Recent Progresses of Inorganic Scintillators for Future HEP Experiments

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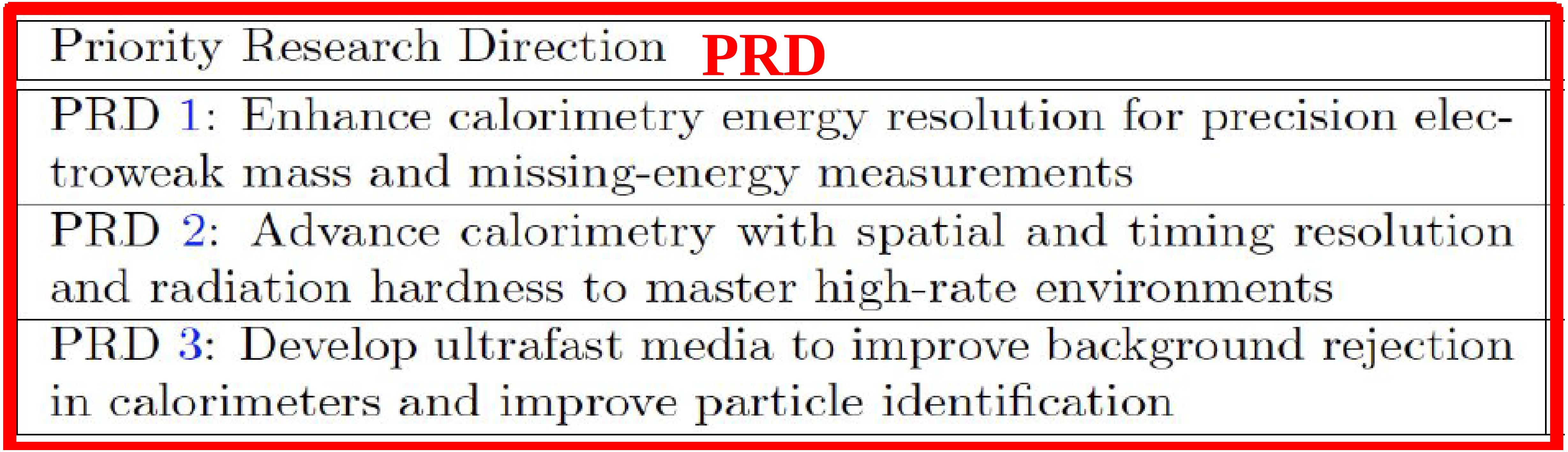
2019 DOE Basic Research Needs Study on Instrumentation for Calorimetry



Priority Research Direction **PRD**
PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements
PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification

Snowmass 2022 White Paper "Materials for Future Calorimeters"
arXiv 2203.07154, or https://doi.org/10.48550/2203.07154
Fast/ultrafast, radiation hard and cost-effective active material

Why Inorganic Scintillators

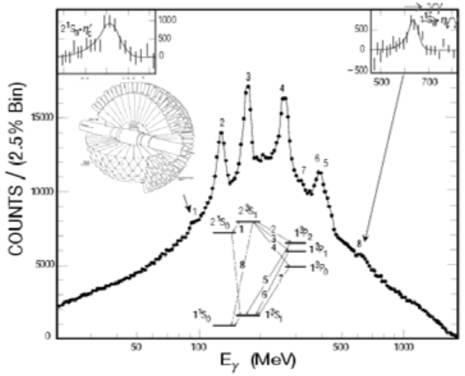
- **Precision photons and electrons enhance physics discovery potential.**
- **Crystal performance is well understood:**
  - **The best possible energy resolution and position resolution;**
  - **Good e/γ identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout,: C/S or F/S gate.**
- **Challenges at future HEP Experiments:**
  - **Fast and radiation hard scintillators for the HL-LHC and FCC-hh;**
  - **Ultrafast scintillators to break ps timing barrier & Mu2e-II ECAL;**
  - **Cost-effective crystals for the proposed Higgs factory.**
- **Inorganic scintillators at Caltech Crystal Lab:**
  - **Radiation hard LYSO:Ce and LuAG:Ce ceramics;**
  - **Ultrafast BaF_2:Y crystals and Lu_2O_3:Yb ceramics;**
  - **BGO, BSO & PWO crystals and heavy scintillating glasses.**

arXiv: 2203.06731 and arXiv: 2203.06788

Crystal ECAL Physics

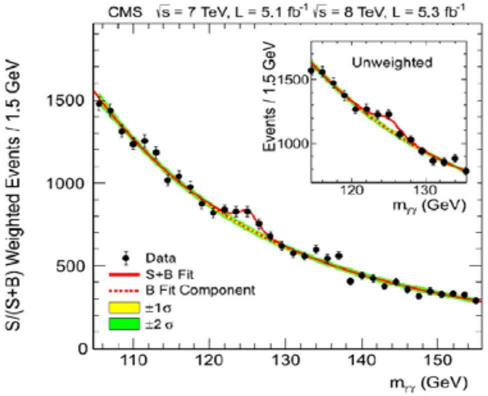
Charmonium system observed by CB through Inclusive photons

CB NaI(Tl)



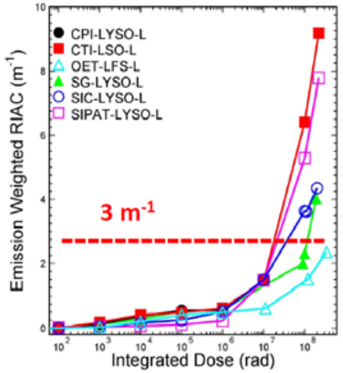
Higgs -> γγ by CMS through reconstructing photon pairs

CMS PWO

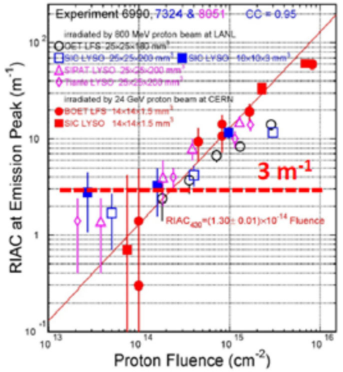


LYSO:Ce Crystals for CMS BTL

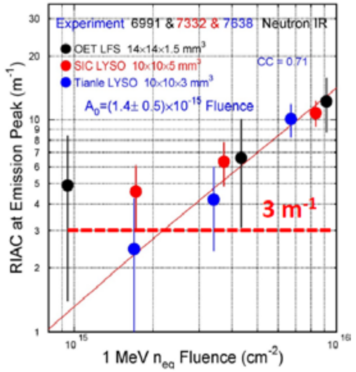
NIM A **824** (2016) 726-728



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



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

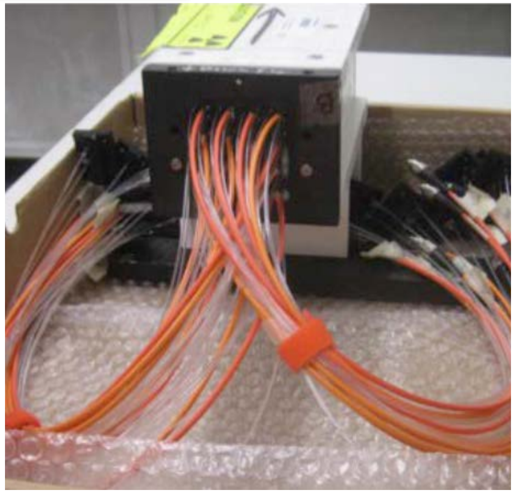


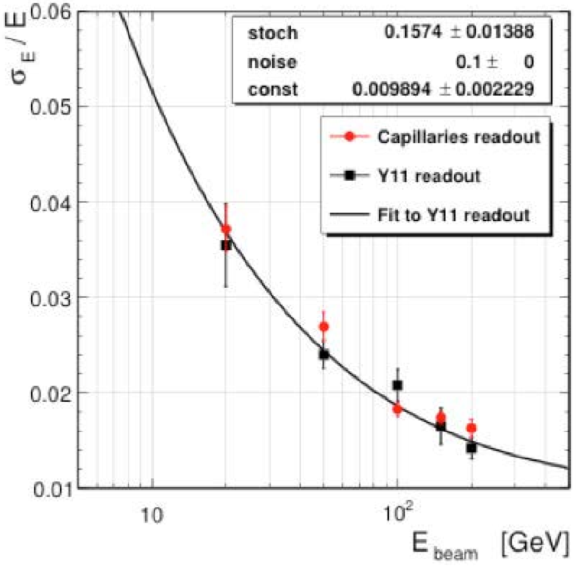
Crystals damaged by both proton and neutron. Damage by proton is larger than that from neutrons because of ionization energy loss in addition to displacement and nuclear breakup

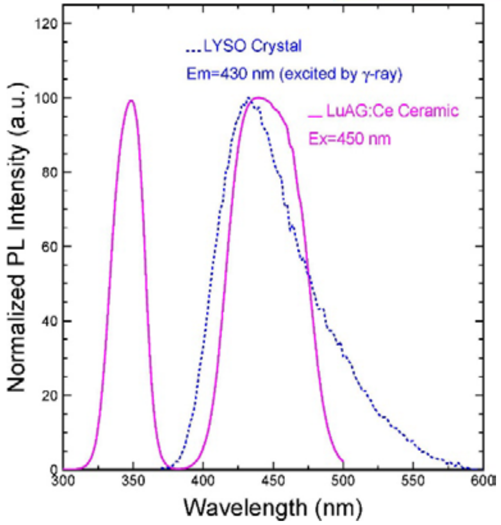
RADiCAL: LYSO/LuAG Shashlik ECAL

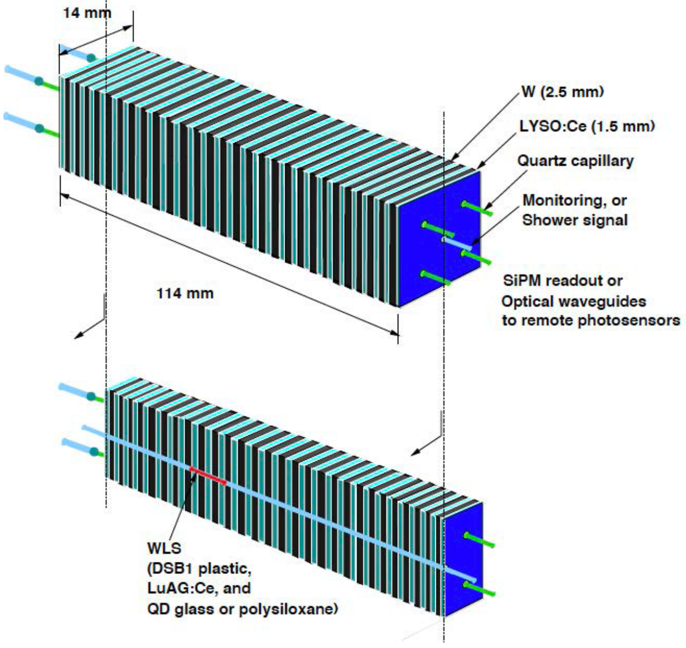
arXiv: 2203.12806 (N35-6)

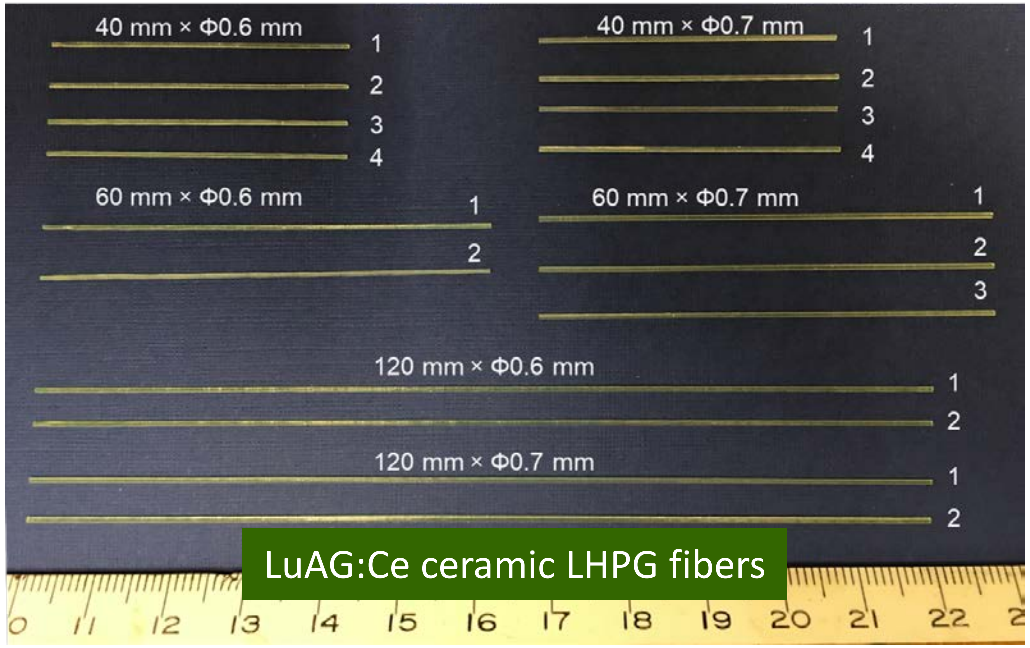
RADiation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission



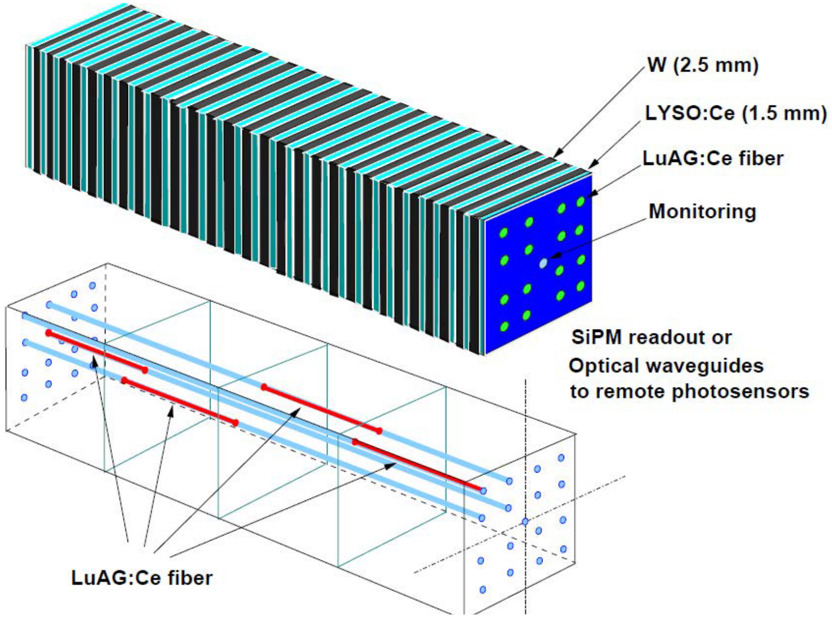








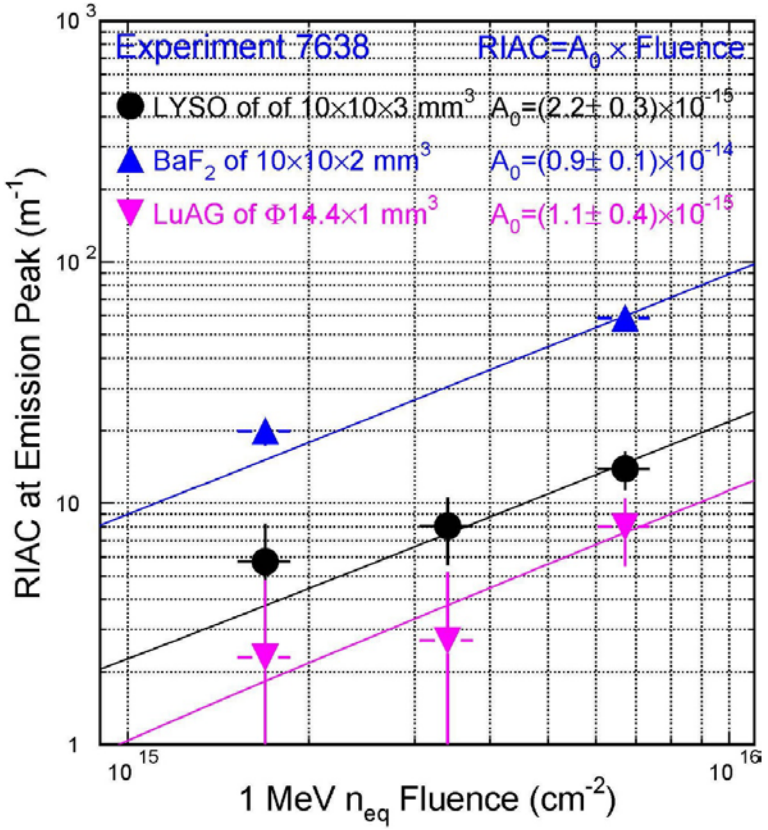
LuAG:Ce ceramic LHPG fibers

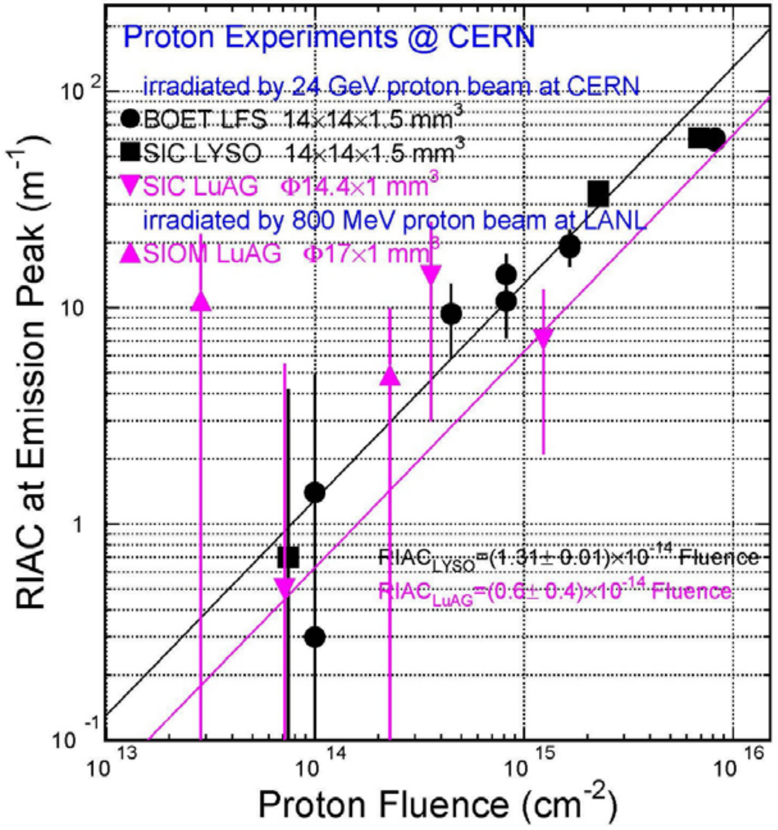


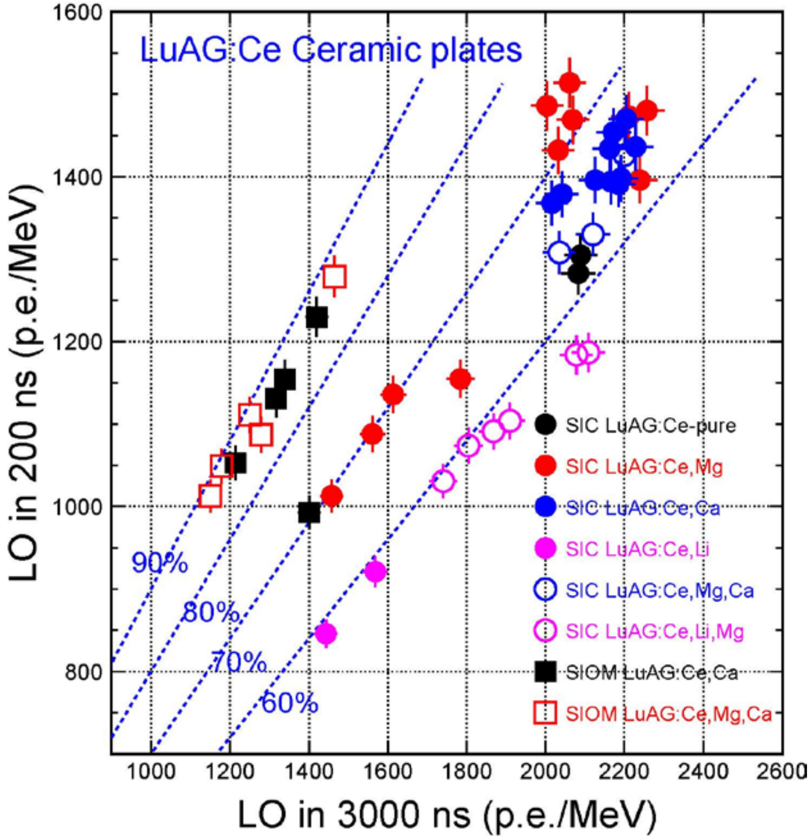
LuAG:Ce Ceramics Radiation Hardness

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



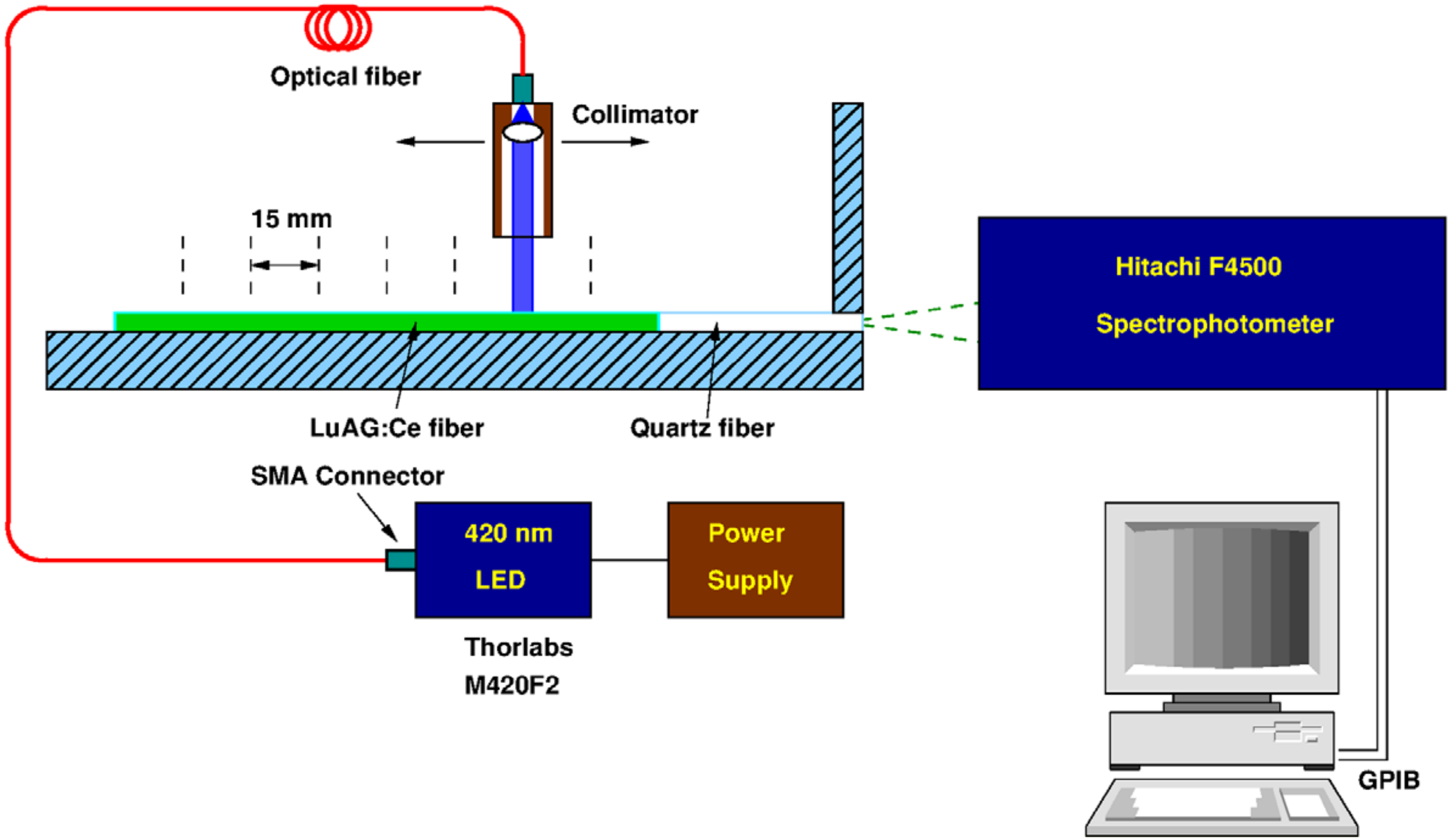


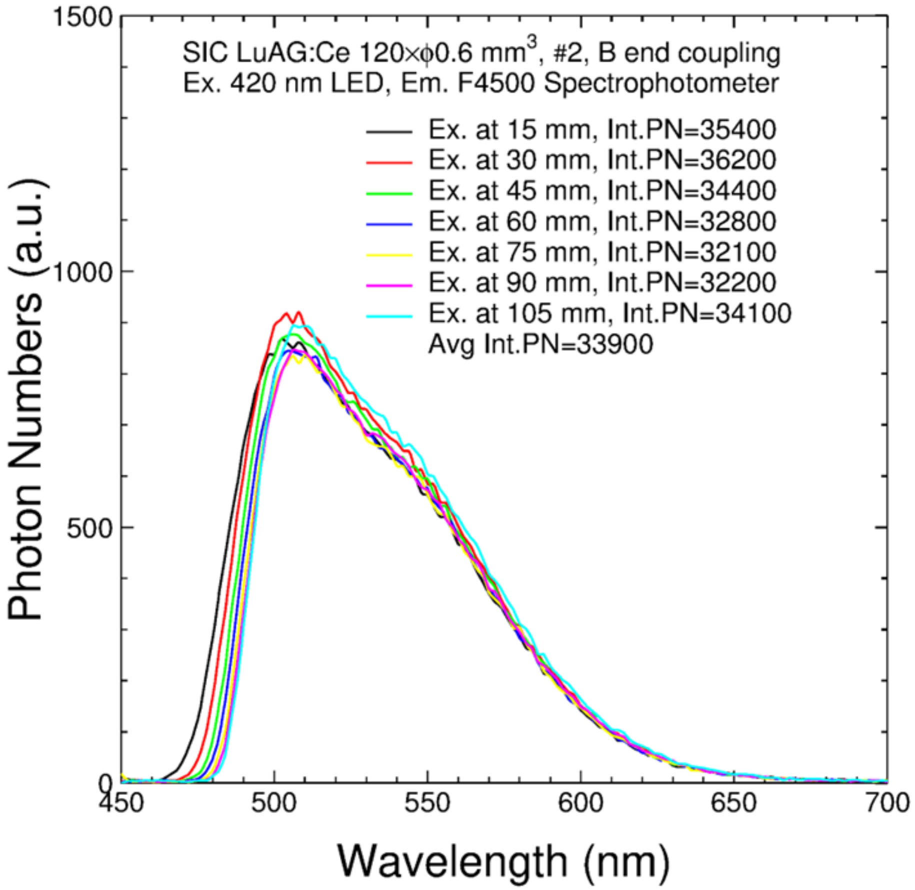


R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

Light Output and Response Uniformity

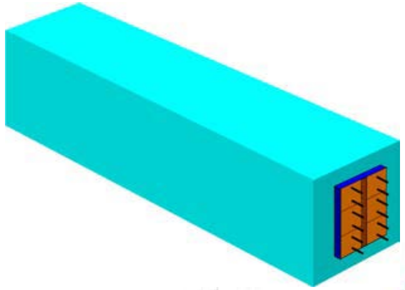
Excellent longitudinal uniformity observed for a Φ0.6 ×120 mm³ LuAG:Ce ceramic excited by a 420 nm LED at different location, with a solid coupling to a quartz fiber, mimicking its application in RADiCAL





Ultrafast BaF_2:Y Calorimeter for Mu2e-II

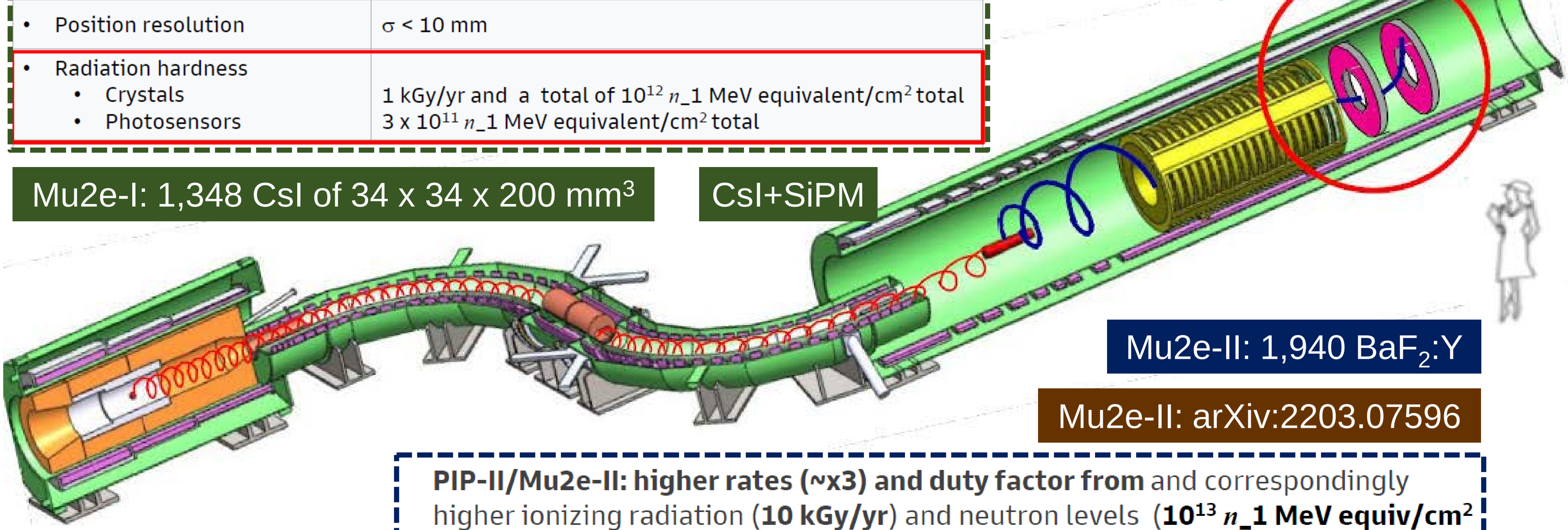
Use ultrafast material to mitigate pile-up



• 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



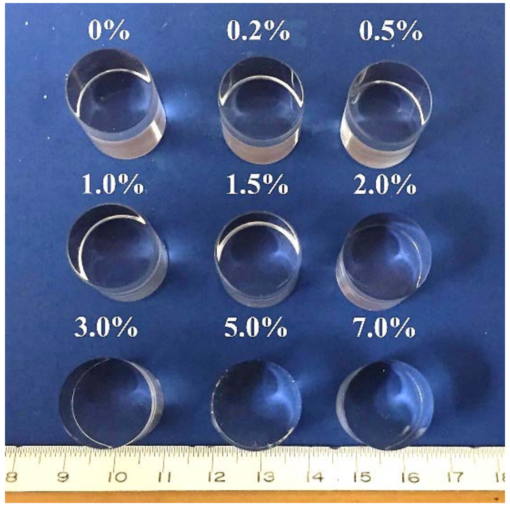
Mu2e-II: 1,940 BaF_2:Y

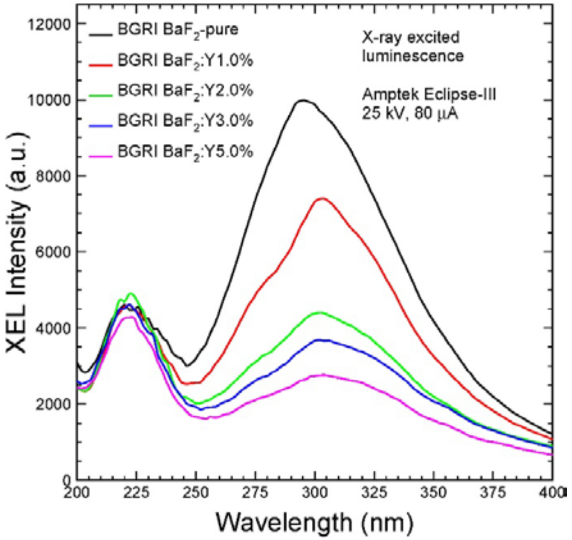
Mu2e-II: arXiv:2203.07596

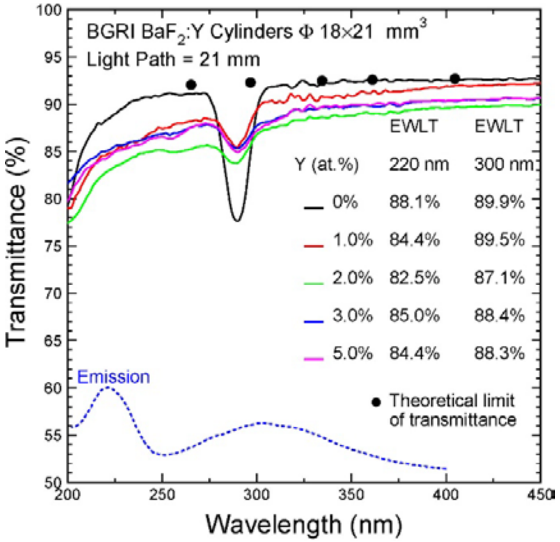
PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm^2 total**), which are particularly important at the inner radius of disk 1

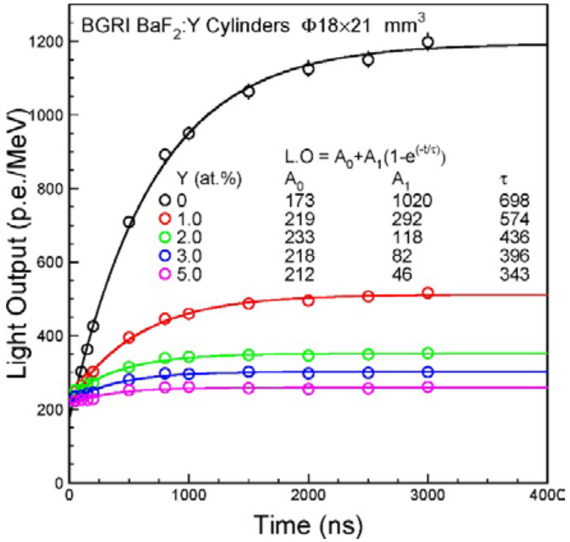
BaF$_2$:Y for Calorimetry & Imaging

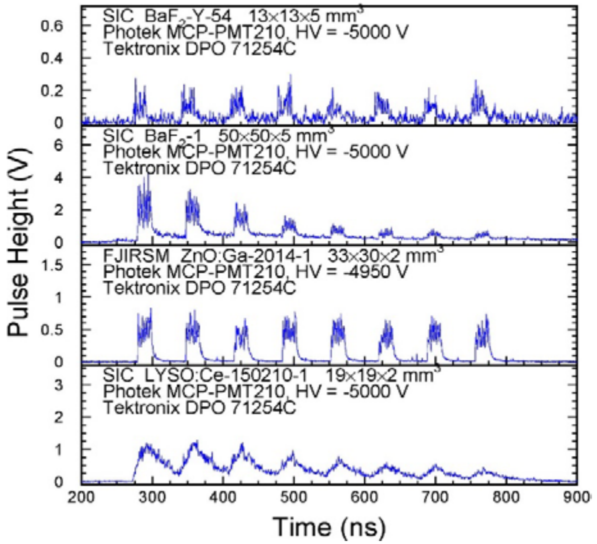
Increased F/S ratio observed in BGRI BaF$_2$:Y crystals: Proc. SPIE 10392 (2017)

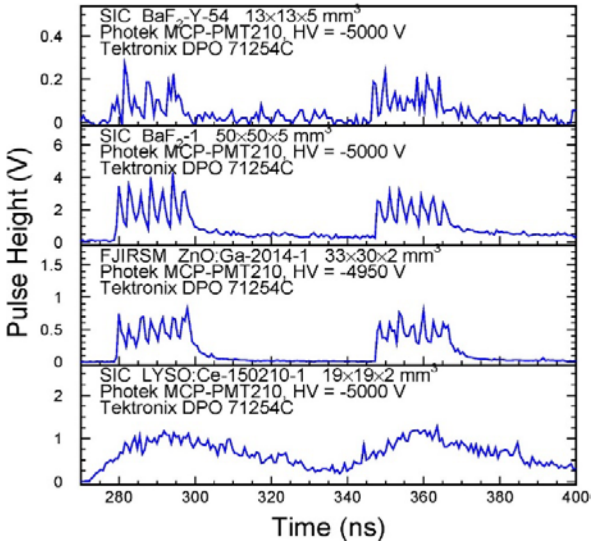


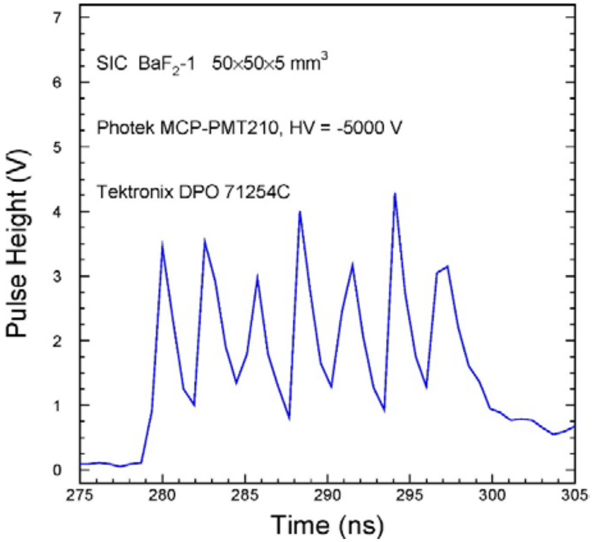








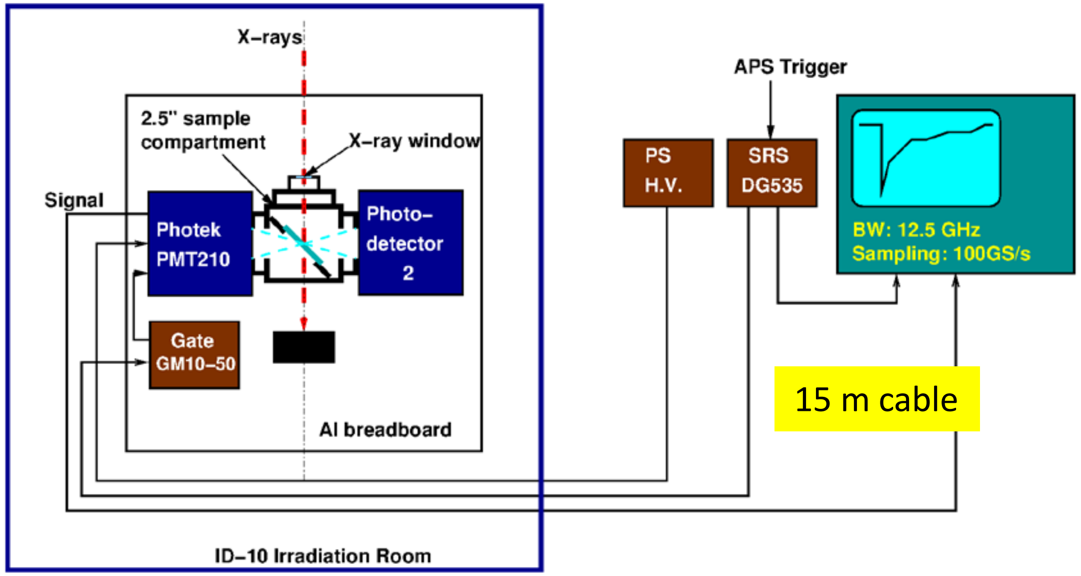


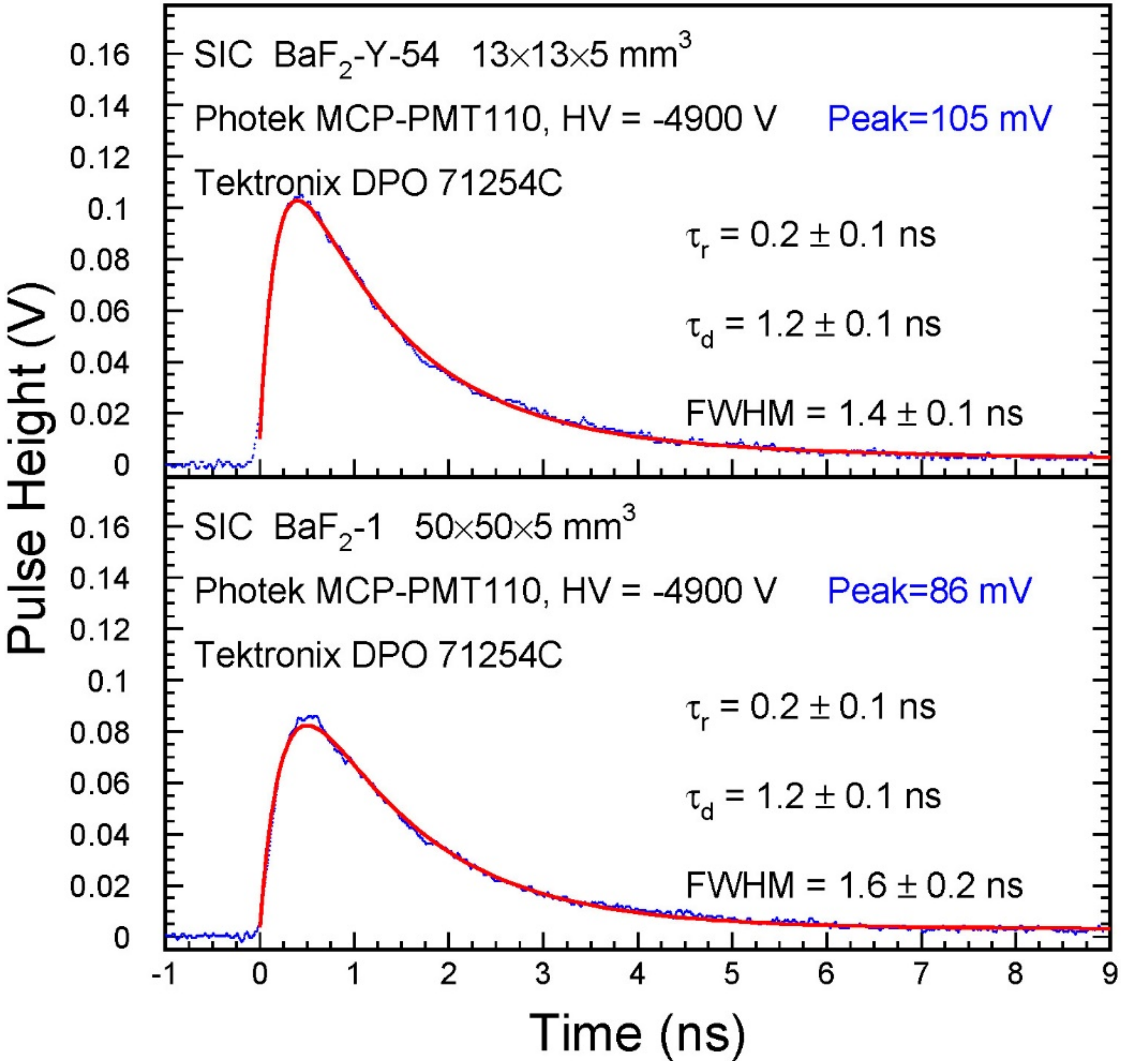


X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF$_2$:Y and BaF$_2$ crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

A Puzzle of Long Decay Observed at APS

NIM A **940** (2019) 223–229

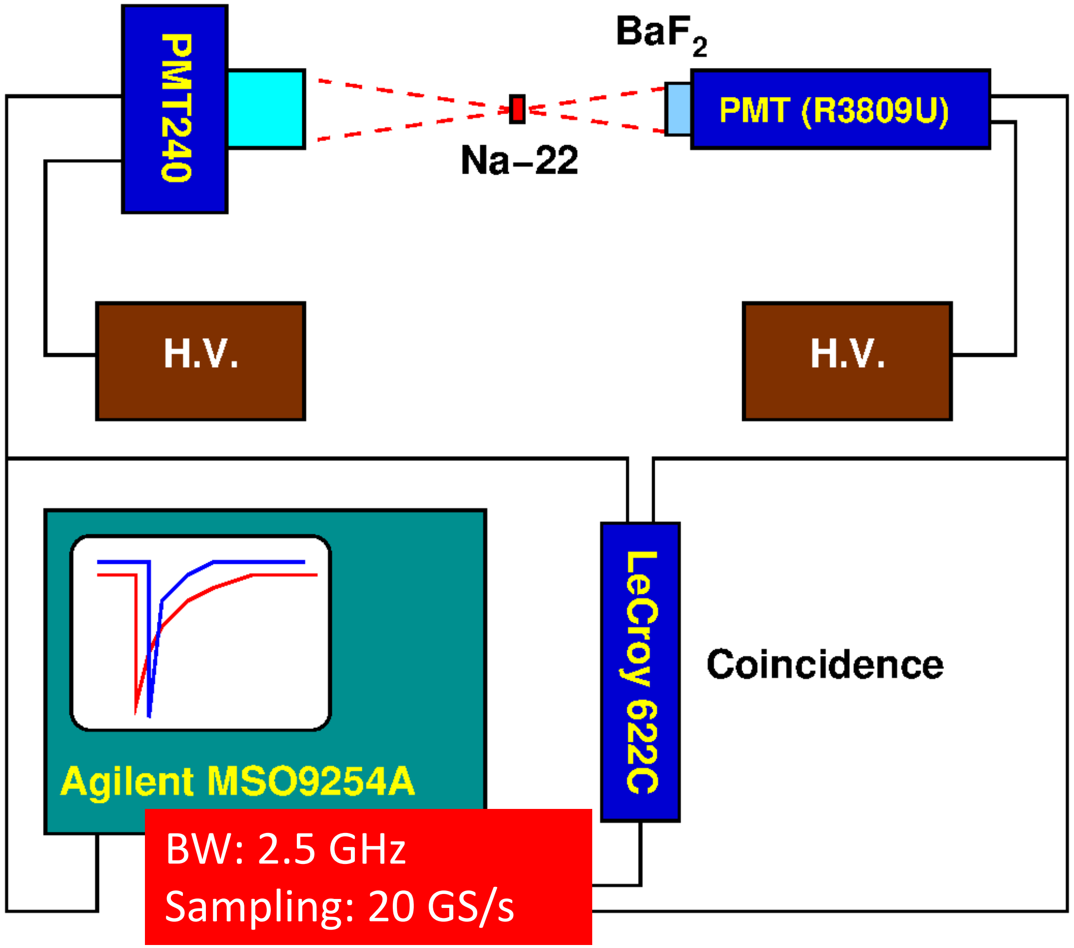




The decay time of BaF$_2$ measured at APS for septuplet X-ray bunches with 2.83 ns spacing is longer than 1 ns. This is suspected to be caused by the 15 m long cable used between the MCP-PMT and the MSO

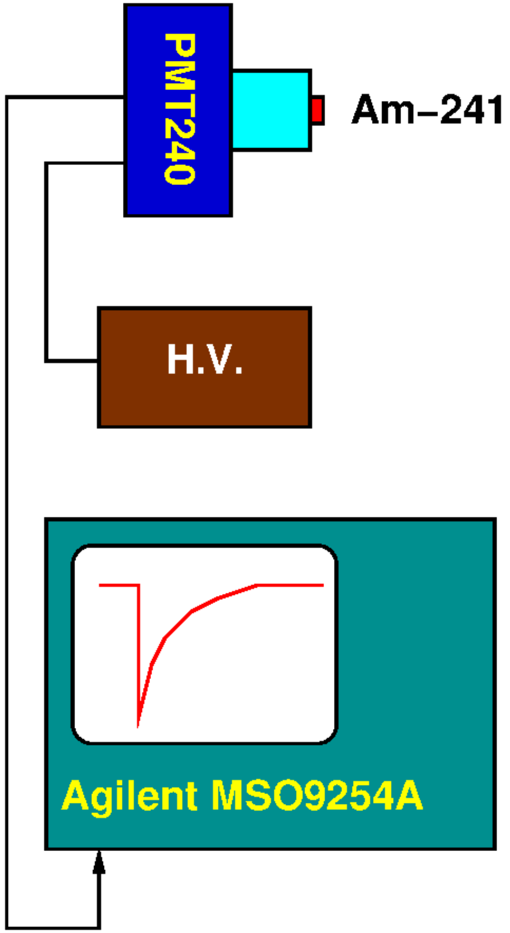
An MCP-PMT 240-Based Test Bench

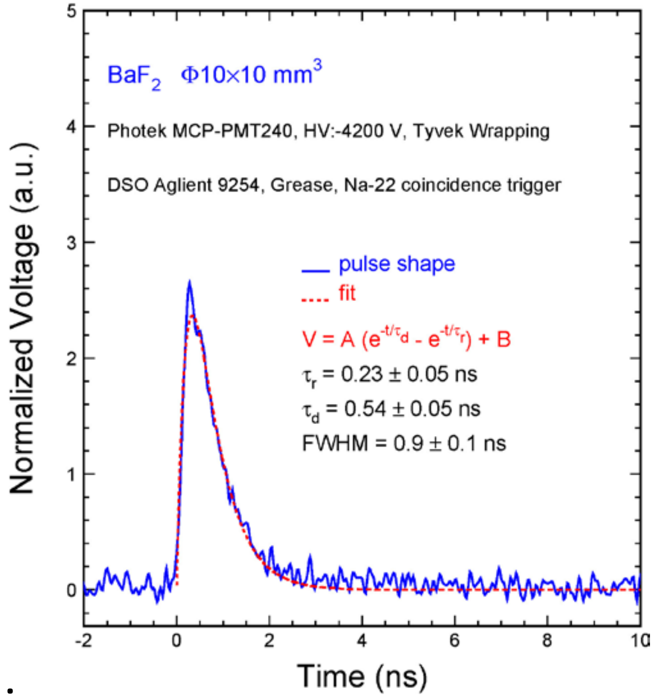
Na-22 Coincidence Trigger



BW: 2.5 GHz
Sampling: 20 GS/s

Am-241 Self Trigger





Fitting:

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

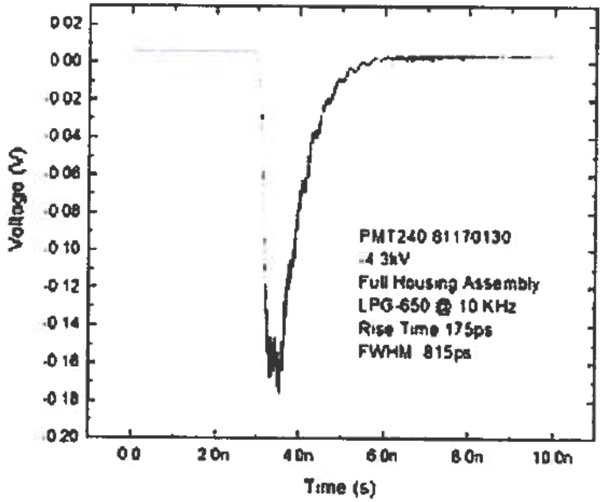
B: background noise
or slow component,
τ_r: rise time,
τ_d: decay time.

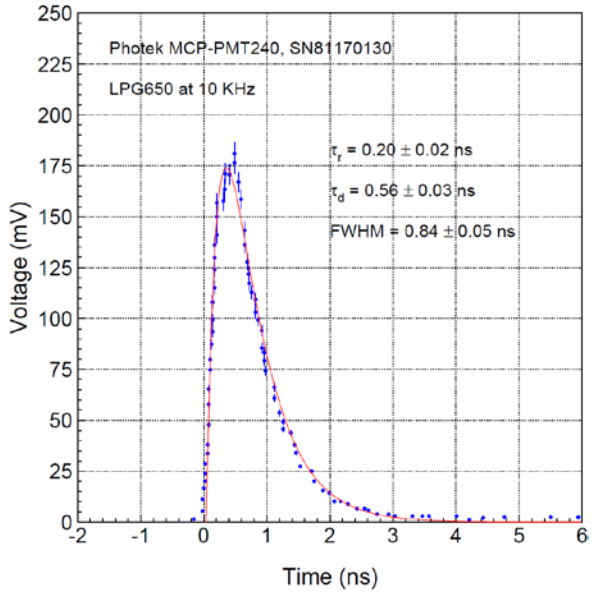
Rise, decay and FWHM obtained by fitting temporal response

MCP-PMT 240 Temporal Response

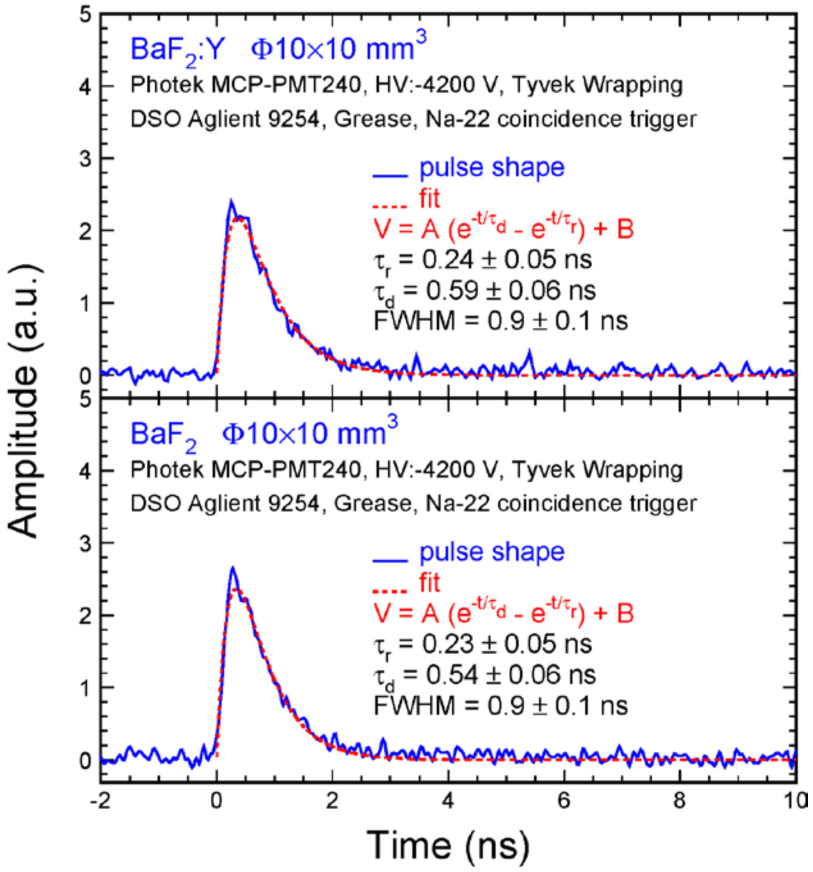
A fit to response of the Photek MCP-PMT 240 for pico-second laser pulses shows both the rise and FWHM consistent with the specification

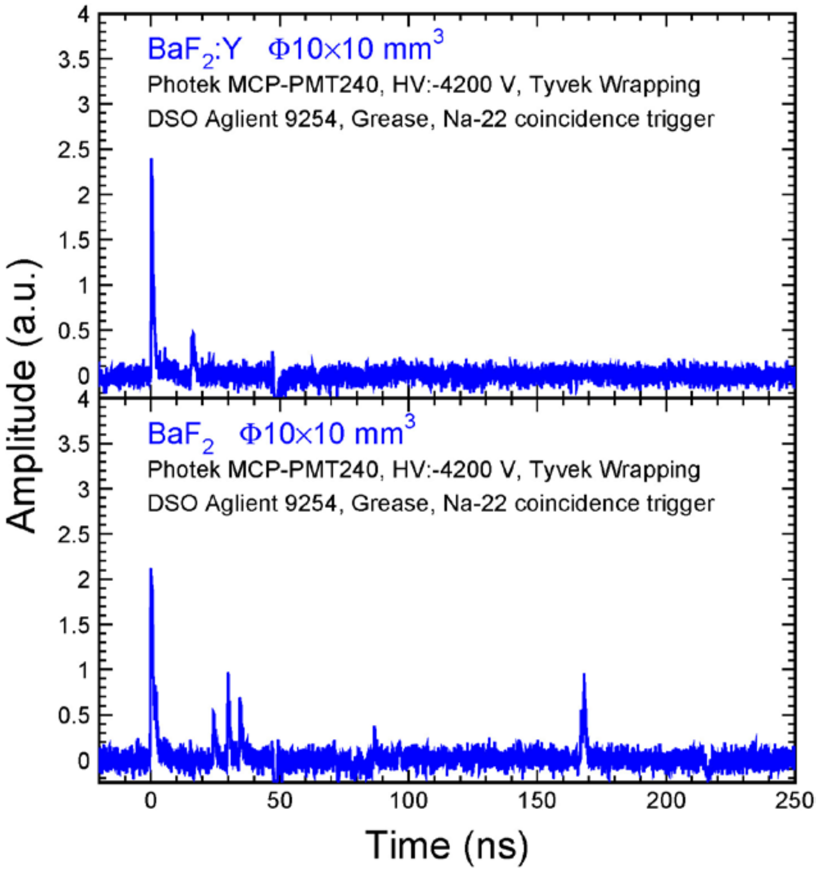
Photodetector	Active diameter (mm)	Spectral range (nm)	Peak Sen. (nm)	Gain	Rise time (ns)	FWHM (ns)
Photek MCP-PMT 240	**40**	**160-850**	**280-450**	**1×10^6**	**0.180**	**0.82**
Hamamatsu MCP-PMT R3809U-50	**11**	**160-850**	**430**	**3×10^5**	**0.160**	**0.30**
Photek MCP-PMT 110	10	160-850	280-450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

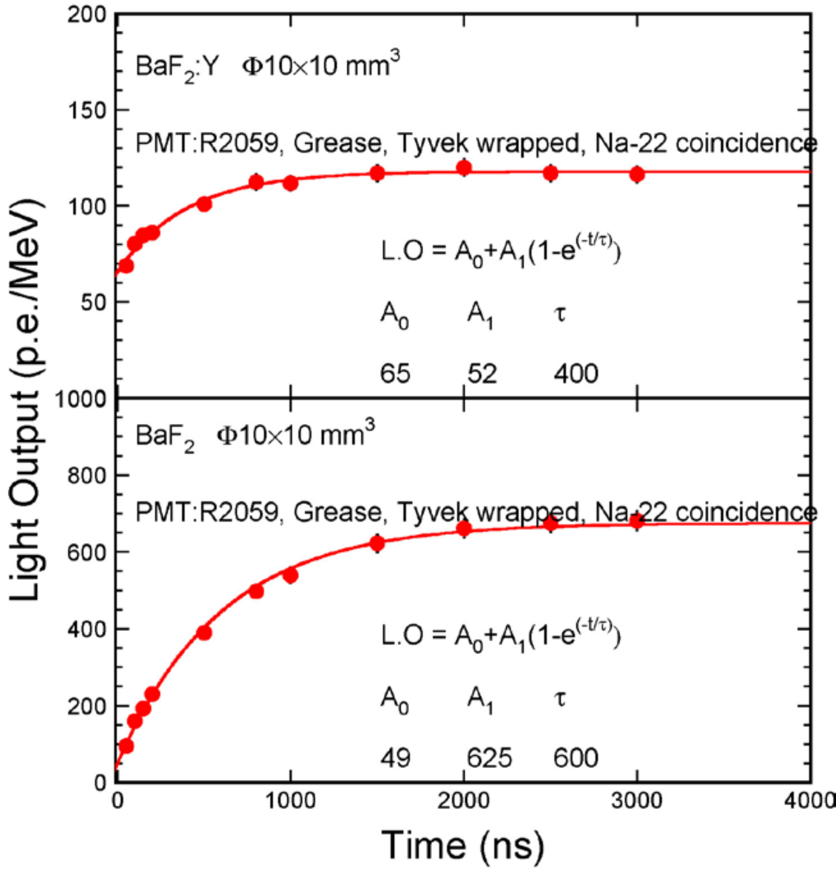




Temporal Response: BaF_2 & BaF_2:Y

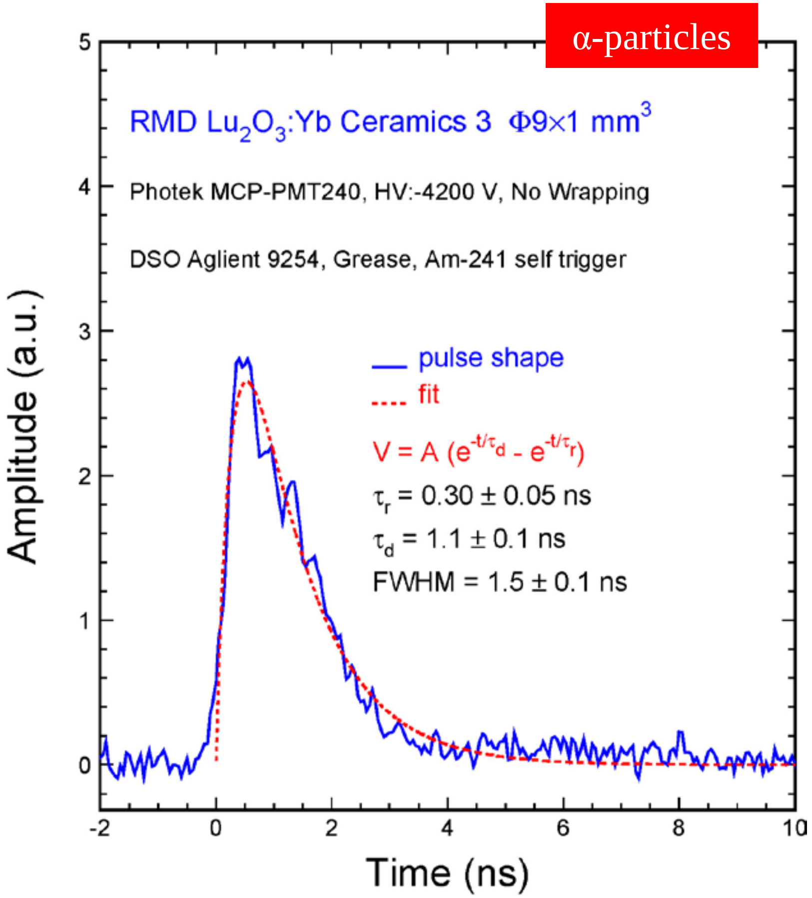


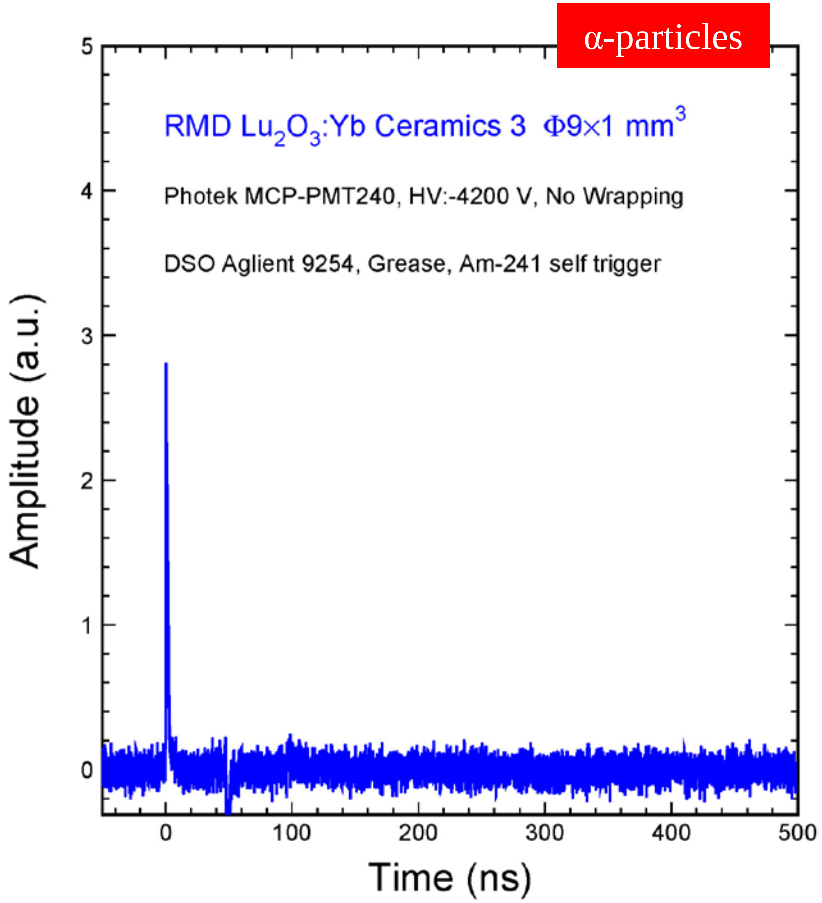


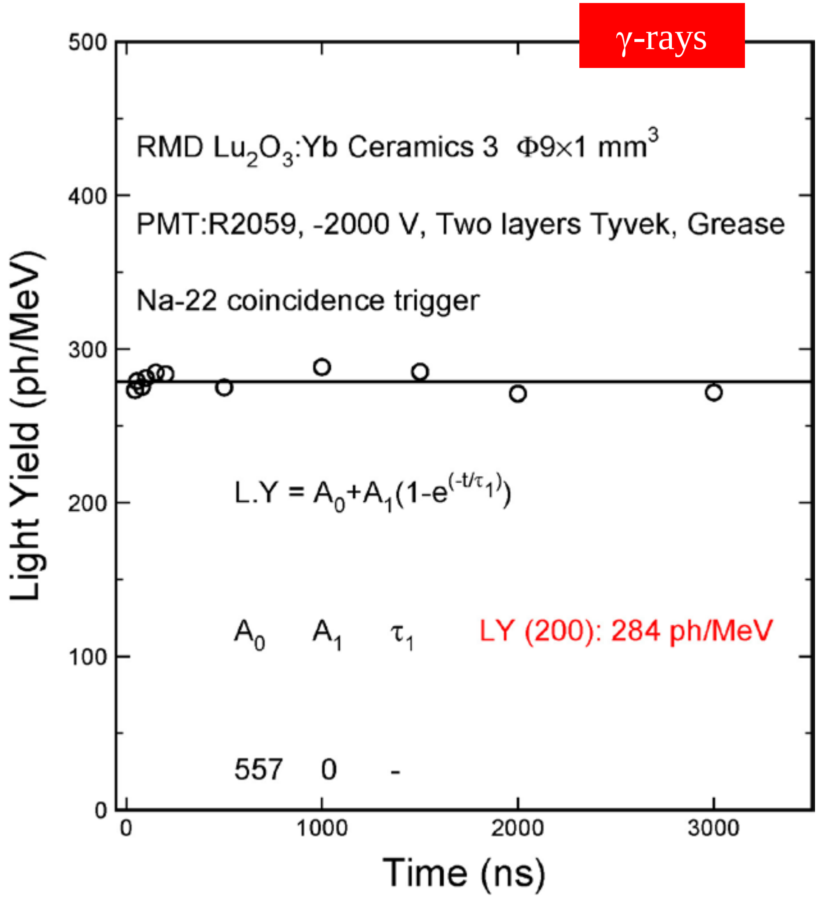


Ultrafast response of 0.2/0.6/0.8 ns observed for BaF_2 and BaF_2:Y crystals
The response is consistent with the Photek MCP-PMT 240 specification

Temporal Response: Lu_2O_3:Yb Ceramics



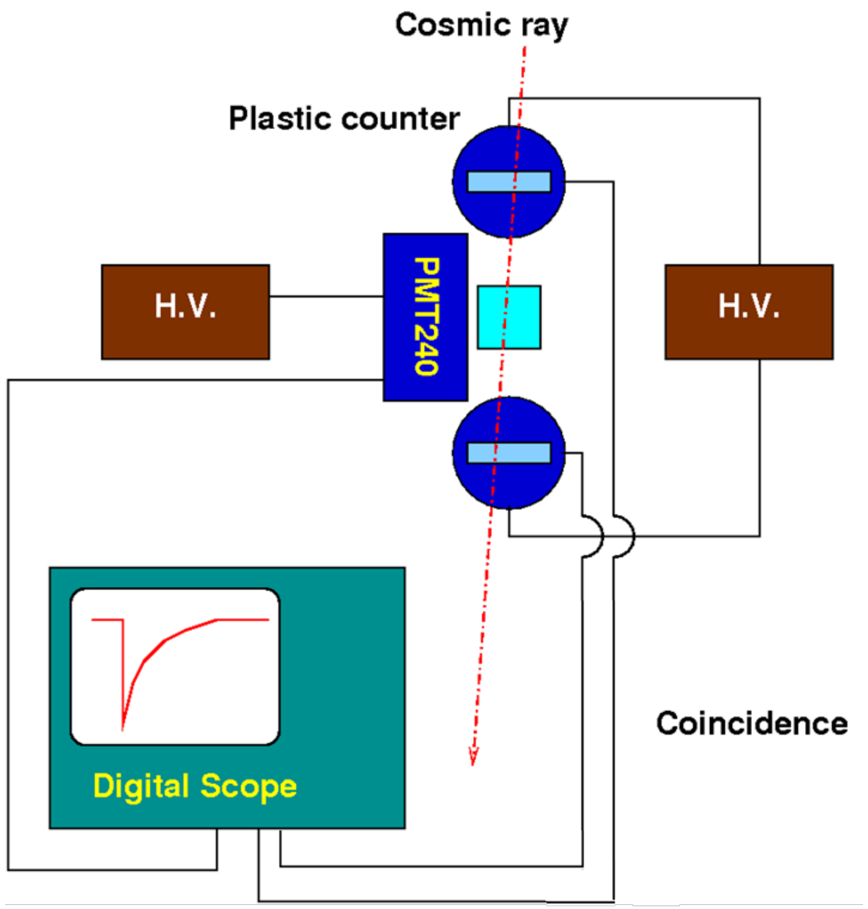


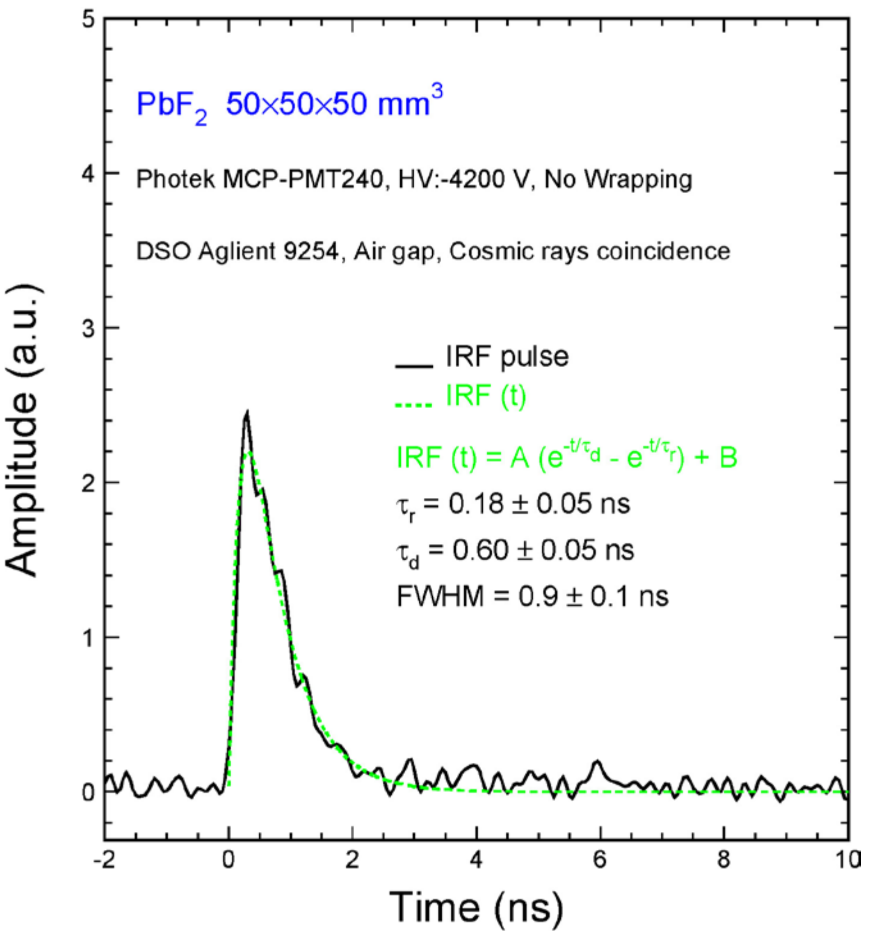


Lu_2O_3:Yb ceramic of 9.4 g/cc shows an ultrafast decay time of 1.1 ns by Am-241 with negligible slow component observed in integrated light output measurement

The Instrument Response Function

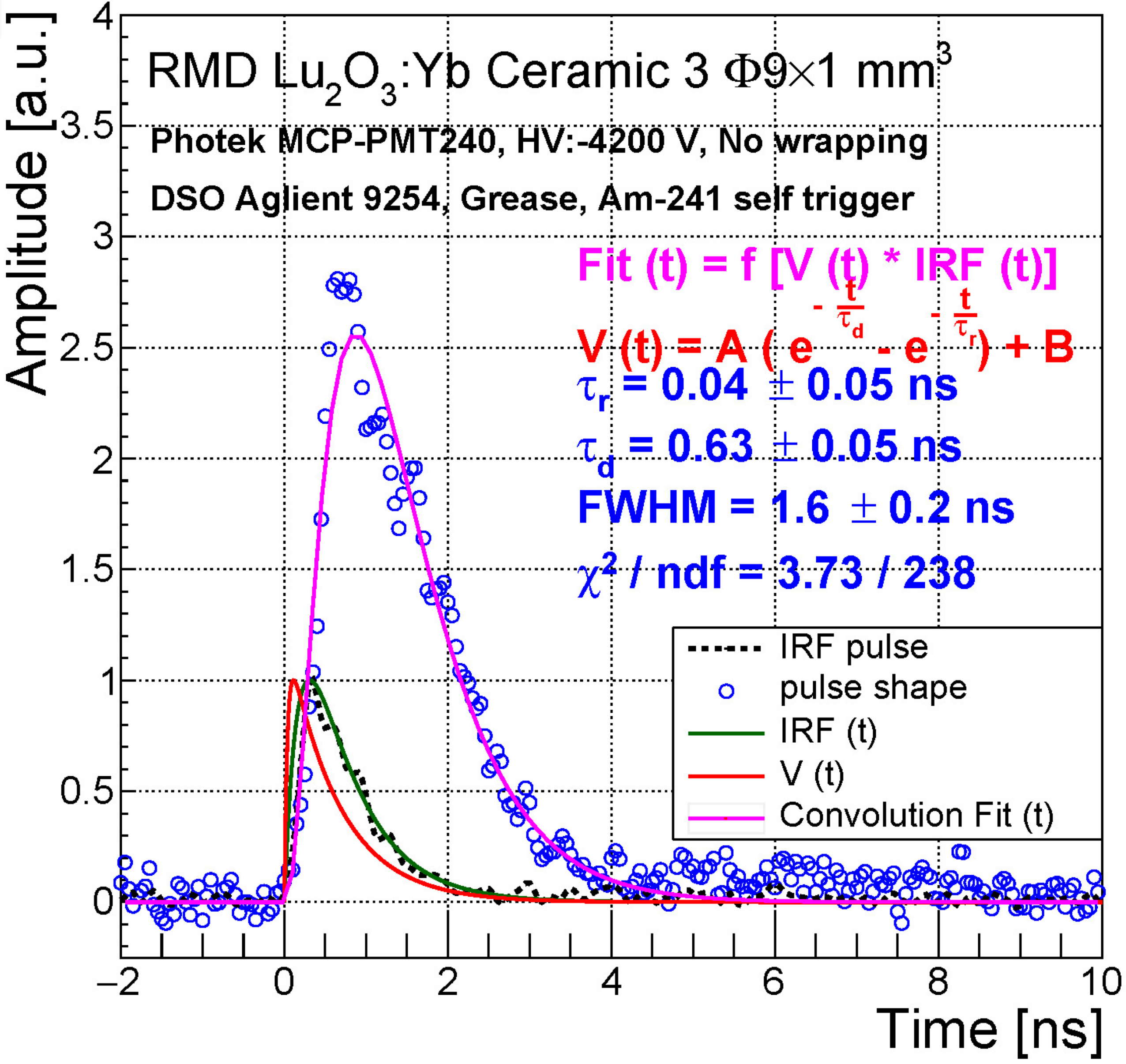
$$Fit(t) = f[V(t) * IRF(t)] = \int_{-\infty}^{+\infty} V(\tau) * IRF(t-\tau)\, d\tau$$





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

Fast and Ultrafast Inorganic Scintillators

arXiv: 2203.06788

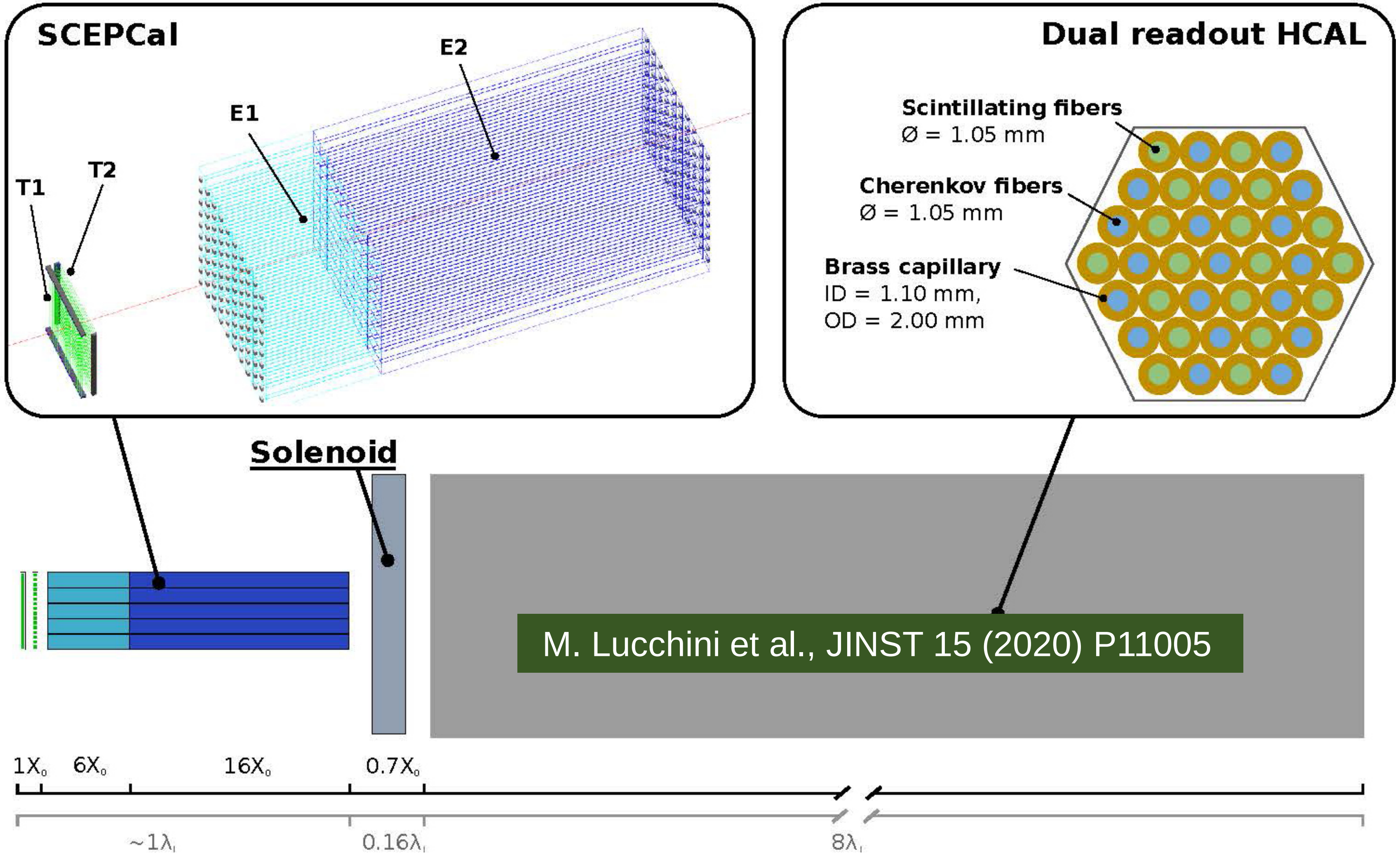
	BaF$_2$	BaF$_2$:Y	Lu$_2$O$_3$:Yb	YAP:Yb	YAG:Yb	ZnO:Ga	β-Ga$_2$O$_3$	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	9.42	5.35	4.56	5.67	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	2490	1870	1940	1975	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	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.

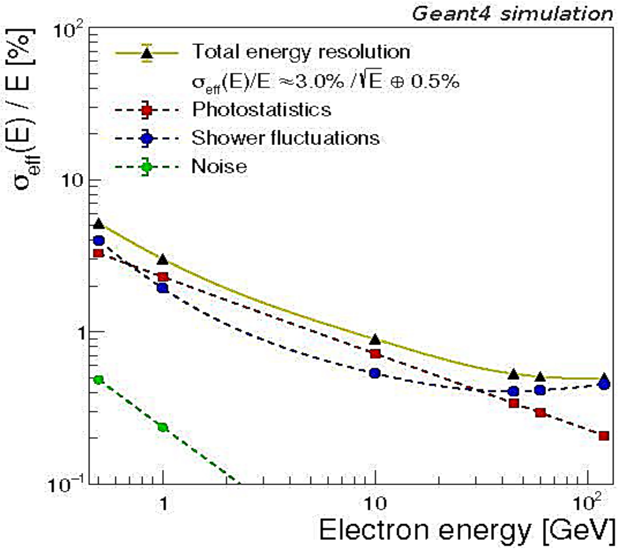
CalVision: Segmented Crystal ECAL

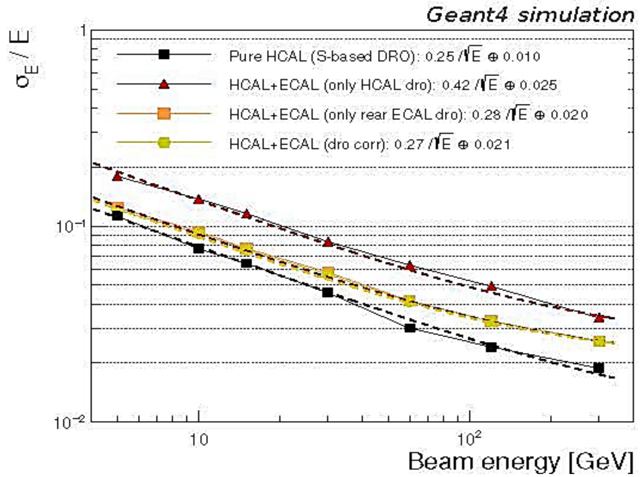
arXiv: 2203.04312

Followed by the IDEA DR HCAL, aiming at both EM and jet resolution

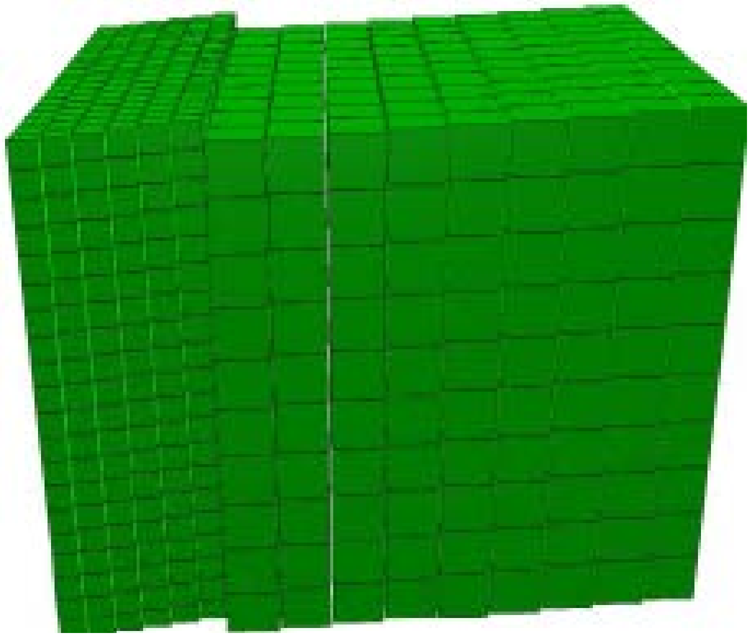


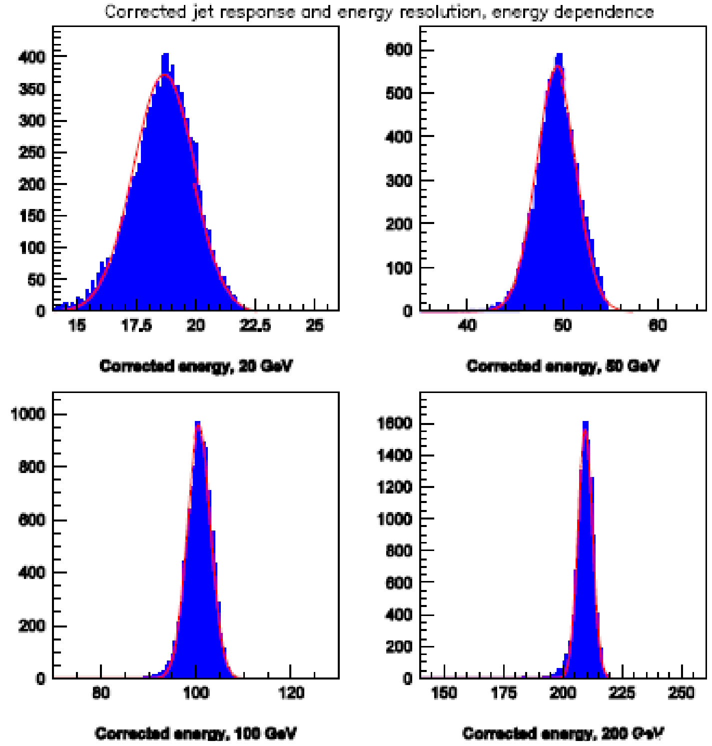
M. Lucchini et al., JINST 15 (2020) P11005





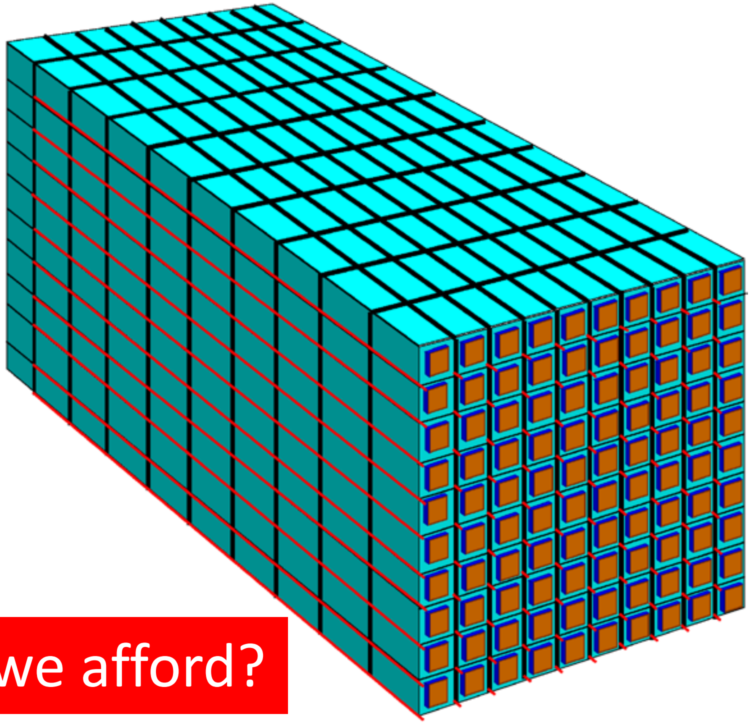
The HHCAL Concept

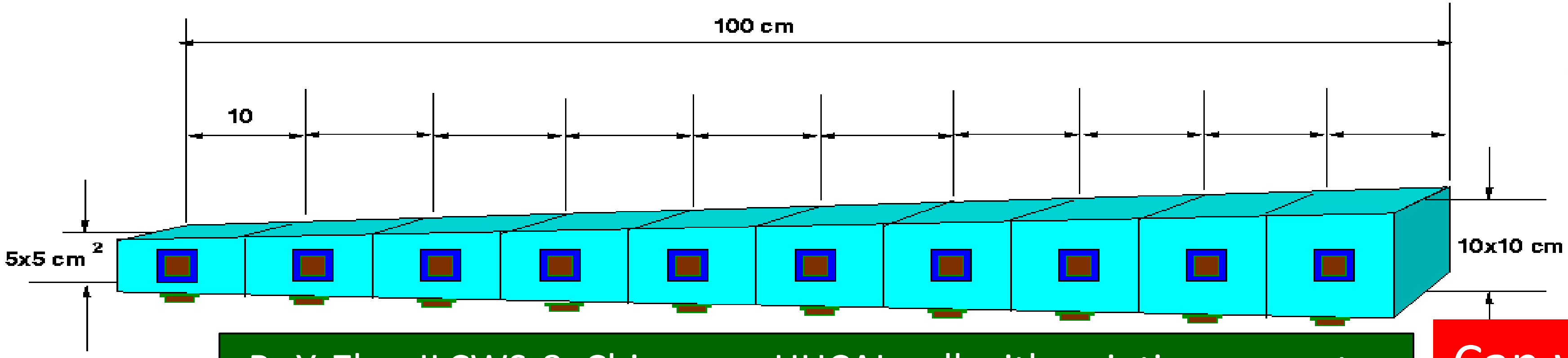




A. Para, H. Wenzel and S. McGill in Callor2012 Proceedings and A. Benaglia *et al*., IEEE TNS **63** (2016) 574-579: a jet energy resolution at a level of 20%/√E by HHCAL with dual readout of S/C or dual gate.

M. Demarteau, 2021 CPAD Workshop





R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

Can we afford?

Inorganic Scintillators: HHCAL

arXiv.2203.06788

	BGO	BSO	PWO	PbF$_2$	PbFCl	Sapphire:Ti	AFO Glass	DSB:Ce Glass[1]	BGS Glass[2]	ABS Glass[3]	DSB:Ce,Gd Glass[4,5]	HFG Glass[6]
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	3.8	4.2	4.53	4.7 - 5.4[d]	5.95
Melting point (℃)	1050	1030	1123	824	608	2040	980[7]	1420[8]	1550	?	1420[8]	570
X$_0$ (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	3.36	2.62	2.41	2.14	1.74
R$_M$ (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.90	3.52	3.33	3.09	2.56	2.45
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	32.8	31.8	28.8	24.2	23.2
Z$_{eff}$ value	71.5	73.8	73.6	76.7	74.7	11.1	41.4	42.9	49.6	51.9	47.2	55.7
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	5.56	5.90	6.42	7.68	8.24
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	440	430	396	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	~500	2,500	800	1,300	150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	180 30	400 90	1200 260	120, 400 50	25 8
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?	?	?	-0.04	0.3	?	?	-0.37
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6	?	2.0	2.0	?	2.0	?

a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. At room temperature (20°C) with PMT QE taken out.
d. Gd loaded.

1. E. Auffray, et al., J. Phys. Conf. Ser. 587, 2015
2. V. Dormenev, et al., NIMA 1015, 2021
3. G. Tang, et al., Opt. Mater. 130, 2022
4. R. W. Novotny, et al., J. Phys. Conf. Ser. 928, 2017
5. V. Dormenev , et al., the ATTRACT Final Conference
6. E. Auffray, et al., CERN-PPE/96-35, 1996
7. R. A. McCauley et al., Trans. Br. Ceram. Soc., 67. 1968
8. I. G. Oehlschlegel, Glastech. Ber. 44, 1971

Summary

The HL-LHC and FCC-hh require fast and radiation hard inorganic scintillator.

The **RADiCAL** concept uses LuAG:Ce ceramics as wavelength shifter for LYSO:Ce crystals for an ultra-compact, fast timing and longitudinally segmented shashlik calorimeter. R&D is on-going to suppress the slow components in LuAG:Ce.

An ultrafast BaF_2:Y calorimeter is proposed for **Mu2e-II**. R&D is on-going to investigate radiation hardness of large size BaF_2:Y crystals.

A longitudinally segmented **Calvision** crystal ECAL with dual readout combined with the IDEA HCAL promises excellent EM and Hadronic resolutions for the proposed Higgs factory.

Homogeneous HCAL (**HHCAL**) promises the best jet mass resolution by total absorption. Crucial R&D is needed for cost-effective mass-produced inorganic scintillators

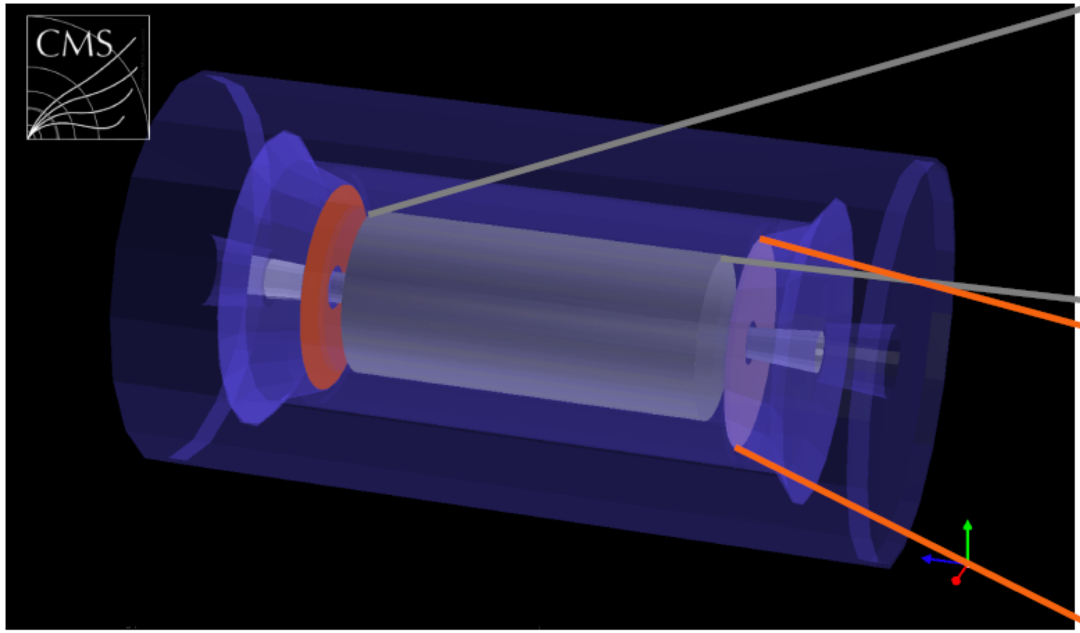
Acknowledgements: DOE HEP Award DE-SC0011925

LYSO:Ce for CMS MIP Timing Detector

MTD performance goal: 30-40 ps at the start degrading to < 60 ps at 3000 fb^{-1}

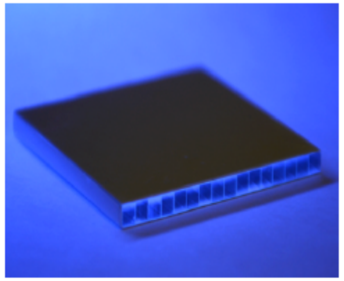
Barrel Timing Layer: arrays of LYSO crystal bars connected to SiPMs at both ends and readout by TOFHIR

Ultrafast inorganic scintillators would help to break the pico-second time barrier



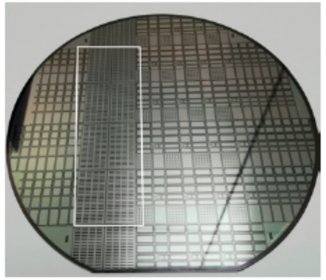
BTL: LYSO bars + SiPM read-out

- ▻ TK / ECAL interface ~ 45 mm thick
- ▻ $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- ▻ Active area ~ 38 m^2 ; 332k channels
- ▻ Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2



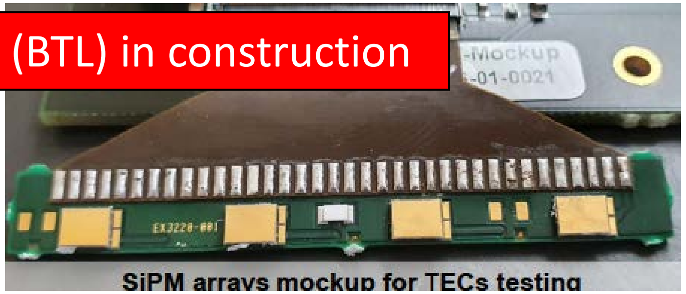
ETL: Si with internal gain (LGAD)

- ▻ On the HGC nose ~ 65 mm thick
- ▻ $1.6 < |\eta| < 3.0$
- ▻ Active area ~ 14 m^2; ~ 8.5M channels
- ▻ Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2



LYSO + SiPM with Thermal Electric Cooler (TEC) for CMS Barrel Timing Layer (BTL) in construction

SiPM array prototypes from FBK



SiPM arrays mockup for TECs testing

Expected Radiation for CMS MTD

CMS BTL/EMEC: 4.8/68 Mrad, 2.5/21×10^{13} p/cm^2 & 3.2/24×10^{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**

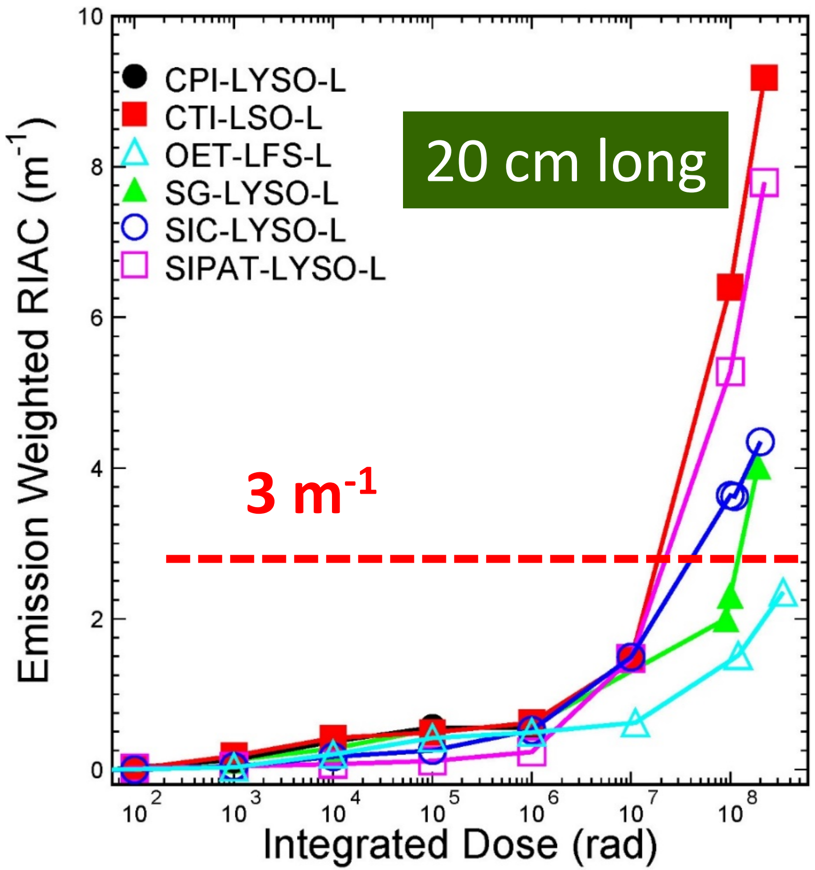
Much higher at FCC-hh: up to 0.1/500 Grad and 3/500 x10^{16} n_{eq}/cm^2 at EMEC/EMF

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

LYSO:Ce Radiation Hardness

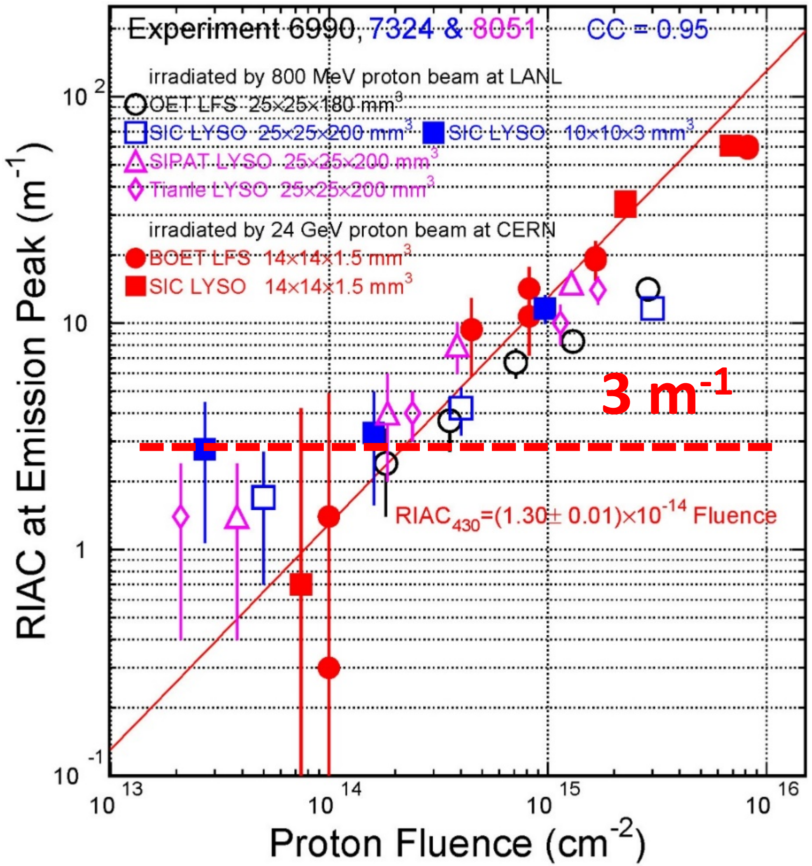
IEEE TNS 63 (2016) 612-619

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

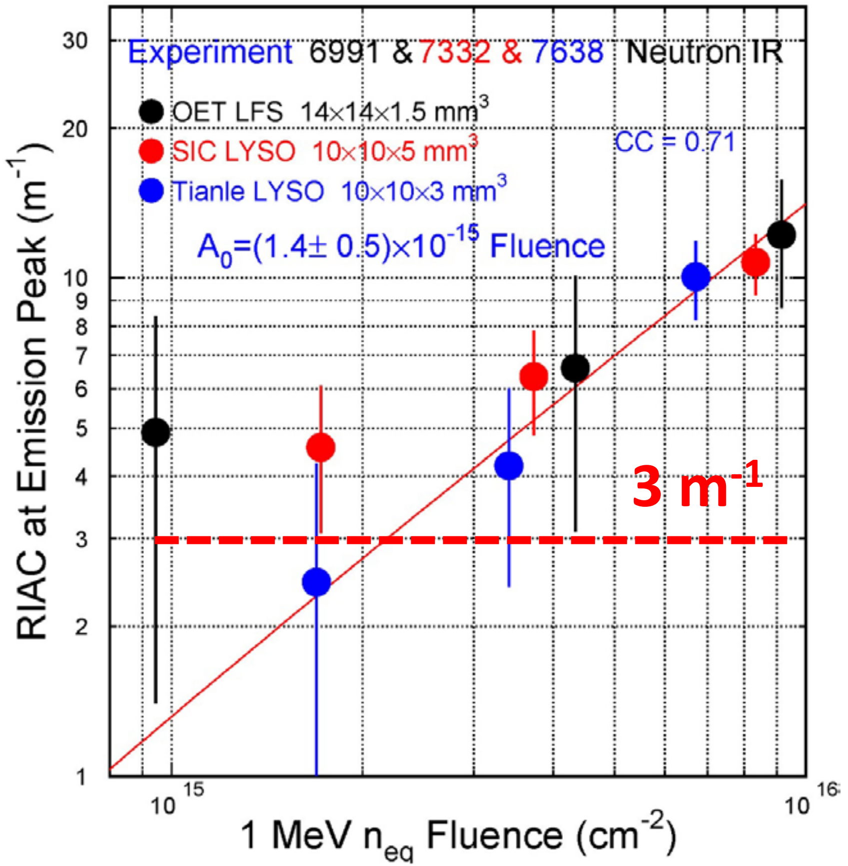


20 cm long

3 m^{-1}



3 m^{-1}



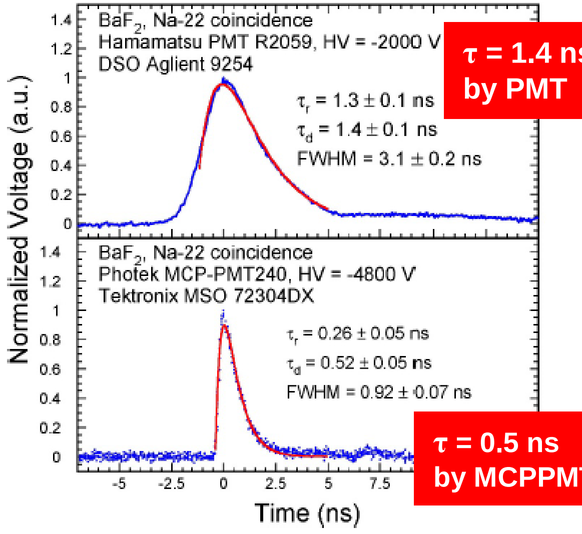
3 m^{-1}

Damage induced by protons larger than that from neutrons

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

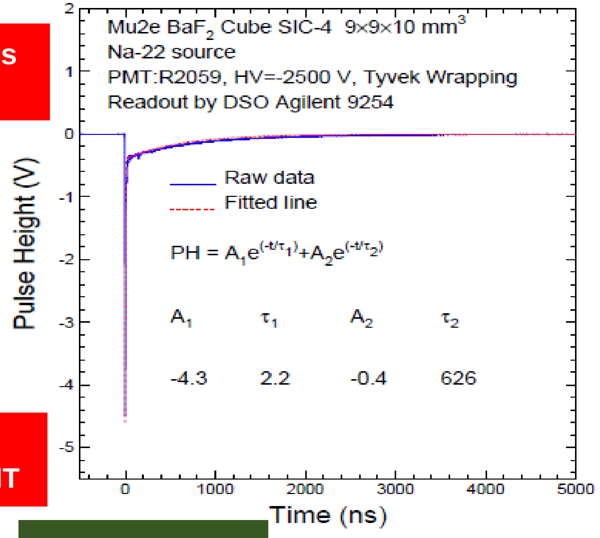
Ultrafast and Radiation Hard BaF_2

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

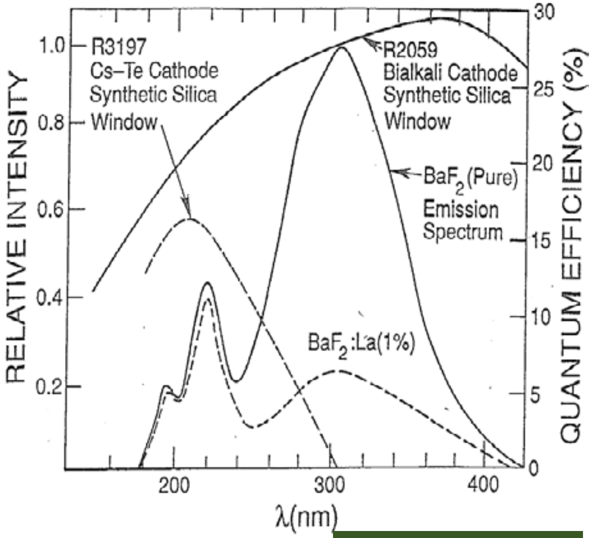


τ = 1.4 ns by PMT

τ = 0.5 ns by MCPPMT

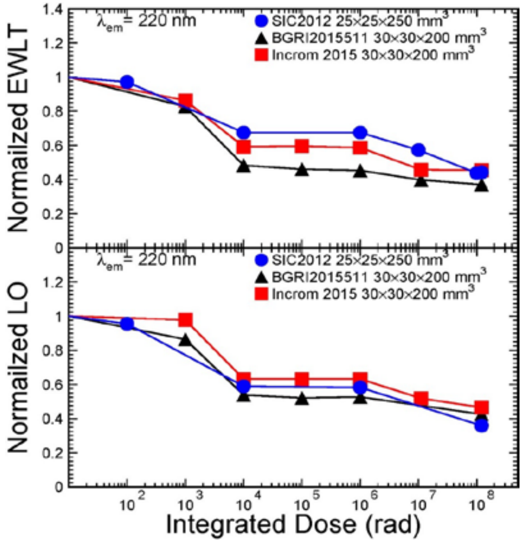


NIMA 340 (1994) 442-457



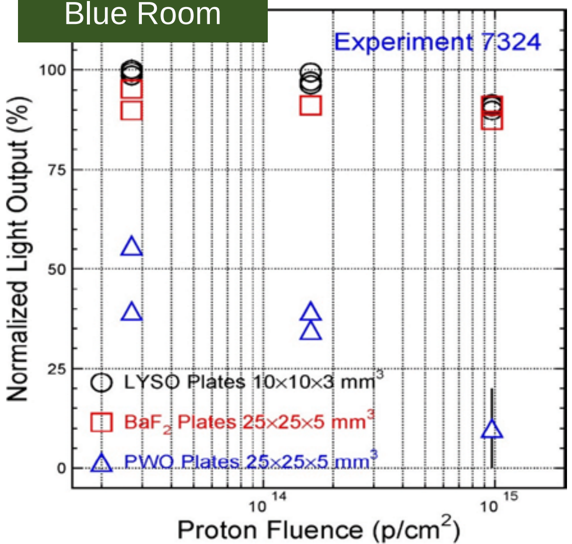
BaF$_2$ has an ultrafast scintillation component @ 220 nm with **0.5 ns** decay time and a much larger slow component @ 300 nm with 600 ns decay time.

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



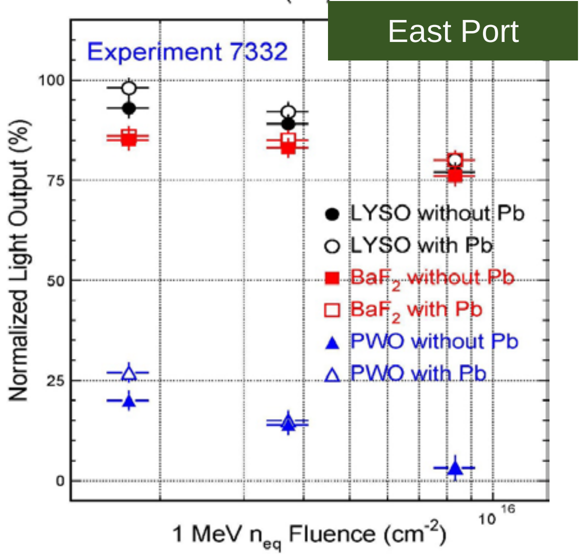
IEEE TNS **63** (2016) 612-619

Blue Room



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

East Port



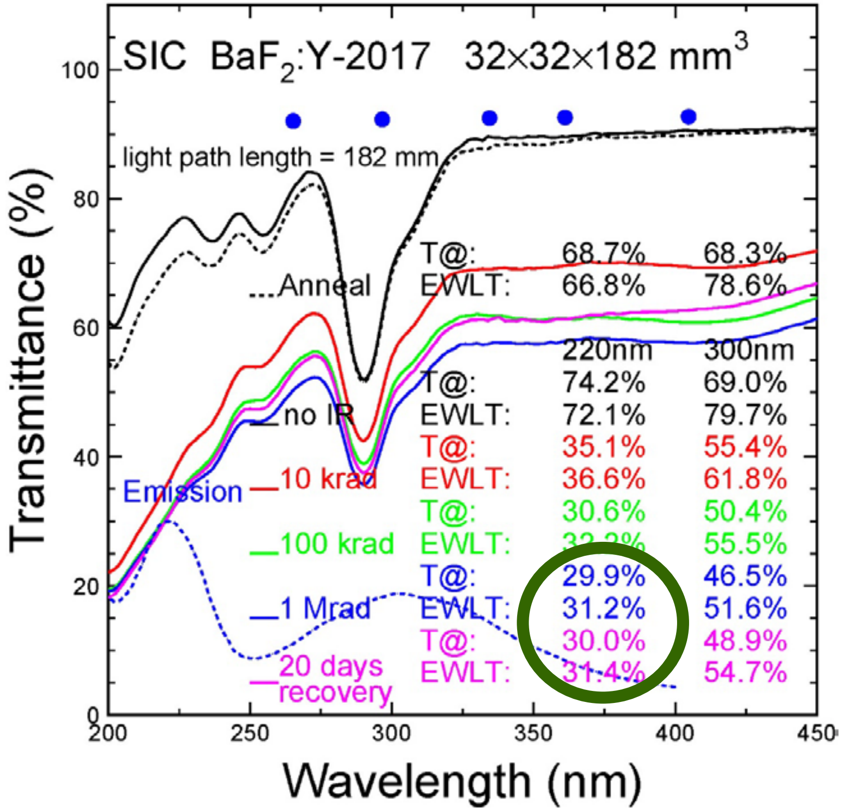
IEEE TNS **67** (2020) 1018-1024

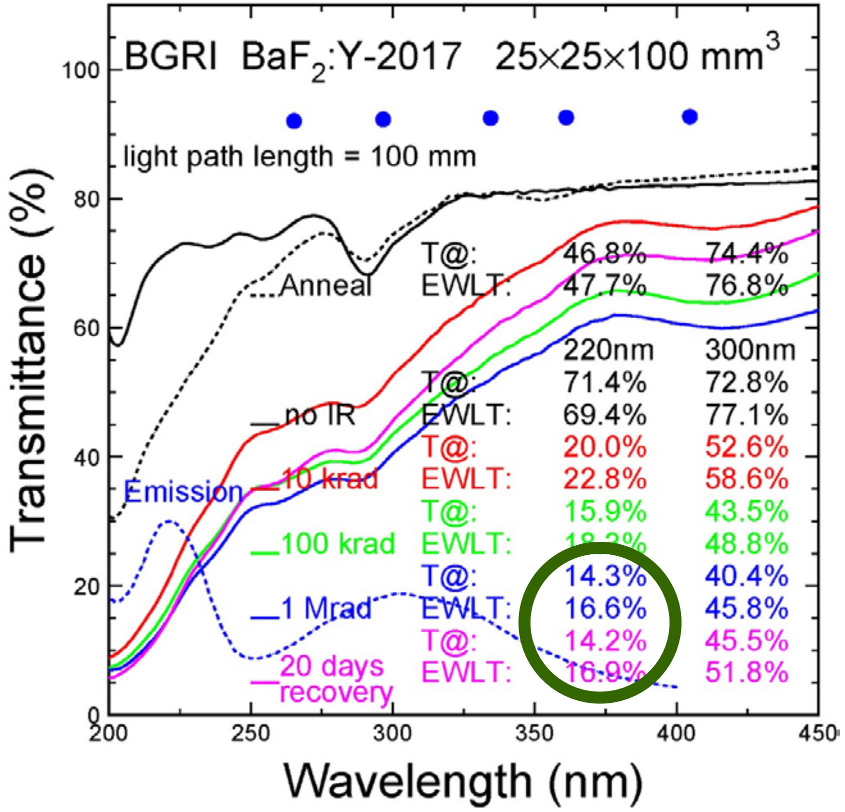
BaF$_2$ shows saturated damage from 10 krad to 100 Mrad, indicating good radiation resistance against ɣ-rays

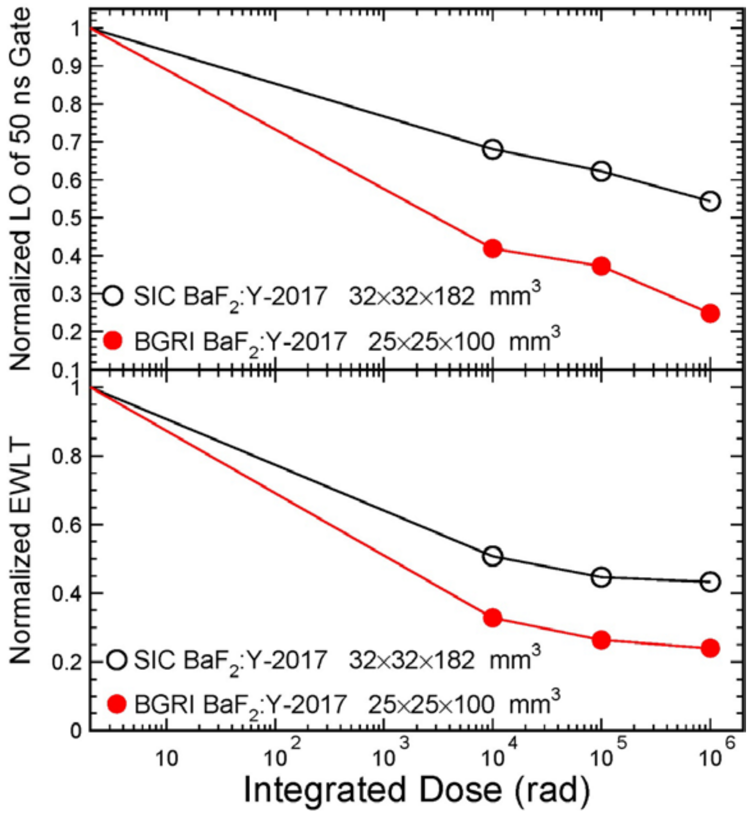
BaF$_2$ also survives after proton irradiation up to 9.7×10^{14} p/cm^2, and neutron irradiation up to 8.3×10^{15} n_{eq}/cm^2

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

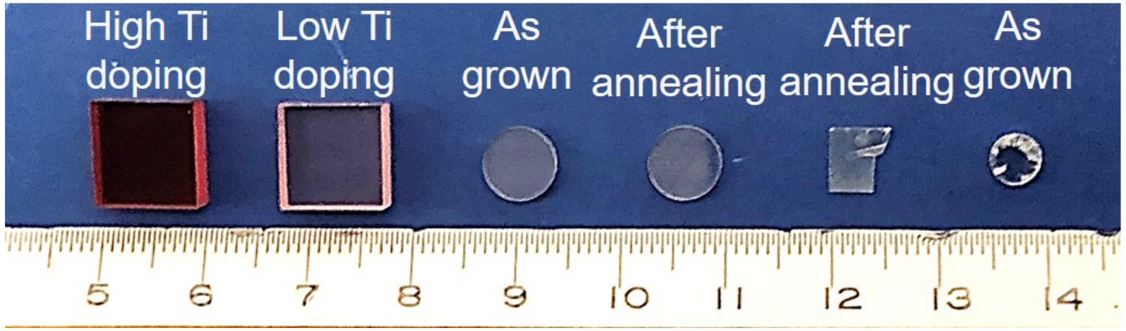






Diverse crystal quality at this stage of R&D, needs improvement

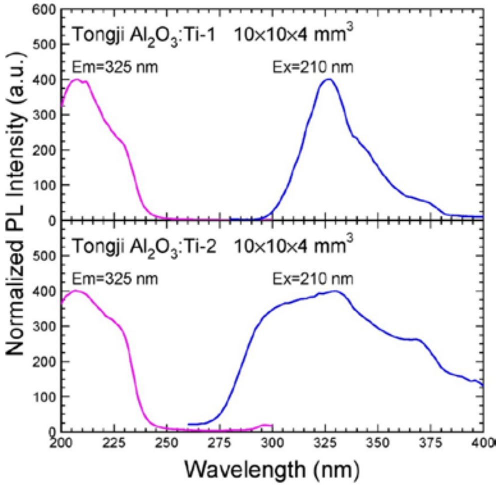
Sapphire:Ti Emission and Transmittance



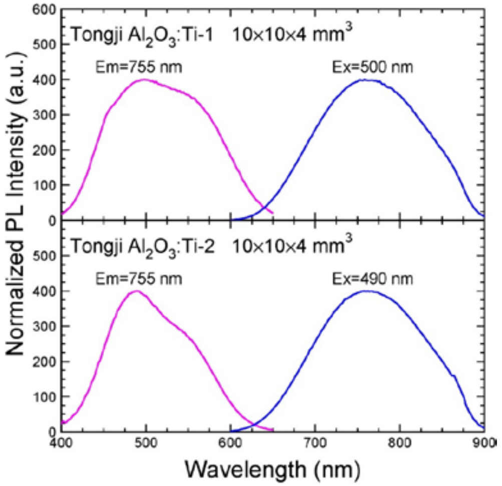
A weak emission at 325 nm with 150 ns decay time
A strong emission at 755 nm with 3 μs decay time

ID	Dimension (mm³)	#	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

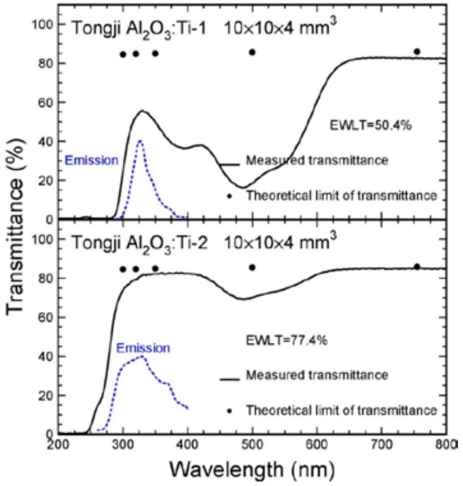
Fast @325 nm



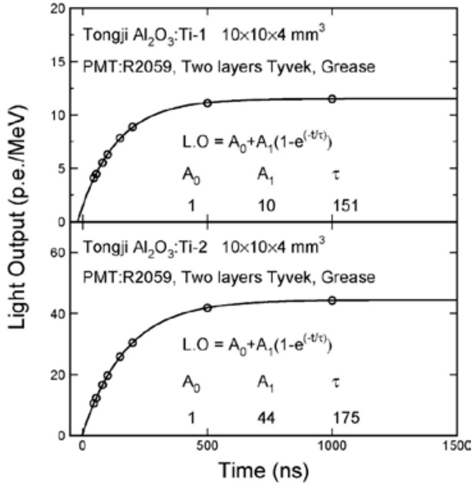
Slow @755 nm



EWLT for Fast & Slow



Fast = 162 ns



Slow = 3.2 μs