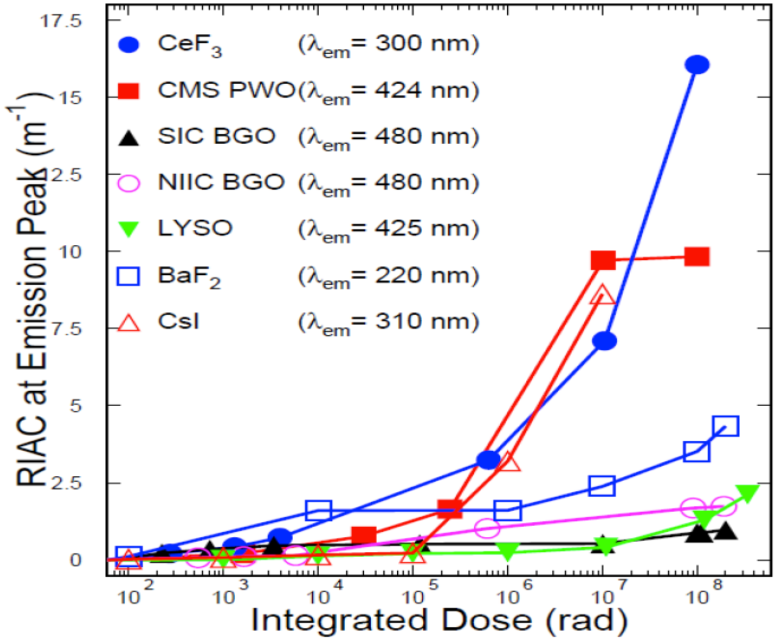
Samples are ordered based on its FWHM to singlet bunches

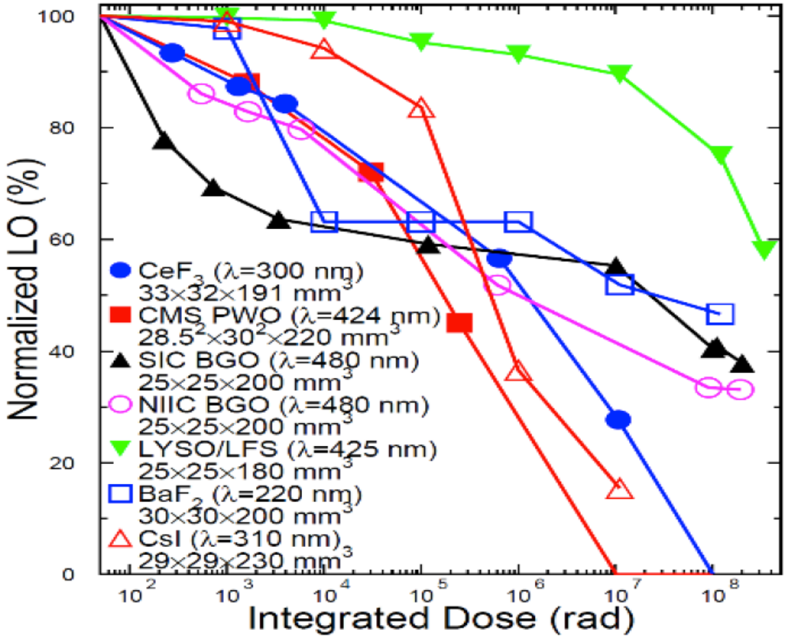
γ-Ray Induced Damage in Large Samples



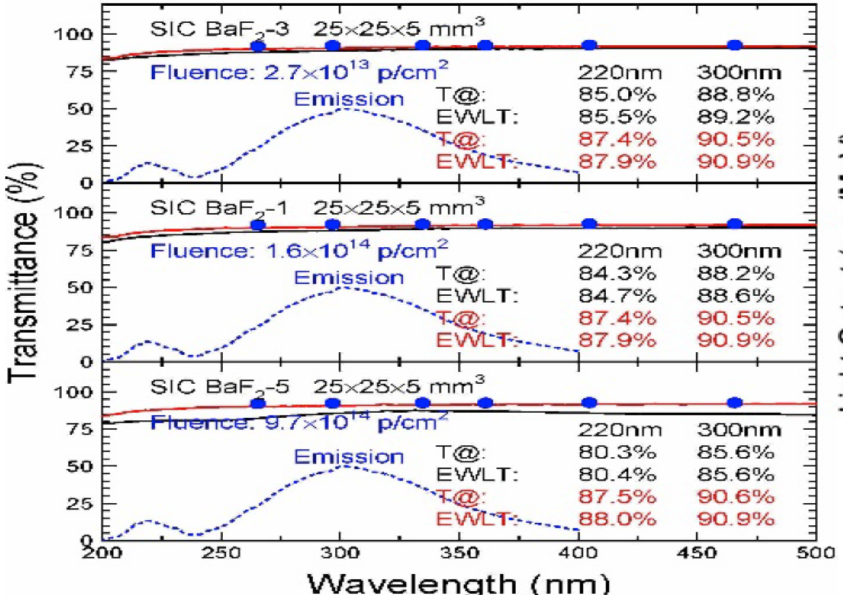


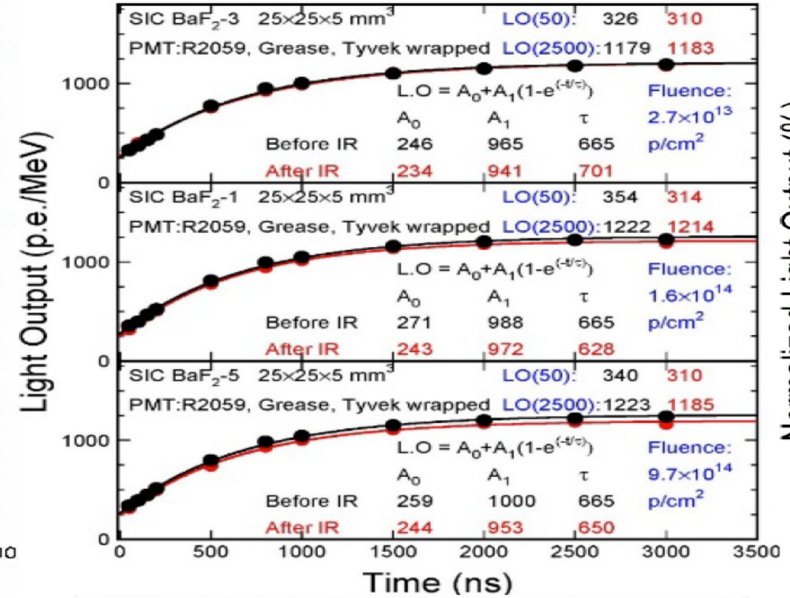


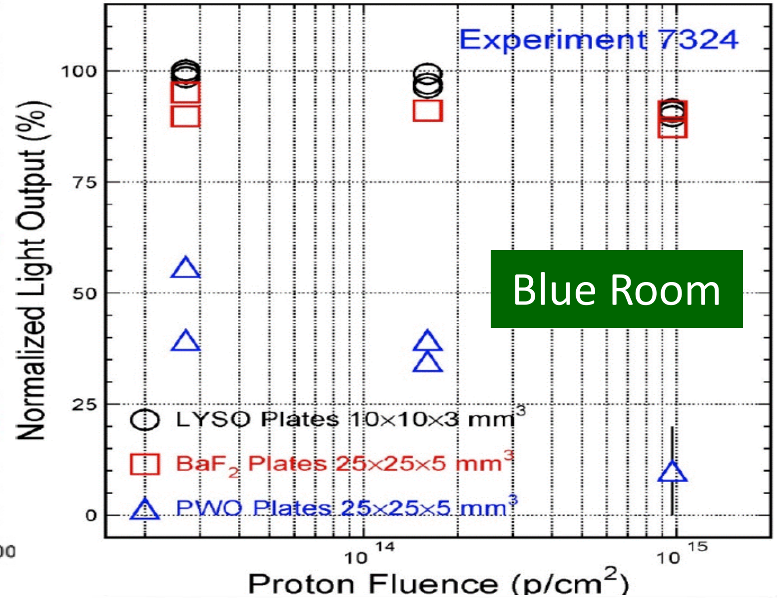


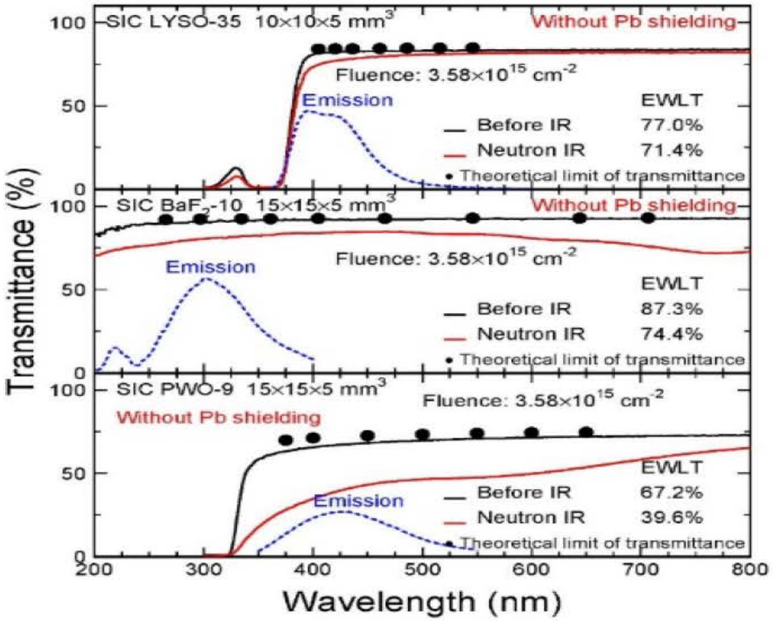


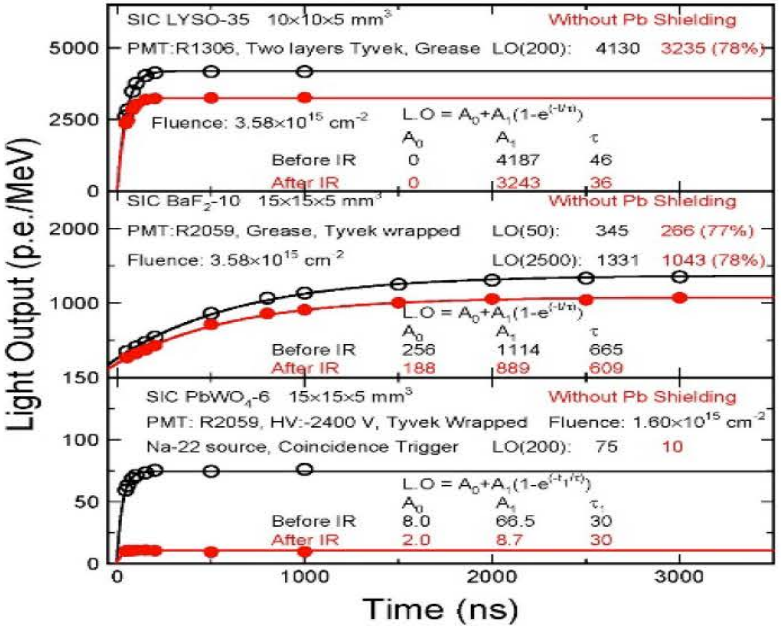
Proton and Neutron Induced Damage

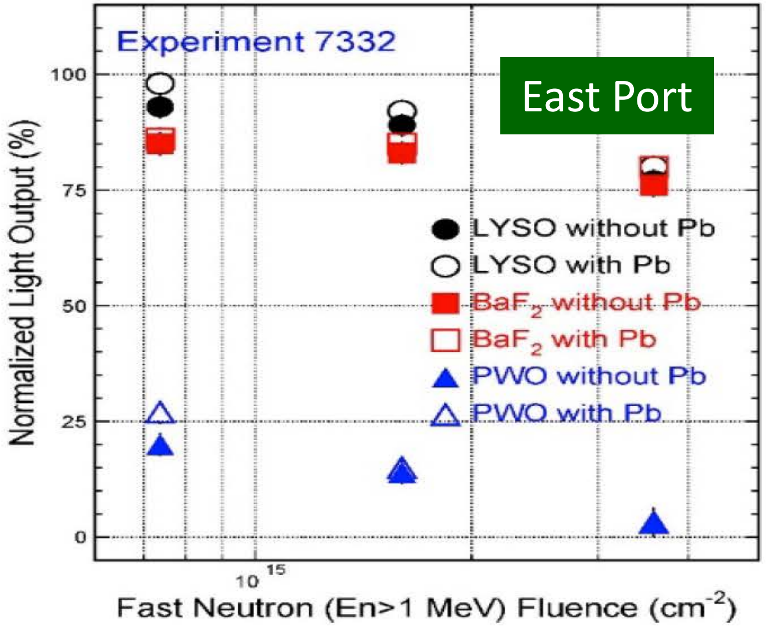






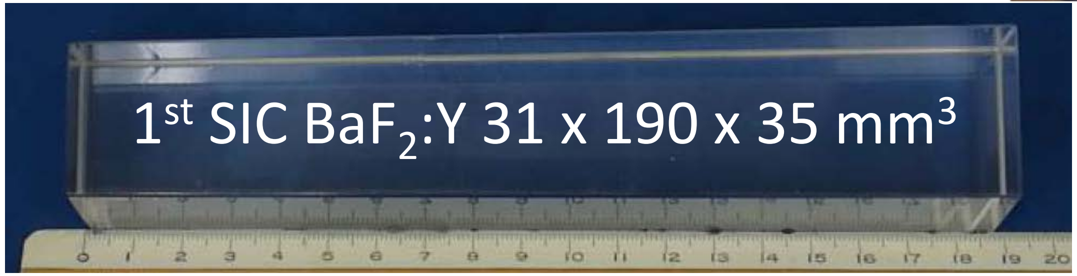


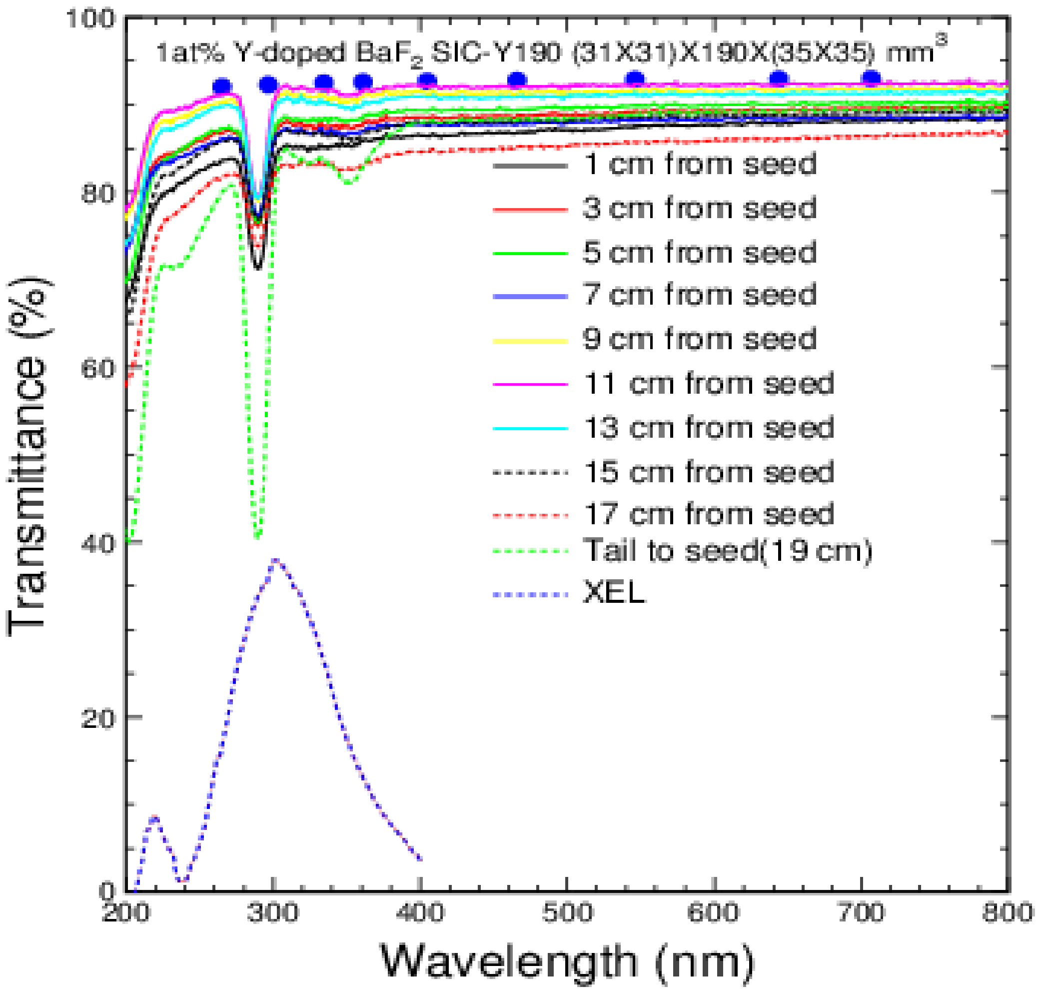


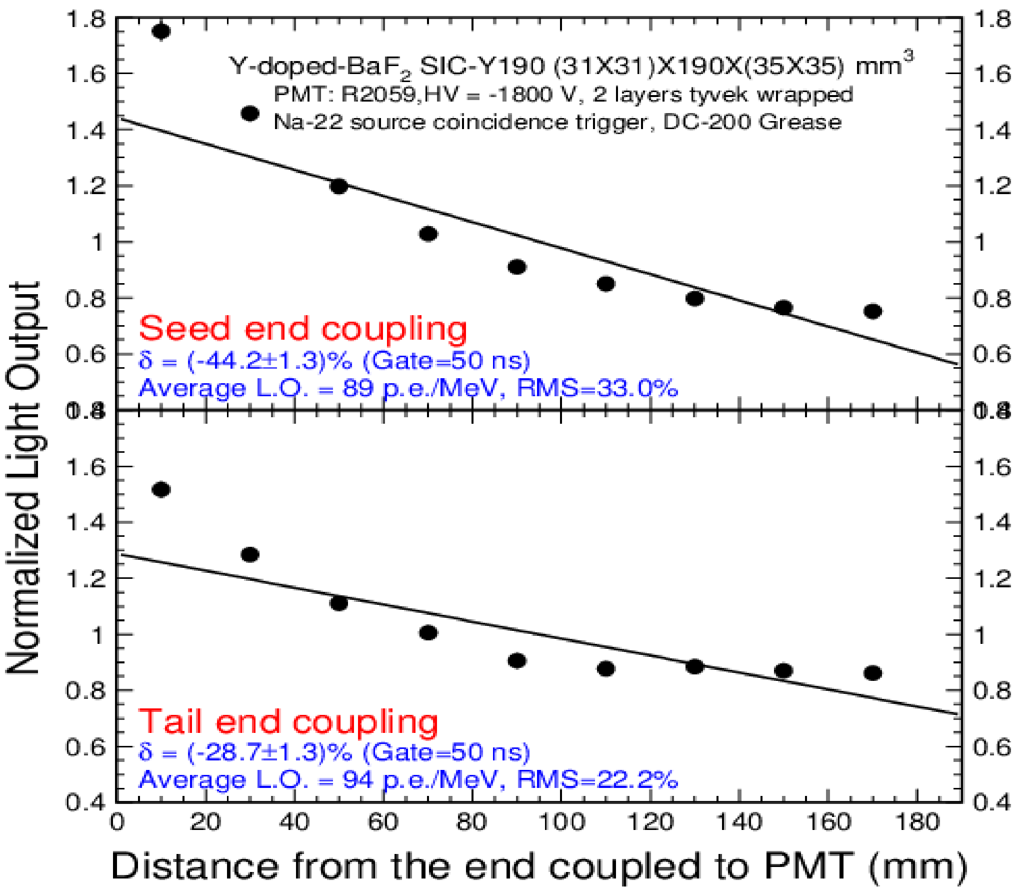


The 1st 19 cm BaF_2:Y from SIC

J. Chen *et al*, IEEE TNS 65 (2018) 2147-2151
F/S ratio: 1.3; LRU: 22% & 33%

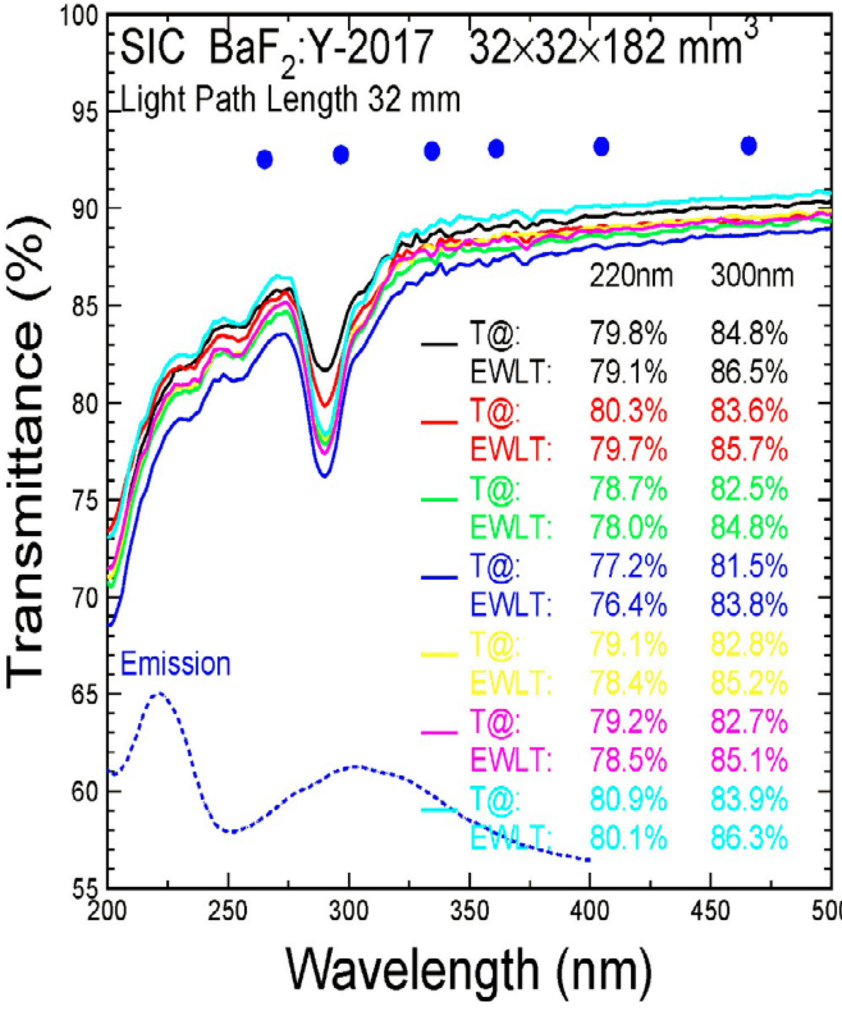


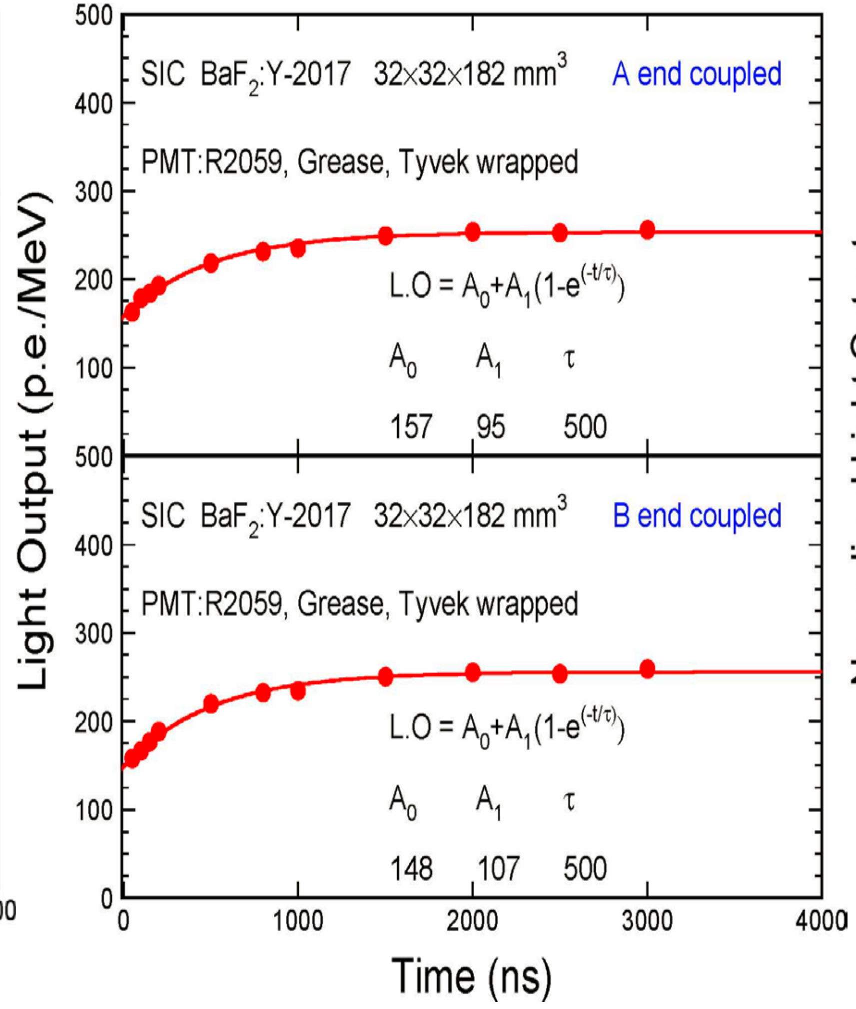


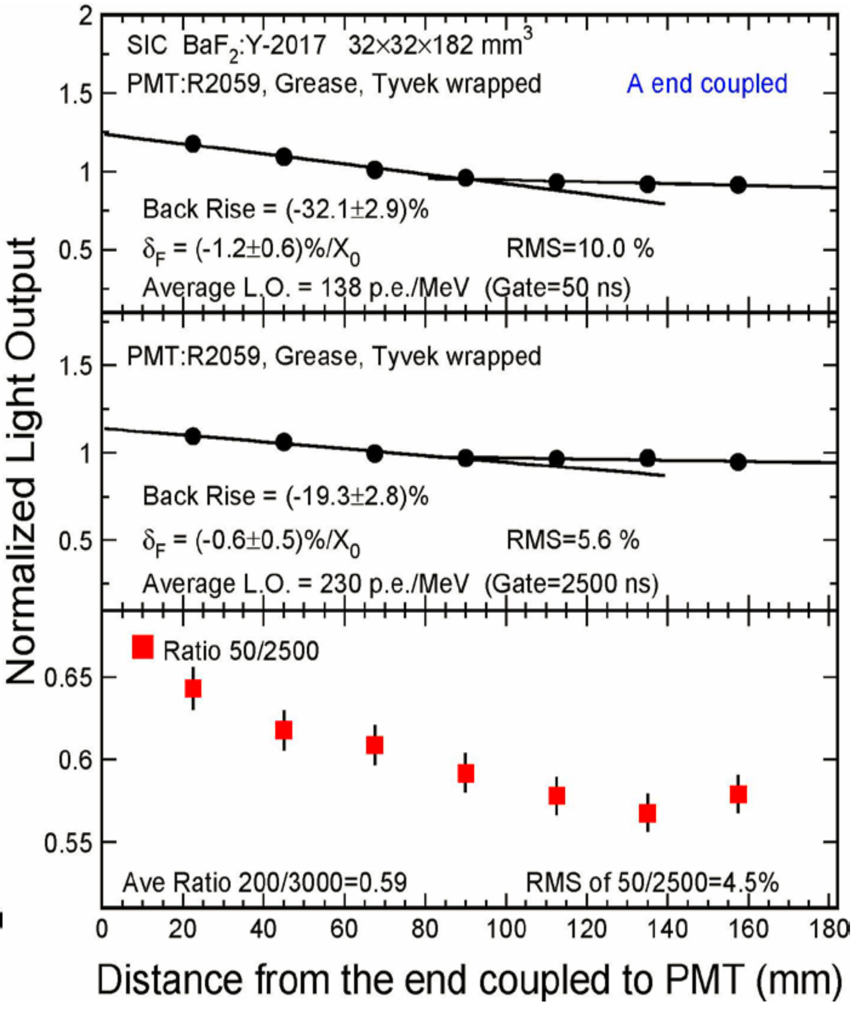


Performance of the 2nd SIC 18 cm BaF_2:Y

F/S of 1.6 and LRU of 10% for the fast

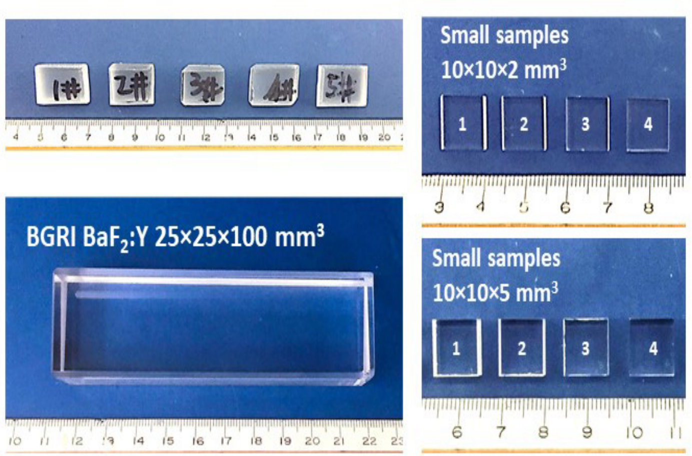


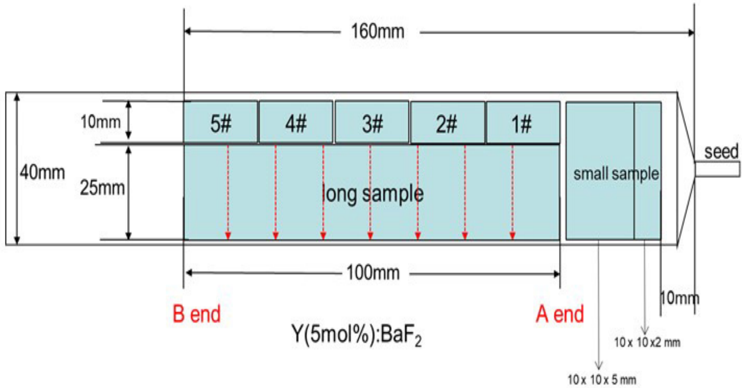


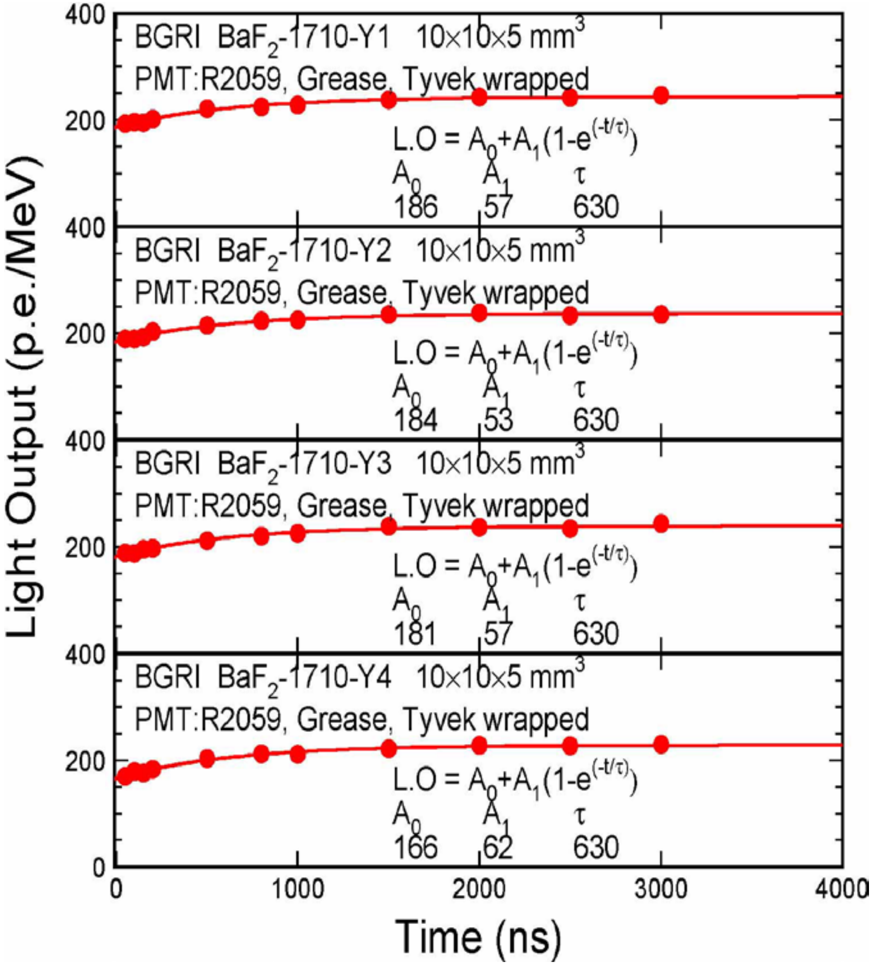


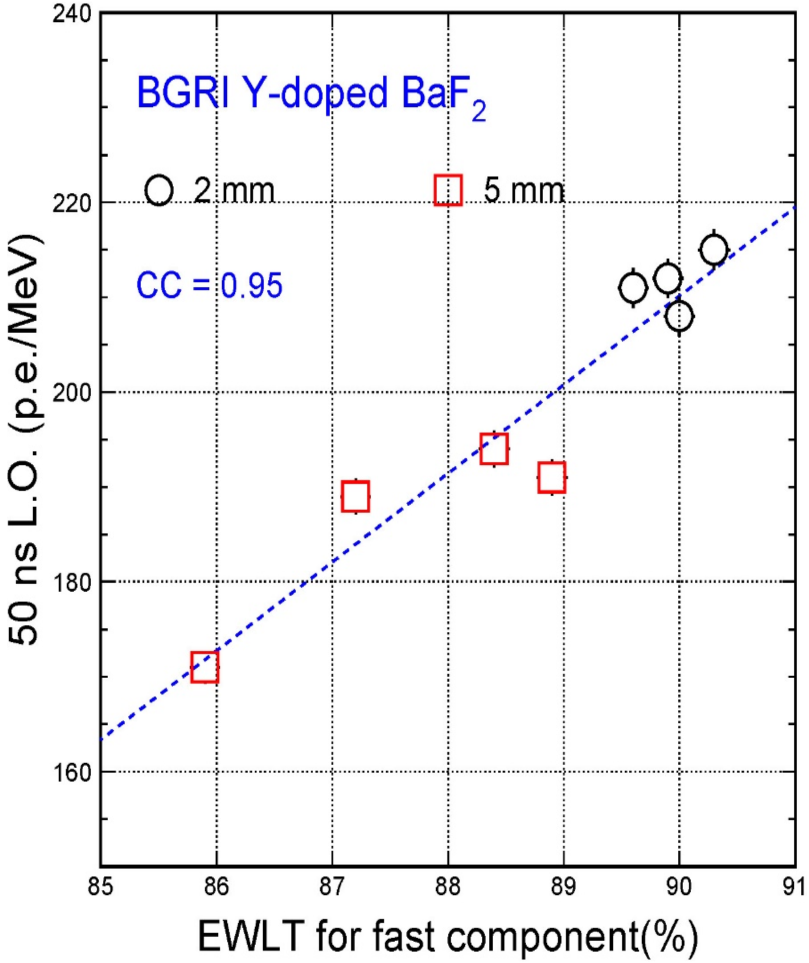
1^{st} BGRI 10 cm BaF_2:Y Sample

F/S of 3.5 is found, and good correlation between LO and EWLT



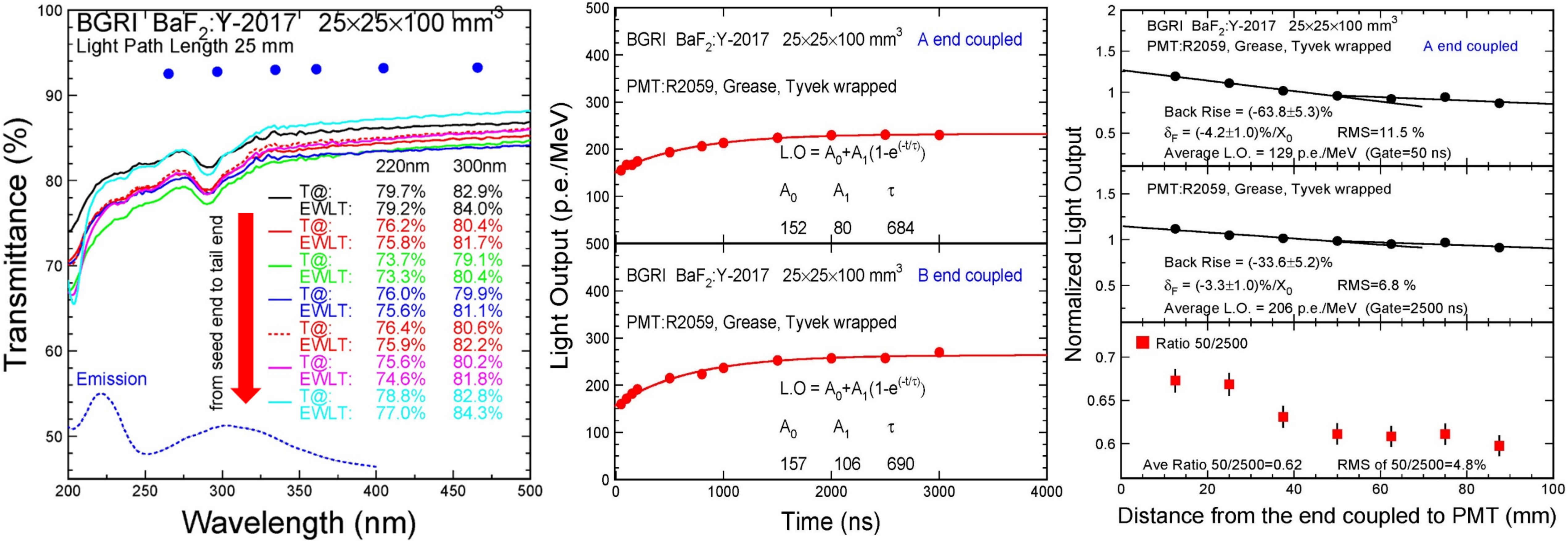




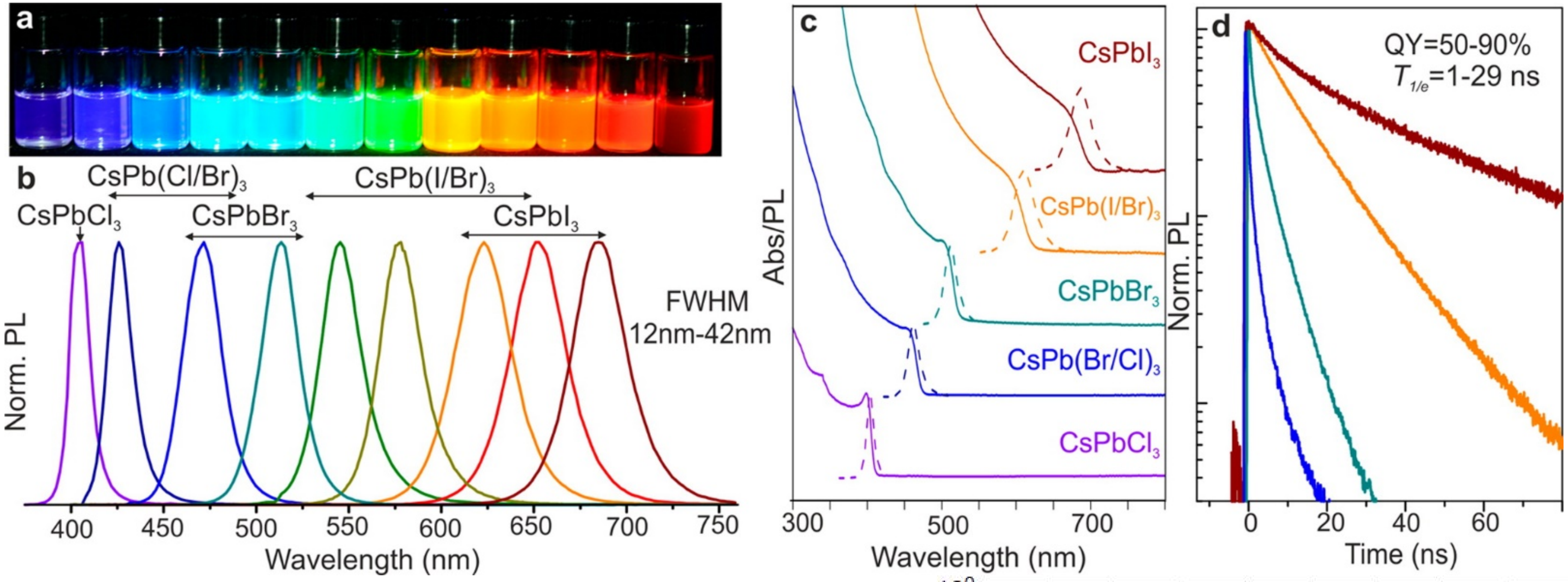


Performance of BGRI 10 cm BaF_2:Y

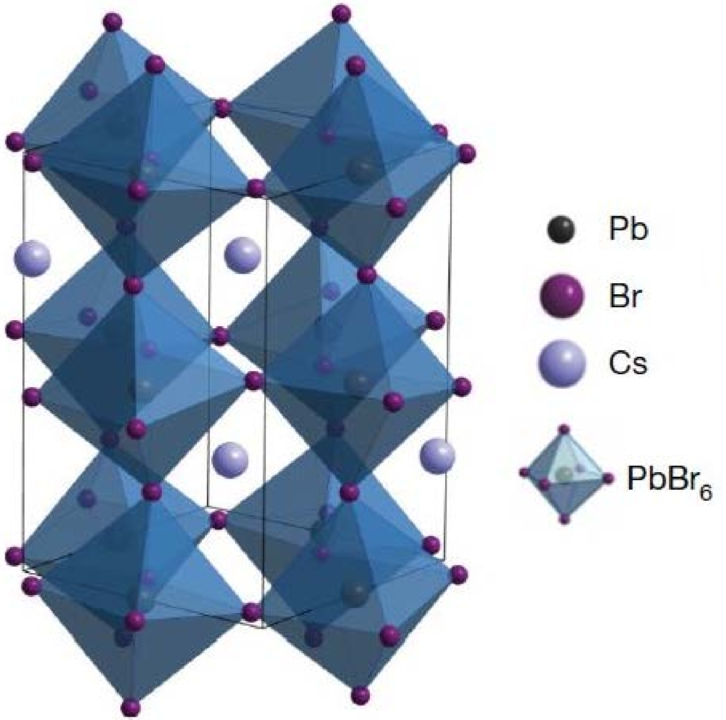
F/S increased up to 1.9; LRU: 12% and 6.8% for fast and total



All Inorganic Cs Pb Halide Perovskite QD

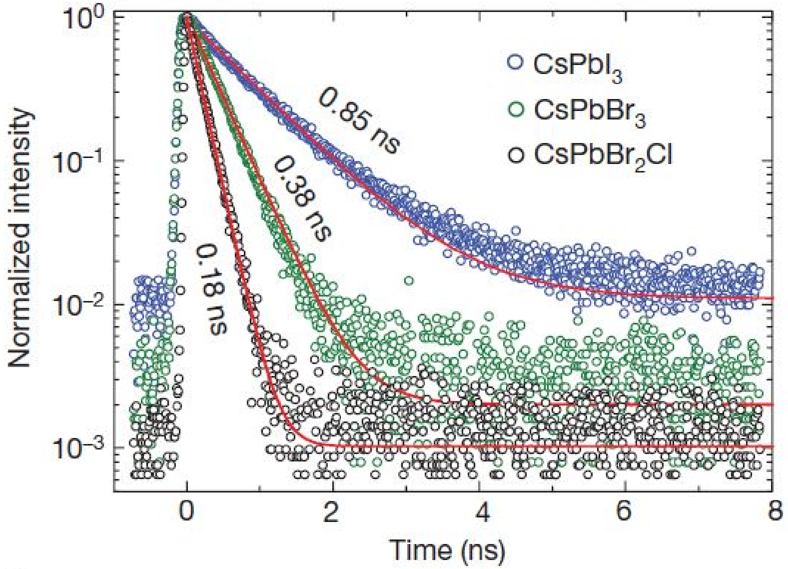


2015 | VOL 15 | Nano Lett. | 3692-3696



11 january 2018 | VOL 553 | Nature | 189

Absorption, emission wavelength and decay time can be tuned for size and composition with quantum efficiency up to 90%.

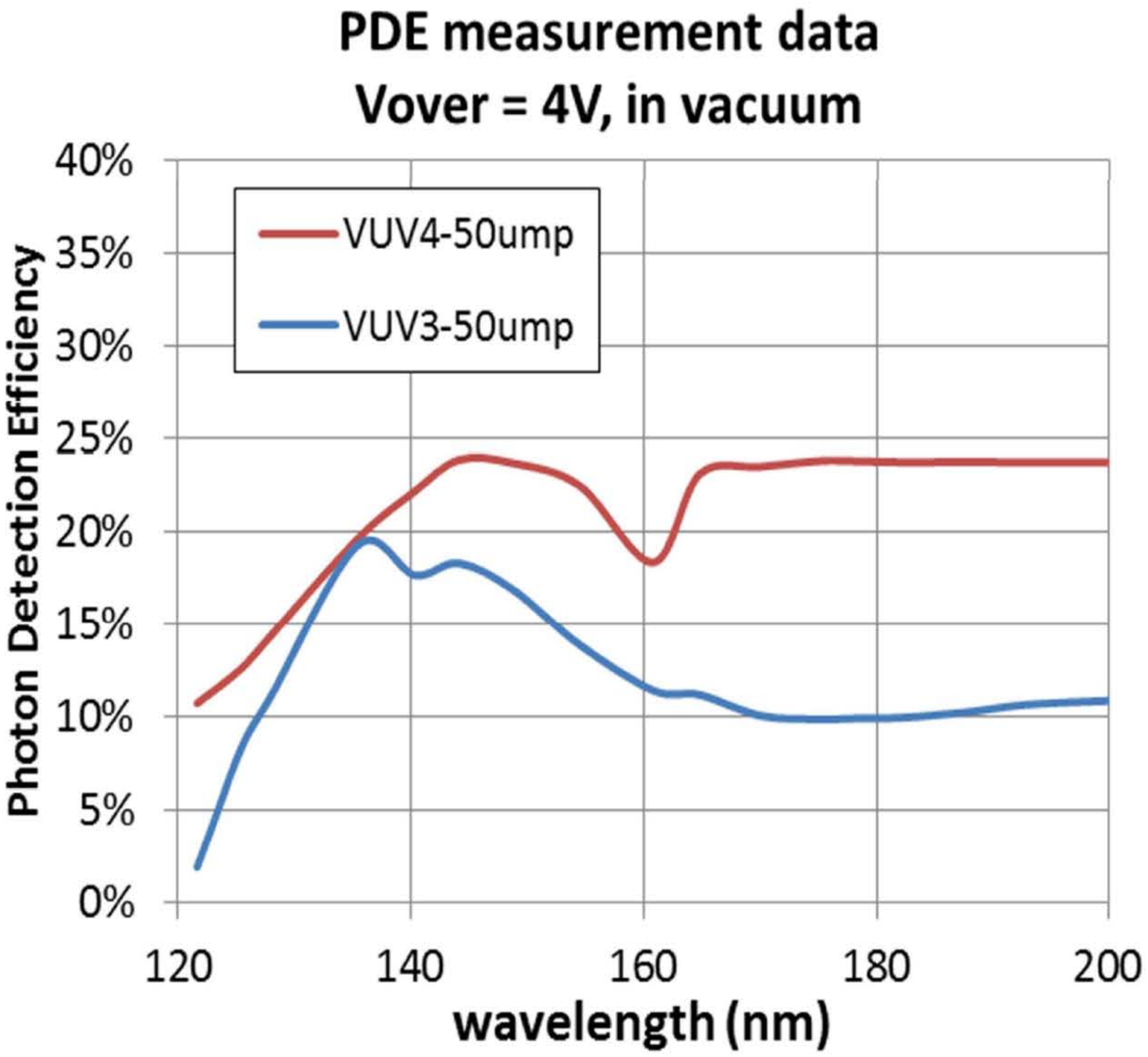


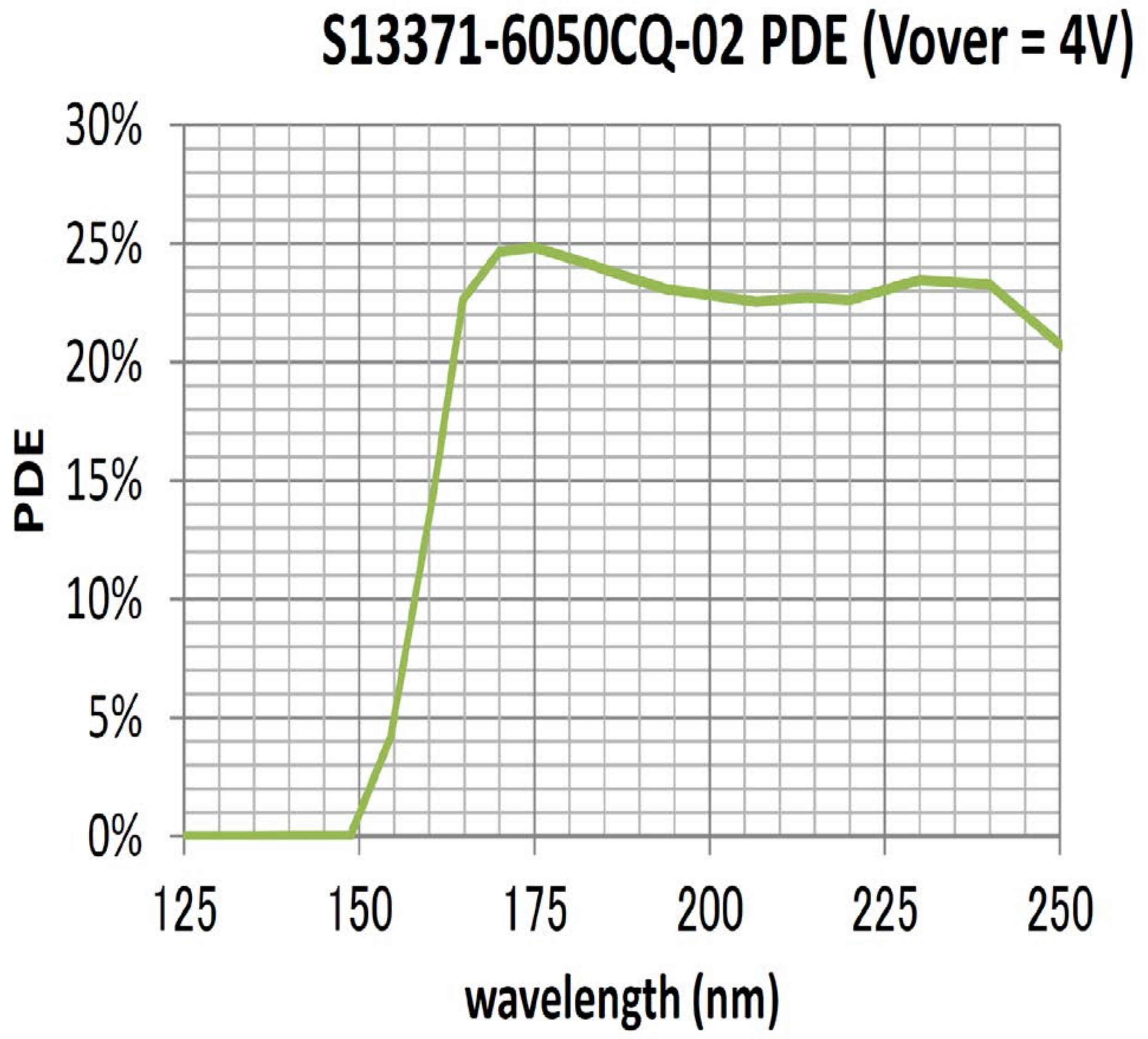
Summary

- Commercially available undoped BaF_2 crystals provide ultrafast 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. With sub-ns pulse width BaF_2:Y is a promising material for the proposed Mu2e-II calorimeter and the front imager for GHz hard X-ray imaging.
- 20 cm long BaF_2 crystals are rad hard up to 120 Mrad. Results of the LANL irradiation experiments show 800 MeV protons and fast neutrons up to 1 x 10^{15} p/cm^2 and 3.6 x 10^{15} n/cm^2 respectively do not cause significant light output loss in 5 mm thick LYSO and BaF_2 plates, promising a very fast and robust detector in a severe radiation environment, such as the HL-LHC.
- Additional ultrafast scintillators under development are ZnO:Ga films, quantum confinement based all inorganic Cs Pb halide perovskite QD.

Acknowledgements: DOE HEP Award DE-SC0011925

Hamamatsu S13371 VUV SiPM





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)

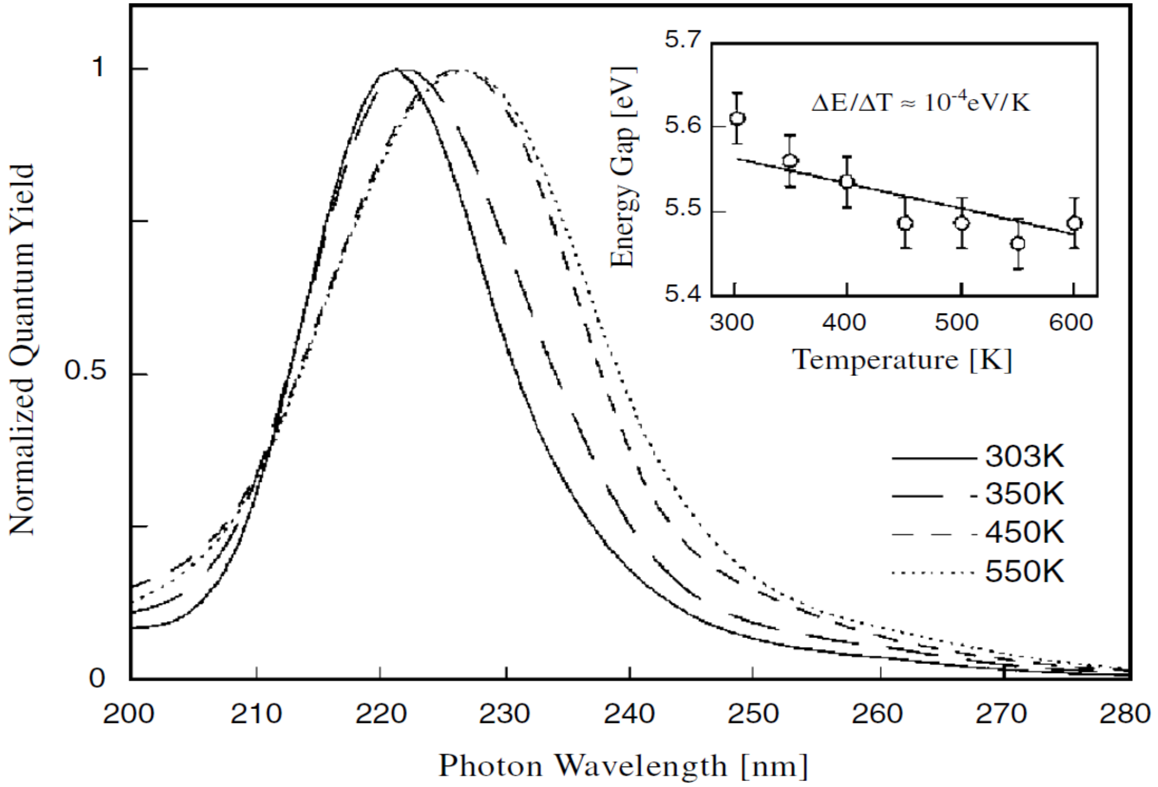


Figure 6. Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

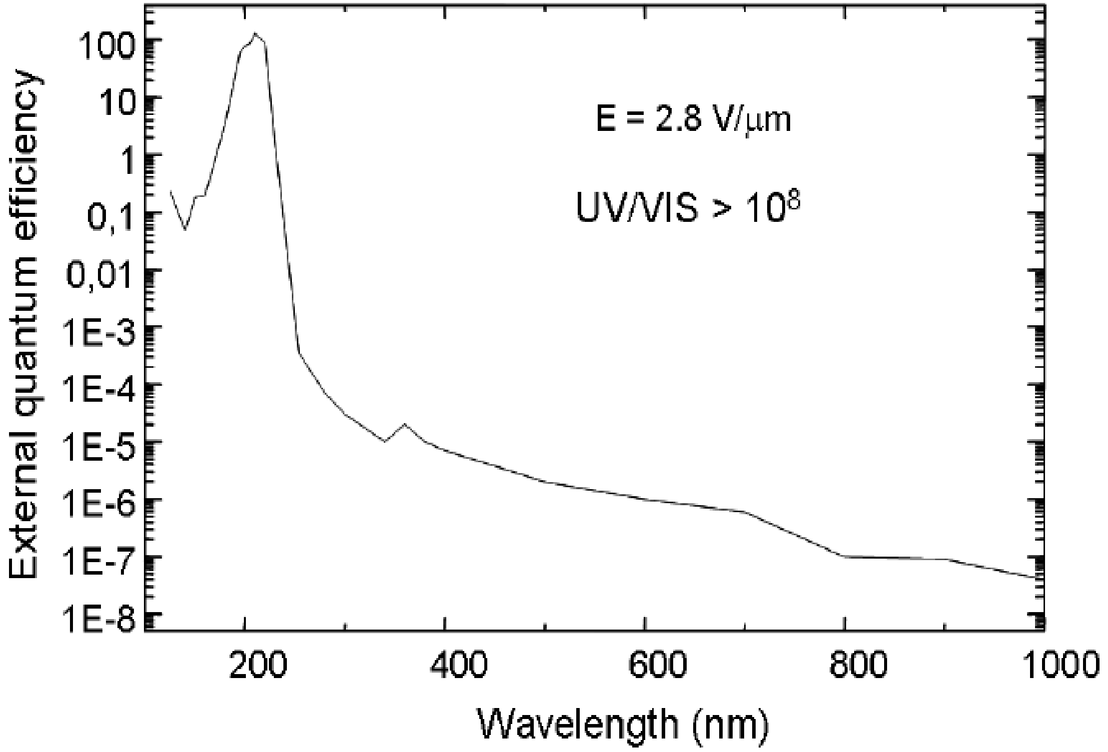


Fig. 4. External quantum efficiency extended to visible and near infrared wavelength regions. The

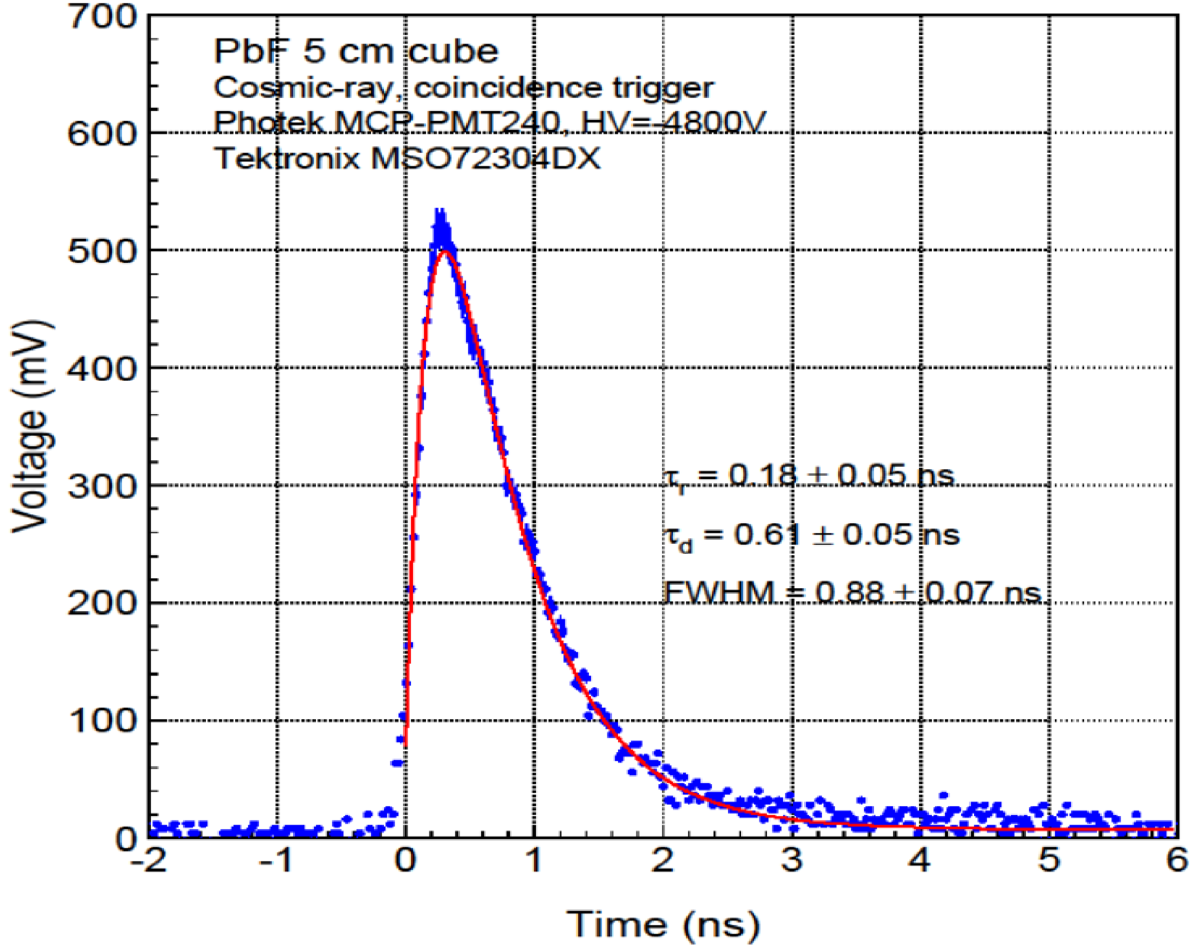
Existing Crystal Calorimeters in HEP

Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	BaBar	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	Tevatron	PEP	KEKB	LHC
Laboratory	SLAC	CERN	Cornell	CERN	FNAL	SLAC	KEK	CERN
Crystal Type	NaI:Tl	BGO	CsI:Tl	CsI:Tl	CsI	CsI:Tl	CsI:Tl	PWO
B-Field（T）	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Crystal number	672	11,400	7,800	1,400	3,300	6,580	8,800	75,848
Crystal Depth（X_0）	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume（m^3）	1	1.5	7	1	2	5.9	9.5	11
Light Output（p.e./MeV）	350	1,400	5,000	2,000	40	5,000	5,000	2
Photo-detector	PMT	Si PD	Si PD	WS+Si PD	PMT	Si PD	Si PD	Si APD
Gain of Photo-detector	Large	1	1	1	4,000	1	1	50
σ_N/Channel（MeV）	0.05	0.8	0.5	0.2	Small	0.15	0.2	40

Future HEP experiments need brighter and faster crystals with better radiation hardness

Fitting Temporal Response

Rise time, decay time and FWHM pulse width are estimated by a simple fit with two exponential components



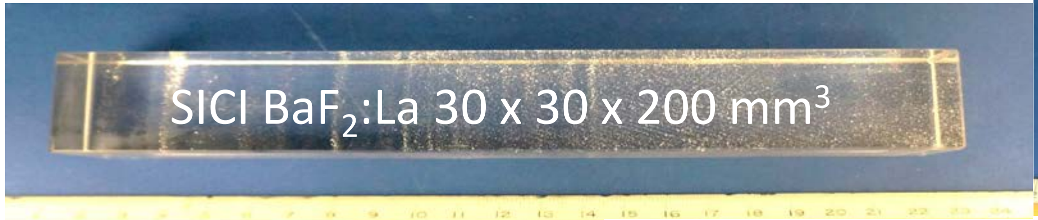
Fitting:

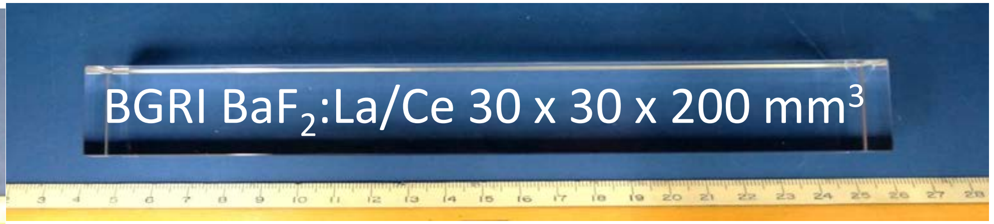
$$V = A(e^{-\frac{t}{\tau_d}} - e^{-\frac{t}{\tau_r}}) + B$$

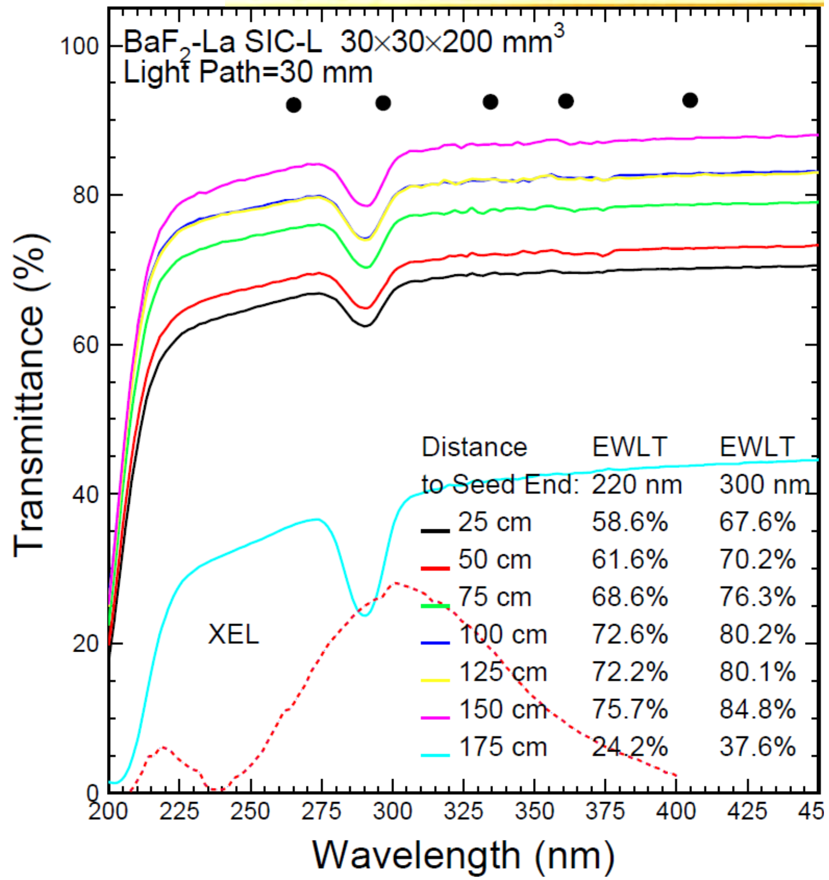
A: amplitude,
B: background noise or slow component,
τ_r: rise time,
τ_d: decay time.

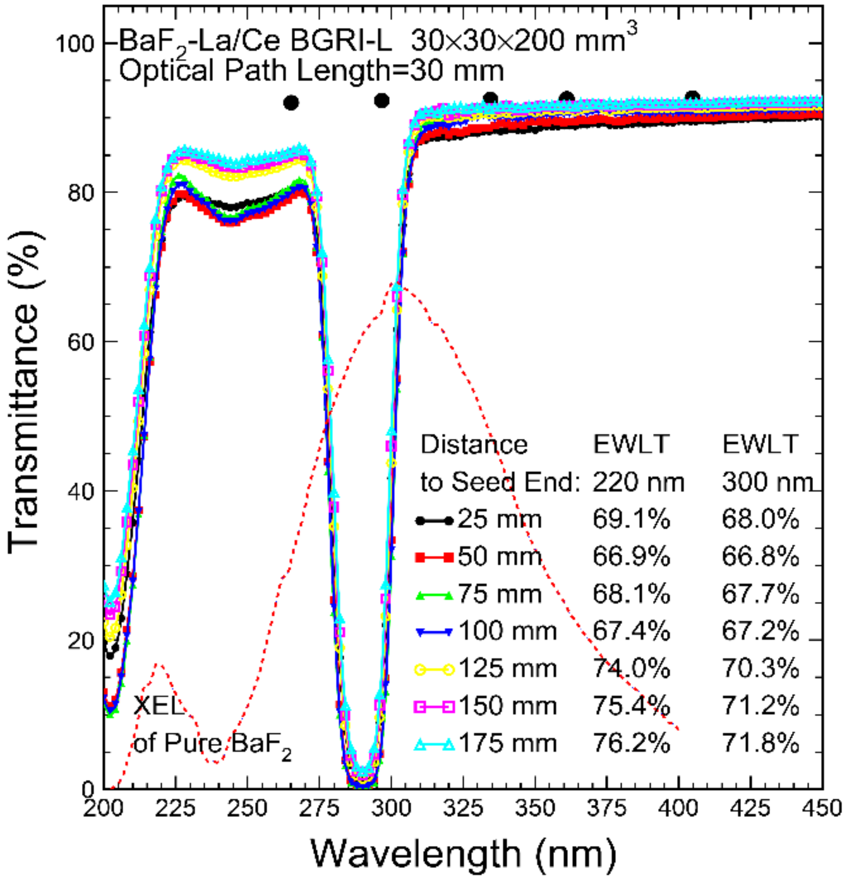
Sub-ns pulse observed by Photek MCP-PMT 240 for Cherenkov light

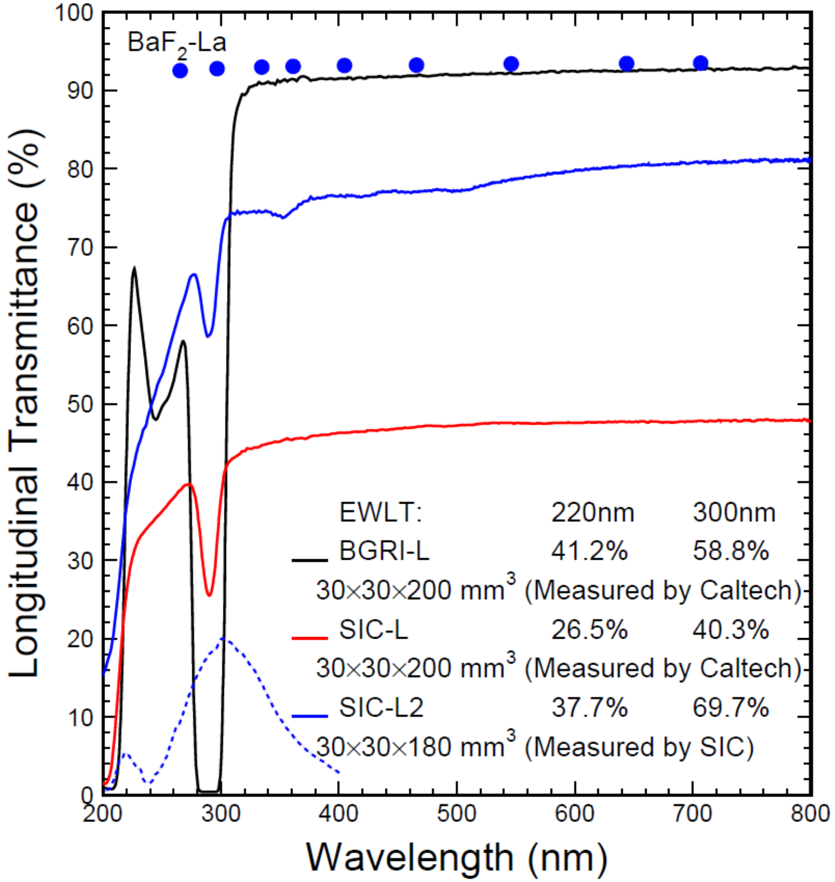
Transmittance of BaF_2:La and BaF_2:La/Ce





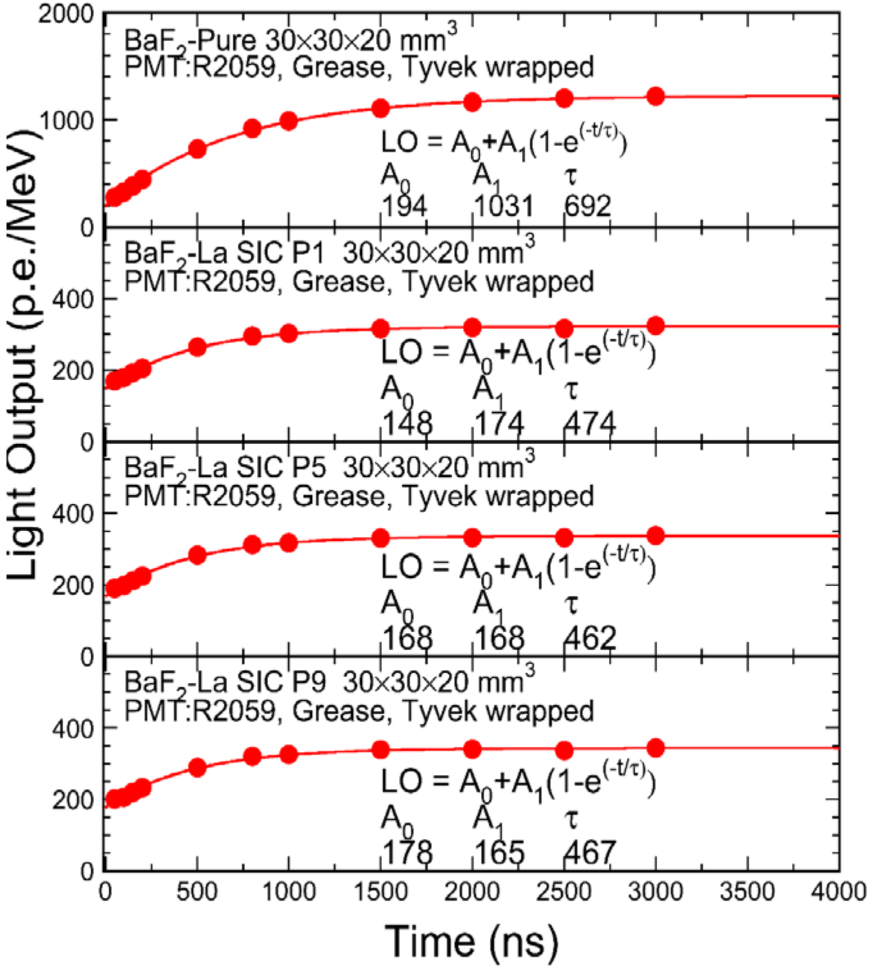


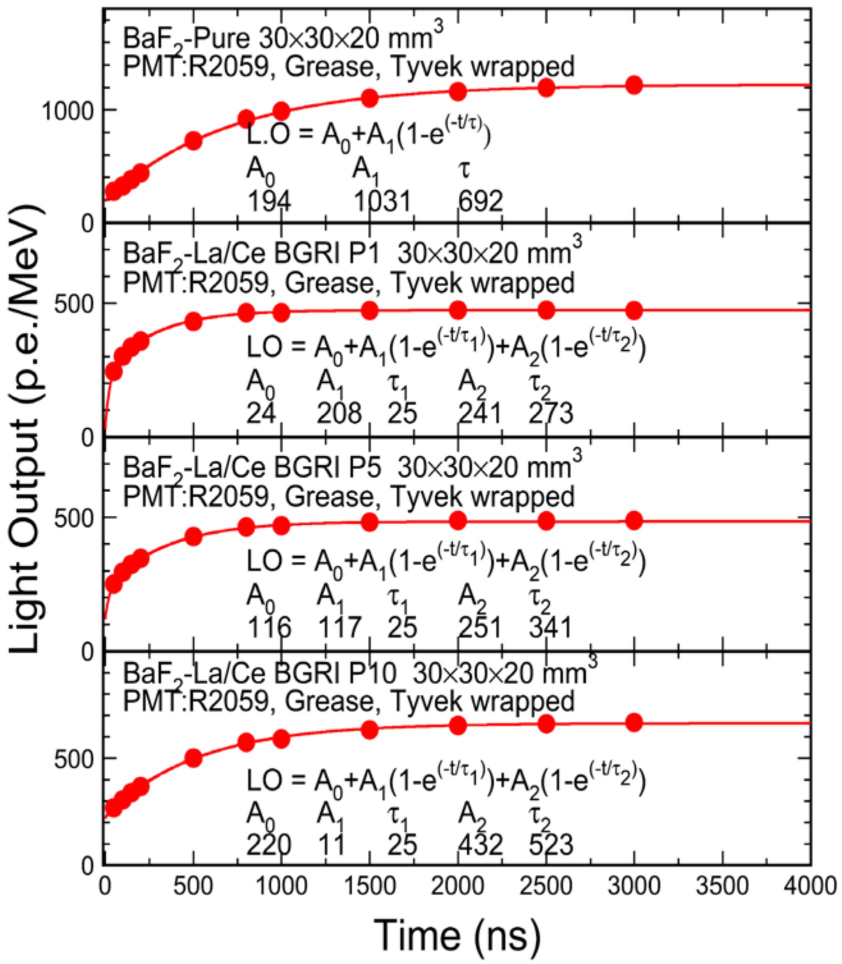


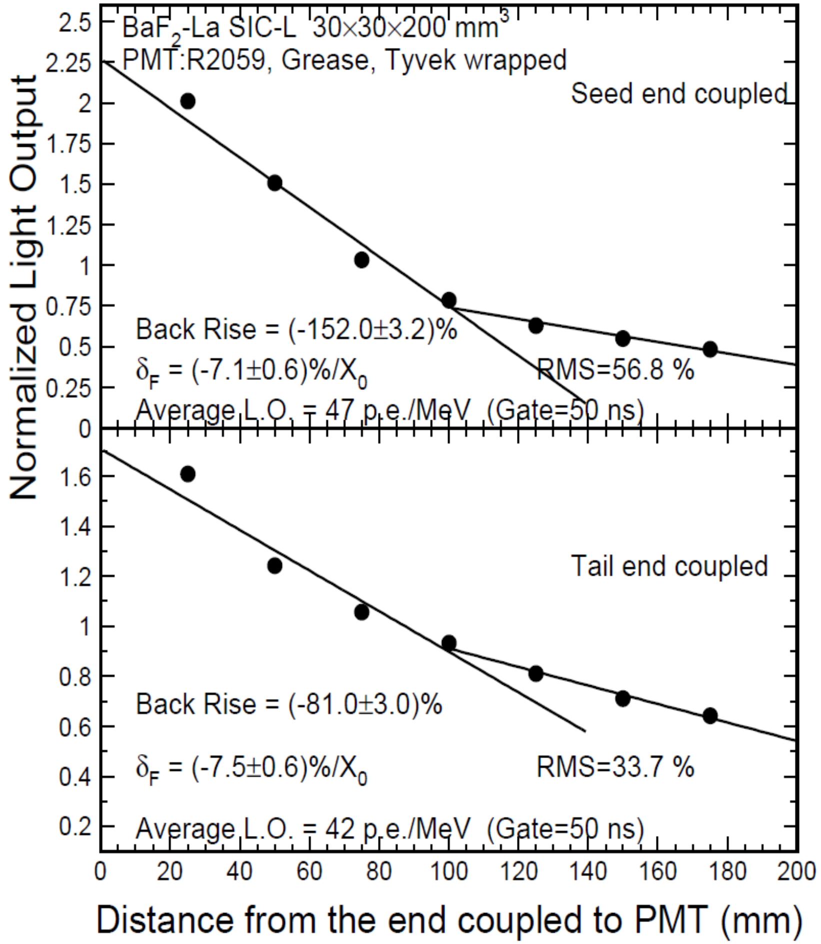
Significant absorptions observed in both La and La/Ce doped BaF_2

Light Output of BaF_2:La and BaF_2:La/Ce

F/S increased up to 1; LRU: Poor LRU for the fast component

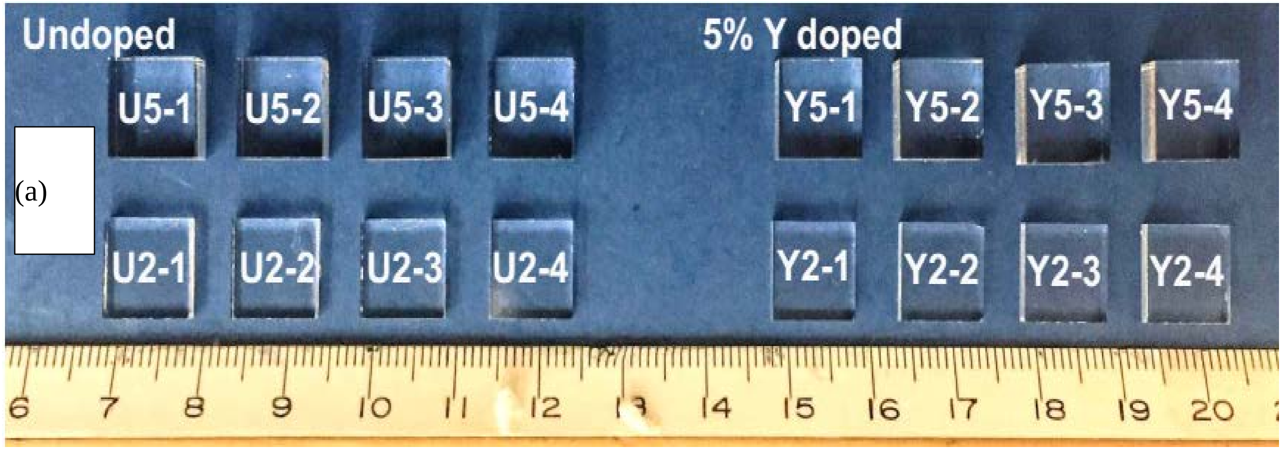




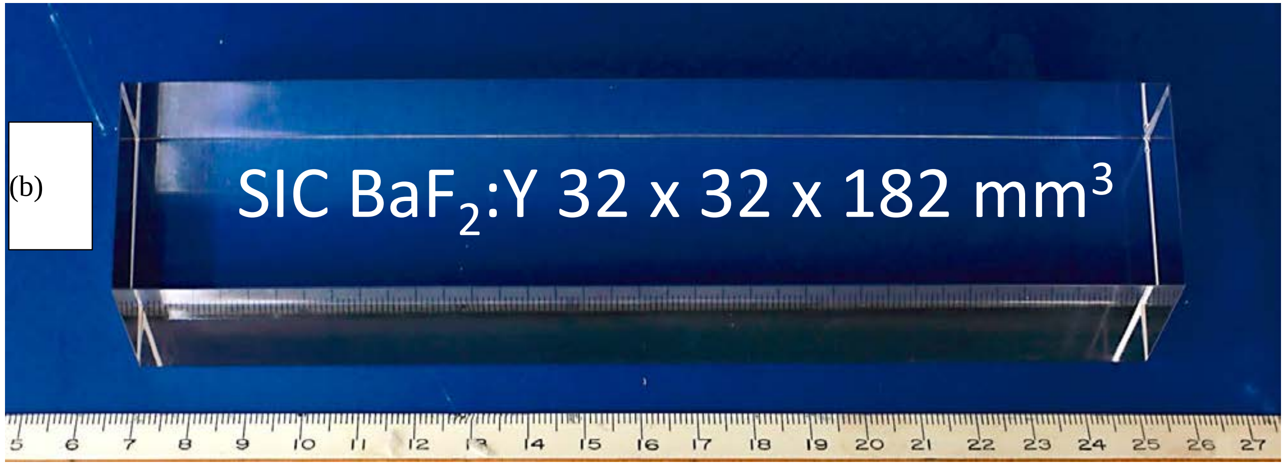


The 2nd SIC BaF_2:Y Sample of 18 cm

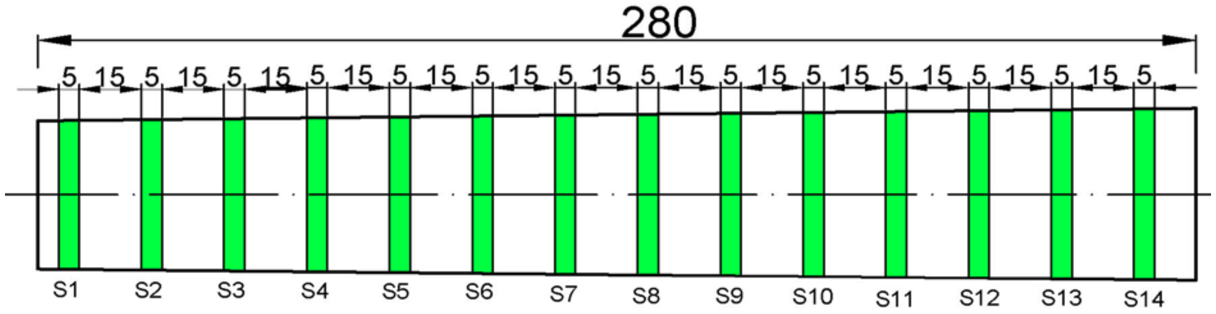
Low yttrium doping level needs to be optimized

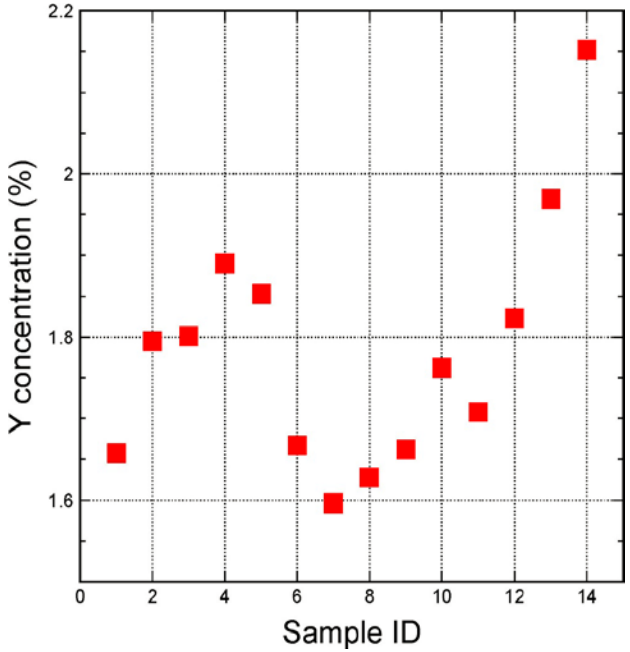


(a)



(b)





Sample ID	Concentration (%)		
	Ce	Pb	Y
S1	<0.0007	<0.002	1.658
S2	<0.0007	<0.002	1.795
S3	<0.0007	<0.002	1.801
S4	<0.0007	<0.002	1.890
S5	<0.0007	<0.002	1.853
S6	<0.0007	<0.002	1.667
S7	<0.0007	<0.002	1.596
S8	<0.0007	<0.002	1.628
S9	<0.0007	<0.002	1.662
S10	<0.0007	<0.002	1.762
S11	<0.0007	<0.002	1.708
S12	<0.0007	<0.002	1.823
S13	<0.0007	<0.002	1.969
S14	<0.0007	<0.002	2.152