Temporal Response of Ultrafast Inorganic Scintillators for future HEP Applications

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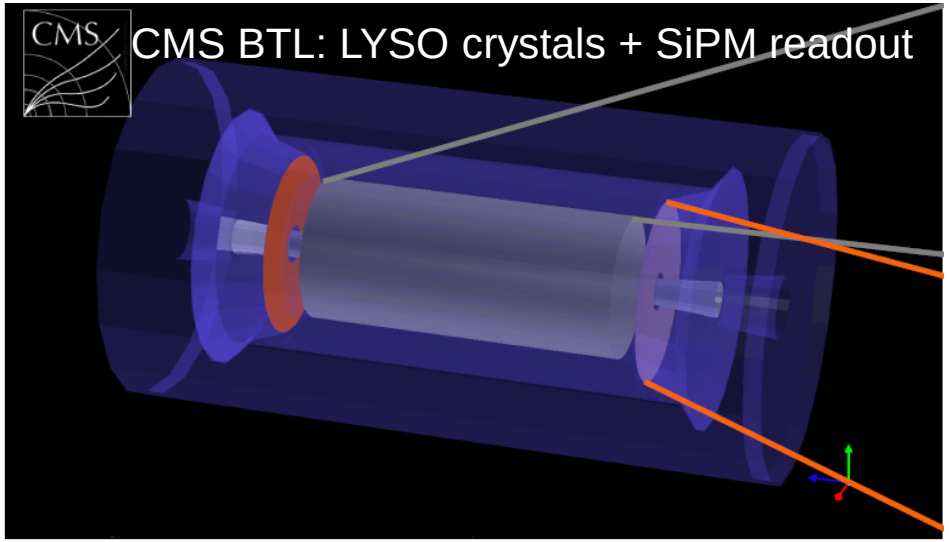
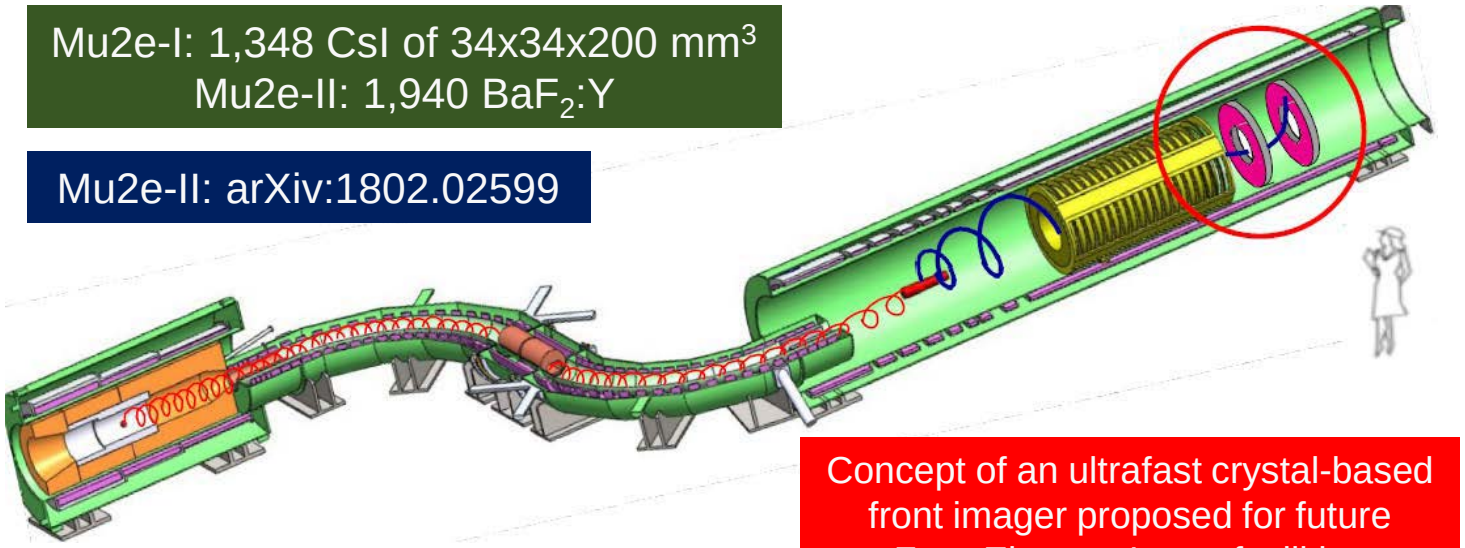
Application of Ultrafast Crystals

Figures of merit for TOF: light yield in the 1st ns and 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

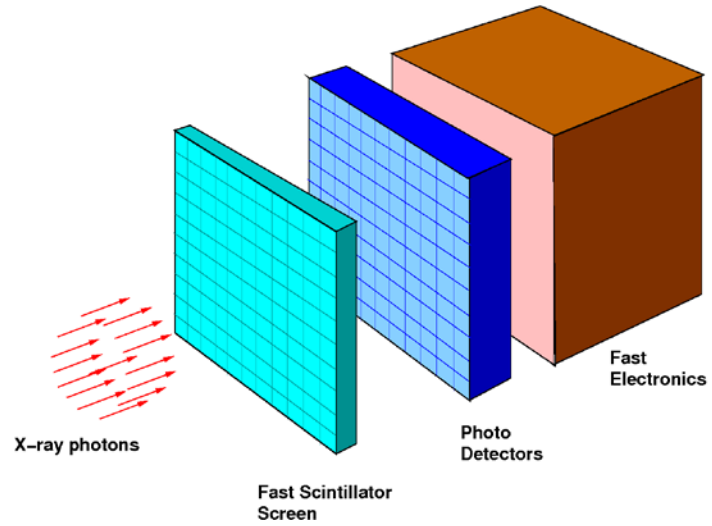


Concept of an ultrafast crystal-based front imager proposed for future Free-Electron Laser facilities

GHz Hard X-ray Imaging for FEL

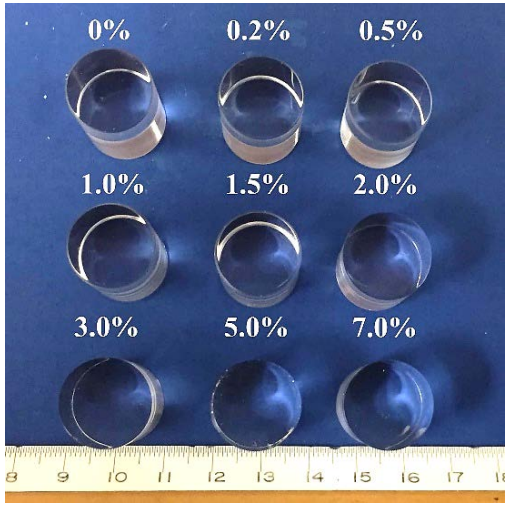
2 ns and 300 ps inter-frame time requires ultrafast sensor

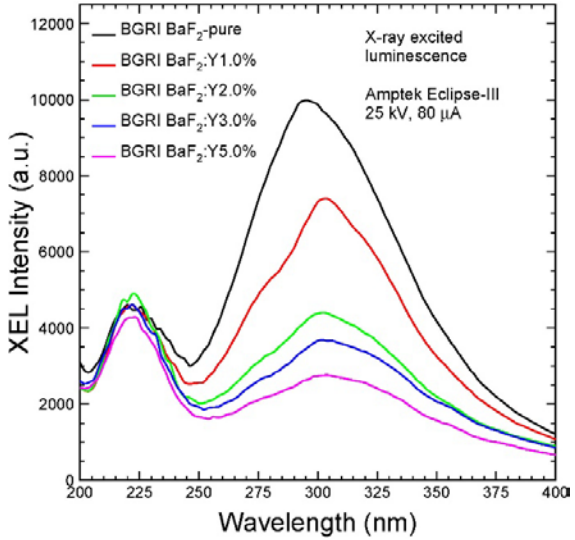
Performance	Type I imager	Type II imager
X-ray energy	**up to 30 keV**	**42-126 keV**
Frame-rate/inter-frame time	**0.5 GHz / 2 ns**	**3 GHz / 300 ps**
Number of frames per burst	≥ 10	10 - 30
X-ray detection efficiency	above 50%	above 80%
Pixel size/pitch	**≤ 300 µm**	**< 300 µm**
Dynamic range	10^3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

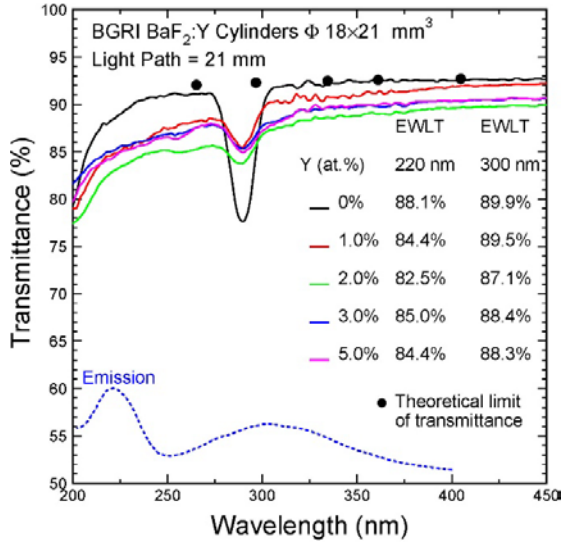


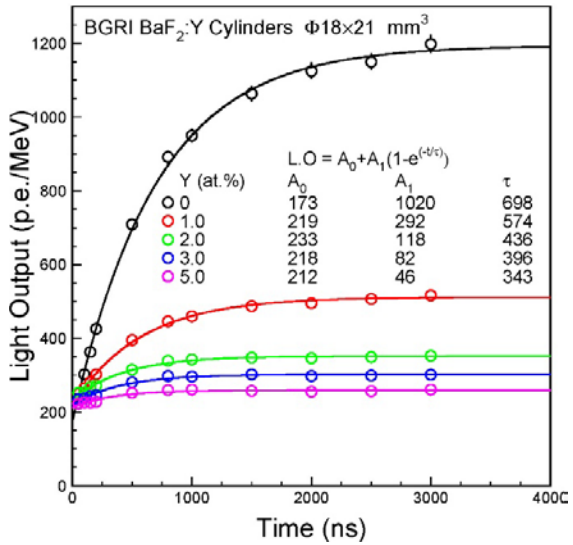
BaF_2:Y for Ultrafast Calorimetry

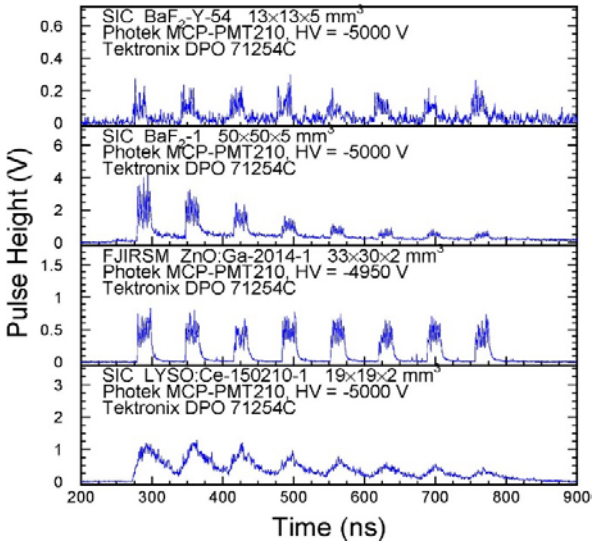
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

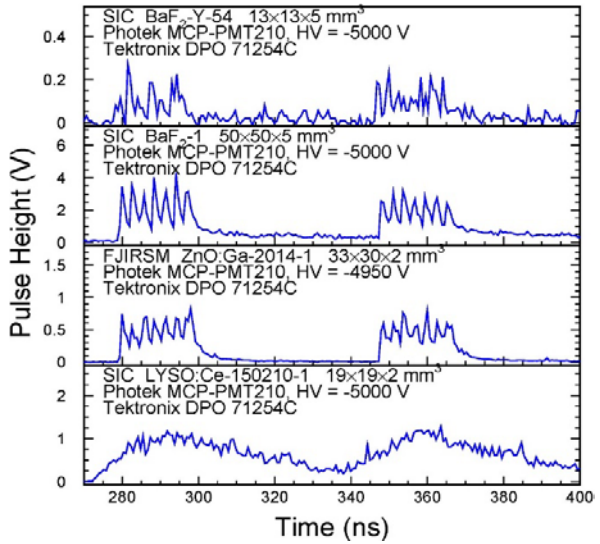


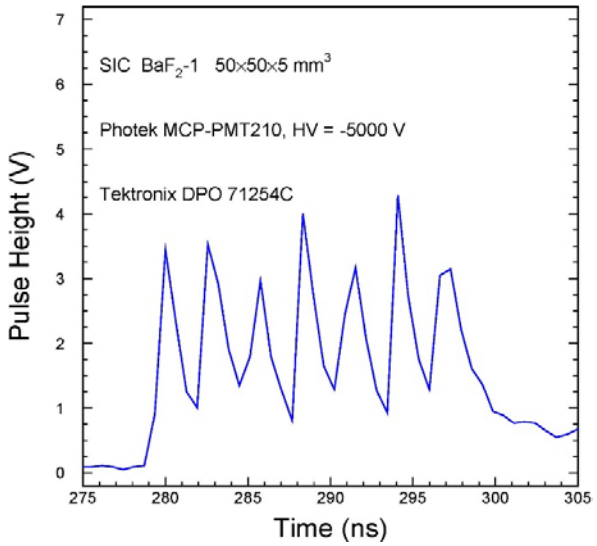












X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

A Puzzle of Long Decay Observed at APS

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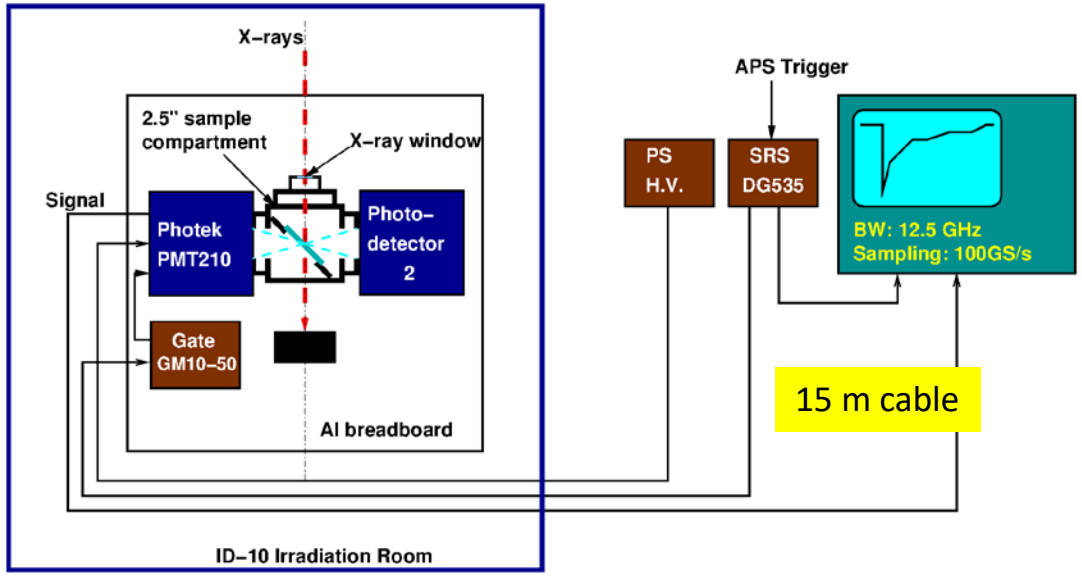
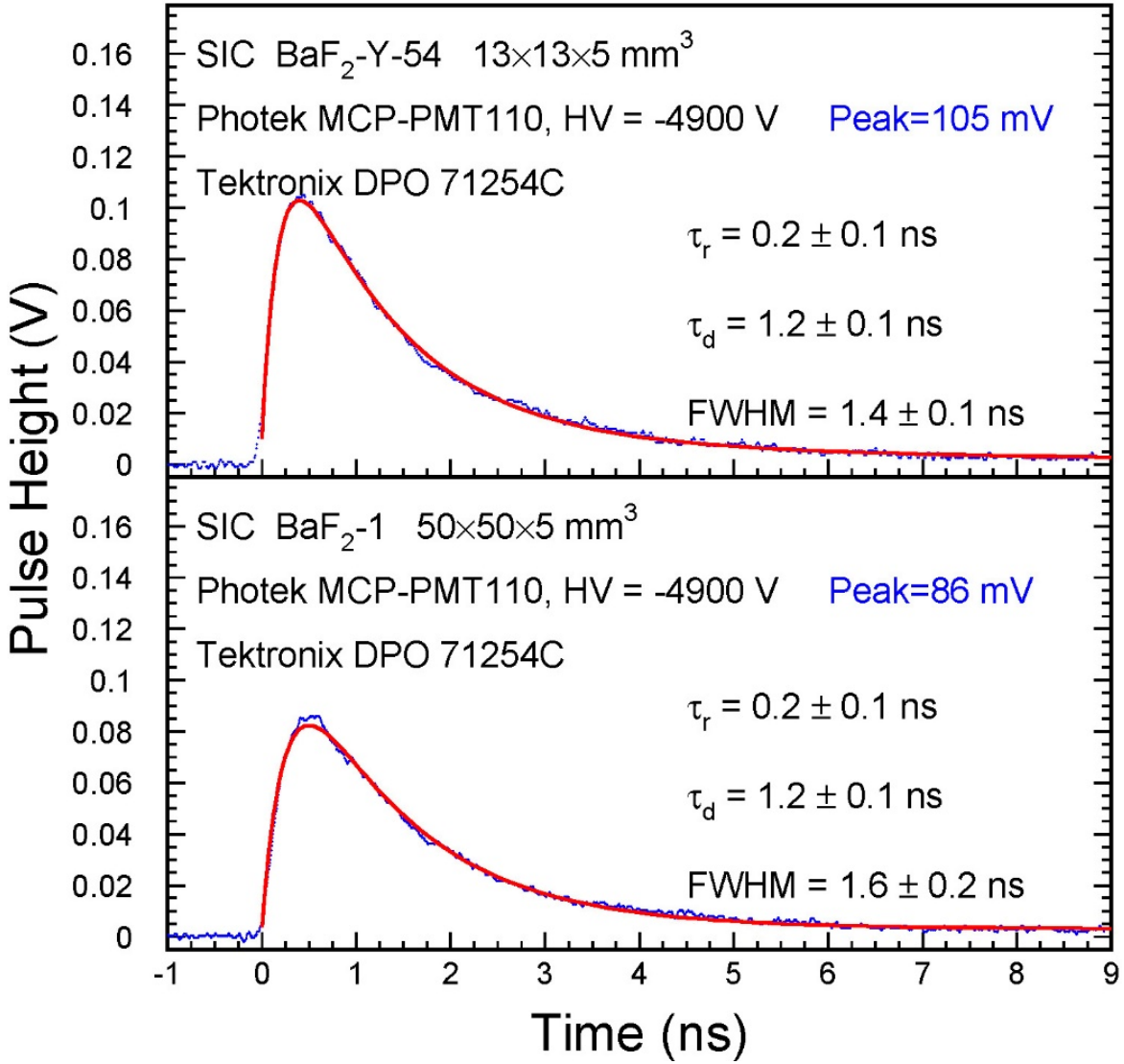


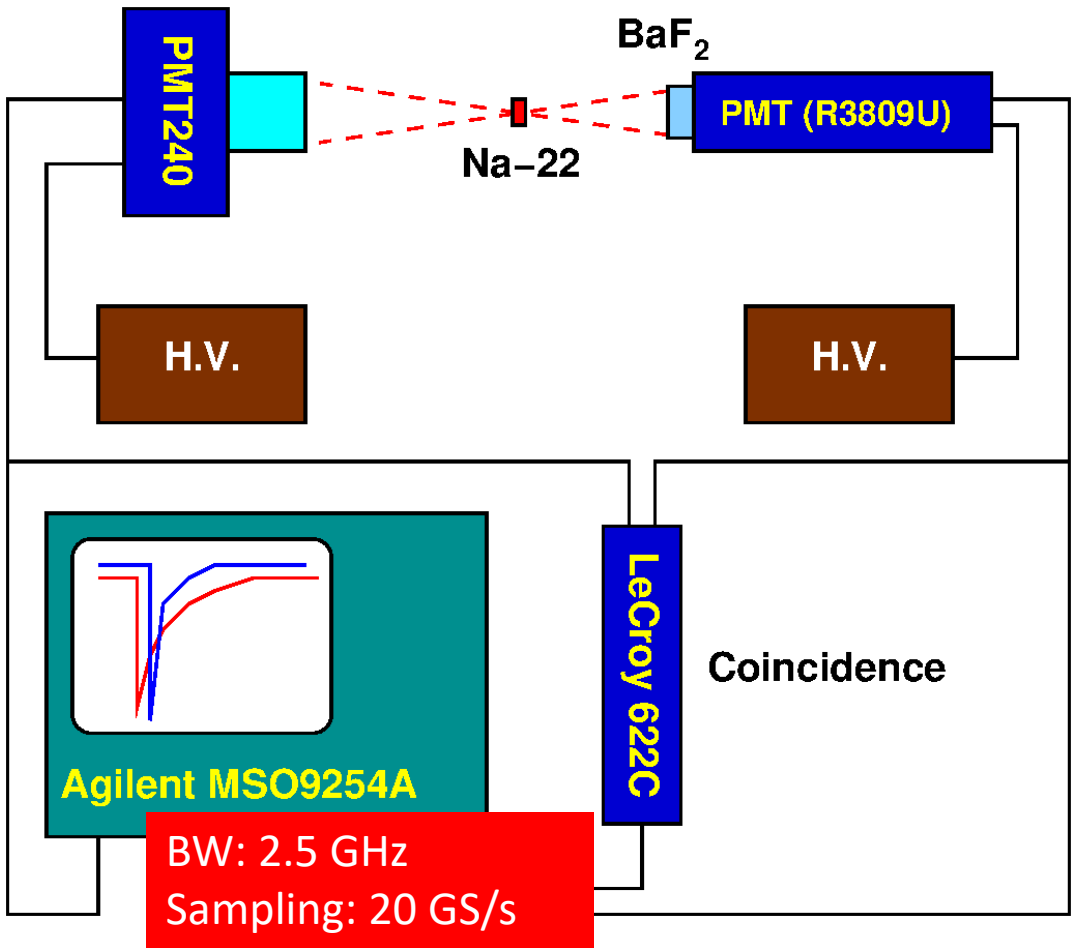
The decay time of BaF_2 measured at APS for septuplet X-ray bunches with 2.83 ns spacing is longer than 1 ns. This is suspected to be caused by the 15 m long cable used between the MCP-PMT and the MSO



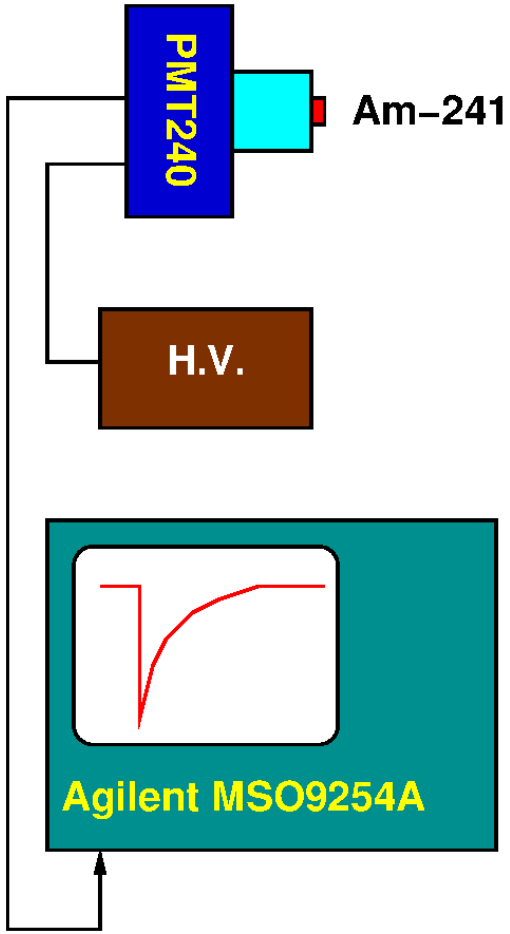
An MCP-PMT 240-Based Test Bench

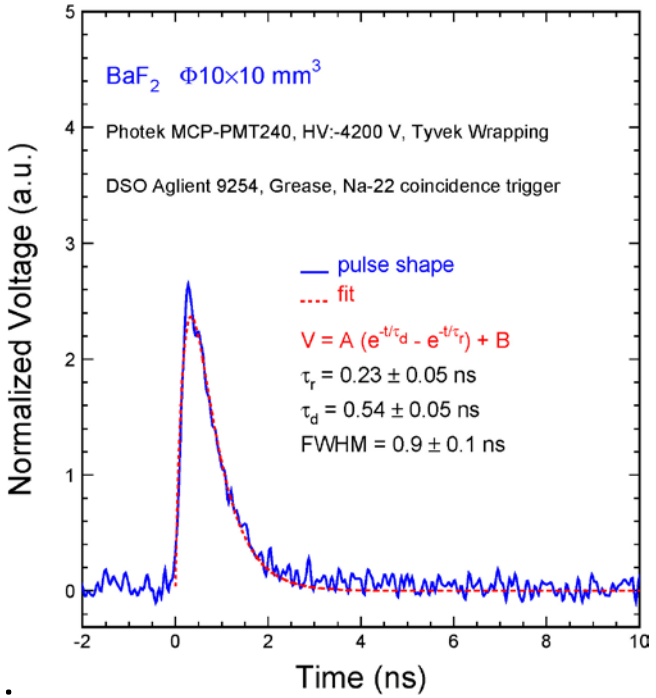
2022 IEEE NSS MIC RTSD MILANO

Na-22 Coincidence Trigger



Am-241 Self Trigger





Fitting:

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

B: background noise or slow component,

τ_r: rise time,

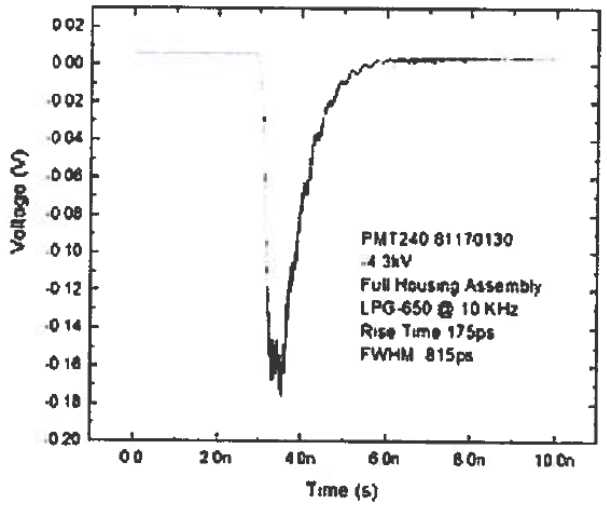
τ_d: decay time.

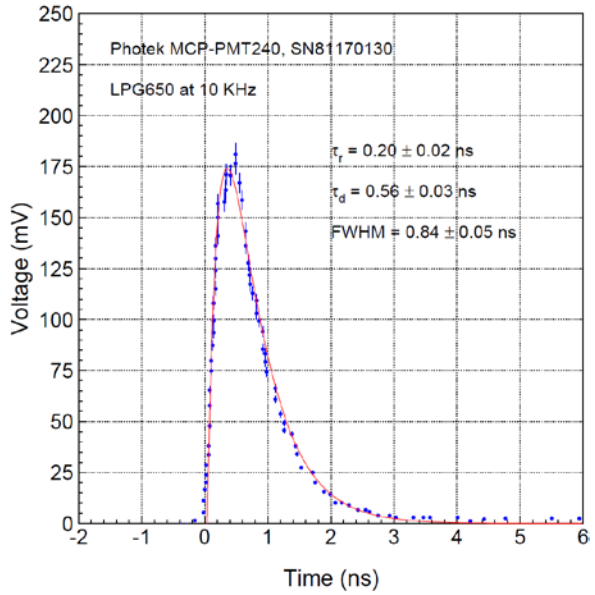
Rise, decay and FWHM obtained by fitting temporal response

Temporal Response of MCP-PMT 240

A fit to response of the Photek MCP-PMT 240 for pico-second laser pulses shows both the rise and FWHM consistent with the specification

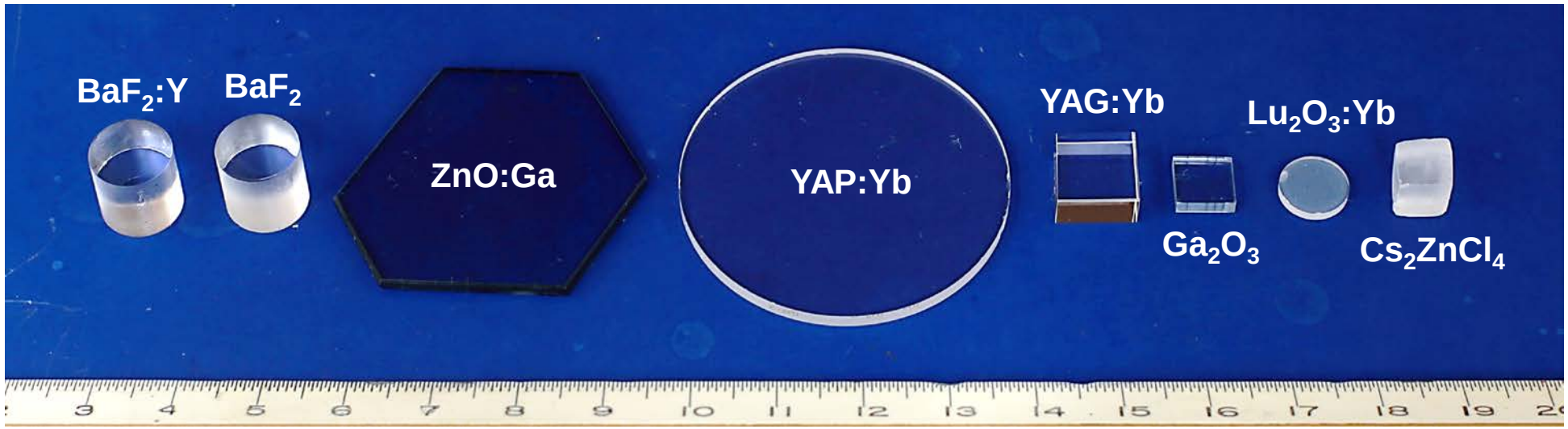
Photodetector	Active diameter (mm)	Spectral range (nm)	Peak Sen. (nm)	Gain	Rise time (ns)	FWHM (ns)
Photek MCP-PMT 240	**40**	**160-850**	**280-450**	**1×10^6**	**0.180**	**0.82**
Hamamatsu MCP-PMT R3809U-50	**11**	**160-850**	**430**	**3×10^5**	**0.160**	**0.30**
Photek MCP-PMT 110	10	160-850	280-450	1×10^4	0.065	0.11
Photek MCP-PMT 210	10	160-850	280-450	1×10^6	0.085	0.15
Hamamatsu PMT R2059	46	160-650	450	2×10^7	1.3	





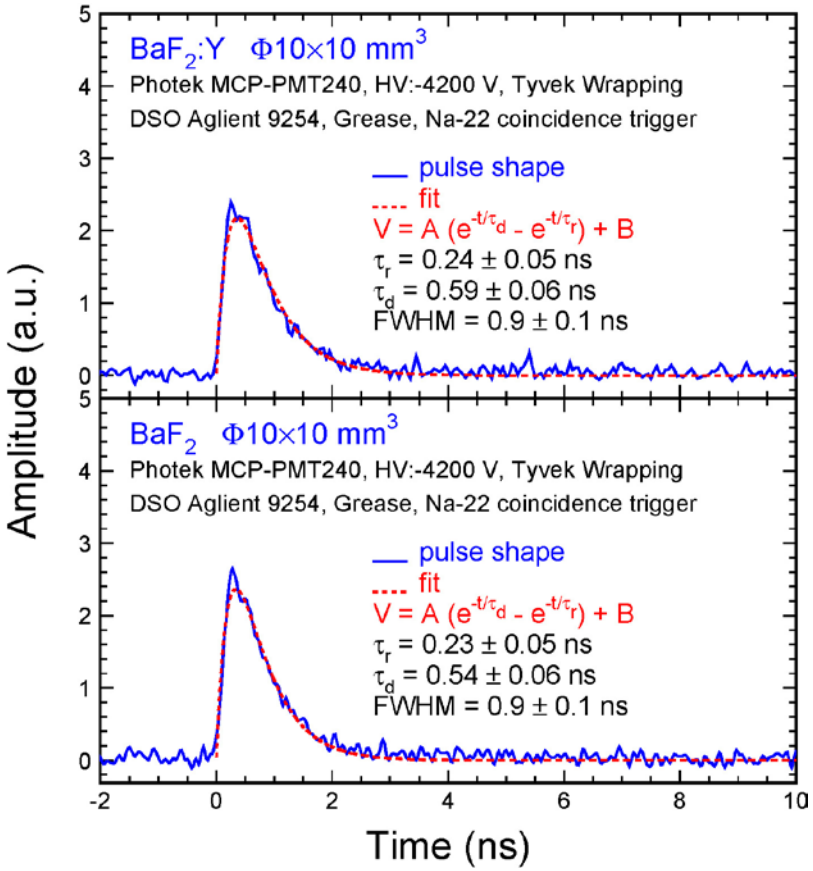
Ultrafast Inorganic Scintillator Samples

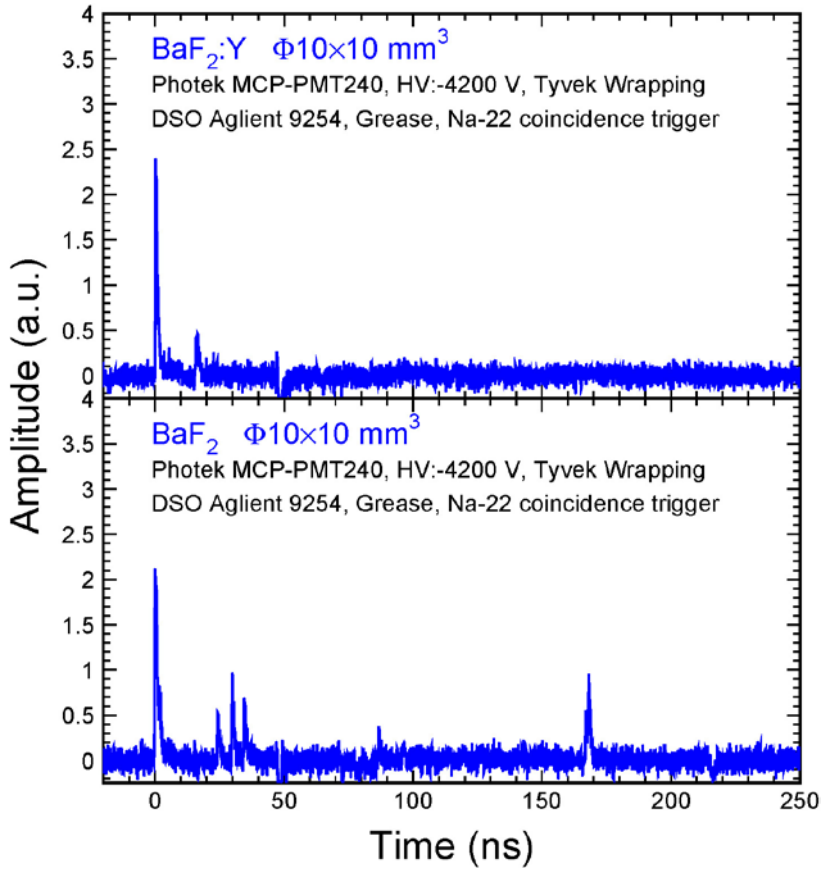
8 fast/ultrafast crystals samples used in this investigation

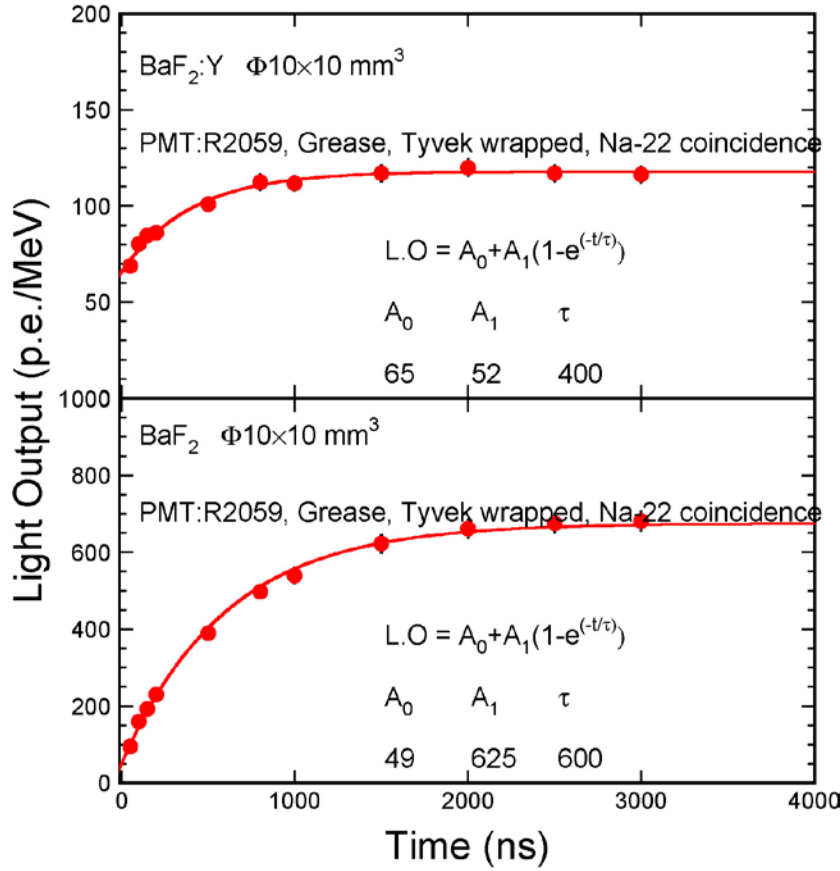


	BaF_2:Y	BaF_2	ZnO:Ga	YAP:Yb	YAG:Yb	Ga_2O_3	Lu_2O_3:Yb	Cs_2ZnCl_4
Producer	BGRI	BGRI	FJIRSM	Dongjun	Dongjun	Tongji	RMD	RMD
Dimension (mm^3)	Φ10×10	Φ10×10	33×30×2	Φ40×2	10×10×5	7×7×2	Φ9×1	6×6×7

Temporal Response of BaF_2 & BaF_2:Y

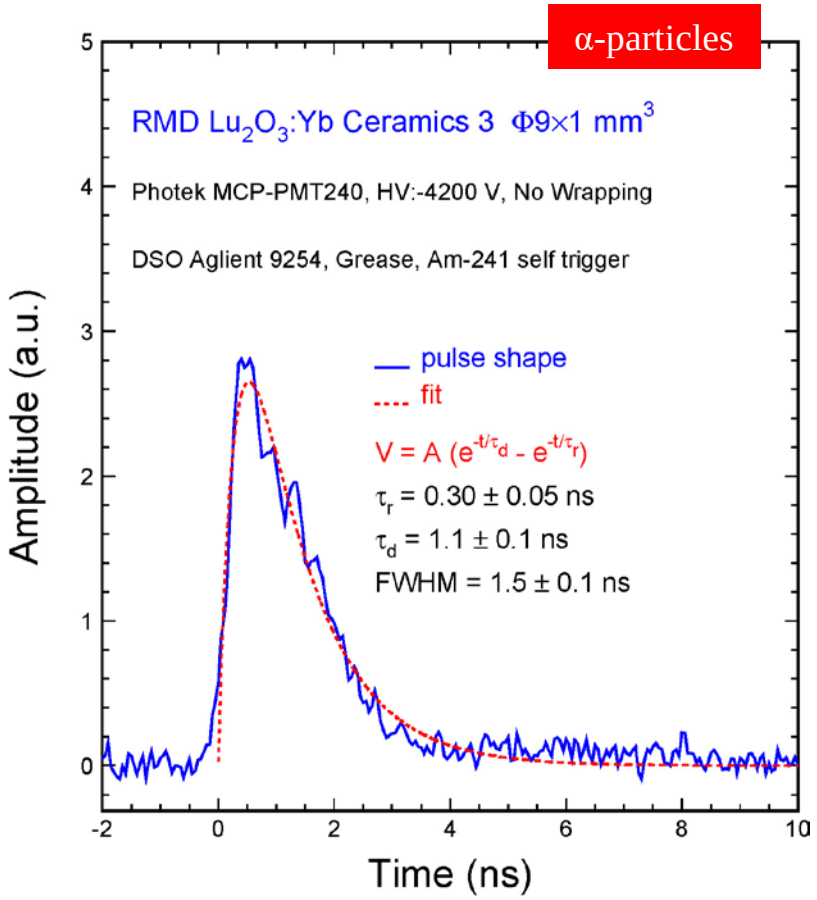


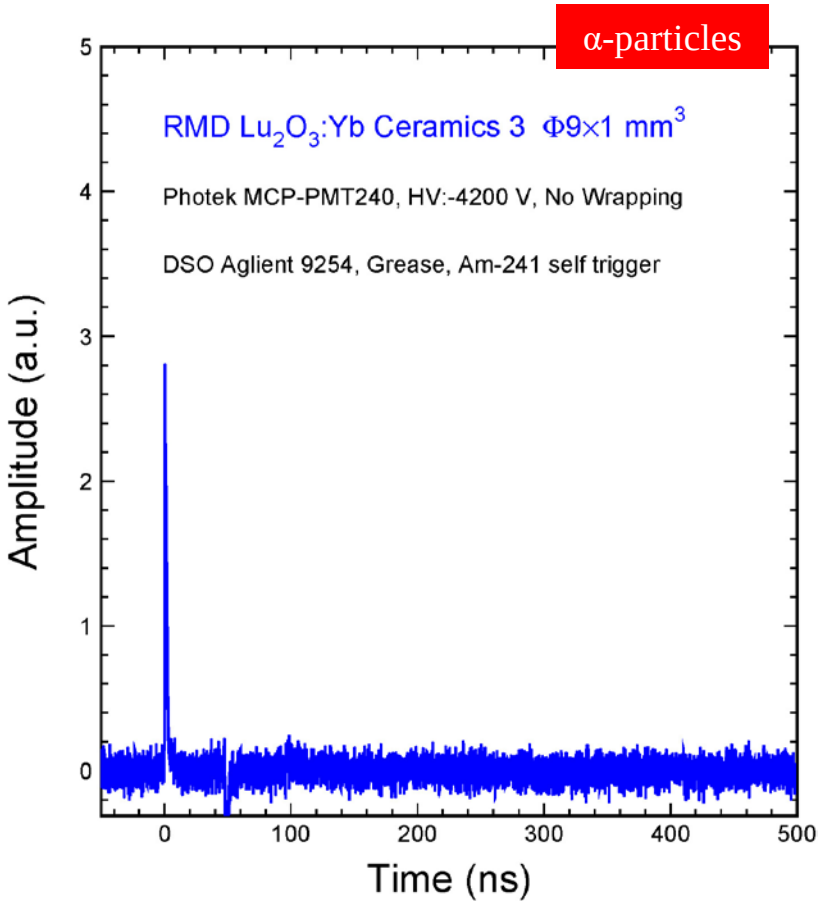


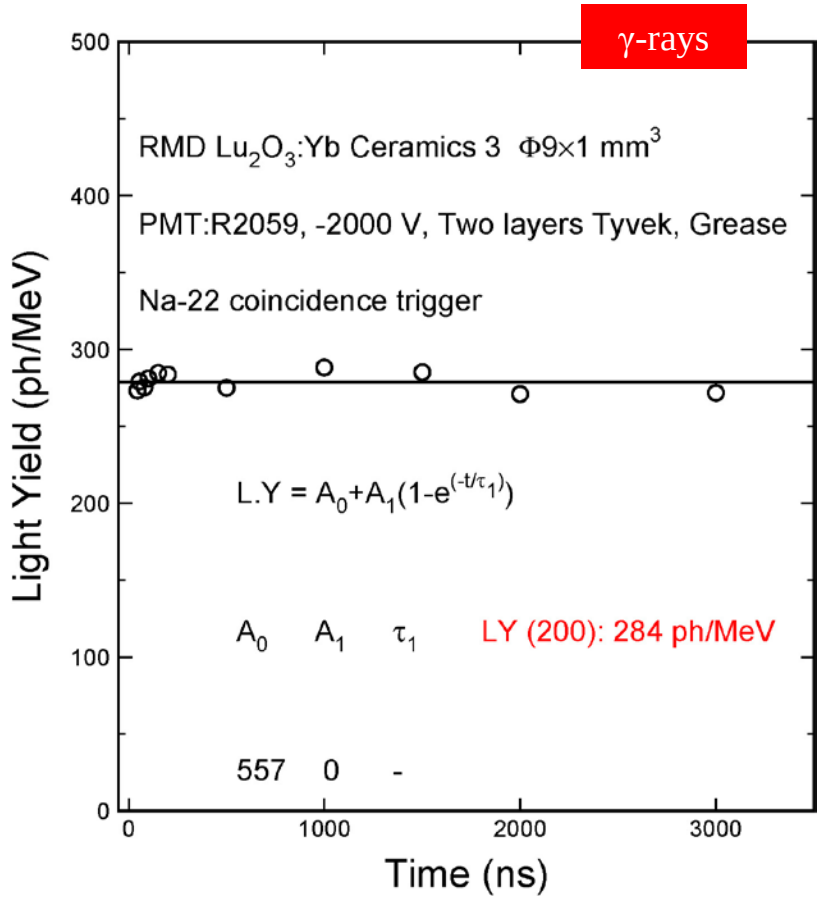


Ultrafast response of 0.2/0.6/0.8 ns observed for BaF_2 and BaF_2:Y crystals
The response is consistent with the Photek MCP-PMT 240 specification

Temporal Response of Lu_2O_3:Yb Ceramics



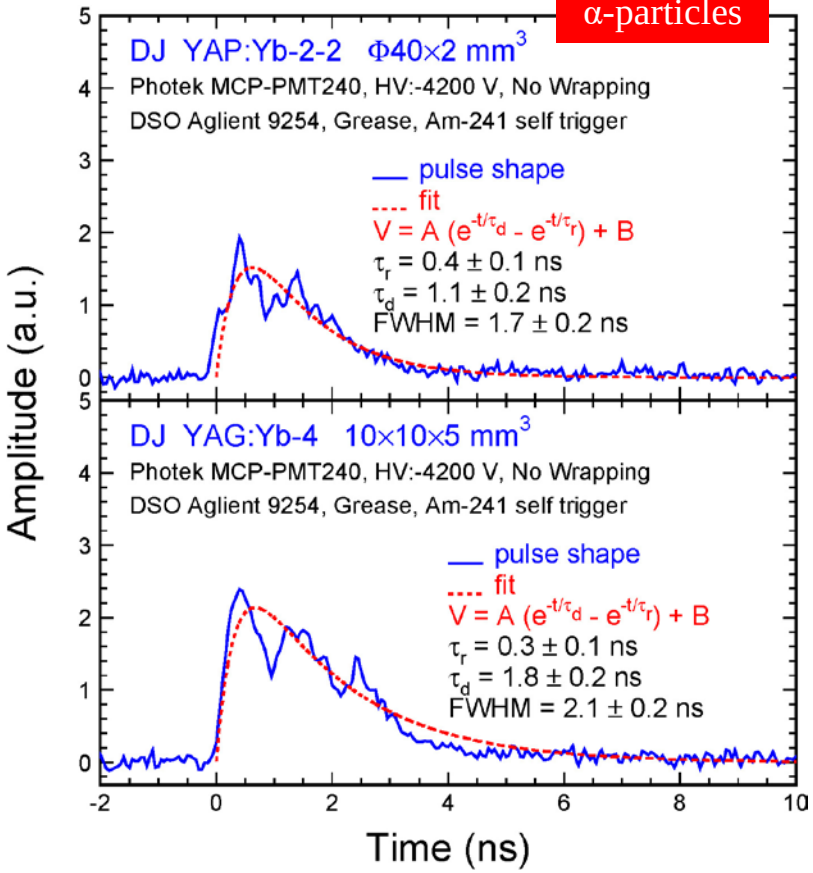




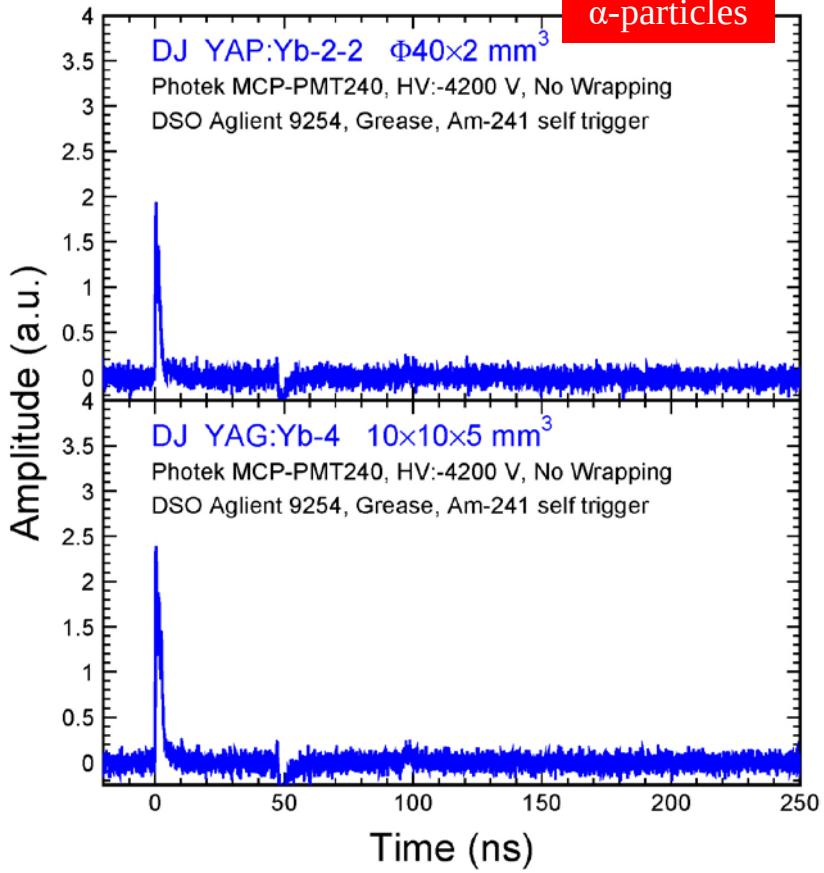
Lu_2O_3:Yb ceramic of 9.4 g/cc shows an ultrafast decay time of **1.1 ns** by Am-241 with negligible slow component observed in integrated light output measurement

Temporal response of YAP:Yb & YAG:Yb

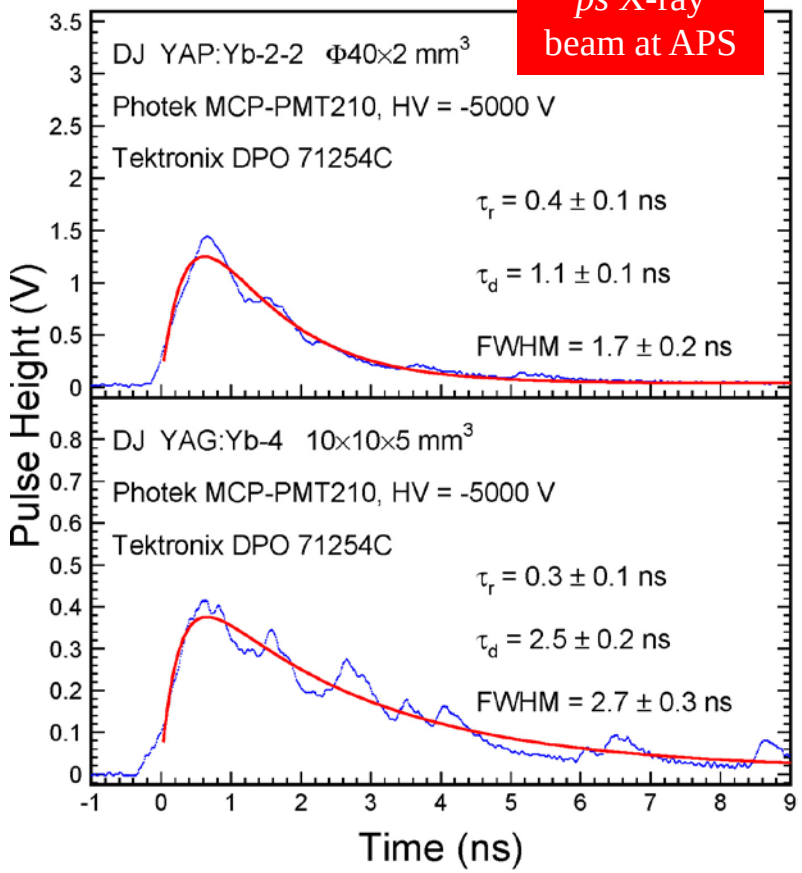
α-particles



α-particles



ps X-ray beam at APS



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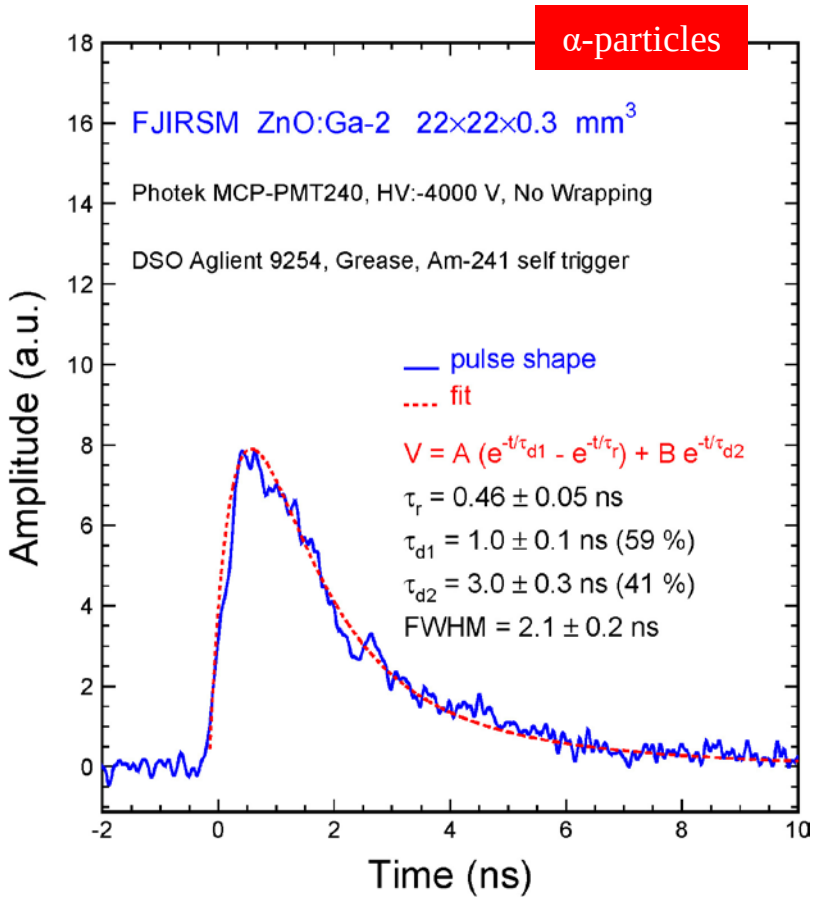
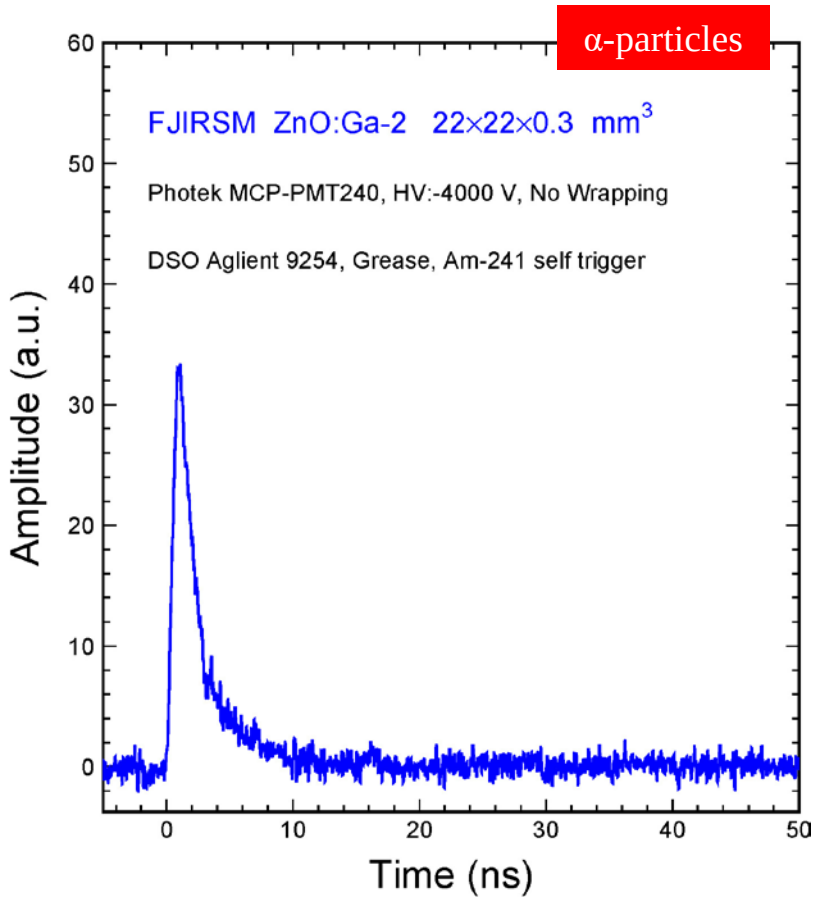
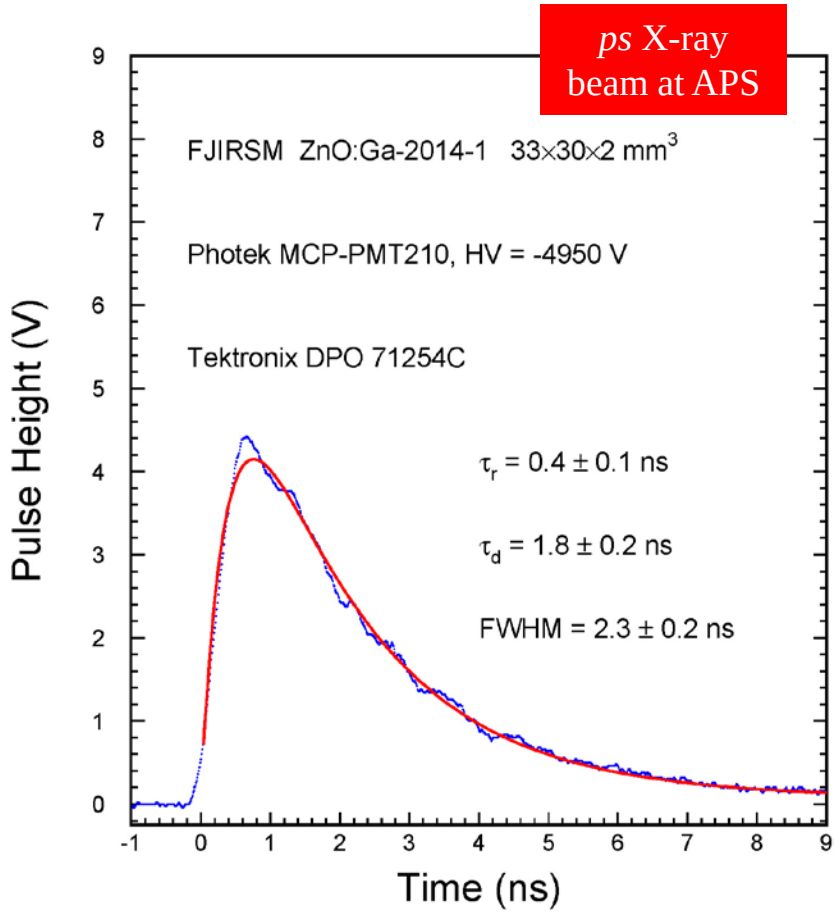
YAP:Yb & YAG:Yb show a decay time of 1.1 ns and 1.8 ns by Am-241 with negligible slow component

Temporal Response of ZnO:Ga







ZnO:Ga shows decay time of 1.0/3.0 ns by Am-241 with negligible slow component

Fast and Ultrafast Inorganic Scintillators

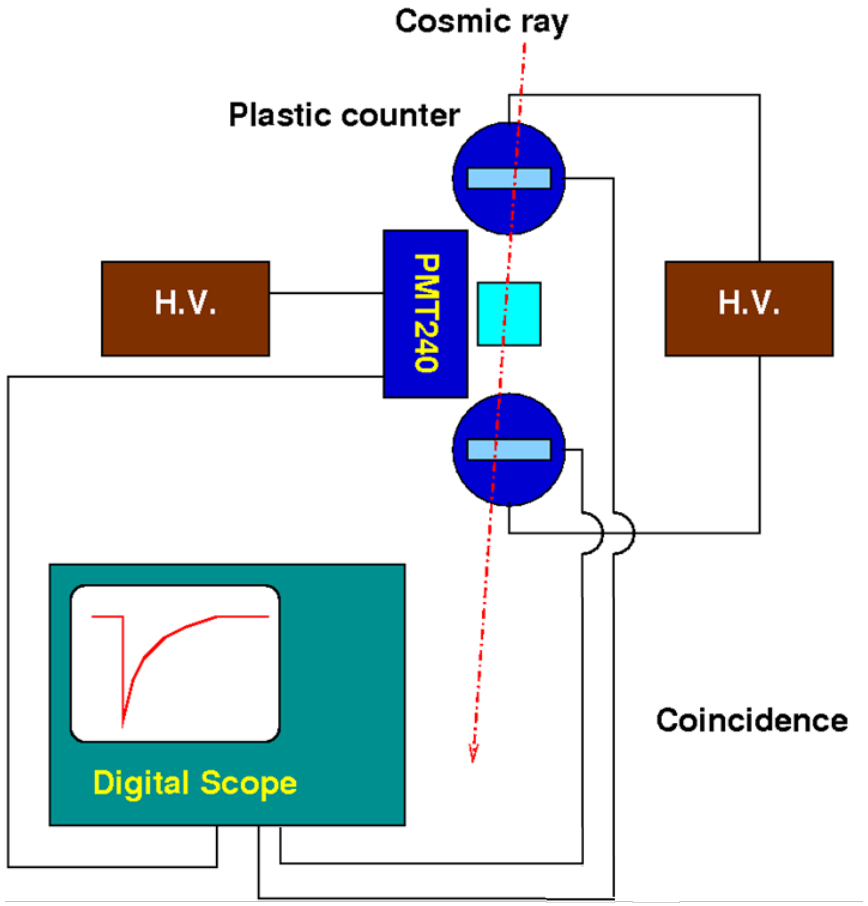
arXiv: 2203.06788

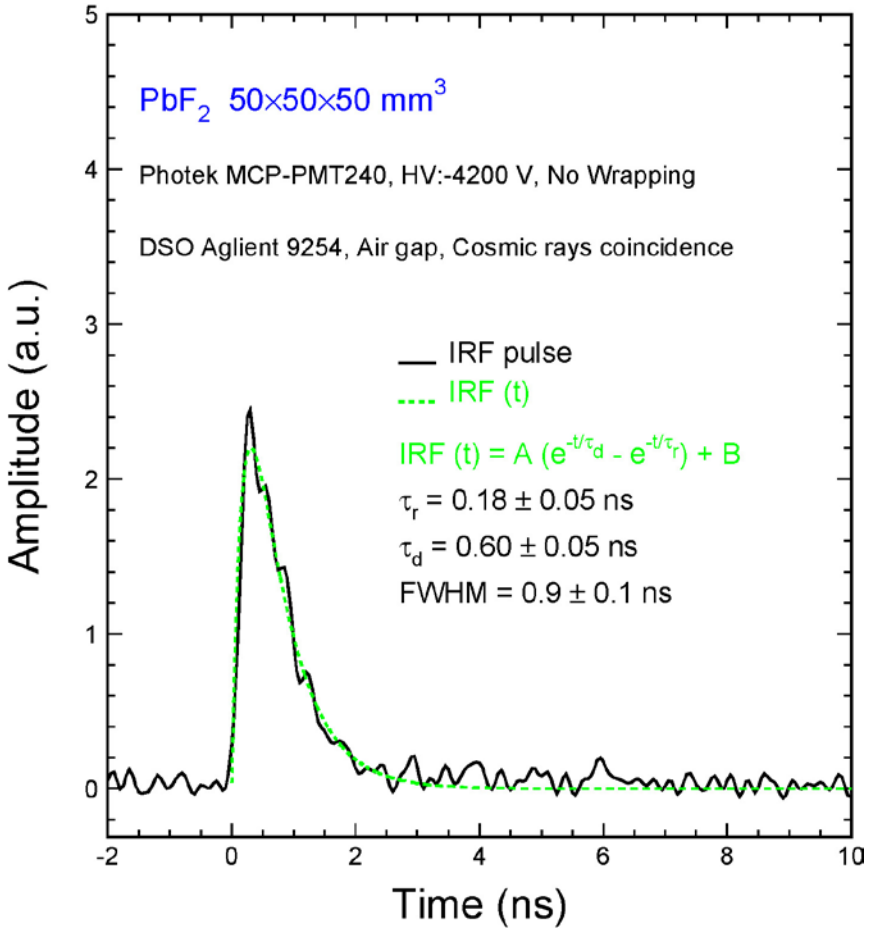
	BaF_2	BaF_2:Y	Lu_2O_3:Yb	YAP:Yb	YAG:Yb	ZnO:Ga	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	9.42	5.35	4.56	5.67	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (^{o}C)	1280	1280	2490	1870	1940	1975	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	0.81	2.59	3.53	2.51	2.51	1.14	1.45	2.59	1.63	1.37	3.10
R_M (cm)	3.1	3.1	1.72	2.45	2.76	2.28	2.20	2.07	2.15	2.45	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	18.1	23.1	25.2	22.2	20.9	20.9	20.6	23.1	21.5	19.5	27.8
Z_{eff}	51.0	51.0	67.3	32.8	29.3	27.7	27.8	63.7	58.7	32.8	50.6	57.1	32.8
dE/dX (MeV/cm)	6.52	6.52	11.6	7.91	7.01	8.34	8.82	9.55	9.22	7.91	8.96	9.82	6.57
λ_{peak} [a] (nm)	300 220	300 220	370	350	350	380	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.0	1.96	1.87	2.1	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	0.95	0.19[d]	0.36[d]	2.6[d] 4.0[d]	6.5 0.5	100	35[e] 48[e]	9 32	190	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	280	57[d]	110[d]	2,000[d]	2,100	30,000	25,000[e]	12,000	58,000	10,000	24,000
Decay time[a] (ns)	600 0.5	600 0.5	1.1[d]	1.1[d]	1.8[d]	3.0[d] 1.0[d]	110 5.3	40	820 50	191 25	570 130	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	170	34[d]	46[d]	980[d]	43	740	240	391	400	125	318
LY in 1st ns /Total LY (%)	9.0	64	60	60	43	49	2.0	2.5	1.2	3.3	0.7	1.4	1.3
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.127	0.314	0.439	0.407	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.

The Instrument Response Function

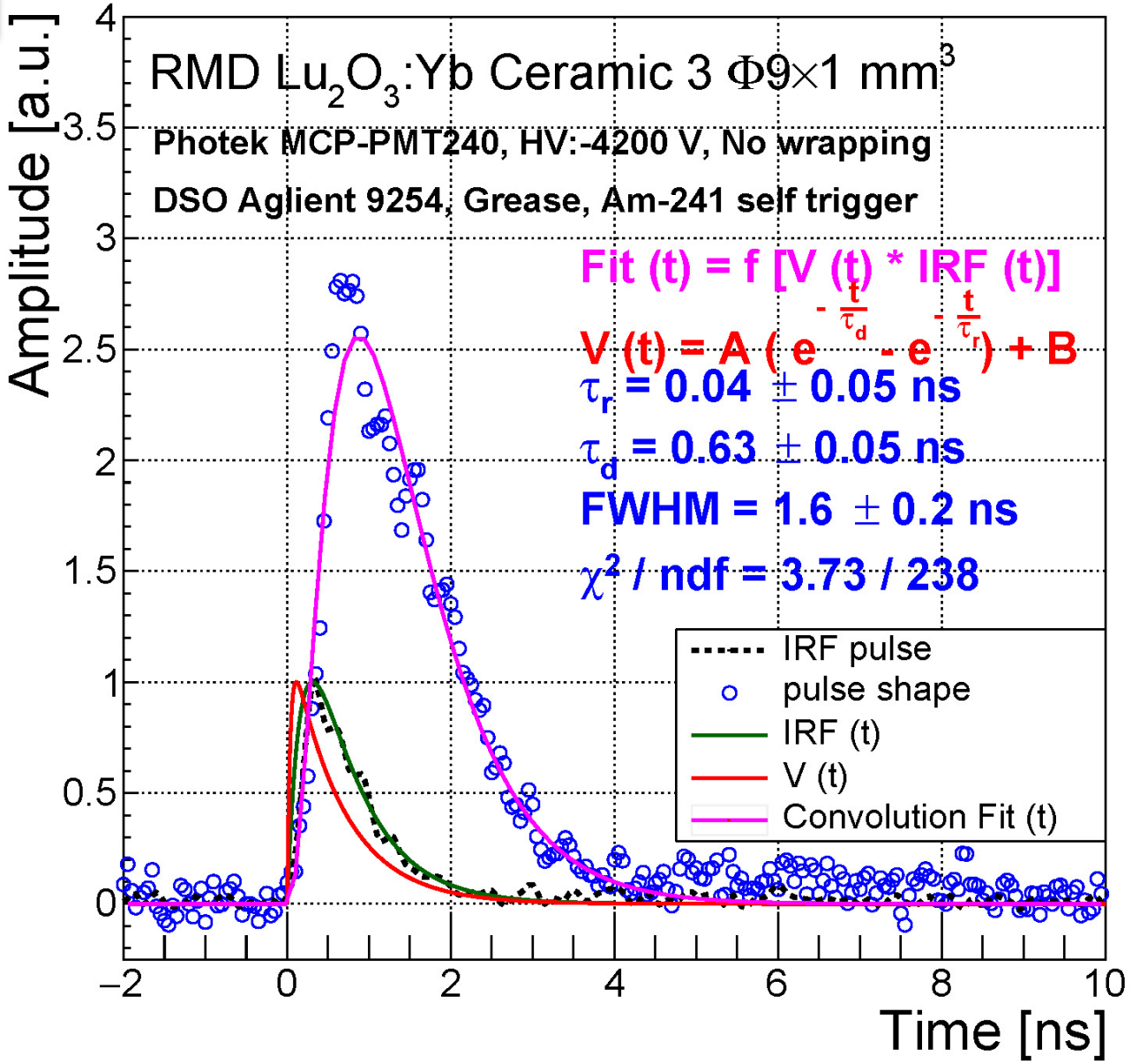
$$Fit(t) = f[V(t) * IRF(t)] = \int_{-\infty}^{+\infty} V(\tau) * IRF(t-\tau)d\tau$$





Intrinsic ultrafast response time can be extracted by taking out the IRF of the set-up. It was measured by fitting Cerenkov light pulse from a PbF_2 crystal, which agrees well with Photek spec.

Intrinsic Decay Time of Lu_2O_3:Yb

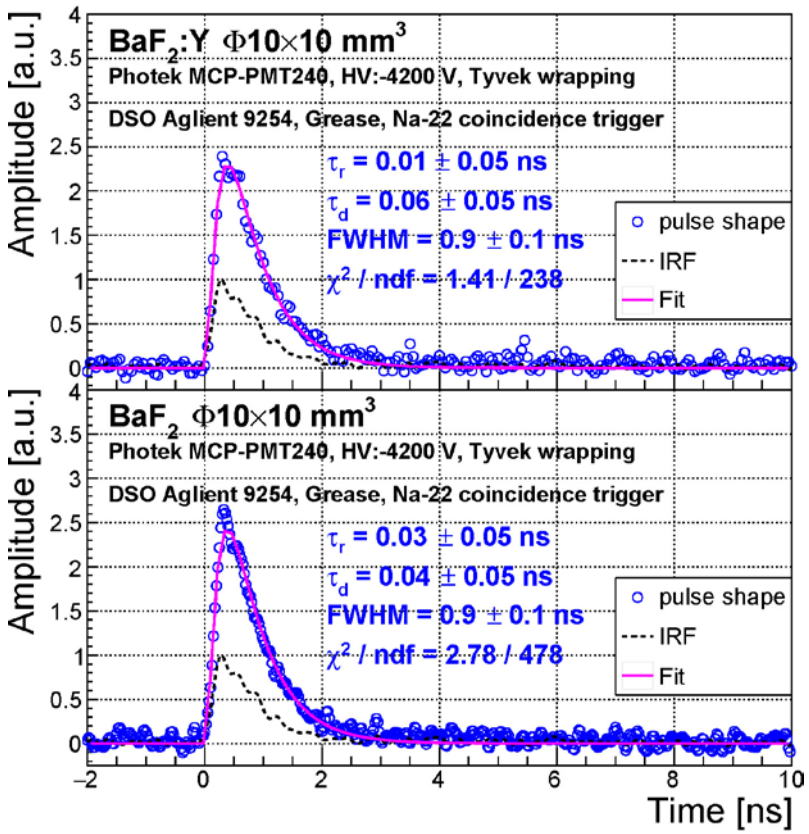


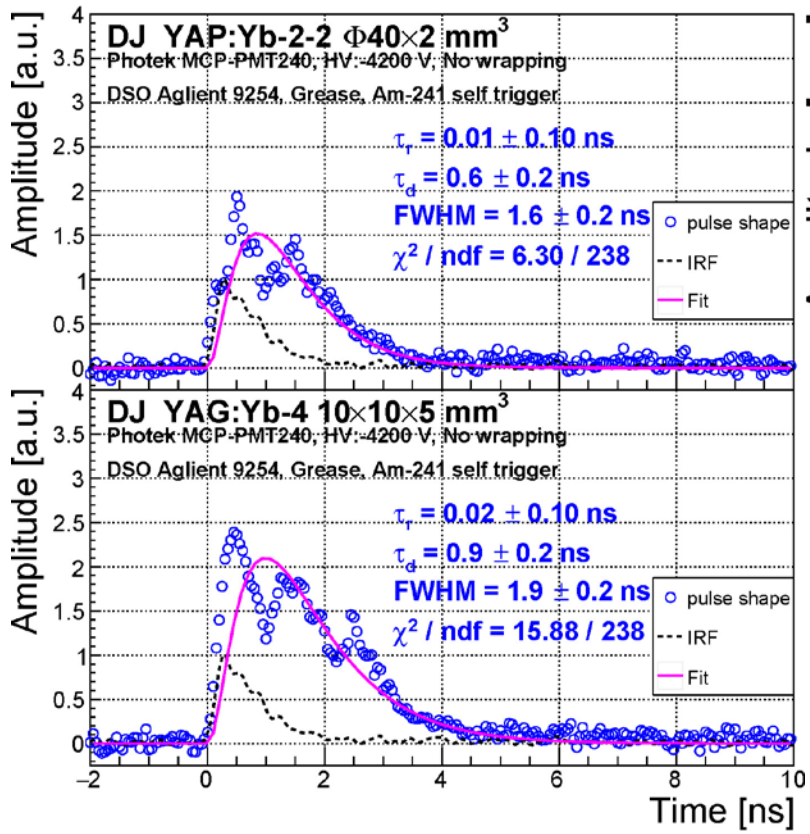
The magenta line shows the convolution fit. The numerical values of the fit after taking out the IRF are shown in blue

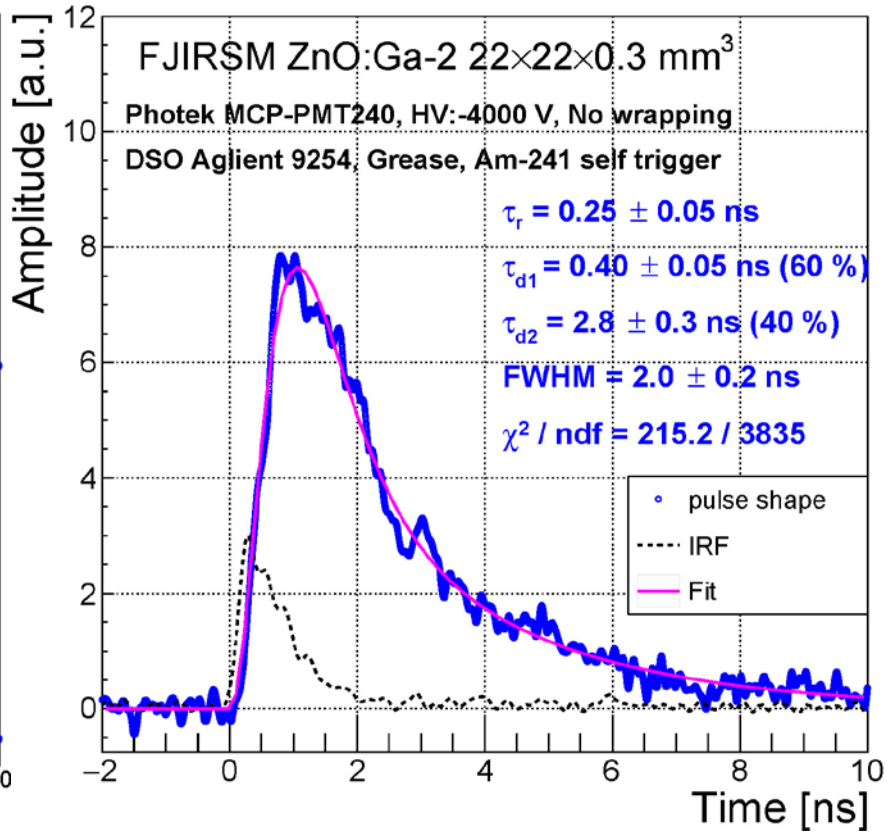
The result of the 0.63 ns decay time is the intrinsic decay time of Lu_2O_3:Yb

Decay time of BaF_2, YAP:Yb, YAG:Yb &ZnO:Ga

The intrinsic decay time of YAP:Yb, YAG:Yb and ZnO:Ga are 0.6, 0.9 & 0.4/2.8 ns, respectively
The rise/decay time for the BaF_2/BaF_2:Y ultrafast light is within the IRF of the set-up







Summary

- Ultrafast crystals with sub-nanosecond decay time are important to break the ps timing barrier for future HEP TOF system, ultrafast calorimetry and GHz hard X-ray imaging.
- Temporal response was measured by using a Photek MCP-PMT 240-based test bench. The measured decay time of ~0.5 ns for BaF_2 and BaF_2:Y is much shorter than the 1.2 ns measured at APS, which is due to the 15 m long cable used between the MCP-PMT & the MSO at APS.
- Lu_2O_3:Yb ceramics show a decay time of 1.1 ns with negligible slow component. With its 9.4 g/cc density, it is a very interesting ultrafast inorganic scintillator.
- YAP:Yb and YAG:Yb samples show decay time of 1.1 and 1.8 ns. Both samples also have negligible slow component.
- ZnO:Ga show decay time of 1.0/3.0 ns.
- Taking out the instrument response function, the intrinsic decay time of BaF_2, Lu_2O_3:Yb, YAP:Yb, YAG:Yb and ZnO:Ga are <0.5, 0.6, 0.6, 0.9 and 0.4/3 ns, respectively.
- Investigation will continue at APS of ANL by using high intensity ps x-ray pulses.

Acknowledgements: DOE HEP Award DE-SC0011925