Ultrafast Inorganic Scintillator Based Front Imager for GHz Hard X-Ray Imaging

Chen Hu, Liyuan Zhang, Ren-Yuan Zhu

California Institute of Technology

for

The Ultrafast Materials and Application Collaboration

Presented in the ULITIMA Conference at ANL, Chicago, Sept 14

The Ultrafast Materials and Applications (UMA) Collaborators

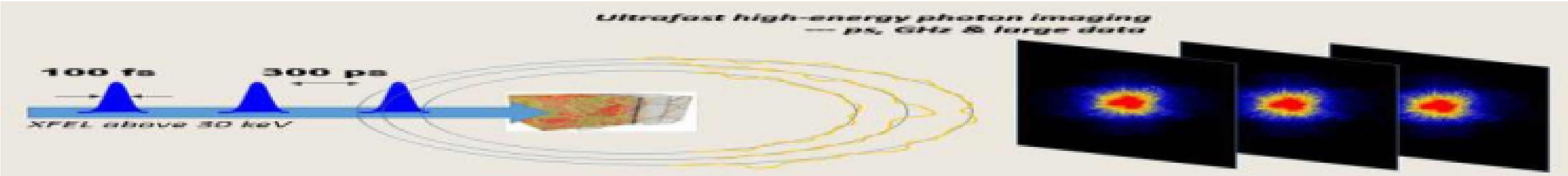
Marcel Demarteau, Robert Wagner, Lei Xia, Junqi Xie
Argonne National Laboratory

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 site on July 2 -3, 2018
See reports by Junqi Xie, Xuan Li and Thomas Smith in this conference

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

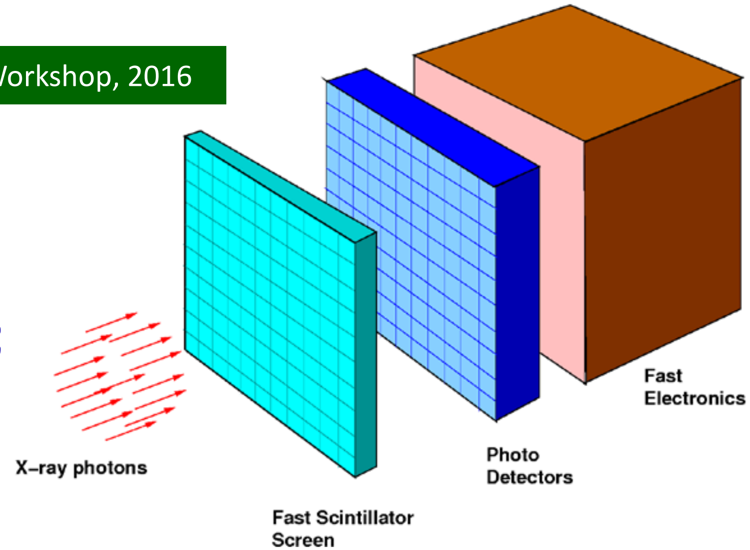
2 ns and 300 ps inter-frame time requires ultrafast sensor

Scintillator 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 ultrafast crystal screen;
  - Pixelized ultrafast photodetector;
  - Fast electronics readout.
- Discussed in this report:

  Ultrafast crystals and photodetectors.

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



12 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 (°C)	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

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;

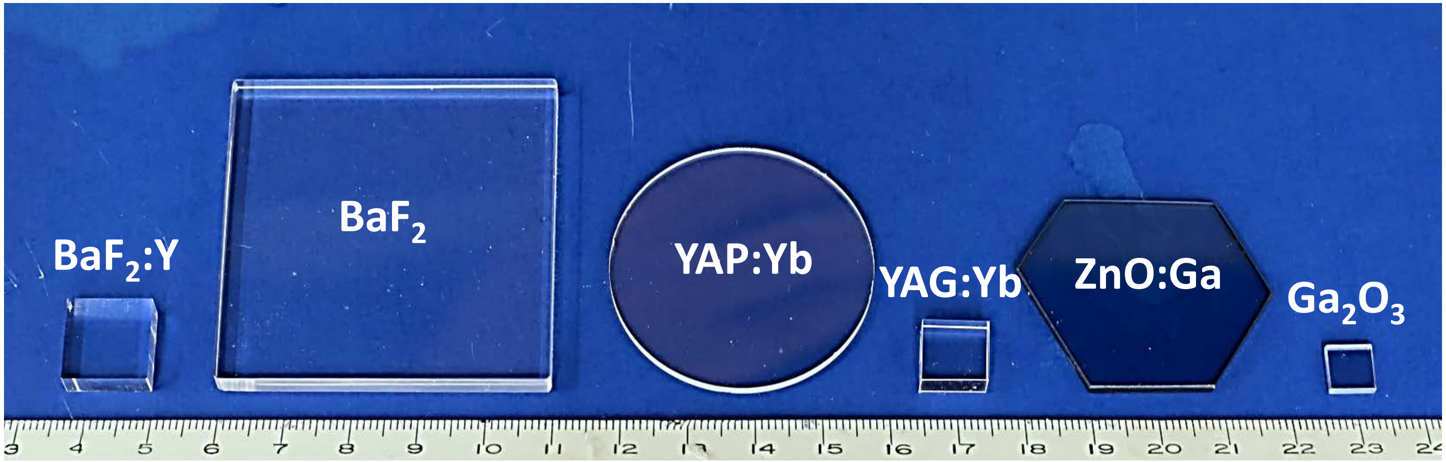
d. Excited by Alpha particles.

e. Ceramic with 0.3 Mg at% co-doping

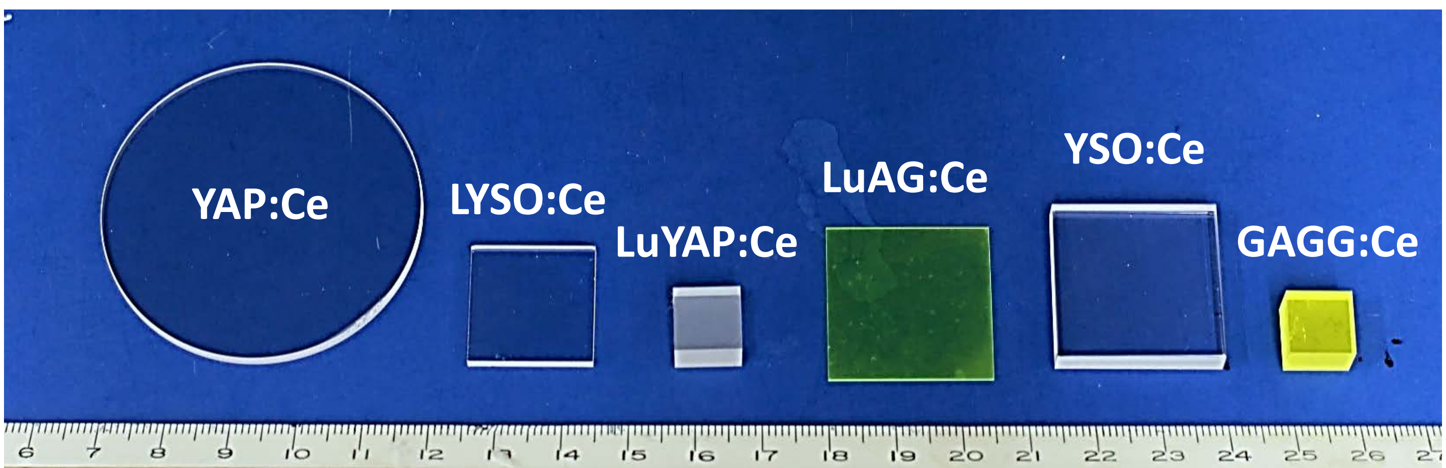
f. Based on $Lu_{0.7}Y_{0.3}AlO_3$:Ce

12 Samples Tested with X-Rays

Scintillators with ultrafast decay time



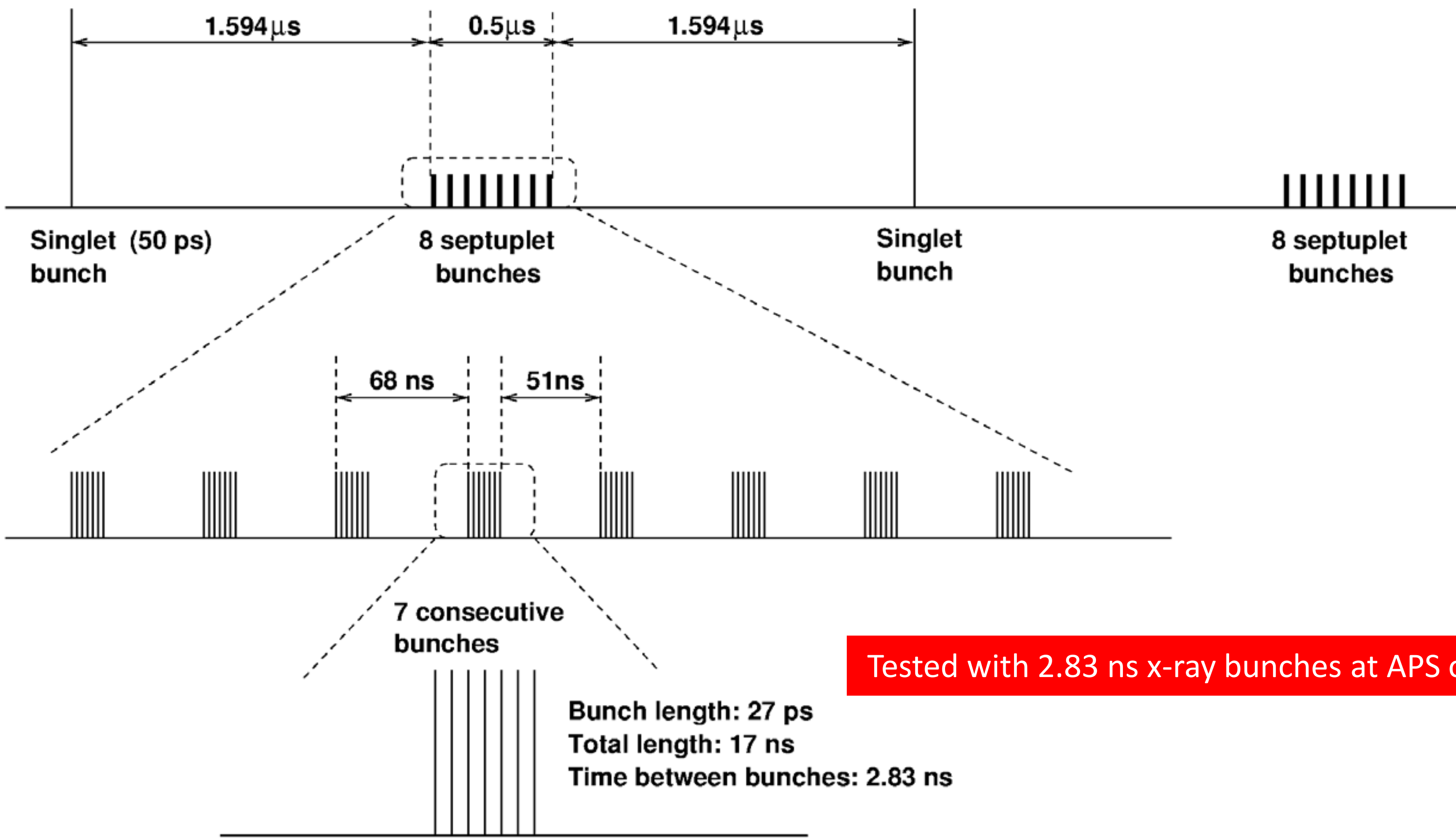
Scintillators with fast decay time



APS Hybrid Beam Characteristics

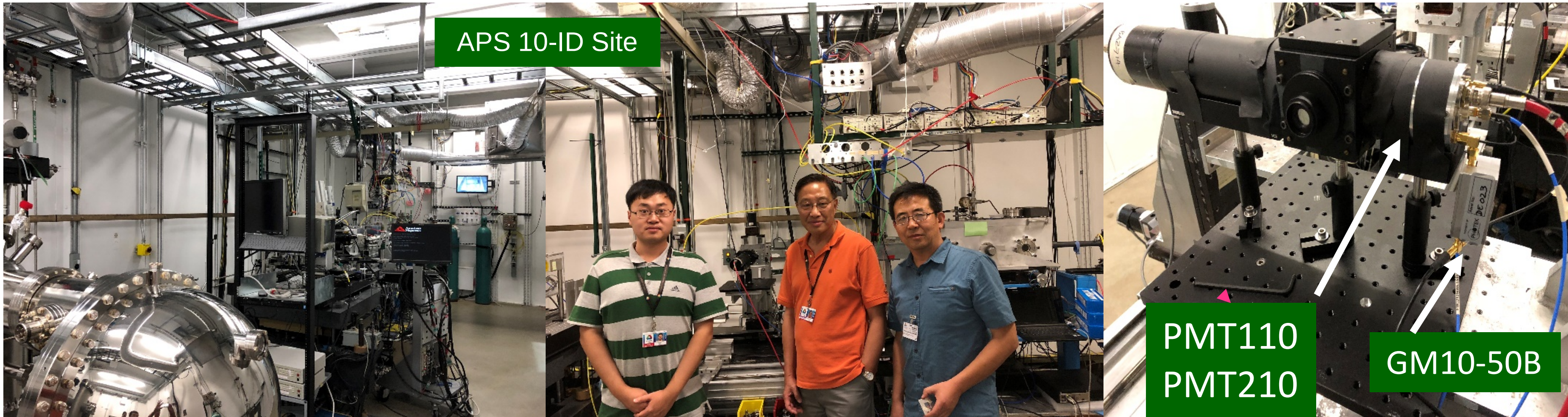
https://ops.aps.anl.gov/SRparameters/node5.html

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.



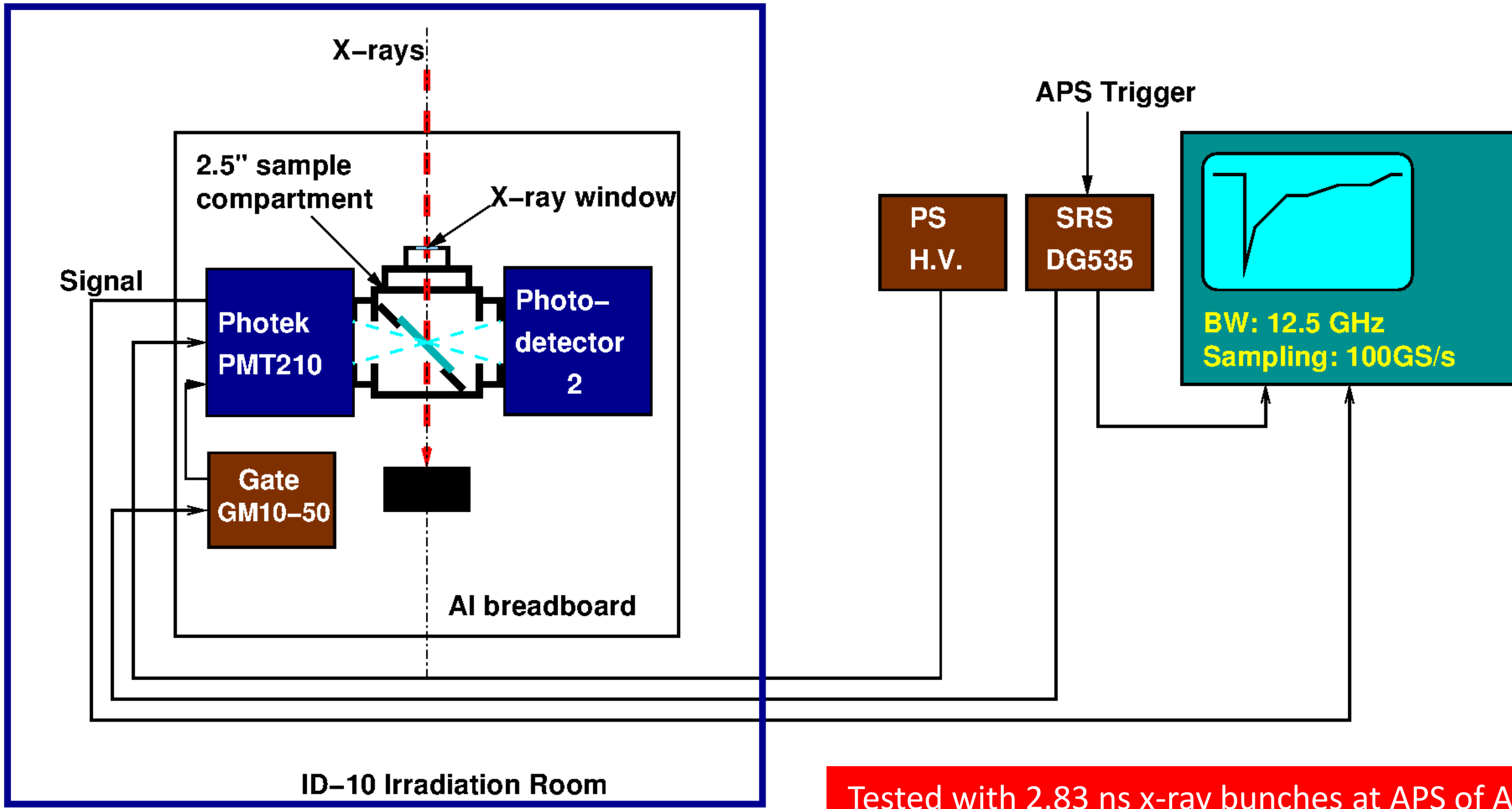
Tested with 2.83 ns x-ray bunches at APS of ANL

Photos Taken During Beam Test at APS 10-ID Site (July 2 -3, 2018)



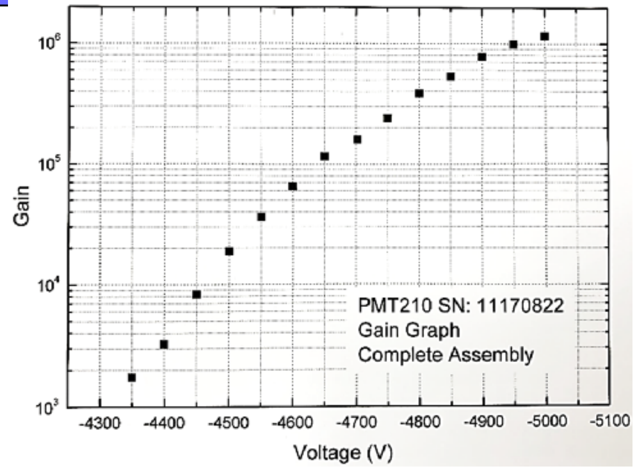
The Test Setup at APS

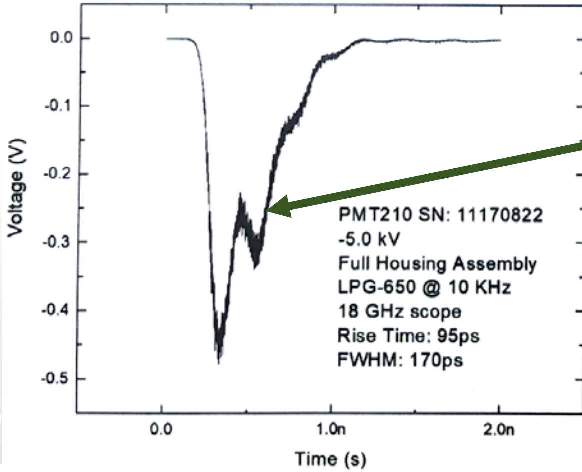
Crystals, MCP-PMT and gate unit were in the hutch at APS 10-ID site. Tektronix DPO71254C, delay unit and HV supplier were in the control room. Signal from MCP-PMT went through a 15 m wideband SMA cable, which compromises PMT's temporal response.



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

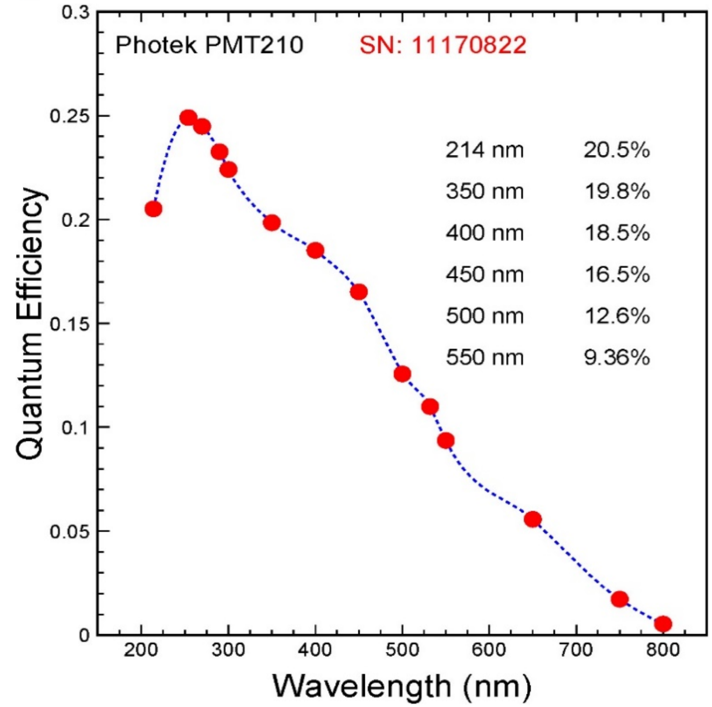
Ultrafast Photodetectors





The ringing caused by a known impedance mismatch in the PMT

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
Hamamstsu MCP-PMT R3809U-50	Φ11	160-850	430	3×10^5	0.15	0.36
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

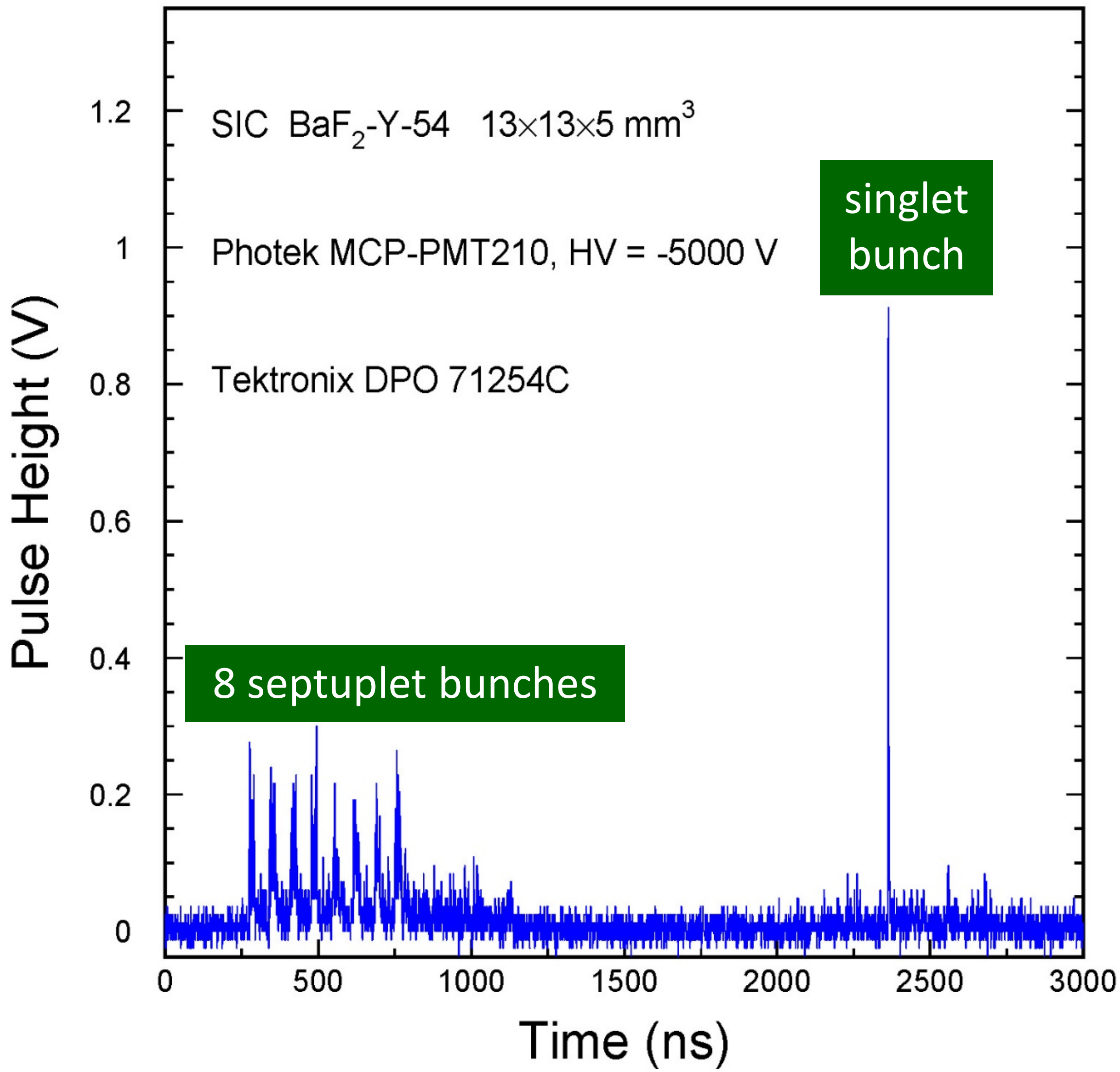


Photek MCP-PMT 110 and 210 are ultrafast

Hybrid Beam Measured by BaF_2:Y

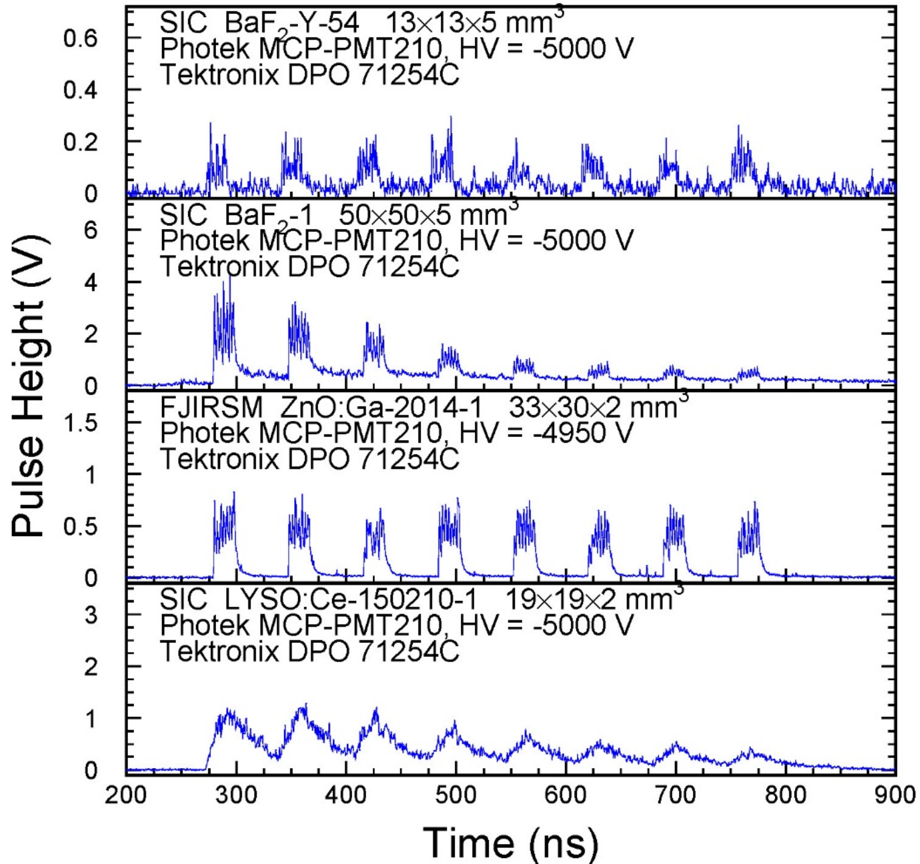
Data taken with Photek PMT & gate unit for septuplet bunches show crystal's capability for hard X-ray imaging with 2.83 ns bunch spacing.

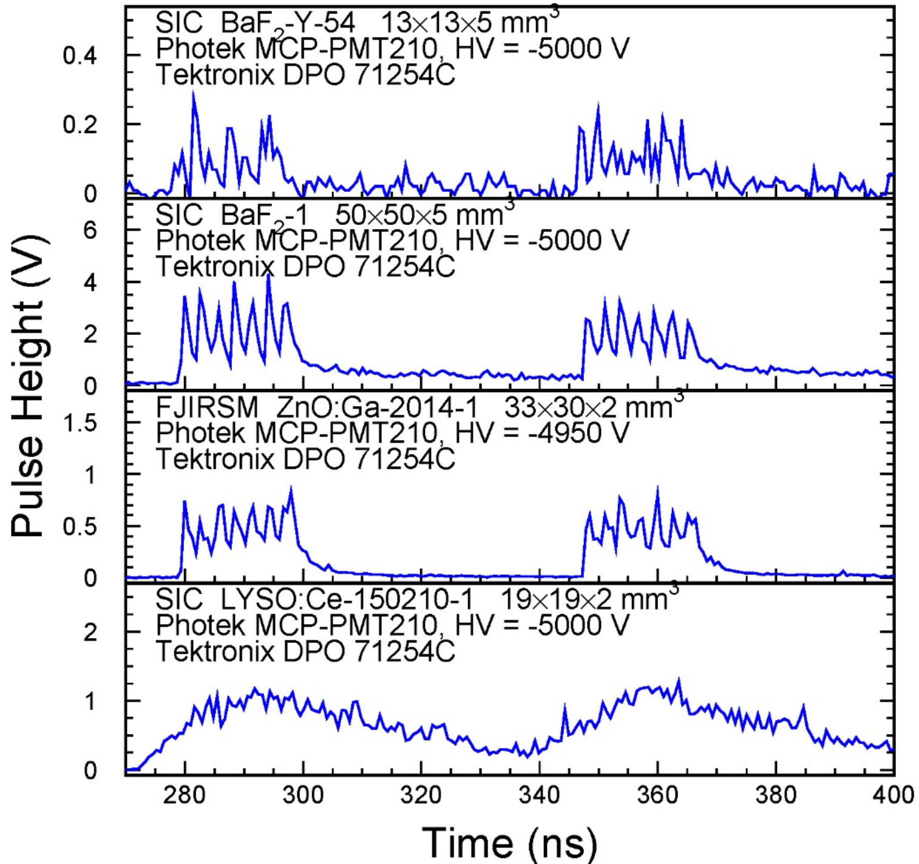
Data were also taken for singlet bunches to show crystal's temporal response.



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

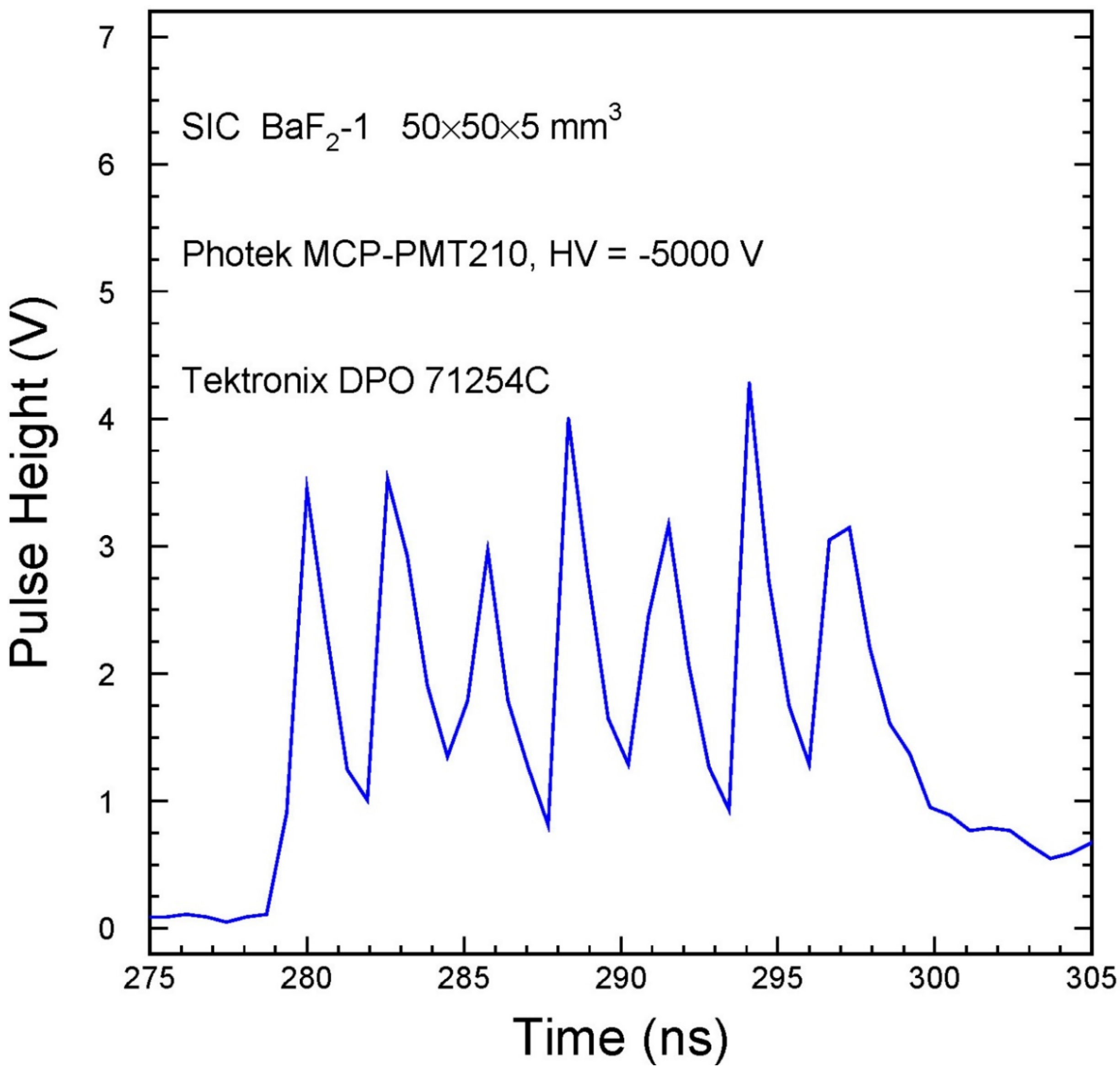




Amplitude reduction for septuplets observed in BaF_2 and LYSO due to space charge in PMT caused by slow scintillation component, but not in BaF_2:Y.

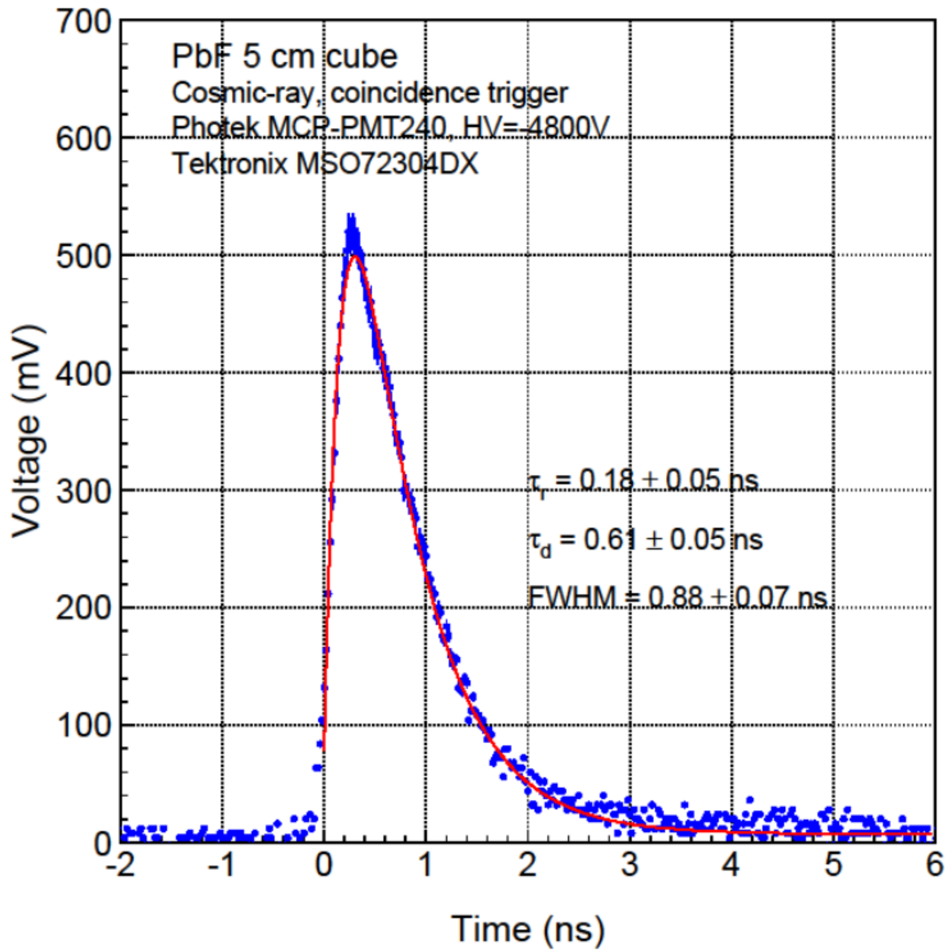
2.83 ns X-ray Bunch Imaging by BaF_2

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 MaRIE type –I imager.



Fitting Temporal Response

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



Fitting:

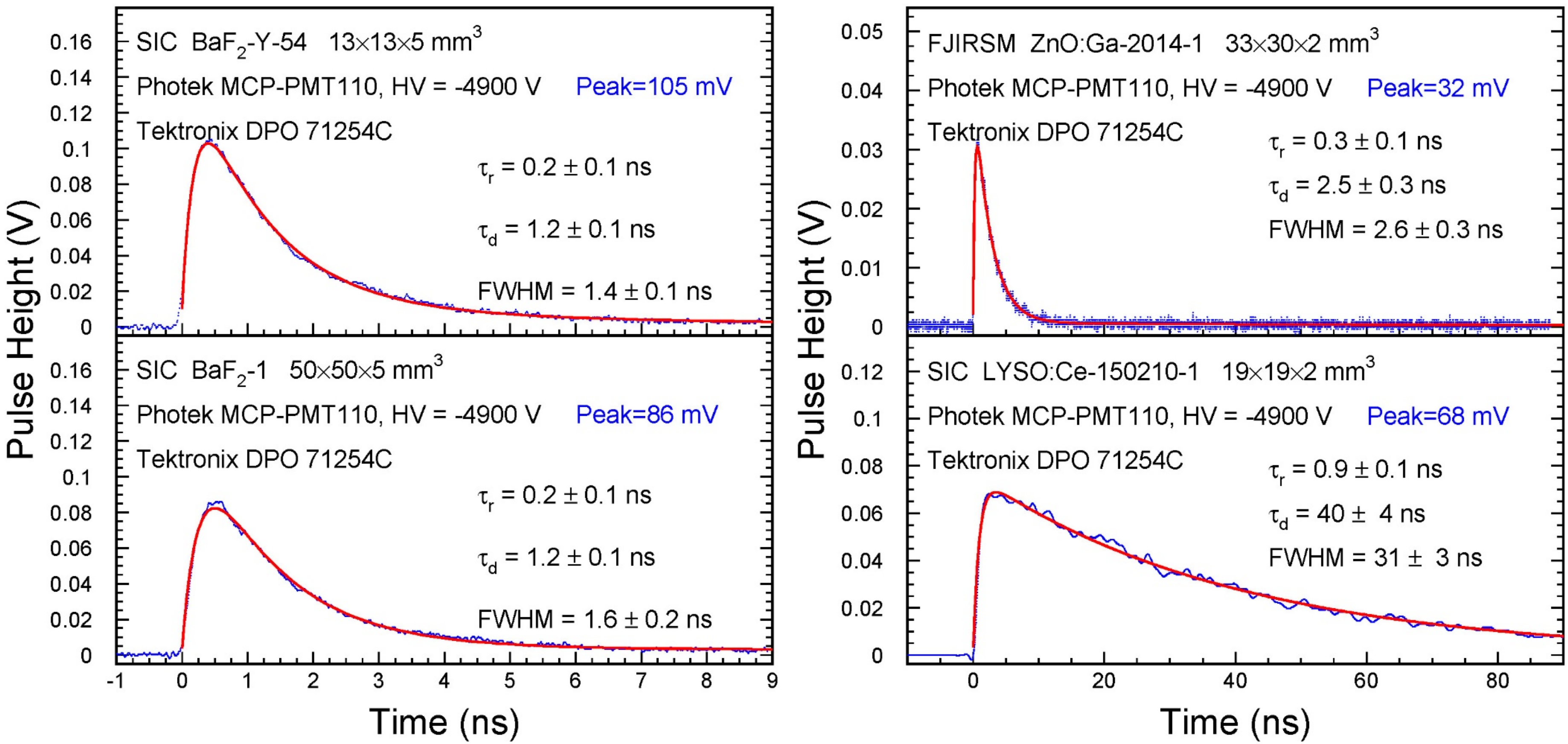
$$V = A\left(e^{-\frac{t}{\tau_d}} - e^{-\frac{t}{\tau_r}}\right) + B$$

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

Singlet Bunch by Ultrafast Crystals

Peak amplitude of BaF_2 and BaF_2:Y higher than ZnO:Ga and LYSO
Rise/decay time of BaF_2 and BaF_2:Y shorter than ZnO:Ga and LYSO

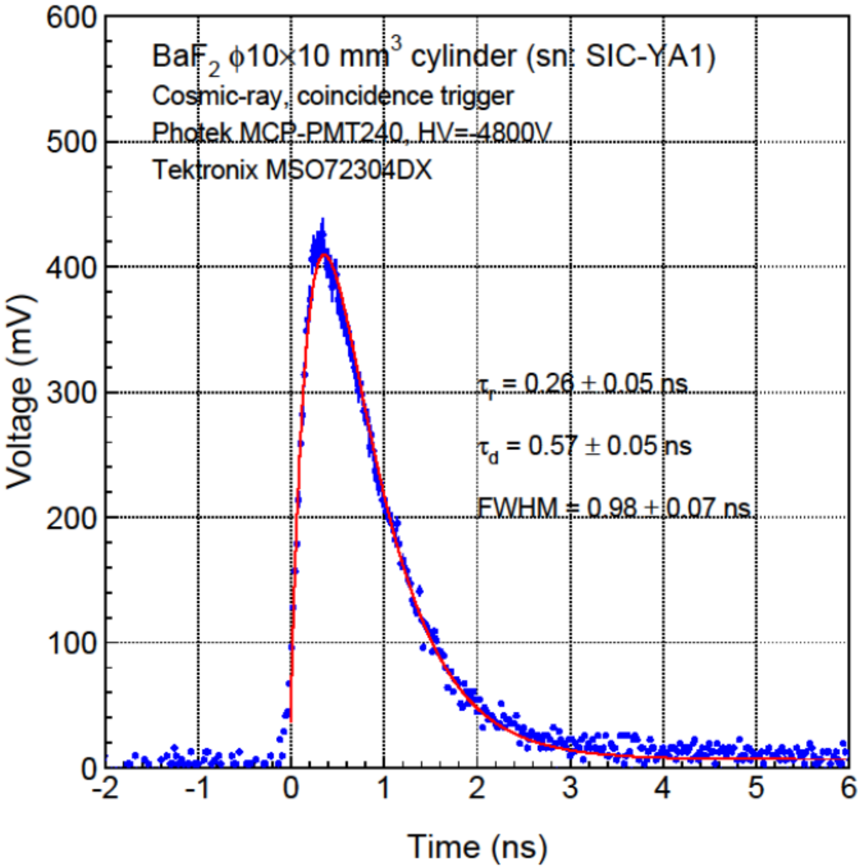


Rise/decay time of BaF_2 and BaF_2:Y longer than the γ-ray source data measured at Caltech because of the 15 m cable length

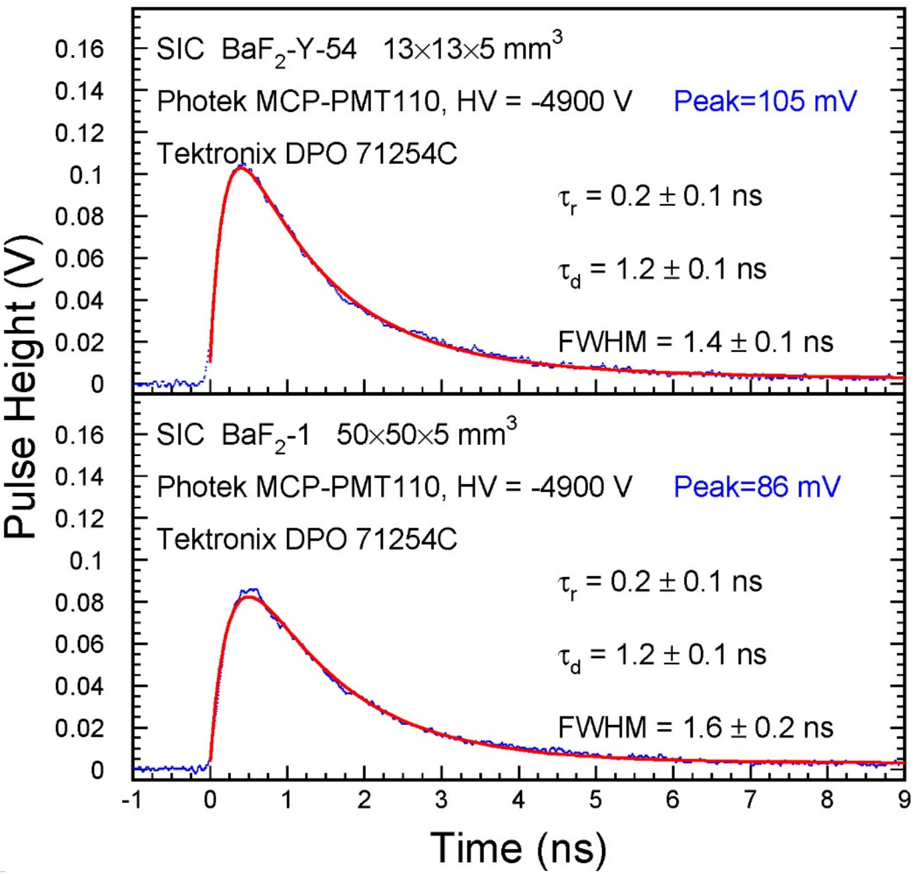
Temporal Response of BaF_2:Y

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

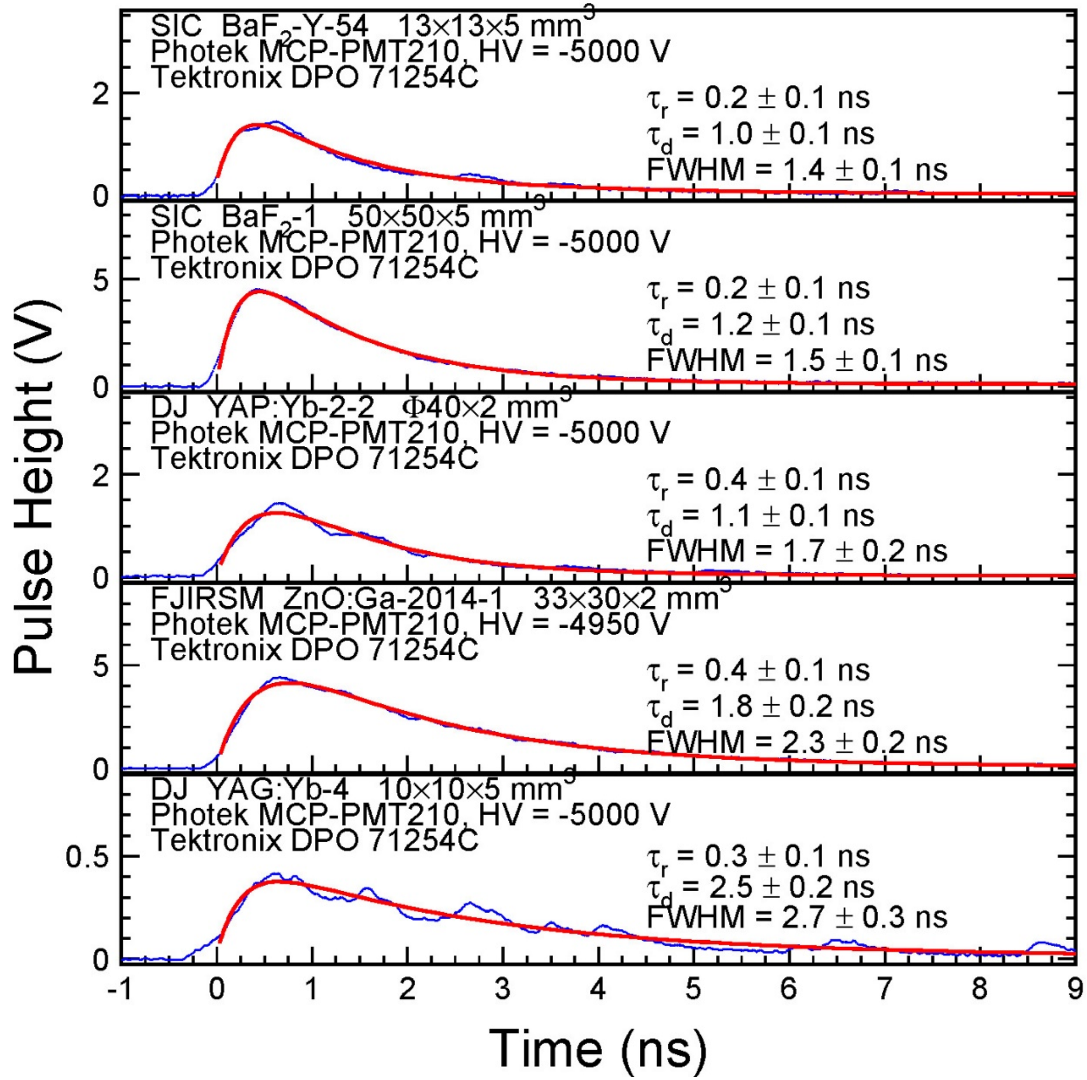
Caltech Data



APS Data



Singlet Bunches by Ultrafast Crystals

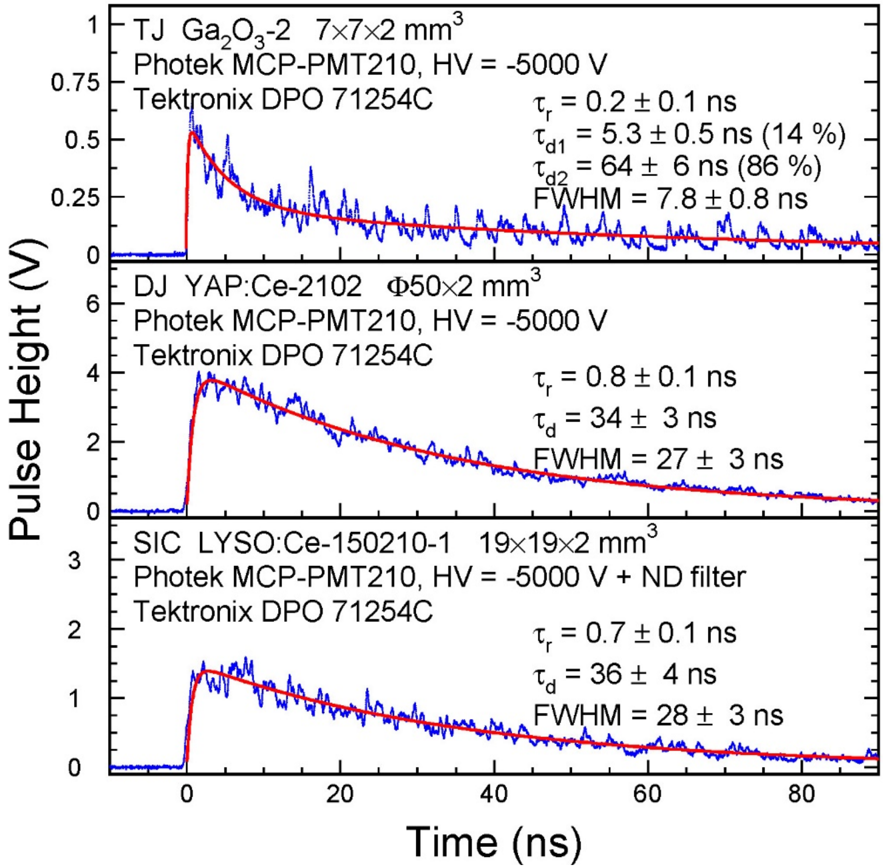


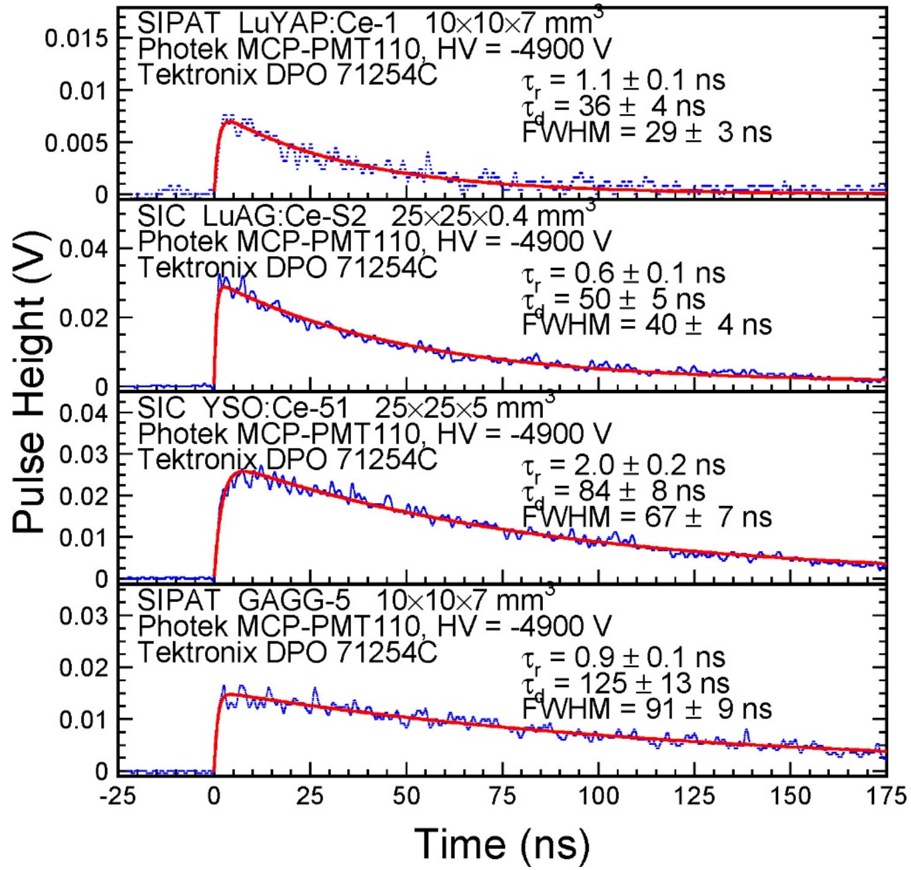
BaF_2:Y and BaF_2 show ultrafast temporal response.

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

Singlet Bunches by Fast Crystals

Decay time consists with Lab data measured with source





All fast 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 singlet bunches

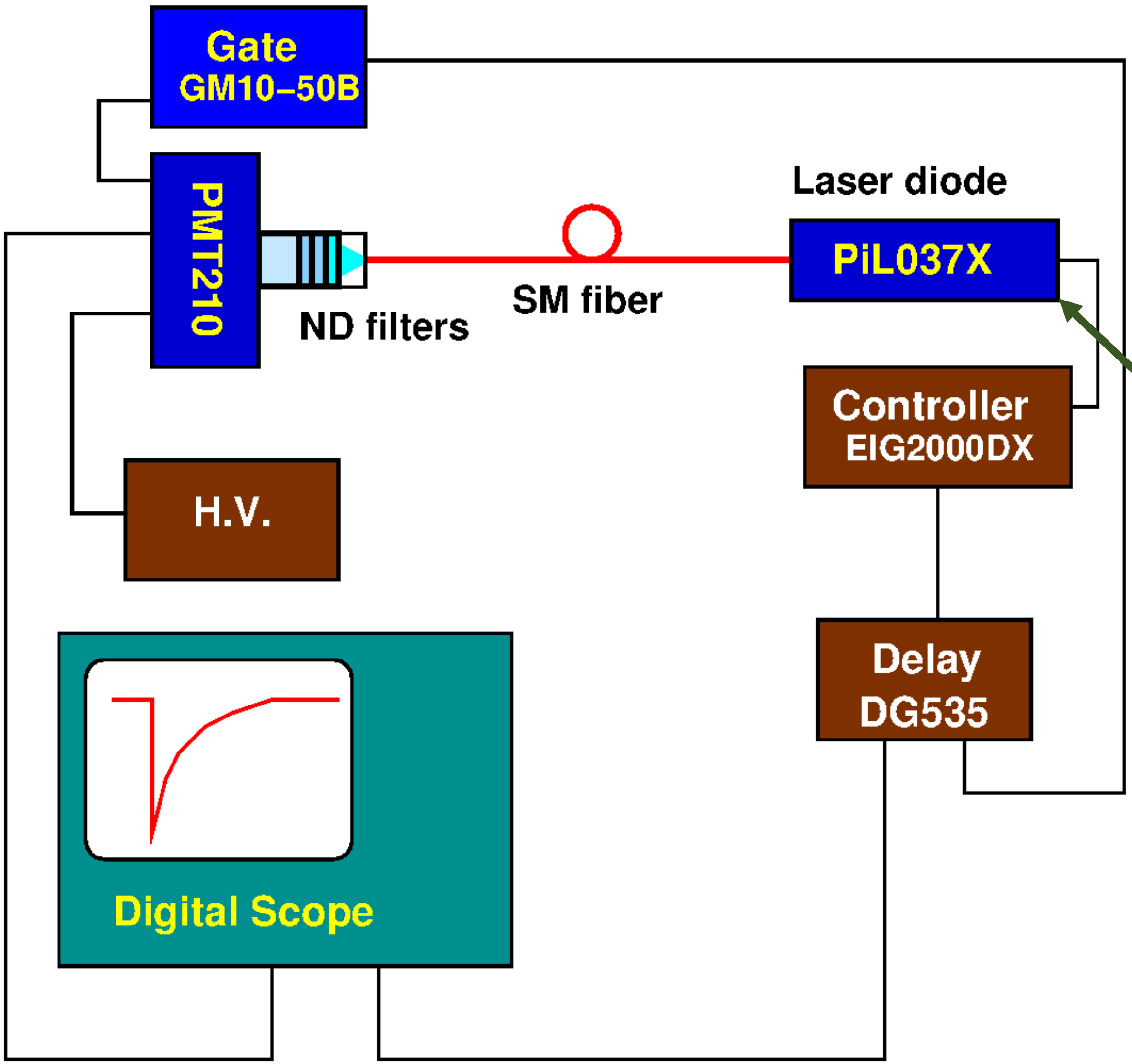
Photodetector and Cable Length

- Significantly slower temporal responses observed in the APS data taken with a 15 m cable and a gate unit as compared to the Caltech data taken with an 1 m cable without gate unit.

- Temporal responses of various photodetectors to 40 ps laser pulses from an Advanced Laser Diode PiL037X at 373 nm were measured at Caltech after the APS beam test with both 1 and 15 m cables connected to the Tektronix DPO71254C scope (12.5 GHz, 100 GS/s) used in the beam test with and without the gate unit.

- Temporal responses of Cherenkov light from PbF_2 and scintillation light from BaF_2 were measured at Caltech by the Photek PMT 210 for both 1 and 15 m cables, and compared to the Caltech and APS data with 240, respectively.

Test Setup for Photo-detectors

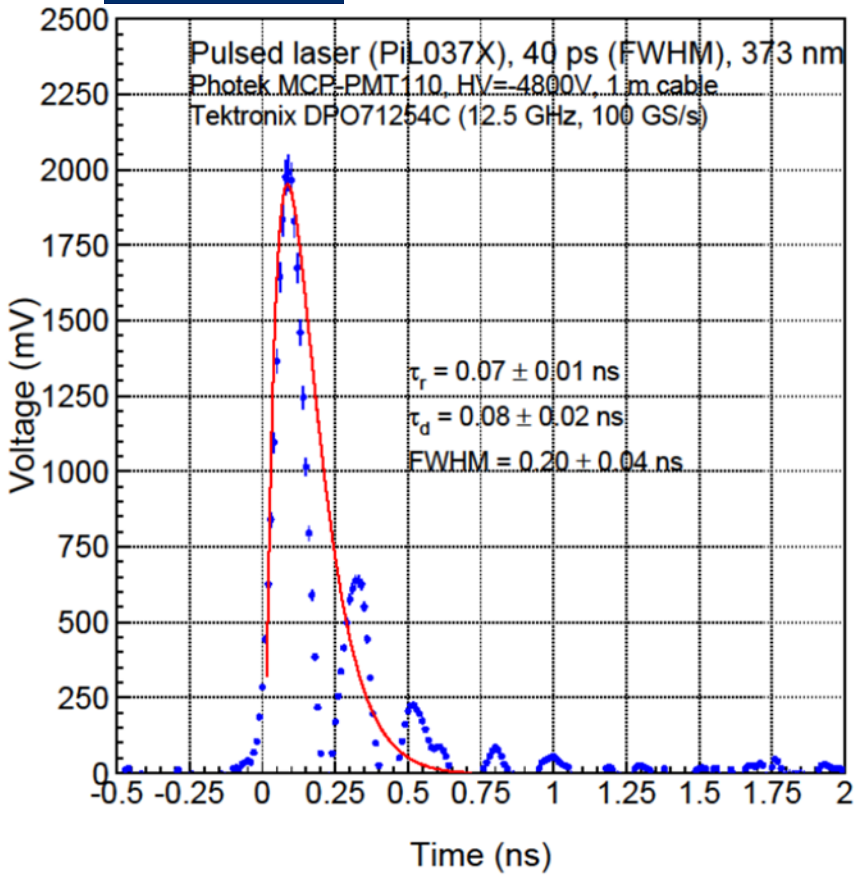


Advanced Laser Diode Systems: PiL037X, 40 ps (FWHM), 373 nm.

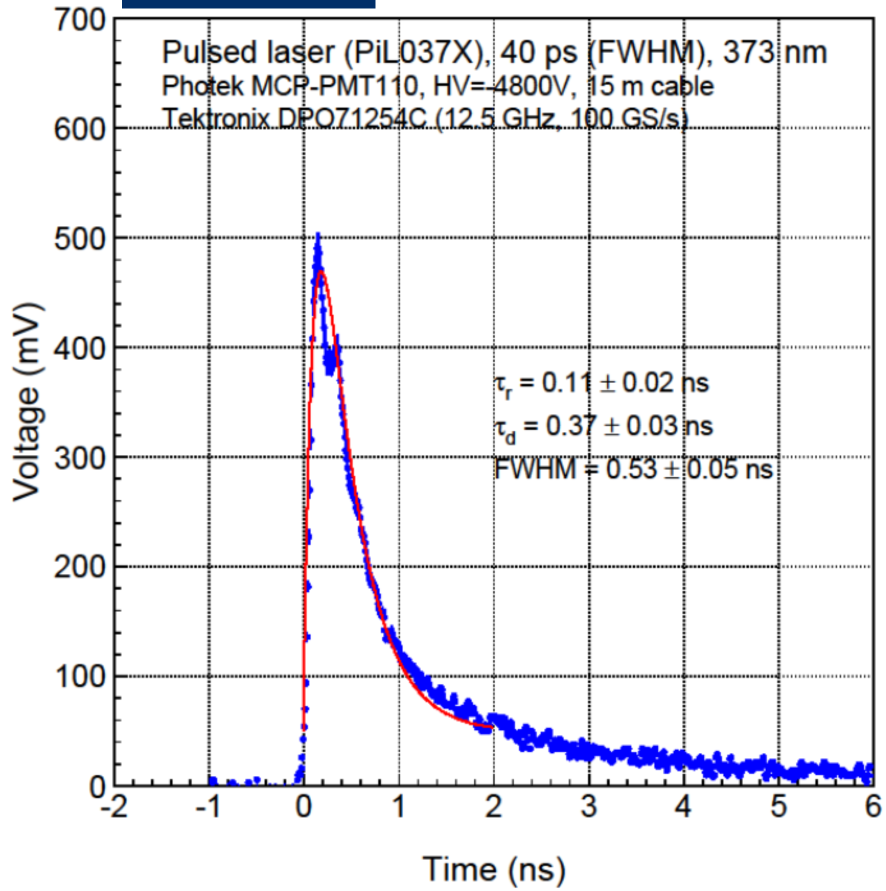
Photek PMT110: Laser Diode

Pulse shape measured with 1 m cable consists with the Photek data
Pulse width measured with 15 m cable is broadened from 0.20 to 0.53 ns

1 m cable



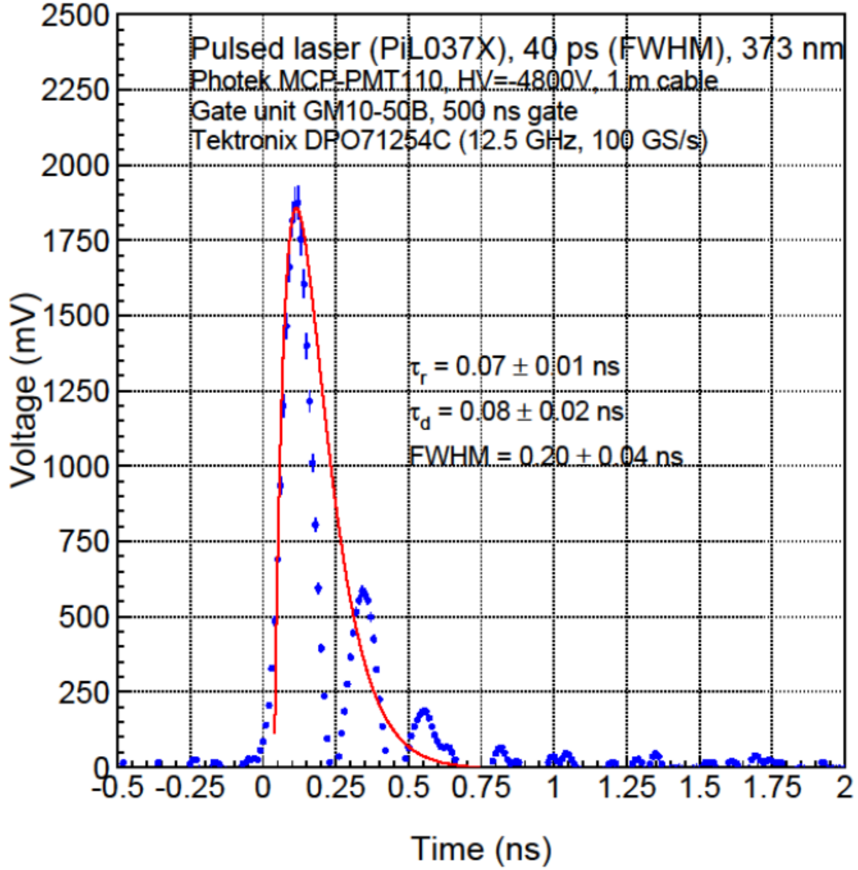
15 m cable



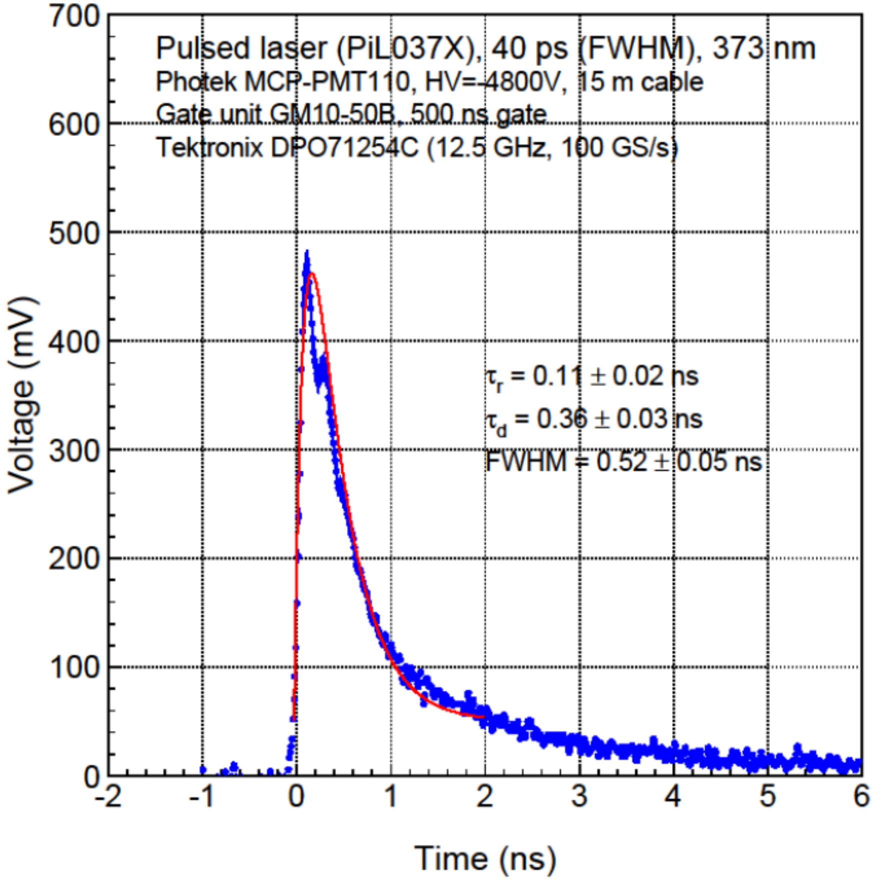
PMT110: Laser Diode & Gate Unit

The gate unit GM10-50B does not change pulse shape

1 m cable



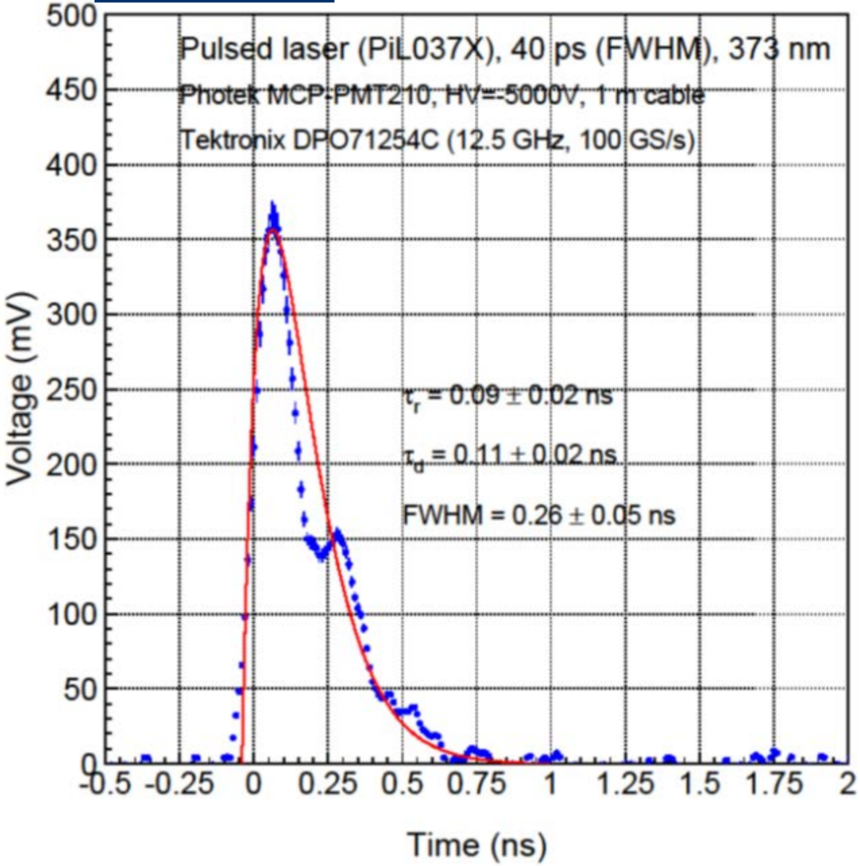
15 m cable



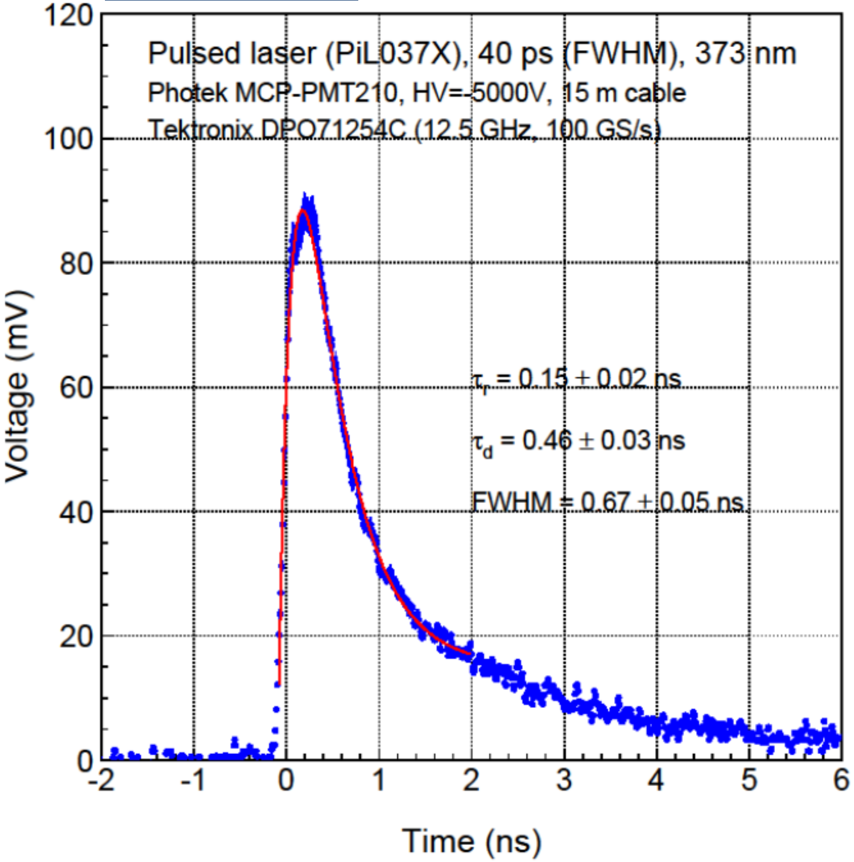
Photek PMT210: Laser Diode

Pulse shape measured with 1 m cable consists with the Photek data
Pulse width measured with 15 m cable is broadened from 0.26 to 0.67 ns

1 m cable



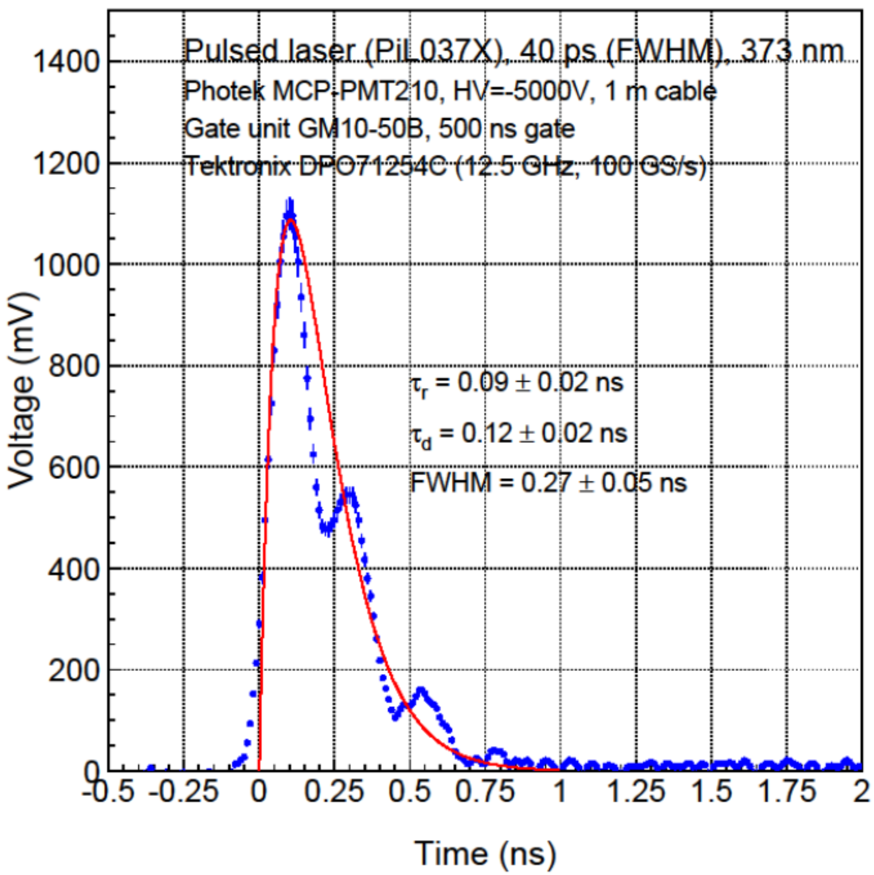
15 m cable



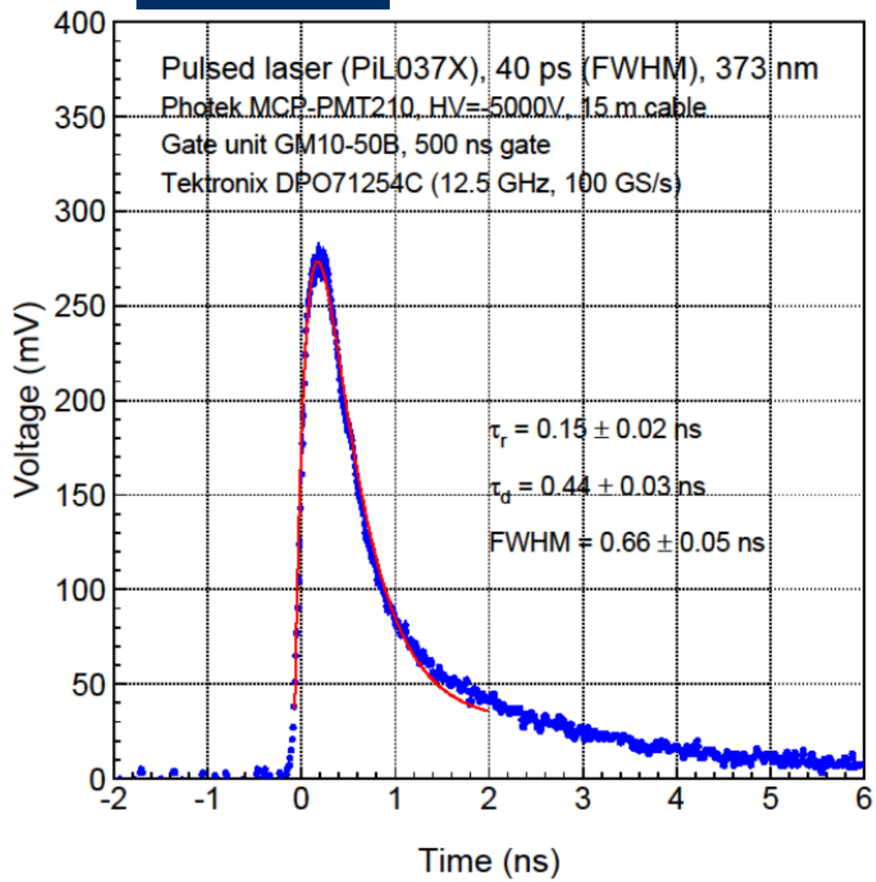
PMT210: Laser Diode & Gate Unit

The gate unit GM10-50B does not change pulse shape

1 m cable



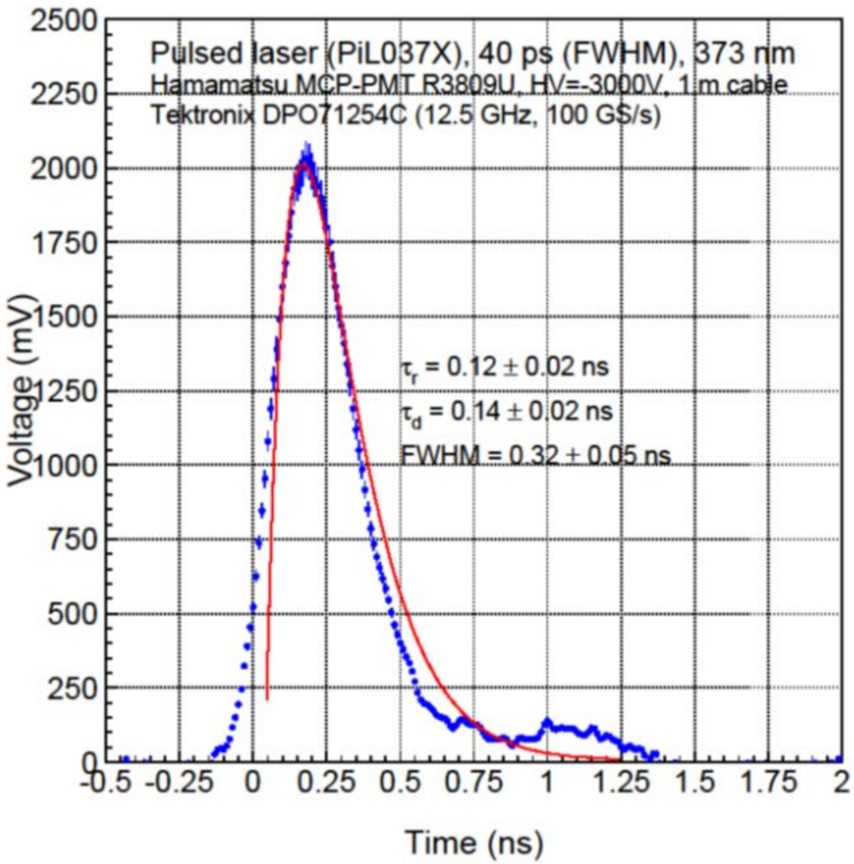
15 m cable



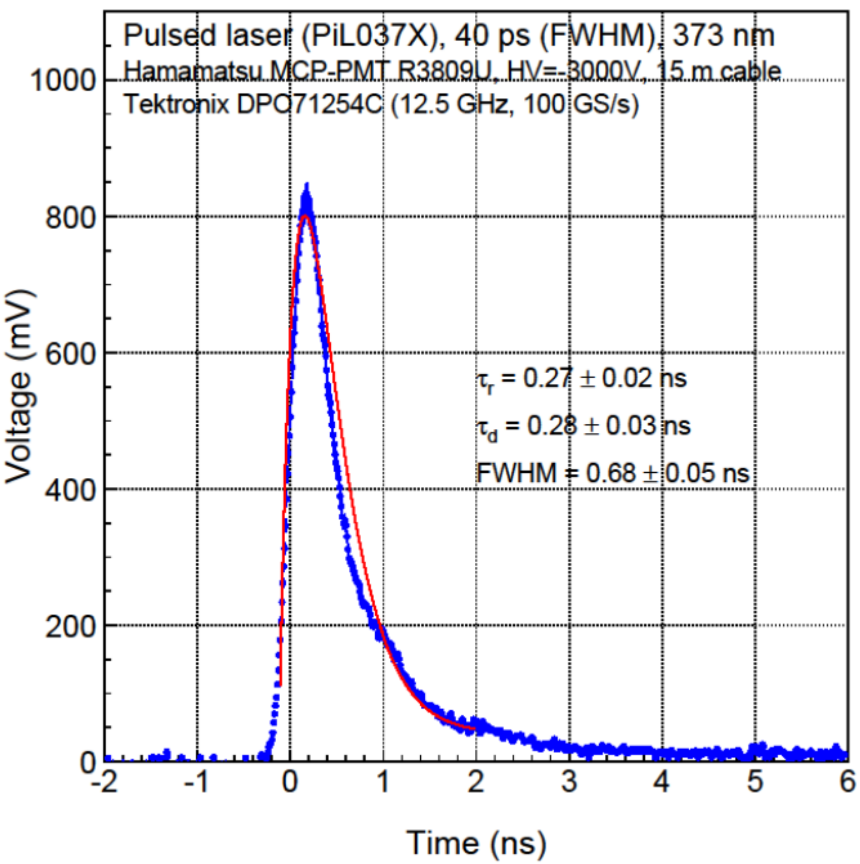
Hamamatsu R3809U: Laser Diode

Pulse shape measured with 1 m cable consists with the Hamamatsu data
Pulse width measured with 15 m cable is broadened from 0.32 to 0.68 ns

1 m cable



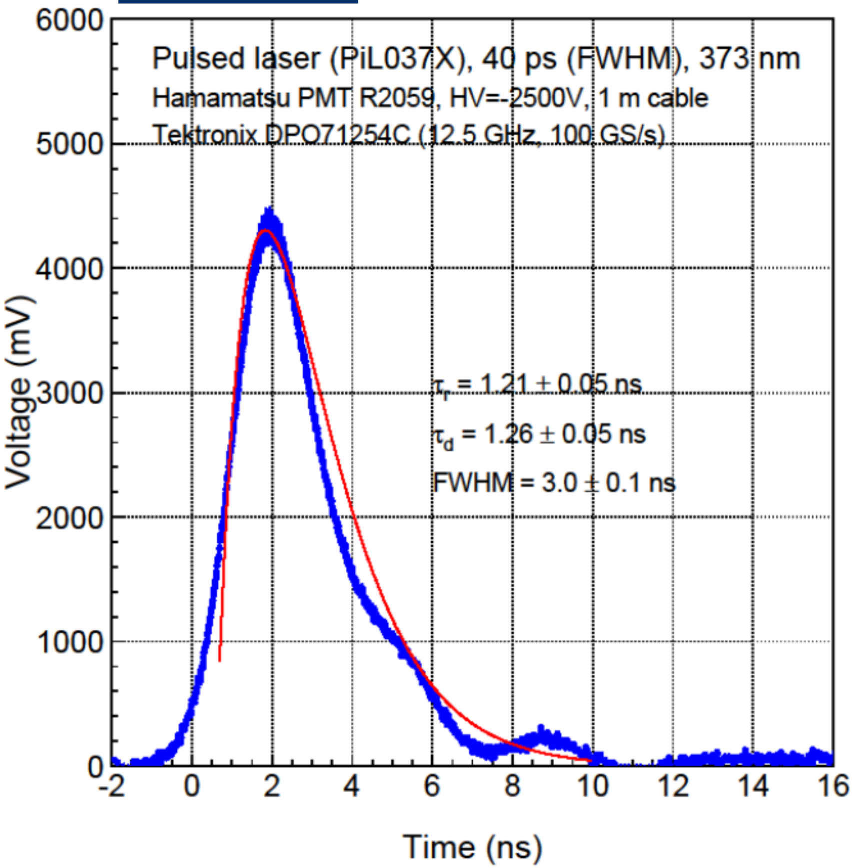
15 m cable



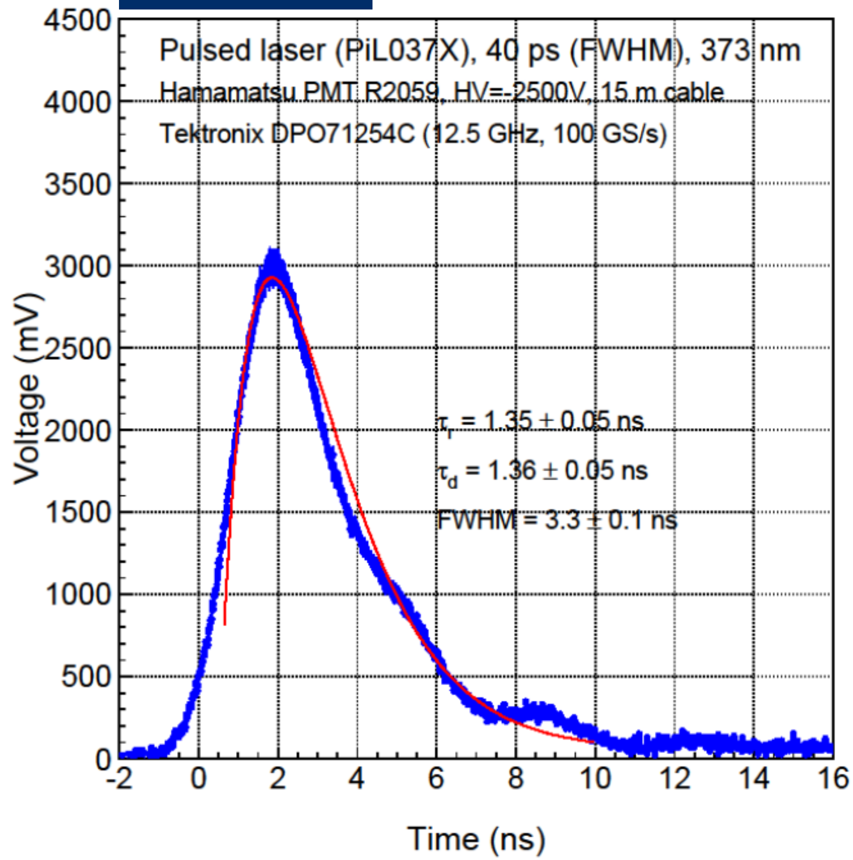
Hamamatsu R2059: Laser Diode

1.3 ns rise time measured with 1 m cable consists with Hamamatsu data
15 m cable has a minor effect on the pulse shape compared to 1 m cable

1 m cable



15 m cable



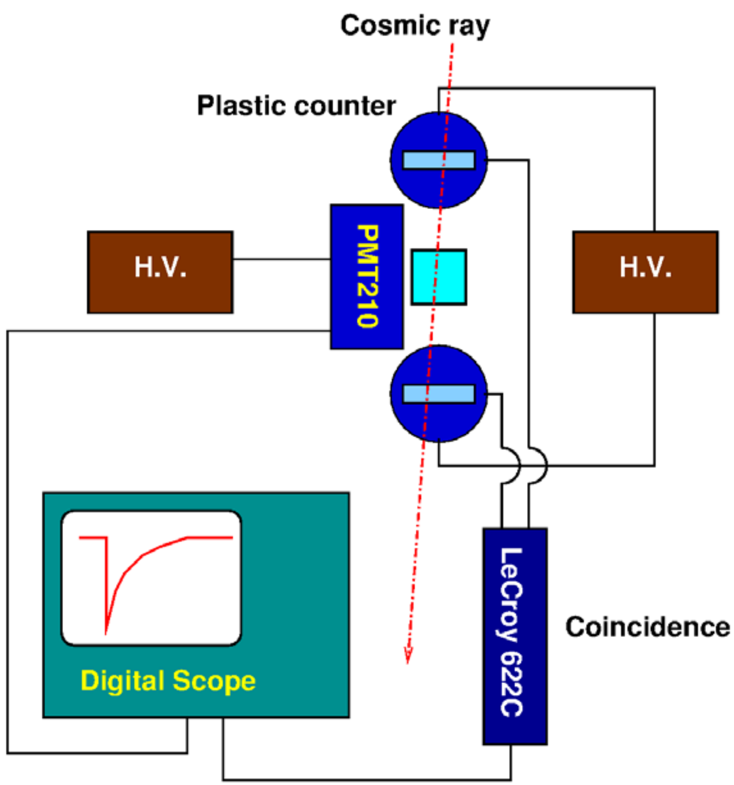
All Photodetectors: Laser Diode

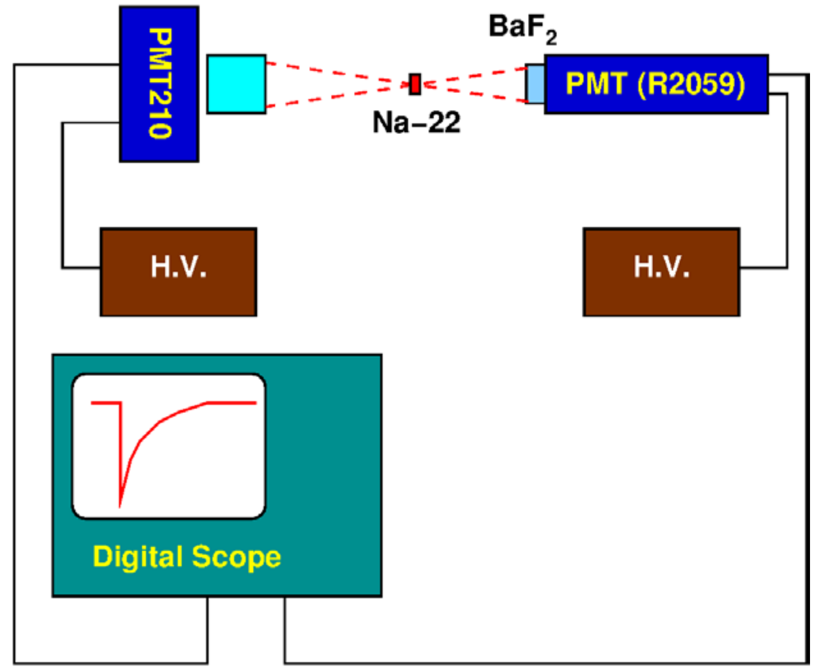
15 m cable slows down ultrafast photo-detector response significantly

Photodetector	Dimensions	Mode	Cable (m)	τ_r (ns)	τ_d (ns)	FWHM (ns)
Photek MCP-PMT110	Φ10 mm	DC	1	0.07±0.01	0.08±0.02	0.20±0.04
Photek MCP-PMT110	Φ10 mm	Gate (500 ns)	1	0.07±0.01	0.08±0.02	0.20±0.04
Photek MCP-PMT210	Φ10 mm	DC	1	0.09±0.02	0.11±0.02	0.26±0.05
Photek MCP-PMT210	Φ10 mm	Gate (500 ns)	1	0.09±0.02	0.12±0.02	0.27±0.05
Hamamatsu MCP-PMT U3809U	Φ11 mm	DC	1	0.12±0.02	0.14±0.02	0.32±0.05
Hamamatsu PMT R2059	Φ50 mm	DC	1	1.21±0.05	1.26±0.05	3.0±0.1
Photek MCP-PMT110	Φ10 mm	DC	15	0.11±0.02	0.37±0.03	0.53±0.05
Photek MCP-PMT110	Φ10 mm	Gate (500 ns)	15	0.11±0.02	0.36±0.03	0.52±0.05
Photek MCP-PMT210	Φ10 mm	DC	15	0.15±0.02	0.46±0.04	0.67±0.05
Photek MCP-PMT210	Φ10 mm	Gate (500 ns)	15	0.15±0.02	0.44±0.03	0.66±0.05
Hamamatsu MCP-PMT U3809U	Φ11 mm	DC	15	0.27±0.02	0.28±0.03	0.68±0.05
Hamamatsu PMT R2059	Φ50 mm	DC	15	1.35±0.05	1.36±0.05	3.3±0.1

Test Setup for Crystals

Temporal response of crystals for cosmic-rays and 511 keV ɣ-rays from a Na-22 source was measured by the Photek PMT 210

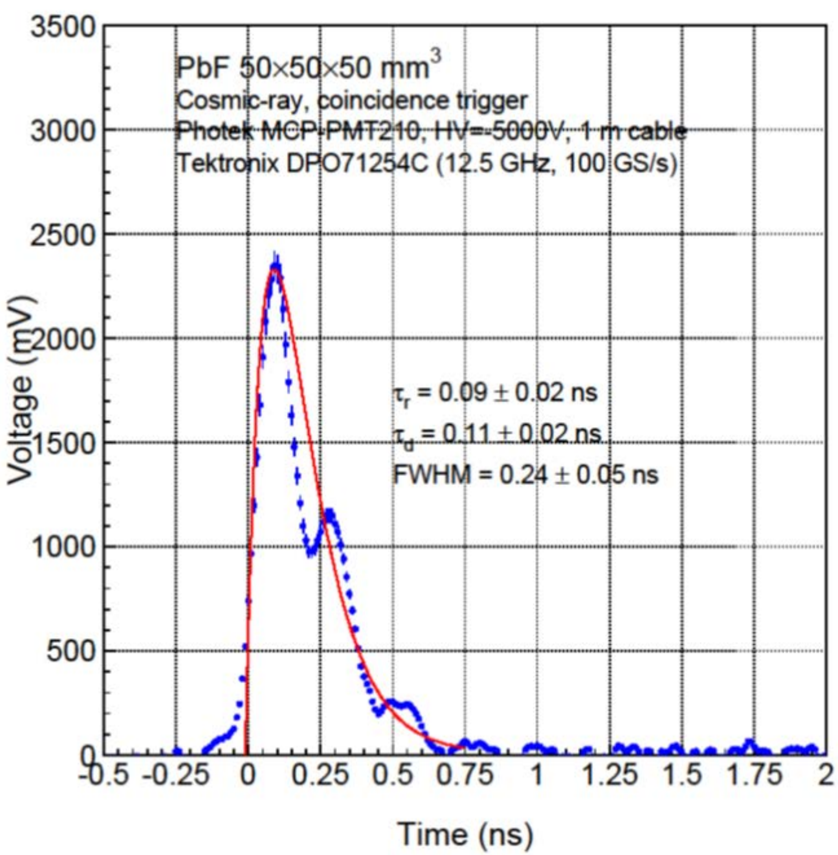




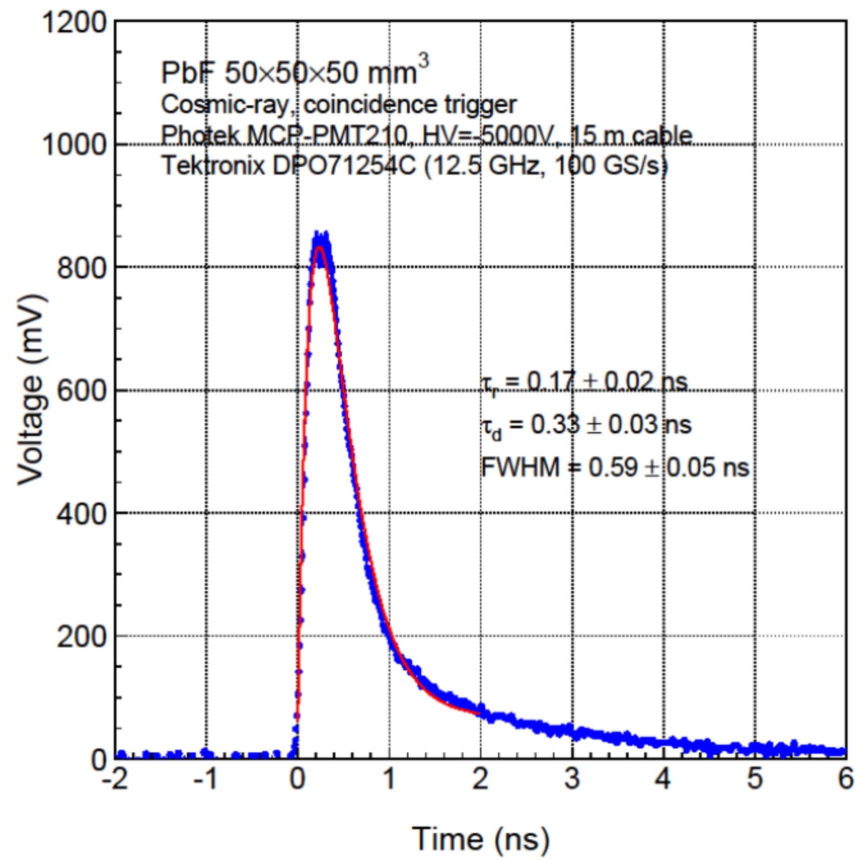
Cerenkov: 5 cm PbF_2 Cube

PMT 210 + 1 m cable: Cherenkov consists with the 40 ps laser
PMT210 + 15 m cable: significantly slower pulse shape

1 m cable



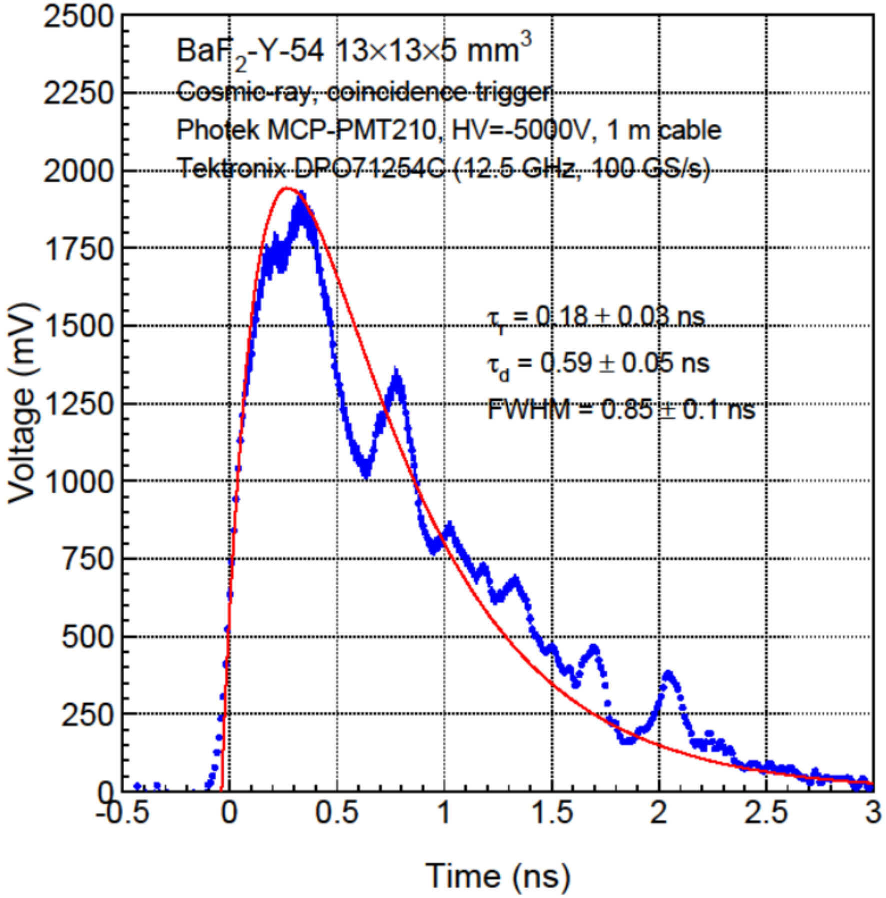
15 m cable



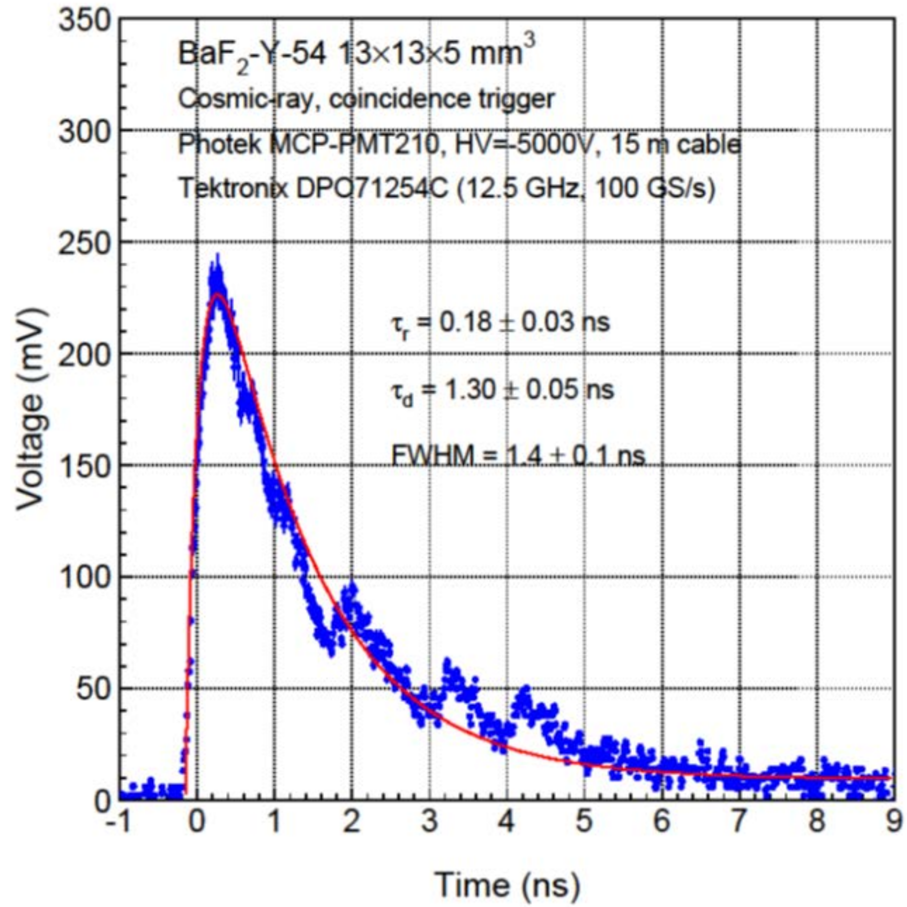
Scintillation: BaF_2-Y-54

PMT 210 + 1 m cable: scintillation consists with the PMT 240 data
PMT 210 + 15 m cable: scintillation consists with the APS data

1 m cable



15 m cable



Summary

- Test beam data for septuplet bunches with 2.83 ns spacing at the APS 10-ID beam site show clearly separated X-ray pulses observed by ultrafast inorganic scintillators, such as BaF_2:Y, coupled to ultrafast photodetectors, such as Photek MCP-PMT, demonstrating feasibility of an ultrafast scintillator based front imager for GHz hard X-ray imaging. YAP:Yb, ZnO:Ga and YAG:Yb are slower.
- Temporal response of BaF_2 shows the highest amplitude, fastest response among a dozen fast inorganic scintillators. With suppressed slow component, response of BaF_2:Y shows no pile-up for 8 septuplet bunches with 2.83 ns spacing.
- Temporal responses of BaF_2 crystals measured by Photek MCP-PMTs with 1 and 15 m cable confirm that the 1.5 ns pulse width observed at APS is caused by the 15 m cable length. It is crucial to keep all connections short in the ultrafast front imager design.

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