Temporal Response of Ultrafast Inorganic Scintillators for future HEP Applications

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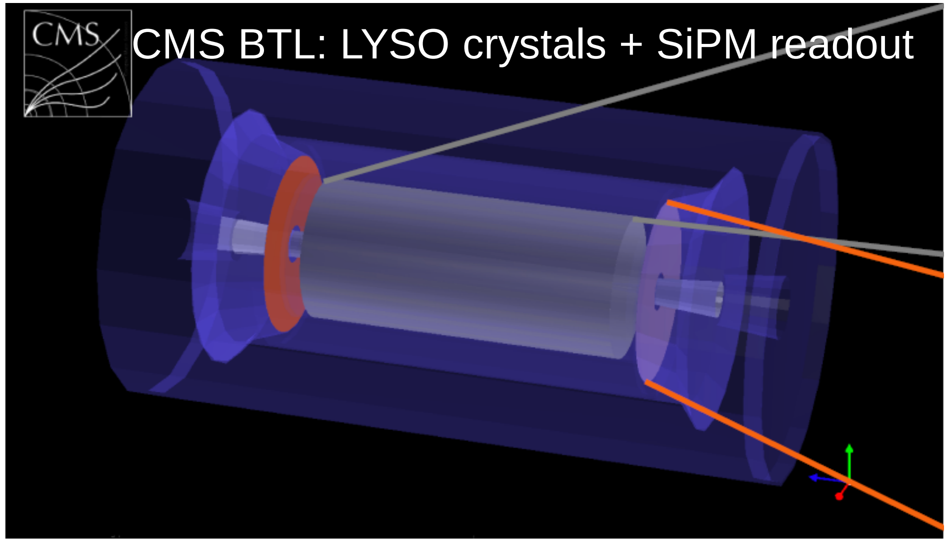
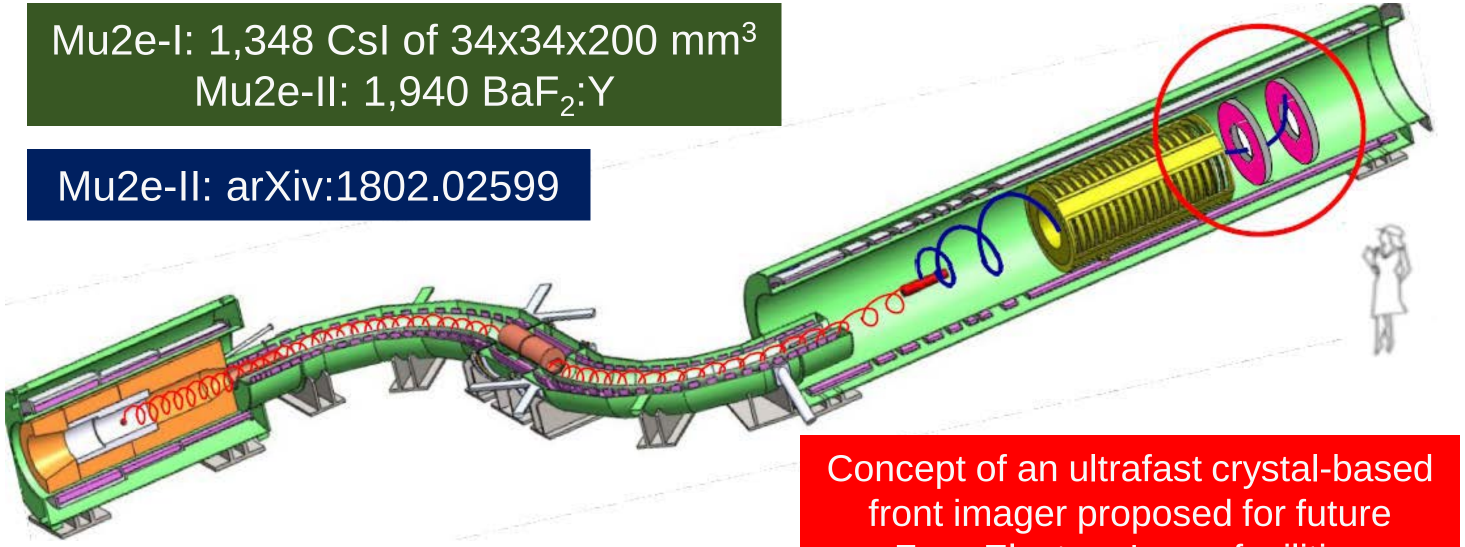
Application of Ultrafast Crystals

Figures of merit for TOF: light yield in the 1st ns & the ratio between fast and total



Mu2e-I: 1,348 CsI of 34x34x200 mm^3
Mu2e-II: 1,940 BaF_2:Y

Mu2e-II: arXiv:1802.02599

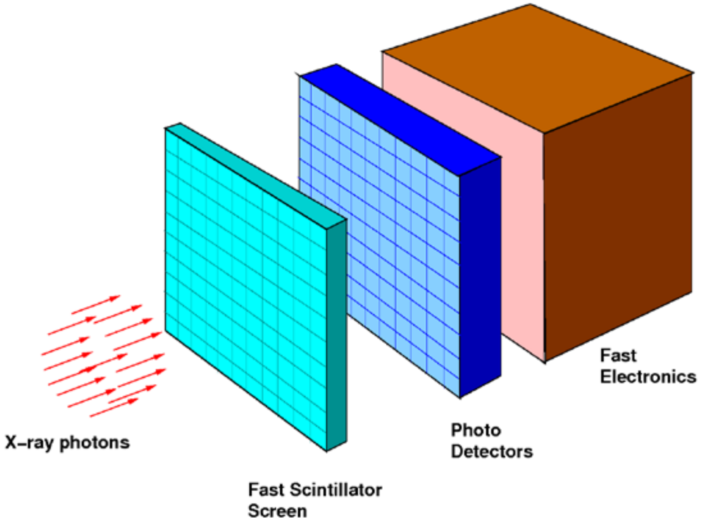


Concept of an ultrafast crystal-based front imager proposed for future Free-Electron Laser facilities

GHz Hard X-ray Imaging for FEL

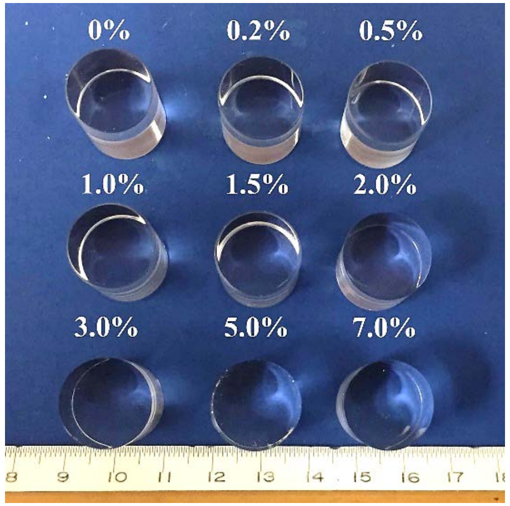
2 ns and 300 ps inter-frame time requires ultrafast sensor

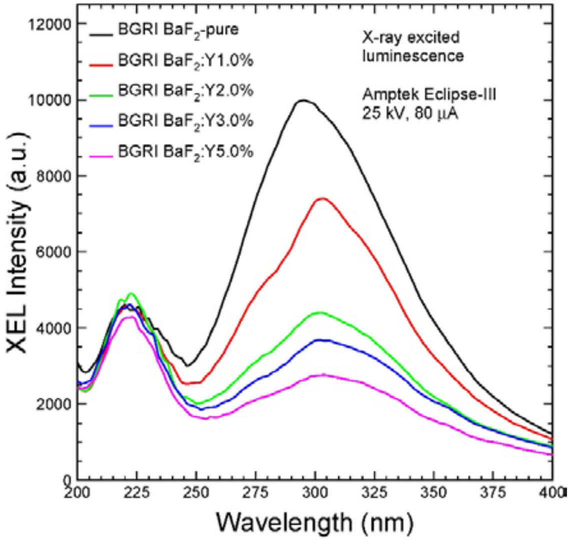
Performance	Type I imager	Type II imager
X-ray energy	**up to 30 keV**	**42-126 keV**
Frame-rate/inter-frame time	**0.5 GHz / 2 ns**	**3 GHz / 300 ps**
Number of frames per burst	≥ 10	10 - 30
X-ray detection efficiency	above 50%	above 80%
Pixel size/pitch	**≤ 300 μm**	**< 300 μm**
Dynamic range	10^3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

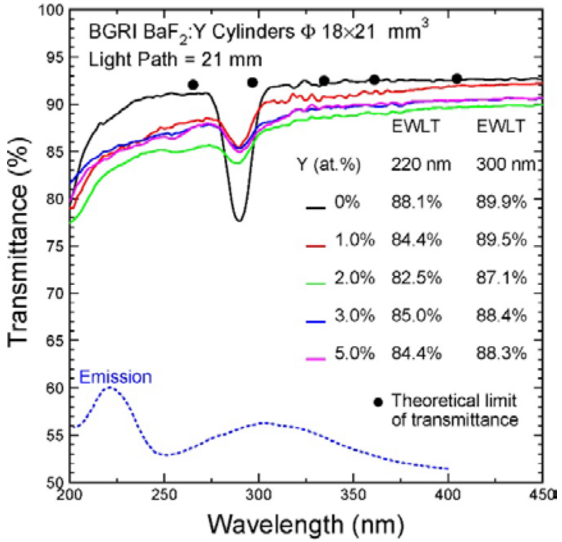


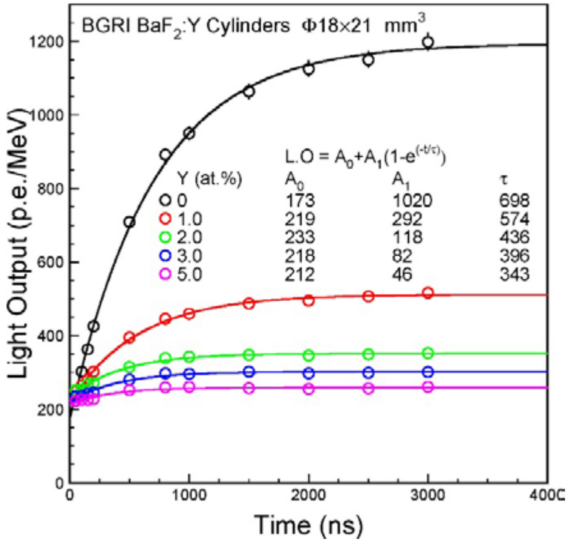
BaF_2:Y for Ultrafast Calorimetry

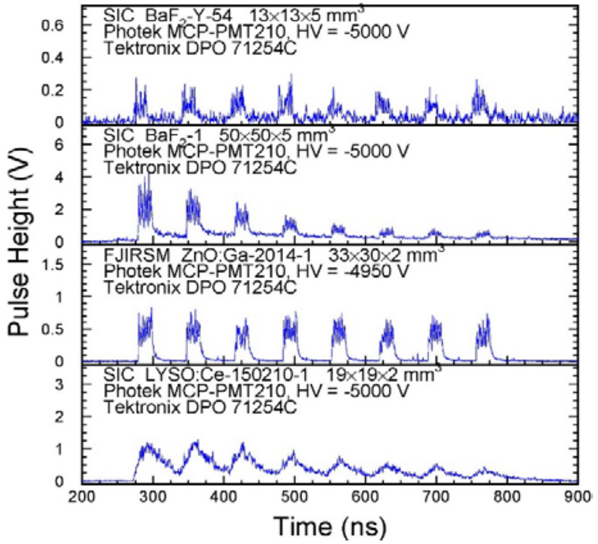
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

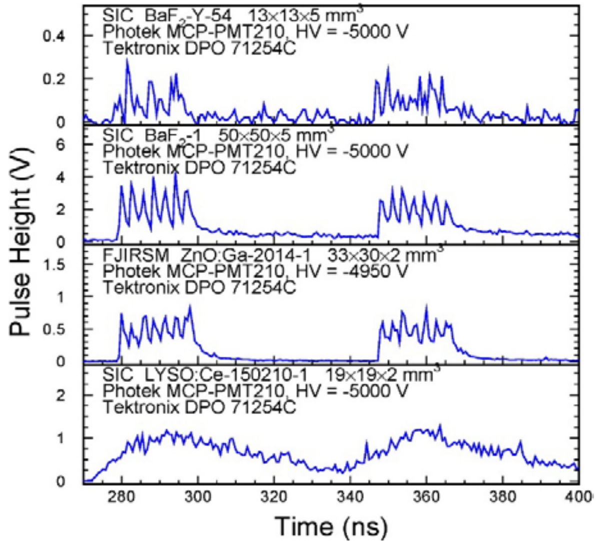


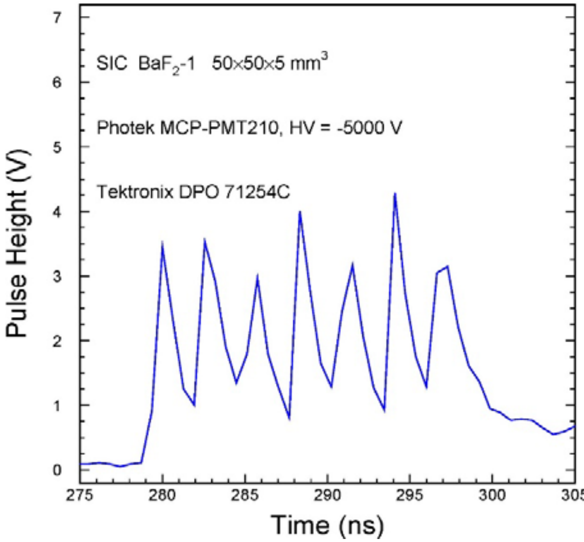








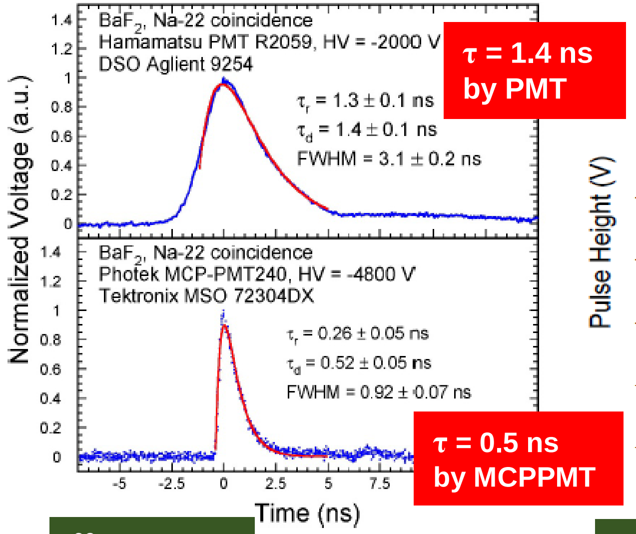


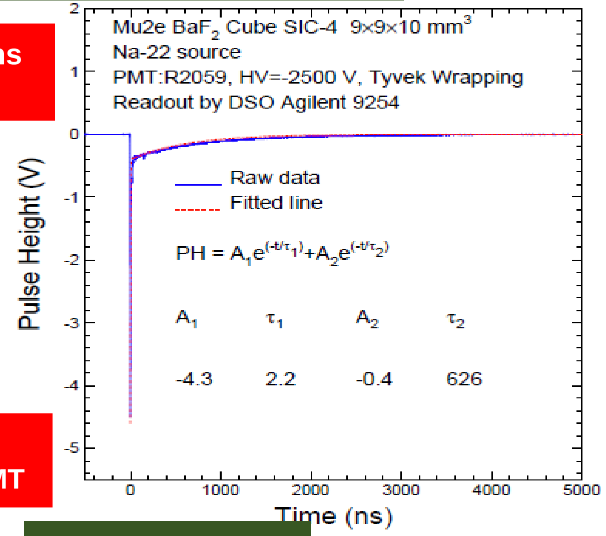


X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

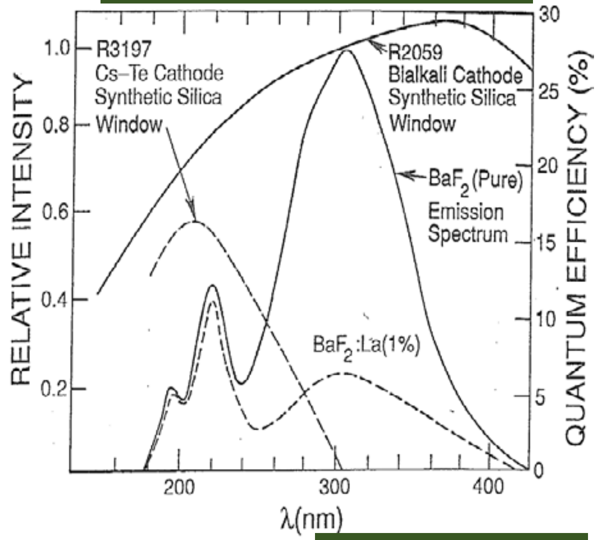
Ultrafast and Radiation Hard BaF_2

IEEE TNS NS 67, NO. 6 (2020) 1014-1019





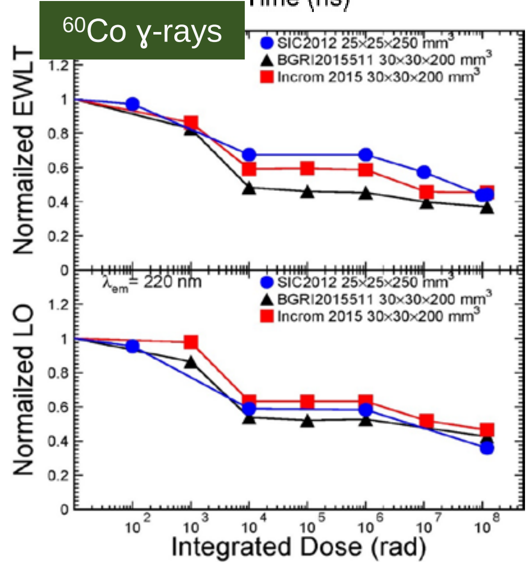
NIMA 340 (1994) 442-457



BaF₂ has an ultrafast scintillation component @ 220 nm with **0.5 ns** decay time and a much larger slow component @ 300 nm with 600 ns decay time.

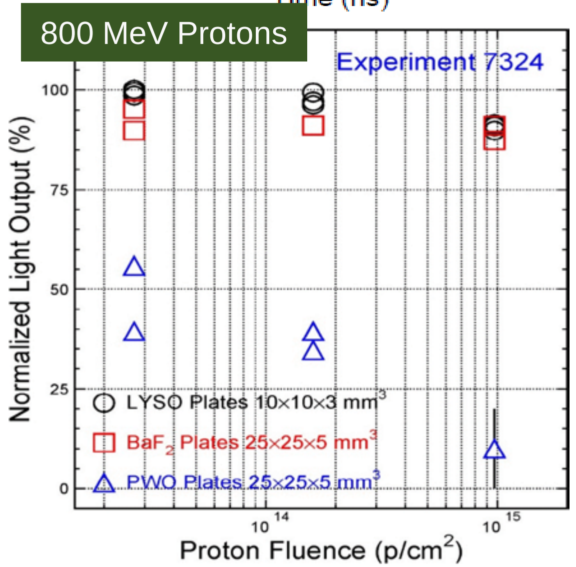
Slow suppression may be achieved by rare earth doping, and/or solar-blind photo-detectors

^{60}Co γ-rays



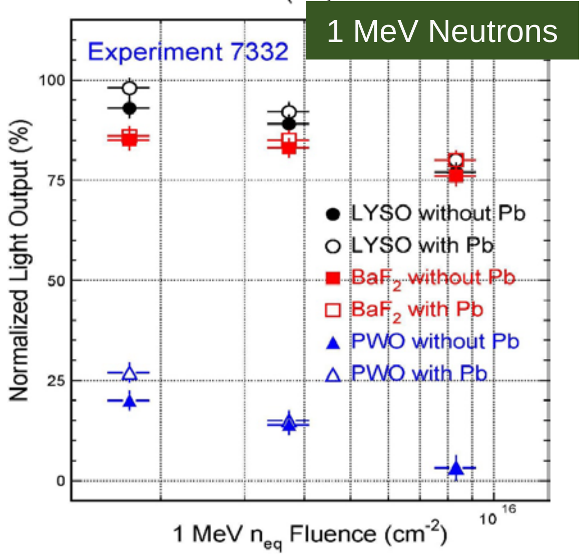
IEEE TNS **63** (2016) 612-619

800 MeV Protons



IEEE TNS **65** (2018) 1086-1092

1 MeV Neutrons



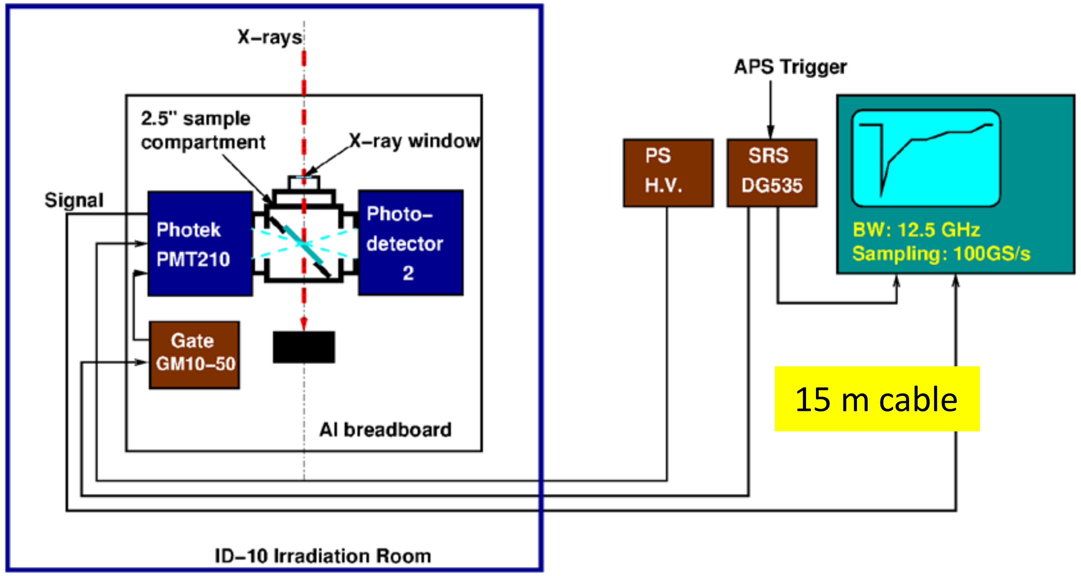
IEEE TNS **67** (2020) 1018-1024

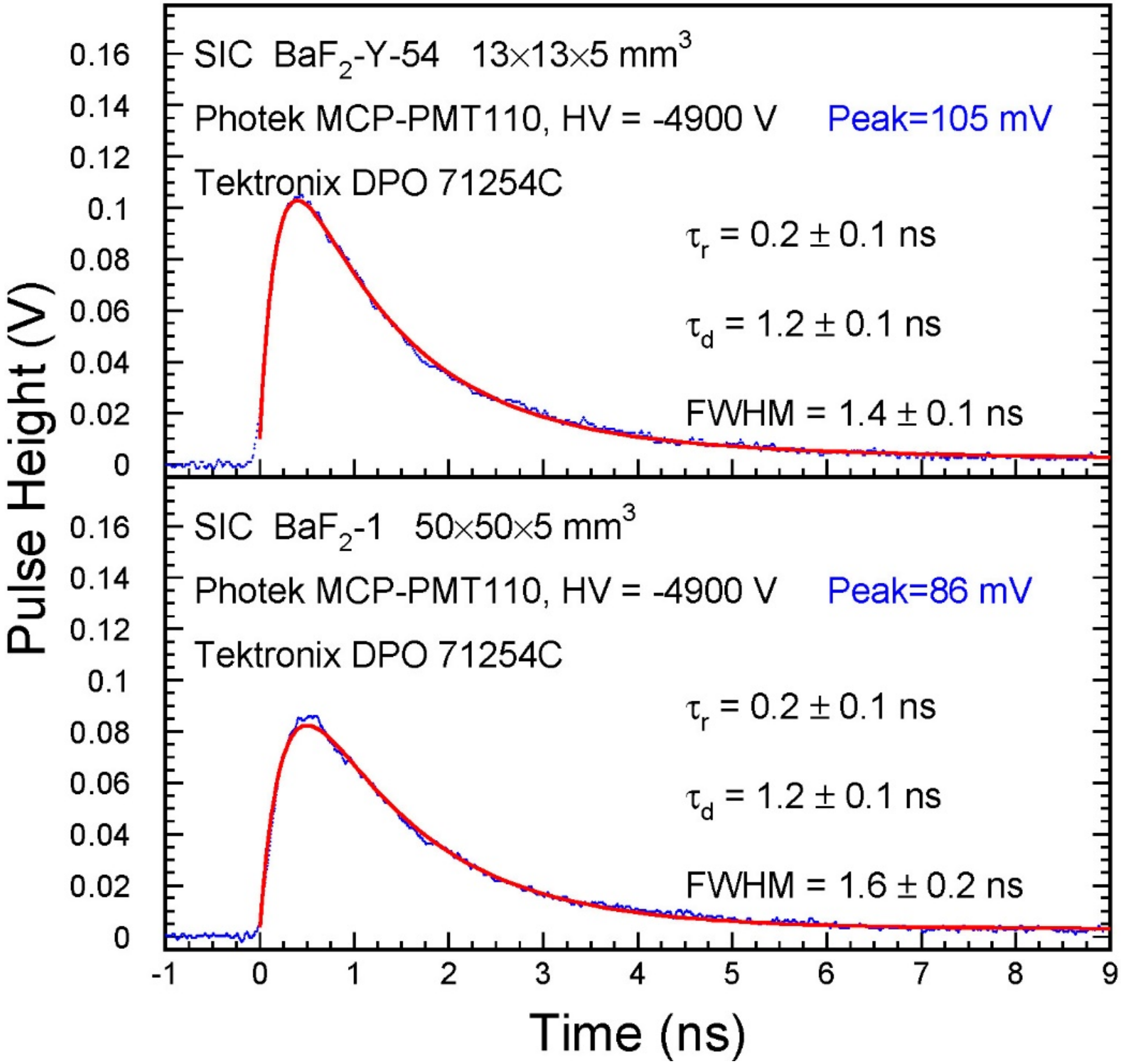
BaF_2 shows saturated damage from 10 krad to 100 Mrad, indicating good radiation resistance against γ-rays

BaF_2 also survives after proton irradiation up to 9.7×10^{14} p/cm², and neutron irradiation up to 8.3×10^{15} n_{eq}/cm^2

A Puzzle of Long Decay Observed at APS

NIM A **940** (2019) 223–229

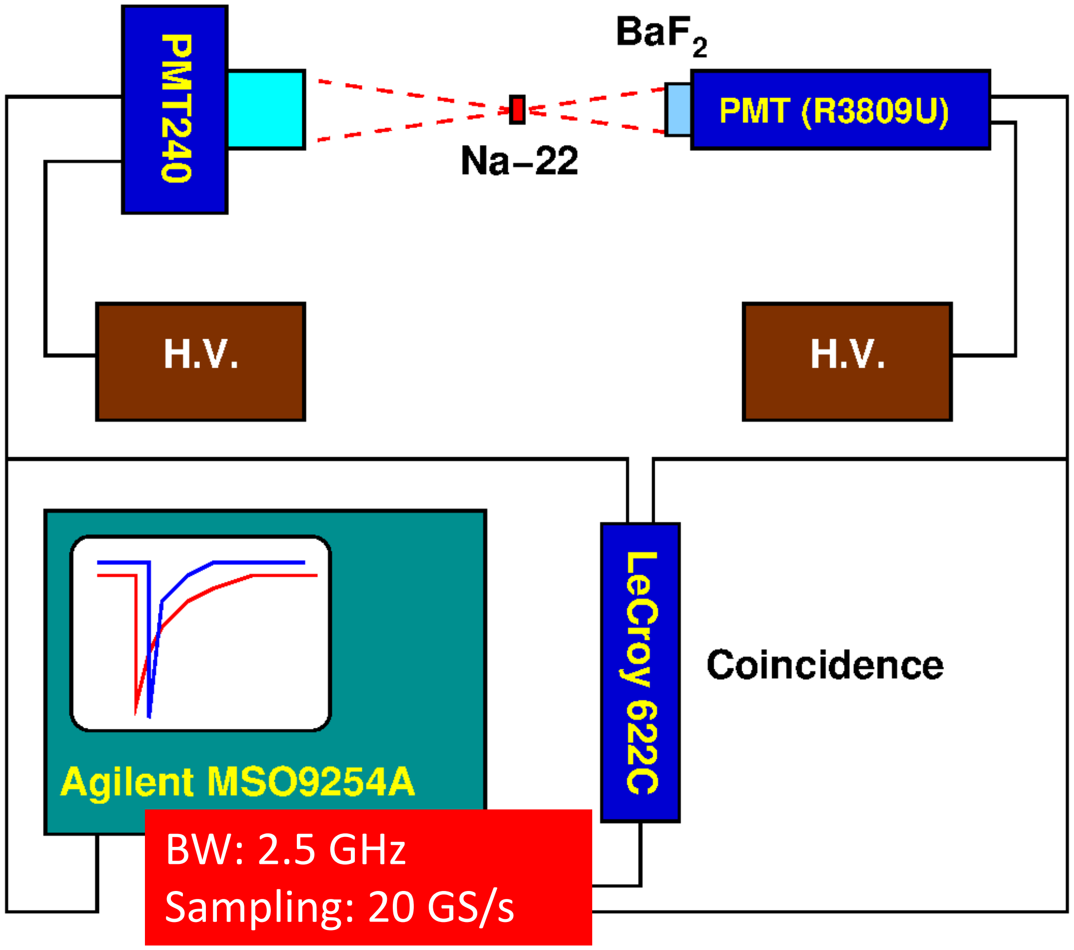




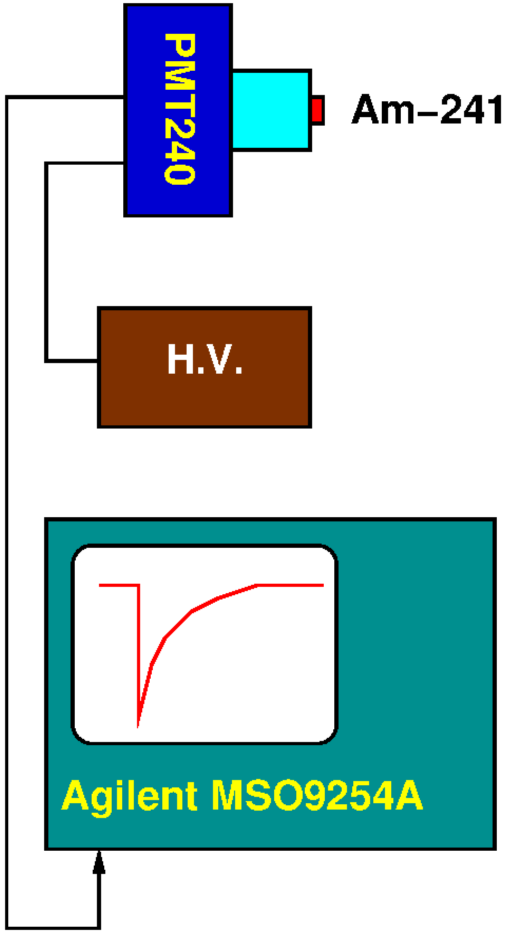
The decay time of BaF_2 measured at APS for septuplet X-ray bunches with 2.83 ns spacing is longer than 1 ns. This is suspected to be caused by the very long cable used between MCP-PMT and MSO

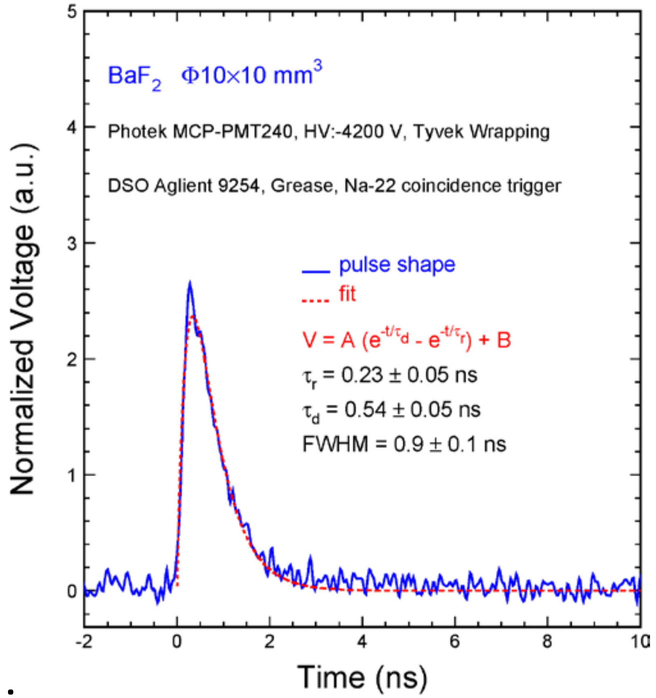
An MCP-Based Test Bench

Na-22 Coincidence Trigger



Am-241 Self Trigger





Fitting:

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

B: background noise or slow component,

τ_r: rise time,

τ_d: decay time.

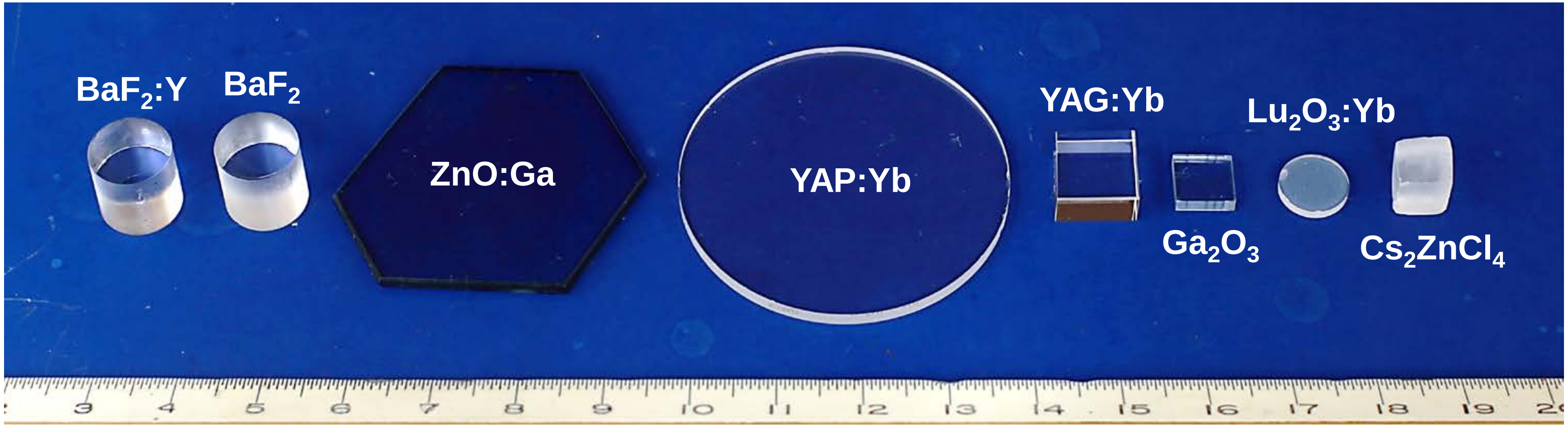
Rise, decay and FWHM obtained by fitting temporal response

MCP-PMT Comparison

Photodetector	Active diameter (mm^2)	Spectral range (nm)	Peak Sen. (nm)	Gain	Rise time (ns)	FWHM (ns)
Photek MCP PMT240	**40**	**160-850**	**280-450**	**1×10^6**	**0.180**	**0.82**
Hamamatsu MCP-PMT R3809U-50	**11**	**160-850**	**430**	**3×10^5**	**0.160**	**0.30**
Photek MCP PMT110	10	160-850	280-450	1×10^4	0.065	0.11
Photek MCP PMT210	10	160-850	280-450	1×10^6	0.085	0.15
Hamamatsu PMT R2059	46	160-650	450	2×10^7	1.3	

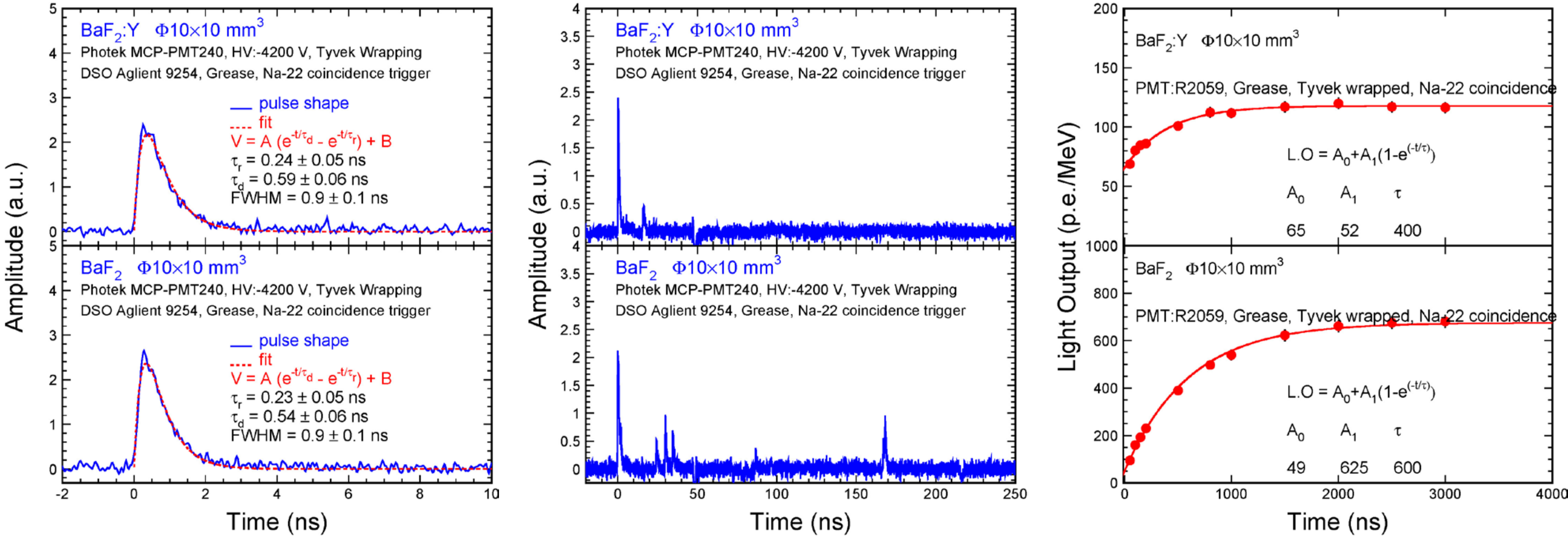
Ultrafast Inorganic Scintillator Samples

8 ultrafast crystals used in this investigation



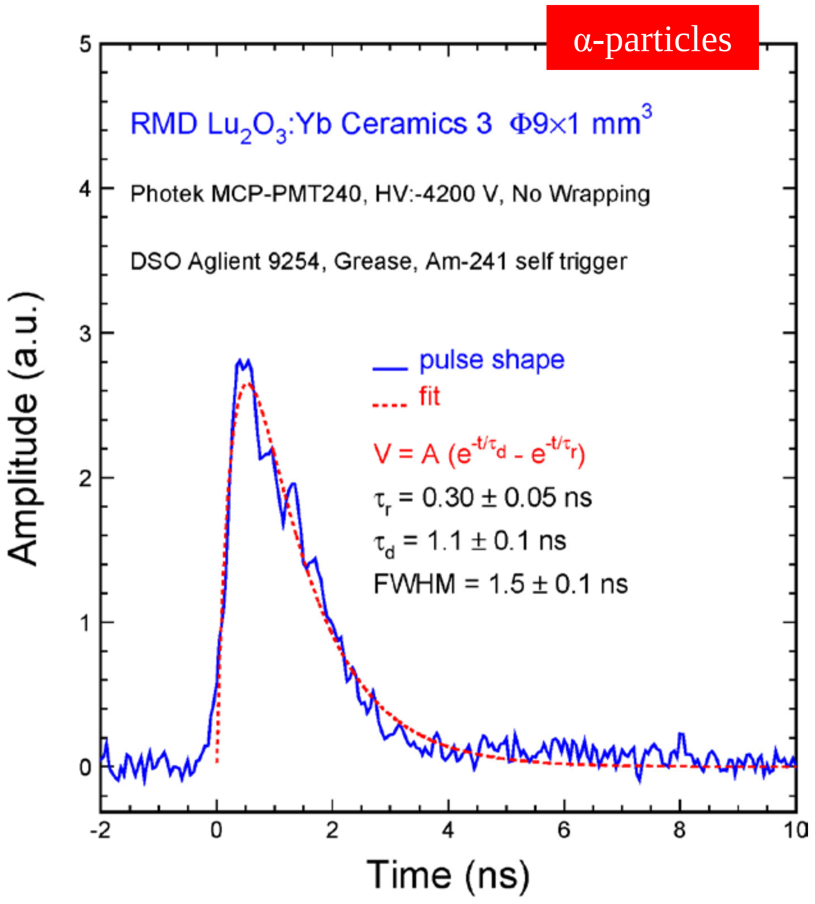
	BaF_2:Y	BaF_2	ZnO:Ga	YAP:Yb	YAG:Yb	Ga_2O_3	Lu_2O_3:Yb	Cs_2ZnCl_4
Producer	BGRI	BGRI	FJIRSM	Dongjun	Dongjun	Tongji	RMD	RMD
Dimension (mm^3)	Φ10×10	Φ10×10	33×30×2	Φ40×2	10×10×5	7×7×2	Φ9×1	6×6×7

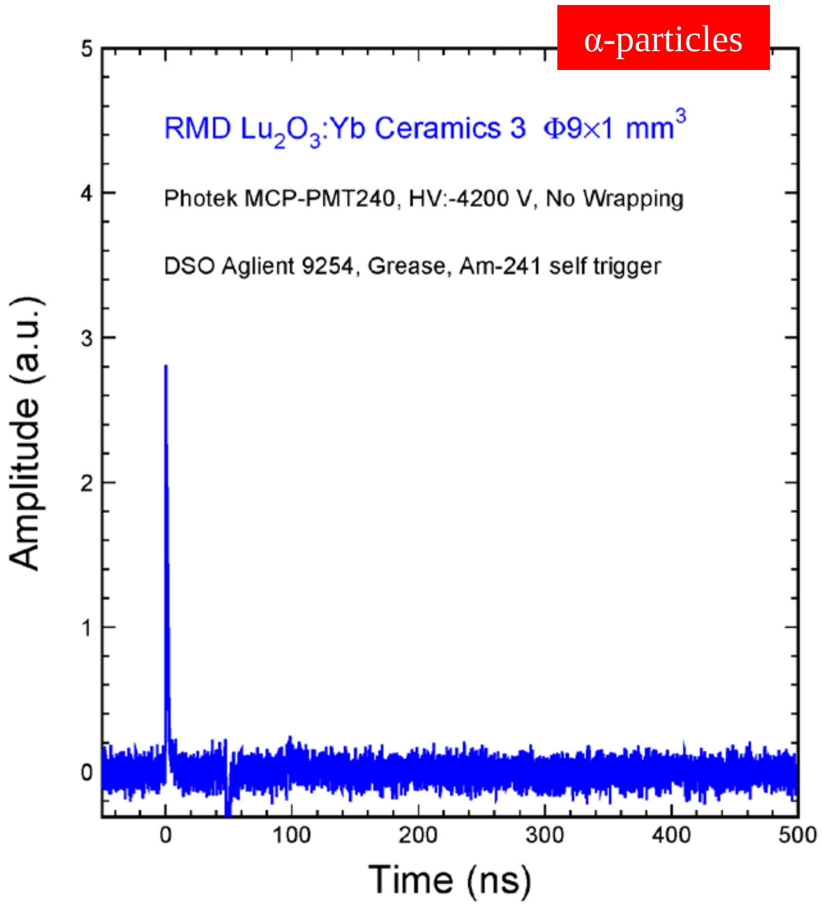
Temporal Response of BaF_2 & BaF_2:Y

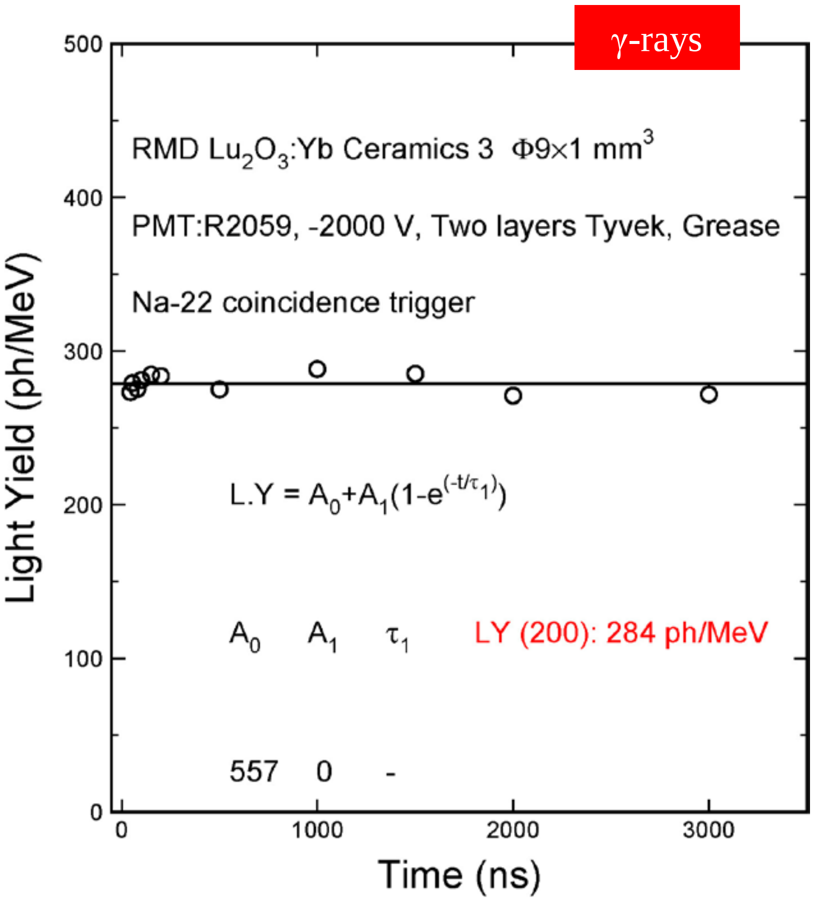


Ultrafast response of 0.2/0.6/0.8 ns observed for BaF_2 and BaF_2:Y crystals

Temporal Response of Lu_2O_3:Yb Ceramics

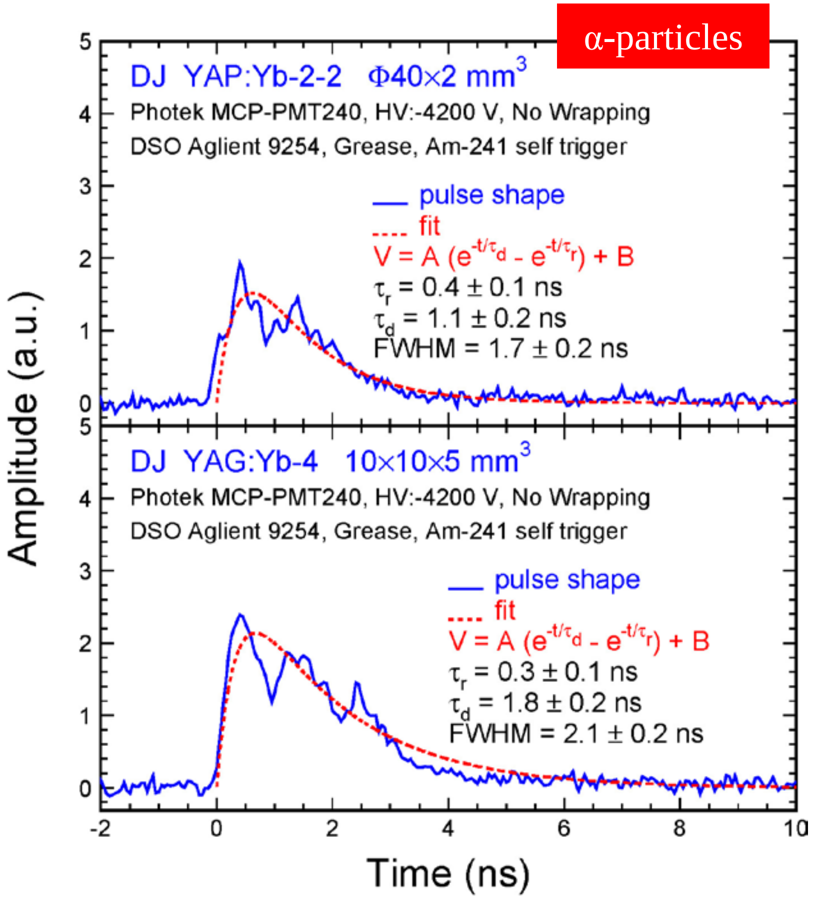


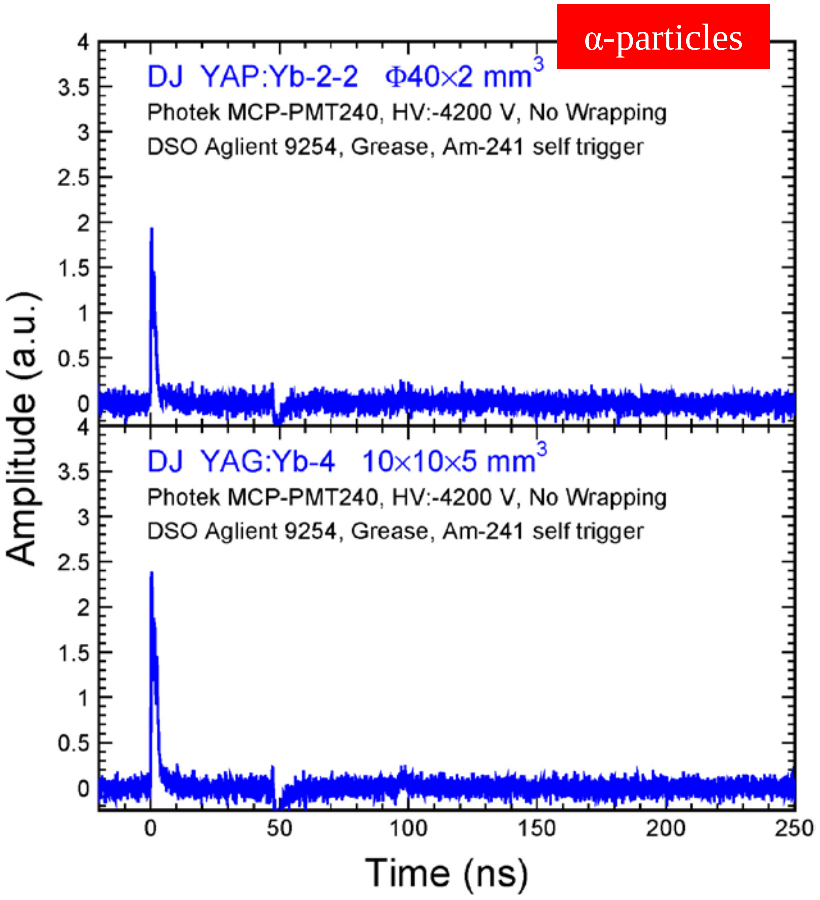


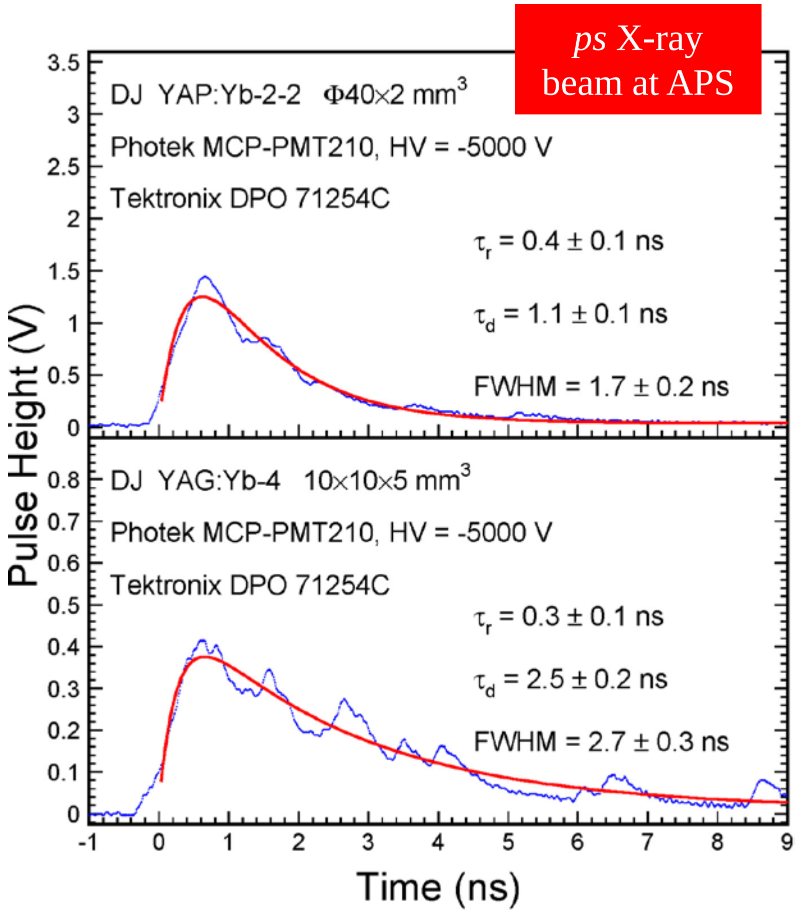


Lu_2O_3:Yb ceramic of 9.4 g/cc shows an ultrafast decay time of 1.1 ns by Am-241 with negligible slow component confirmed by light output measurement

Temporal response of YAP:Yb & YAG:Yb







NIM A **940** (2019) 223–229

YAP:Yb & YAG:Yb show a decay time of 1.1 ns and 1.8 ns by Am-241

Fast and Ultrafast Inorganic Scintillators

arXiv: 2203.06788

	BaF_2	BaF_2:Y	ZnO:Ga	Lu_2O_3:Yb	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	9.42	5.35	4.56	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (ºC)	1280	1280	1975	2490	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	0.81	2.59	3.53	2.51	1.14	1.45	2.59	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	1.72	2.45	2.76	2.20	2.07	2.15	2.45	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	18.1	23.1	25.2	20.9	20.9	20.6	23.1	21.5	19.5	27.8
Z_{eff}	51.0	51.0	27.7	67.3	32.8	29.3	27.8	63.7	58.7	32.8	50.6	57.1	32.8
dE/dX (MeV/cm)	6.52	6.52	8.34	11.6	7.91	7.01	8.82	9.55	9.22	7.91	8.96	9.82	6.57
λ_{peak} [a] (nm)	300 220	300 220	380	370	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	2.0	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]	0.95	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]	280	57[d]	110[d]	2,100	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 0.5	600 0.5	<1	1.1[d]	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]	170	28[d]	24[d]	43	740	240	391	640	125	318
LY in 1[st] ns /Total LY (%)	9.2	60	31	61	49	22	2.0	2.5	1.0	3.3	1.9	1.3	1.3
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.127	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

[a] top/bottom row: slow/fast component; [b] at the emission peak; [c] normalized to LYSO:Ce; [d] excited by Alpha particles; [e] 0.3 Mg at% co-doping; [f] $Lu_{0.7}Y_{0.3}AlO_3$:Ce.

Summary

- Development of ultrafast heavy crystals with sub-nanosecond decay time is important to break the ps timing barrier for future HEP TOF system and ultrafast calorimetry, as well as GHz hard X-ray imaging. Temporal response of various ultrafast crystals, such as BaF_2 and Lu_2O_3:Yb etc., are measured by an MCP-PMT based test bench.
- BaF_2 and BaF_2:Y show an ultrafast decay of 0.5 ns responding to Na-22,which is much sorter than the 1.2 ns data measured at the APS due to a 15 m long cable between MCP-PMT and MSO.
- Lu_2O_3:Yb ceramic sample shows a decay time of 1.1 ns with negligible slow component. With its 9.4 g/cc density, it is an interesting fast inorganic scintillator.
- YAP:Yb and YAG:Yb samples show decay time of 1.7 and 2.1 ns, shorter than the APS data which were affected by the long cable.
- Measurements will continue to complete this investigation.

Acknowledgements: DOE HEP Award DE-SC0011925