Temporal Response of Ultrafast Inorganic Scintillators

Chen Hu, Liyuan Zhang, Ren-Yuan Zhu
California Institute of Technology

for

The Ultrafast Materials and Application Collaboration

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The Ultrafast Materials and Applications (UMA) Collaborators

Marcel Demarteau, Robert Wagner, Lei Xia, Junqi Xie
Argonne National Laboratory

Xuan Li, Zhehui Wang
Los Alamos National Laboratory

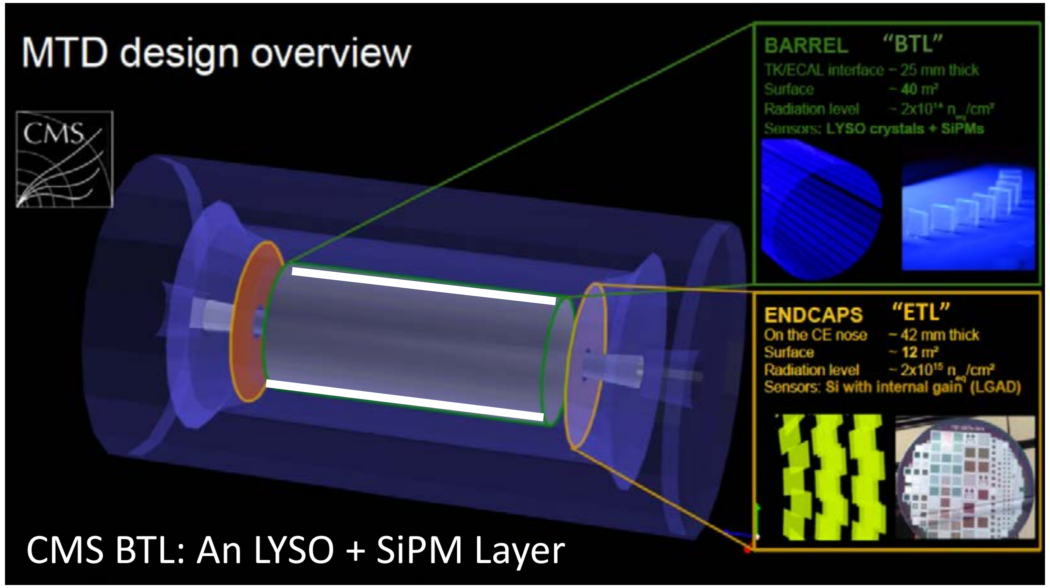
Yahua Shih, Thomas Smith
University of Maryland

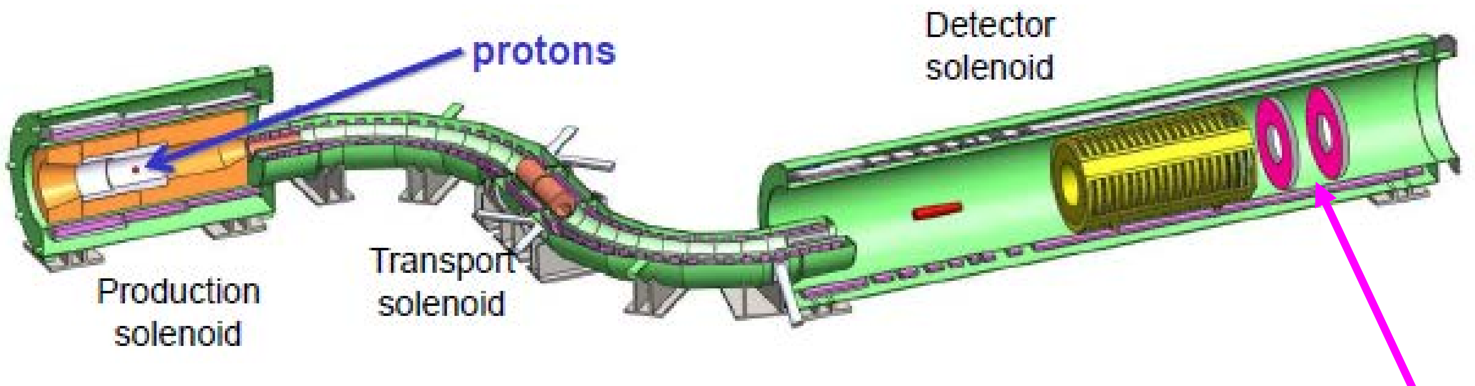
A beam test carried out at the APS 10-ID-B site on July 2 -3, 2018

Why Ultrafast Crystals?

- **Precision photons and electrons measurements enhance physics discovery potential in HEP experiments.**
- **Performance of crystal calorimeter in e/γ measurements is well understood:**
  - **The best possible energy resolution;**
  - **Good position resolution;**
  - **Good e/γ identification and reconstruction efficiency.**
- **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).**

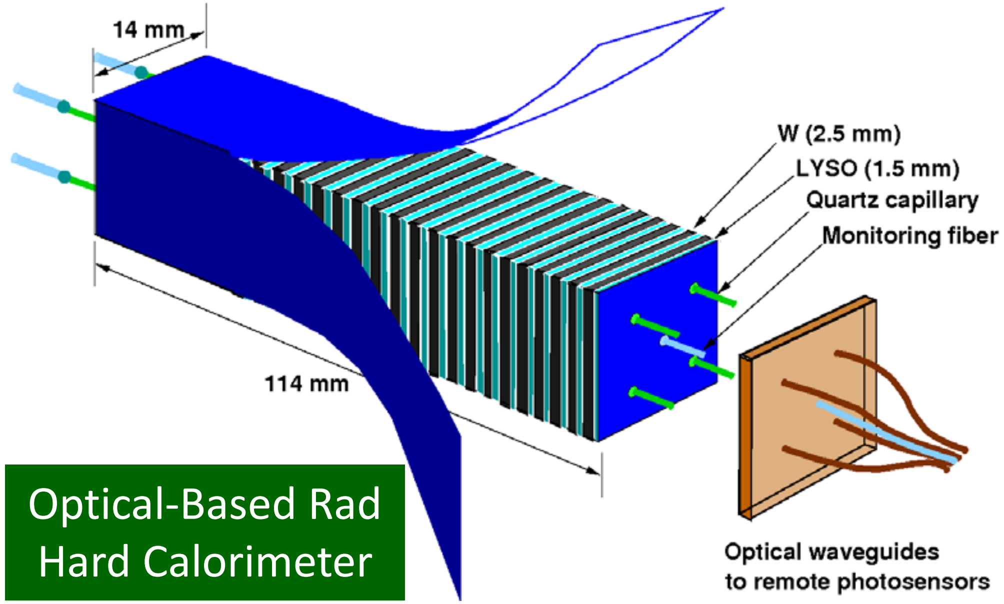
Application of Ultrafast Crystals



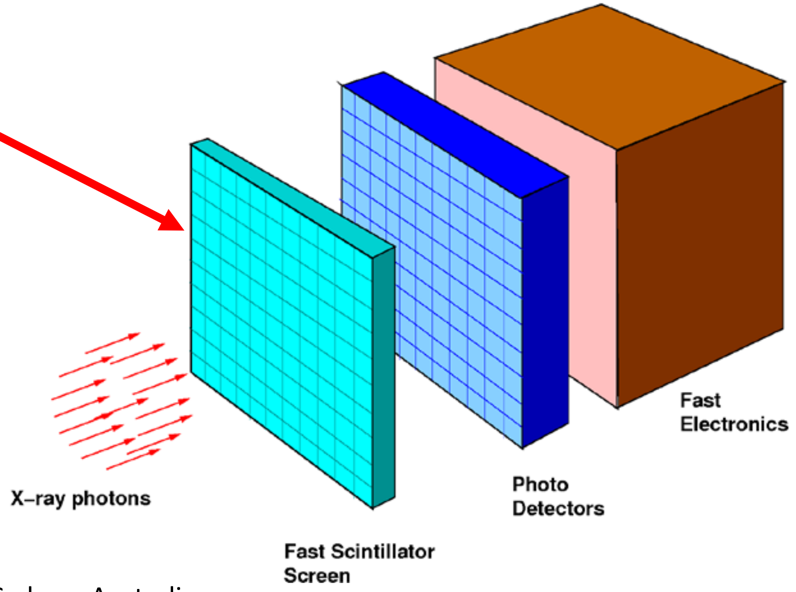


Mu2e-II: arXiv:1802.02599
See papers N21-4, N37-4

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



A BaF_2 crystal based ultrafast front imager proposed for GHz hard X-ray imaging for the proposed MaRIE project in the 2016 workshop at Santa Fe



Fast and Ultrafast Inorganic Scintillators

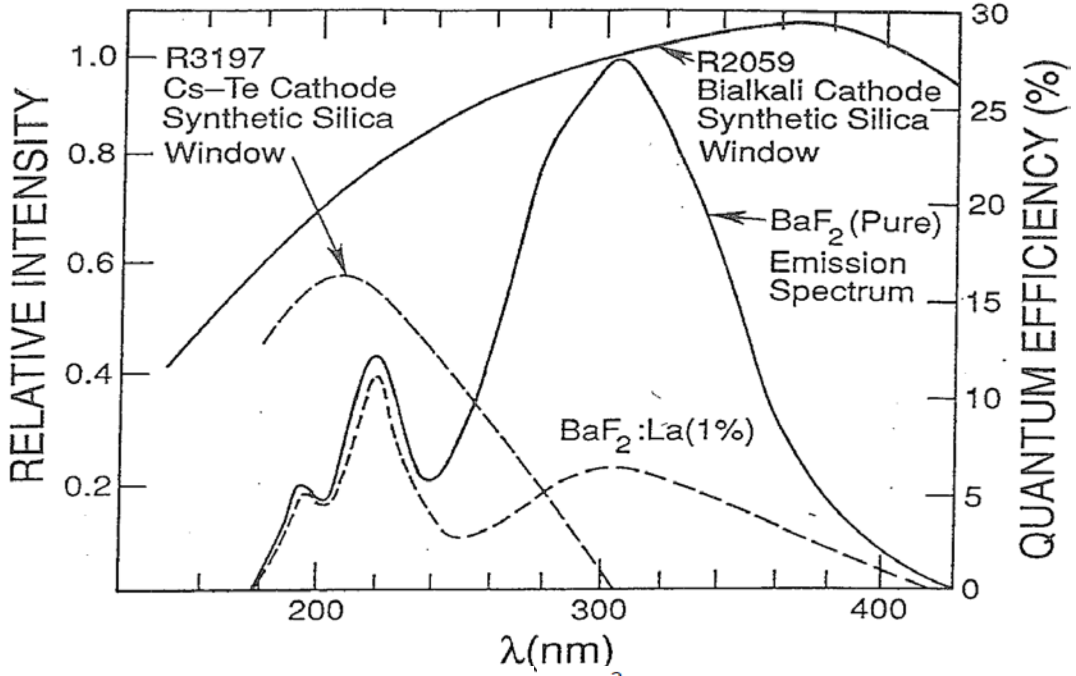
	BaF_2	BaF_2 :Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (^oC)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	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 1st 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

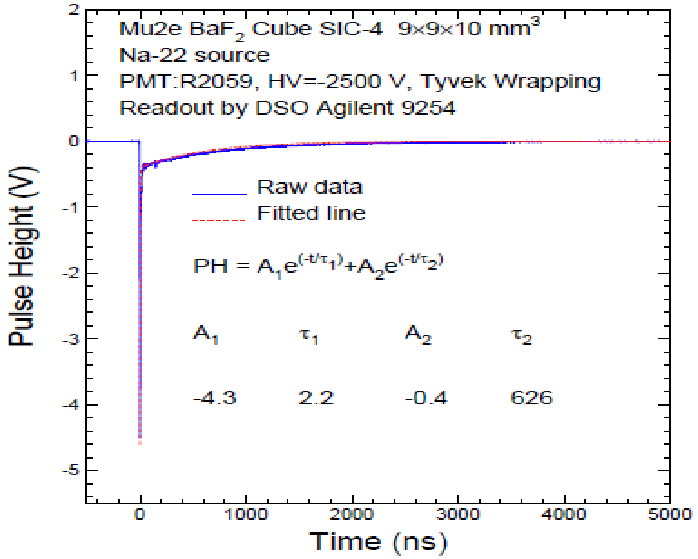
Ultrafast and Slow Light from BaF_2

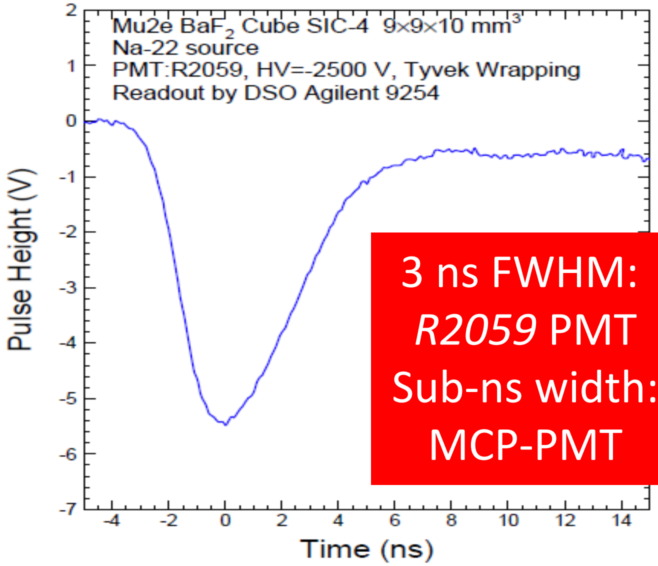
BaF_2 has a fast scintillation component with sub-ns decay time, and a 600 ns slow component.

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

Spectroscopic readout of the fast component may be realized by (1) selective doping with rare earths or (2) a solar blind photodetector.



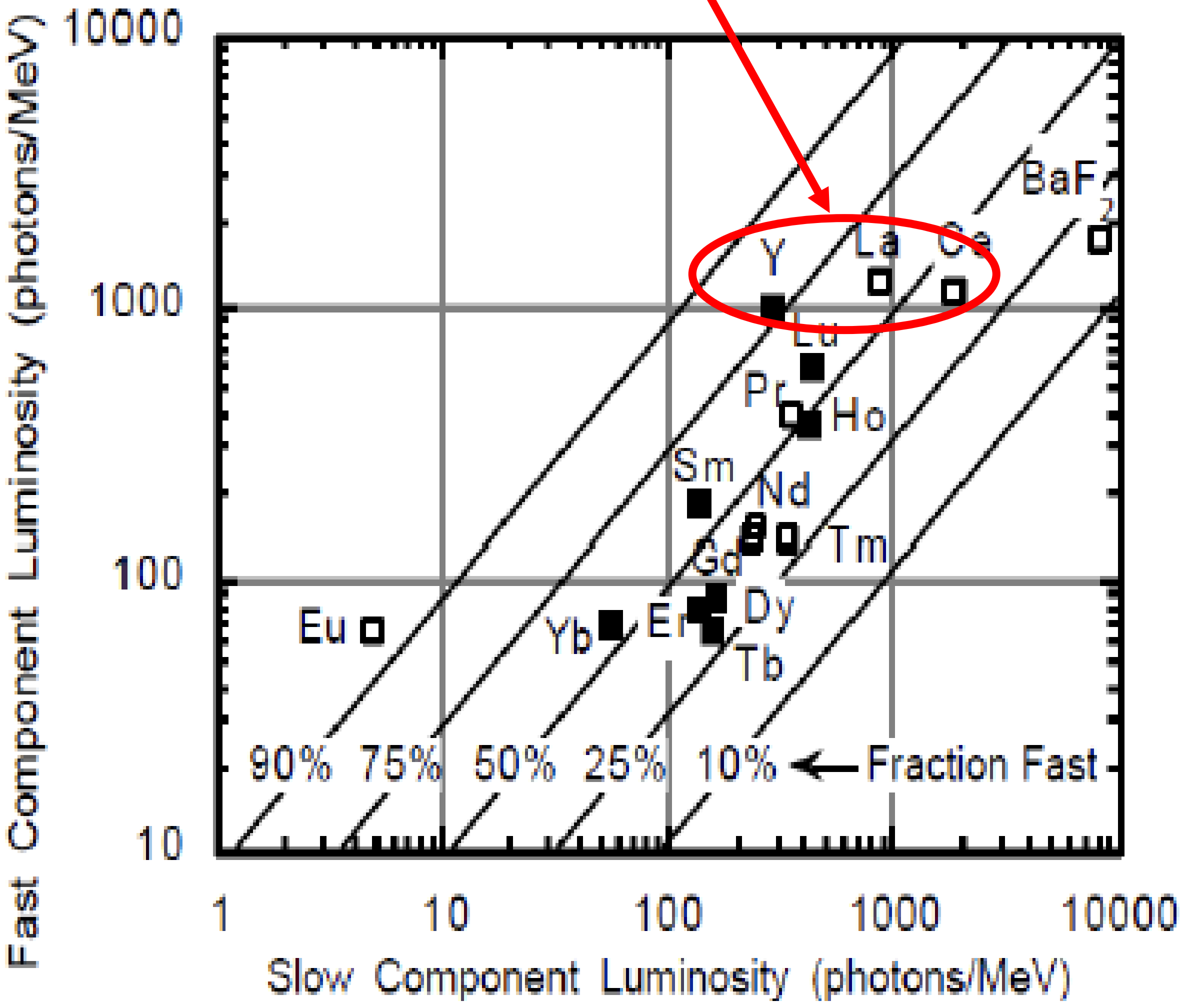


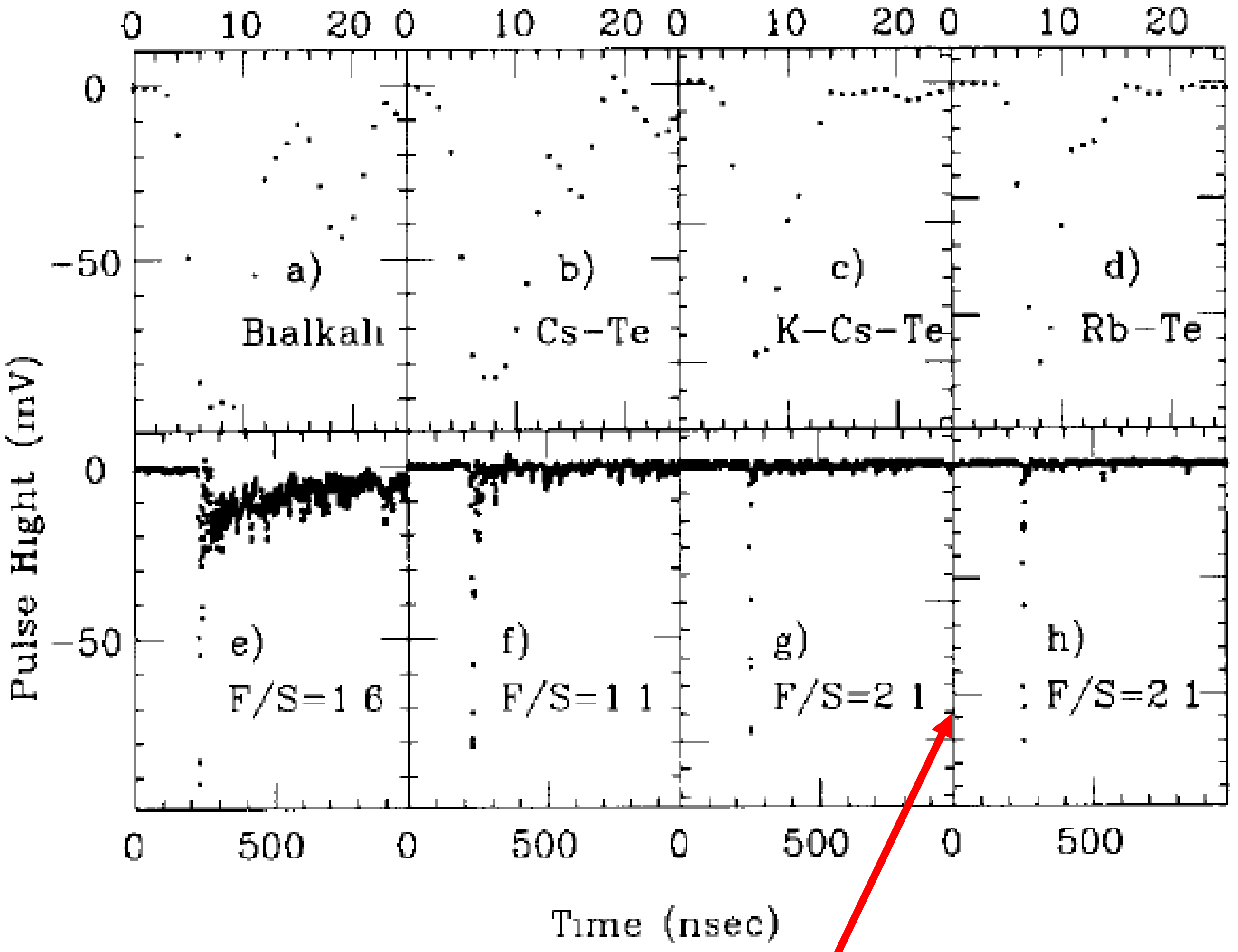


3 ns FWHM: *R2059* PMT
Sub-ns width: MCP-PMT

Slow Suppression: RE Doping & SB Readout

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

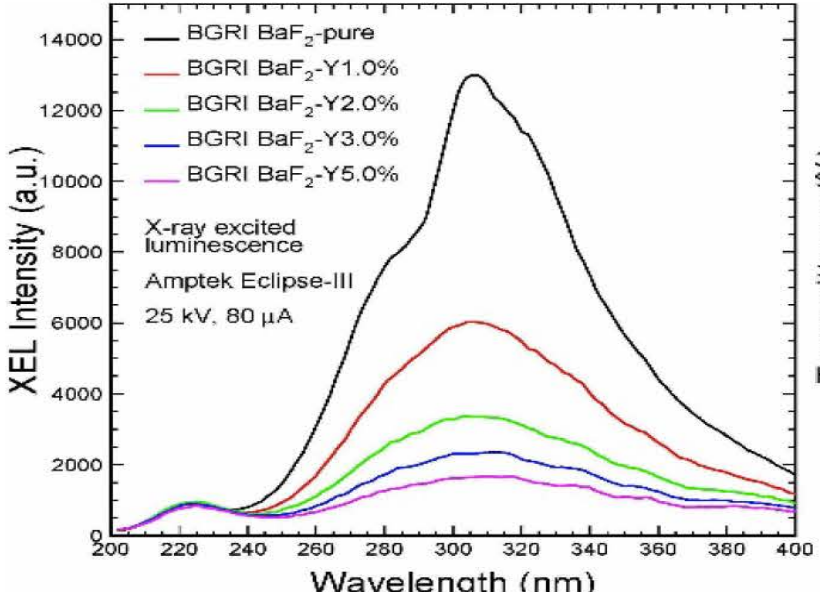


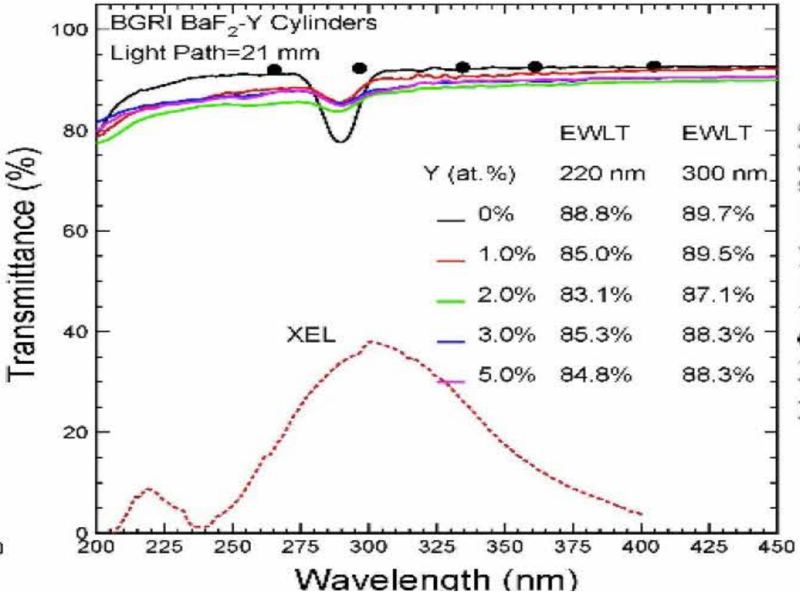


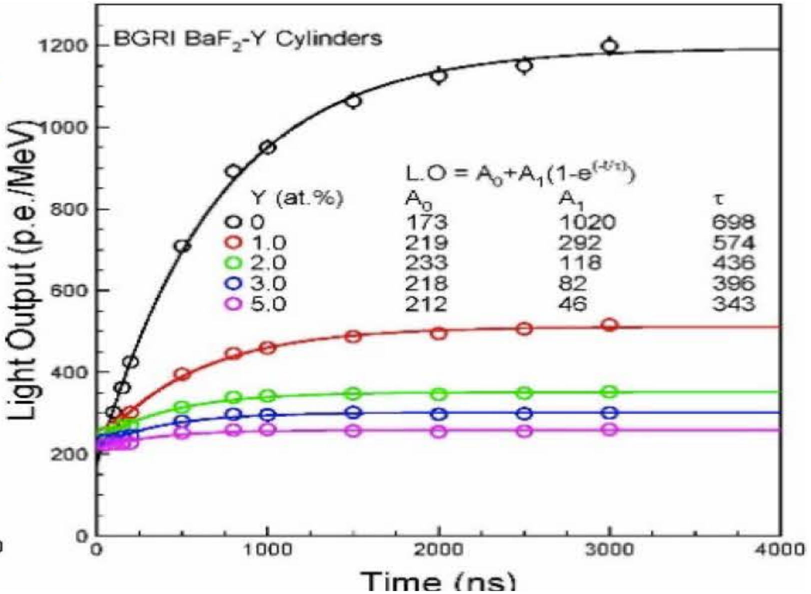
NIM 240 (1994) 442: Cs-Te, K-Cs-Te and Rb-Te cathode achieved F/S = 2/1

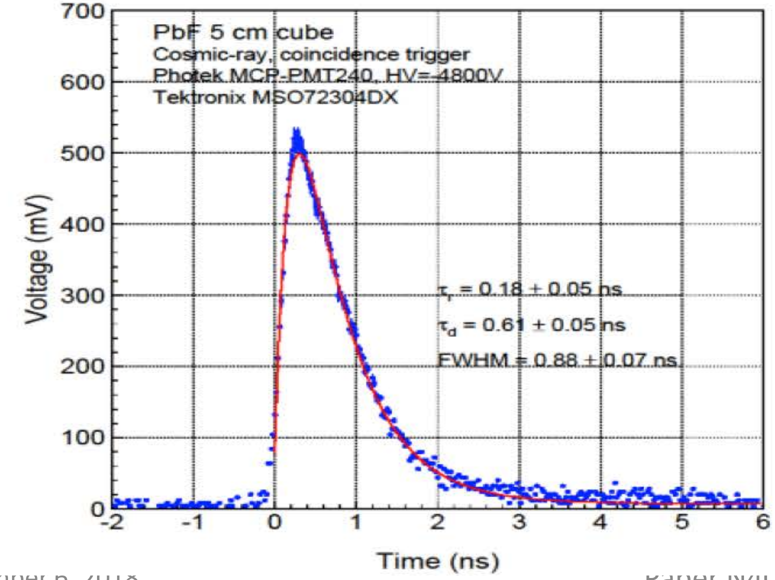
Yttrium Doped Barium Fluoride: BaF_2:Y

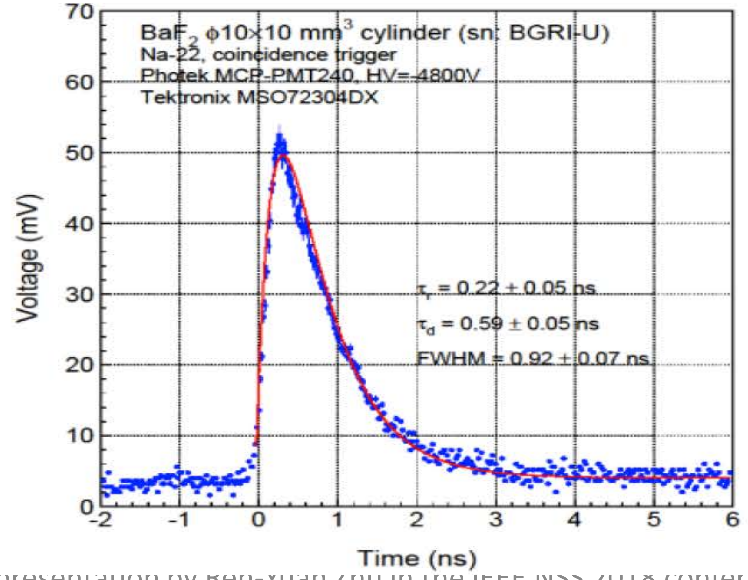
Significant increased F/S ratio in BaF_2:Y; Sub-ns FWHM by MCP-PMT

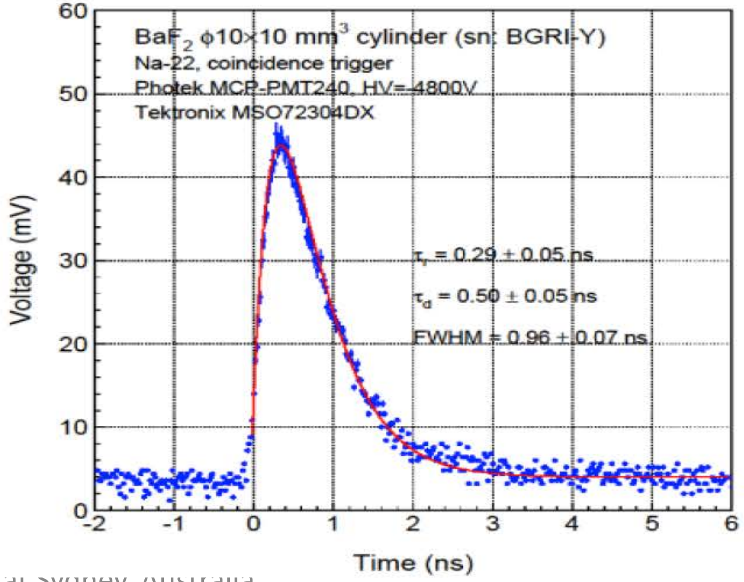




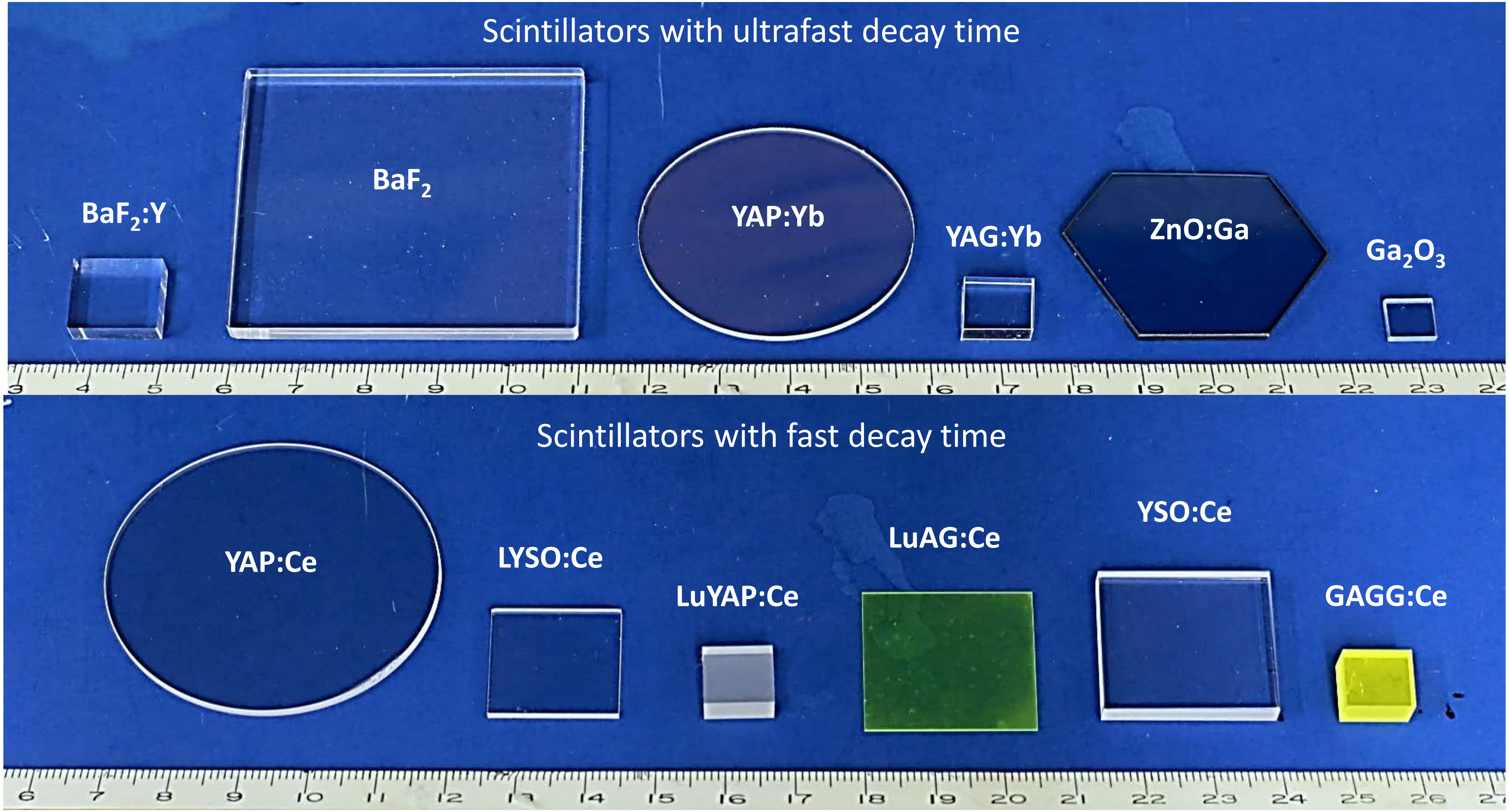








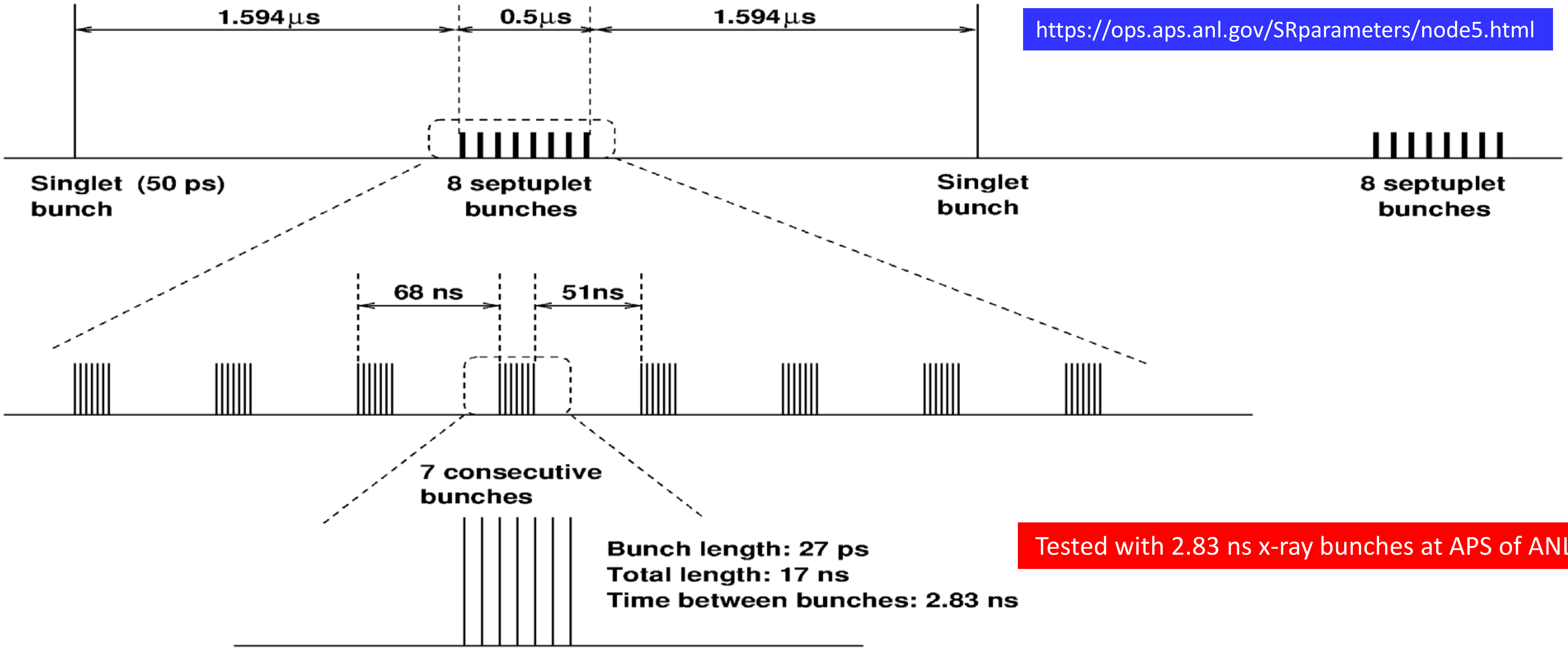
Temporal Response Measured at APS



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.

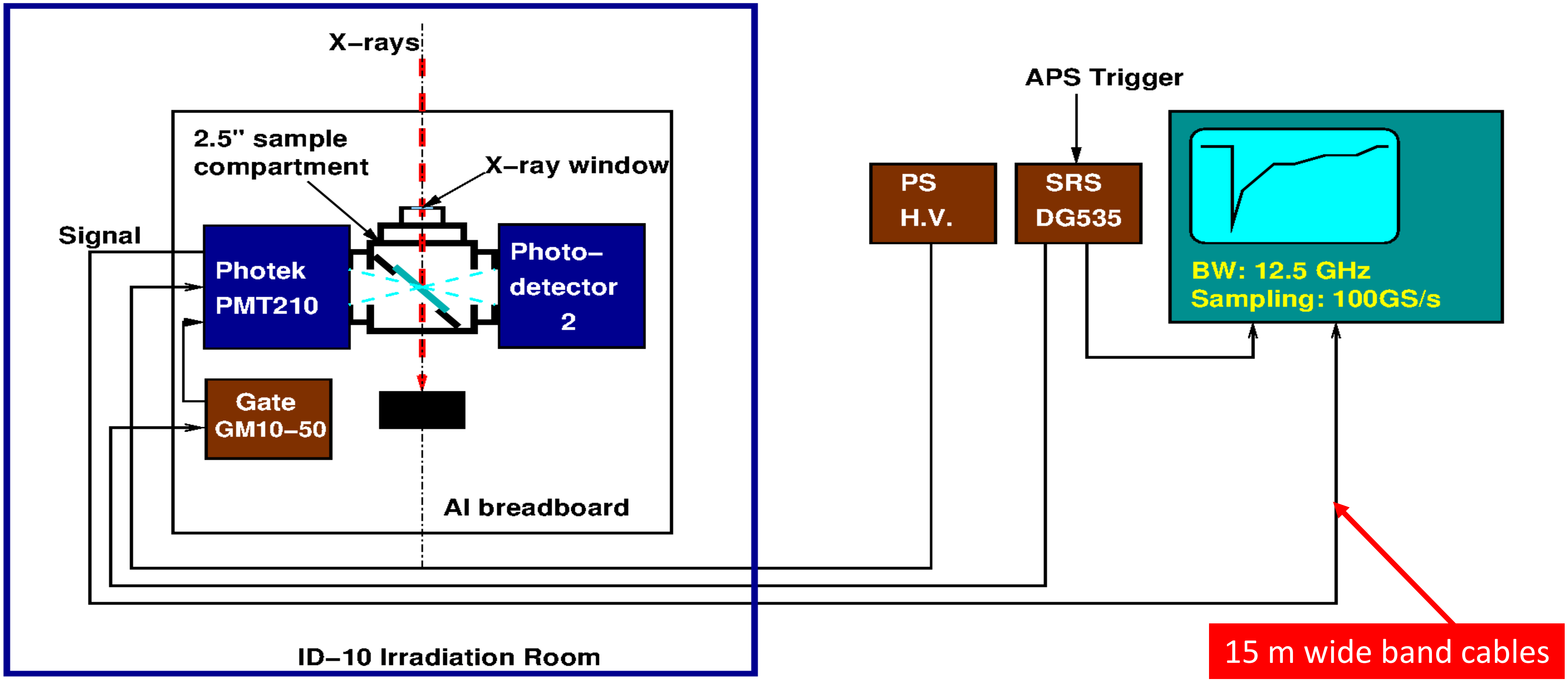
https://ops.aps.anl.gov/SRparameters/node5.html



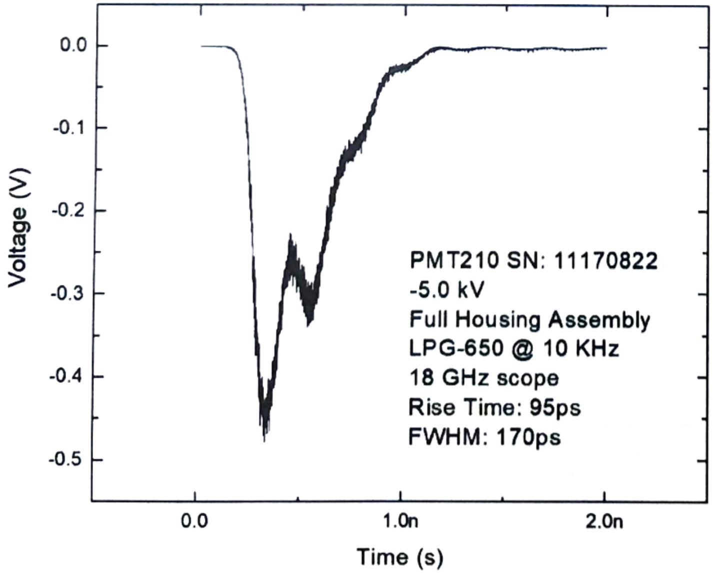
Tested with 2.83 ns x-ray bunches at APS of ANL

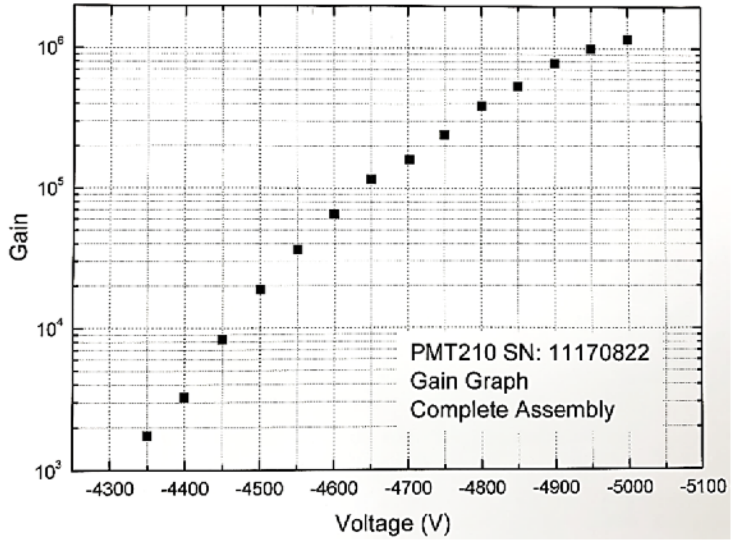
Test Setup at Advanced Photon Source

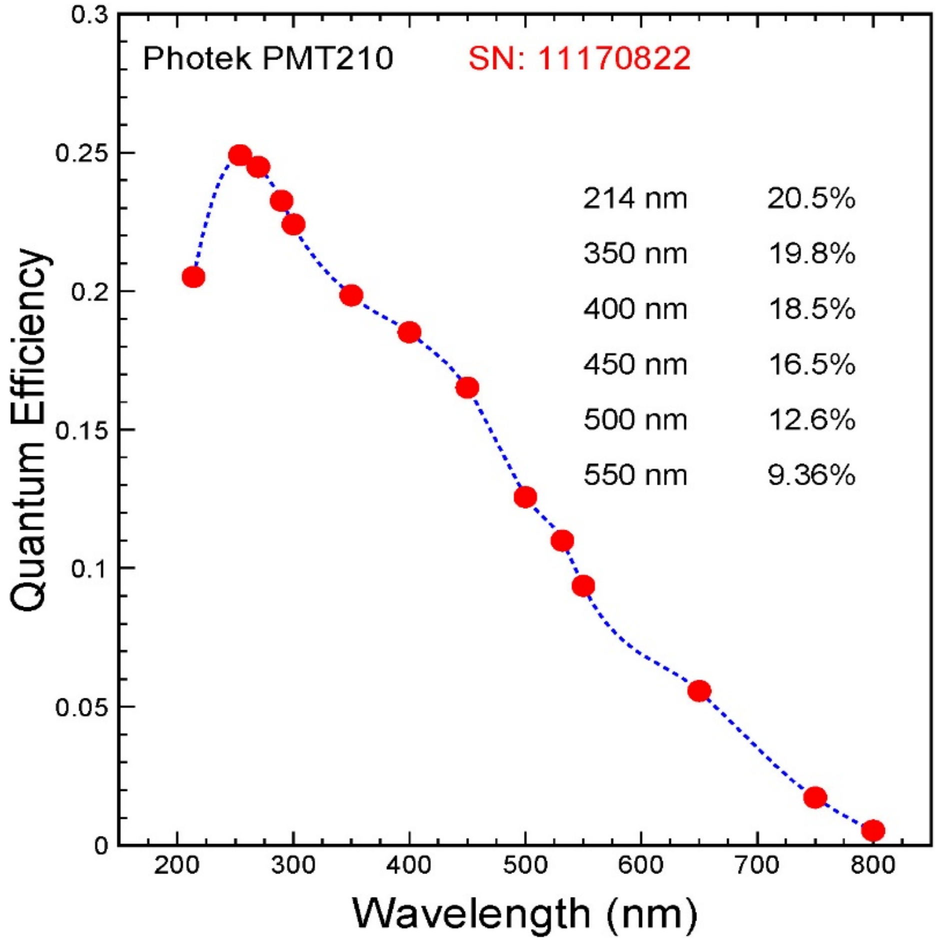
Crystals, MCP-PMT and gate unit were in the hutch of the APS 10-ID site; DPO, delay generator and HV power supplier were in the control room; MCP-PMT signal went through a 15 m wideband SMA cable to DPO



Photek MCP-PMT 110, 210, 240

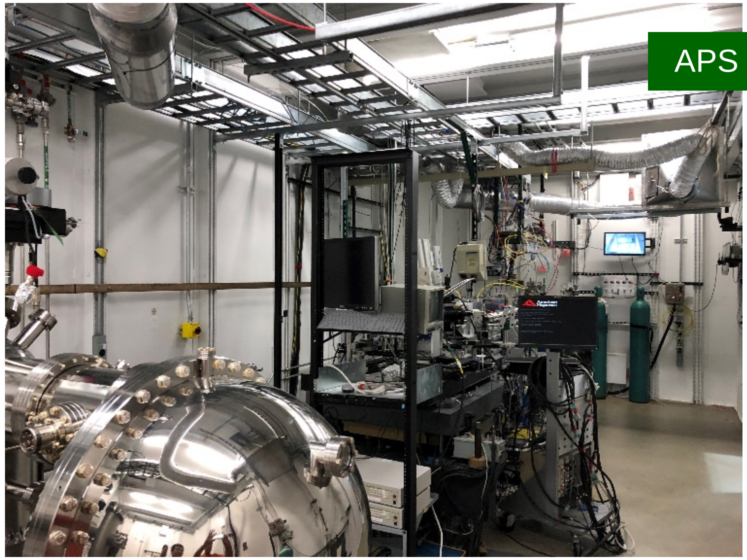


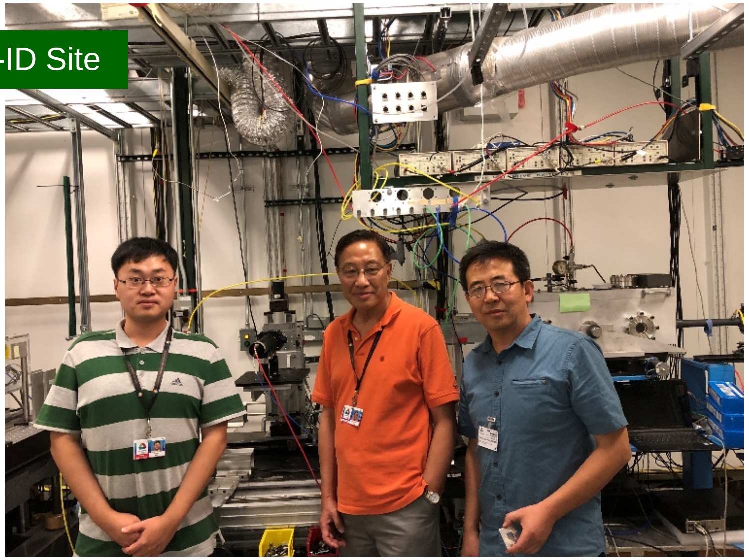


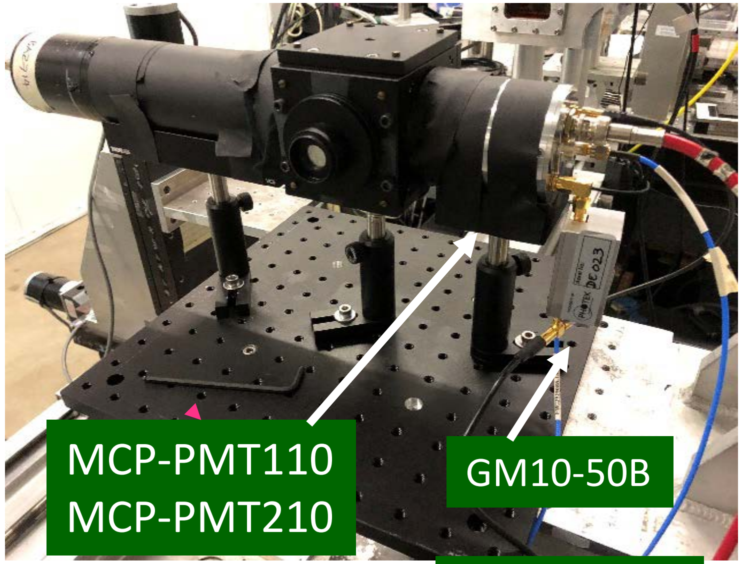


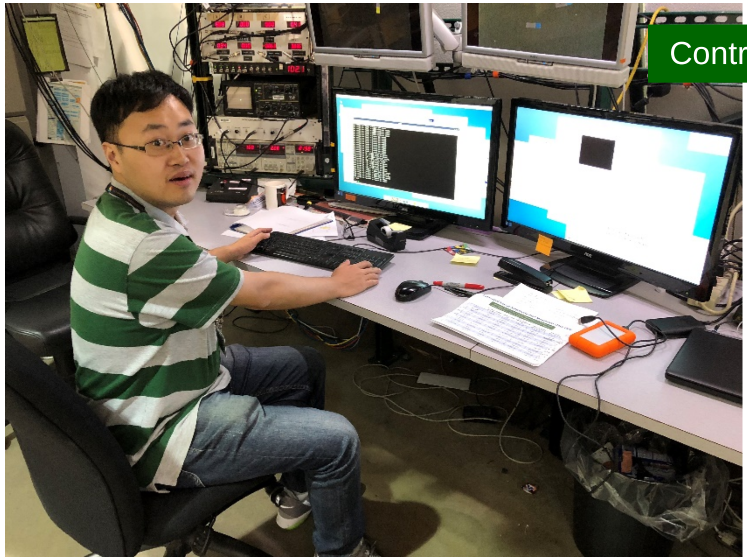
PD	Active area (mm^2)	Spectral range (nm)	Peak sensitivity (nm)	Gain	Rise time (ns)	FWHM (ns)
Hamamatsu PMT R2059	Φ46	160-650	450	2×10^7	1.3	3
Photek MCP PMT110	Φ10	160-850	280-450	1×10^4	**0.065**	**0.11**
Photek MCP PMT210	Φ10	160-850	280-450	1×10^6	**0.095**	**0.17**
Photek MCP PMT240	Φ40	160-850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

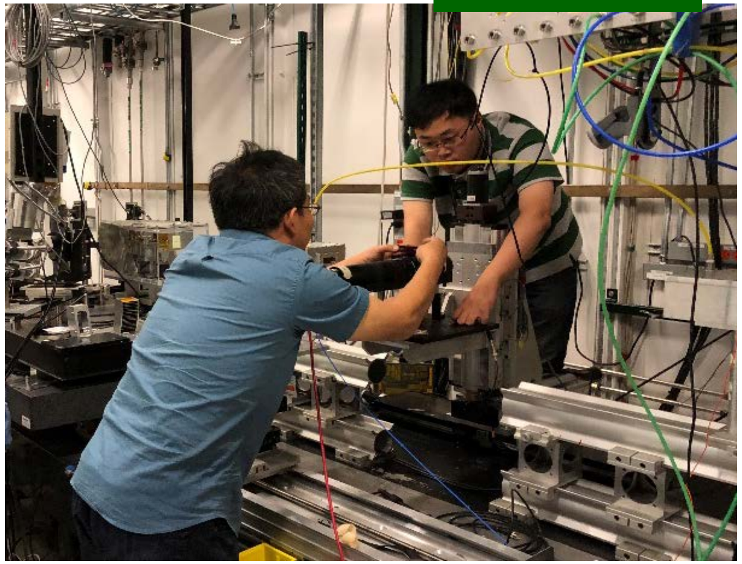
Caltech Team at APS of ANL (July 2 -3, 2018)







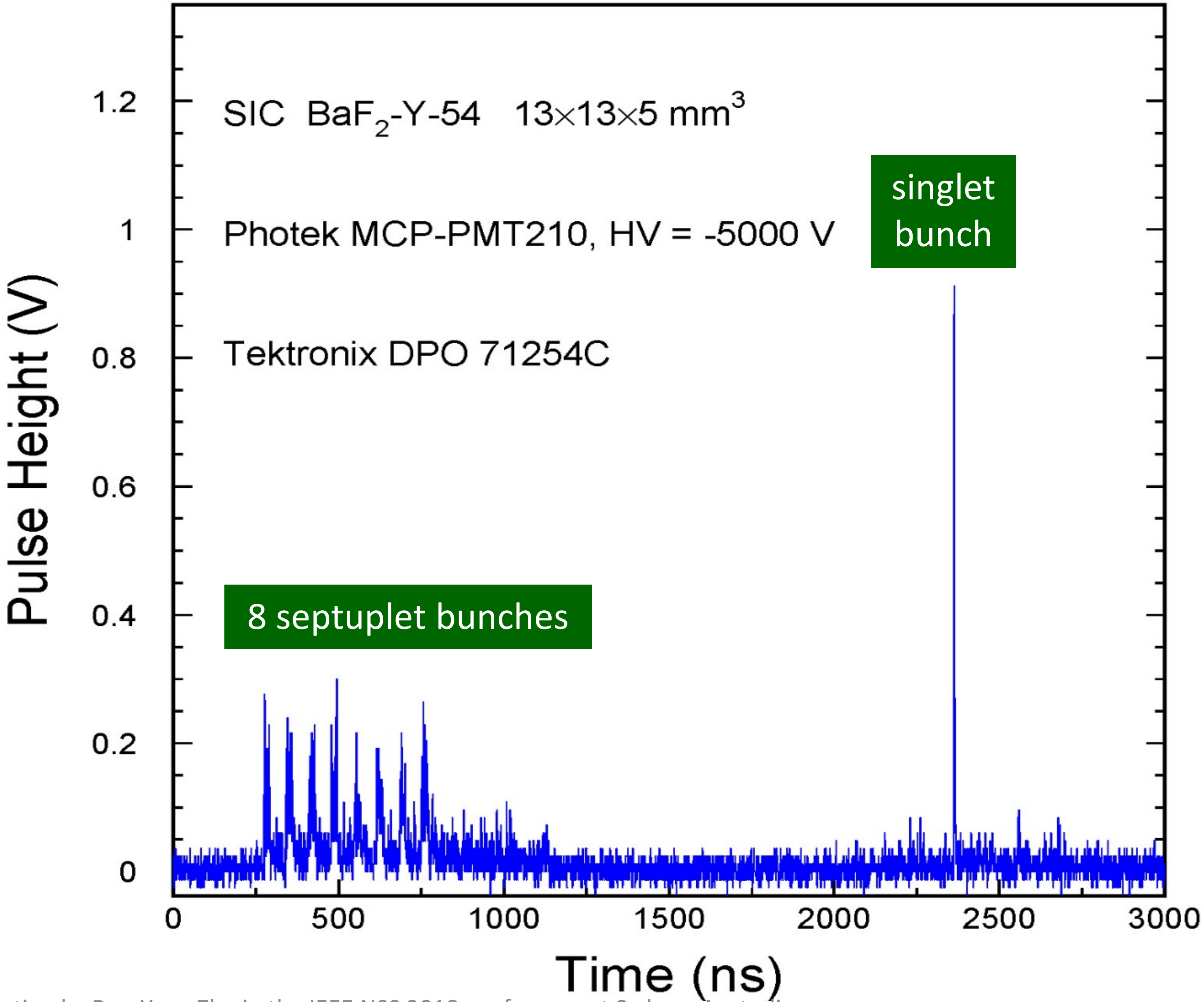




BaF_2:Y Response to Hybrid Beam

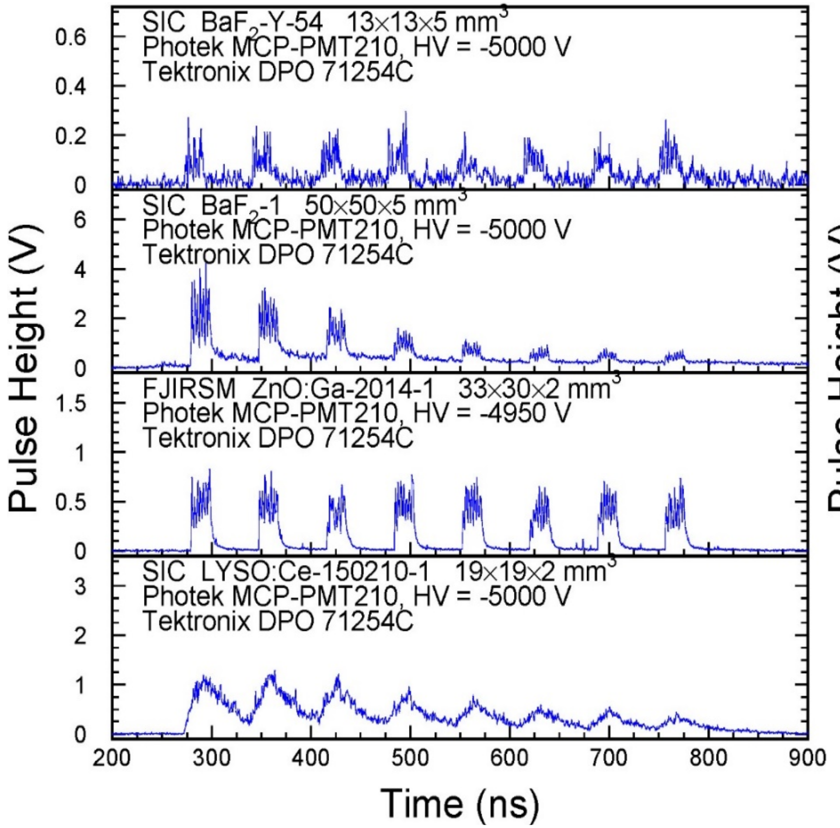
Data taken with Photek PMT & gate unit for septuplet bunches show BaF_2:Y's capability for hard X-ray imaging with 2.83 ns bunch spacing.

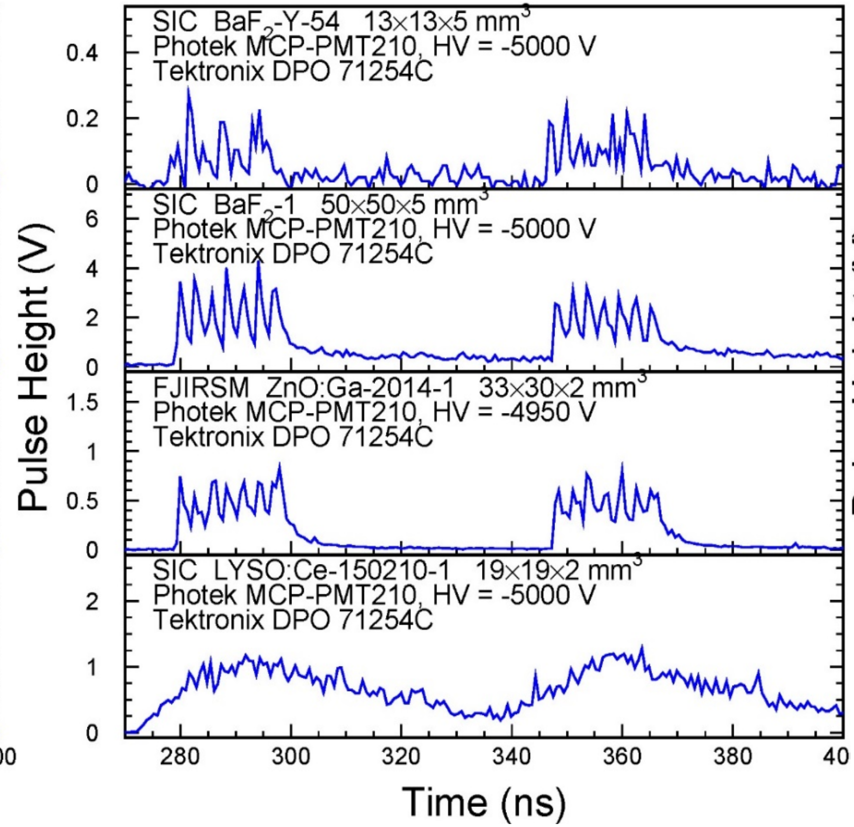
Data were also taken for singlet bunches to show various crystal's temporal response.

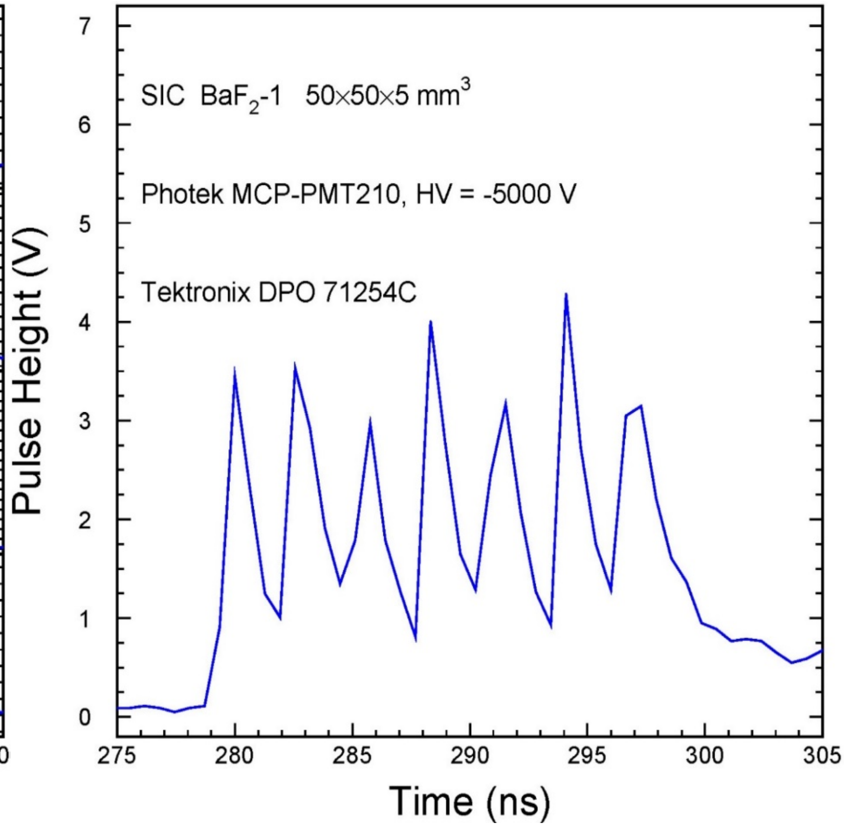


Septuplets: BaF_2:Y, BaF_2, ZnO:Ga & LYSO

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



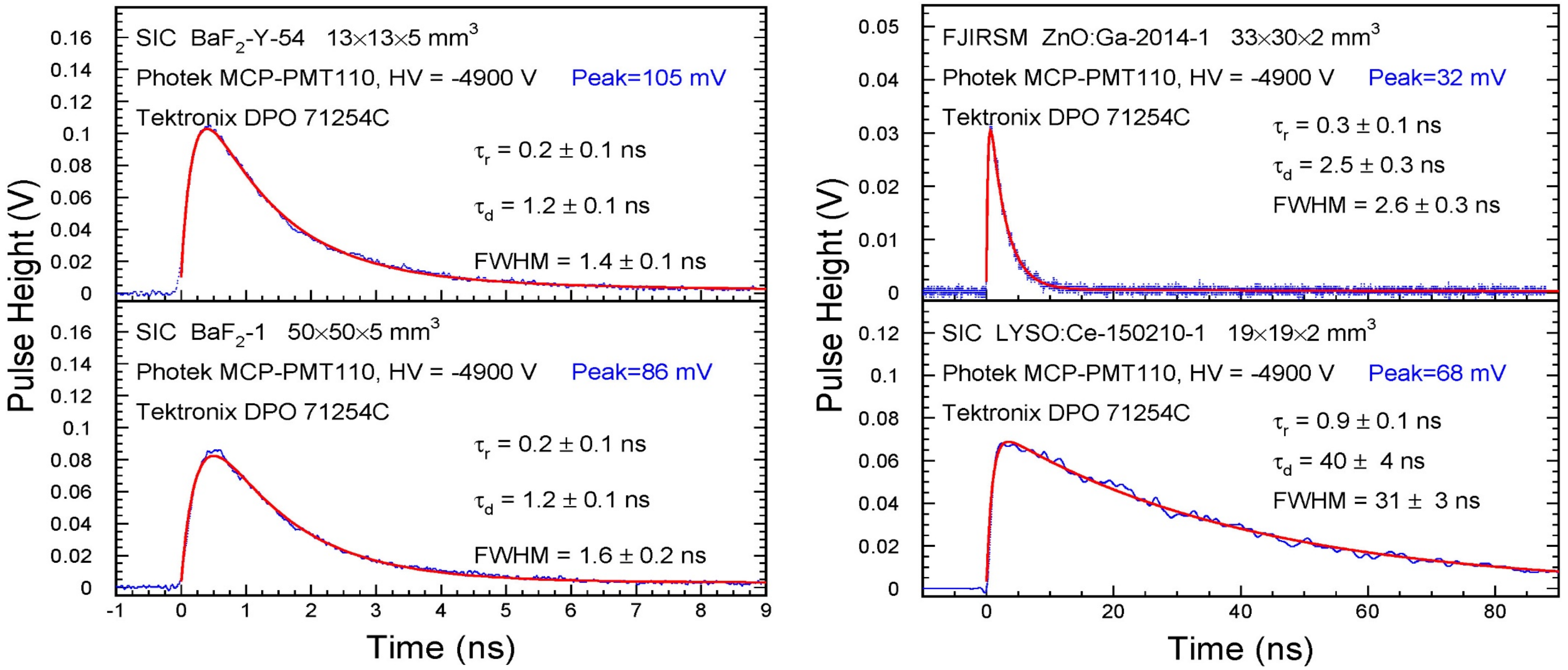




Amplitude reduction in BaF_2 and LYSO due to space charge in PMT from slow scintillation, but not in BaF_2:Y
Reducing the 15 m cable length reduces BaF_2 pulse width to sub-ns for a much better bunch separation

Singlet: BaF_2:Y, BaF_2, ZnO & LYSO

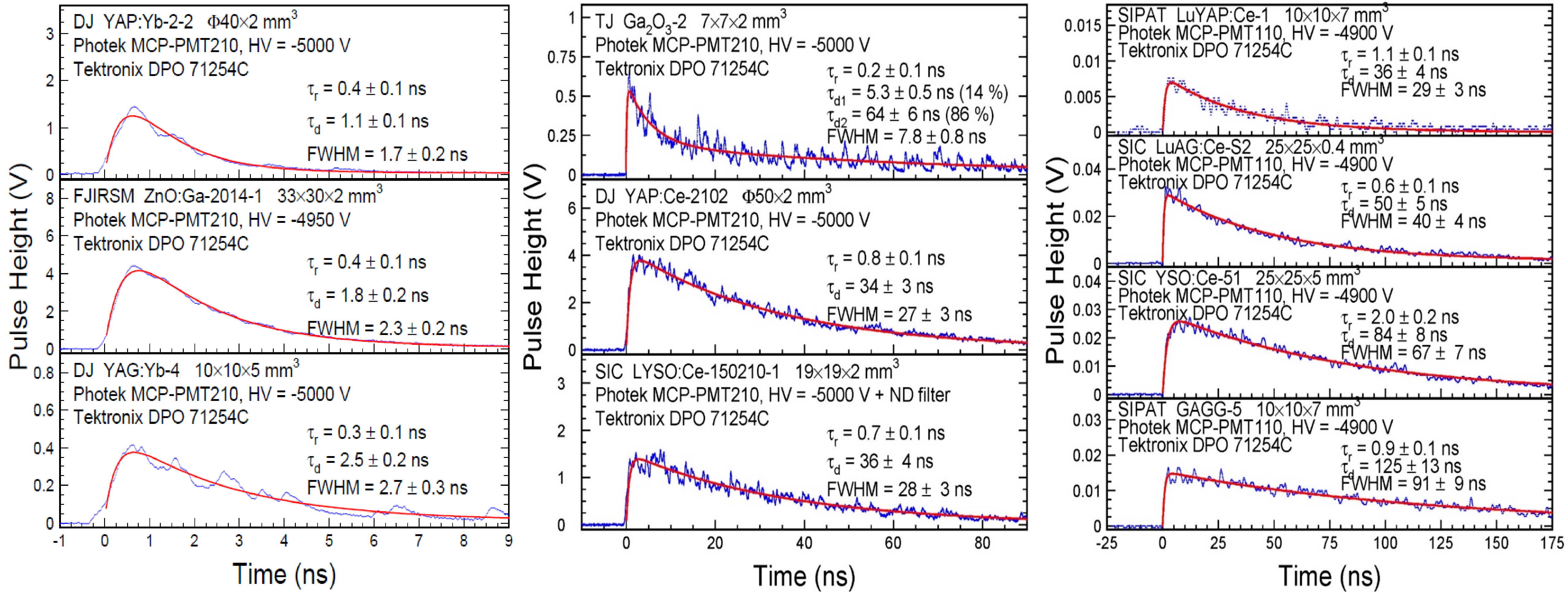
Amplitude of BaF_2:Y and BaF_2 higher than LYSO and ZnO:Ga, expected as light output in the 1st ns



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

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 source

Summary: Temporal Response

Crystal	Vendor	ID	Dimension (mm^3)	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**

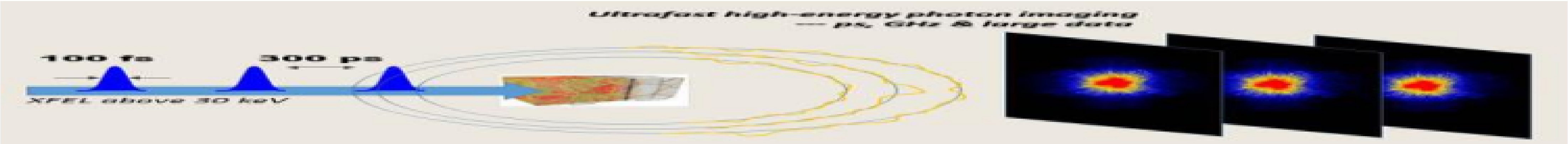
Samples are ordered based on its FWHM to singlet bunches

Summary

- Temporal response of a dozen fast and ultrafast inorganic scintillators was measured at the APS 10-ID test beam site by using 30 keV x-ray bunches with ps bunch length.
- Septuplet structure with 2.83 ns spacing are clearly observed by ultrafast inorganic scintillators, such as BaF_2:Y and BaF_2 coupled to ultrafast photodetectors, such as Photek MCP-PMT. This observation demonstrates the feasibility of the ultrafast scintillator-based front imager concept for aging for the proposed MaRIE project.
- Other ultrafast inorganic scintillators, such as YAP:Yb, ZnO:Ga and YAG:Yb, show a significantly wider pulse width than BaF_2. Conventional cerium doped fast inorganic scintillators, such as LYSO:Ce, LuAG:Ce and GAGG:Ce, are a way too slow to observe septuplet structure with 2.83 ns bunch spacing.
- BaF_2 shows the highest amplitude and fastest response to singlet, consisting with the calculated light output in the 1^{st} ns. BaF_2:Y shows no pile-up for multiple septuplets, demonstrating importance of slow component suppression.

Acknowledgements: DOE Award DE-SC001192

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.

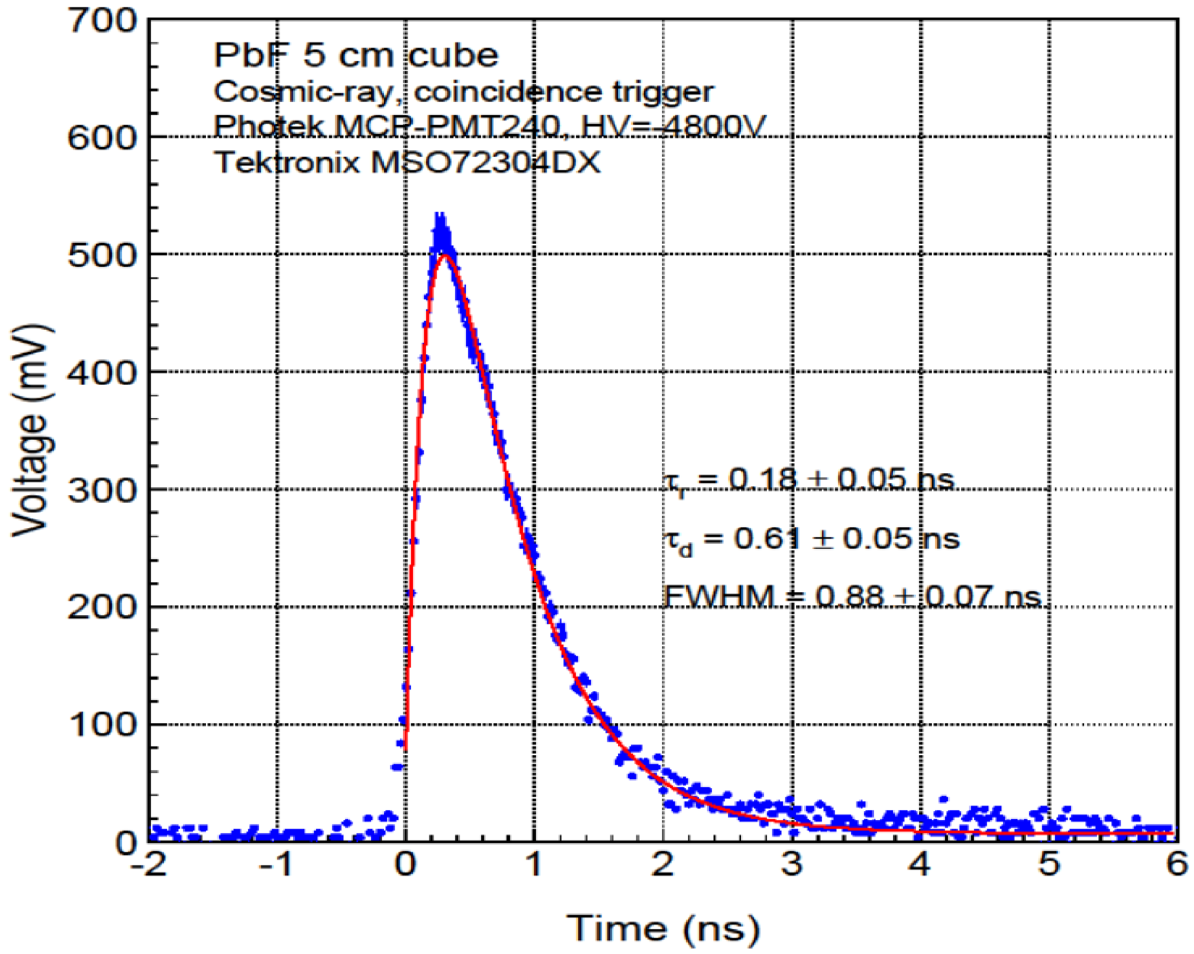
Table I. High-energy photon imagers for MaRIE XFEL

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

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

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