Inorganic Scintillators for Future HEP Experiments

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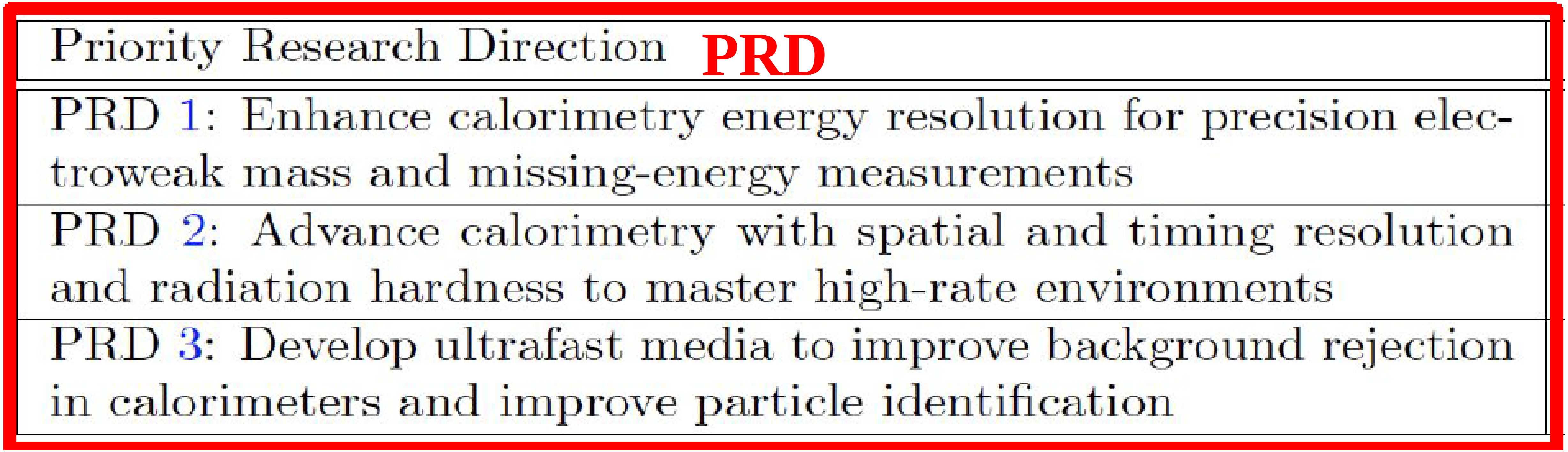
Presented in the SCINT 2022 Conference, Santa Fe, New Mexico

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 materials

Inorganic Scintillators

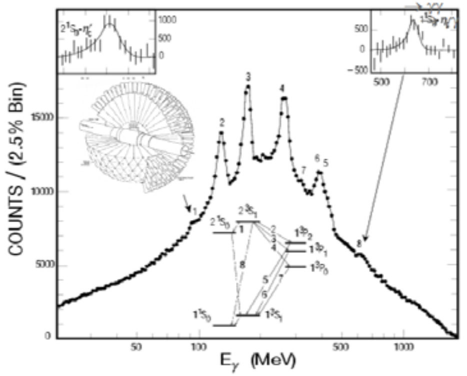
- **Precision photons and electrons enhance physics discovery potential.**
- **Crystal performance is well understood:**
  - **The best possible energy resolution and position resolution;**
  - **Good e/γ identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout,: 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 BaF_2 crystals, and LuAG:Ce ceramics;**
  - **Ultrafast BaF_2:Y crystals and Lu_2O_3 ceramics (Talk by Dr. C. Hu);**
  - **BGO, BSO & PWO crystals and heavy scintillating glasses.**

arXiv: 2203.06731 & arXiv: 2203.06788

Crystal ECAL Physics

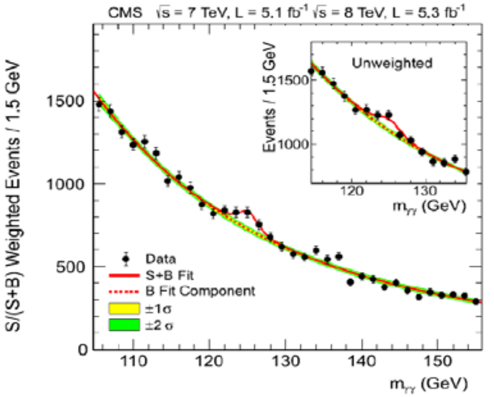
Charmonium system observed by CB through Inclusive photons

CB NaI(Tl)



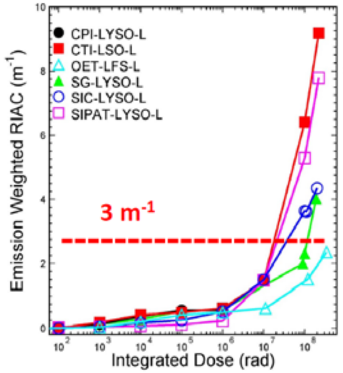
Higgs -> γγ by CMS through reconstructing photon pairs

CMS PWO

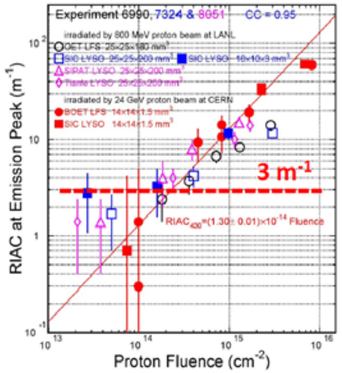


LYSO:Ce Crystals for CMS BTL

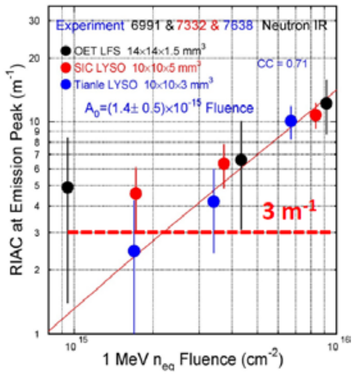
NIM A **824** (2016) 726-728



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

CMS MTD: Expected Radiation

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**

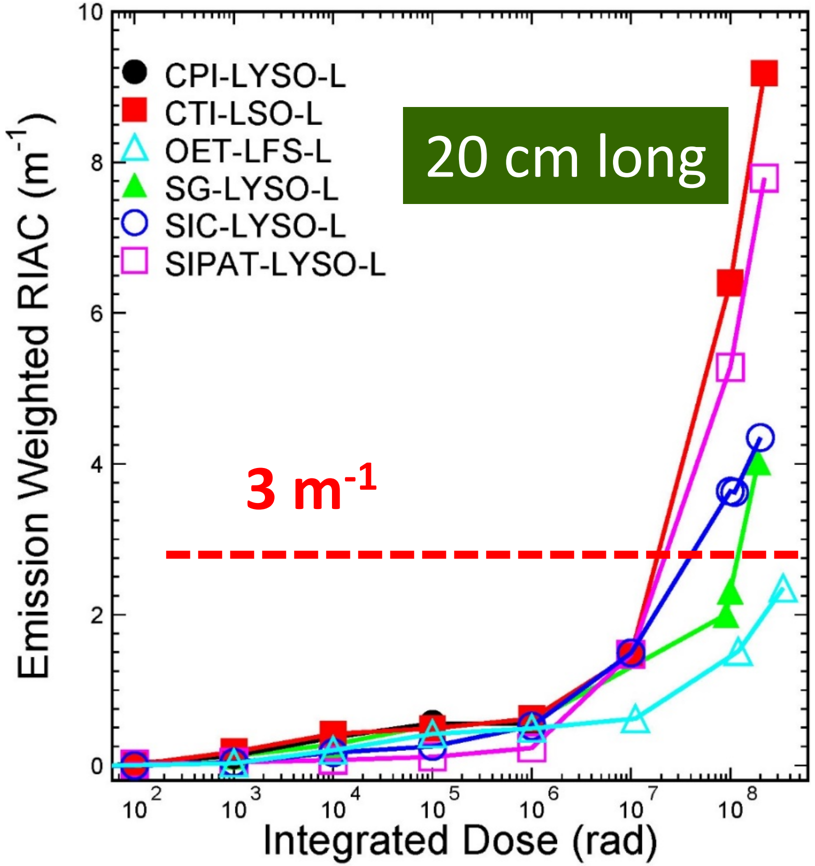
Much higher at FCC-hh: up to 0.1/500 Grad and 3/500 x10^{16} n_{eq}/cm^2 at EMEC/EMF

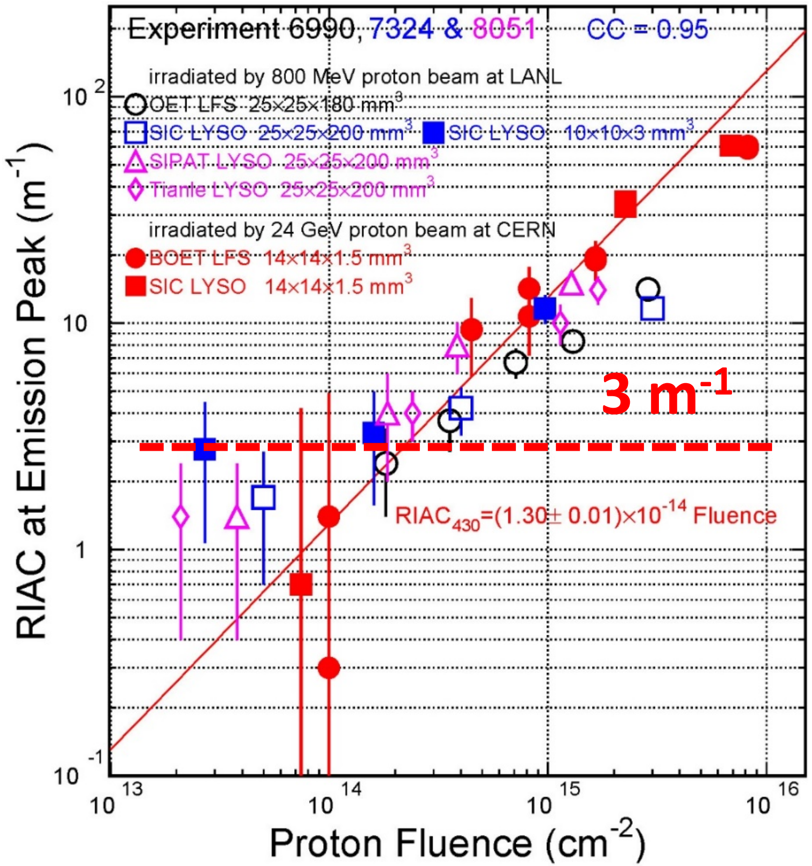
Aleksa *et al.*, Calorimeters for the FCC-hh CERN-FCCPHYS-2019-0003, Dec 23, 2019

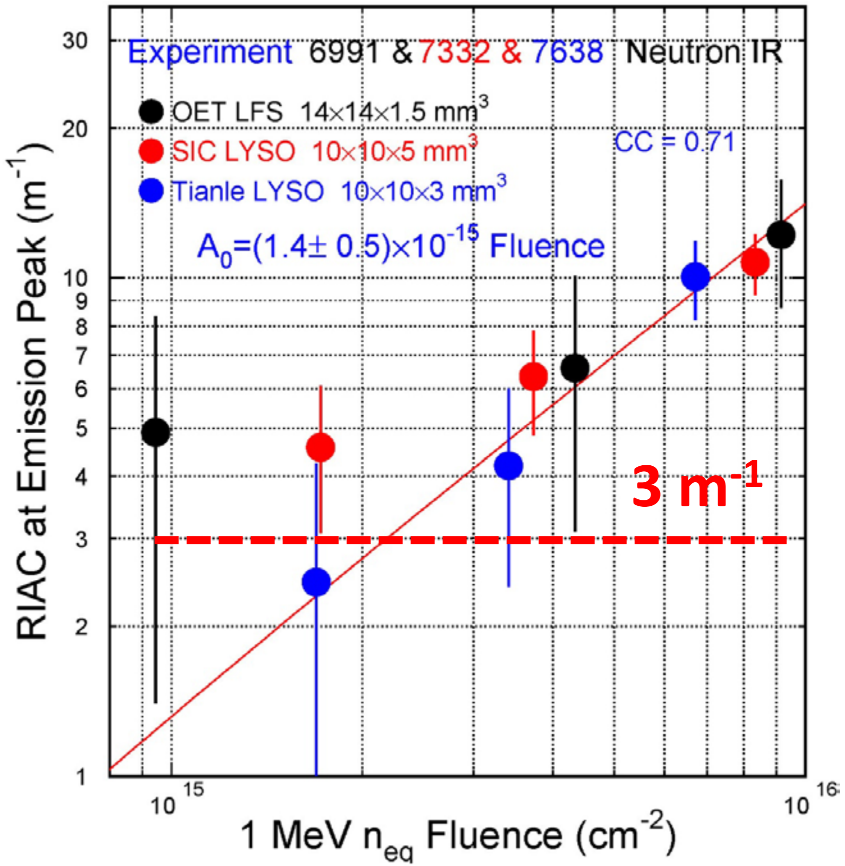
LYSO:Ce Radiation Hardness

IEEE TNS 63 (2016) 612-619

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





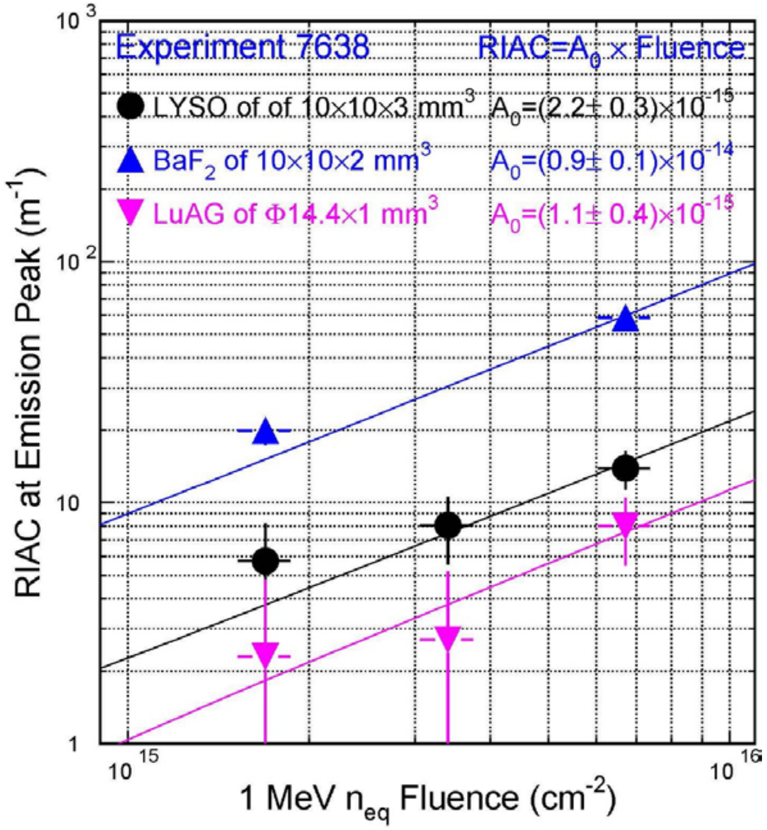


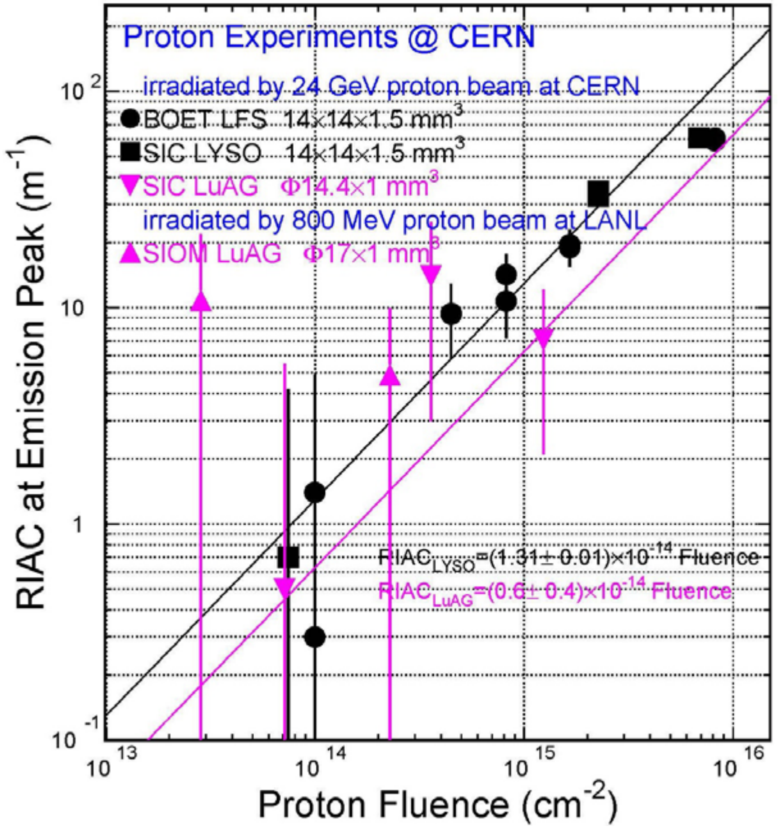
Damage induced by protons larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup

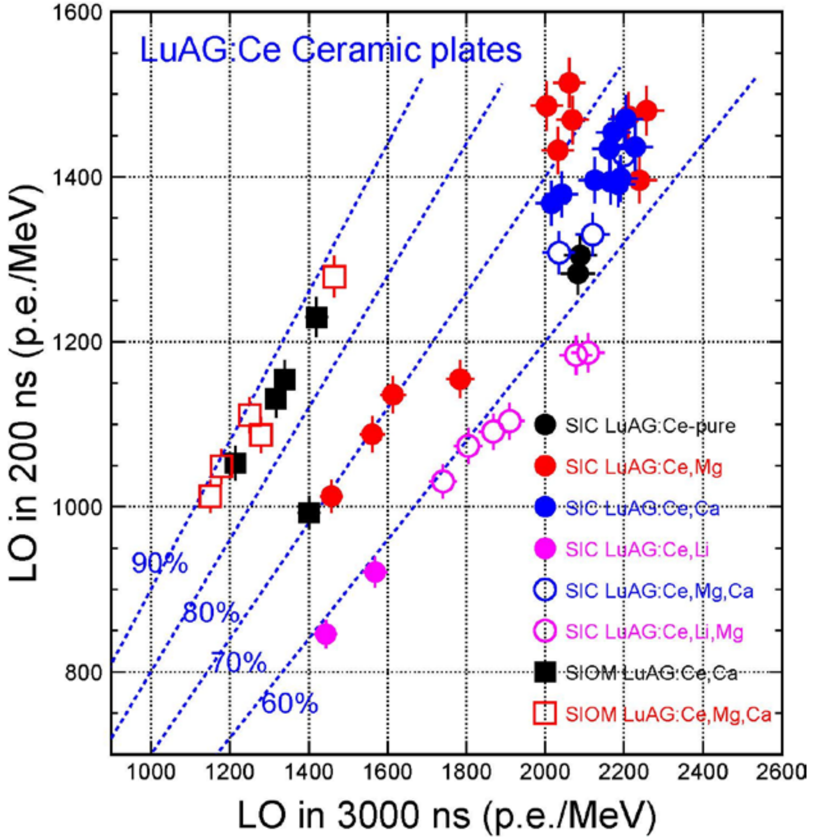
LuAG:Ce Ceramics Radiation Hardness

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

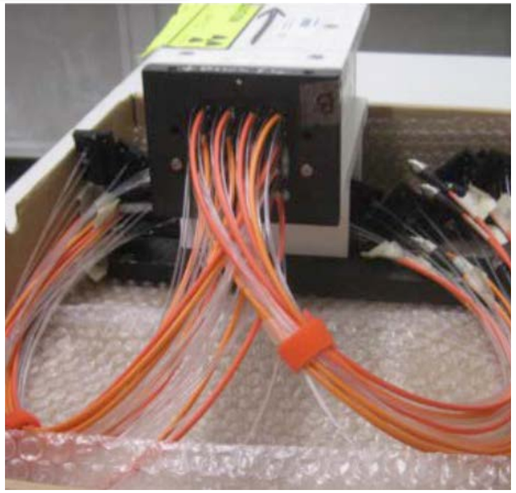


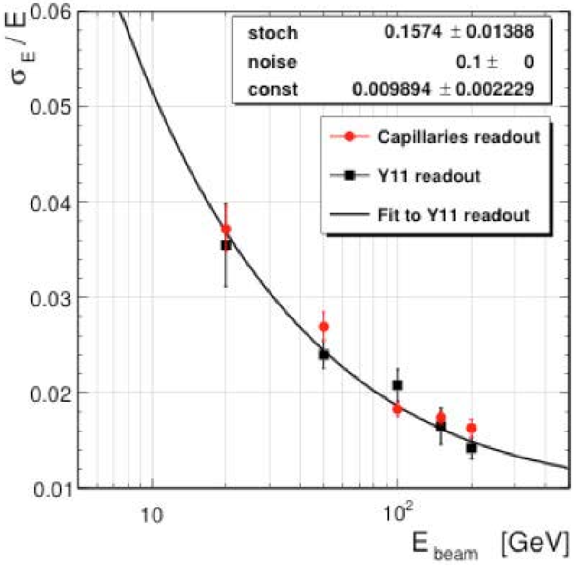




R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

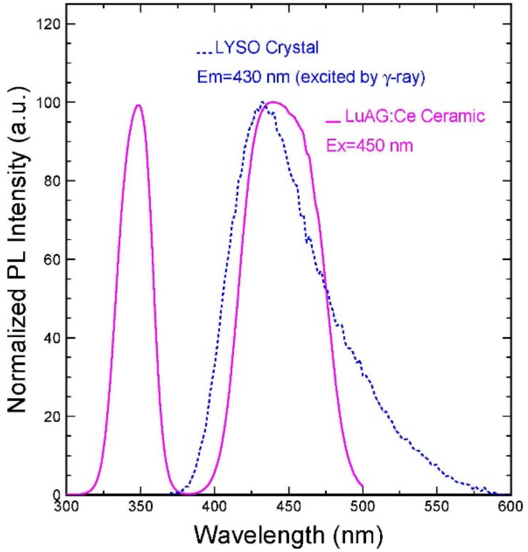
RADiCAL: LYSO/LuAG Shashlik CAL

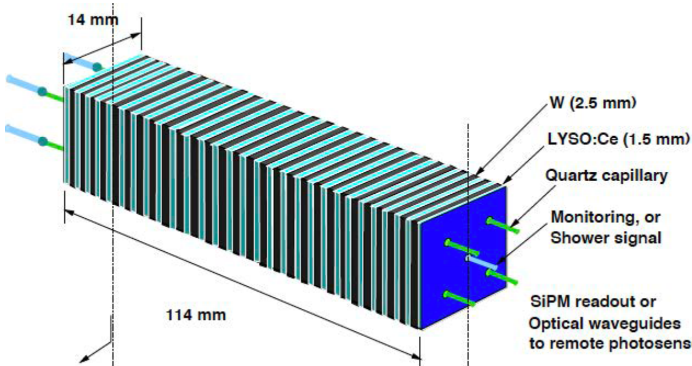


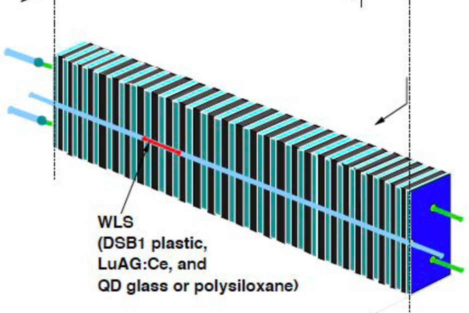


arXiv: 2203.12806

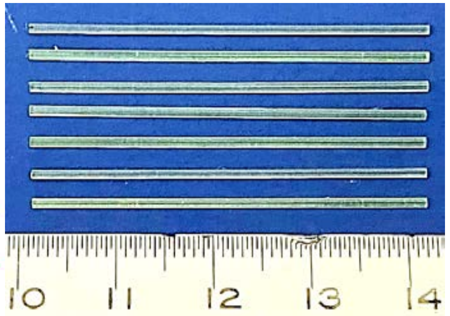
RADiation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission

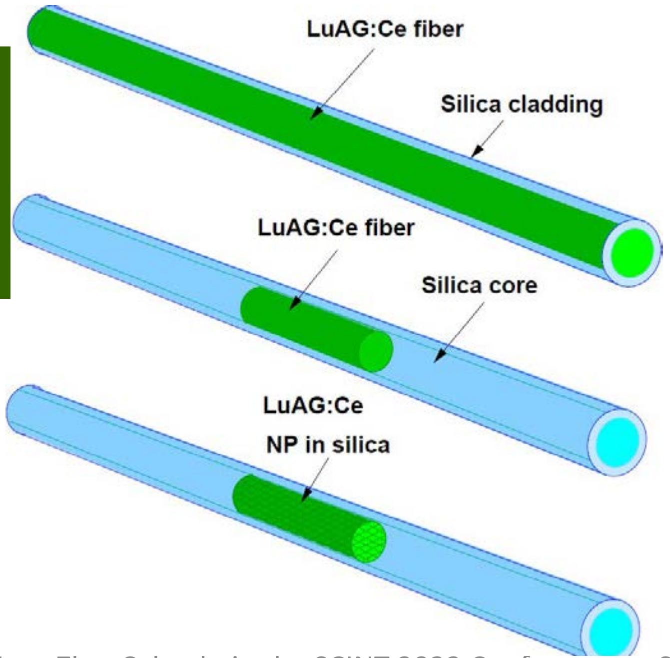


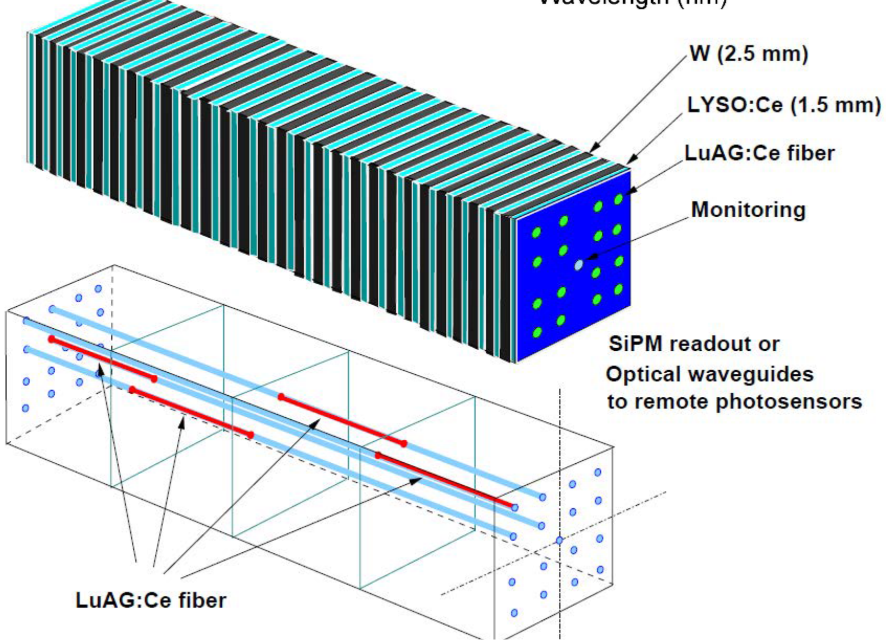




Φ1x40 mm
SIC LuAG:Ce ceramic LHPG fibers

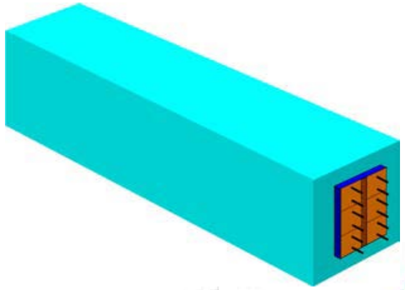




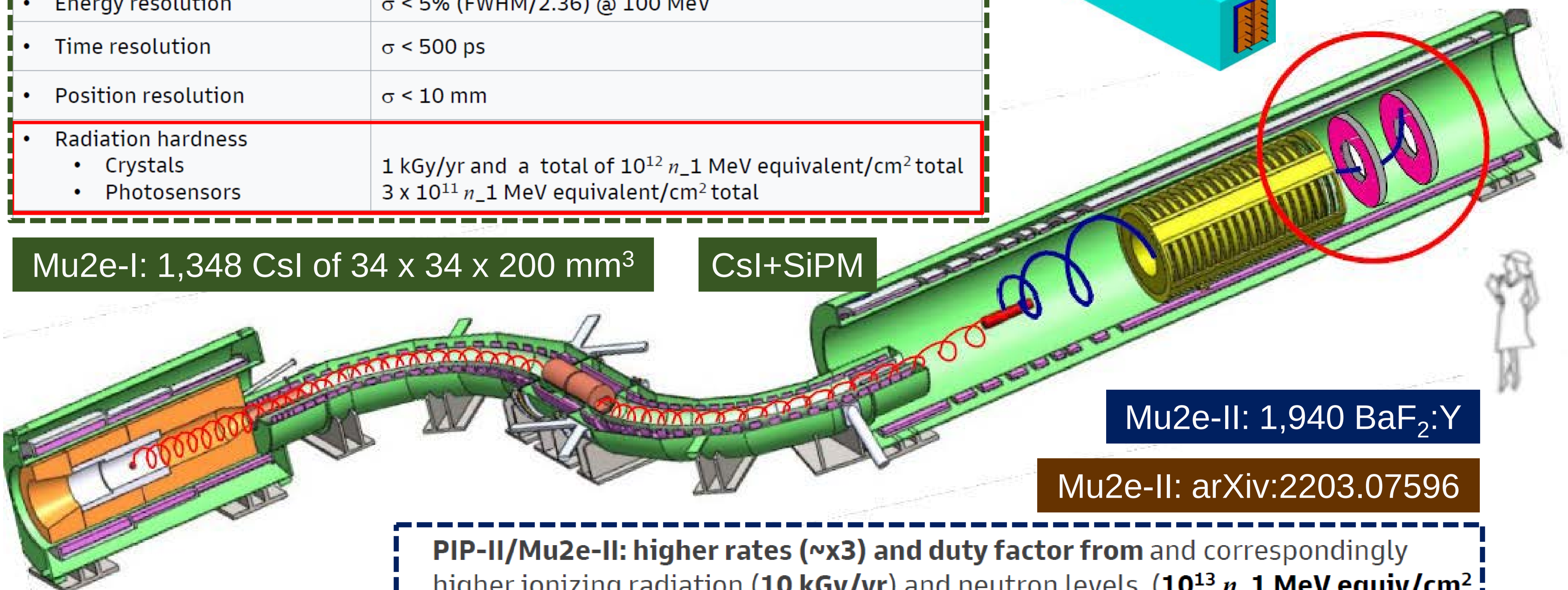


Mu2e-II BaF$_2$:Y Calorimeter

Use ultrafast material to mitigate pile-up



• Energy resolution	$\sigma < 5\%$ (FWHM/2.36) @ 100 MeV
• Time resolution	$\sigma < 500$ ps
• Position resolution	$\sigma < 10$ 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

Fast and Ultrafast Inorganic Scintillators

arXiv: 2203.06788

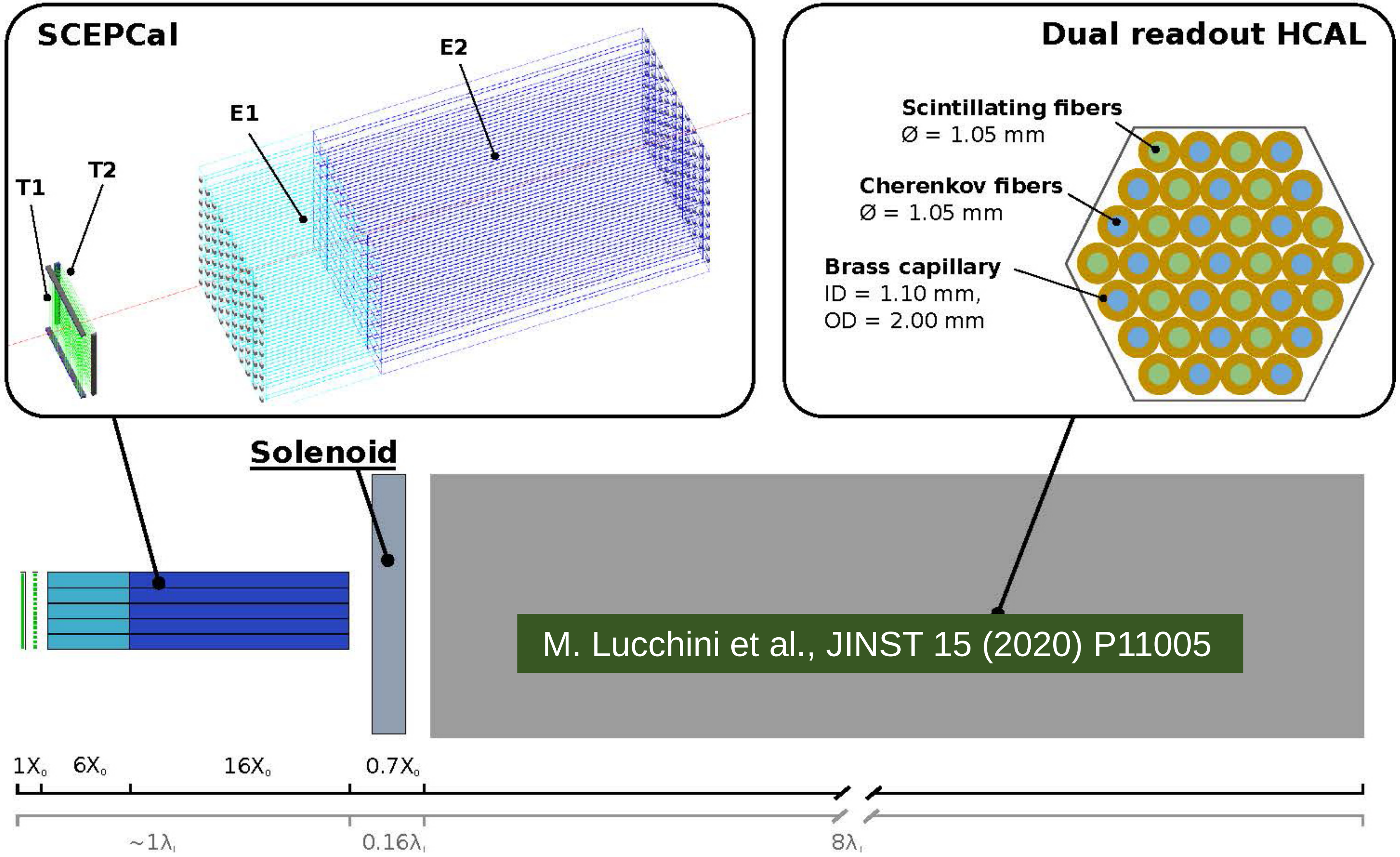
	BaF$_2$	BaF$_2$:Y	ZnO:Ga	Lu$_2$O$_3$:Yb	YAP:Yb	YAG:Yb	β-Ga$_2$O$_3$	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	9.42	5.35	4.56	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (^{o}C)	1280	1280	1975	2490	1870	1940	1725	2050	2060	1870	1850	1930	2070
X$_0$ (cm)	2.03	2.03	2.51	0.81	2.59	3.53	2.51	1.14	1.45	2.59	1.63	1.37	3.10
R$_M$ (cm)	3.1	3.1	2.28	1.72	2.45	2.76	2.20	2.07	2.15	2.45	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	18.1	23.1	25.2	20.9	20.9	20.6	23.1	21.5	19.5	27.8
Z$_{eff}$	51.0	51.0	27.7	67.3	32.8	29.3	27.8	63.7	58.7	32.8	50.6	57.1	32.8
dE/dX (MeV/cm)	6.52	6.52	8.34	11.6	7.91	7.01	8.82	9.55	9.22	7.91	8.96	9.82	6.57
λ_{peak}[a] (nm)	300 220	300 220	380	370	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	2.0	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]	0.95	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]	280	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	1.1[d]	1.5	4	148 6	40	820 50	191 25	53	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610[d]	170	28[d]	24[d]	43	740	240	391	640	125	318
LY in 1st ns /Total LY (%)	9.2	60	31	61	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	0.127	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] 0.3 Mg at% co-doping; [f] Lu$_{0.7}$Y$_{0.3}$AlO$_3$:Ce.

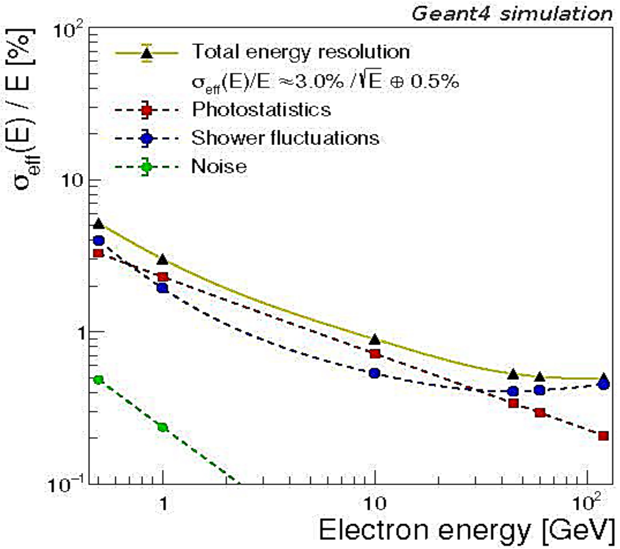
CalVision: A Longitudinally Segmented Crystal ECAL

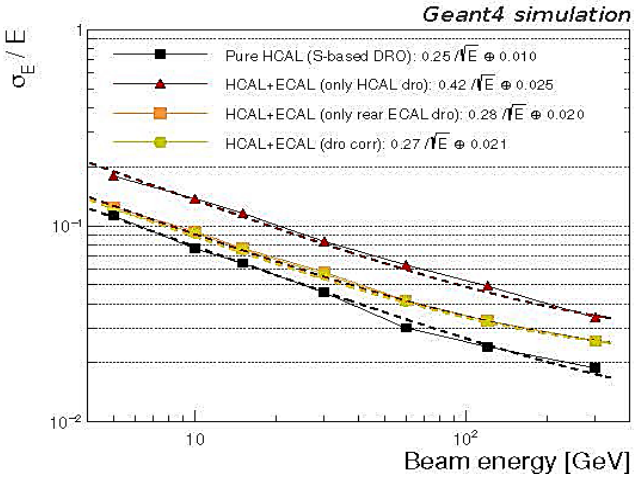
arXiv: 2203.04312, M. Lucchini in this conference

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

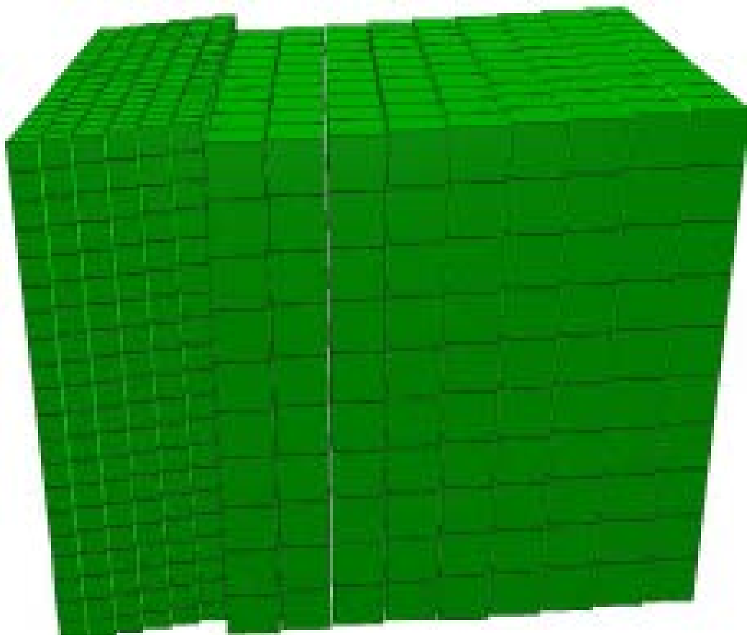


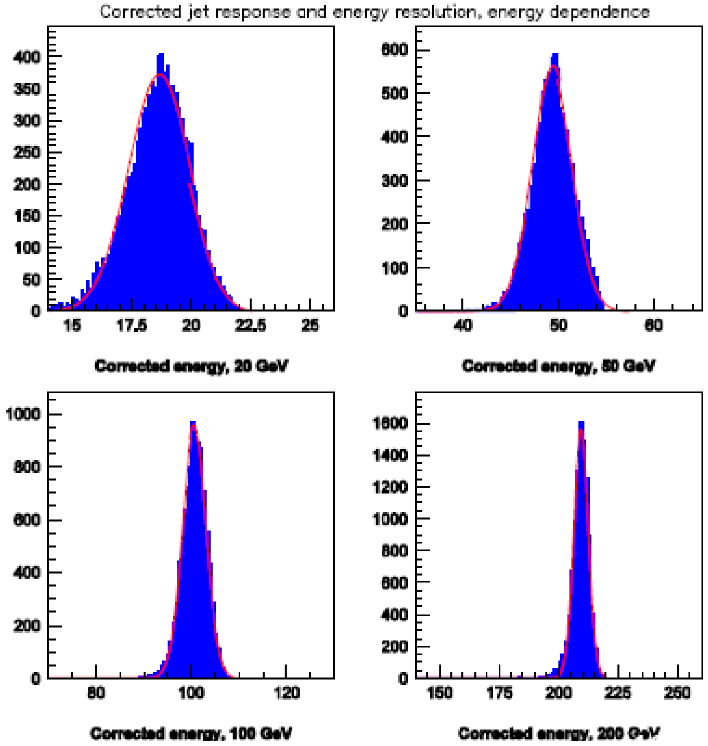
M. Lucchini et al., JINST 15 (2020) P11005



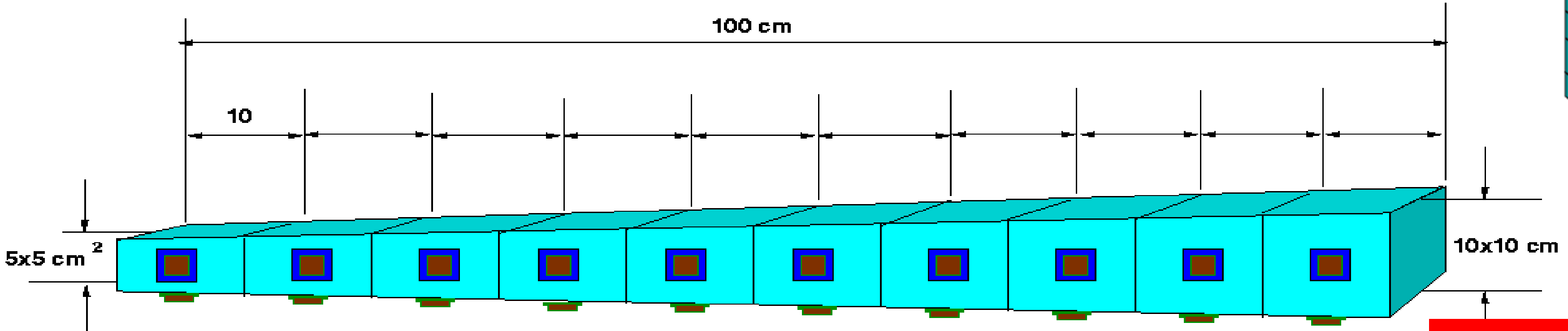


The HHCAL Concept



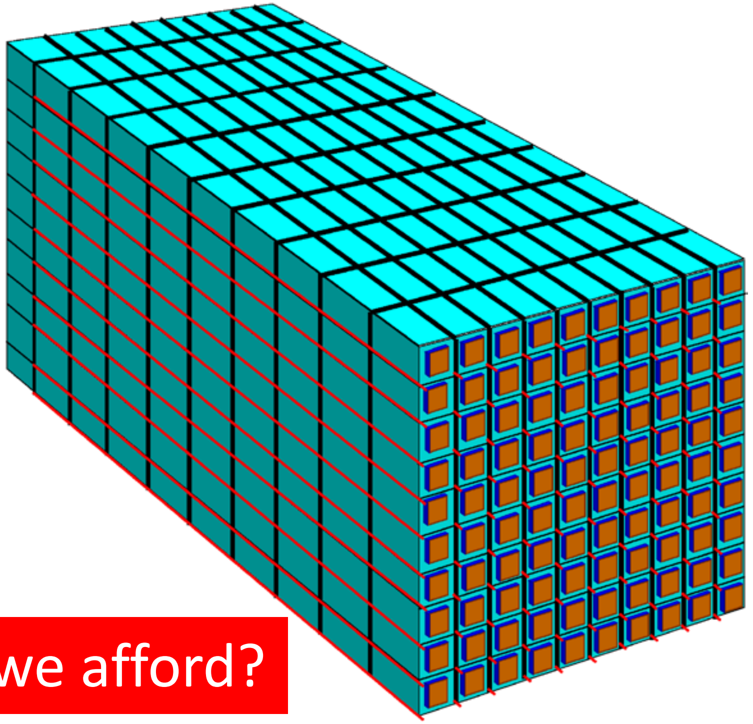


A. Para, H. Wenzel and S. McGill in Callor2012 Proceedings and A. Benaglia *et al*., IEEE TNS **63** (2016) 574-579: a jet energy resolution at a level of 20%/√E by HHCAL with dual readout of S/C or dual gate.
M. Demarteau, 2021 CPAD Workshop



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

Can we afford?



Inorganic Scintillators for HHCAL

Snowmass 2022 White Paper: https://doi.org/10.48550/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 needed for optimizing yttrium doping and radiation hardness in 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.

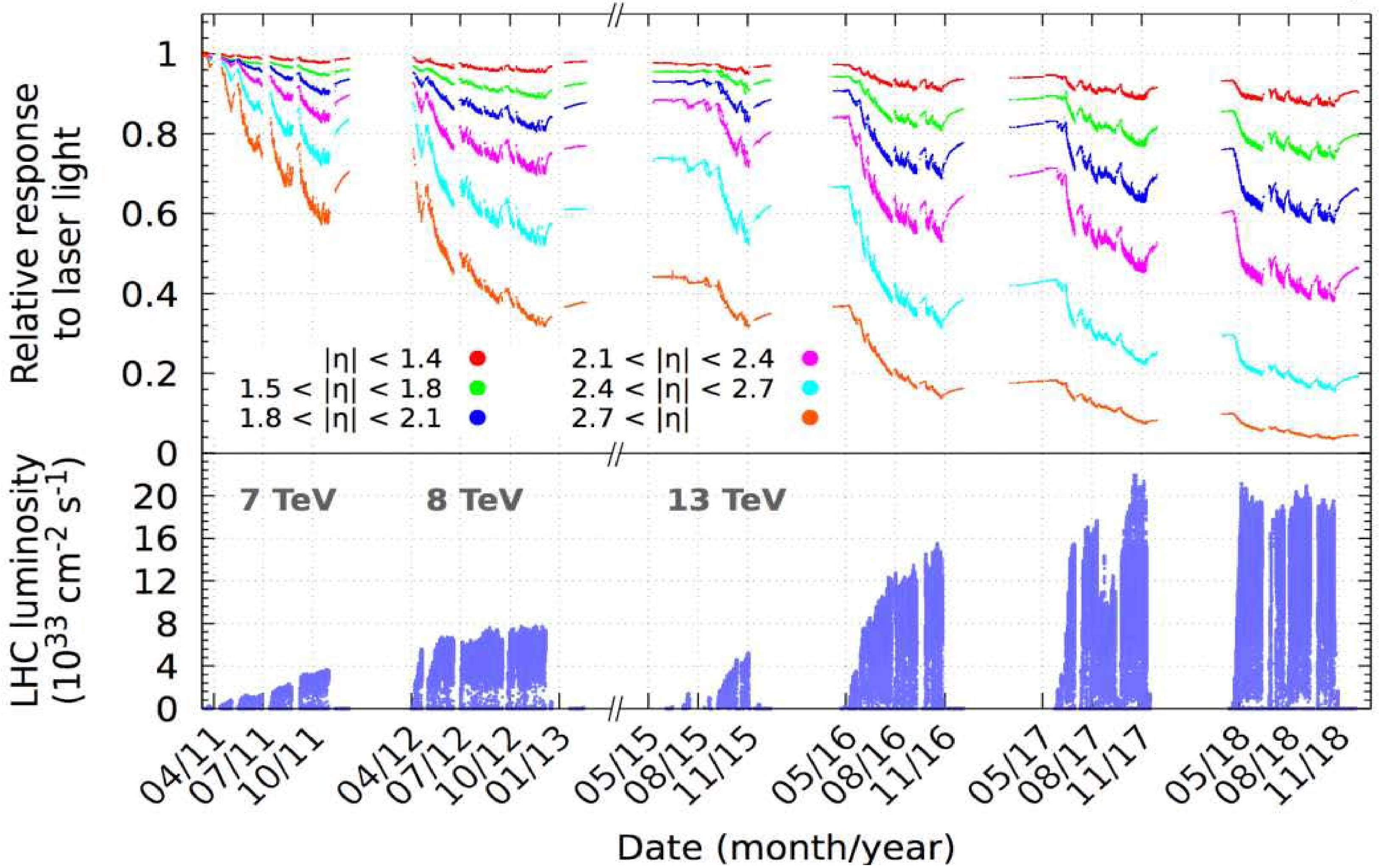
Homogeneous HCAL (**HHCAL**) promises the best jet mass resolution by total absorption. Crucial R&D is needed for cost-effective mass-produced inorganic scintillators

The SCINT community can make critical contributions

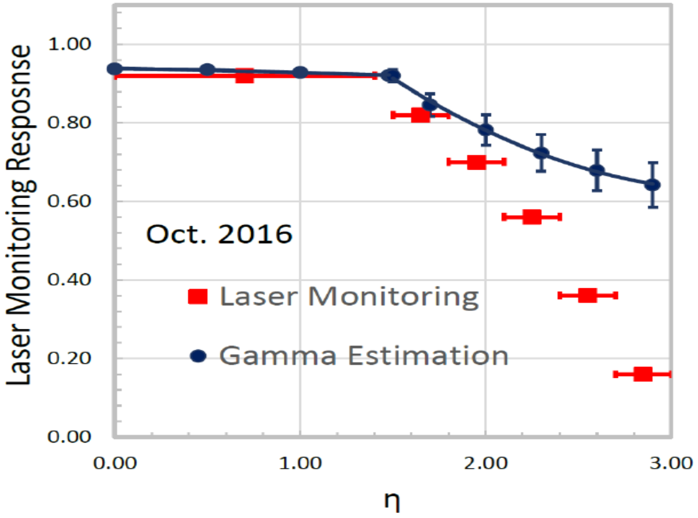
Acknowledgements: DOE HEP Award DE-SC0011925

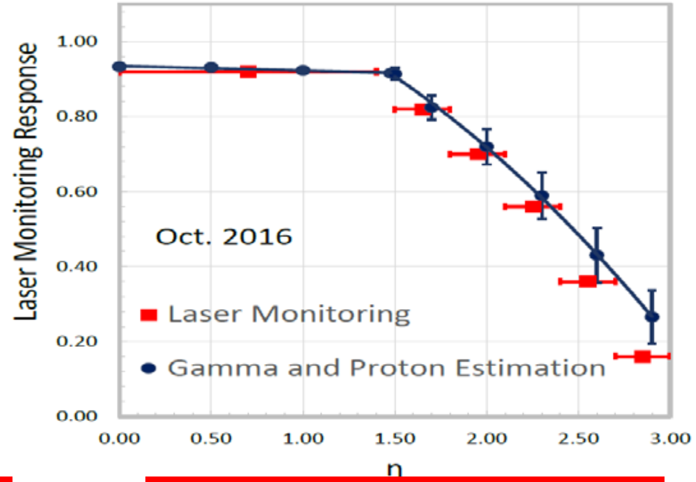
Challenge: Radiation Damage at LHC

F. Ferri, Calor 2022, https://indico.cern.ch/event/847884/timetable/#20220515



http://www.hep.caltech.edu/~zhu/talks/ryz_161028_PWO_mon.pdf



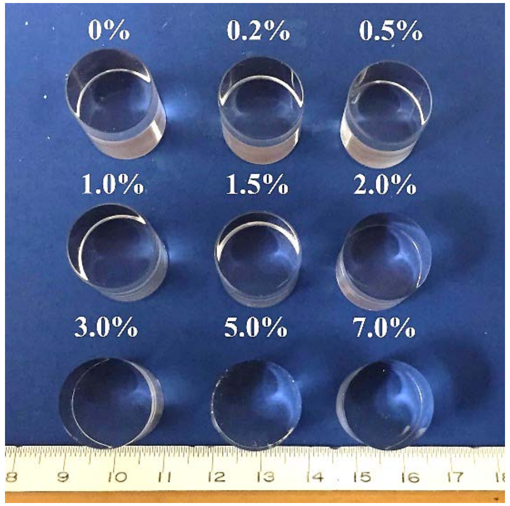


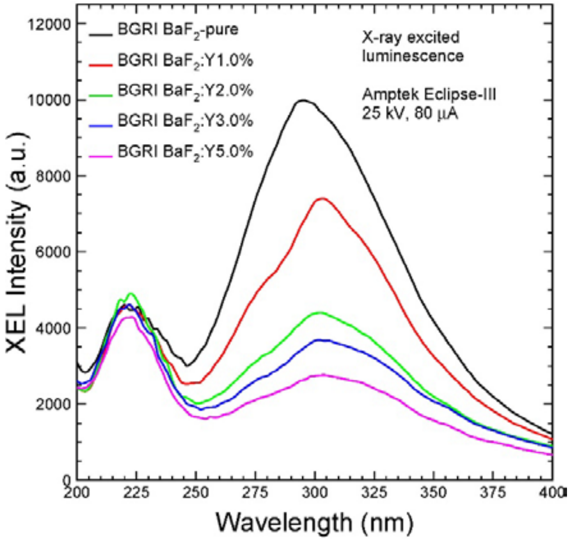
Use materials with monotonic damage: BaF_2, CsI, LYSO:Ce, LuAG:Ce

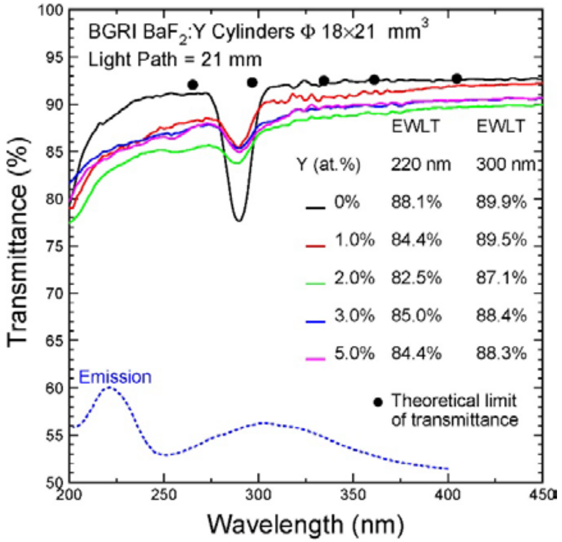
Neutron damage?

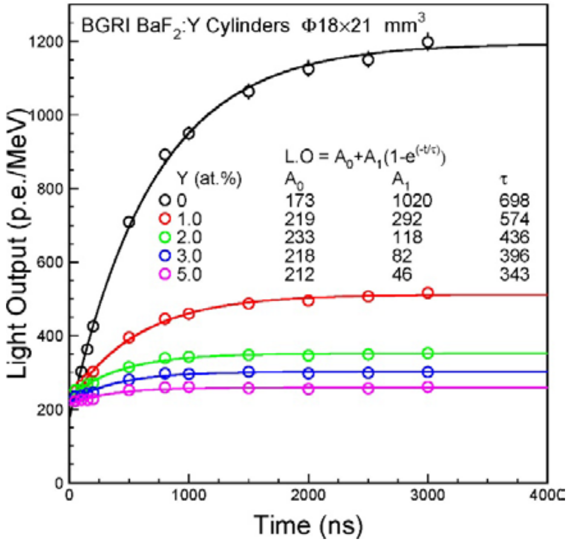
BaF$_2$:Y for **Ultrafast** Calorimetry

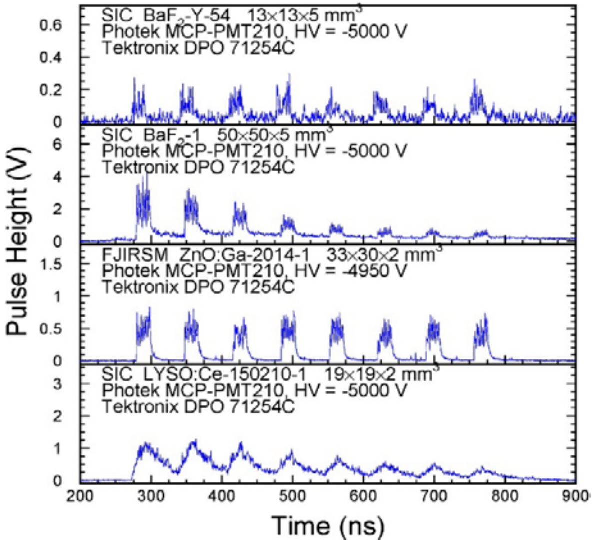
Increased F/S ratio observed in BGRI BaF$_2$:Y crystals: Proc. SPIE 10392 (2017)

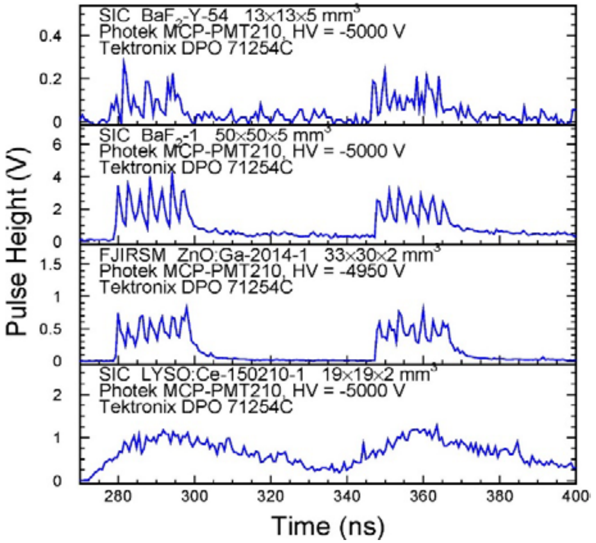


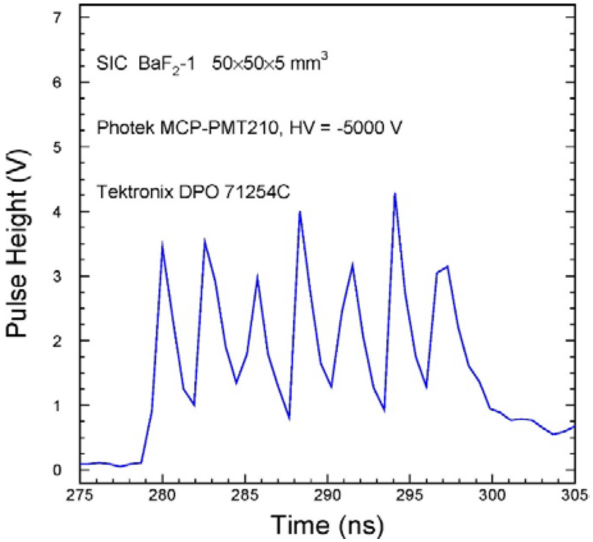








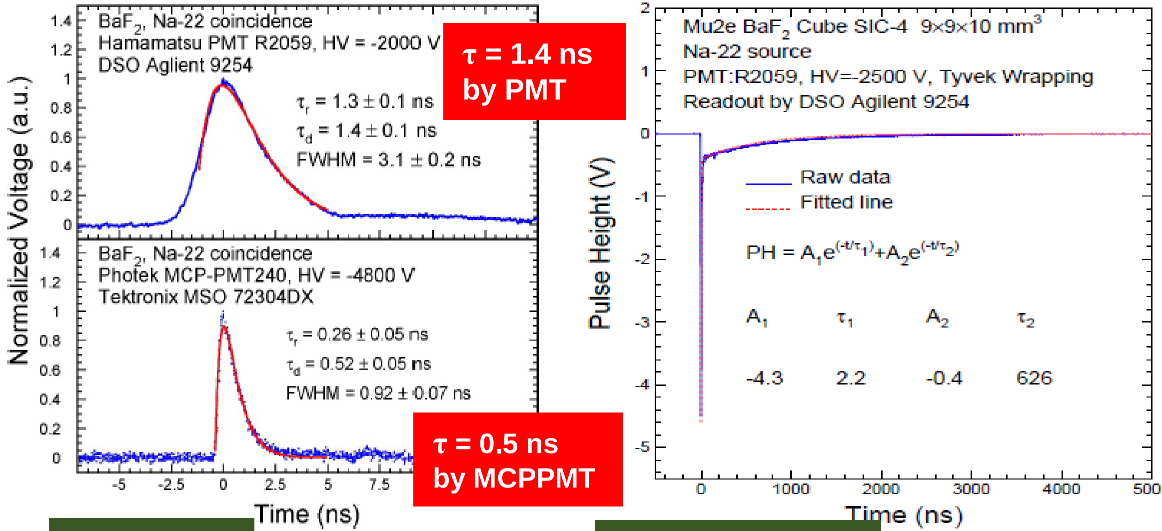




X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF$_2$:Y and BaF$_2$ crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

Ultrafast and Radiation Hard BaF$_2$

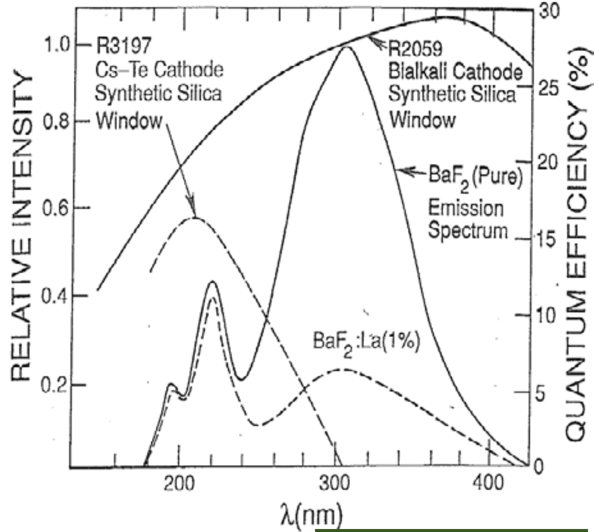
IEEE TNS NS 67, NO. 6 (2020) 1014-1019



τ = 1.4 ns by PMT

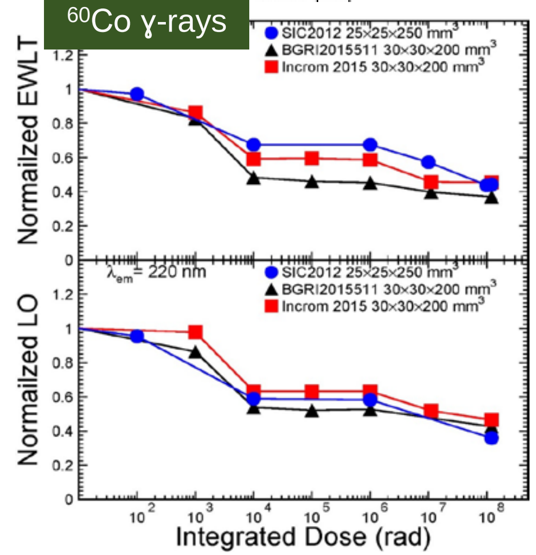
τ = 0.5 ns by MCPPMT

NIMA 340 (1994) 442-457

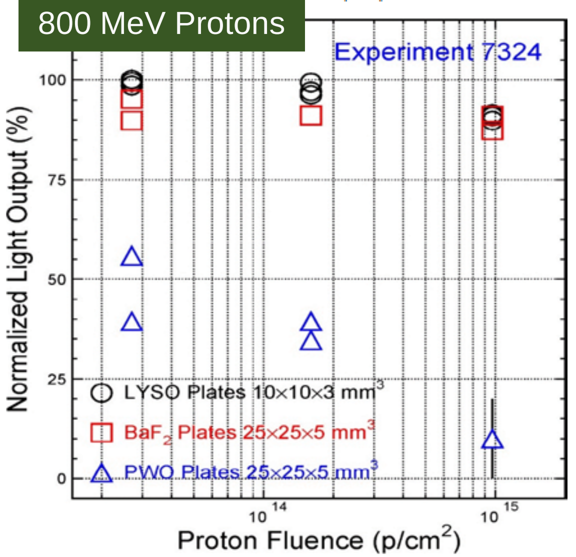


BaF$_2$ has an ultrafast scintillation component @ 220 nm with **0.5 ns** decay time and a much larger slow component @ 300 nm with 600 ns decay time.

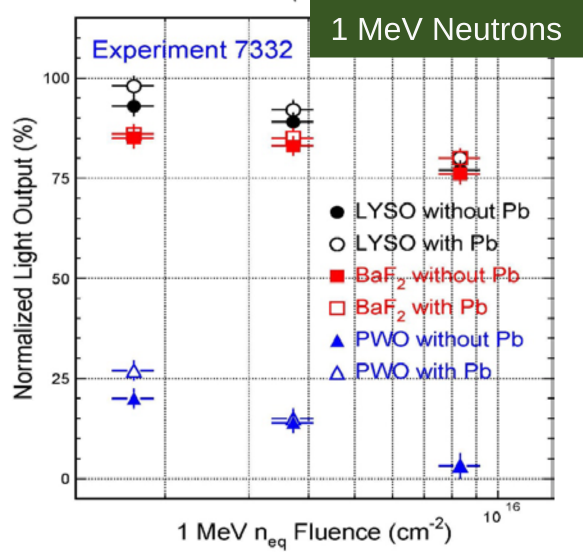
Slow suppression may be achieved by rare earth doping, and/or solar-blind photo-detectors



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



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



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

Mass-Produced Crystal Cost (Mar 2019)

http://www.hep.caltech.edu/~zhu/talks/ryz_210316_EIC_Crystal_CAL.pdf

Item	Size (R_MxR_Mx25 X_0)	1 m^3	10 m^3	100 m^3	Scaled to X_0
BGO	22.3×22.3×280 mm	$8/cc	$7/cc	$6/cc	1.23
BaF_2:Y	31.0×31.0×507.5 cm	$12/cc	$11/cc	$10/cc	2.28
LYSO:Ce	20.7x20.7x285 mm	$36/cc	$34/cc	$32/cc	1.28
PWO	20x20x223 mm	$9/cc	$8/cc	$7.5/cc	1.00
BSO	22x22x274 mm	$8.5/cc	$7.5/cc	$7.0/cc	1.29
CsI	35.7x35.7x465 mm	$4.6/cc	$4.3/cc	$4.0/cc	2.09

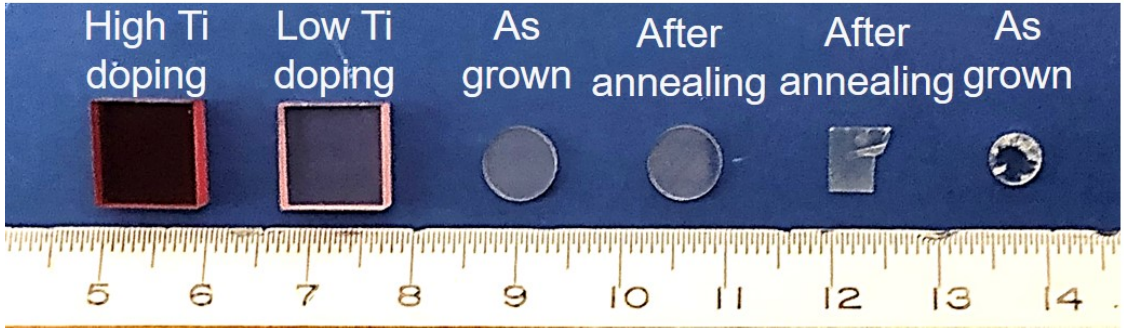
Cost-Effective Sapphire Crystals for HHCAL

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

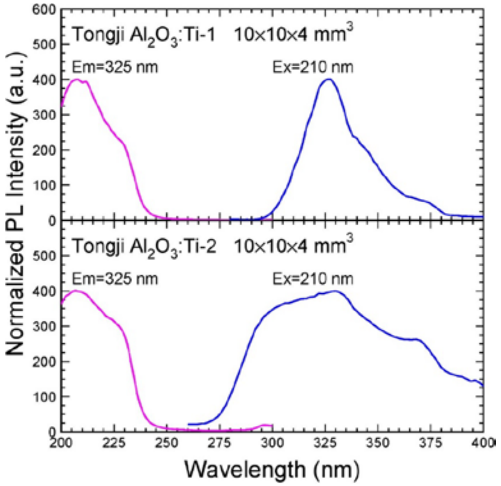
Sapphire:Ti Emission and Transmittance



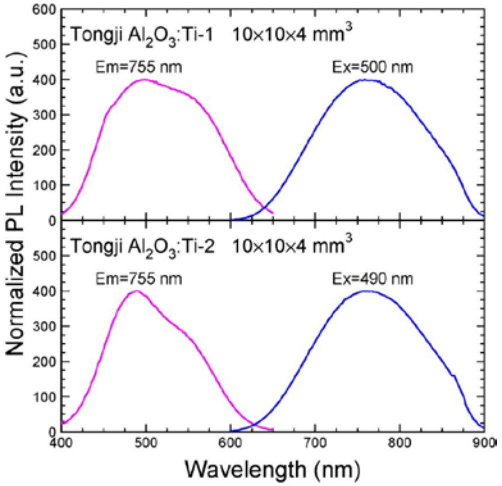
ID	Dimension (mm^3)	#	Polishing
Tongji Al_2O_3:Ti-1,2	**10×10×4**	**2**	**Two faces**
Tongji Al_2O_3:C-1,2	Φ7×1	2	Two faces
Tongji Lu_2O_3:Yb	6.4×4.8×0.4	1	Two faces
Tongji $LuScO_3$:Yb	Φ4.8×1.3	1	Two faces

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

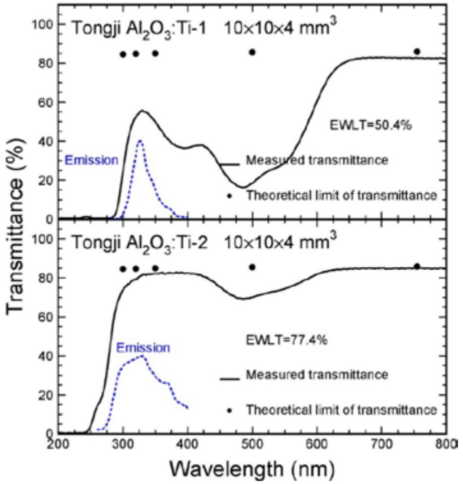
Fast @325 nm



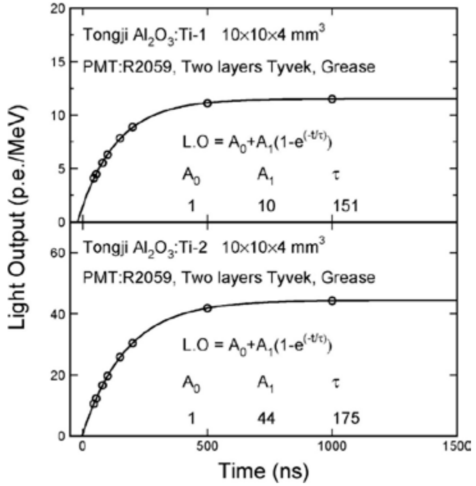
Slow @755 nm



EWLT for Fast & Slow



Fast = 162 ns



Slow = 3.2 μs