Application of LYSO Crystals in HEP Experiments

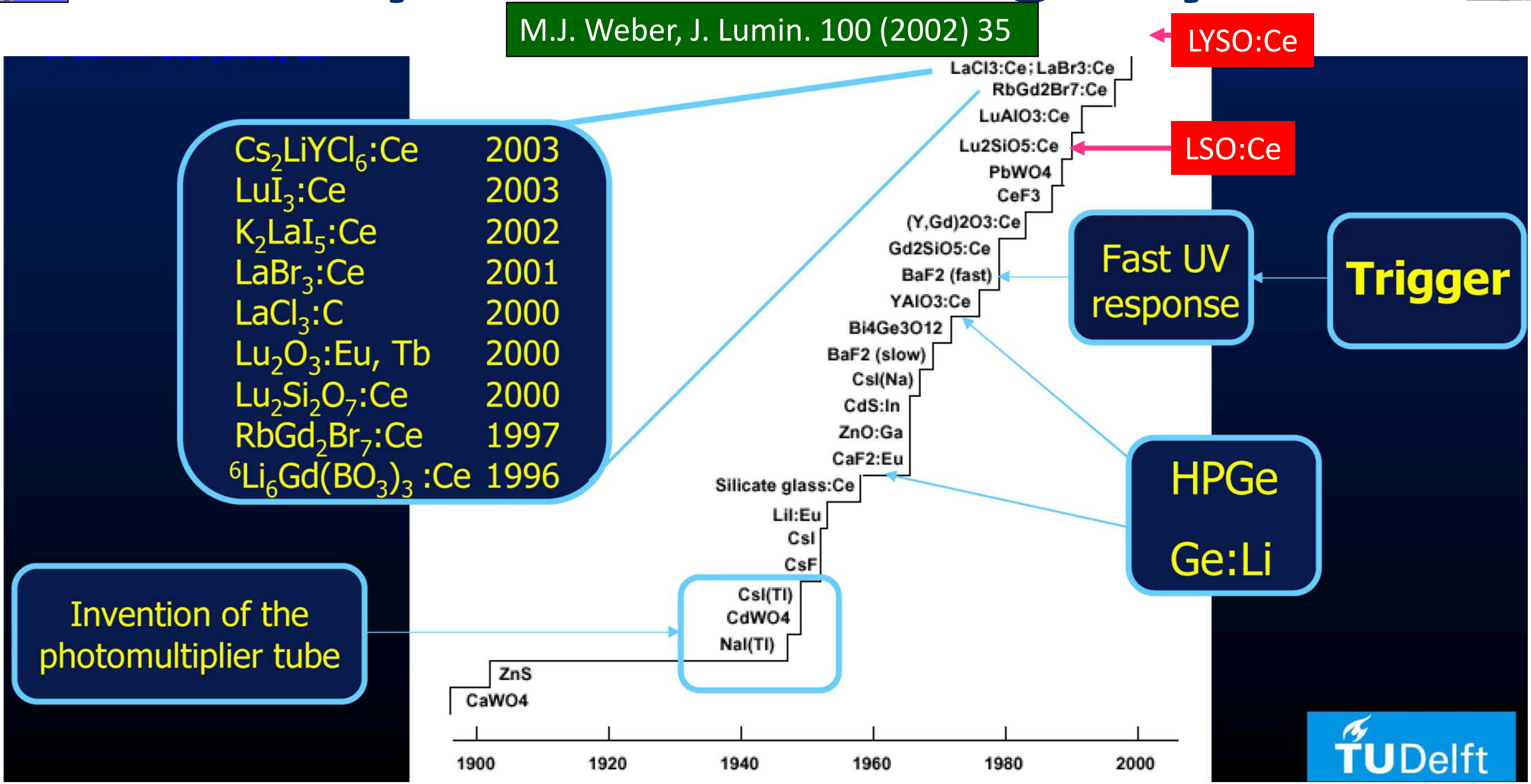
Ren-Yuan Zhu

California Institute of Technology

October 12, 2021

Presentation in the PIENUX Group Meeting, University of Washington

History of Scintillating Crystals



History of LYSO:Ce Crystals

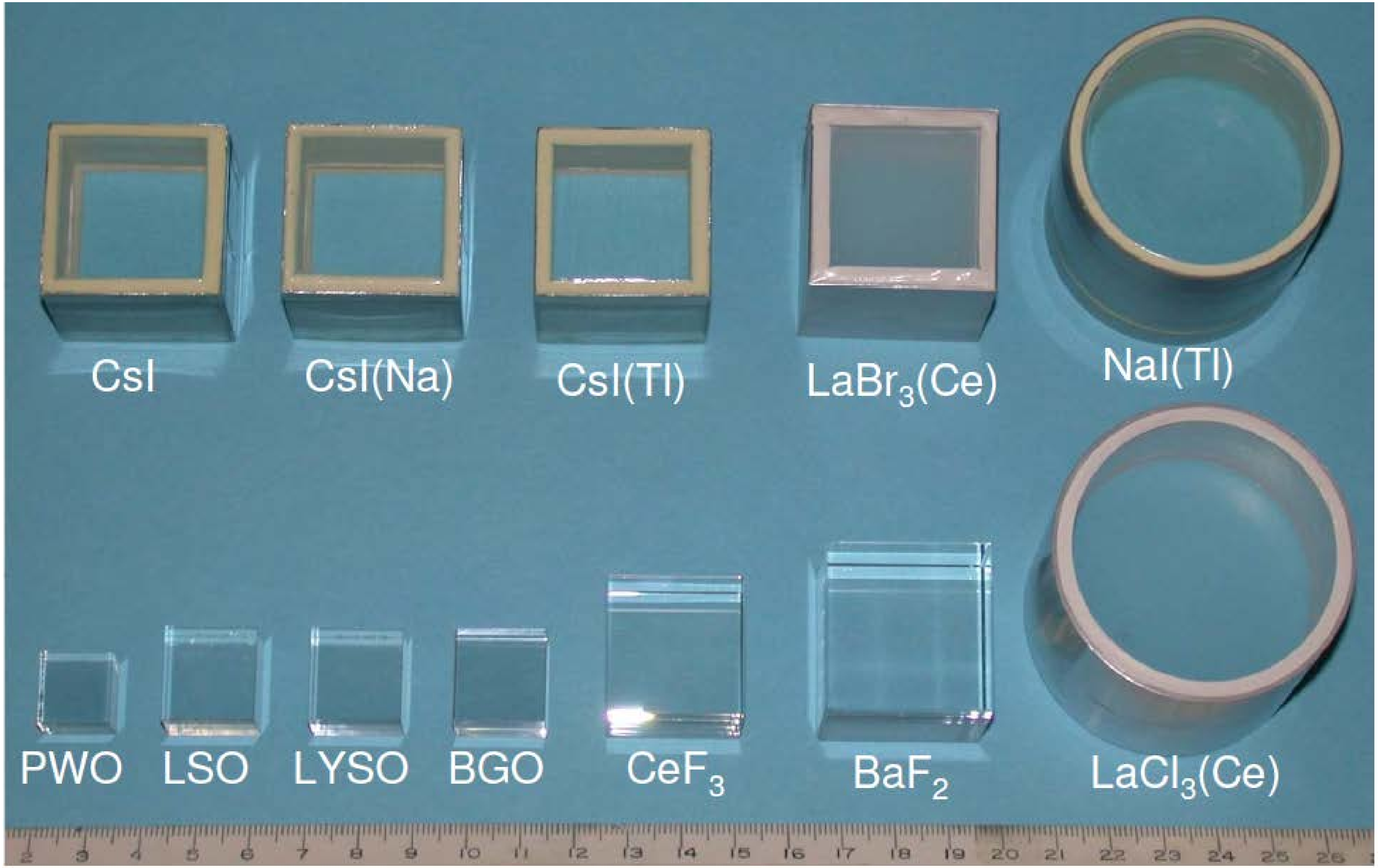
- LSO:Ce was discovered by Dr. Charles Melcher in Schlumberger-Doll Research and was patented by Schlumberger-Doll Research in 1990. Chuck later joined CTI and is now a Research Professor & Director-Scintillation Materials Research Center at the University of Tennessee. The LSO:Ce patent was expired in 2008.
- LYSO:Ce was discovered by Dr. Bruce Chai [1] in University of Central Florida who holds the LYSO:Ce patent since 2003. Bruce started Crystal Photonics Inc. which is now the main producer of LYSO:Ce crystals for the PET industry. The LYSO:Ce patent was expired in 2020.
- There are additional patents for Ca^{2+} co-doping to make LSO:Ce/LYSO:Ce faster, and thermal annealing in oxygen atmosphere etc., which are expected to be expired soon.

[1] http://www.hep.caltech.edu/~zhu/papers/02_nim_pwo_y.pdf; and https://science.osti.gov/-/media/hep/pdf/files/Banner-PDFs/TTT-connections-May14.pdf?la=en&hash=209C9F2B483868A886421452993292D7EA76AE36

Crystals with Mass Production Capability

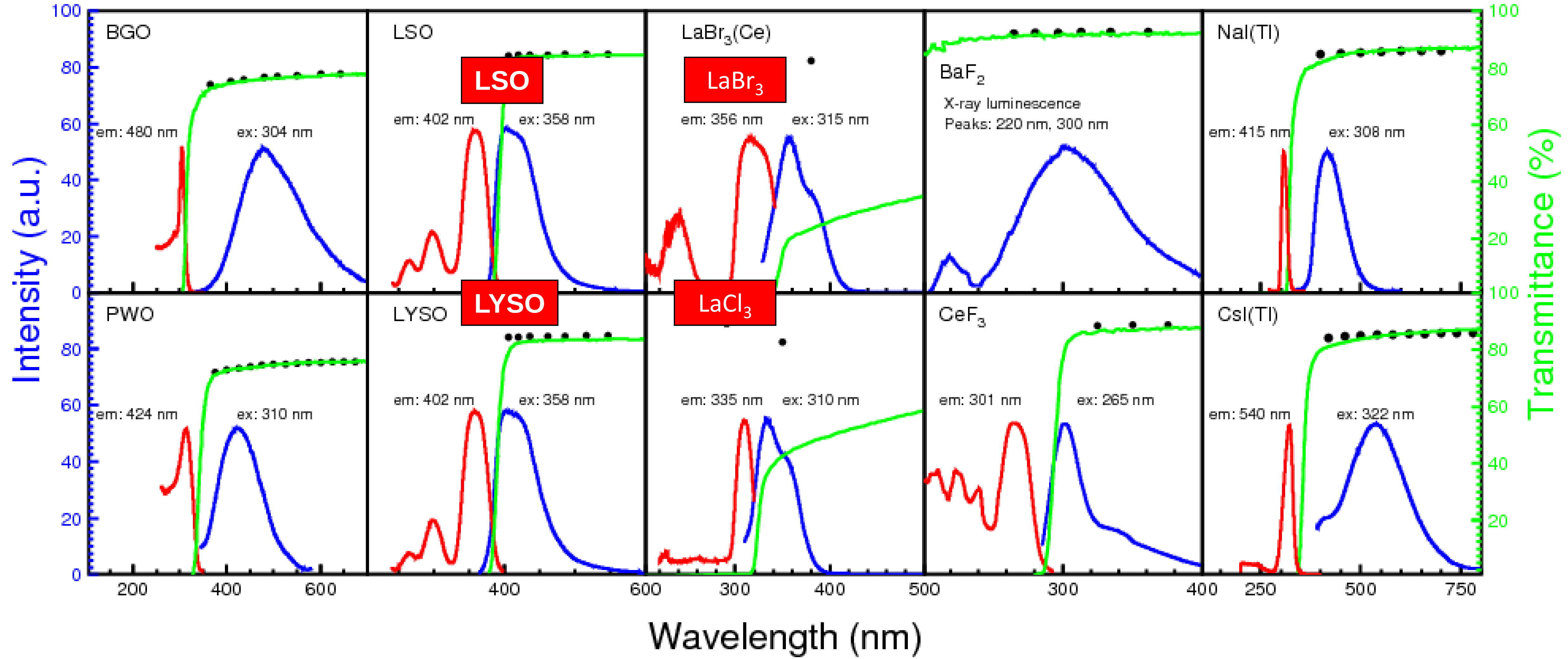
Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	CeF_3	PbF_2	BGO	BSO	$PbWO_4$	LYSO:Ce	AFO Glasses	Sapphire:Ti
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.77	7.13	6.8	8.3	7.40	4.6	3.98
Melting points (^oC)	651	621	621	1280	1460	824	1050	1030	1123	2050	\	2040
X_0 (cm)	2.59	1.86	1.86	2.03	1.65	0.94	1.12	1.15	0.89	1.14	2.96	7.02
R_M (cm)	4.13	3.57	3.57	3.10	2.39	2.18	2.23	2.33	2.00	2.07	2.89	2.88
λ_I (cm)	42.9	39.3	39.3	30.7	23.2	22.4	22.7	23.4	20.7	20.9	26.4	24.2
Z_{eff}	50.1	54.0	54.0	51.6	51.7	77.4	72.9	75.3	74.5	64.8	42.8	11.2
dE/dX (MeV/cm)	4.79	5.56	5.56	6.52	8.40	9.42	8.99	8.59	10.1	9.55	6.84	6.75
λ_{peak} [a] (nm)	410	560	420 310	300 220	340 300	\	480	470	425 420	420	365	750
Refractive Index[b]	1.85	1.79	1.95	1.50	1.62	1.82	2.15	2.68	2.20	1.82	\	1.76
Normalized Light Yield[a,c]	120	190	4.2 1.3	42 4.8	8.6	\	25	5	0.4 0.1	100	1.5	\
Total Light yield (ph/MeV)	35,000	58,000	1700	13,000	2,600	\	7,400	1,500	130	30,000	450	\
Decay time[a] (ns)	245	1220	30 6	600 0.5	30	\	300	100	30 10	40	40	3200
Hygroscopic	Yes	Slight	Slight	No	No	No	No	No	No	No	No	No
Experiment	Crystal Ball	CLEO BaBar BELLE BES III	KTeV Mu2e S. BELLE	TAPS Mu2e-II	\	A4 g-2	L3 BELLE CalVision	\	CMS ALICE PrimEx Panda	COMET HERD CMS BTL RADiCAL	HHCAL	HHCAL

Twelve Crystal Scintillators of 1.5 X_0



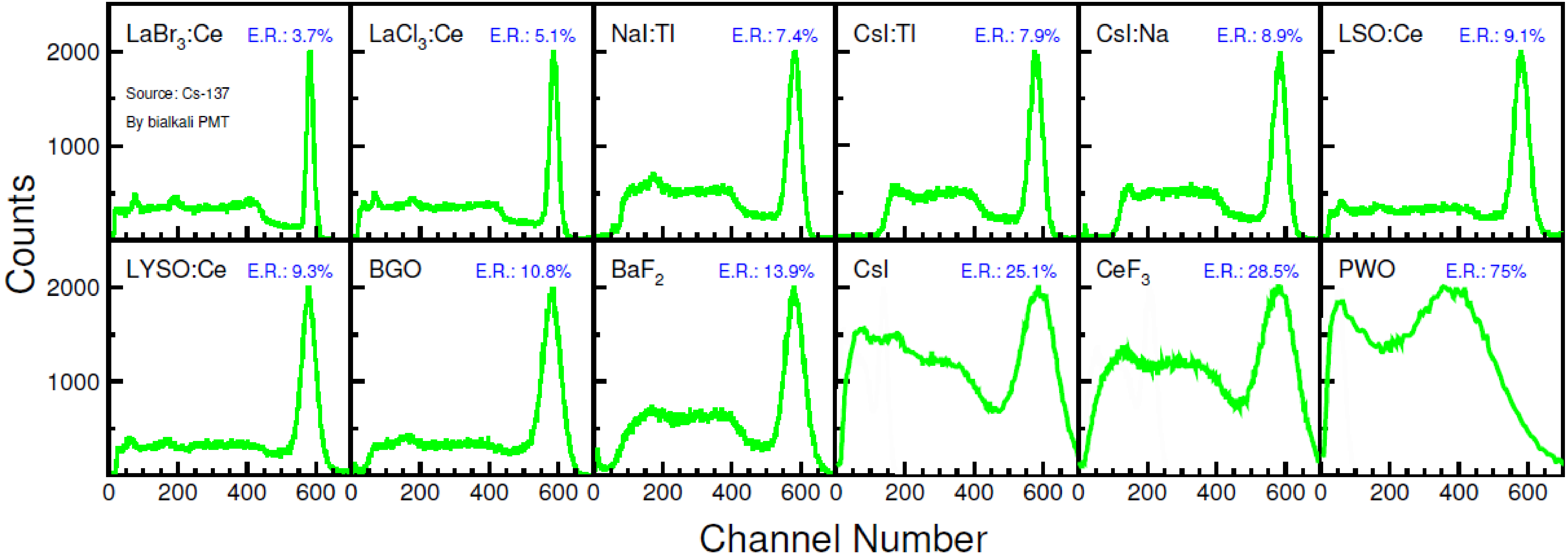
Excitation, Emission, Transmission

Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422



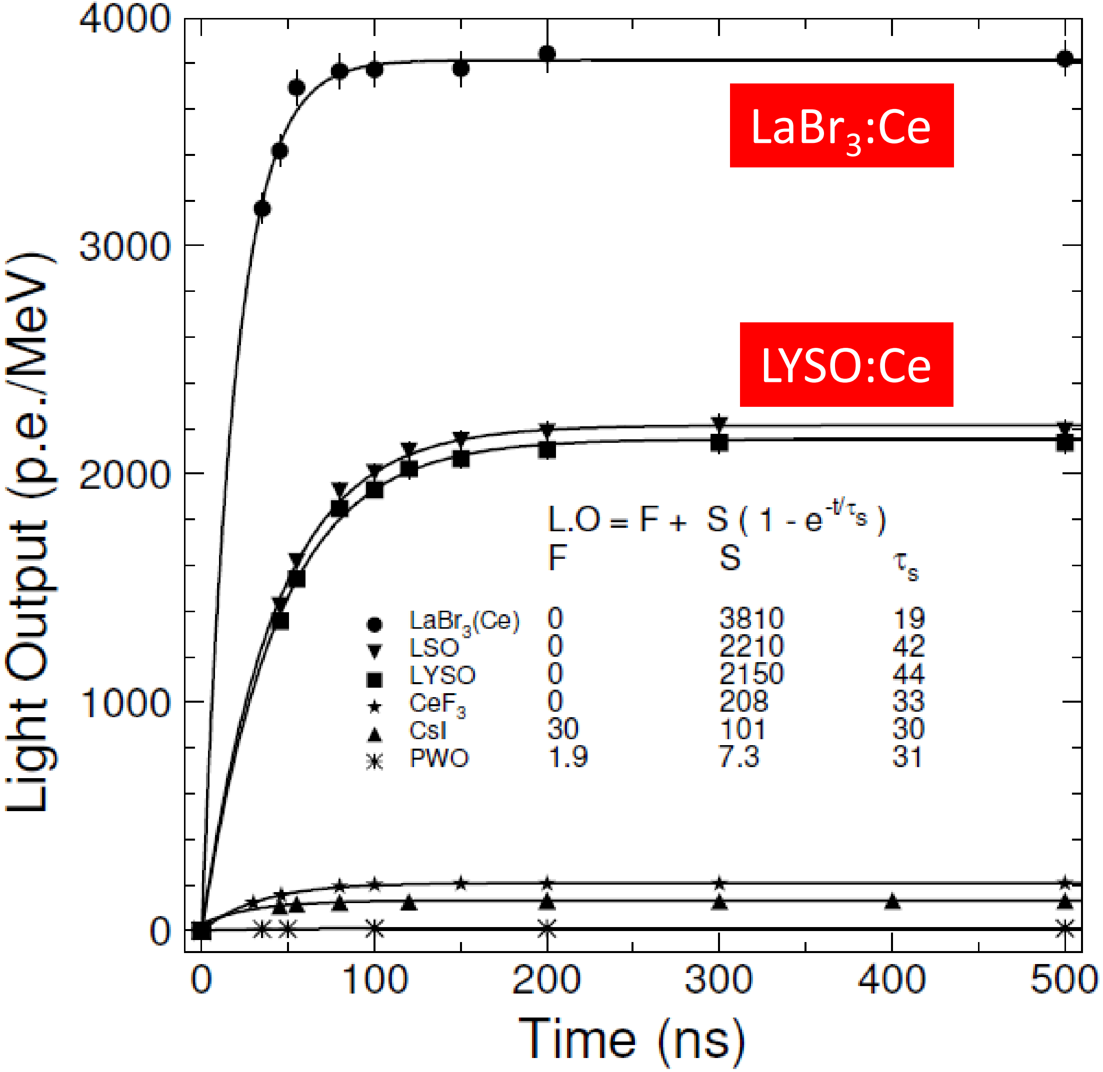
Cs-137 Pulse Hight Spectra

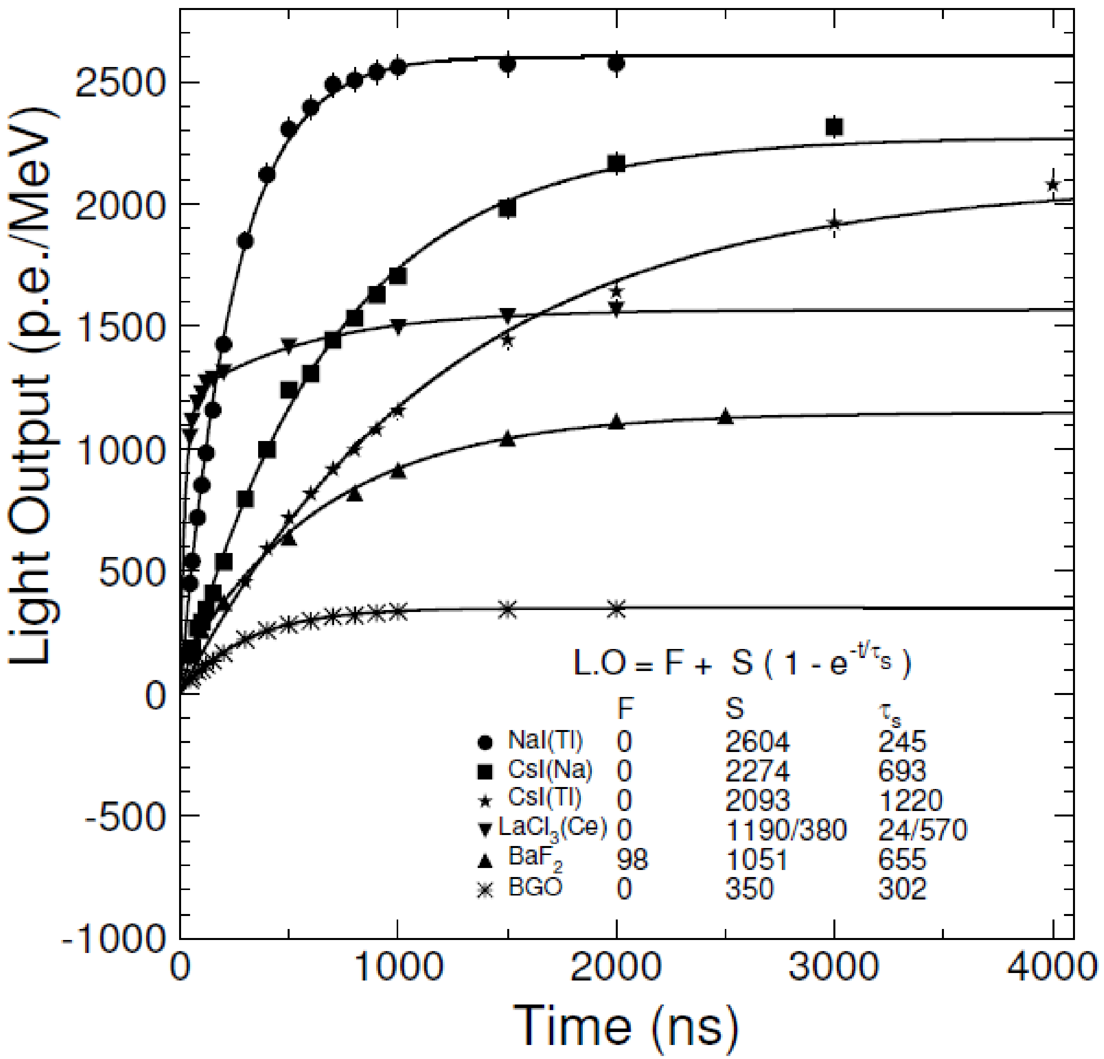
Gool FWHM energy resolution of 9%, corresponding to 3.8% in σ



Light Output and Decay Time

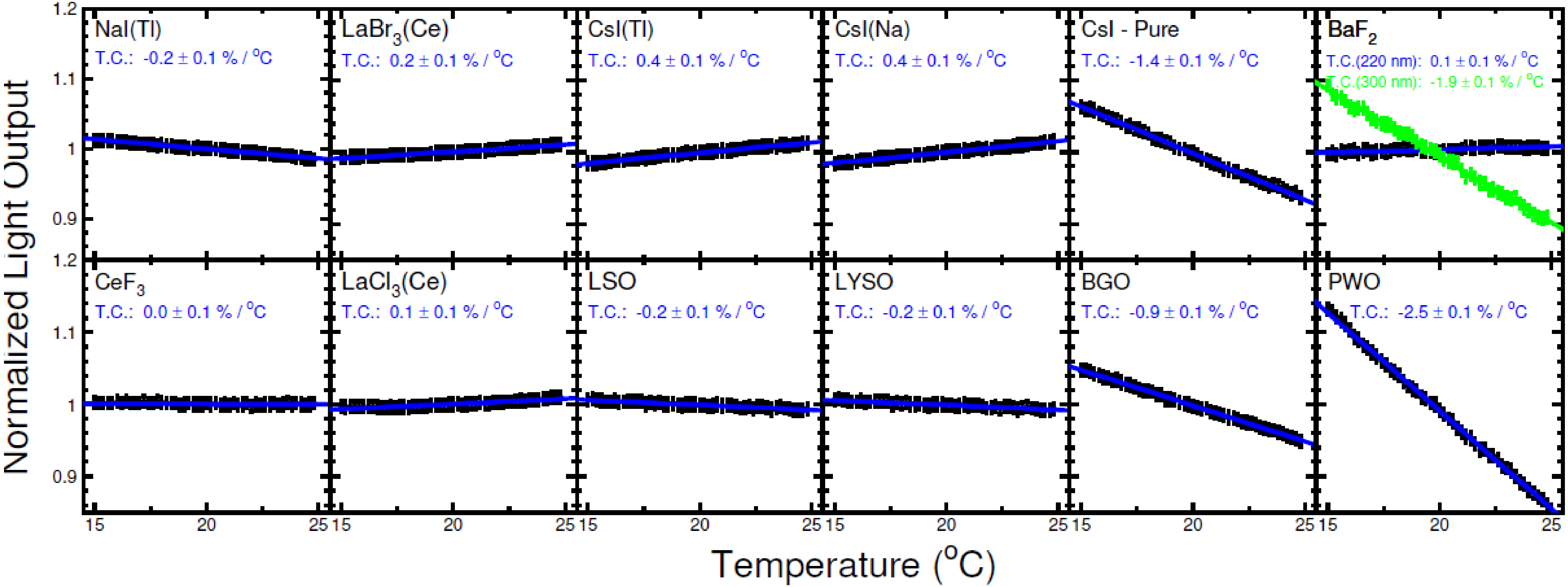
Bright (200 times of PWO) and fast (40 ns decay time)



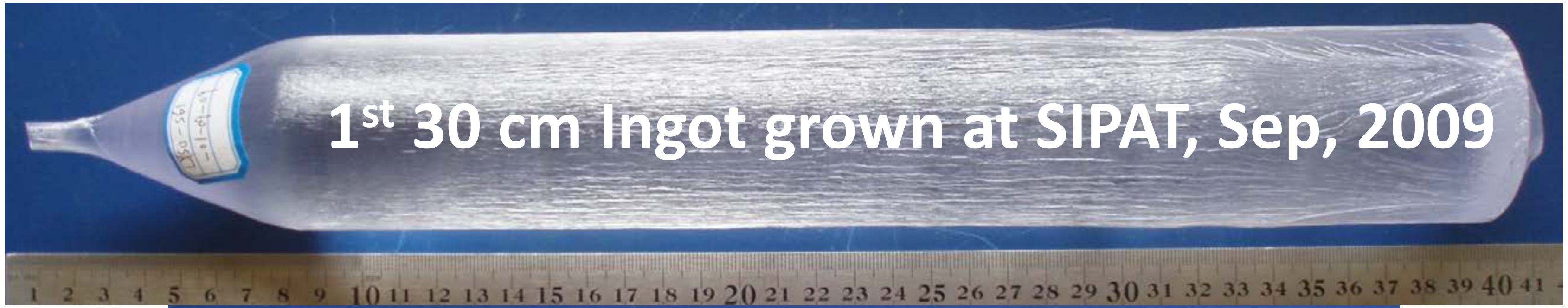


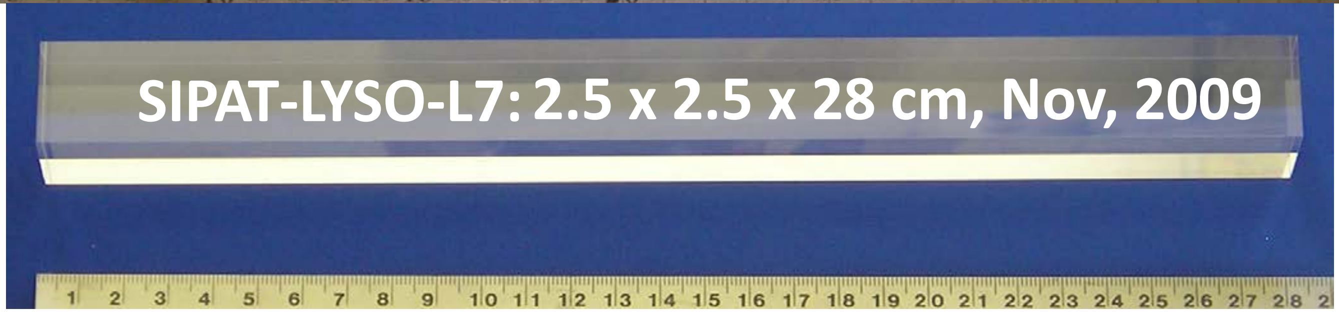
Light Output Temperature Dependence

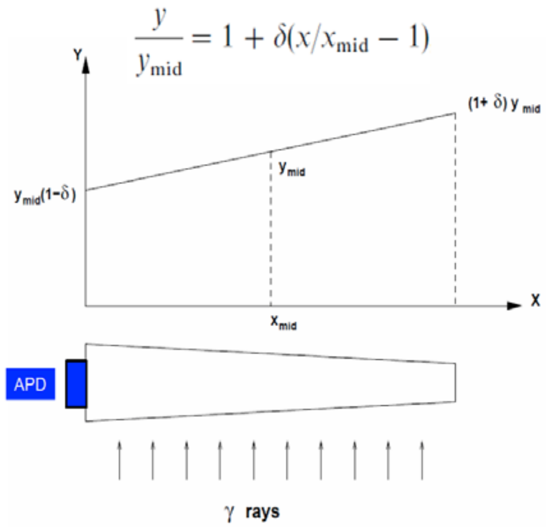
Small temperature variation: -0.2%/^{o}C

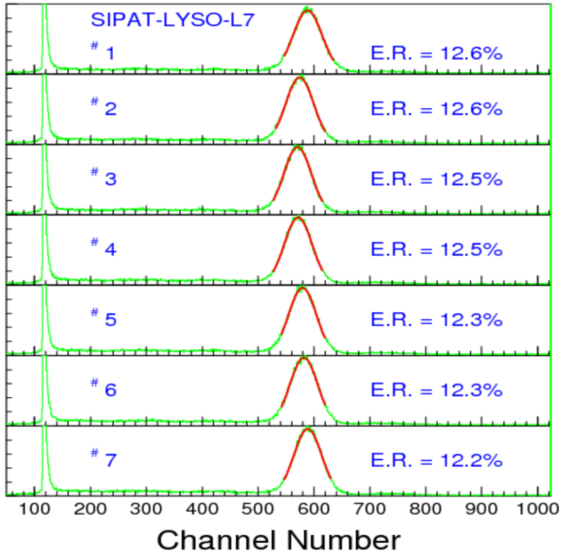


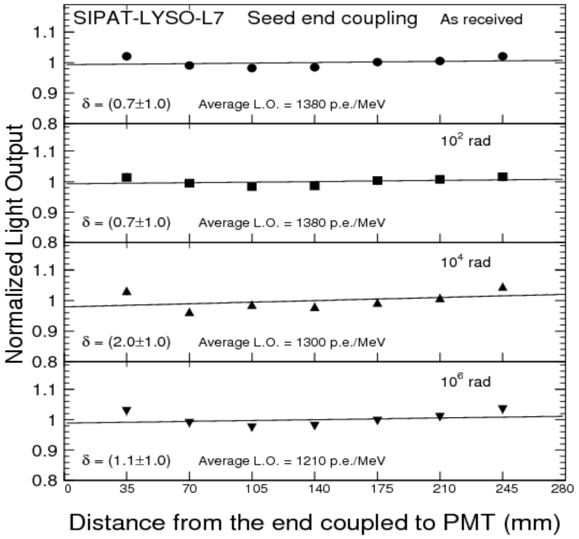
A LYSO Sample of 2.5 x 2.5 x 28 cm^3

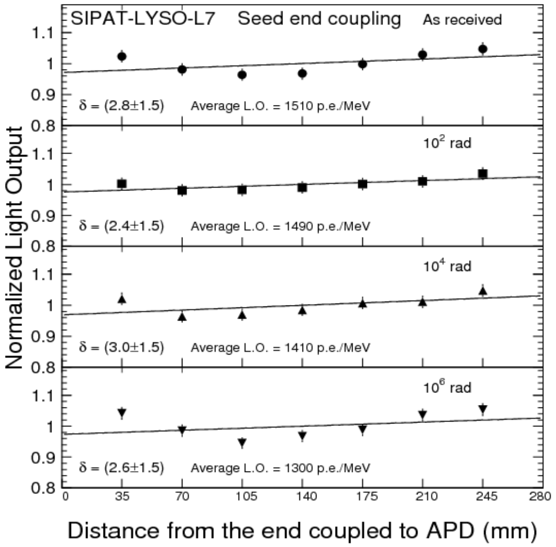






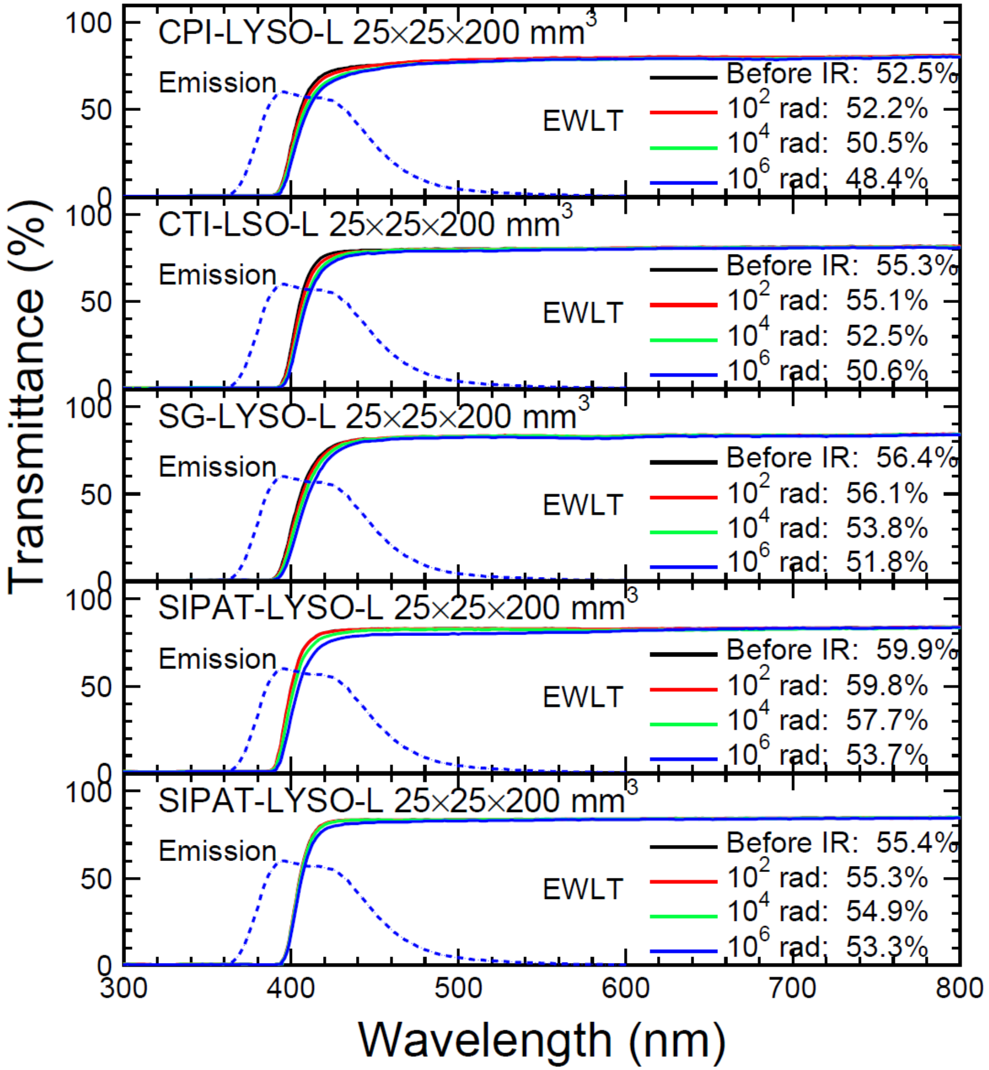


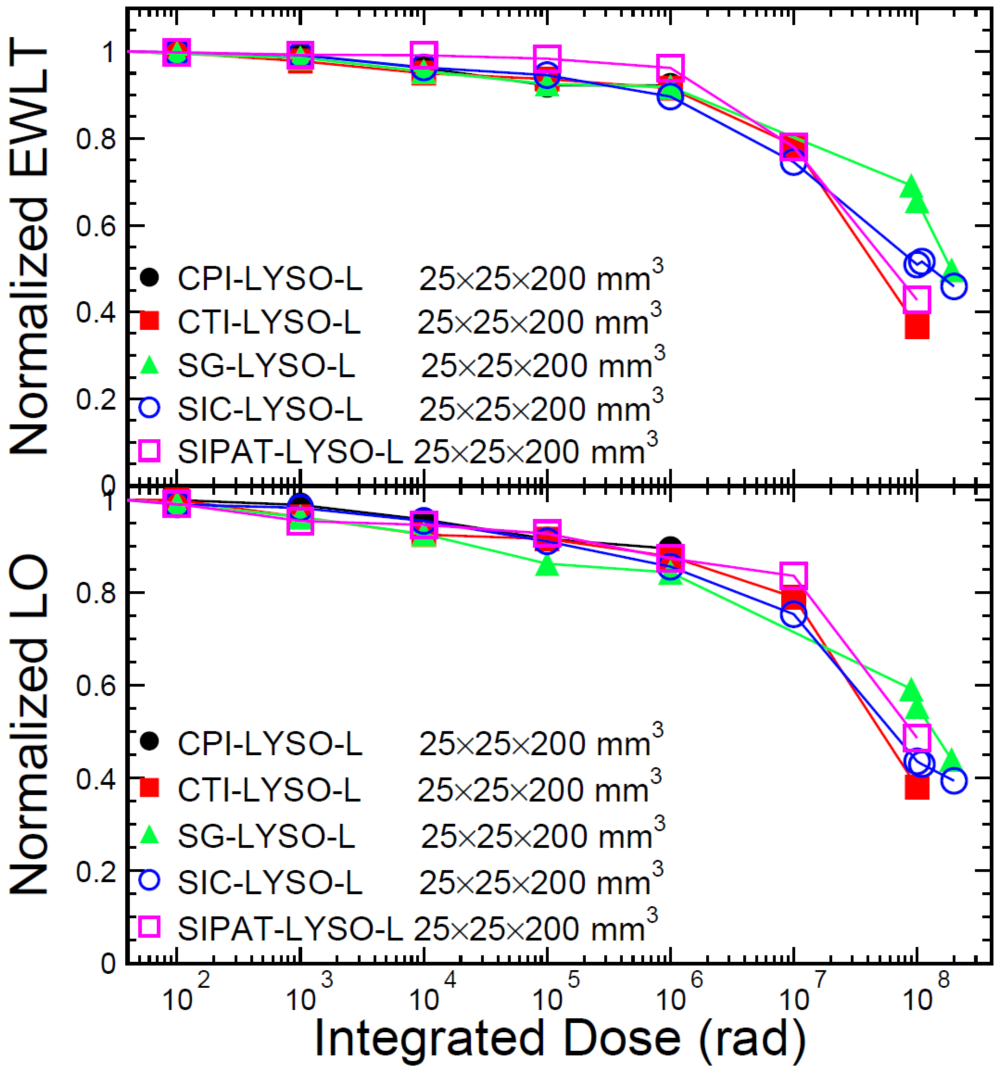




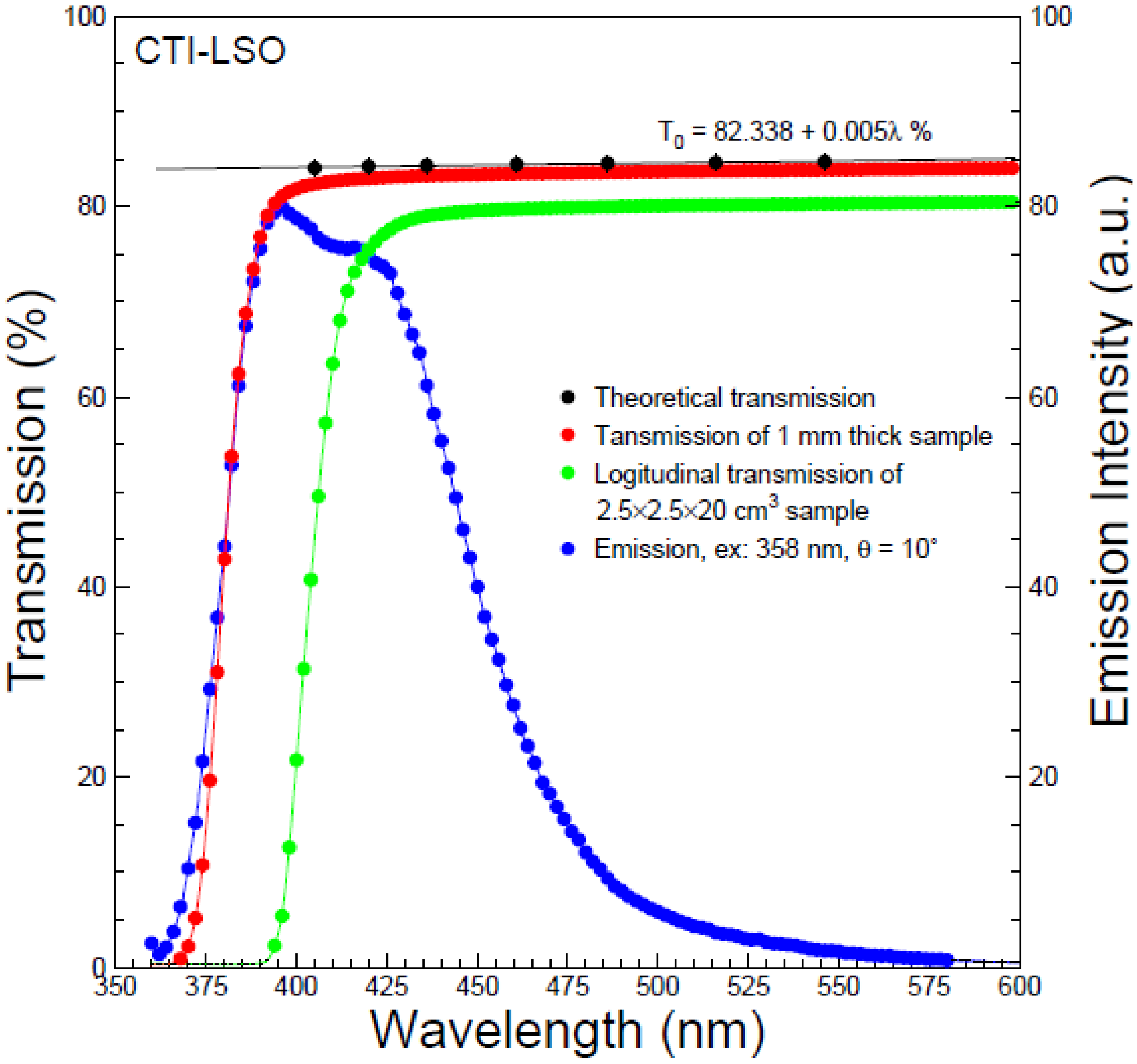
Radiation Hard against Ionization Dose

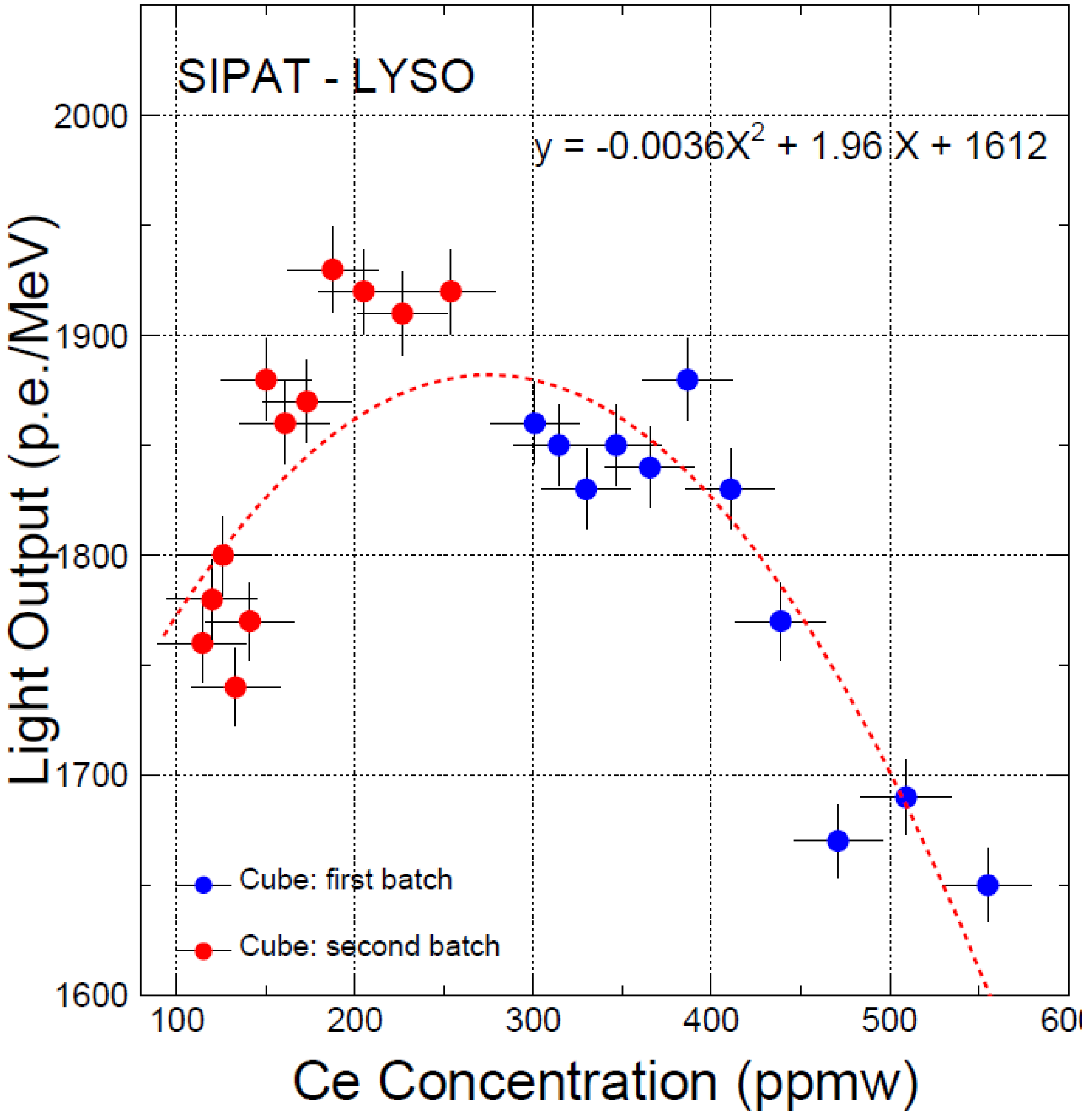
EWLT/LO damage: 8%/10% after 1 Mrad for 2.5×2.5×20 cm^3 LYSO





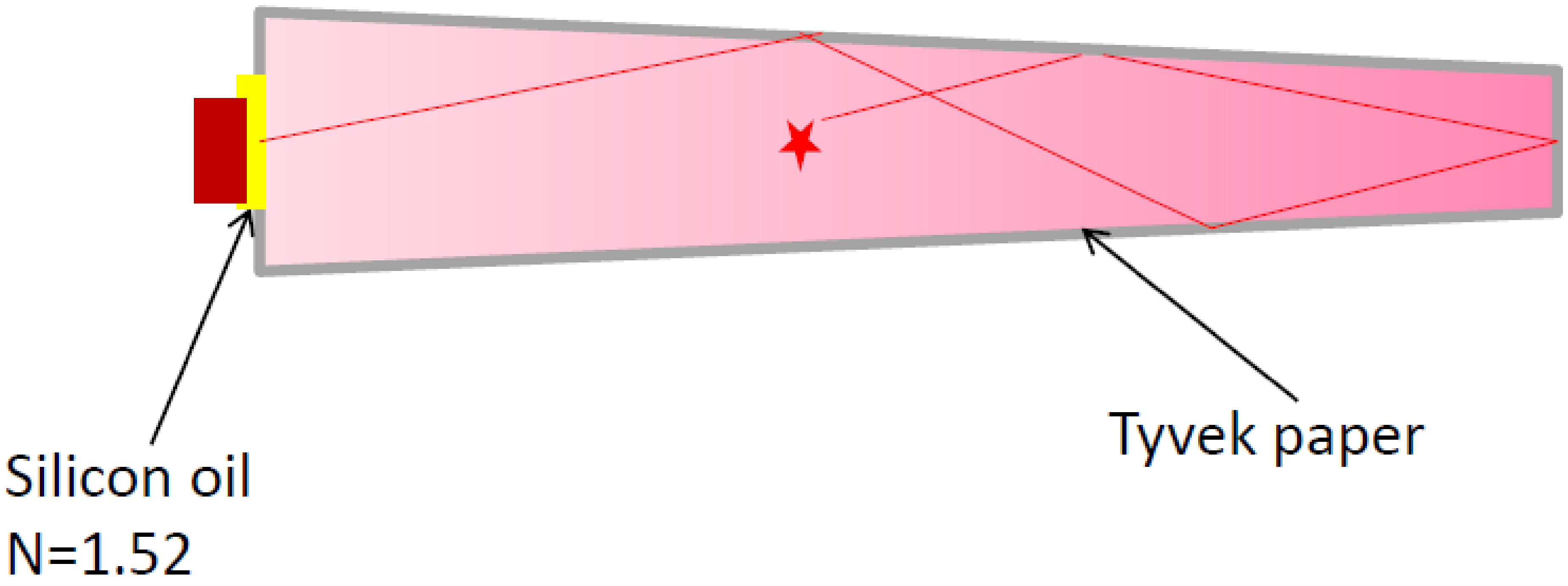
Self-Absorption and Cerium Segregation





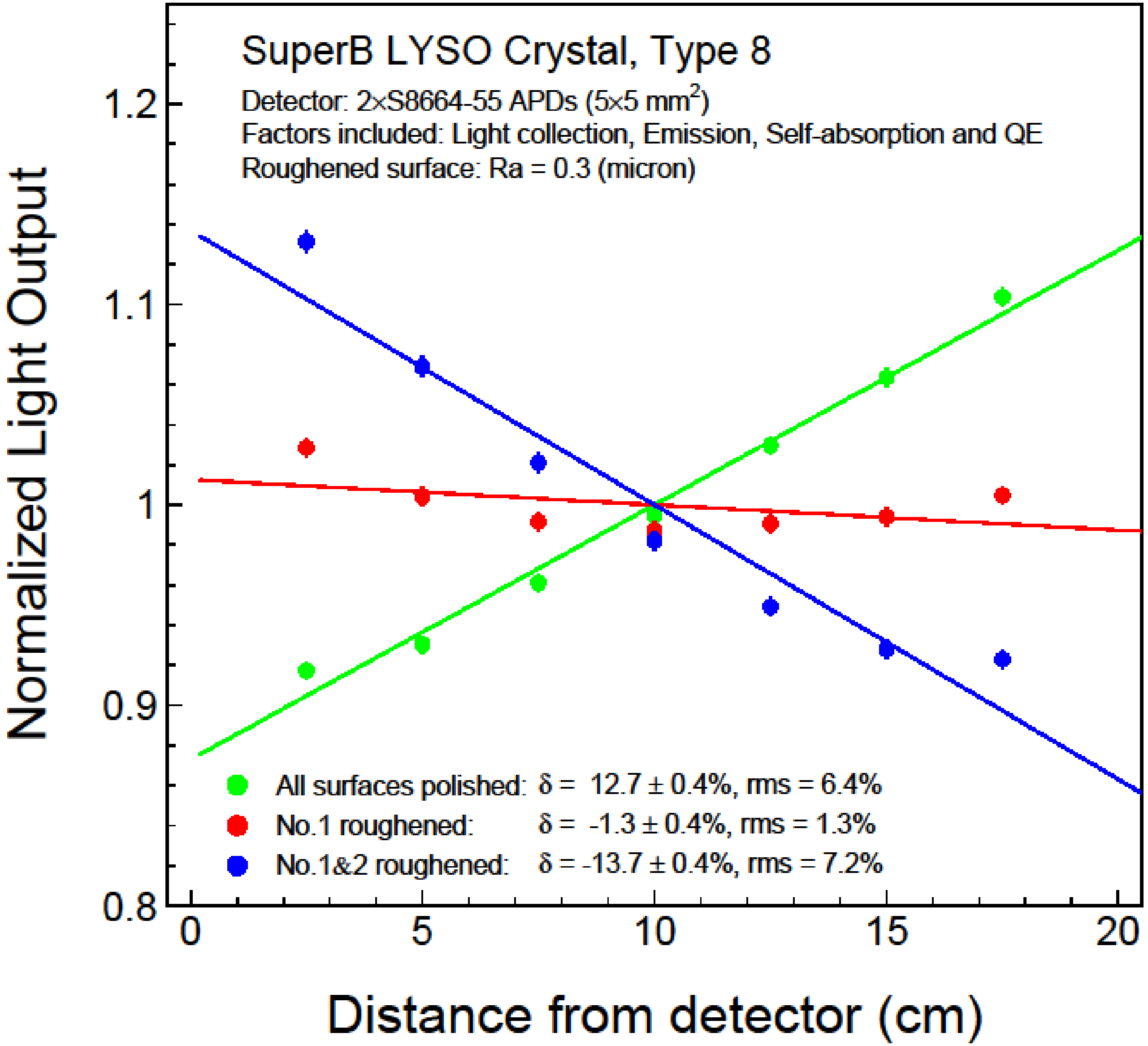
Ray-Tracing Simulation

2 Hamamatsu
S8664-55
(2×5×5 mm²)



$$LO(z) = LY(z)\int Em(\lambda)LCE(\lambda,z)QE(\lambda)d\lambda$$

Polished and Roughened Surfaces



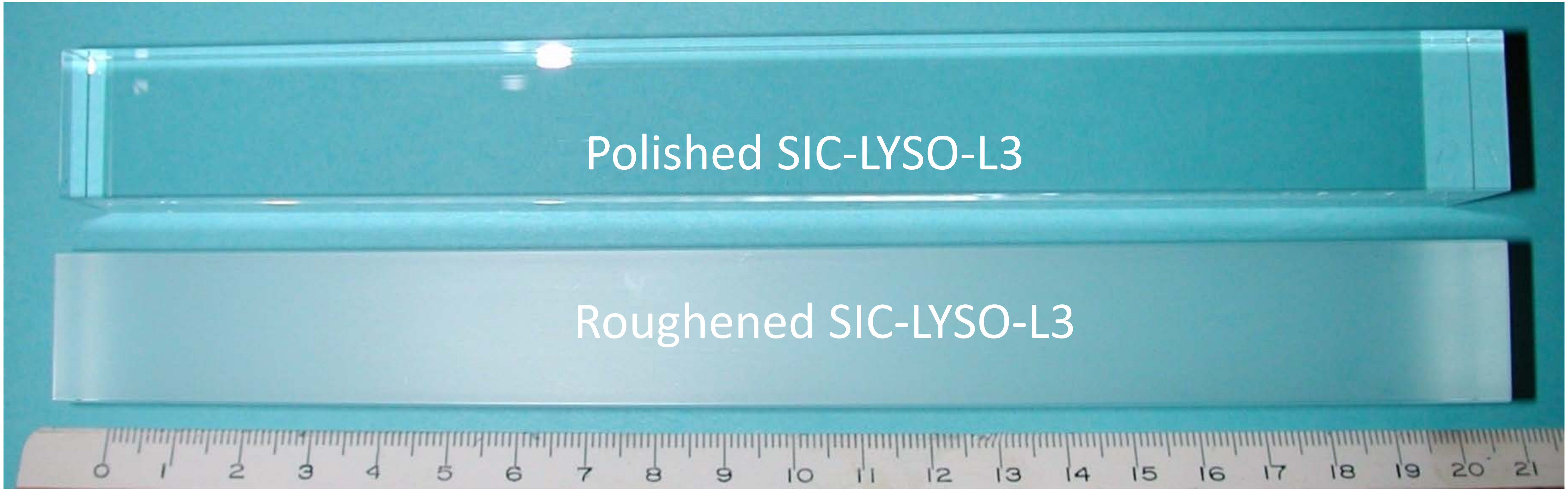
The optical focusing, effect dominates non-uniformity: δ is about 13% for all polished surfaces.

Roughened surface(s) can compensate the optical focusing effect.

The best result is achieved by roughening only one side surface.

Real Exercise: Roughening SIC-LYSO-L3

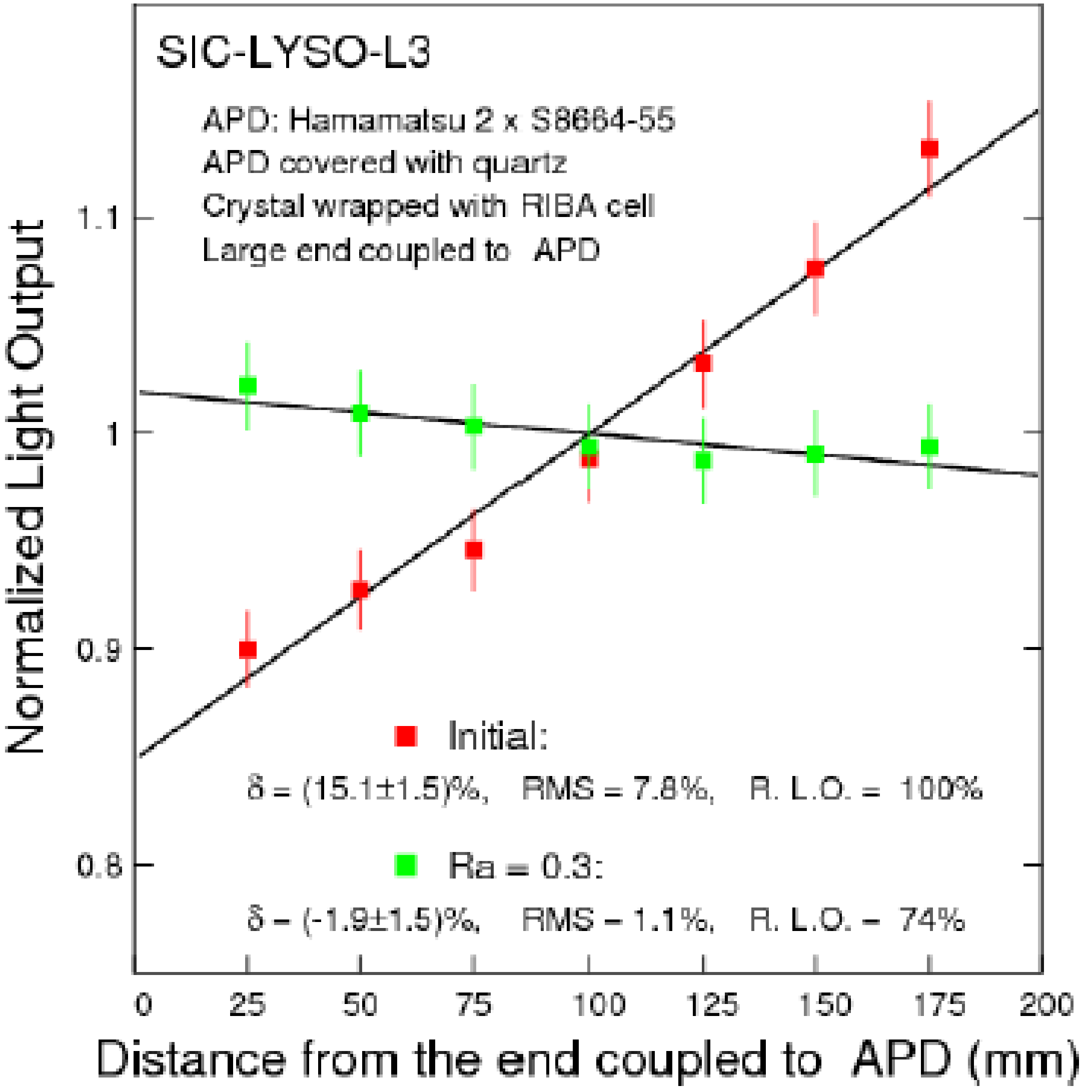
The smallest side surface of SIC-LYSO-L3 was roughened to Ra = 0.3 at SIC via a two step process

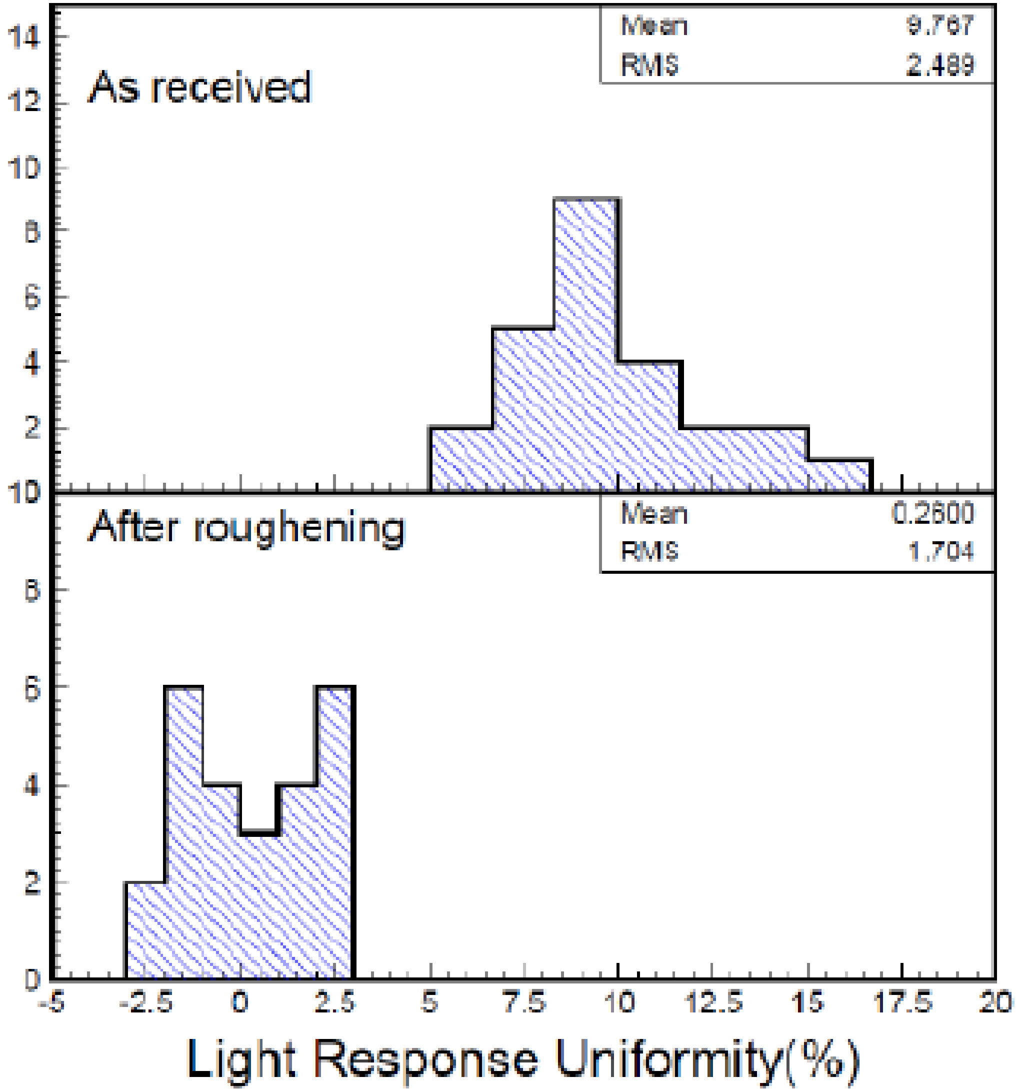


1st: lapped to Ra = 0.5 by using 11 µm Al_2O_3 powder for 10 min with 2.5 kg weight
2nd: lapped to Ra = 0.3 by using 6.5 µm SiC powder for 3 min with 1.5 kg weight

Light Response Uniformization

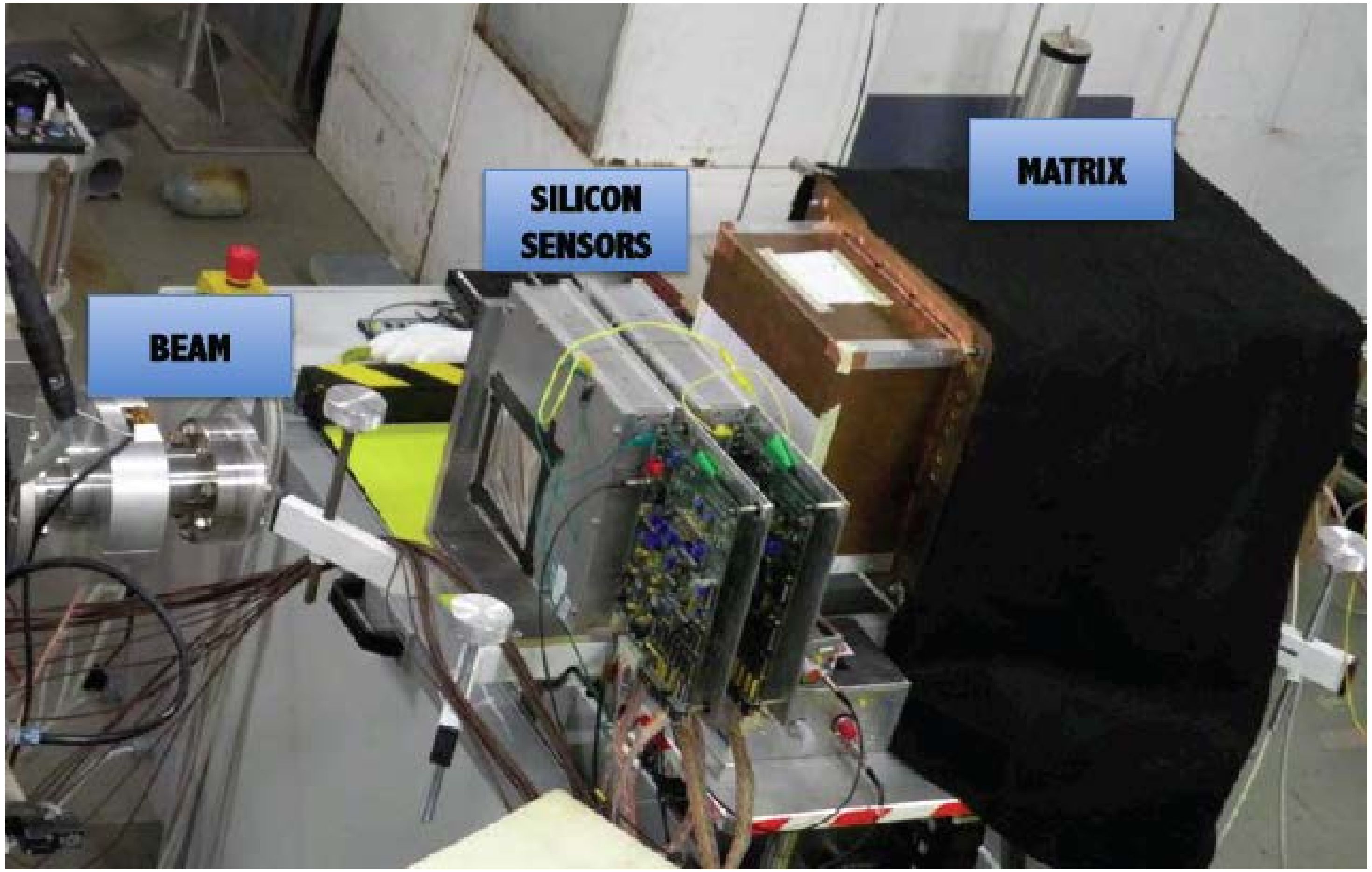
Ra = 0.3 uniformizes SIC-L3 to < 2%

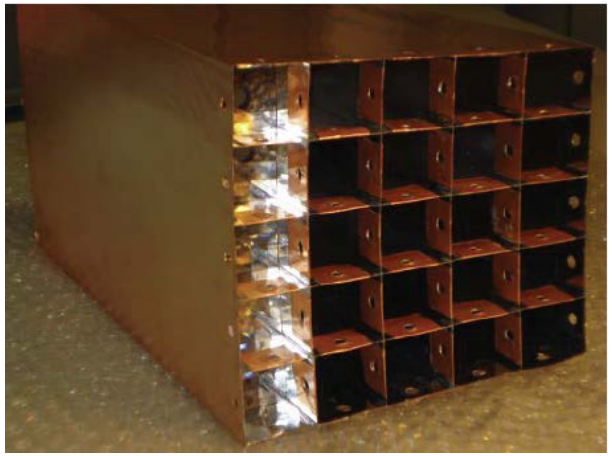


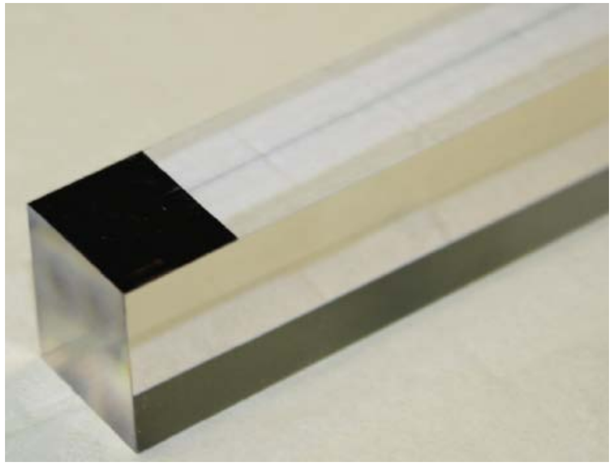


SuperB Test Beam at BTF, Frascati

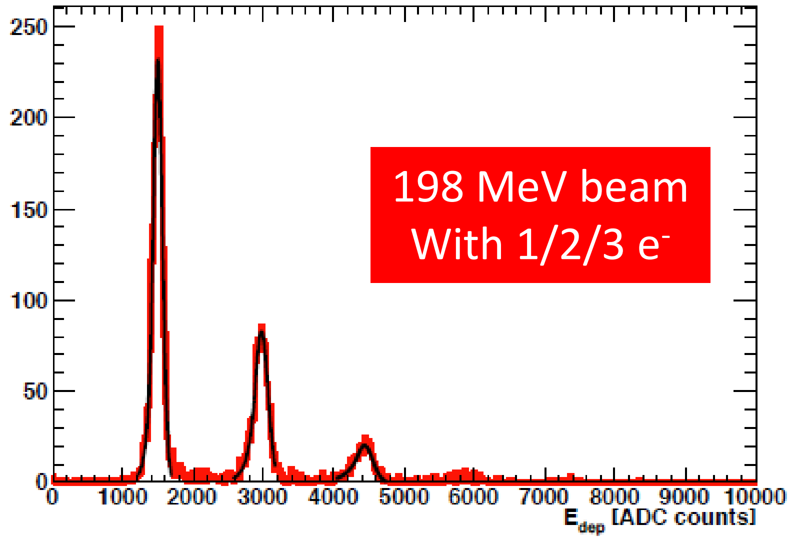
A LYSO matrix of 25 crystals was tested in May, 2011. Crystals were uniformized by black painting of 15 mm at the small end of the smallest side surface

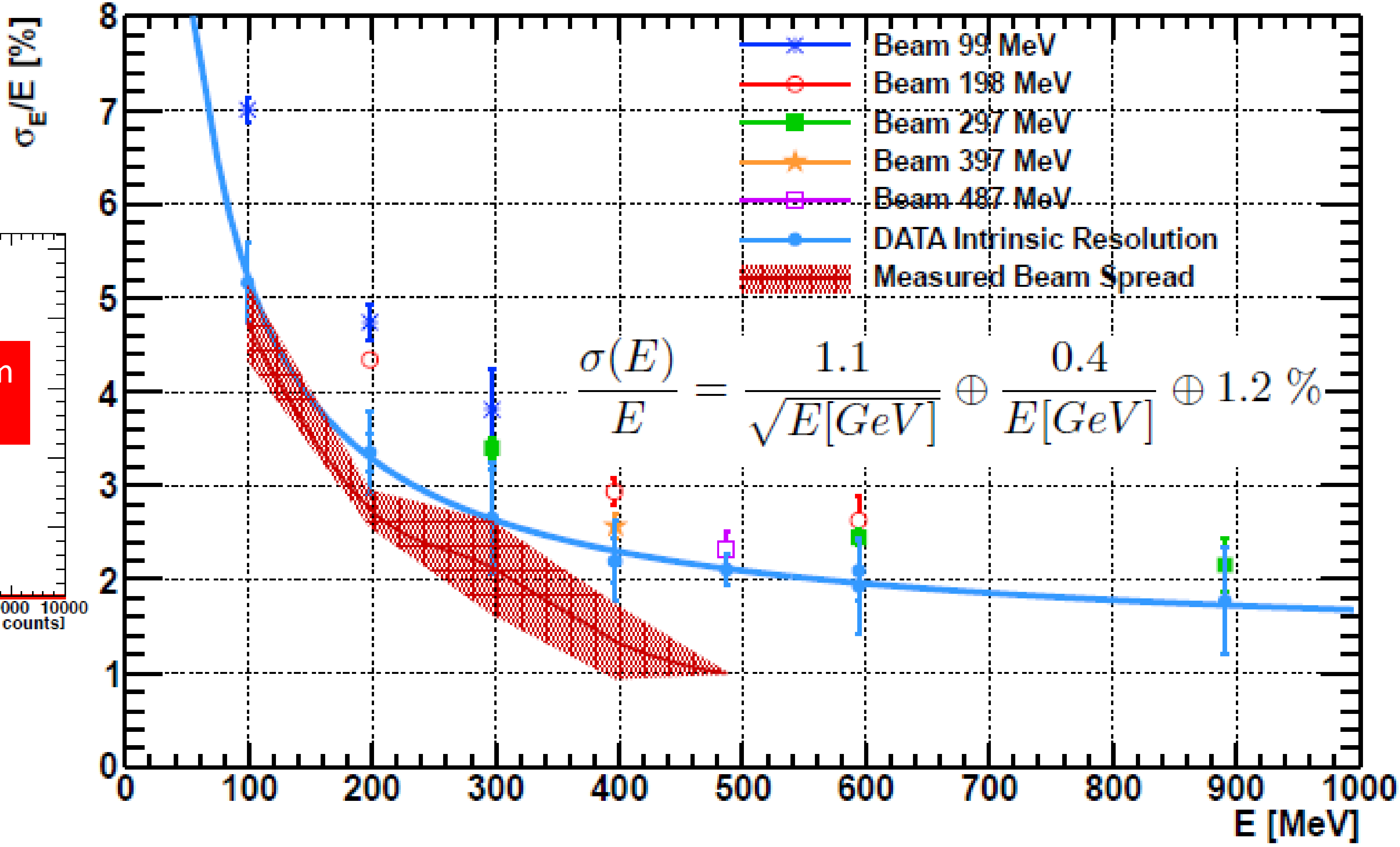






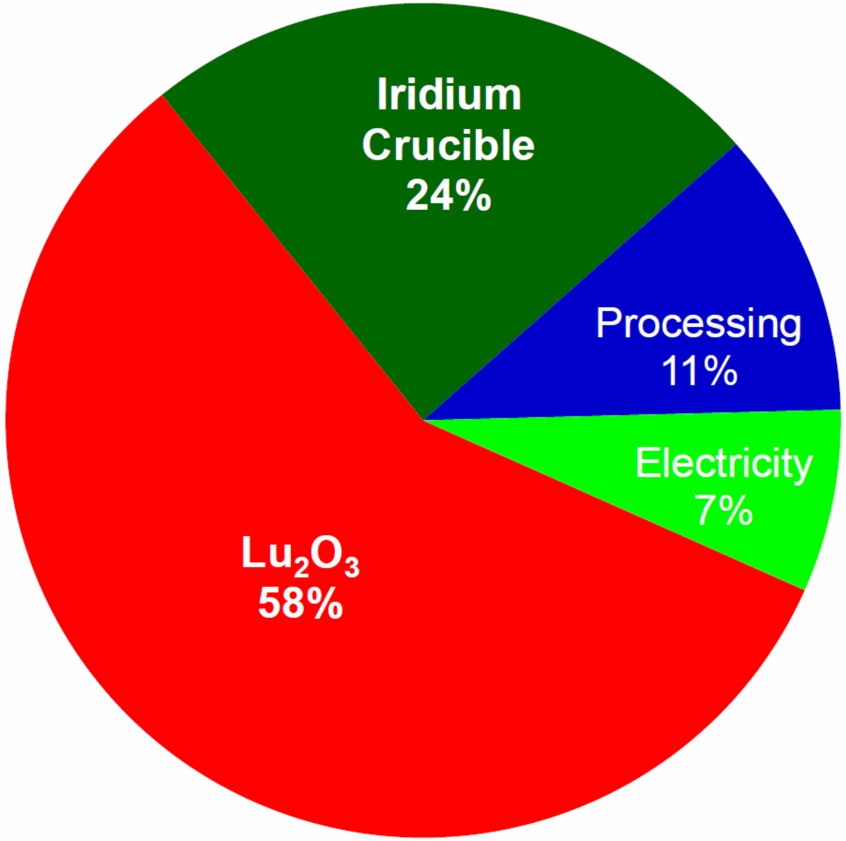
Mu2e LYSO Beam Test

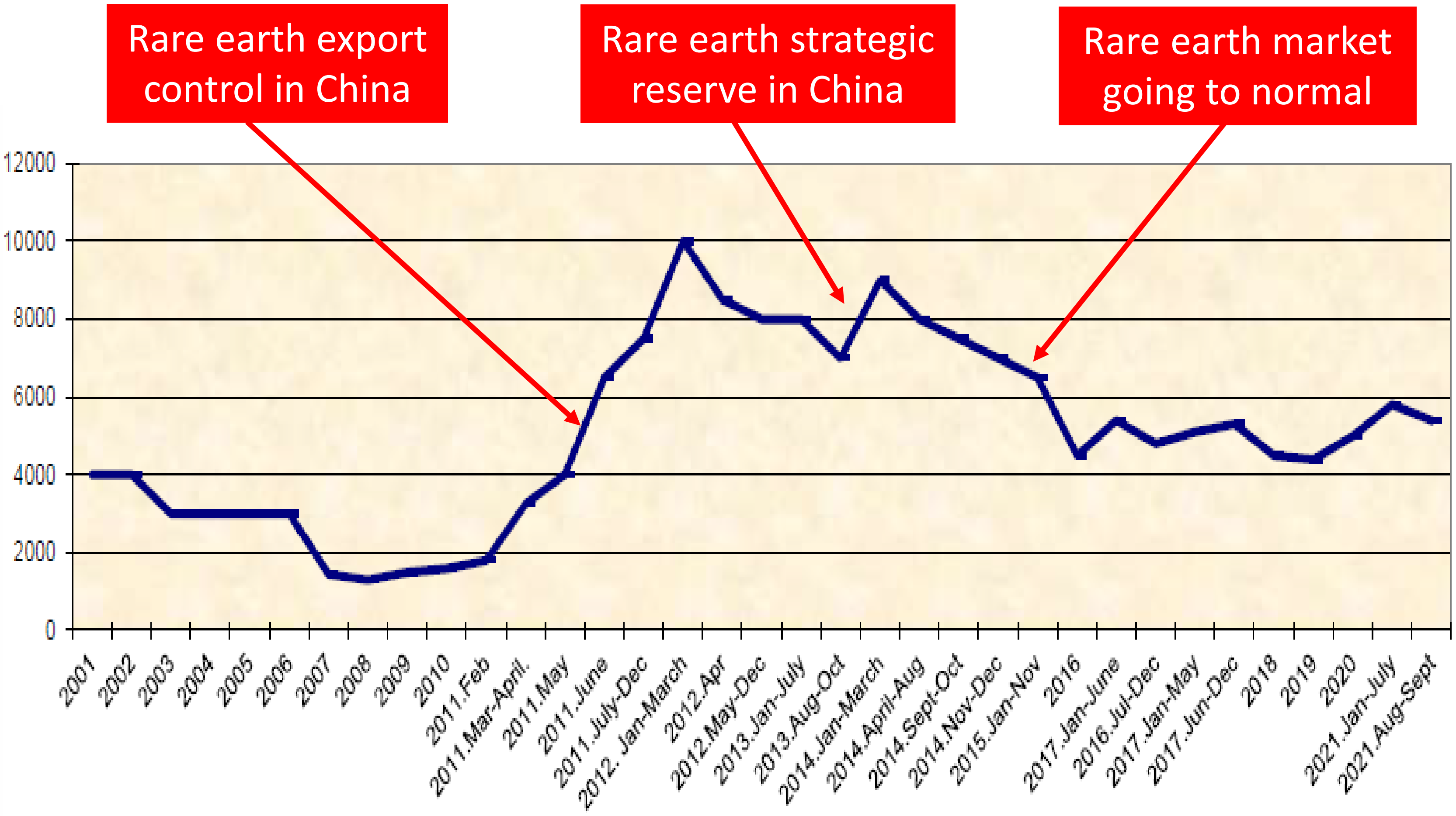




LSO/LYSO/LFS Crystal Cost

Crystal Cost Breakdown





Assuming Lu_2O_3 at \$400/kg and 33% yield the cost is about \$18/cc. Quotations received at \$22-25/cc.

Current Lu_2O_3 price indicates that LYSO price is at a level of \$35/cc

Crystal Cost for CEPC (Mar 2019)

Cost-effectiveness scaled with X_0: PWO, BGO, CsI, BSO, BaF_2:Y, LYSO

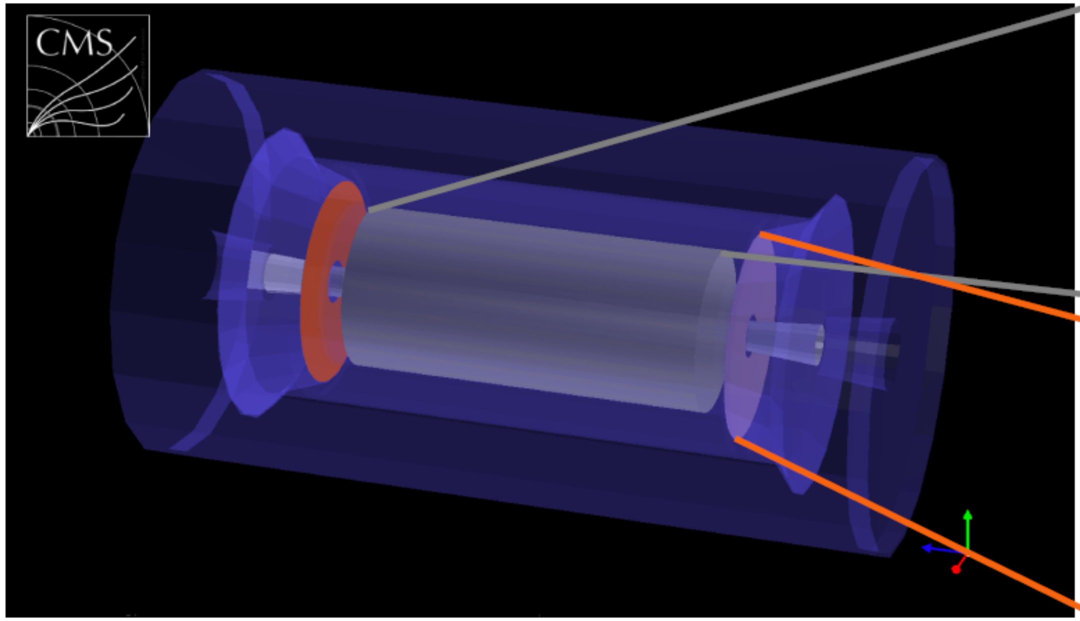
Item	Size (R_MxR_Mx25 X_0)	1 m^3	10 m^3	100 m^3	Scaled to X_0
BGO	22.3×22.3×280 mm	$8/cc	$7/cc	$6/cc	1.23
BaF_2:Y	31.0×31.0×507.5 cm	$12/cc	$11/cc	$10/cc	2.28
LYSO:Ce	20.7x20.7x285 mm	$36/cc	$34/cc	$32/cc	1.28
PWO	20x20x223 mm	$9/cc	$8/cc	$7.5/cc	1.00
BSO	22x22x274 mm	$8.5/cc	$7.5/cc	$7.0/cc	1.29
CsI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

LYSO:Ce for CMS Barrel Timing Layer

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

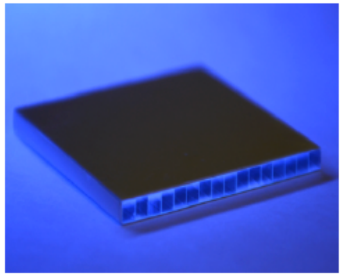
Barrel Timing Layer: arrays of LYSO crystal bars connected to SiPMs at both ends and readout by TOFHIR

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



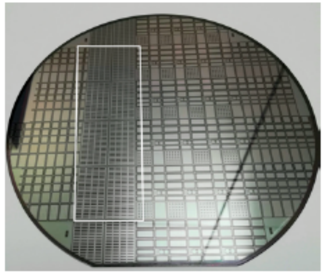
BTL: LYSO bars + SiPM read-out

- 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



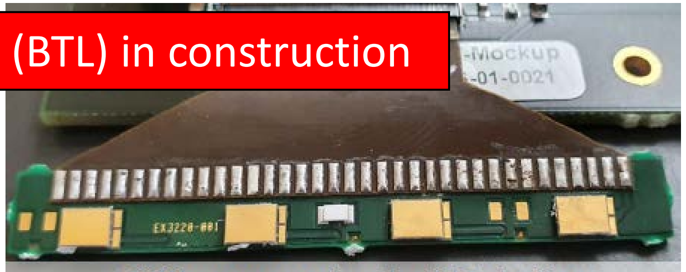
ETL: Si with internal gain (LGAD)

- 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

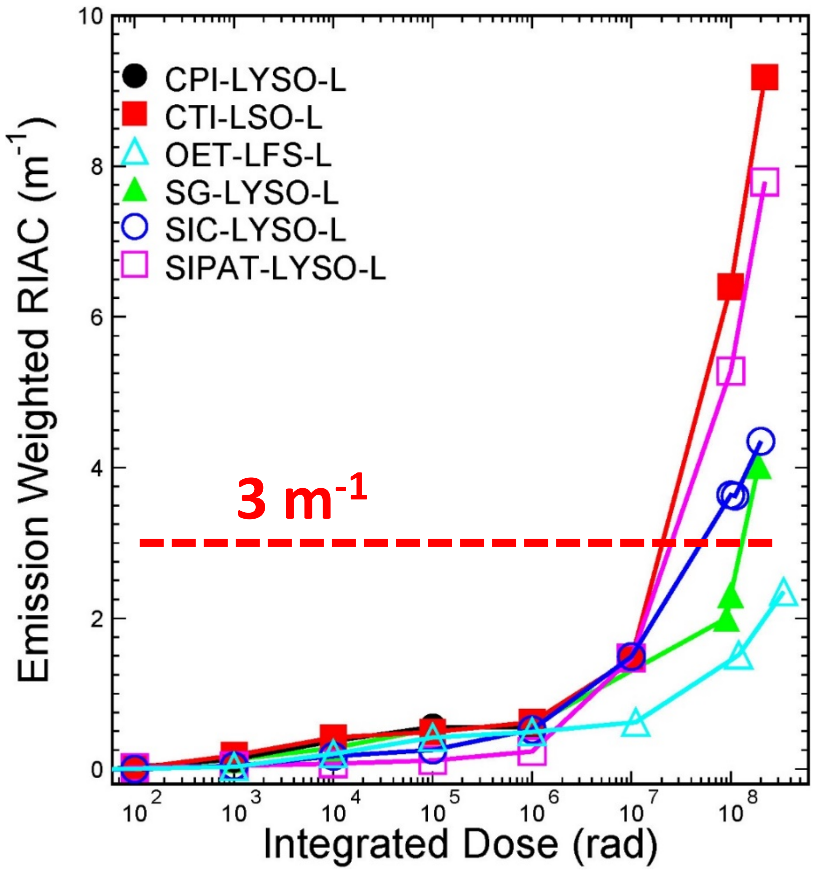
CMS MTD	η	n_{eq} (cm^{-2})	n_{eq} Flux (cm^{-2}s^{-1})	Proton (cm^{-2})	p Flux (cm^{-2}s^{-1})	Dose (Mrad)	Dose rate (rad/h)
Barrel	0.00	2.5E+14	2.8E+06	2.2E+13	2.4E+05	2.7	108
Barrel	1.15	2.7E+14	3.0E+06	2.4E+13	2.6E+05	3.8	150
Barrel	**1.45**	**2.9E+14**	**3.2E+06**	**2.5E+13**	**2.8E+05**	**4.8**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

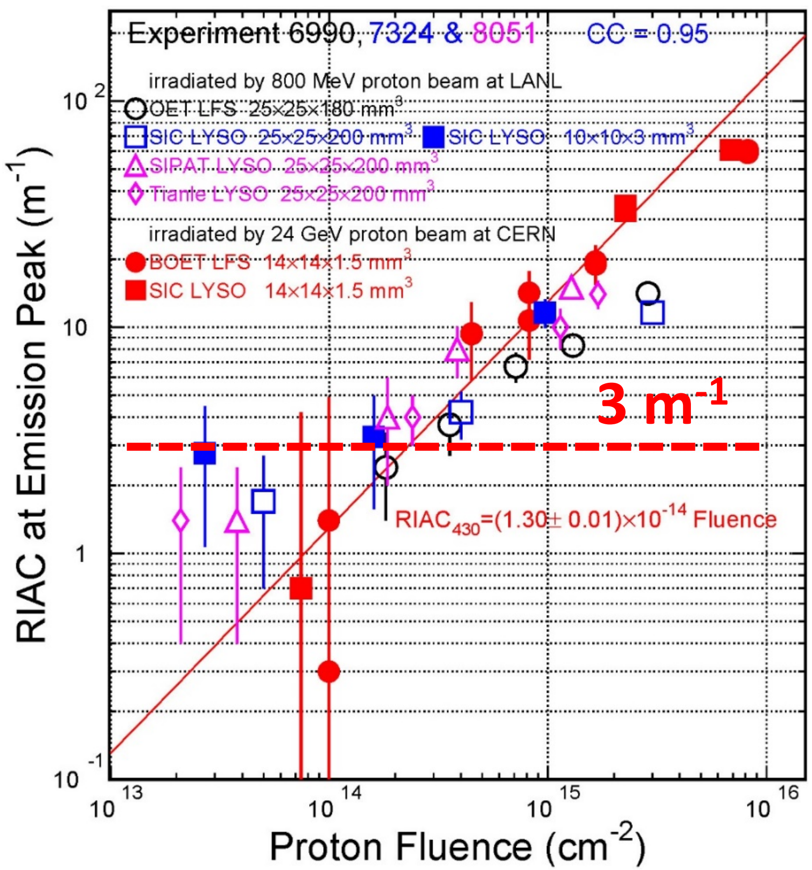
Much higher at FCC-hh: up to 0.1/500 Grad and $3\times10^{16}/5\times10^{18}$ n_{eq}/cm^2 at EMEC/EMF

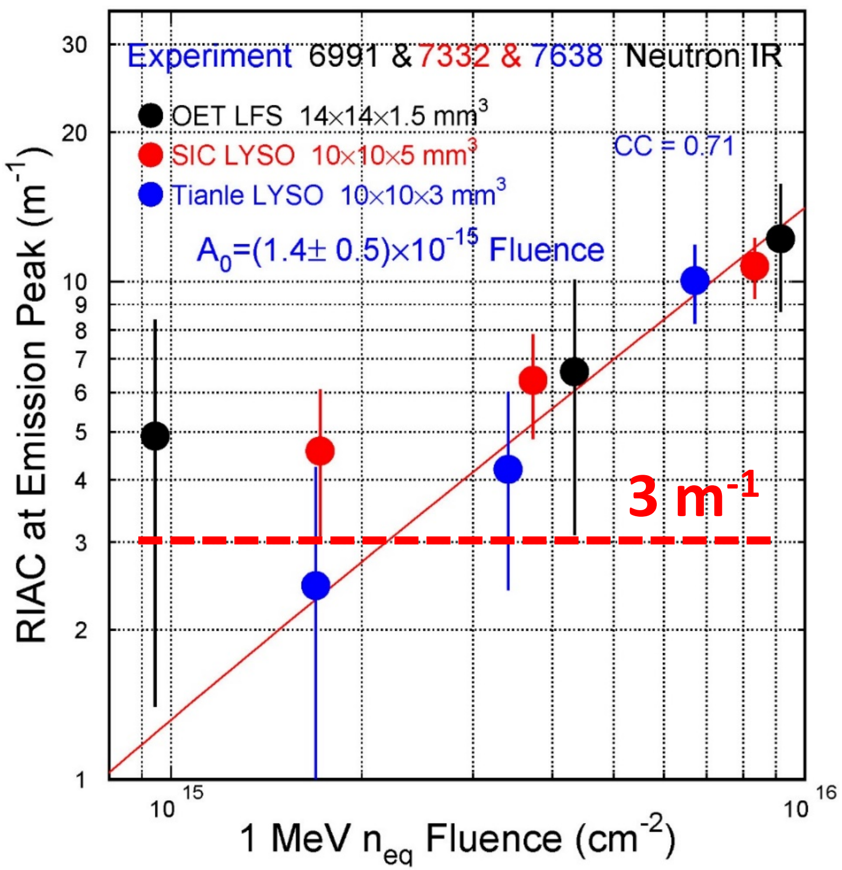
M. Aleksa *et al.*, Calorimeters for the FCC-hh CERN-FCCPHYS-2019-0003, Dec 23, 2019

LYSO:Ce for CMS Barrel Timing Layer

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

2019 DOE Basic Research Needs Study on HEP Instrumentation: Calorimetry

https://science.osti.gov/hep/Community-Resources/Reports

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

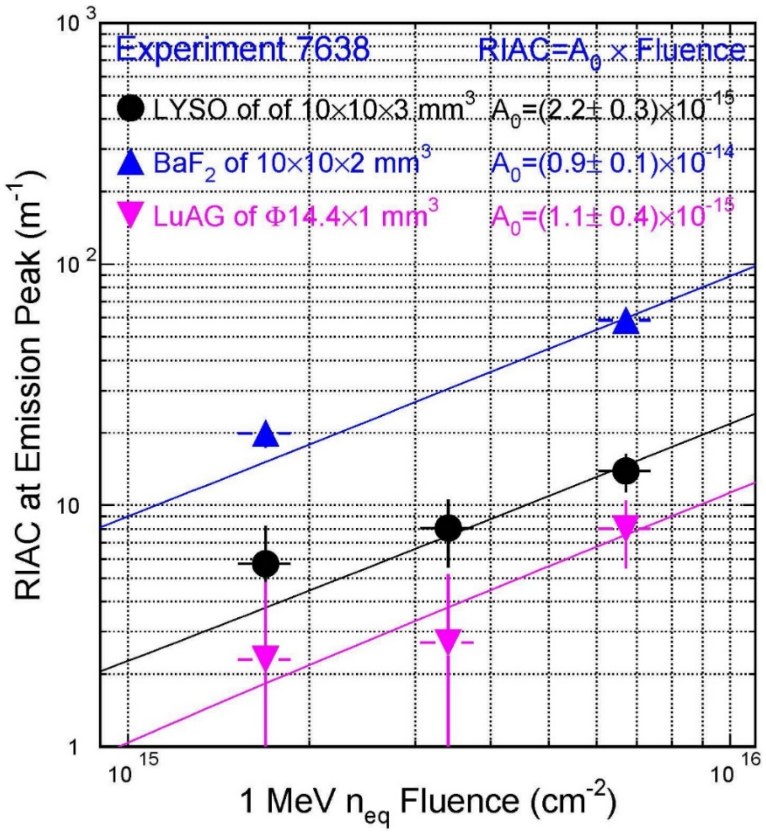
Fast/ultrafast, radiation hard and cost-effective inorganic scintillators needed to achieve energy, spatial and timing resolution for future HEP calorimetry

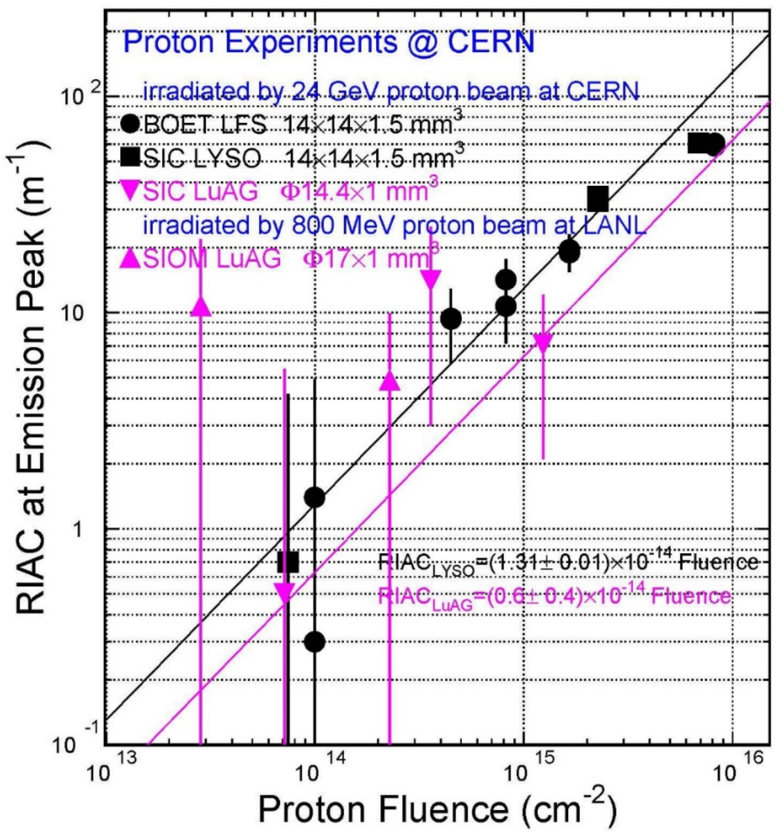
2021 HEP CPAD Meeting: https://indico.fnal.gov/event/46746/timetable/#all.detailed

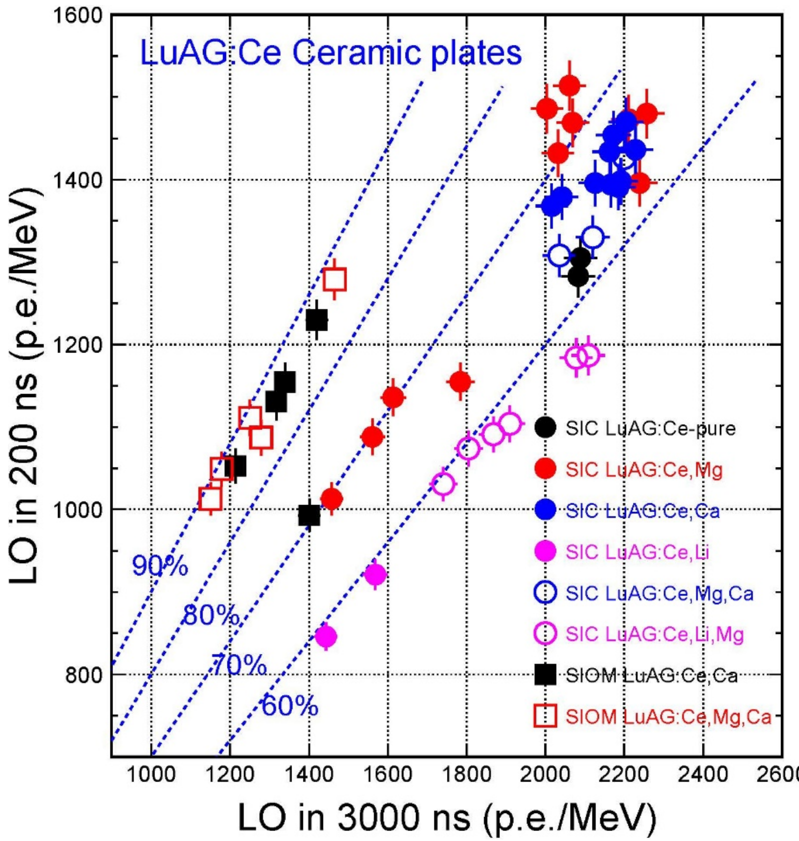
LuAG:Ce Ceramics Radiation Hardness

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 2020 NSS CR, DOI: 10.1109/NSS/MIC42677.2020.9507969

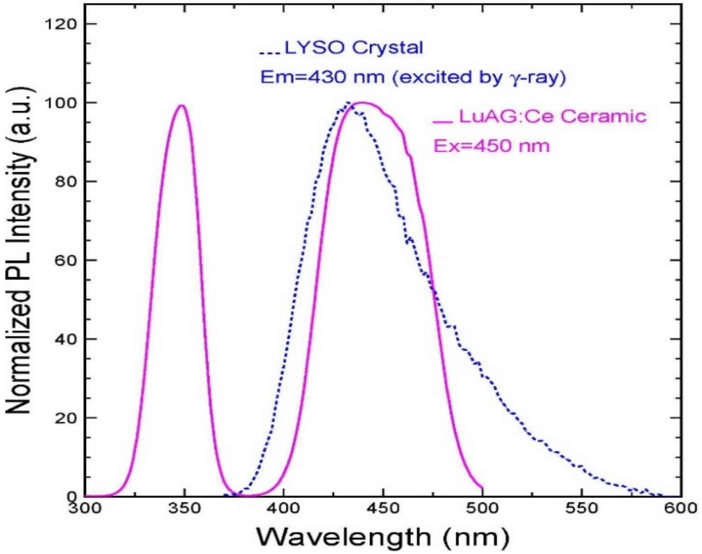






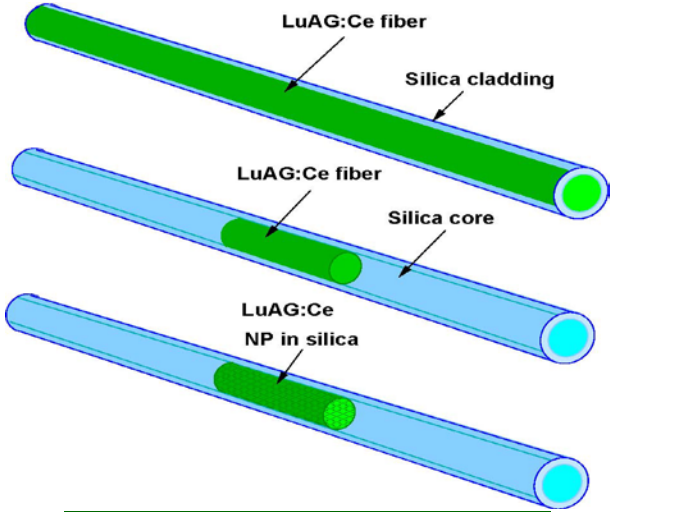
R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

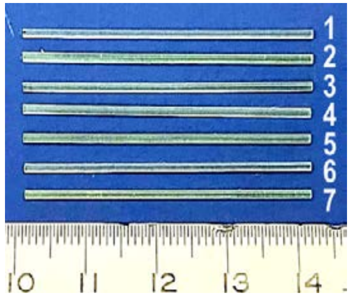
RADiCAL: LYSO/W/LuAG Shashlik ECAL



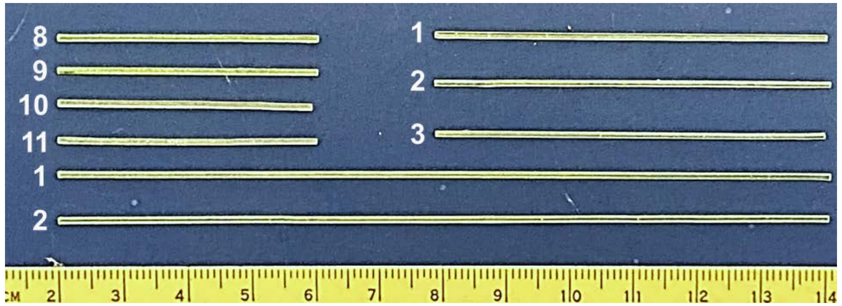
Excitation of LuAG:Ce ceramics matches well LYSO:Ce emission:

RADiCAL
RADiation hard **i**nnovative **CAL**orimetry
See R. Ruchti, in the CPAD meeting

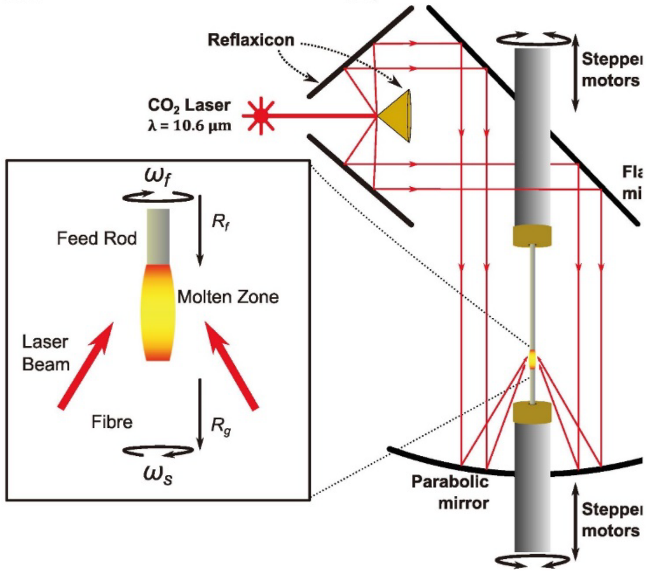




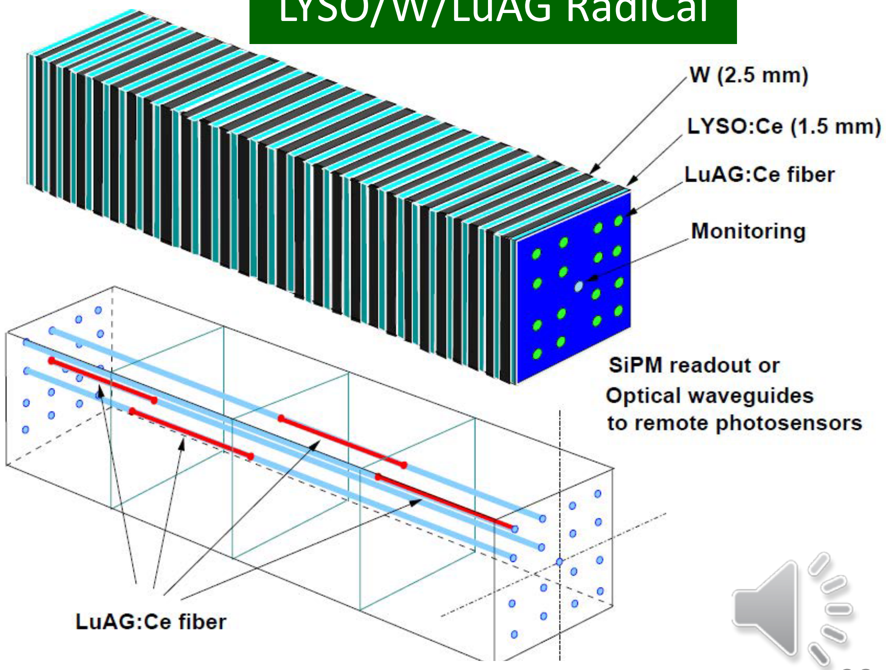
11 Φ1x40 mm³
3 Φ1x60 mm³
2 Φ1x120 mm³
SIC LuAG:Ce
Ceramic LHPG fiber



16 LuAG:Ce ceramic fibers
Laser Heated Pedestal Growth



LYSO/W/LuAG RadiCal

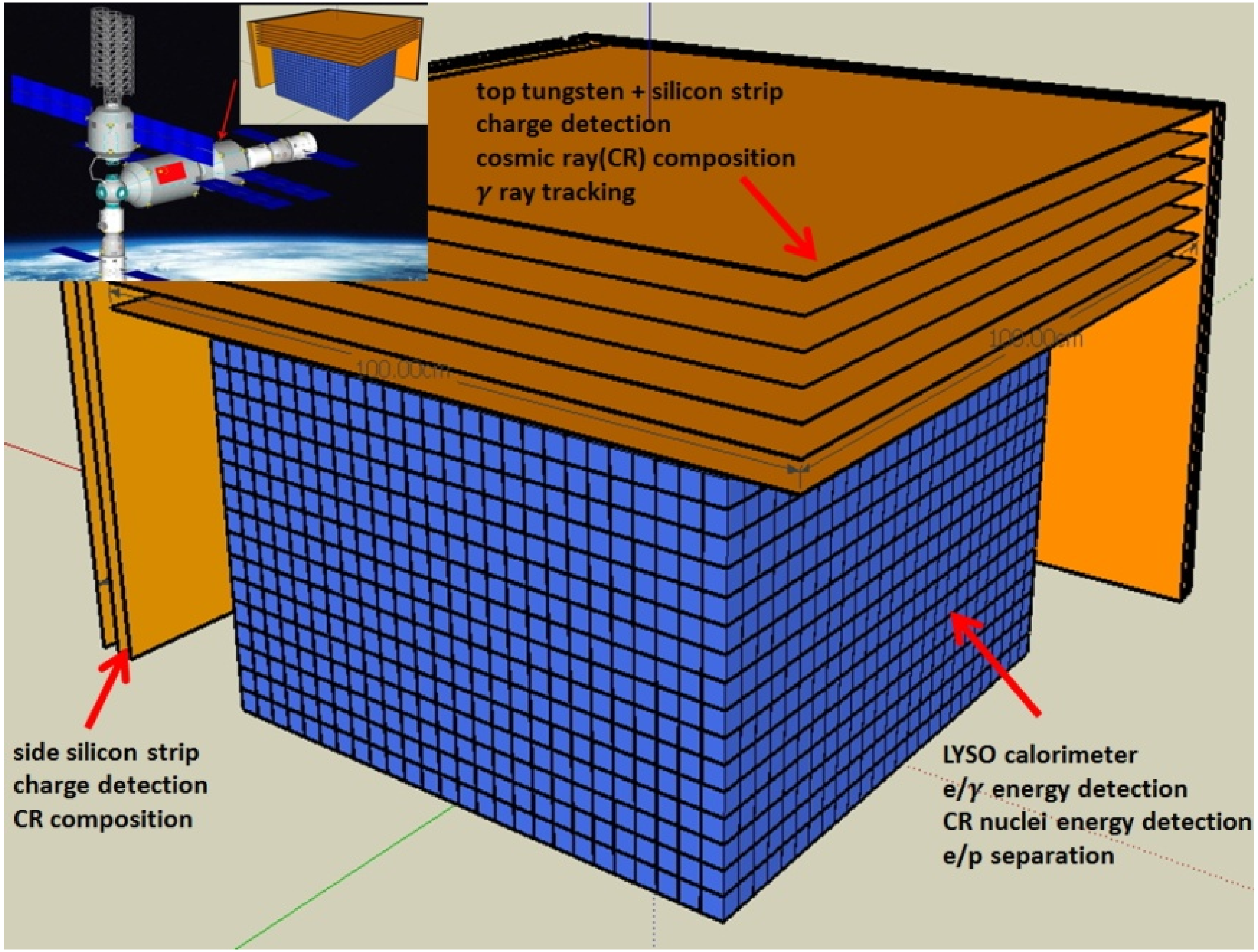


Summary

- LYSO:Ce is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator. The light output loss is at a level of 10% for 28 cm long crystal after 1 Mrad γ–ray irradiation, much better than all other crystals.
- The longitudinal light response non-uniformity issue caused by self-absorption, cerium segregation and tapered geometry can be addressed by roughening crystal's side surface.
- LYSO:Ce is widely used in the medical industry. Existing mass production capability would help in cost control.
- LYSO is widely used in HEP experiments: COMET, HERD and CMS BTL. The proposed **RADiCAL** concept use LYSO:Ce plates and LuAG:Ce WLS for an ultra-compact, radiation hard and longitudinally segmented shashlik calorimeter for the HL-LHC and FCC-hh.

Acknowledgements: DOE HEP Award DE-SC0011925

The HERD LYSO Calorimeter



9261 LYSO crystals of 3 cm cube with WLF readout: 55 X_0 and 3 λ in Space

Good resolutions for γ/e energy, position and direction