Inorganic Scintillators for Future HEP Experiments

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Why Inorganic Scintillators?

- **Precision photons and electrons enhance physics discovery potential in HEP experiments.**
- **Performance of crystal calorimeters is well understood for e/γ, and is promising for jets measurements :**
  - **The best possible energy resolution and position resolution;**
  - **Good e/γ identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout, either C/S and F/S gate.**
- **Challenges at future HEP Experiments:**
  - **Radiation hard scintillators at the energy frontier: HL-LHC and FCC-hh;**
  - **Ultra-fast scintillators at the intensity frontier: Mu2e-II;**
  - **Cost-effective crystals for Higgs factory.**

2019 DOE Basic Research Needs Study on Instrumentation: Calorimetry

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

Fast and Ultrafast Inorganic Scintillators

Snowmass 2022 White Paper: https://doi.org/10.48550/arXiv.2203.06788

	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	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
LY in 1st ns/Total LY	9.2%	60%	31%	49%	22%	2.0%	2.5%	1.0%	3.3%	1.9%	1.3%	1.3%
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

[a] top/bottom row: slow/fast component; [b] at the emission peak; [c] normalized to LYSO:Ce; [d] excited by alpha particles; [e] ceramic with 0.3 Mg at% co-doping; [f] density for composition $Lu_{0.7}Y_{0.3}AlO_3$:Ce

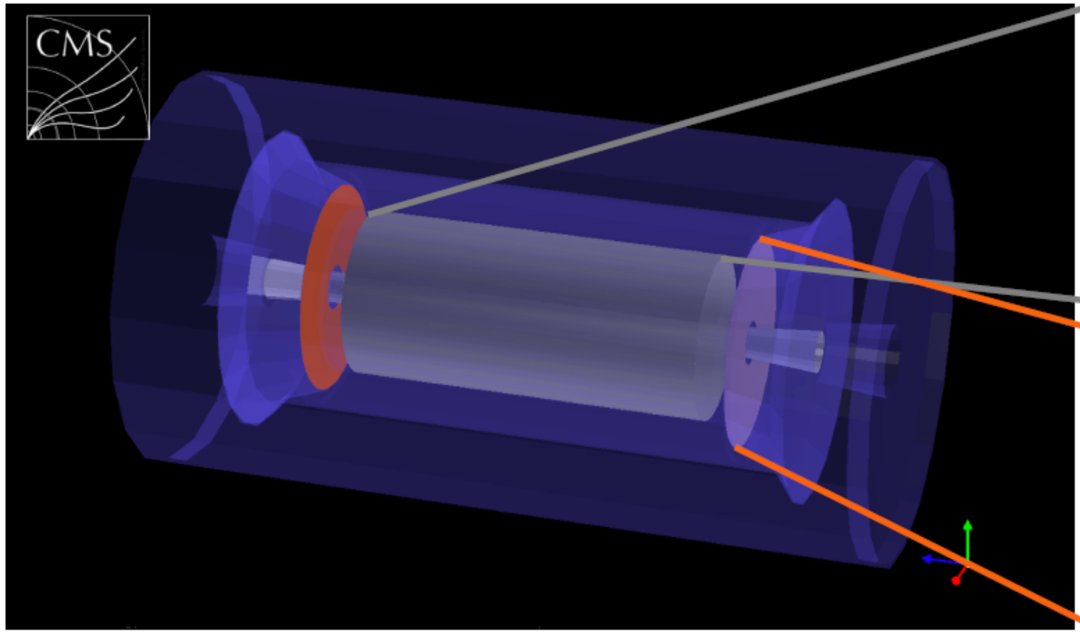
See C. Hu in this conference

LYSO:Ce for CMS Barrel Timing Layer

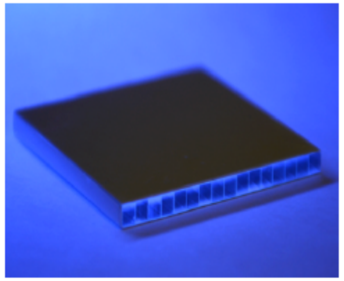
MTD performance goal: 30-40 ps at the start degrading to < 60 ps at 3000 fb^{-1}

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

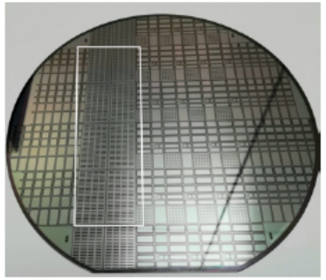
Ultrafast inorganic scintillators would help to break the pico-second time barrier



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

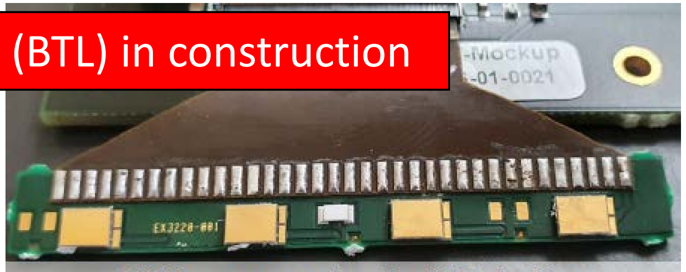


ETL: Si with internal gain (LGAD)
- On the HGC nose ~ 65 mm thick
- 1.6 < $|\eta|$ < 3.0
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2



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


SiPM array prototypes from FBK

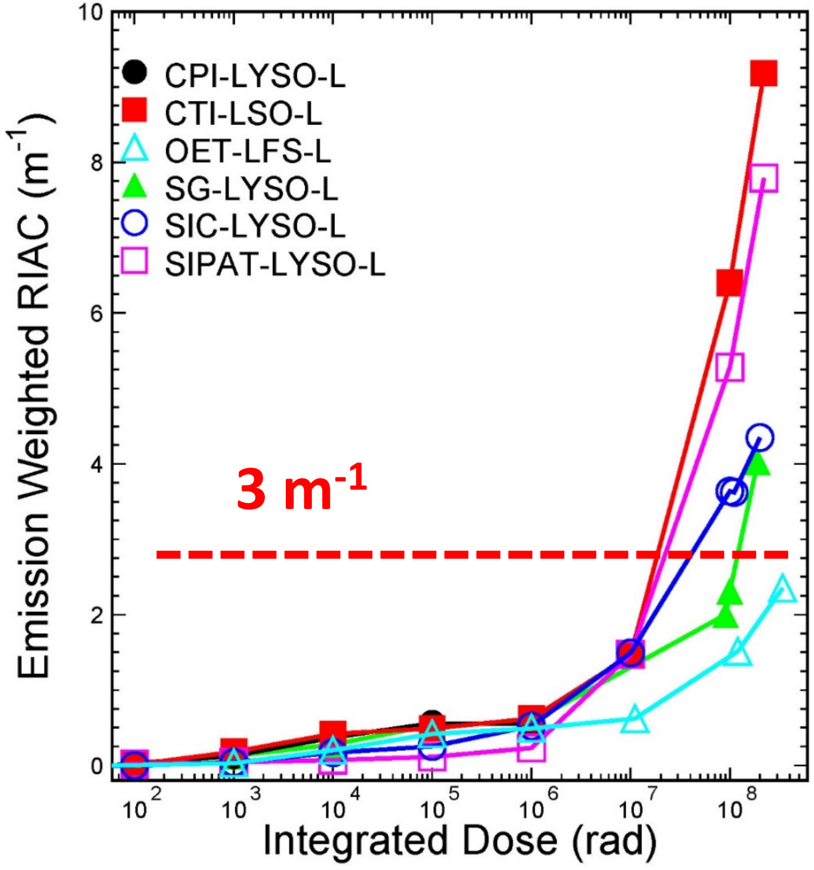


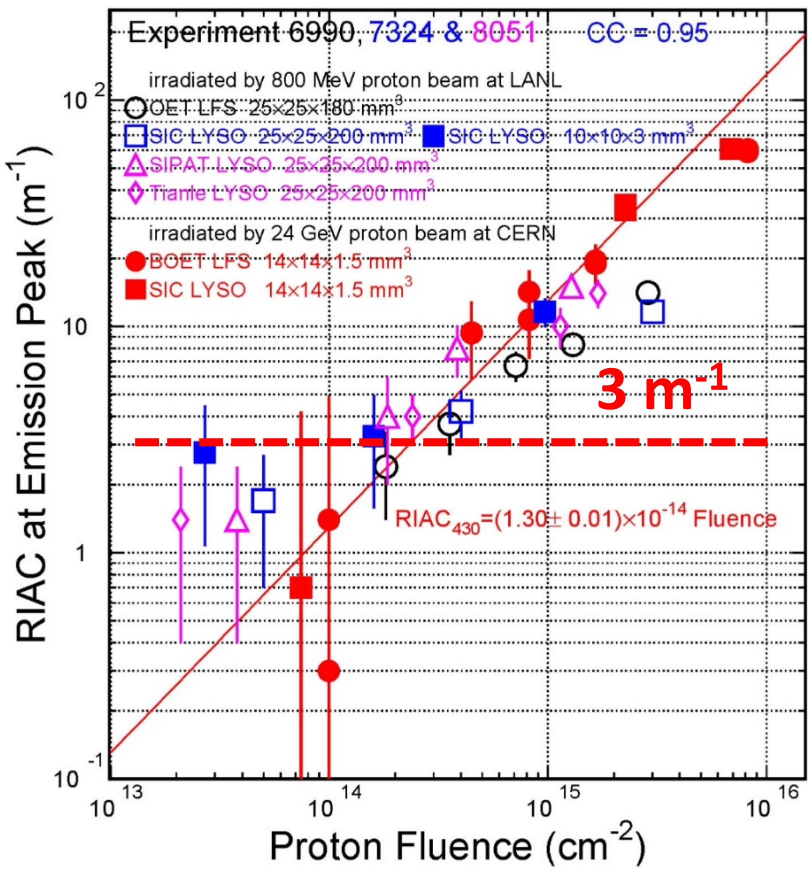
SiPM arrays mockup for TECs testing

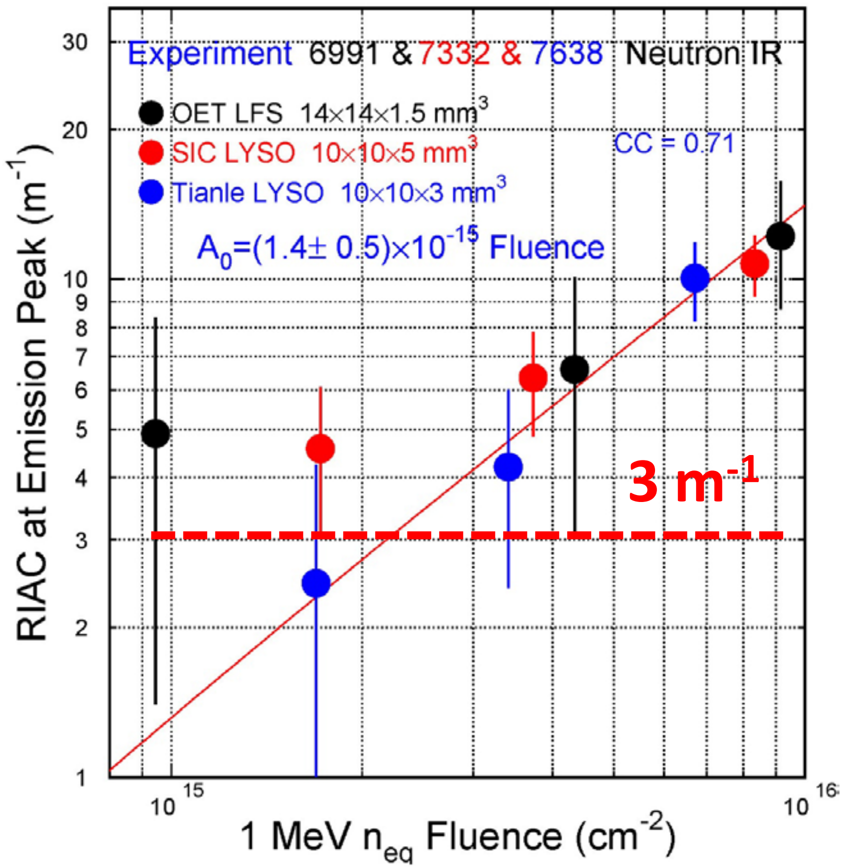
LYSO Radiation Hardness

See IEEE TNS 63 (2016) 612-619 (2016) and L. Zhang in this conference

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





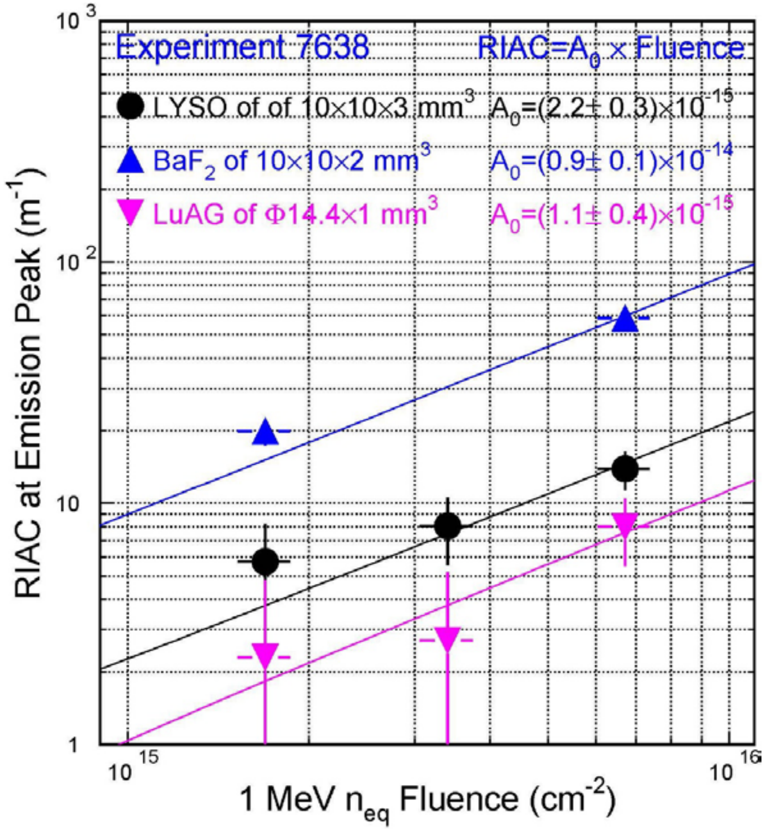


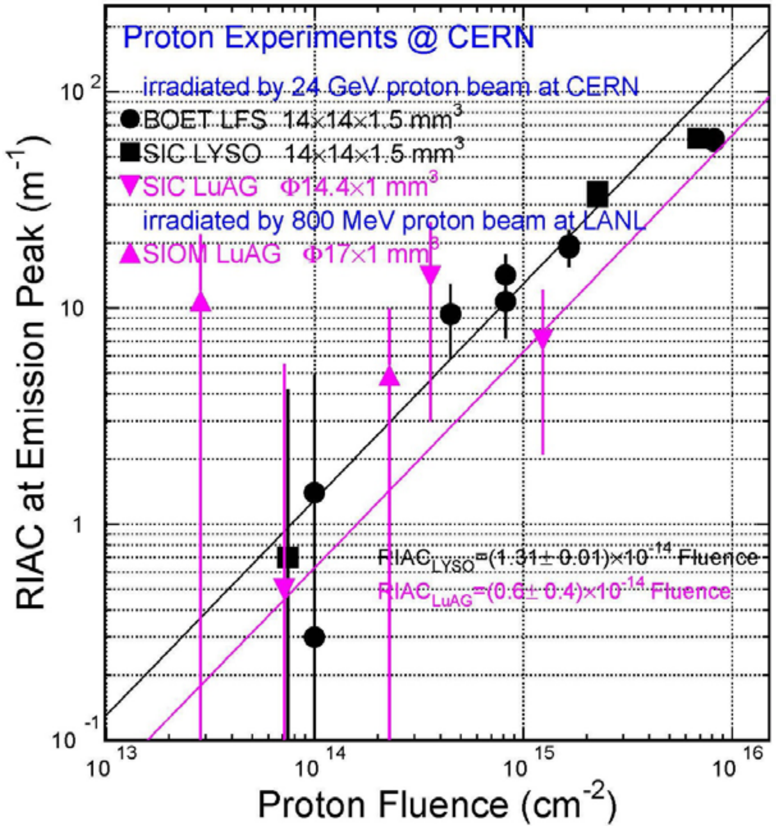
Damage induced by protons is a factor of ten larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup

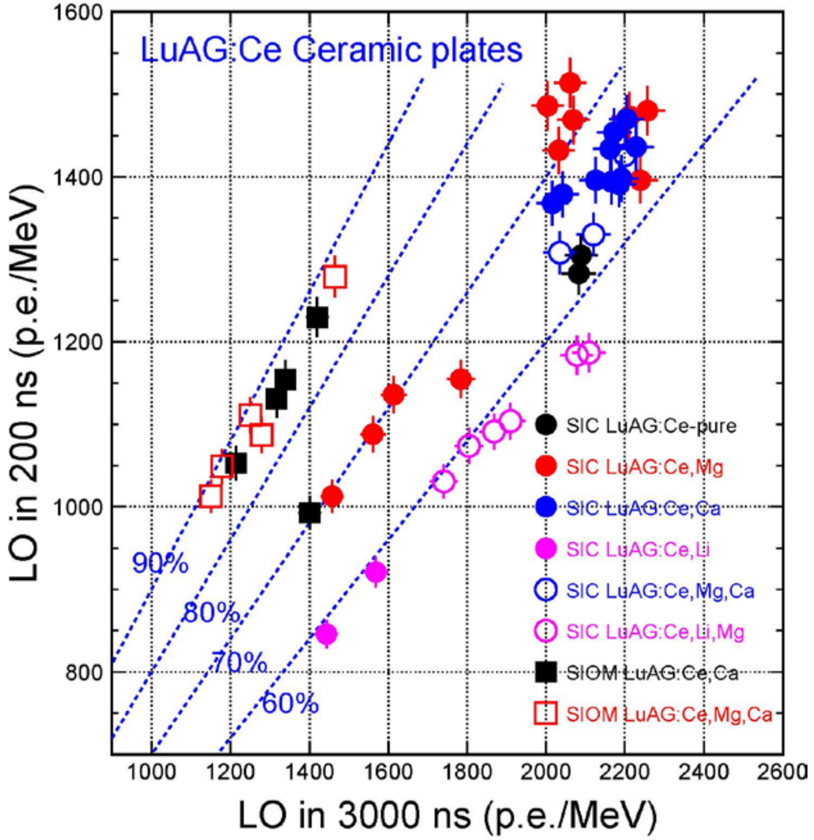
LuAG:Ce Ceramics Radiation Hardness

IEEE TNS 69 (2022) 181-186

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

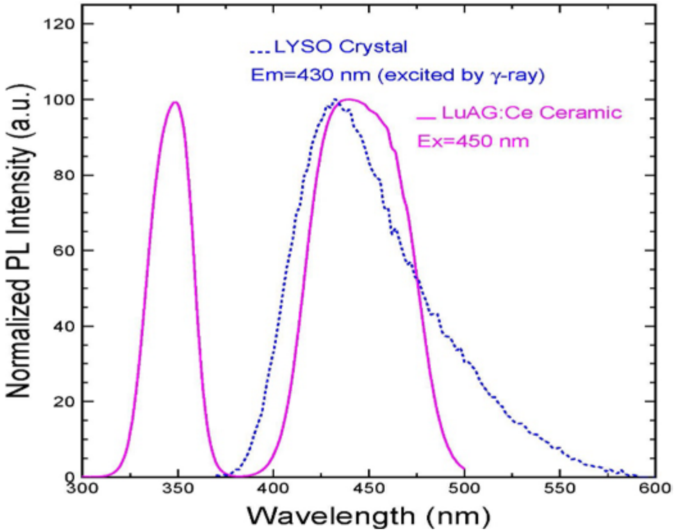






R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

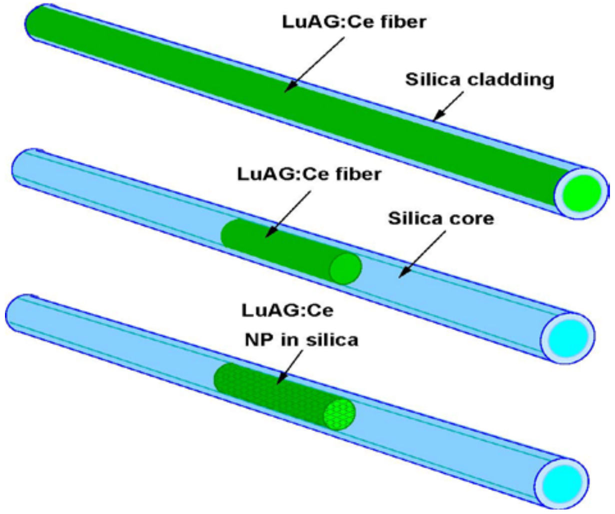
RADiCAL: LYSO/LuAG Shashlik ECAL



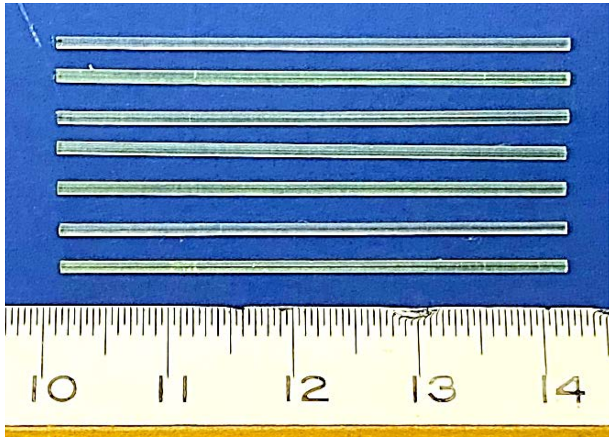
See R. Ruchti in this conference

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

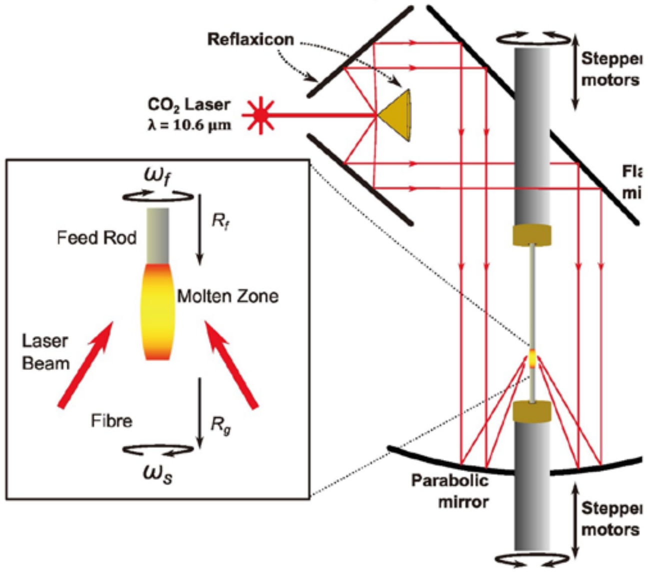
RADiCAL
RADiation hard **i**nnovative **CAL**orimetry

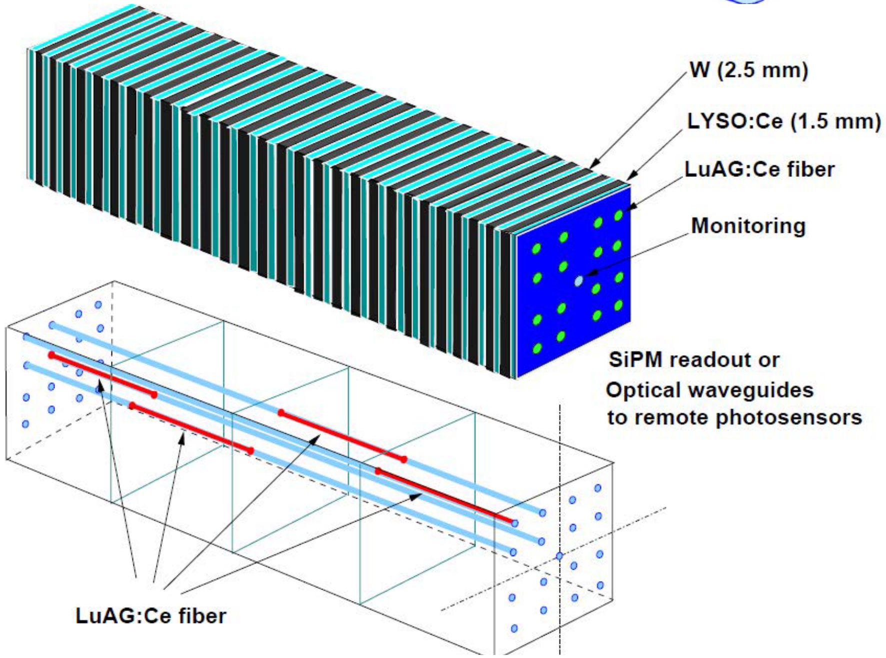


Φ1x40 mm³ SIC LuAG:Ce Ceramic LHPG fibers



Laser Heated Pedestal Growth





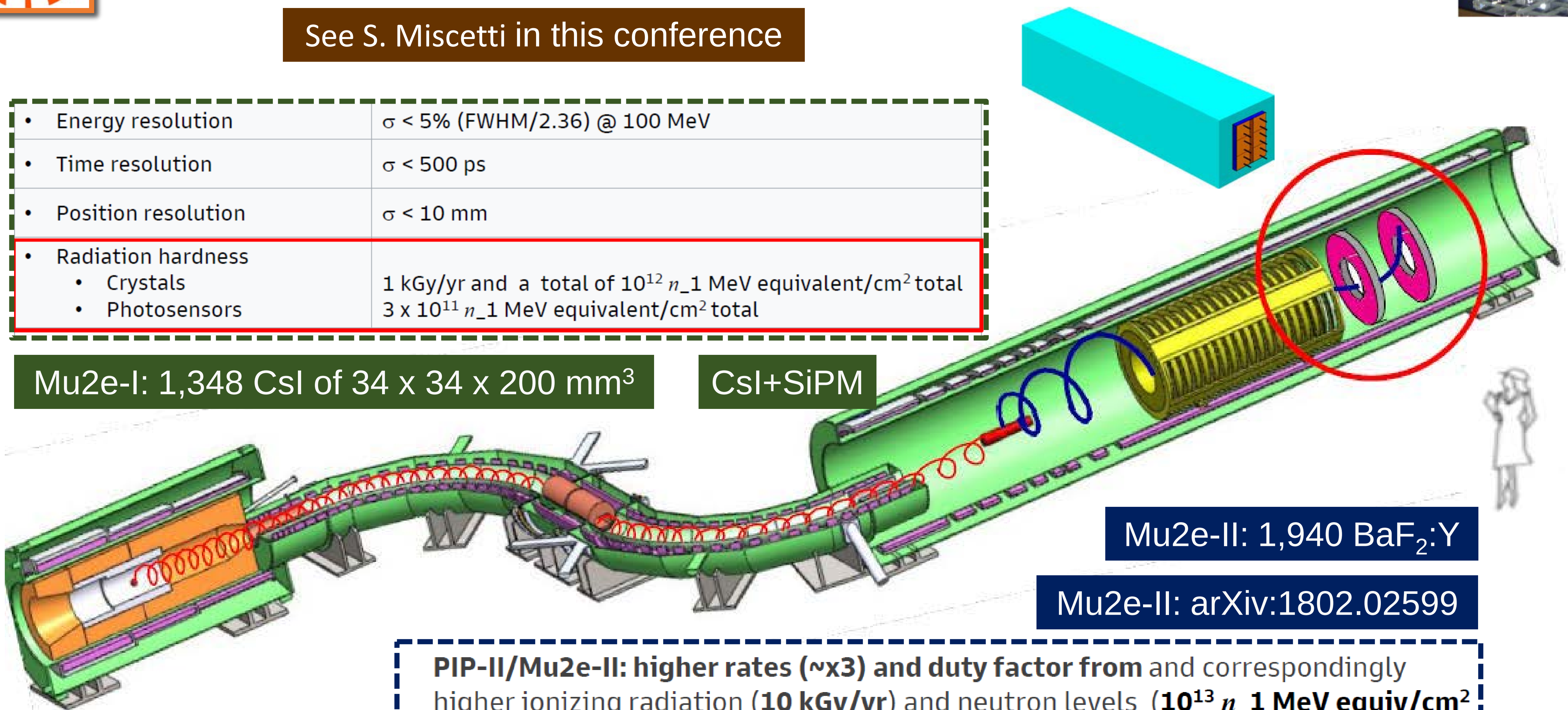
Mu2e Calorimeter Requirements

See S. Miscetti in this conference

• 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



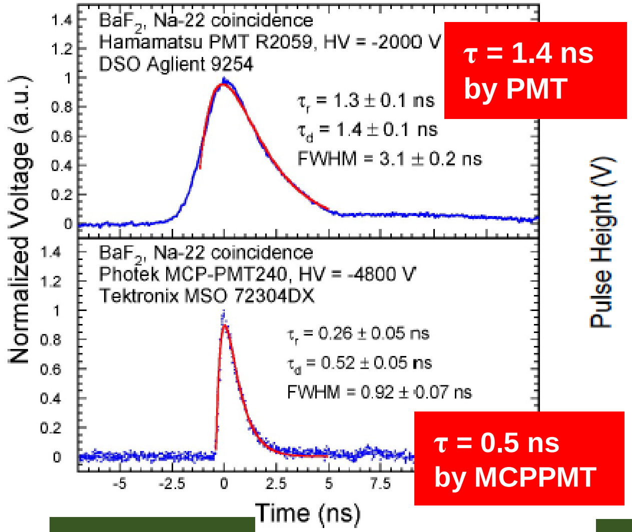
Mu2e-II: 1,940 BaF_2:Y

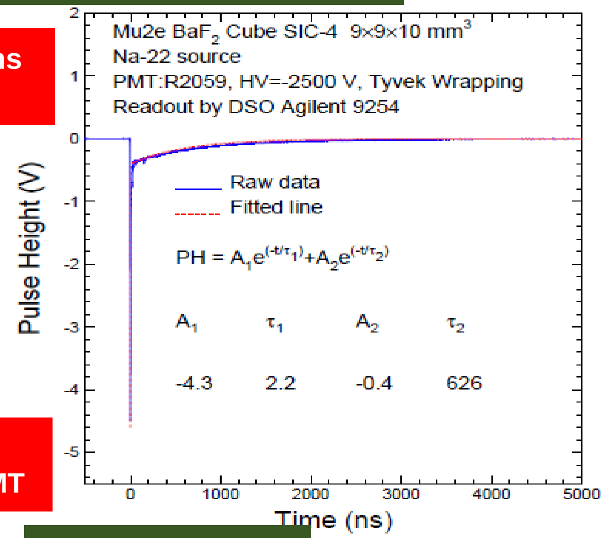
Mu2e-II: arXiv:1802.02599

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

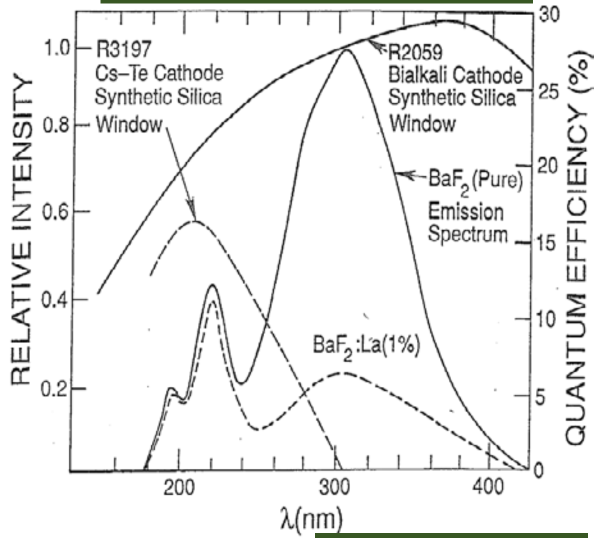
Ultrafast and Radiation Hard BaF_2

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





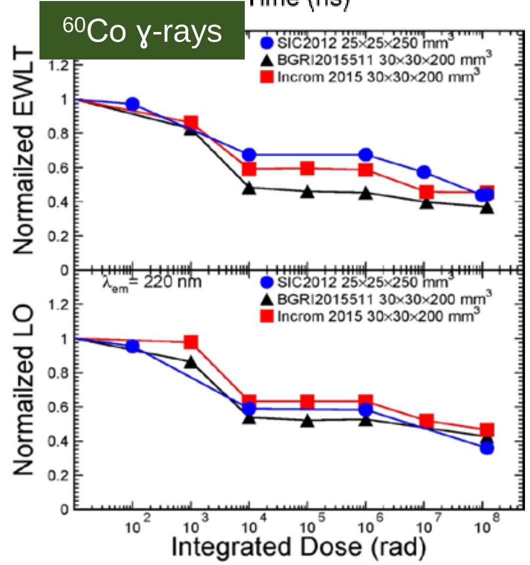
NIMA 340 (1994) 442-457



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.

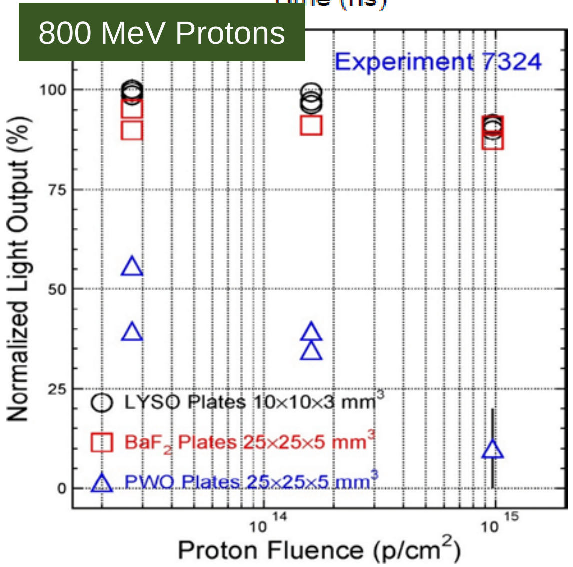
Slow suppression may be achieved by rare earth doping, and/or solar-blind photo-detectors

^{60}Co ɣ-rays



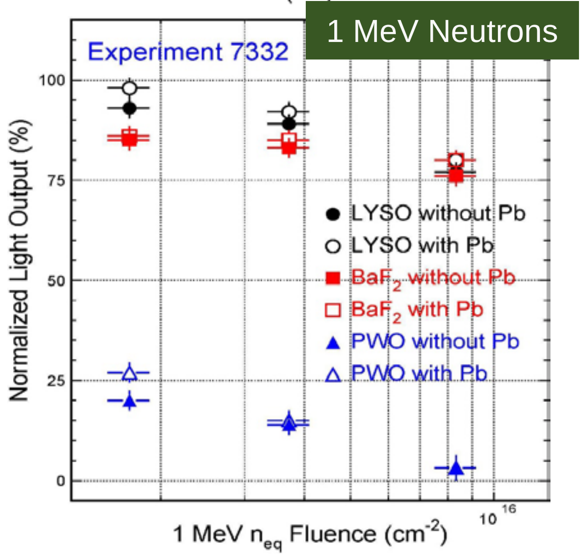
IEEE TNS **63** (2016) 612-619

800 MeV Protons



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

1 MeV Neutrons



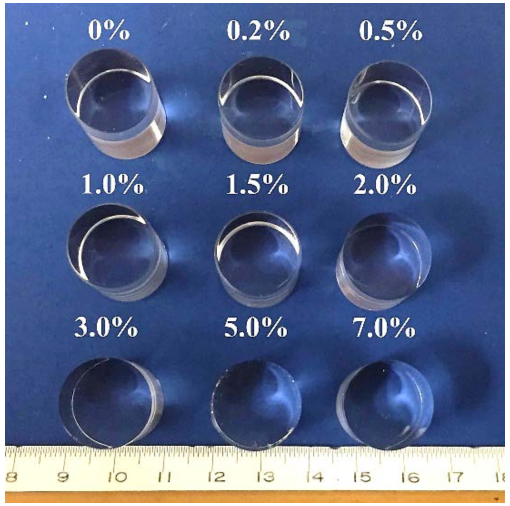
IEEE TNS **67** (2020) 1018-1024

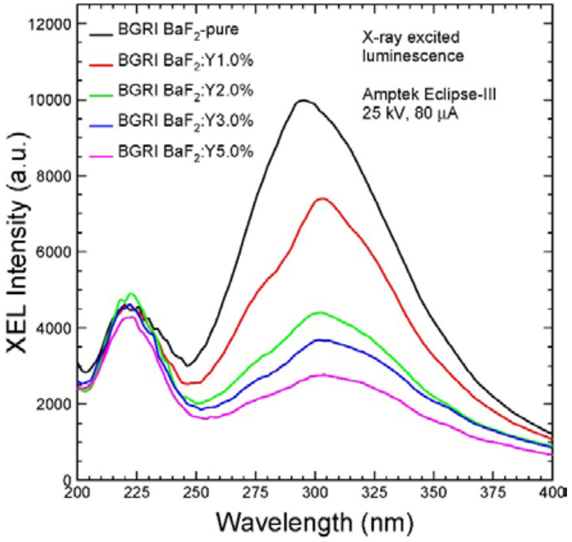
BaF_2 shows saturated damage from 10 krad to 100 Mrad, indicating good radiation resistance against ɣ-rays

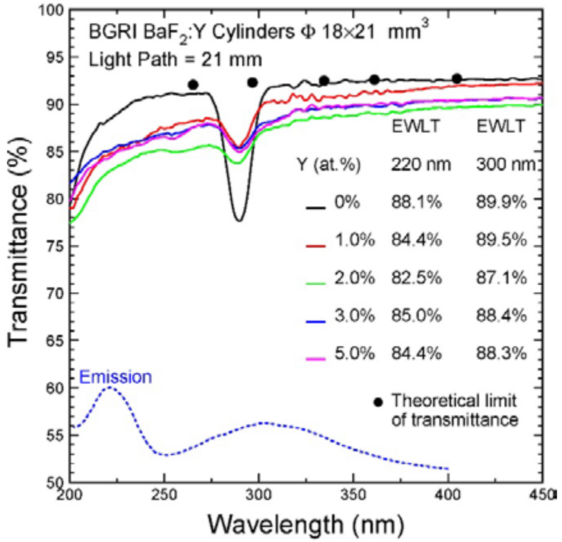
BaF_2 also survives after proton irradiation up to 9.7×10^{14} p/cm^2, and neutron irradiation up to 8.3×10^{15} n_{eq}/cm^2

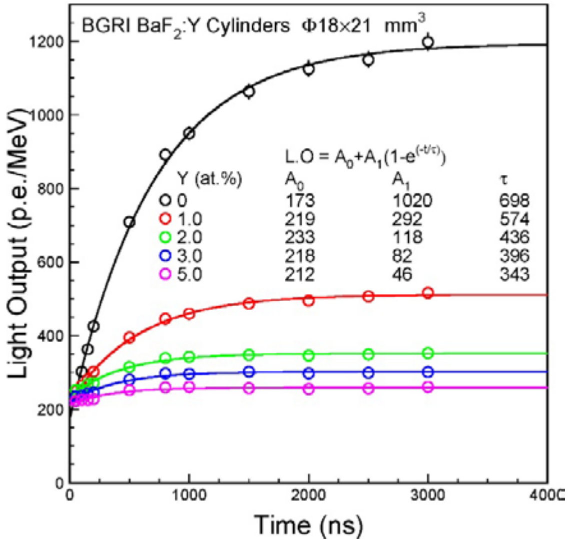
BaF_2:Y for Ultrafast Calorimetry

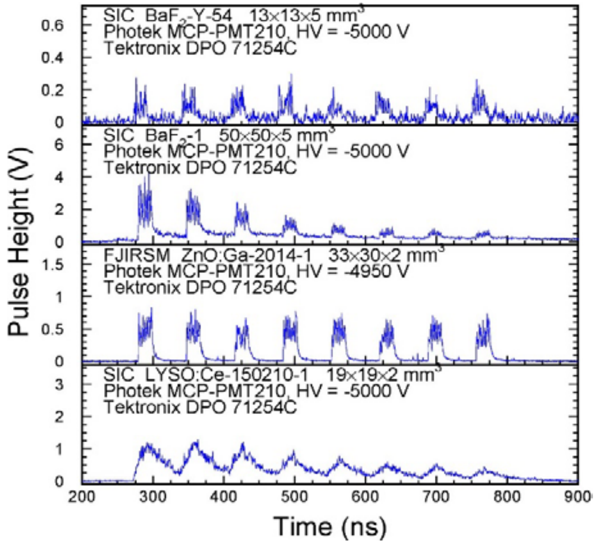
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

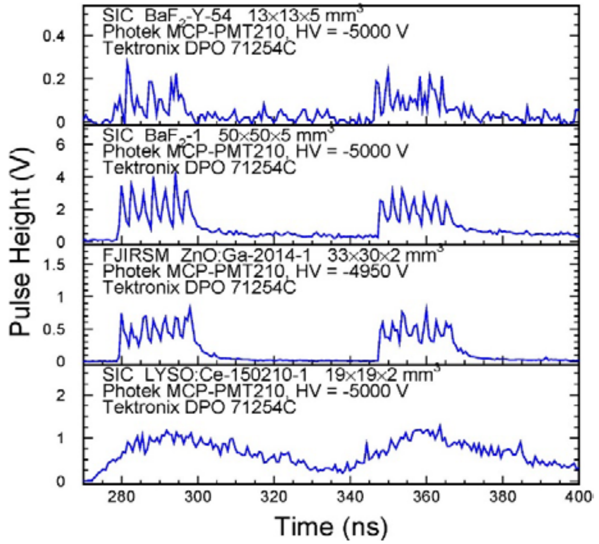


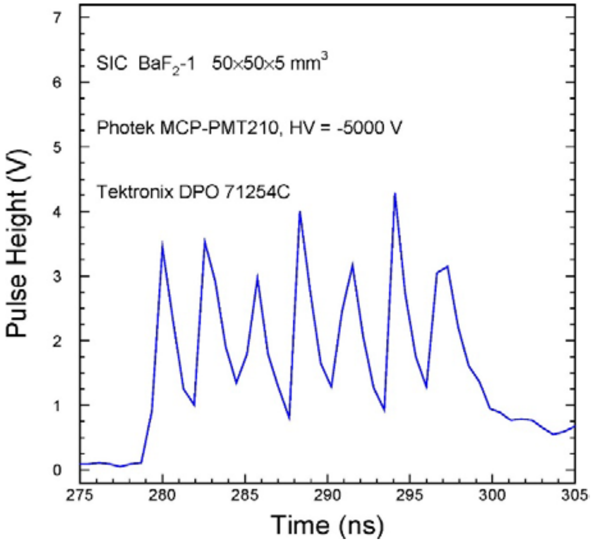






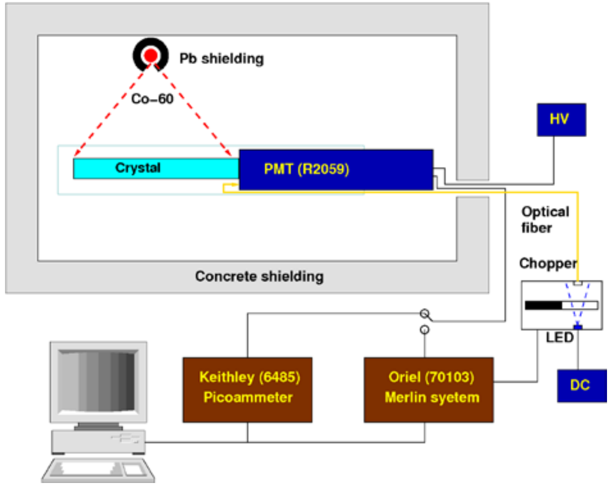






X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

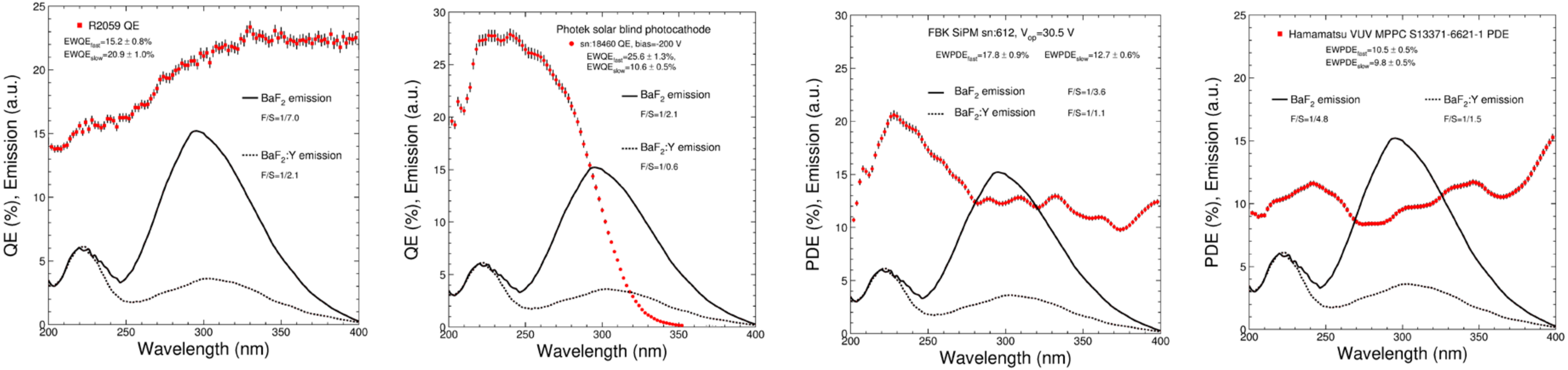
Gamma-ray Induced Readout Noise RIN:γ



BaF$_2$ crystals wrapped by Tyvek with an air gap coupling to a Hamamatsu PMT R2059, were irradiated by Co-60 with dose rates of 2 and 23 rad/h

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

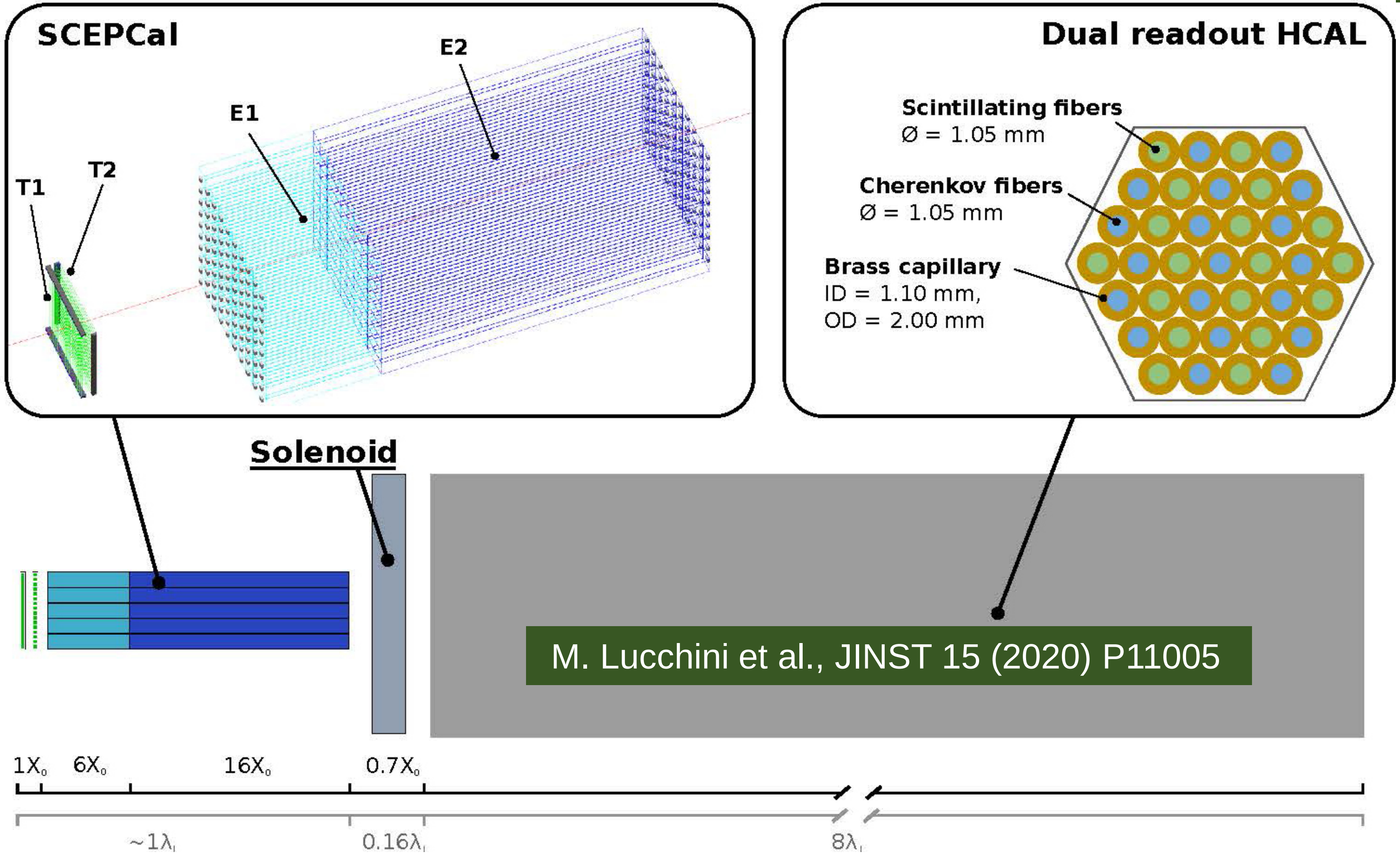
QE/PDE of four VUV photodetectors for BaF$_2$ and BaF$_2$:Y, IEEE TNS **69** (2022) 958-964

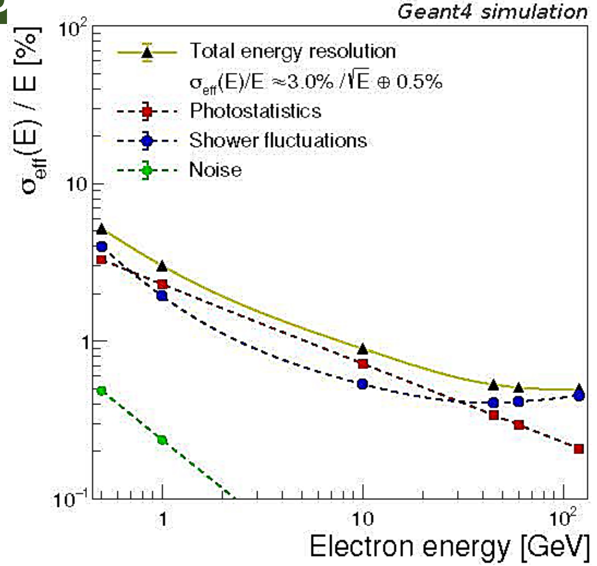


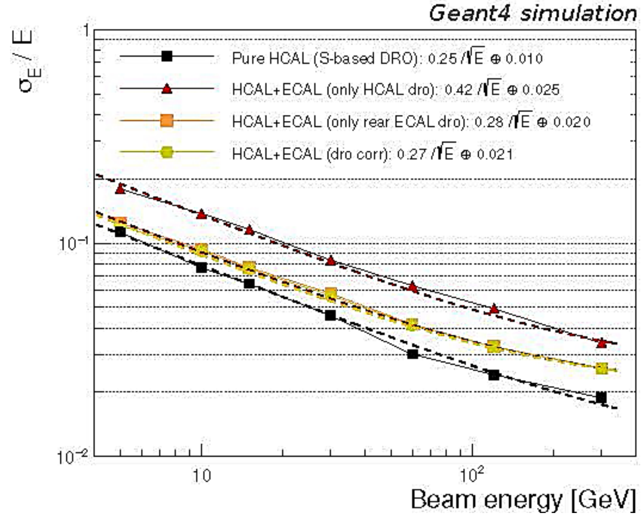
Calvision: A Longitudinally Segmented Crystal ECAL

See Y. Lai in this conference

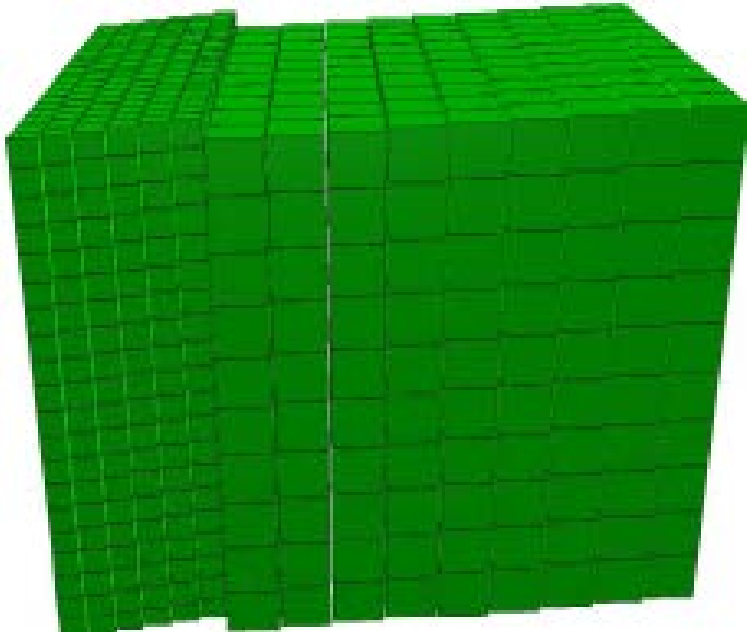
Aiming at excellent EM and jet resolutions for Higgs Factory

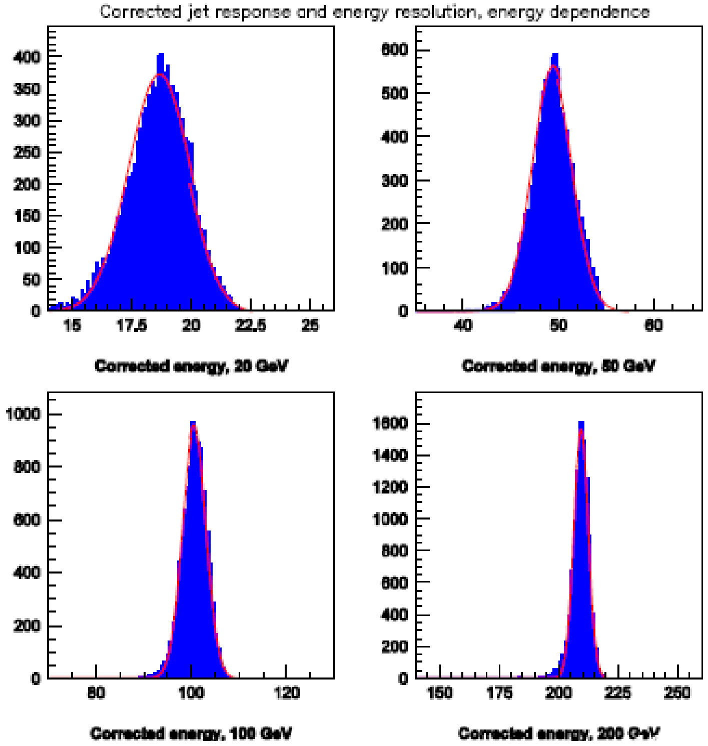




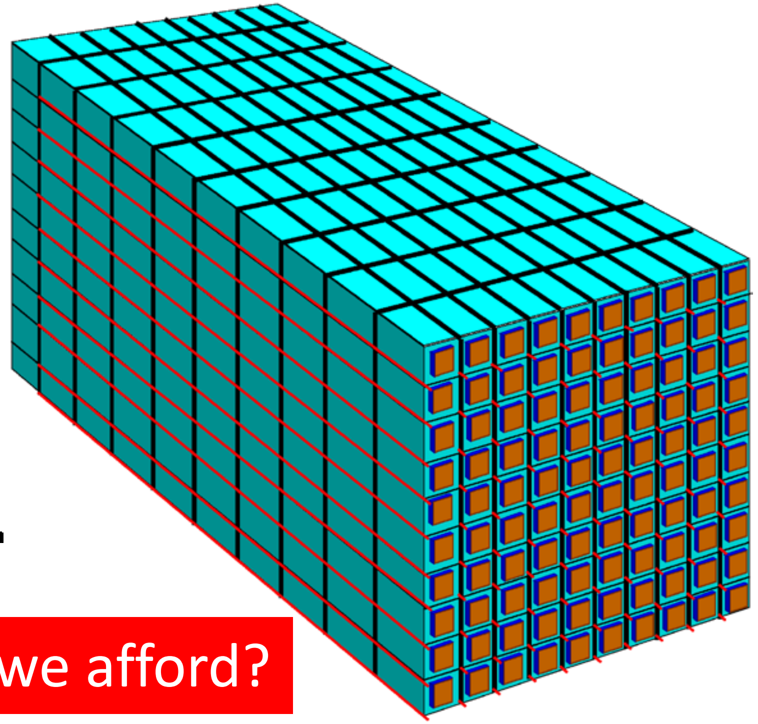


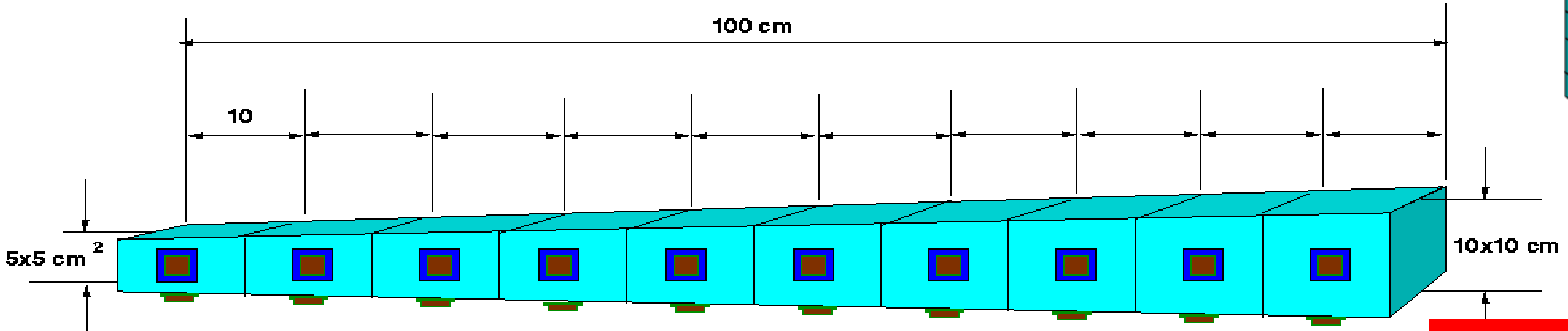
The HHCAL Concept





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 for HHCAL

Snowmass 2022 White Paper: https://doi.org/10.48550/arXiv.2203.06788

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO Glass	$BaO{\cdot}2SiO_2$ Glass[1]	HFG Glass[2]
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	3.8	5.95
Melting point (℃)	1050	1030	1123	824	608	2040	980[3]	1420[4]	570
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	3.36	1.74
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.89	3.52	2.45
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	32.8	23.2
Z_{eff} value	72.9	75.3	74.5	77.4	75.8	11.2	42.8	44.4	56.9
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	5.56	8.24
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	425	325
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	\	\	1.50
Relative Light Output by PMT[a,c]	100	20	1.6 0.4	\	2.0	0.2 0.9	2.6	5.0 4.0	3.3 6.1
LY (ph/MeV)[d]	35,000	1,500	130	\	150	7,900	450	3,150	150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	180 30	25 8
d(LY)/dT (%/°C)[d]	-0.9	?	-2.5	\	?	?	?	-0.04	-0.37
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6	?	?	?

a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. Relative light yield normalized to the light yield of BGO
d. At room temperature (20°C) with PMT QE taken out.

Low density crystals/glasses

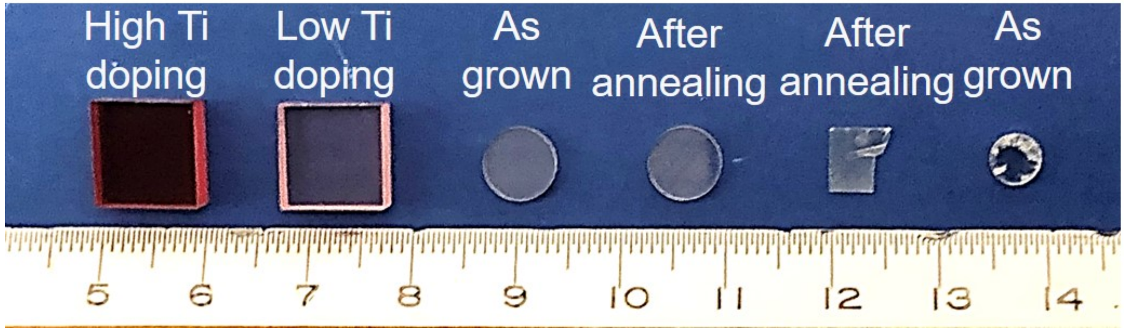
Cost-Effective Sapphire Crystals for HHCAL

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

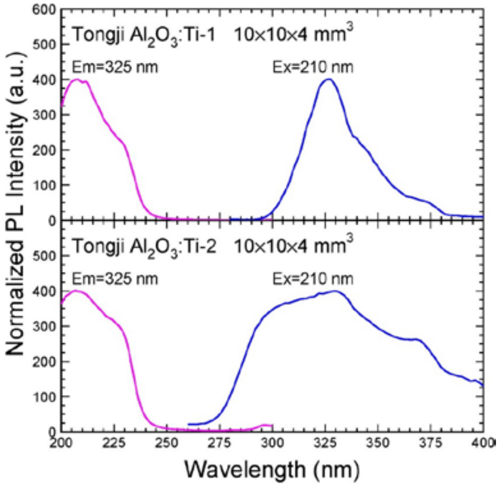
Sapphire:Ti Emission and Transmittance



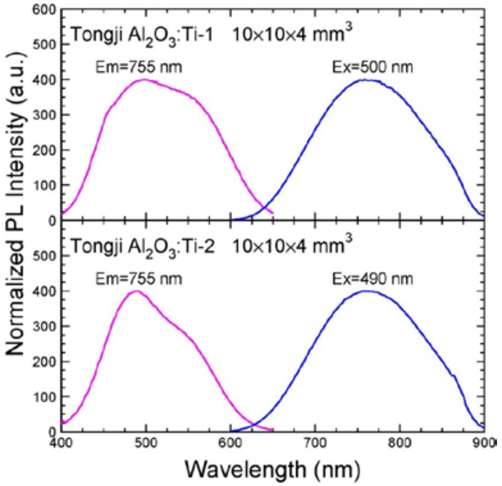
ID	Dimension (mm^3)	#	Polishing
Tongji Al_2O_3:Ti-1,2	**10×10×4**	**2**	**Two faces**
Tongji Al_2O_3:C-1,2	Φ7×1	2	Two faces
Tongji Lu_2O_3:Yb	6.4×4.8×0.4	1	Two faces
Tongji $LuScO_3$:Yb	Φ4.8×1.3	1	Two faces

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

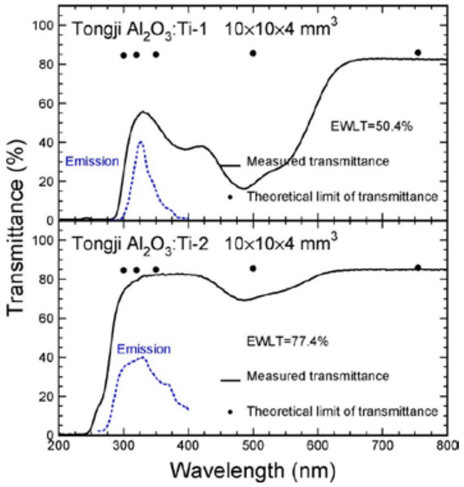
Fast @325 nm



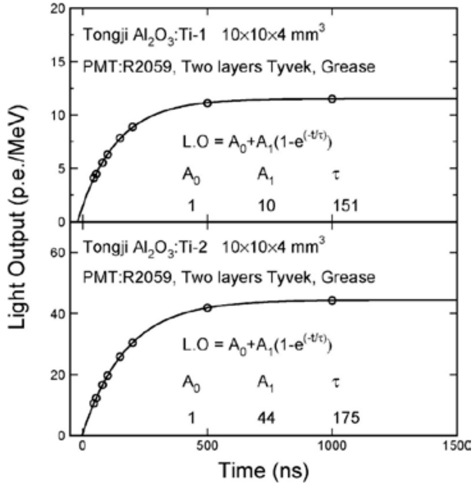
Slow @755 nm



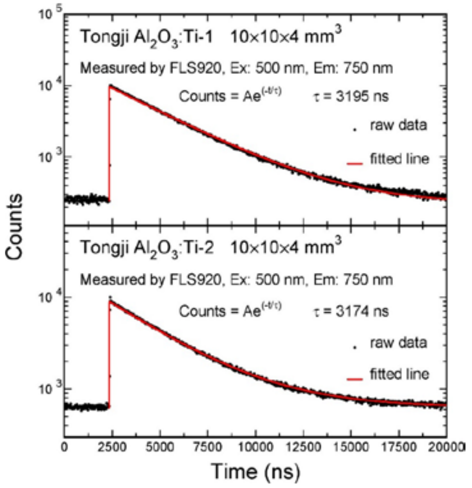
EWLT for Fast & Slow



Fast = 162 ns



Slow = 3.2 μs



Summary

The HL-LHC and FCC-hh require fast and radiation hard calorimetry. The **RADiCAL** concept uses radiation hard LuAG:Ce ceramics as wavelength shifter for LYSO:Ce crystals for an ultra-compact, fast timing and longitudinally segmented shashlik calorimeter.

Undoped BaF_2 crystals provide ultrafast light with sub-ns decay time and a good radiation hardness up to 100 Mrad. Yttrium doping suppresses its slow light and promises a **ultrafast calorimeter**. R&D is needed for optimizing yttrium doping and radiation hardness in large size BaF_2:Y crystals for Mu2e-II. Solar-blind VUV photo-detectors are also needed to control radiation induced readout noise.

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

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

Novel inorganic scintillators are needed for all these novel calorimeter concepts

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