Recent Progress on Inorganic Scintillators for Future High Energy Physics Experiments

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Why Inorganic Scintillators?

- **Precision e/γ enhance physics discovery potential.**
- **Performance of total absorption crystal calorimeters is well understood for e/γ, and is also promising for jets:**
  - **The best possible energy resolution;**
  - **Good position resolution;**
  - **Good identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout: C/S light or S/L gate.**
- **HEP calorimetry requires novel inorganic scintillators:**
  - **RADiCAL for HL-LHC and FCC-hh: rad hard LYSO:Ce crystals and LuAG:Ce ceramics;**
  - **Ultrafast calorimetry for Mu2e-II: ultrafast BaF_2:Y crystals;**
  - **Calvision and HHCAL for the Higgs factory: cost-effective inorganic scintillators.**

2019 DOE Basic Research Needs Study on Instrumentation: Calorimetry

https://science.osti.gov/-/media/hep/pdf/Reports/2020/DOE_Basic_Research_Needs_Study_on_High_Energy_Physics.pdf?la=en&hash=A5C00A96314706A0379368466710593A1A5C4482

Priority Research Direction
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

Fast/ultrafast, radiation hard and cost-effective inorganic scintillators needed to achieve energy, spatial and timing resolution for future HEP calorimetry

[1] CPAD 2021 workshop: https://indico.fnal.gov/event/46746/timetable/#all.detailed

Fast and Ultrafast Inorganic Scintillators

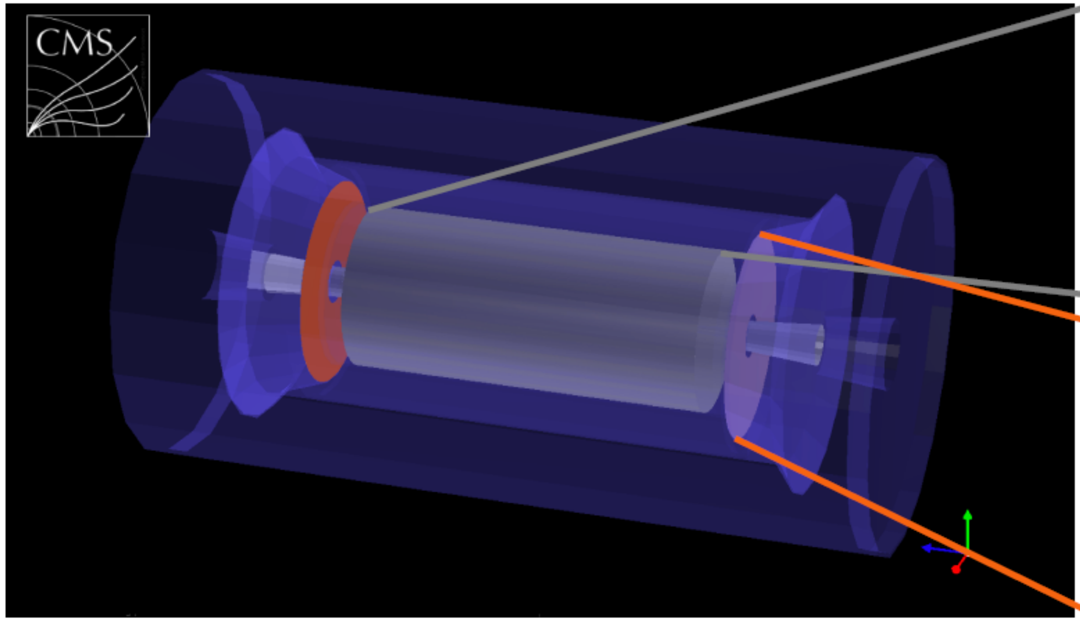
	BaF_2	BaF_2:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	2.4	2.76	2.20	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	22.4	25.2	20.9	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	31.9	30	28.1	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	8.05	7.01	8.82	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak}[a] (nm)	300 220	300 220	380	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	1.96	1.87	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	6.6[d]	0.19[d]	0.36[d]	6.5 0.5	100	35[e] 48[e]	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000[d]	57[d]	110[d]	2,100	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 0.5	600 0.5	<1	1.5	4	148 6	40	820 50	191 25	53	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610[d]	28[d]	24[d]	43	740	240	391	640	125	318
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

LYSO:Ce for CMS Barrel Timing Layer

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

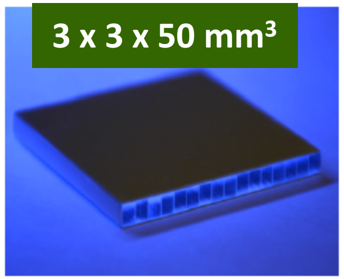
Barrel Timing Layer: arrays of LYSO crystal bars connected to SiPMs at both ends and readout by TOFHIR

LYSO QC: Low temperature (-35°C) performance, RIN:γ, RIN:n, TID, TF:p and TF:n



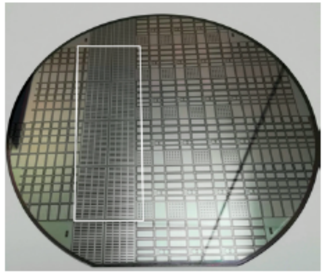
BTL: LYSO bars + SiPM read-out

- 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



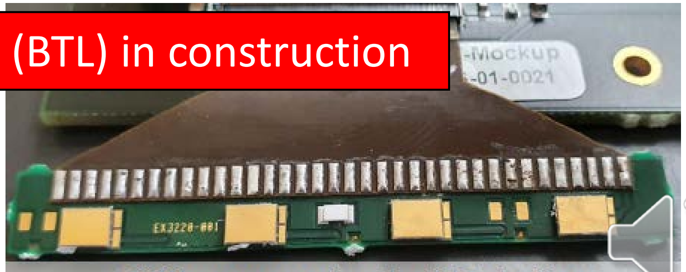
ETL: Si with internal gain (LGAD)

- 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

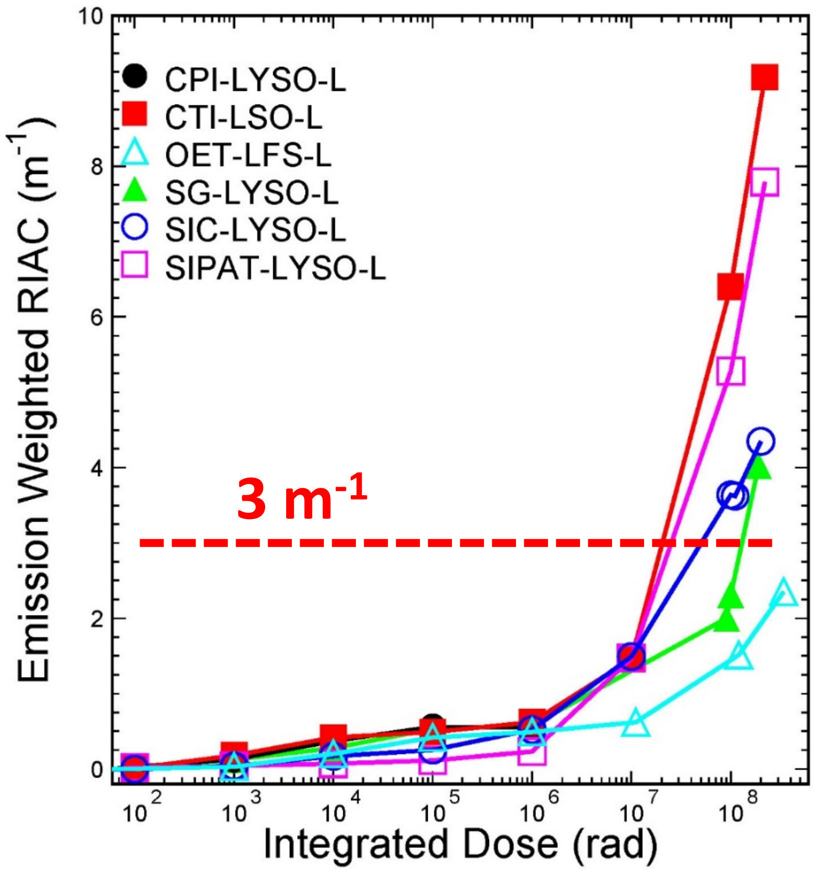
SiPM array prototypes from FBK

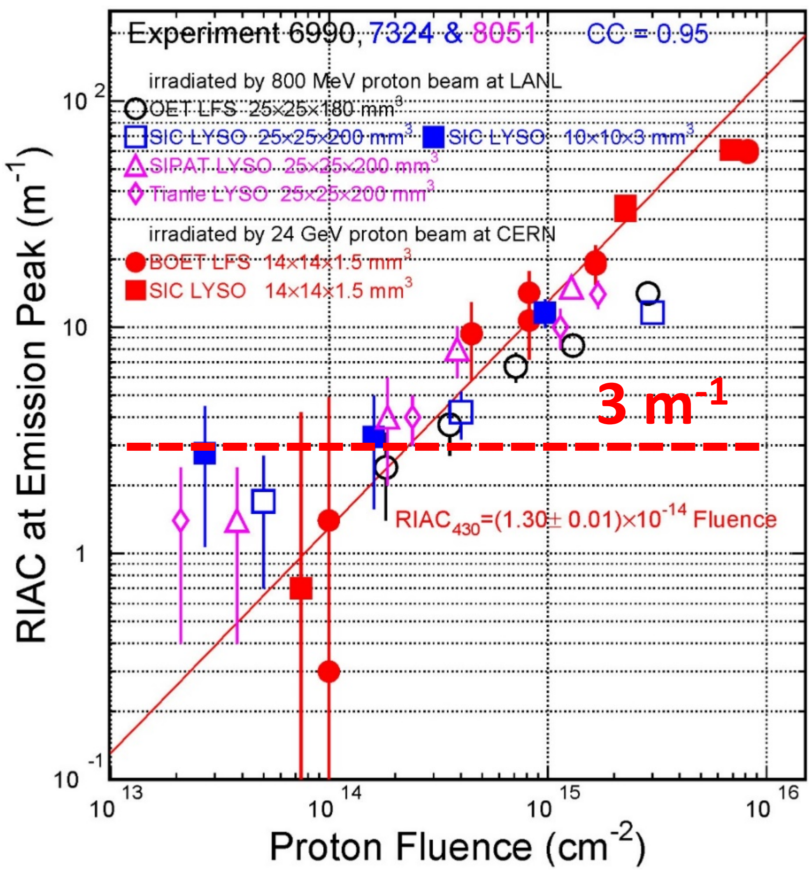


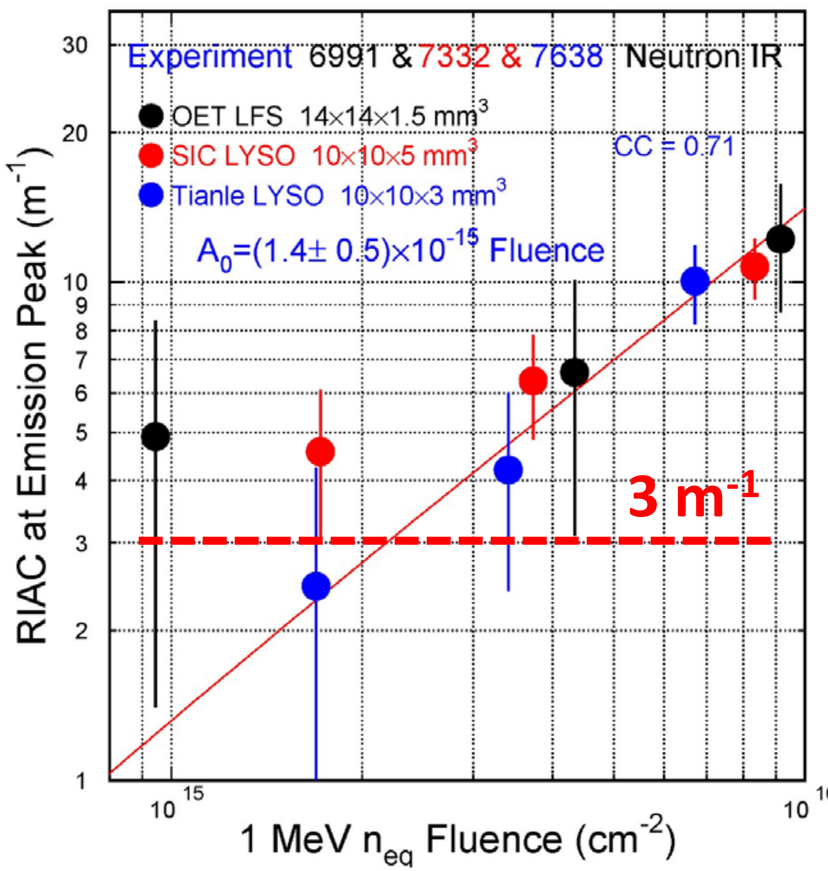
SiPM arrays mockup for TECs testing

LYSO Radiation Hardness

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



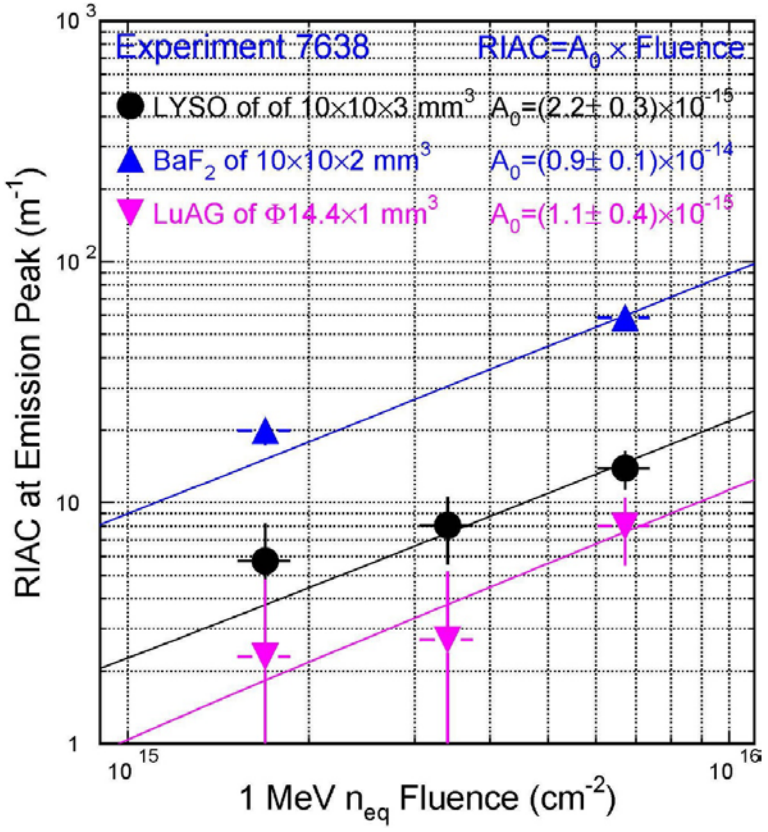


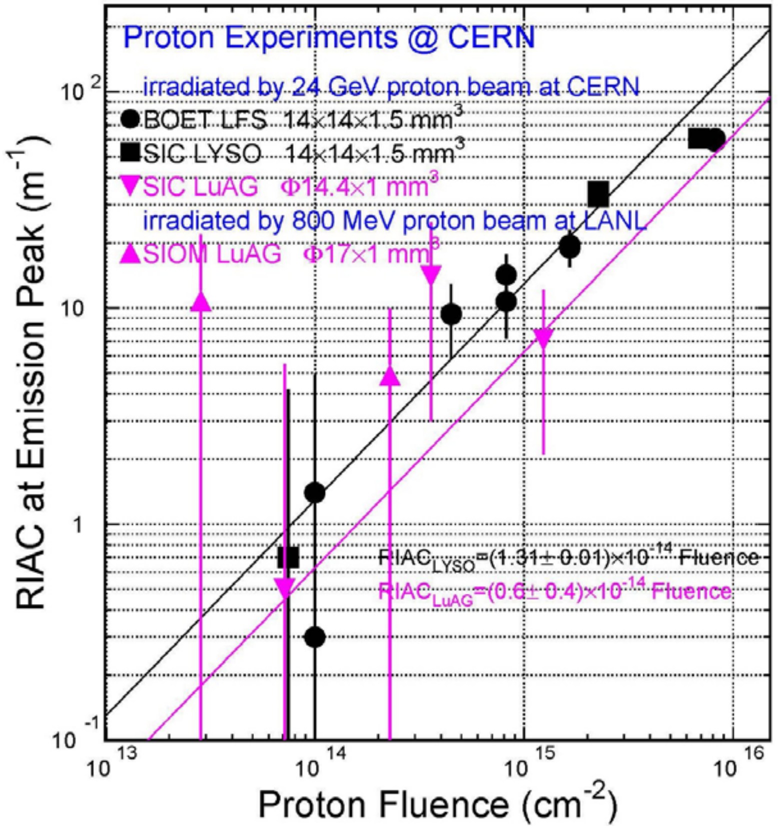


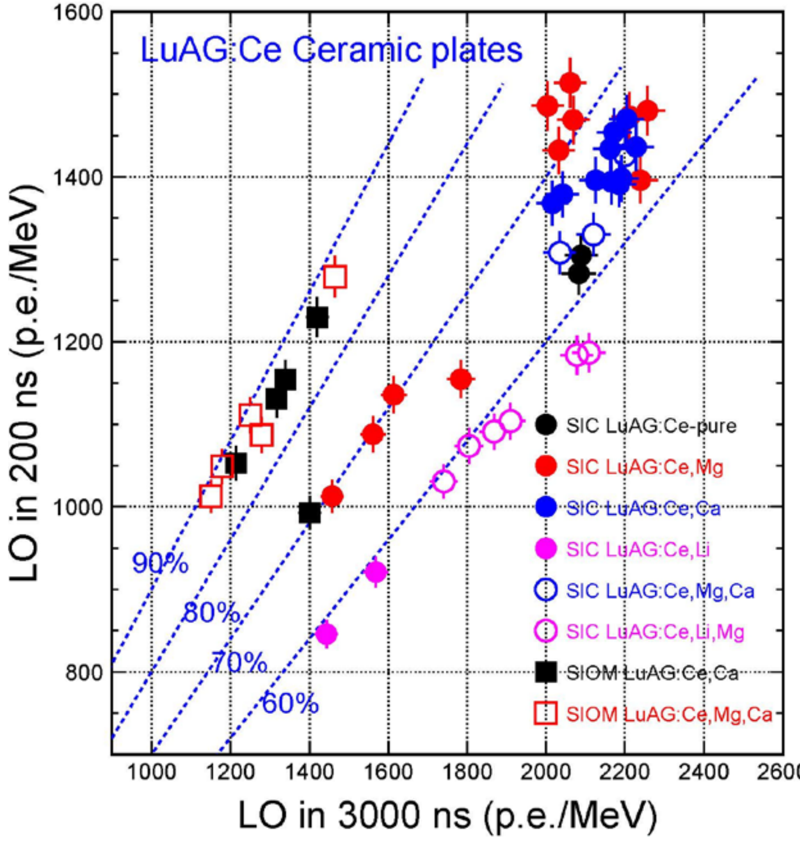
Damage induced by protons is an order of magnitude larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup

LuAG:Ce Ceramics Radiation Hardness

LuAG:Ce ceramics show a factor of two better radiation hardness than LYSO crystals up to 6.7×10^{15} n_{eq}/cm^2 and 1.2×10^{15} p/cm^2, promising for FCC-hh
Paper N18-05 in the virtual IEEE NSS/MIC 2020 Conference Record (2020)

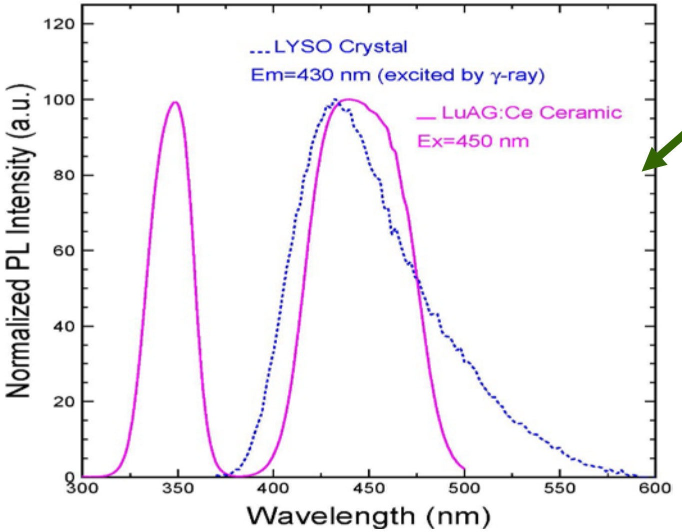






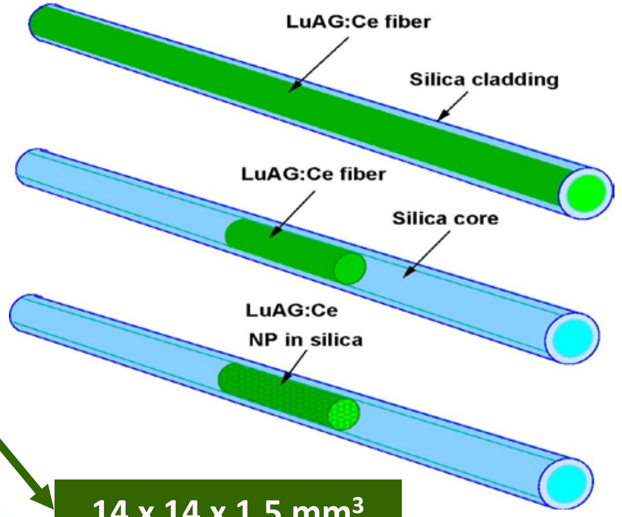
R&D on slow suppression by Ca co-doping, and radiation hardness by ɣ/p/n

RADiCAL: LYSO/LuAG Shashlik ECAL

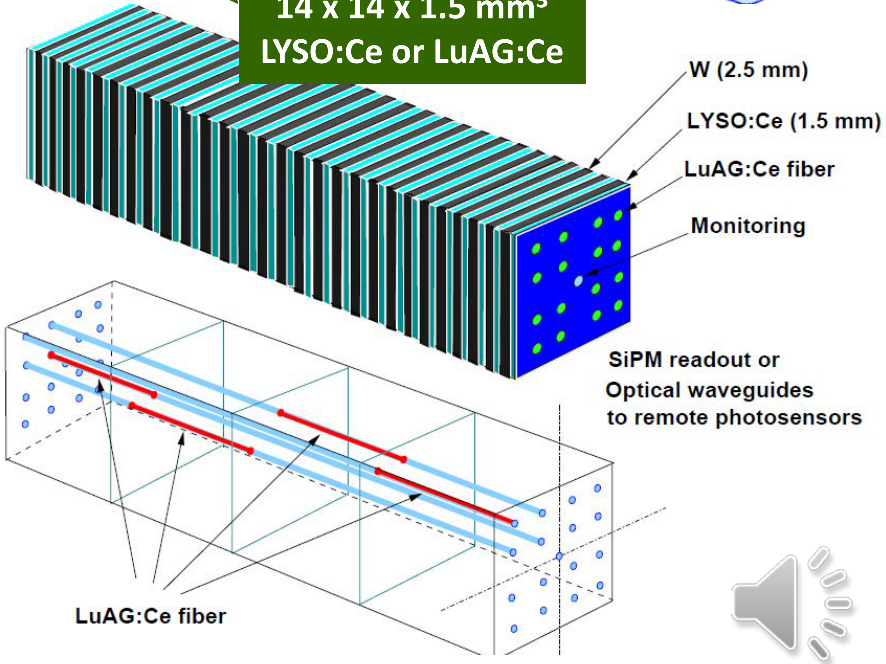


Excitation of LuAG:Ce ceramics matches well LYSO:Ce emission:

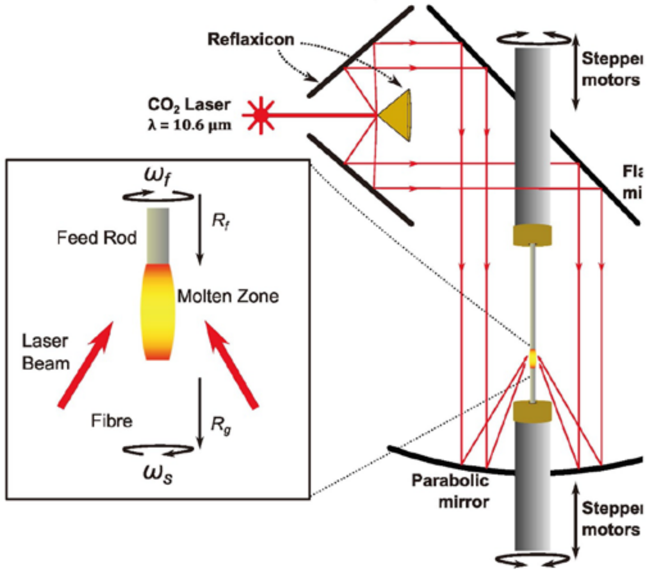
RADiCAL
RADiation hard **i**nnovative **CAL**orimetry
R. Ruchti, in the CPAD 2021 workshop [1]



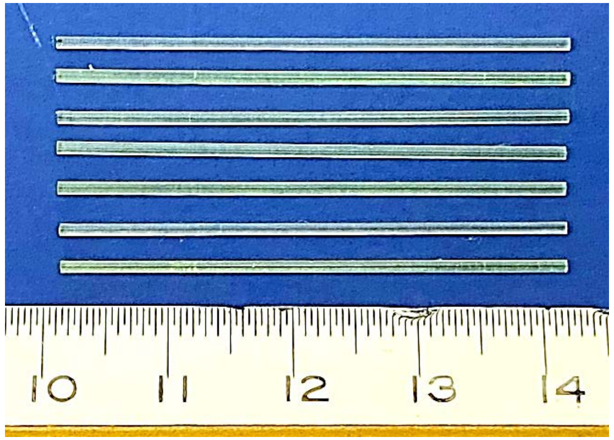
14 x 14 x 1.5 mm^3 LYSO:Ce or LuAG:Ce



Laser Heated Pedestal Growth



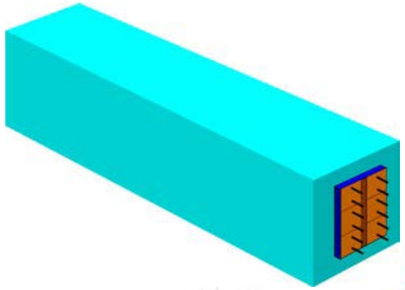
Φ1x40 mm^3 SIC LuAG:Ce Ceramic LHPG fibers



Mu2e Calorimeter Requirements

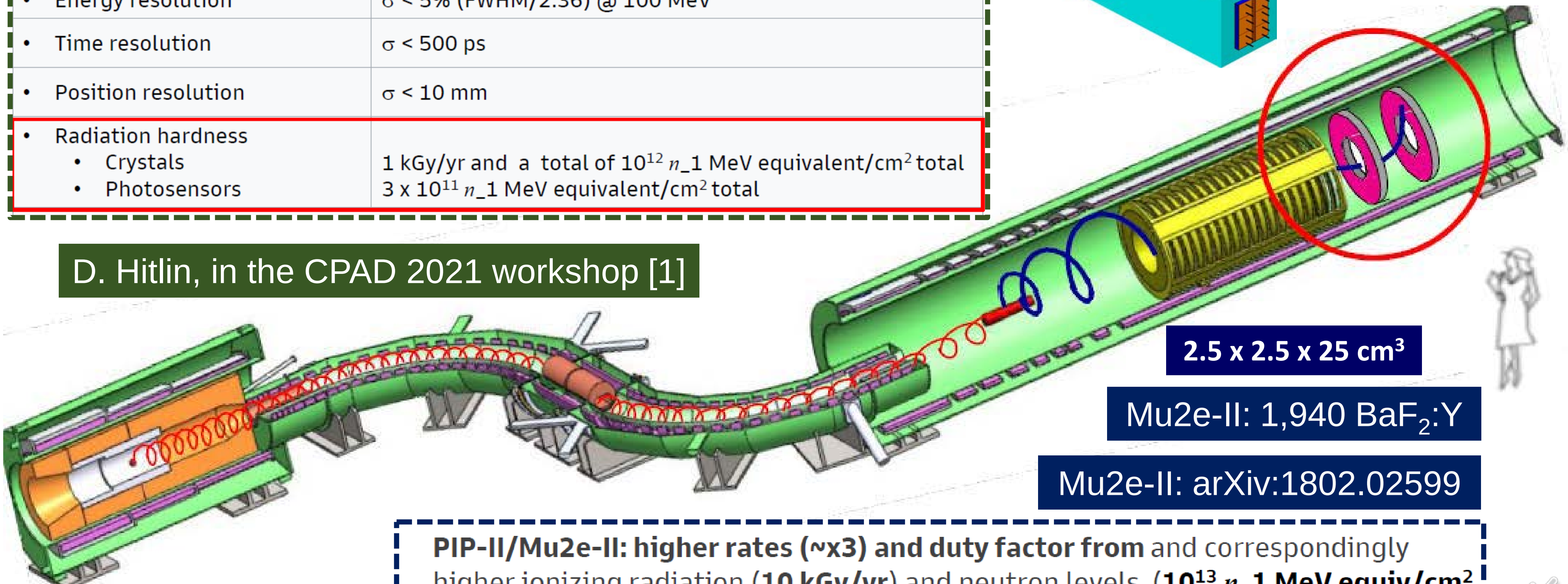
Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm^3

CsI+SiPM



• 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

D. Hitlin, in the CPAD 2021 workshop [1]



2.5 x 2.5 x 25 cm^3

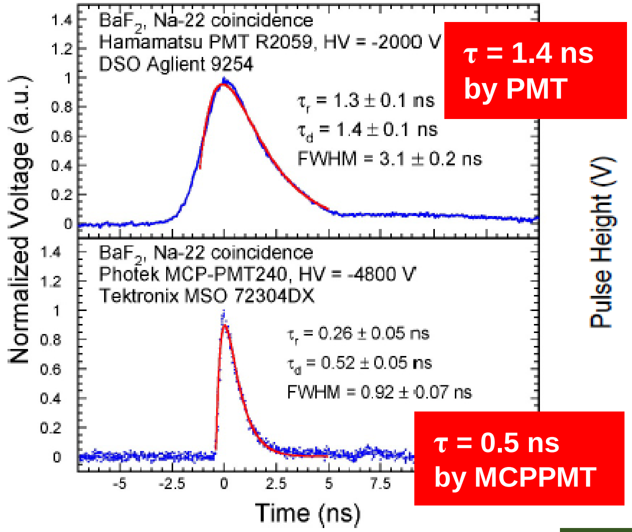
Mu2e-II: 1,940 BaF_2:Y

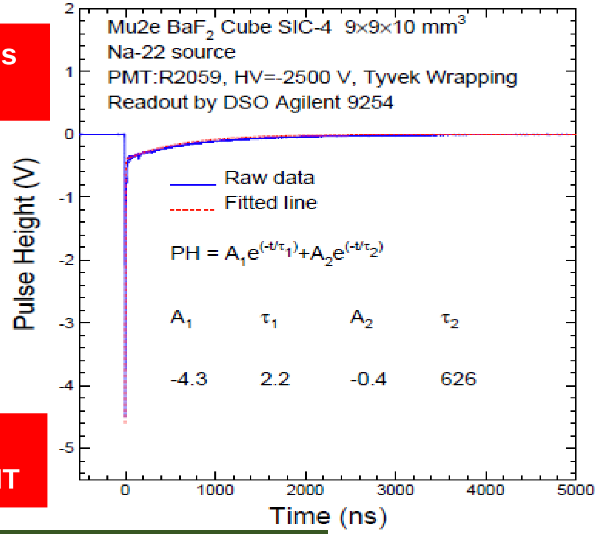
Mu2e-II: arXiv:1802.02599

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

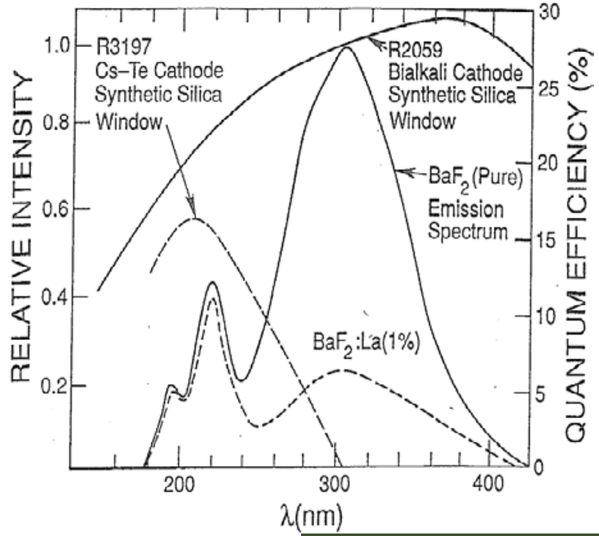
Ultrafast and Radiation Hard BaF_2

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



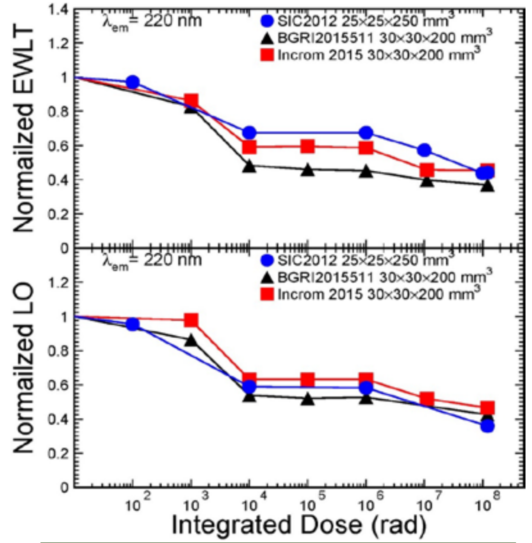


NIMA 340 (1994) 442-457

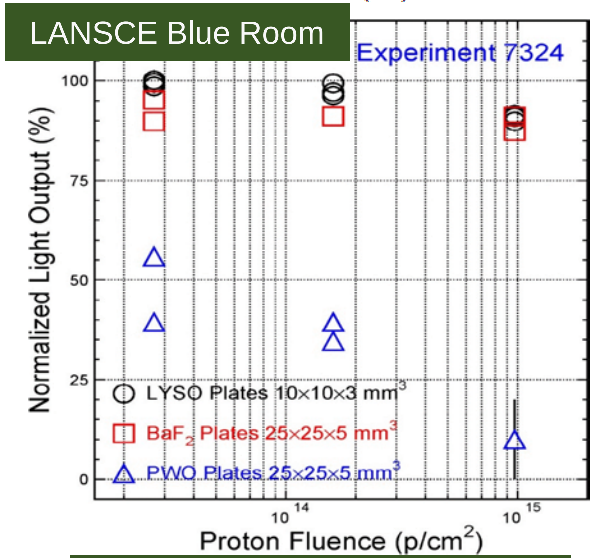


BaF_2 has an ultrafast scintillation component @ 220 nm with **0.5 ns** decay time and a much larger slow component @ 300 nm with 600 ns decay time.

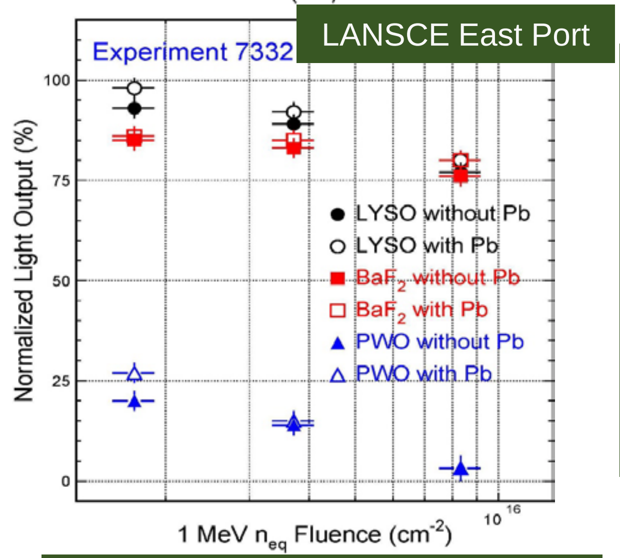
Slow suppression may be achieved by rare-earth-doping, and/or solar-blind photo-detectors



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



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



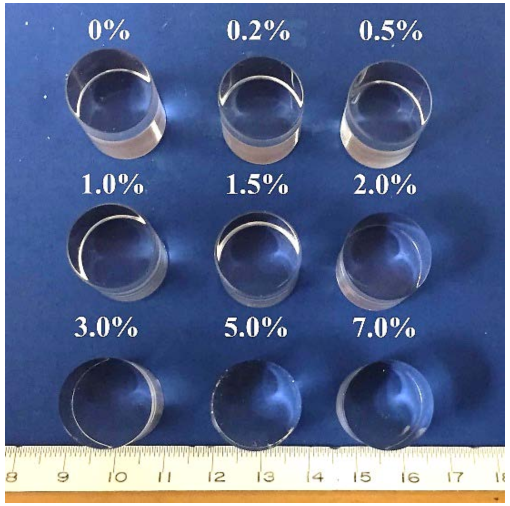
IEEE TNS **67** (2020) 1018-1024

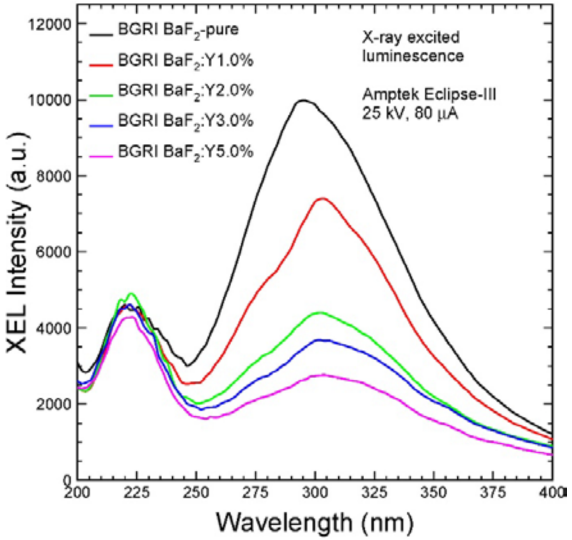
BaF_2 shows saturated damage from 10 krad to 100 Mrad, indicating limited defect density

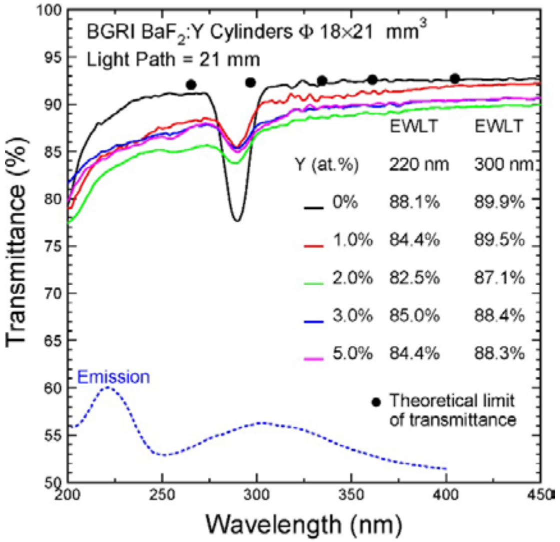
This is confirmed by proton irradiation up to 9.7×10^{14} p/cm^2, and neutron irradiation up to 8.3×10^{15} n_{eq}/cm^2

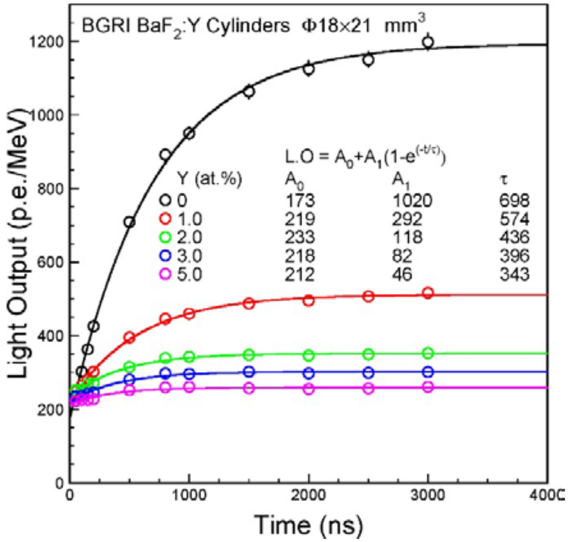
BaF_2:Y for Ultrafast Calorimetry

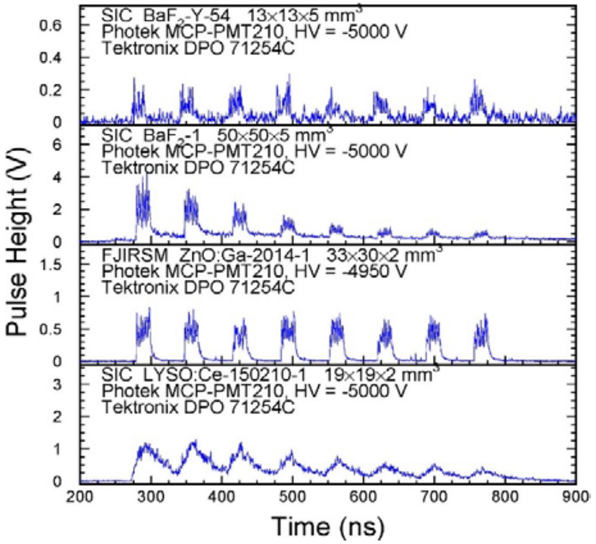
Suppressed slow and increased F/S in BaF_2:Y crystals: Proc. SPIE 10392 (2017)

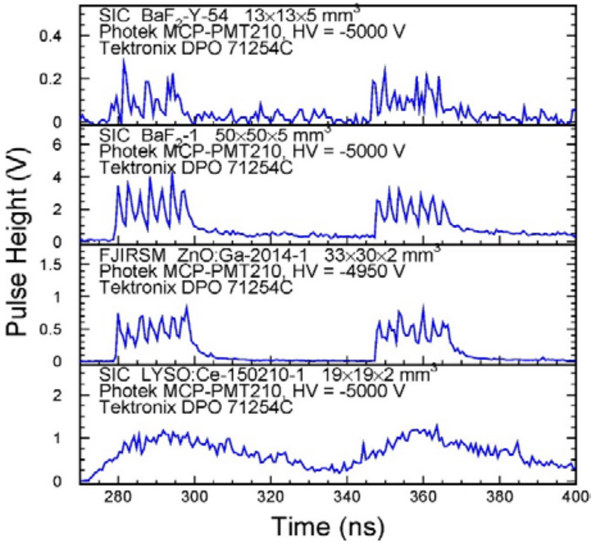


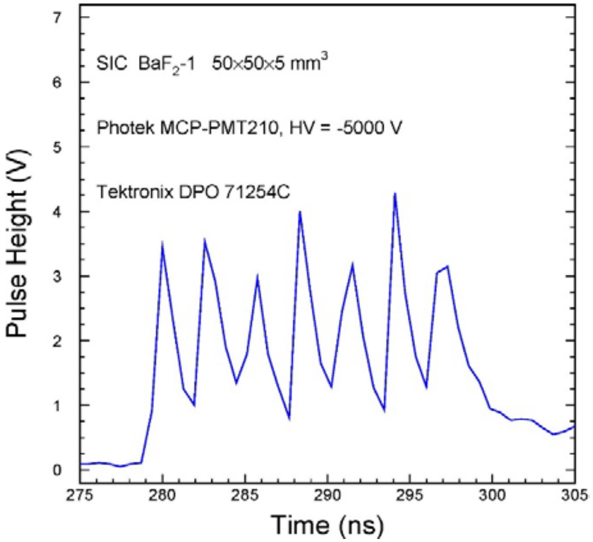






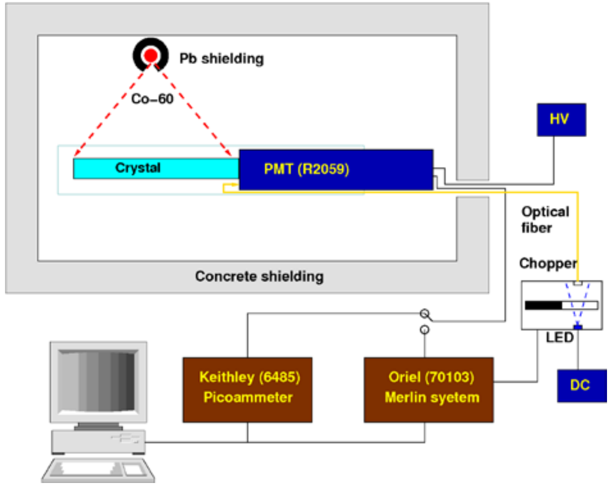






X-ray bunches of 2.83 ns spacing in septuplet clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

Solar-Blind Photodetectors

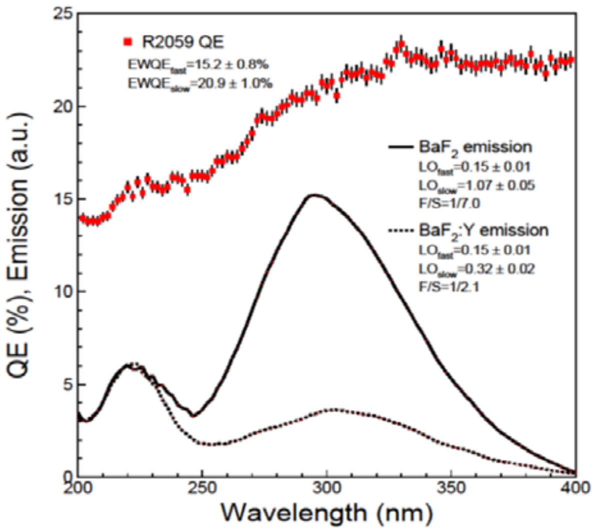


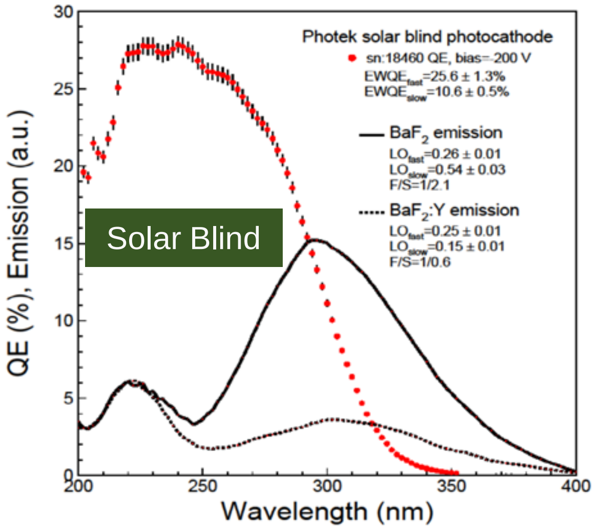
Gamma-ray induced readout noise (RIN:γ) of less than 1 MeV observed in BaF_2:Y crystals with solar-blind photodetector under a dose rates of 23 rad/h

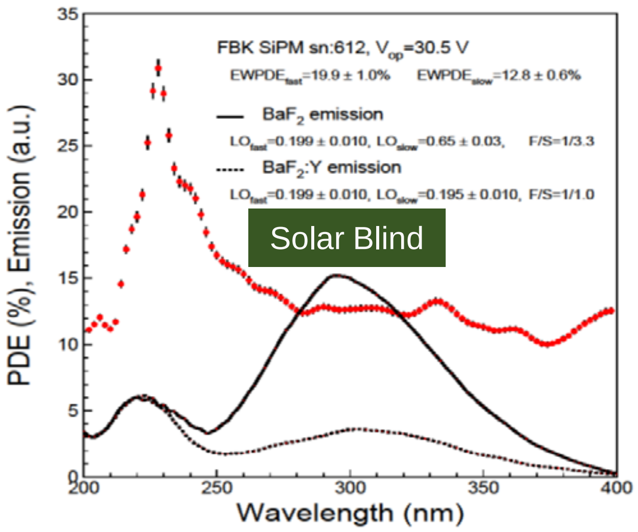
$$F = \frac{\dfrac{Photocurrent}{Charge_{electron} \times Gain_{SiPM}}}{Dose\ rate_{\gamma-ray}\ or\ Flux_{neutron}} \qquad \sigma = \frac{\sqrt{Q}}{LO} \quad \text{(MeV)}$$

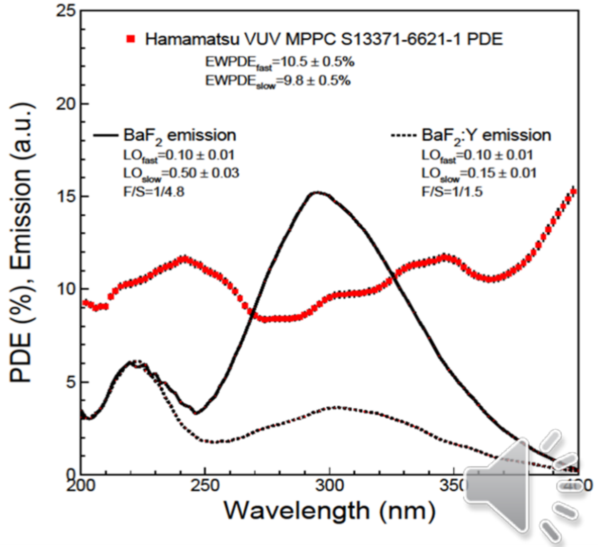
QE/PDE of four VUV photodetectors for BaF2 and BaF2:Y

Paper N05-03 in the virtual IEEE NSS/MIC 2020 Conference Record (2020)



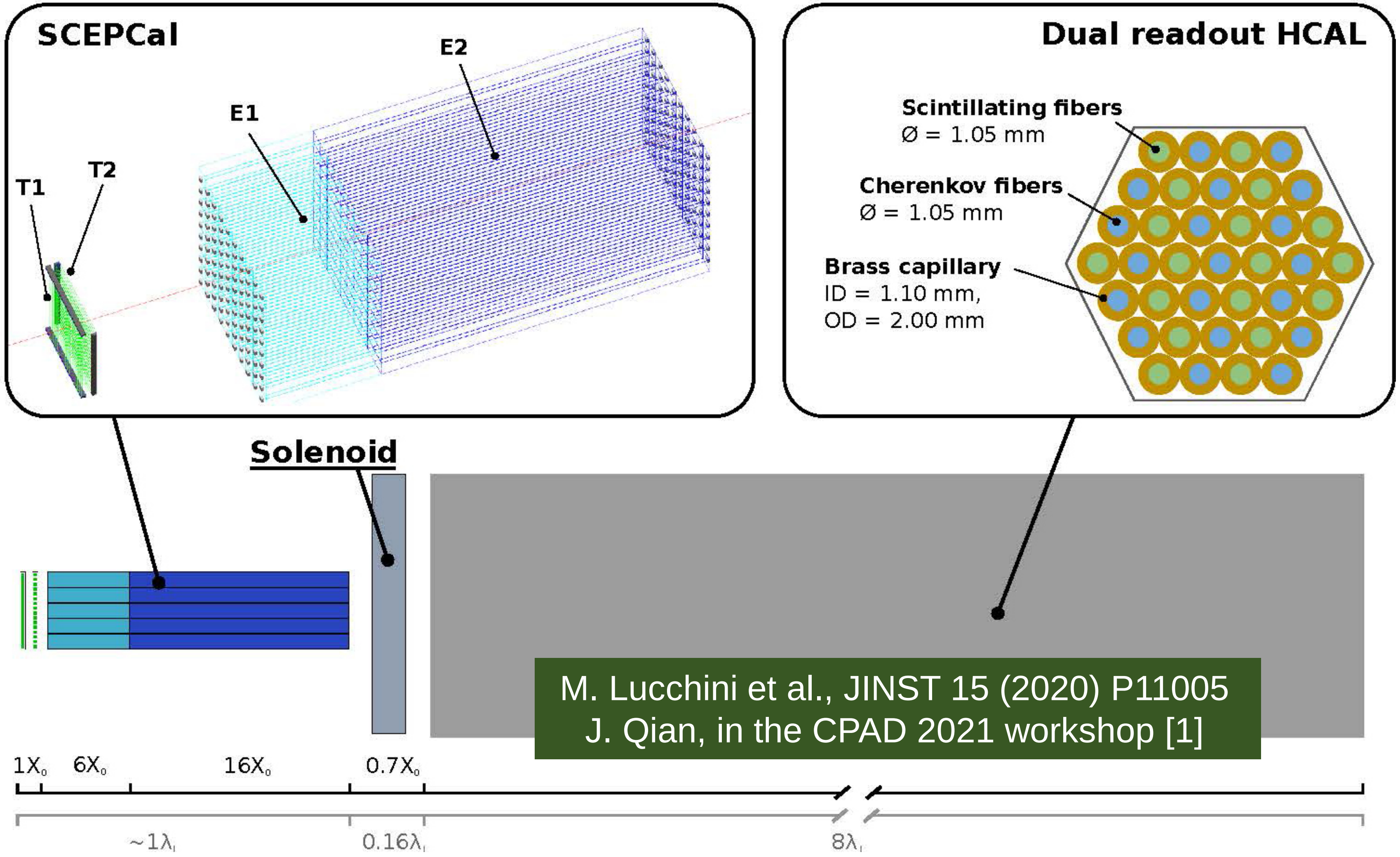




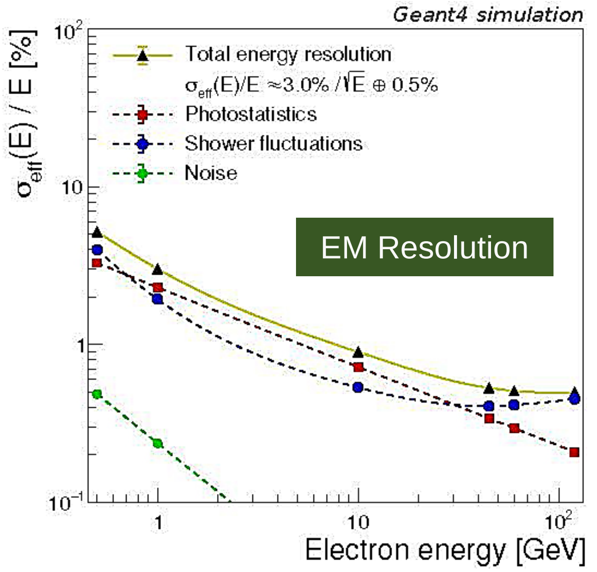


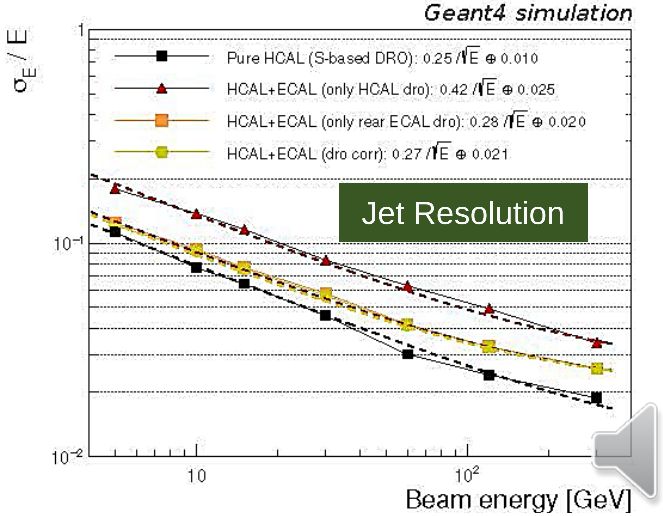
Calvision: A Dual Readout Crystal ECAL

Excellent EM and jet resolutions with IDEA DR HCAL for Higgs Factory



M. Lucchini et al., JINST 15 (2020) P11005
J. Qian, in the CPAD 2021 workshop [1]



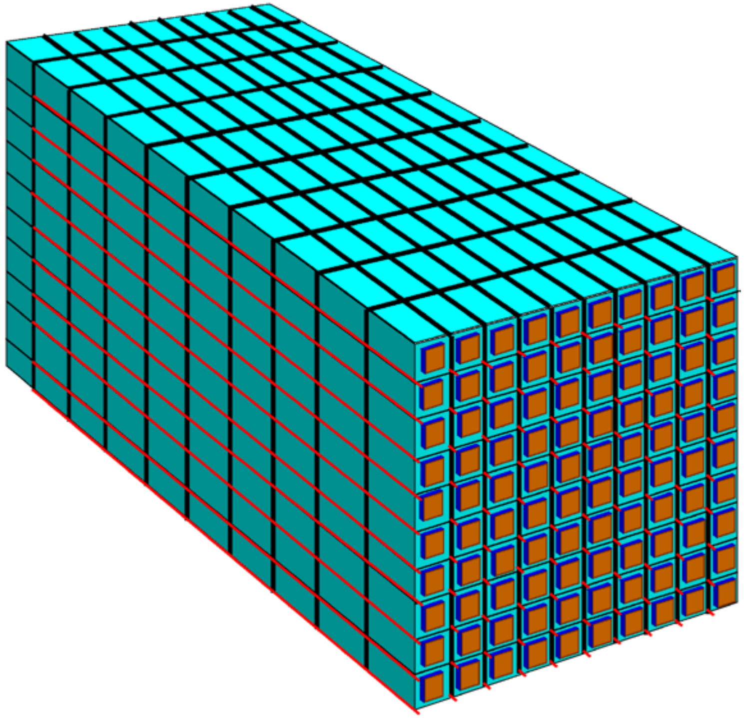


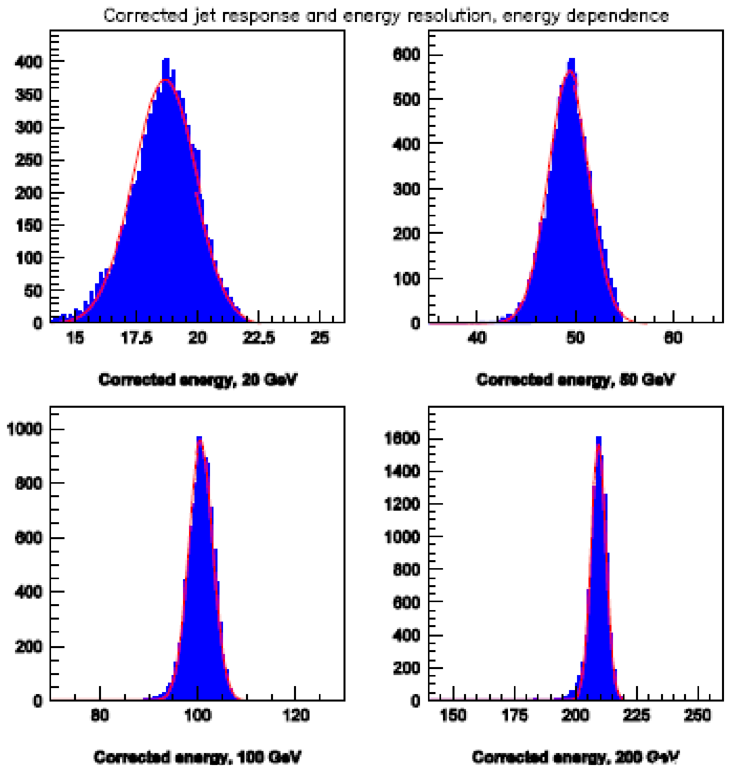
The HHCAL Concept

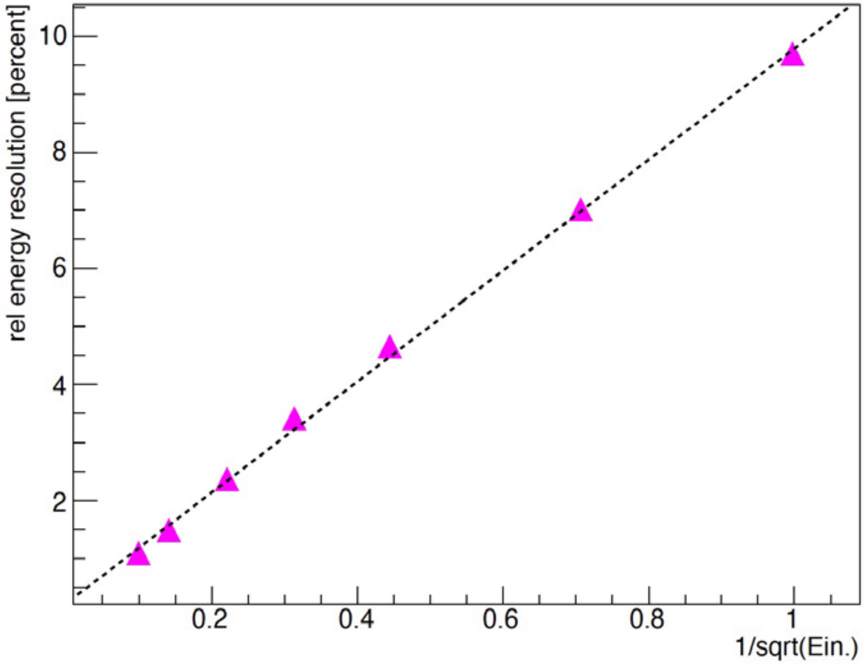
A jet energy resolution at a level of 20%/√E by HHCAL with dual readout:
Either scintillation and Cerenkov light or light in short and long gate.

See A. Para, H. Wenzel, and S. McGill in Callor2012 Proceedings

A. Benaglia *et al*., IEEE TNS **63** (2016) 574-579; M. Demarteau, in 2021 CPAD Workshop [1]







Can we afford?

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?	?

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

Low density crystals/glasses

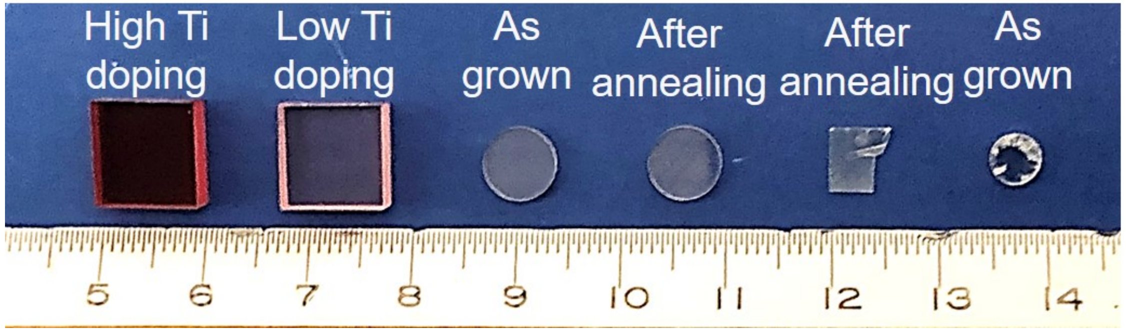
Cost-Effective Sapphire Crystals for HHCAL

Large sapphire crystal of 400-450 kg

Prof. Xu Jun of Tongji University: Sapphire crystals by Kyropoulos (KY) technology A producer can grow 1,000 tons ingots annually with 400 to 450 kg/ingot Cost of mass-produced Sapphire crystals including processing: less than $1/cc

	Weight (kg)	Size (cm)	Unit Price	Comment
ingot boule	400	Φ50×55	US$12000/pc	for undoped
cutting/polishing	4	1×1×1	**~US$0.6/cc**	for undoped

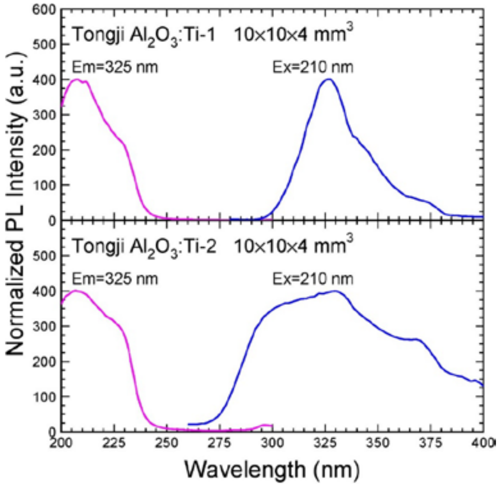
Sapphire:Ti Optical/Scintillation Properties



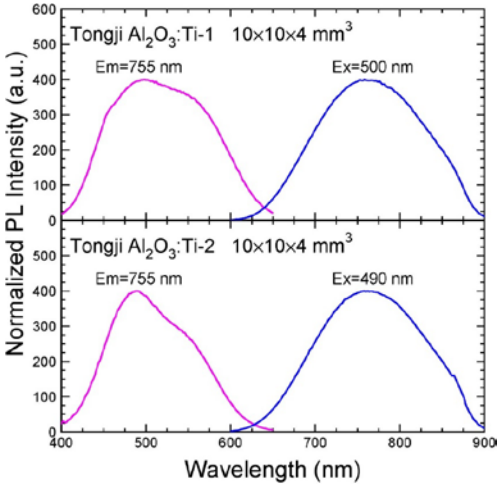
ID	Dimension (mm^3)	#	Polishing
Tongji Al_2O_3:Ti-1,2	**10×10×4**	**2**	**Two faces**
Tongji Al_2O_3:C-1,2	Φ7×1	2	Two faces
Tongji Lu_2O_3:Yb	6.4×4.8×0.4	1	Two faces
Tongji $LuScO_3$:Yb	Φ4.8×1.3	1	Two faces

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

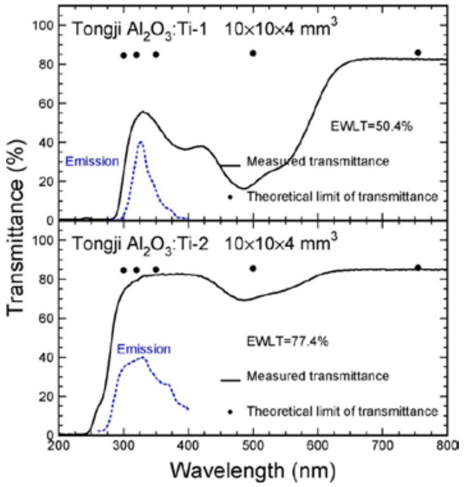
Fast @325 nm



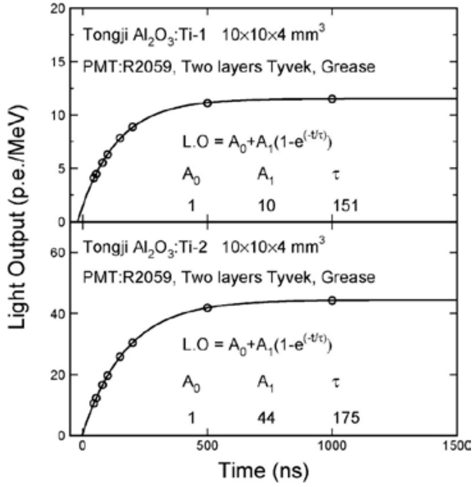
Slow @755 nm



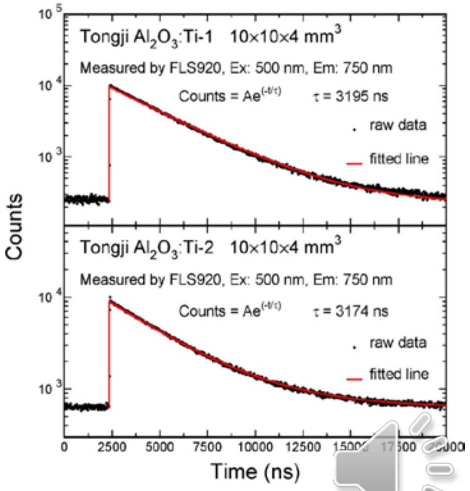
EWLT for Fast & Slow



Fast = 162 ns



Slow = 3.2 μs



Summary

HEP at the energy frontier require fast and radiation hard calorimetry. The **RADiCAL** concept utilizes bright and fast LYSO:Ce crystals and LuAG:Ce WLS for an ultra-compact, ultra-radiation hard and longitudinally segmented shashlik calorimeter for HL-LHC and FCC-hh.

HEP at the intensity frontier requires **ultrafast calorimetry**. R&D is on-going to develop large size BaF_2:Y crystals and solar-blind VUV photodetectors for Mu2e-II.

The proposed lepton Higgs factory requires good EM and jet resolutions. The dual readout **Calvision** crystal ECAL followed by the IDEA HCAL provides an excellent option.

Because of total absorption for hadrons the **HHCAL** concept promises the best jet mass resolution. Crucial R&D is to develop cost-effective inorganic scintillators of large volume.

Novel inorganic scintillators are needed for all these calorimeter concepts

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