Ultrafast Inorganic Scintillators for Future HEP and Imaging Applications

Ren-Yuan Zhu

California Institute of Technology

March 14, 2023

Inorganic Scintillators for HEP

- **Precision photons and electrons enhance HEP discovery potential.**
- **Crystal performance well understood:**
  - **Best possible energy and position resolution;**
  - **Good e/γ identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout.**
- **Challenges at future HEP Experiments:**
  - **Rad-hard LYSO:Ce/LuAG:Ce for HL-LHC and FCC-hh;**
  - **Ultrafast BaF_2:Y/Lu_2O_3:Yb to break the ps timing barrier and for ultrafast calorimetry;**
  - **Cost-effective crystals for the proposed Higgs factory.**

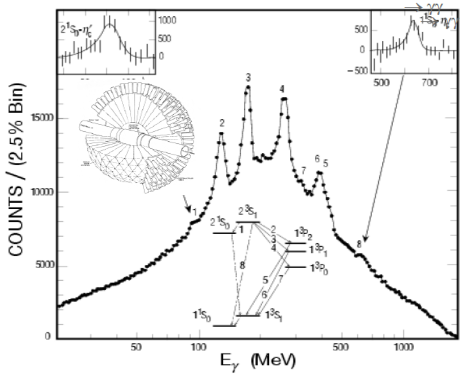
arXiv: 2203.06731 and arXiv: 2203.06788

Crystal Calorimetry Physics

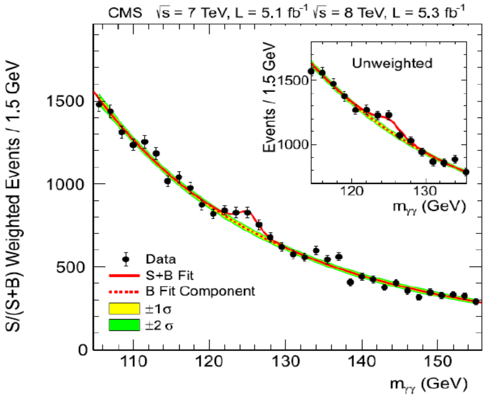
Charmonium system observed by CB through Inclusive photons

Higgs -> γγ by CMS through reconstructing photon pairs

CB NaI(Tl)

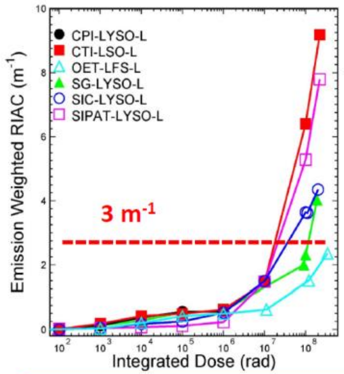


CMS PWO

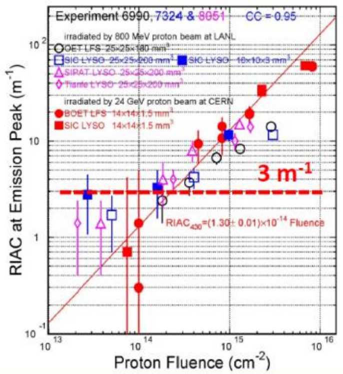


LYSO:Ce Crystals for CMS BTL

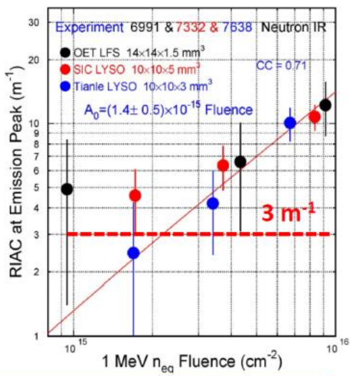
NIM A **824** (2016) 726-728



IEEE TNS **64** (2017) 665-672 , **65** (2018) 1018-1024



IEEE TNS **67** (2020) 1086-1092



Crystals damaged by both proton and neutron. Damage by proton is larger than that from neutrons because of ionization energy loss in addition to displacement and nuclear breakup

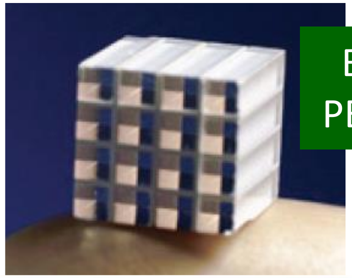
Inorganic Scintillators for Imaging

TNS 65 (2018) 2097; NIM A 940 (2019) 223; TNS 67 (2020) 1086

- **Pixelized detector is standard in medical industry. Laser slicing & micropore provide excellent coverage and position resolution.**
- **Ultrafast scintillators are needed for GHz Hard X-Ray Imaging at Future FEL facilities.**

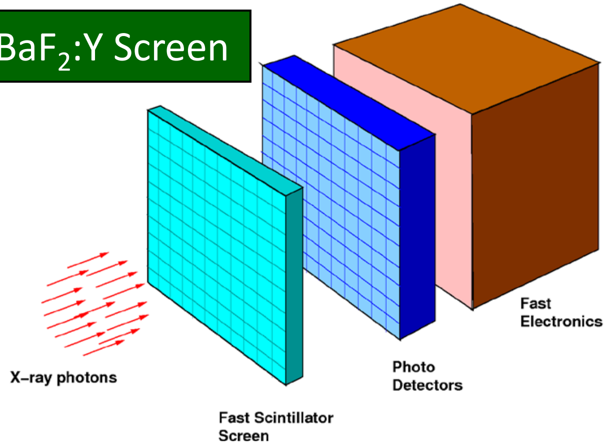
Performance	Type I imager	Type II imager
X-ray energy	**up to 30 keV**	**42-126 keV**
Frame-rate/inter-frame time	**0.5 GHz / 2 ns**	**3 GHz / 300 ps**
Number of frames per burst	≥ 10	10 - 30
X-ray detection efficiency	above 50%	above 80%
Pixel size/pitch	**≤ 300 µm**	**< 300 µm**
Dynamic range	10^3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

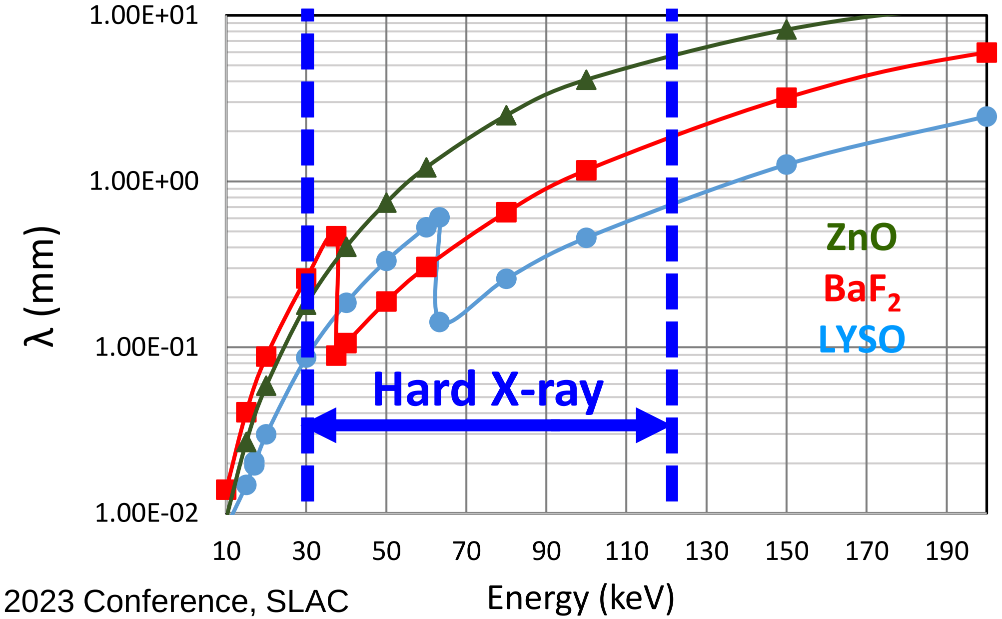
- **Detection efficiency for hard X-ray requires bulk detector; 2 ns and 300 ps inter-frame time requires ultrafast sensor.**



BGO pixels for PET: 1x1x10 mm

BaF_2:Y Screen





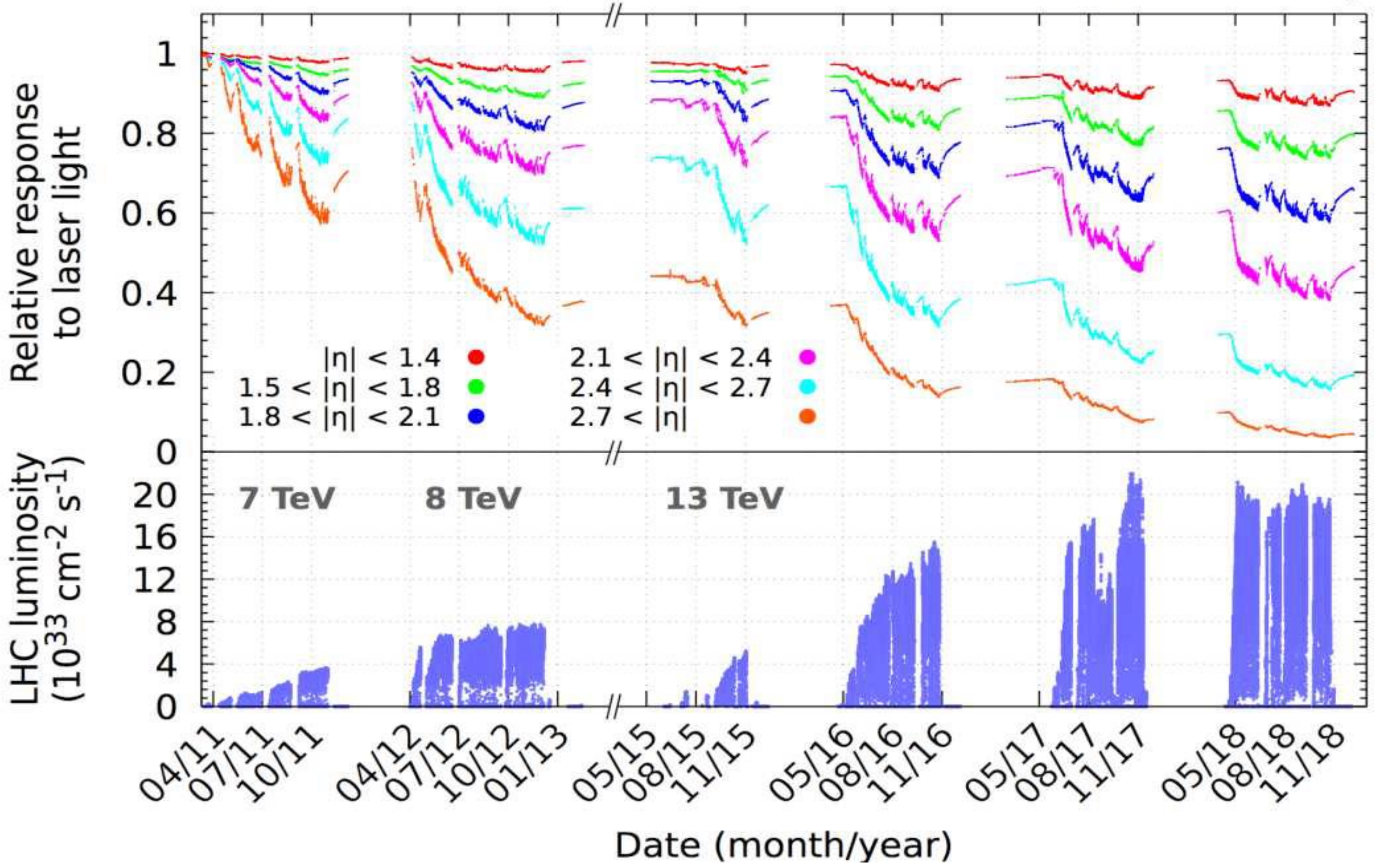
2019 DOE Basic Research Needs Study Priority Research Directions for Calorimetry

- Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements;
- Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments;
- Develop ultrafast media to improve background rejection in calorimeters and particle identication detectors.

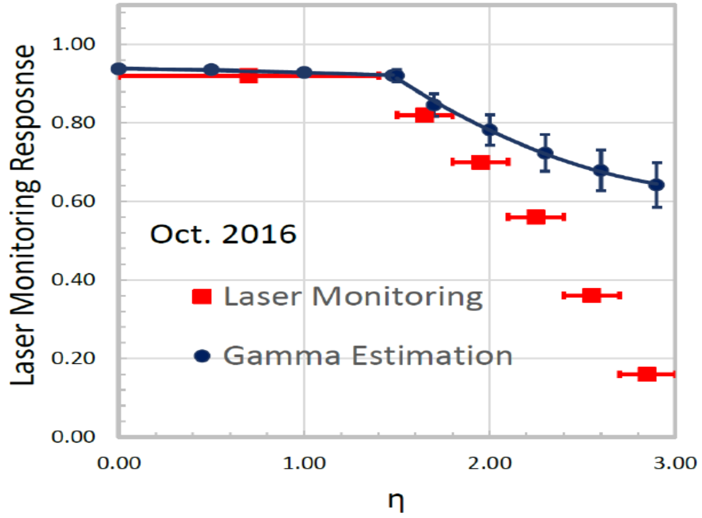
DOE 2019: https://www.osti.gov/servlets/purl/1659761
ECFA 2021: https://cds.cern.ch/record/2784893
Snowmass 2021: https://arxiv.org/abs/2209.14111
Fast/ultrafast, radiation hard and cost-effective inorganic scintillators

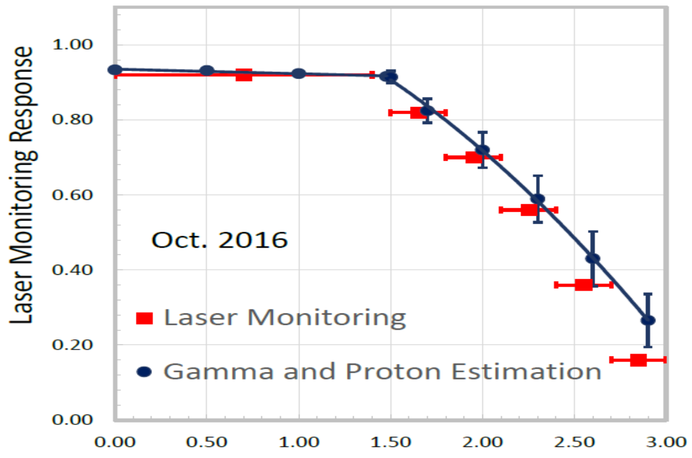
Challenge: Radiation Damage at LHC

F. Ferri, Calor 2022, https://indico.cern.ch/event/847884/timetable/#20220515



http://www.hep.caltech.edu/~zhu/talks/ryz_161028_PWO_mon.pdf





Use materials with monotonic damage: BaF_2, CsI, LYSO:Ce, LuAG:Ce

Neutron damage?

Expected Radiation for CMS ECAL

CMS Barrel/Endcaps: 4.8/68 Mrad, 2.5/21 $\times 10^{13}$ p/cm^2 & 3.2/24 $\times 10^{14}$ n_{eq}/cm^2

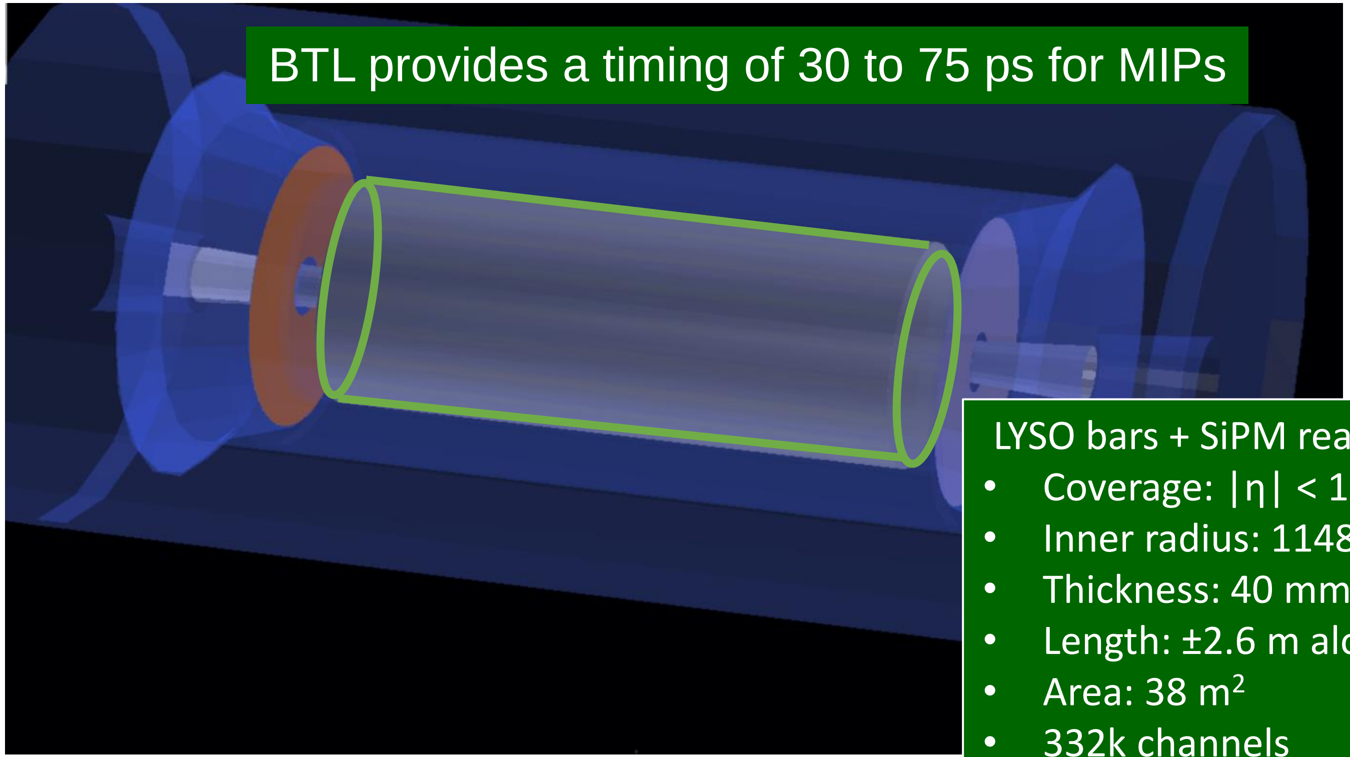
CMS MTD	η	n_{eq} (cm^{-2})	n_{eq} Flux (cm^{-2}s^{-1})	Proton (cm^{-2})	p Flux (cm^{-2}s^{-1})	Dose (Mrad)	Dose rate (rad/h)
Barrel	0.00	2.5E+14	2.8E+06	2.2E+13	2.4E+05	2.7	108
Barrel	1.15	2.7E+14	3.0E+06	2.4E+13	2.6E+05	3.8	150
Barrel	**1.45**	**2.9E+14**	**3.2E+06**	**2.5E+13**	**2.8E+05**	**4.8**	**192**
Endcap	1.60	2.3E+14	2.5E+06	2.0E+13	2.2E+05	2.9	114
Endcap	2.00	4.5E+14	5.0E+06	3.9E+13	4.4E+05	7.5	300
Endcap	2.50	1.1E+15	1.3E+07	9.9E+13	1.1E+06	26	1020
Endcap	**3.00**	**2.4E+15**	**2.7E+07**	**2.1E+14**	**2.3E+06**	**68**	**2700**

Much higher at FCC-hh: up to 0.1/500 Grad and 3/500 x10^{16} n_{eq}/cm^2 at EMEC/EMF

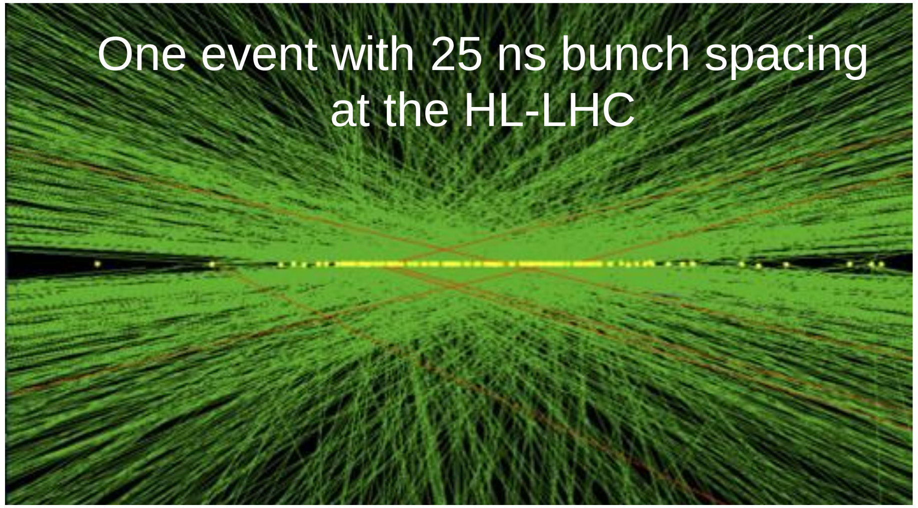
Aleksa *et al.*, Calorimeters for the FCC-hh CERN-FCCPHYS-2019-0003, Dec 23, 2019

CMS Barrel Timing Detector for HL-LHC

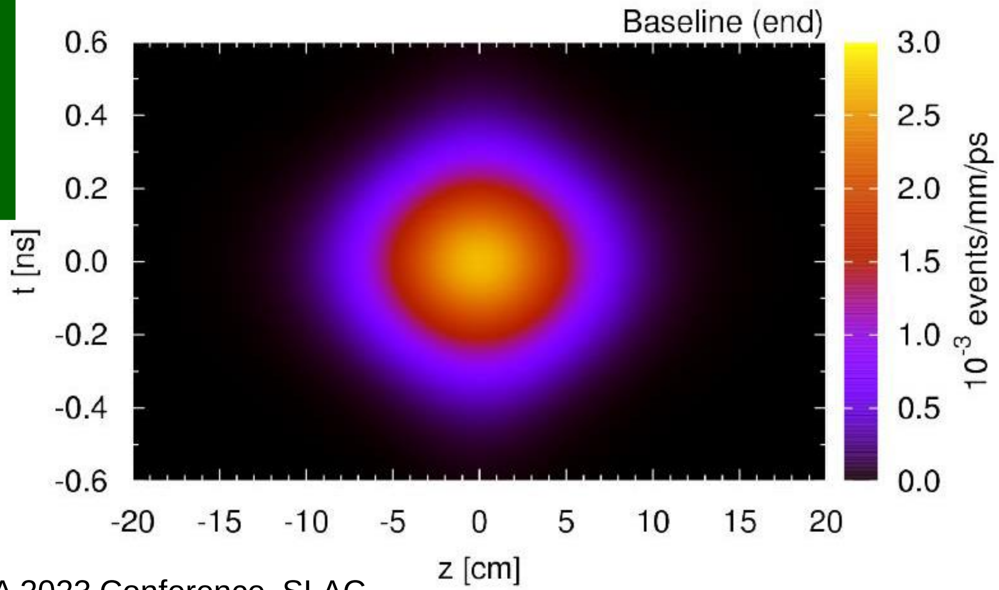
To face challenge of pileup at HL-LHC by using 4D tracking in space and time

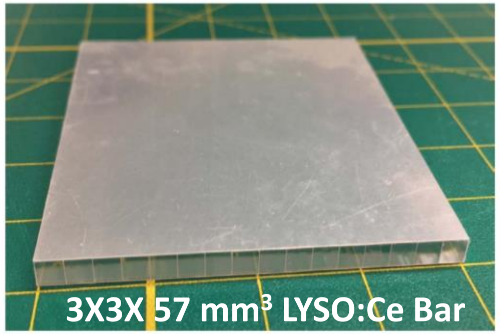


BTL provides a timing of 30 to 75 ps for MIPs

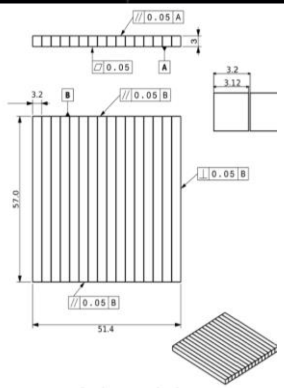


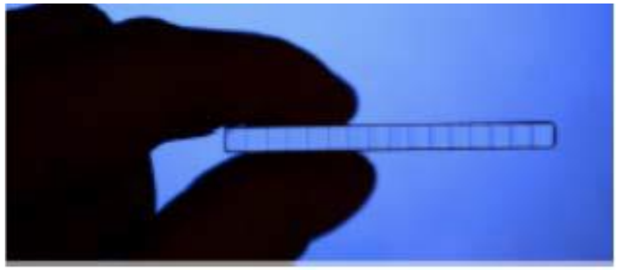
LYSO bars + SiPM readout
- Coverage: $|\eta| < 1.45$
- Inner radius: 1148 mm
- Thickness: 40 mm
- Length: ±2.6 m along z
- Area: 38 m^2
- 332k channels





3X3X 57 mm^3 LYSO:Ce Bar

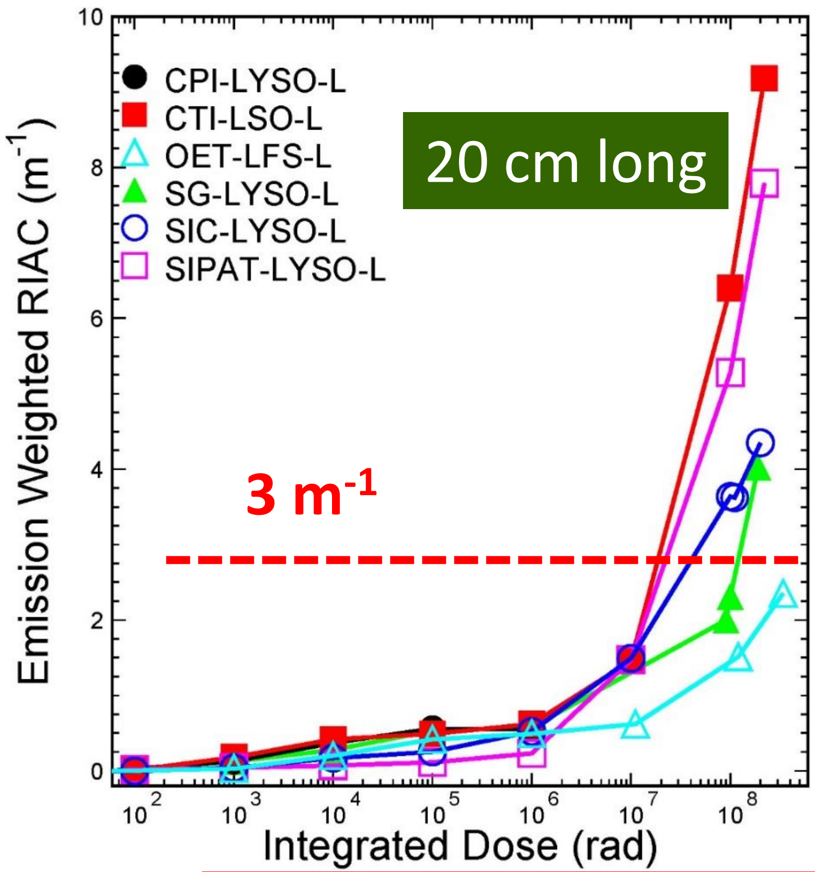


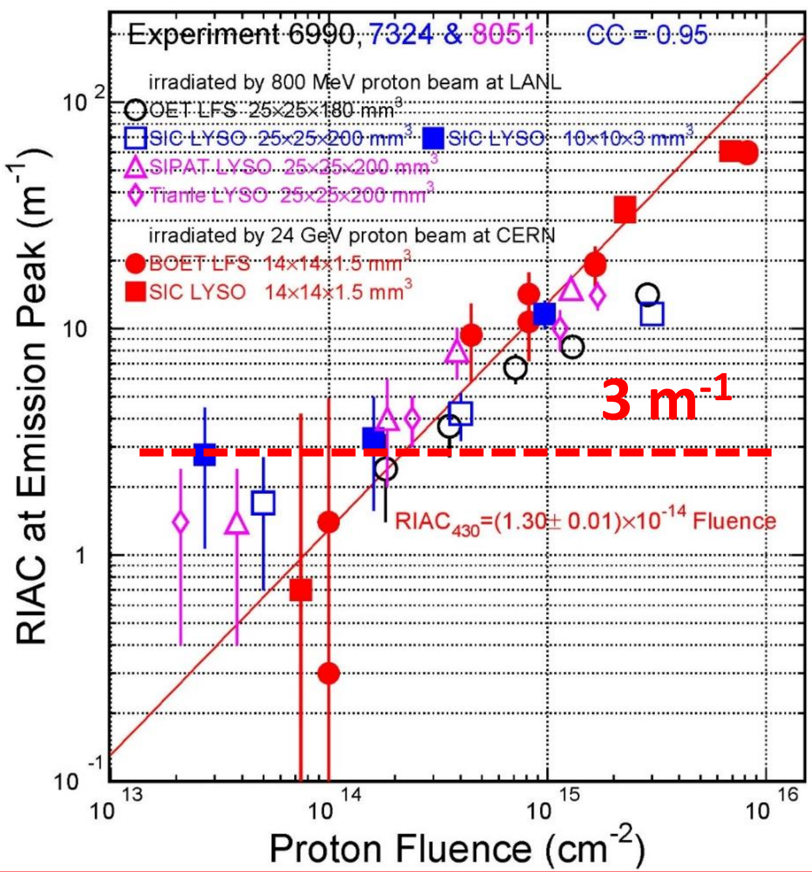


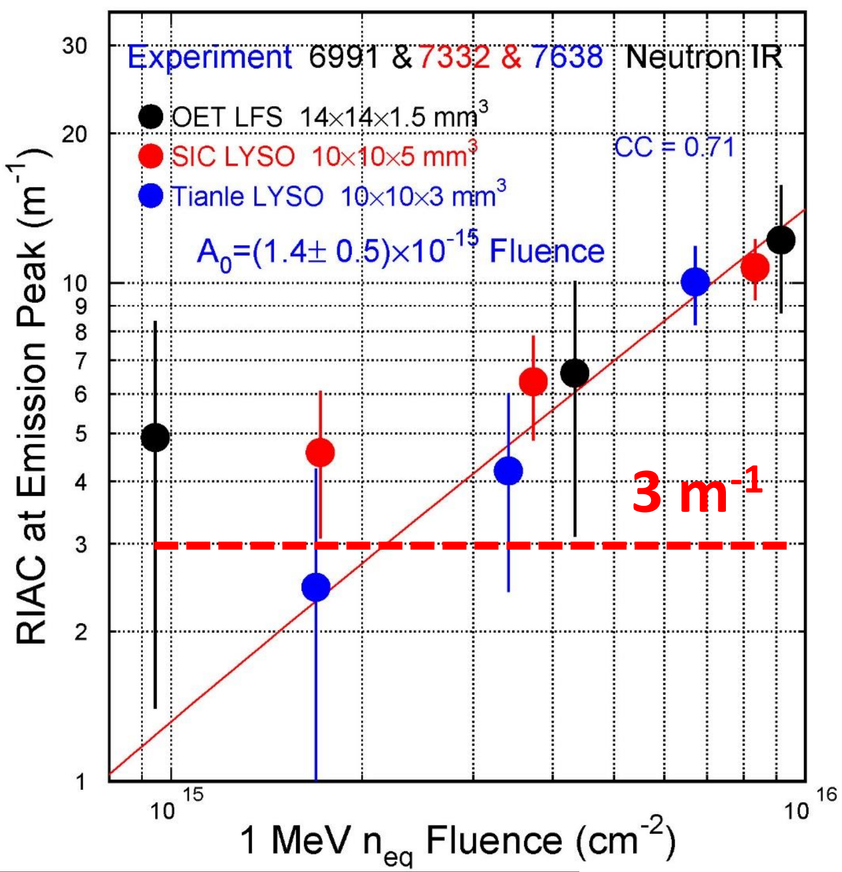
LYSO:Ce Radiation Hardness

IEEE TNS 63 (2016) 612-619

CMS LYSO spec: RIAC < 3 m^{-1} after 4.8 Mrad, 2.5 x 10^{13} p/cm^2 and 3.2 x 10^{14} n_{eq}/cm^2







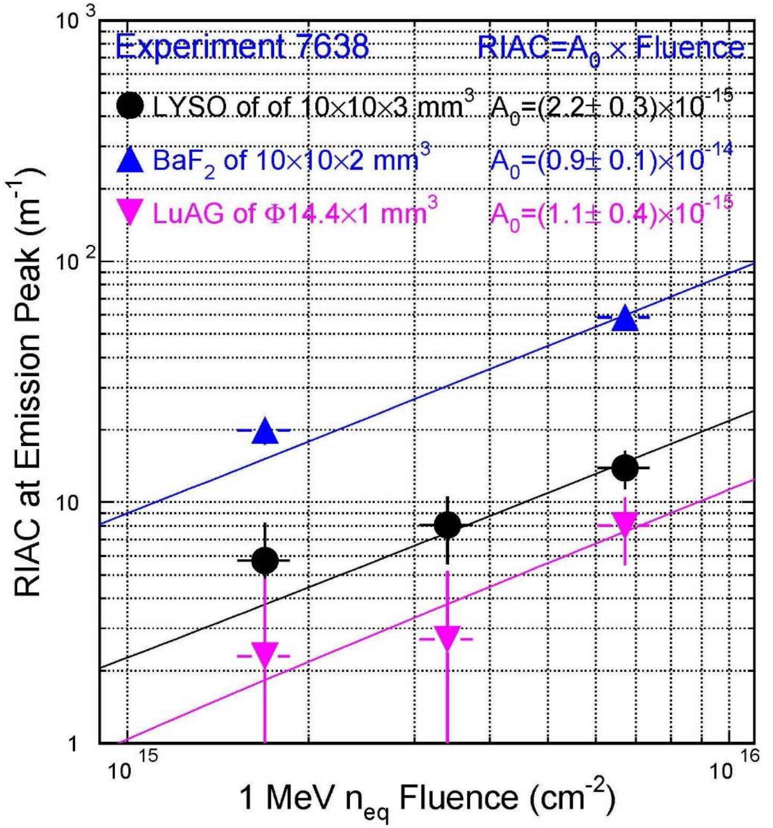
Damage induced by protons is larger than that from neutrons

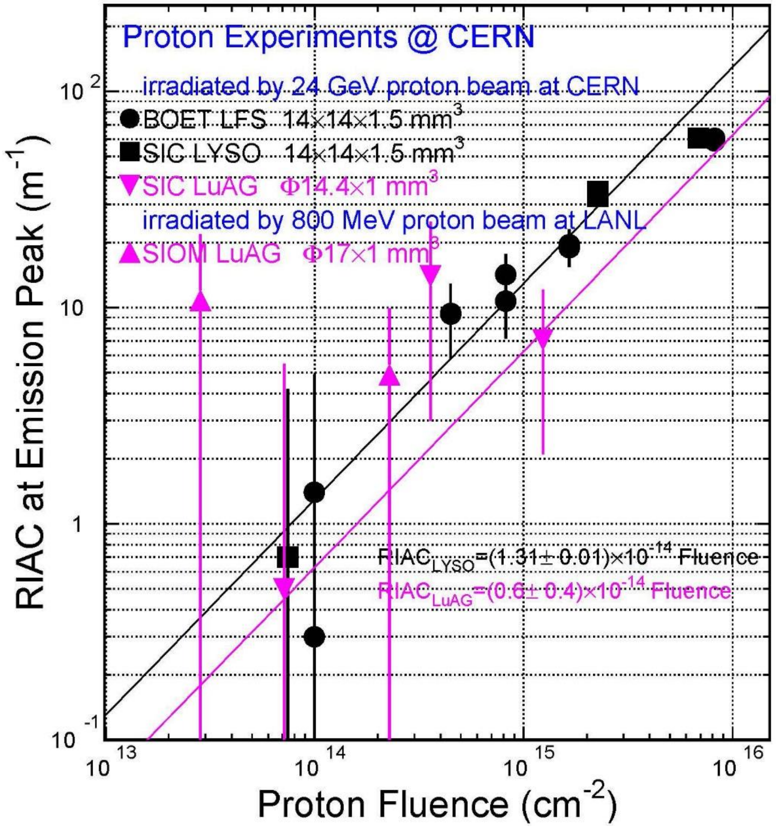
Due to ionization energy loss in addition to displacement and nuclear breakup

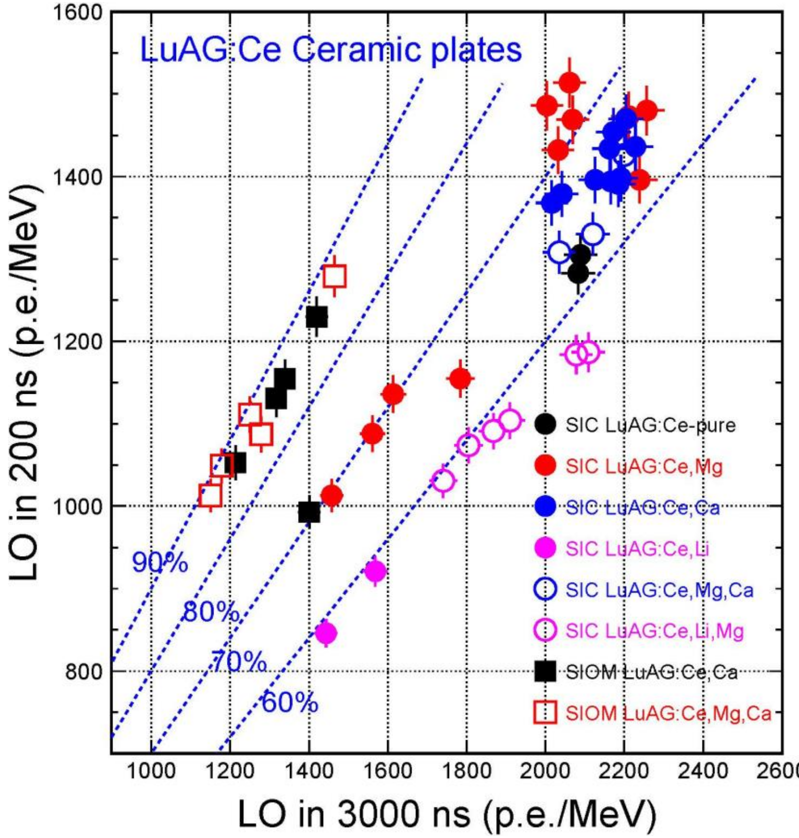
LuAG:Ce Ceramics Radiation Hardness

IEEE TNS 69 (2022) 181-186

LuAG:Ce ceramics show a factor of two smaller RIAC values than LYSO:Ce up to 6.7×10^{15} n_{eq}/cm^2 and 1.2×10^{15} p/cm^2, promising for FCC-hh





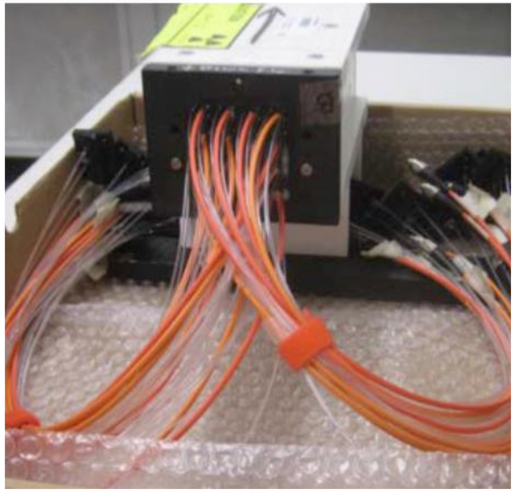


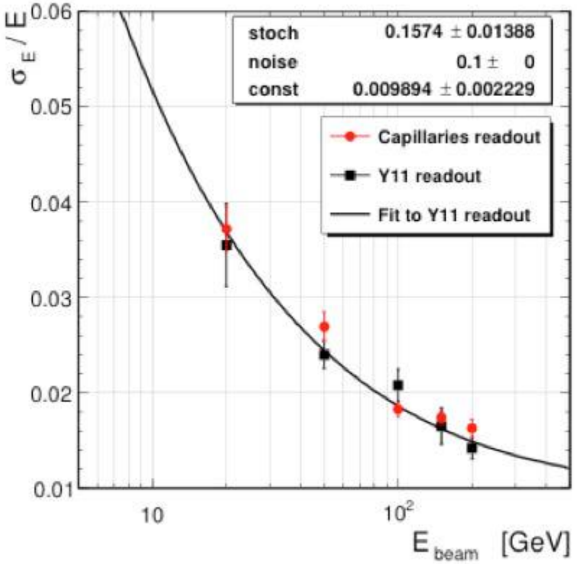
R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

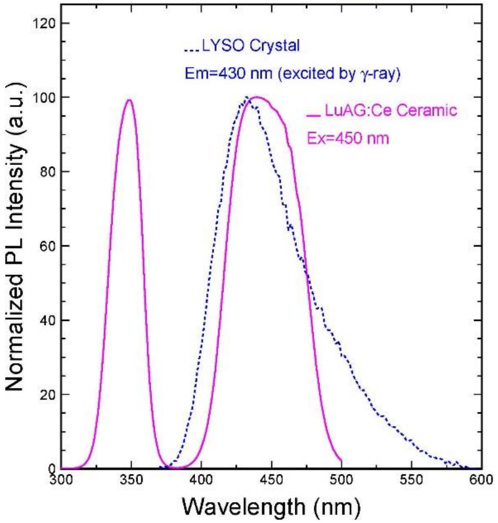
RADiCAL: LYSO/LuAG Shashlik ECAL

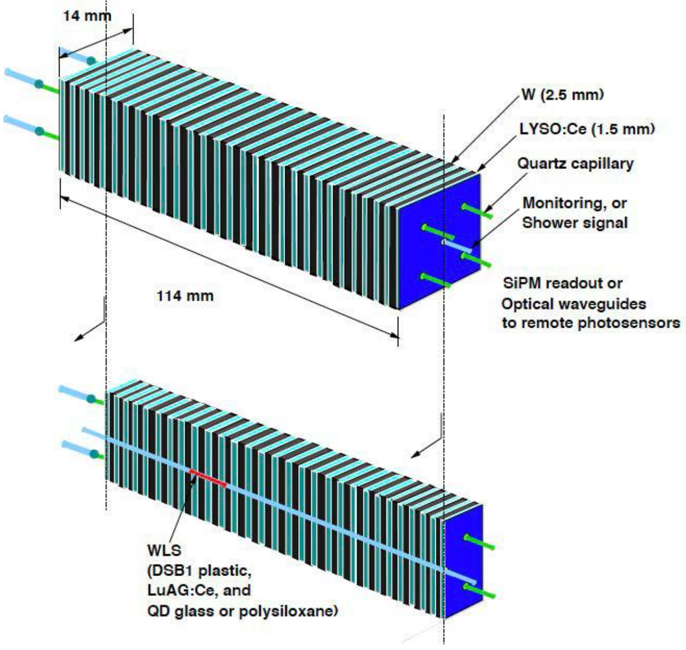
arXiv: 2203.12806 (N35-6)

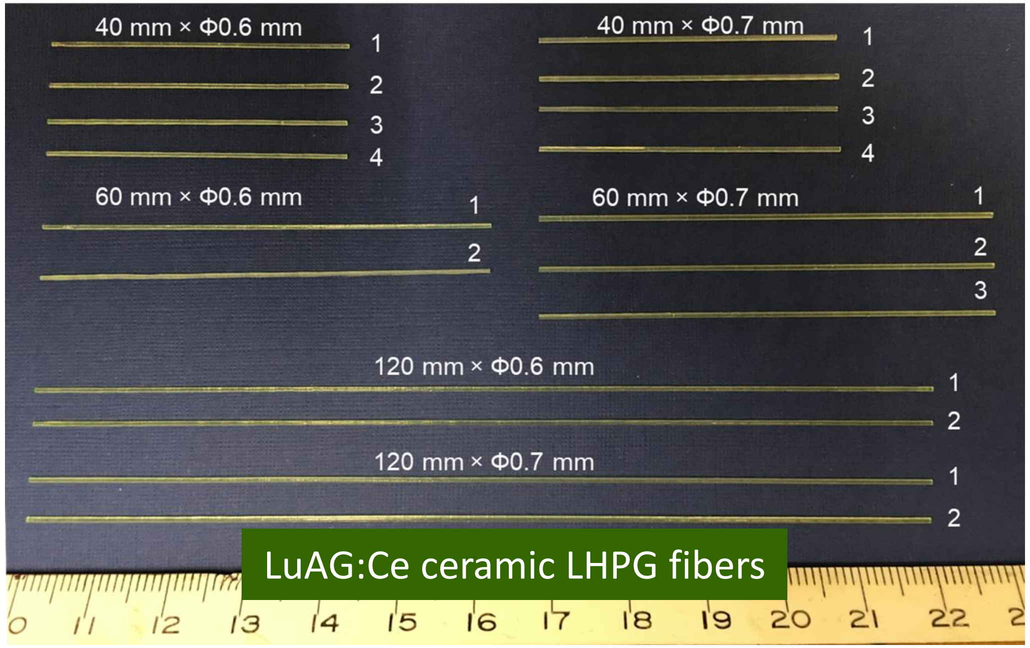
RADiation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission



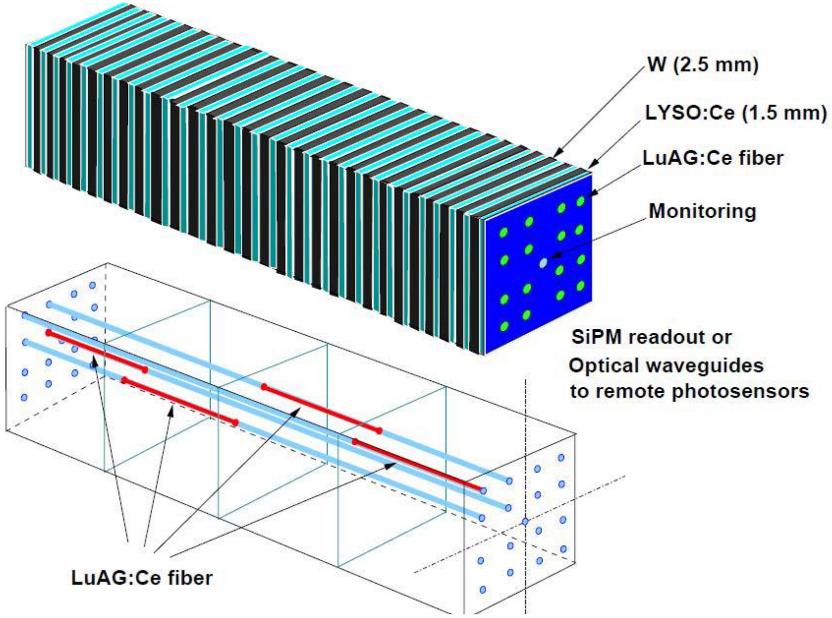




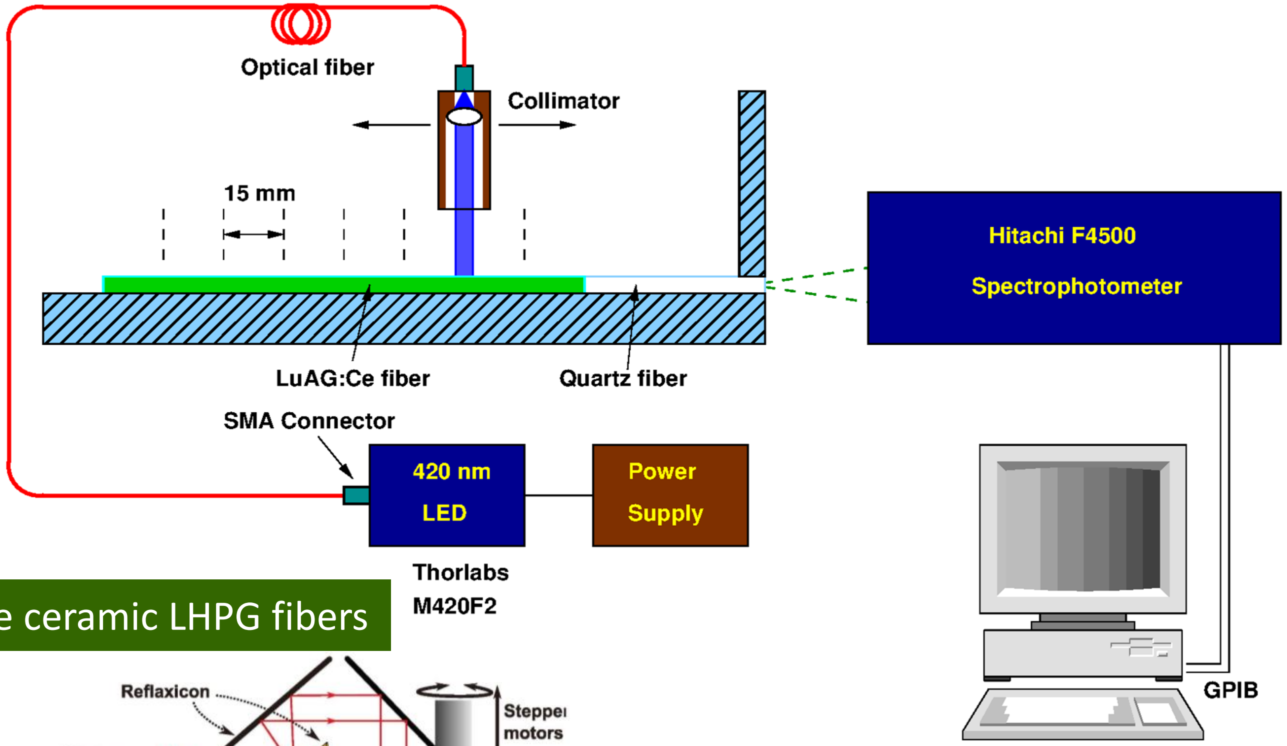


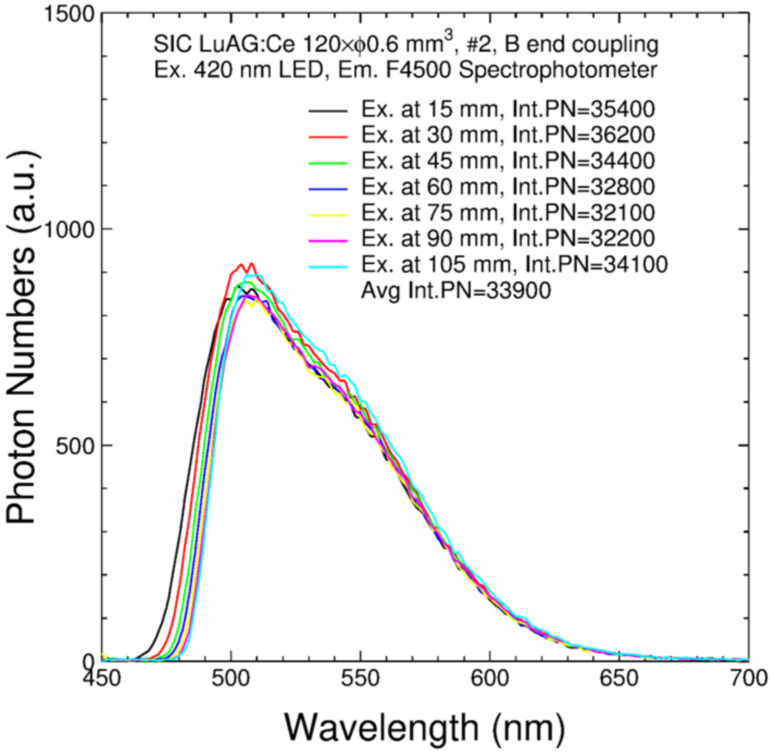


LuAG:Ce ceramic LHPG fibers

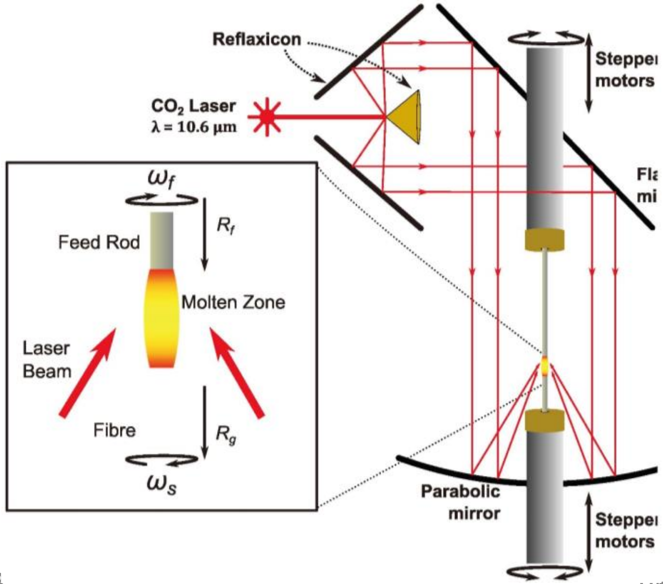


LuAG:Ce Fiber Light Output and Uniformity





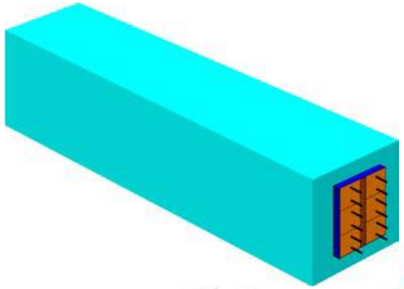
LuAG:Ce ceramic LHPG fibers



Excellent uniformity observed for Φ0.6 ×120 mm³ LuAG:Ce ceramic fibers excited by a 420 nm LED at different longitudinal location, with a solid coupling to a quartz fiber, mimicking its application in RADiCAL Calorimetry

Ultrafast BaF_2:Y Calorimeter for Mu2e-II

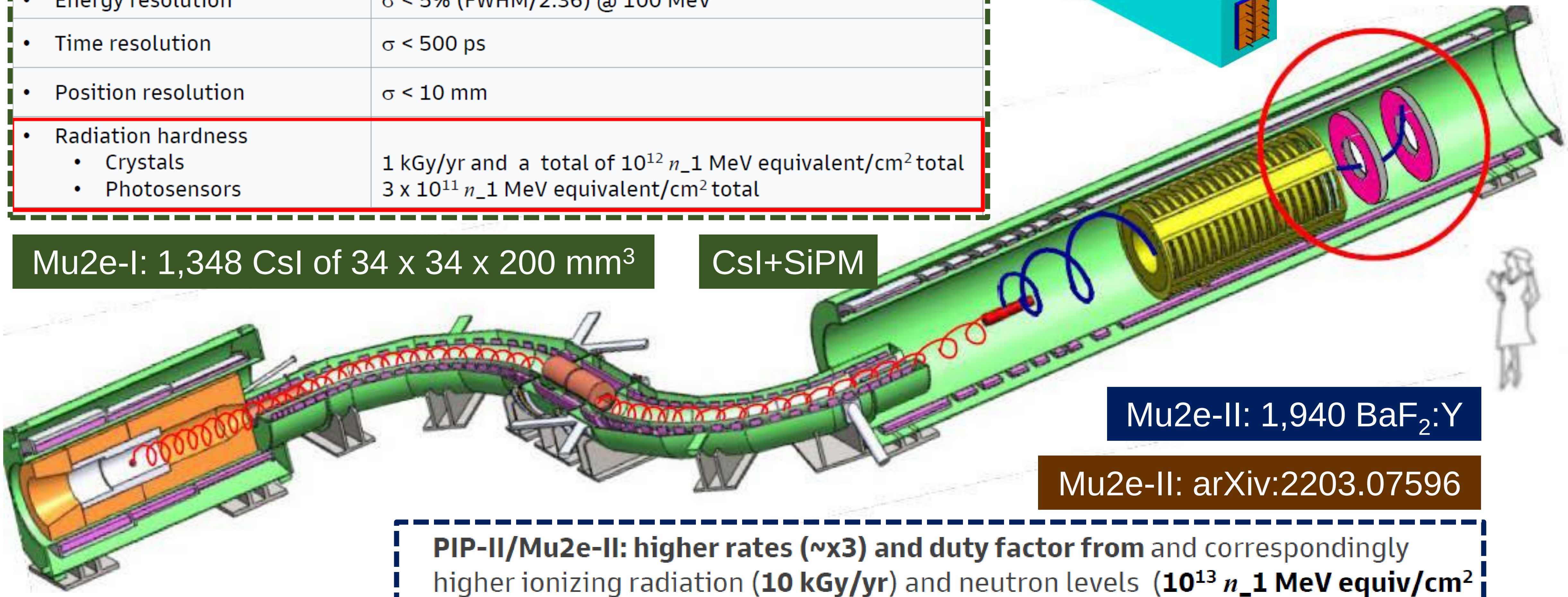
Use ultrafast material to mitigate pile-up



• Energy resolution	σ < 5% (FWHM/2.36) @ 100 MeV
• Time resolution	σ < 500 ps
• Position resolution	σ < 10 mm
• Radiation hardness • Crystals • Photosensors	 1 kGy/yr and a total of 10^{12} n_1 MeV equivalent/cm^2 total 3 x 10^{11} n_1 MeV equivalent/cm^2 total

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm^3

CsI+SiPM



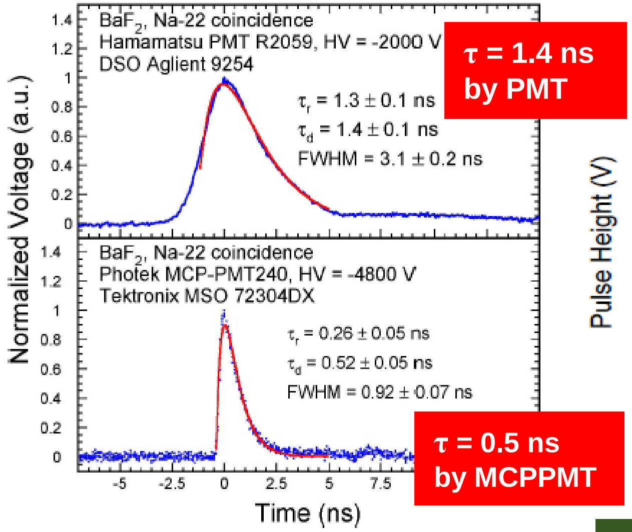
Mu2e-II: 1,940 BaF_2:Y

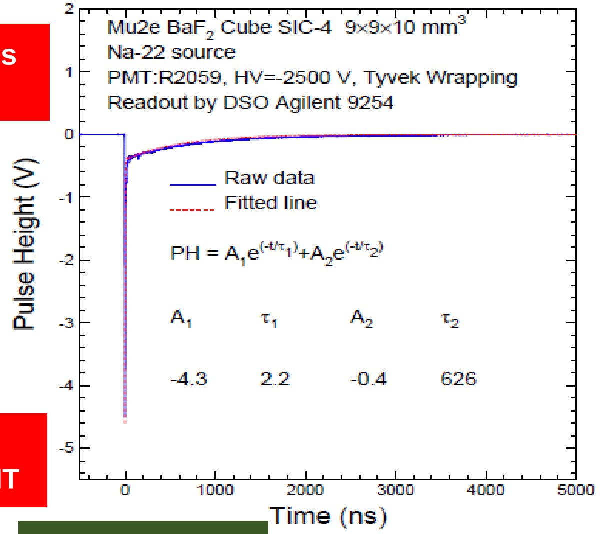
Mu2e-II: arXiv:2203.07596

PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm^2 total**), which are particularly important at the inner radius of disk 1

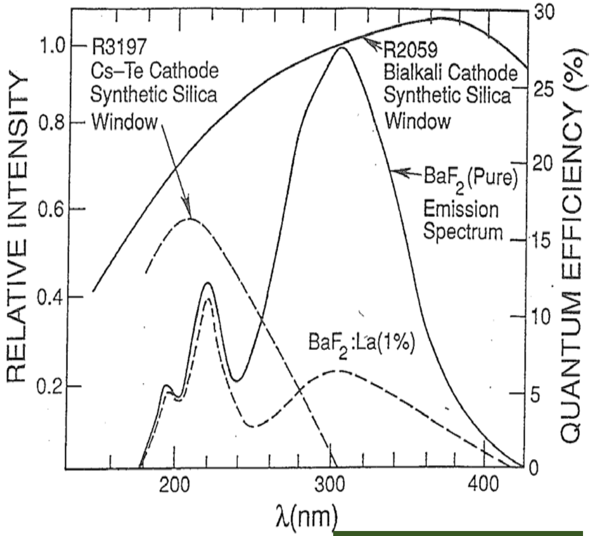
Ultrafast and Radiation Hard BaF_2

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



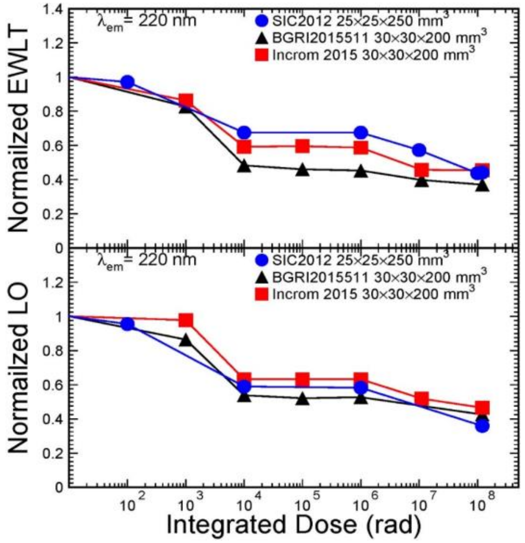


NIMA 340 (1994) 442-457

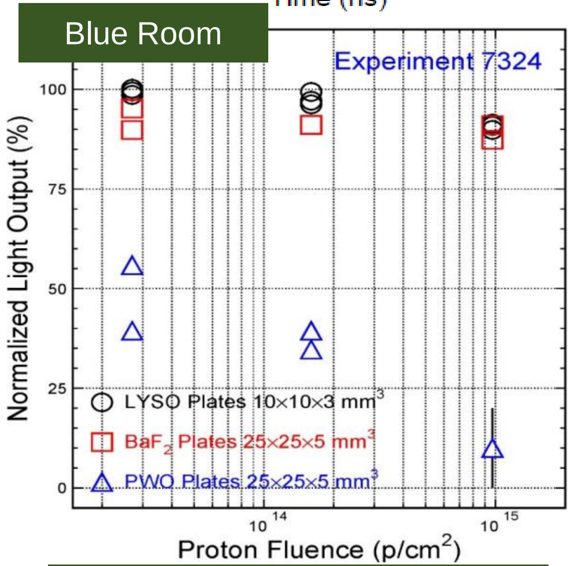


BaF₂ has an ultrafast scintillation component @ 220 nm with **0.5 ns** decay time and a much larger slow component @ 300 nm with 600 ns decay time.

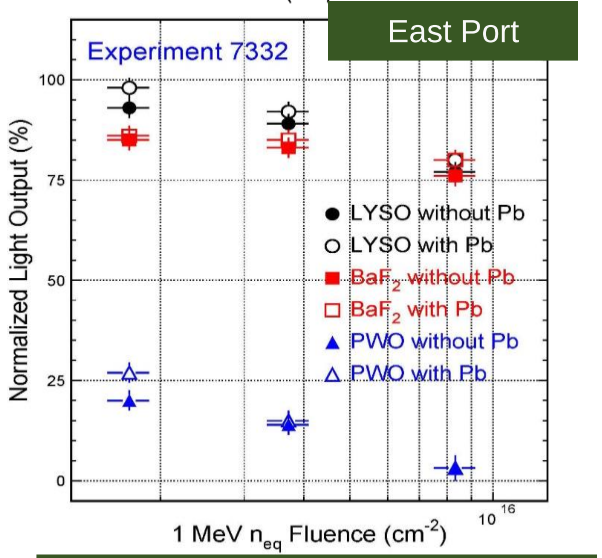
Slow suppression may be achieved by rare earth doping, and/or solar-blind photo-detectors



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



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



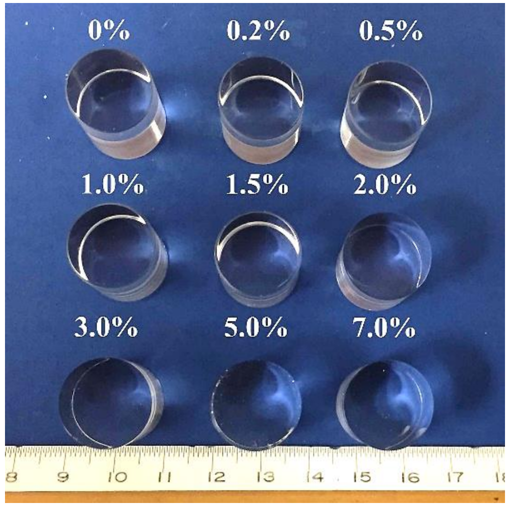
IEEE TNS **67** (2020) 1018-1024

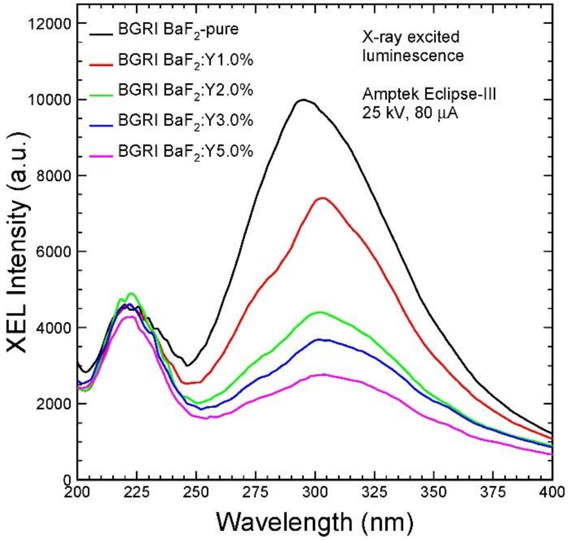
BaF_2 shows saturated damage from 10 krad to 100 Mrad, indicating good radiation resistance against ɣ-rays

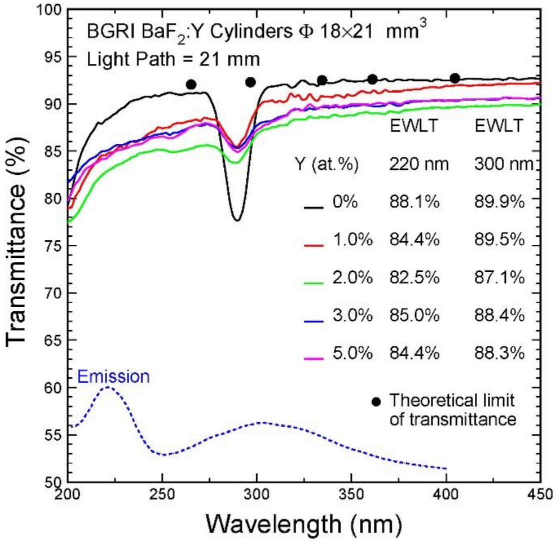
BaF_2 also survives after proton irradiation up to 9.7×10^{14} p/cm^2, and neutron irradiation up to 8.3×10^{15} n_{eq}/cm^2

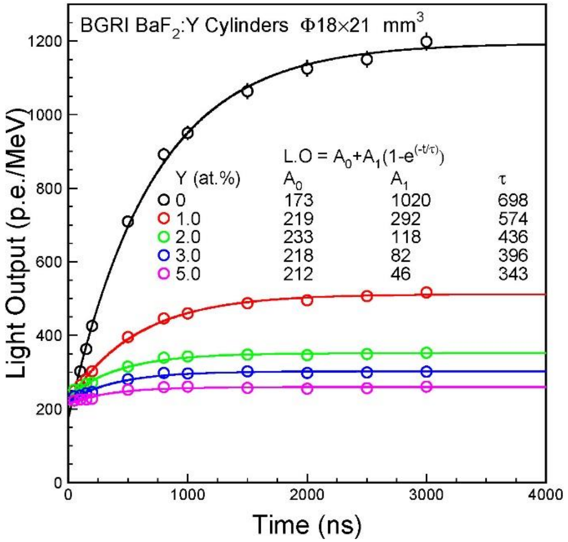
BaF_2:Y for Calorimetry & Imaging

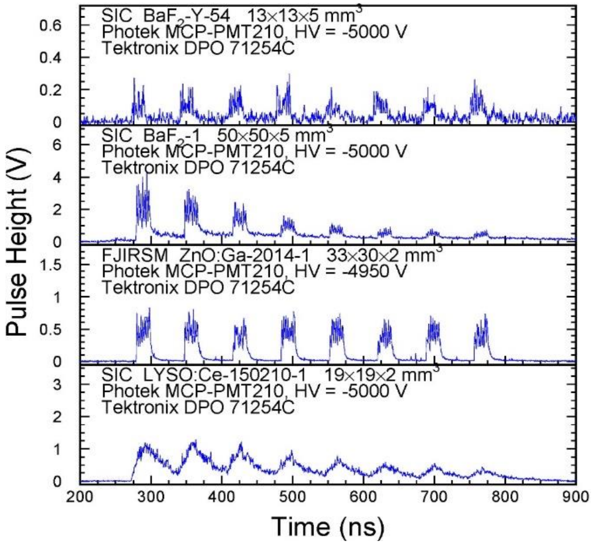
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

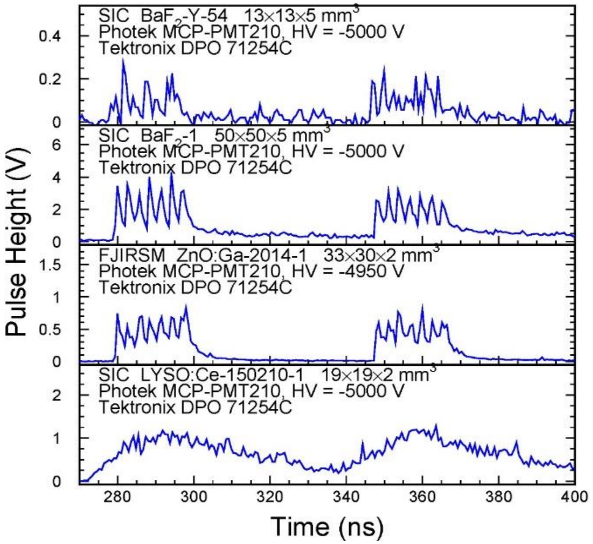


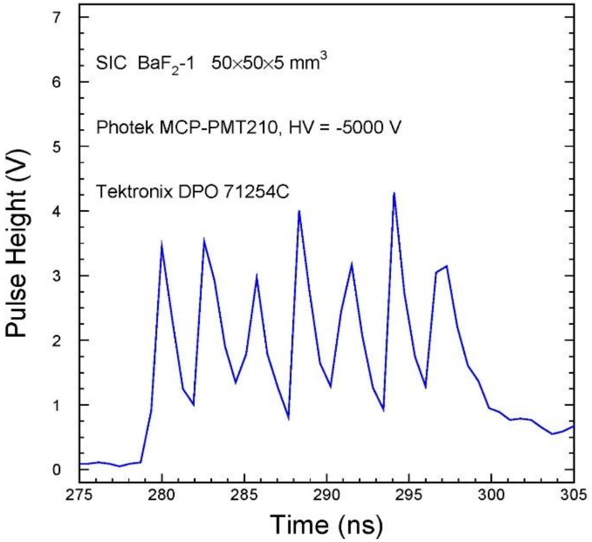








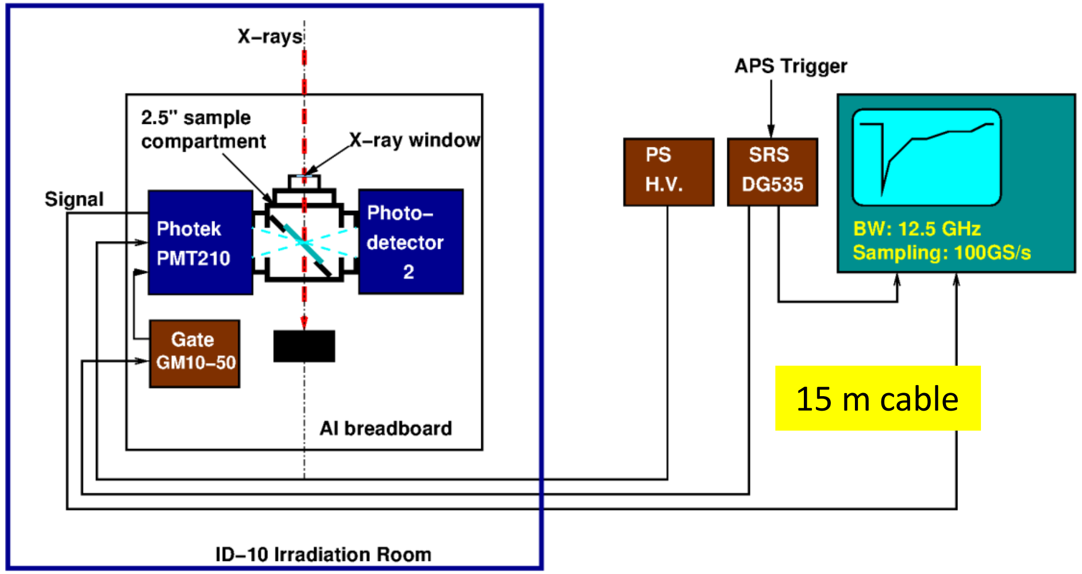


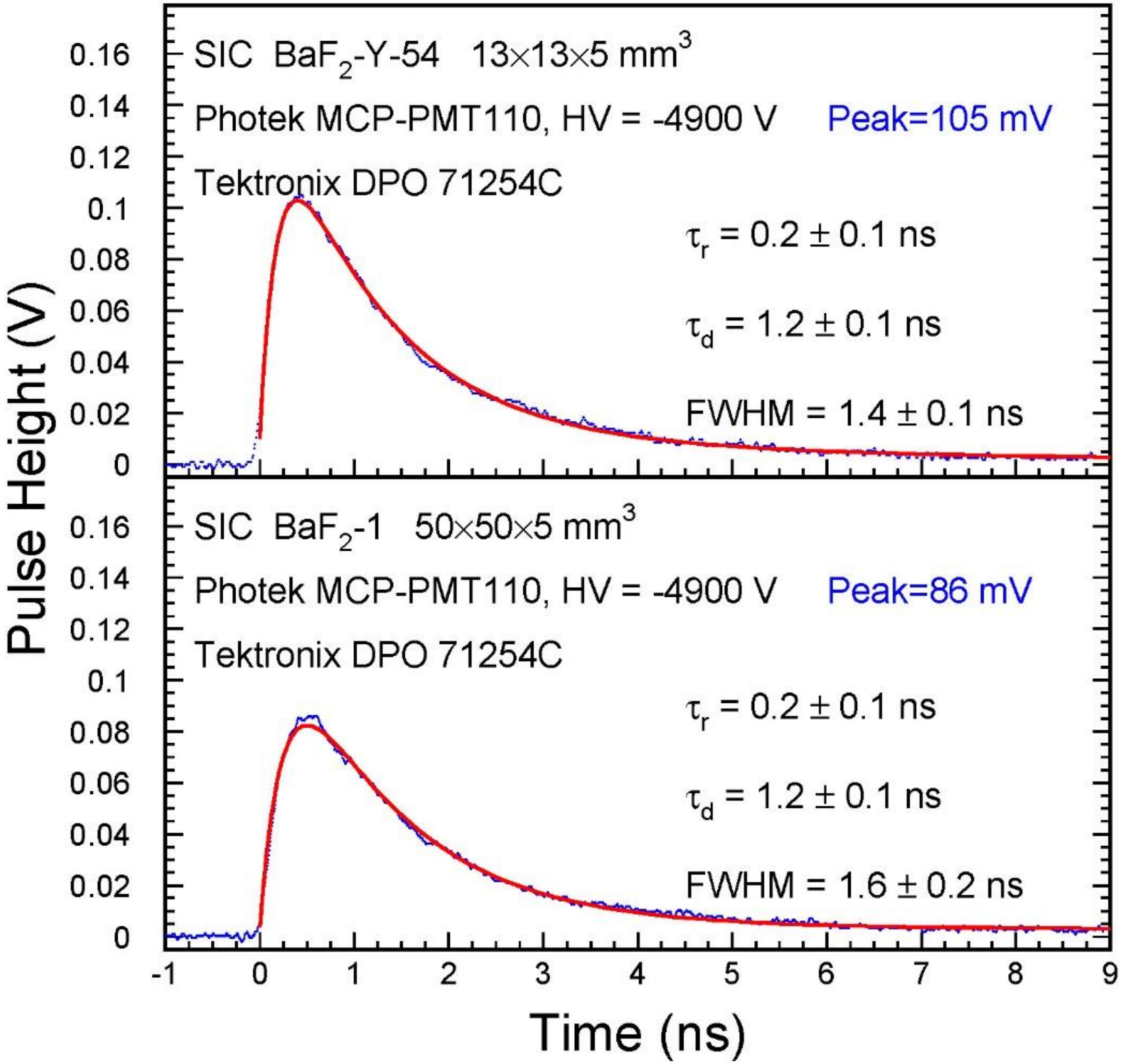


X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

A Puzzle of Long Decay Observed at APS

NIM A **940** (2019) 223–229

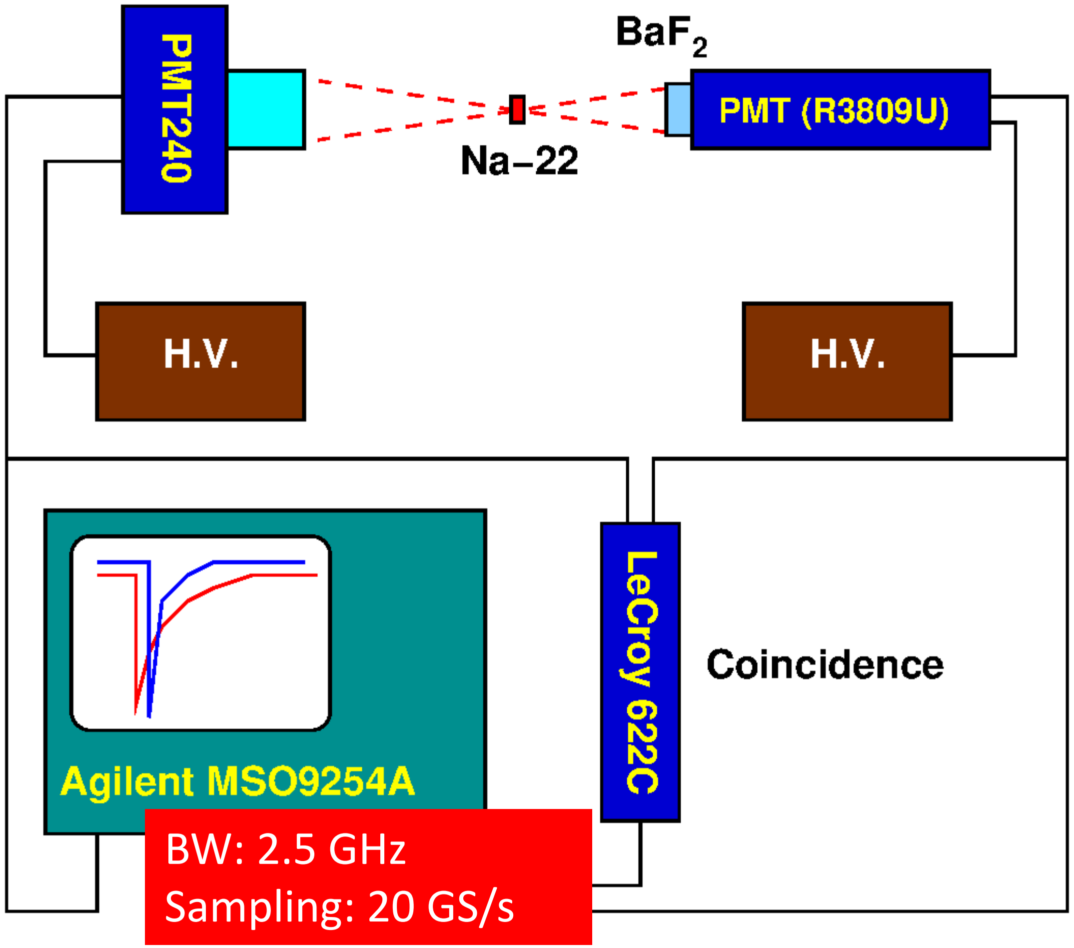




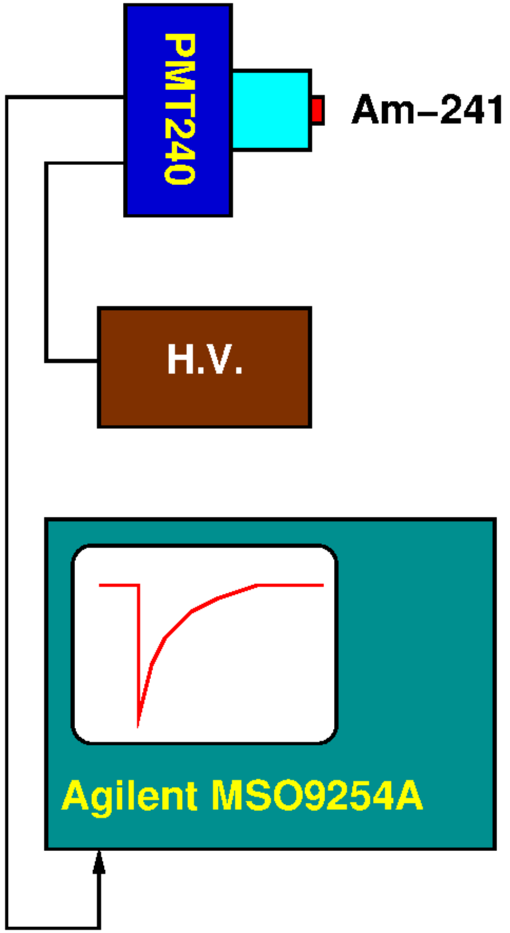
The decay time of BaF_2 measured at APS for septuplet X-ray bunches with 2.83 ns spacing is longer than 1 ns. This is suspected to be caused by the 15 m long cable used between the MCP-PMT and the MSO

An MCP-PMT 240-Based Test Bench

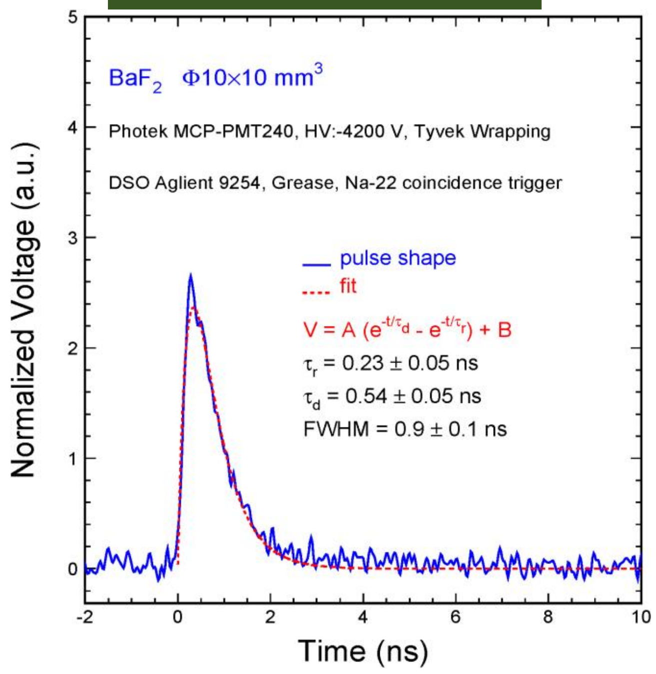
Na-22 Coincidence Trigger



Am-241 Self Trigger



P. Rodny, CRC Press,
Boca Raton, FL, USA, 2020



Fitting:

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

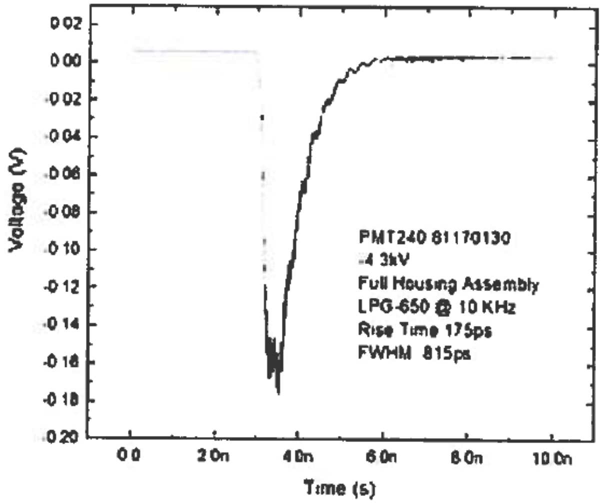
B: background noise
or very slow component,
τ_r: rise time, τ_d: decay time.

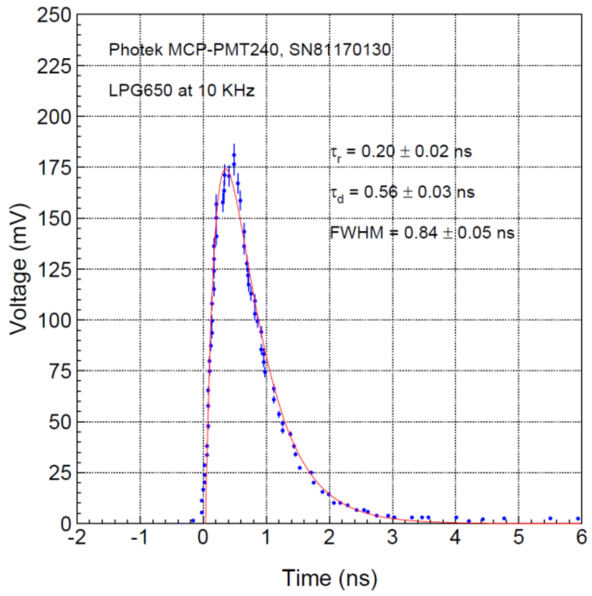
Rise, decay and FWHM obtained by fitting temporal response

MCP-PMT 240 Temporal Response

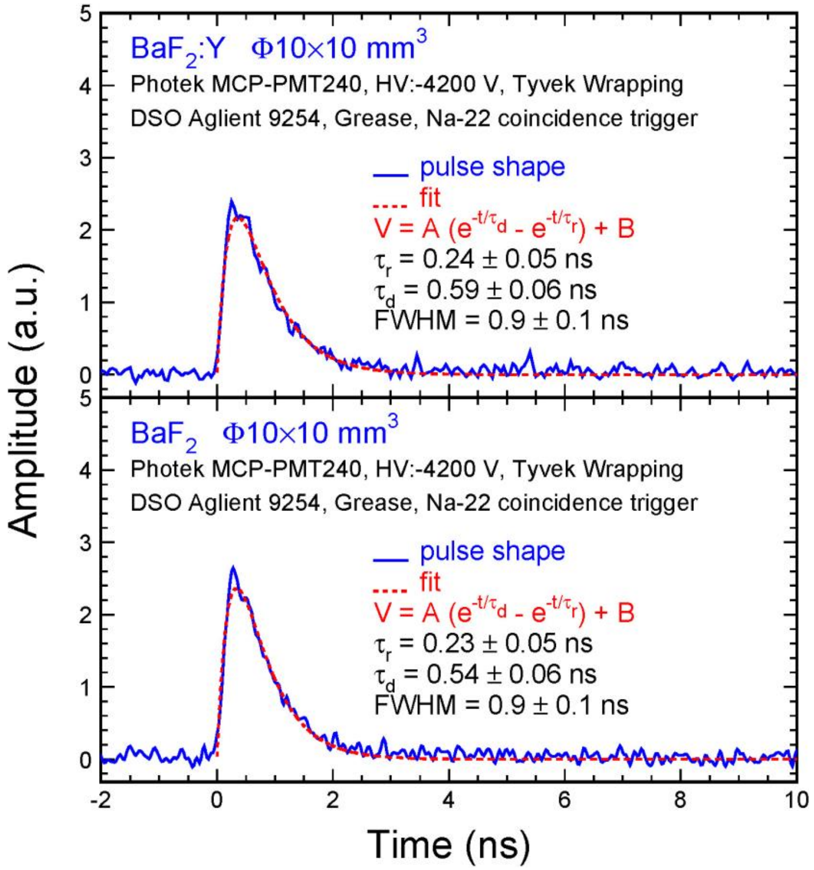
A fit to response of the Photek MCP-PMT 240 for pico-second laser pulses shows both the rise and FWHM consistent with the specification

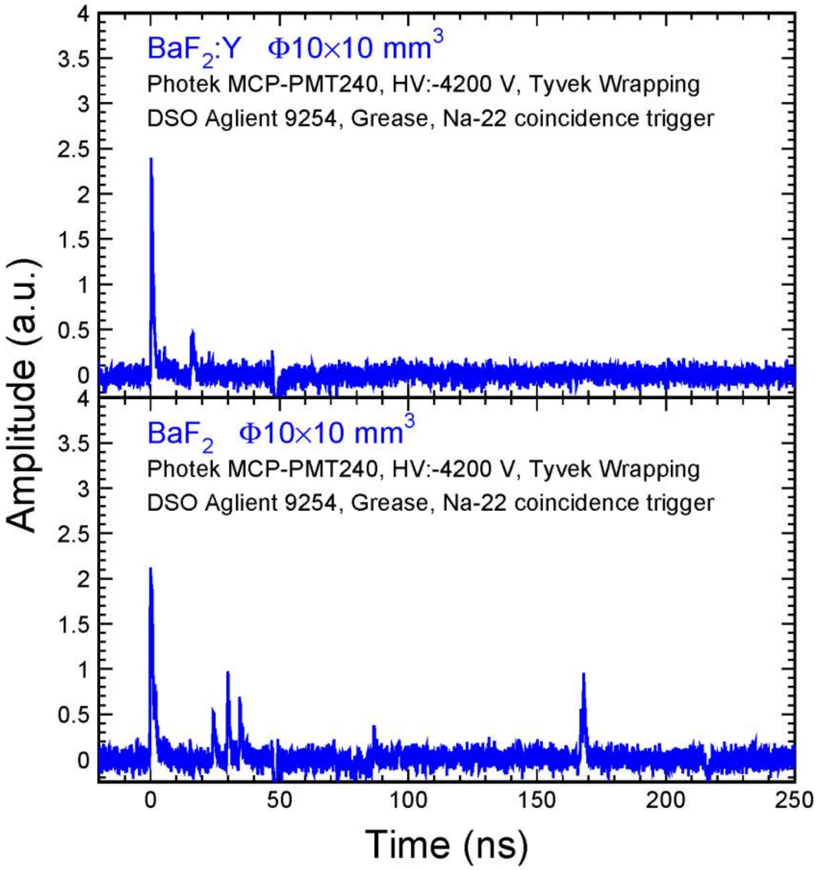
Photodetector	Active diameter (mm)	Spectral range (nm)	Peak Sen. (nm)	Gain	Rise time (ns)	FWHM (ns)
Photek MCP-PMT 240	**40**	**160-850**	**280-450**	**1×10^6**	**0.180**	**0.82**
Hamamatsu MCP-PMT R3809U-50	**11**	**160-850**	**430**	**3×10^5**	**0.160**	**0.30**
Photek MCP-PMT 110	10	160-850	280-450	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	

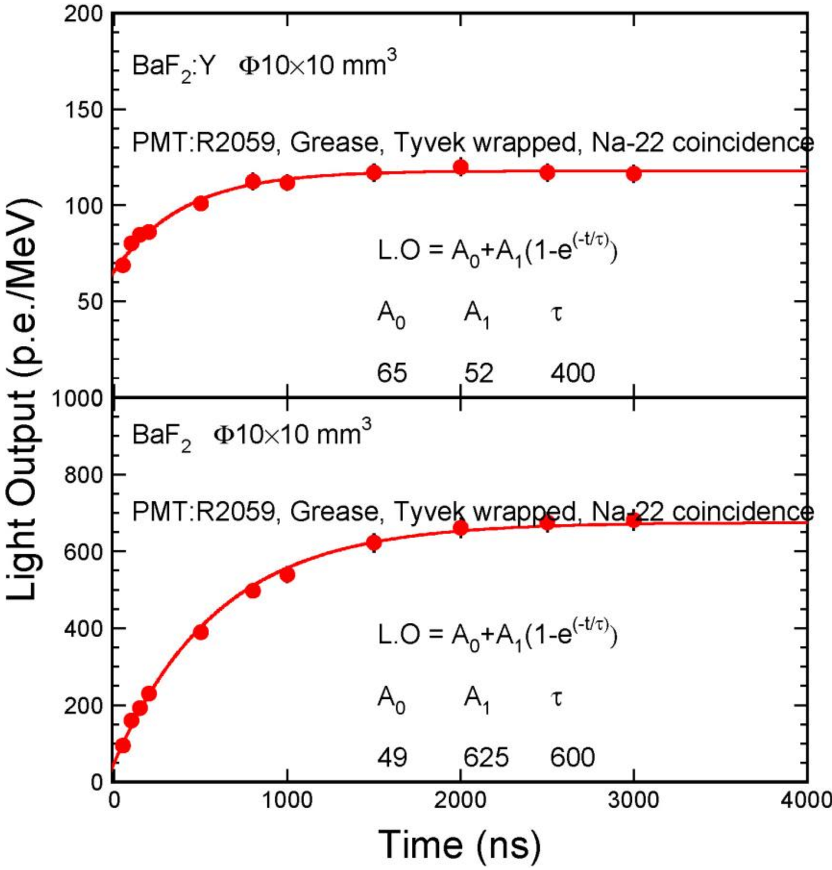




Temporal Response: BaF_2 & BaF_2:Y

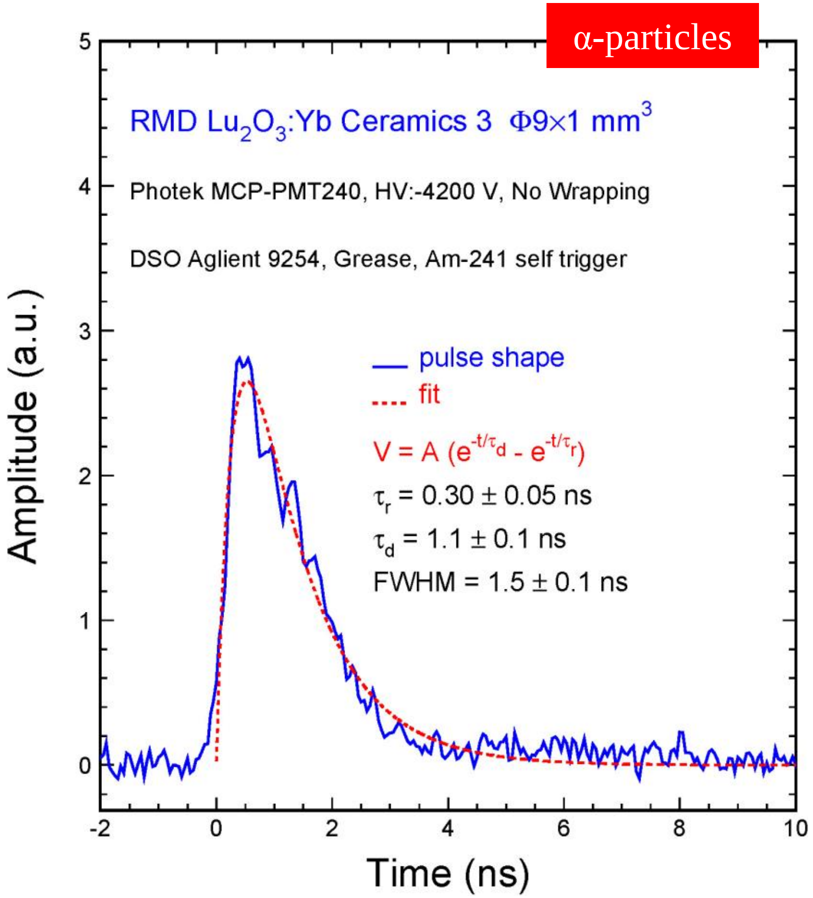


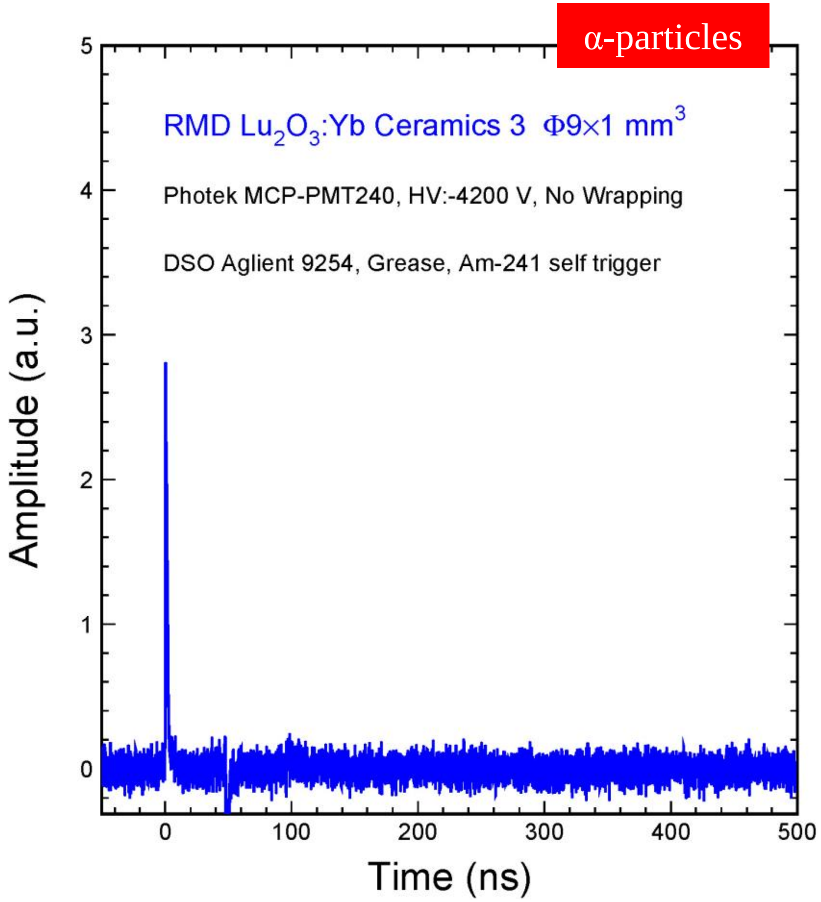


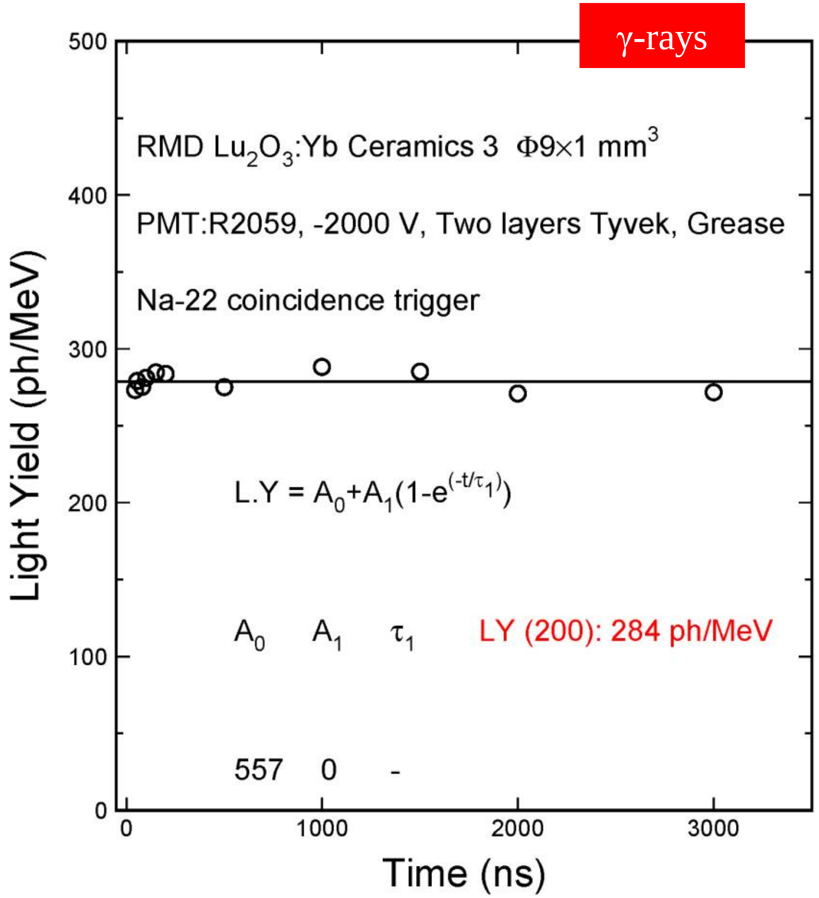


Ultrafast response of 0.2/0.6/0.8 ns observed for BaF_2 and BaF_2:Y crystals
The response is consistent with the Photek MCP-PMT 240 specification

Temporal Response: Lu_2O_3:Yb Ceramics

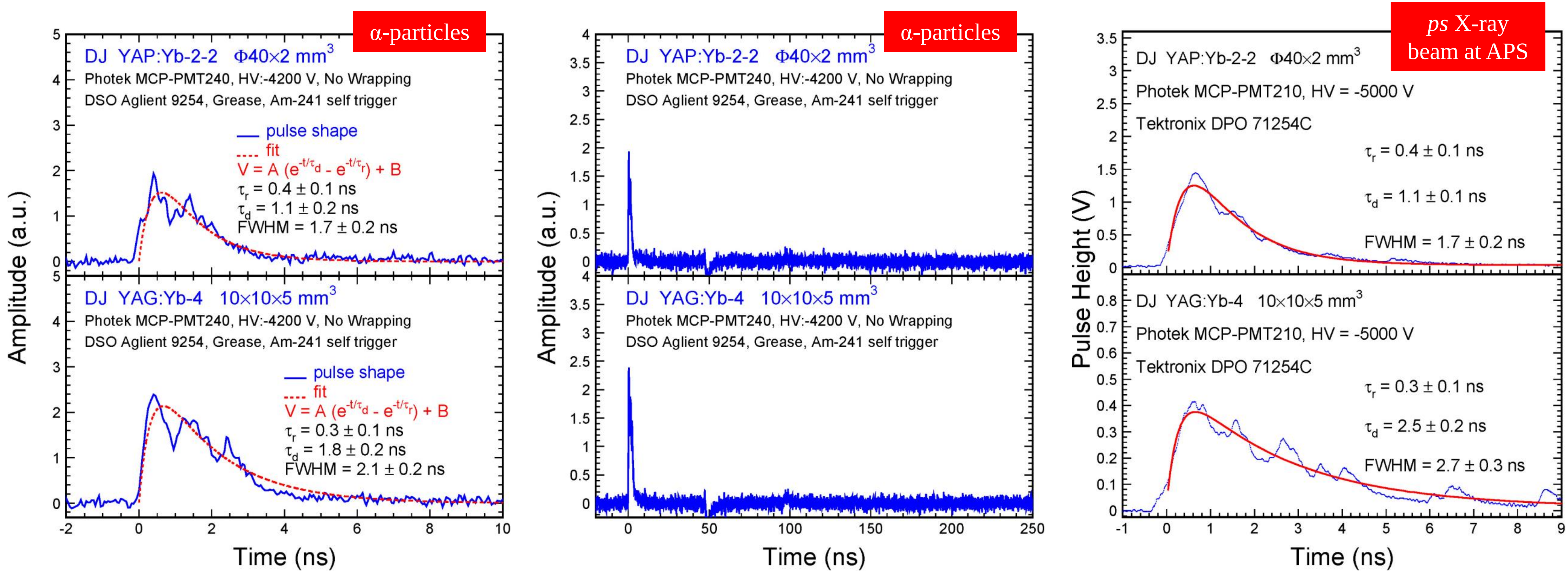






Lu_2O_3:Yb ceramic of 9.4 g/cc shows an ultrafast decay time of **1.1 ns** by Am-241 with negligible slow component observed in integrated light output measurement

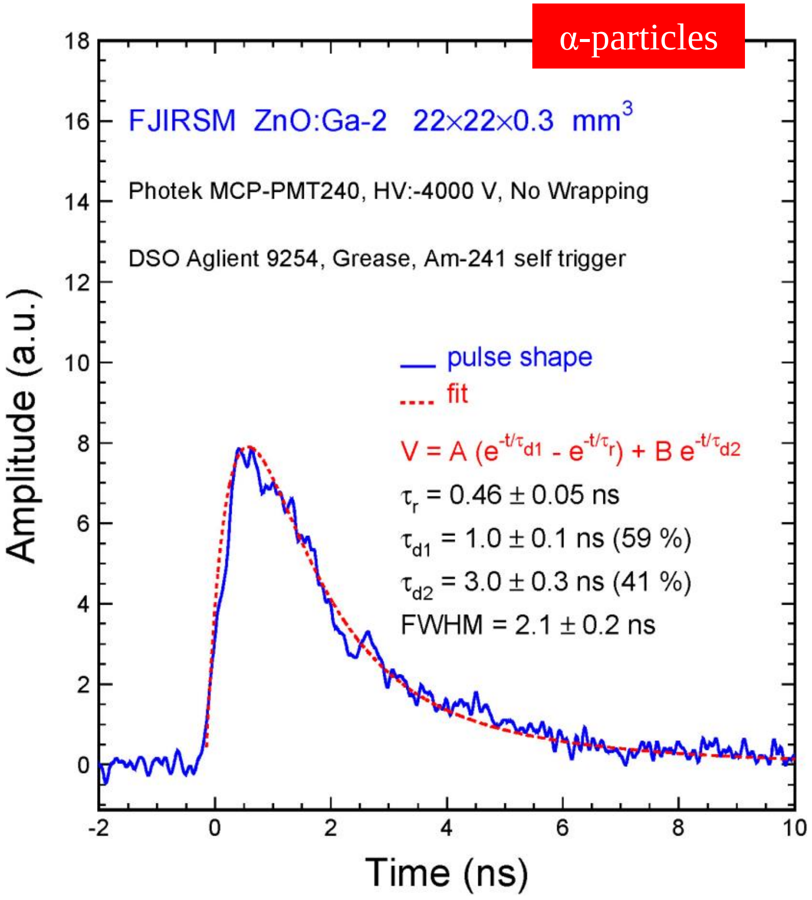
Temporal Response of YAP:Yb & YAG:Yb

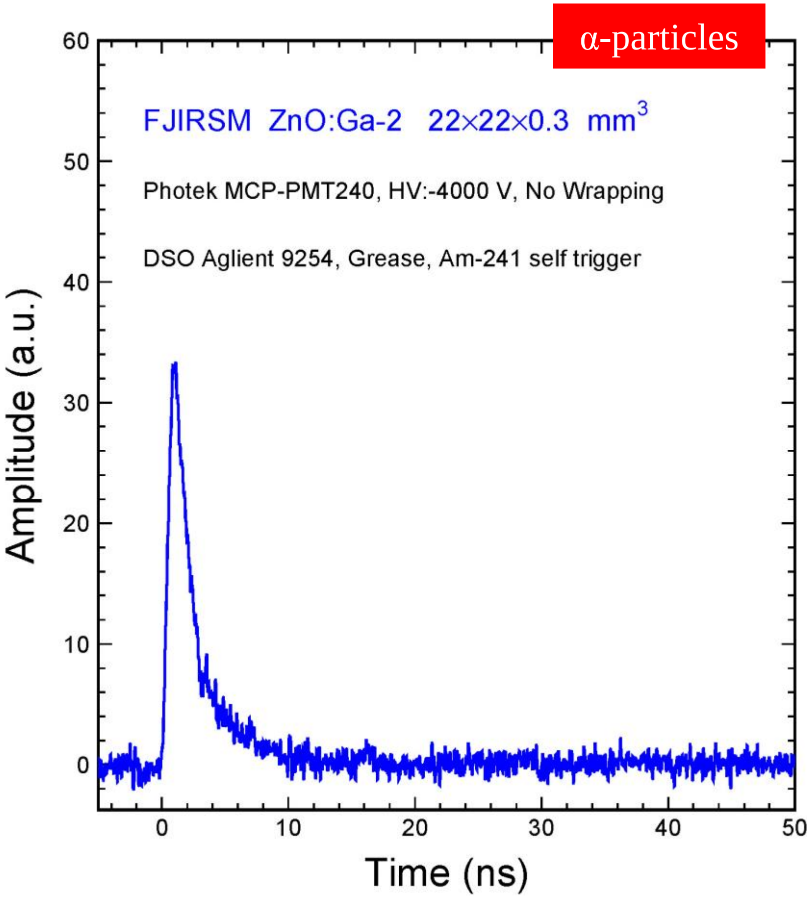


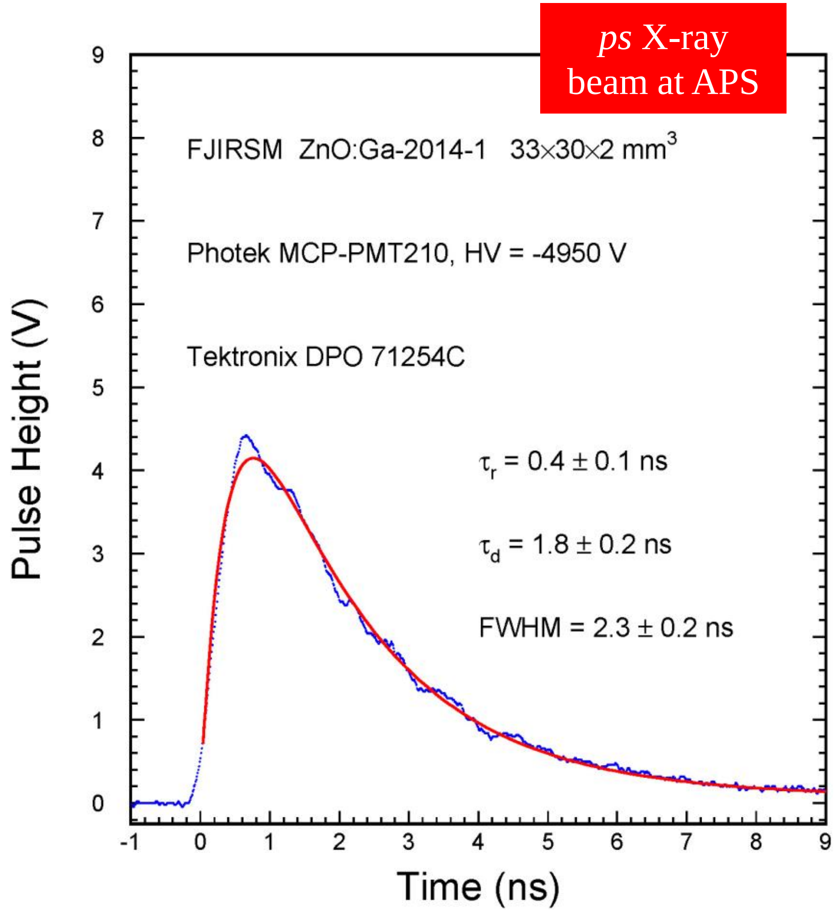
NIM A **940** (2019) 223–229

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

Temporal Response of ZnO:Ga



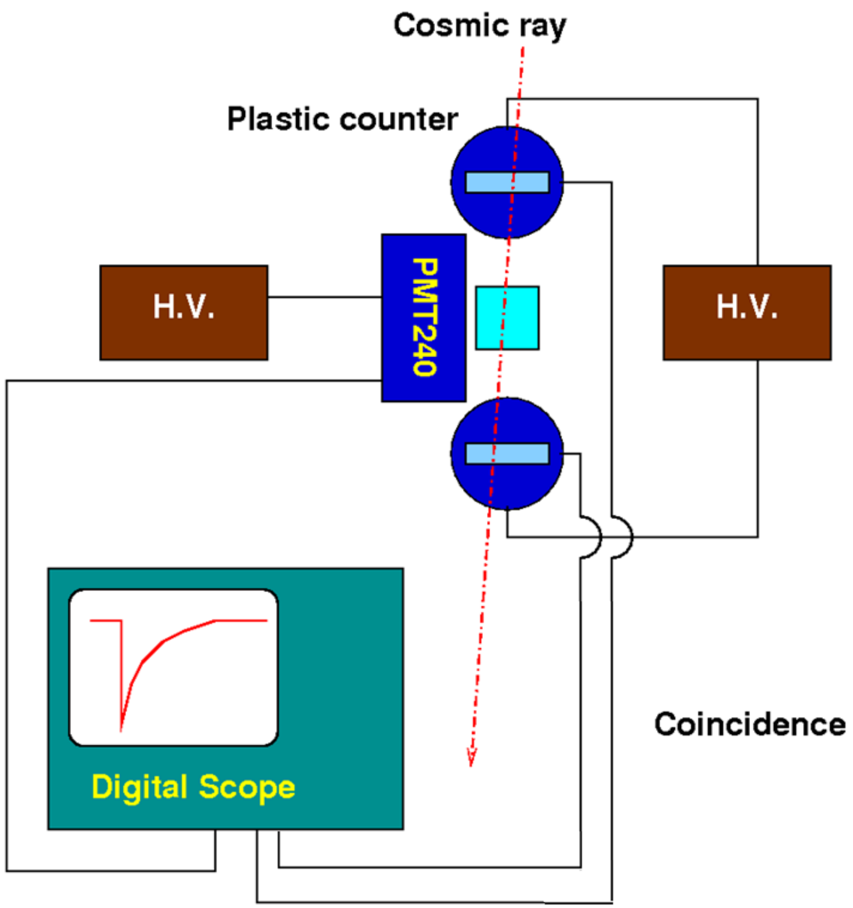


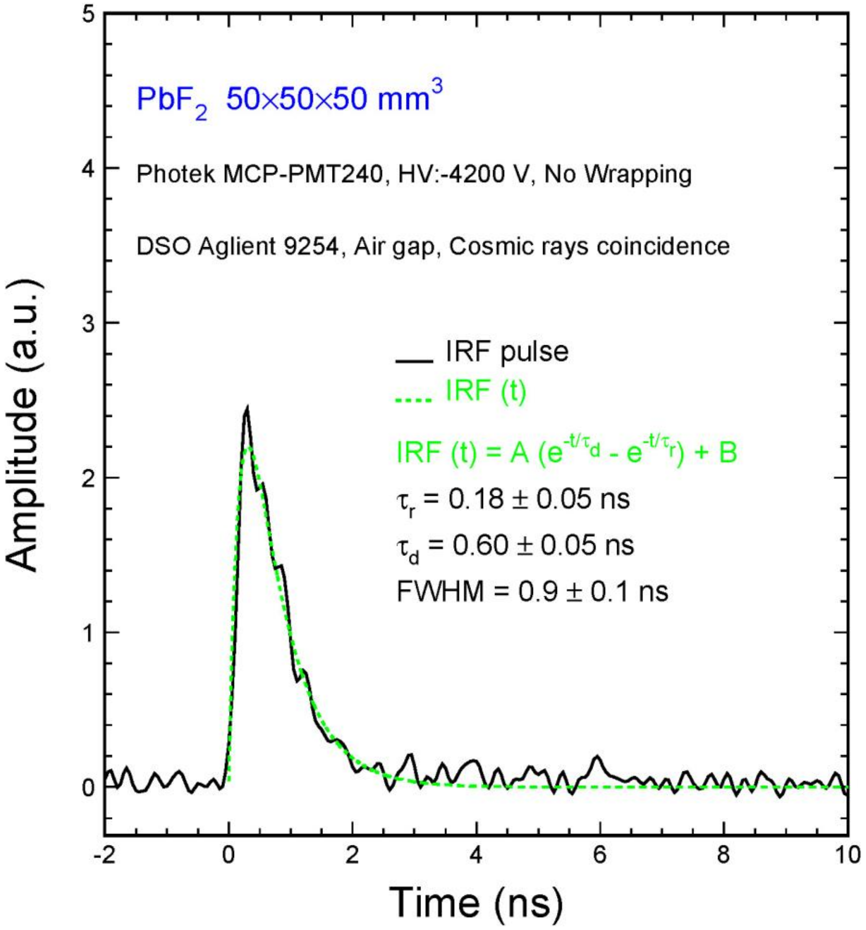


ZnO:Ga shows decay time of 1.0/3.0 ns by Am-241 with negligible slow component

The Instrument Response Function

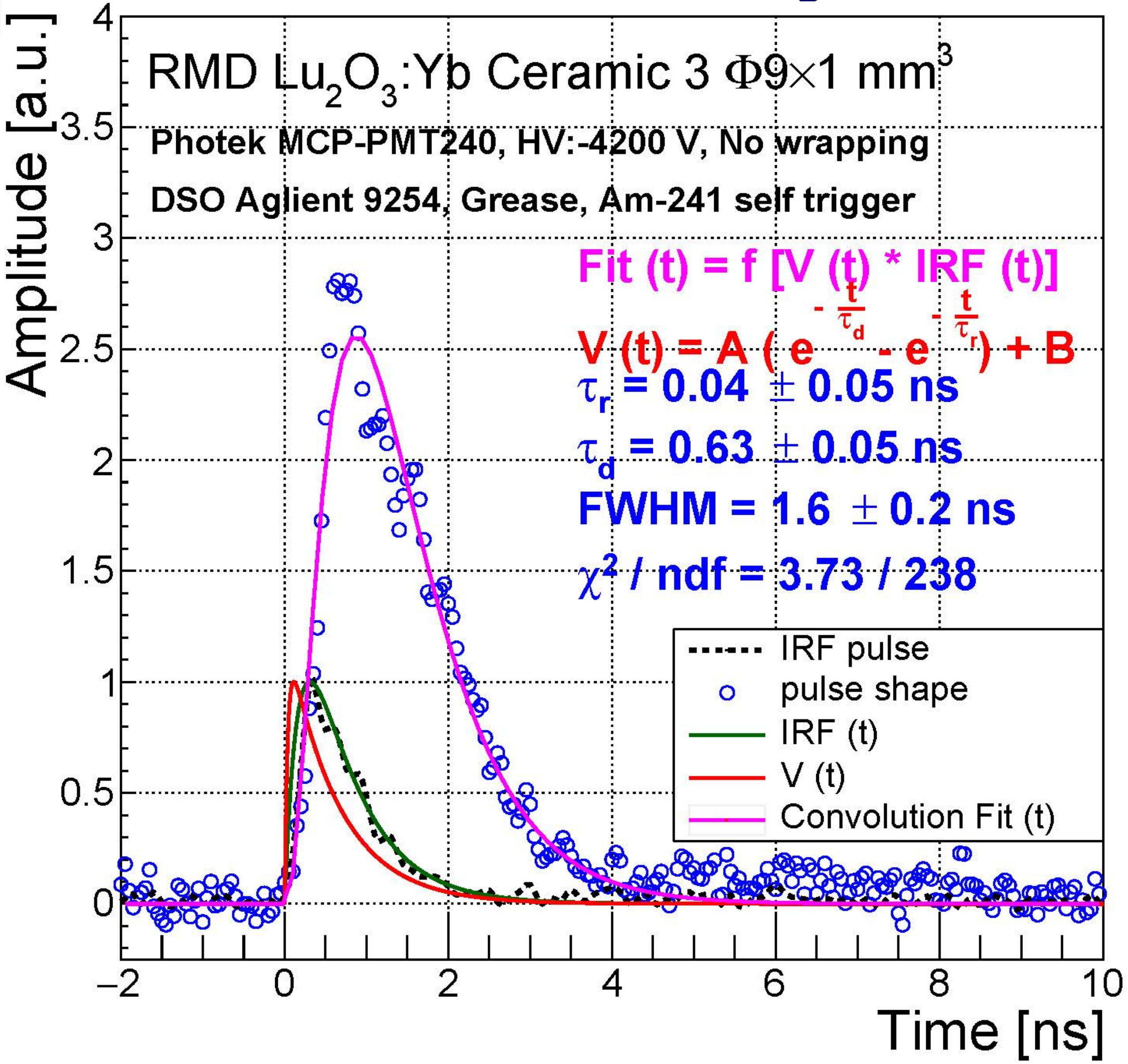
$$Fit(t) = f[V(t) * IRF(t)] = \int_{-\infty}^{+\infty} V(\tau) * IRF(t-\tau)d\tau$$





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

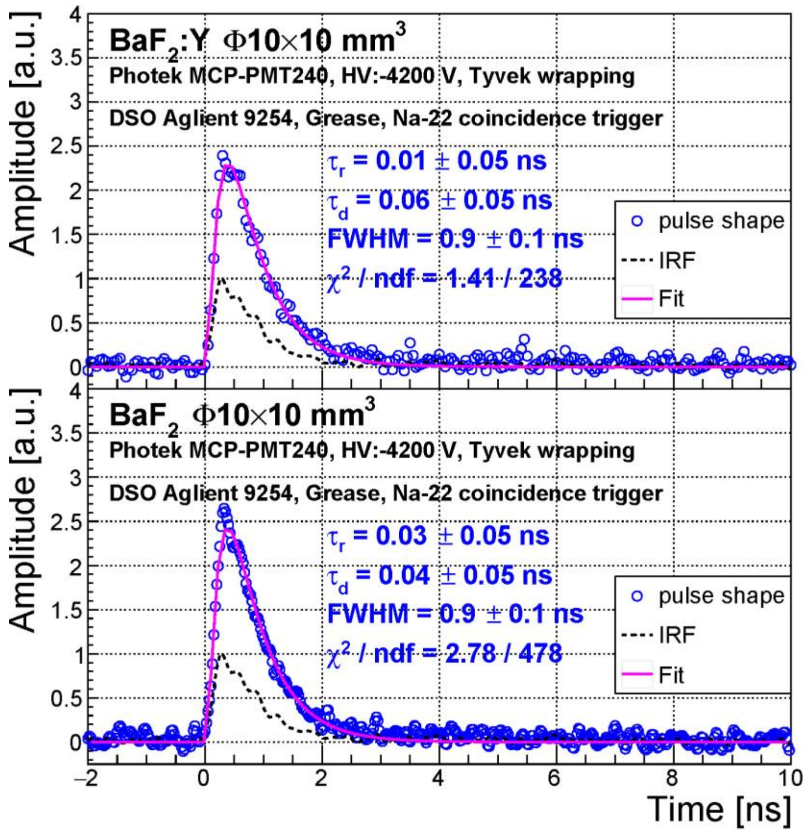


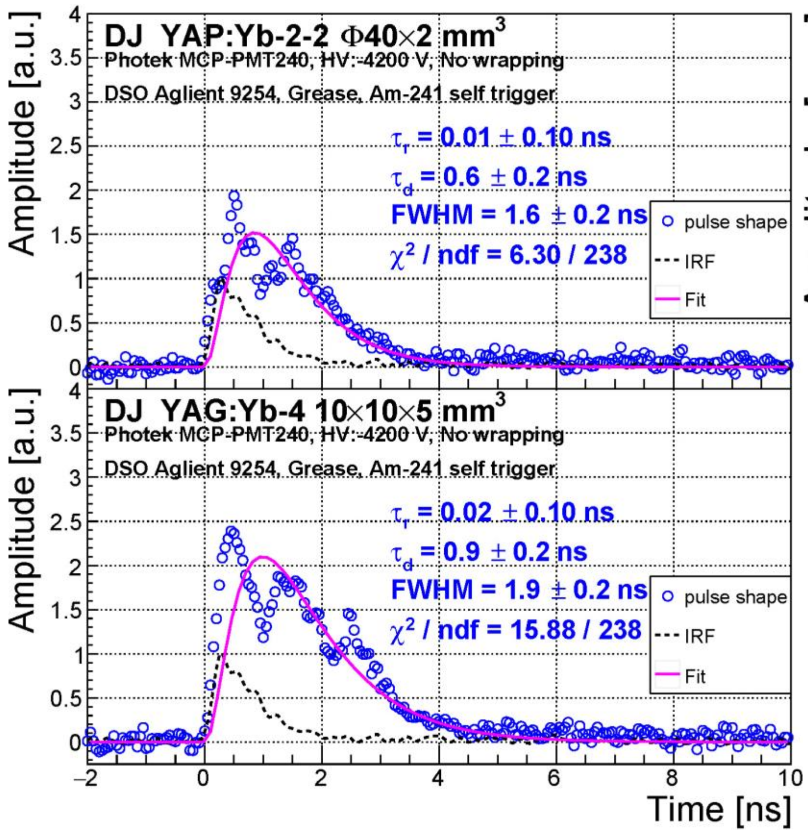
The magenta line shows the convolution fit. The numerical result of the fit after taking out the IRF are shown in blue

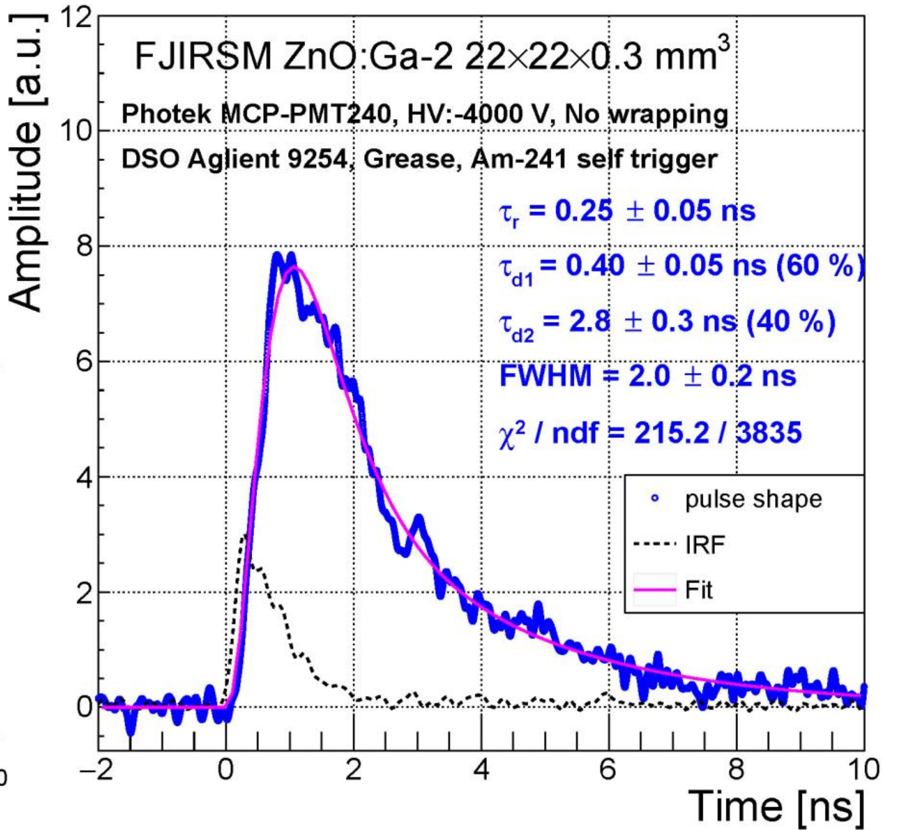
The result of the 0.63 ns decay time is the intrinsic decay time of Lu_2O_3:Yb

BaF_2, YAP:Yb, YAG:Yb and 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







Fast/Ultrafast Inorganic Scintillators for Imaging

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 (°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.

Summary

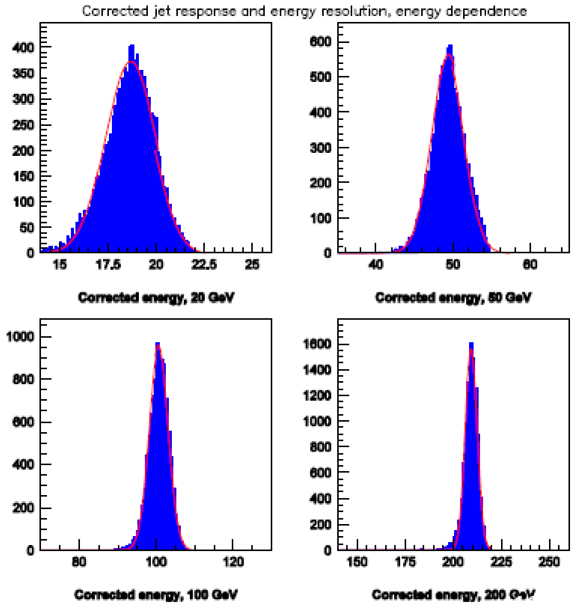
- The HEP community is developing rad-hard, fast/ultrafast and cost-effective inorganic scintillators for future HEP experiments at the energy and intensity frontiers.
- Ultrafast inorganic scintillators under development for HEP applications, such as BaF_2:Y and Lu_2O_3:Yb, may help to break the pico-second timing barrier for HEP as well as provide a GHz hard X-ray imager for future free electron laser facilities.
- Hard X-ray beams with ns bunch spacing, e.g. the APS beam in hybrid mode or the SLAC LCLS facility, are very useful for our investigation on ultrafast inorganic scintillators.

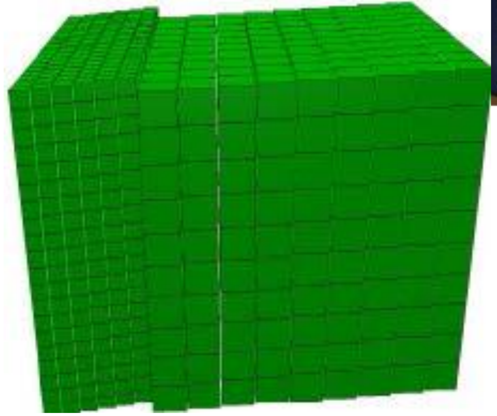
Acknowledgements: DOE HEP Award DE-SC0011925

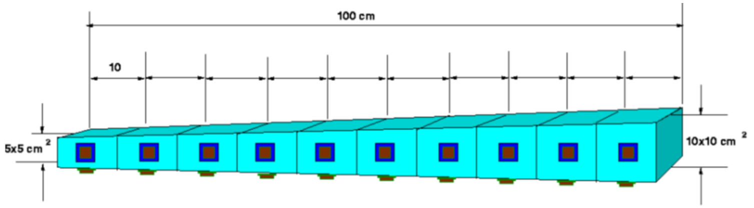
Cost-Effective Inorganic Scintillators for FCC-ee

CalVision Crystal Calorimetry

- A longitudinally segmented Calvision crystal ECAL with dual readout combined with the IDEA HCAL promises excellent EM and Hadronic resolution.
- Dense, UV-transparent and cost-effective inorganic scintillators are crucial for the homogeneous hadron calorimeter (HHCAL) detector concept, promising a jet mass resolution at a level of 20%/√E by dual readout for either Cerenkov and scintillation light or dual integration gate.
- Doped PbF_2, PbFCl, BSO, titanium doped sapphire (Al_2O_3:Ti) crystals and AFO glass have been investigated. Cost-effective inorganic glasses from RMD and Scintillex etc. are under investigation for FCC-ee

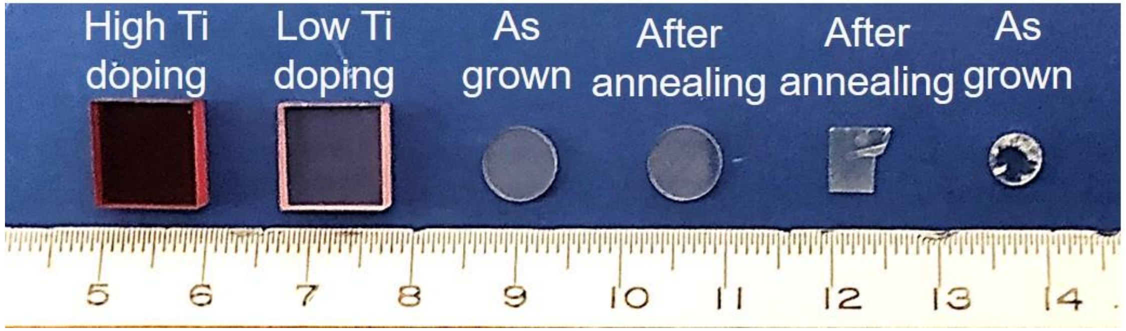






	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO Glass	BaO·2SiO$_2$ Glass[1]	HFG Glass[2]
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	3.8	5.95
Melting point (°C)	1050	1030	1123	824	608	2040	980[3]	1420[4]	570
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	3.36	1.74
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.89	3.52	2.45
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	32.8	23.2
Z_{eff} value	72.9	75.3	74.5	77.4	75.8	11.2	42.8	44.4	56.9
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	5.56	8.24
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	425	325
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	\	\	1.50
Relative Light Output by PMT[a,c]	100	20	1.6 0.4	\	2.0	0.2 0.9	2.6	5.0 4.0	3.3 6.1
LY (ph/MeV)[d]	35,000	1,500	130	\	150	7,900	450	3,150	150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	180 30	25 8
d(LY)/dT (%/°C)[d]	-0.9	?	-2.5	\	?	?	?	-0.04	-0.37
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6	?	?	?

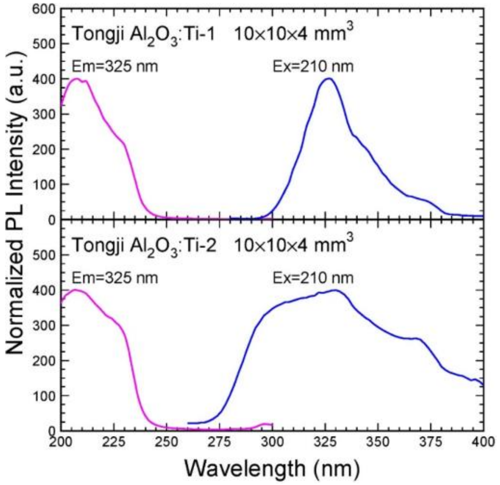
Sapphire:Ti Emission and Transmittance



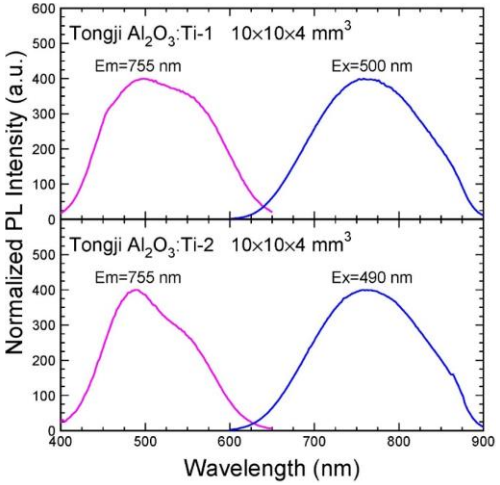
ID	Dimension (mm^3)	#	Polishing
Tongji Al_2O_3:Ti-1,2	**10×10×4**	**2**	**Two faces**
Tongji Al_2O_3:C-1,2	Φ7×1	2	Two faces
Tongji Lu_2O_3:Yb	6.4×4.8×0.4	1	Two faces
Tongji $LuScO_3$:Yb	Φ4.8×1.3	1	Two faces

A weak emission at 325 nm with 150 ns decay time
A strong emission at 755 nm with 3 μs decay time

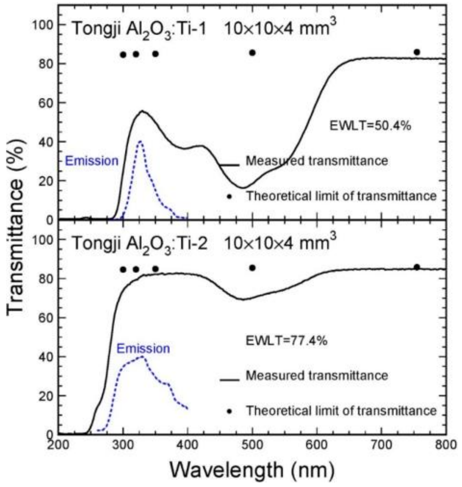
Fast @325 nm



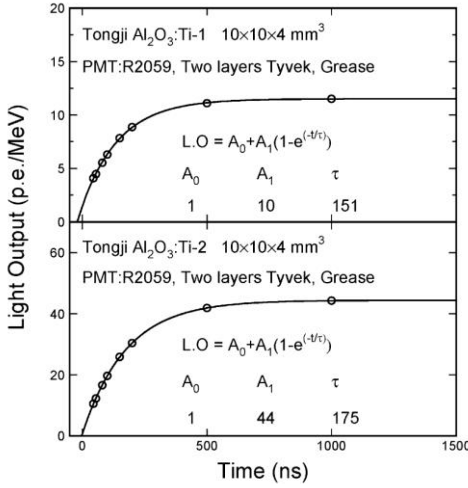
Slow @755 nm



EWLT for Fast & Slow



Fast = 162 ns



Slow = 3.2 μs