The Next Generation of Crystal Detectors

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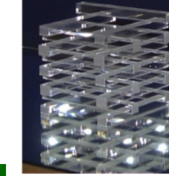
Why Crystal Calorimeter in HEP?

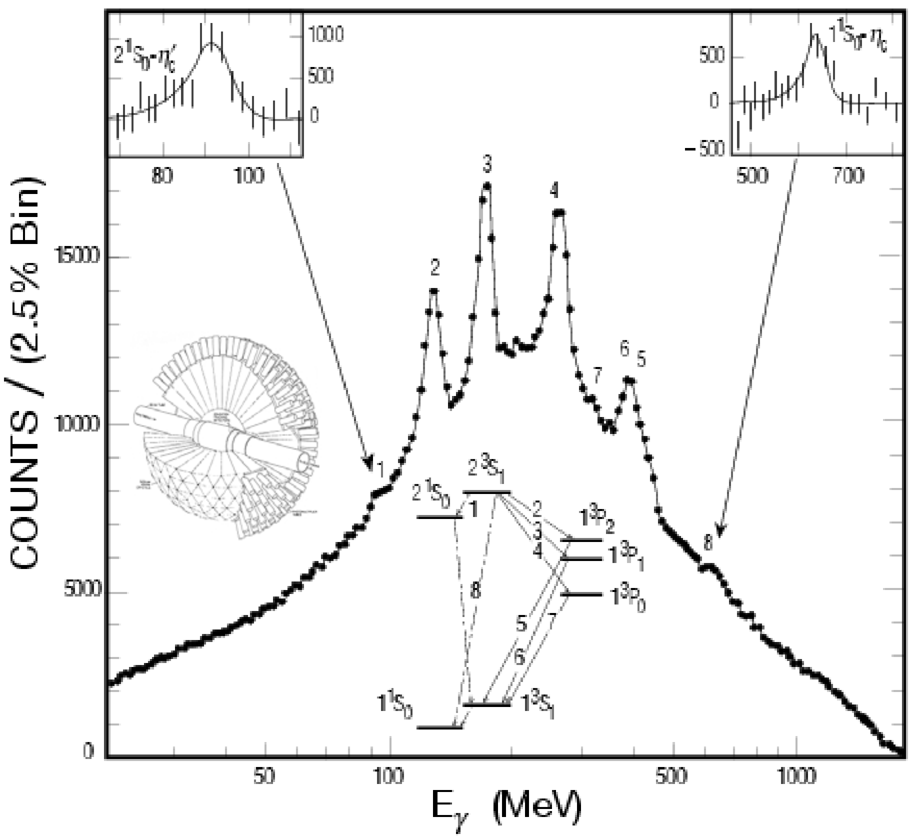
- Photons and electrons are fundamental particles. Precision e/γ measurements enhance physics discovery potential for future HEP experiments.
- Performance of crystal calorimeter in e/γ measurements is well understood:
  - The best possible energy resolution;
  - Good position resolution;
  - Good e/ 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;
  - Good jet mass resolution at the energy frontier (ILC/CLIC).

Physics with Crystal Calorimeters (II)



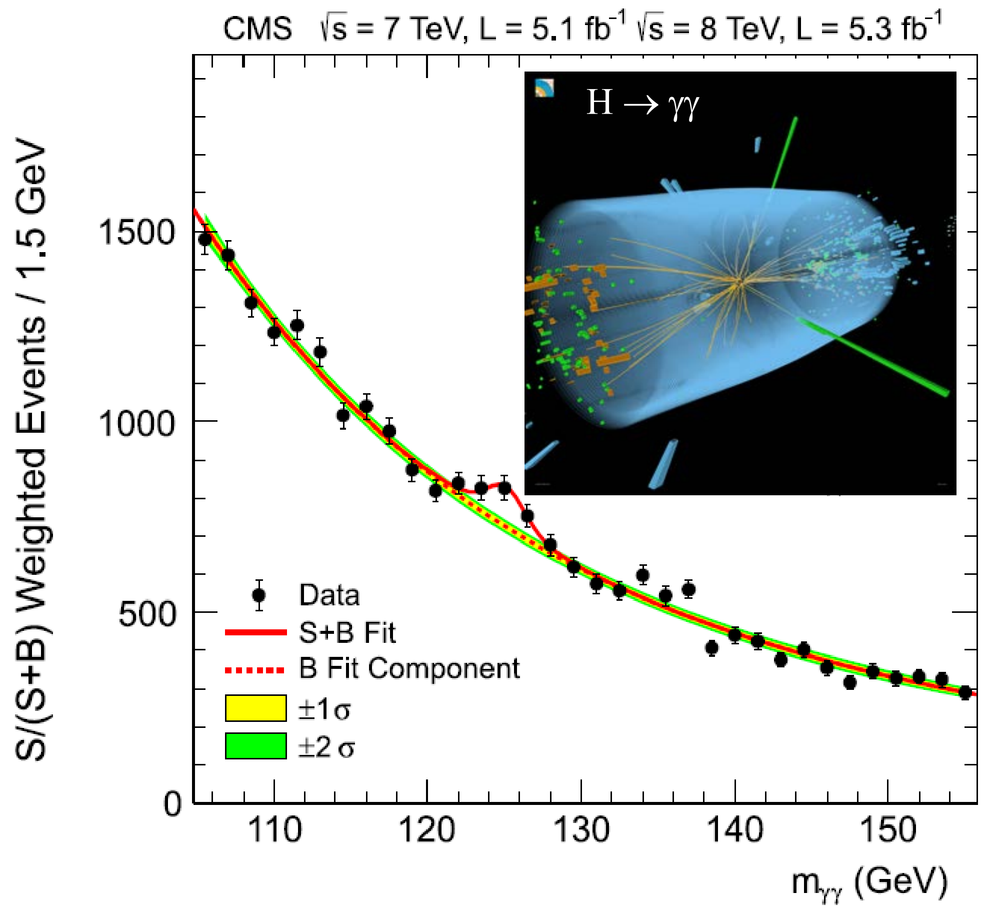
Charmonium system observed by CB through Inclusive photons

CB NaI(Tl)



Higgs -> $\gamma\gamma$ by CMS through reconstructing photon pairs

CMS PWO



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

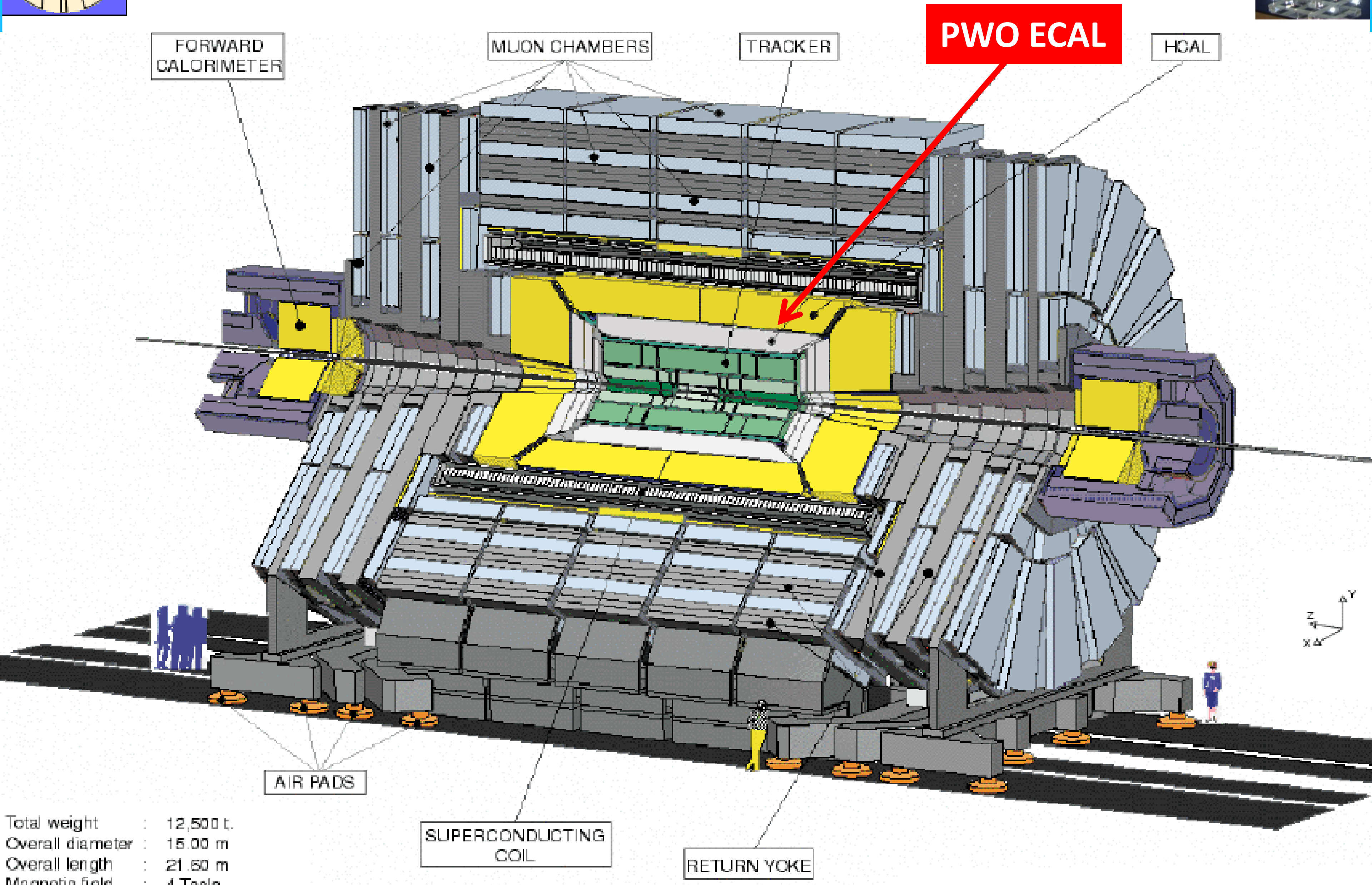
Future Crystal Calorimeters in HEP:

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

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

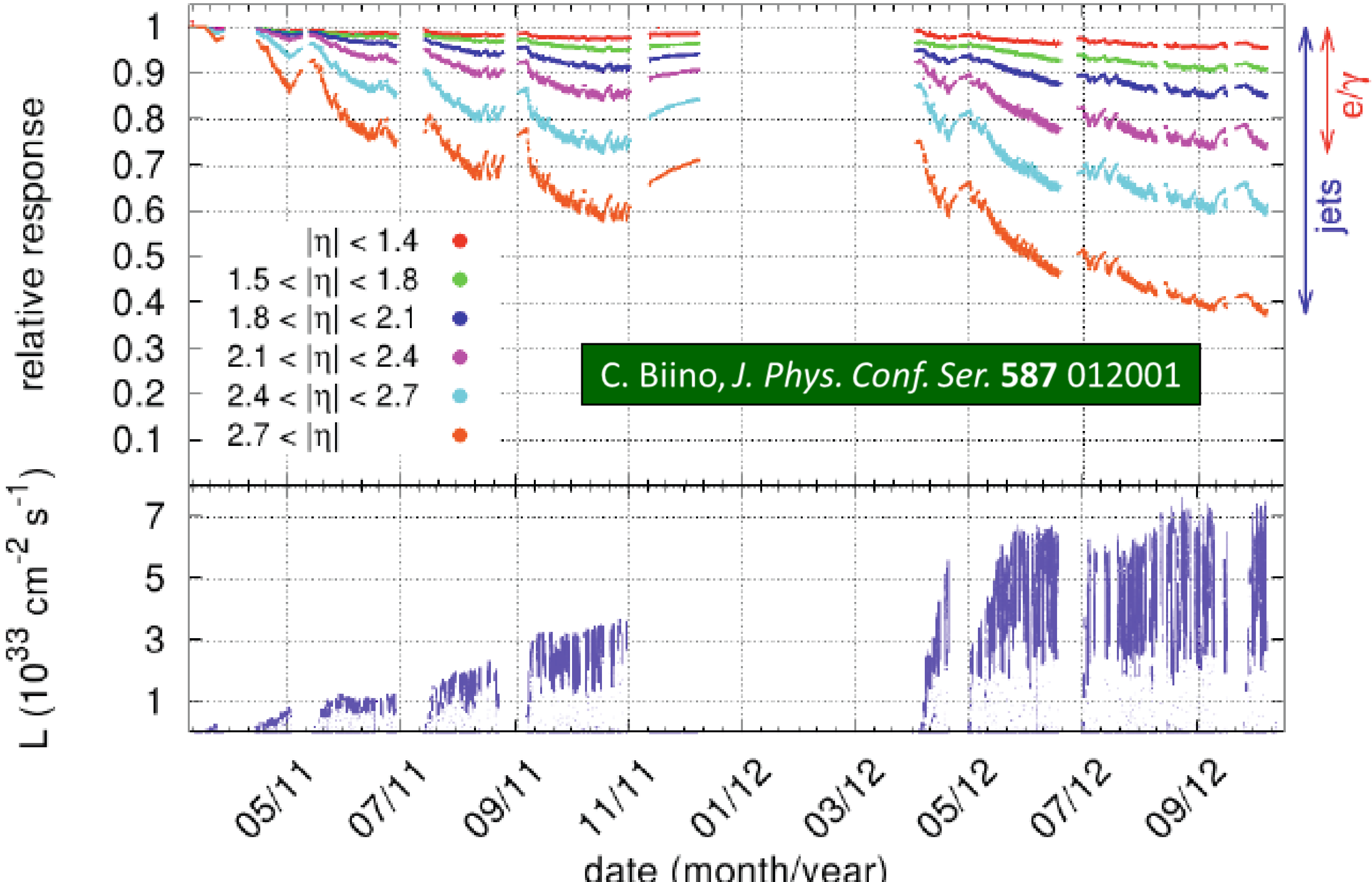
PbF_2, PbFCl and BSO for Homogeneous HCAL for ILC

CMS Experiment at LHC



CMS PWO Monitoring Response

The observed degradation is well understood



Dose Rate Dependent Damage in LO

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

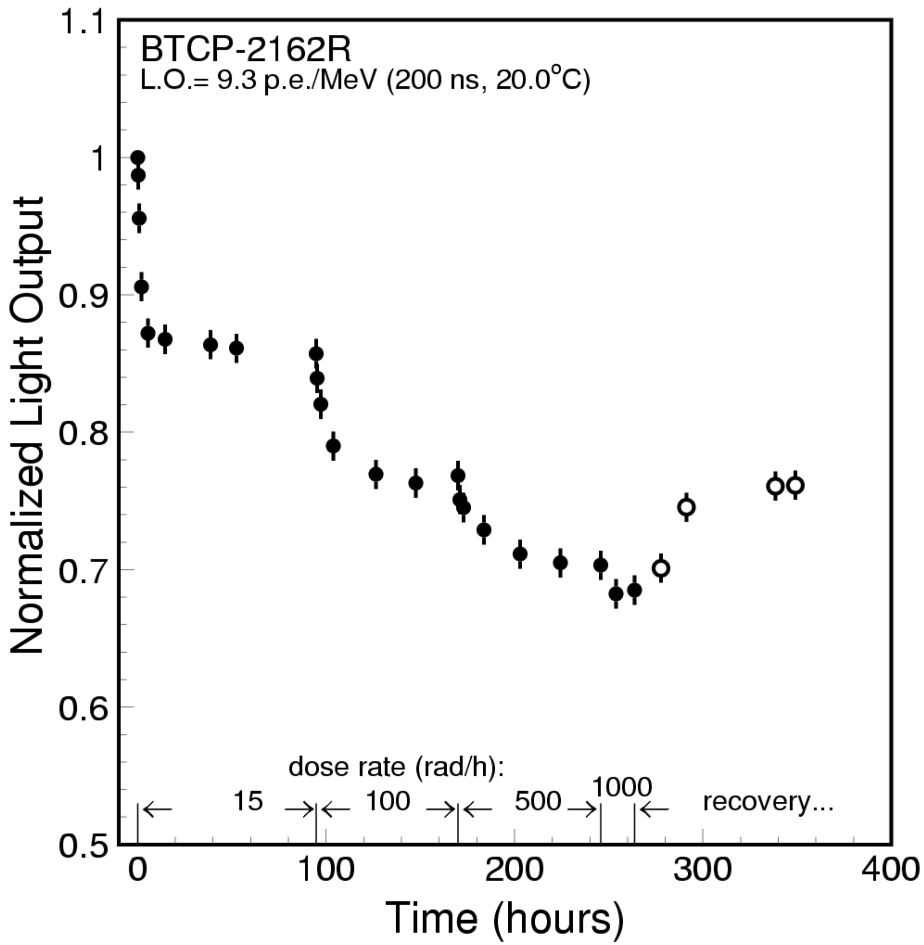
Light output reaches an equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

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

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

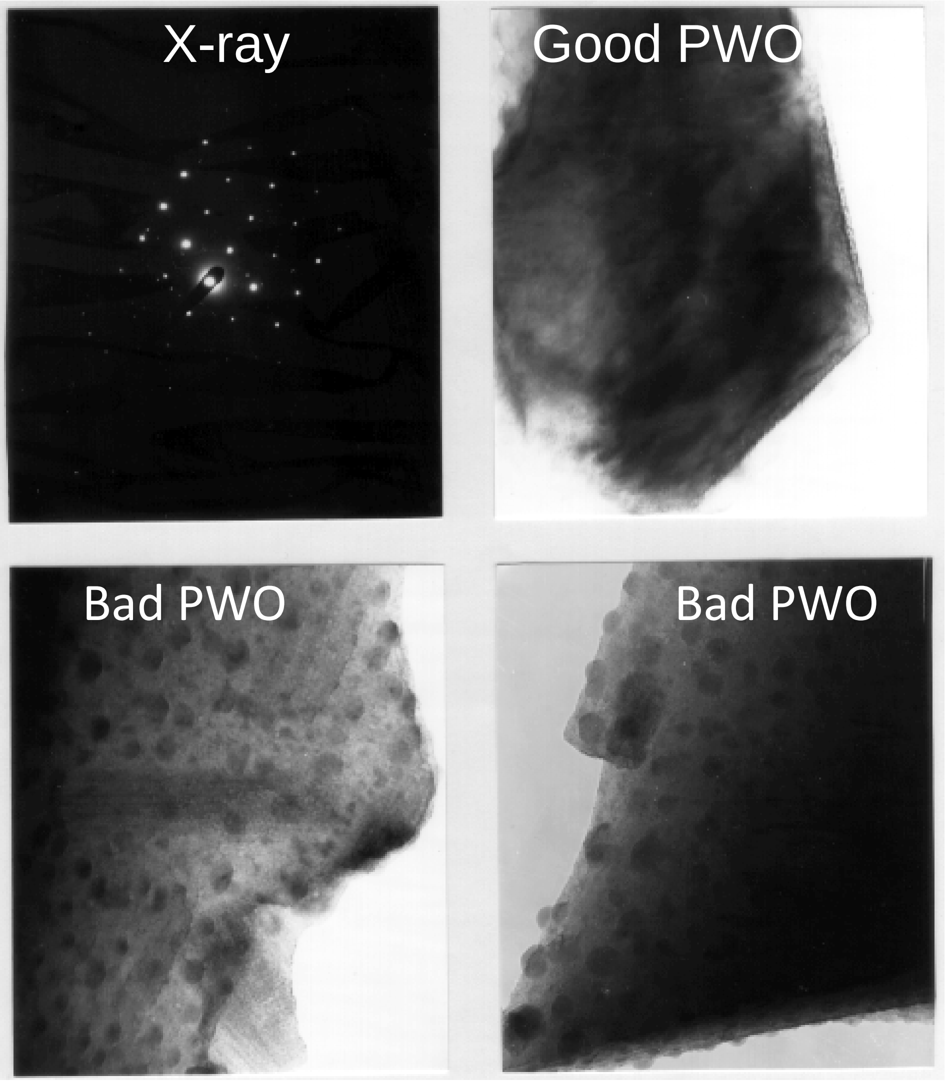
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of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

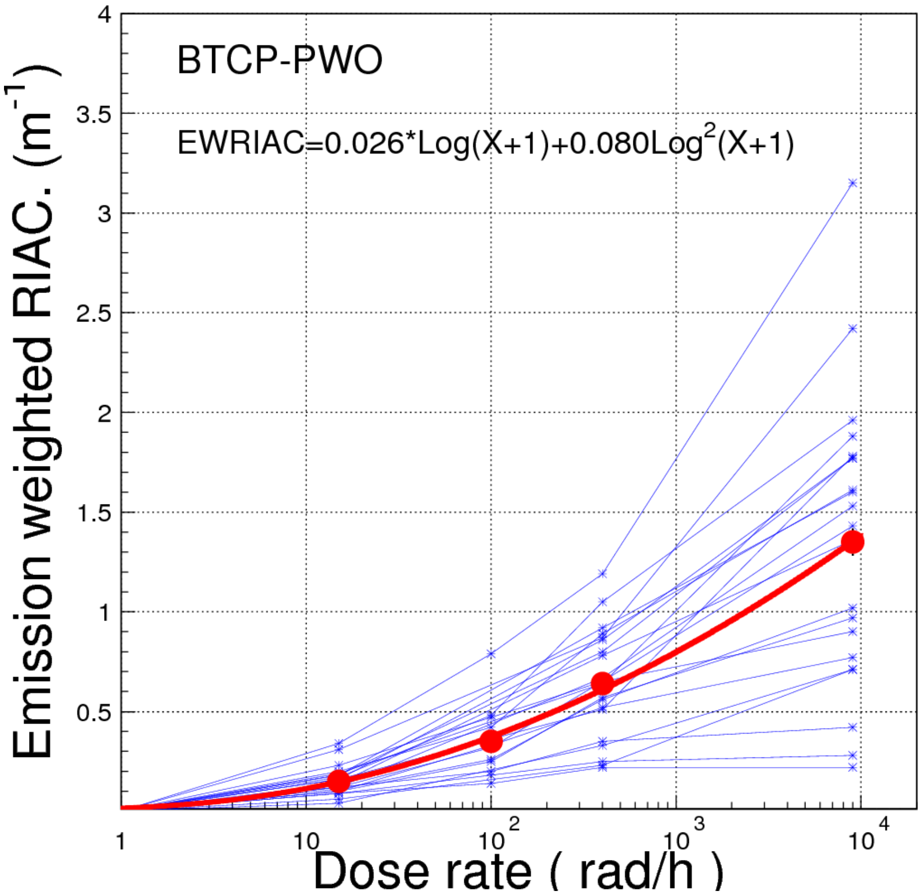
Element	Black Spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

The Same Sample after Oxygen Compensation

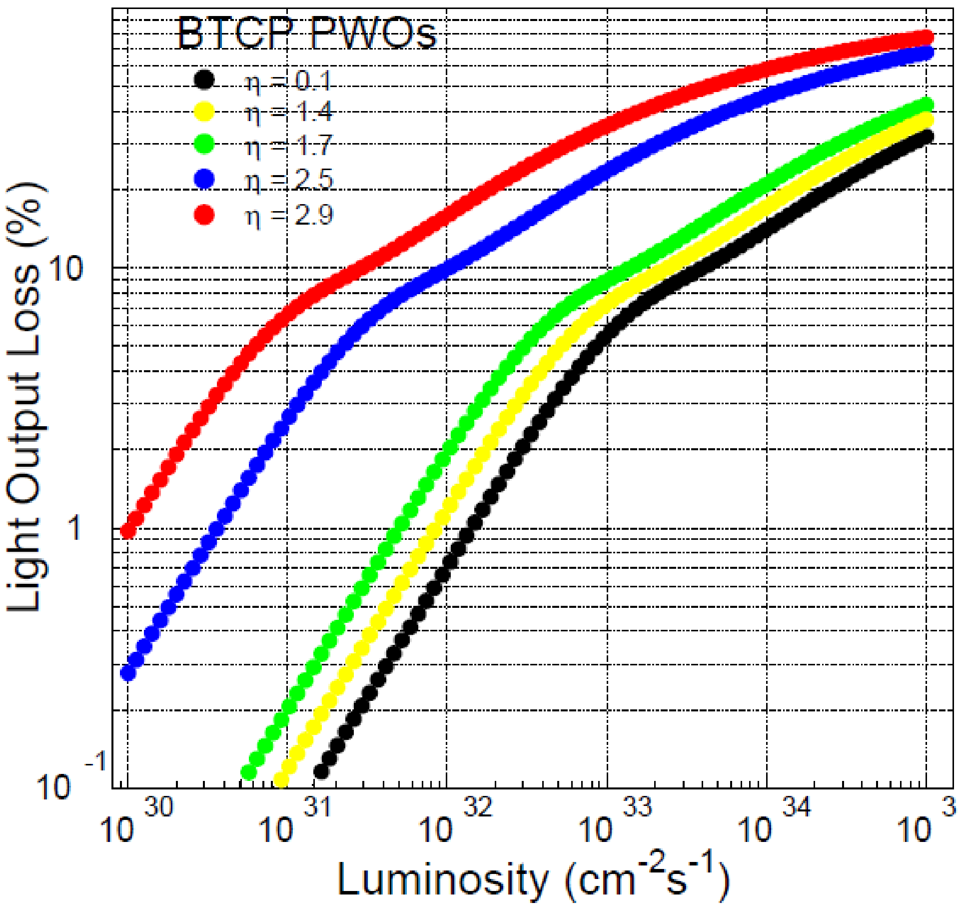
Element	$Point_1$	$Point_2$	$Point_3$	$Point_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

Prediction of PWO Radiation Damage

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



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



Predicted EM dose induced damage agrees well with the LHC data

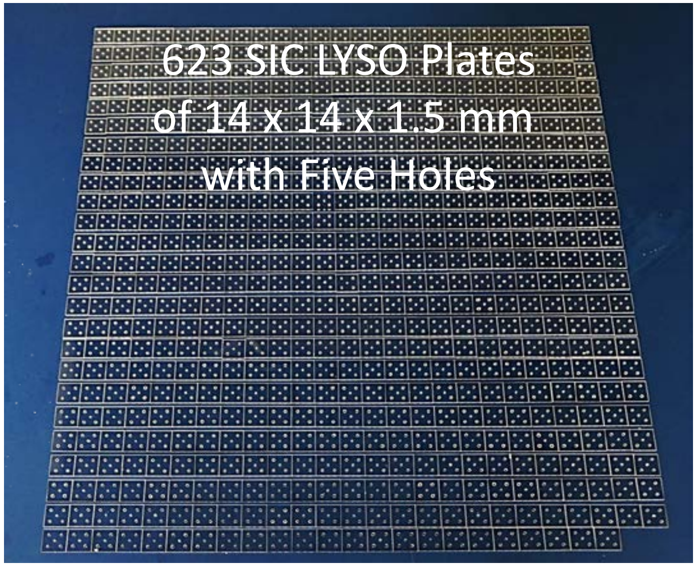
In addition, there is cumulative hadron induced damage in PWO

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 S. BELLE	(GEM) TAPS Mu2e	L3 BELLE EIC?	Comet {Mu2e,SuperB) CMS?	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.

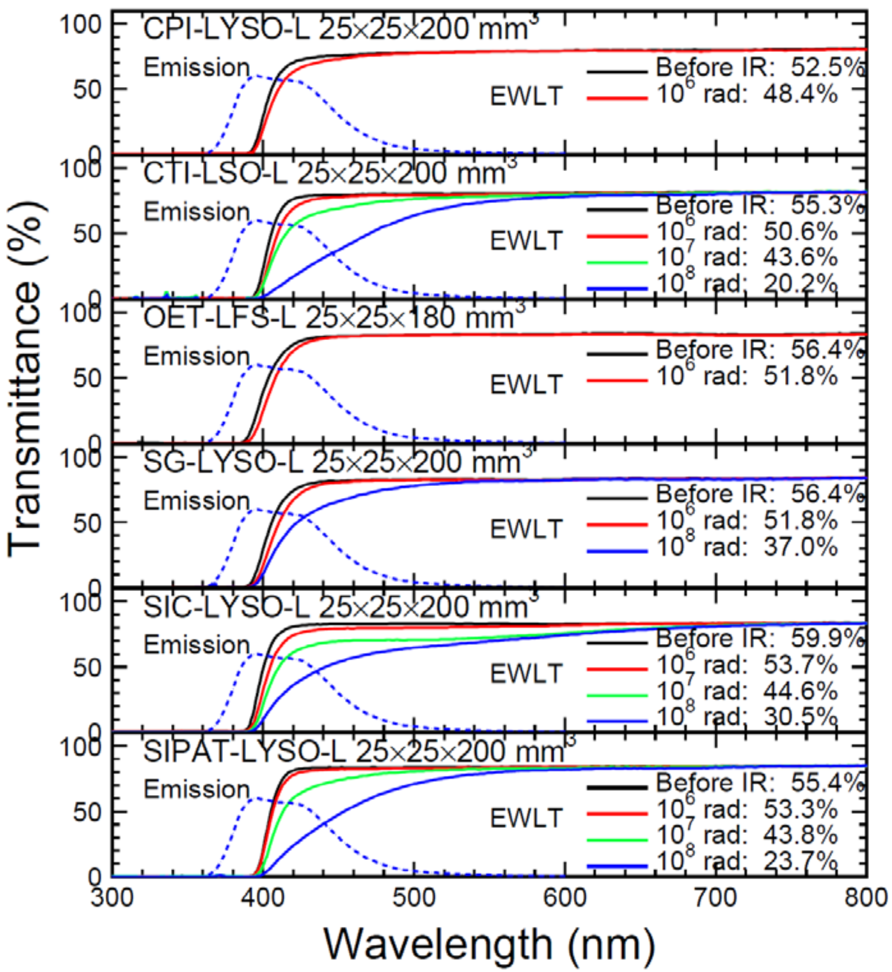
Bright, Fast & Rad Hard LYSO

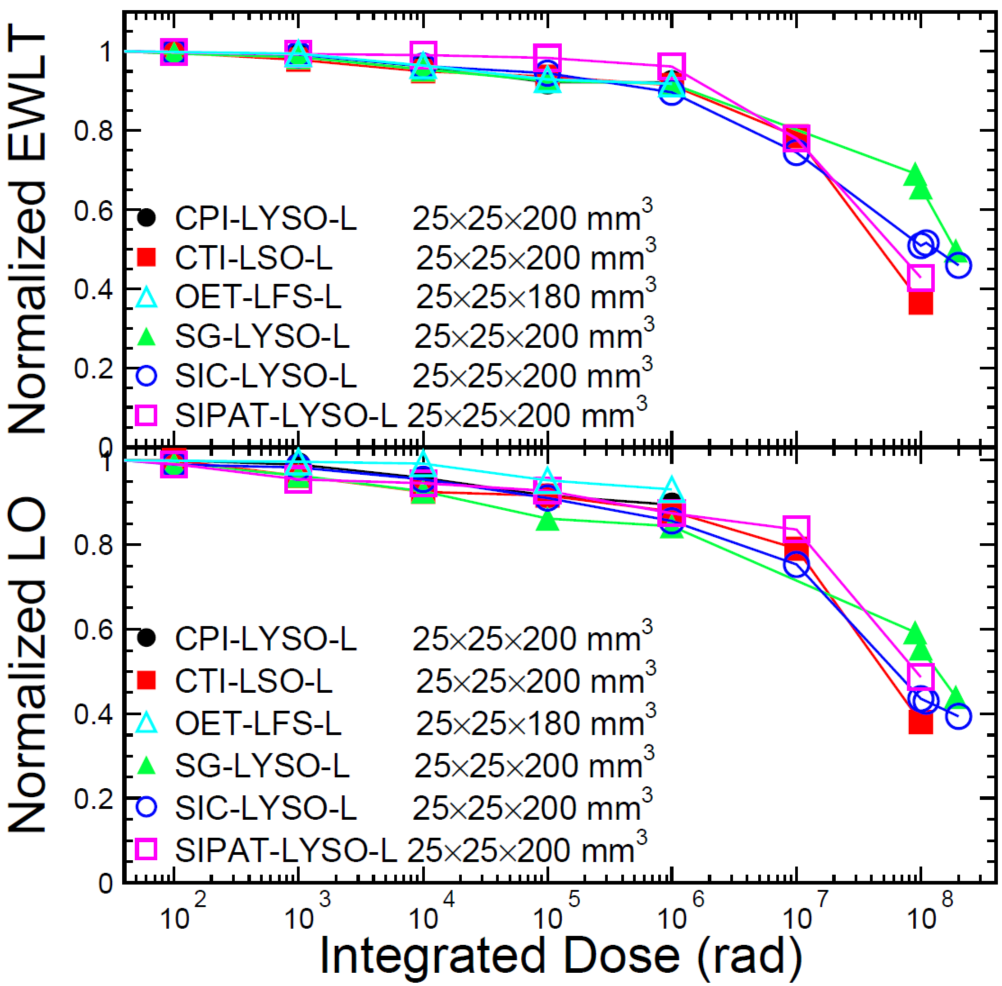


- LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator.
- No variation in emission spectrum was observed after γ-rays irradiation, indicating scintillation mechanism is not damaged.
- γ-ray induced radiation damage in LYSO does not recover at room temperature, indicating a stable calorimeter *in situ*.
- γ-ray induced absorption coefficient measured for 20 cm long LYSO crystals after 200 Mrad irradiation is about 2 m^{-1}.
- γ-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.

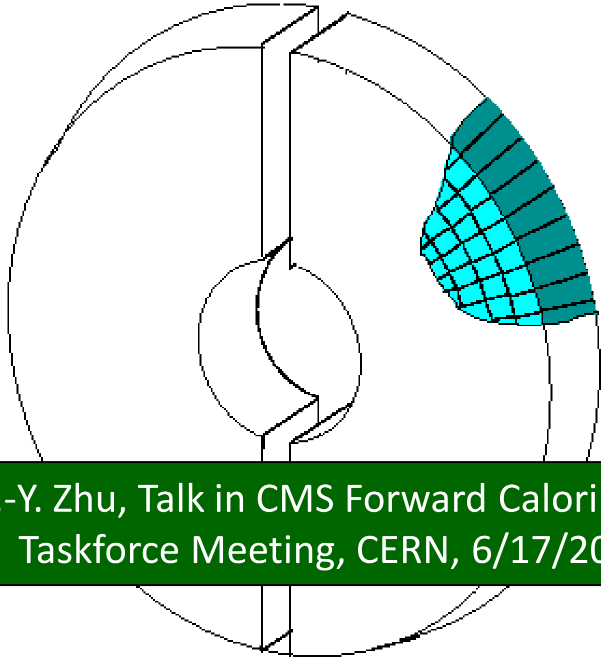
Radiation Hardness of 20 cm LYSO

About 20% loss and <5% divergence for six vendors after 10 Mrad

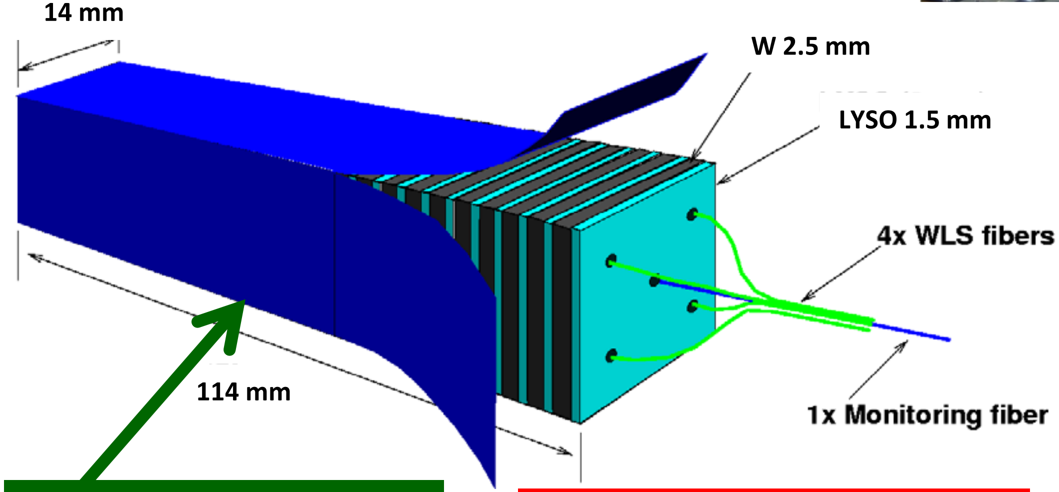




An Option for CMS FCAL Upgrade

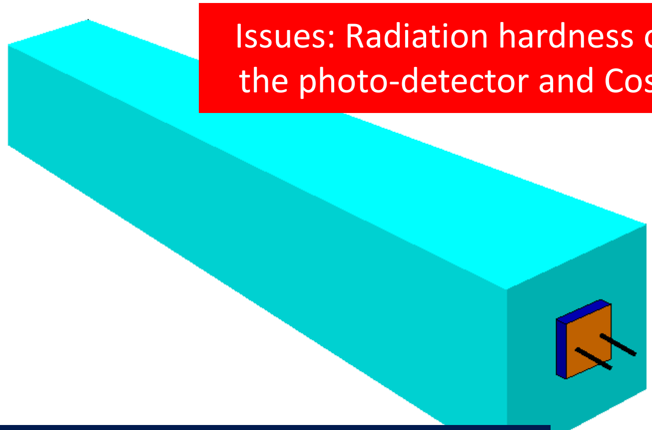


R.-Y. Zhu, Talk in CMS Forward Calorimeter Taskforce Meeting, CERN, 6/17/2010



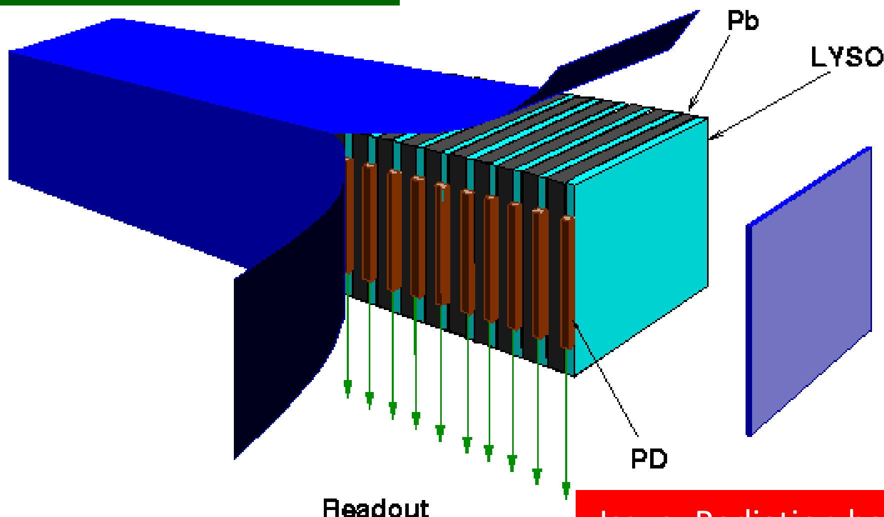
One of two options for CMS Upgrade

Issues: Radiation hardness of photo-detector and WLS fiber



Issues: Radiation hardness of the photo-detector and Cost

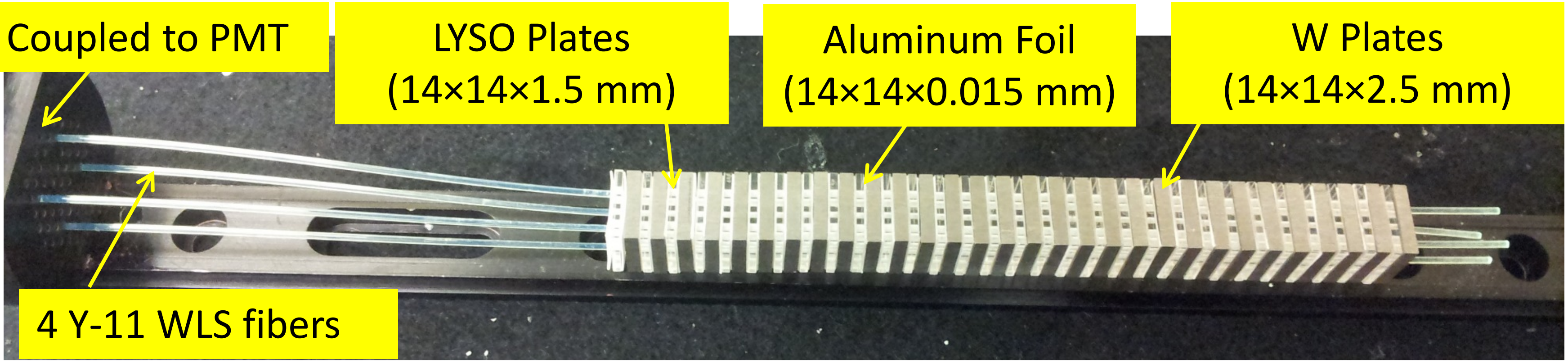
CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 3 m^3

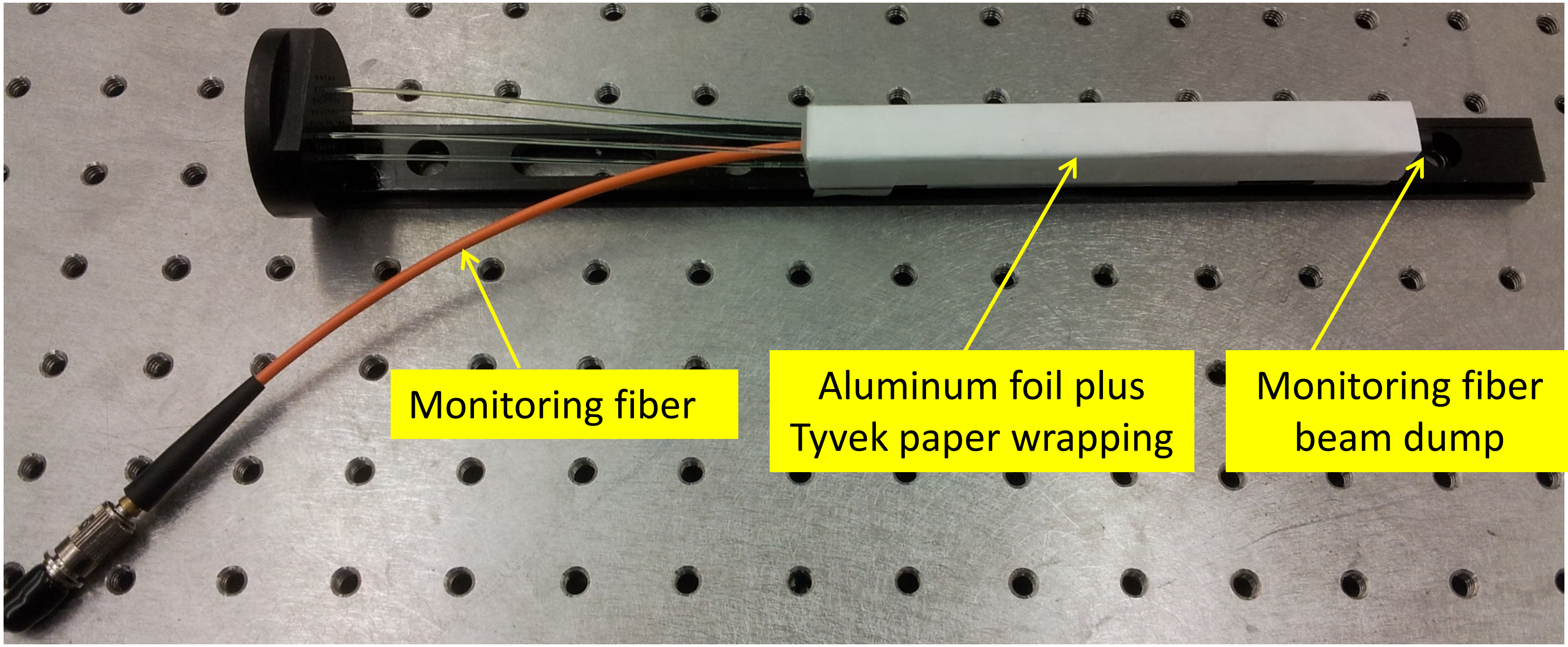


Reduced Crystal Cost & damage

Issue: Radiation hardness of the photo-detector

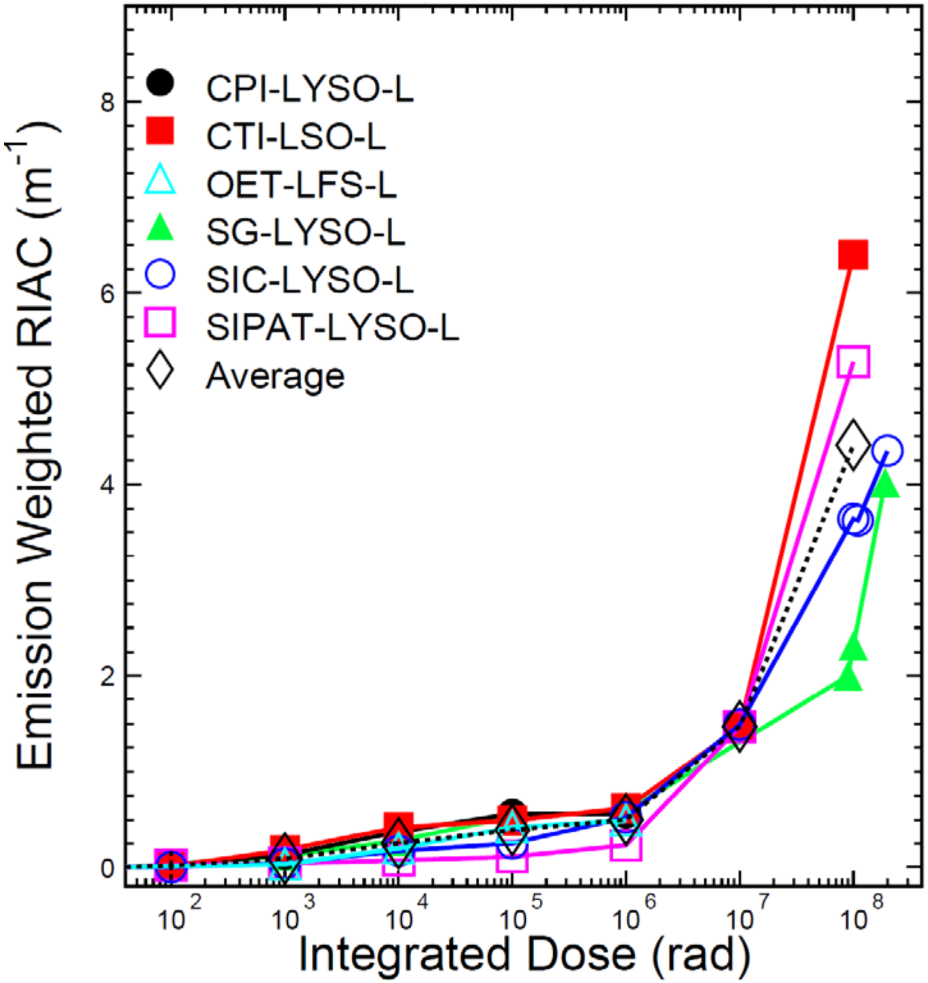
A Shashlik Cell Irradiated at JPL

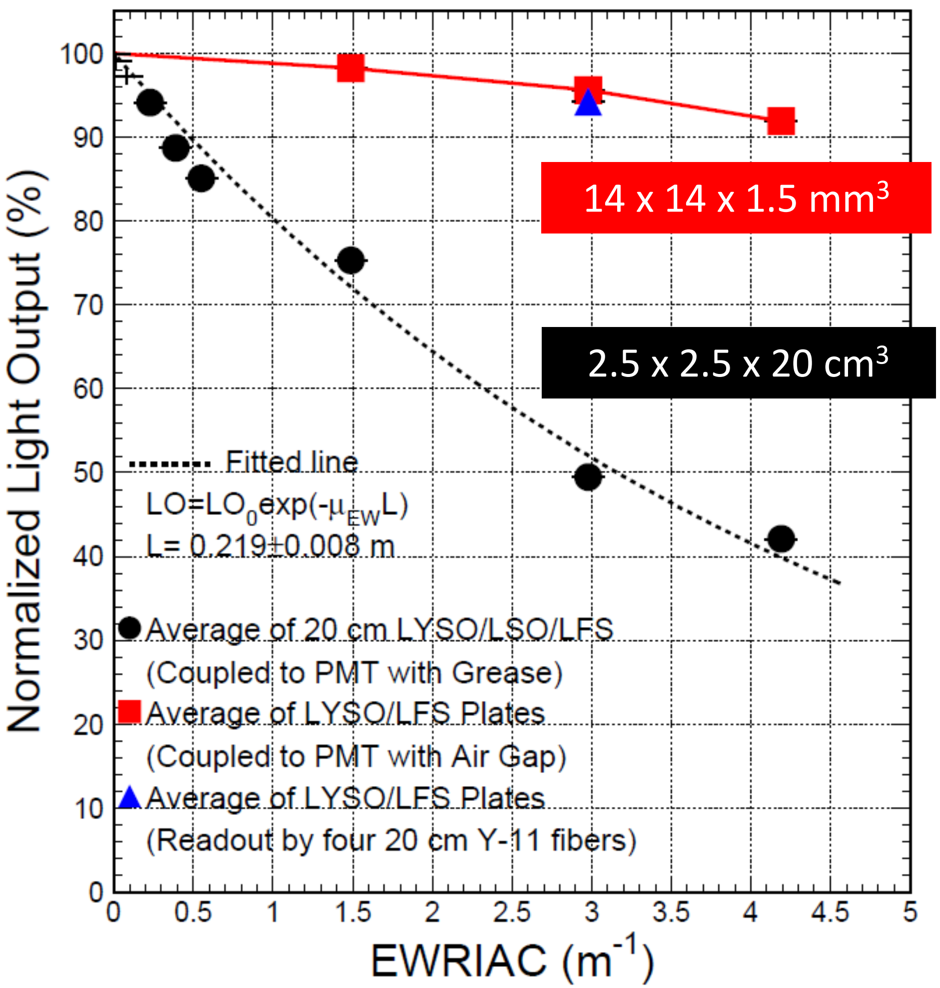




Summary of γ-ray Induced Damage

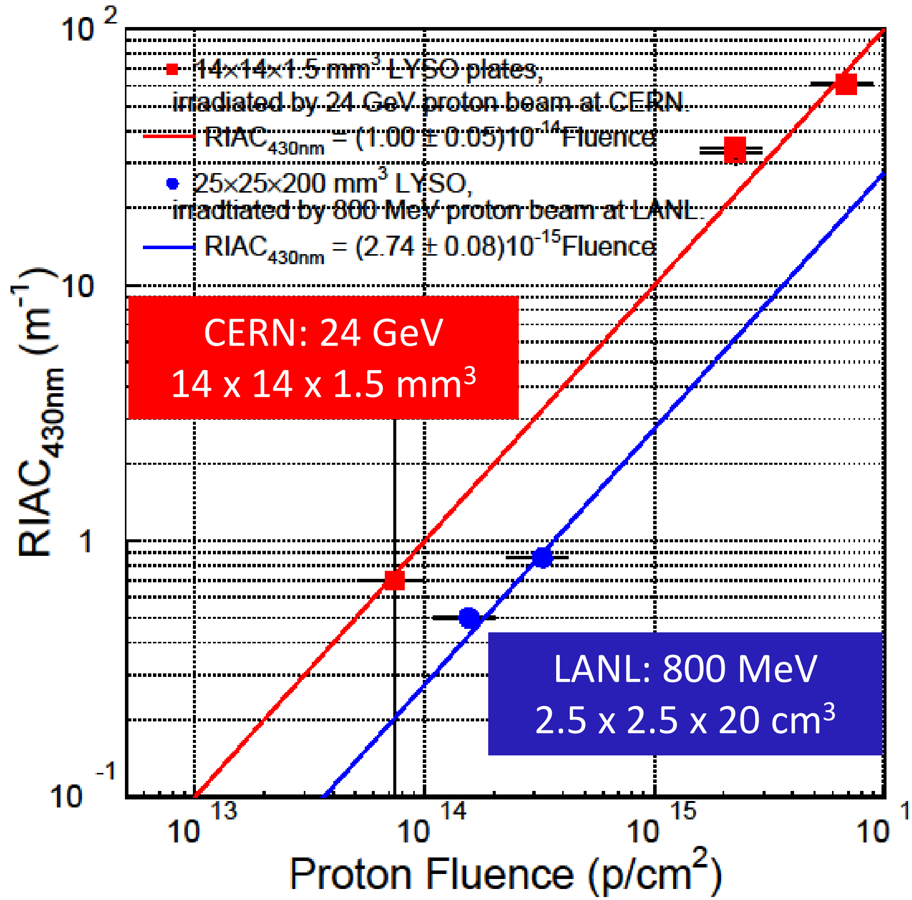
EWRIAC = 1.5, 3 and 4 m^{-1} after 10, 100 and 180 Mrad
LO loss after 100 Mrad is 4 and 6% respectively for direct and WLS readout

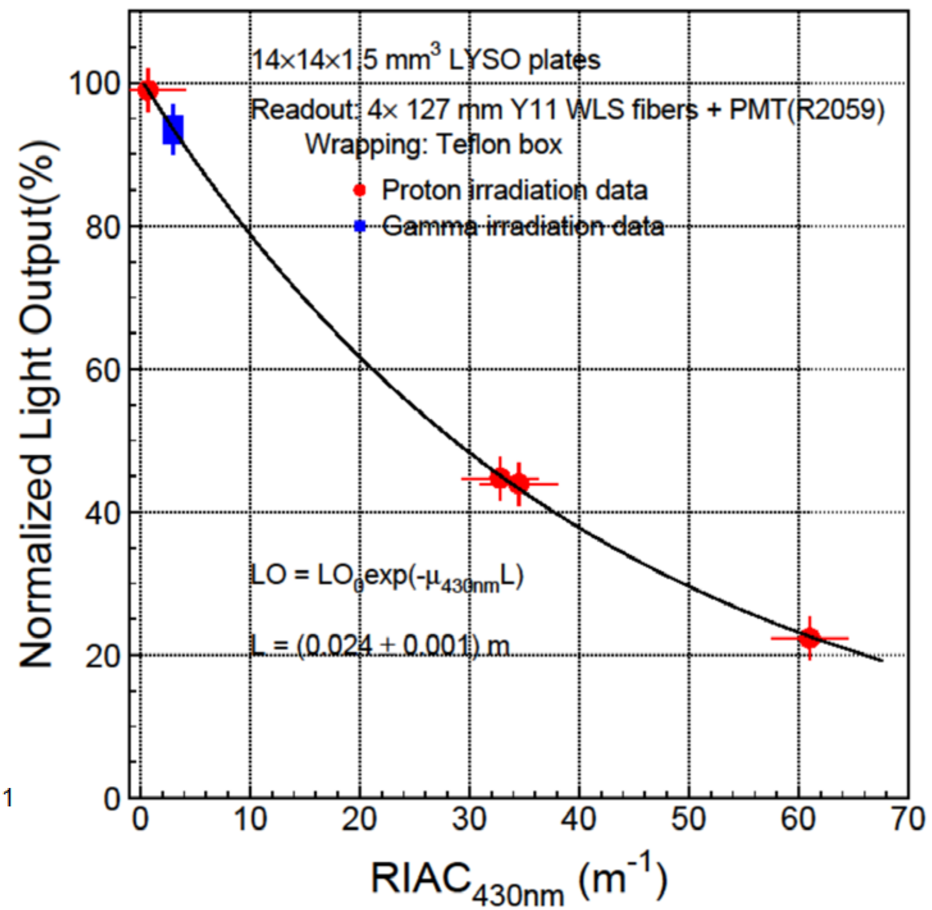




Summary of Proton Induced Damage

A 20 cm and four 14×14×1.5 mm^3 LYSO were irradiated by 800 MeV and 24 GeV protons at LANL and CERN respectively. The result shows that the expected RIAC at the HL-LHC is about a few m^{-1}, indicating loss of 4 and 6% respectively for direct and WLS readout.





Alternative Fast Crystals

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

	LSO/LYSO	GSO	YSO[1]	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

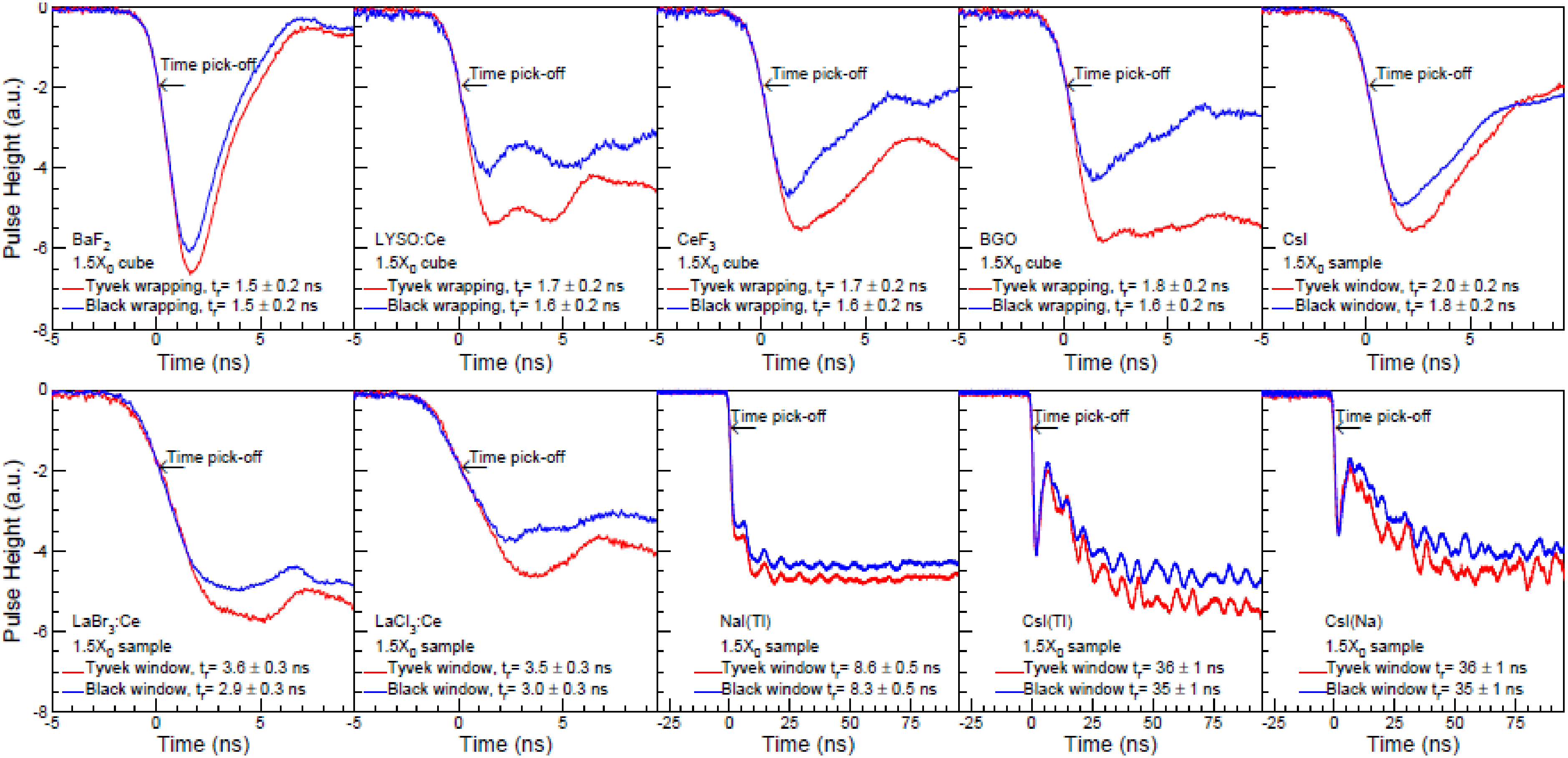
a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.

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: Agilent MSO9254A (2.5 GHz) DSO with 0.14 ns rise time Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns



Measured rising time is dominated by photo-detector response, and is affected by light propagation in crystal.

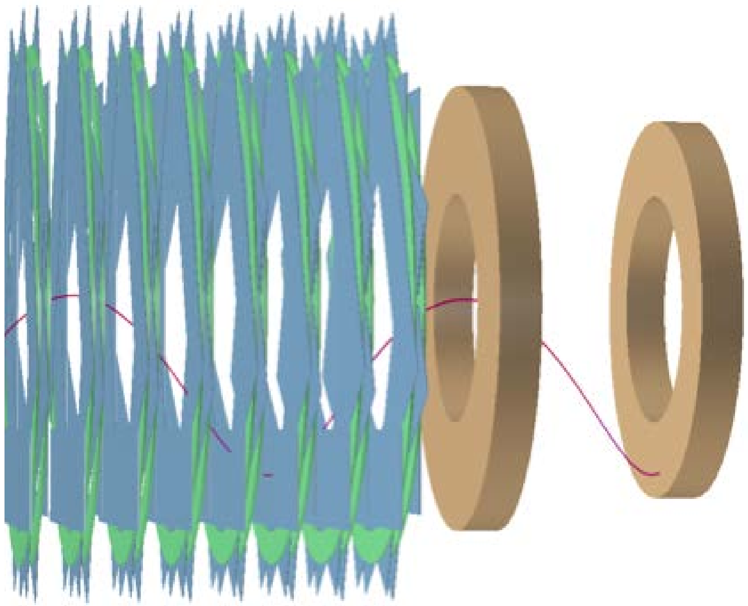
Figure of Merit for Timing

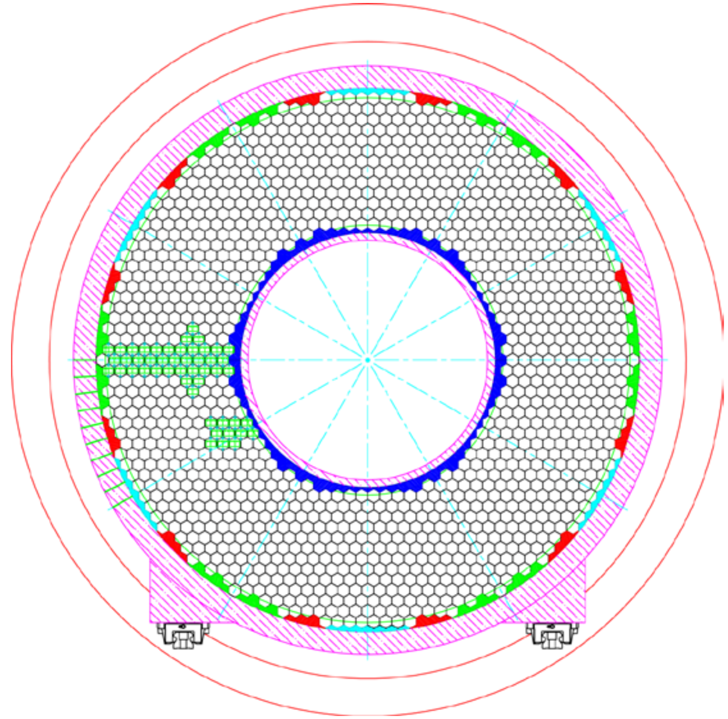
FoM is calculated as the LY in 1st ns obtained by using light output and decay time data measured for 1.5 X_0 crystal samples.

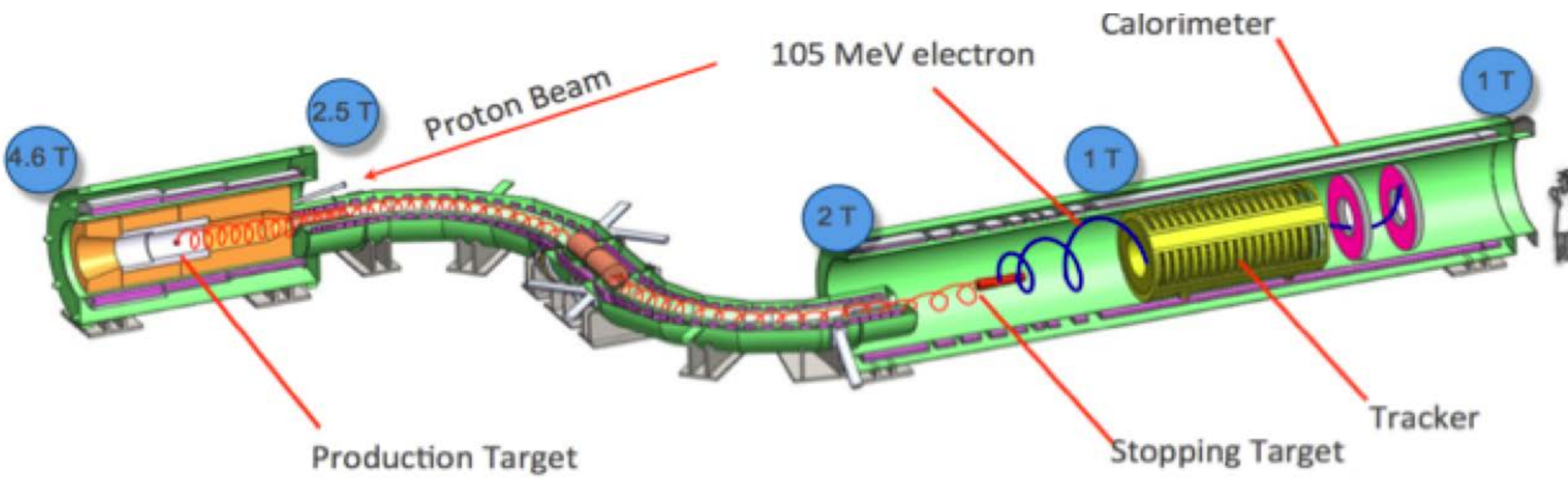
Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	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 and LSO(Ce/Ca) and LYSO(Ce). $LaBr_3$ is a material with high potential.

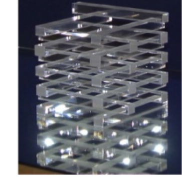
A Mu2e BaF_2 Calorimeter





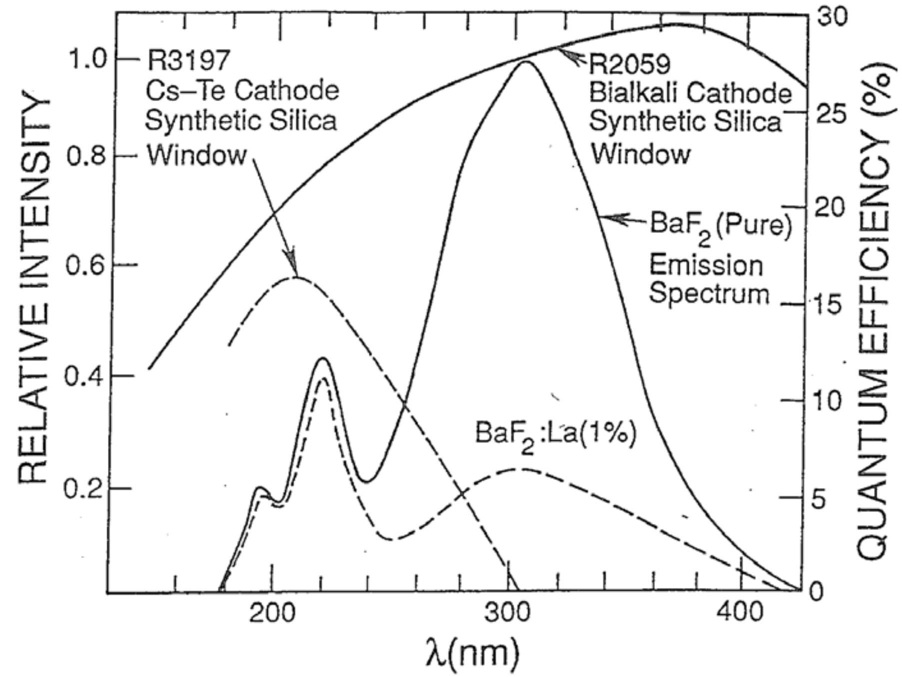


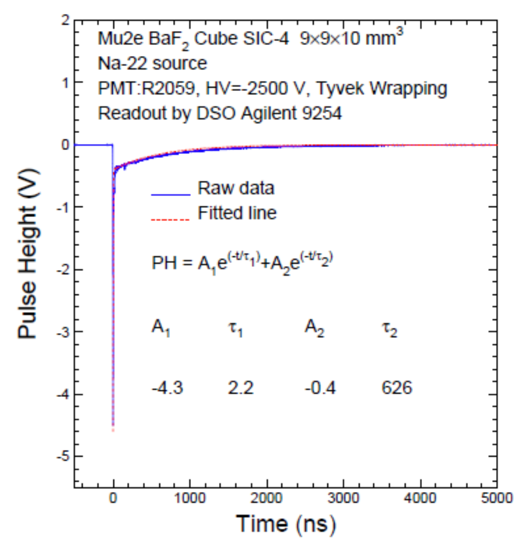
BaF_2 for Very Fast Calorimeter

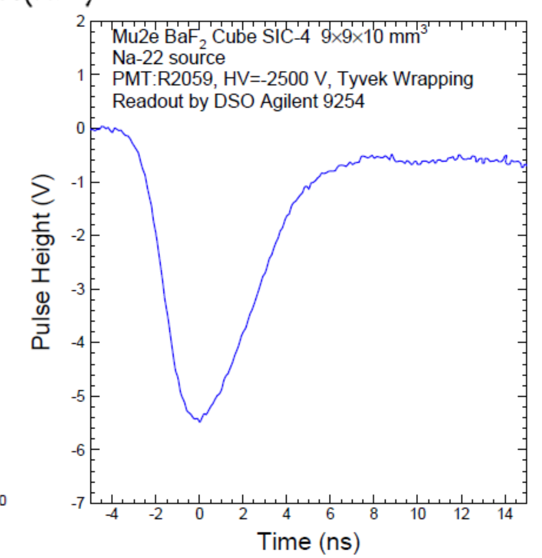


The Light output of the fast component of BaF_2 crystals at 220 nm with sub-ns decay time is similar to pure CsI.

Spectroscopic selection of fast component may be achieved with solar blind photocathode and/or selective doping.



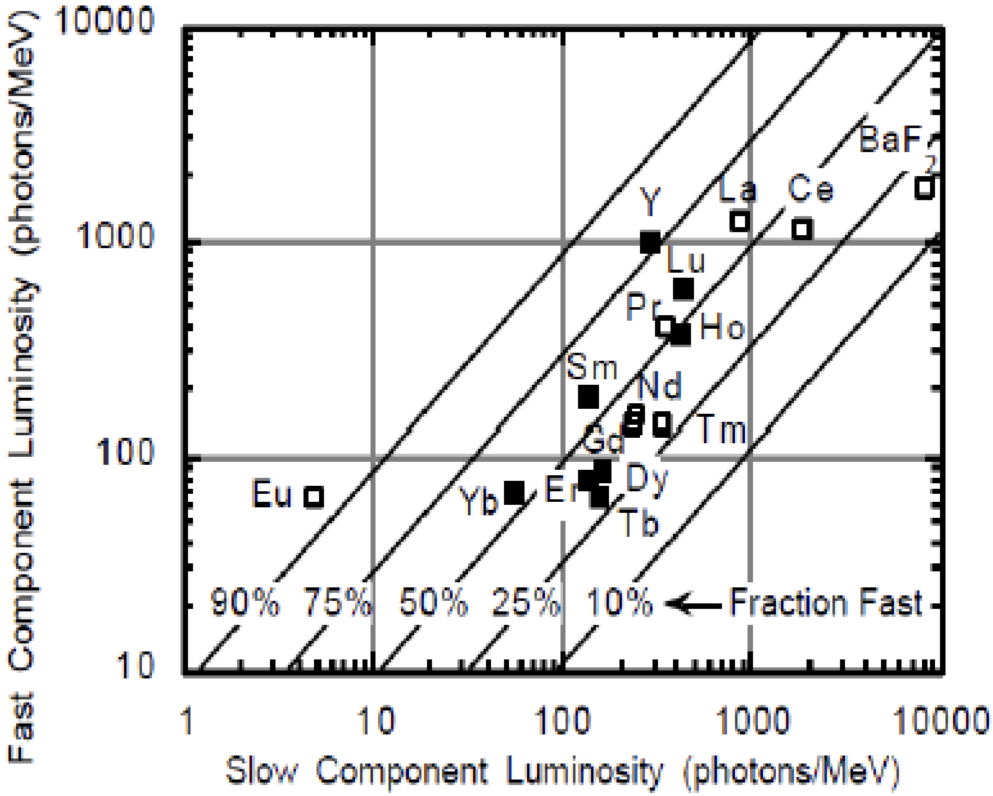


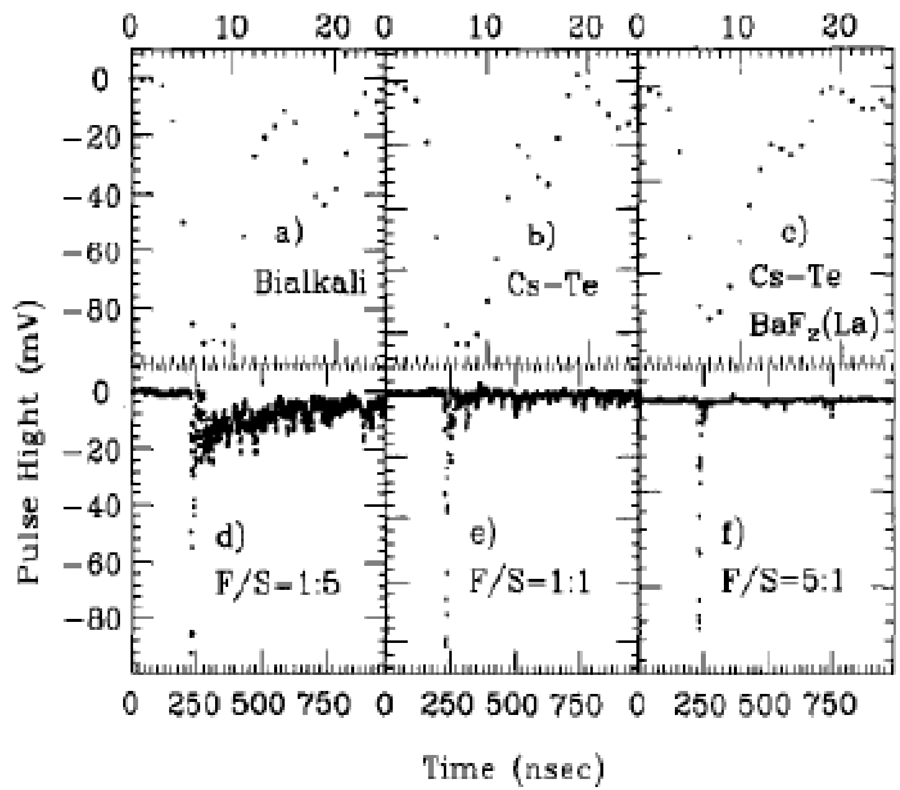


Slow Suppression by Doping and Readout

Y or La 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.





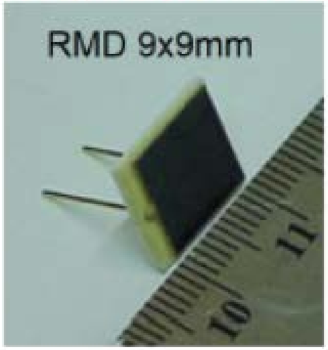
Solar blind cathode is also effective. R&D on doping will be carried out in 2015.

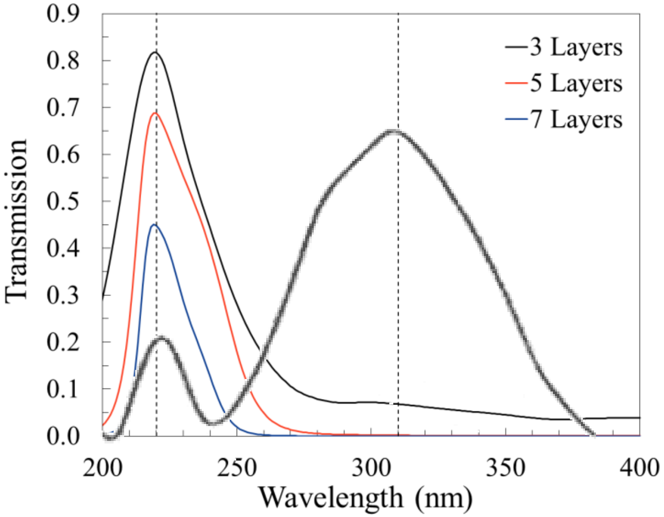
Z. Y. Wei, R. Y. Zhu, H. Newman, and Z. W. Yin, "Light Yield and Surface-Treatment of Barium Fluoride-Crystals," *Nucl Instrum Meth B*, vol. 61, pp. 61-66, Jul 1991.

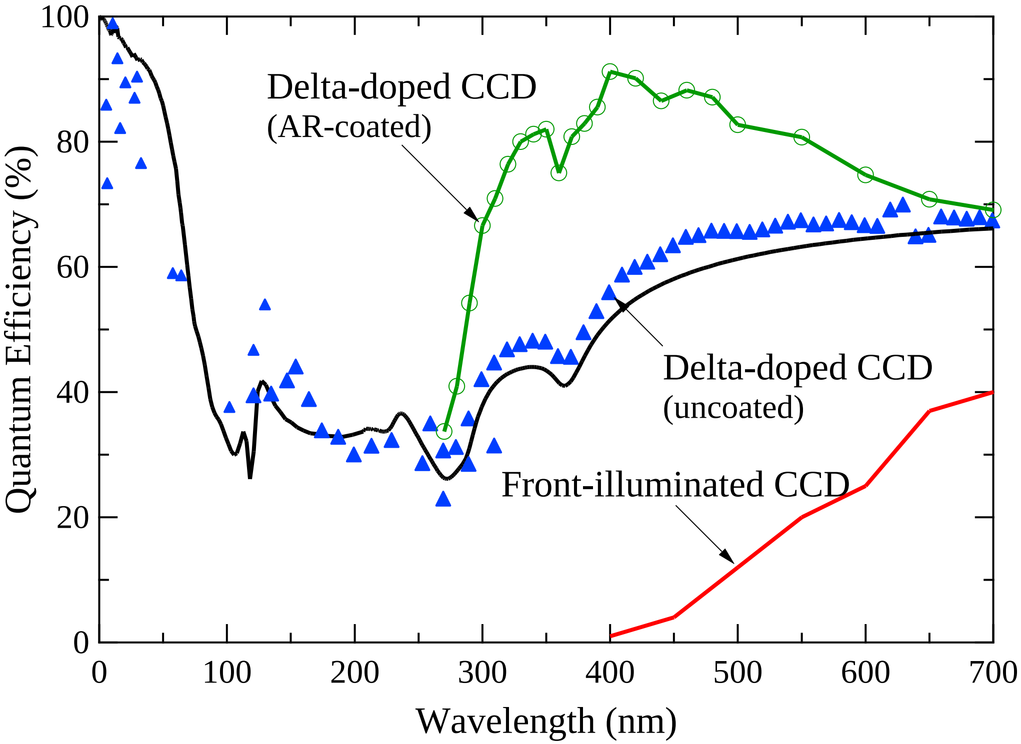
Solar Blind UV APD

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

deltadoped APD from RMD



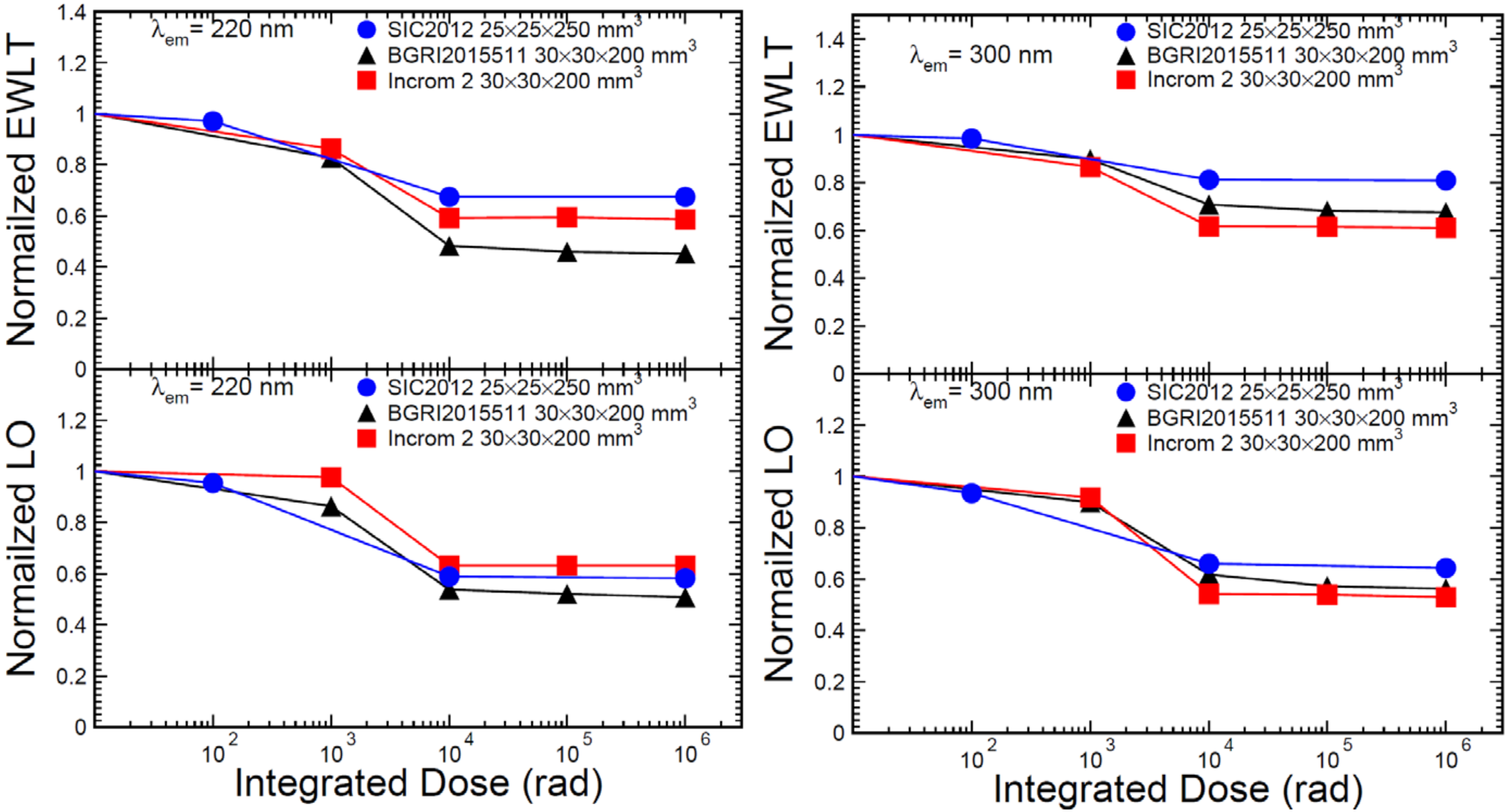




S. Nikzad, "Ultrastable and uniform EUV and UV detectors," *SPIE Proc.*, Vol. 4139, pp. 250-258 (2000).

Damage in Long BaF_2 Crystals

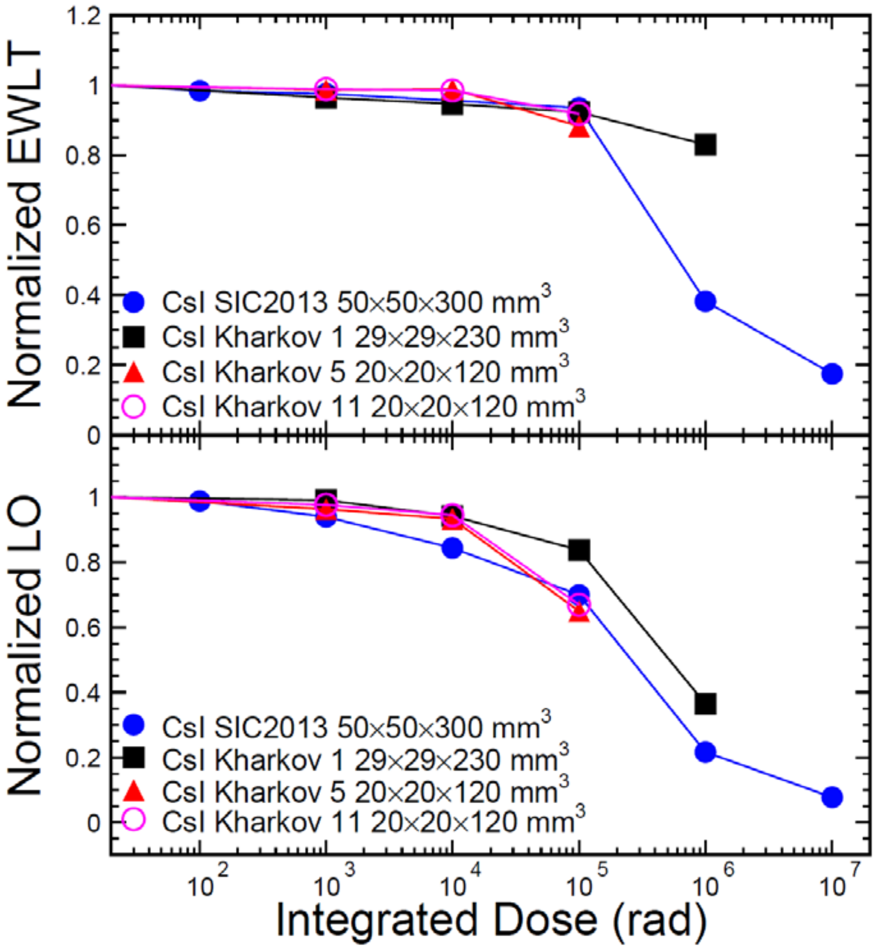
Radiation damage in BaF2 crystals saturates at 10 krad

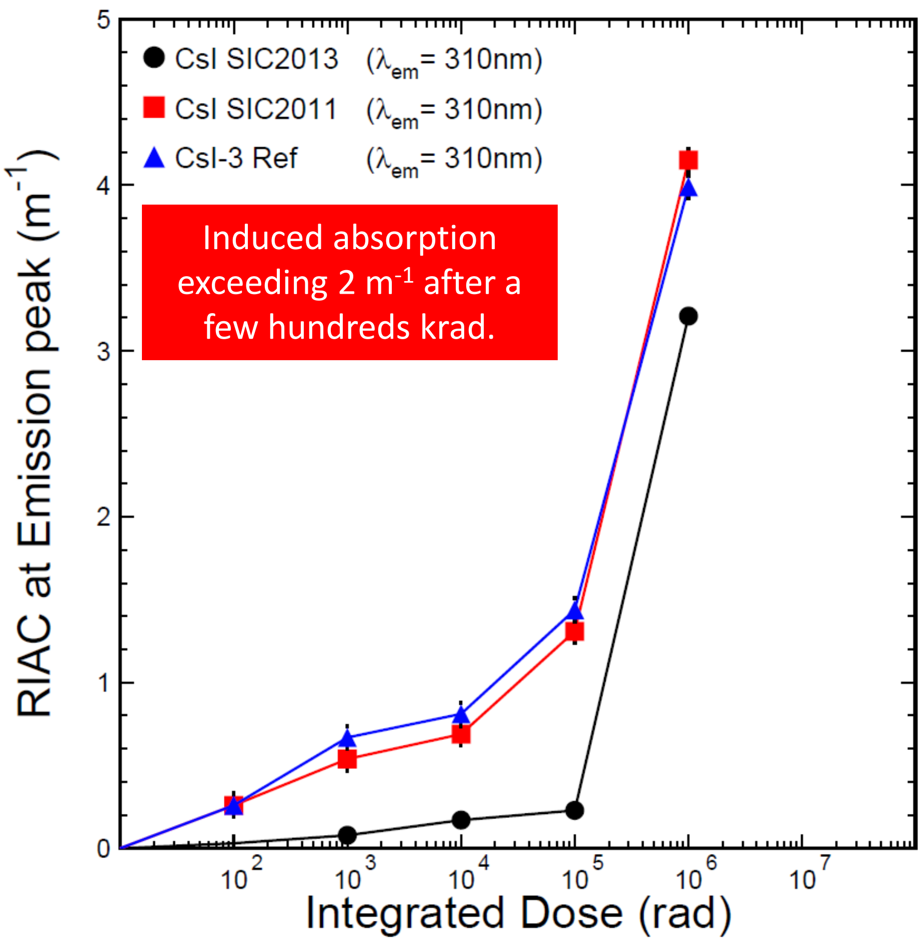


Consistent performance observed in crystals from three vendors

Damage in Long Pure CsI Crystals

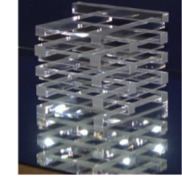
Consistent damage in long pure CsI from SIC/Kharkov



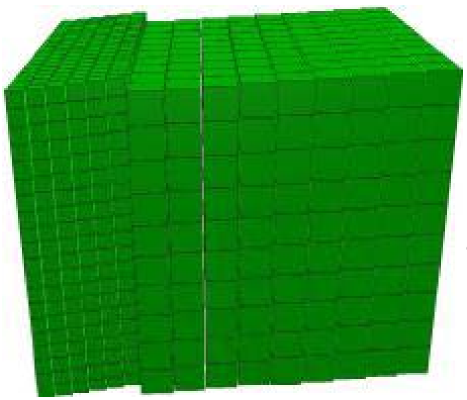


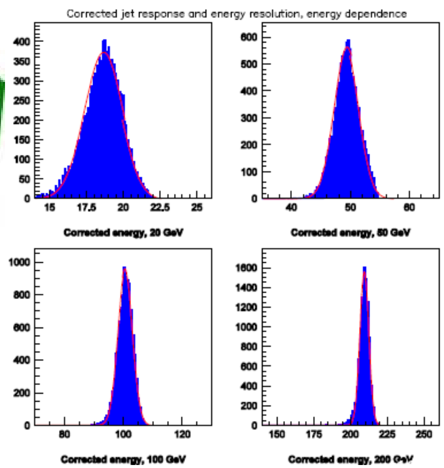
CsI crystals are radiation hard up to a few 10 krad

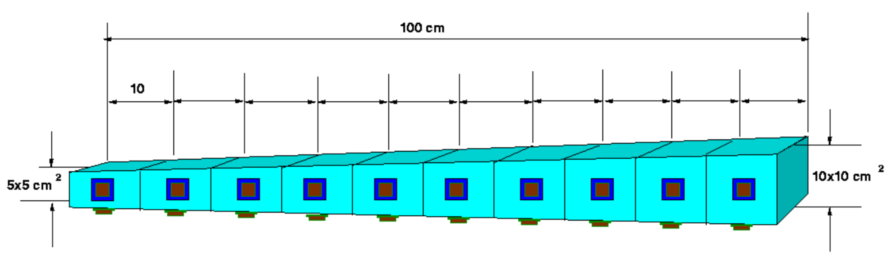
Homogeneous Hadronic Calorimeter



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.





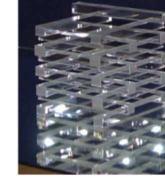


ILCWS-08, Chicago: a HHCAL cell with pointing geometry

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.

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

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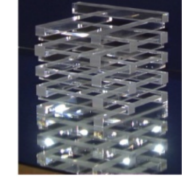
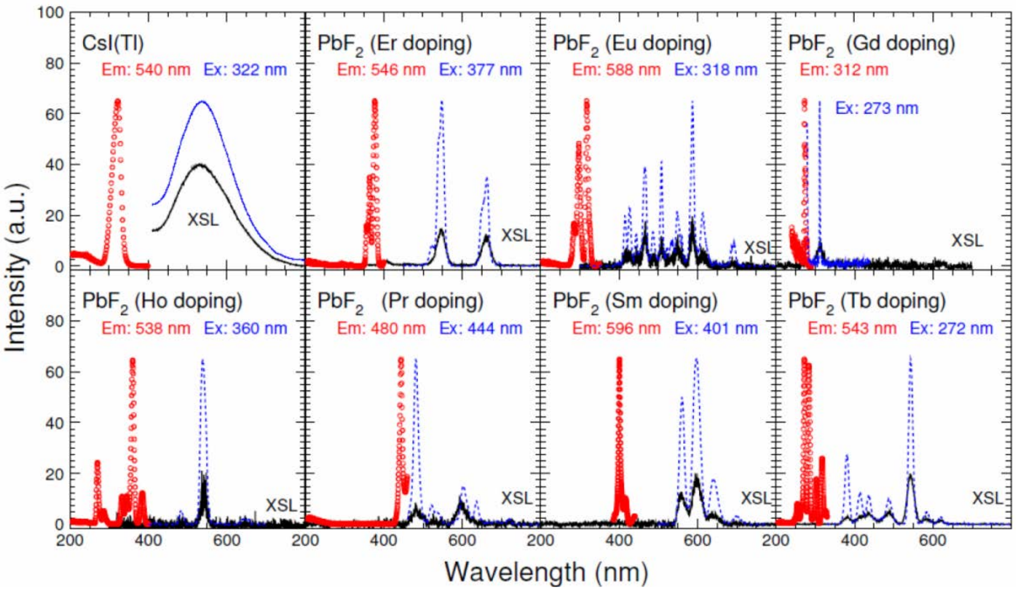
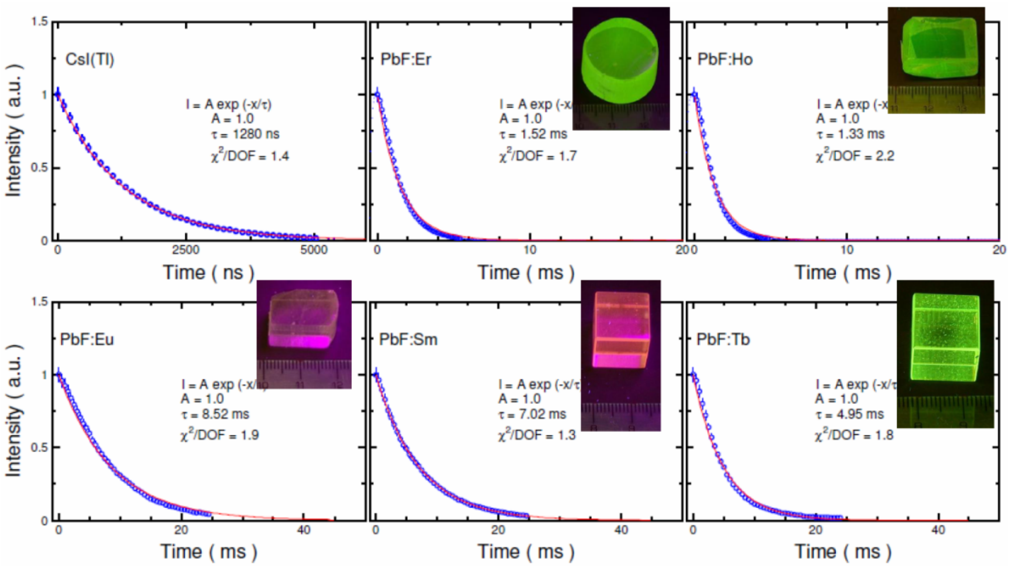
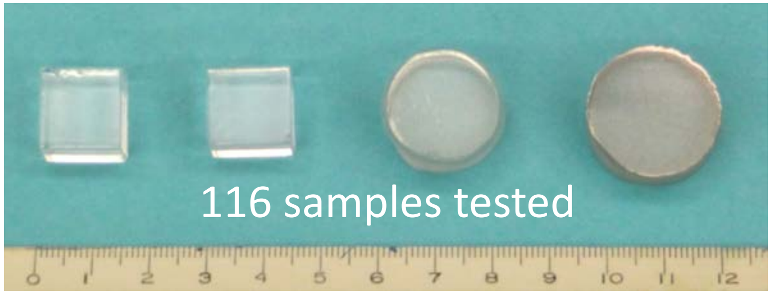
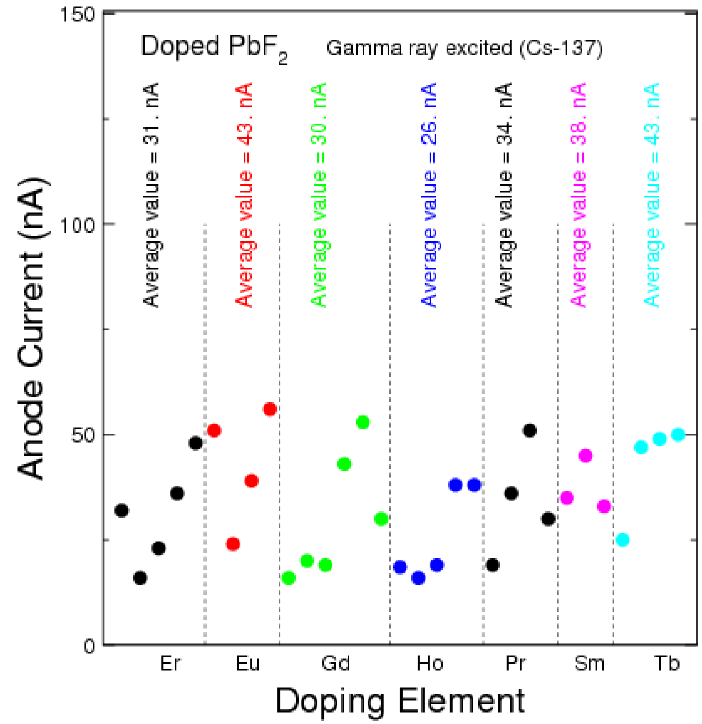
Search for Scintillation in Doped PbF_2





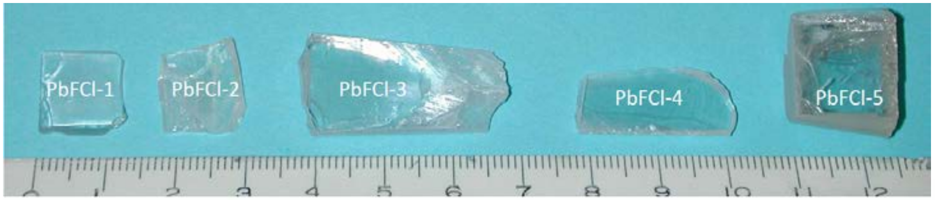


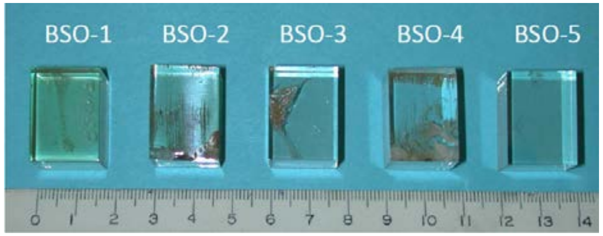




Will look performance at low temperature with the FLS920 fluorescence lifetime spectrometer

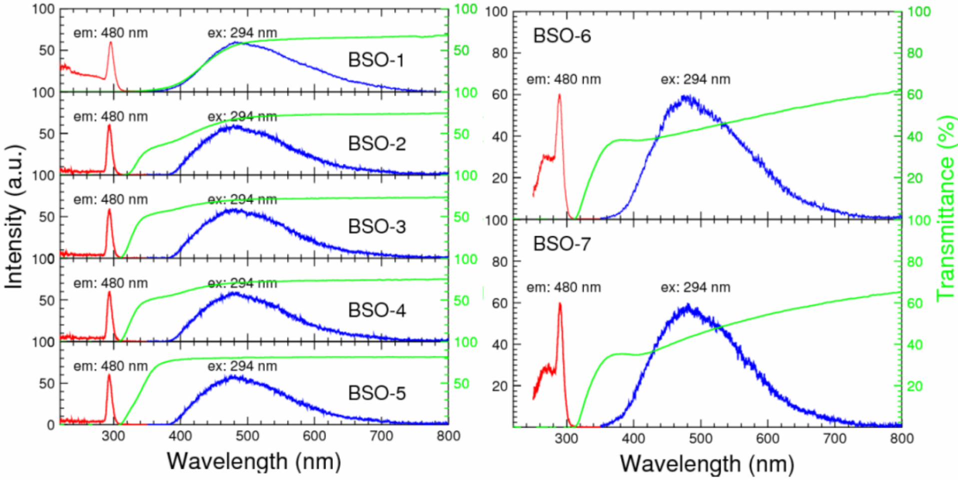
Other Materials: PbFCl & BSO

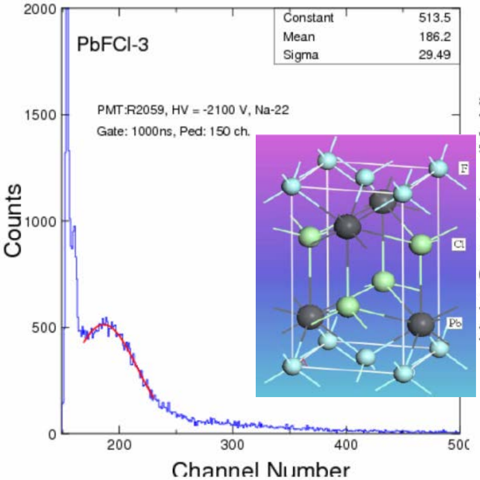


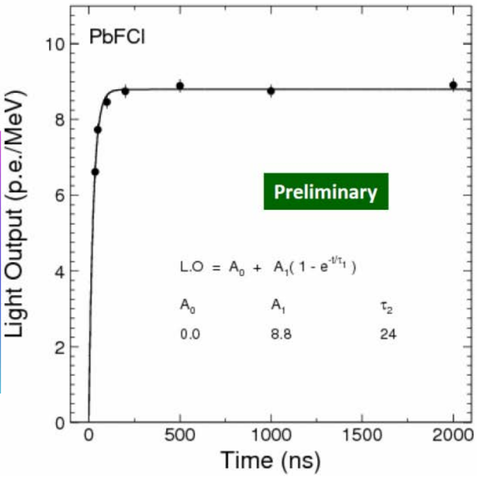


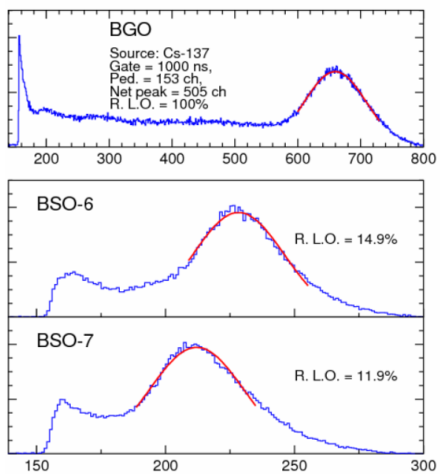
ID	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
Doping	--	Na 0.5at%	--	--	
Dimension (mm)	10x10x2	10x10x2	30x10x5	20x10x3	~10x10x9

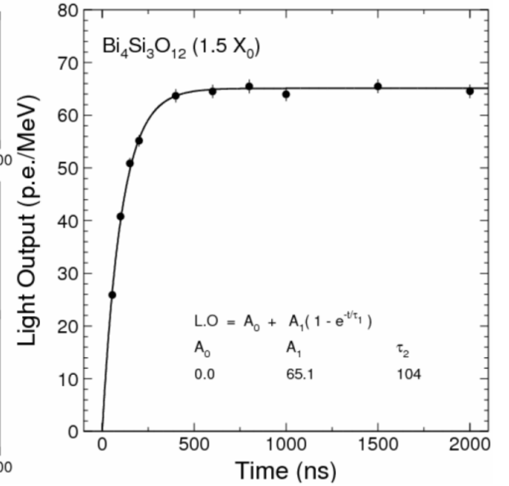
ID	PWO	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
X-luminescence		Peaked @ 420 nm				
L.O. (% PWO)	100	14	64	33	35	31
L.O. (% BGO)	1.8	0.25	1.1	0.59	0.63	0.56



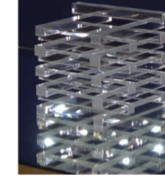






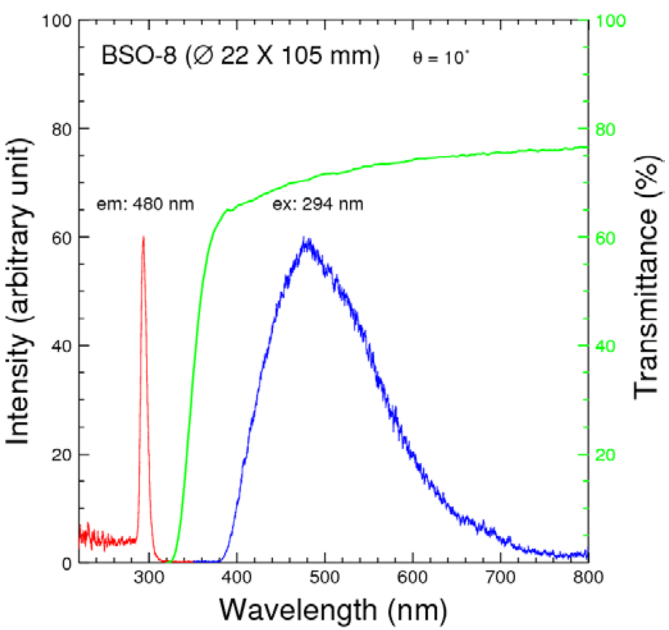


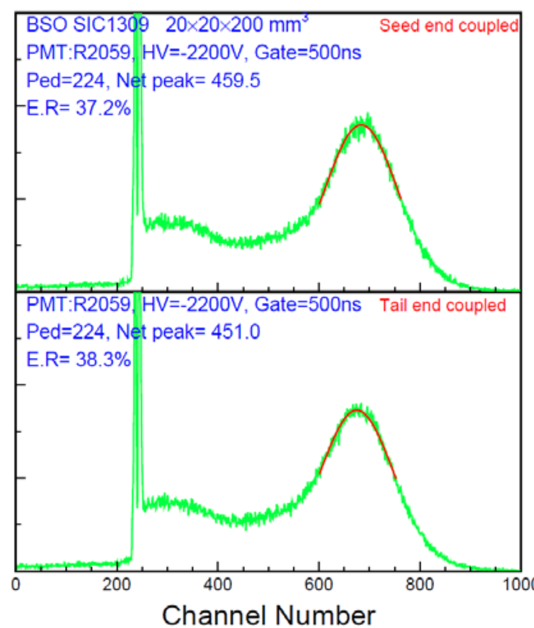
Large Size BSO Sample

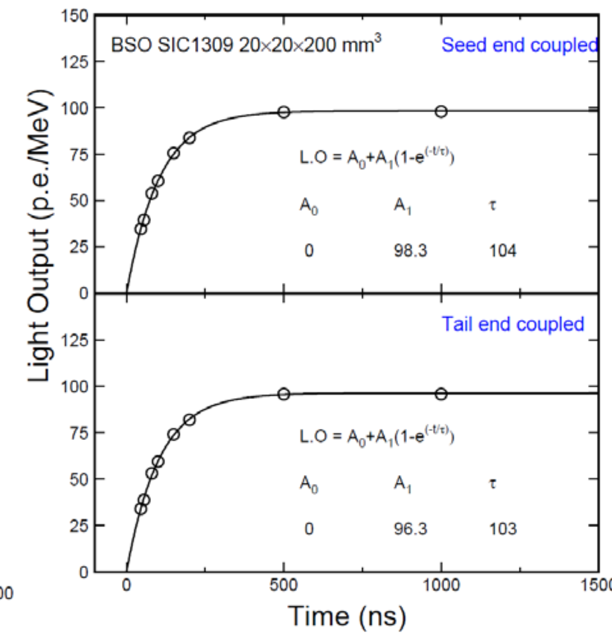


20 x 20 x 200 mm BSO crystals shows good optical and scintillation properties.

Presented in SORMA2014.







Summary

- Bright, fast and radiation hard LSO/LYSO crystals are base-lined for a total absorption ECAL for COMET at J-PARC. LYSO crystal based sampling calorimeter offers a robust stable calorimeter for the proposed HL-LHC.
- Future crystal calorimeters with more than ten times faster rate/timing capability require very fast crystals, e.g. BaF_2 with a sub-ns scintillation component.
- Cost effective crystals (PbF_2, PbFCl & BSO) may provide a foundation for a homogeneous hadron calorimeter with dual readout for both Cherenkov and scintillation light to achieve good jet mass resolution for ILC/CLIC.
- Novel scintillators in crystals, ceramics and glasses, may play important role for future HEP experiments.