The Next Generation of Crystal Detectors for Future High Energy Physics Calorimetry

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Why Crystal Calorimeter in HEP

- **Photons and electrons are fundamental particles. Precision e/γ measurements enhance physics discovery potential for future HEP experiments.**
- **Performance of crystal calorimeter in e/γ measurements is well understood:**
  - **The best possible energy resolution;**
  - **Good position resolution;**
  - **Good e/γ identification and reconstruction efficiency.**
- **Challenges at future HEP Experiments:**
  - **Radiation damage at the energy frontier (HL-LHC);**
  - **Ultra-fast rate at the intensity frontier;**
  - **e/ɣ and Jet mass resolution for future lepton colliders (ILC/CLIC/FCC).**

Existing Crystal Calorimeters

Date	**75-85**	**80-00**	**80-00**	**80-00**	**90-10**	**94-10**	**94-10**	**95-20**
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS[a]+Si PD	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5

Future Crystal Calorimeters in HEP:

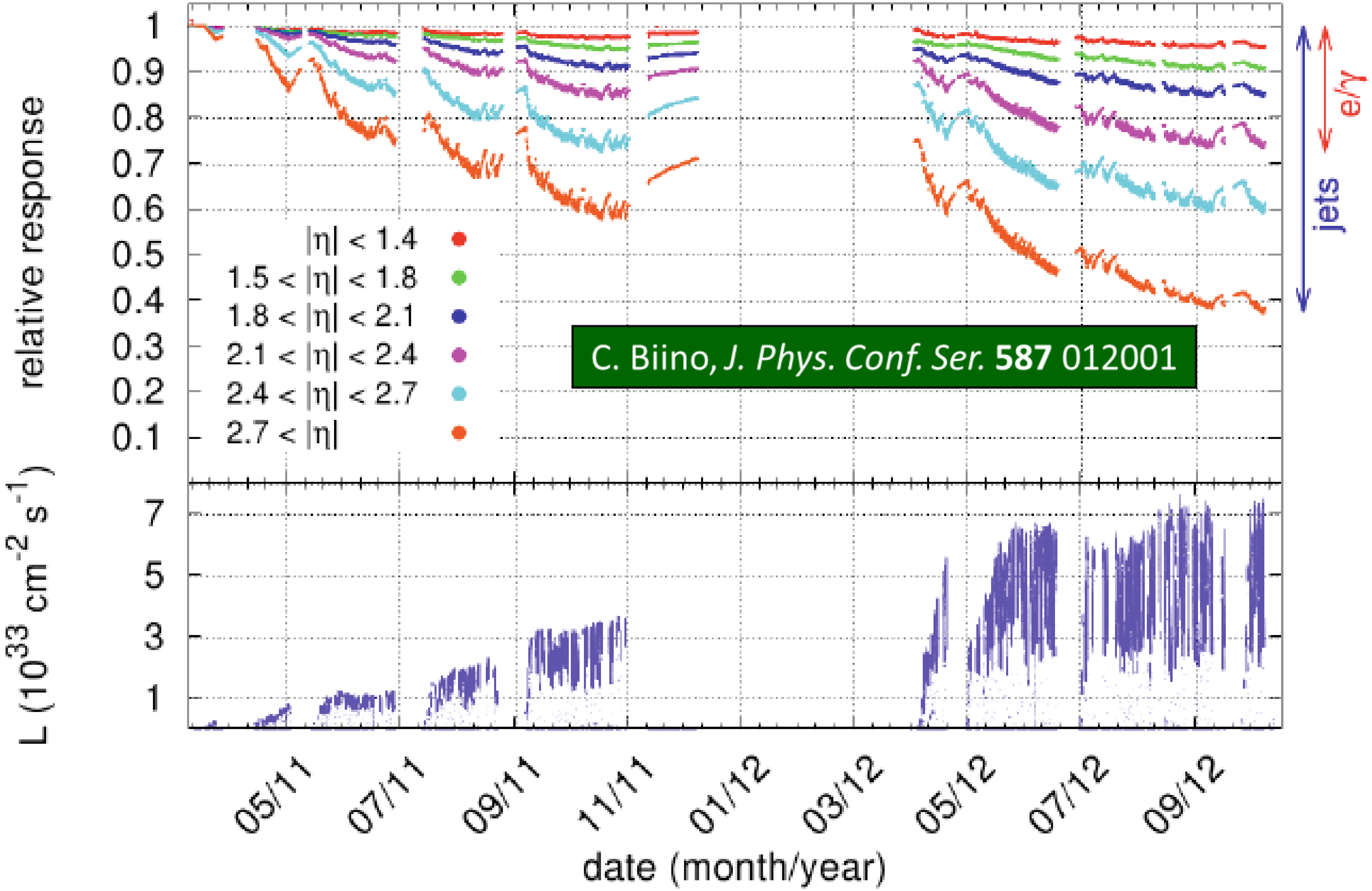
LYSO for COMET (Mu2e, Super B and CMS at HL-LHC)

BaF_2 and PbF_2 for Mu2e and g-2 respectively at Fermilab

PbF_2, PbFCl, BSO and BGO for Homogeneous HCAL for LC

CMS PWO Monitoring Response

The observed degradation is well understood


C. Biino, *J. Phys. Conf. Ser.* **587** 012001

Dose Rate Dependent Damage

IEEE Trans. Nucl. Sci., Vol. 44 (1997) 458-476

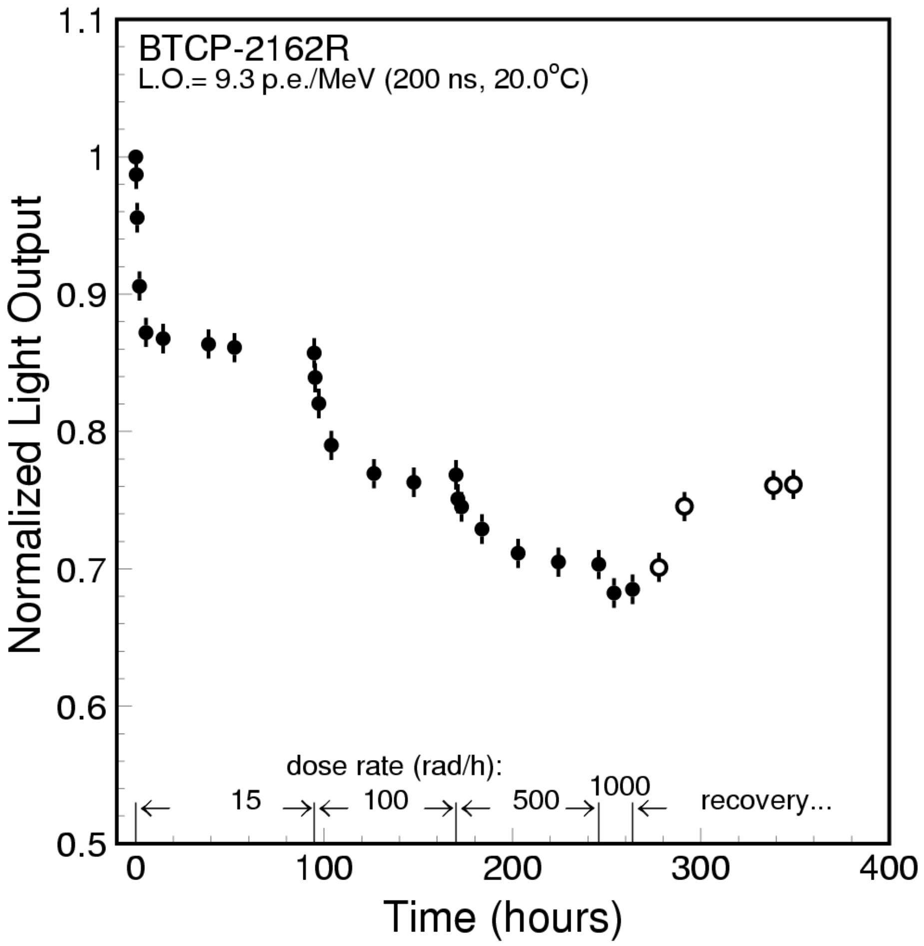
Light output reaches an equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

$$dD = \sum_{i=1}^{n}\{-a_i D_i dt + (D_i^{all} - D_i)\, b_i R dt\}$$

$$D = \sum_{i=1}^{n}\{\frac{b_i R D_i^{all}}{a_i + b_i R}\,[1 - e^{-(a_i+b_iR)t}] + D_i^0 e^{-(a_i+b_iR)t}\}$$

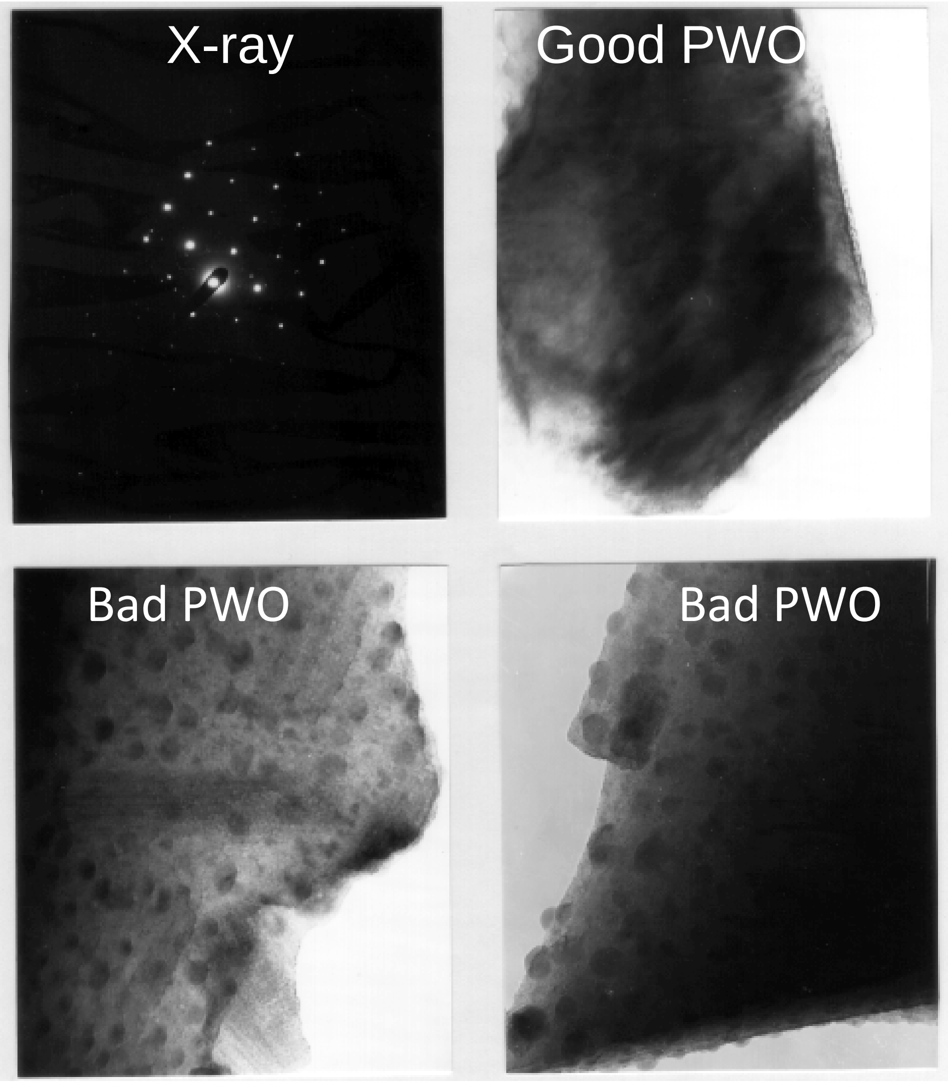
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of kRad/hr.

$$D_{eq} = \sum_{i=1}^{n}\frac{b_i R D_i^{all}}{a_i + b_i R}$$



Oxygen Vacancies Identified by TEM/EDS

5 to10 nm black spots identified by TOPCON-002B scope, 200 kV, 10 uA
Localized stoichiometry analysis by JEOL JEM-2010 scope and Link ISIS EDS



NIM A413 (1998) 297

Atomic Fraction (%) in $PbWO_4$

As Grown Sample

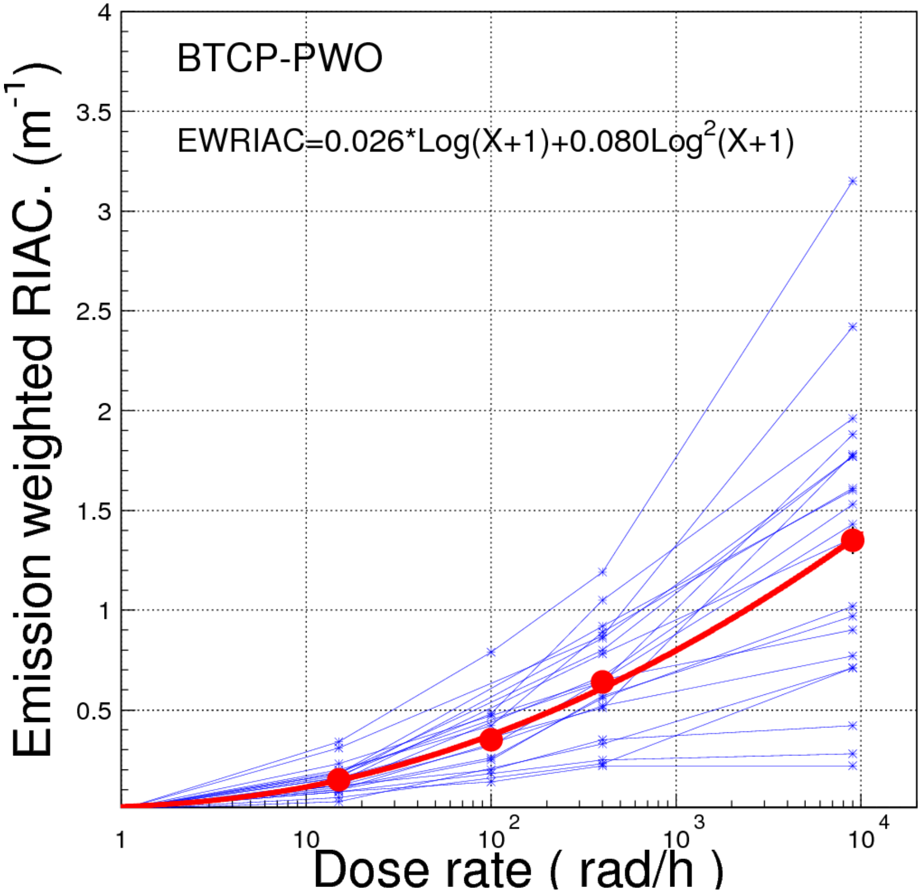
Element	Black Spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

The Same Sample after Oxygen Compensation

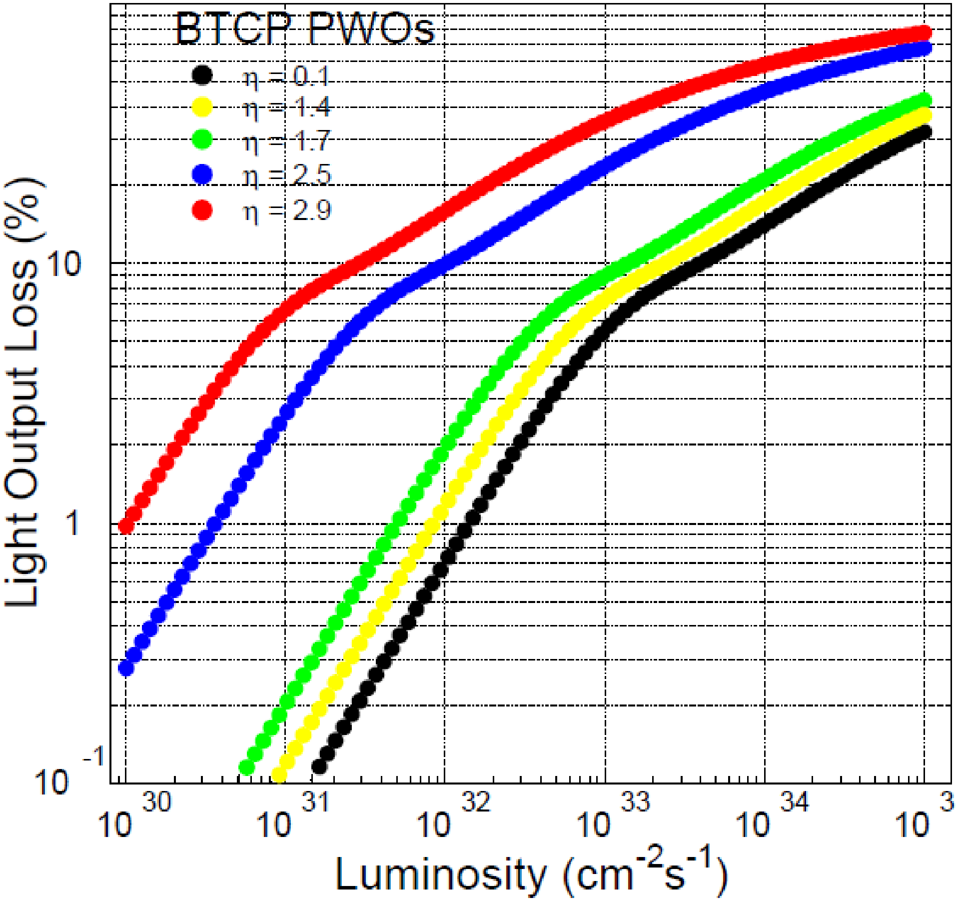
Element	$Point_1$	$Point_2$	$Point_3$	$Point_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

Prediction of PWO Damage

IEEE Trans. Nucl. Sci. NS-51 1777 (2004)



Talk in CMS Forward Calorimeter Taskforce Meeting, CERN, 12/10/2010



Predicted ionization dose induced damage agrees with the LHC data

In addition, there is hadron induced damage at LHC

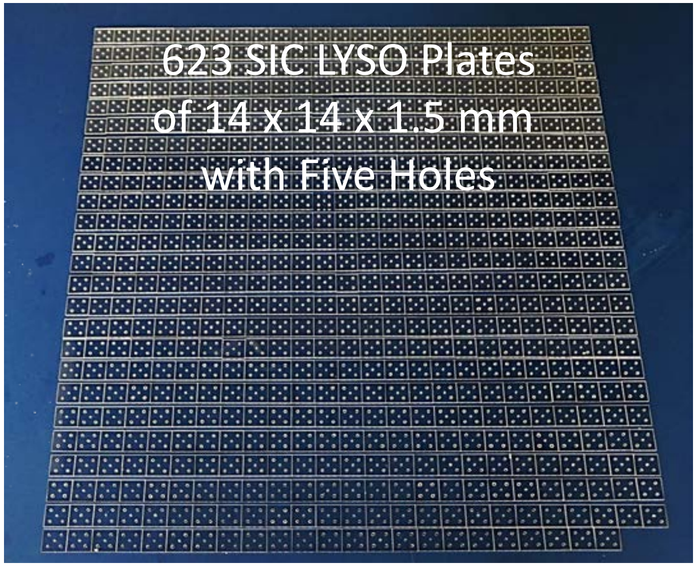
Bright, Fast Scintillator: LSO/LYSO

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (°C)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	26	650 0.9	300	40	30 10	?
Light Yield [b,c] (%)	100	165	4.7	36 4.1	21	85	0.3 0.1	?
d(LY)/dT [b] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV KOTO S. BELLE	(GEM) TAPS Mu2e	L3 BELLE HHCAL?	COMET (CMS, Mu2e, SuperB)	CMS ALICE PANDA	A4 g-2 HHCAL?

a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

Bright, Fast & Rad Hard LYSO

2.5 x 2.5 x 20 cm

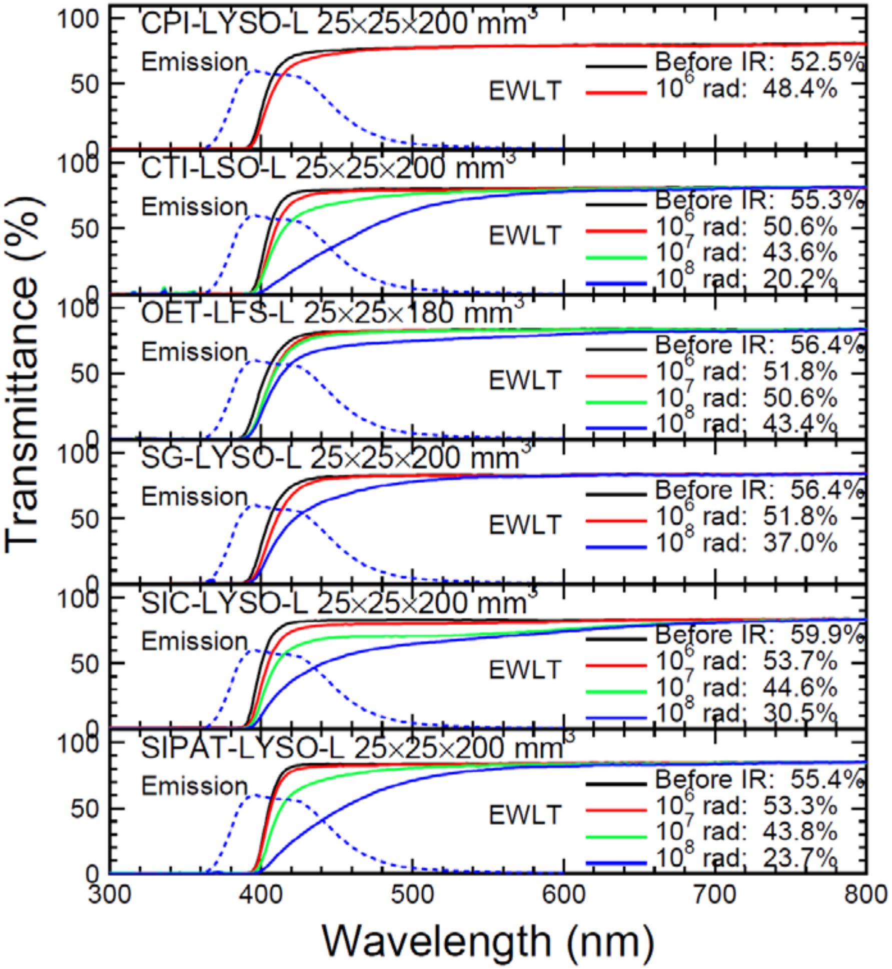


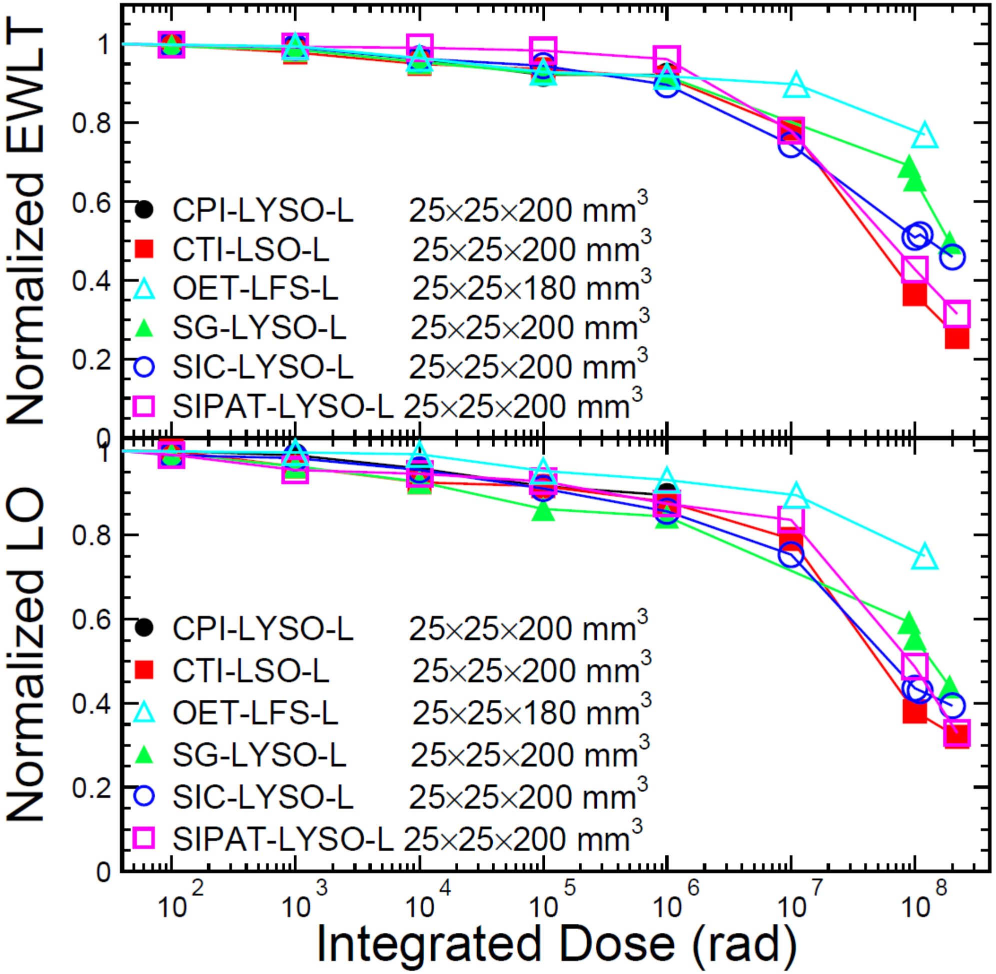
623 SIC LYSO Plates of 14 x 14 x 1.5 mm with Five Holes

- LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator.
- No variation in emission spectrum was observed after ɣ-rays irradiation, indicating scintillation mechanism is not damaged.
- ɣ-ray induced radiation damage in LYSO does not recover at room temperature, indicating a stable calorimeter *in situ*.
- ɣ-ray induced absorption coefficient measured for 20 cm long LYSO crystals after 200 Mrad irradiation is about 2 m^{-1}.
- ɣ-ray induced light output loss measured for 14 x 14 x 1.5 mm plates after 100 and 200 Mrad irradiation is about 6 and 8% respectively.
- The material is widely used in the medical industry with existing mass production capability.

Radiation Hardness of 20 cm LYSO

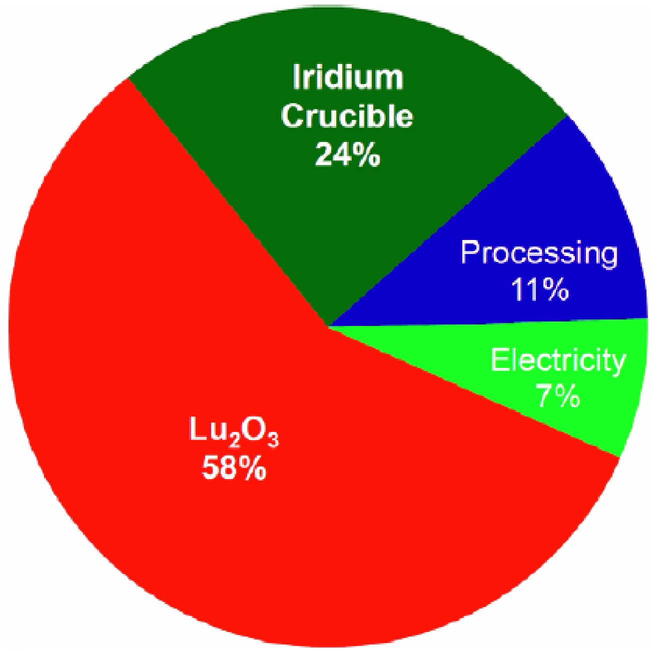
Consistent damage with the best OET/Zecotek: 80% light after 100 Mrad





LYSO Crystal Cost: Lu$_2$O$_3$ Price

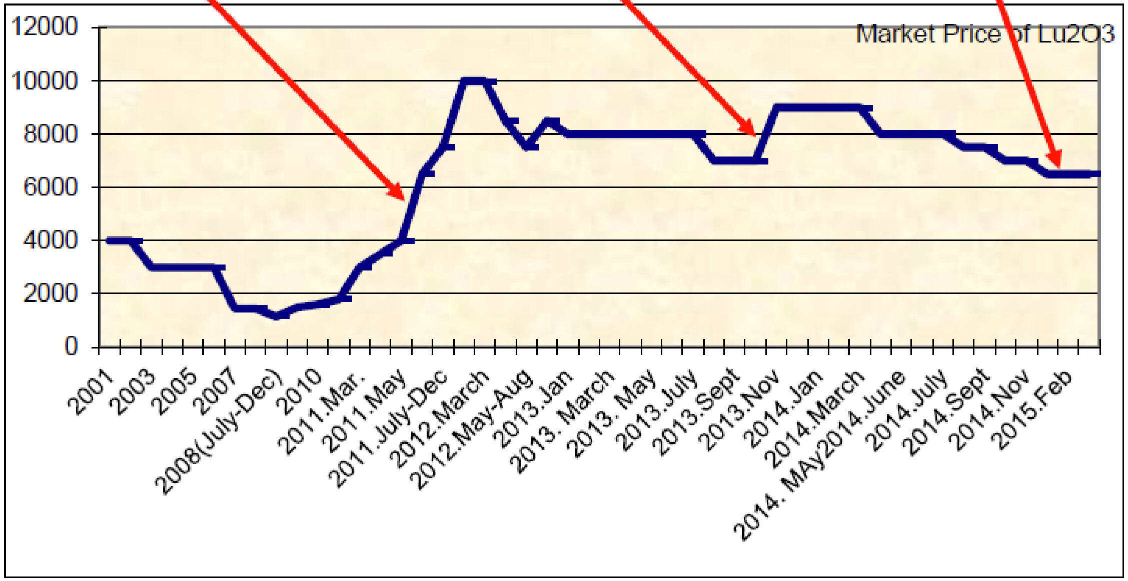
Crystal Cost Breakdown



Rare earth export control in China

Rare earth strategic reserve in China

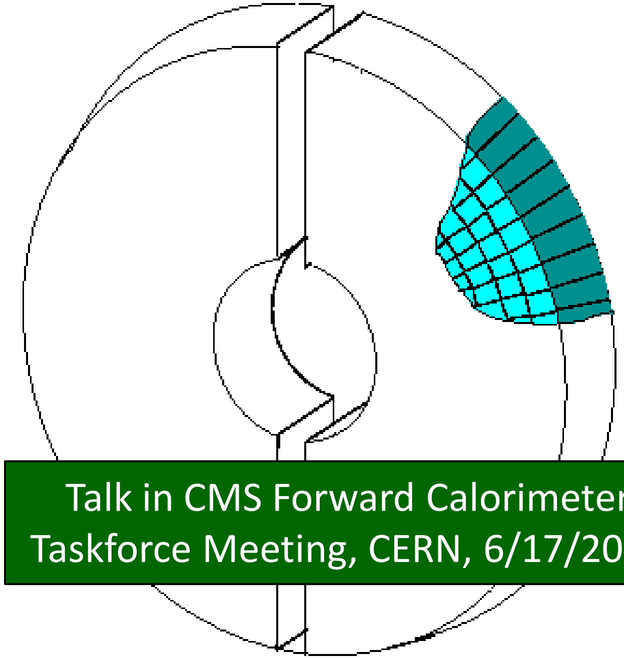
Rare earth market going to normal



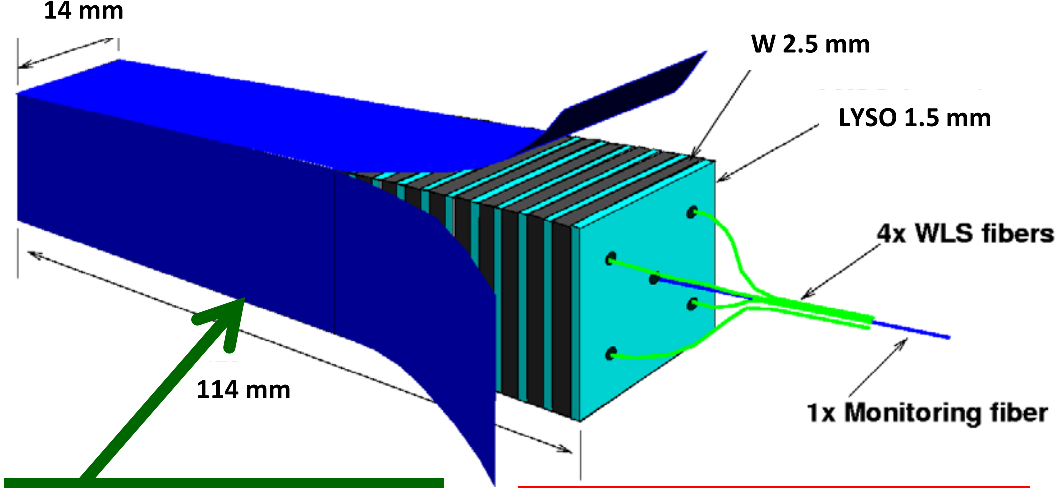
Assuming Lu$_2$O$_3$ at \$400/kg and 33% yield the cost is about \$18/cc. Quotations received at \$22-25/cc.

Current Lu$_2$O$_3$ price indicates that LYSO price is going down from \$42/cc last year

An Option for CMS FCAL Upgrade

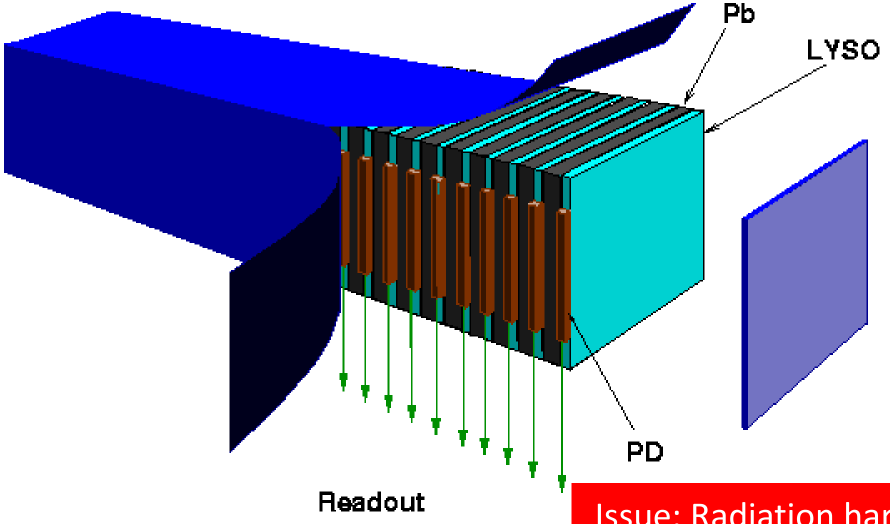


Talk in CMS Forward Calorimeter Taskforce Meeting, CERN, 6/17/2010

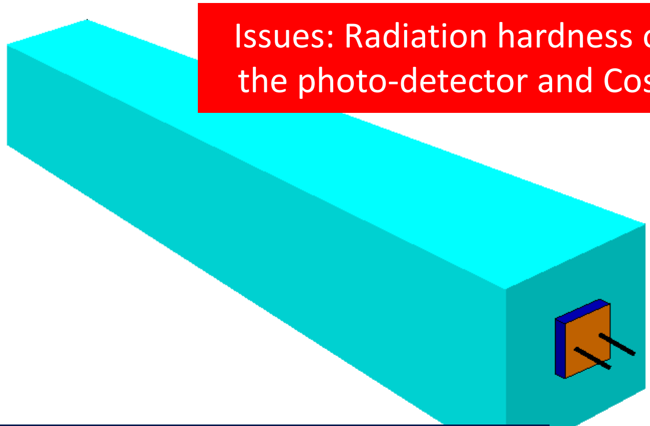


One of two options for CMS Upgrade

Issues: Radiation hardness of photo-detector and WLS fiber



Issues: Radiation hardness of the photo-detector and Cost

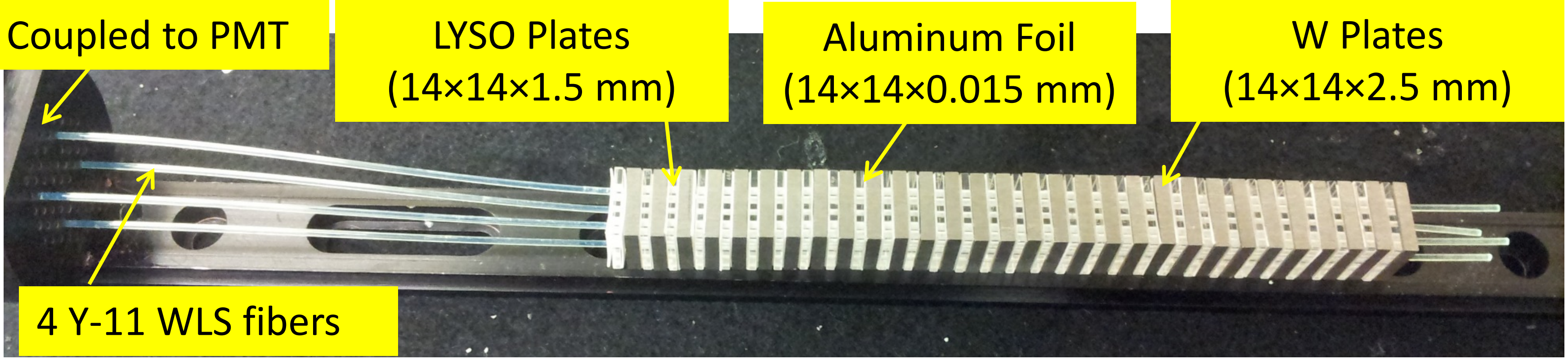


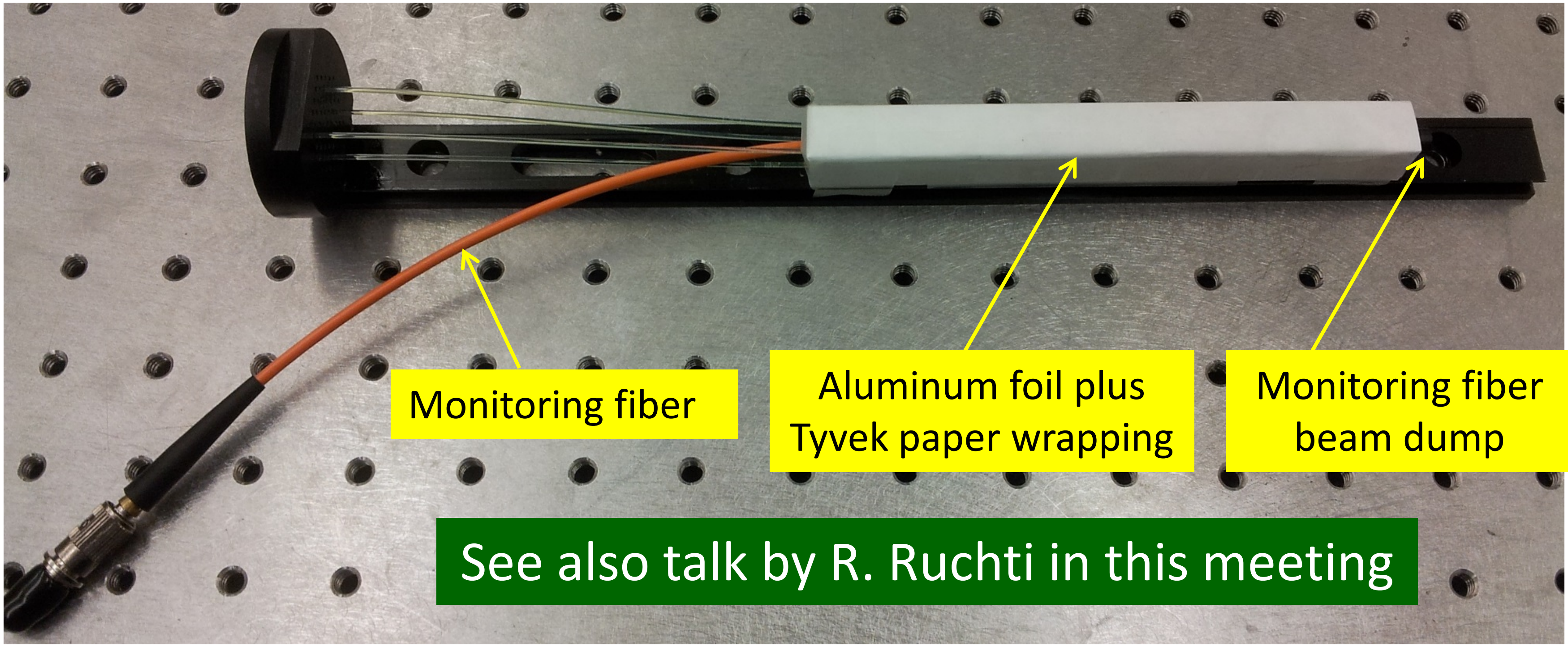
CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 3 m^3

Reduced Crystal Cost & Damage

Issue: Radiation hardness of the photo-detector

A Shashlik Cell Irradiated at JPL

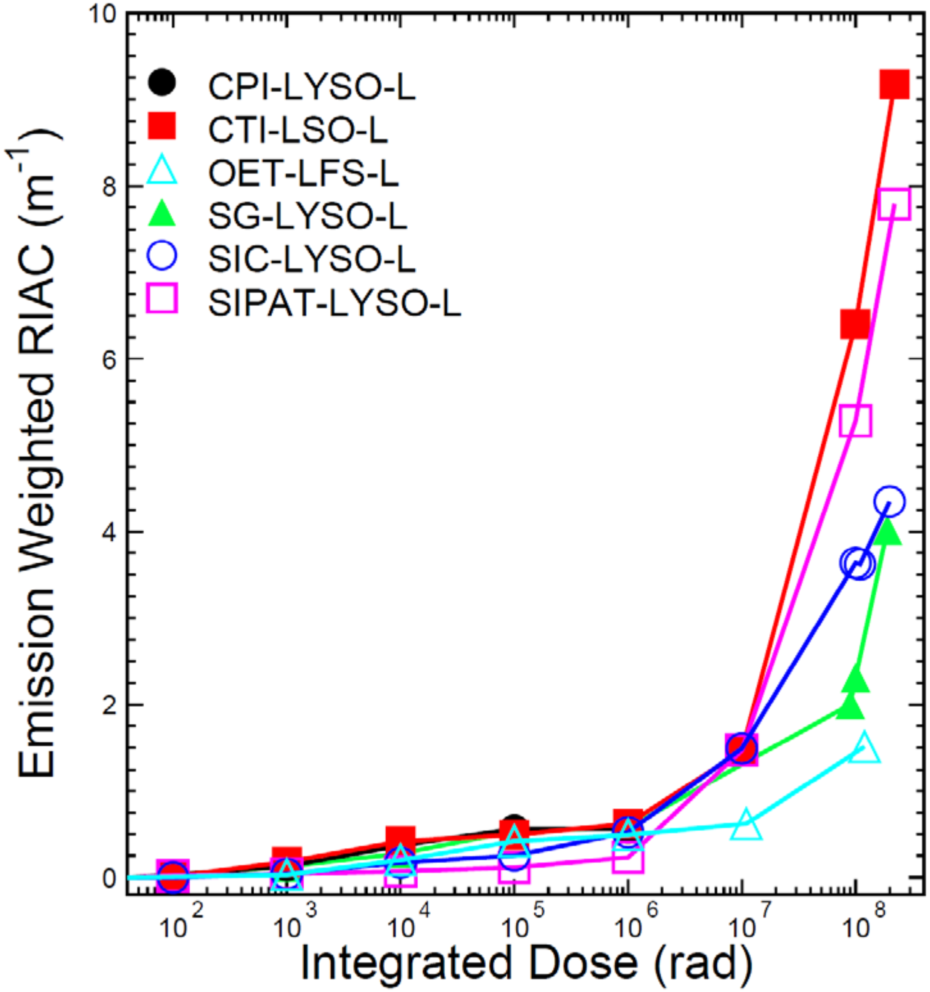


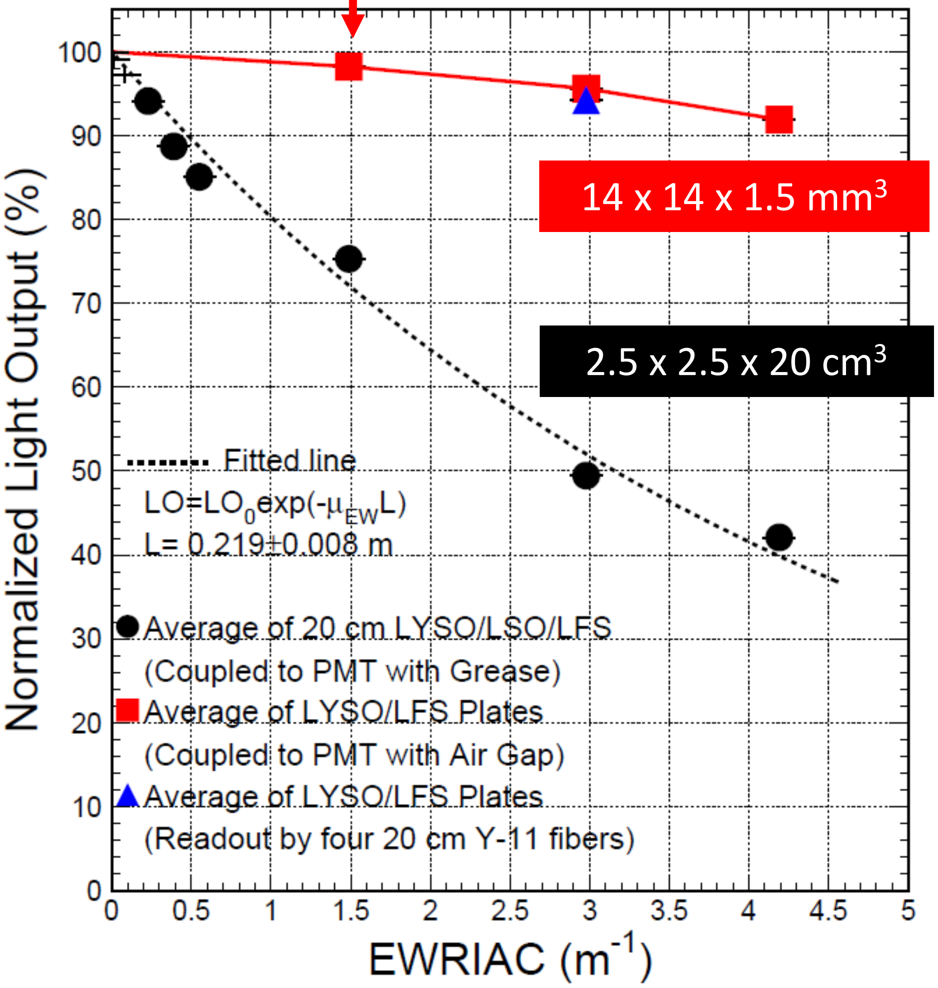


See also talk by R. Ruchti in this meeting

γ-ray Induced Damage in LYSO

OET/Zecotek LFS: EWRIAC = 1.5 m^{-1} after 100 Mrad, corresponding to 25%/2% LO loss for 2.5x2.5x20 cm/14x14x1.5 mm after 100 Mrad



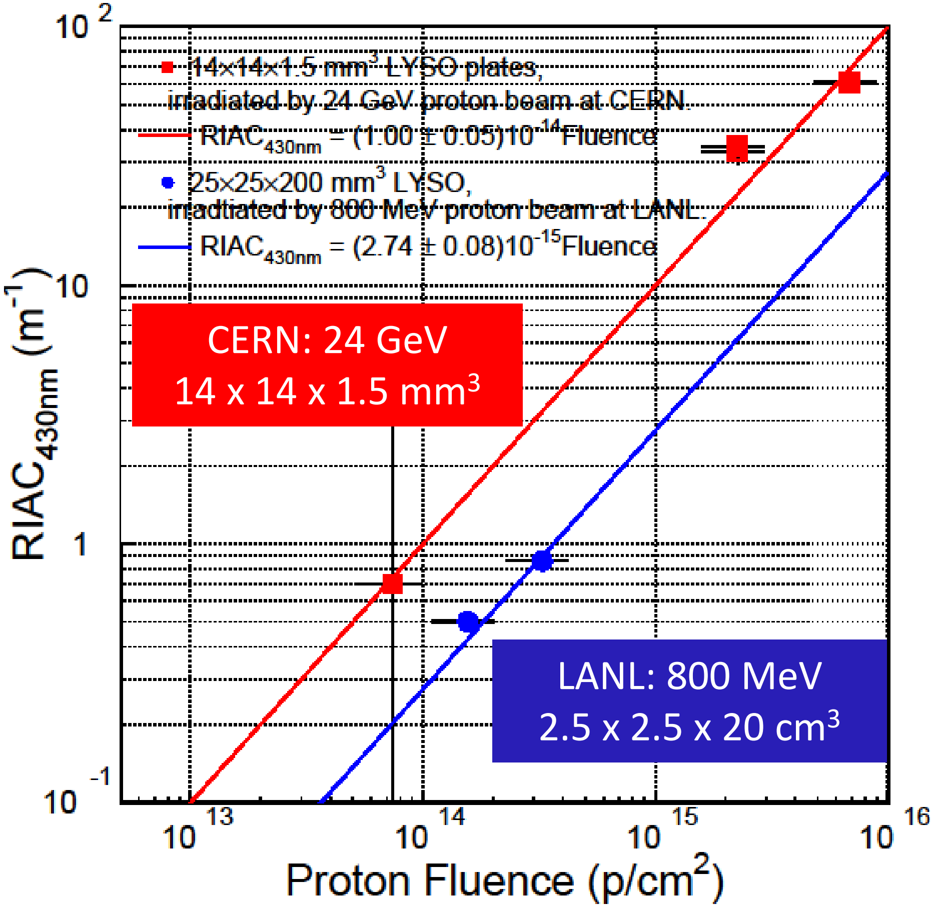


14 x 14 x 1.5 mm^3

2.5 x 2.5 x 20 cm^3

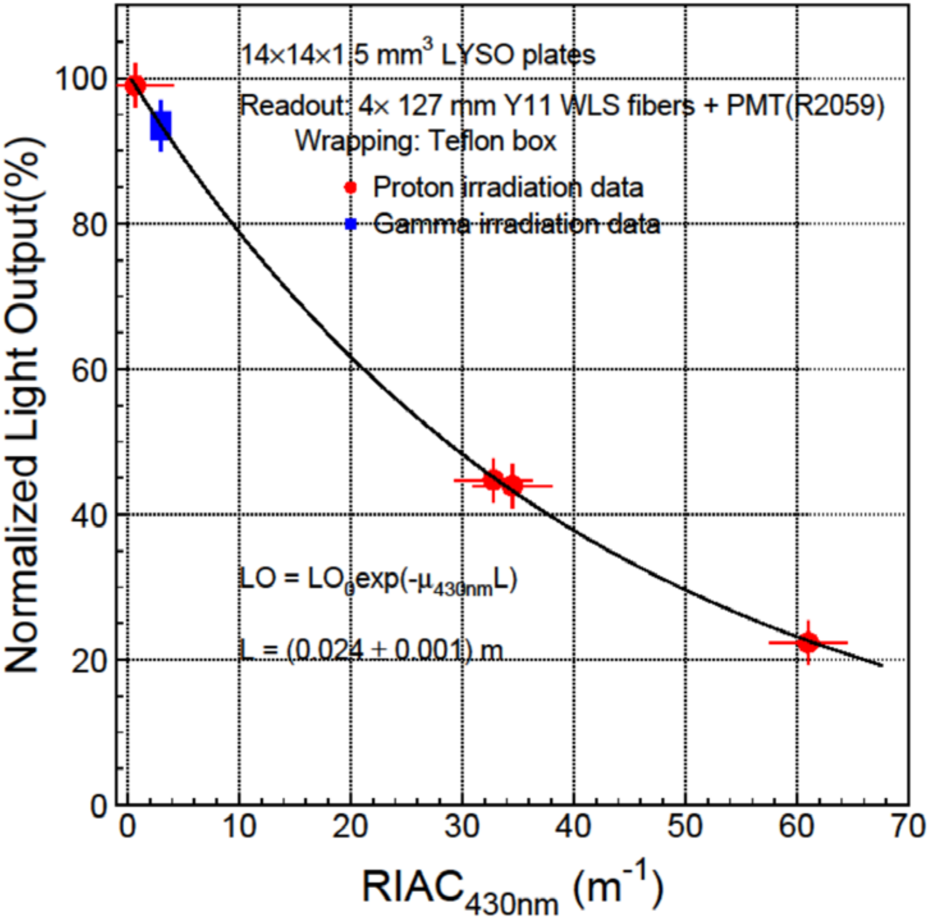
Proton Induced Damage in LYSO

A 2.5x2.5x20 cm and four 14×14×1.5 mm LYSO were irradiated by 800 MeV and 24 GeV protons at LANL and CERN respectively. The expected RIAC at η=3 is about 3 m^{-1}, indicating a light output loss of 4 and 6% respectively for direct and WLS readout.



CERN: 24 GeV
14 x 14 x 1.5 mm^3

LANL: 800 MeV
2.5 x 2.5 x 20 cm^3



Alternative Fast Crystals

Talk in CMS Forward Calorimetry Task Force Meeting, CERN, June 27, 2012

	LSO/LYSO	GSO	YSO①	CsI	BaF_2	CeF_3	$CeBr_3$②	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404) ③
Density (g/cm^3)	7.40	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70[#]
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.70	1.96	2.81	1.88	42.54
Molière Radius (cm)	2.07	2.23	2.93	3.57	3.10	2.41	2.97	3.71	2.85	9.59
Interaction Length (cm)	20.9	22.2	27.9	39.3	30.7	23.2	31.5	37.6	30.4	78.8
Z value	64.8	57.9	33.3	54.0	51.6	50.8	45.6	47.3	45.6	-
dE/dX (MeV/cm)	9.55	8.88	6.56	5.56	6.52	8.42	6.65	5.27	6.90	2.02
Emission Peak[a] (nm)	420	430	420	310	300 220	340 300	371	335	356	408
Refractive Index[b]	1.82	1.85	1.80	1.95	1.50	1.62	1.9	1.9	1.9	1.58
Relative Light Yield[a,c]	100	45	76	4.2 1.3	42 4.8	8.6	141	15 49	153	35
Decay Time[a] (ns)	40	73	60	30 6	650 0.9	30	17	570 24	20	1.8
d(LY)/dT[d] (%/°C)	-0.2	-0.4	-0.3	-1.4	-1.9 0.1	~0	-0.1	0.1	0.2	~0

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 LSO

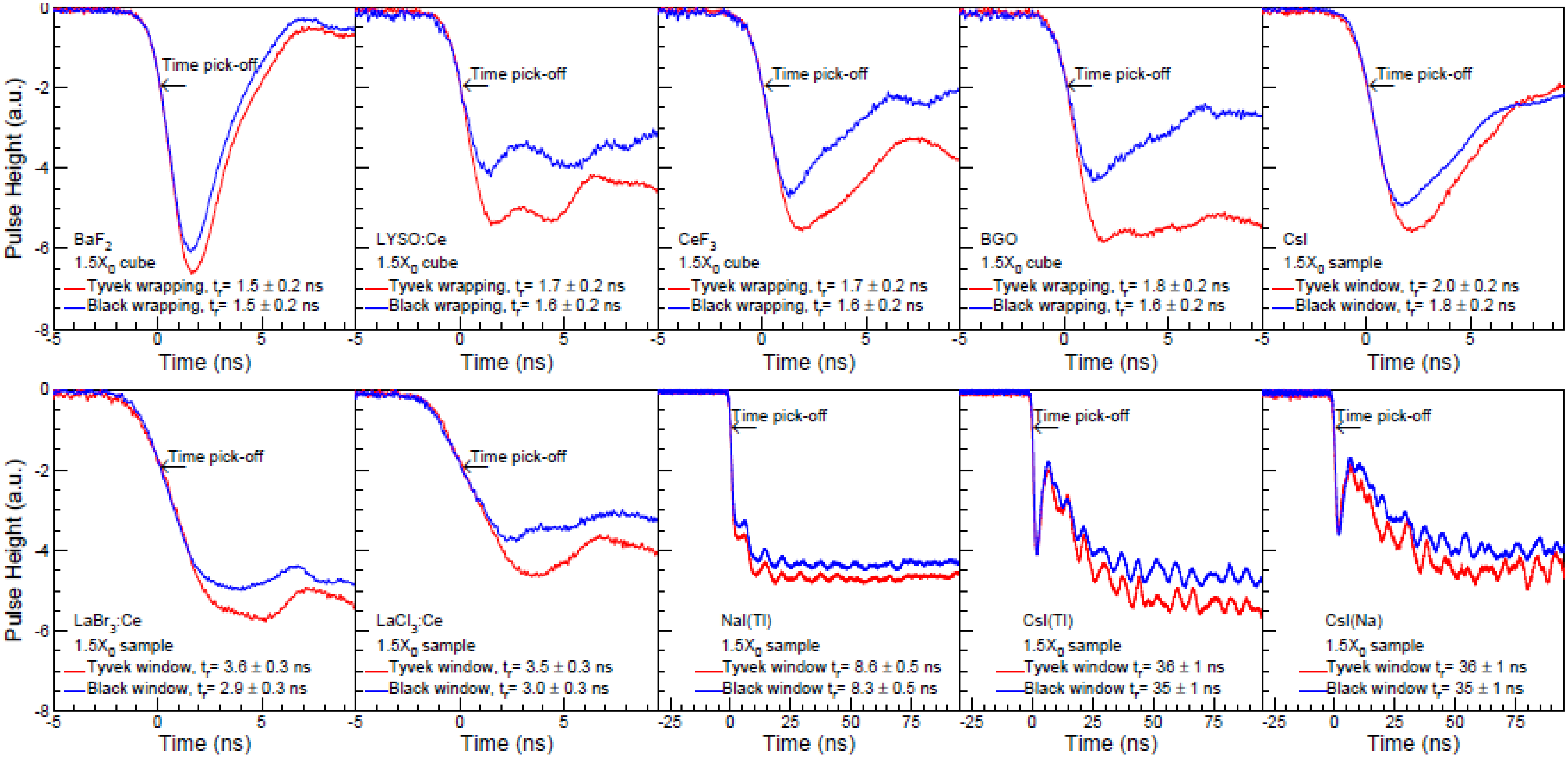
d. At room temperature (20°C)

#. Softening point

1. N. Tsuchida et al ***Nucl. Instrum. Methods Phys. Res. A,*** 385 (1997) 290-298
   http://www.hitachi-chem.co.jp/english/products/cc/017.html
2. W. Drozdowski et al. ***IEEE TRANS. NUCL. SCI***, VOL.55, NO.3 (2008) 1391-1396
   Chenliang Li et al, ***Solid State Commun***, Volume 144, Issues 5–6 (2007),220–224
   http://scintillator.lbl.gov/
3. http://www.detectors.saint-gobain.com/Plastic-Scintillator.aspx
   http://pdg.lbl.gov/2008/AtomicNuclearProperties/HTML_PAGES/216.html

Rising Time for 1.5 X_0 Samples

Talk in the time resolution workshop at U. Chicago, 4/28/2011



Measured rising time is dominated by photo-detector response, and is affected by light propagation in crystals. Rise time of Agilent MSO9254A (2.5 GHz) DSO and Hamamatsu R2059 PMT (2500 V) is 0.14 ns and 1.3 ns respectively.

Figure of Merit for Timing

FoM is calculated as the LY in 1st ns obtained by using light output and decay time data measured for 1.5 X_0 crystal samples

Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF_3	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
$LaBr_3$:Ce	130	100	20			3810	185.8	19.0	229.9
$LaCl_3$:Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5

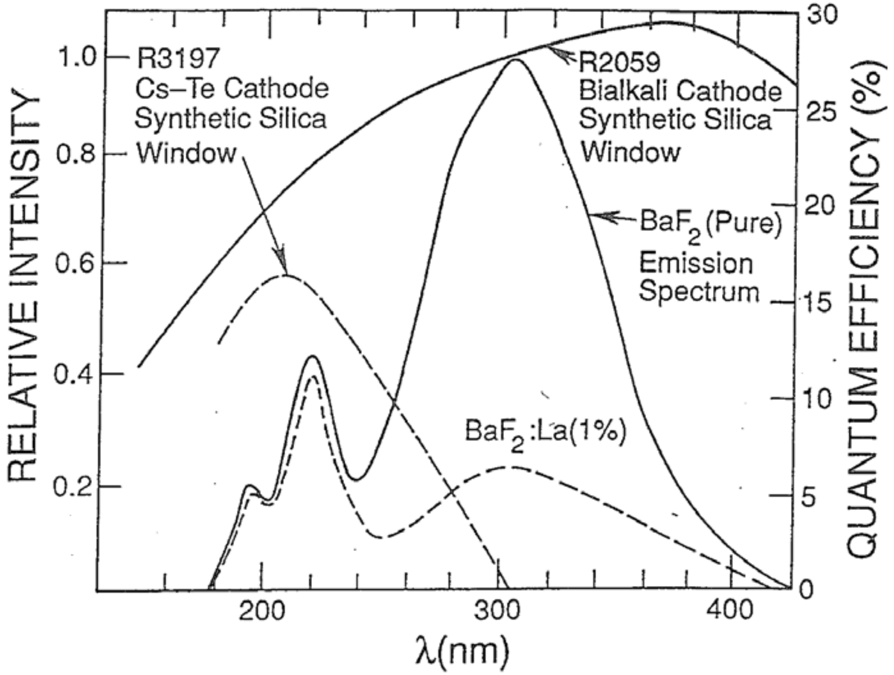
The best crystal scintillator for ultra-fast timing is BaF_2, LSO(Ce/Ca) and LYSO(Ce) with $LaBr_3$ and $CeBr_3$ as materials of high potential

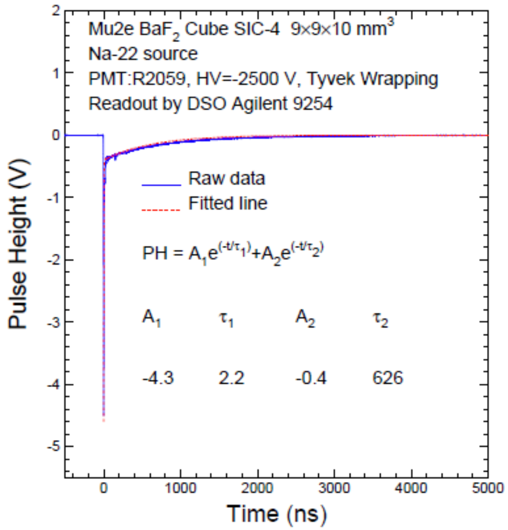
BaF_2 for Mu2e Calorimeter

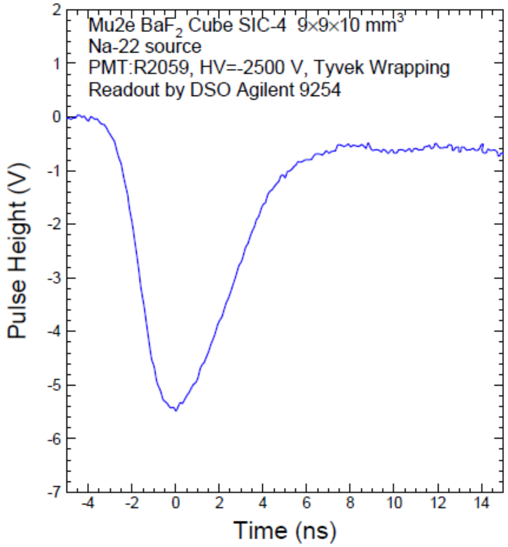
"On Quality Requirements to the Barium Fluoride-Crystals"
NIMA **340** (1994) 442-457

The light output of the BaF_2 fast component at 220 nm with sub-ns decay time is sufficient for the Mu2e experiment.

R&D on going in two directions for Spectroscopic selection of the fast component: (1) solar blind photo-detector; and (2) selective doping.



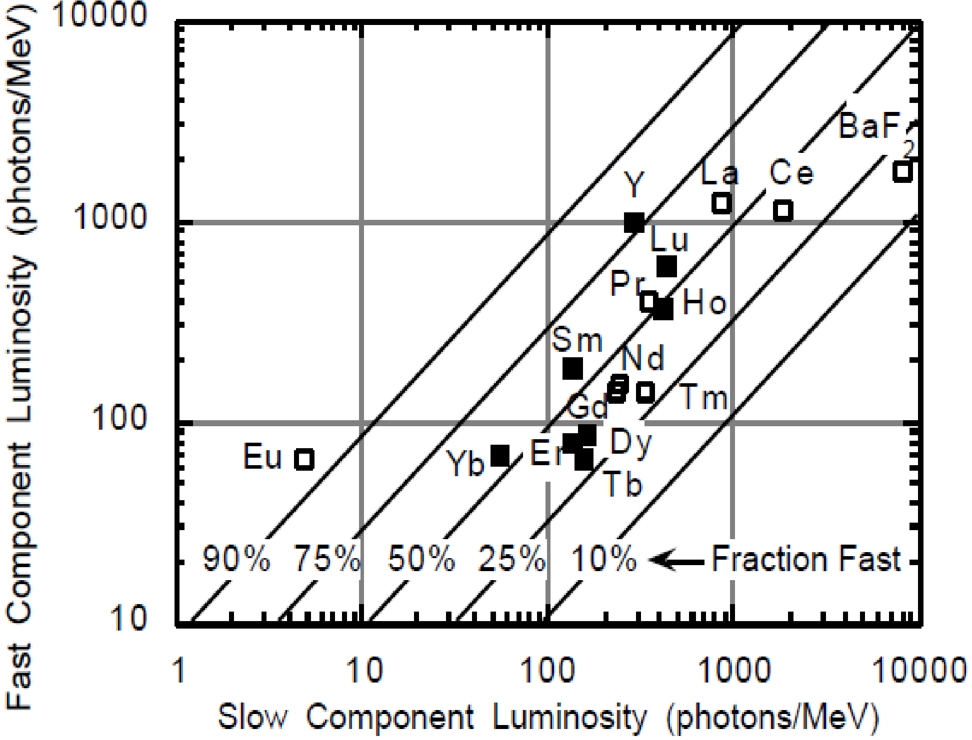


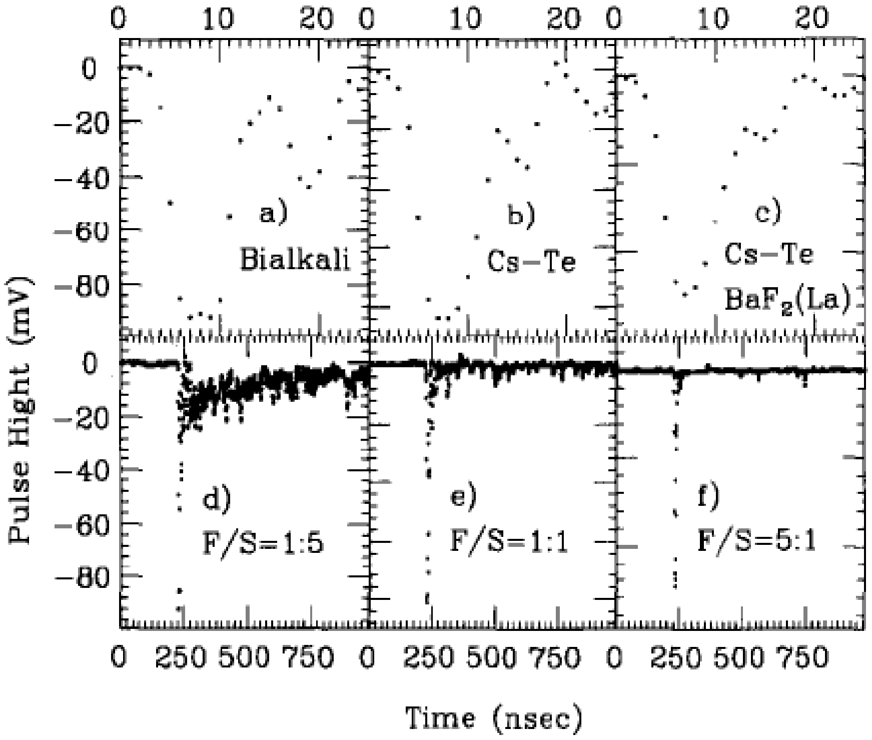


Slow Suppression: Doping and Readout

RE doping is effective in improving the F/S ratio for $Ba_{0.9}R_{0.1}F_2$ powders

B.P. SOBOLEV et al., "SUPPRESSION OF BaF2 SLOW COMPONENT OF X-RAY LUMINESCENCE IN NON-STOICHIOMETRIC Ba0.9R0.1F2 CRYSTALS (R=RARE EARTH ELEMENT)," *Proceedings of The Material Research Society: Scintillator and Phosphor Materials,* pp. 277-283, 1994.





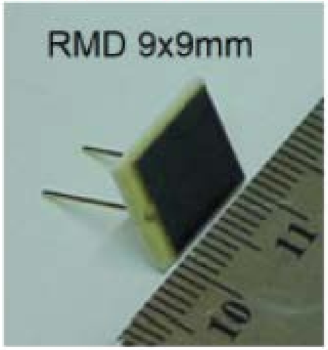
The 1st batch of doped samples will be delivered late October

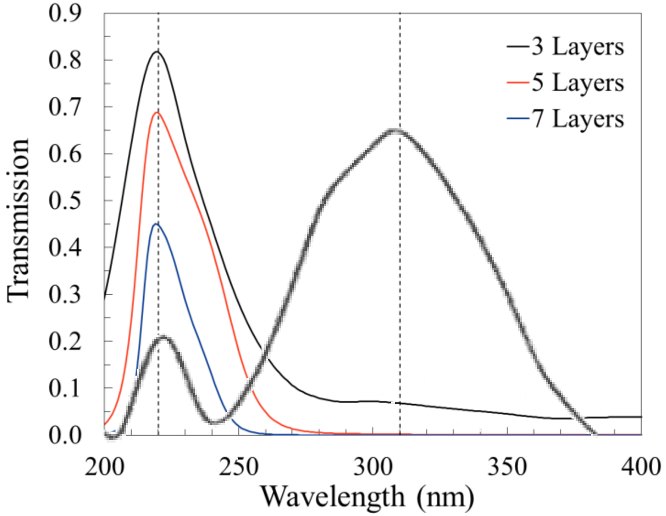
Z. Y. Wei, R. Y. Zhu, H. Newman, and Z. W. Yin, "Light Yield and Surface-Treatment of Barium Fluoride-Crystals," *Nucl Instrum Meth B,* vol. 61, pp. 61-66, Jul 1991.

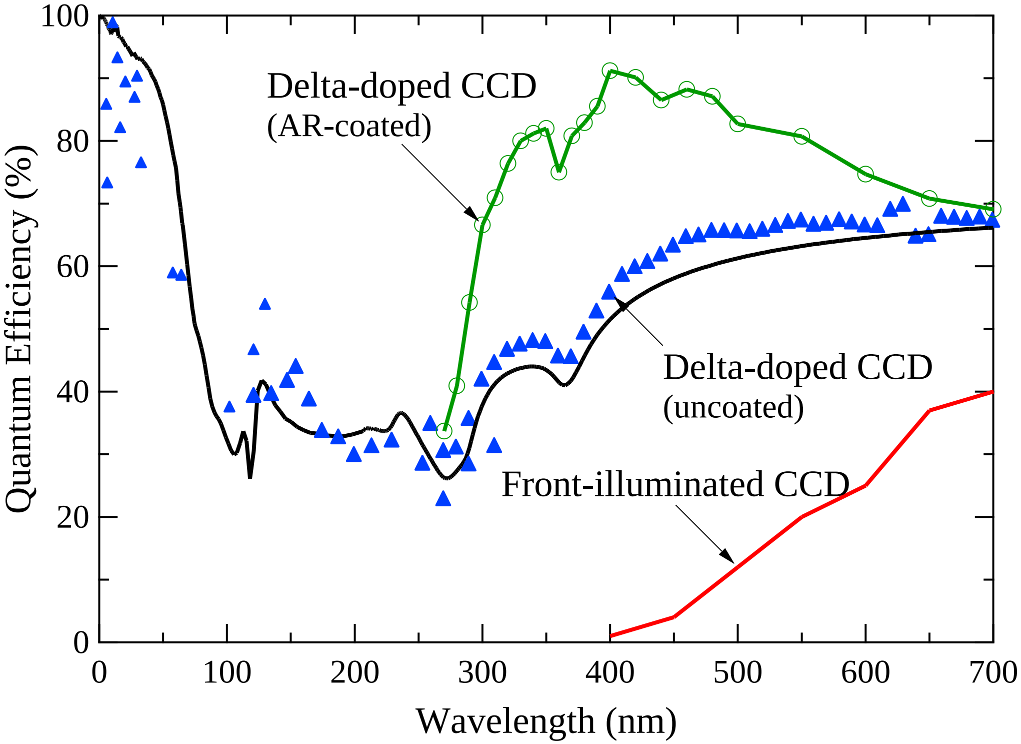
Solar Blind UV APD

A Caltech/JPL/RMD consortium is developing large area RMD APD into a delta-doped super lattice APD with high QE @ 220 nm as well as an ALD antireflection filter to reduce > 300 nm. See D. Hitlin talk in this meeting.

deltadoped APD from RMD



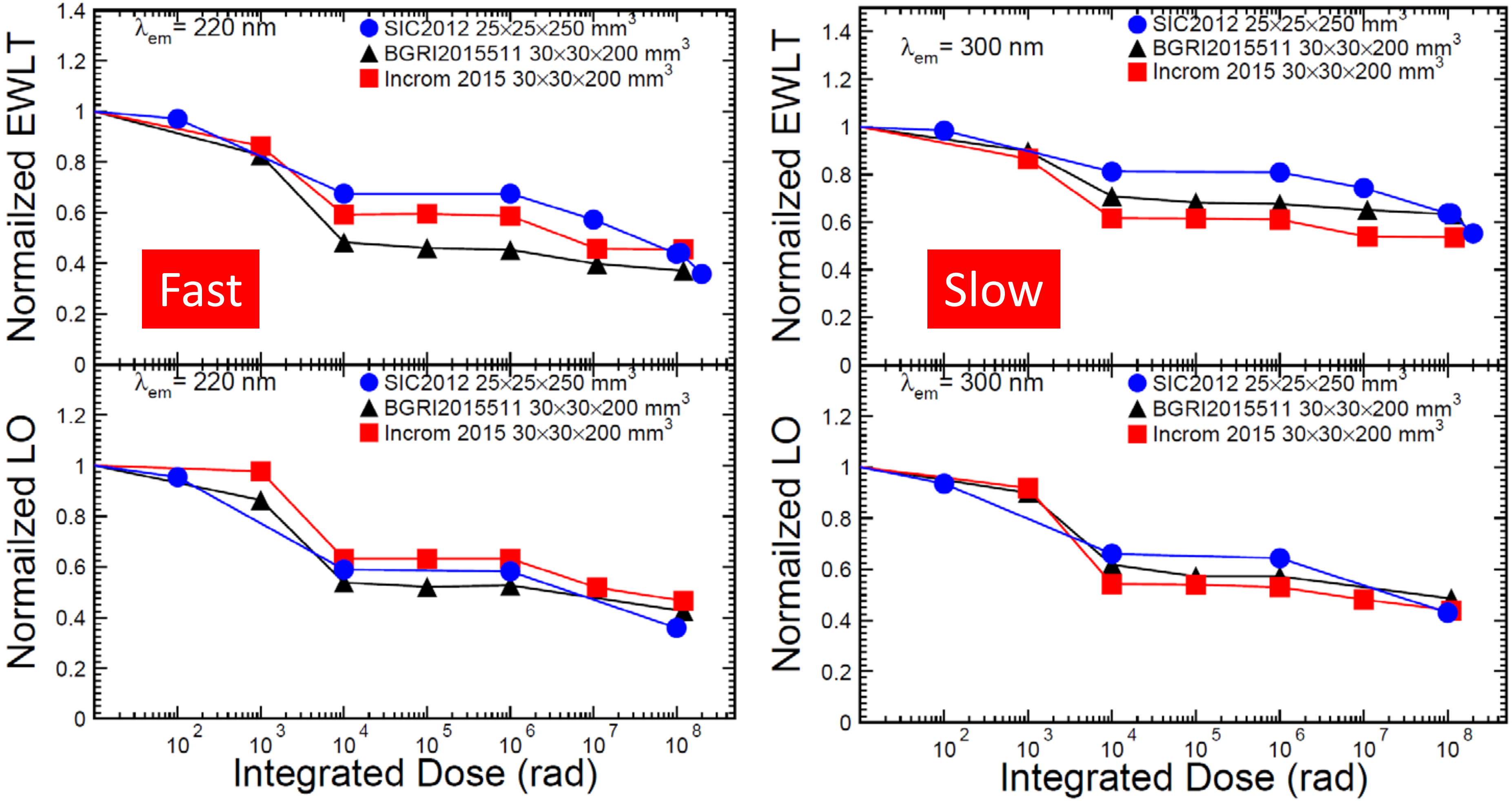




S. Nikzad, "Ultrastable and uniform EUV and UV detectors," *SPIE Proc.*, Vol. 4139, pp. 250-258 (2000).

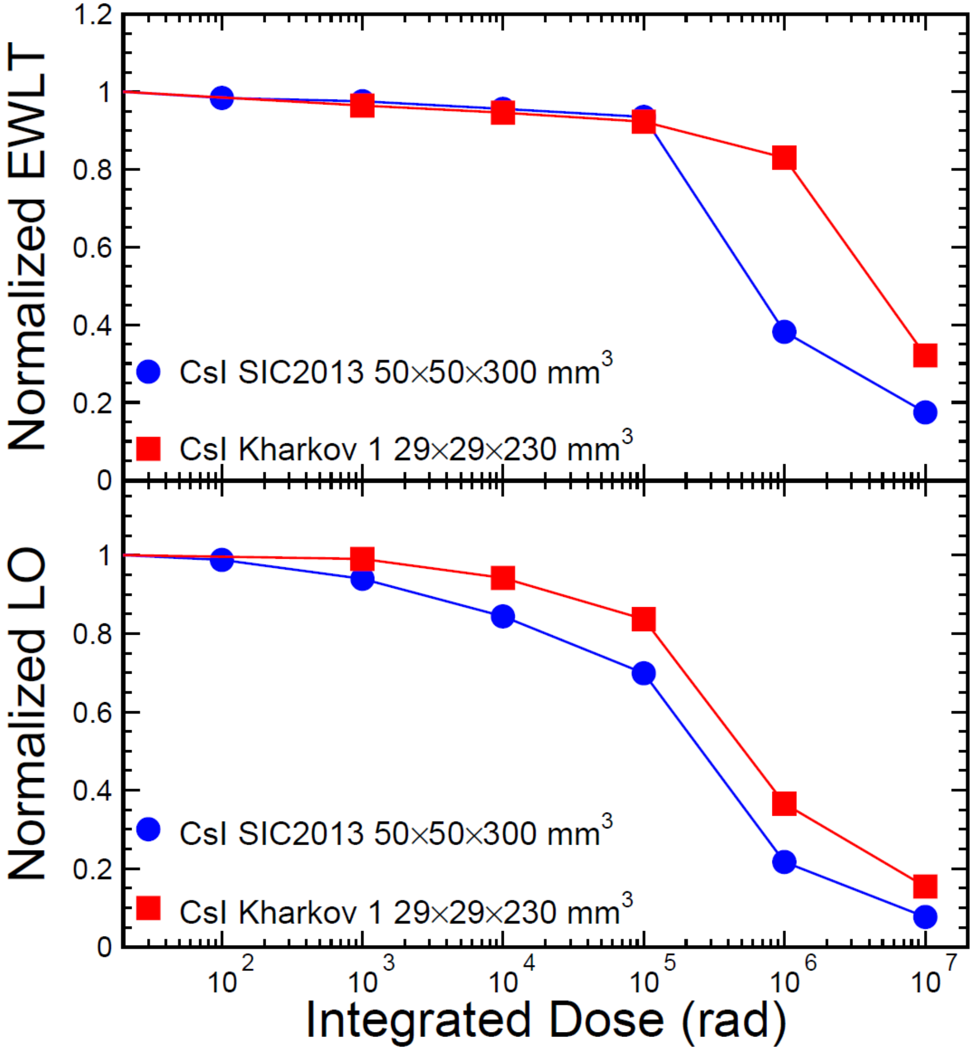
γ-ray Induced Damage in BaF_2

Consistent radiation hardness in crystals from three vendors



BaF2 crystals are radiation hard up to 120 Mrad

γ-ray Induced Damage in CsI



Consistent radiation hardness from two vendors: no significant degradation in LO and LRU up to 100 krad.

Cost-Effective Scintillating Ceramics

1964—The 1st Ceramic Laser CaF_2:Dy
- Hatch et al., *Appl. Phys. Lett.* 5, 153 (1964)

1980's—The 1st Ceramic Scintillator** (**Y,Gd)$_2$O$_3$:Eu
- Greskovich C et al. *Am. Ceram. Soc. Bull.* 71, 1120 (1992)

1985—1st Ceramic YAG ($Y_3Al_5O_{12}$)
- G. de With and H.J.A. van Dijk, *Meter. Sci. Bull.*, 19, 1669 (1985).

1988—The Gd_2O_2S:Pr,Ce Ceramic Scintillator
- Yukio Ito et al. *Japanese Journal of Applied Physics* . 27, 1371 (1988)

1997—Ce doped YAG scintillating ceramics ($Y_3Al_5O_{12}$)
- E. Zych et al. *J. Lumin.*, 75, 193 (1997)

2002—Lu_2O_3:Eu scintillating ceramics
- A. Lempicki et al. *Nucl. Inst. Meth. A*488, 579 (2002)

2007—LuAG:Ce scintillating ceramics ($Lu_3Al_5O_{12}$)
- N. J. Cherepy et al. *Nucl. Inst. Meth. A.*, 579, 38 (2007).

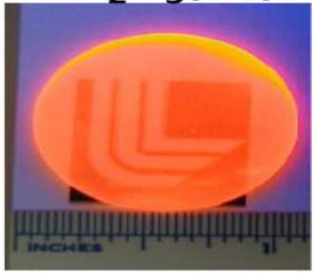
2009—LuAG:Pr scintillating ceramics ($Lu_3Al_5O_{12}$)
- T. Yanagida et al. *IEEE Trans. Nucl. Sci.*, 56 , 2955 (2009).

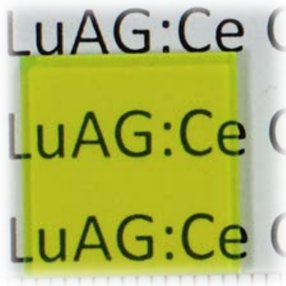
2010—GYGAG:Ce scintillating ceramics (Lu3Al5O12)
- N. J. Cherepy et al. *Proc. SPIE*, 7805, 7805(2010).

YAG:Nd Ceramics

10x10x2 cm with 0.3 at. % Nd:YAG ceramic slab

Lu_2O_3(Eu)





GYGAG(Ce)

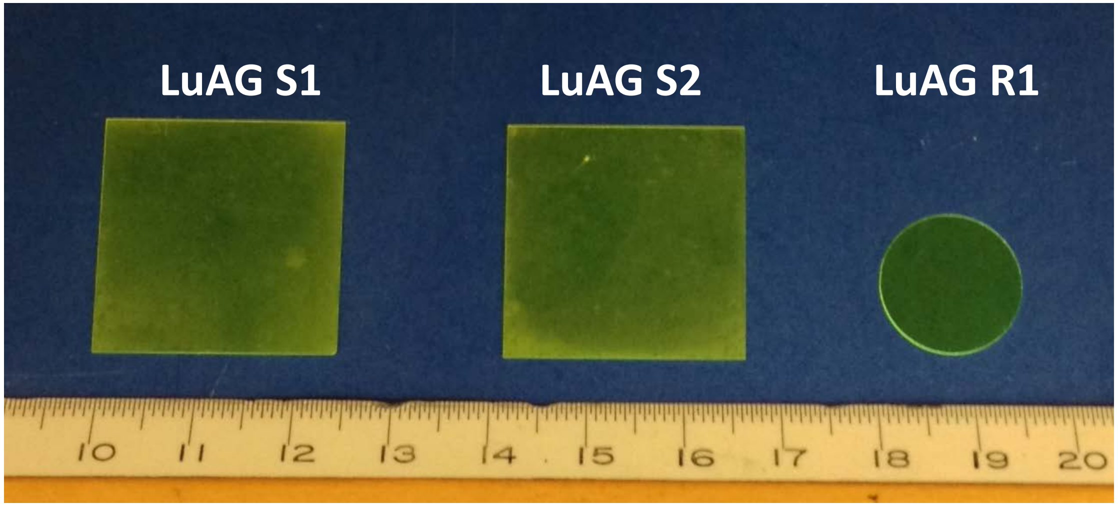
Properties of Scintillating Ceramics

Ceramics	$Y_{1.4}Gd_{0.6}O_3$:Eu①	Gd_2O_2S:Pr,Ce,F①	YAG:Ce②	Lu_2O_3:Eu③,④	LuAG:Ce⑤	LuAG:Pr⑥	$Gd_{1.5}Y_{1.5}Ga_2Al_3O_{12}$:Ce⑦,⑧
Density (g/cm^3)*	5.92	7.34	4.57	9.42	6.76	6.76	5.80
Radiation Length (cm)*	1.73	1.16	3.53	0.81	1.45	1.45	2.11
Molière Radius (cm)*	2.44	2.13	2.76	1.72	2.15	2.15	2.43
Interaction Length (cm)*	24.5	22.3	25.2	18.1	20.6	20.6	22.4
Z value*	49.2	60.1	30.0	68.0	60.3	60.3	45.4
dE/dX (MeV/cm)*	8.02	9.30	7.01	11.6	9.22	9.22	8.32
Emission Peak (nm)	610	510	526	611	520	310	560
Light Yield (photons/MeV)	38000	43000	20000	90000	16000	22000	50000
Decay time (ns)	1000	3000	80 263 >5000	1600	37	20 770	100

* Data based on crystals

1. *C. Greskovich and S. Duclos,* **CERAMIC SCINTILLATORS**, *Annu. Rev. Mater. Sci. 27(1997)*
2. Takayuki Yanagida et al, **Evaluation of Properties of YAG (Ce) Ceramic Scintillators**, *IEEE TRANSACTIONS ON NUCLEAR SCIENCE*, 52(2005)
3. Y. Shi et al., **Processing and scintillation properties of Eu3+ doped Lu2O3 transparent ceramics**. *Opt Mater,* 31(2009)
4. Qiwei Chen et al. **Fabrication and Photoluminescence Characteristics of Eu-Doped Lu2O3 Transparent Ceramics**, *J. Am. Ceram. Soc*., 89(2006)
5. Takayuki Yanagida et al, **Scintillation properties of LuAG (Ce) ceramic and single crystalline scintillator,** *Nuclear Science Symposium Conference Record (NSS/MIC), 2010 IEEE*
6. Takayuki Yanagida et al, **Scintillation Properties of Transparent Ceramic Pr:LuAG for Different Pr Concentration**, *IEEE TRANSACTIONS ON NUCLEAR SCIENCE,* 59(2012)
7. N. J. Cherepy et al, **Development of Transparent Ceramic Ce-Doped Gadolinium Garnet Gamma Spectrometers**, *IEEE TRANSACTIONS ON NUCLEAR SCIENCE*, 60(2013)
8. N. J. Cherepy et al, **Transparent Ceramics Scintillators for Gamma Spectroscopy and MeV Imaging**, *Proc. SPIE* 9593

Recent SIC LuAG:Ce Samples



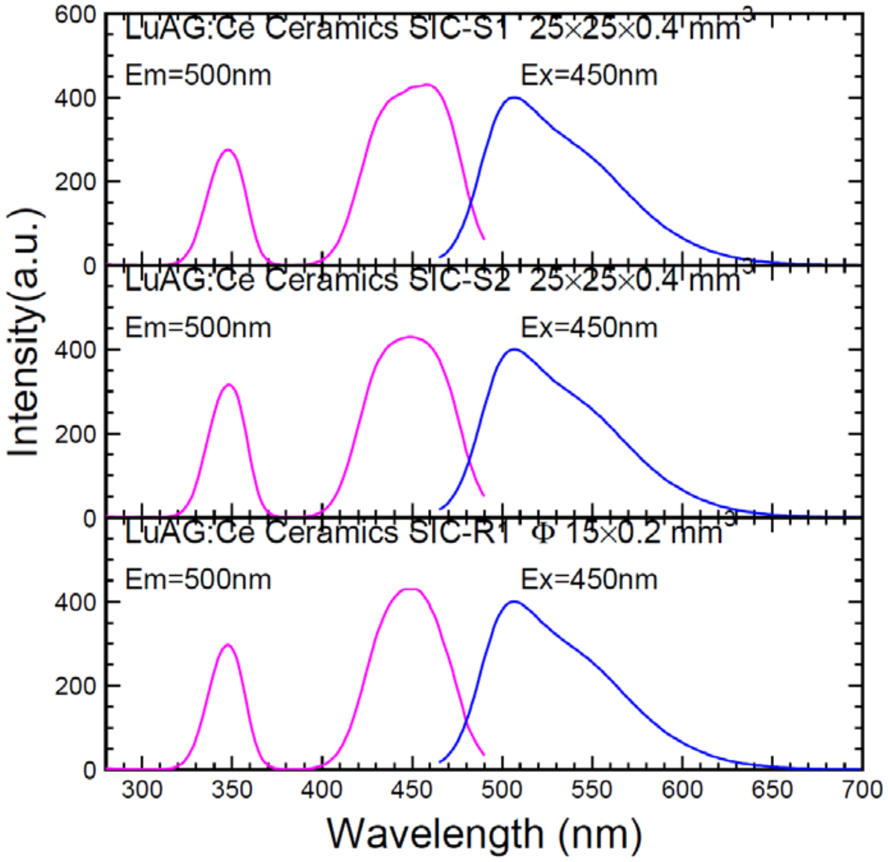
Sample ID	Dimension (mm)	Polishing
LuAG S1	25×25×0.4	Two surfaces
LuAG S2	25×25×0.4	Two surfaces
LuAG RI	Φ15×0.2	Two surfaces

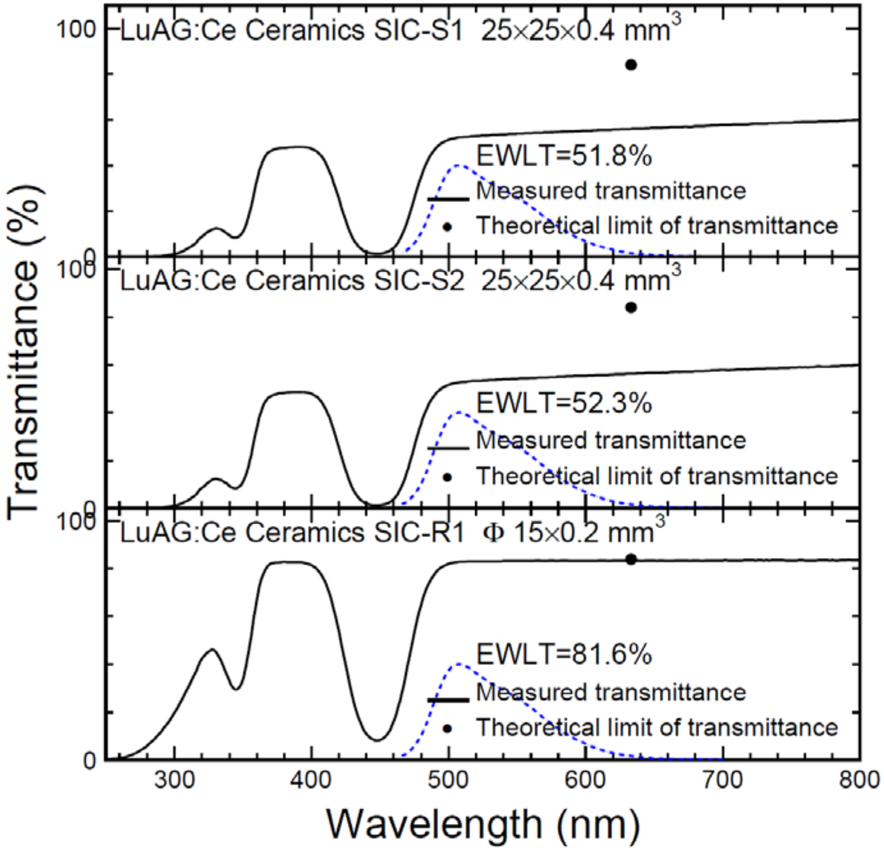
Experiments

- Properties measured at room temperature: Transmittance, Photo-luminescence, Light Output, Decay Time and Radiation Damage

PL and Transmittance

Two excitation peaks at 350 and 450 nm and one emission peak at 500 nm

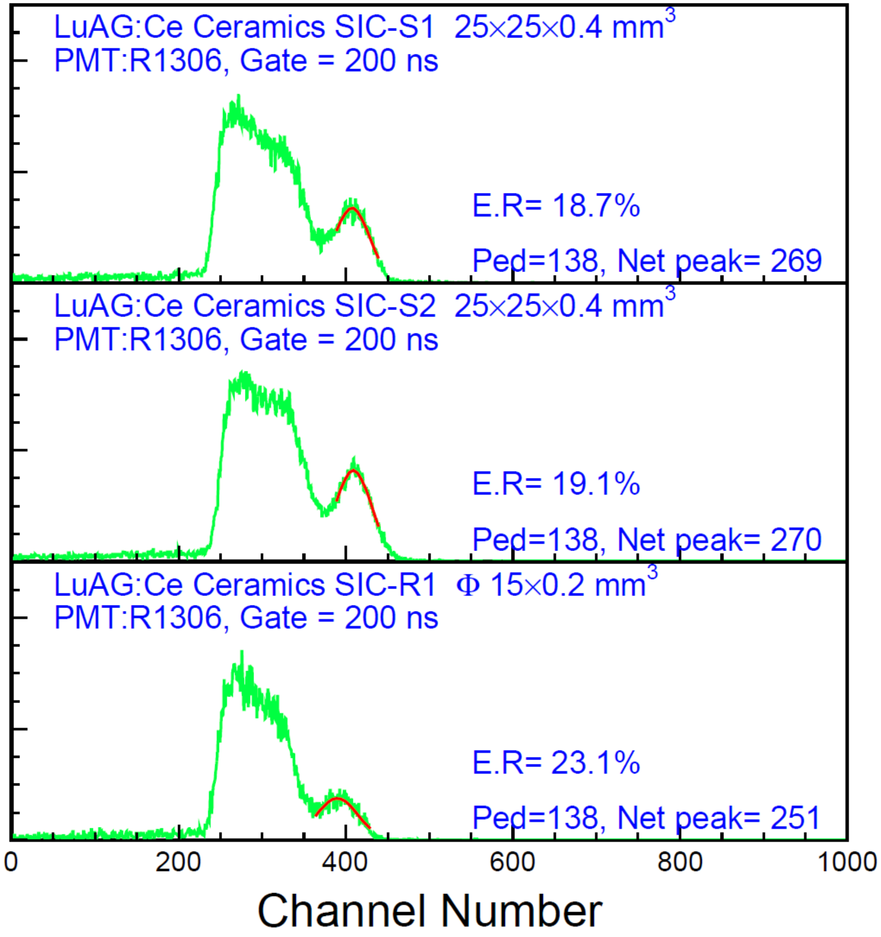


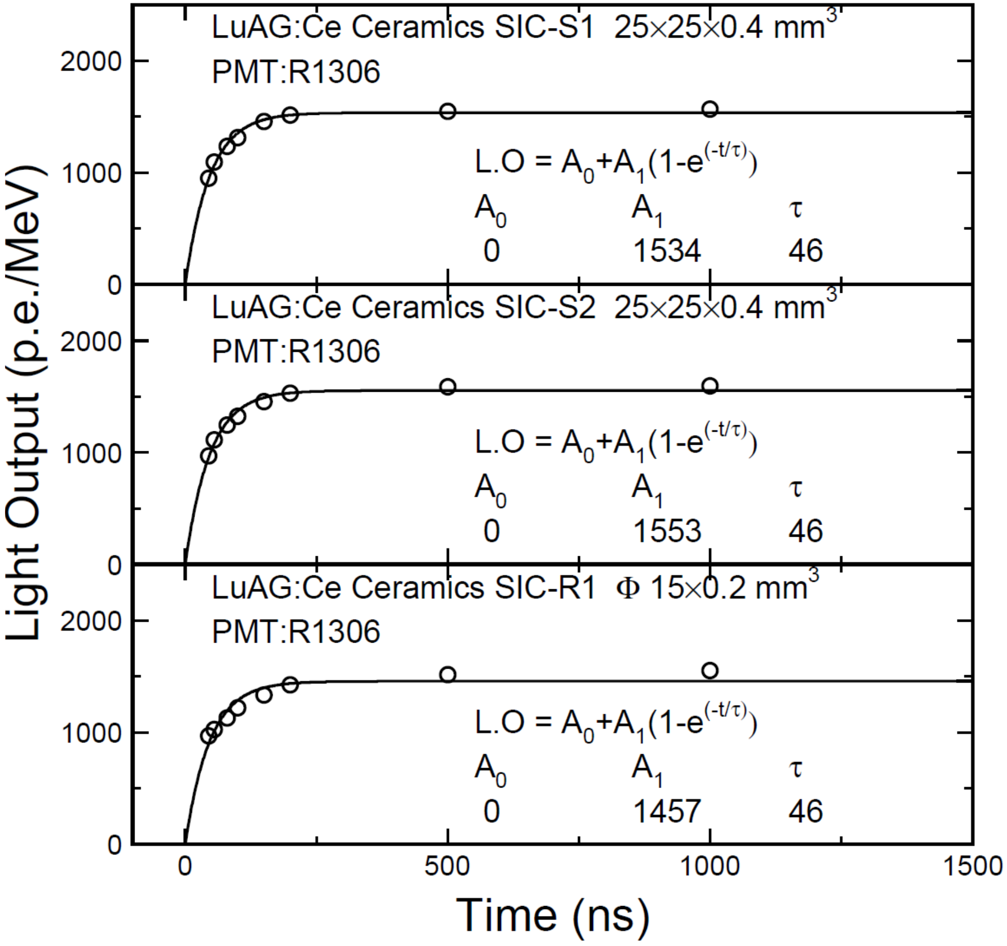


Good Optical quality of the 0.2 mm sample approaching theoretical limit
Scattering centers observed in 0.4 mm samples

PHS, Light Output and Decay Time

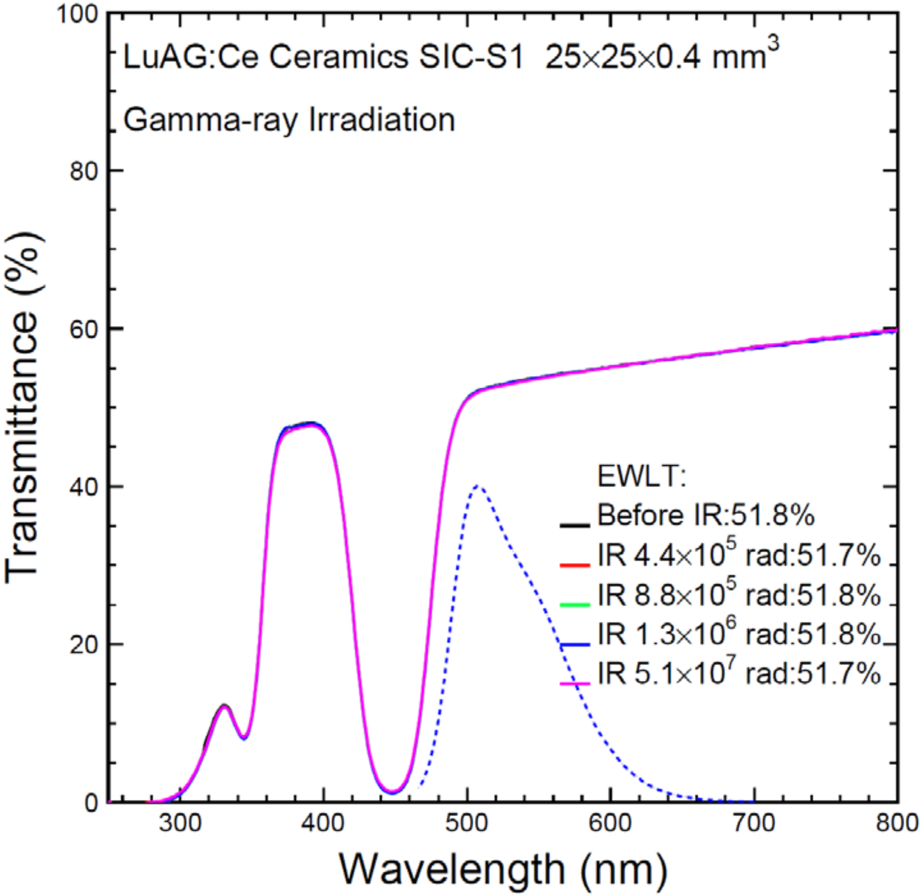
Cs-137 peaks: 20% resolution, 1,500 p.e./MeV and 46 ns decay time

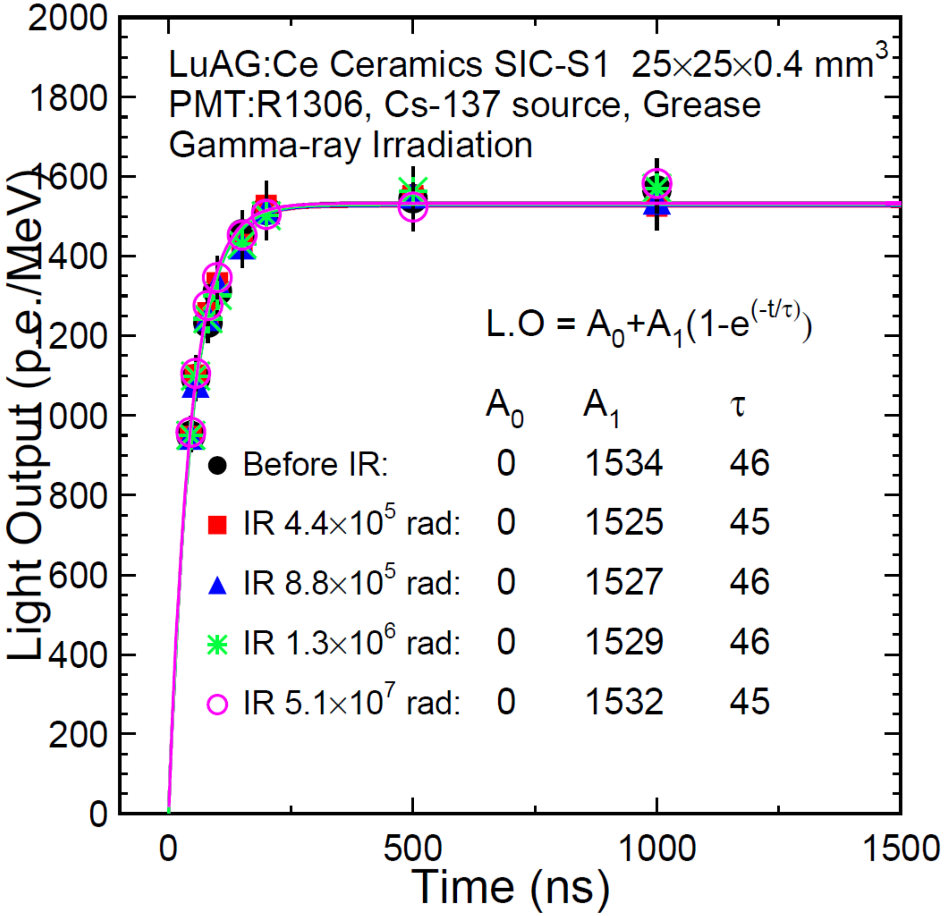




Excellent Radiation Hardness

No damage up to 51 Mrad in both transmittance and light output





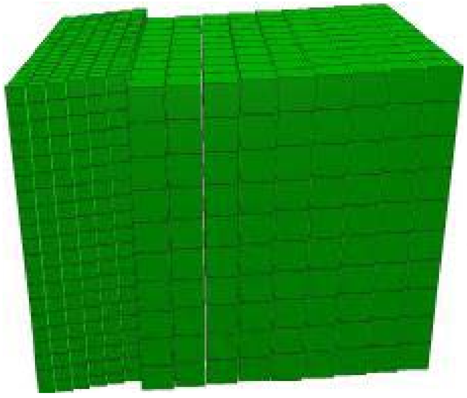
$L.O = A_0+A_1(1-e^{(-t/\tau)})$

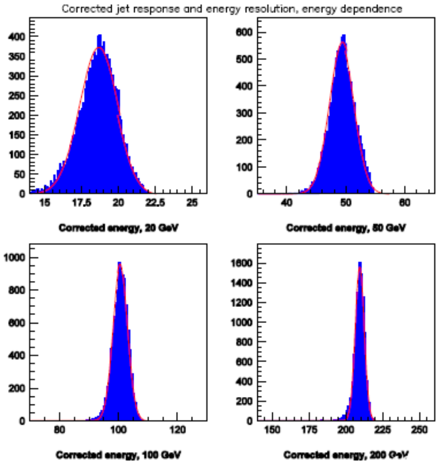
	A_0	A_1	τ
● Before IR:	0	1534	46
■ IR 4.4×10^5 rad:	0	1525	45
▲ IR 8.8×10^5 rad:	0	1527	46
✳ IR 1.3×10^6 rad:	0	1529	46
○ IR 5.1×10^7 rad:	0	1532	45

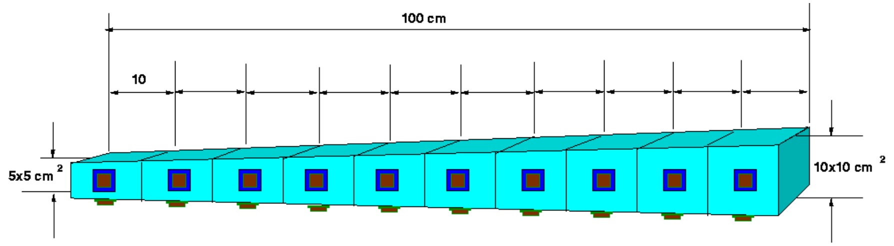
Very promising for a scintillating ceramics based calorimeter

Homogeneous Hadronic Calorimeter

A Fermilab team (A. Para et al.) proposed a total absorption homogeneous hadronic calorimeter (HHCAL) detector concept to achieve good jet mass resolution by measuring both Cherenkov and Scintillation light.







ILCWS-08, Chicago: a HHCAL cell with pointing geometry

Requirements for the Materials:

- Cost-effective material: for 70~100 m^3
- Short nuclear interaction length: ~ 20 cm.
- Good UV transmittance: UV cut-off < 350 nm, for readout of Cherenkov light.
- Some scintillation light, not necessary bright and fast.
- Discrimination between Cherenkov and scintillation lights, in spectral or temporal domain.

See Adam's talk in this meeting

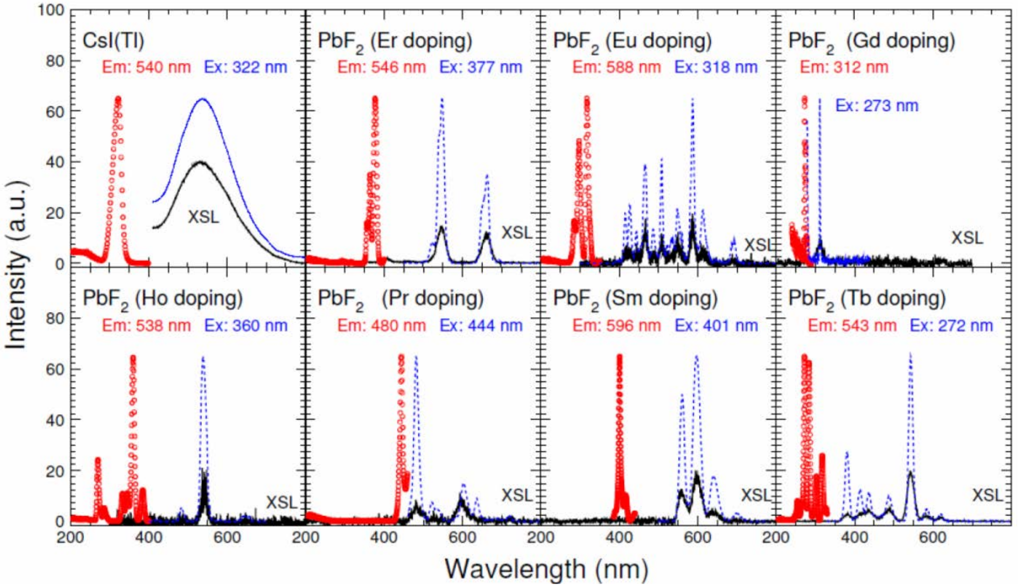
Candidate Crystals for HHCAL

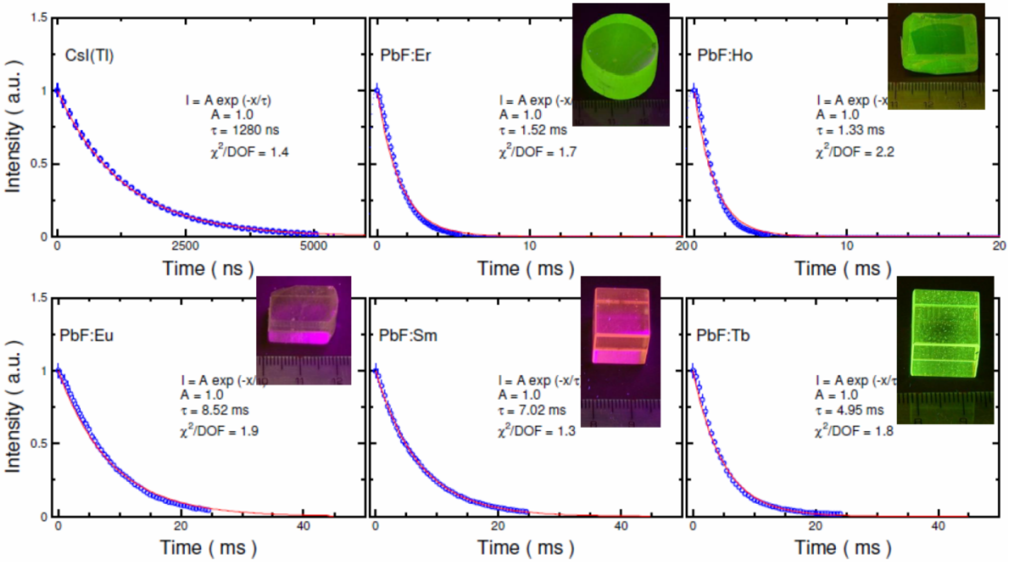
Cost-effective, UV transparent crystals with both scintillation and Cherenkov light

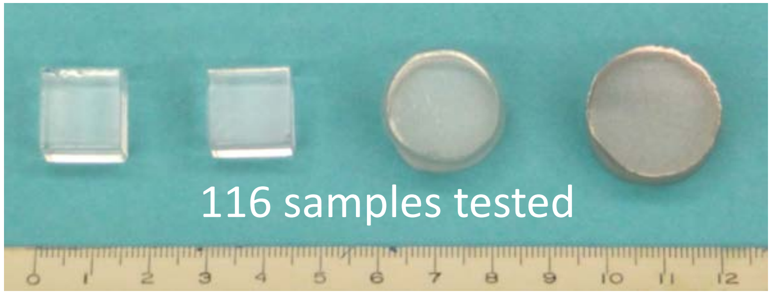
Parameters	$Bi_4Ge_3O_{12}$ (BGO)	$PbWO_4$ (PWO)	PbF_2	PbClF	$Bi_4Si_3O_{12}$ (BSO)
ρ (g/cm^3)	7.13	**8.29**	**7.77**	7.11	6.8
λ_I (cm)	22.8	**20.7**	**21.0**	24.3	23.1
n @ λ_{max}	2.15	2.20	1.82	2.15	2.06
τ_{decay} (ns)	300	30/10	**?**	30	100
λ_{max} (nm)	480	425/420	**?**	420	470
Cut-off λ (nm)	**310**	350	**250**	**280**	**300**
Light Output (%)	100	1.4/0.37	**?**	17	20
Melting point (°C)	**1050**	**1123**	**842**	**608**	**1030**
Raw Material Cost (%)	100	49	**29**	**29**	47

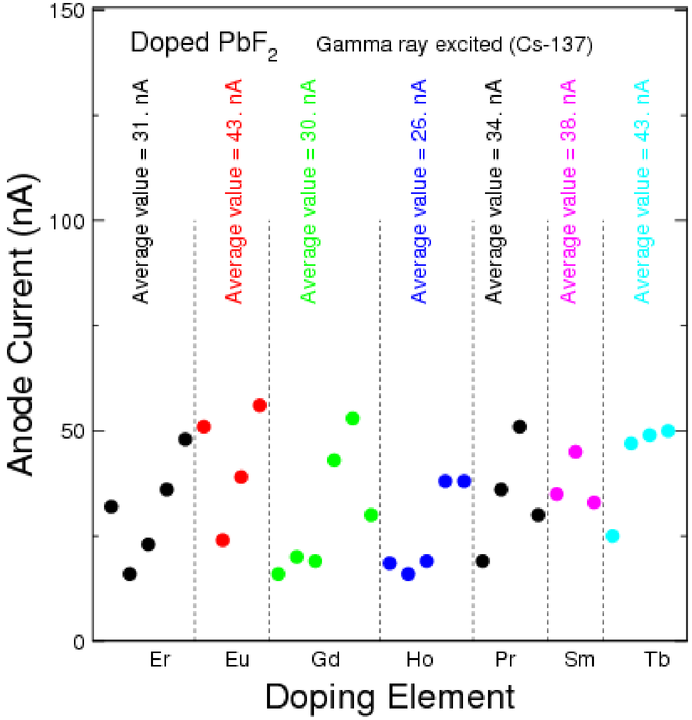
IEEE Trans. Nucl. Sci. **59** *(2012) 2229-2236*

Search for Scintillation in Doped PbF_2



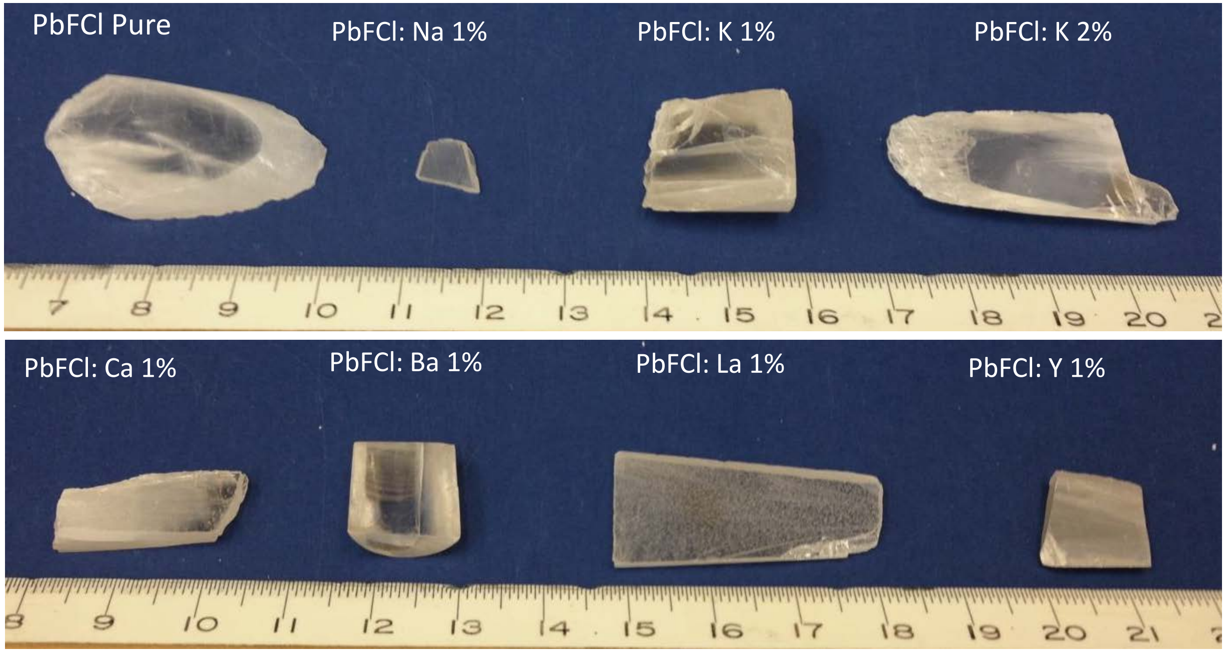


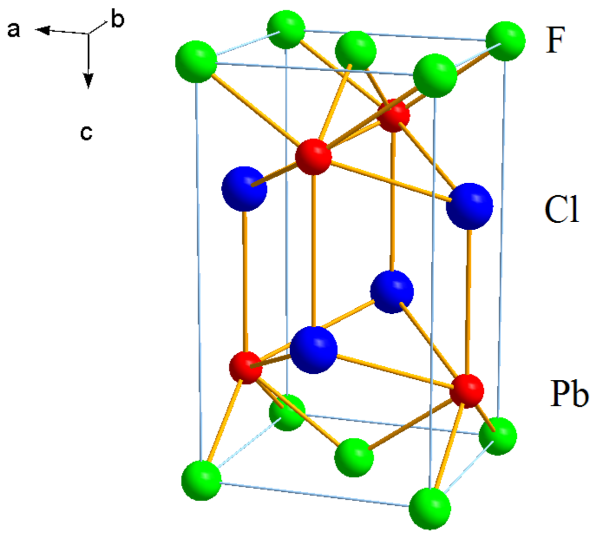




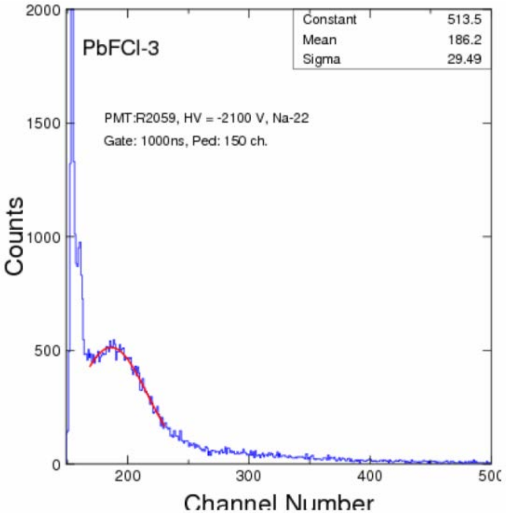
IEEE Trans. Nucl. Sci. NS-59 (2012) 2229-2236, also in NSS2012

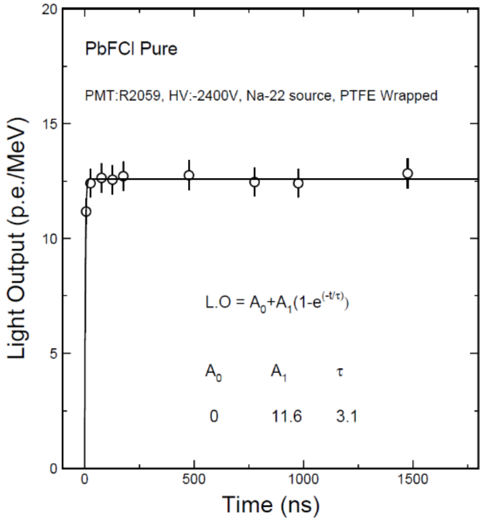
Pure and Doped PbFCl

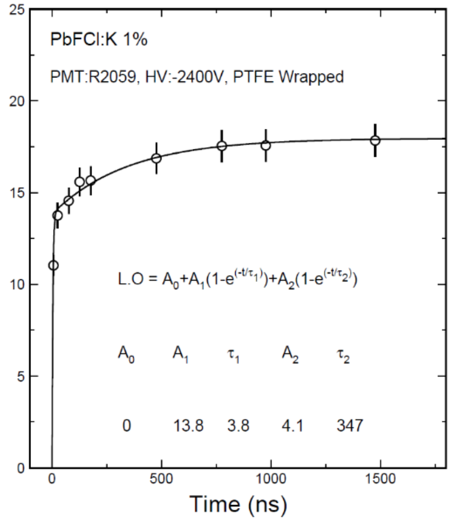


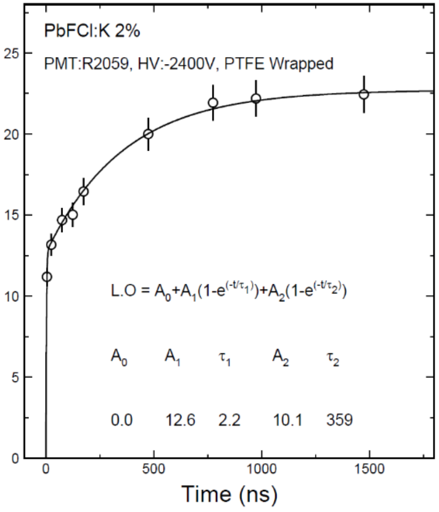


IEEE Trans. Nucl. Sci. NS-61 (2014) 489-494, also in SCINT2013





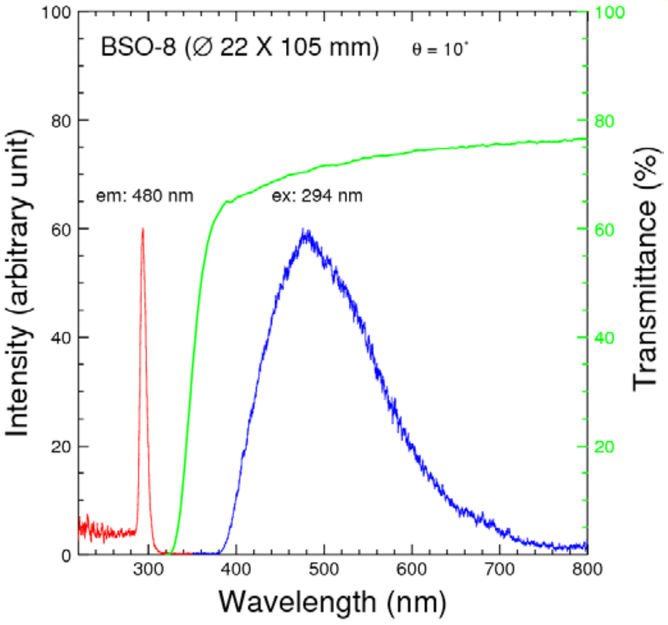


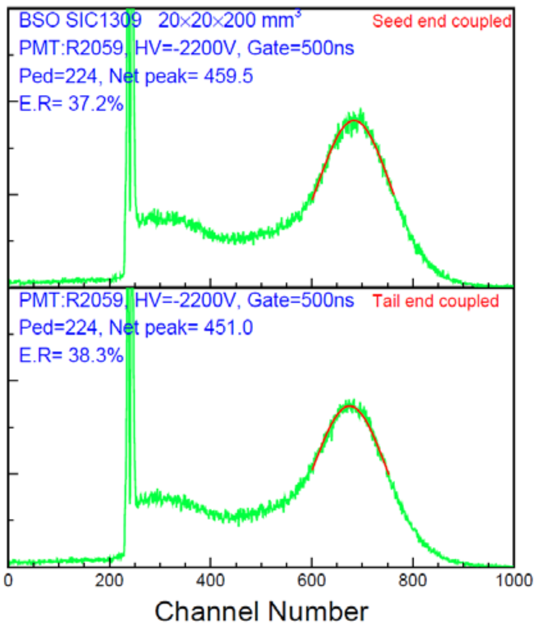


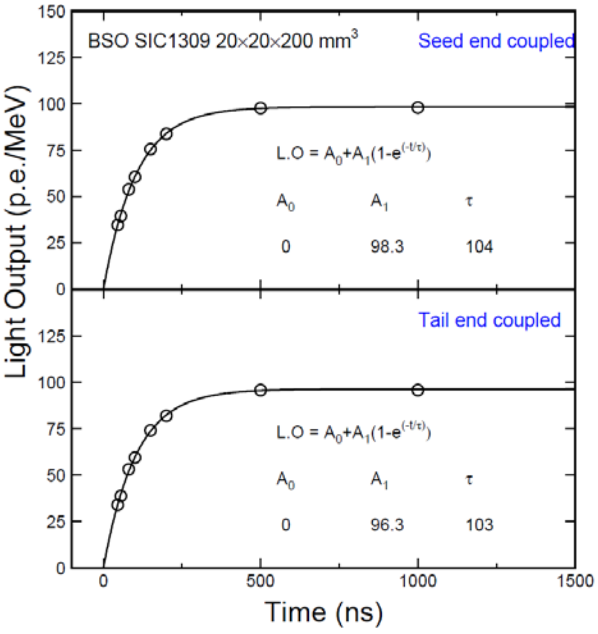
Large Size BSO Samples

20 x 20 x 200 mm BSO crystals show good optical and scintillation properties, and are used for an EIC beam test.

J. Phys. Conf. Ser. **587** (2015) 012064, also in SORMA2014

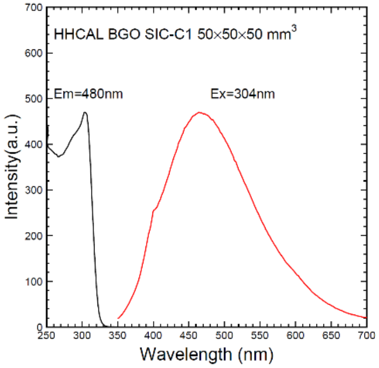


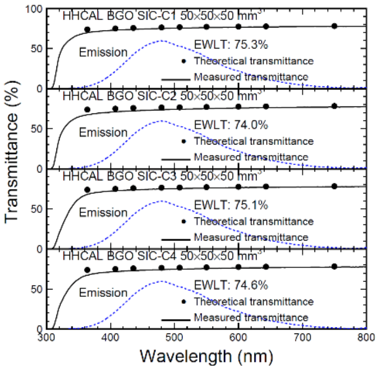


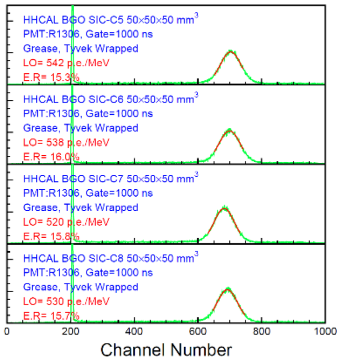


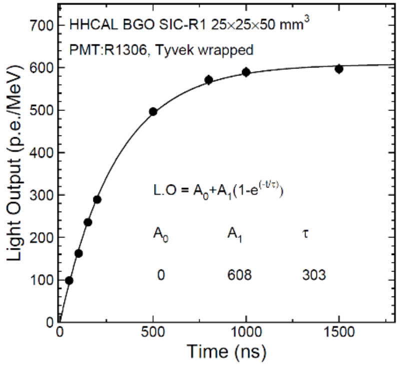
BGO Crystals for Beam Test

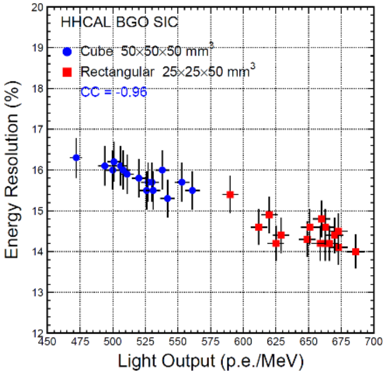
ID	Dimension (mm)	Polishing
BGO SIC2015-C1 to C16	50x50x50	Six faces
BGO SIC2015-R1 to R16	25x25x50	Six faces











A BGO crystal based segmented 4 x 4 test beam matrix is being constructed at Fermilab for cosmic and beam tests to understand the crucial calibration issue for a segmented total absorption calorimeter.

Summary

- Bright, fast and radiation hard LSO/LYSO crystals offer a robust crystal calorimeter for future HEP experiment at the energy frontier.
- Fast and radiation hard BaF_2 crystals offer a very fast crystal calorimeter with more than ten times rate/timing capability for future HEP experiment at the intensity frontier.
- Novel inorganic scintillators, e.g. LuAG:Ce and LuAG:Pr, may offer a cost-effective rad hard calorimeter solution for future HEP experiments.
- Cost effective crystals, glasses and ceramics may provide a foundation for a homogeneous hadron calorimeter for future lepton collider.