Development of Novel Inorganic Scintillators for Future High Energy Physics Experiments

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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 are needed to achieve energy, spatial and timing resolutions required by BRN

Fast and Ultrafast Inorganic Scintillators

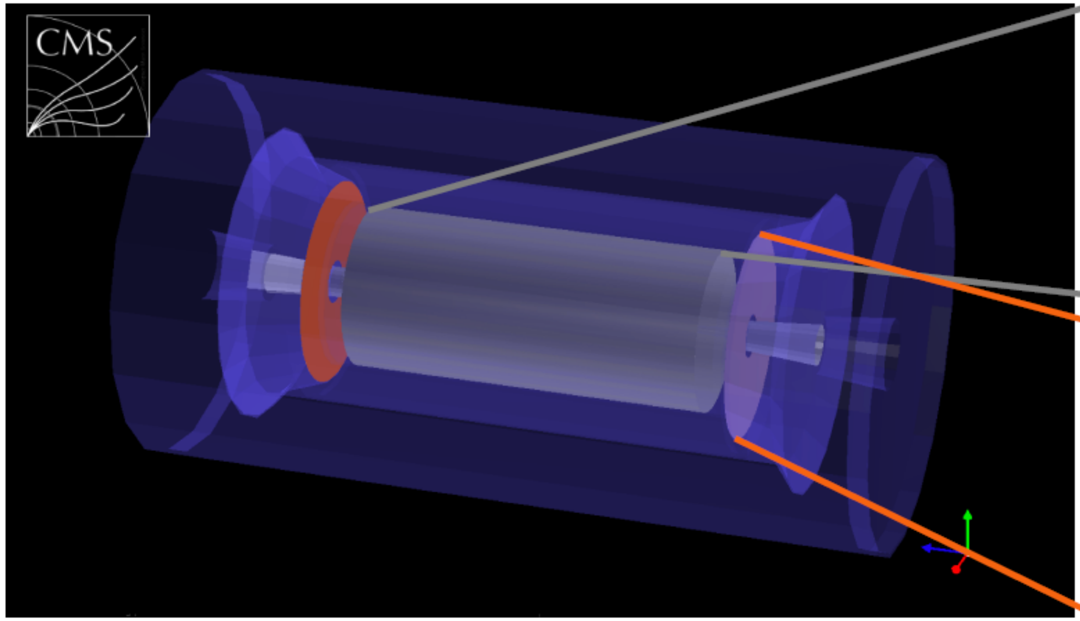
	BaF_2	BaF_2:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (ºC)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	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 1^{st} 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}

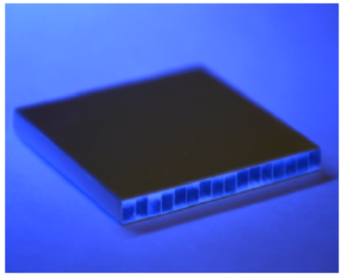
Barrel Timing Layer: arrays of LYSO crystal bars connected to SiPMs at both ends and readout by TOFHIR

LYSO quality control: Low temperature performance, RIN:ɣ, RIN:n, TID, TF:p and TF:n



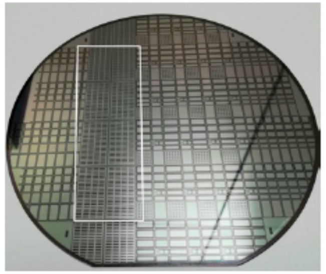
BTL: LYSO bars + SiPM read-out

- 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



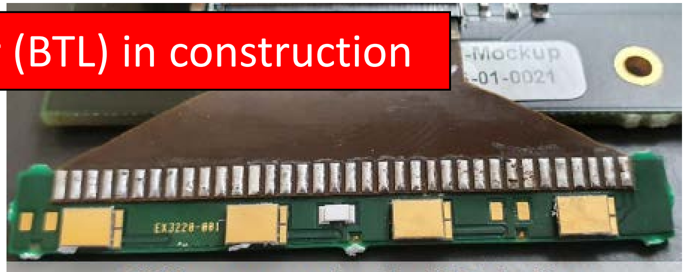
ETL: Si with internal gain (LGAD)

- 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

CMS MTD: Expected Radiation

CMS BTL/EMEC: 4.8/68 Mrad, $2.5\times10^{13}/2.1\times10^{14}$ p/cm^2 & $3.2\times10^{14}/2.4\times10^{15}$ n_{eq}/cm^2

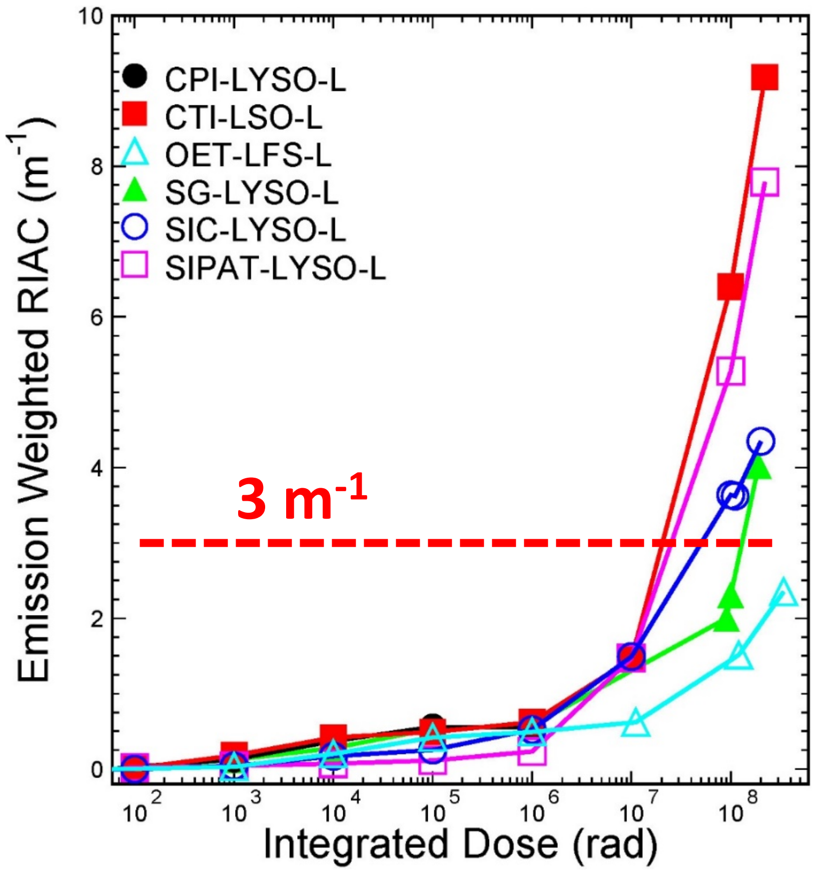
CMS MTD	η	n_{eq} (cm^{-2})	n_{eq} Flux (cm^{-2}s^{-1})	Proton (cm^{-2})	p Flux (cm^{-2}s^{-1})	Dose (Mrad)	Dose rate (rad/h)
Barrel	0.00	2.5E+14	2.8E+06	2.2E+13	2.4E+05	2.7	108
Barrel	1.15	2.7E+14	3.0E+06	2.4E+13	2.6E+05	3.8	150
Barrel	**1.45**	**2.9E+14**	**3.2E+06**	**2.5E+13**	**2.8E+05**	**4.8**	**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**

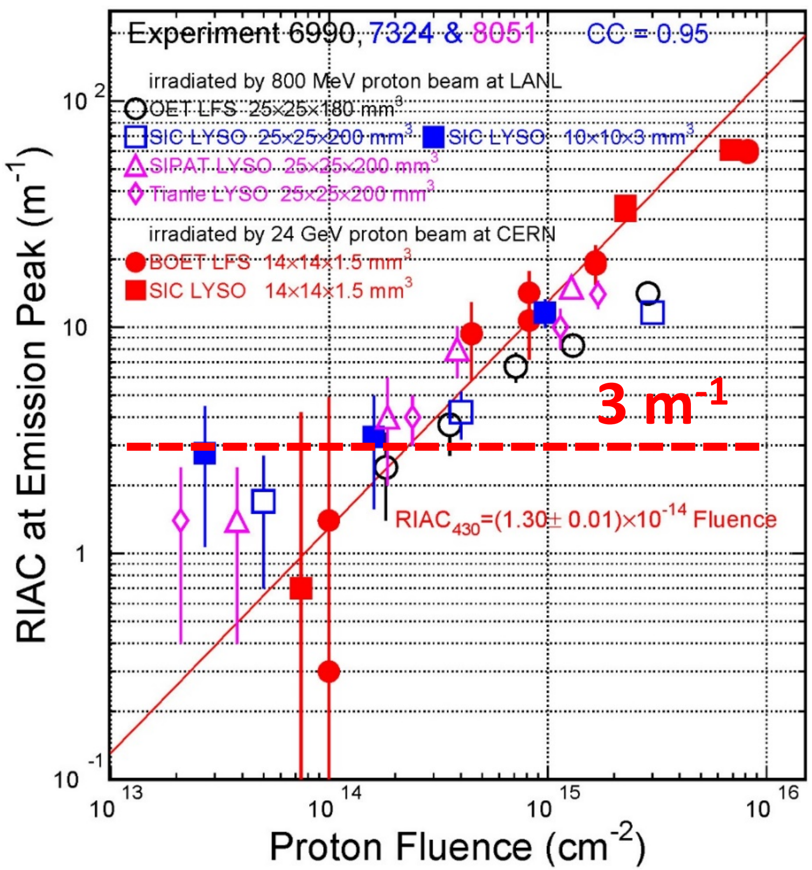
Much higher at FCC-hh: up to 0.1/500 Grad and $3\text{x}10^{16}/5\text{x}10^{18}$ n_{eq}/cm^2 at EMEC/EMF

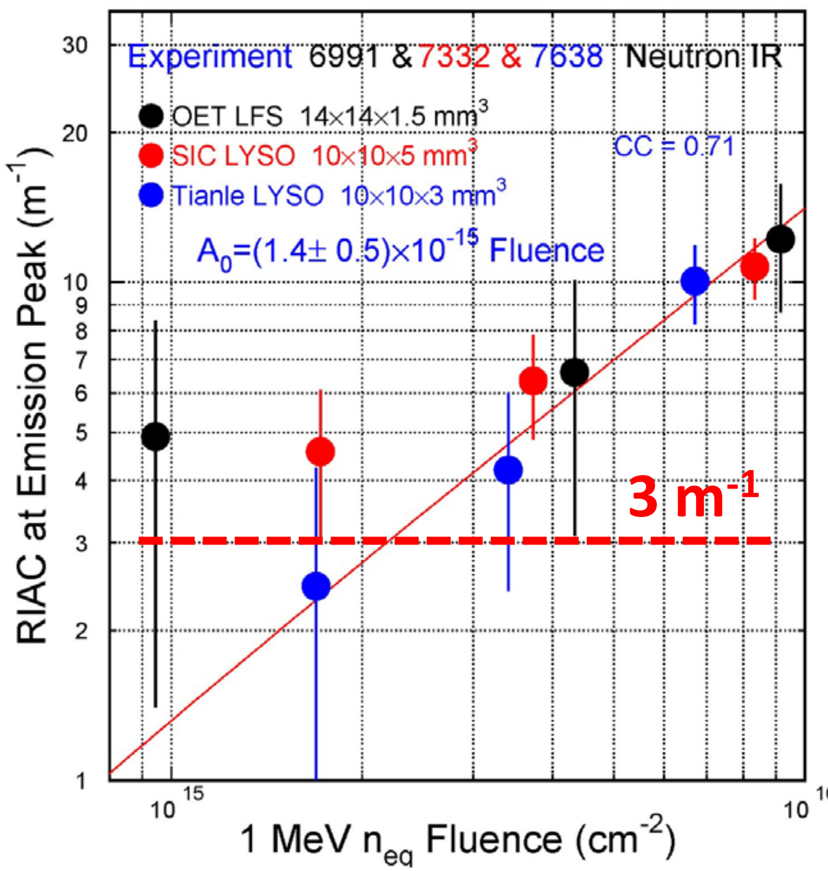
M. Aleksa *et al.*, Calorimeters for the FCC-hh CERN-FCCPHYS-2019-0003, Dec 23, 2019

LYSO Radiation Hardness

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





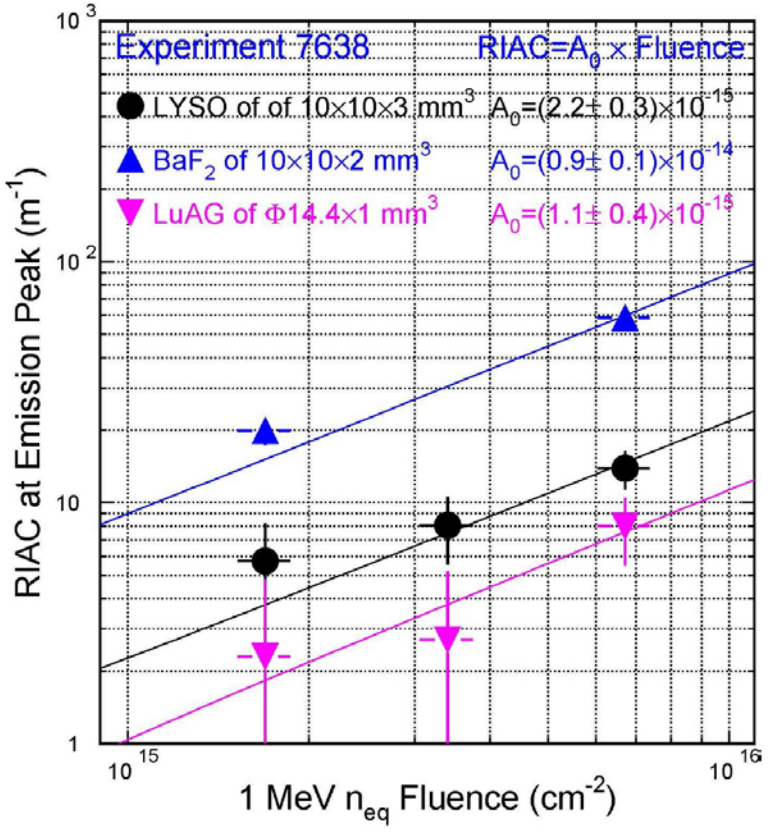


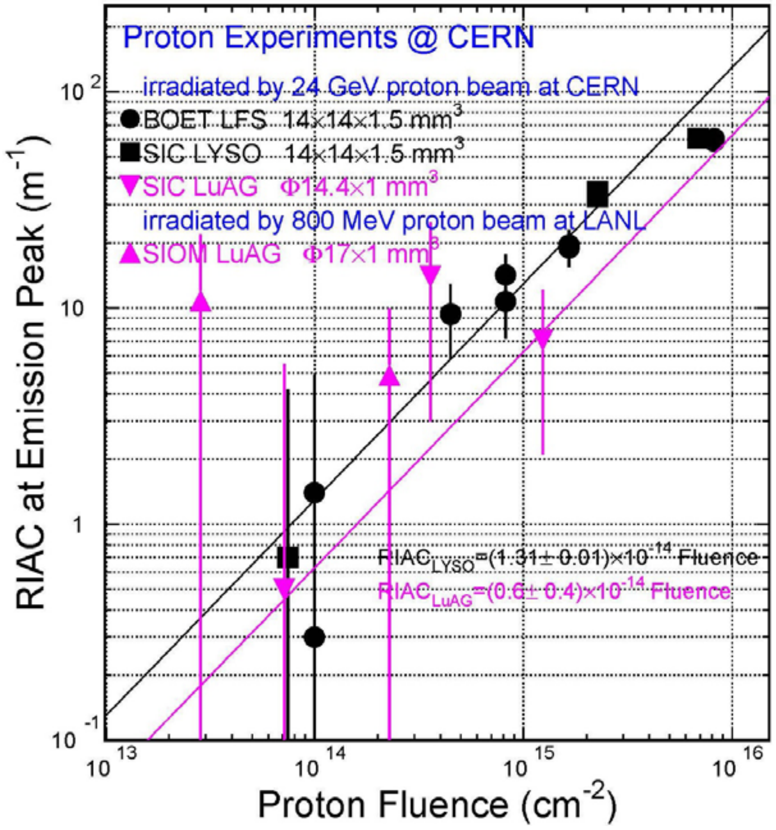
Damage induced by protons is an order of magnitude larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup

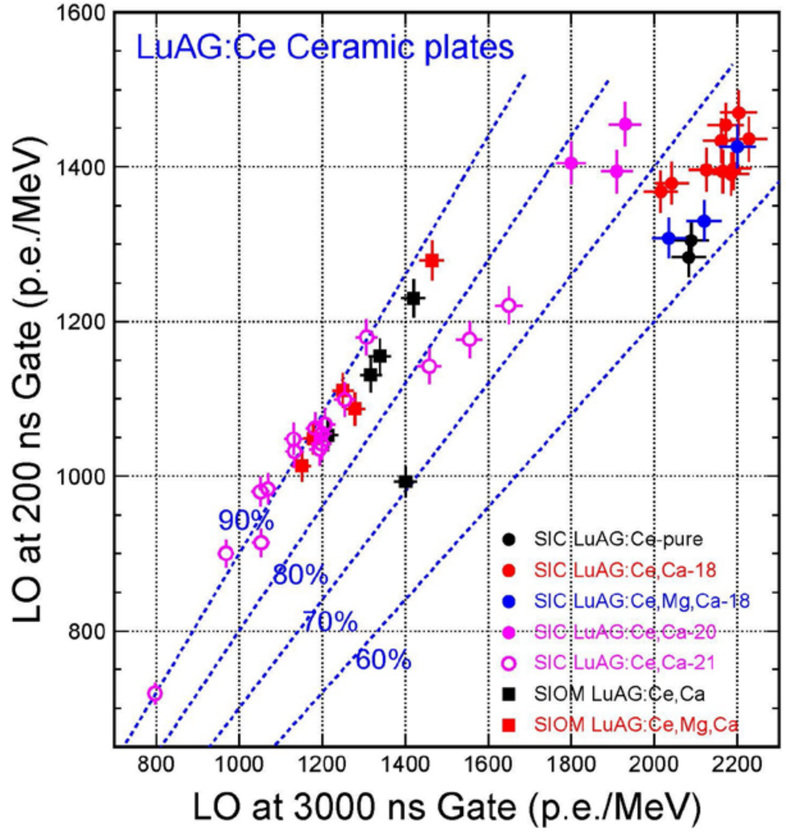
LuAG:Ce Ceramics Radiation Hardness

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)

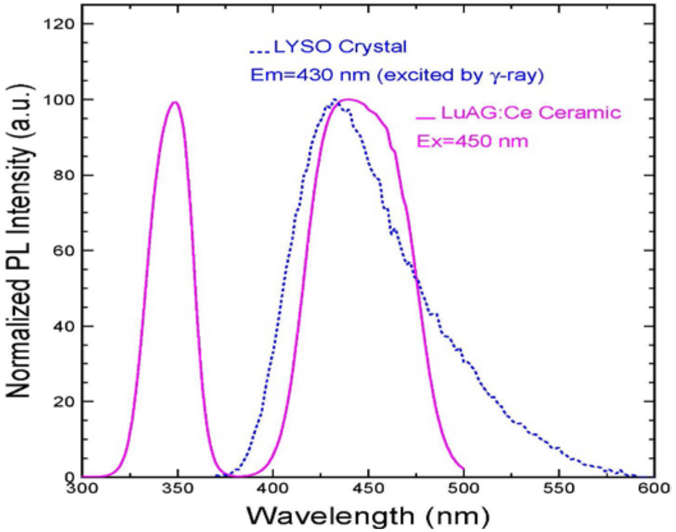






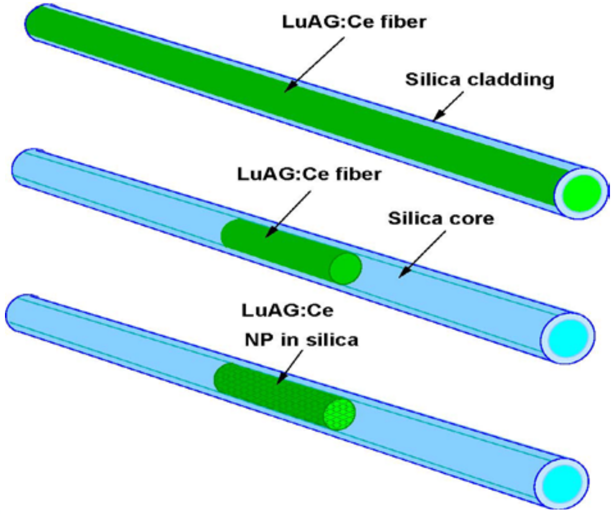
R&D on slow component suppression by e.g. Ca co-doping, and radiation hardness by ɣ/p/n

RADiCAL: LYSO/LuAG Shashlik ECAL

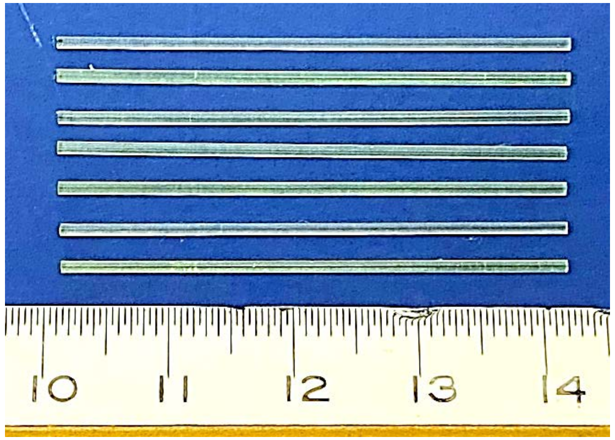


Excitation of LuAG:Ce ceramics matches well LYSO:Ce emission:

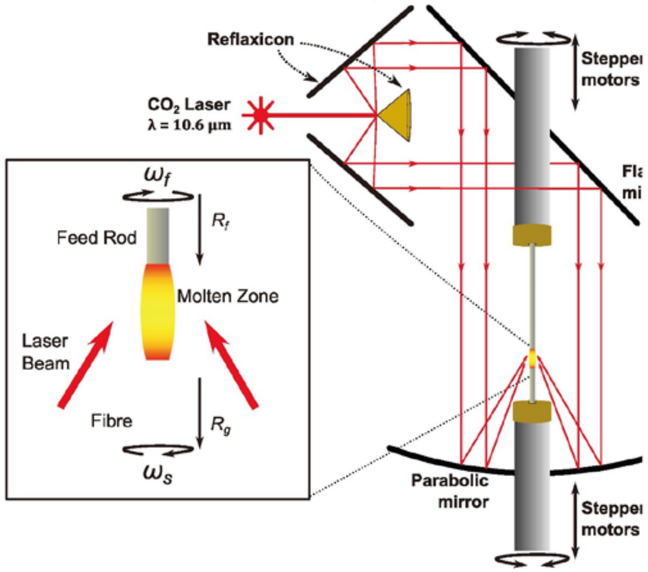
RADiCAL
RADiation hard **i**nnovative **CAL**orimetry
See R. Ruchti, in this session

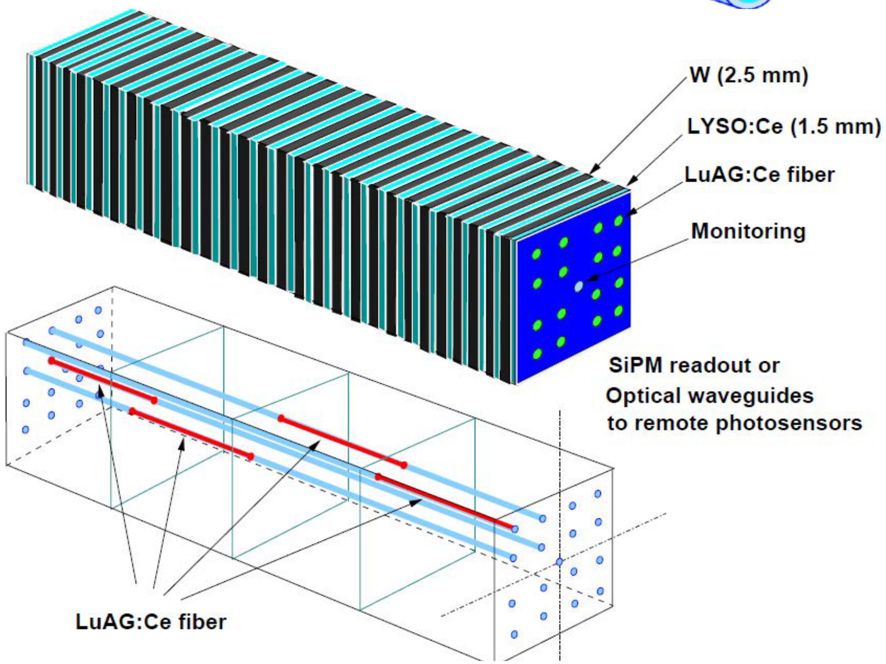


Φ1x40 mm³ SIC LuAG:Ce Ceramic LHPG fibers



Laser Heated Pedestal Growth

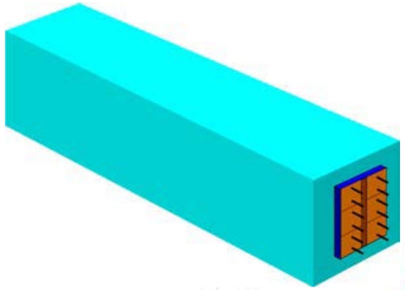




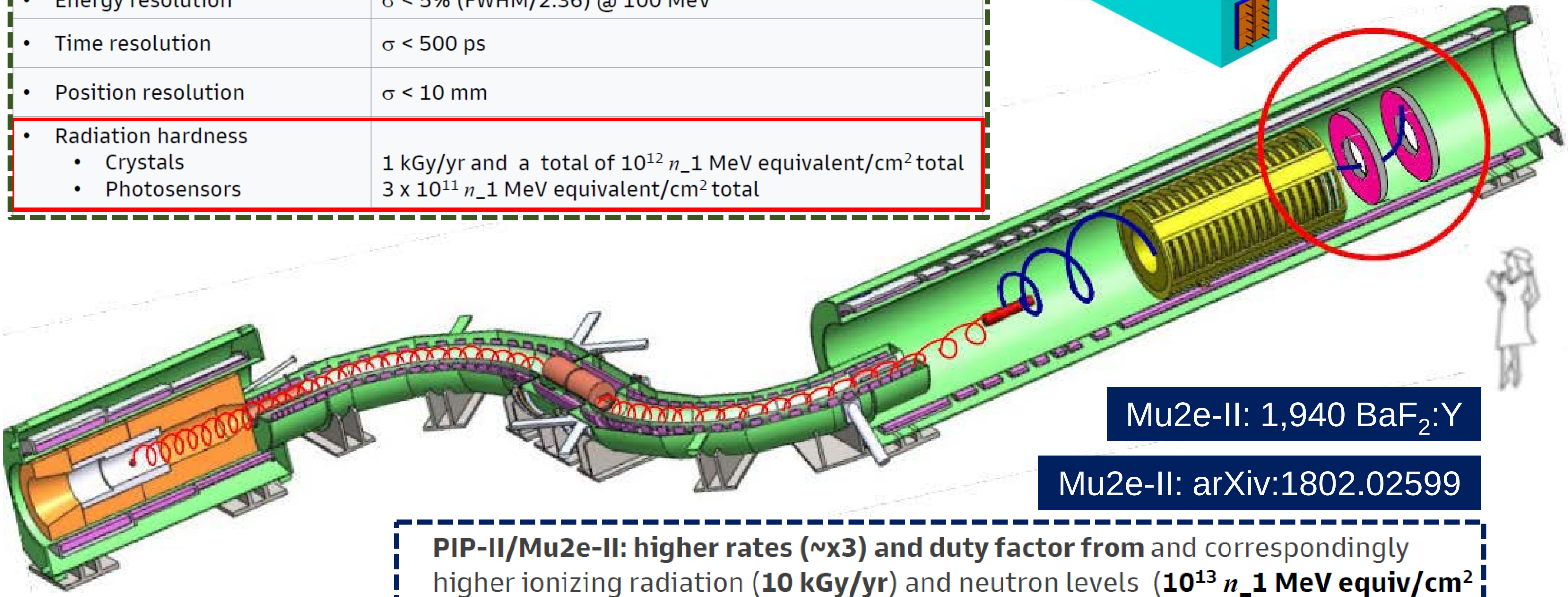
Mu2e Calorimeter Requirements

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



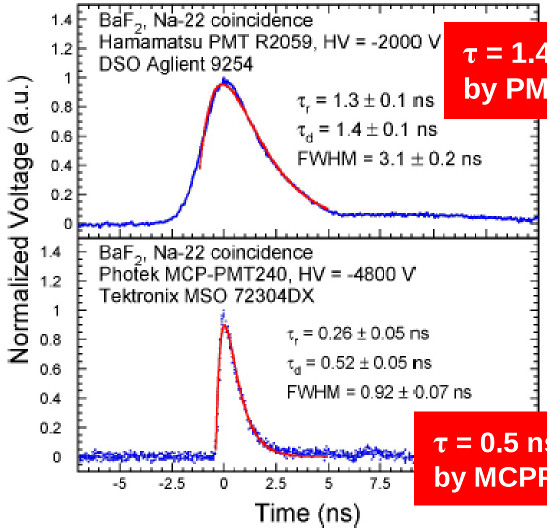
Mu2e-II: 1,940 BaF_2:Y

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

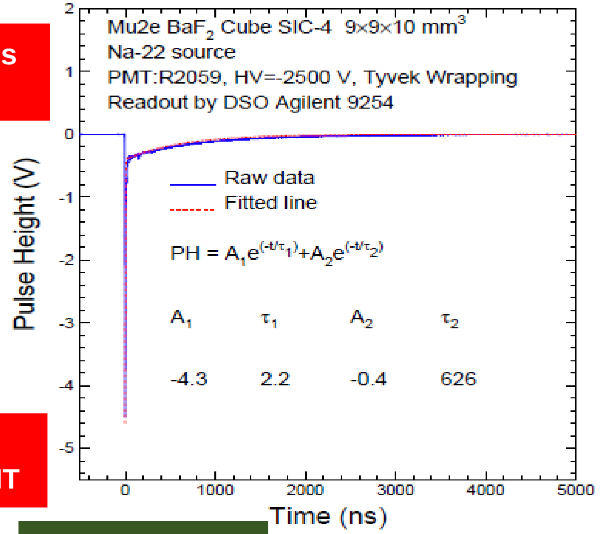
Ultrafast and Radiation Hard BaF_2

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

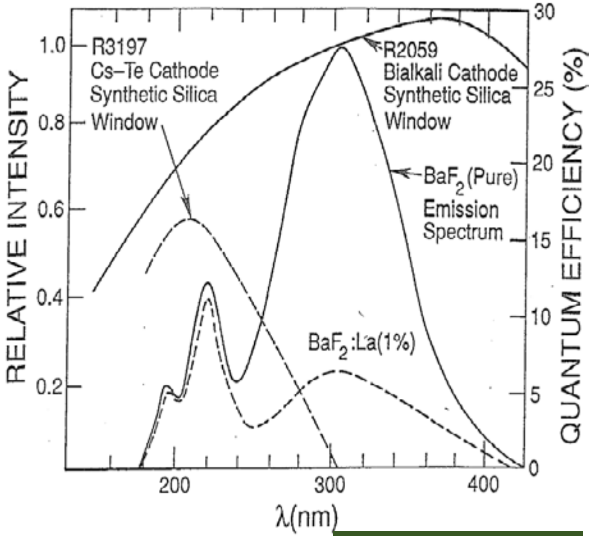


τ = 1.4 ns by PMT

τ = 0.5 ns by MCPPMT

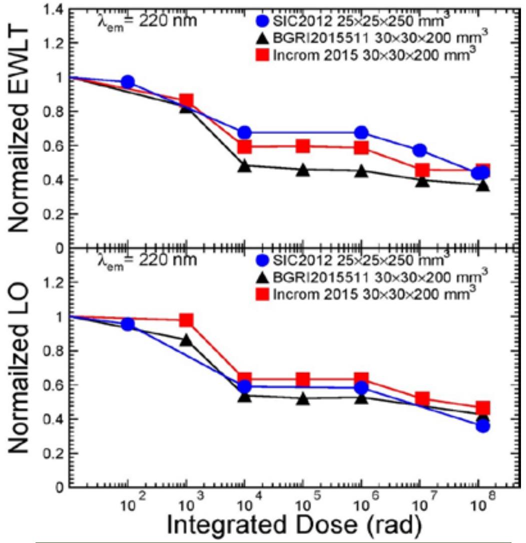


NIMA 340 (1994) 442-457



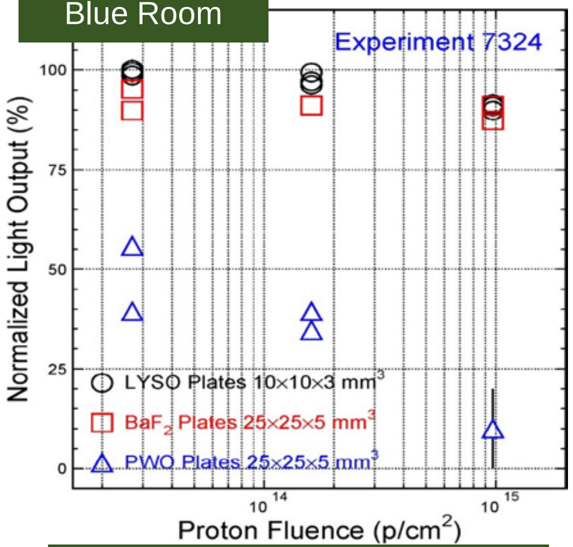
BaF_2 has an ultrafast scintillation component @ 220 nm with **0.5 ns** decay time and a much larger slow component @ 300 nm with 600 ns decay time.

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



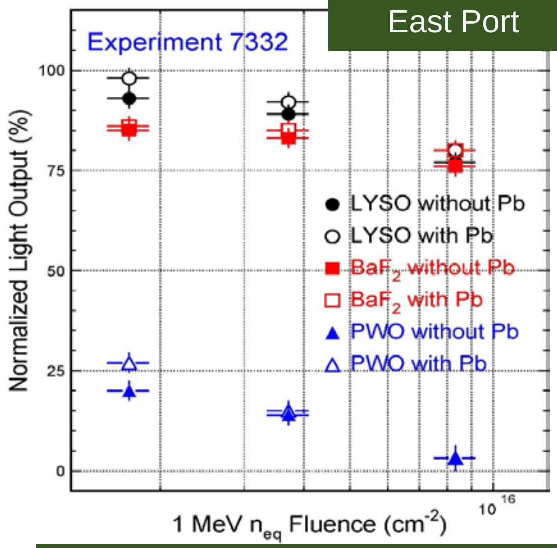
IEEE TNS **63** (2016) 612-619

Blue Room



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

East Port

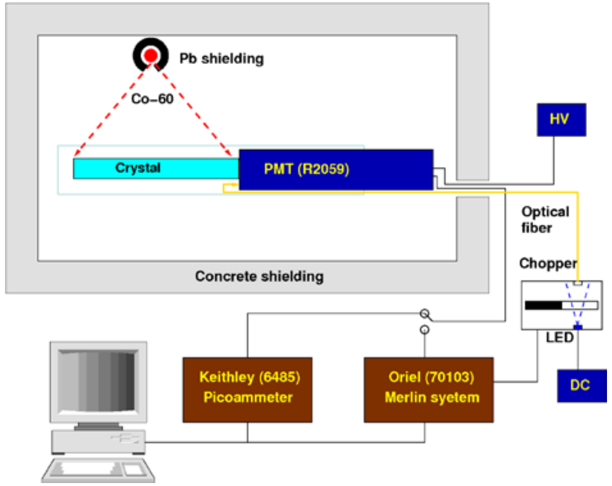


IEEE TNS **67** (2020) 1018-1024

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

Gamma-ray Induced Readout Noise RIN:γ

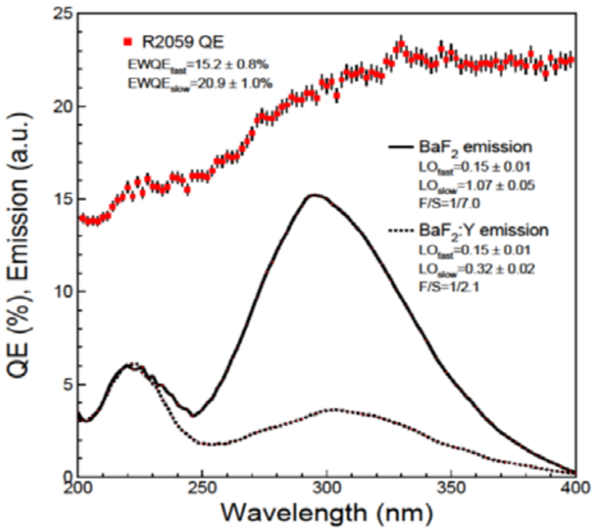


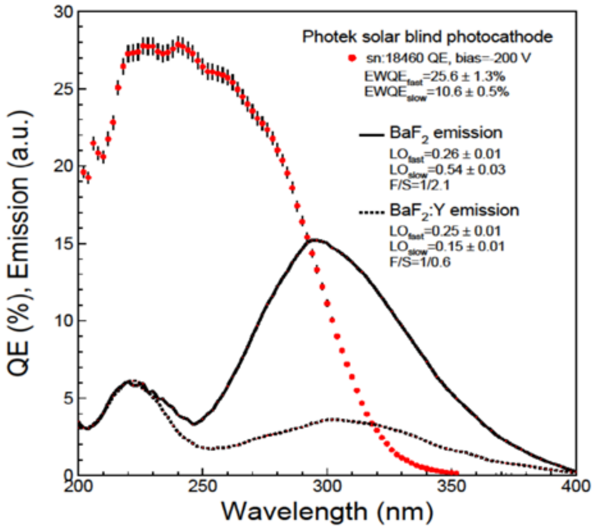
BaF$_2$ crystals wrapped by Tyvek with an air gap coupling to a Hamamatsu PMT R2059, were irradiated by Co-60 with dose rates of 2 and 23 rad/h

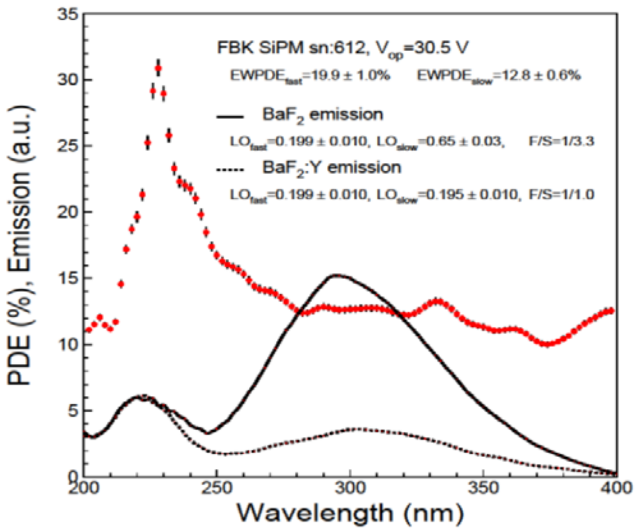
$$F = \frac{\dfrac{Photocurrent}{Charge_{electron} \times Gain_{SiPM}}}{Dose\ rate_{\gamma-ray}\ or\ Flux_{neutron}} \qquad \sigma = \frac{\sqrt{Q}}{LO} \quad \text{(MeV)}$$

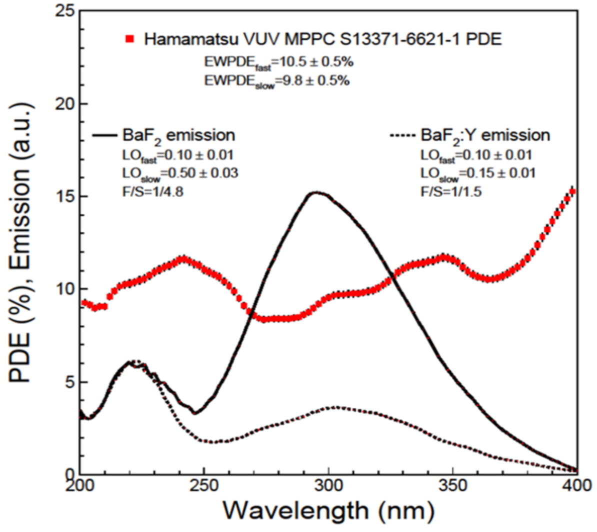
QE/PDE of four VUV photodetectors for BaF2 and BaF2:Y

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









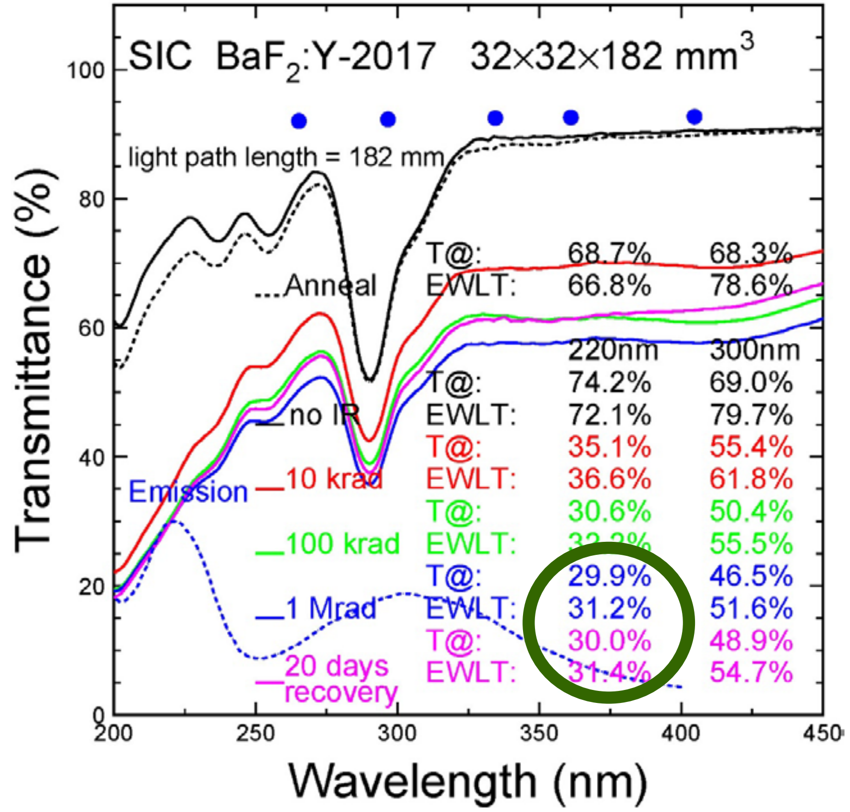
RIN:γ for Four VUV Photodetector

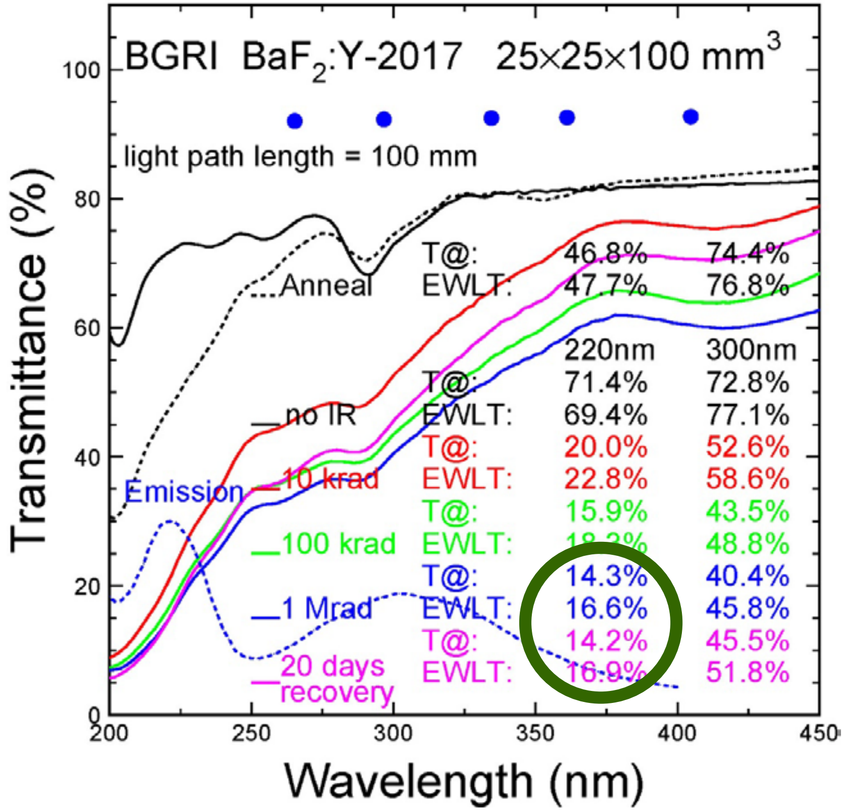
Photodetector	EWQE/PDE$_{fast}$ (%)	EWQE/PDE (%)	LO (50 ns) p.e./MeV	F	RIN:γ (keV)
BGRI BaF_2:Y-2020					
Hamamatsu R2059 PMT	15.2	18.7	53	3.1×10^9	1050
Photek PMT Solar Blind	25.6	16.1	89	2.7×10^9	**580**
FBK SiPM w/UV Filter-I	17.8	14.7	62	2.4×10^9	800
Hamamatsu VUV MPPC	10.5	10.2	37	1.7×10^9	1120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

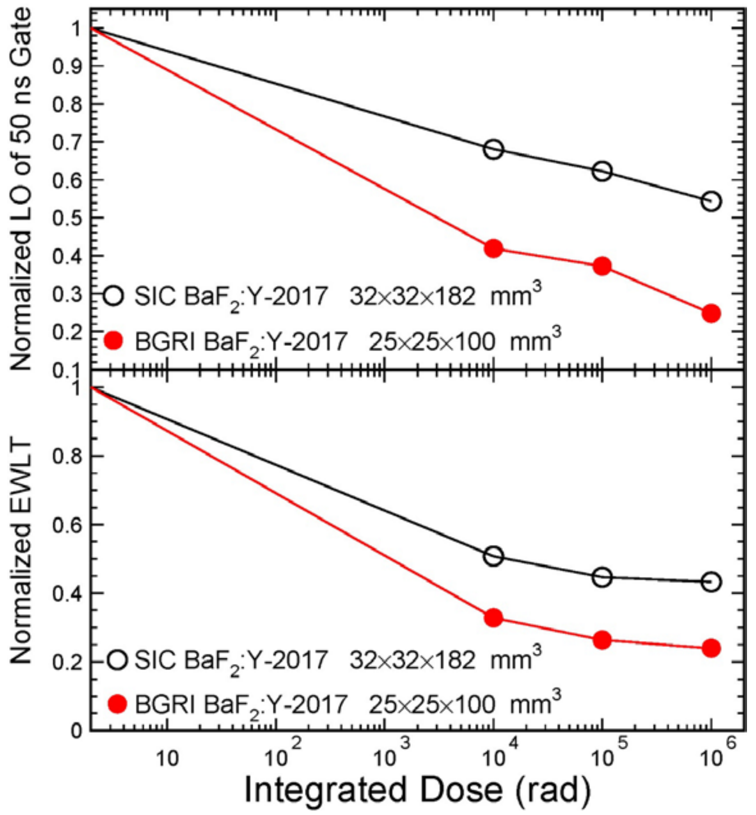
RIN:ɣ is dominated by the slow light, so is reduced by yttrium doping
Solar blind PD is required to reduce the RIN:ɣ values to less than 0.6 MeV

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



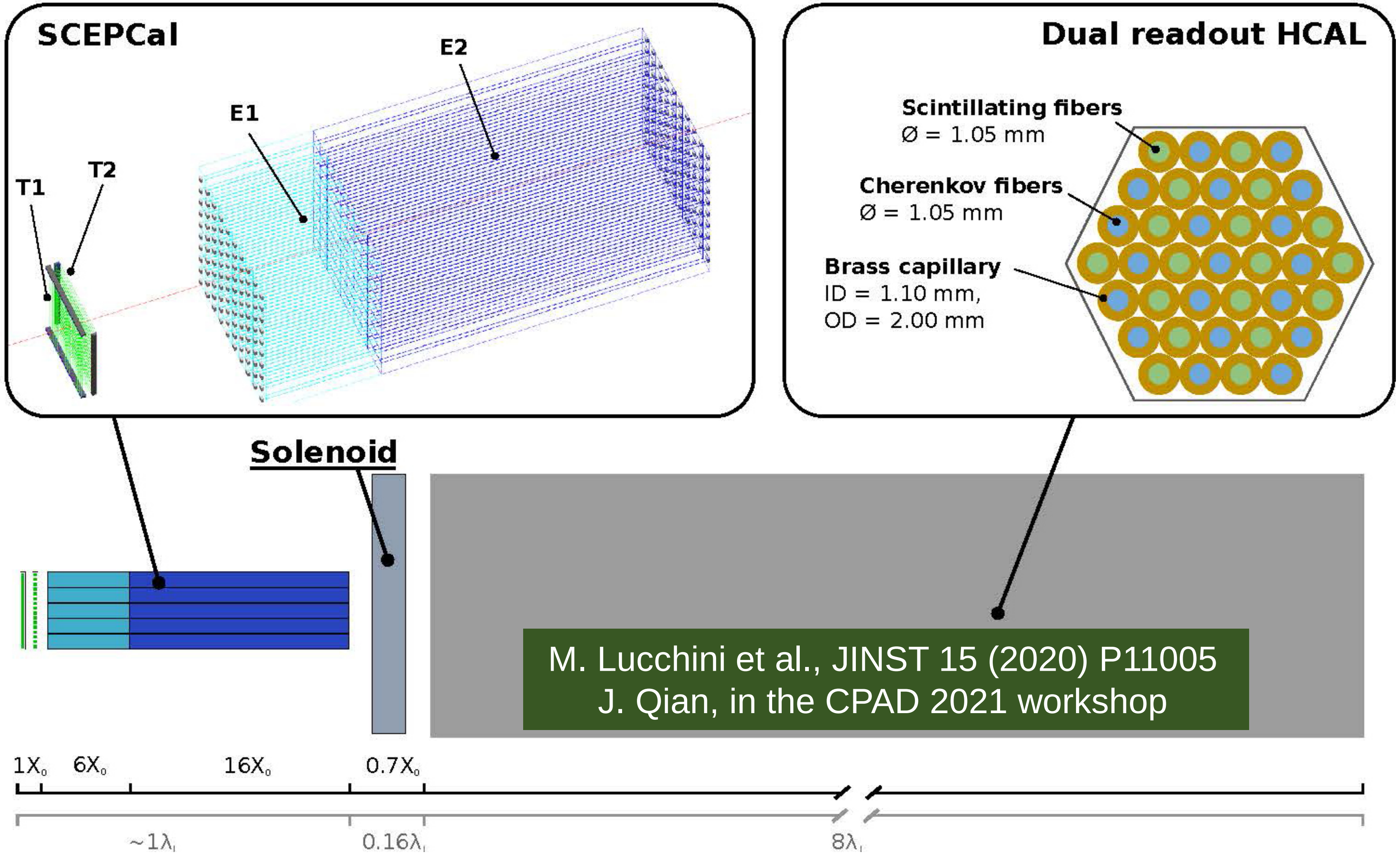


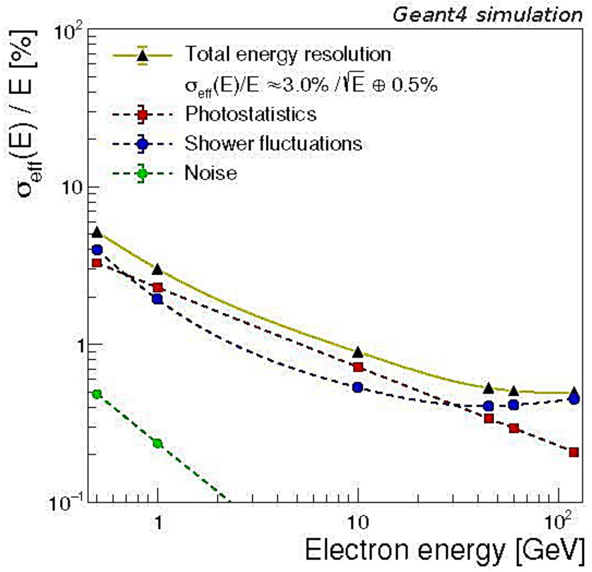


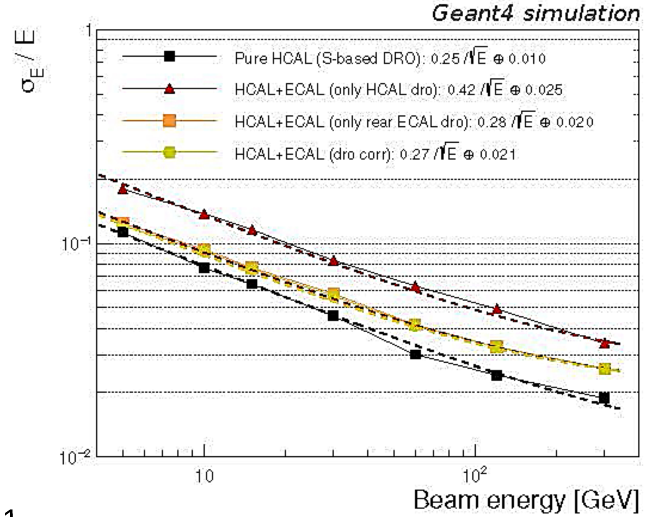
Diverse crystal quality at this stage of R&D, needs improvement

Calvision: A Longitudinally Segmented Crystal ECAL

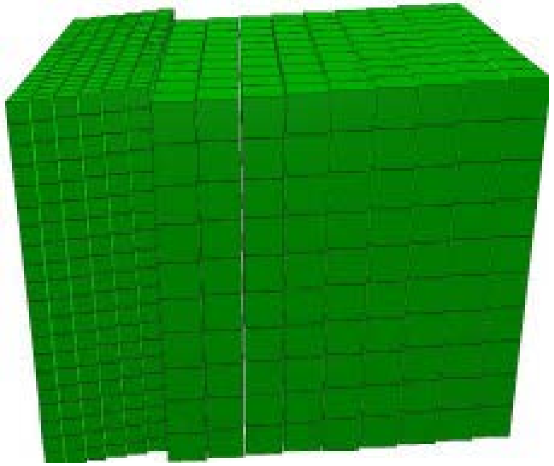
Aiming at excellent EM and jet resolutions for Higgs Factory

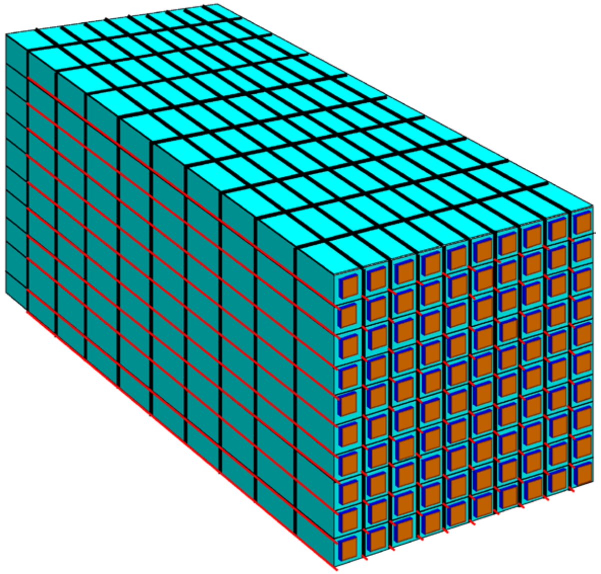






HHCAL : A Total Absorption Hadron Calorimeter

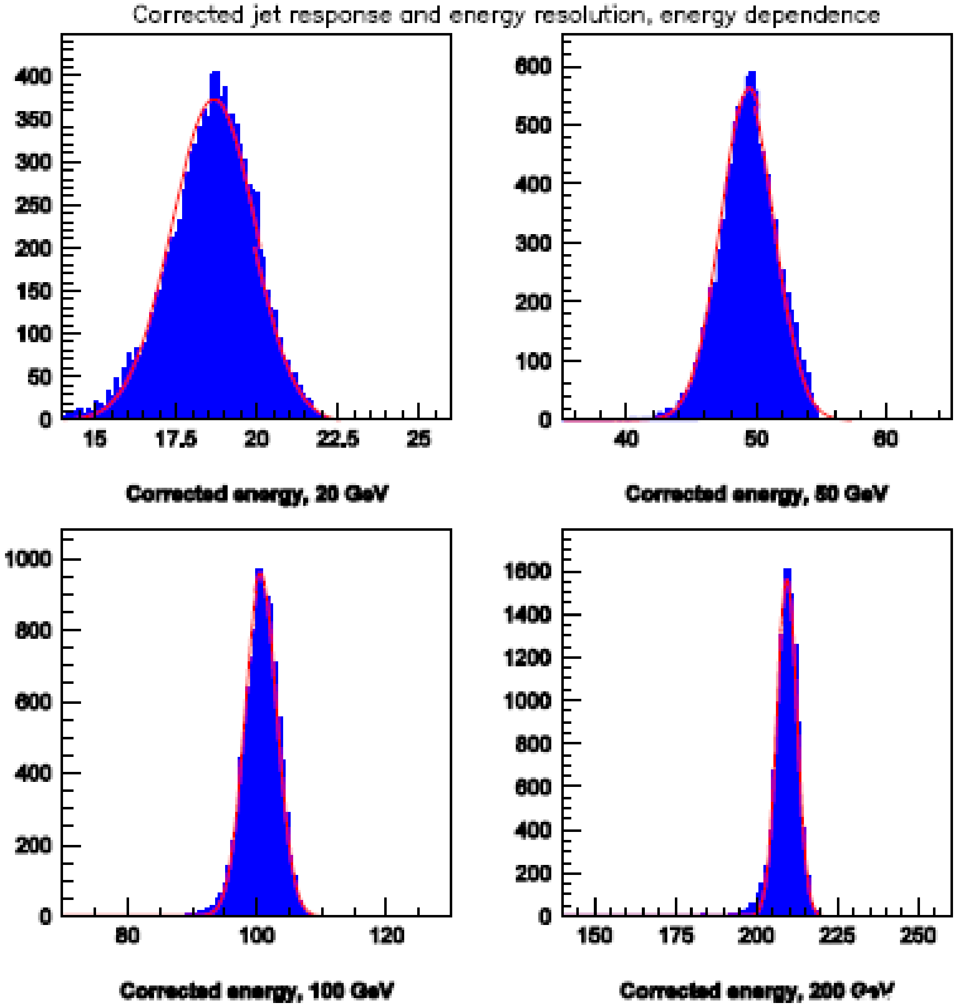




A. Para, H. Wenzel, and S. McGill in Callor2012 Proceedings;
A. Benaglia *et al*., IEEE TNS **63** (2016) 574:
Jet energy resolution of 20%/√E is achievable by HHCAL with dual readout of S/C or dual gate

See presentations by H. Wenzel and M. Demarteau in this session

Can we afford?



Inorganic Scintillators for HHCAL

	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

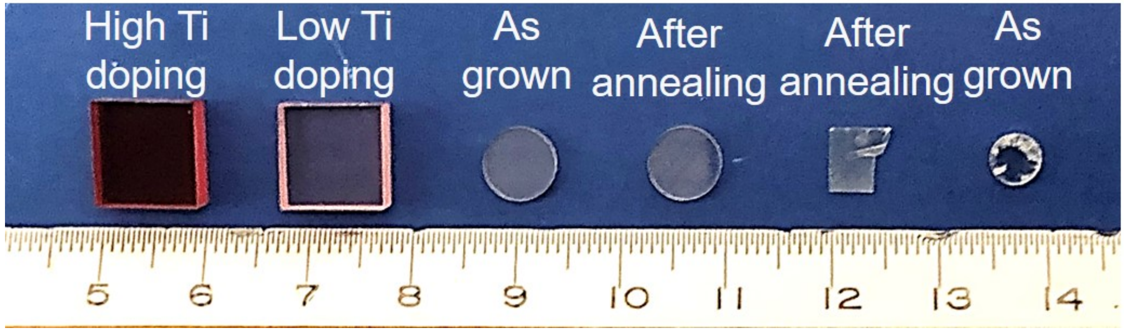
Cost-Effective Sapphire Crystals for HHCAL

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

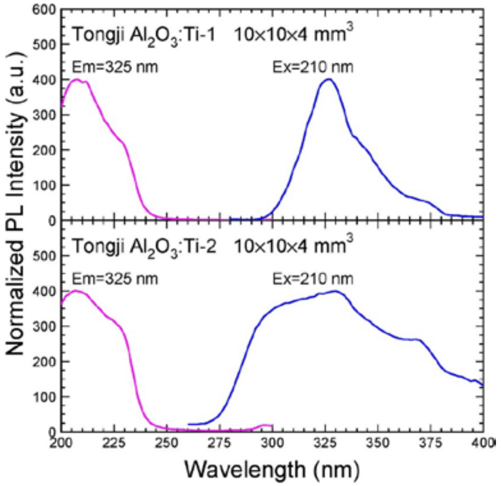
Sapphire:Ti Emission and Transmittance



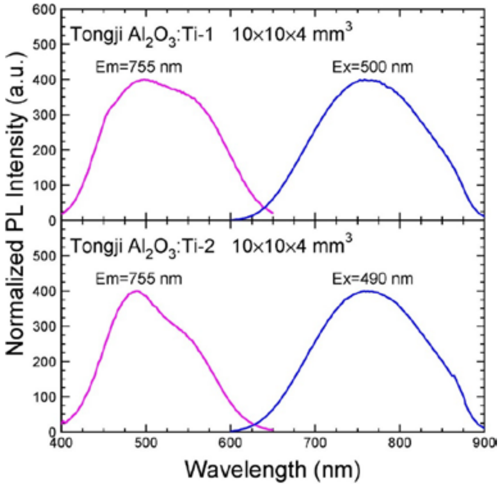
ID	Dimension (mm^3)	#	Polishing
Tongji Al_2O_3:Ti-1,2	**10×10×4**	**2**	**Two faces**
Tongji Al_2O_3:C-1,2	Φ7×1	2	Two faces
Tongji Lu_2O_3:Yb	6.4×4.8×0.4	1	Two faces
Tongji $LuScO_3$:Yb	Φ4.8×1.3	1	Two faces

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

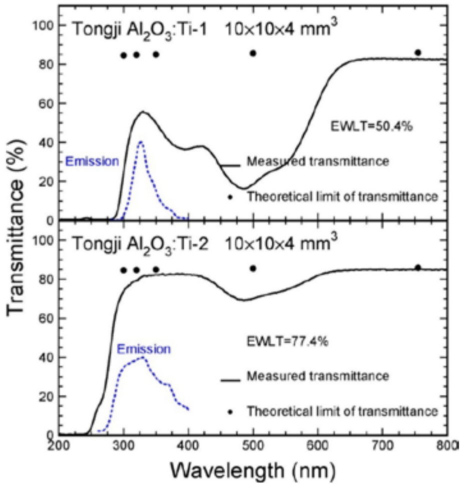
Fast @325 nm



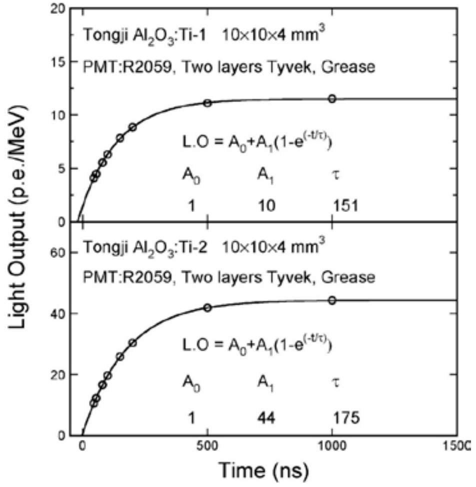
Slow @755 nm



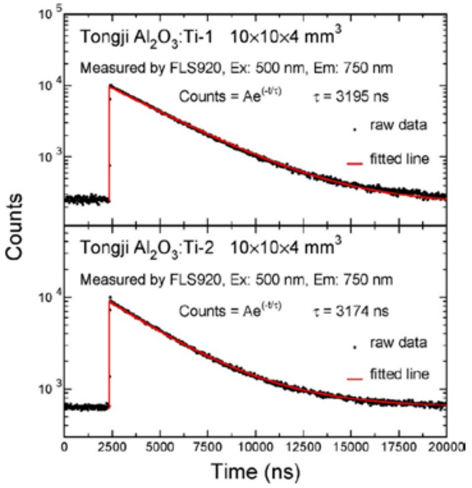
EWLT for Fast & Slow



Fast = 162 ns



Slow = 3.2 μs



Summary

The HL-LHC and FCC-hh requires fast and rad hard calorimetry. The **RADiCAL** concept uses radiation hard LuAG:Ce ceramics as WLS for LYSO:Ce crystals for an ultra-compact, fast 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 for controlling the radiation induced readout noise.

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

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

Novel inorganic scintillators will play important role in all these calorimeter concepts

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