Fast/Ultrafast Inorganic Scintillators for Future High-Rate HEP Experiments

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March 28, 2023

Presentation in the Workshop on a Future Muon Program at Fermilab, Caltech

Inorganic Scintillators for HEP

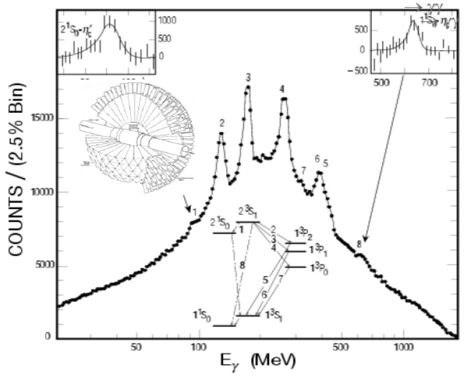
- **Precision photons and electrons enhance HEP discovery potential.**
- **Crystal performance well understood:**
  - Best possible energy and position resolution;
  - Good e/γ identification and reconstruction efficiency;
  - Excellent jet mass resolution with dual readout.
- **Development in Caltech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

arXiv: 2203.06731 and arXiv: 2203.06788

Crystal Calorimetry Physics

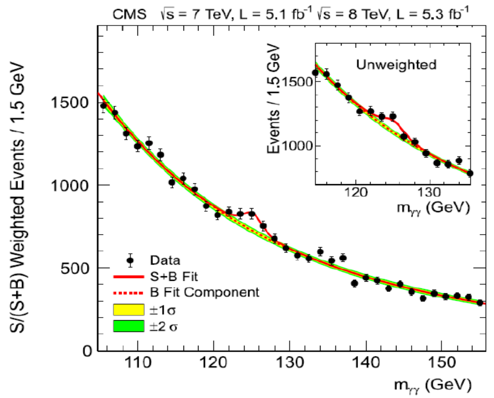
Charmonium system observed by CB through Inclusive photons

CB NaI(Tl)



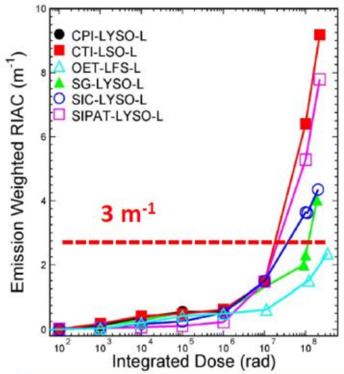
Higgs -> γγ by CMS through reconstructing photon pairs

CMS PWO

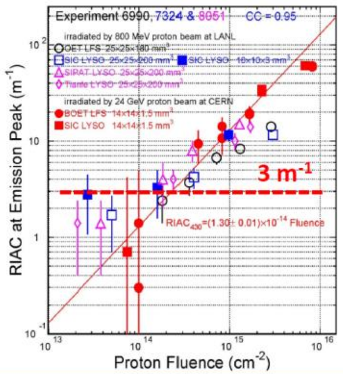


LYSO:Ce Crystals for CMS BTL

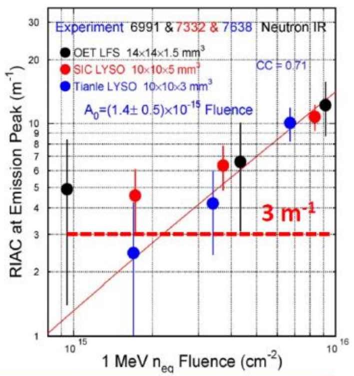
NIM A **824** (2016) 726-728



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

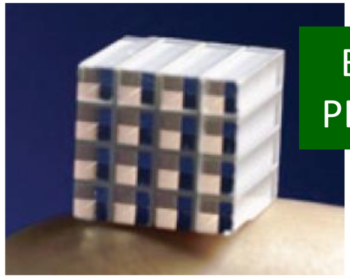
Inorganic Scintillators for Imaging

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

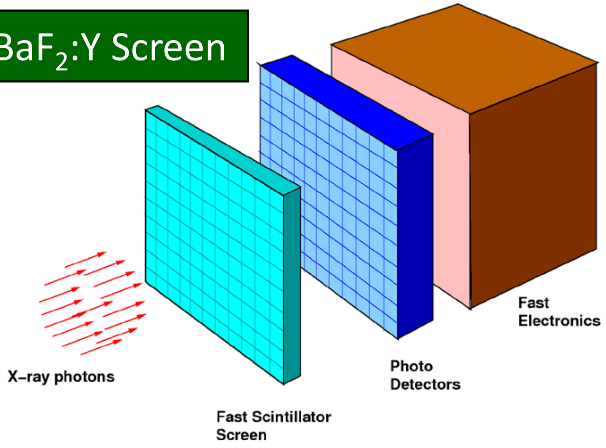
- **Detection efficiency for hard X-ray requires bulk detector; 2 ns and 300 ps inter-frame time requires ultrafast sensor.**

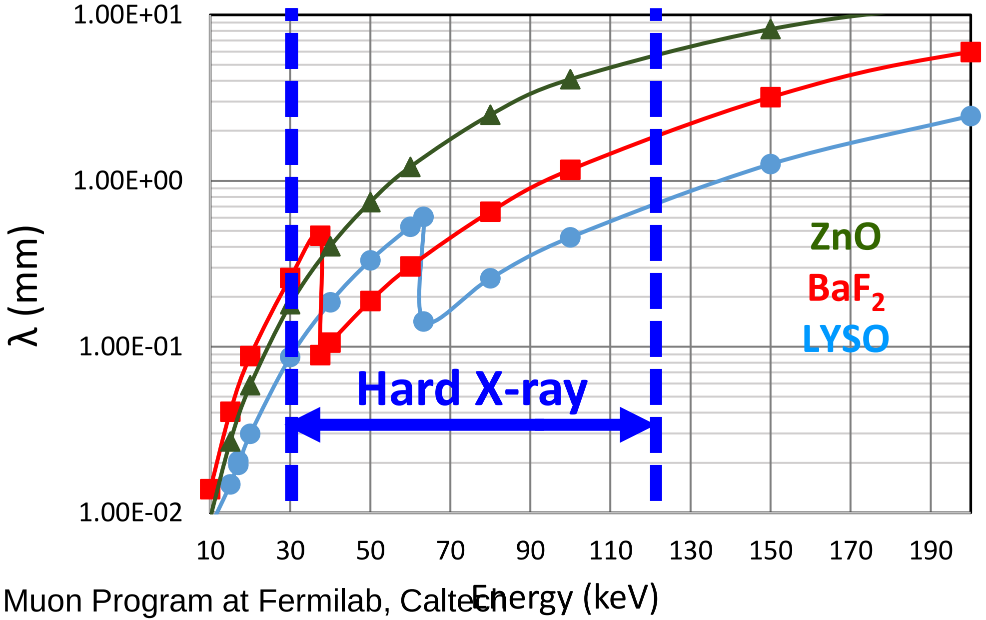


BGO pixels for PET: 1x1x10 mm

CsI:Tl pixel panel for CT
30 x 40 cm panel
0.3x0.3x10 mm

BaF$_2$:Y Screen





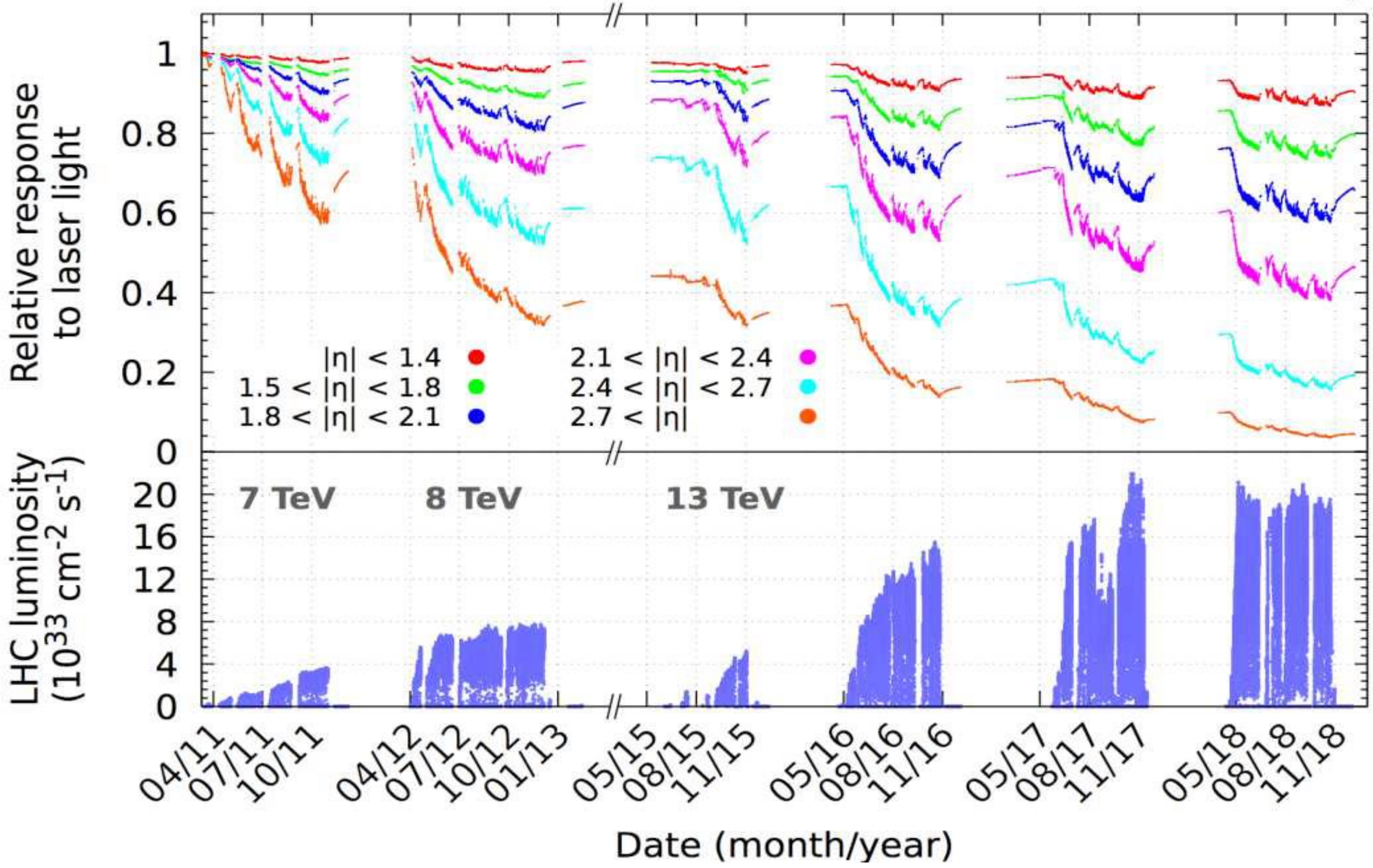
2019 DOE Basic Research Needs Study
Priority Research Directions for Calorimetry

- 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.

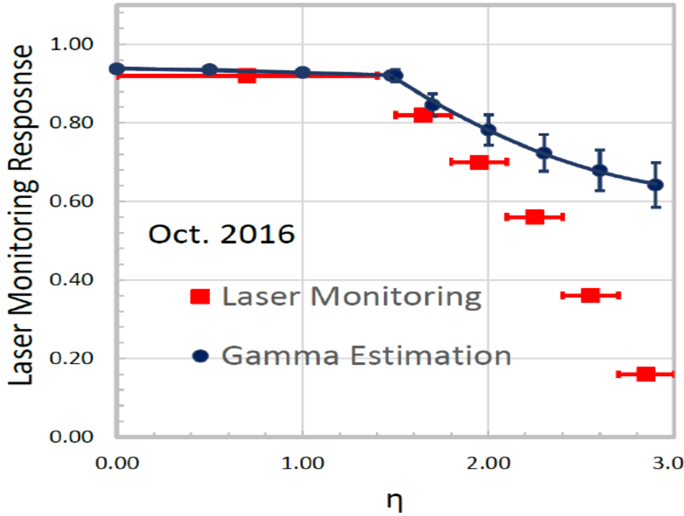
DOE 2019: https://www.osti.gov/servlets/purl/1659761
ECFA 2021: https://cds.cern.ch/record/2784893
Snowmass 2021: https://arxiv.org/abs/2209.14111
Fast/ultrafast, radiation hard and cost-effective inorganic scintillators

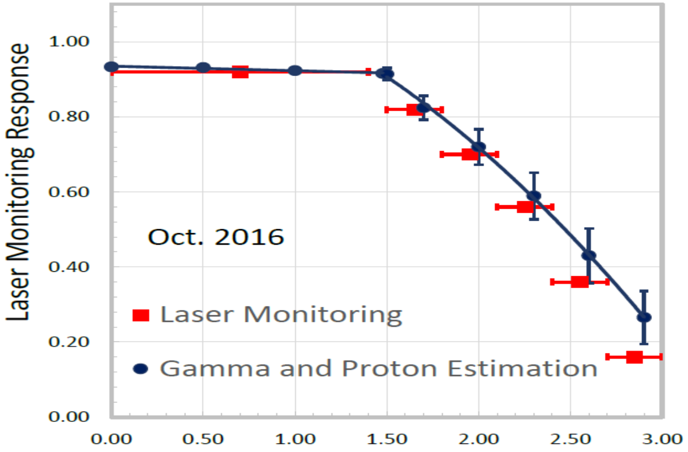
Challenge: Radiation Damage at the LHC

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



http://www.its.caltech.edu/~rzhu/talks/ryz_161028_PWO_mon.pdf

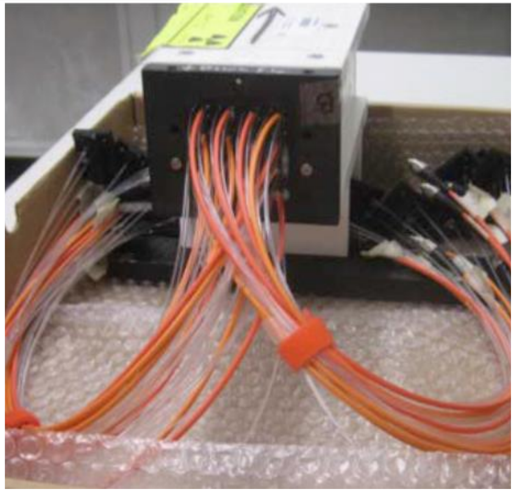


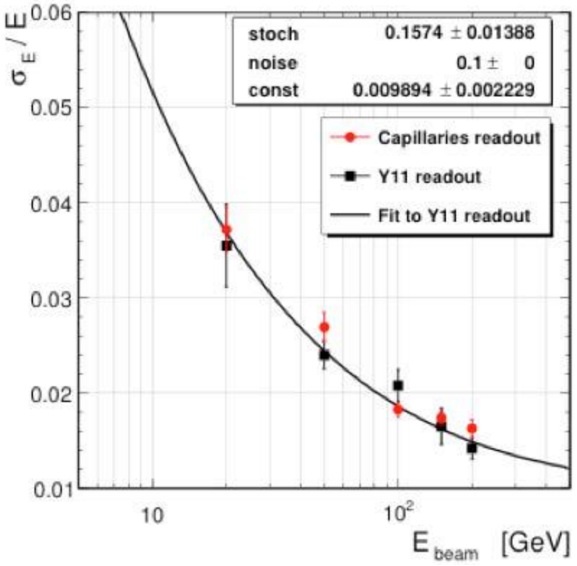


Use materials with monotonic damage: BaF_2, CsI, LYSO:Ce, LuAG:Ce

Neutron damage?

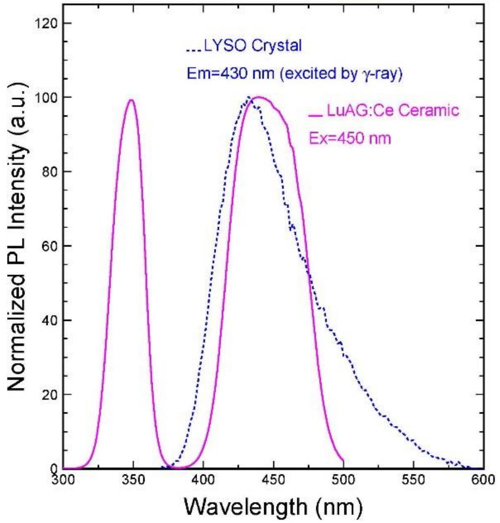
RADiCAL: LYSO/LuAG Shashlik ECAL

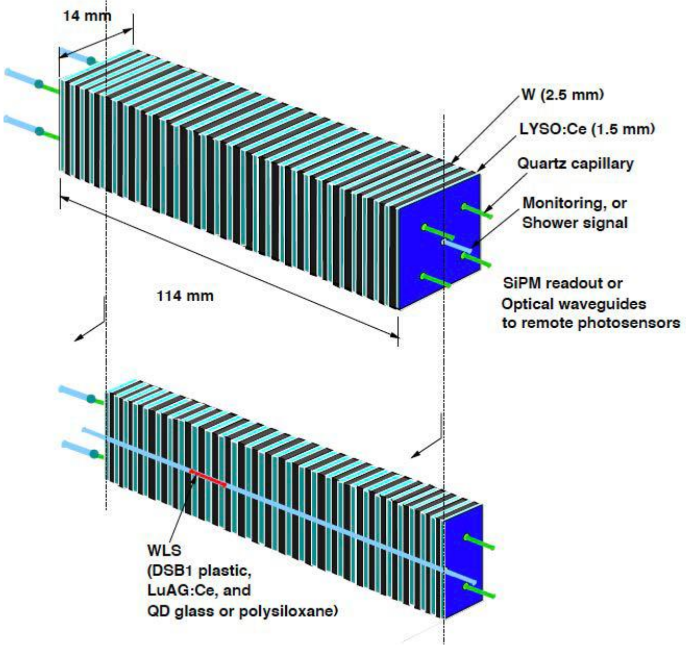


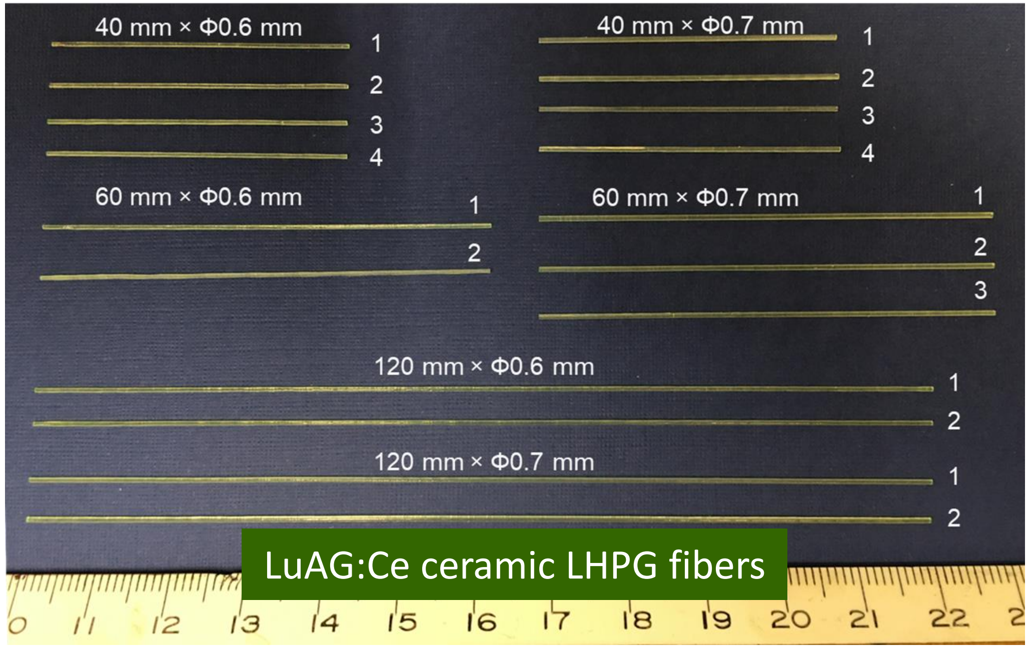


arXiv: 2203.12806 (N35-6)

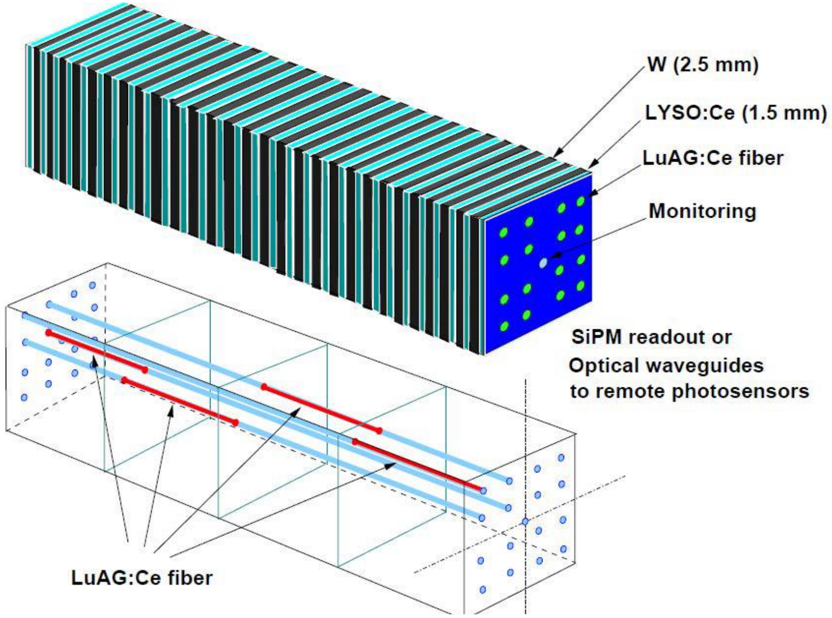
RADiation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission







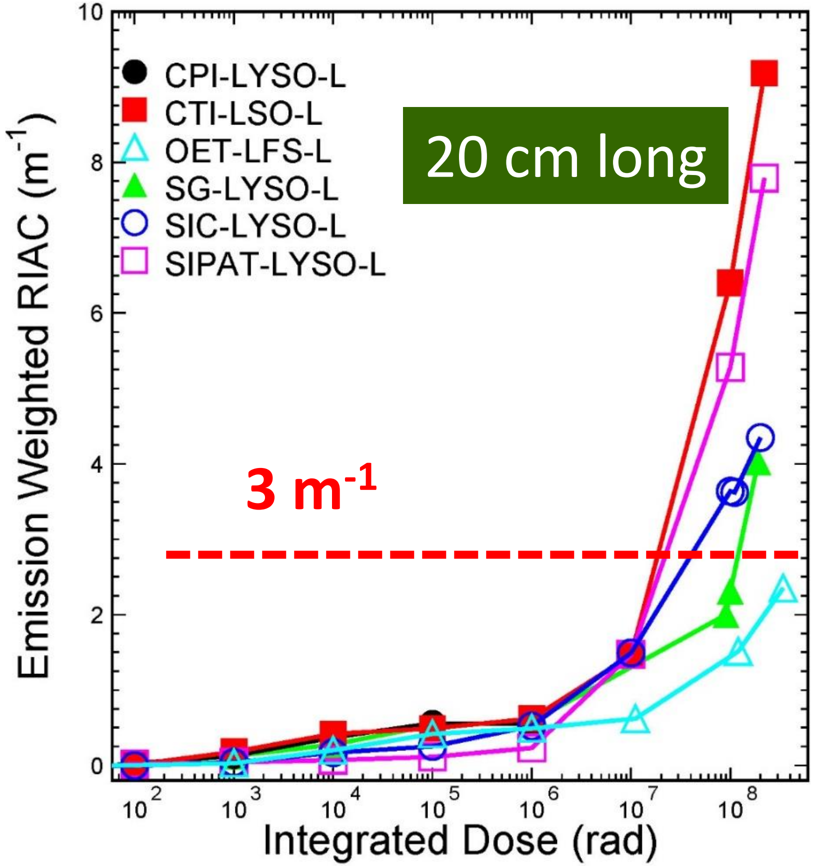
LuAG:Ce ceramic LHPG fibers

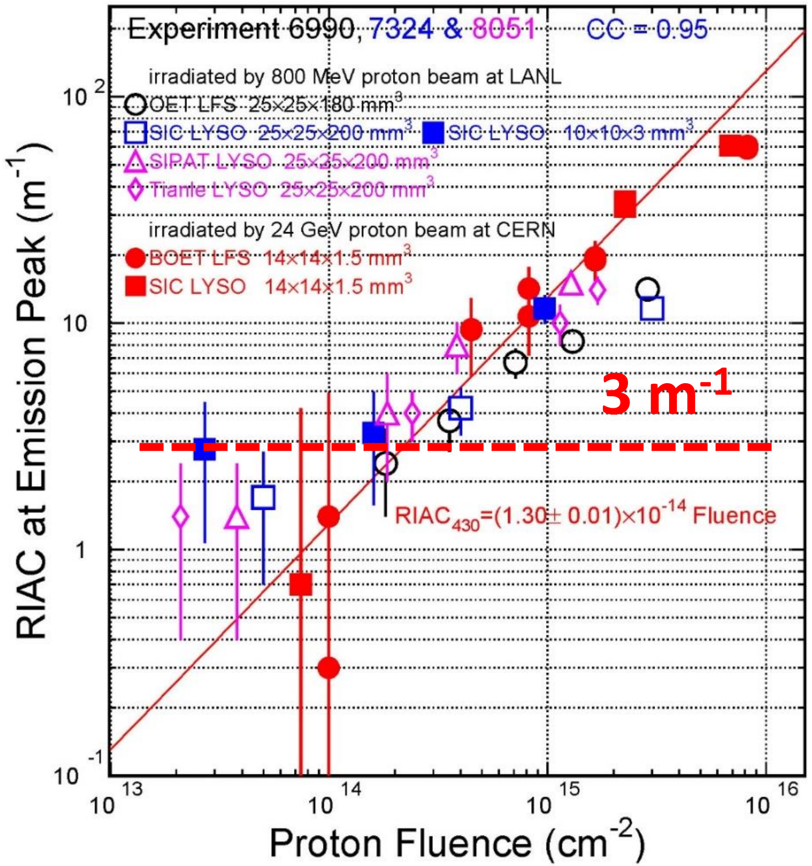


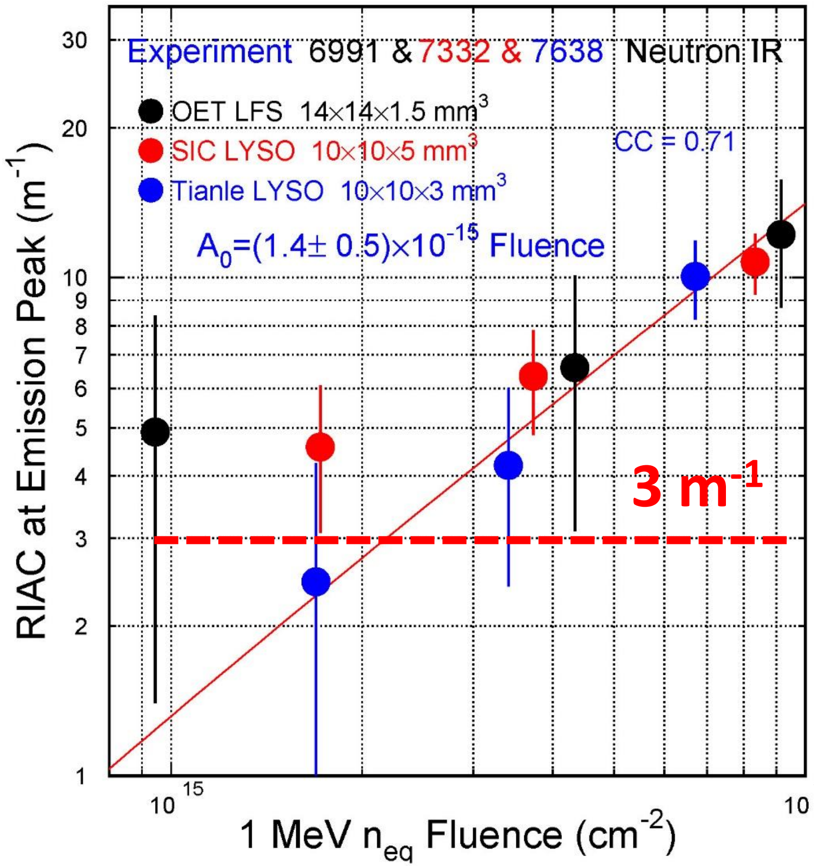
LYSO:Ce Radiation Hardness

IEEE TNS 63 (2016) 612-619

CMS BTL 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



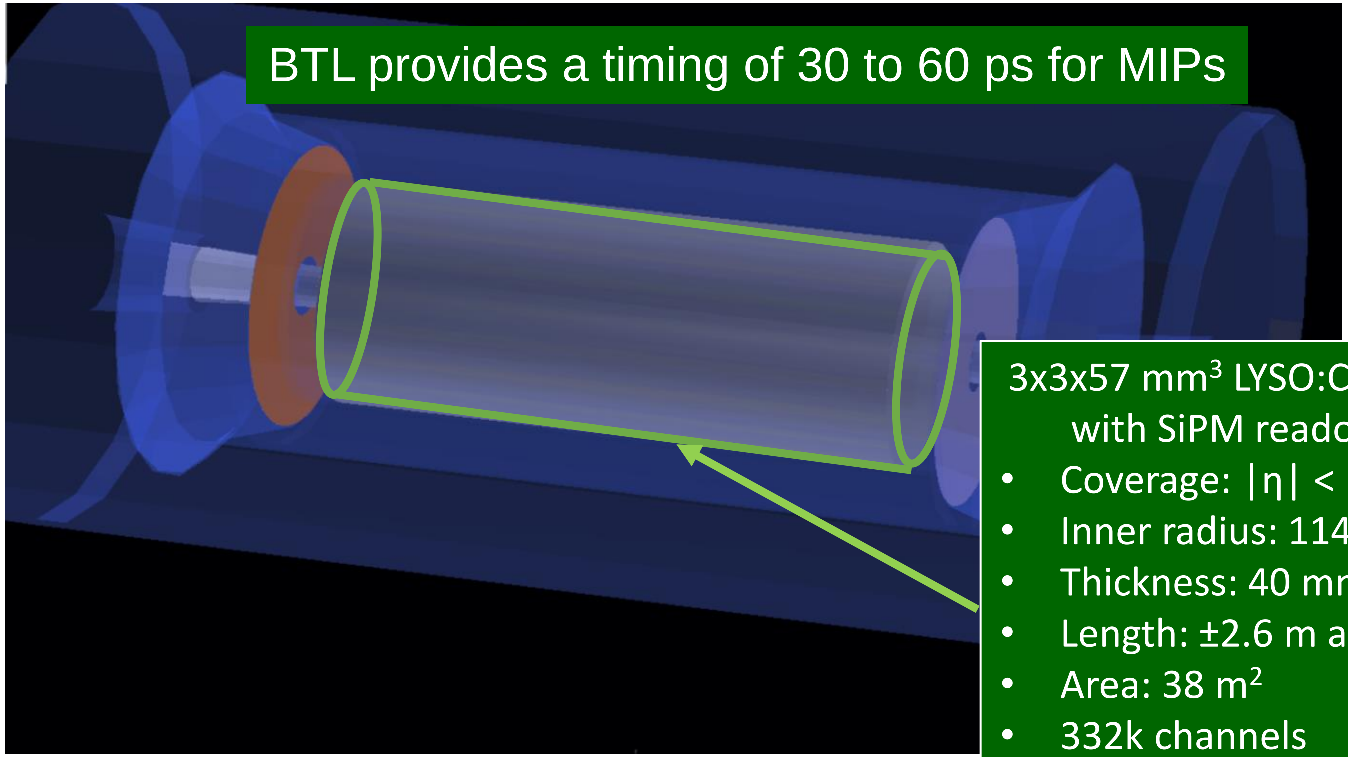




Damage induced by protons is larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup

CMS Barrel Timing Detector for HL-LHC

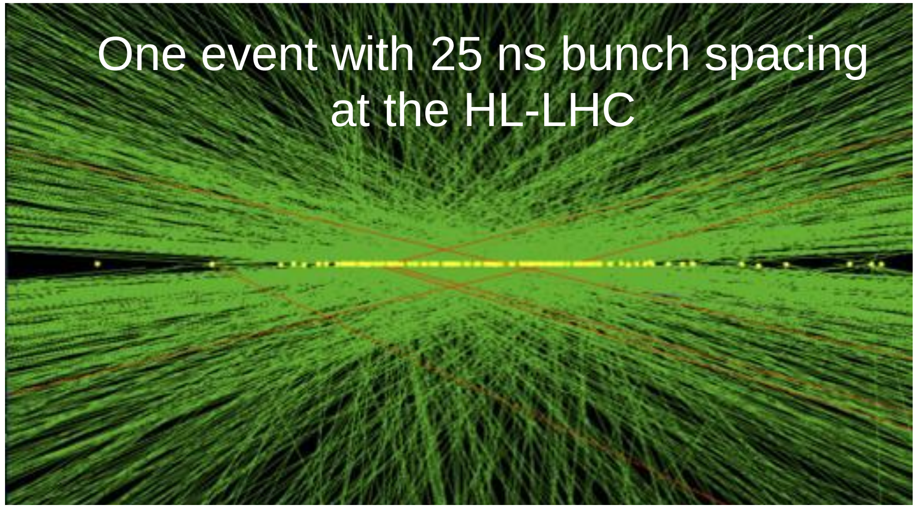
To face challenge of pileup at HL-LHC by using 4D tracking in space and time



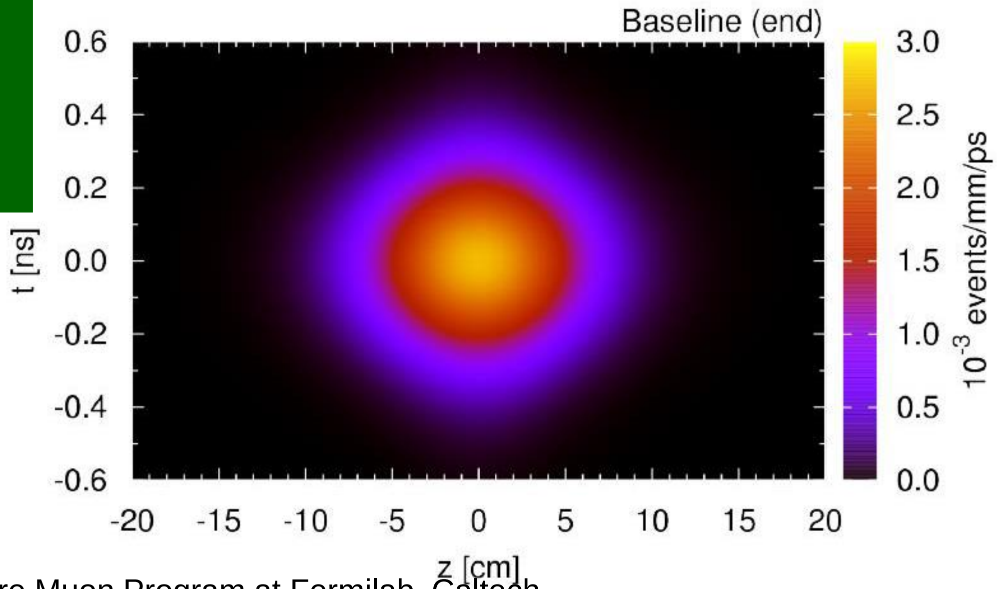
BTL provides a timing of 30 to 60 ps for MIPs

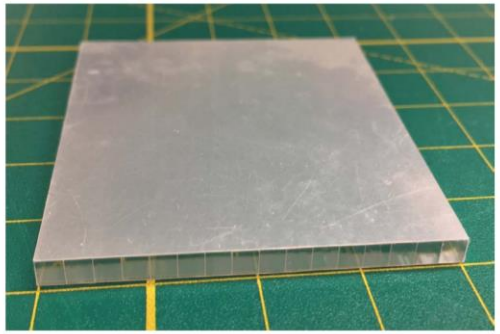
3x3x57 mm^3 LYSO:Ce bars with SiPM readout

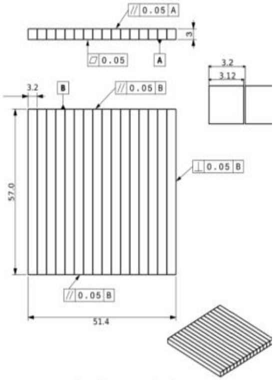
- Coverage: |η| < 1.45
- Inner radius: 1148 mm
- Thickness: 40 mm
- Length: ±2.6 m along z
- Area: 38 m^2
- 332k channels

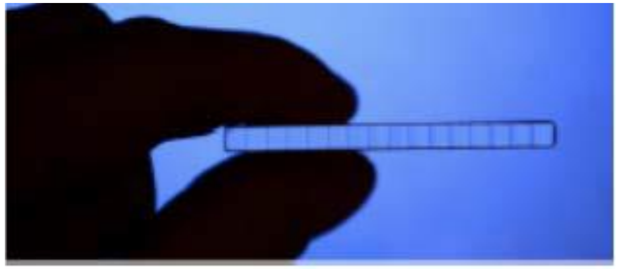


One event with 25 ns bunch spacing at the HL-LHC





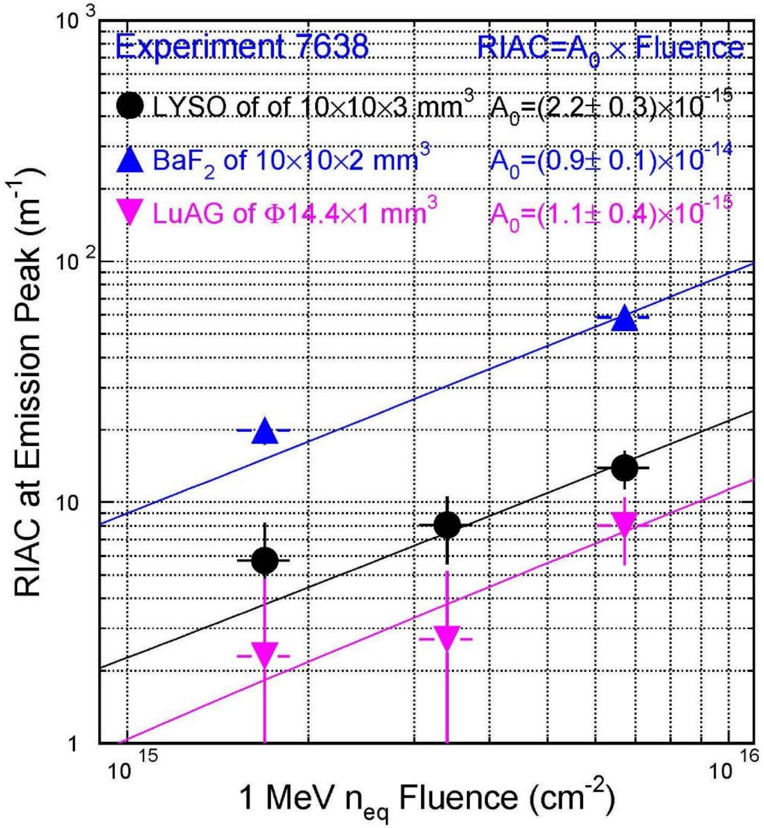


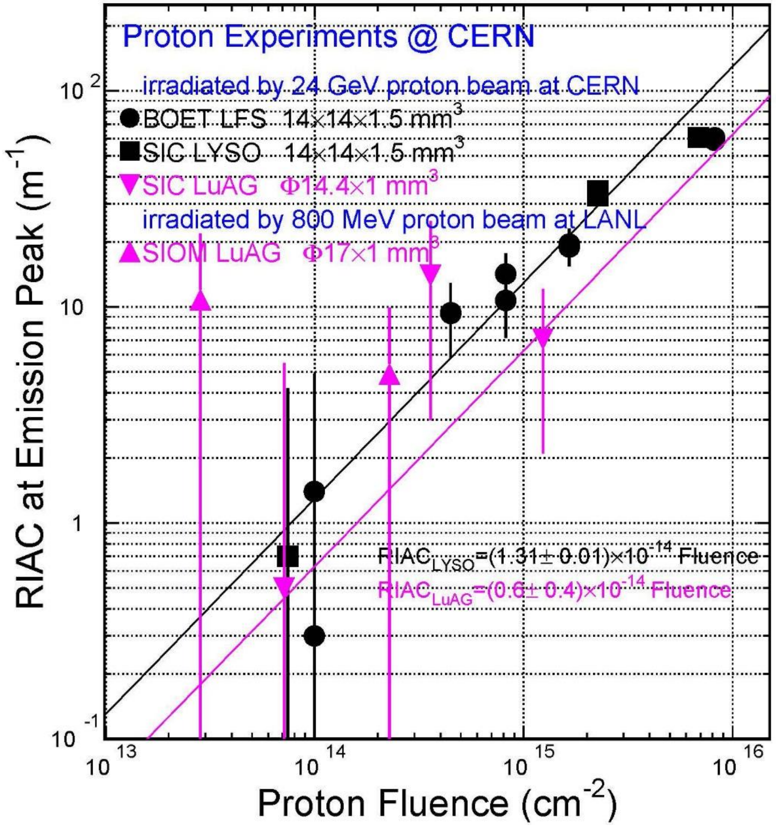


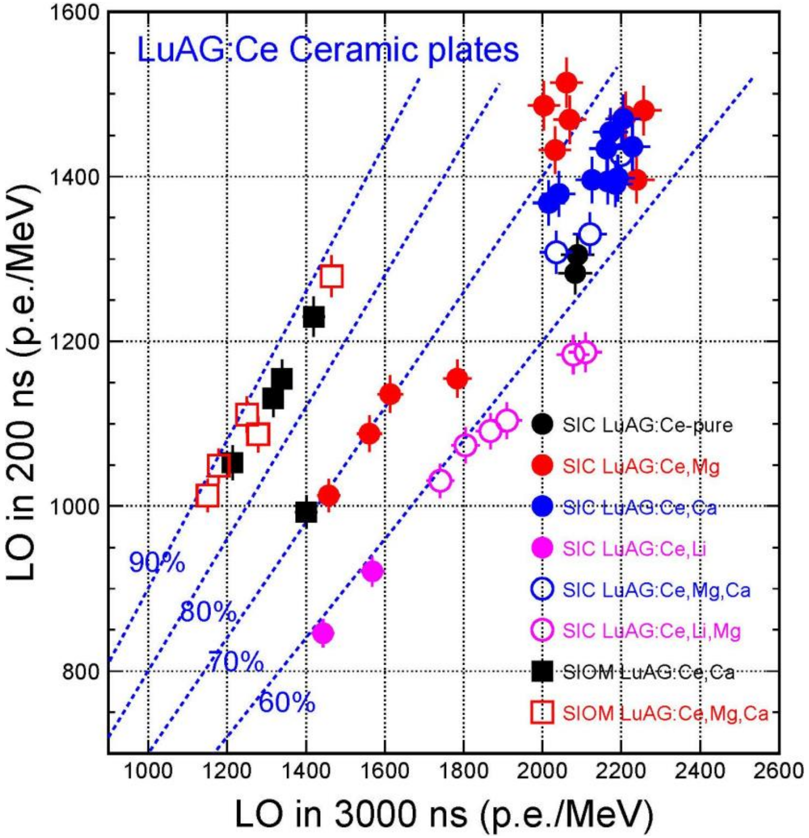
LuAG:Ce Ceramics Radiation Hardness

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

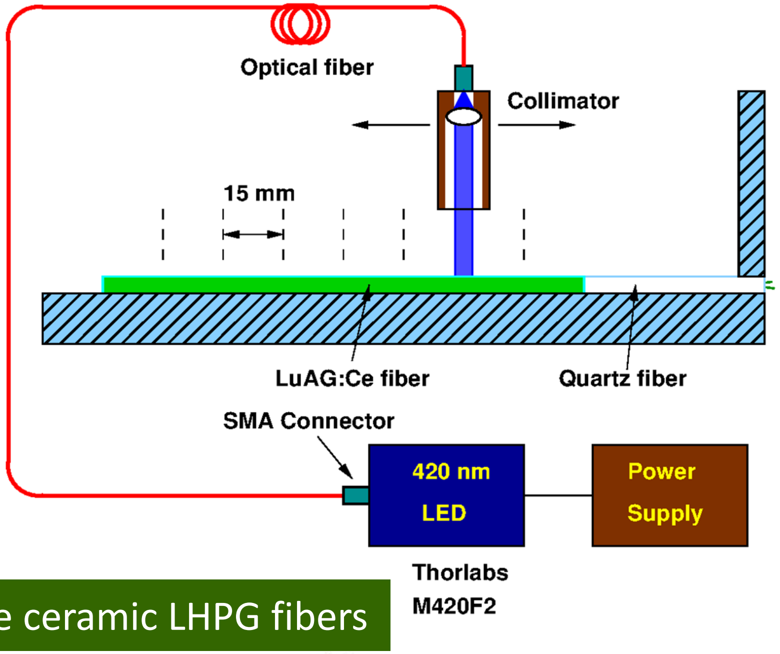


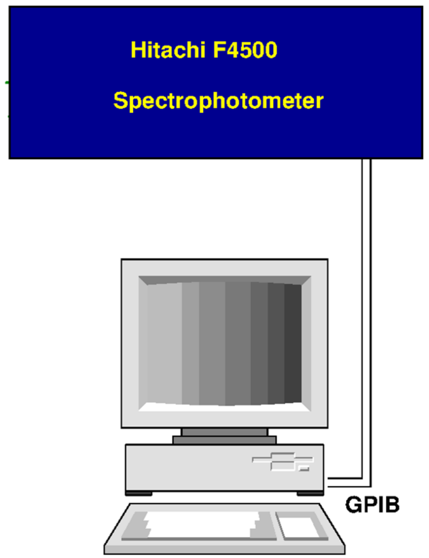


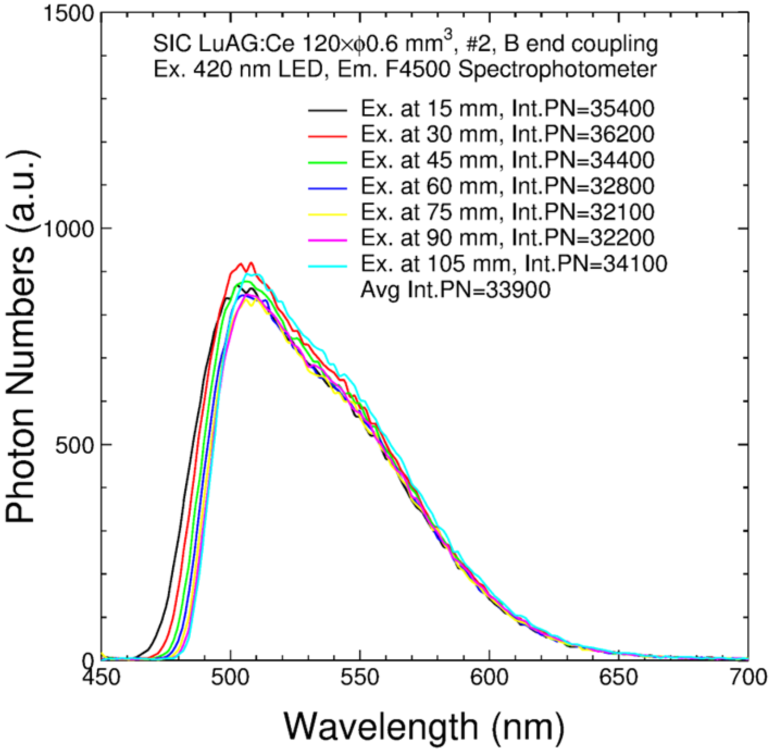


R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

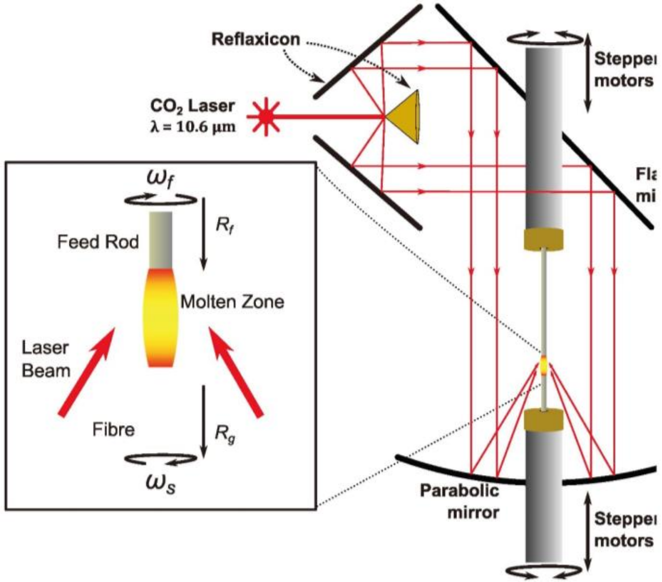
LuAG:Ce Fiber Light Output and Uniformity







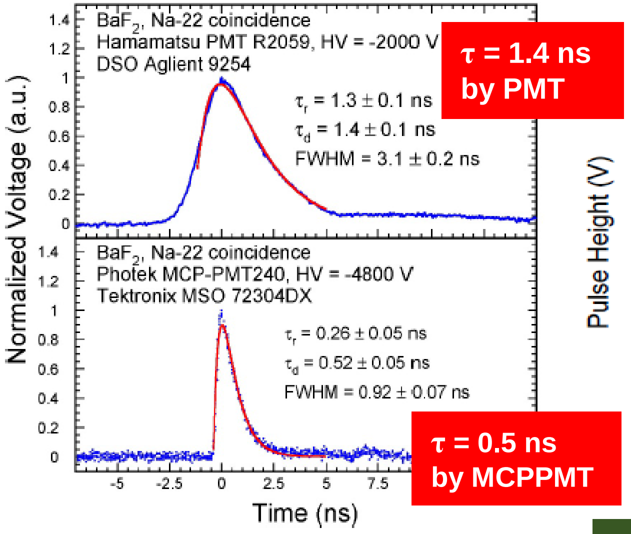
LuAG:Ce ceramic LHPG fibers



Excellent uniformity observed for Φ0.6 ×120 mm^3 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

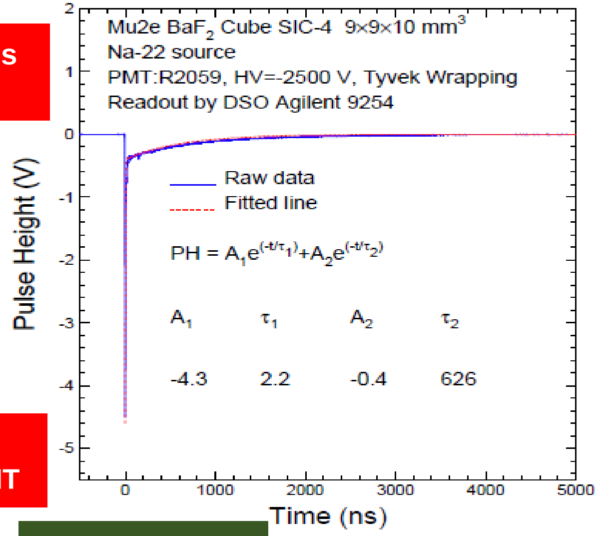
Ultrafast and Radiation Hard BaF_2

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

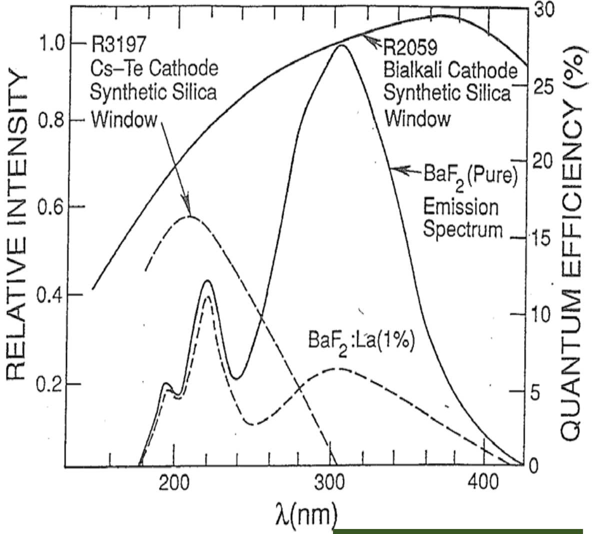


τ = 1.4 ns by PMT

τ = 0.5 ns by MCPPMT

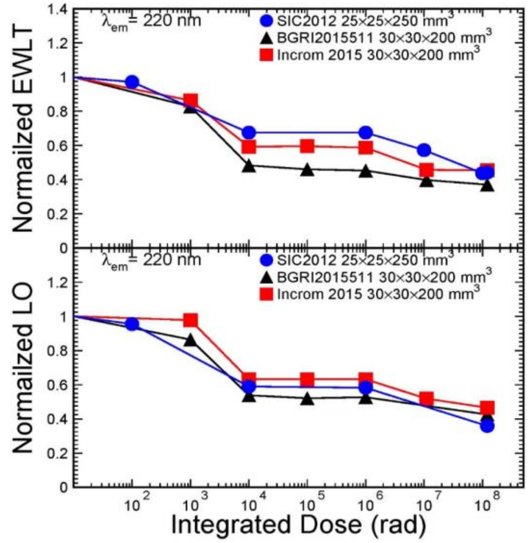


NIMA 340 (1994) 442-457



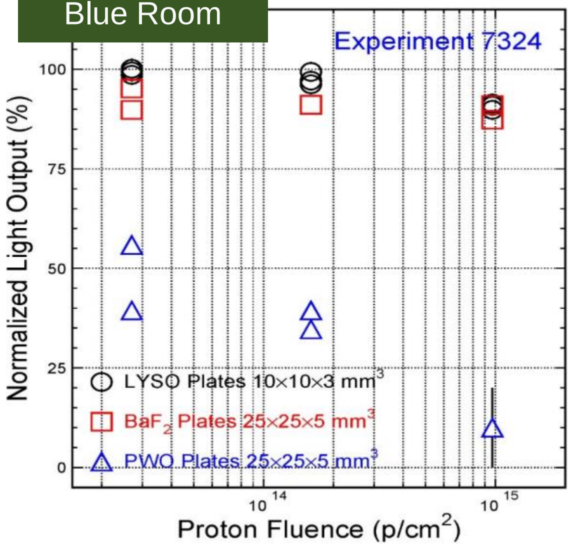
BaF_2 has an ultrafast scintillation component @ 220 nm with **0.5 ns** decay time and a much larger slow component @ 300 nm with 600 ns decay time.

Slow suppression may be achieved by rare earth **doping**, or **solar-blind photo-detector**



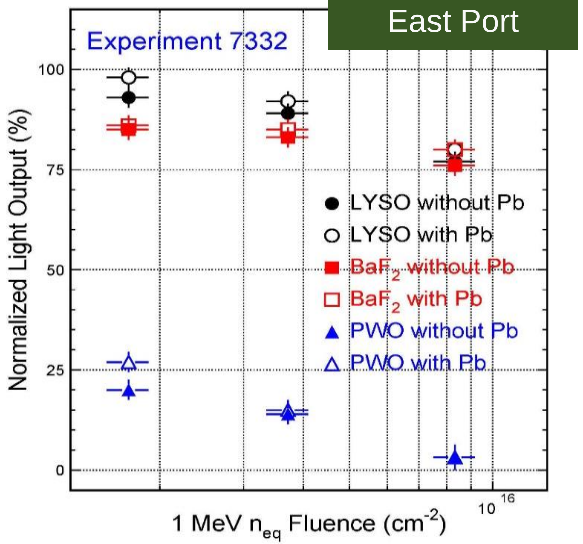
IEEE TNS **63** (2016) 612-619

Blue Room



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

East Port



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

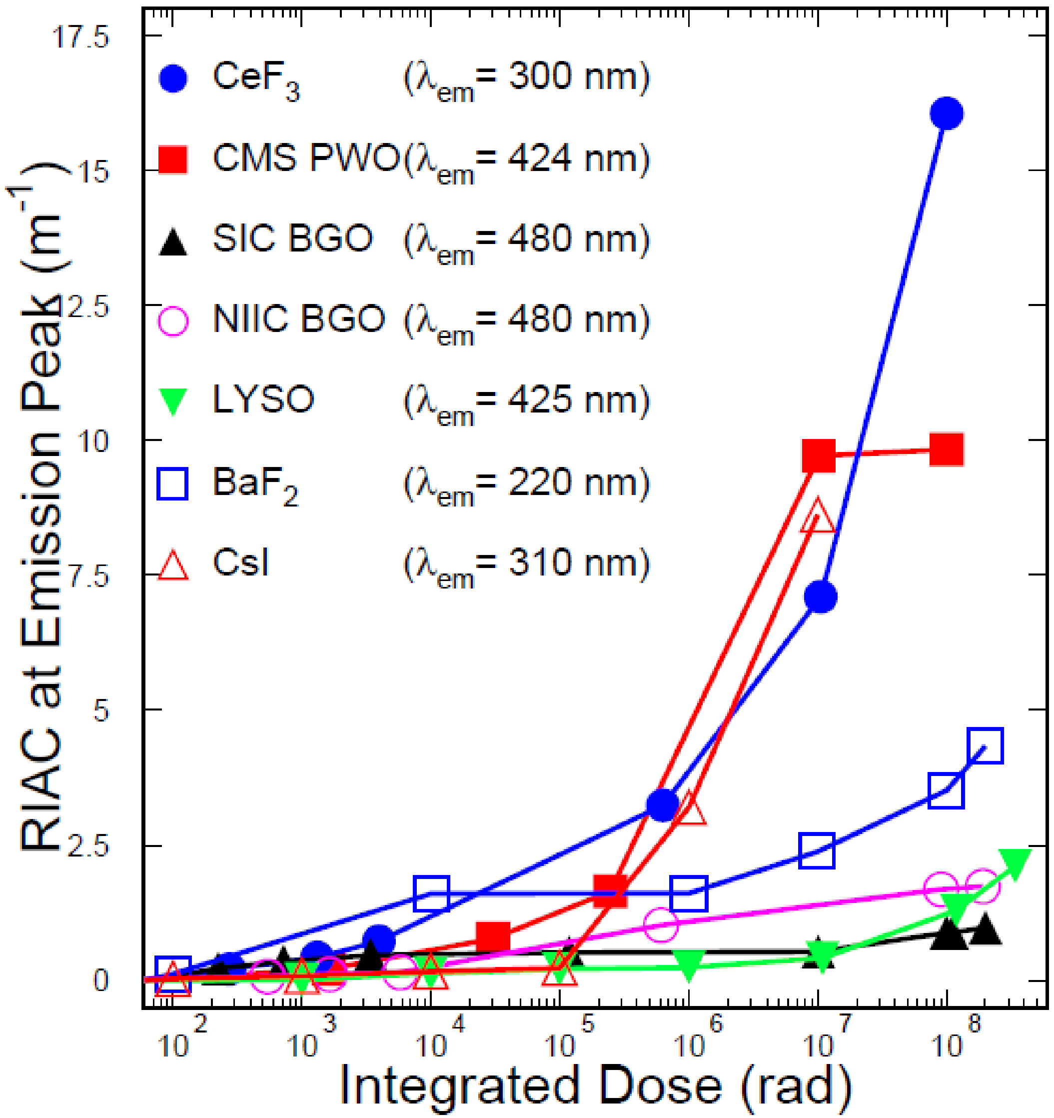
Long BaF_2 shows saturated damage from 10 krad to 1 Mrad, indicating limited color center density against ɣ-rays

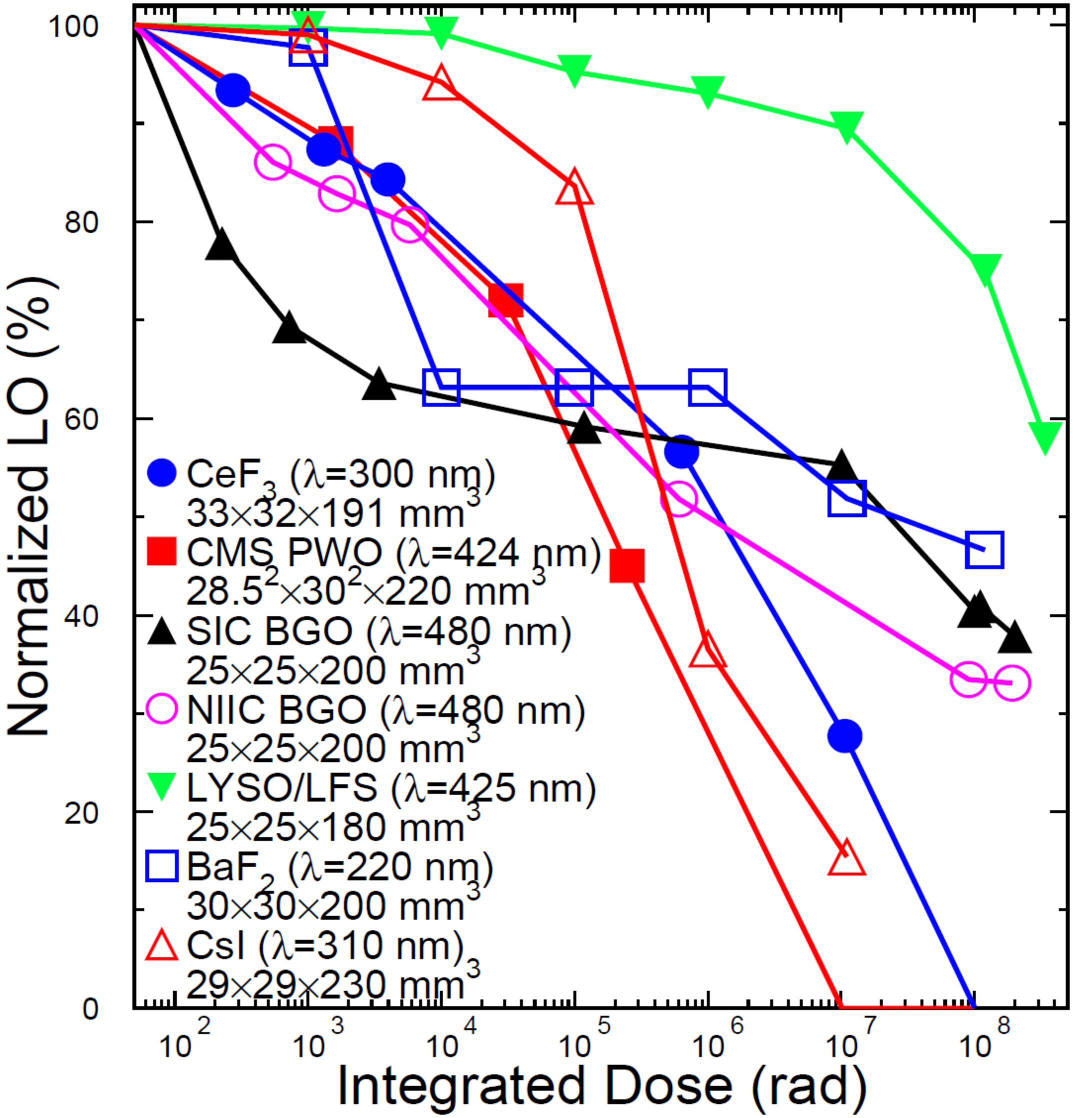
Thin BaF_2 plates survives protons & neutrons up to 9.7×10^{14} p/cm^2 & neutrons 8.3×10^{15} n_{eq}/cm^2

Investigation is to be done for long crystal samples

γ-Ray Induced Damage in Long Crystals

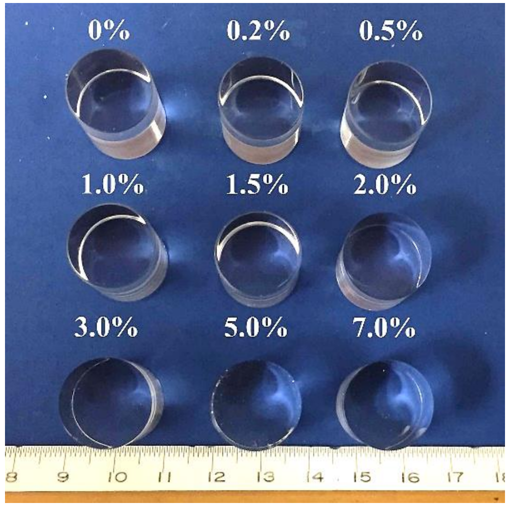
IEEE TNS **63** (2016) 612-619

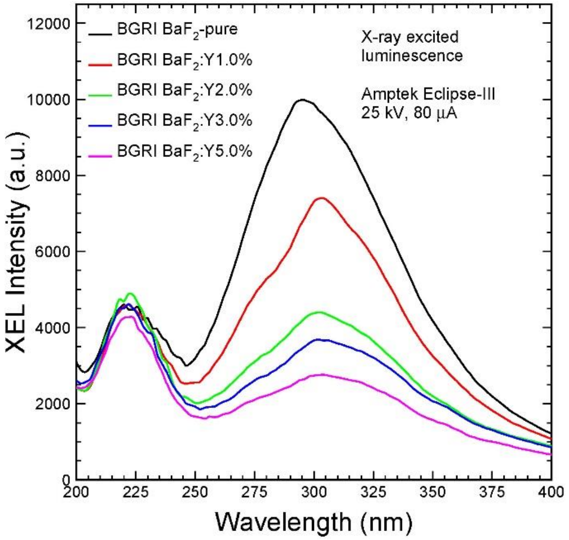


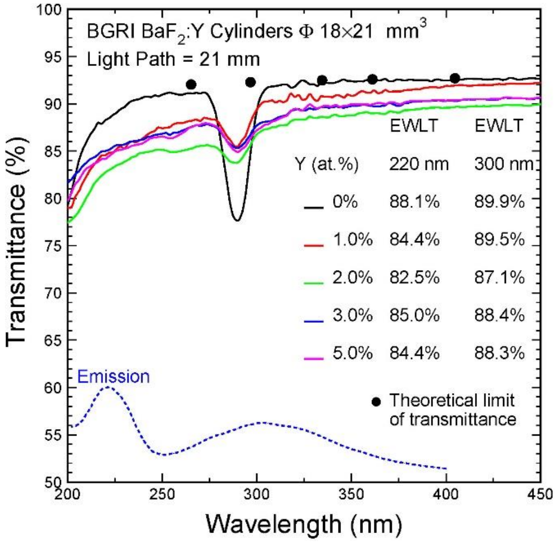


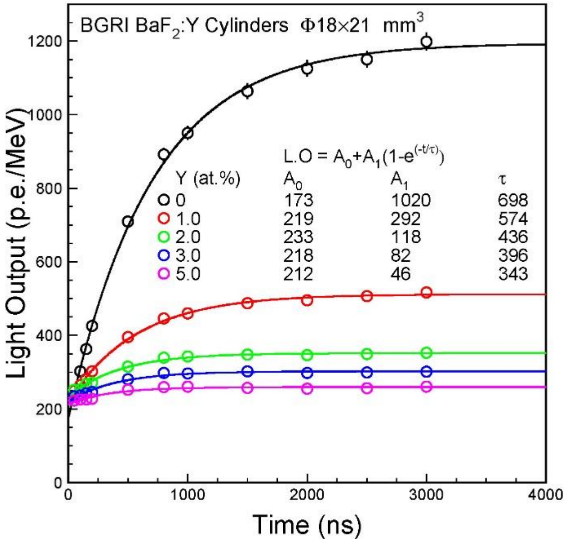
BaF_2:Y for Ultrafast Calorimetry

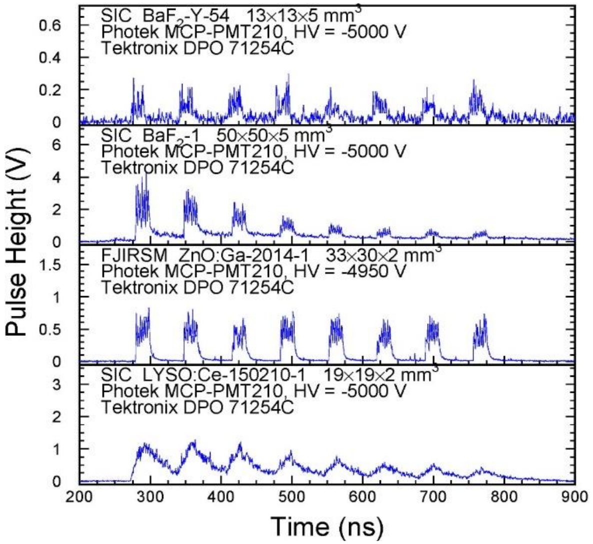
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

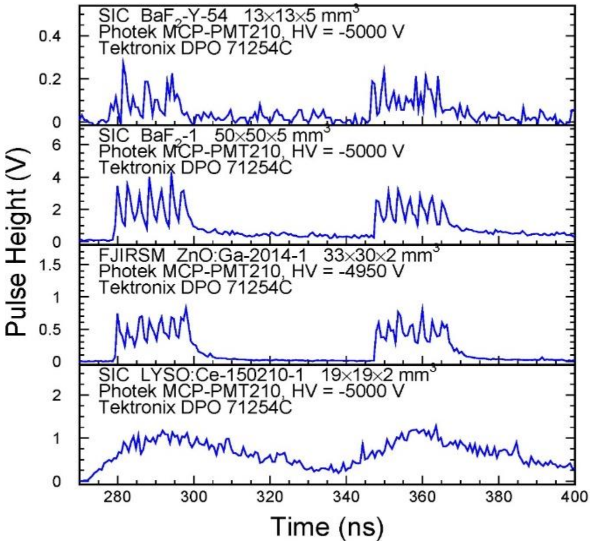


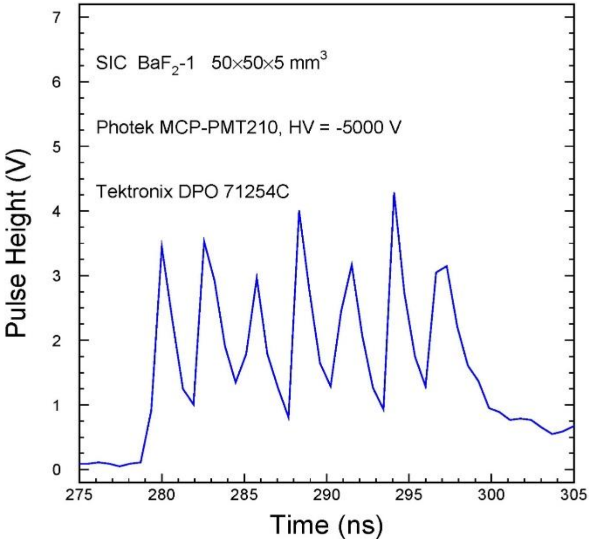












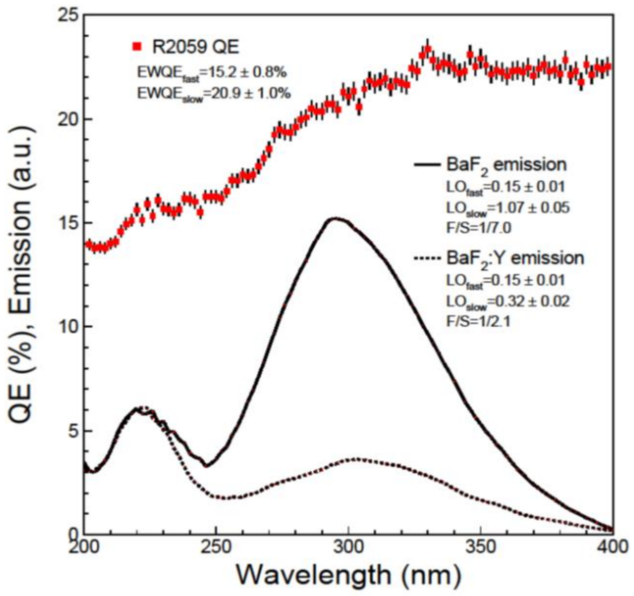
X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

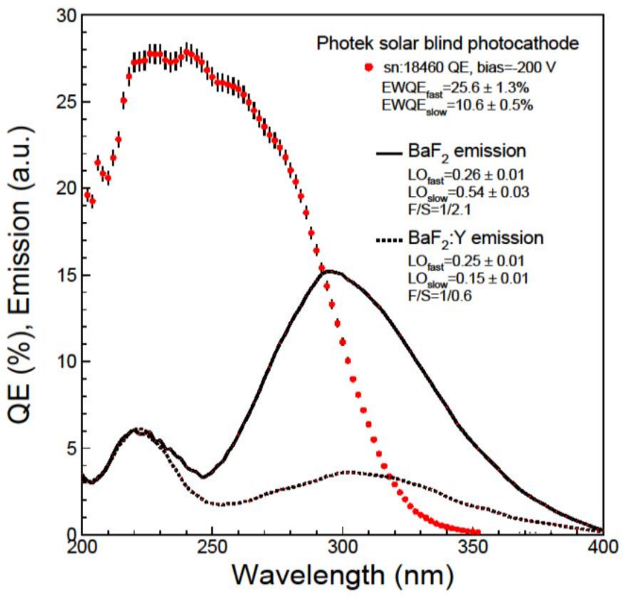
RIN:ɣ affected Photodetector QE/PDE Response

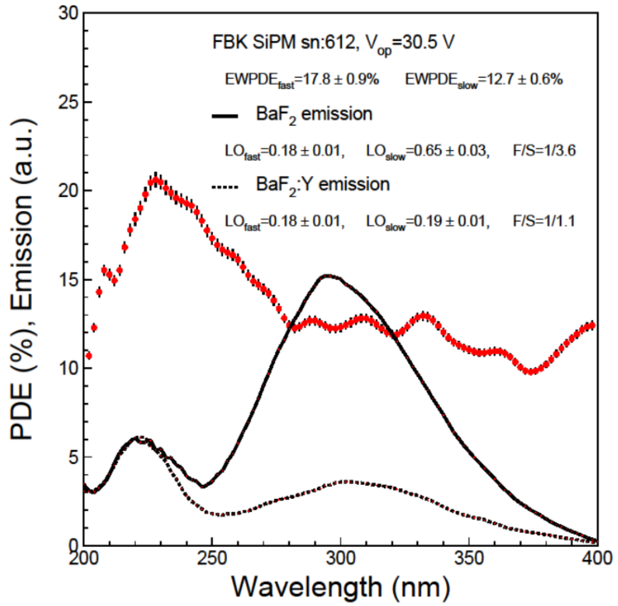
QE/PDE of four VUV photodetectors for BaF_2 and BaF_2:Y

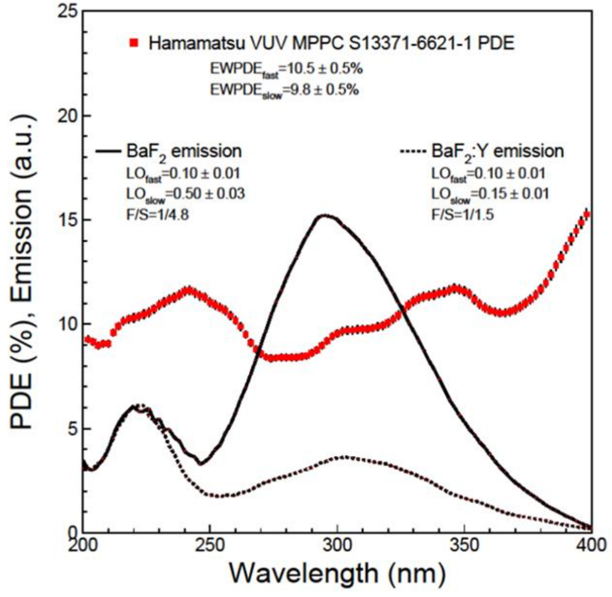
IEEE TNS **69** (2022) 958-964

Photodetector	EWQE/PDE$_{fast}$ (%)	EWQE/PDE$_{slow}$ (%)	EWQE/PDE$_{BaF}$ (%)	EWQE/PDE$_{BaF:Y}$ (%)	Relative LO (50 ns)	Relative F_{BaF}	Relative $F_{BaF:Y}$
Hamamatsu R2059	15.2	20.9	20.0	18.7	1.00	1.00	1.00
Photek Solar-Blind	25.6	10.6	13.0	16.1	1.68	0.65	0.86
FBK SiPM w/UV Filter-I	17.8	12.7	13.5	14.7	1.17	0.68	0.79
Hamamatsu MPPC	10.5	9.8	9.9	10.2	0.69	0.50	0.55









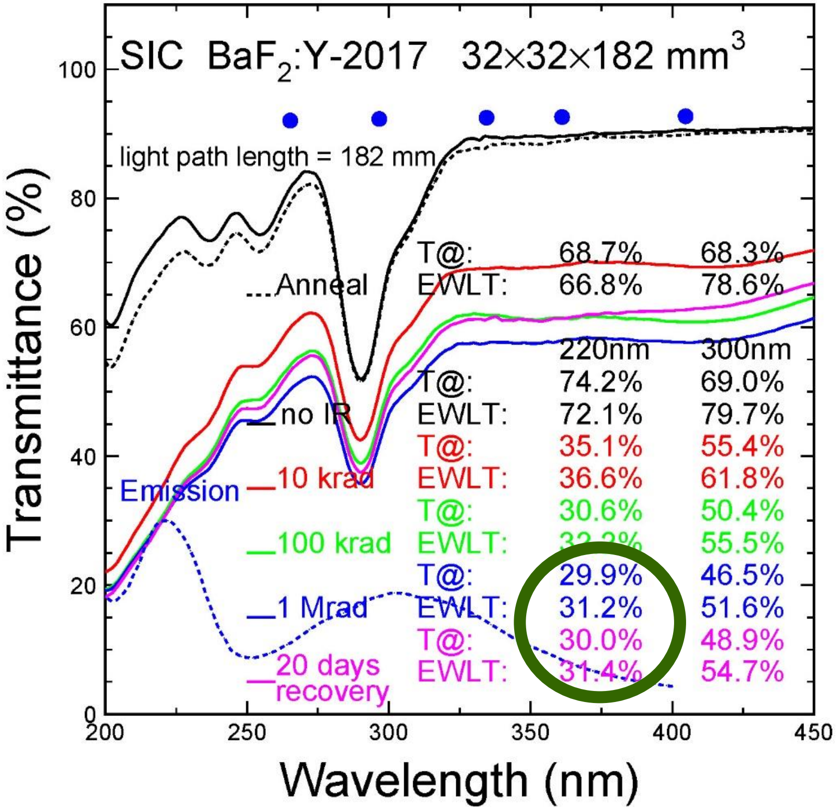
RIN:γ for Four VUV Photodetector

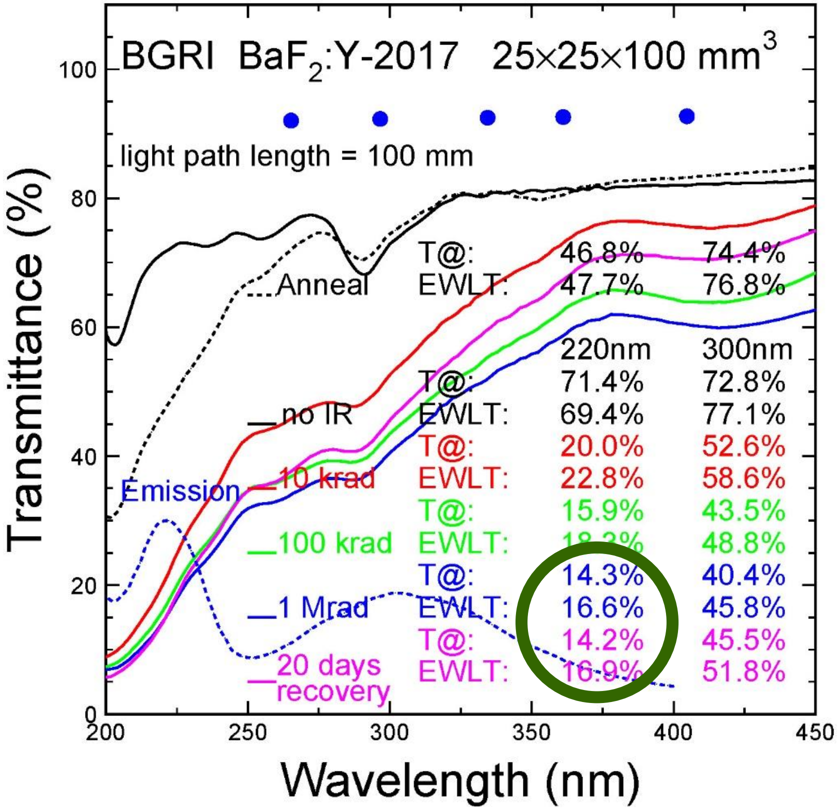
Solar blind photodetector reduces RIN:ɣ significantly

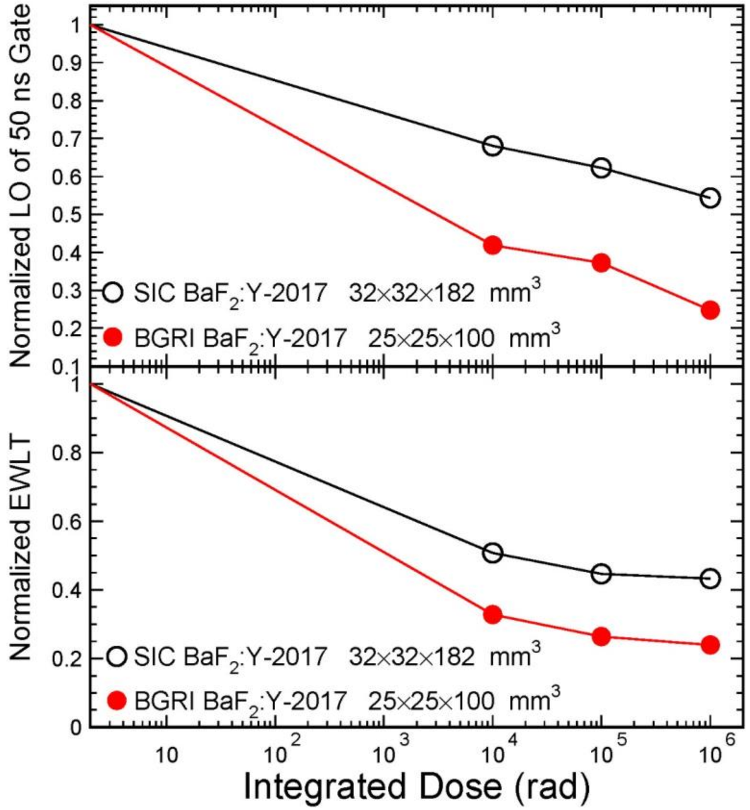
Photodetector	EWQE/PDE$_{fast}$ (%)	EWQE/PDE (%)	LO(50 ns, p.e./MeV)	F	RIN:ɣ (keV)
BGRI BaF_2:Y-2020					
Hamamatsu R2059 PMT	15.2	18.7	53	3.1×10^9	1050
Photek PMT Solar Blind	25.6	16.1	89	2.7×10^9	580
FBK SiPM w/UV Filter-I	17.8	14.7	62	2.4×10^9	800
Hamamatsu VUV MPPC	10.5	10.2	37	1.7×10^9	1120
SIC BaF_2:Y-2020					
Hamamatsu R2059 PMT	15.2	18.7	45	1.3×10^9	810
Photek PMT Solar Blind	25.6	16.1	76	1.1×10^9	450
FBK SiPM w/UV Filter-I	17.8	14.7	53	1.0×10^9	610
Hamamatsu VUV MPPC	10.5	10.2	31	7.1×10^8	870
BGRI BaF_2-1507					
Hamamatsu R2059 PMT	15.2	20.0	46	5.8×10^9	1650
Photek PMT Solar Blind	25.6	13.0	77	3.8×10^9	790
FBK SiPM w/UV Filter-I	17.8	13.5	54	3.9×10^9	1160
Hamamatsu VUV MPPC	10.5	9.9	32	2.9×10^9	1680
SIC BaF_2-2					
Hamamatsu R2059 PMT	15.2	20.0	48	5.8×10^9	1590
Photek PMT Solar Blind	25.6	13.0	81	3.8×10^9	760
FBK SiPM w/UV Filter-I	17.8	13.5	56	3.9×10^9	1120
Hamamatsu VUV MPPC	10.5	9.9	33	2.9×10^9	1620

1 Mrad Damage in Long BaF_2:Y

SIC 2017 BaF_2:Y sample shows a similar performance as BaF_2 crystals
Recovery is very small for the fast scintillation component



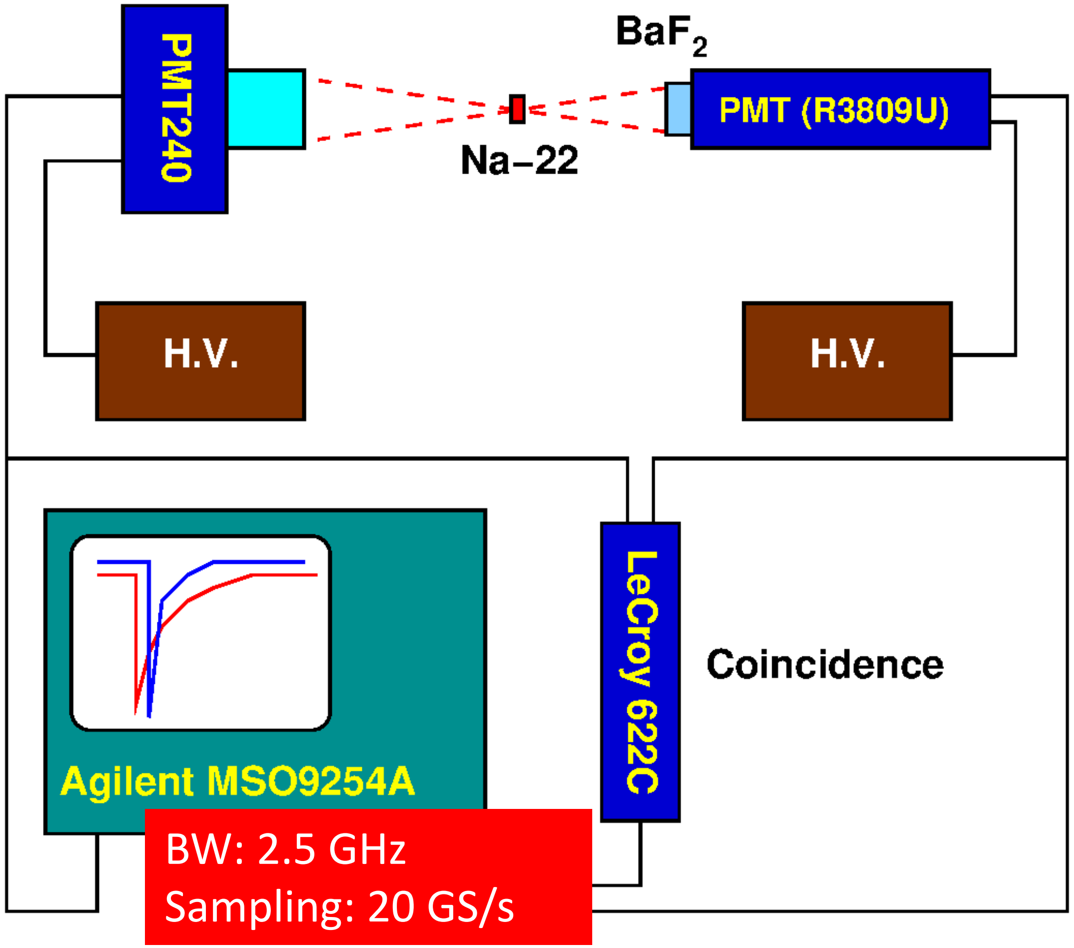




Diverse crystal quality at this stage of R&D, needs improvement

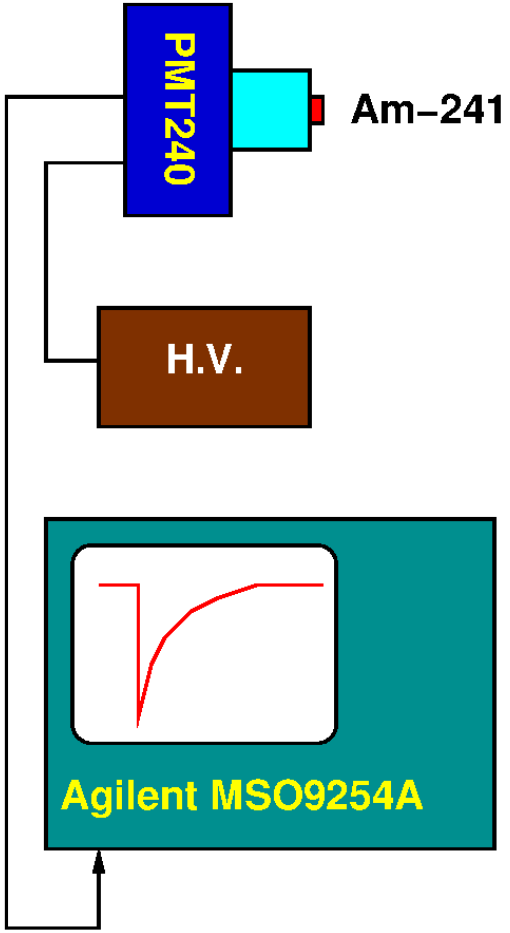
An MCP-PMT 240-Based Test Bench

Na-22 Coincidence Trigger

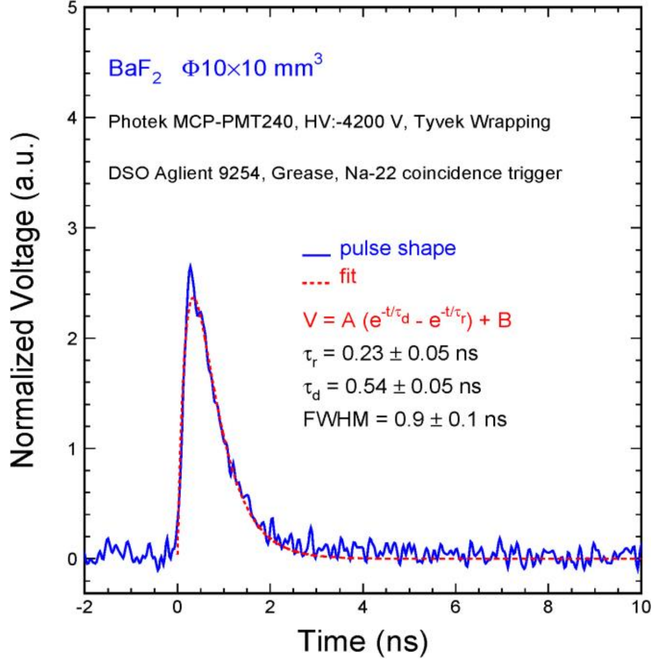


BW: 2.5 GHz
Sampling: 20 GS/s

Am-241 Self Trigger



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



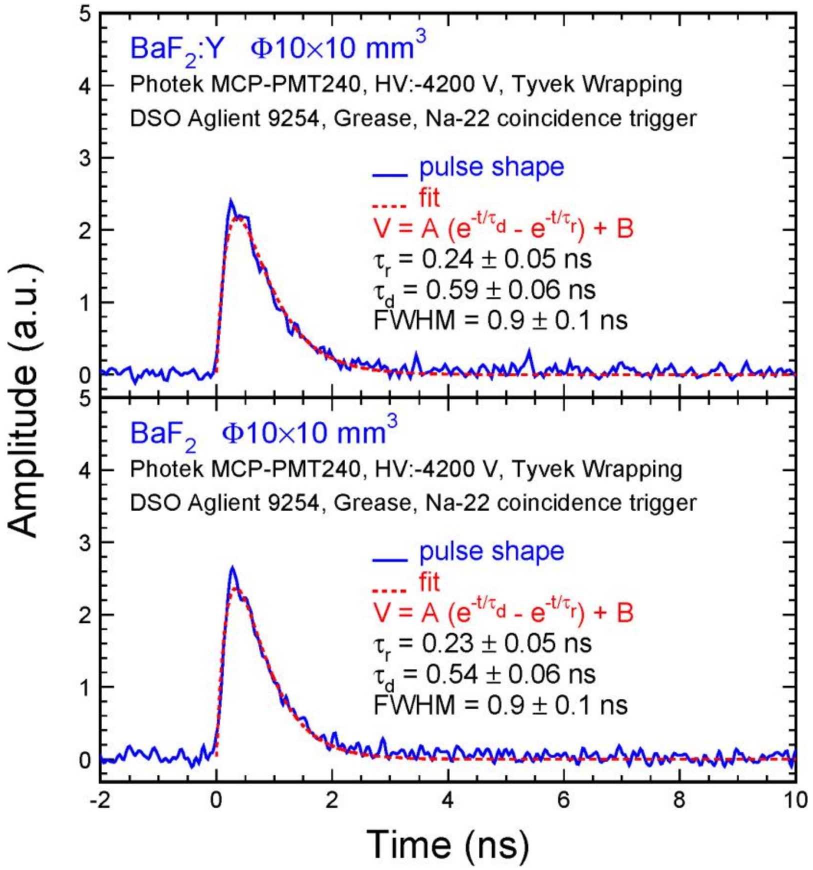
Fitting:

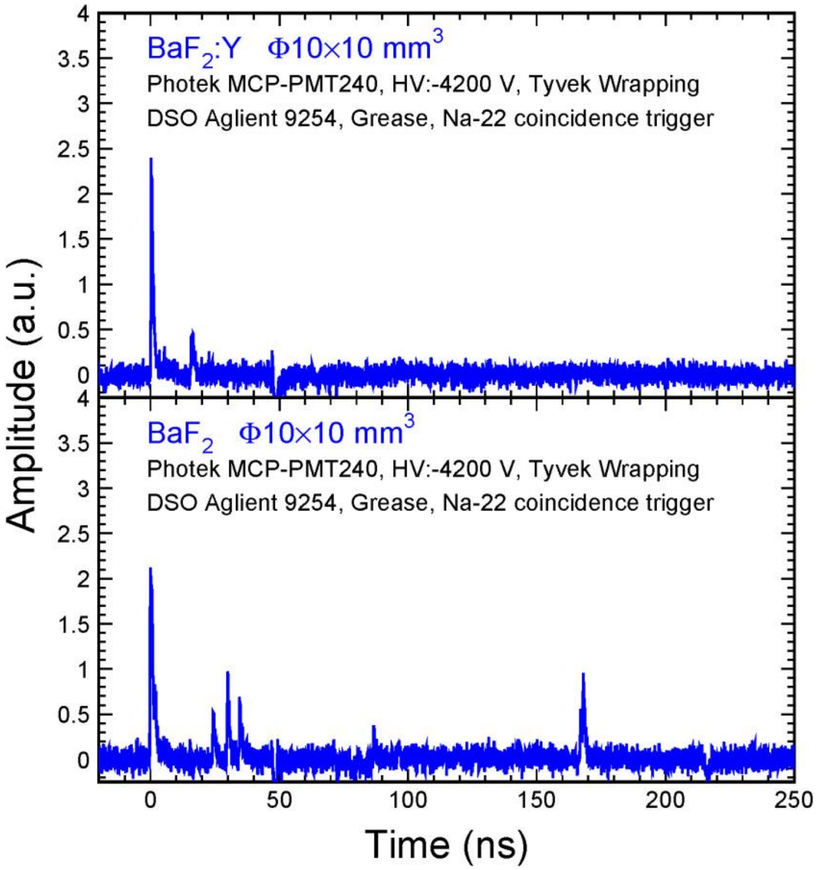
$$V = A(e^{-\frac{t}{\tau_d}} - e^{-\frac{t}{\tau_r}}) + B$$

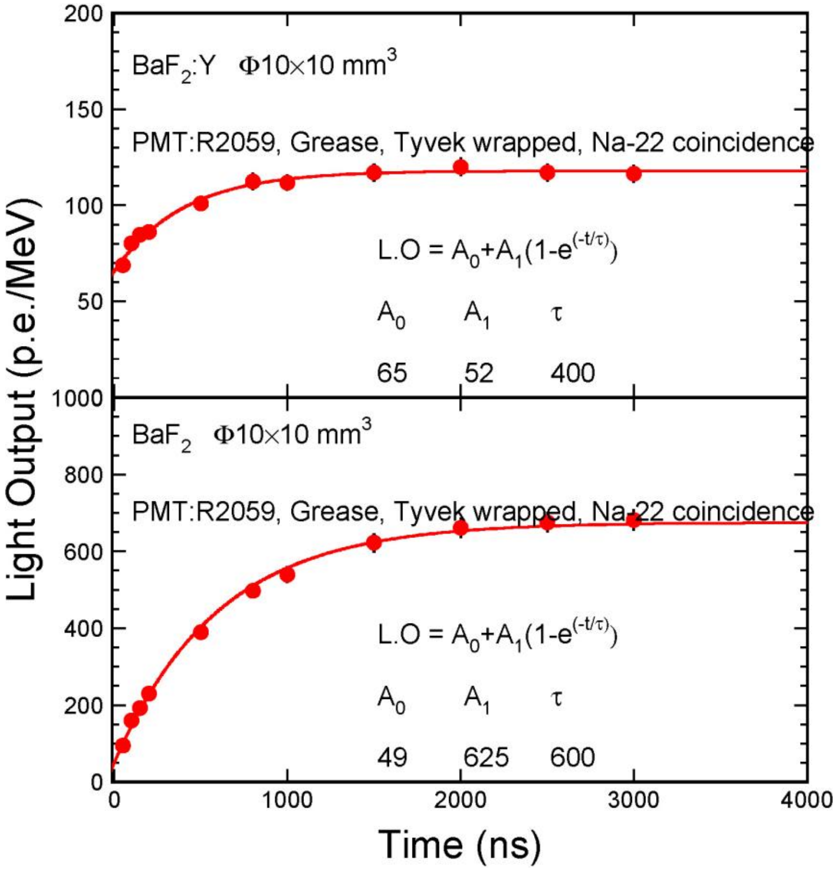
B: background noise
or very slow component,
τ_r: rise time, τ_d: decay time.

Rise, decay and FWHM obtained by fitting temporal response

Temporal Response: BaF_2 & BaF_2:Y

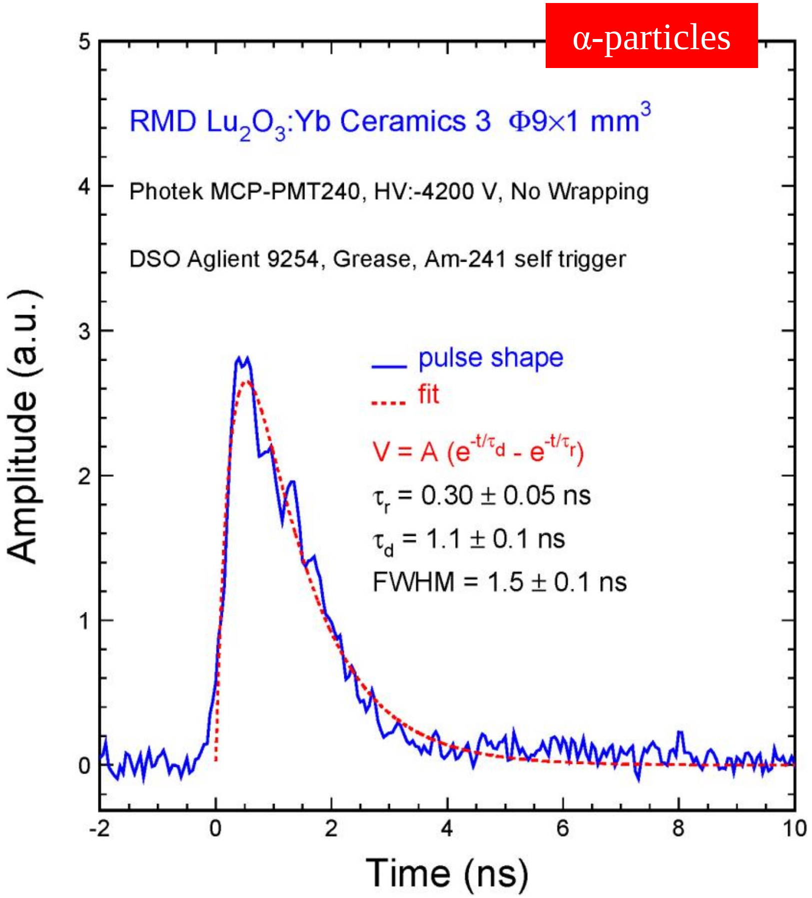


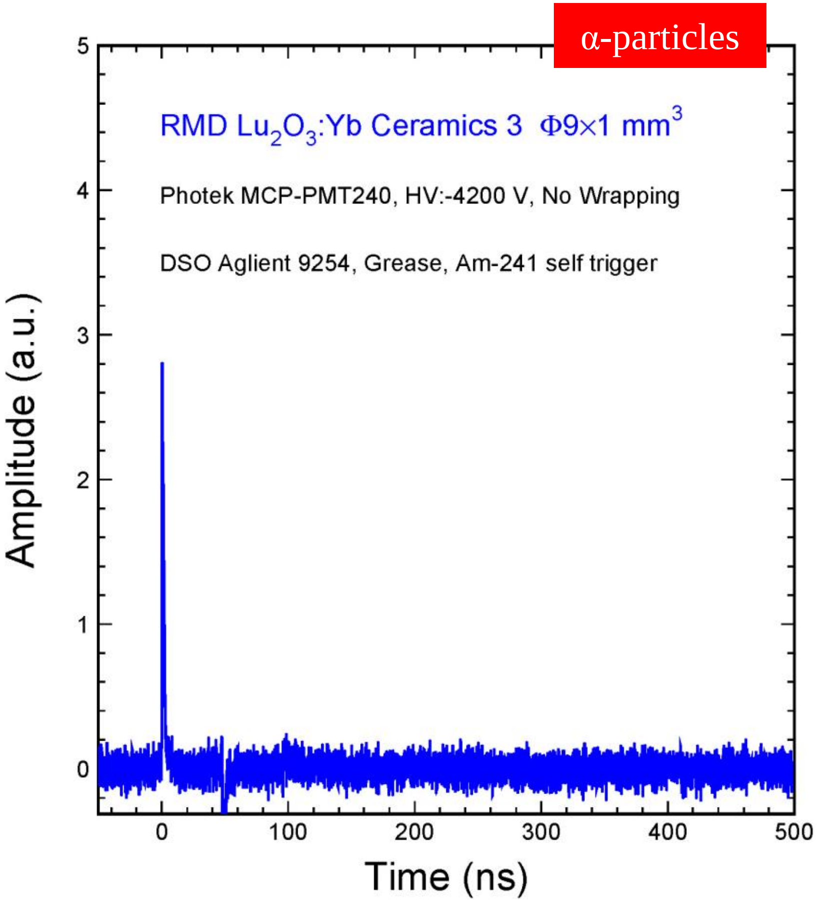


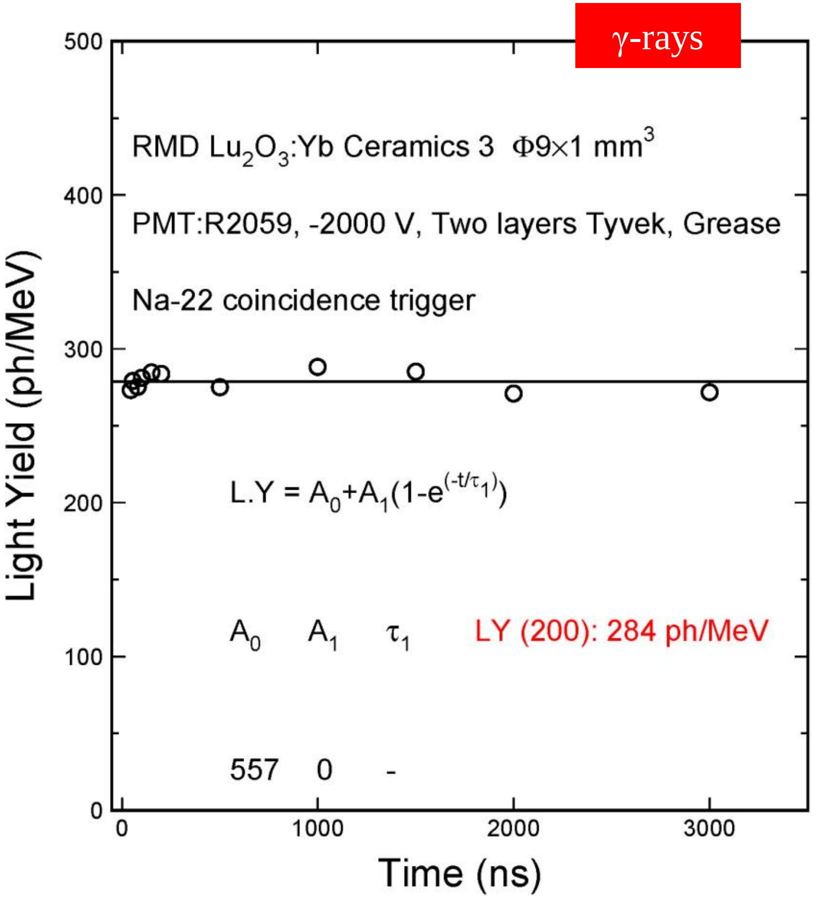


Ultrafast response of 0.2/0.6/0.8 ns observed for BaF_2 and BaF_2:Y crystals
The response is consistent with the Photek MCP-PMT 240 specification

Temporal Response: Lu_2O_3:Yb Ceramics

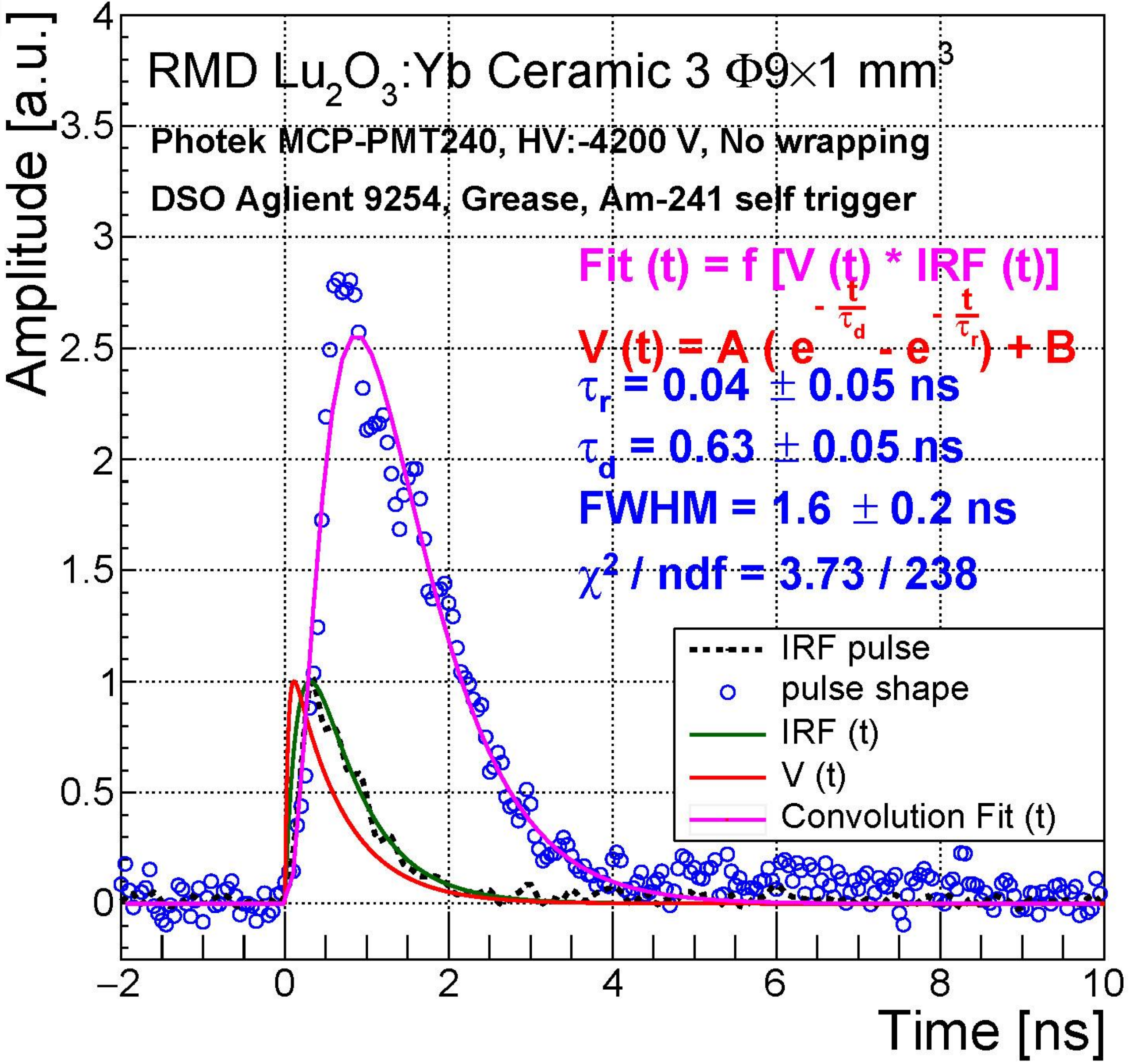






Lu_2O_3:Yb ceramic of 9.4 g/cc shows an ultrafast decay time of **1.1 ns** by Am-241 with negligible slow component observed in integrated light output measurement

Intrinsic Decay Time of Lu_2O_3:Yb

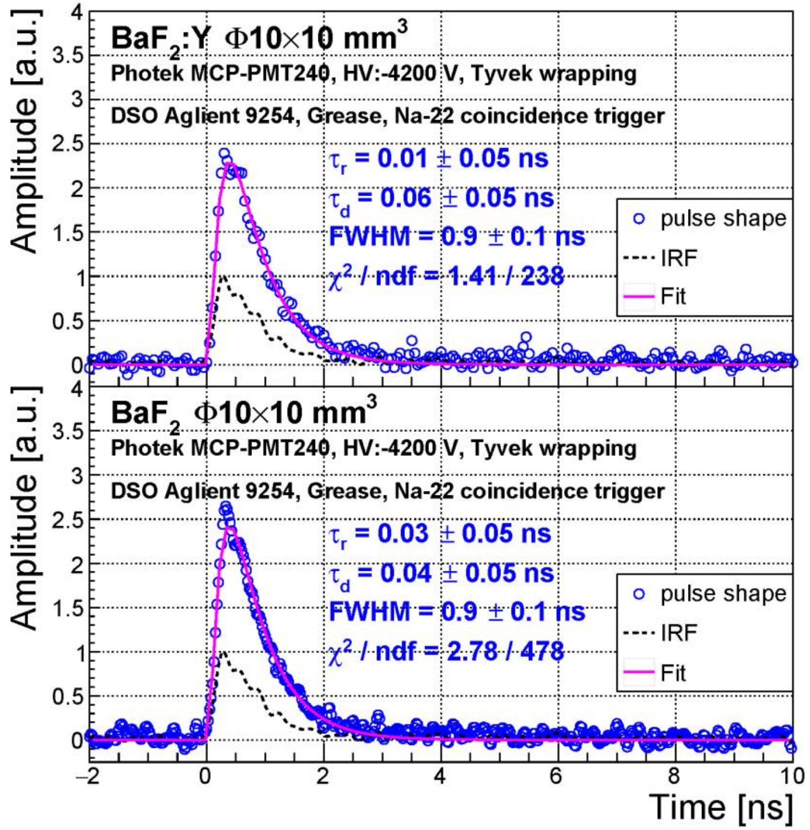


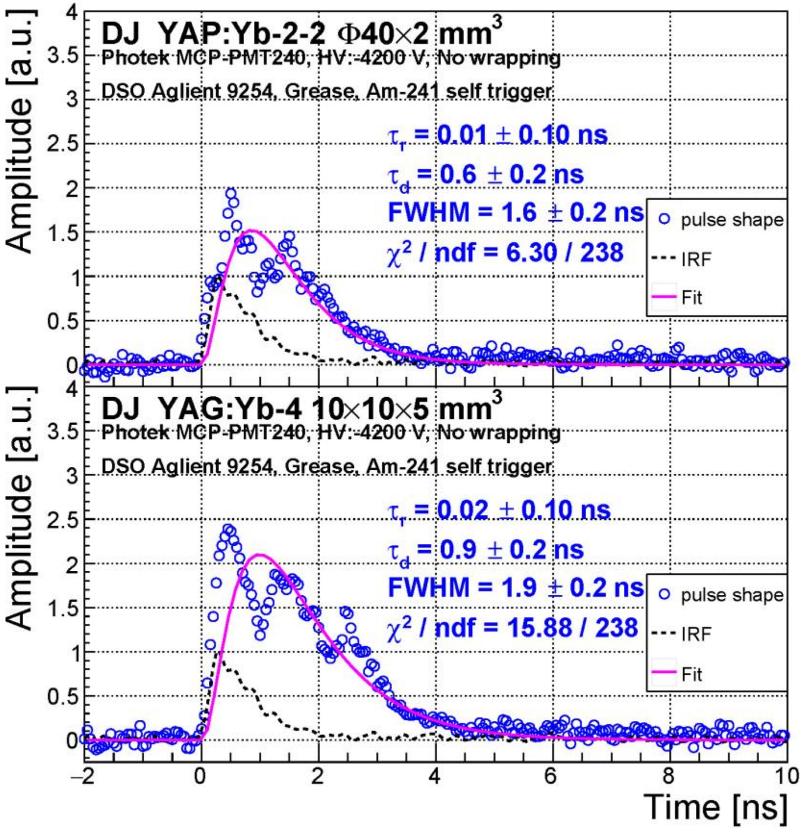
The magenta line shows the convolution fit. The numerical result of the fit after taking out the IRF are shown in blue

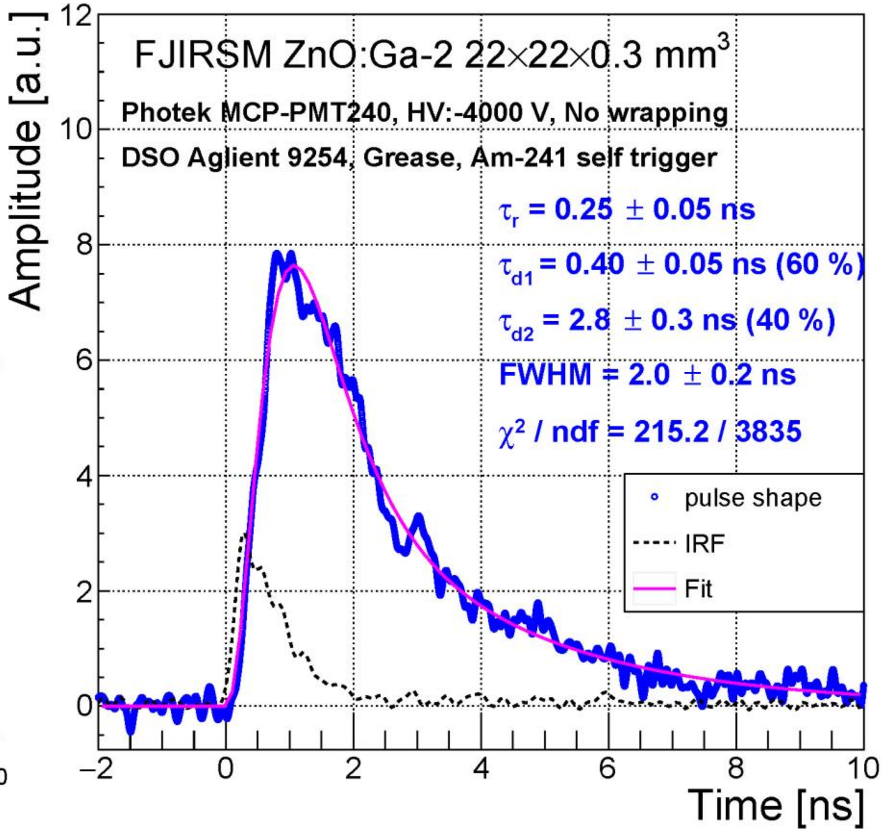
The result of the 0.63 ns decay time is the intrinsic decay time of Lu_2O_3:Yb

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 of BaF_2/BaF_2:Y consists with the IRF, indicating less than 100 ps







Fast/Ultrafast for HEP TOF & X-ray Imaging

arXiv: 2203.06788

	BaF$_2$	BaF$_2$:Y	Lu$_2$O$_3$:Yb	YAP:Yb	YAG:Yb	ZnO:Ga	β-Ga$_2$O$_3$	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.

Bulk Fast/Ultrafast Crystals

Most crystals have mass-production capability or potential

	LSO/LYSO	GAGG	GSO	YSO	CsI	BaF_2:Y	BaF_2	PWO	CeF_3	$CeBr_3$	$LaCl_3$	$LaBr_3$
Density (g/cm^3)	7.4	6.5	6.71	4.44	4.51	4.89	4.89	8.30	6.16	5.23	3.86	5.29
Melting Points (°C)	2050	1850	1950	2070	621	1280	1280	1123	1460	722	858	783
Radiation Length (cm)	1.14	1.63	1.38	3.10	1.86	2.03	2.03	0.89	1.7	1.96	2.81	1.88
Molière Radius (cm)	2.07	2.20	2.23	2.93	3.57	3.1	3.1	2.0	2.41	2.97	3.71	2.85
Interaction Length (cm)	20.9	21.5	22.2	27.8	39.3	30.7	30.7	20.7	23.2	31.5	37.6	30.4
Z value	63.7	50.6	57.9	32.8	54	51.6	51.6	74.5	50.8	45.6	47.3	45.6
dE/dX (MeV/cm)	9.55	8.96	8.88	6.57	5.56	6.52	6.52	10.1	8.42	6.65	5.27	6.9
Emission Peak[a] (nm)	420	540	430	420	310	300 220	300 220	425 420	340 300	371	335	356
Refractive Index[b]	1.82	1.94	1.85	1.8	1.95	1.5	1.5	2.2	1.62	1.9	1.9	1.9
Light Yield[a] (Photons/MeV)	30,000	98,00 48,200	13,500	24,000	1,070 330	600 1,400	11,600 1,400	100 30	2,500	30,000	4,500 14,500	46,000
Decay Time[a] (ns)	40	570 130	73	75	30 6	600 0.5	600 0.5	30 10	30	17	570 24	20
d(LY)/dT[c] (%/°C)	-0.2	~0?	-0.4	-0.1	-1.4	-1.9 0.1	-1.9 0.1	-2.5	~0	-0.1	0.1	0.2

[a] top/bottom row: slow/fast component; [b] at the emission peak; [c] at room temperature (20°C).

LYSO:Ce, BaF_2 and CsI are considered by Mu2e-I, with CsI finally chosen

SIC Mass-Produced Crystals (Mar 2019)

Scaling to X_0, order of crystal cost: PWO, BGO, CsI, BSO, BaF_2:Y, LYSO

Item	Size	1 m^3	10 m^3	100 m^3	Scaled to X_0
BGO	22.3×22.3×280 mm	\$8/cc	\$7/cc	\$6/cc	1.23
BaF_2:Y	31.0×31.0×507.5 cm	\$12/cc	\$11/cc	\$10/cc	2.28
LYSO:Ce	20.7x20.7x285 mm	\$36/cc	\$34/cc	\$32/cc	1.28
PWO	20x20x223 mm	\$9/cc	\$8/cc	\$7.5/cc	1.00
BSO	22x22x274 mm	\$8.5/cc	\$7.5/cc	\$7.0/cc	1.29
CsI	35.7x35.7x465 mm	\$4.6/cc	\$4.3/cc	\$4.0/cc	2.09

Summary

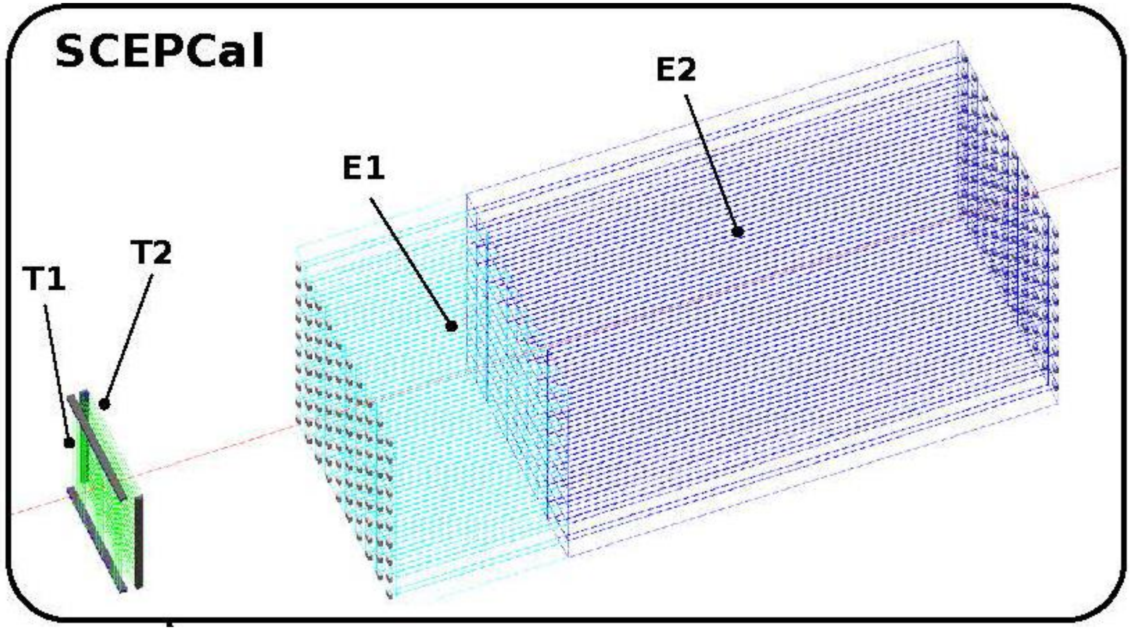
- Caltech HEP Crystal Lab is developing rad-hard, fast/ultrafast and cost-effective inorganic scintillators for future HEP experiments.
- Ultrafast inorganic scintillators under development for HEP applications, such as BaF_2:Y and Lu_2O_3:Yb, may break the pico-second timing barrier for HEP TOF. BaF_2:Y may also offer ultrafast total absorption calorimetry.
- Other inorganic scintillators may be considered:
  - LYSO:Ce if affordable;
  - PWO if readout noise and radiation hardness are tolerable;
  - $LaBr_3$ or $CeBr_3$ if their hygroscopicity can be handled;
  - CeF_3 if self-absorption and high cost can be handled.
- R&D work is required to understand and use fast/ultrafast inorganic scintillator for future high-rate experiments.

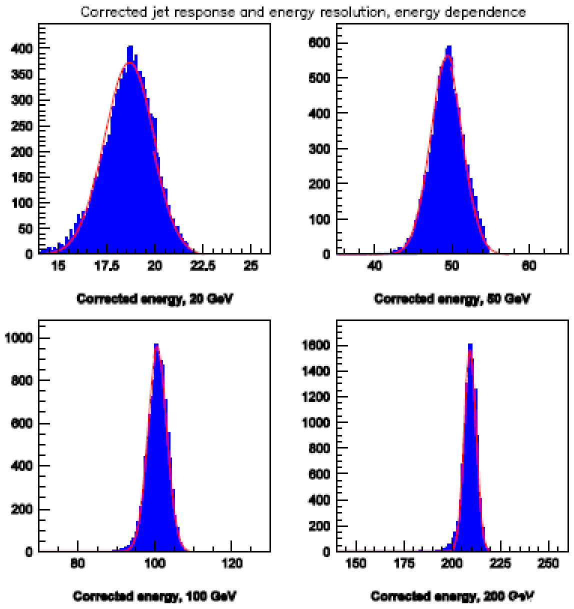
Acknowledgements: DOE HEP Award DE-SC0011925

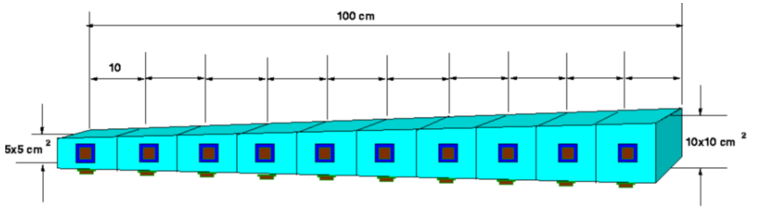
Cost-Effective Inorganic Scintillators for FCC-ee

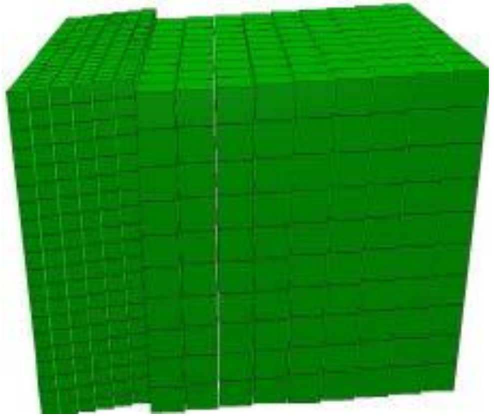
CalVision Crystal Calorimetry

- 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









Low-Cost Inorganic Scintillators

Scintillating glasses will be investigated after crystals

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO Glass	DSB:Ce Glass[1]	DSB:Ce,Gd Glass[2,3]	HFG Glass[4]
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	3.8	4.7 - 5.4	5.95
Melting point (℃)	1050	1030	1123	824	608	2040	980[5]	1420[6]	1420[6]	570
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	3.36	2.14	1.74
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.89	3.52	2.56	2.45
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	32.8	24.2	23.2
Z_{eff} value	72.9	75.3	74.5	77.4	75.8	11.2	42.8	44.4	48.7	56.9
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	5.56	7.68	8.24
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	440 460	440 460	325
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	\	\	\	1.50
LY (ph/MeV)[c]	7,500	1,500	130	\	150	7,900	450	3,150	2,500	150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	180 30	120, 400 50	25 8
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?	?	?	-0.04	-0.04	-0.37
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6?	?	2.0	2.0?	?

Low density crystals/glasses

a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. At room temperature (20°C).

1. E. Auffray, et al., J. Phys. Conf. Ser. 587, 2015
2. R. W. Novotny, et al., J. Phys. Conf. Ser. 928, 2017
3. V. Dormenev , et al., the ATTRACT Final Conference
4. E. Auffray, et al., NIMA 380 (1996), 524-536
5. R. A. McCauley et al., Trans. Br. Ceram. Soc., 67. 1968
6. I. G. Oehlschlegel, Glastech. Ber. 44, 1971