Temporal Response of Ultrafast Inorganic Scintillators to Hybrid Hard X-ray Beam at APS, ANL

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Ultrafast Materials & Applications UMA Collaboration, July 2-3, APS, ANL

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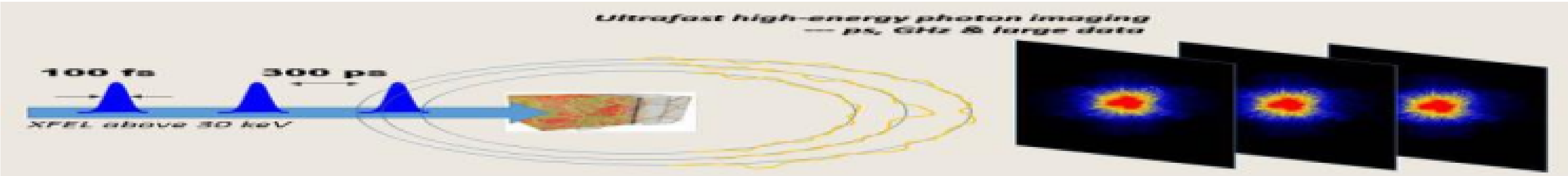
Why Ultrafast Crystals?

- **Photons and electrons are fundamental particles. Precision e/γ measurements enhance physics discovery potential.**
- **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.**
- **Challenges at future HEP & other applications:**
  - **Ultrafast and rad hard crystals at the energy frontier (HL-LHC);**
  - **Ultrafast crystals at the intensity frontier (Mu2e-II);**
  - **Ultrafast crystals for GHz hard X-ray imaging (Marie).**

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

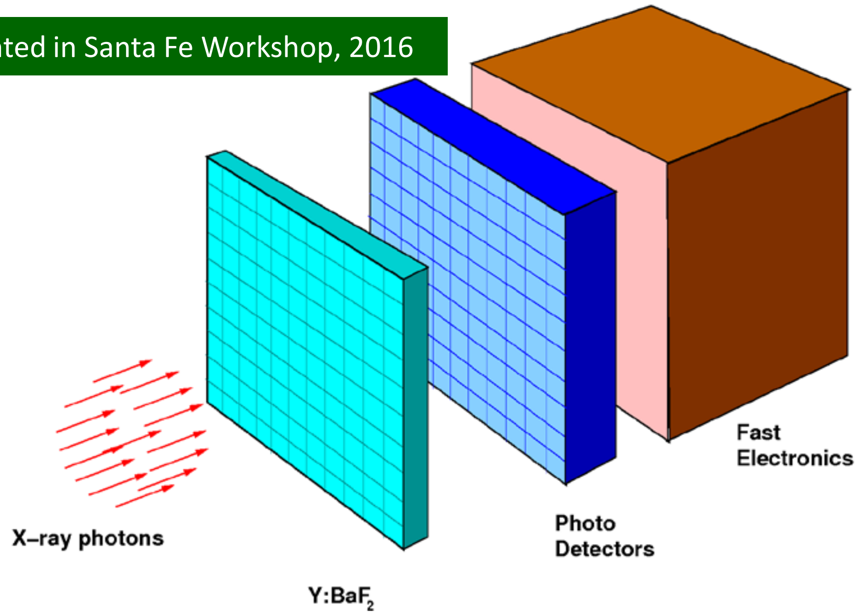
2 ns and 300 ps inter-frame time requires ultrafast sensor

A BaF_2:Y Based Front Imager

- BaF_2 has good efficiency for hard X-rays.
- Its fast scintillation with sub-ns decay time provides bright light in 1st ns with very little tail.
- Yttrium doping in BaF_2 suppresses its slow scintillation significantly and maintains its fast light.
- A detector concept:
  - Pixelized Y:BaF_2 screen;
  - Pixelized fast photodetector;
  - Fast electronics readout.
- To be developed:

  Crystals, DUV photodetectors and readout.

R-Y Zhu, Talk presented in Santa Fe Workshop, 2016



Fast 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

Fast Inorganic Scintillators

[1] S. Geller, *J. Chem. Phys.* 1960, 33: 676.

a. Top line: slow component, bottom line: fast component;

b. At the wavelength of the emission maximum;

c. Excited by Gamma rays;

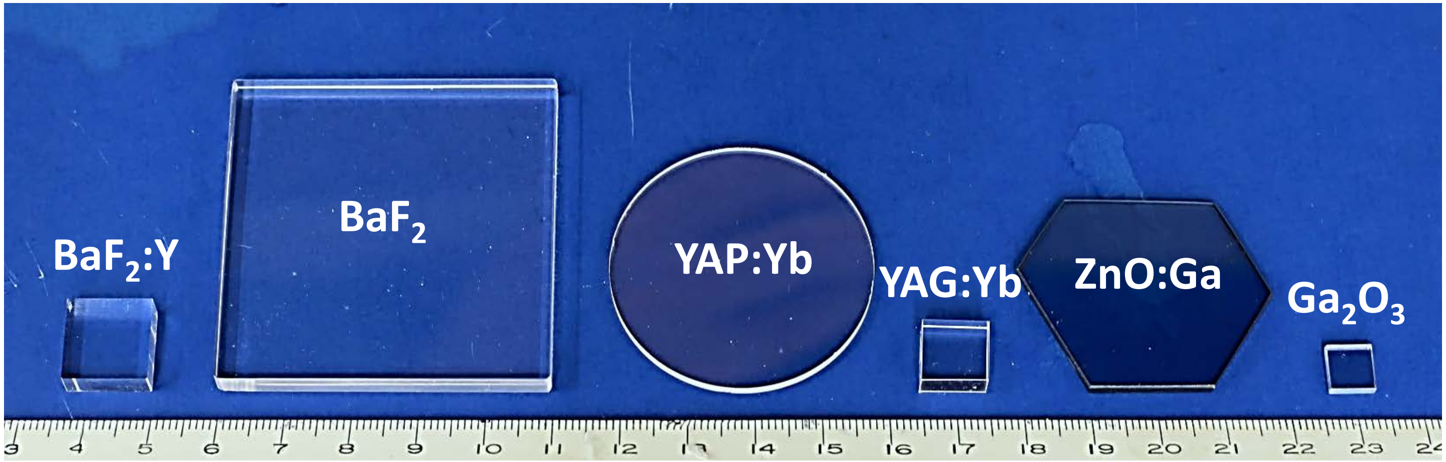
d. Excited by Alpha particles.

e. Ceramic with 0.3 Mg at% co-doping

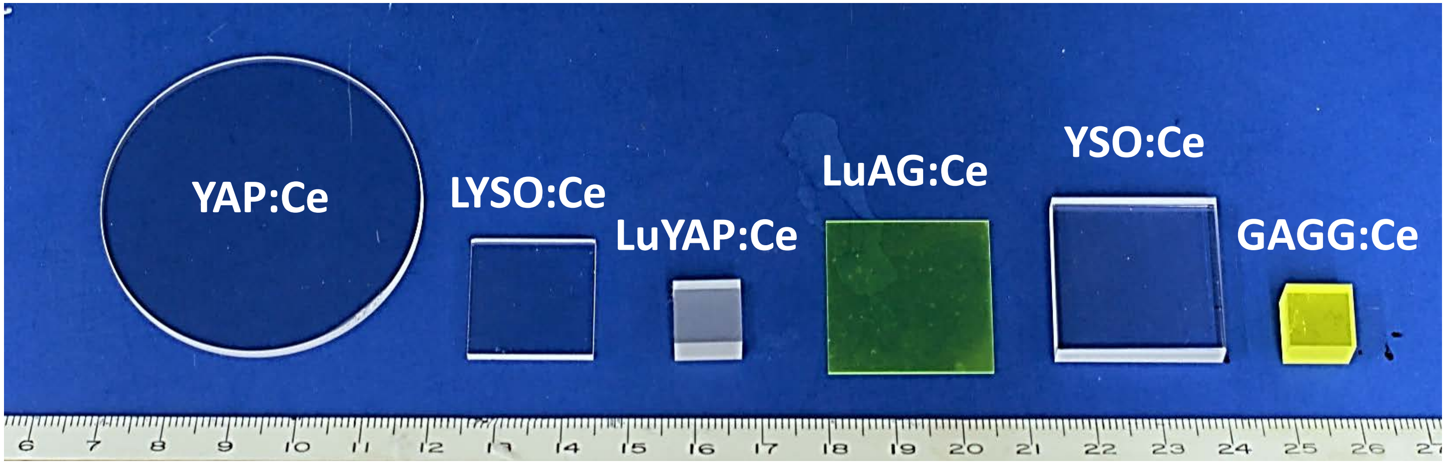
f. Based on $Lu_{0.7}Y_{0.3}AlO_3$:Ce

12 Fast Inorganic Scintillators

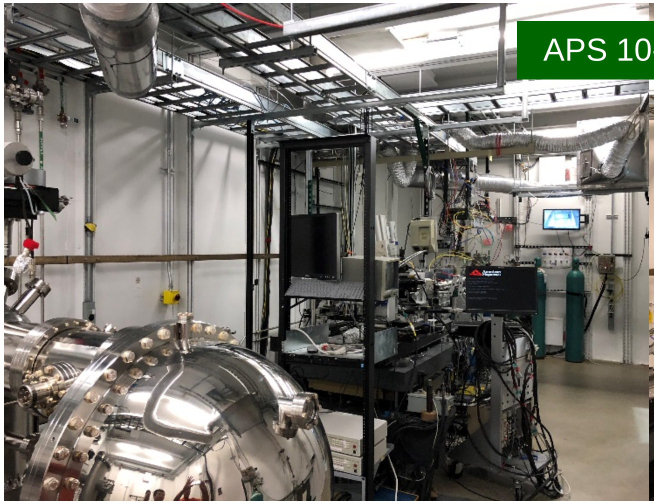
Scintillators with ultrafast decay time

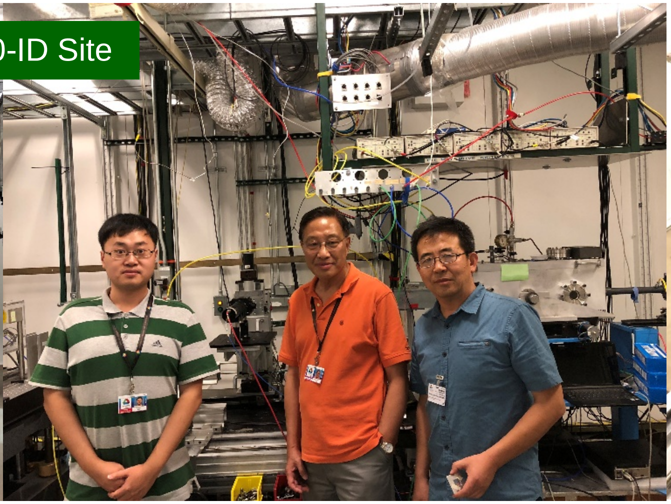


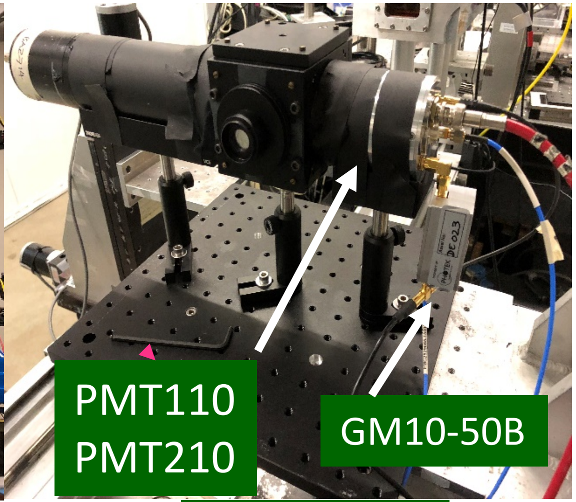
Scintillators with fast decay time

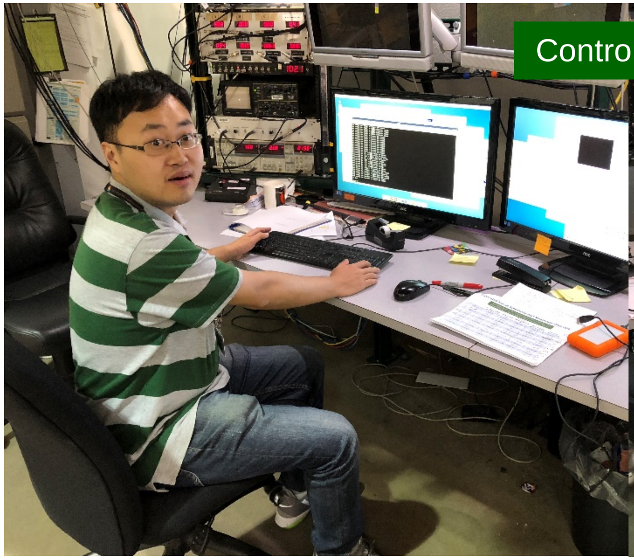


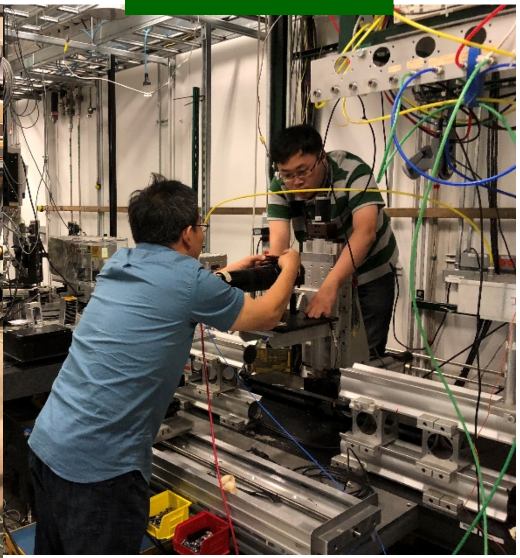
A Few Photos on Beam Test at APS 10-ID Site (July 2 -3, 2018)





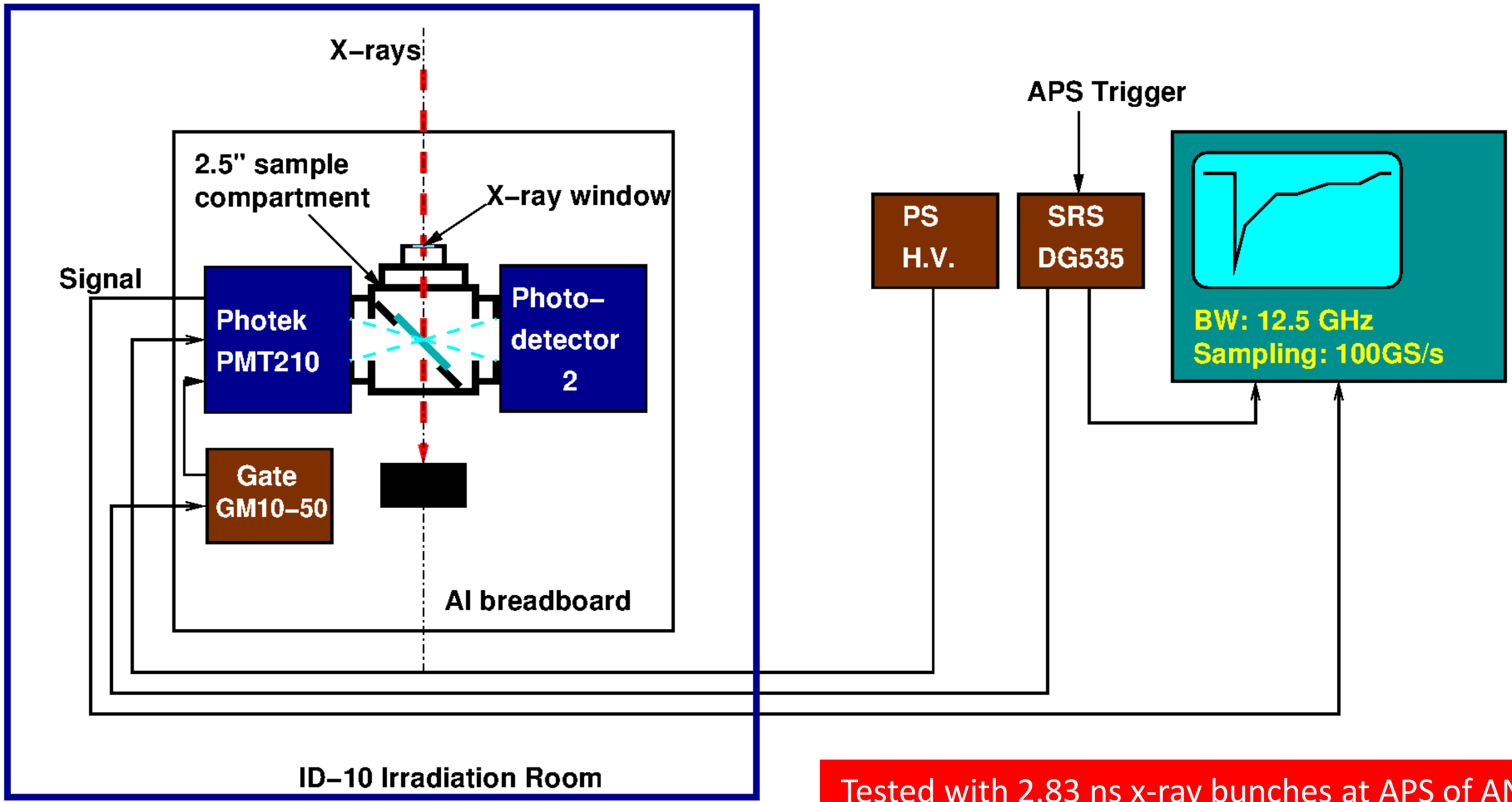






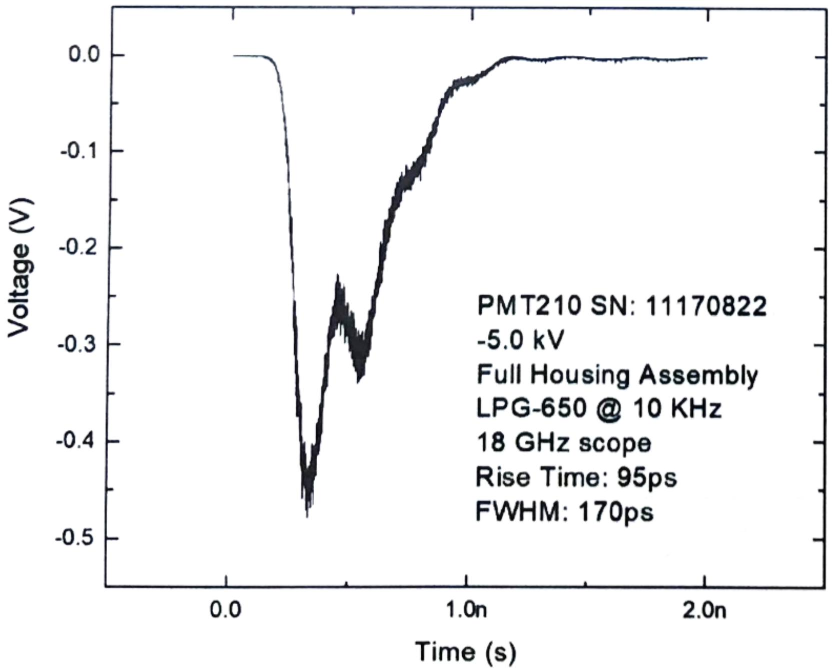
The Test Setup at APS

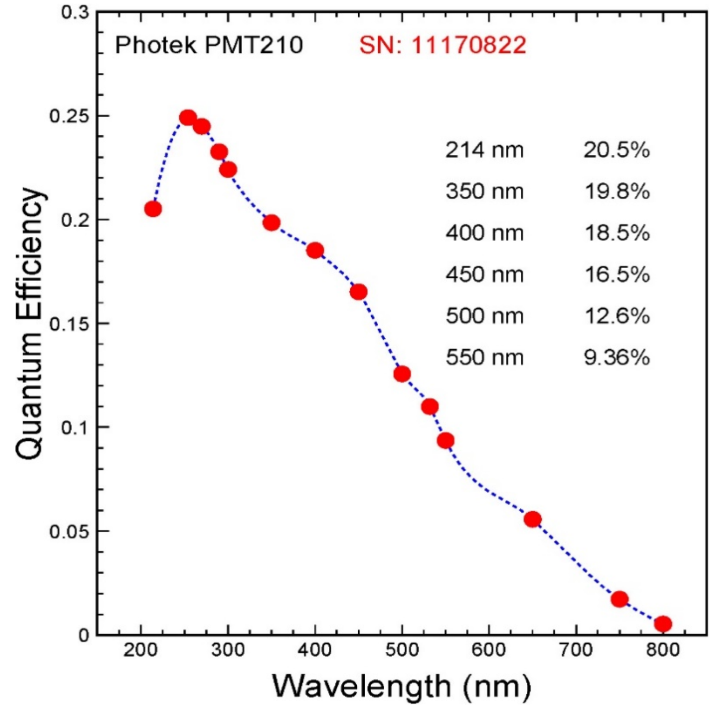
Crystals, MCP-PMT and gate unit were in the hutch at APS 10-ID site.
DPO, delay generator and HV power supplier were in the control room.
Signal from MCP-PMT went through a 15 m wideband SMA cable, which may compromise PMT’s temporal response compared to data obtained with source.



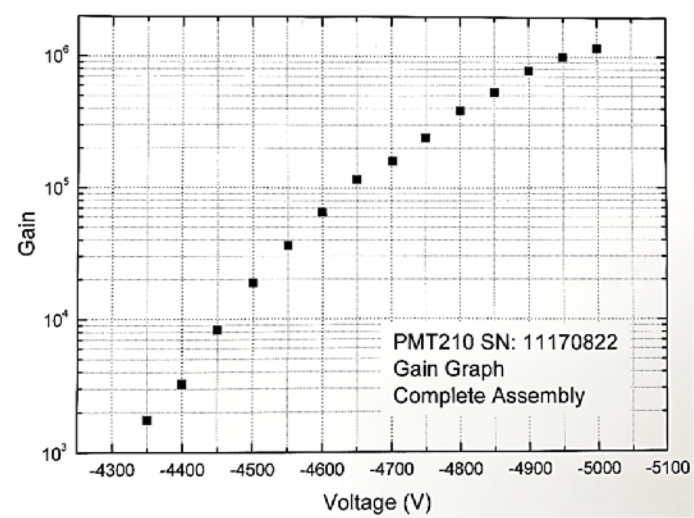
Tested with 2.83 ns x-ray bunches at APS of ANL

Photek MCP-PMT 110, 210, 240





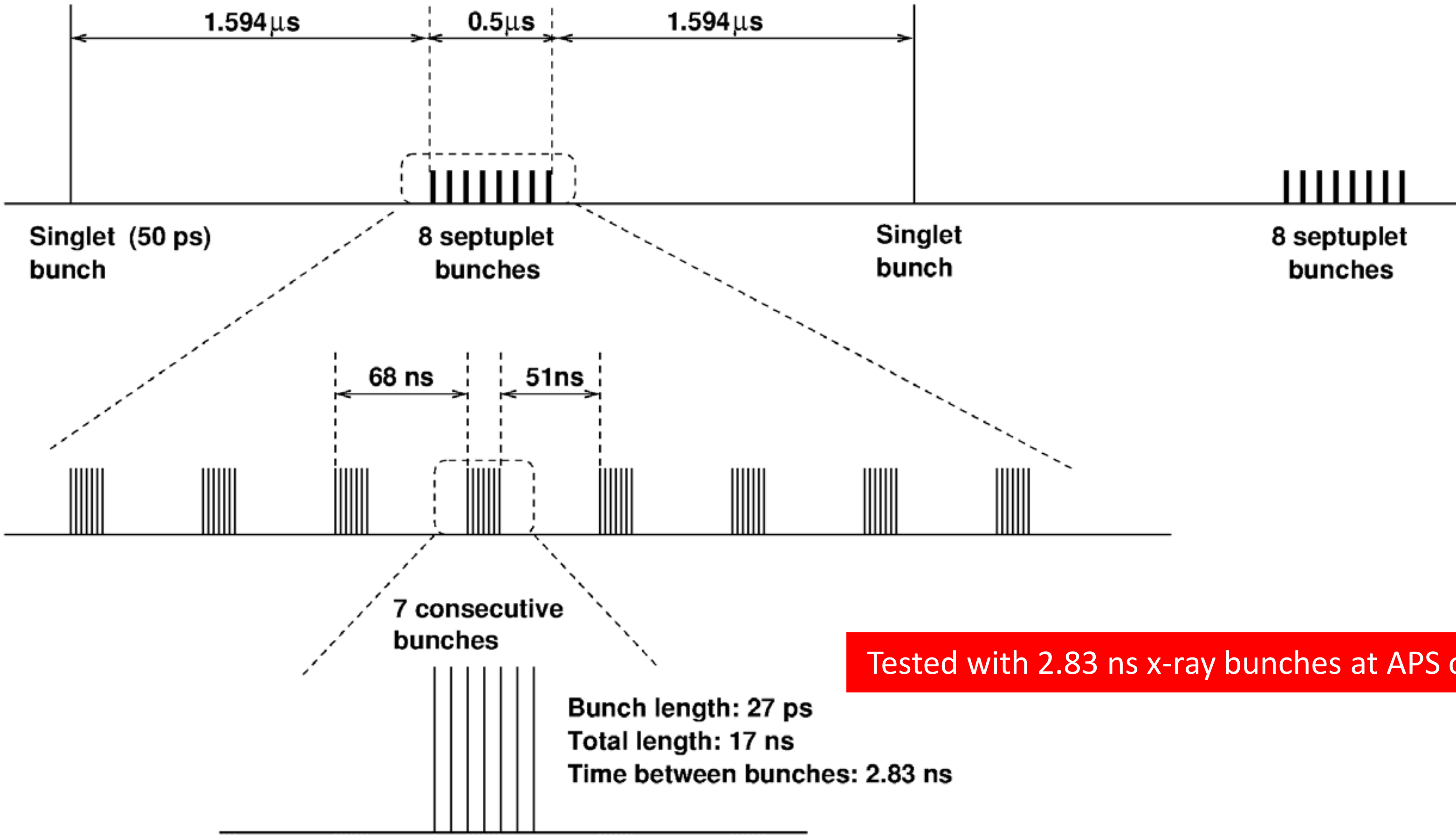
PD	Active area (mm²)	Spectral range (nm)	Peak sensitivity (nm)	Gain	Rise time (ns)	FWHM (ns)
Hamamatsu PMT R2059	Φ46	160-650	450	2×10^7	1.3	3
Photek MCP PMT110	Φ10	160-850	280-450	1×10^4	**0.065**	0.11
Photek MCP PMT210	Φ10	160-850	280-450	1×10^6	**0.095**	0.17
Photek MCP PMT240	Φ40	160-850	280-450	1×10^6	**0.18**	0.85



APS Hybrid Beam Characteristics

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

Singlet (16 mA, 50 ps) isolated from 8 septuplets (88 mA) with 1.594 μs gap.
8 septuplets (88 mA) with a period of 68 ns and a gap of 51 ns.
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.

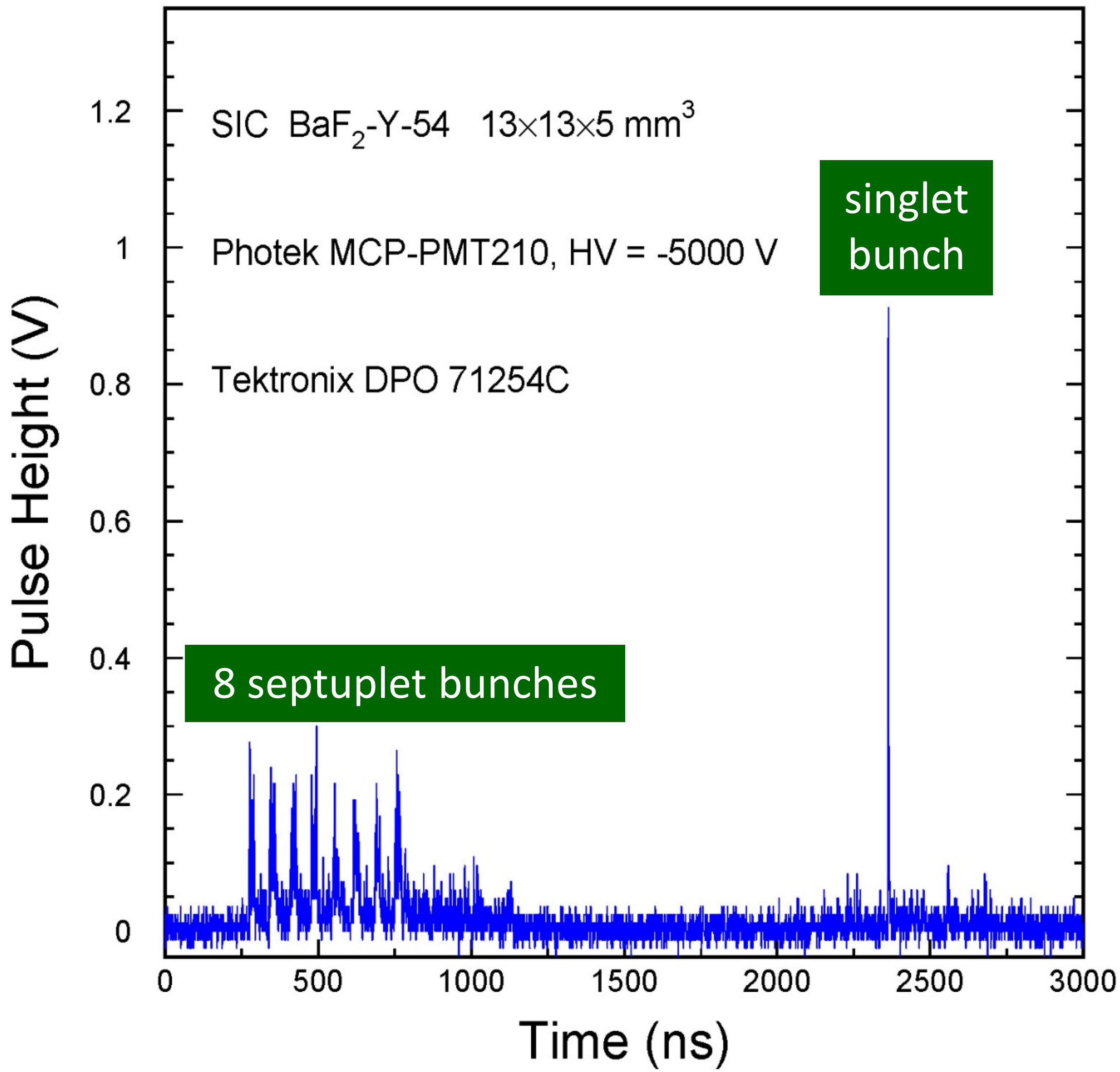


Tested with 2.83 ns x-ray bunches at APS of ANL

Hybrid Beam Measured by BaF_2:Y

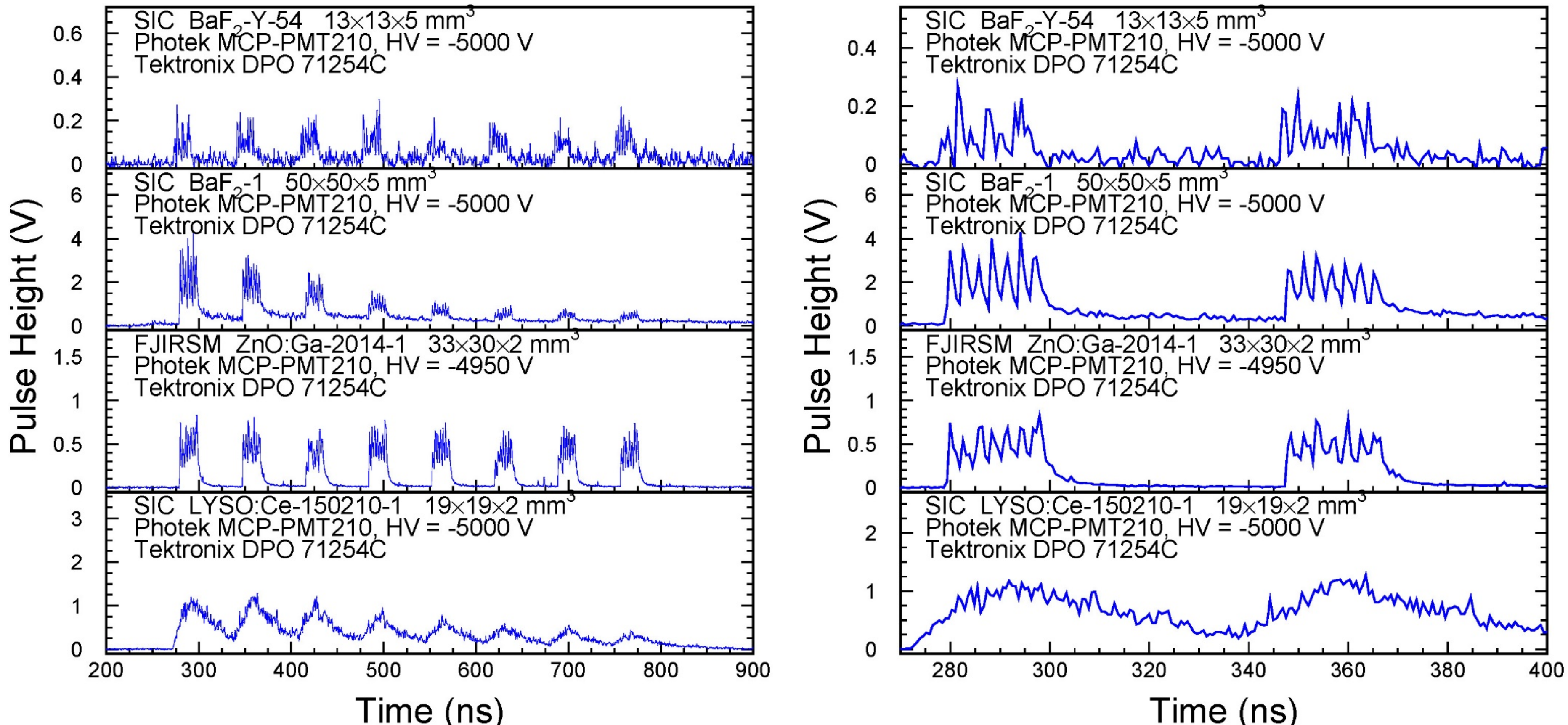
Data were taken with Photek PMT & gate unit for septuplet bunches to see crystal's capability for hard X-ray imaging with 2.83 ns bunch spacing.

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



Septuplet X-ray Imaging

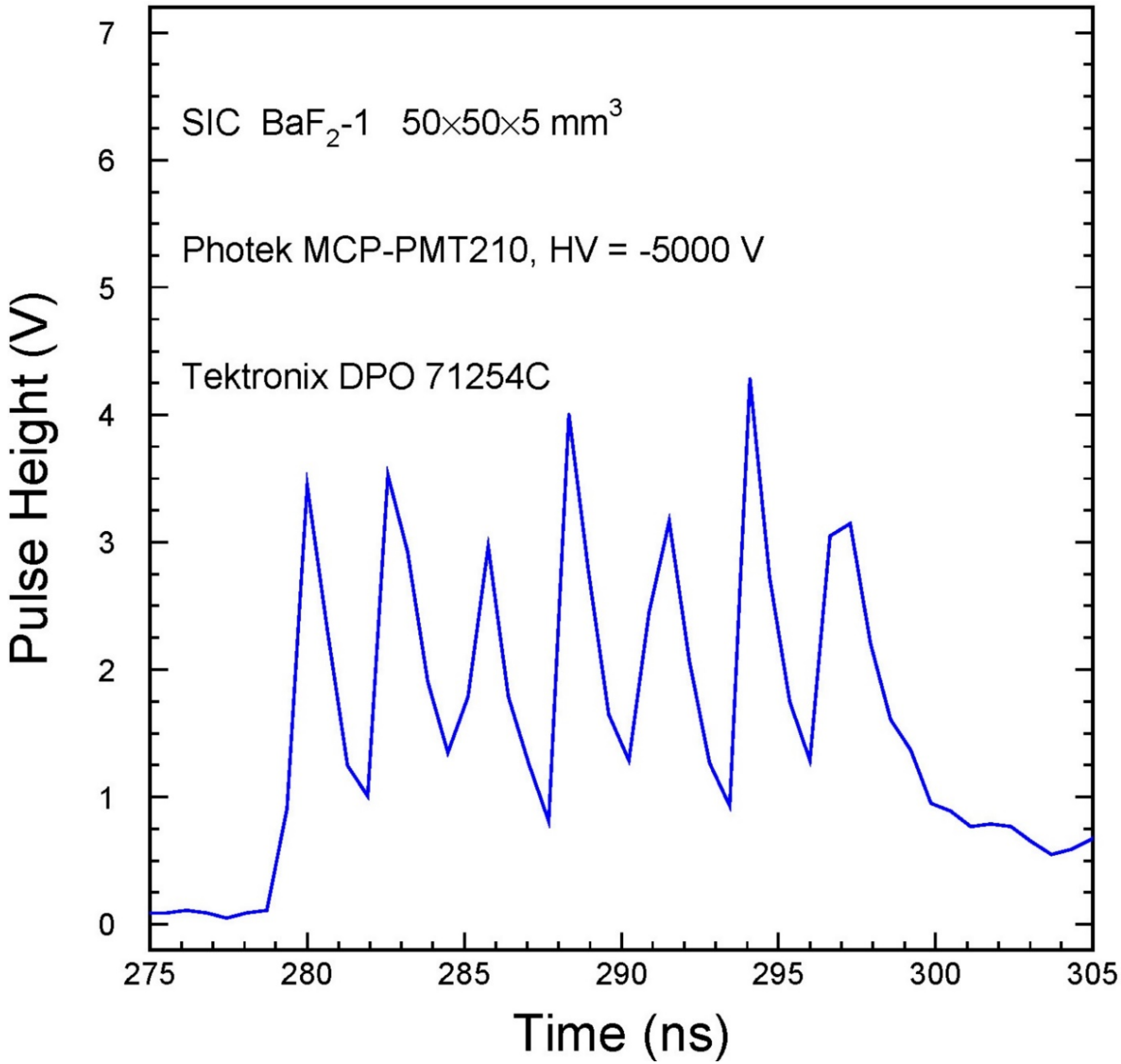
Clear septuplet structure observed by BaF_2:Y, BaF_2 and ZnO:Ga, but not by LYSO:Ce and other crystals with long decay time



Amplitude reduction for septuplets observed in BaF_2 and LYSO due to space charge in PMT caused by slow scintillation component, but not in BaF_2:Y.

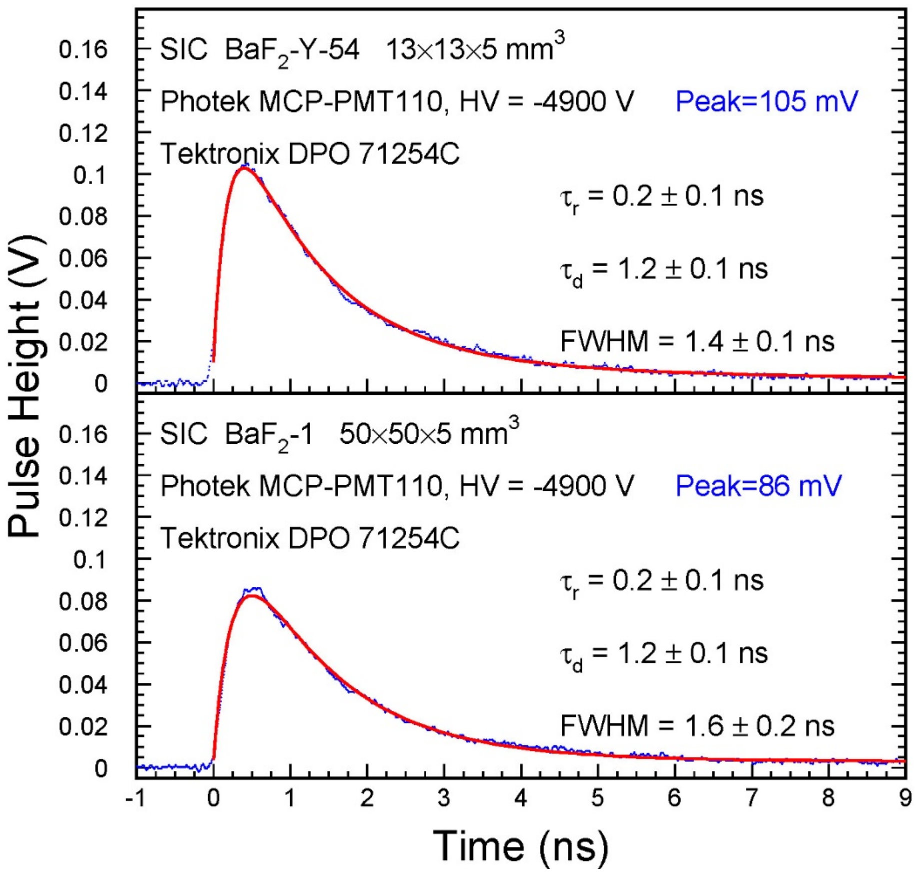
2.83 ns X-ray Bunch Imaging by BaF_2

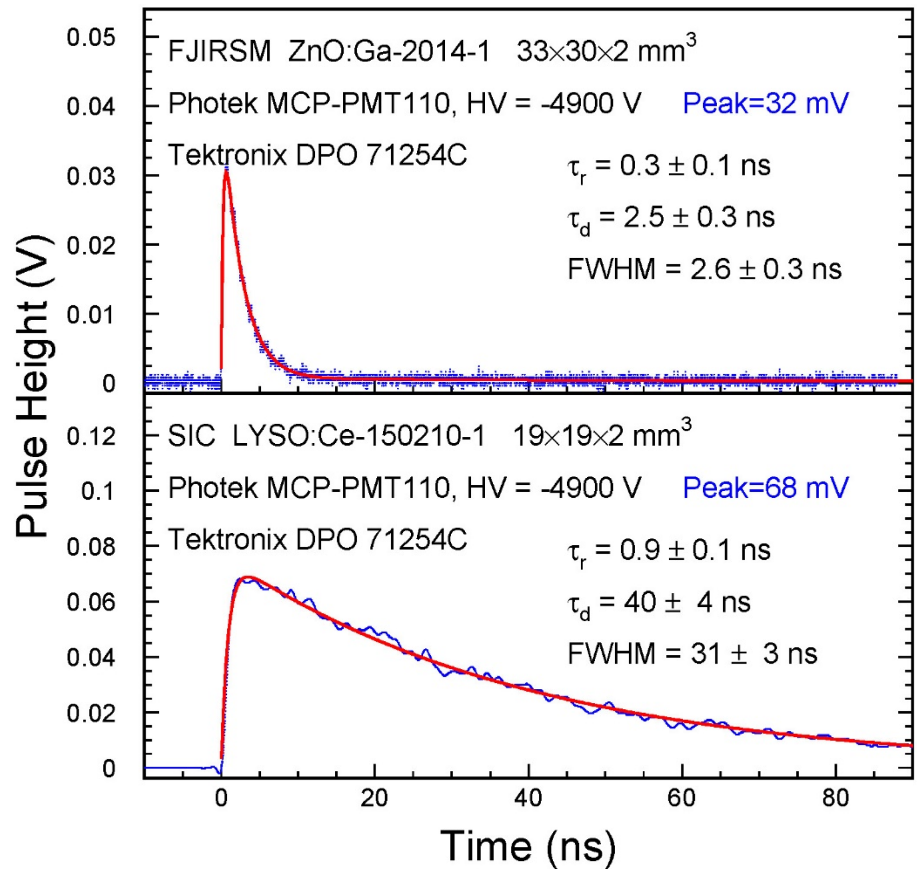
X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2 crystals, showing a proof-of-principle for the type –I imager.



Singlet Bunch by Ultrafast Crystals

Peak amplitude of BaF_2 and BaF_2:Y is higher than ZnO:Ga and LYSO.
Decay time of BaF_2 and BaF_2:Y is much shorter than ZnO:Ga.



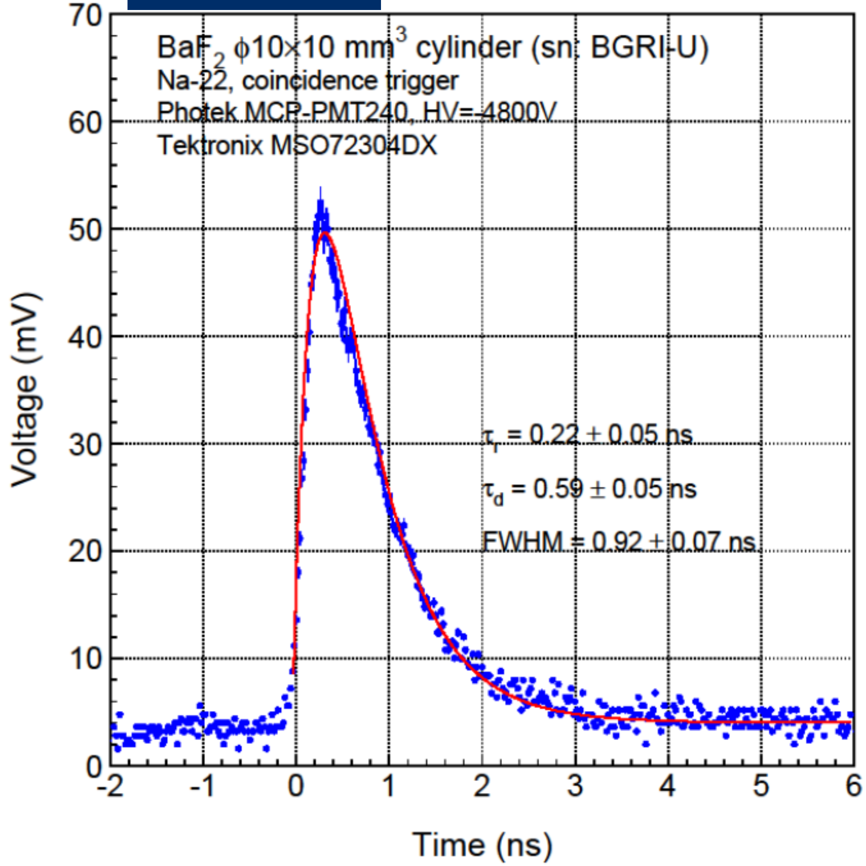


Rise and decay time of BaF_2 and BaF_2:Y is longer than the ɣ-ray source data measured at Caltech because of the 15 m cable length

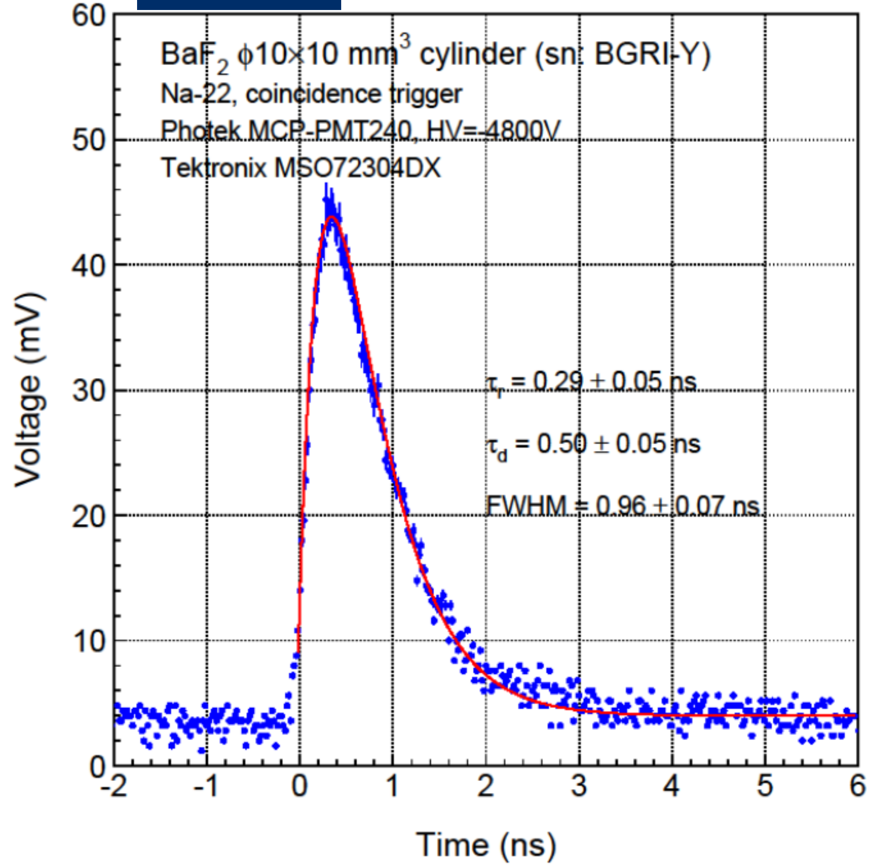
BaF_2 Pulse Shape with ɣ-rays

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 by PMT240

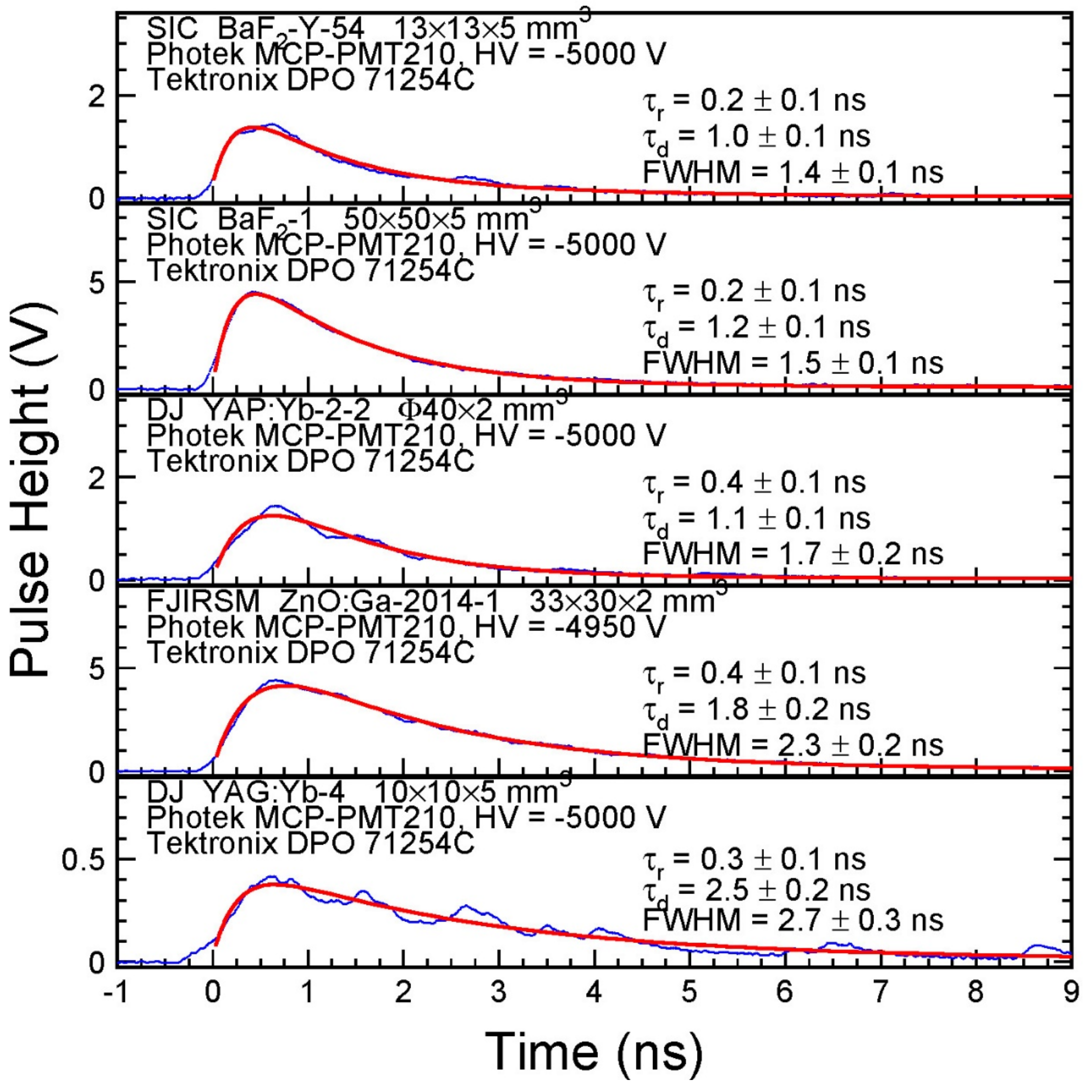
Not-doped



Y-doped



Singlet Bunch by Ultrafast Crystals

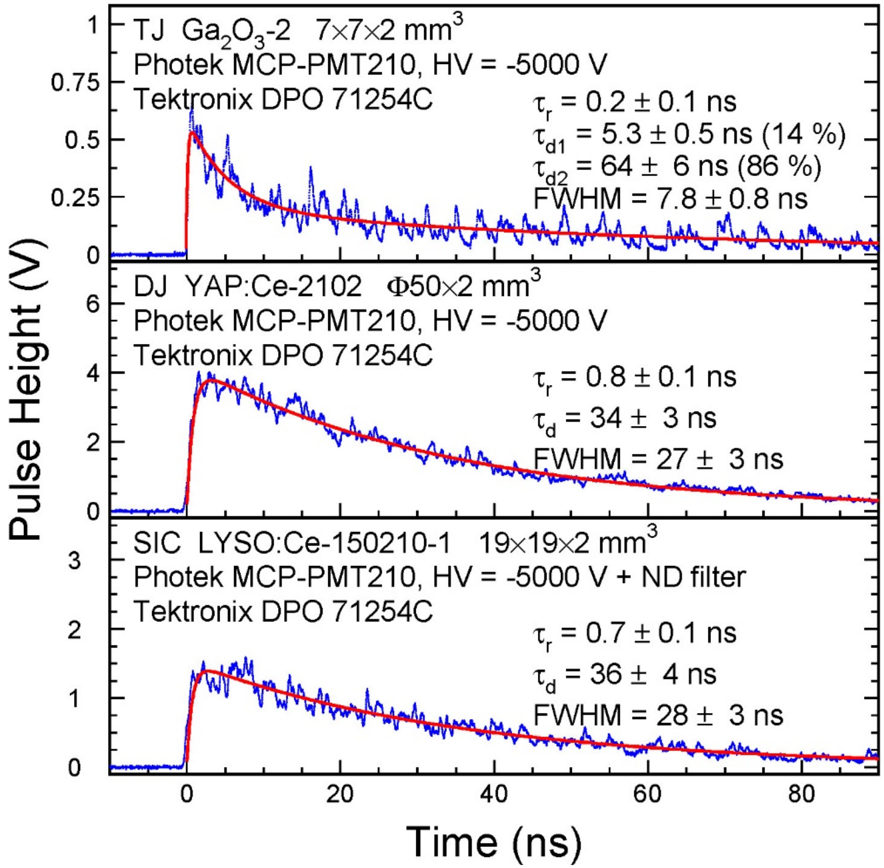


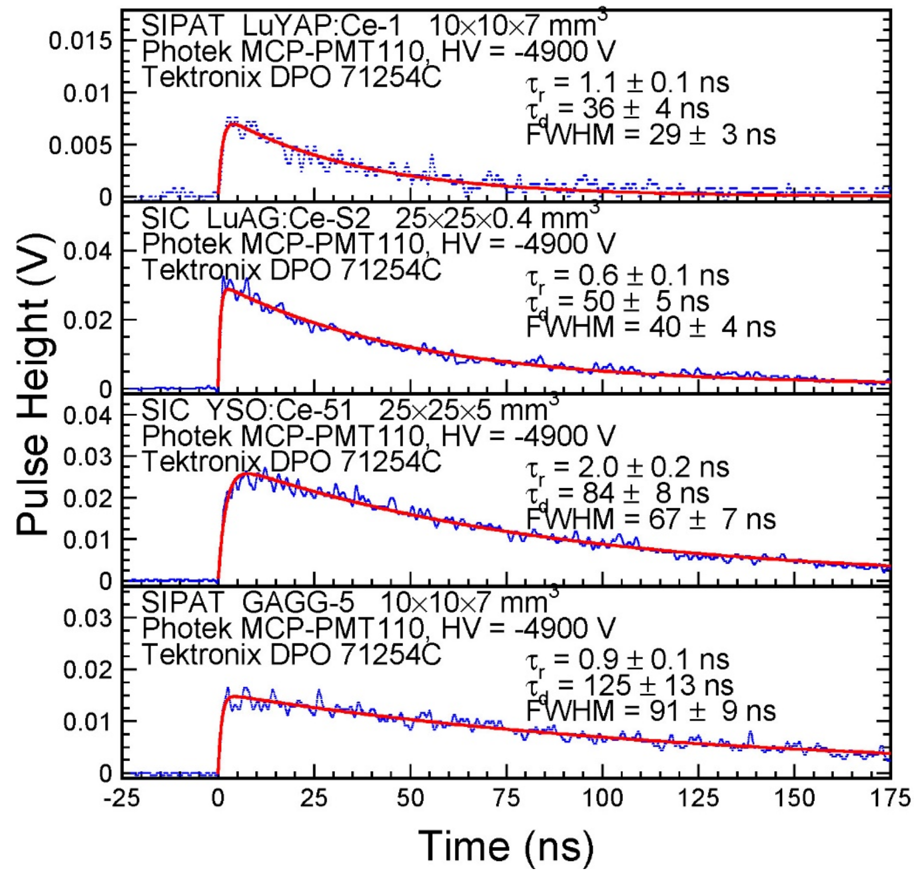
BaF_2:Y and BaF_2 show ultrafast temporal response.

YAP:Yb, YAG:Yb and ZnO:Ga show a slower response.

Singlet bunch by Fast Crystals

Decay time consists with Lab data measured with source





All other crystals are too slow for GHz X-ray imaging

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**	**1.0**	**1.4**
BaF_2	SIC	1	50×50×5	220	85.1	209	1200	**0.2**	**1.2**	**1.5**
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 single bunch

Summary

- Responses to 30 keV X-ray bunches were measured for a dozen of fast inorganic scintillators at the APS 10-ID beam site.
- X-ray imaging for septuplet bunches with 2.83 ns spacing is clearly demonstrated by using ultrafast inorganic scintillators, such as BaF_2:Y and BaF_2, but not others with long decay time, such as LYSO. YAP:Yb, YAG:Yb and ZnO:Ga show slower response than BaF_2.
- With sub-ns decay time BaF_2:Y and BaF_2 show the highest amplitude, fastest response time to X-ray bunches among all inorganic scintillators tested so far. BaF_2:Y crystals with suppressed slow component show no pile-up for septuplets.
- Temporal response measured for BaF_2:Y and BaF_2, however, is slower than the data obtained with γ-ray sources at Caltech last Fall, which is attributed to the APS test set-up, e.g. 15 m long cables between the MCP-PMT and the DPO.

Acknowledgements: DOE Award DE-SC001192, LANL award 483673.