Inorganic Scintillators for Future High Energy Physics Experiments

Ren-Yuan Zhu

California Institute of Technology

December 5, 2023

Invited Talk Presented in the Multi-Probe Radiography Workshop, LANSCE

Why Inorganic Scintillators?

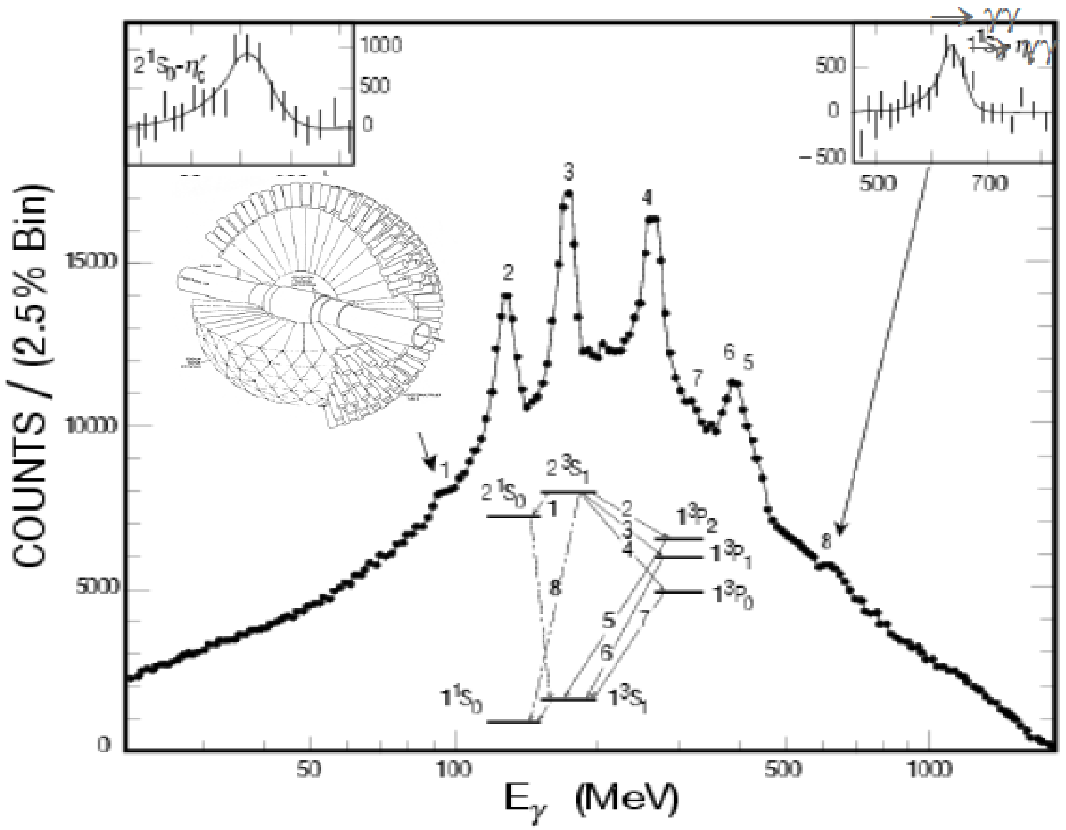
arXiv: 2203.06731 and arXiv: 2203.06788

- **Precision e/γ enhance physics discovery potential.**
- **Performance of total absorption ECAL is well understood for e/γ and jets:**
  - **Energy resolution achieved:** $2\%/\sqrt{E} \oplus 1\%$
  - **Position resolution: sub-mm can be achieved;**
  - **Good identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout: C/S light or S/L gate.**
- **On-going Development in Caltech Crystal Lab:**
  - **Rad-hard LYSO:Ce crystals and LuAG:Ce ceramics (RADiCAL) for HL-LHC and FCC-hh;**
  - **Ultrafast BaF_2:Y and Lu_2O_3:Yb for ultrafast calorimeter and TOF, and GHz Imaging;**
  - **Cost-effective ABS and DSB glasses for Higgs factory (Calvision) and HHCAL.**

Precision e/γ Physics in HEP

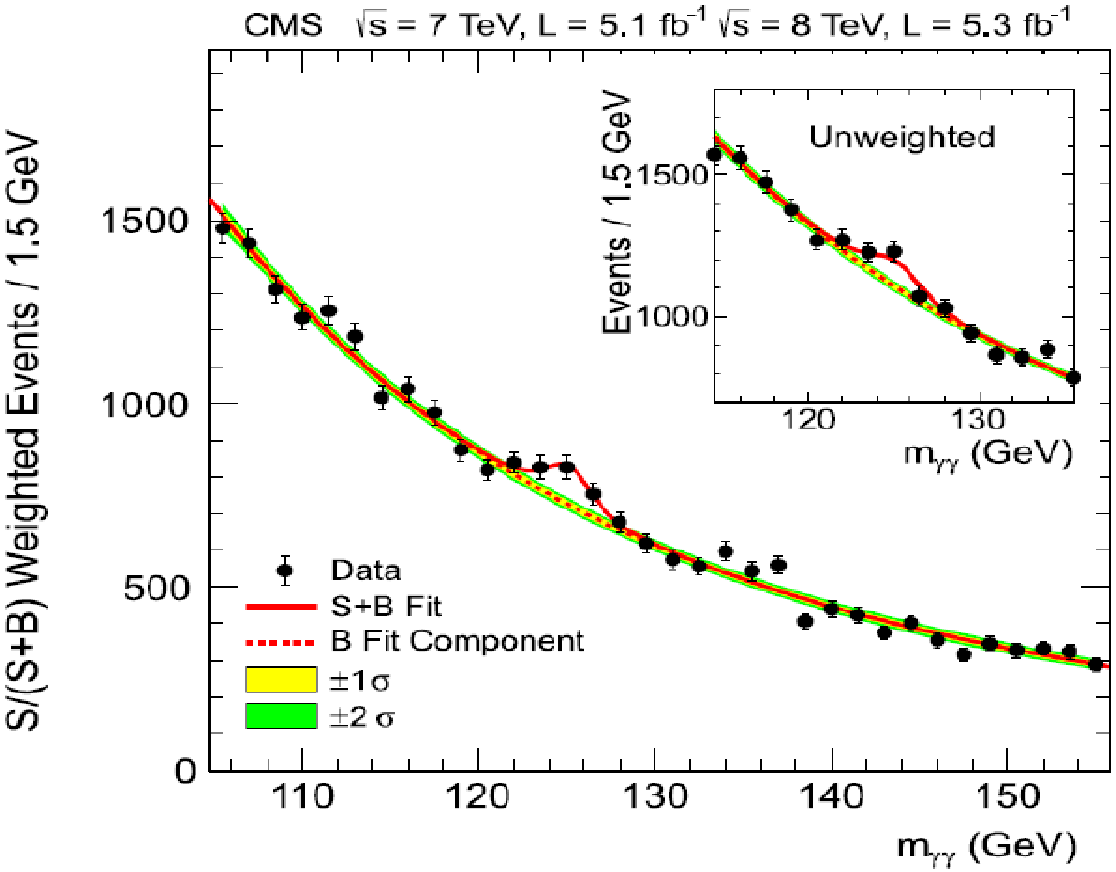
Charmonium system observed by CB through Inclusive photons

CB NaI(Tl)



Higgs -> γγ by CMS through reconstructing photon pairs

CMS PWO



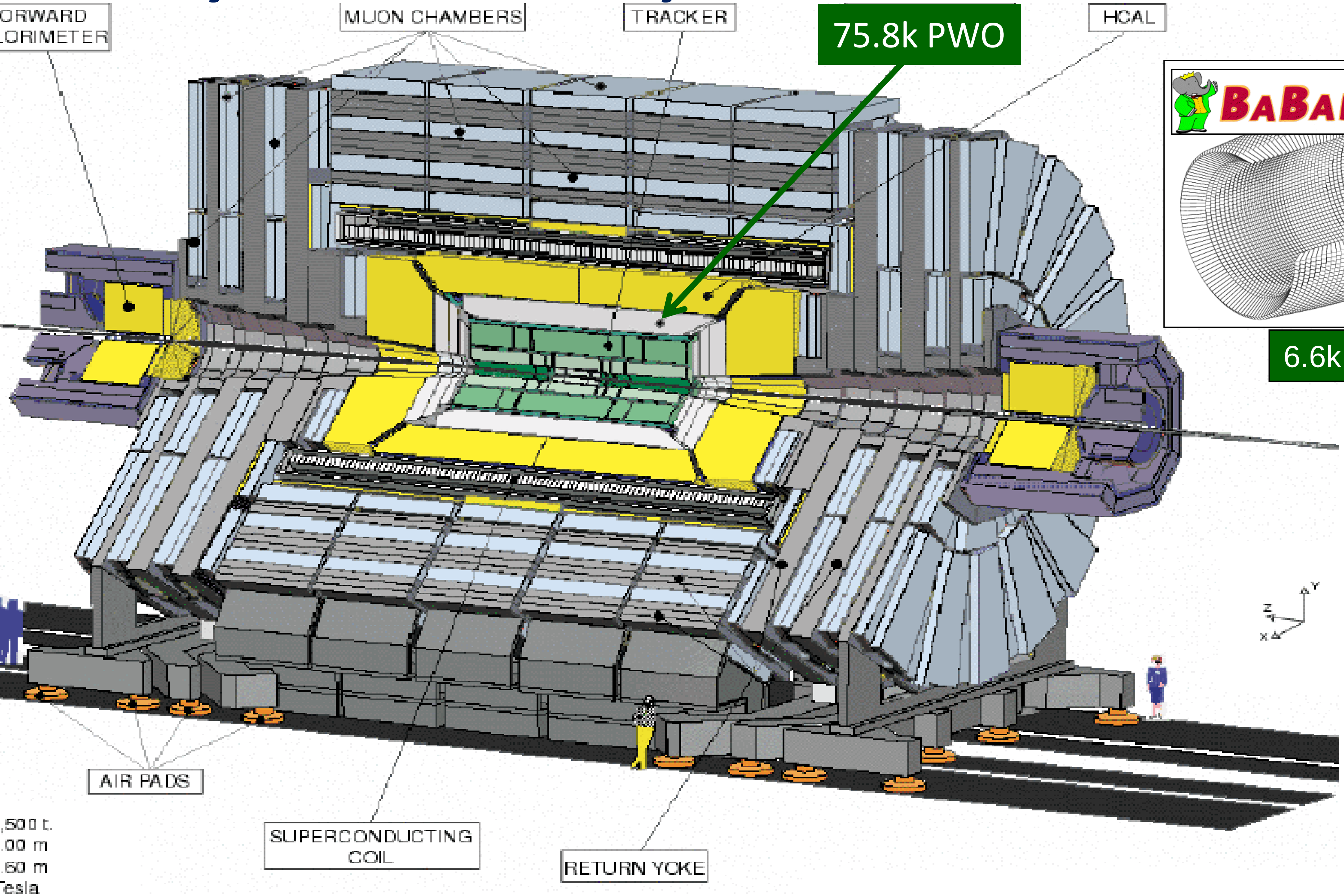
Crystals Used in HEP Calorimeters

Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	BGO	LYSO:Ce	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (ºC)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index[a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence[b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420	-
Decay Time[b] (ns)	245	1220	30 6	650 0.9	300	40	30 10	-
Light Yield[b,c] (photons/MeV)	38,000	63,000	1,400 420	13,680 1,560	8,000	32,000	114 40	-
d(LY)/dT[b] (%/ ºC)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	-
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV Mu2e S. BELLE	TAPS Mu2e-II?	L3 BELLE	COMET CMS BTL PIONEER	CMS ALICE PANDA EIC	A4 G-2

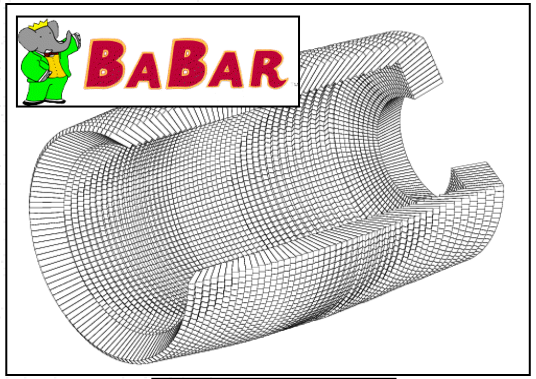
a. at emission peak; b. up/low row: slow/fast component; c. with QE of readout device taken out.

L3 BGO, BaBar CsI, CMS PWO ECAL

11.4k BGO



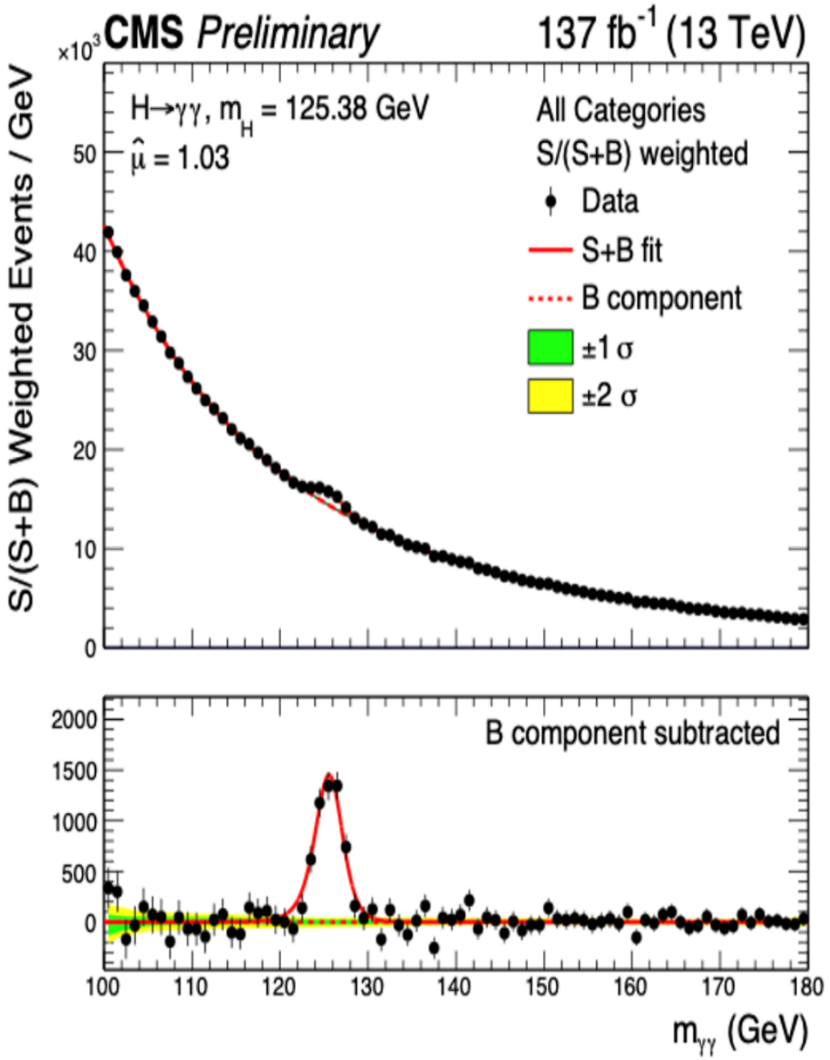
75.8k PWO

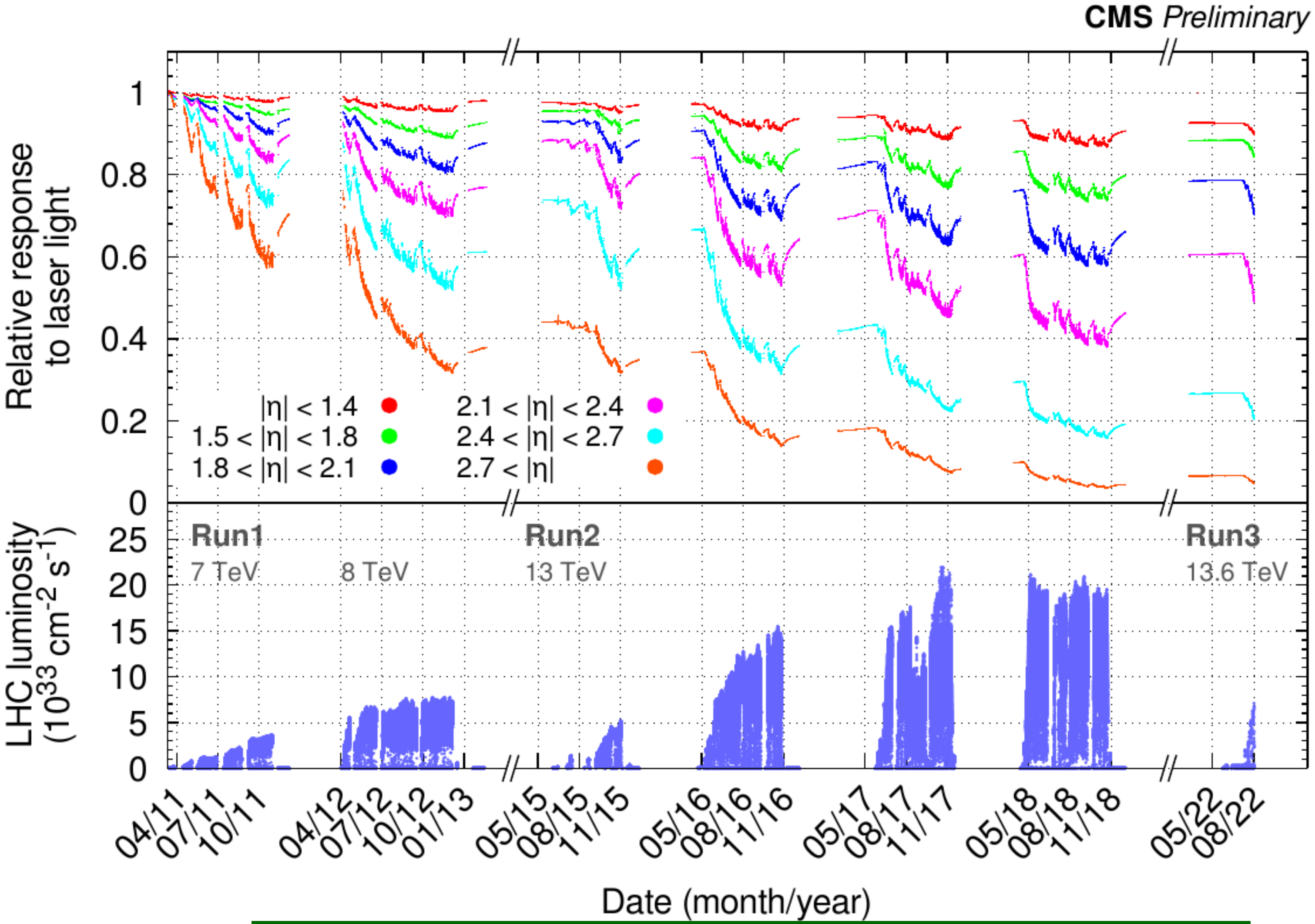


6.6k CsI:Tl

CMS H -> γγ and PWO Damage

T. Dimova, TIPP2023, light monitoring data





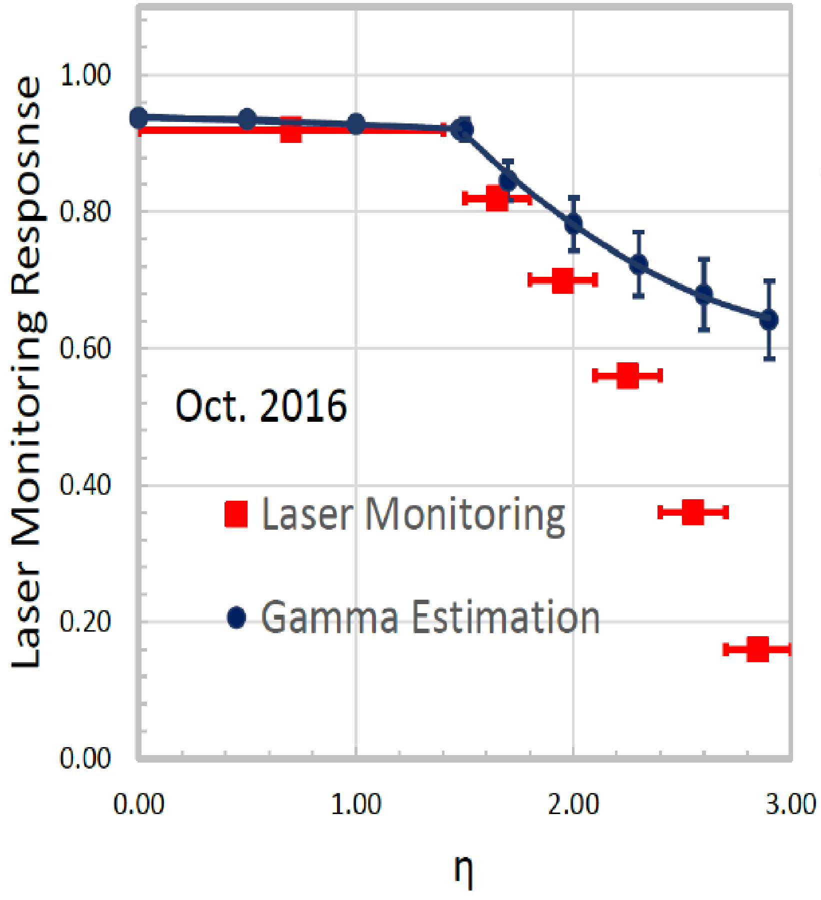
PWO damage due to ionization dose and hadrons

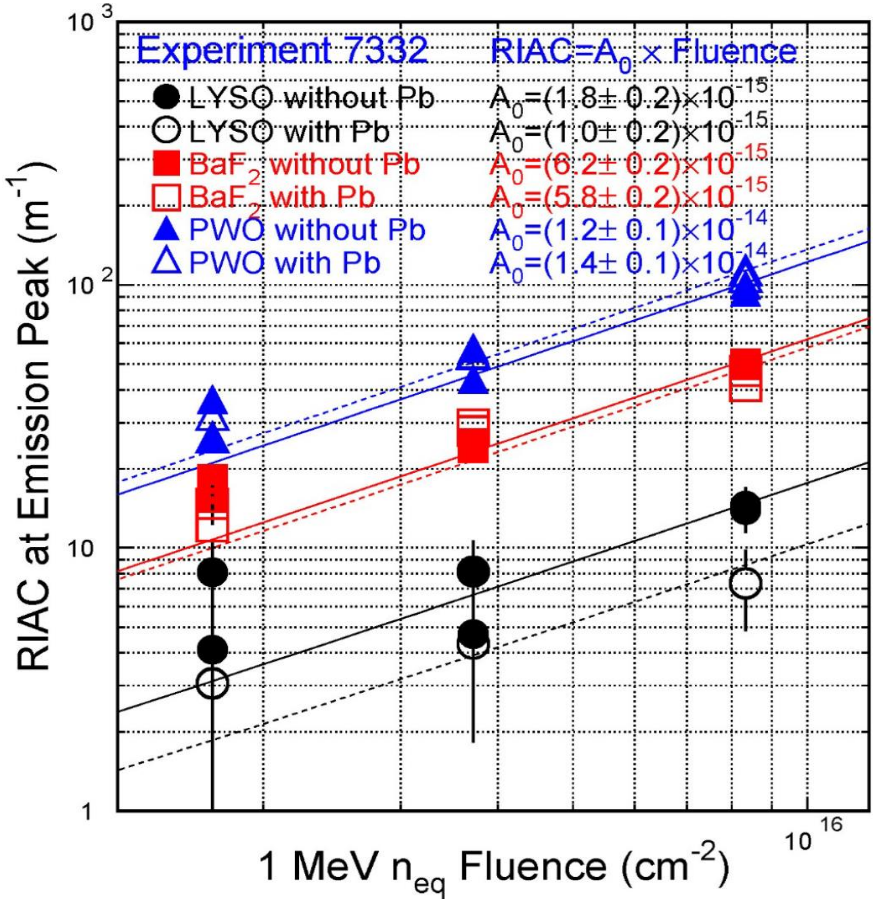
PWO Damage by Ionization & Neutrons

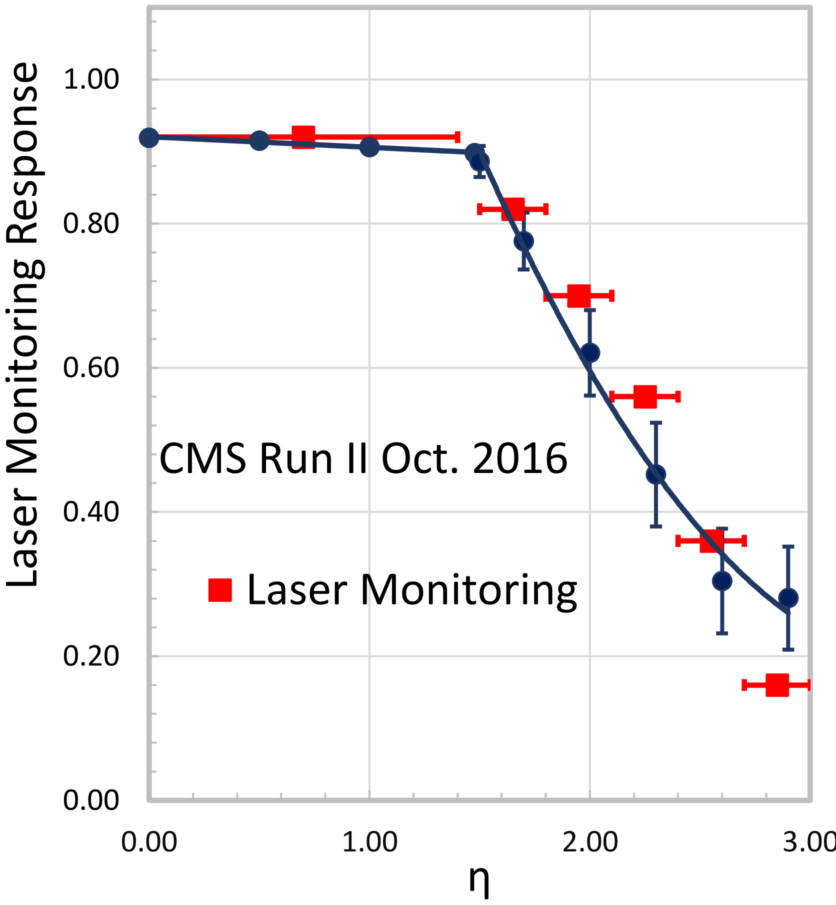
RIAC in PWO = $1.4 \times 10^{-14} \times$ 1 MeV n_{eq} Fluence

γ-ray and hadron induced absorption explains CMS PWO monitoring data

http://www.its.caltech.edu/~rzhu/talks/ryz_161028_PWO_mon.pdf & Trans. NS. 67 (2020) 1086-1092







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

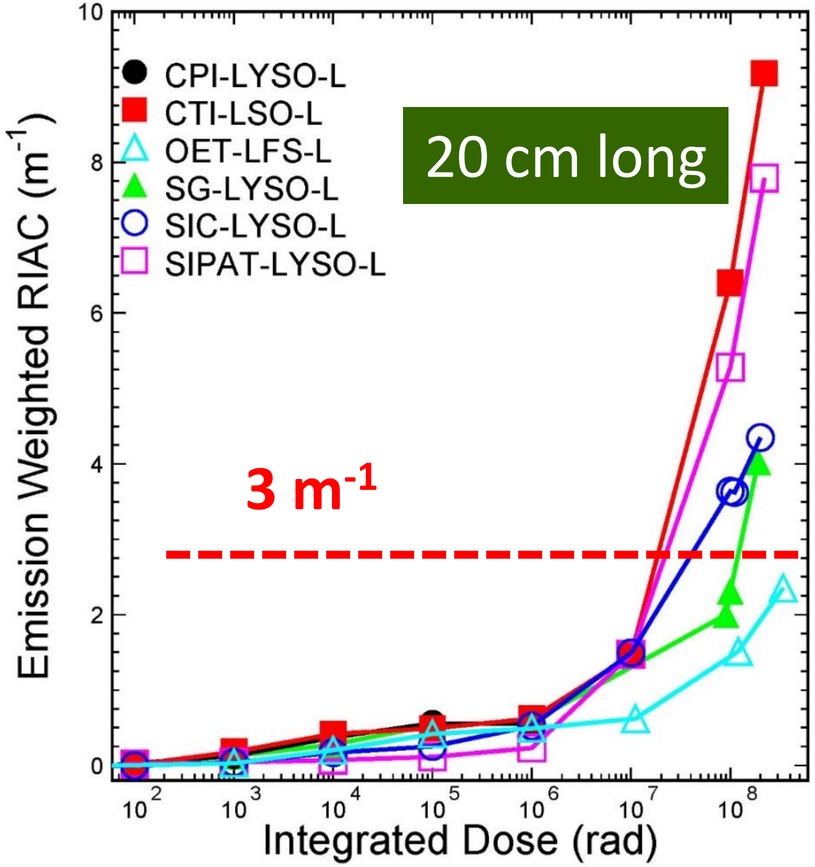
Snowmass 2021: https://arxiv.org/abs/2209.14111

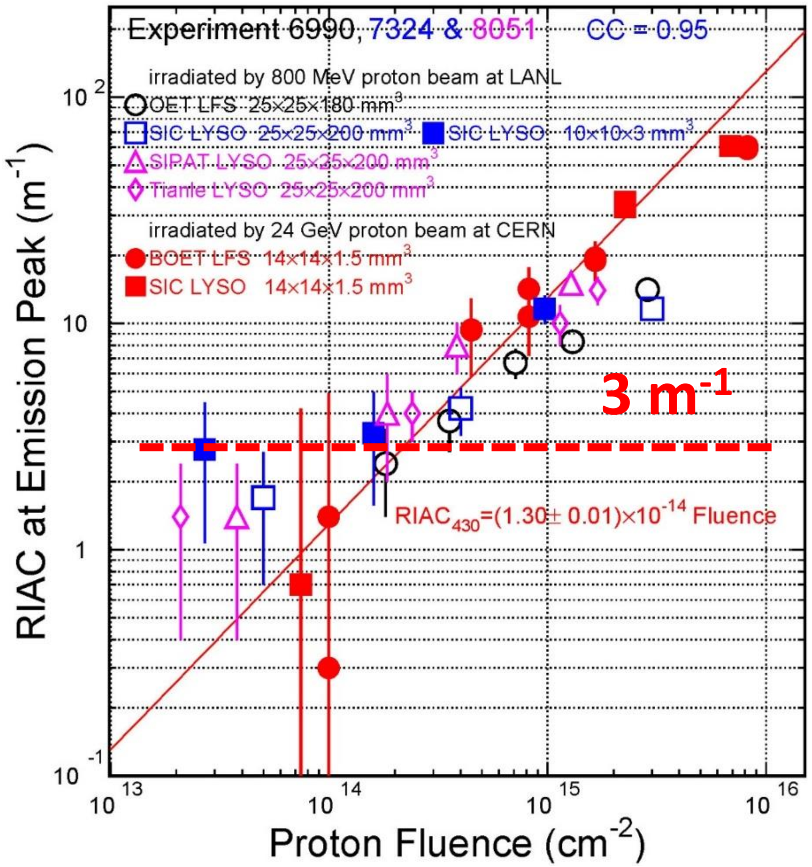
Fast/ultrafast, radiation hard and cost-effective inorganic scintillators

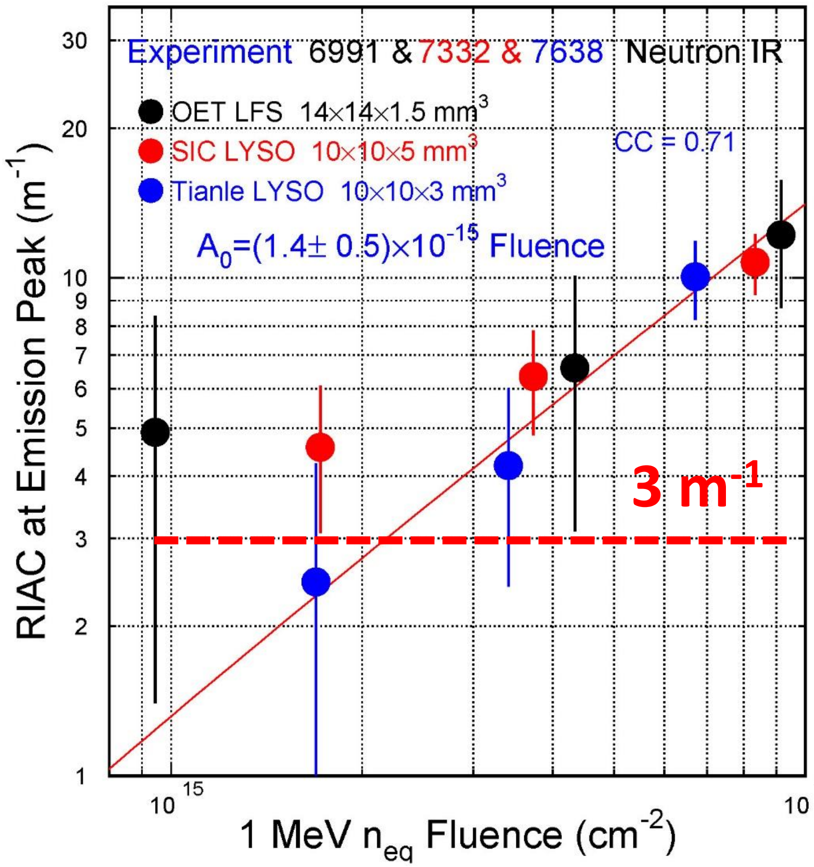
LYSO:Ce Radiation Hardness

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



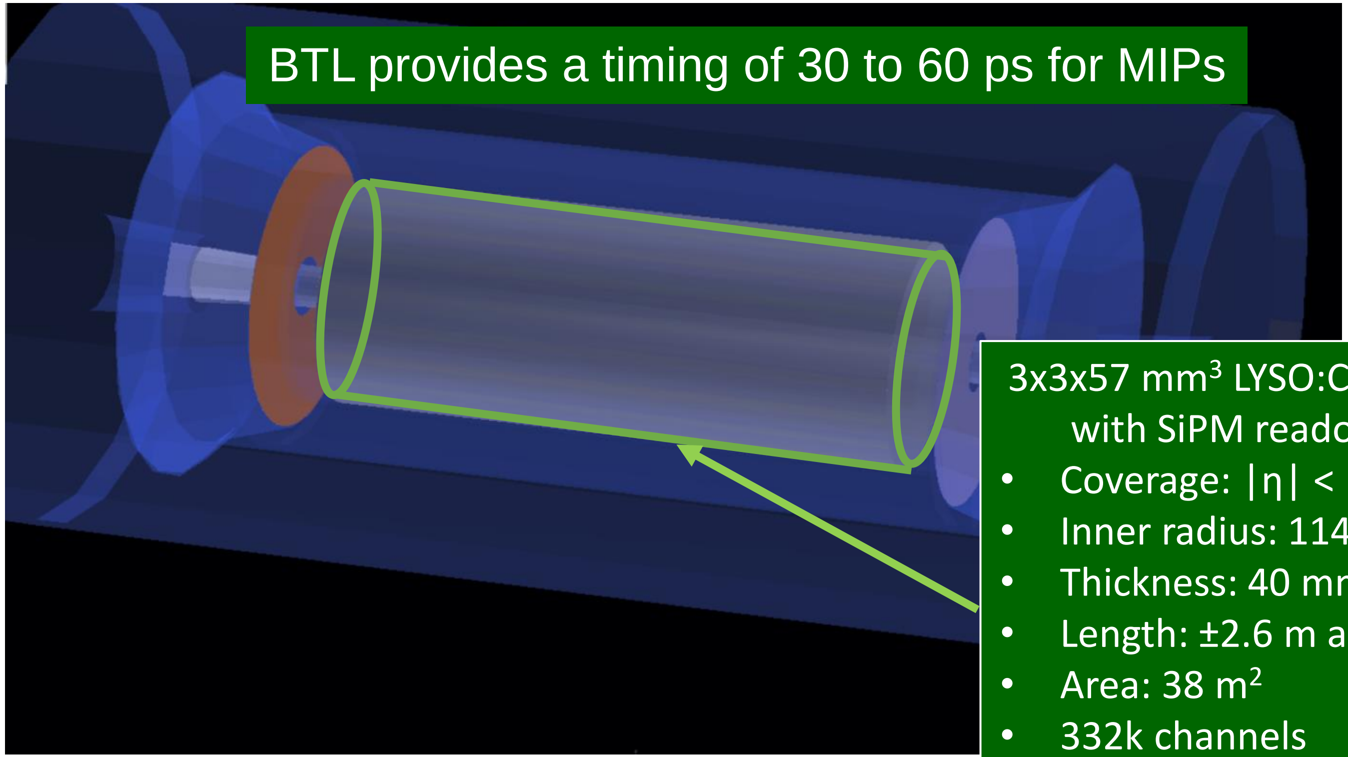




Damage induced by protons is larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup

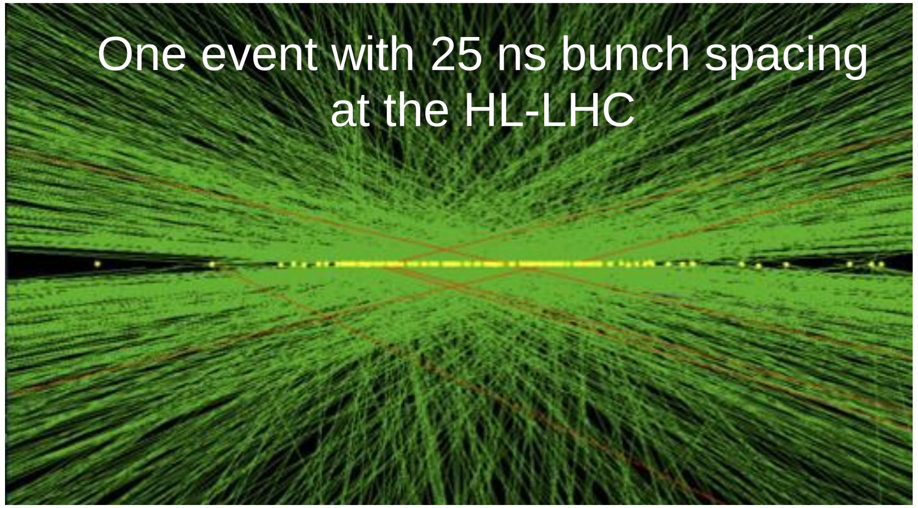
LYSO:Ce for CMS MIP Timing Detector

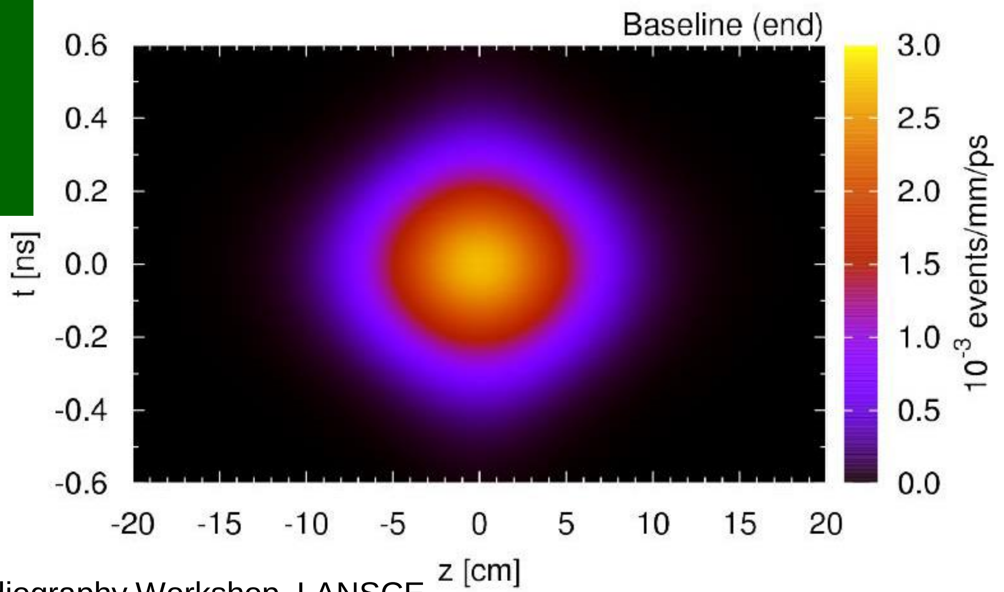
To face challenge of pileup at HL-LHC by using 4D tracking in space and time

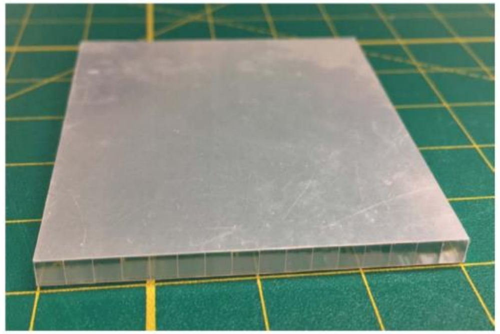


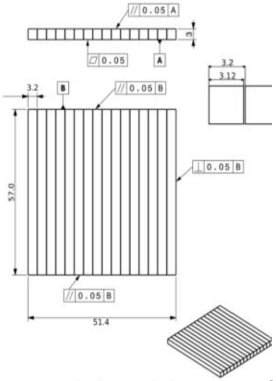
$3\times3\times57$ mm^3 LYSO:Ce bars with SiPM readout

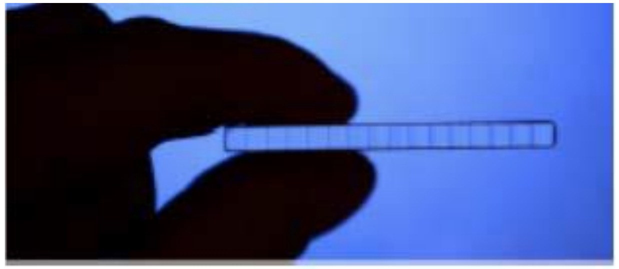
- Coverage: $|\eta| < 1.45$
- Inner radius: 1148 mm
- Thickness: 40 mm
- Length: ±2.6 m along z
- Area: 38 m^2
- 332k channels







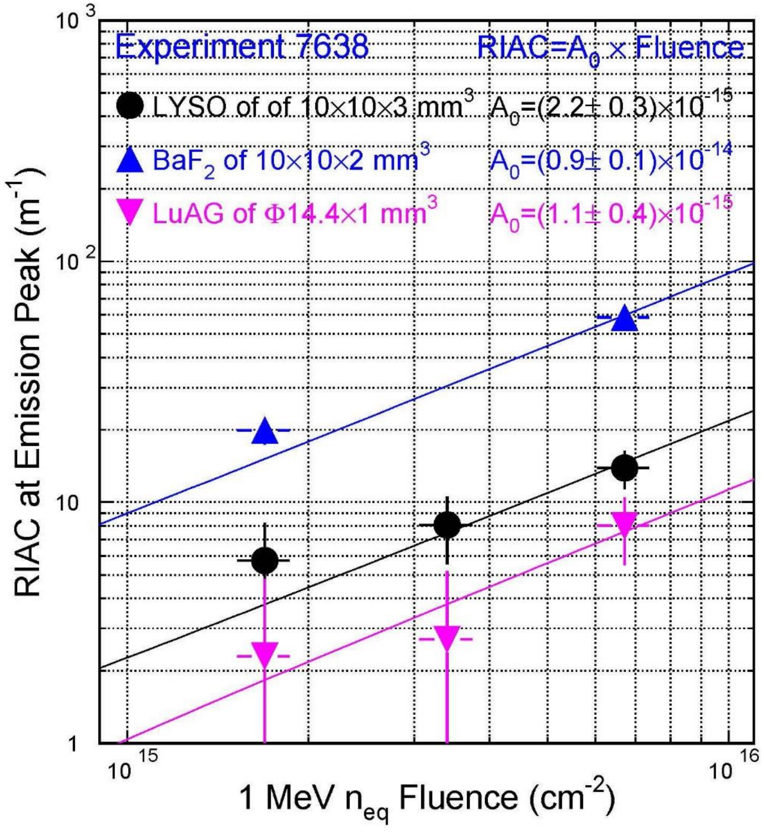


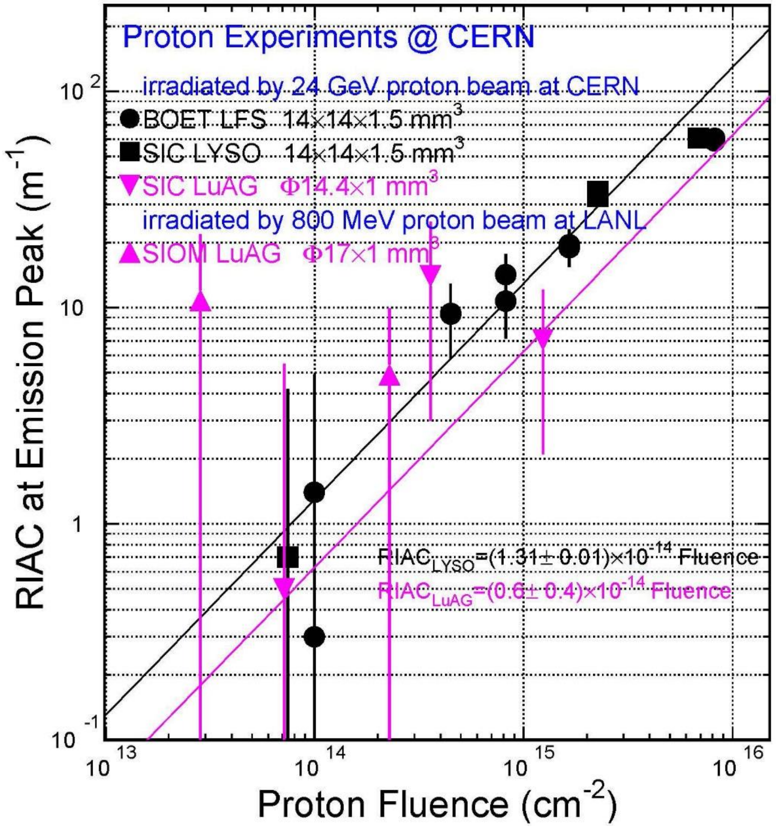


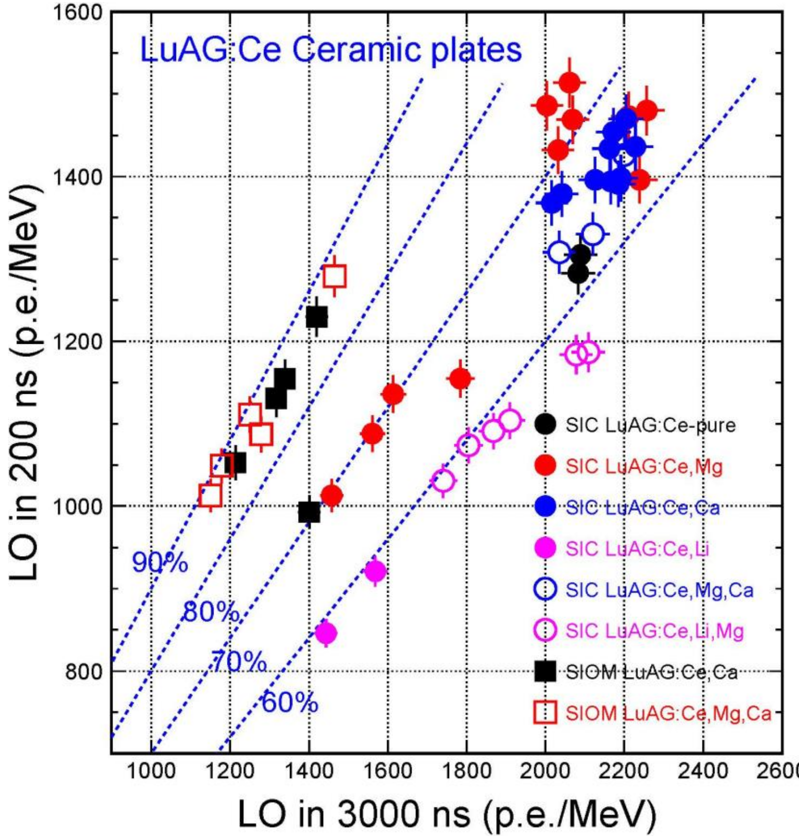
LuAG:Ce Ceramics Radiation Hardness

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

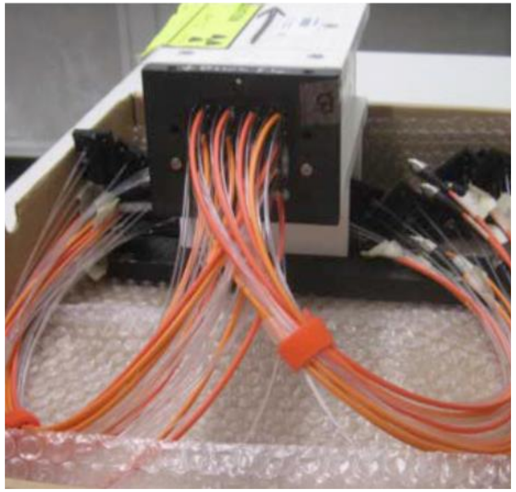


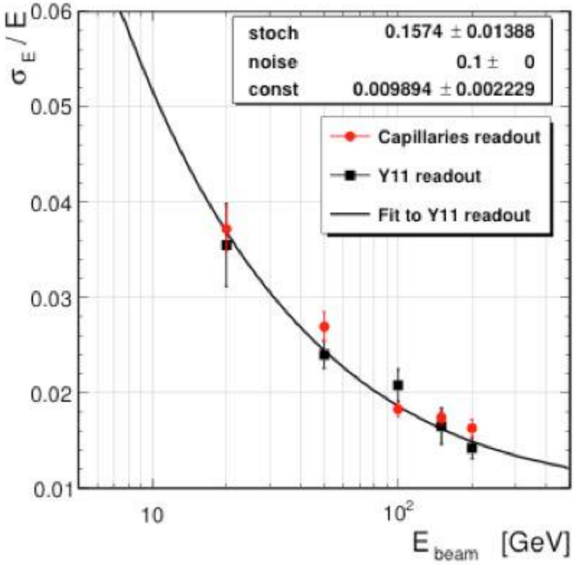




R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

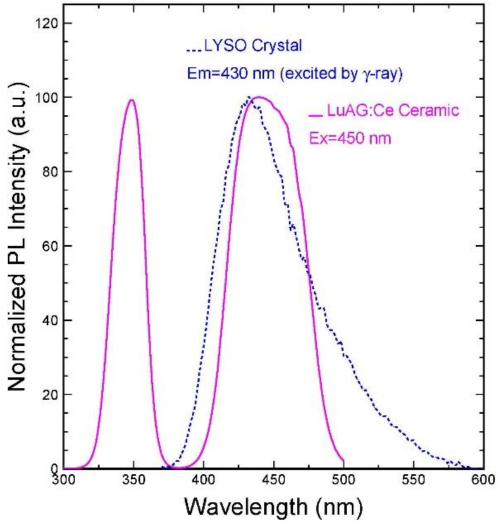
RADiCAL: LYSO/LuAG Shashlik ECAL

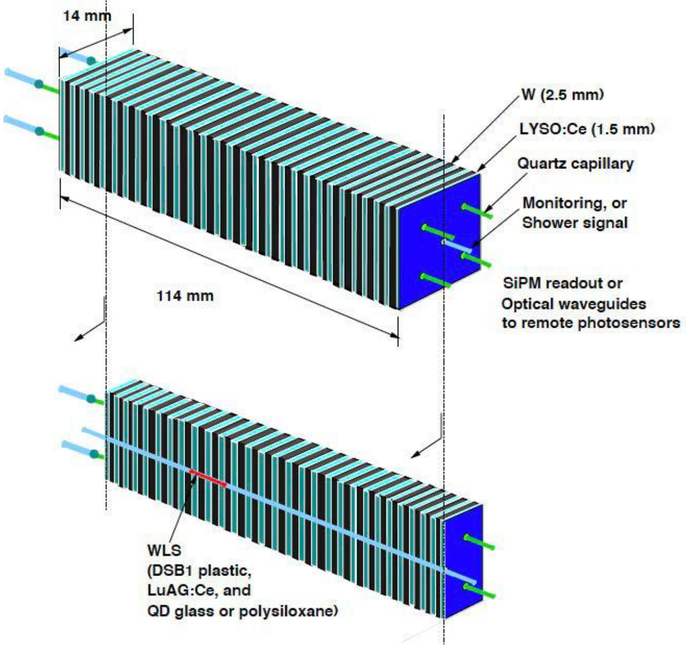


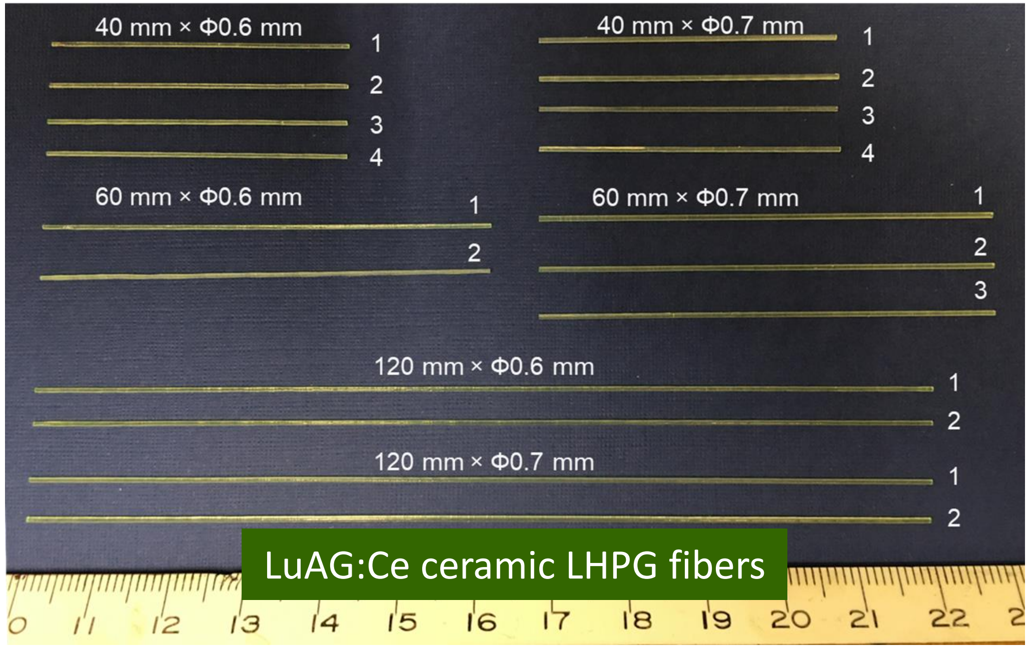


arXiv: 2203.12806

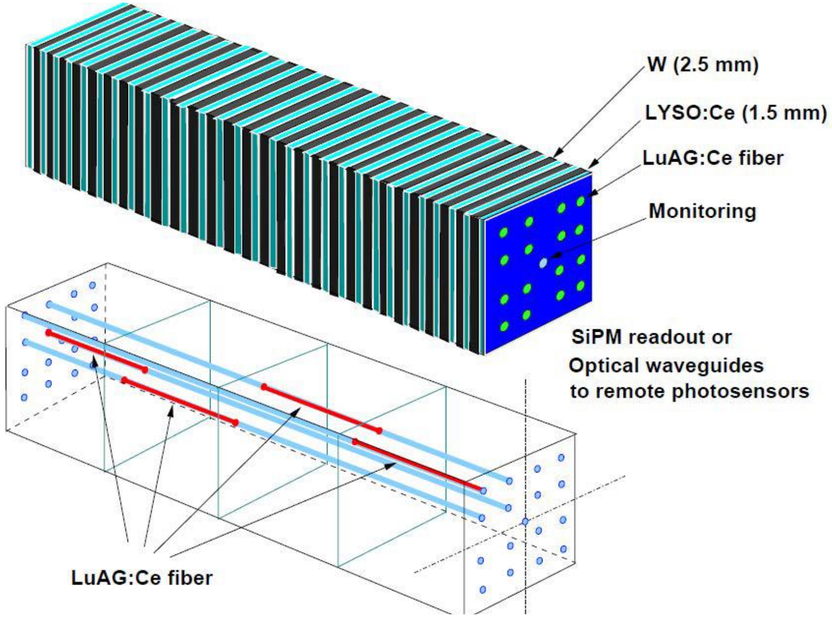
RADiation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission



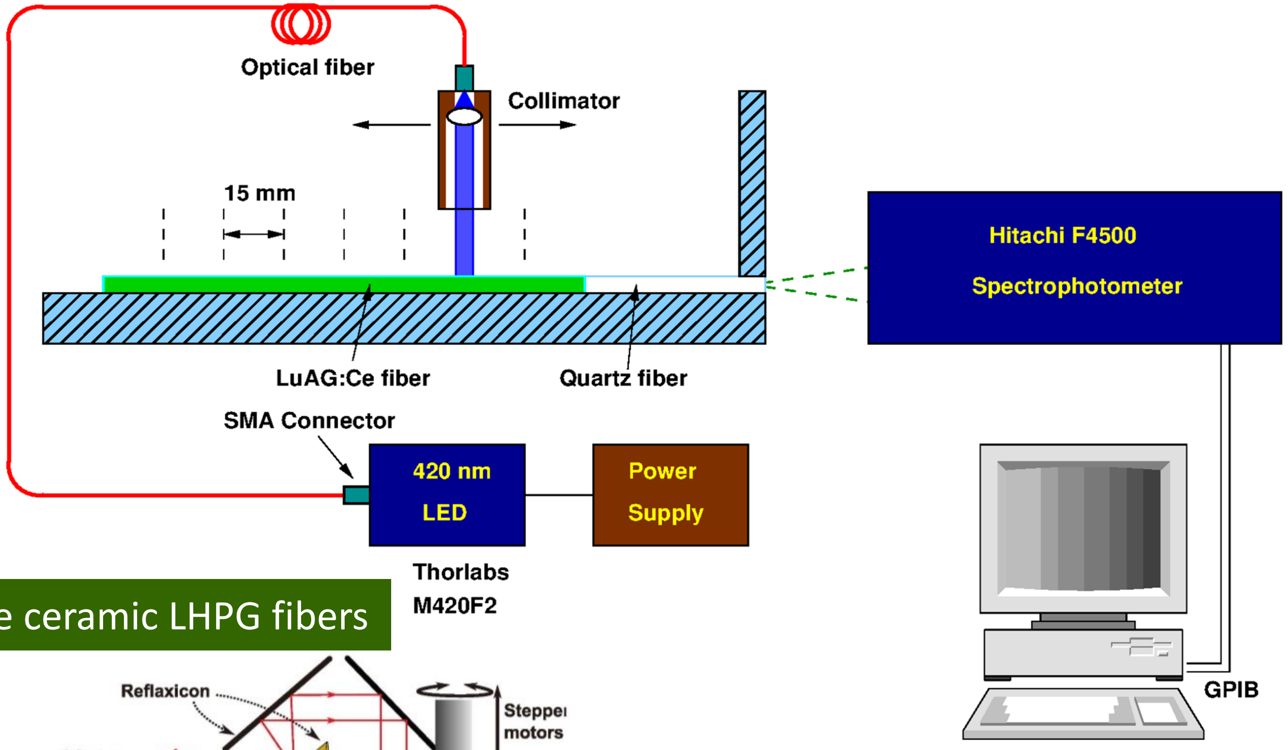


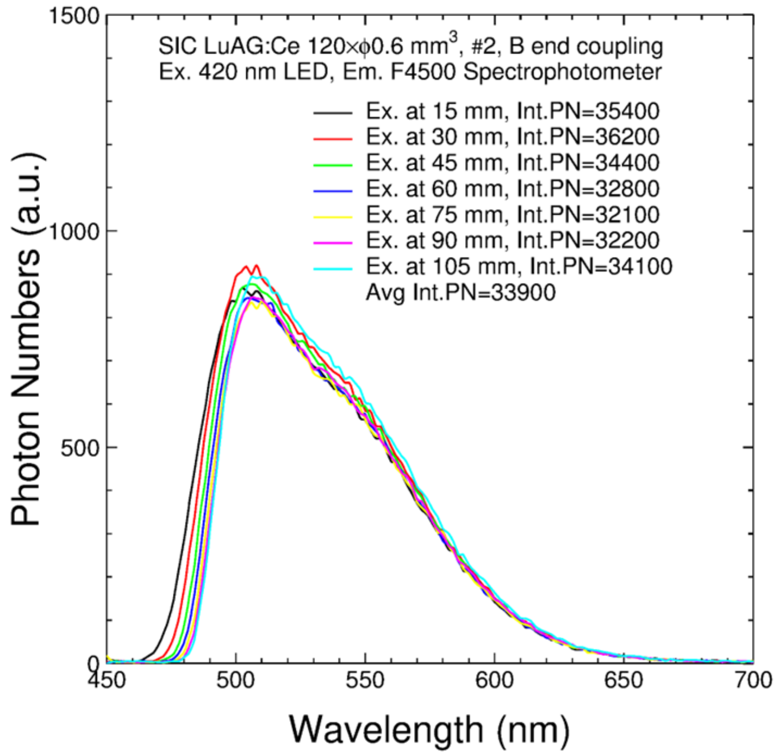


LuAG:Ce ceramic LHPG fibers

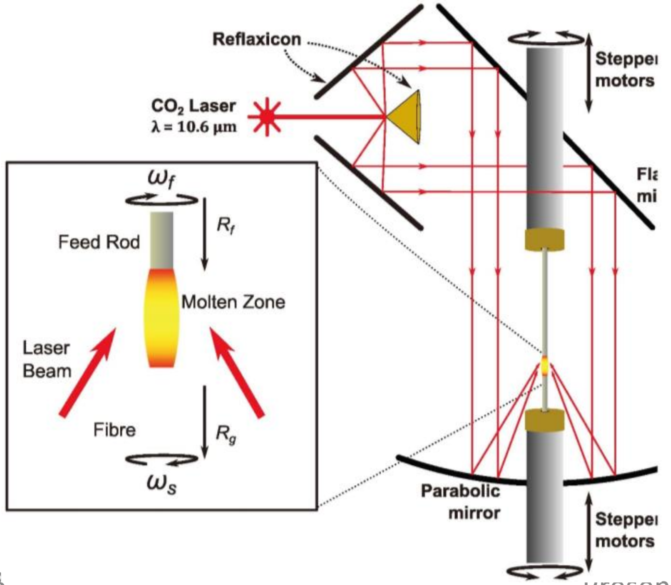


LuAG:Ce Fiber Light Output and Uniformity





LuAG:Ce ceramic LHPG fibers

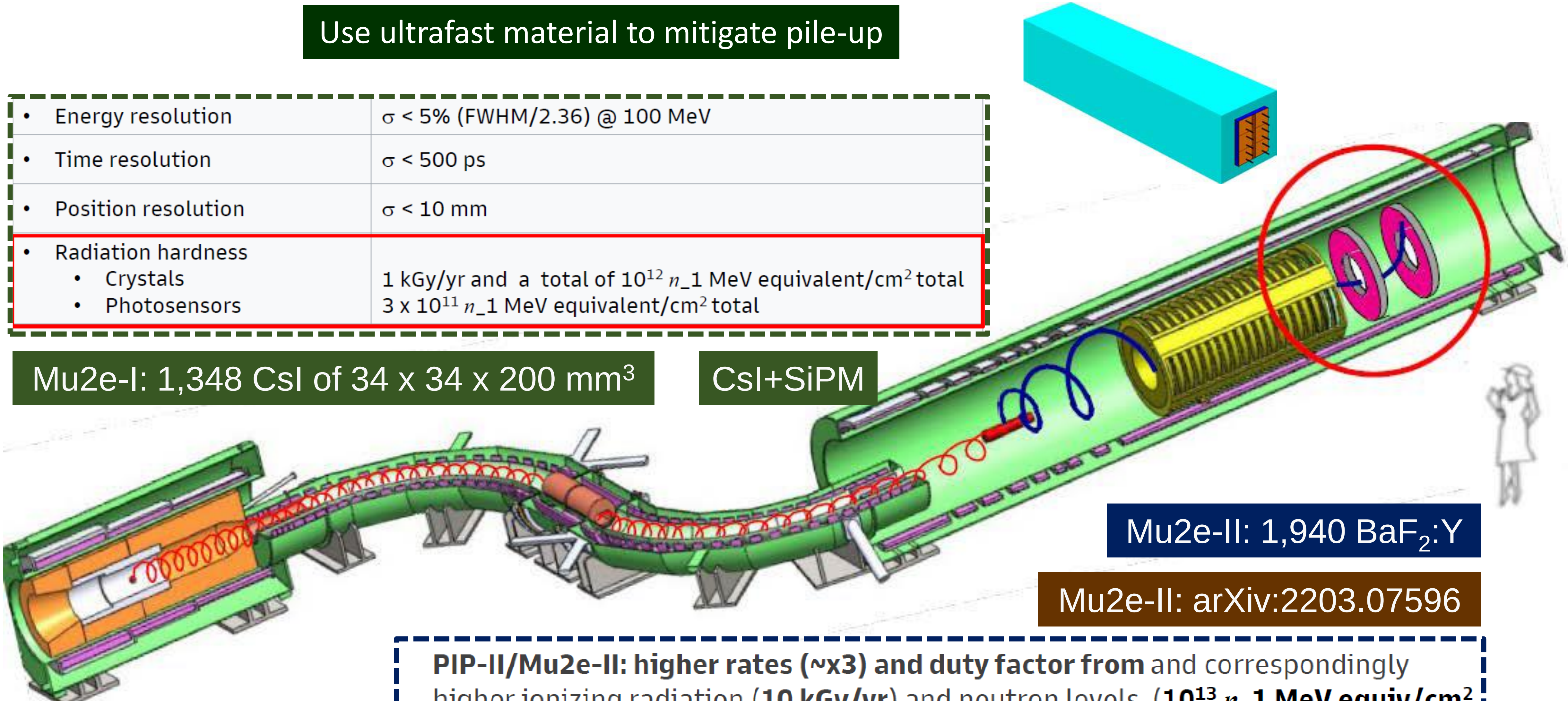


Excellent uniformity observed for Φ0.6 ×120 mm^3 LuAG:Ce ceramic fibers excited by a 420 nm LED at different longitudinal location, with a solid coupling to a quartz fiber, mimicking its application in RADiCAL Calorimetry

Ultrafast 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

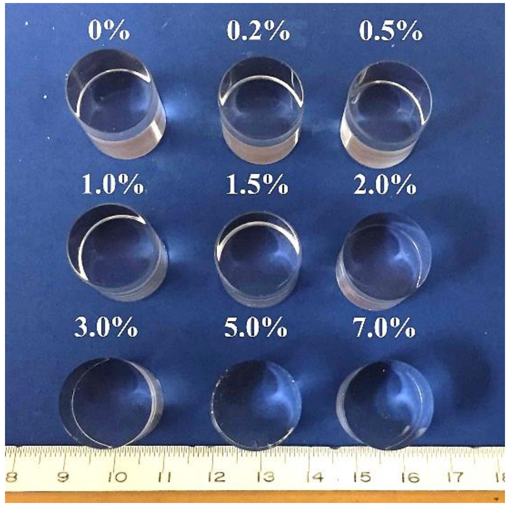
Mu2e-II: 1,940 BaF_2:Y

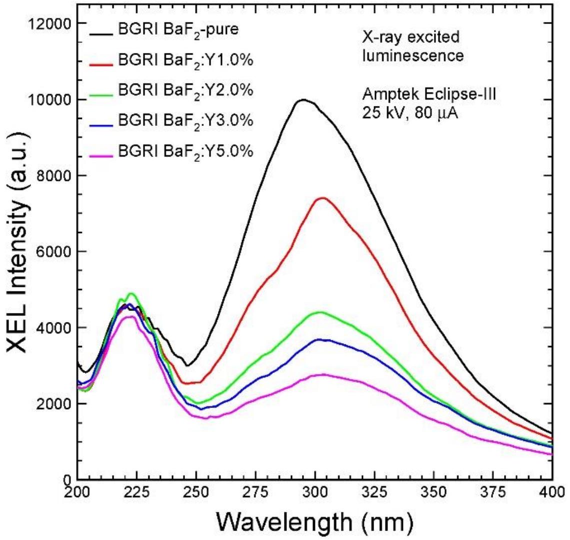
Mu2e-II: arXiv:2203.07596

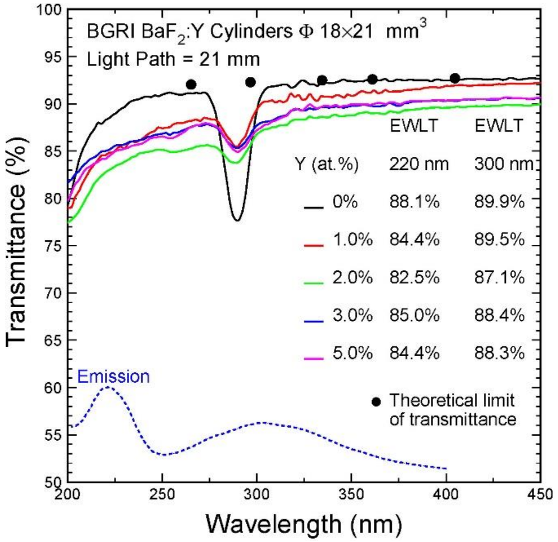
PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm^2 total**), which are particularly important at the inner radius of disk 1

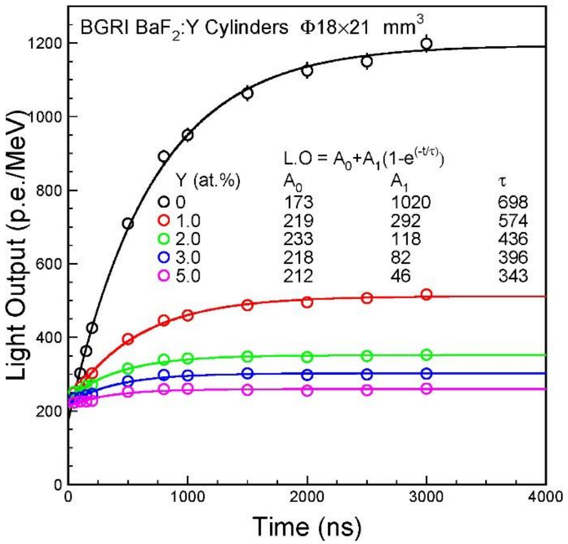
BaF_2:Y for Calorimetry & Imaging

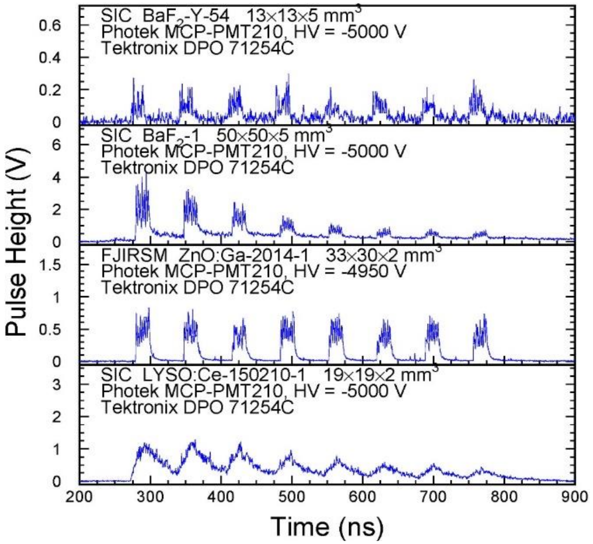
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

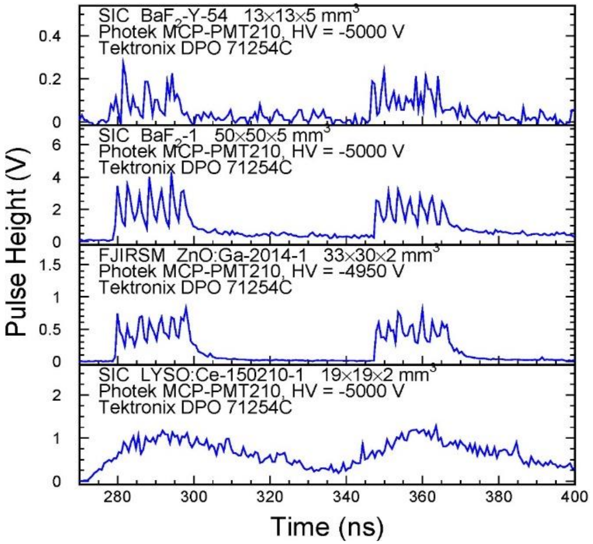


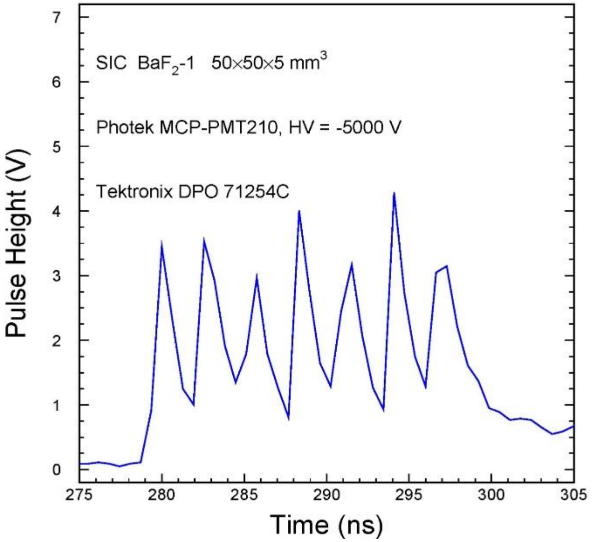








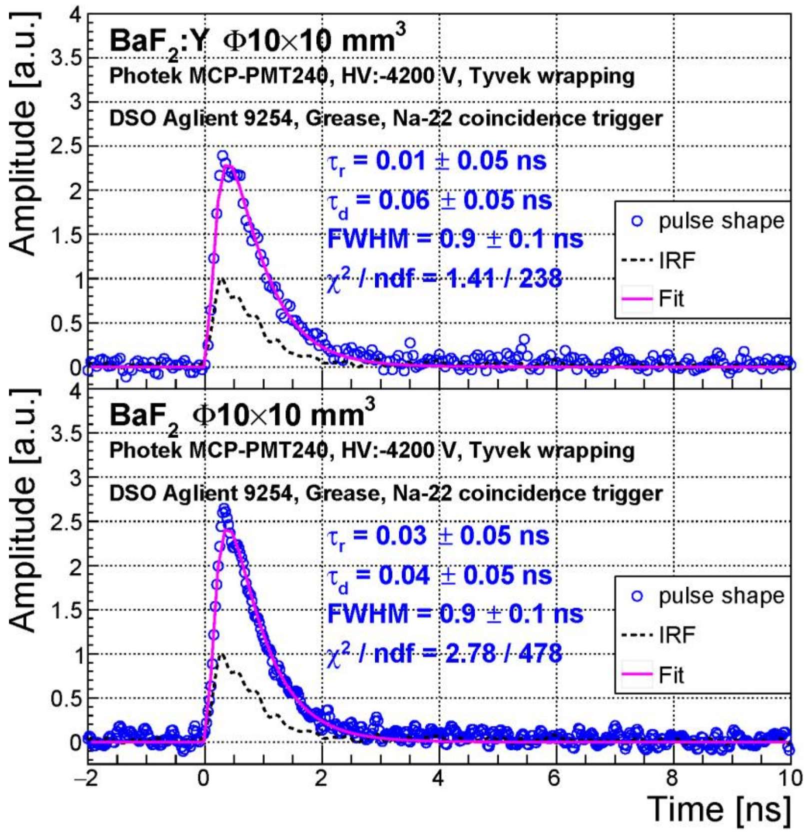


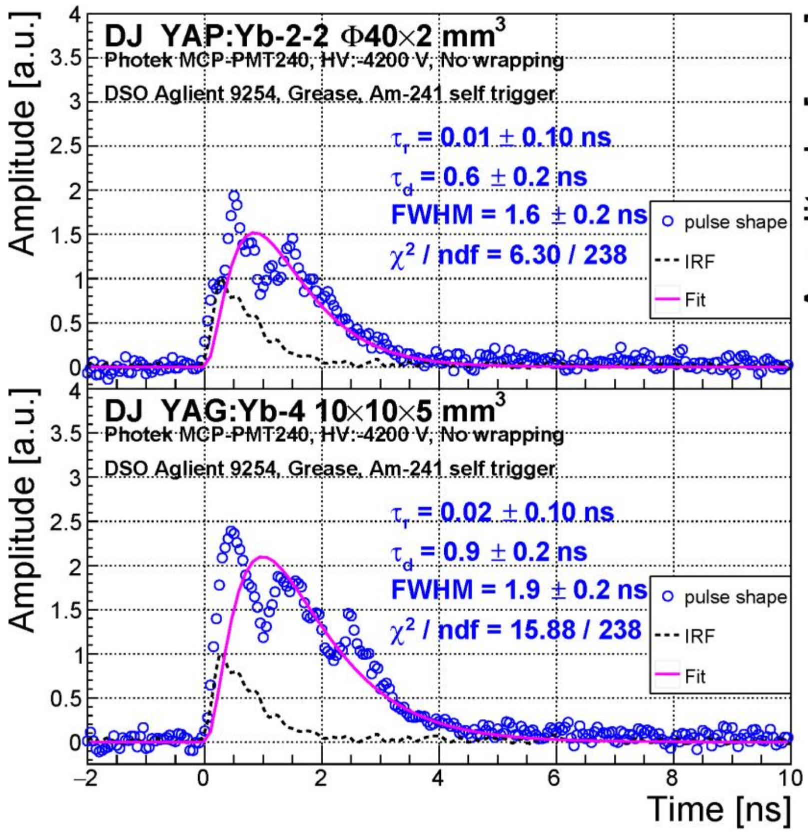


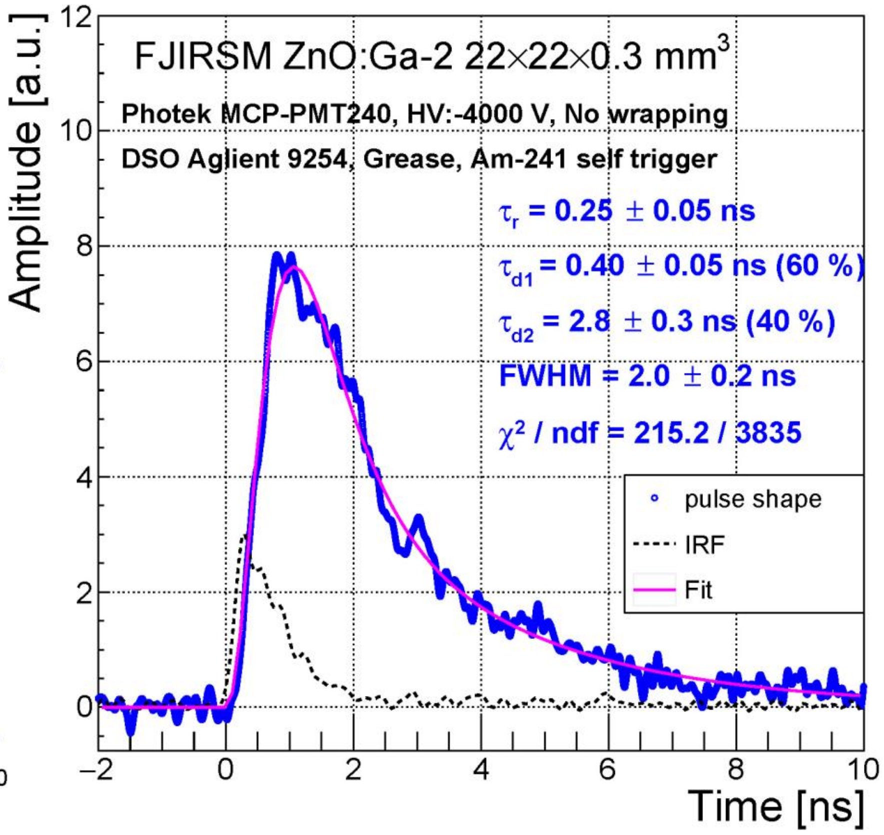
X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

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





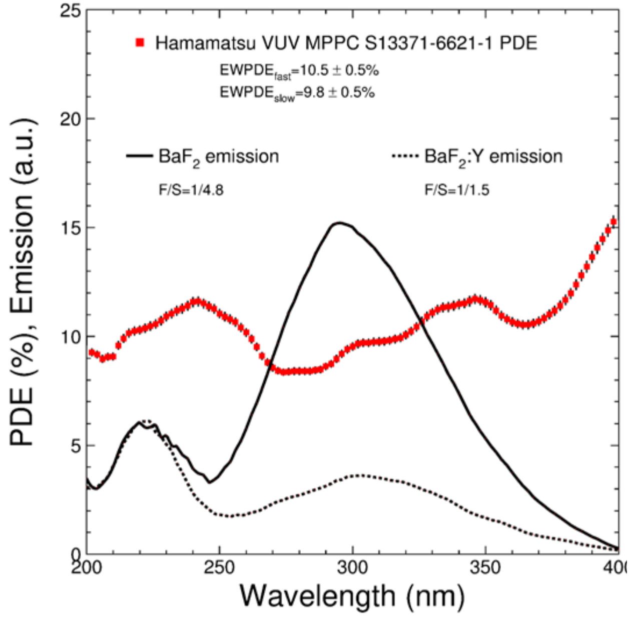


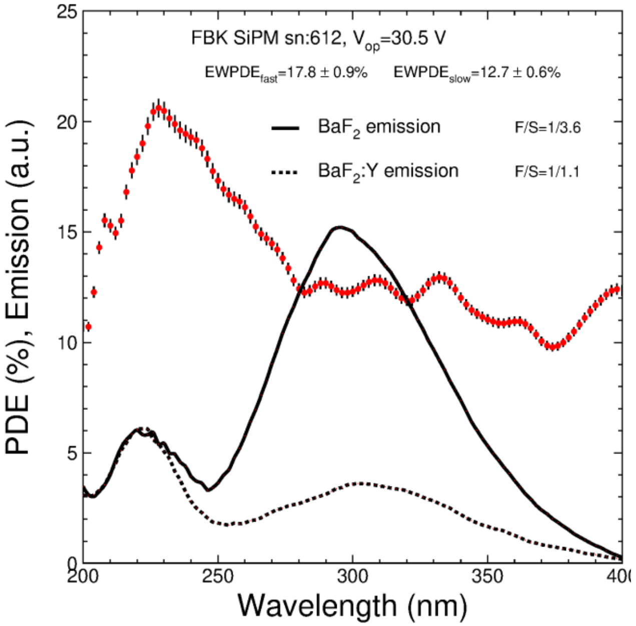
PDE of UV SiPM for BaF_2 and BaF_2:Y

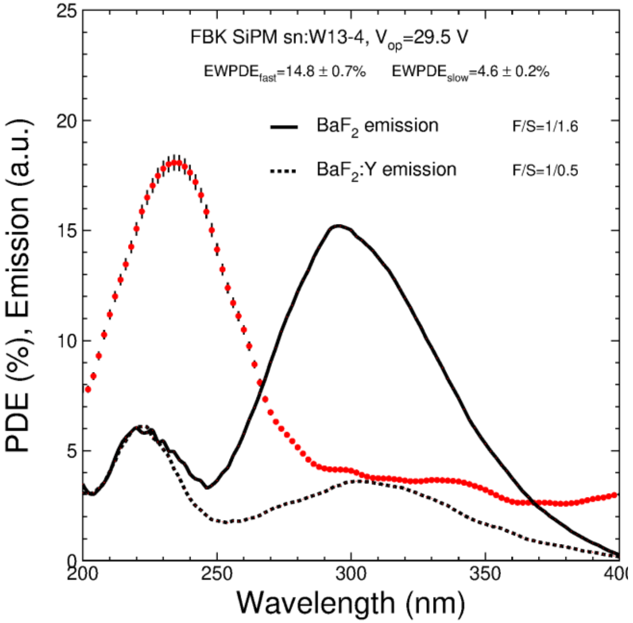
IEEE TNS **69** (2022) 958-964

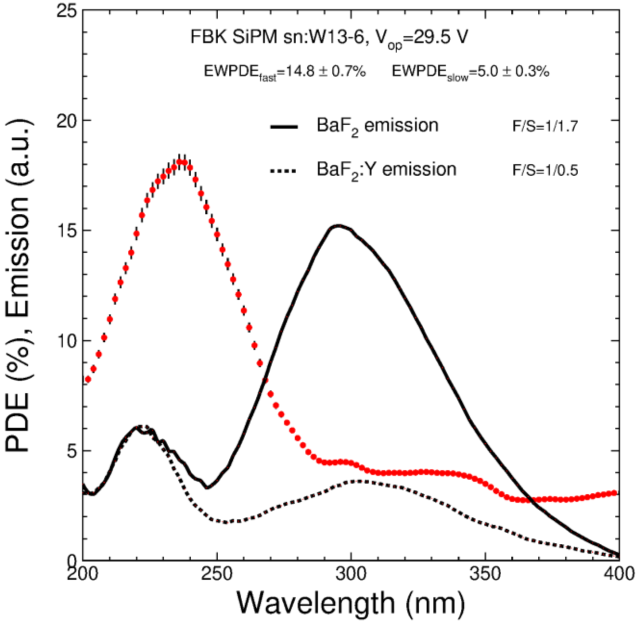
Photodetector	$EWPDE_{fast}$ (%)	$EWPDE_{slow}$ (%)	Relative F/S_{BaF}	Relative $F/S_{BaF:Y}$
Hamamatsu MPPC	10.5	9.8	1/4.8	1/1.5
FBK SiPM 2021	17.8	12.7	1/3.6	1/1.1
FBK SiPM 2023-1	14.8	4.6	1/1.6	1/0.5
FBK SiPM 2023-2	14.8	5.0	1/1.7	1/0.5

γ-ray induced readout noise is reduced by BaF_2:Y slow suppression & solar-blind PDE

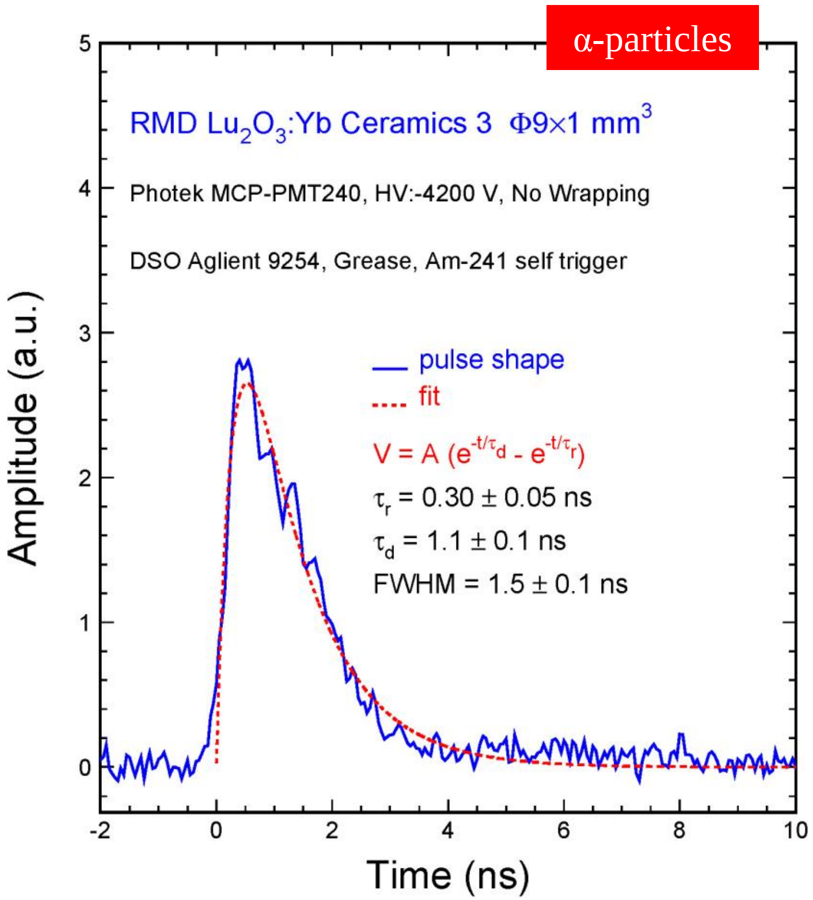


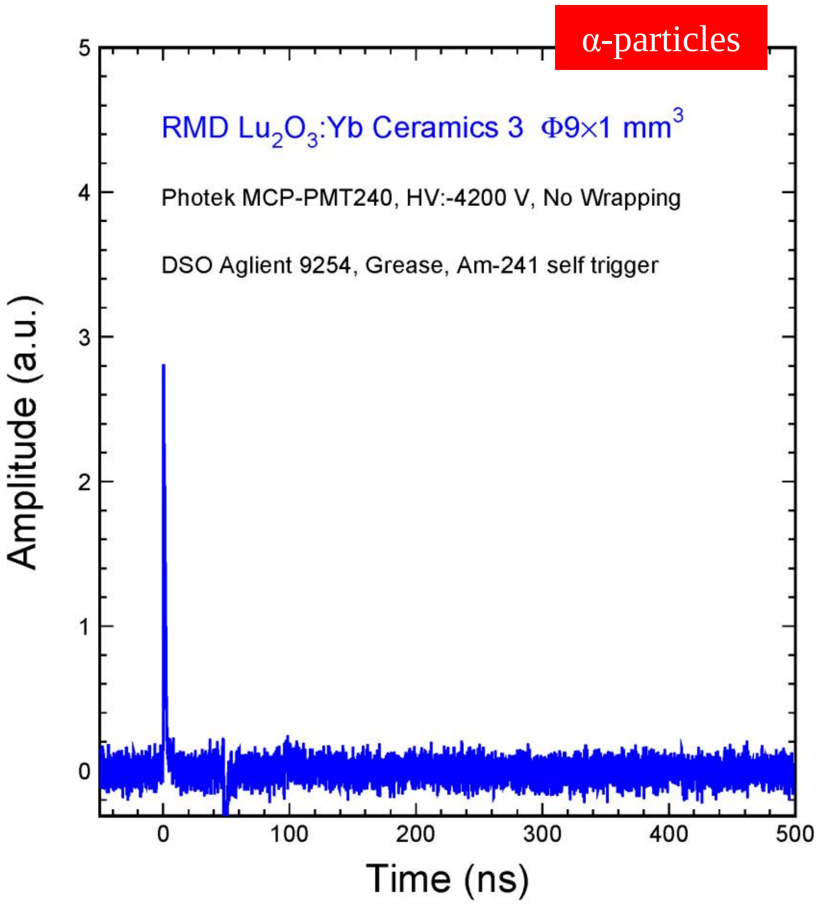


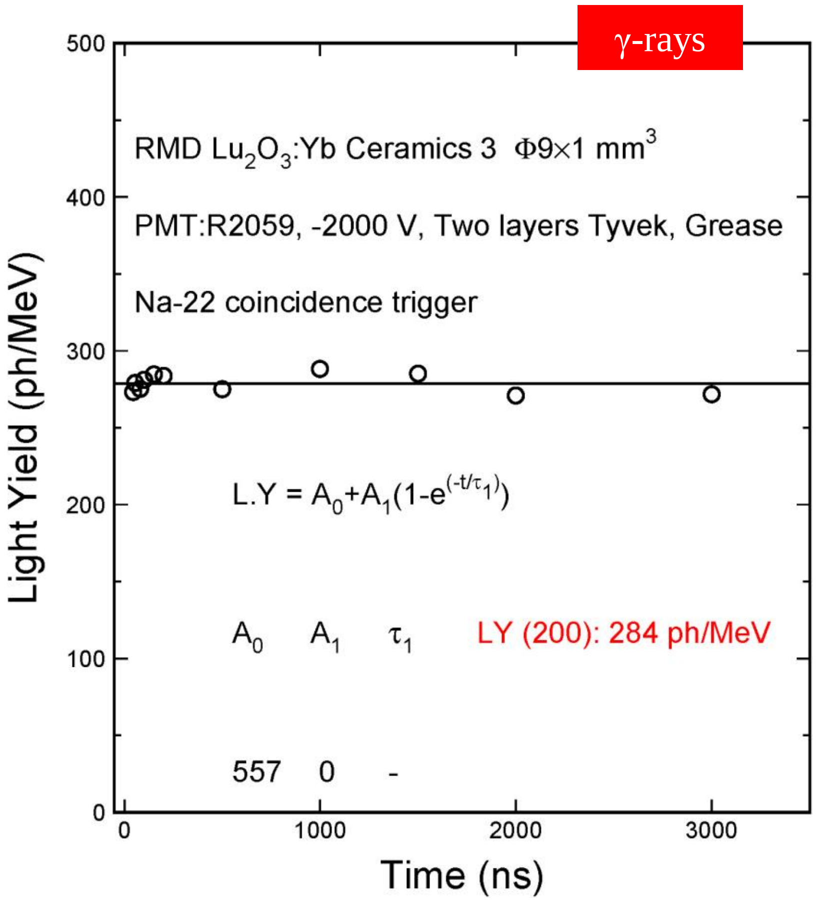




Temporal Response: Lu_2O_3:Yb Ceramics

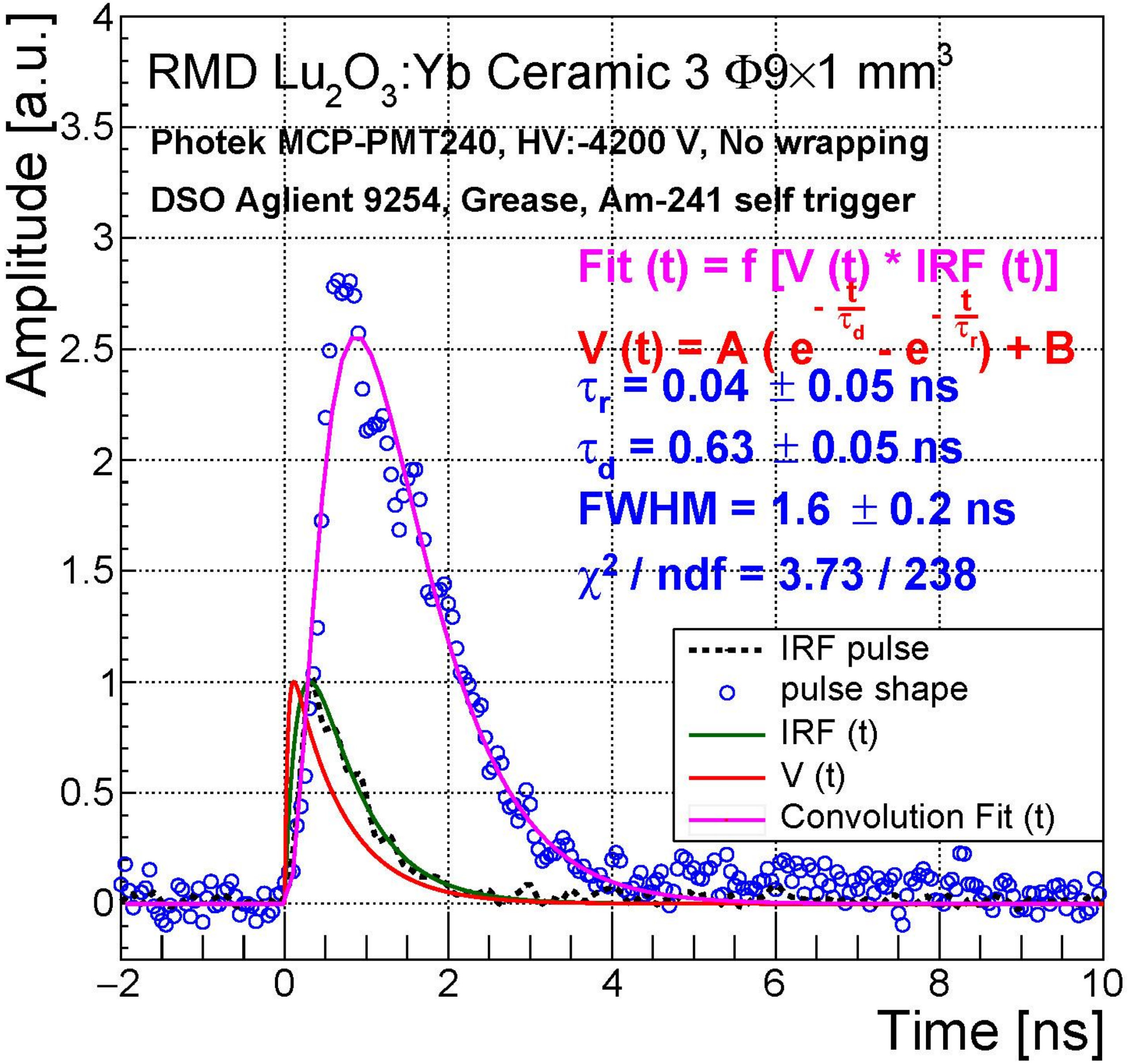






Lu_2O_3:Yb ceramic of 9.4 g/cc shows an ultrafast decay time of **1.1 ns** by Am-241 with negligible slow component observed in integrated light output measurement

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

Fast/Ultrafast for TOF & X-ray 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 (^oC)	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 1[st] ns (photons/MeV)	1200	1200	170	34[d]	46[d]	980[d]	43	740	240	391	400	125	318
LY in 1[st] 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.

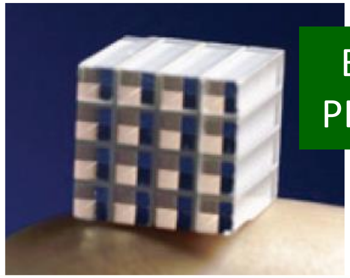
Inorganic Scintillators for Imaging

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.**

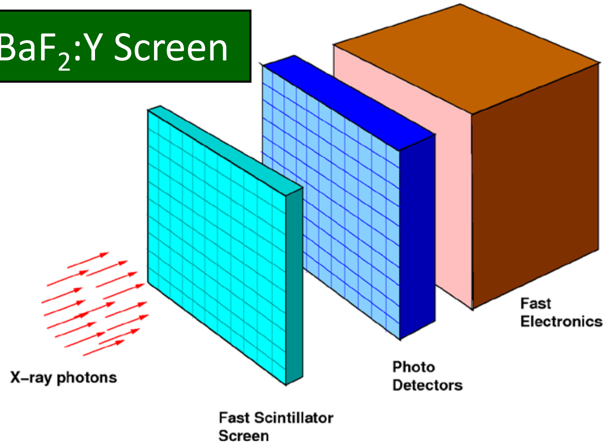
Performance	Type I imager	Type II imager
X-ray energy	**up to 30 keV**	**42-126 keV**
Frame-rate/inter-frame time	**0.5 GHz / 2 ns**	**3 GHz / 300 ps**
Number of frames per burst	≥ 10	10 - 30
X-ray detection efficiency	above 50%	above 80%
Pixel size/pitch	**≤ 300 μm**	**< 300 μm**
Dynamic range	10^3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

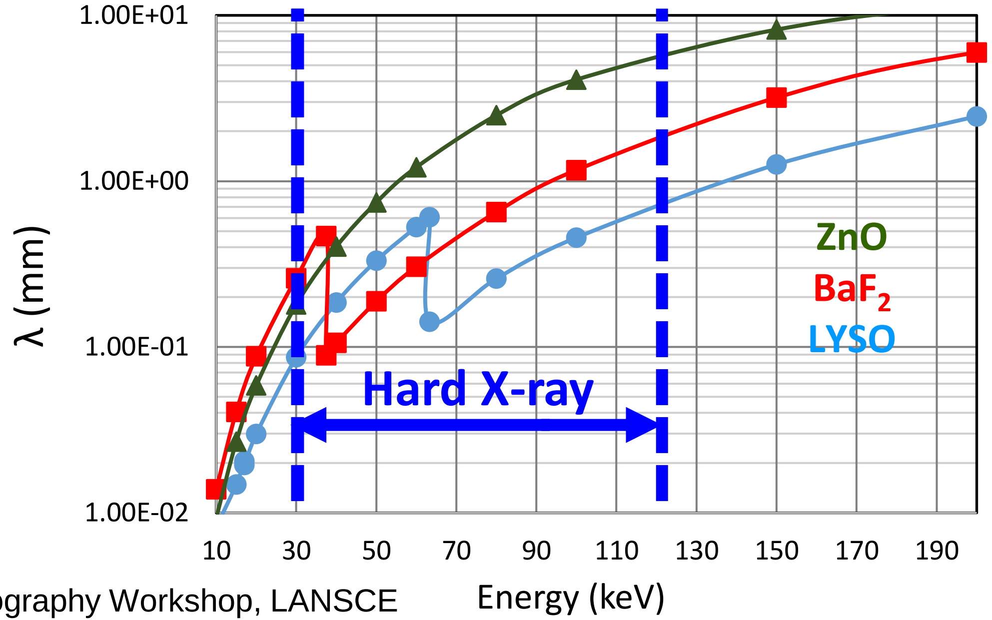
- **Detection efficiency for hard X-ray requires bulk detector; 2 ns and 300 ps inter-frame time requires ultrafast sensor.**



BGO pixels for PET: 1x1x10 mm

BaF$_2$:Y Screen

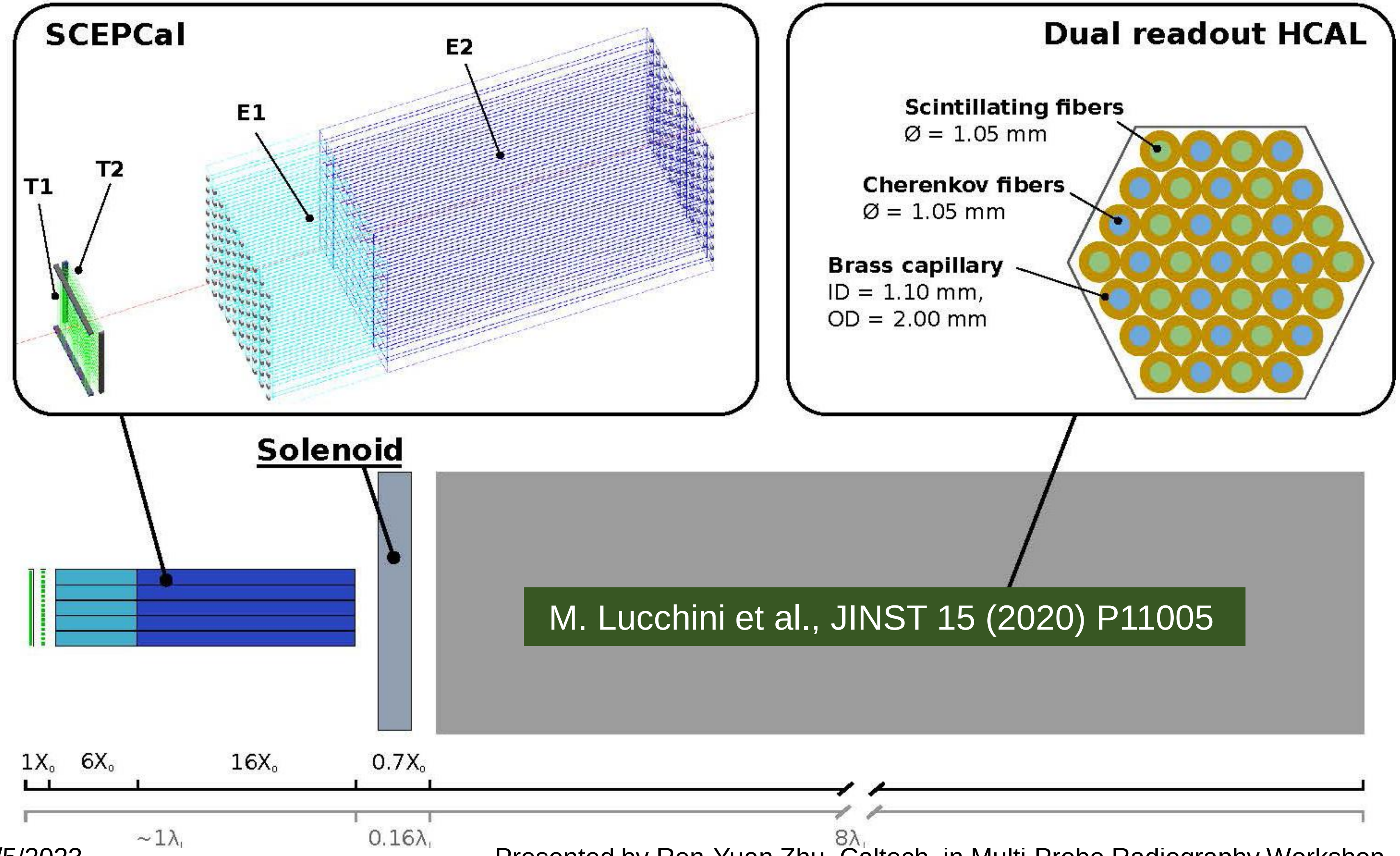




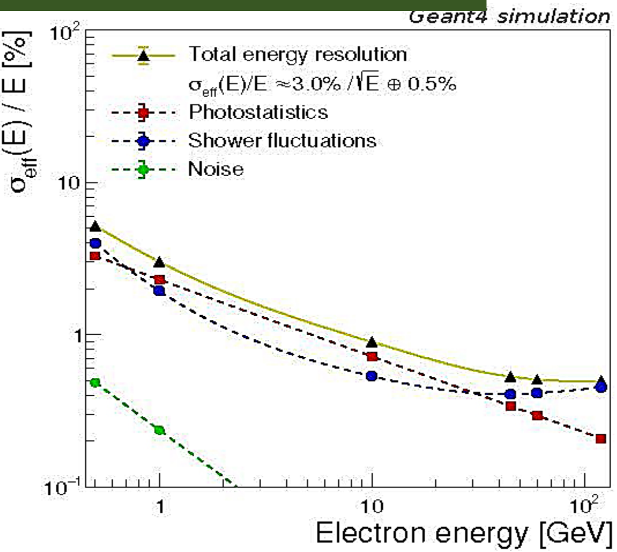
CalVision: Segmented Crystal ECAL

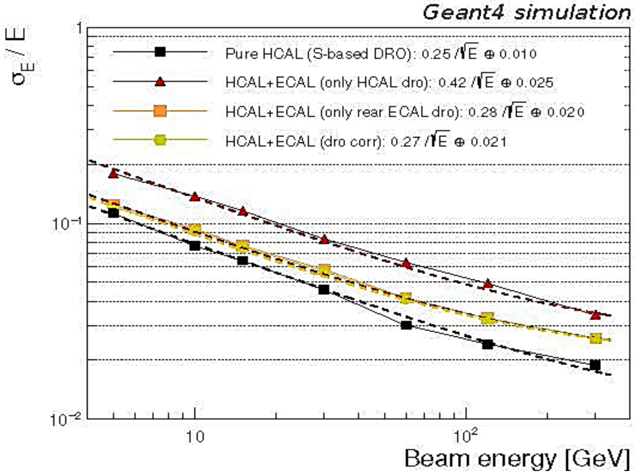
arXiv: 2203.04312

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

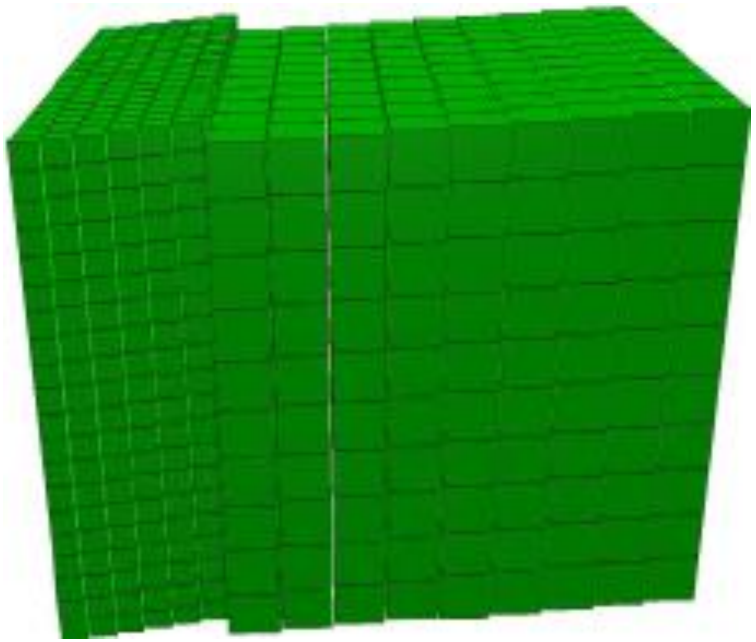


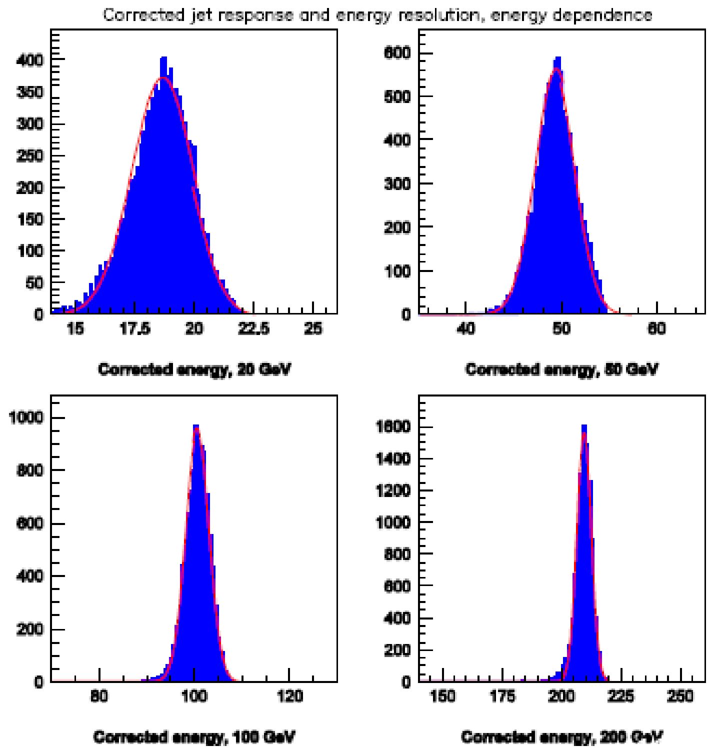
M. Lucchini et al., JINST 15 (2020) P11005



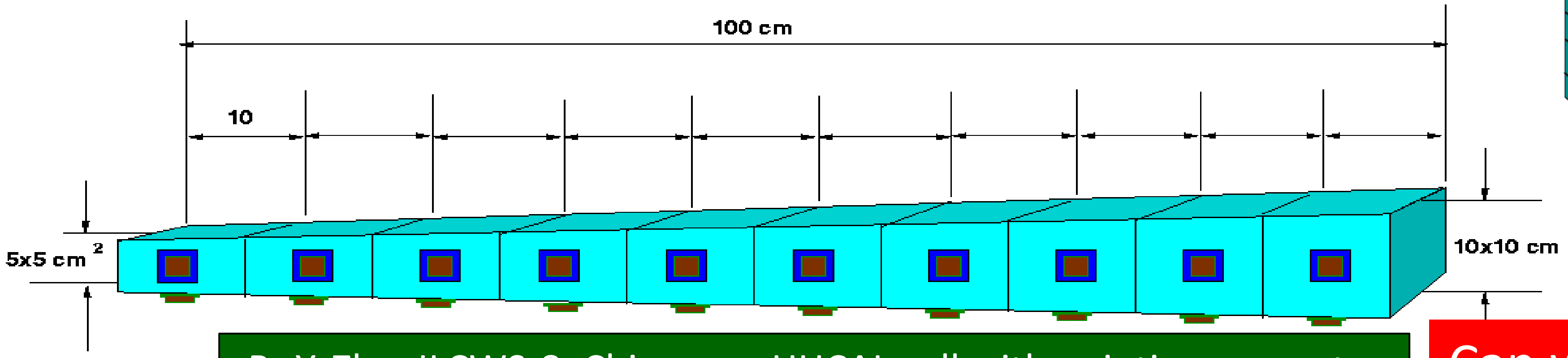


The HHCAL Concept

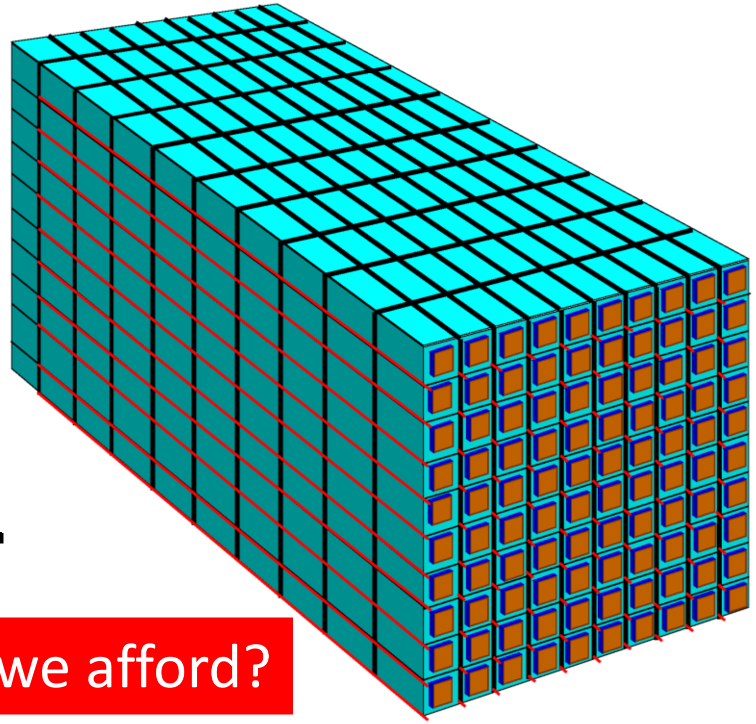




A. Para, H. Wenzel and S. McGill in Callor2012 Proceedings and A. Benaglia *et al*., IEEE TNS **63** (2016) 574-579: a jet energy resolution at a level of 20%/√E by HHCAL with dual readout of S/C or dual gate.
M. Demarteau, 2021 CPAD Workshop

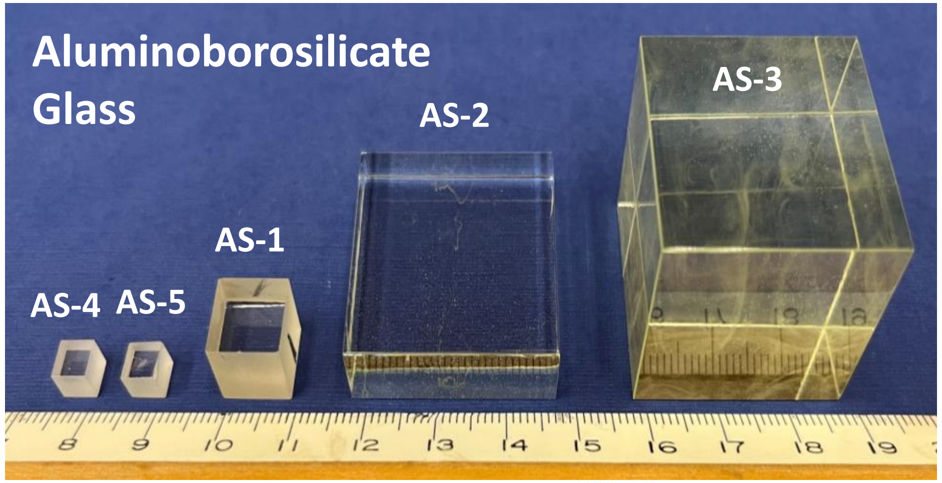


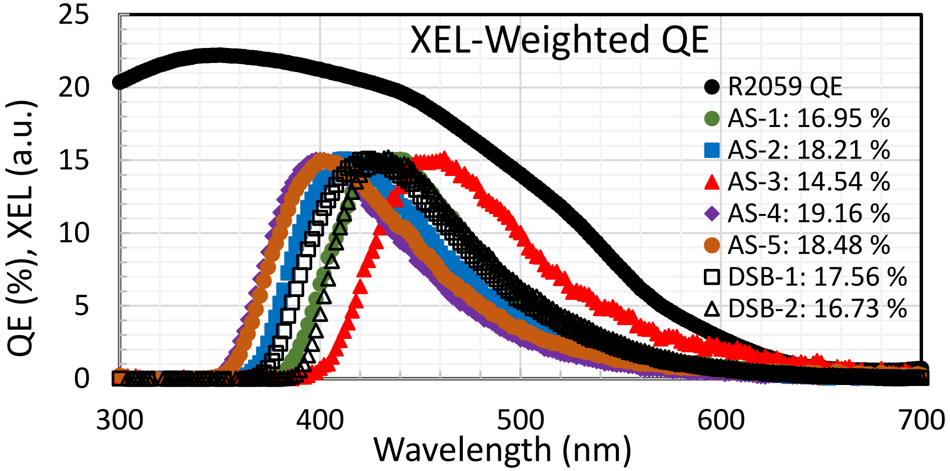
R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

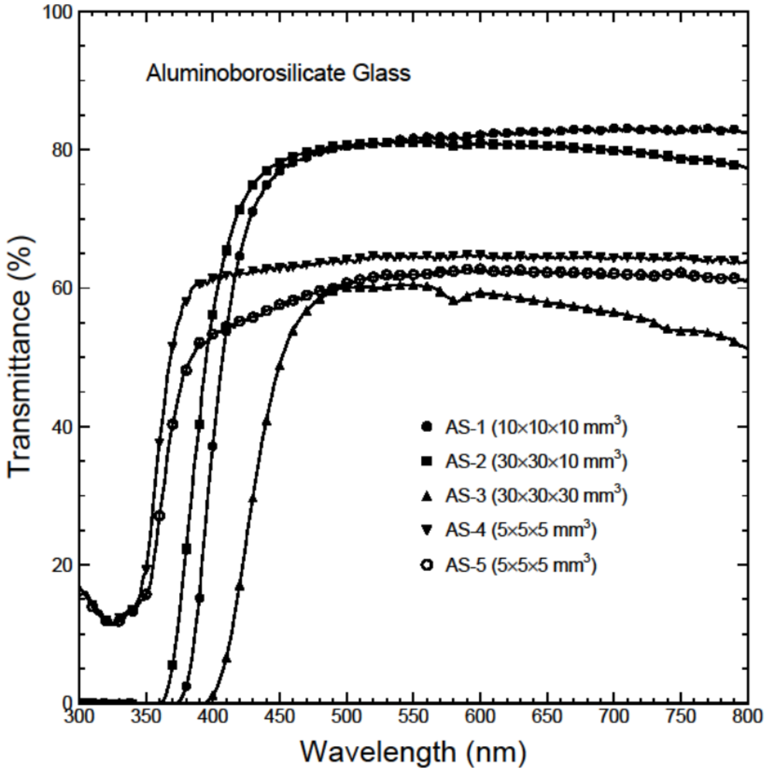


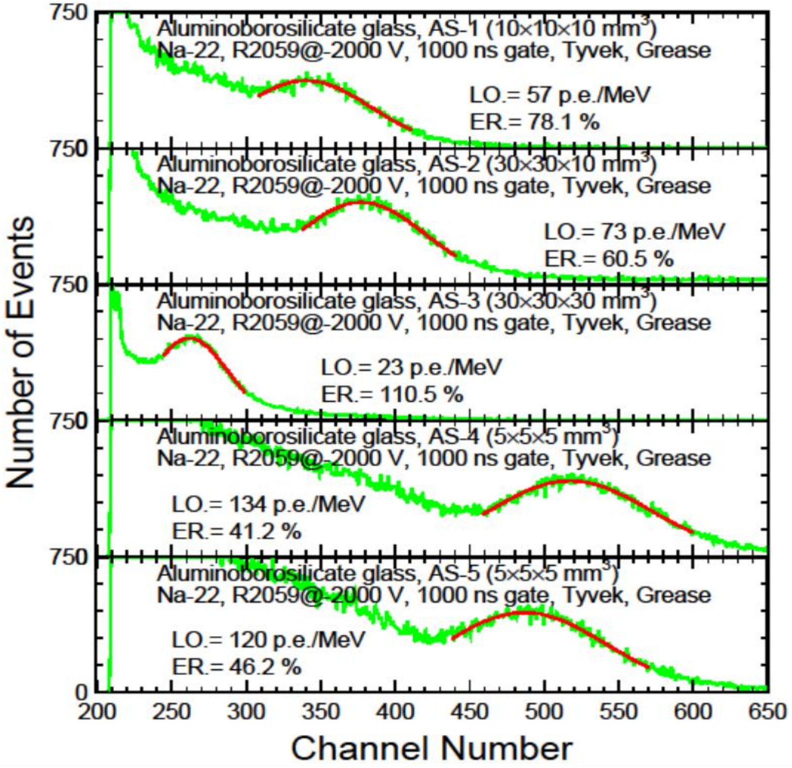
Can we afford?

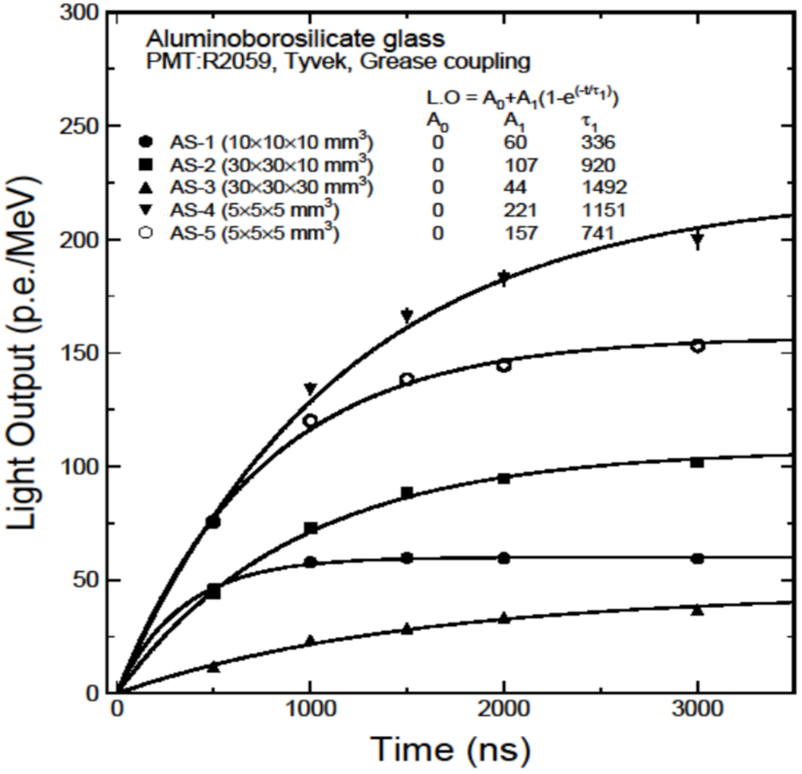
ABS (B_2O_3–SiO_2–Al_2O_3–Gd_2O_3–Ce_2O_3) Glass











Inorganic Scintillators for HHCAL

Presented in the 9/14/2023 CalVision meeting all samples measured at Caltech

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO:Ce Glass	DSB:Ce Glass	ABS:Ce Glass
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	4.3	6.0
Melting point (℃)	1050	1030	1123	824	608	2040	980[7]	1550	?
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	2.58	1.56
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.90	3.24	2.49
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	30.9	24.2
Z_{eff} value	71.5	73.8	73.6	76.7	74.7	11.1	41.4	49.5	56.6
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	6.1	8.0
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	420	400
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	?	?	?
LY (ph/MeV)[c]	7,500	1,500	130	\	150	7,900	450	1,360	1,150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	500	740
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?	?	?	0.3	?
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6	2.0	2.0	<1

Summary

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

RADiCAL proposes an ultra-compact, fast timing and longitudinally segmented shashlik calorimeter with LuAG:Ce ceramics as wavelength shifter for LYSO:Ce.

Mu2e-II considers ultrafast BaF_2:Y calorimeter. R&D is on radiation hardness of BaF_2:Y and solar-blind SiPM. Industry is developing ultrafast Lu_2O_3:Yb ceramics. They are promising for GHz hard x-ray imaging and Multi-Probe Radiography.

CalVision proposes a dual readout longitudinally segmented crystal ECAL combined with the IDEA HCAL promising excellent EM and Hadronic resolutions for the proposed lepton Higgs factory.

Homogeneous HCAL (**HHCAL**) promises the best jet mass resolution by total absorption. Novel cost-effective heavy scintillating glass is under development.

Acknowledgements: DOE HEP Award DE-SC0011925