The Next Generation of Crystal Detectors

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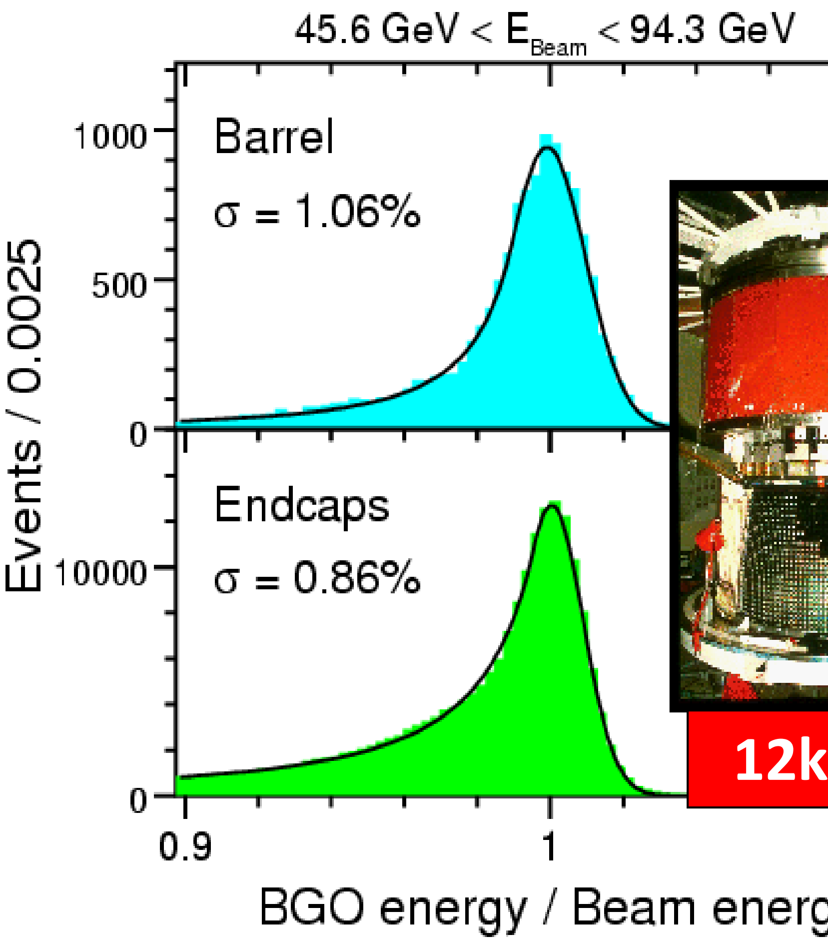
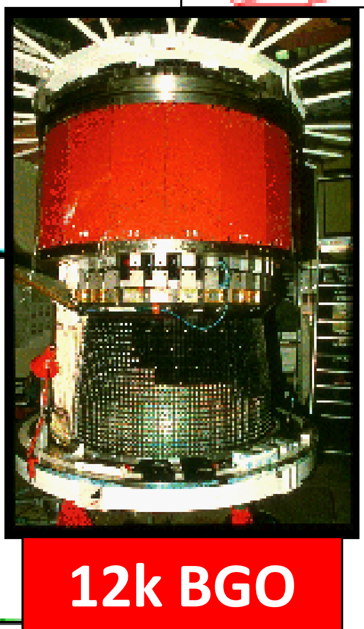
Why Crystal Calorimeter in HEP?

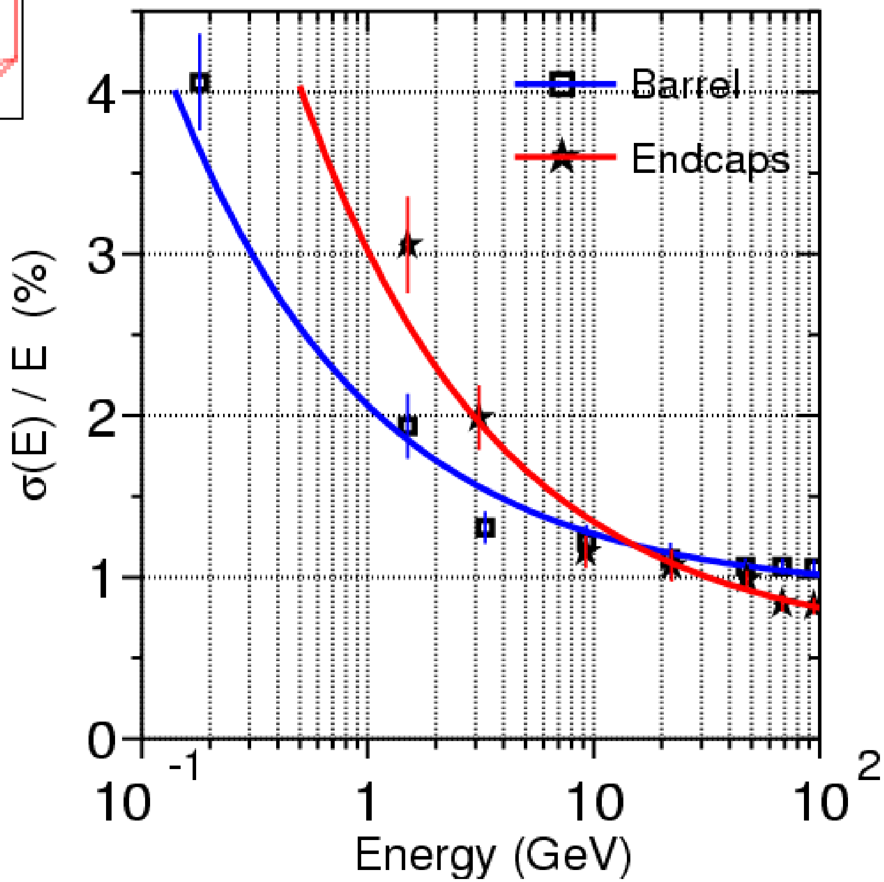
- **Photons and electrons are fundamental particles. Precision e/γ measurements enhance physics discovery potential.**
- **Performance of homogeneous crystal calorimeter in e/γ measurements is well understood:**
  - **The best possible energy resolution;**
  - **Good position resolution;**
  - **Good 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).**

L3 BGO Resolution

Contribution	"Radiative"+Intrinsic	Temperature	Calibration	Overall
Barrel	0.8%	0.5%	0.5%	1.07%
Endcaps	0.6%	0.5%	0.4%	0.88%



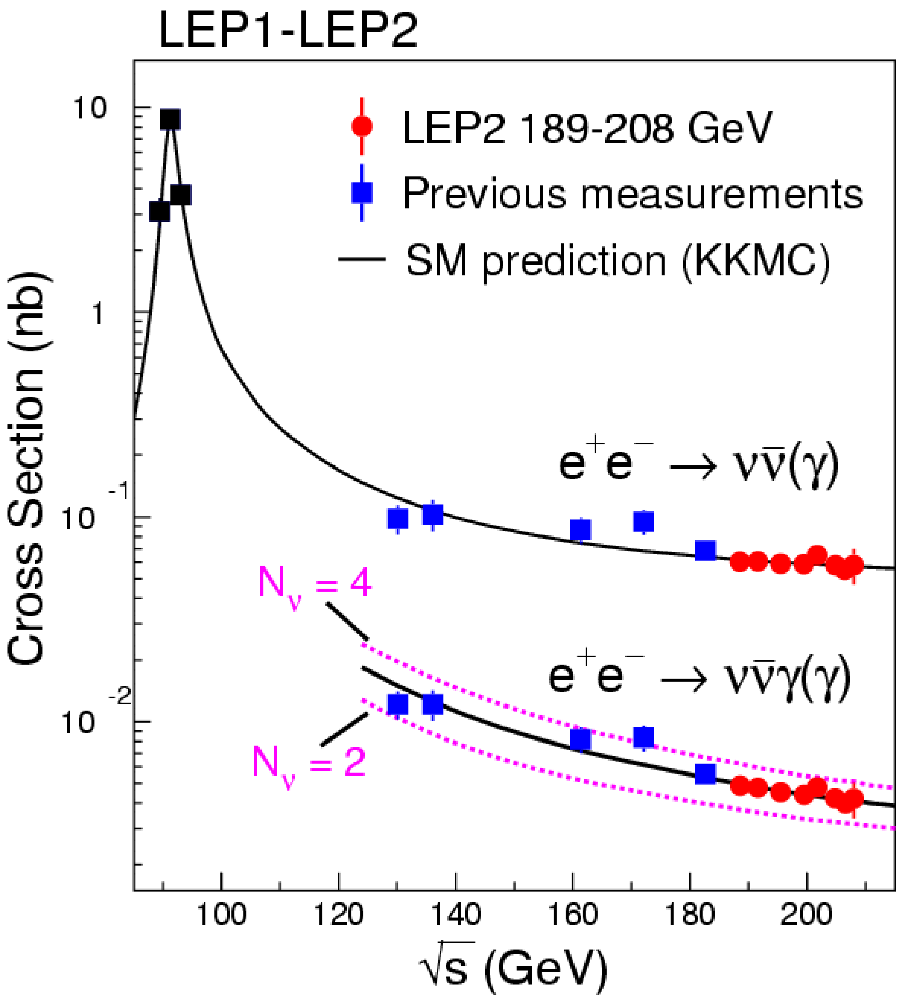




Physics with Crystal Calorimeters (I)

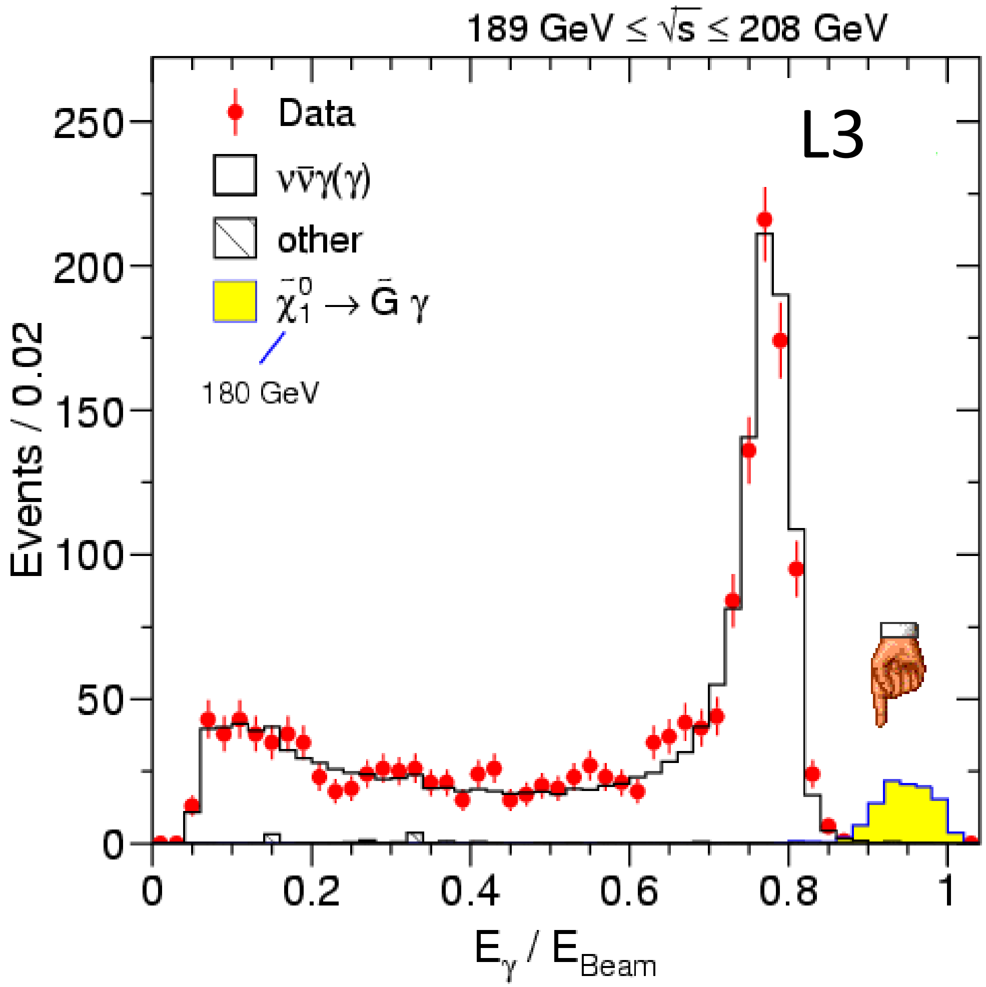
Neutrino Counting in Z Decay

$N_\nu = 2.98 \pm 0.06$



SUSY Breaking with Gravitino

$$e^+e^- \rightarrow \tilde{G}\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma$$



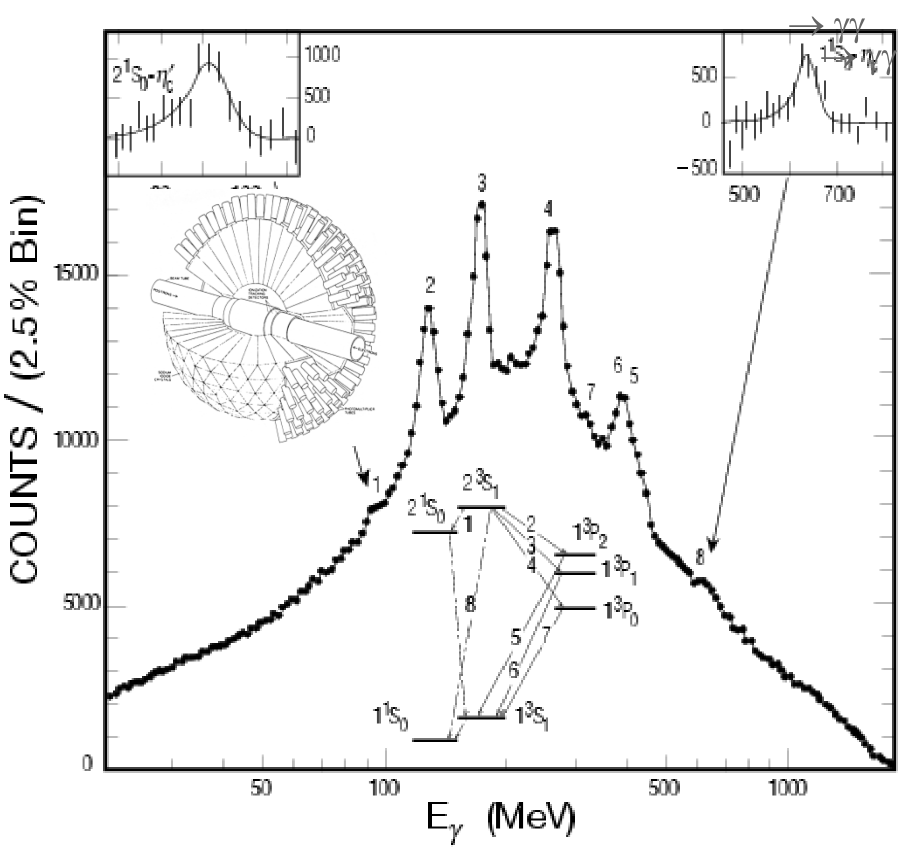
Physics with Crystal Calorimeters (II)

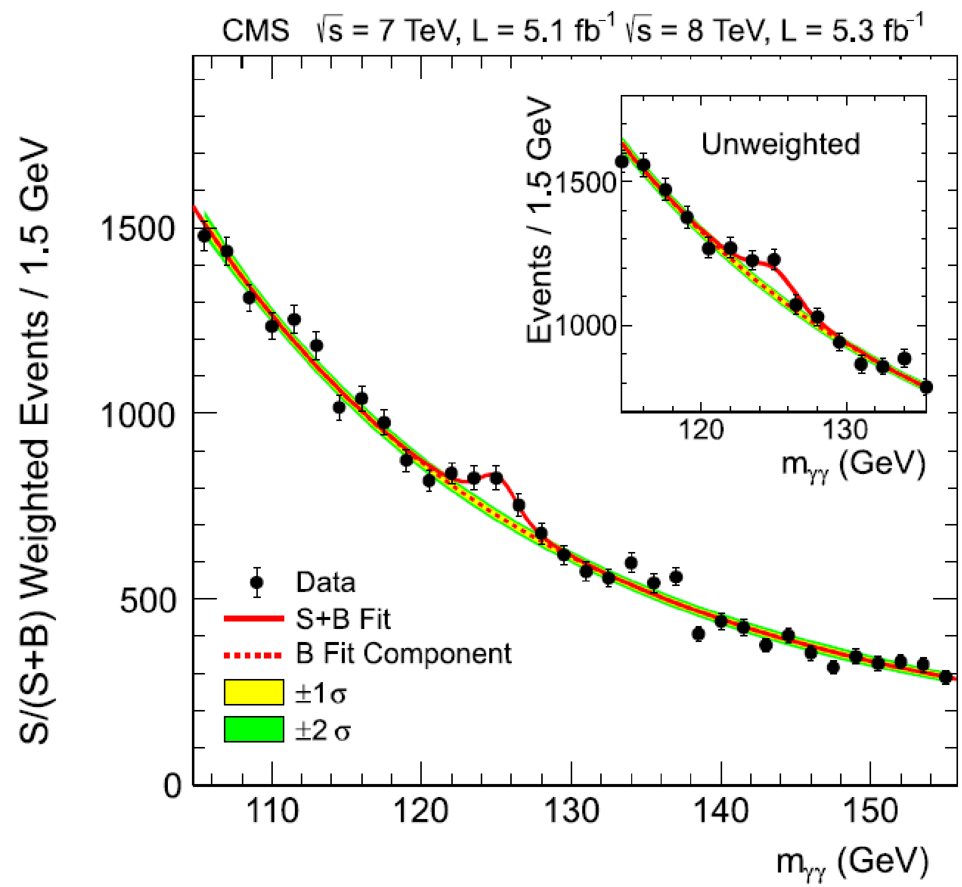
Charmonium system observed by CB through Inclusive photons

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

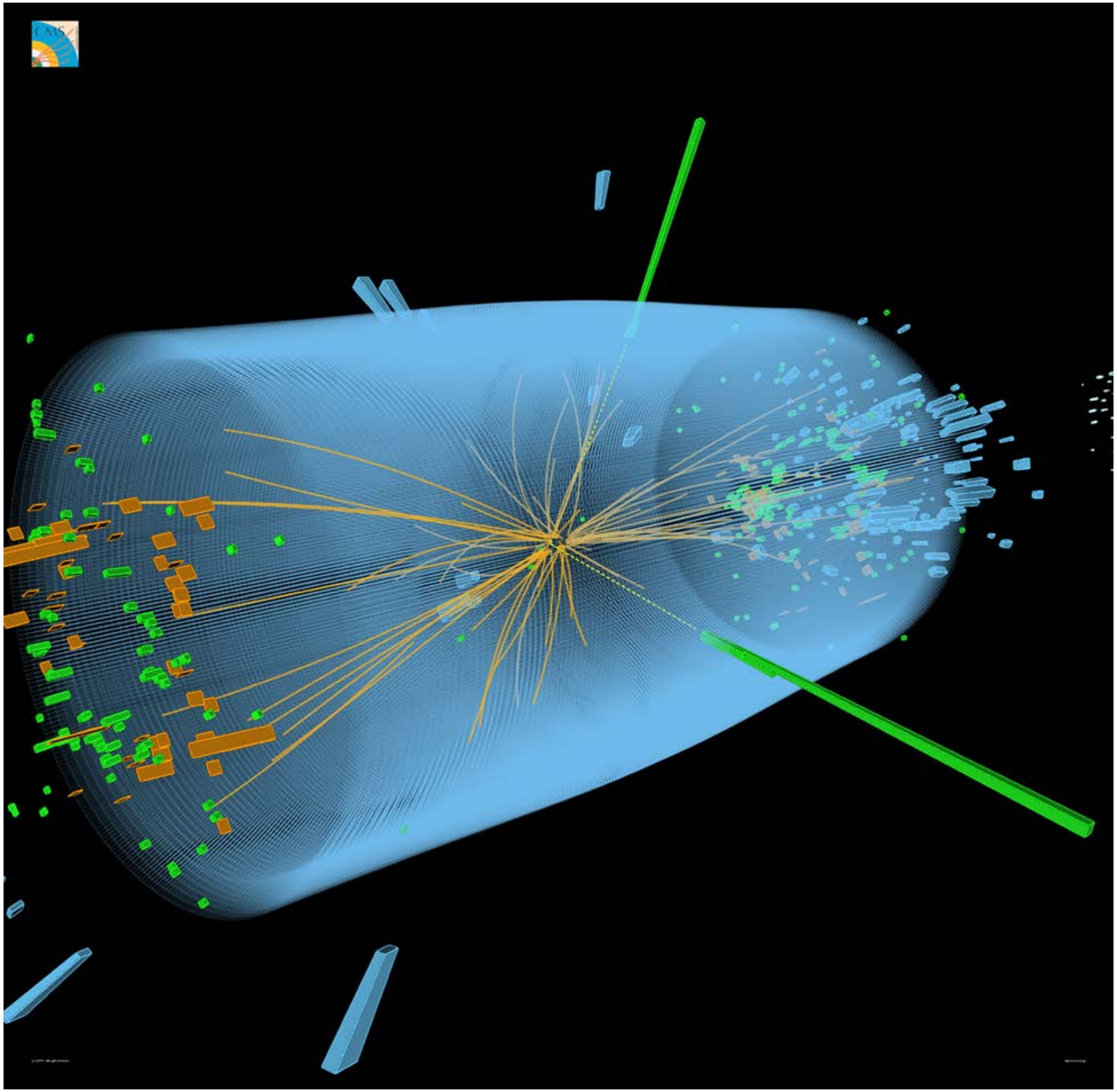
CB NaI(Tl)

CMS PWO





Higgs Discovery in CMS



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

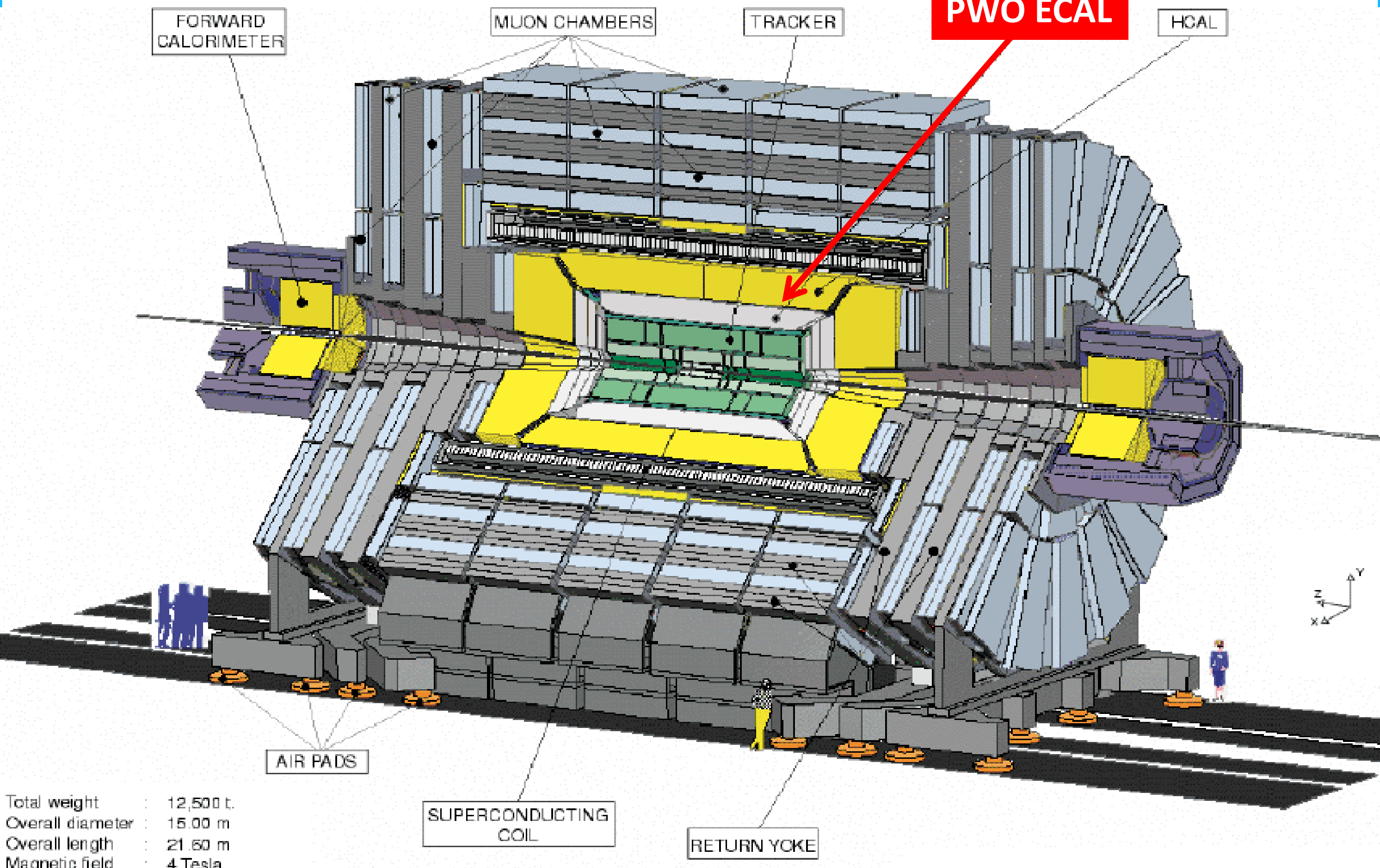
Future Crystal Calorimeters in HEP:

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

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

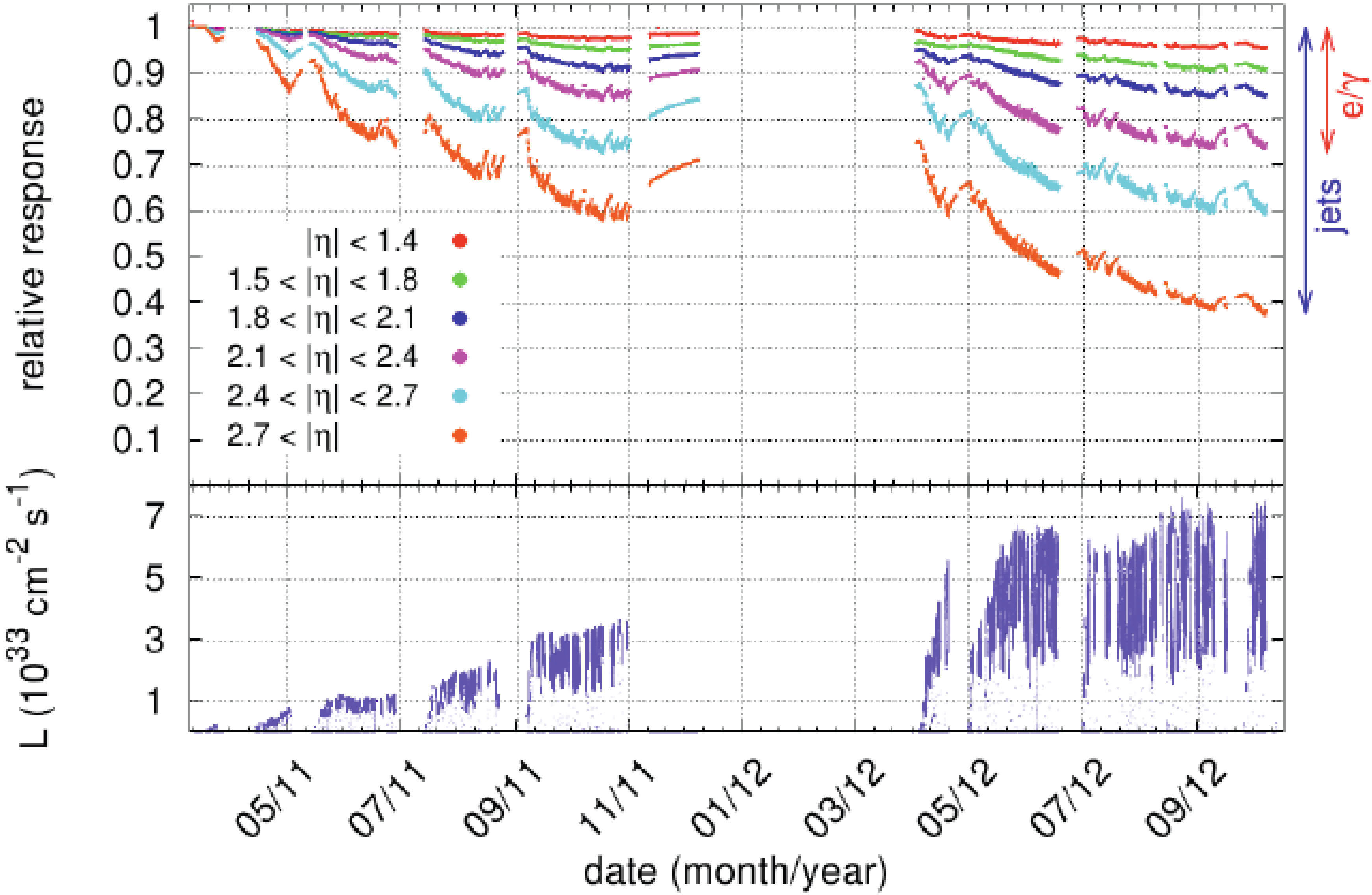
PbF_2, PbFCl and BSO for Homogeneous HCAL for ILC

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

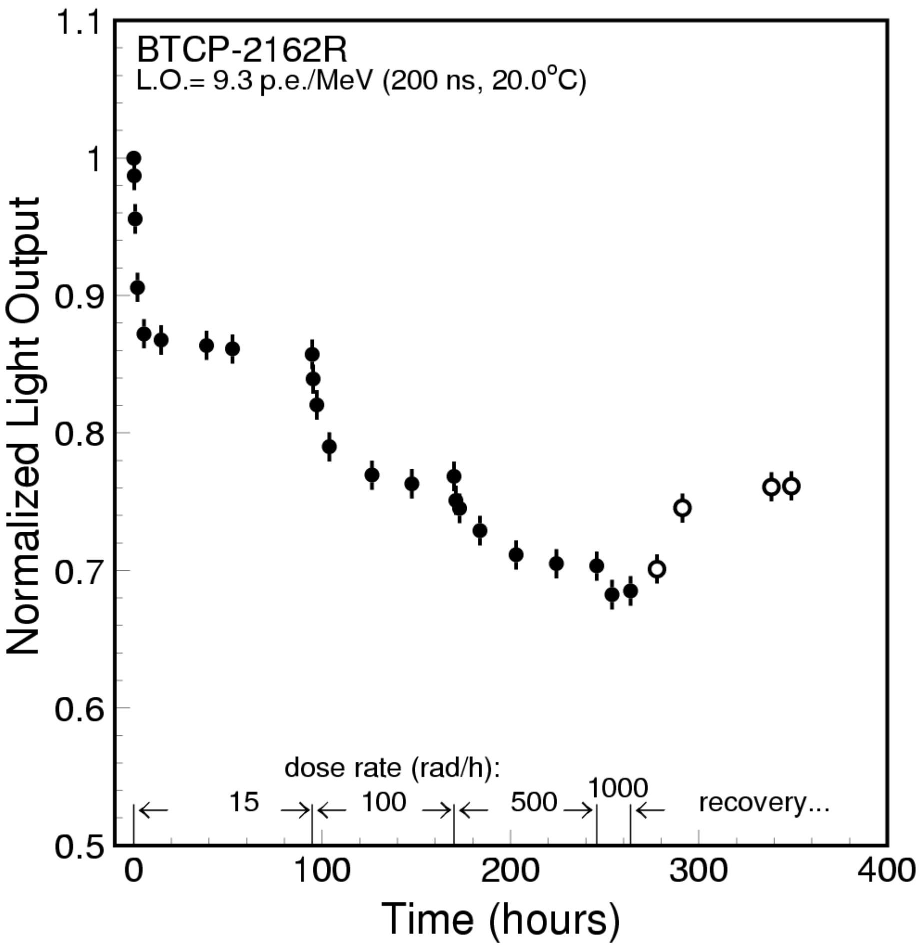
Light output reaches an equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

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

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

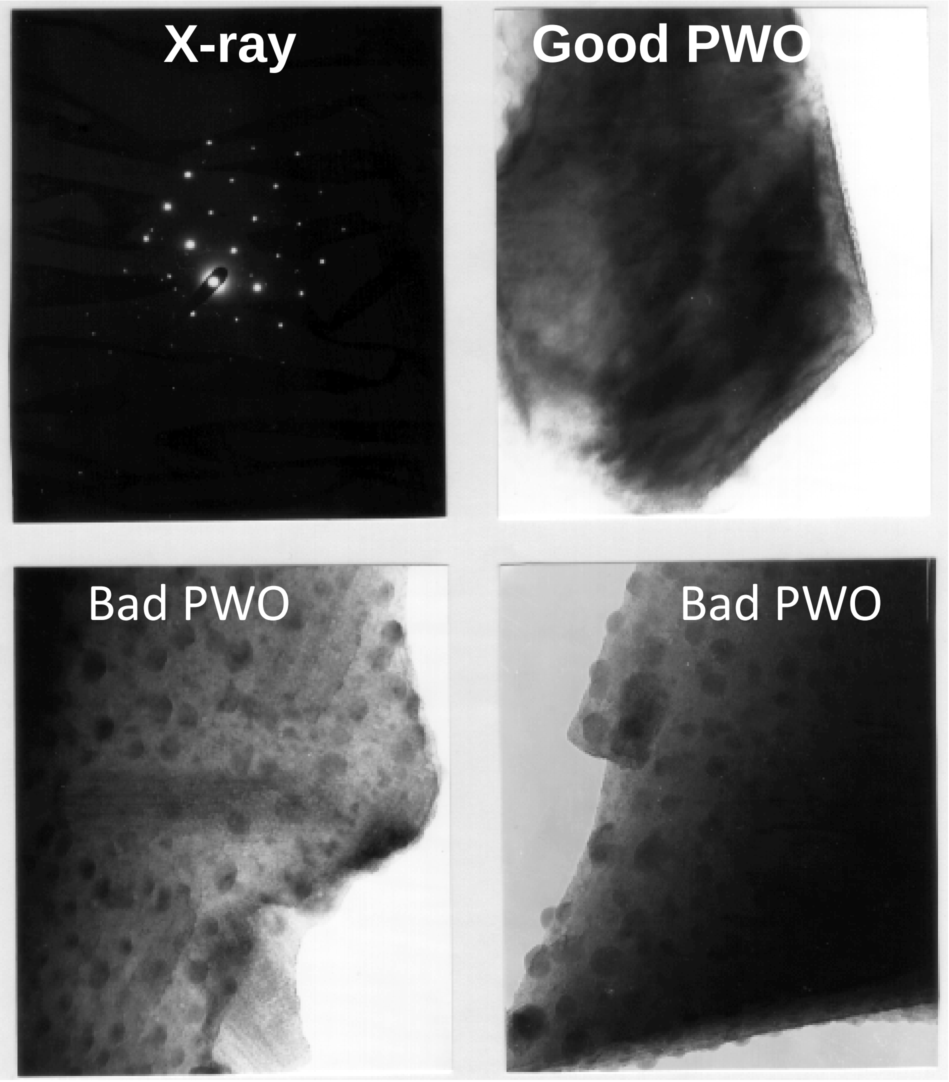
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of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

TOPCON-002B scope, 200 kV, 10 uA, 5 to10 nm black spots identified
JEOL JEM-2010 scope and Link ISIS EDS localized Stoichiometry Analysis



NIM A413 (1998) 297

Atomic Fraction (%) in $PbWO_4$

As Grown Sample

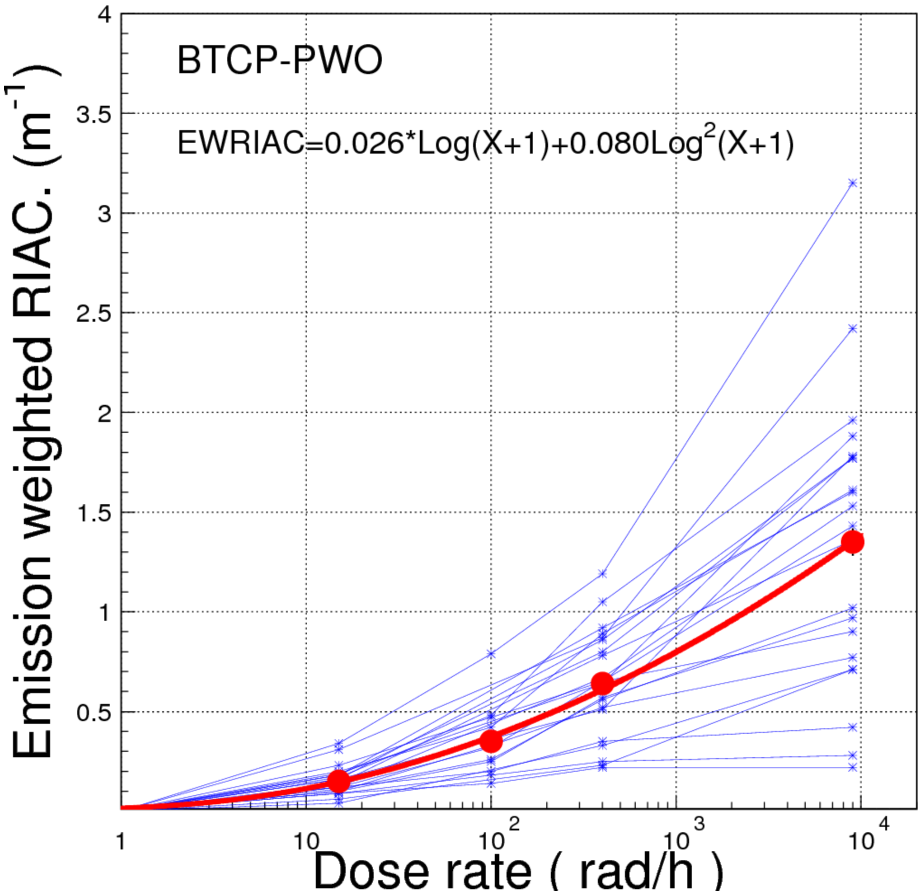
Element	Black Spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

The Same Sample after Oxygen Compensation

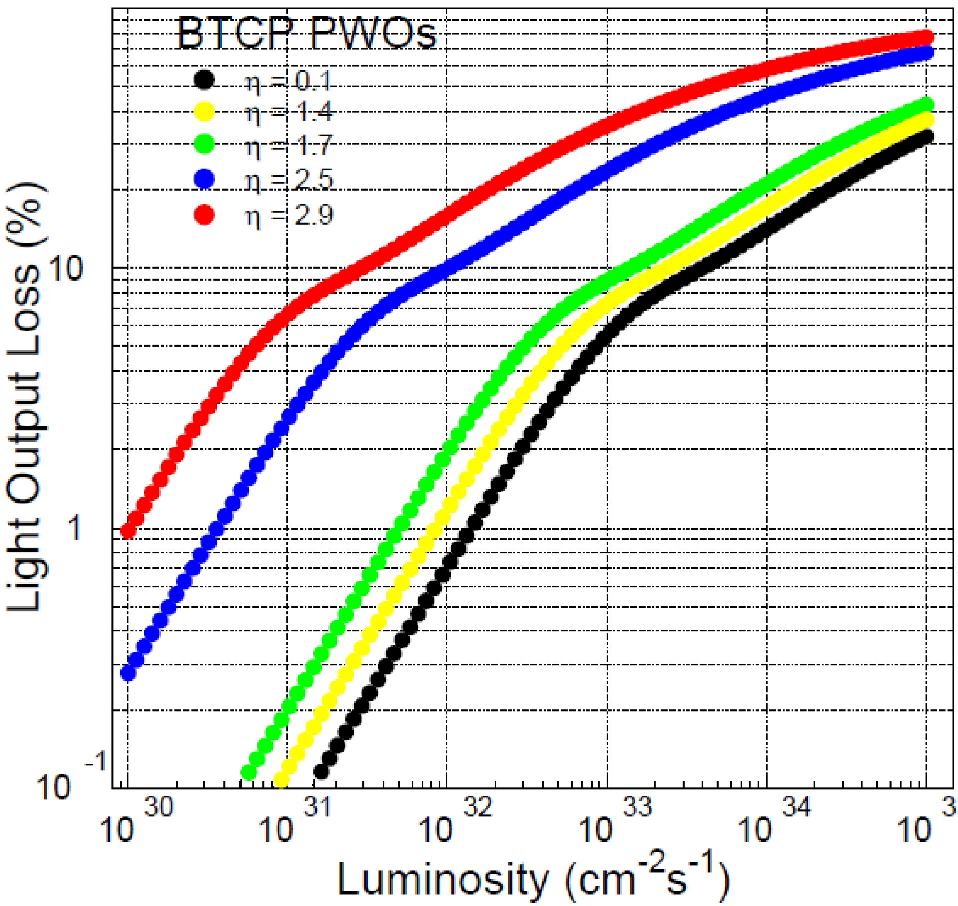
Element	$Point_1$	$Point_2$	$Point_3$	$Point_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

Prediction of PWO Radiation Damage

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



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

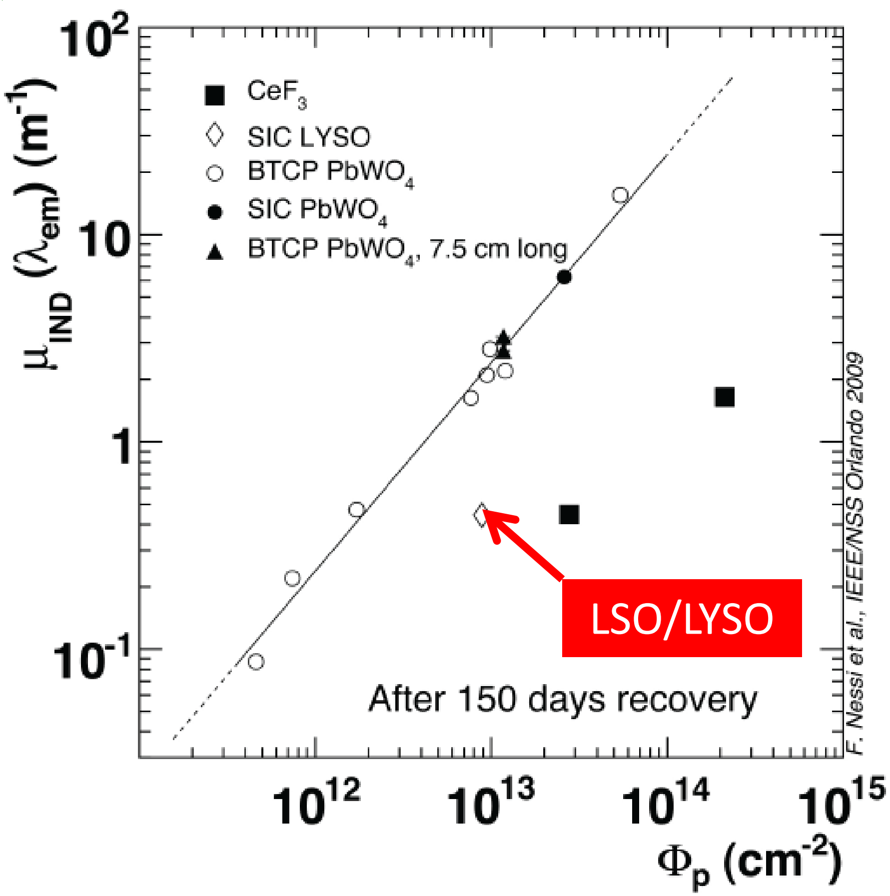


Predicted EM dose induced damage agrees well with the LHC data

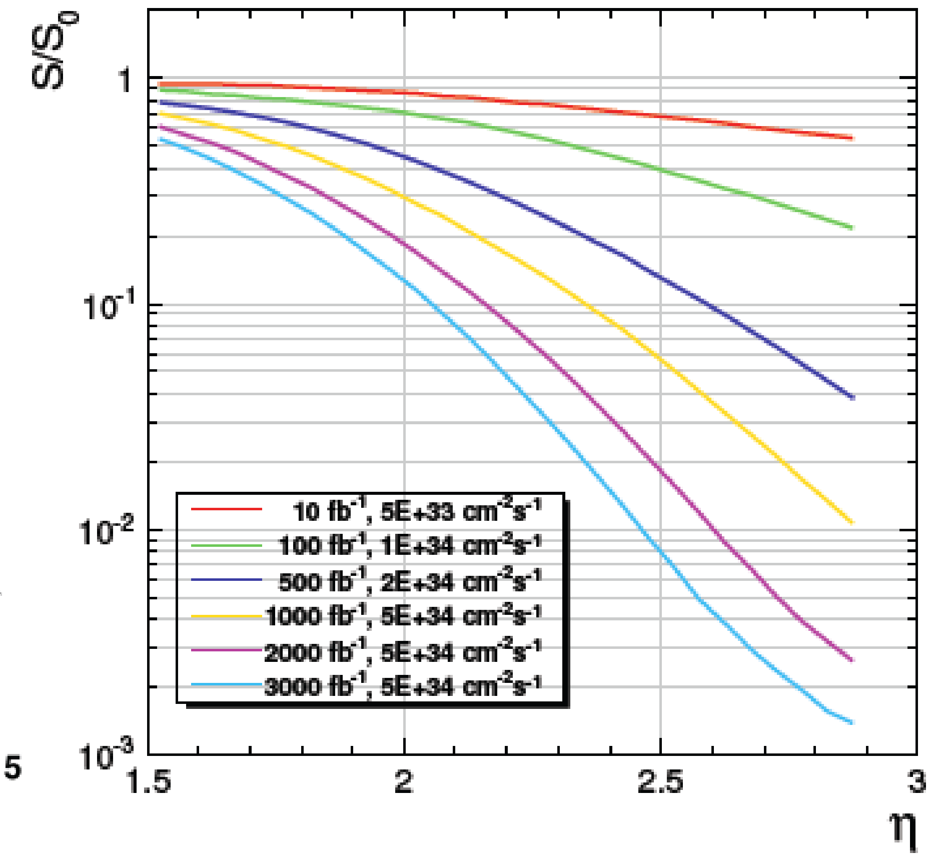
In addition, there is cumulative hadron induced damage in PWO

Proton Induced Damage

G. Dissertori et al., IEEE NSS09, N32-3

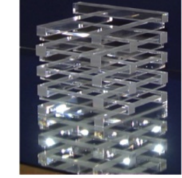


Expected LO loss for CMS endcap PWO

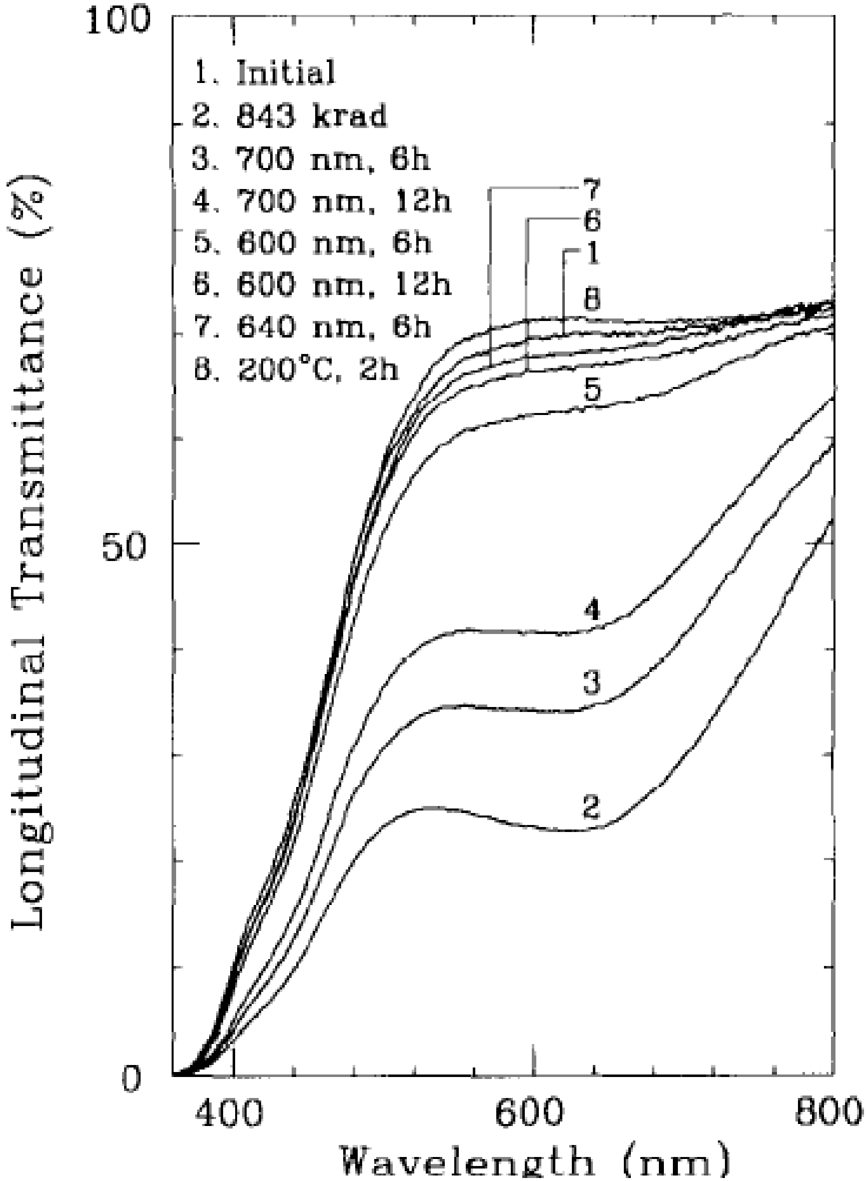


Proton induced absorption in LYSO is 1/5 of PWO
Radiation damage effect is smaller for **short light path**

OB and TA Effective for PWO



NIM A376 (1996) 319-334

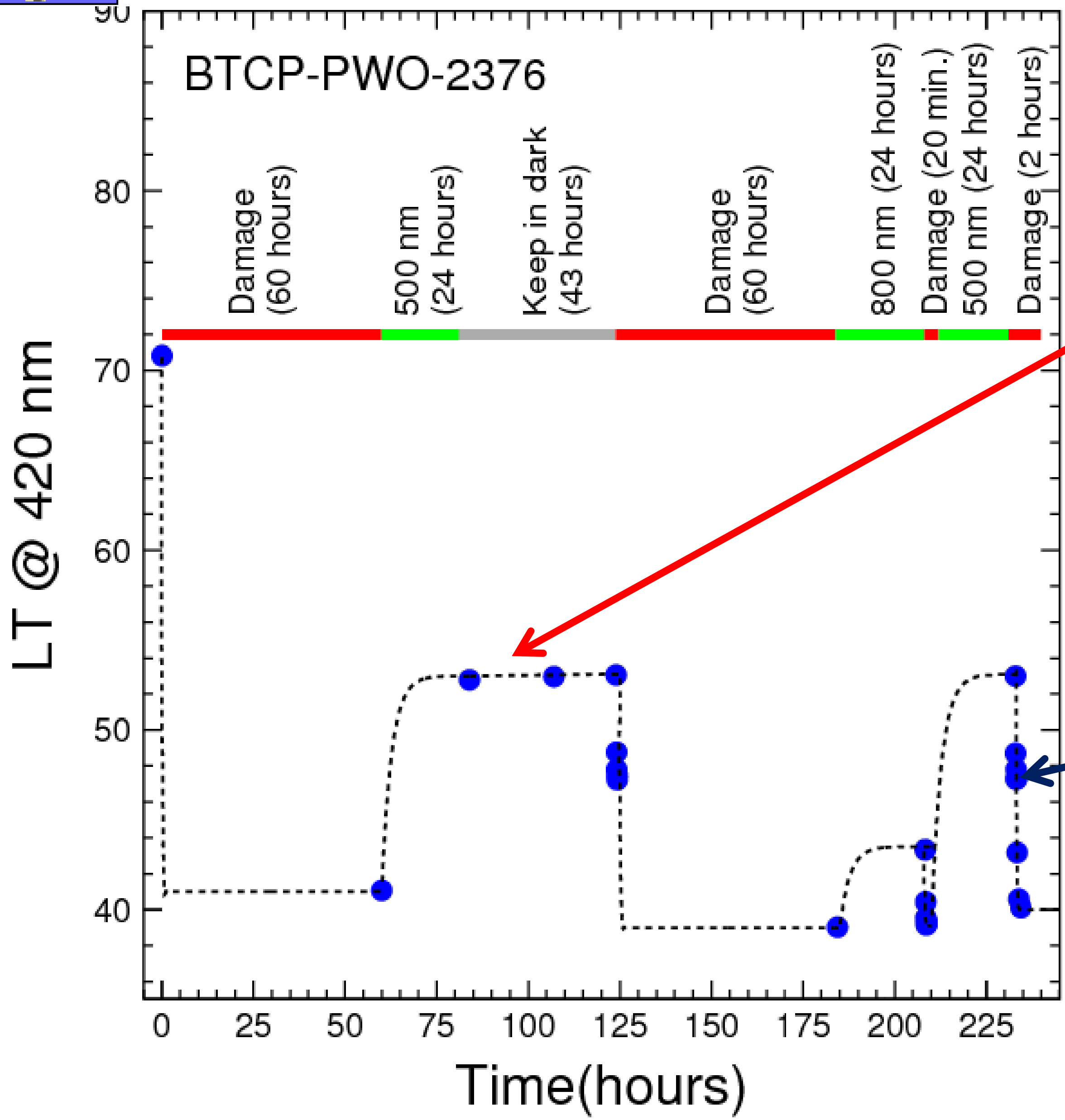


The radiation induced absorption can also be reduced by either optical bleaching or thermal annealing. It is known that the color centers in crystals can often be entirely eliminated by heating the crystal to a high temperature, a process know as thermal annealing [6]. By injecting light into the crystal, the color centers can also be eliminated by the process of color center annihilation [20], and the effectiveness of this optical bleaching is known to be wavelength dependent.

Optical bleaching and thermal annealing for sample 768

Operation	Duration [h]	@486 nm T [%]	@486 nm LAL [cm]	@510 nm T [%]	@510 nm LAL [cm]
Initial	–	51.2	58	60.0	98
After 840 krad	–	21.0	17	24.0	19
700 nm bleaching	6	27.5	21	32.4	26
700 nm bleaching	12	32.7	26	38.5	33
600 nm bleaching	6	45.6	44	54.1	67
600 nm bleaching	12	49.0	52	58.1	86
500 nm bleaching	6	44.6	42	53.6	65
Recovery @ RT	24	45.6	44	54.5	68
640 nm bleaching	6	49.2	52	59.1	92
200° thermal annealing	2	52.9	63	62.5	120
660 nm bleaching	6	51.5	59	61.5	110

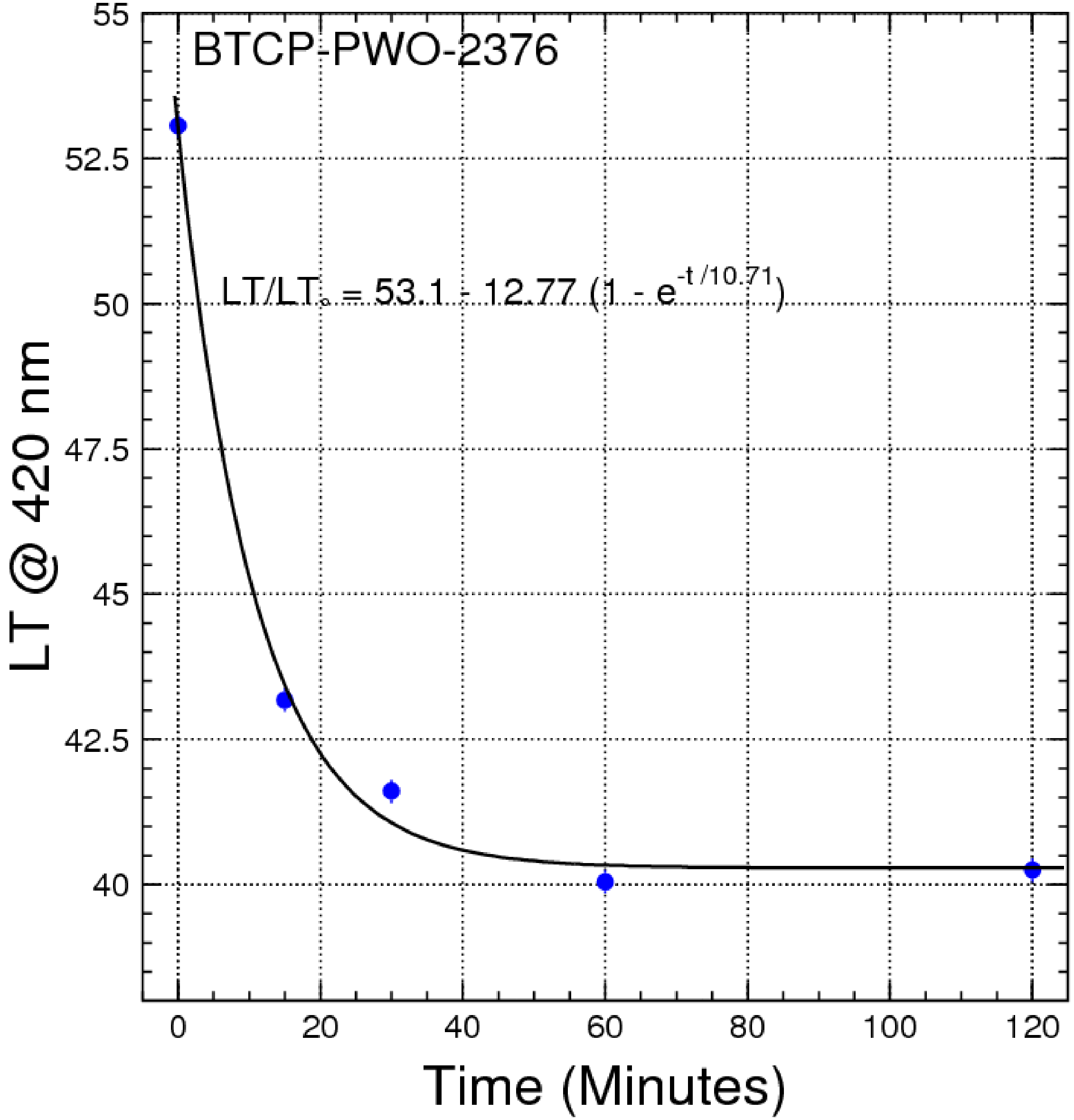
BTCP-2376: Damage/OB/Recovery



After 500 nm bleaching for 24 h no natural recovery was observed at room temperature

The time constant for damage @7,000 rad/h is very short

BTCP 2376: Damage Speed @ 7k rad/h



The time constant for the damage process @7,000 rad/h is about 10 minutes
The transmittance @420 nm changes more than 20% in half hour, indicating difficult for monitoring to follow.

After growth manipulations thus would be useful for the EM dose induced damage only if it is applied constantly.

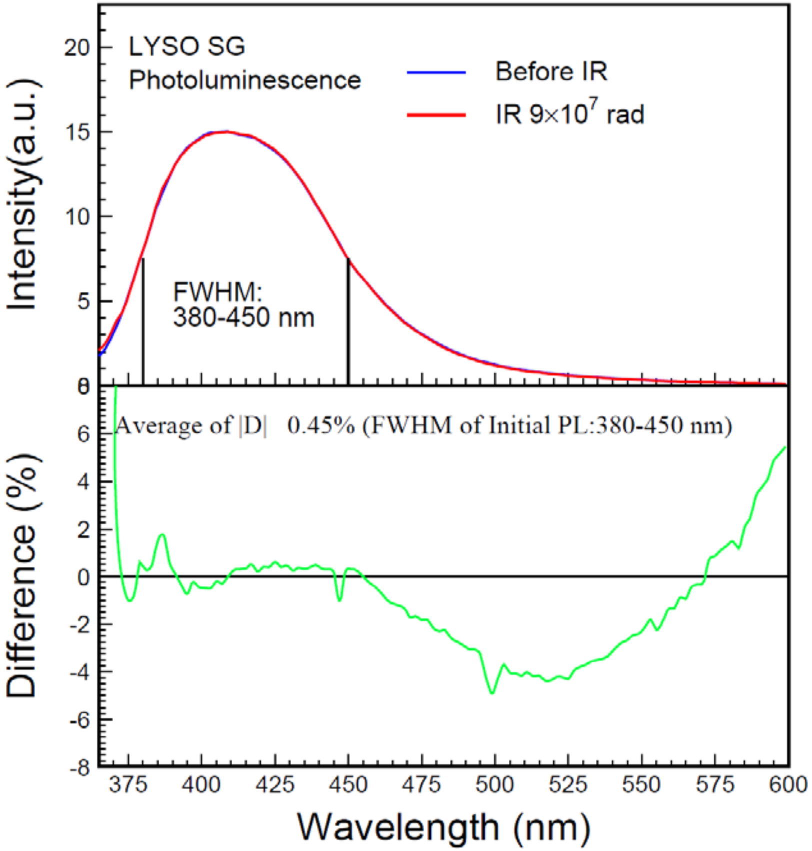
Bright, Fast Scintillator: LSO/LYSO

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm³)	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	3.7	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	(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 LSO/LYSO

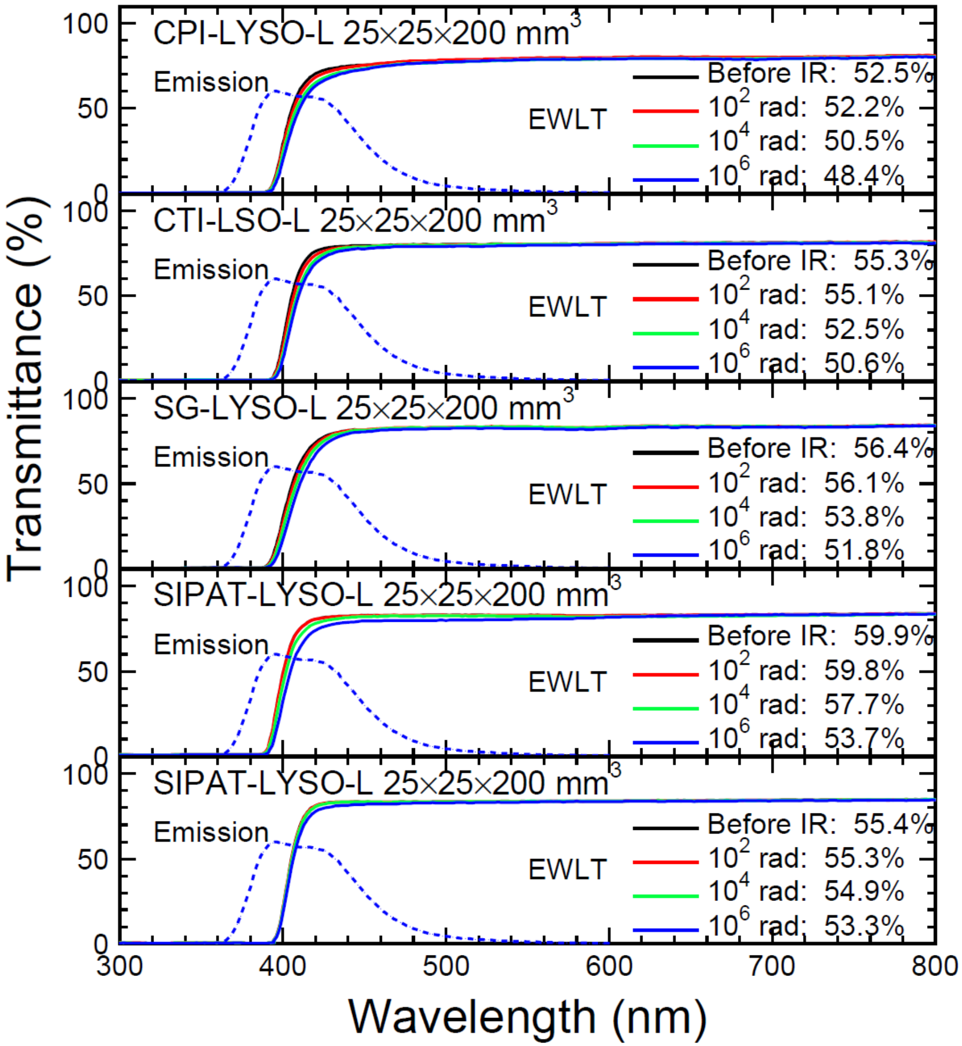
LSO/LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator. The longitudinal non-uniformity issue caused by tapered crystal geometry, self-absorption and cerium segregation can be addressed by roughening one side surface. The material is widely used in the medical industry. Existing mass production capability would help in crystal cost control.

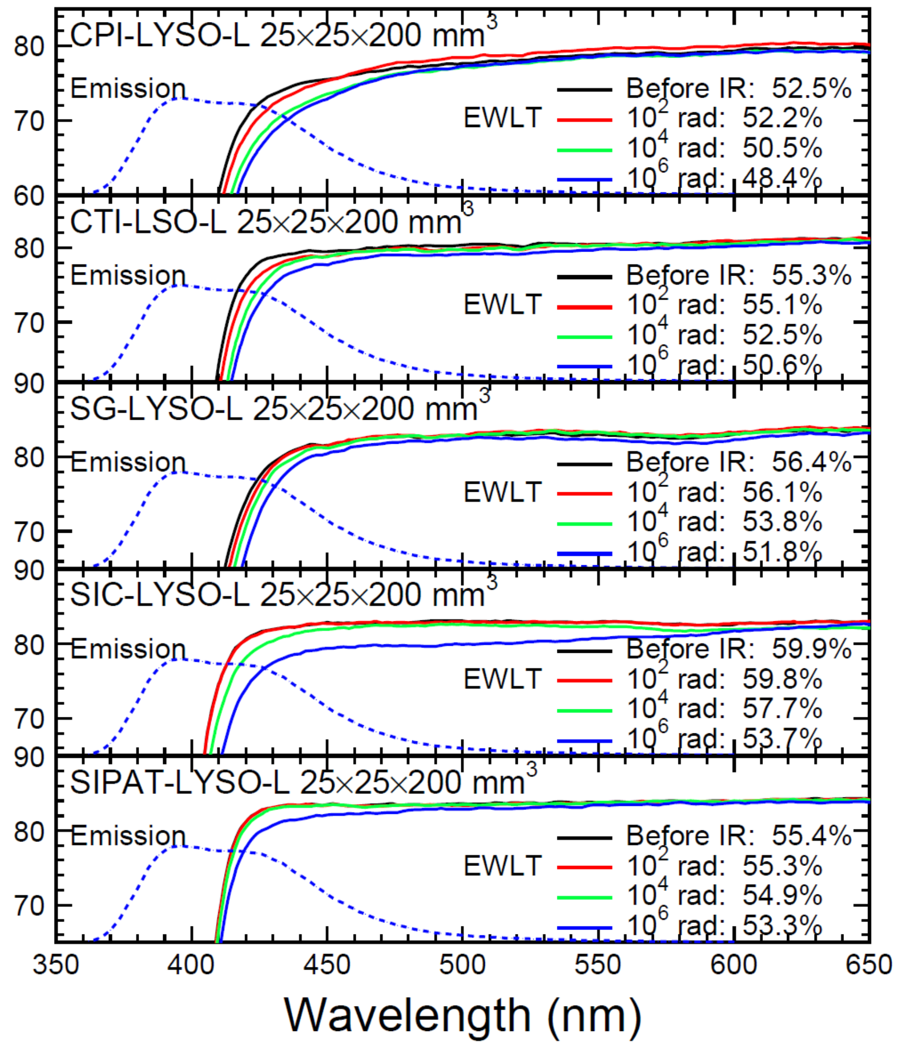


Excellent Radiation Hardness in LT

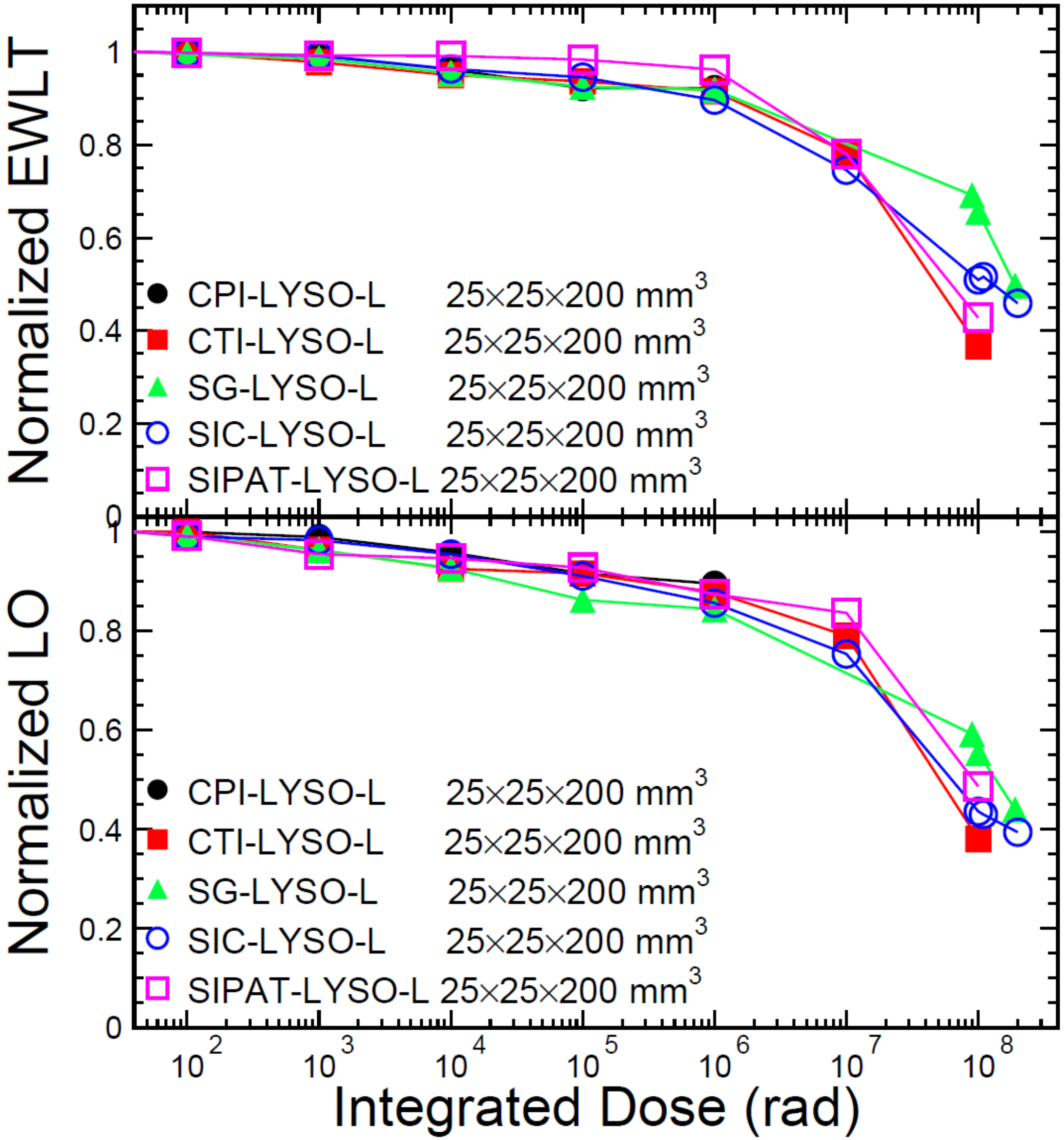
Consistent & Small Damage in LT

Larger variation @ shorter λ





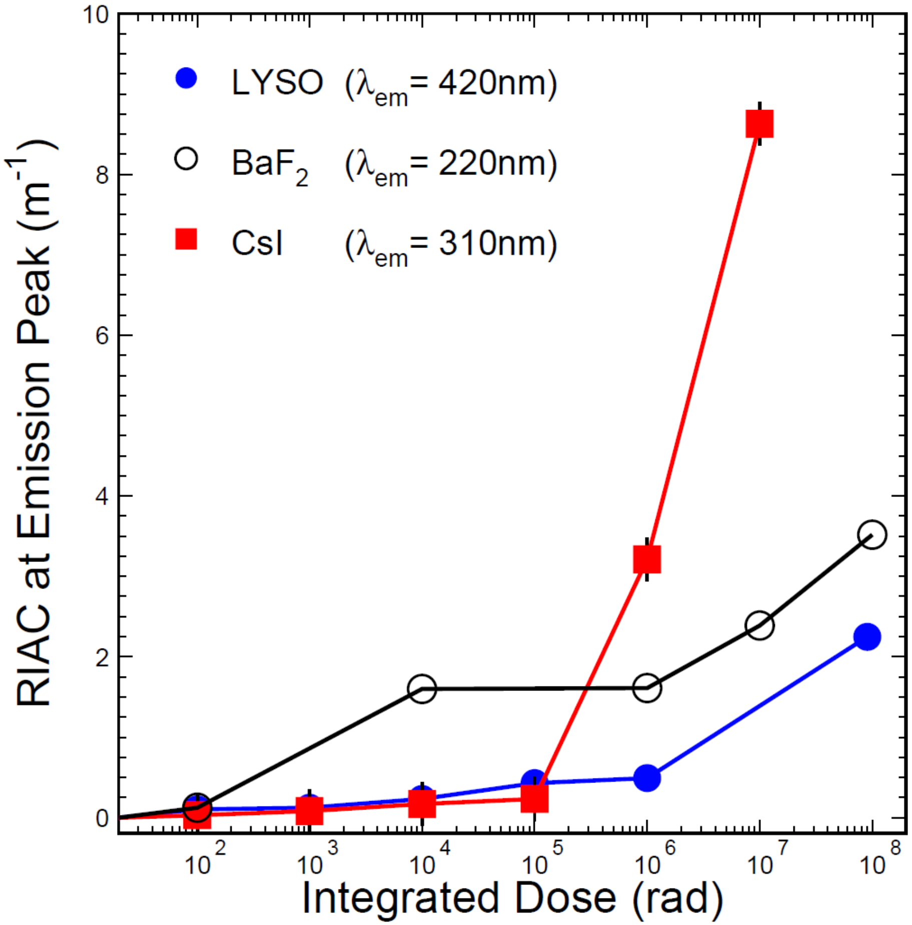
Summary of Long LYSO Samples



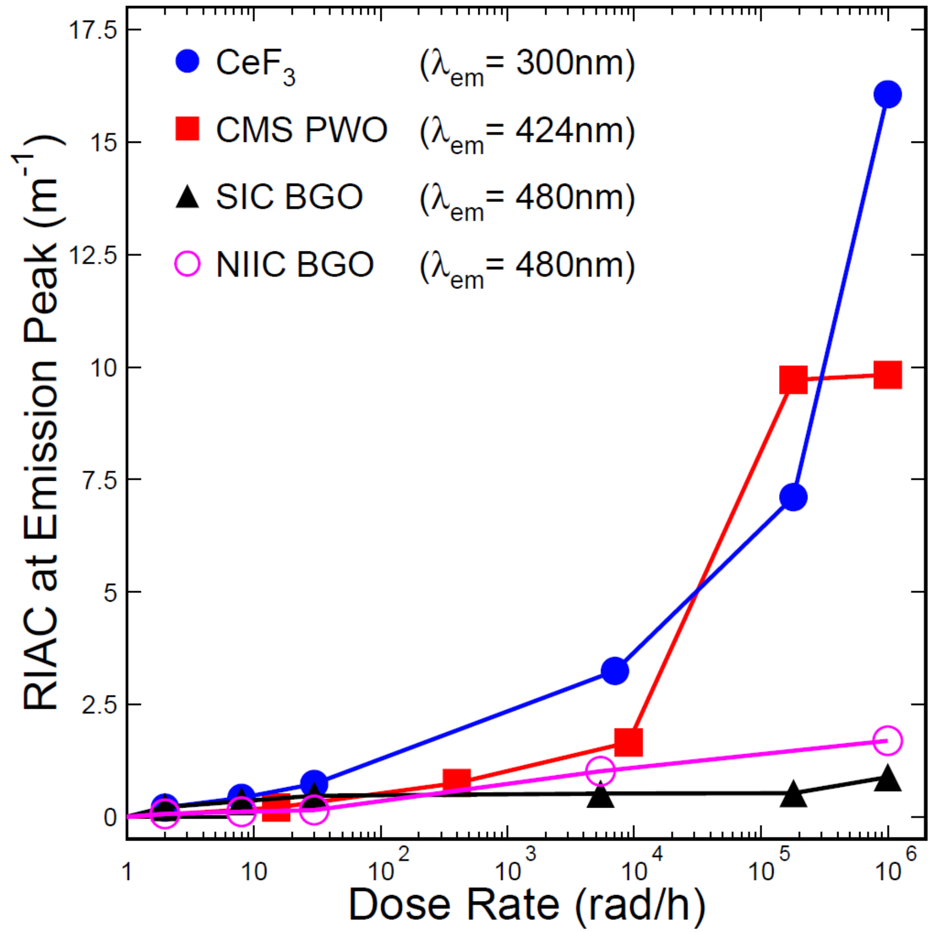
Consistent radiation hardness up to 200 Mrad observed in LYSO samples grown about ten years ago by various vendors

Radiation Induced Absorption Coefficient

Crystals with no recovery



Crystals with recovery



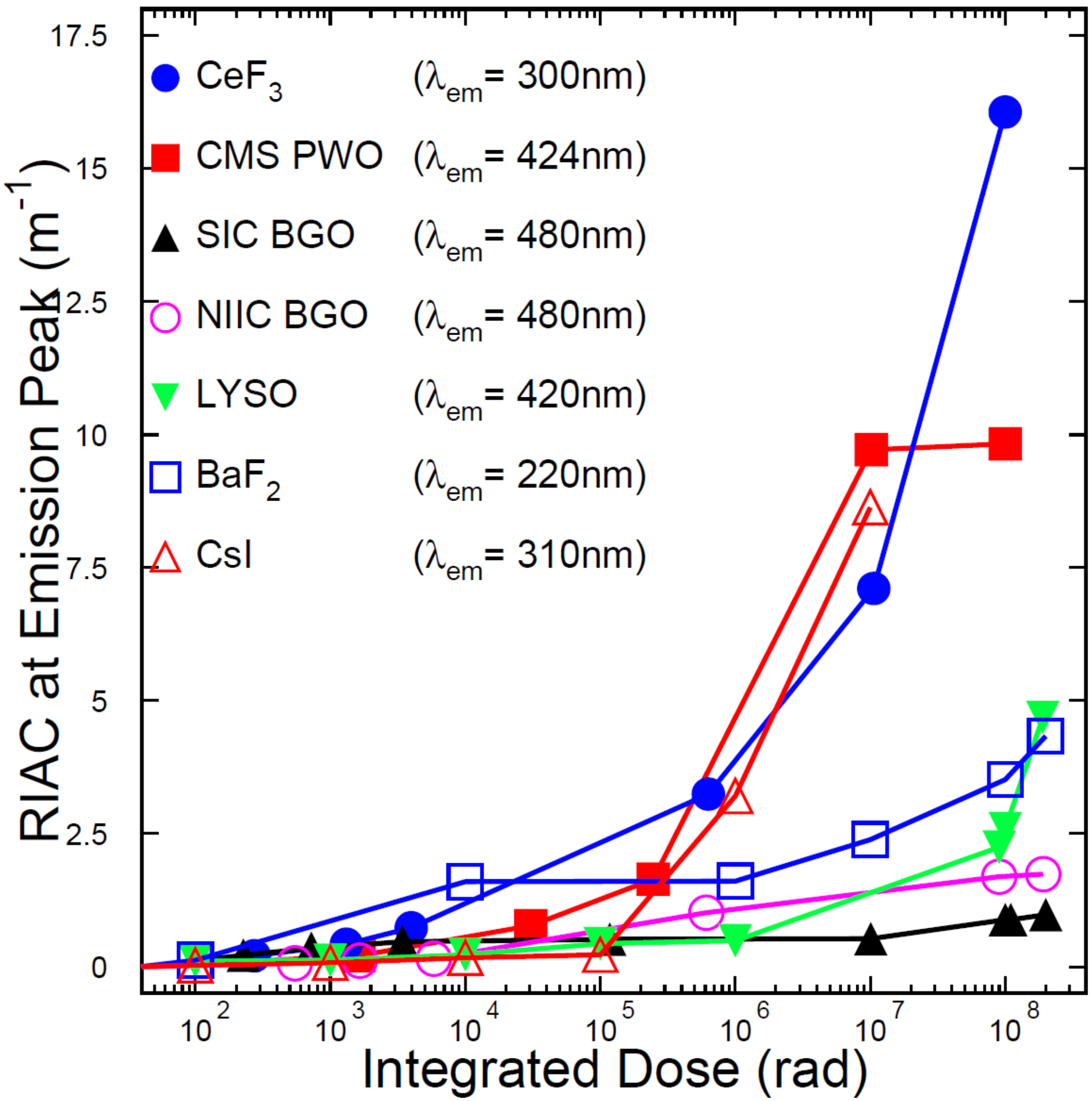
BGO, LYSO and BaF_2 are radiation hard crystals

RIAC as a Function of Integrated Dose

Ignoring the dose rate dependence, the RIAC values are shown as a function of integrated dose for all crystals.

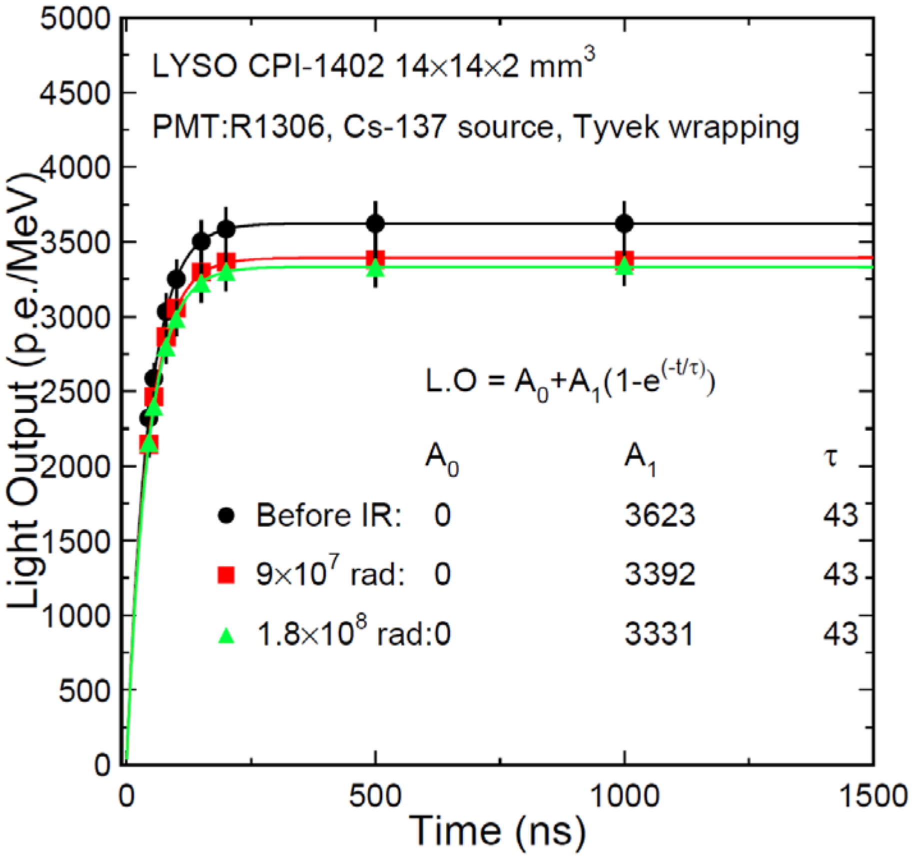
The RIAC values are probably overestimated for crystals have shallow color centers with dose rate dependent damage.

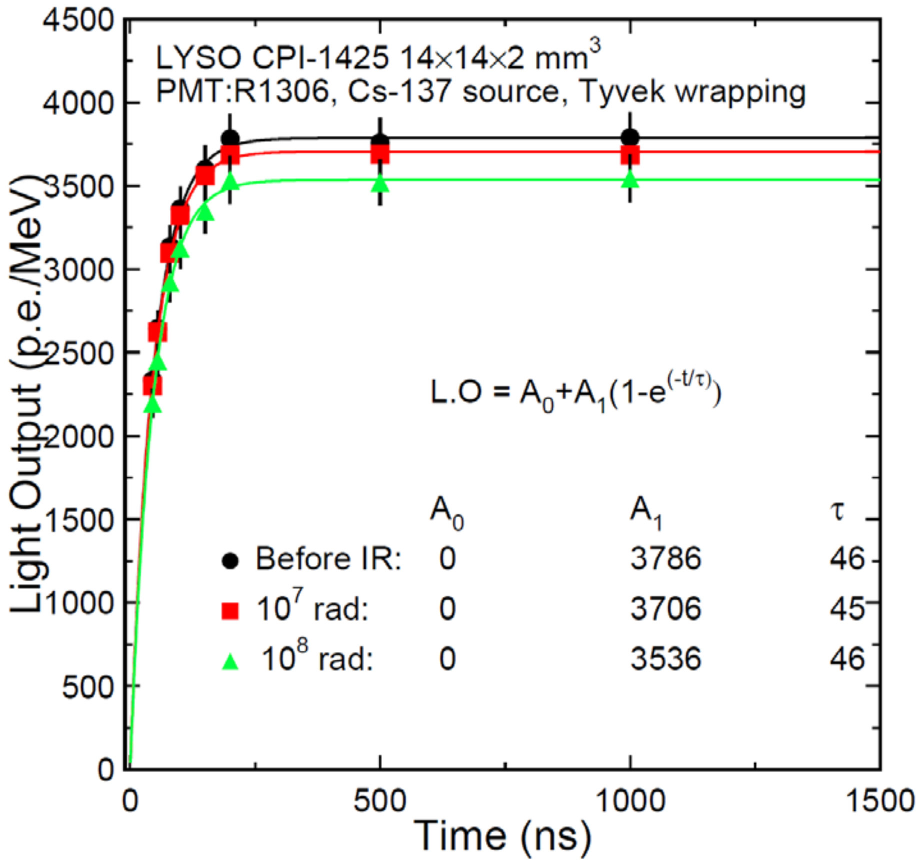
Two CeF_3 crystals were grown about twenty years ago. High quality crystals grown recently need to be tested.



14 x 14 x 2 mm LYSO Plates

Light output and decay kinetics

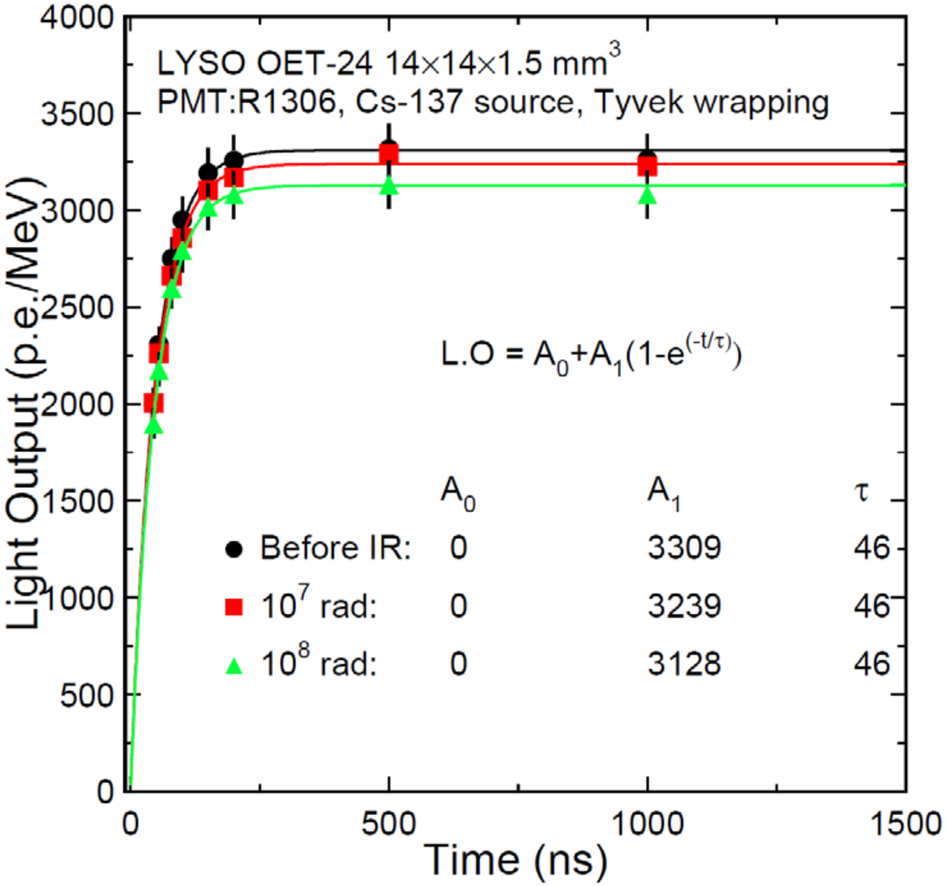


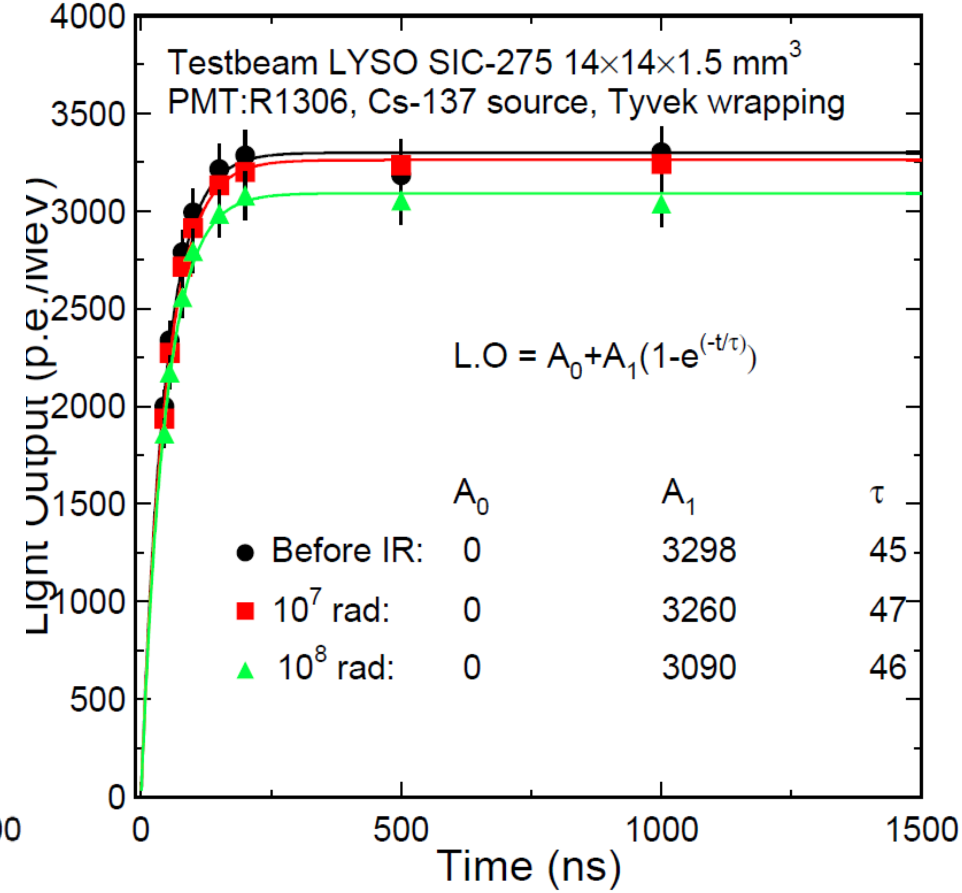


About 6/8% loss in light output is observed up to 100/200 Mrad

14 x 14 x 1.5 mm LYSO Plates

Light output and decay kinetics

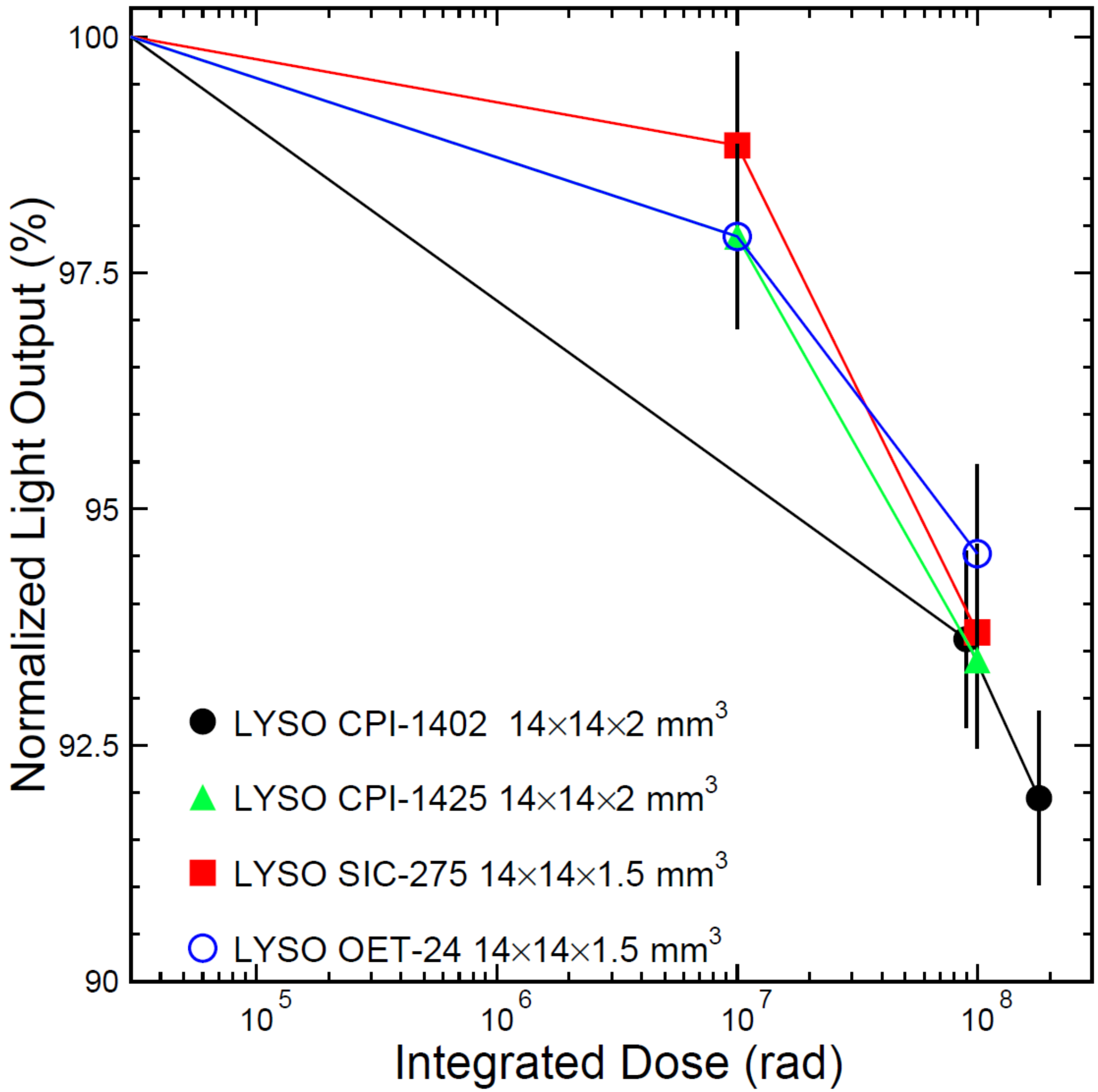




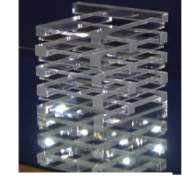
About 6% loss in light output is observed up to 100 Mrad

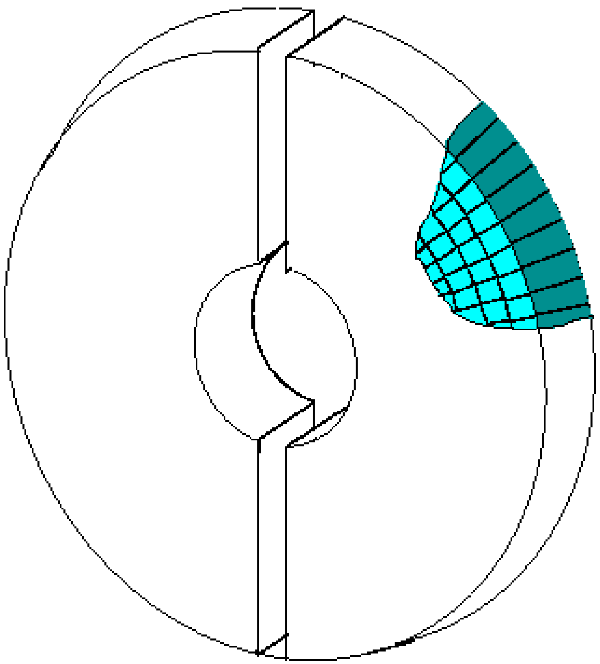
Summary of LYSO Plates

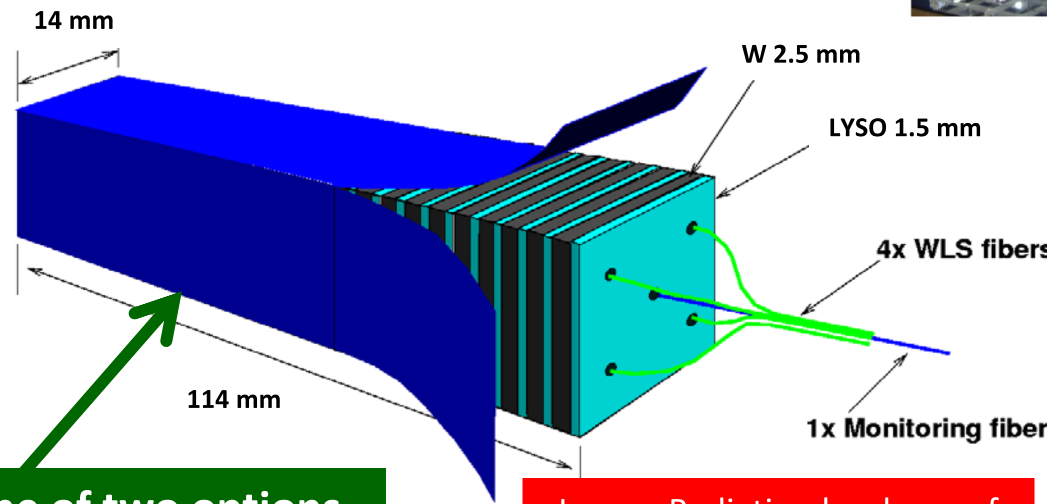
Consistent radiation hardness up to 200 Mrad observed in LYSO plates from various vendors



Option for CMS FCAL Upgrade



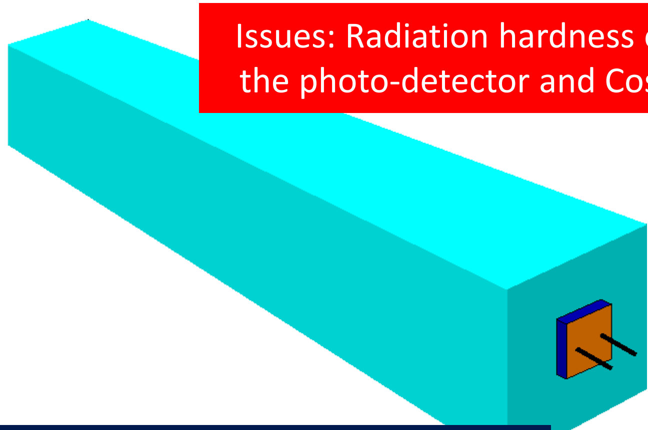


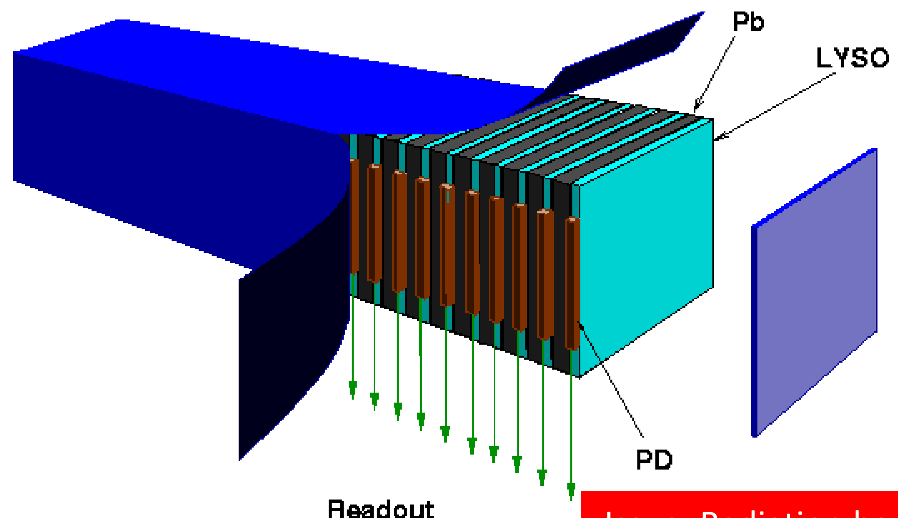


One of two options for CMS Upgrade TR

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

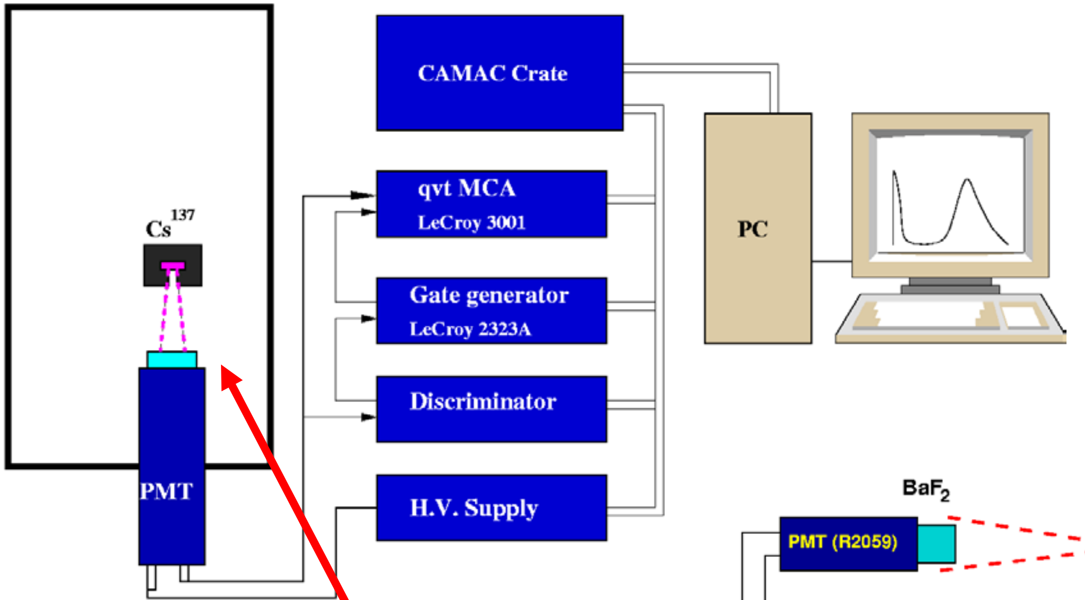
Issue: Radiation hardness of the photo-detector

LYSO Based Shashlik Cell Design

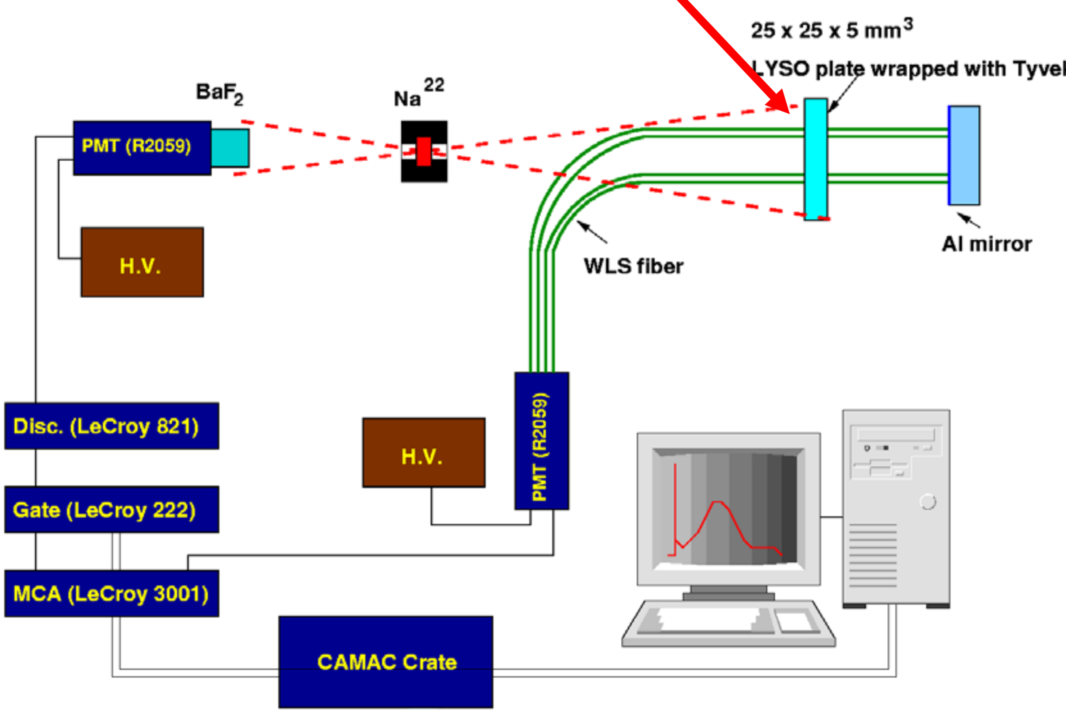
		LHCb	Plan-1	Plan-2
Absorber		Lead (Pb)	Lead (Pb)	Tungsten (W)
	Density (g/cm3)	11.4	11.4	19.3
	Radiation Length (cm)	0.56	0.56	0.35
	Moliere Radius (cm)	1.60	1.60	0.93
	dE/dX (MeV/cm)	12.74	12.74	22.1
	Thickness (mm)	2	4	2.5
	Plates number	66	28	28
Scintillator		BASF-165 Polystyrene (Sc)	LYSO	LYSO
	Density (g/cm3)	1.06	7.4	7.4
	Light Yield (photons/MeV)	5200	30000	30000
	Radiation length (cm)	41.31	1.14	1.14
	Moliere Radius (cm)	9.59	2.07	2.07
	dE/dX (MeV/cm)	2.05	9.55	9.55
	Plate Thickness(mm)	4	2	2
	Plates number	67	29	29
WLS Fiber		Kurarray Y-11(250)	Kurarray Y-11(250)	Kurarray Y-11(250)
	Diameter (mm)	1.2	1.2	1.2
	Number /Cell	16	4	4
Cell Properties	Total Depth (X0)	24.22	25.09	25.09
	Sampling Fraction (MIPs)	0.25	0.28	0.26
	Total Physical Length (cm)	40	17	12.8
	Total Sc Length (cm)	26.8	5.8	5.8
	Absorber Weight Ratio	0.84	0.75	0.76
	Scintillator Weight Ratio	0.16	0.25	0.24
	Average Density (g/cm3)	4.47	10.04	13.91
	Average Radiation Length (cm)	1.65	0.68	0.51
	Average Moliere Radius (cm)	3.6	1.7	1.2
	Transverse Dimension (cm)	4.1	1.9	1.4
	Sc-depth/Total-depth in X0	0.0268	0.2028	0.2028
	WLS Fiber Density (N/cm2)	0.97	1.06	2.07
MIPs Energy Deposition	Sc plates (MeV)	54.94	55.39	55.39
Light Yield using MIPs	Photon Electrons/GeV	3077	17897	17897
Signal of MIPs	Photon Electrons / MIP	169	991	991
Module Properties	Energy Resolution (a, %)	8.2	9.0*	9.0*

* Based on the simulation of Zhigang Wang, IHEP, Beijing.

Two Measurement Setups



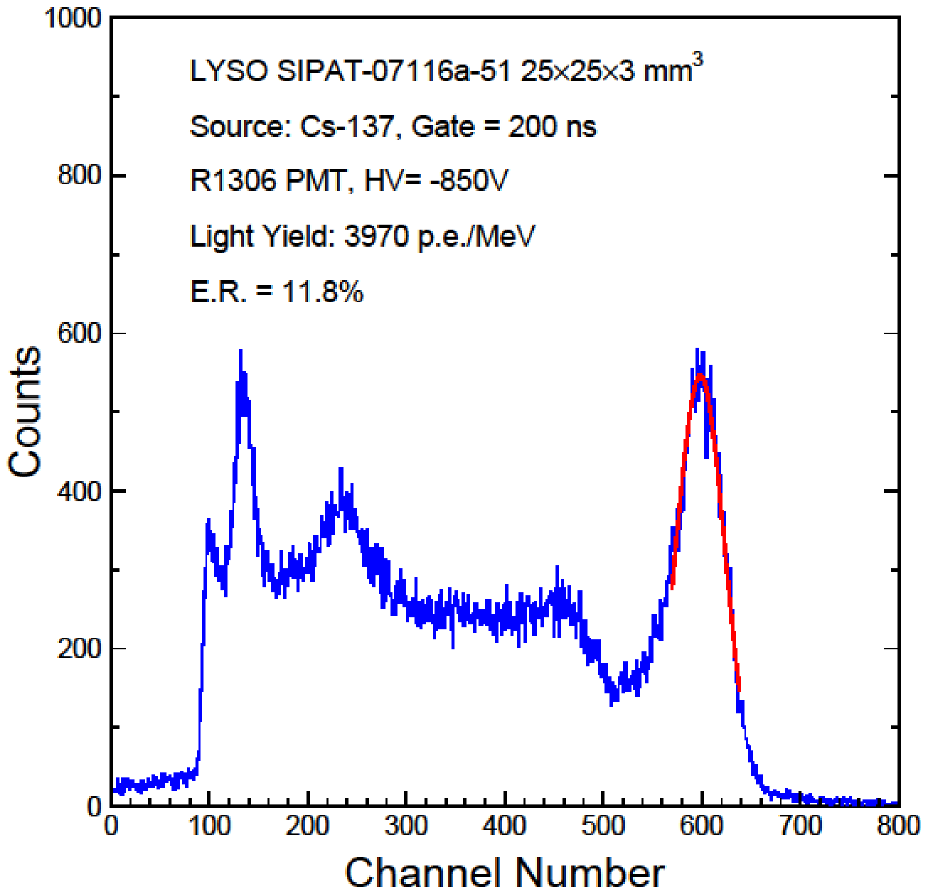
2) LYSO plates with Tyvek wrapping are readout with four Y11 WLS fibers of 40 cm long and a R2059 PMT using a Na-22 γ-ray source and coincidence.



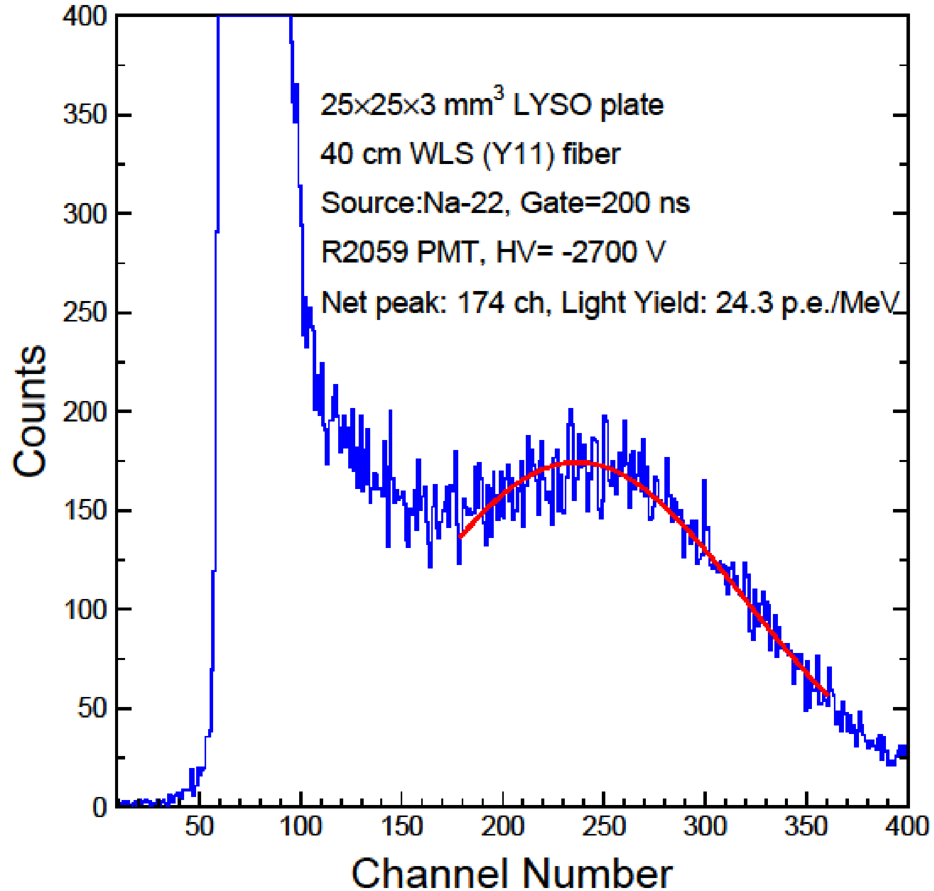
1) LYSO plates with Tyvek wrapping are readout directly by a R1306 PMT using a Cs-137 γ-ray source.

PHS of 3 mm LYSO Plate

LYSO 25 × 25 × 3 mm³



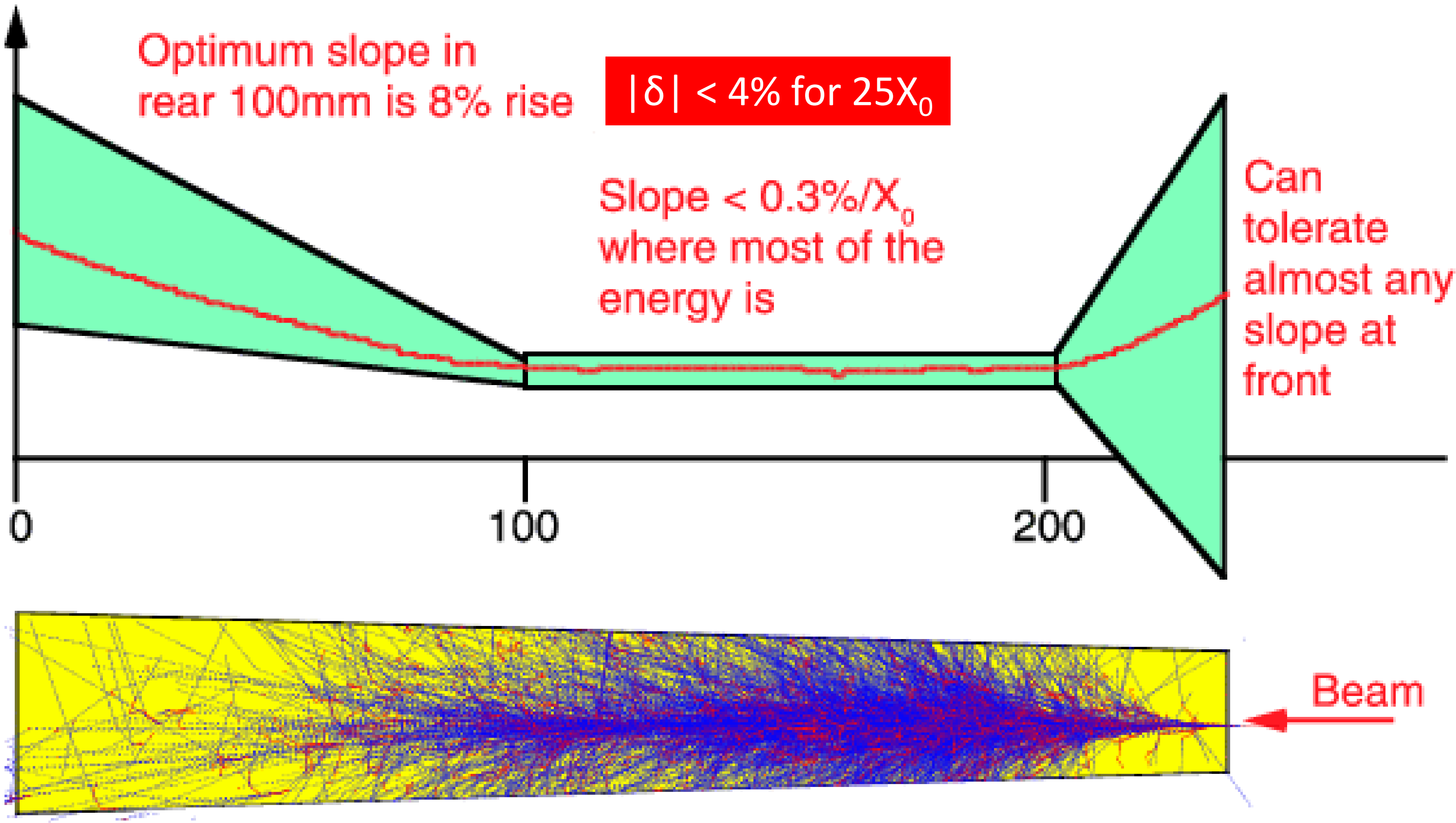
3 mm plate & 4 x 40 cm Y11 fiber



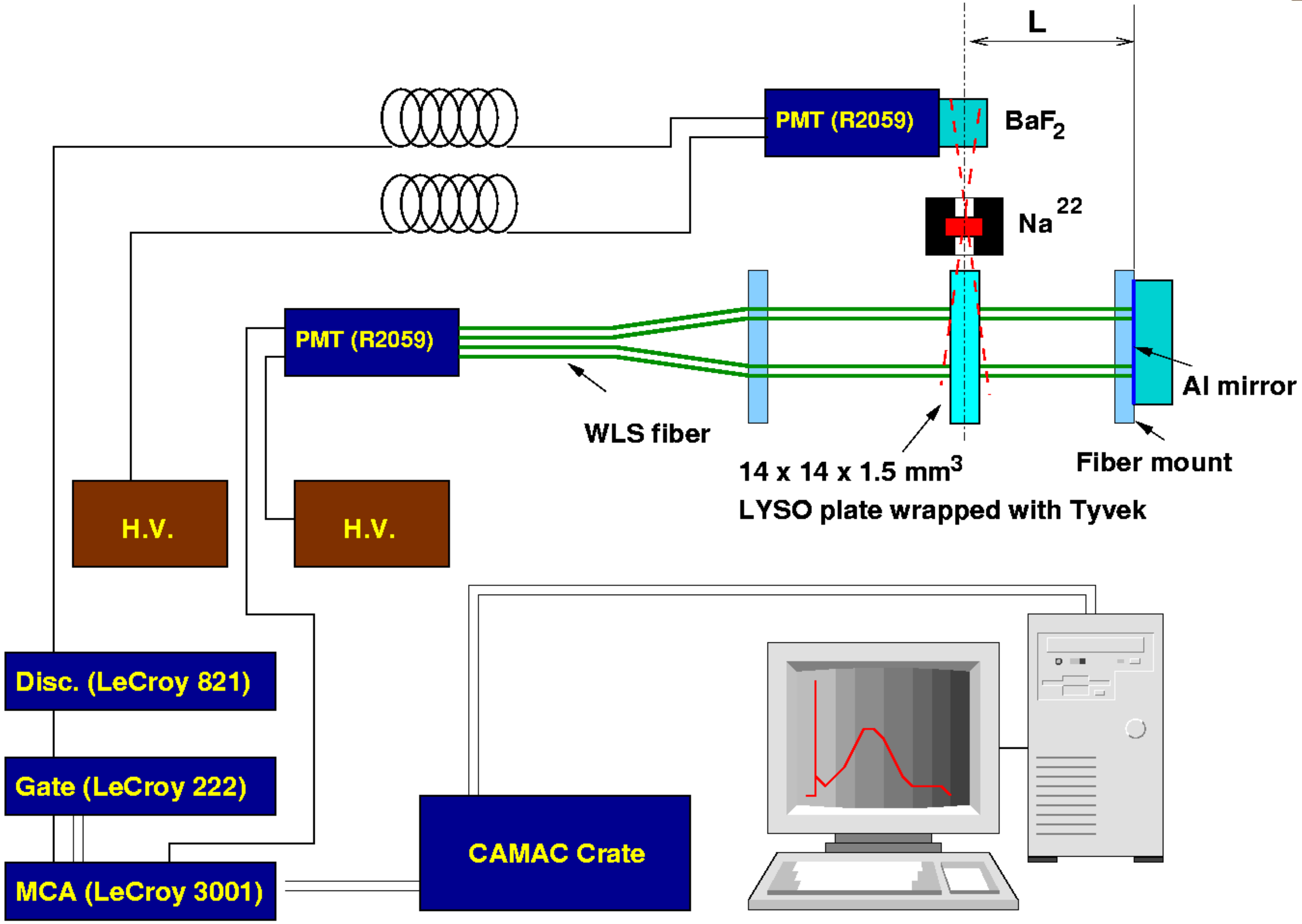
About 1% light collected via WLS

CMS Specification for Uniformity

D. Graham & C. Seez, CMS Note 1996-002

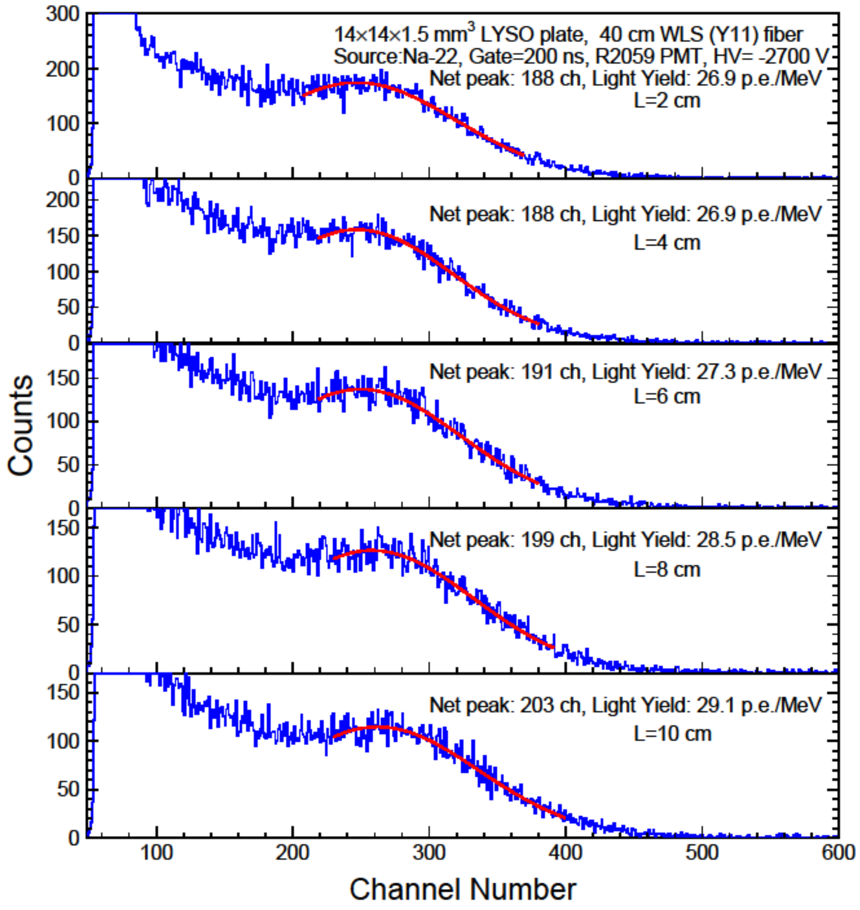


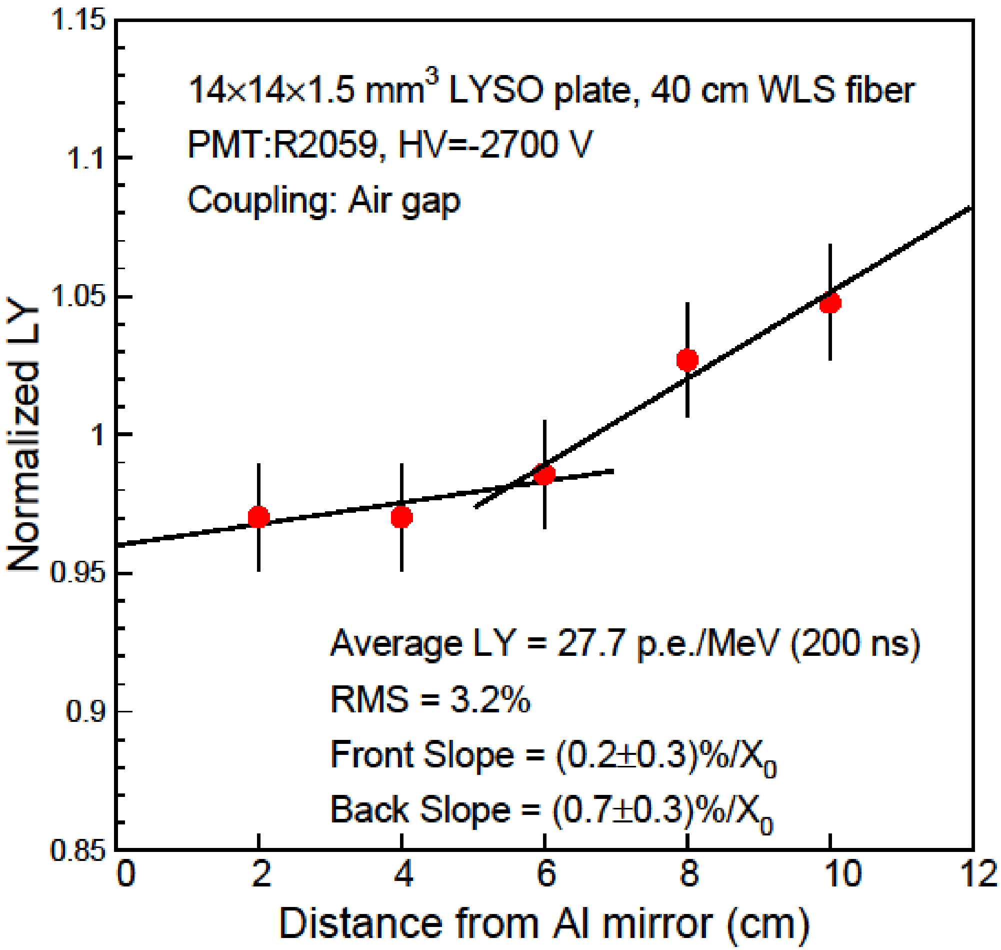
LYSO/W Response Uniformity



LYSO/W Shashlik Uniformity

Front: 0.2%/X_0, Back: 8% rise

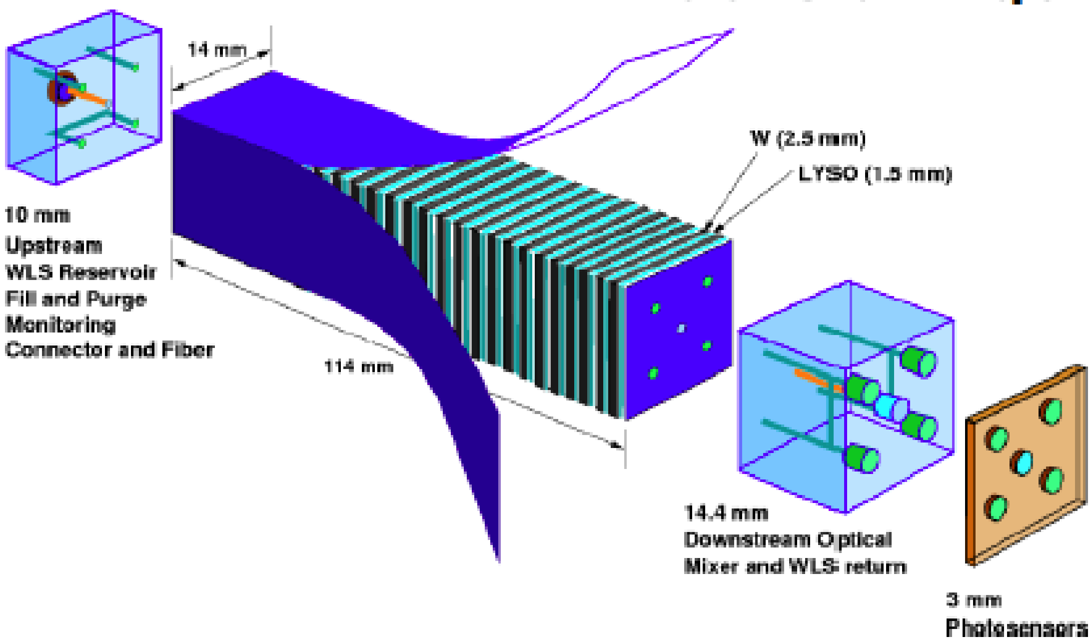


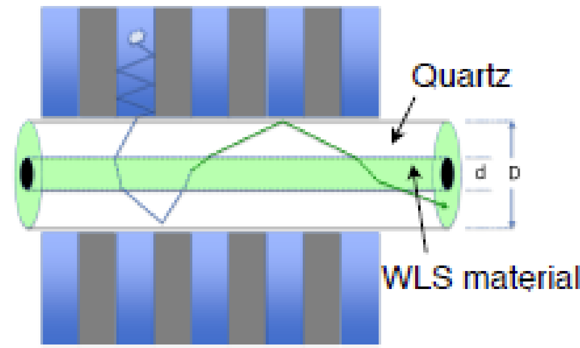


Shashlik Option for CMS Upgrade

D. Petyt, 2nd ECFA Workshop, October 21-23, 2014

Shashlik concept





Capillary concept

Replacement EM calorimeter using radiation tolerant crystal plates (LYSO/CeF_3) interleaved with tungsten absorber. Expected EM resolution: $10\%/\sqrt{E} \oplus 1\%$

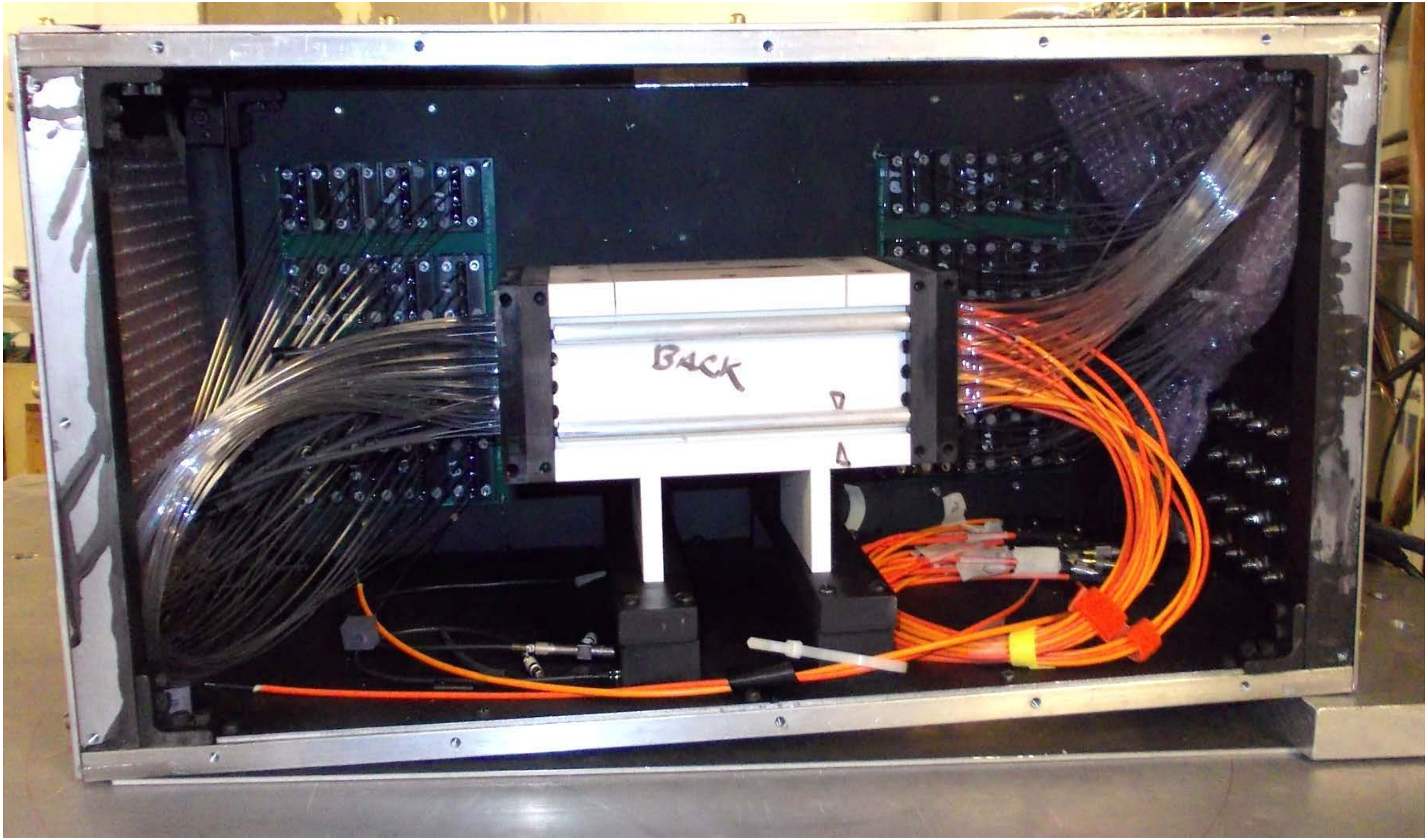
Light from scintillator is wavelength-shifted and propagated to photodetector by embedded capillaries or fibres

- Light path length in crystal material minimised → increased radiation tolerance of device

Compact Shashlik "towers" (Molière radius: 13.7 mm) to minimise PU fluctuations.

- Tower dimensions: 14 x 14 x 114mm³. 60000 towers in total (4x existing EE)

4 x 4 LYSO/W/Y-11 Shashlik Matrix



1st Result of CERN H4 Beam Test

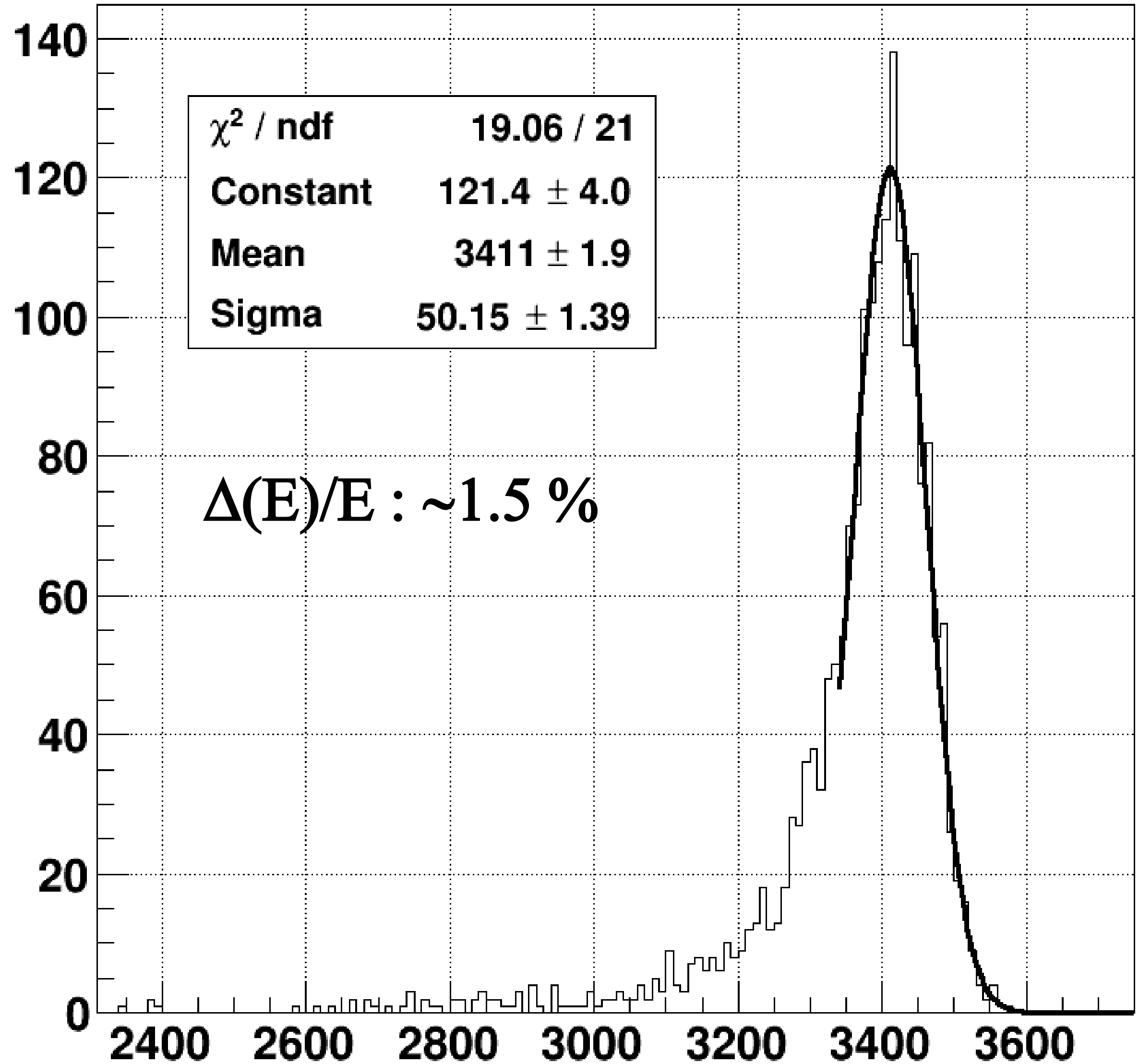
10/29 to 11/2

Electron Beam of 150 GeV

Un-calibrated Shashlik matrix

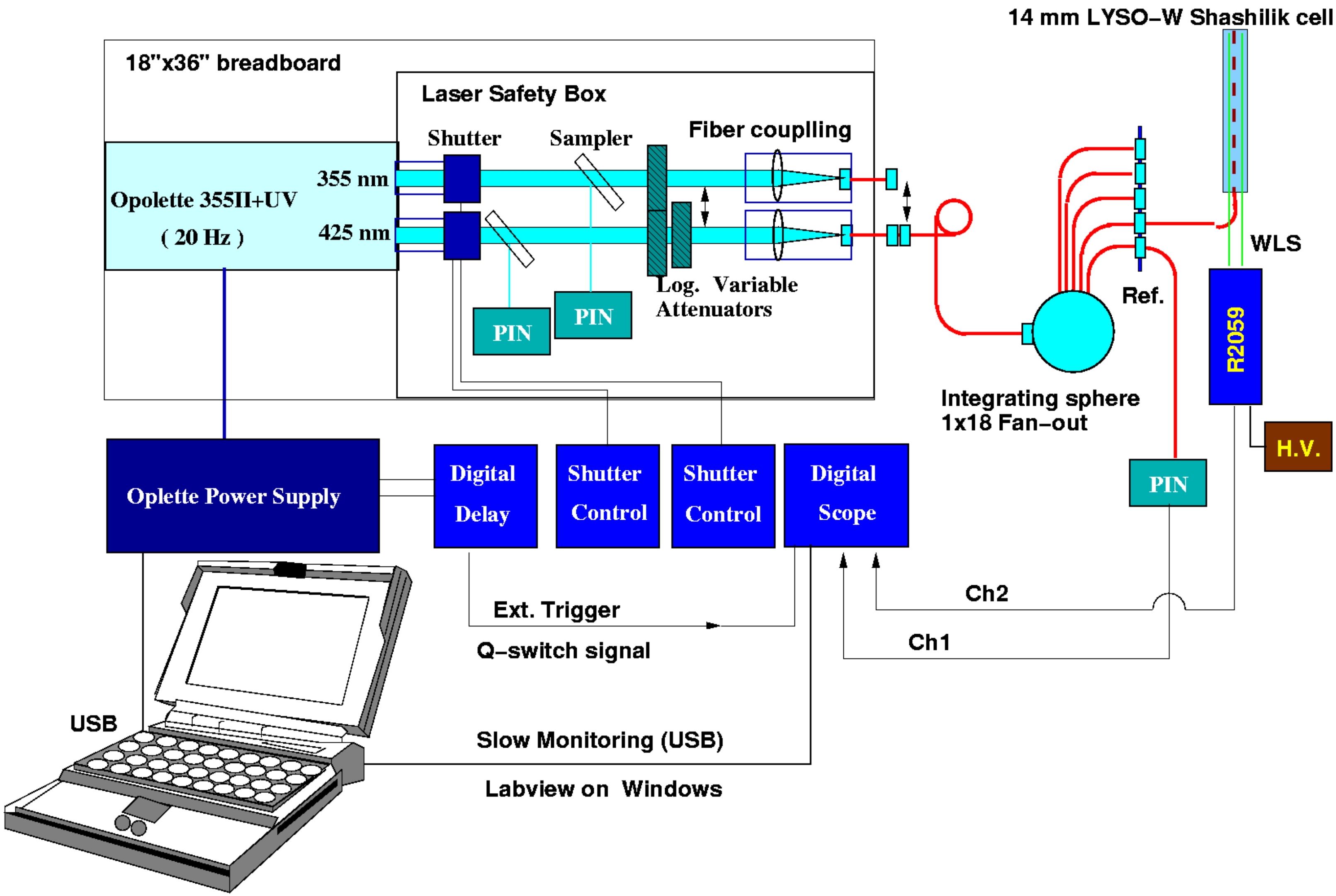
First Look of the Data

Preliminary!!

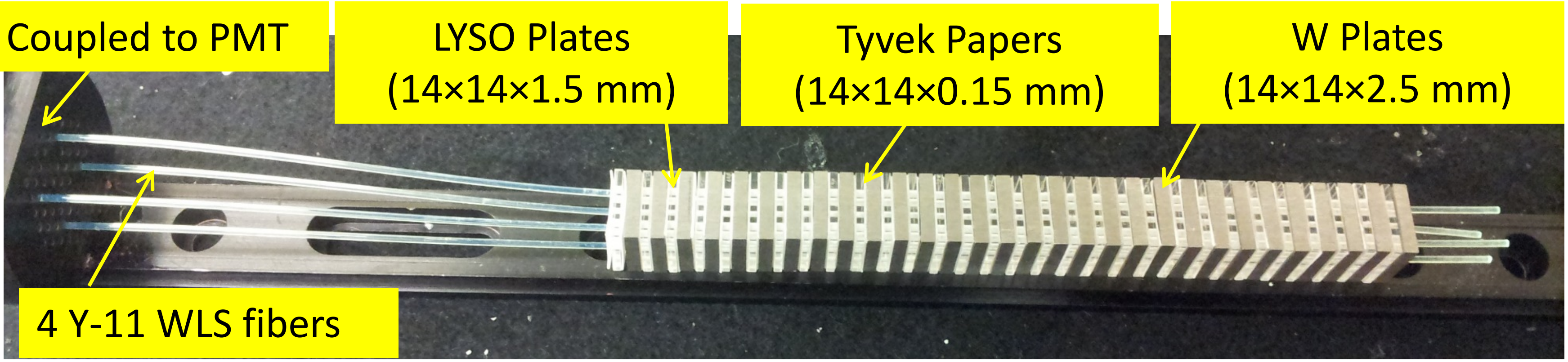


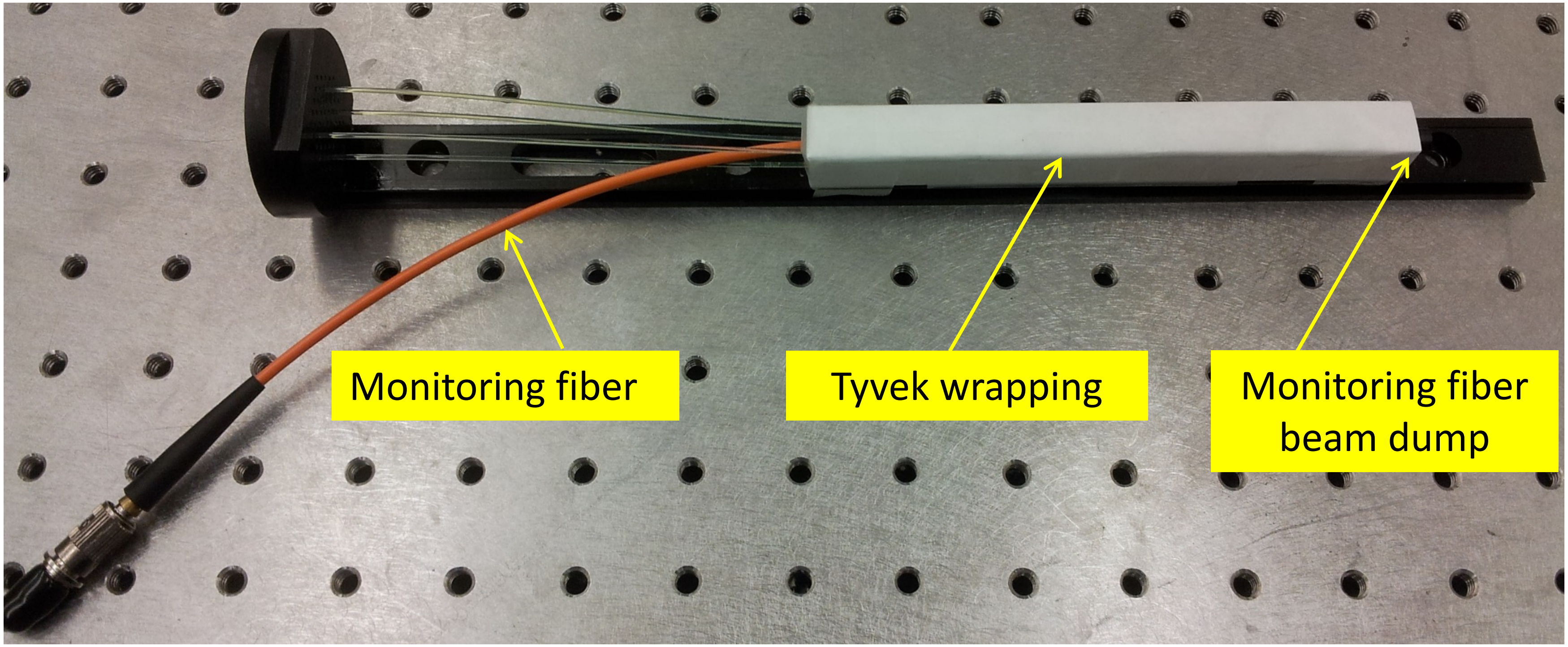
An Opolette Laser Based Monitoring Setup

Two channels from the ½ inch integrating sphere were read out by a R2059 PMT through Shashlik and a PIN diode (Thorlabs DET10A) as a reference



A Shashlik Cell Irradiated at JPL

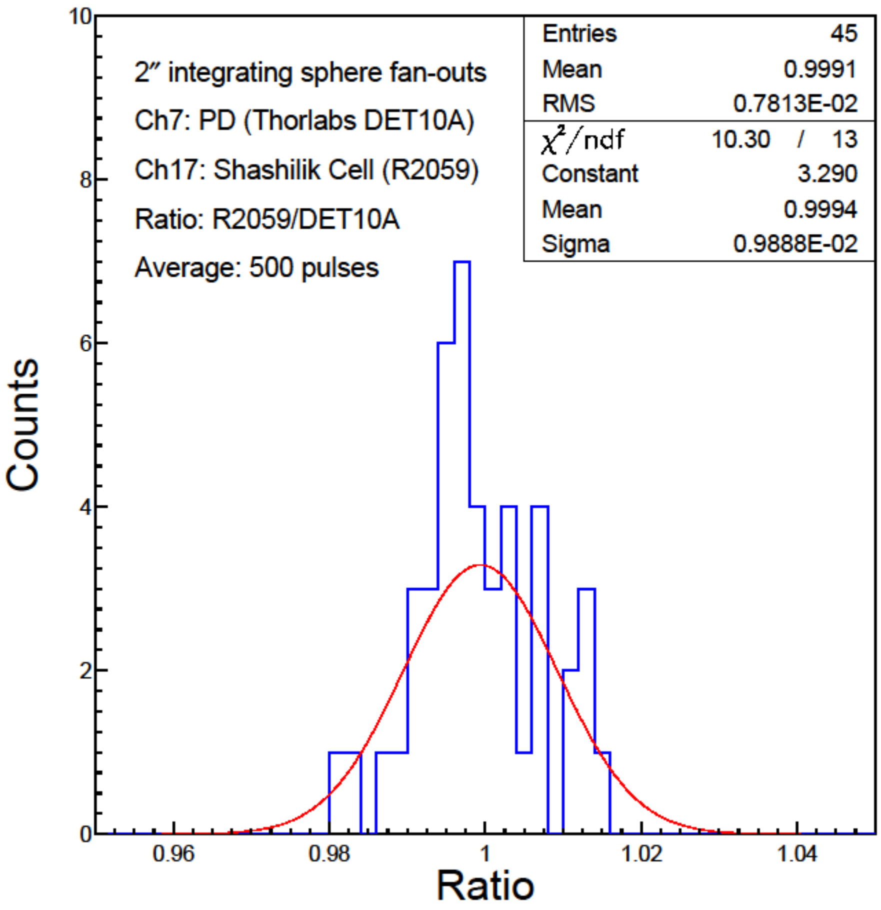




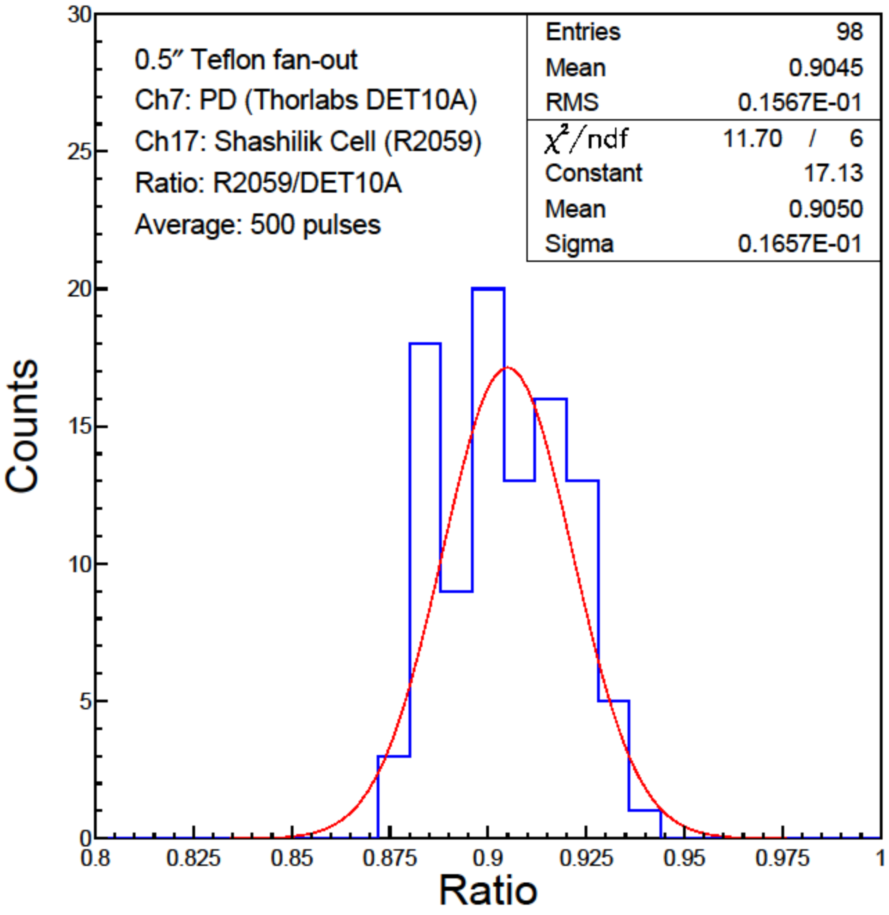
10% Degradation Observed after 100 Mrad

By using 425 nm monitoring light pulses from an OPO laser

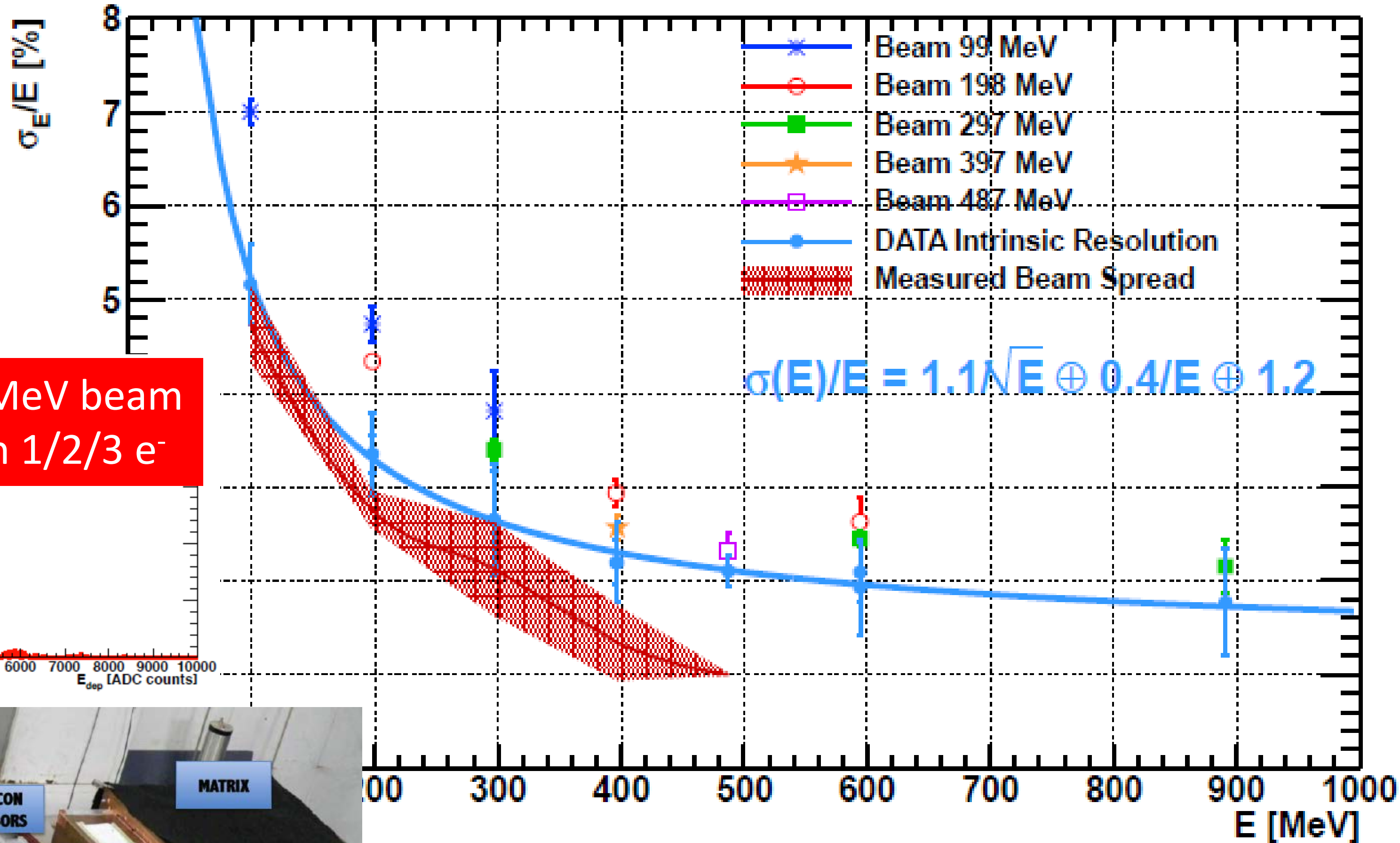
Before irradiation

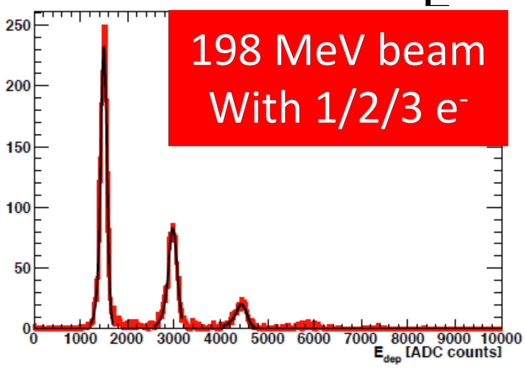


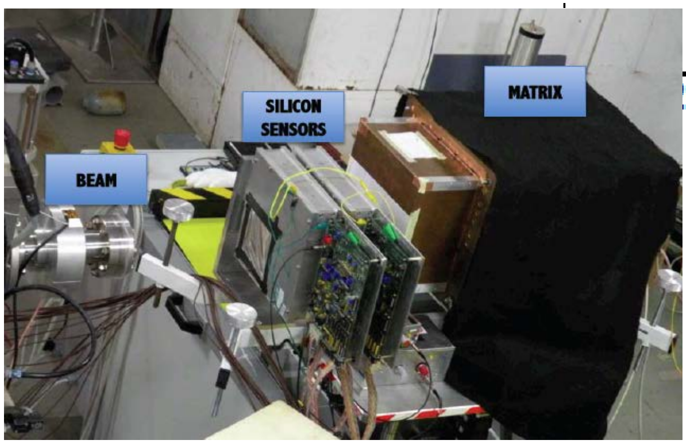
After 100 Mrad



SuperB LYSO Test Beam Result



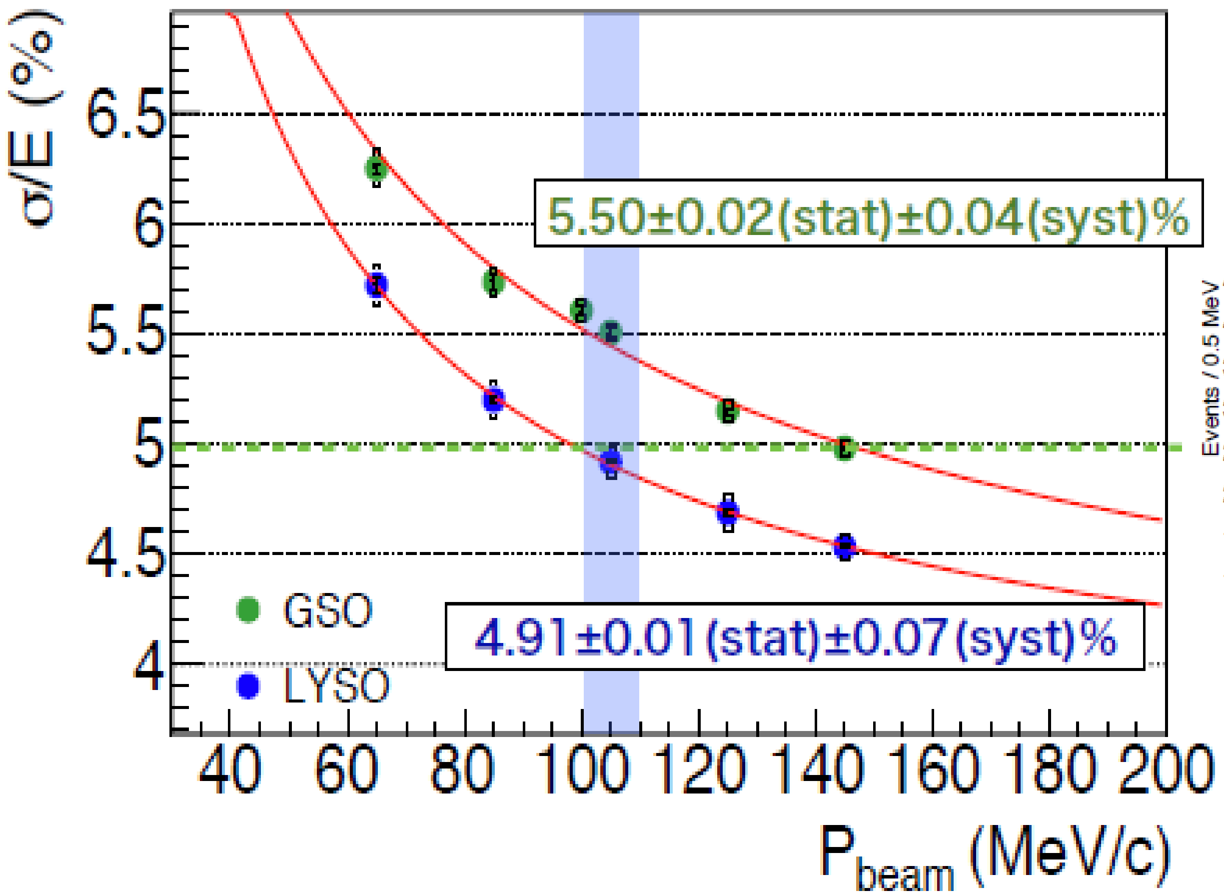




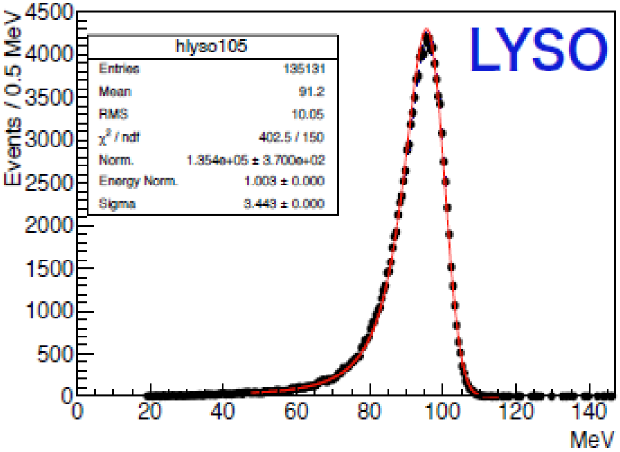
$$\frac{\sigma(E)}{E} = \frac{1.1}{\sqrt{E[GeV]}} \oplus \frac{0.4}{E[GeV]} \oplus 1.2\ \%$$

COMET Test Beam Result

K. Oishi for COMET, paper N47-4 , IEEE NSS2014 at Seattle



< 5% @ 100 MeV



LYSO is chosen

Alternative Fast Crystals

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

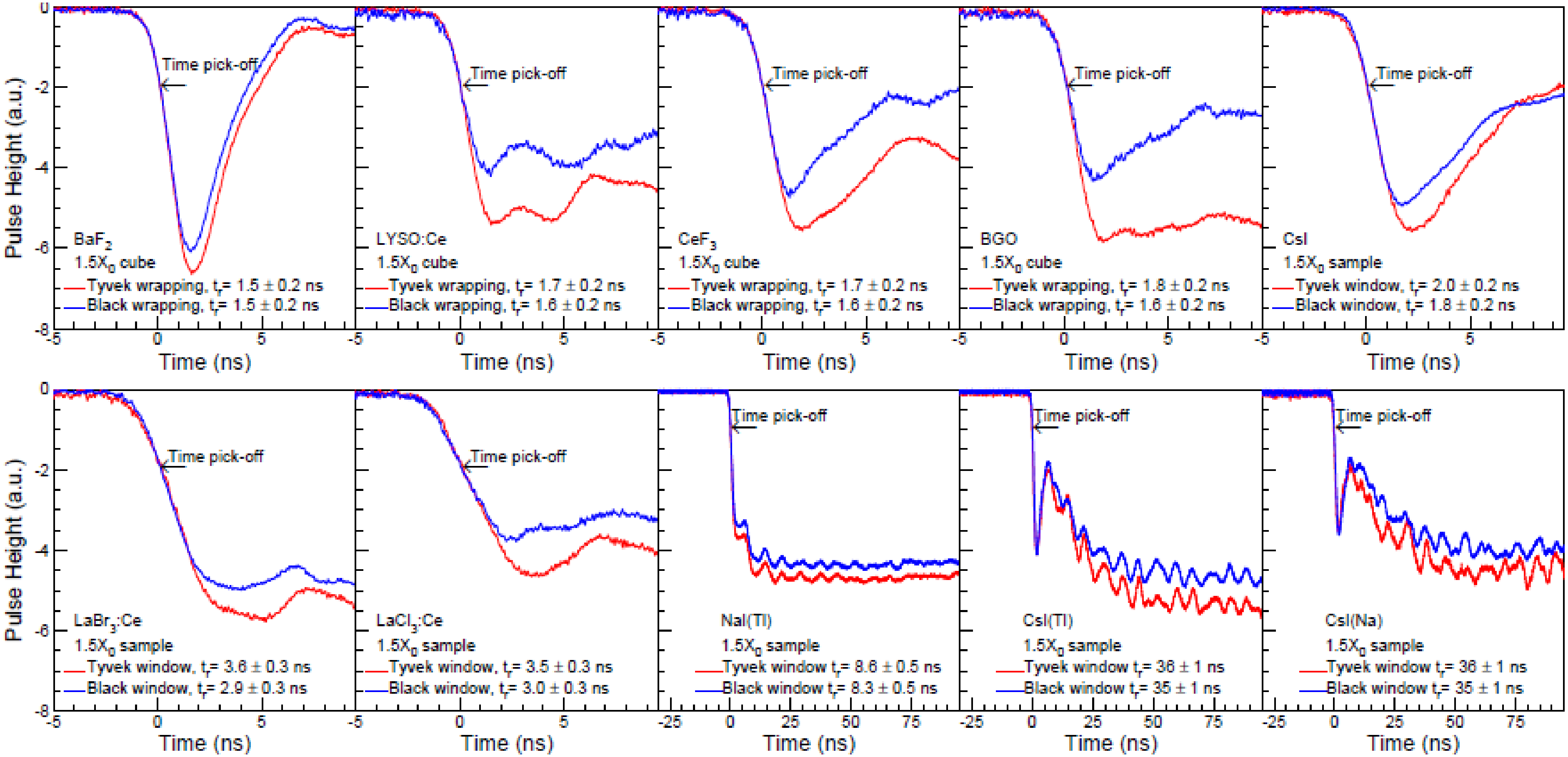
	LSO/LYSO	GSO	YSO [1]	CsI	BaF_2	CeF_3	$CeBr_3$ [2]	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404) [3]
Density (g/cm³)	7.40	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70#
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.70	1.96	2.81	1.88	42.54
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	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.

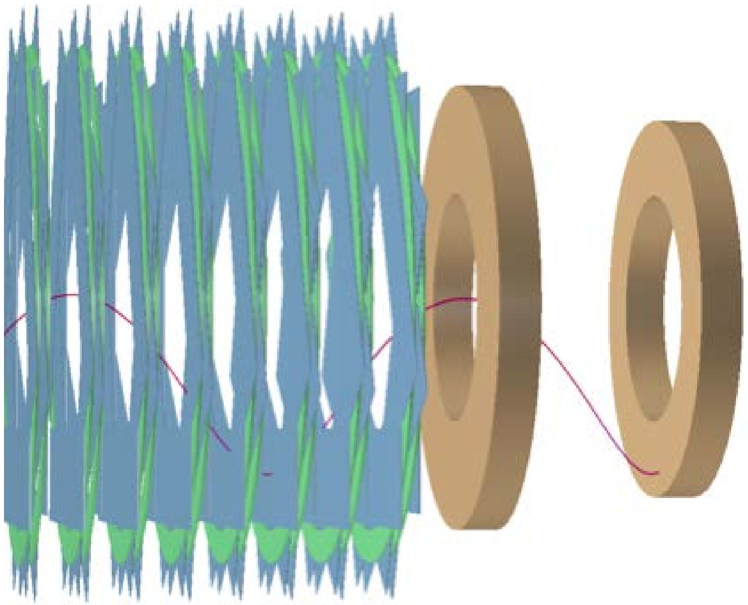
Figure of Merit for Timing

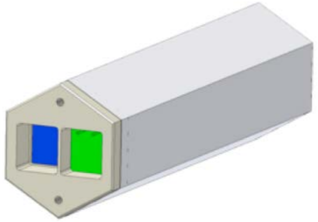
FoM is calculated as the LY in 1st ns obtained by using light output and decay time data measured for 1.5 X_0 crystal samples.

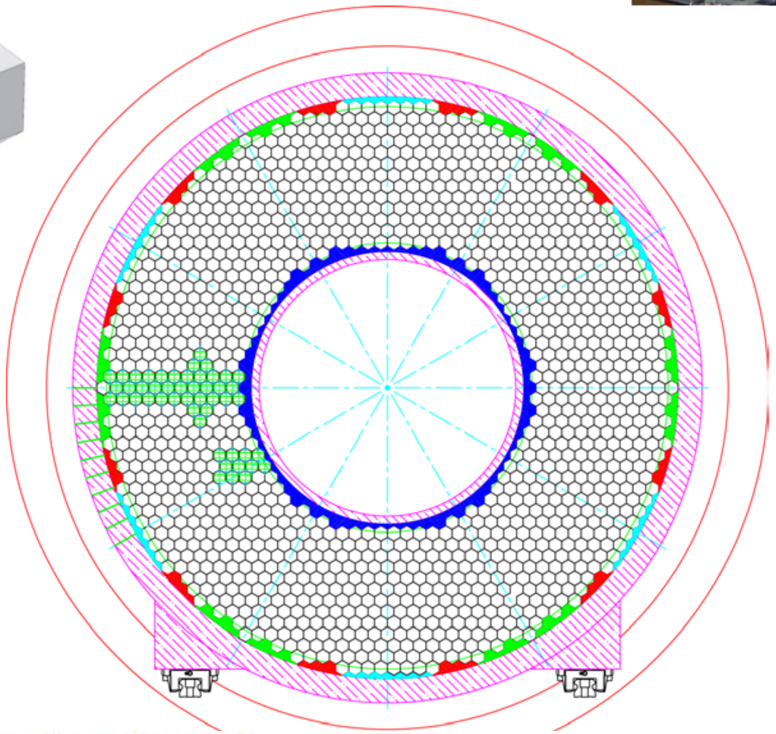
Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180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

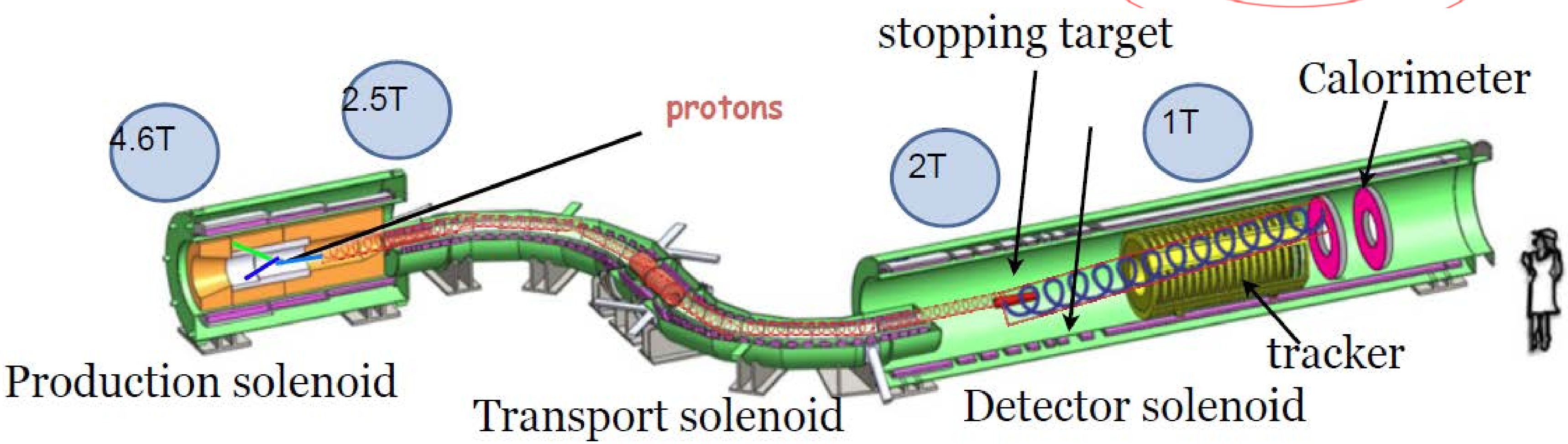
The best crystal scintillator for ultra-fast timing is BaF_2 and LSO(Ce/Ca) and LYSO(Ce). $LaBr_3$ is a material with high potential.

Mu2e BaF_2 Calorimeter





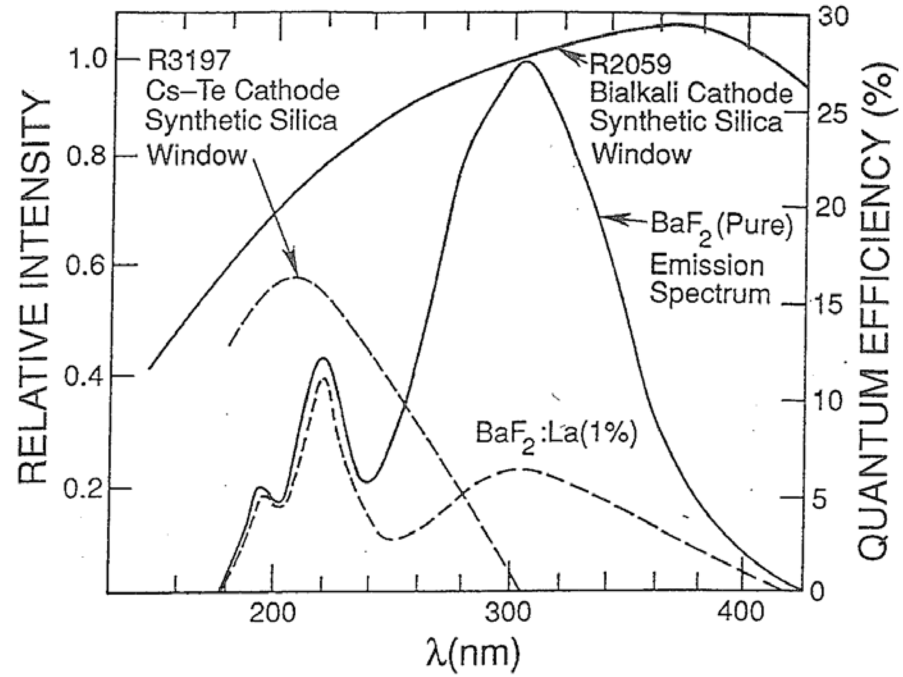


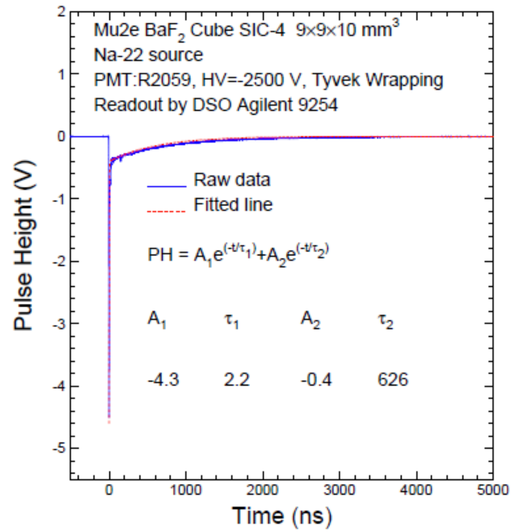


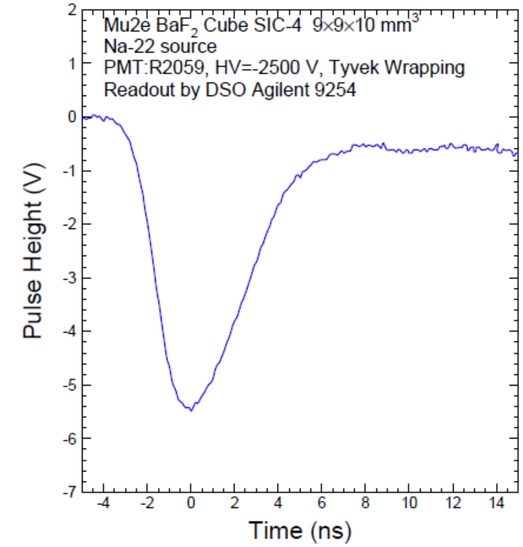
BaF_2 for Very Fast Calorimeter

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.



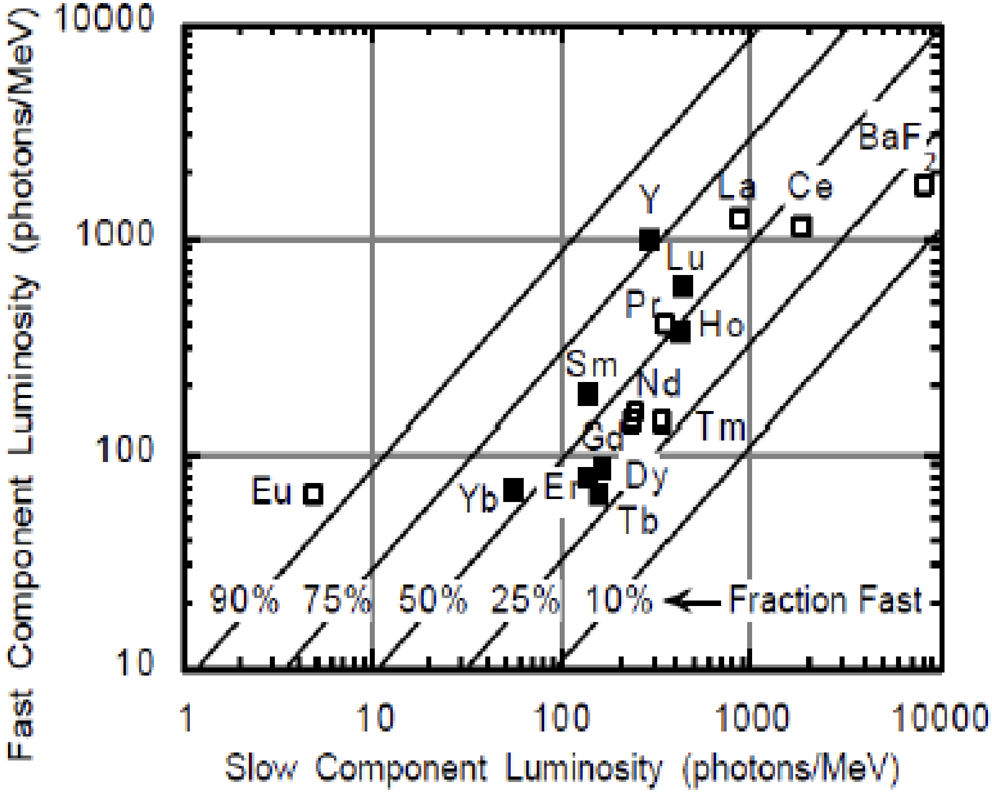


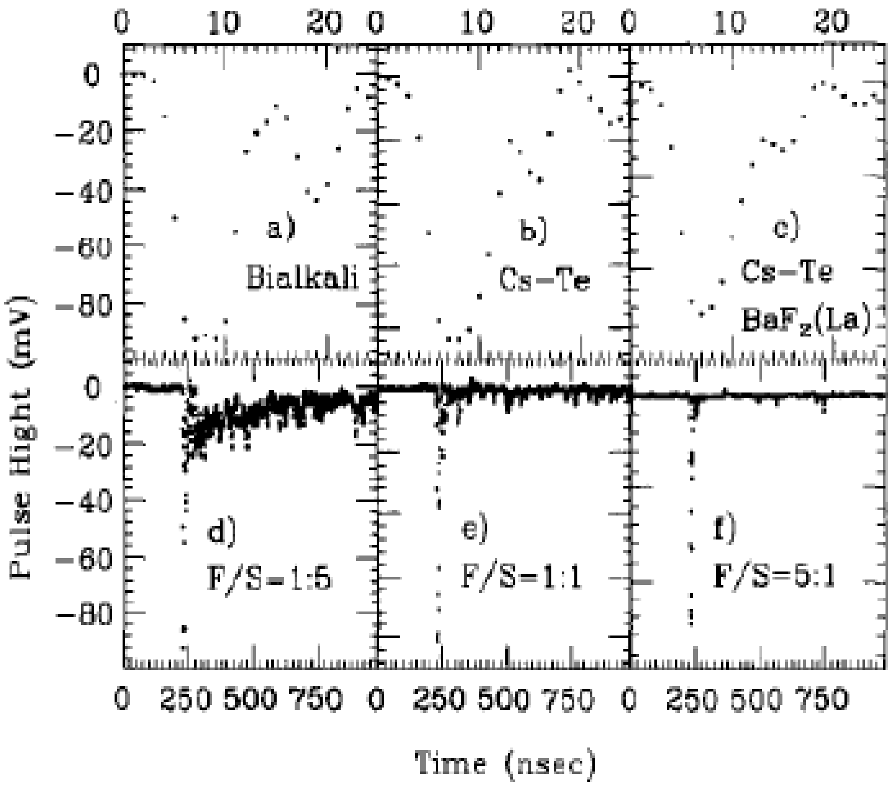


Slow Suppression by Doping and Readout

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.



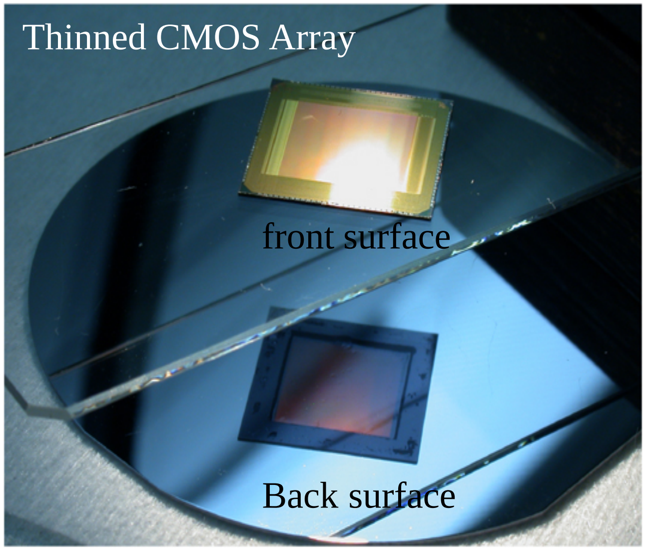


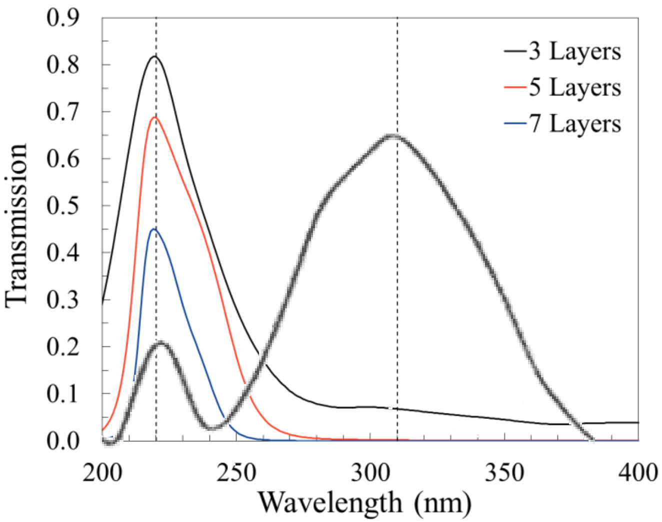
Solar blind cathode is also effective. R&D on doping will be carried out in 2015.

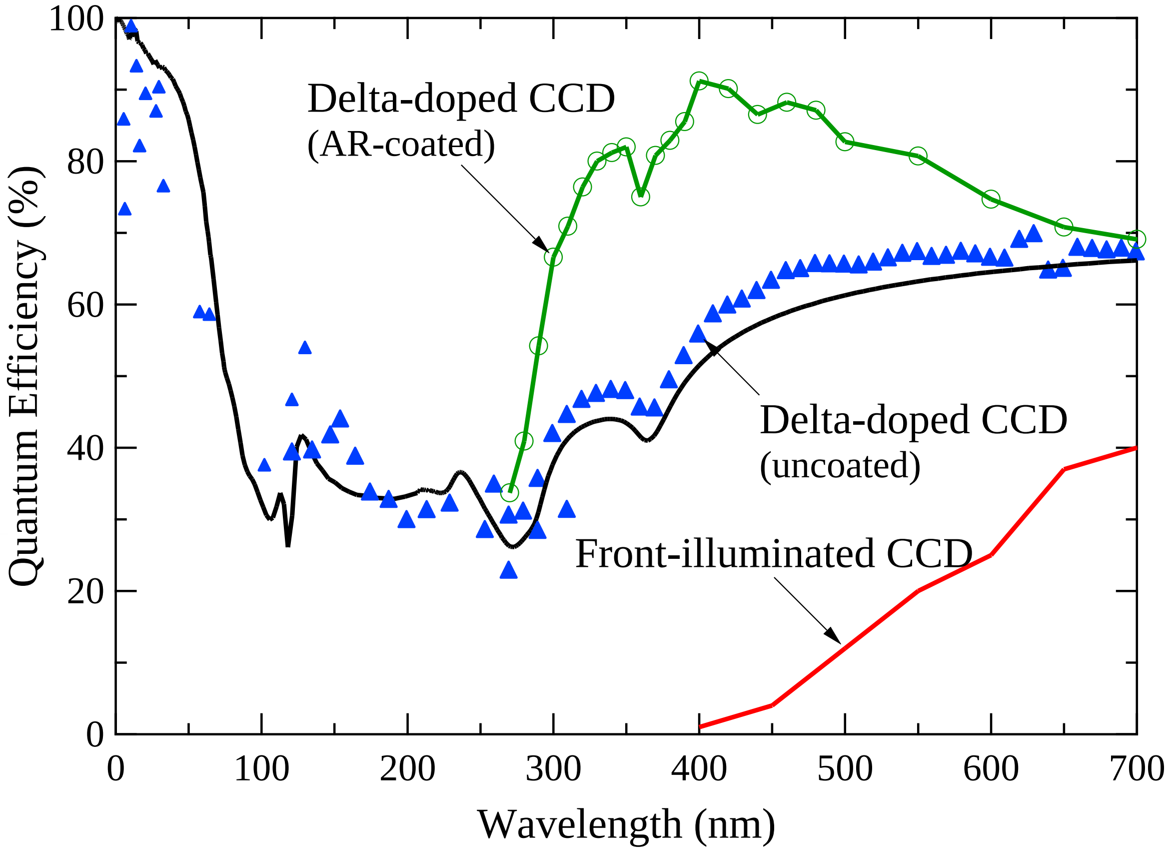
Z. Y. Wei, R. Y. Zhu, H. Newman, and Z. W. Yin, "Light Yield and Surface-Treatment of Barium Fluoride-Crystals," *Nucl Instrum Meth B*, vol. 61, pp. 61-66, Jul 1991.

Delta-doping for CCD detectors

D. Hitlin, Talk in NSTR2014, February 28, 2014, with JPL

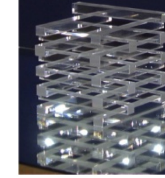




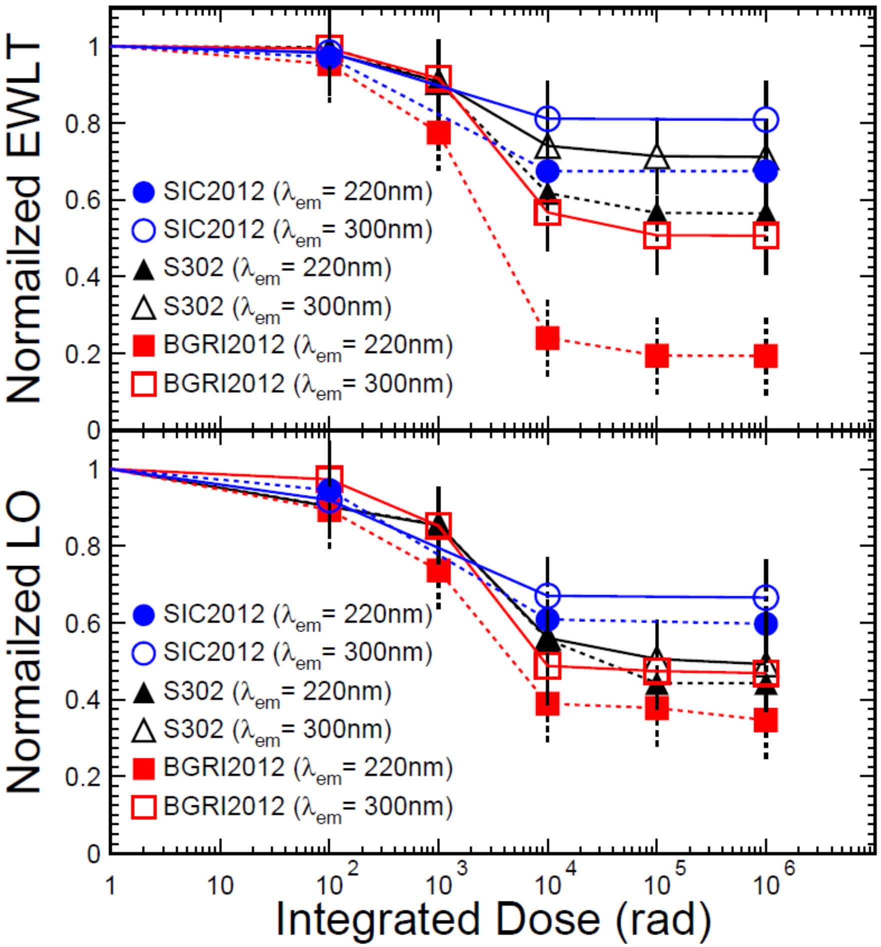


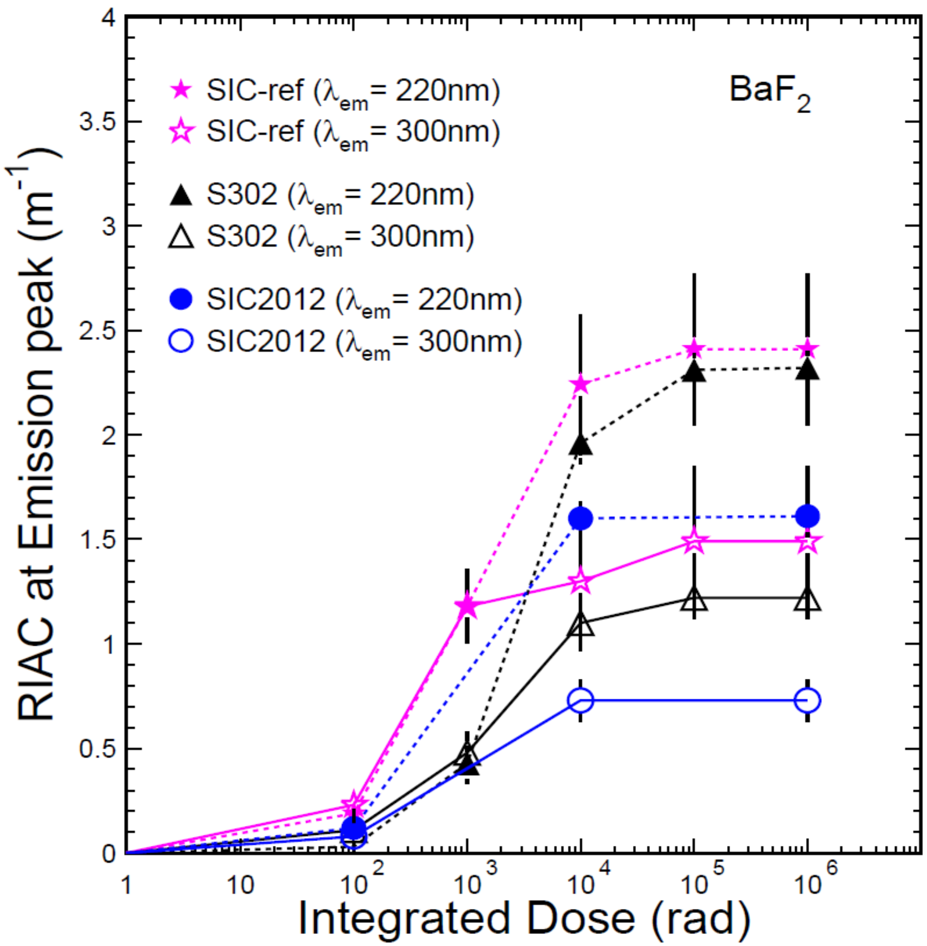
S. Nikzad, "Ultrastable and uniform EUV and UV detectors," *SPIE Proc.*, Vol. 4139, pp. 250-258 (2000).

Damage in Long BaF_2 Crystals



Radiation damage in BaF2 crystals saturates at a few tens of krad
SIC2012 is more radiation hard than other samples
Slow component is more radiation hard than the fast component

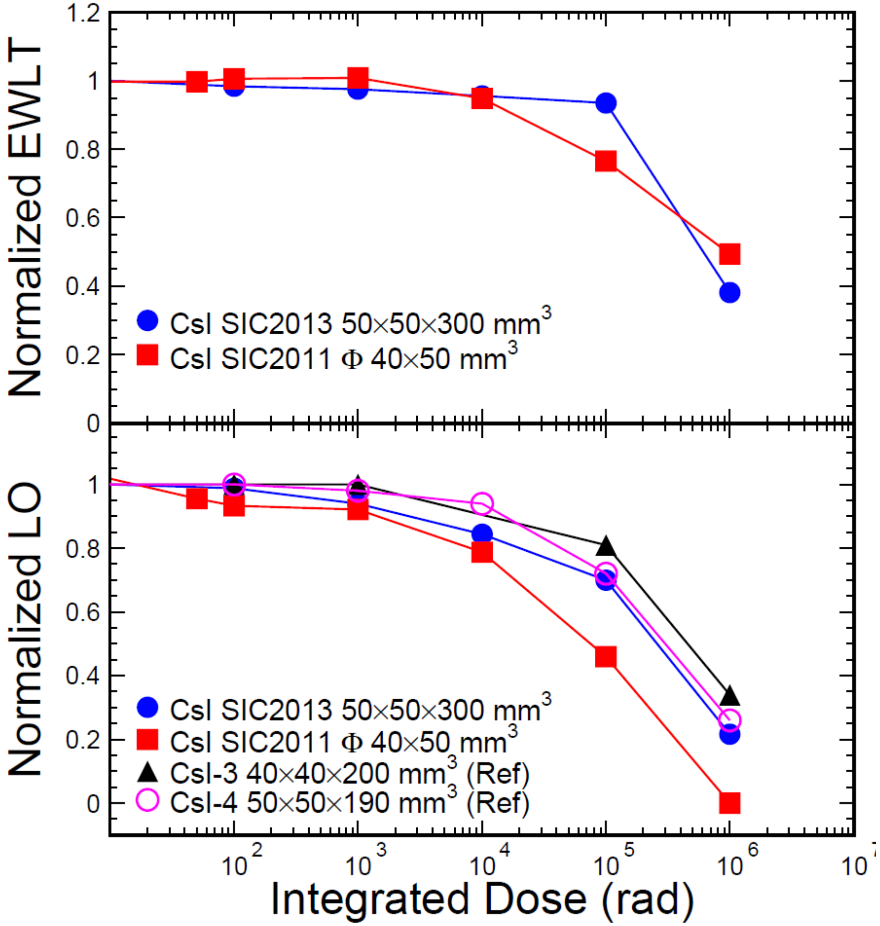


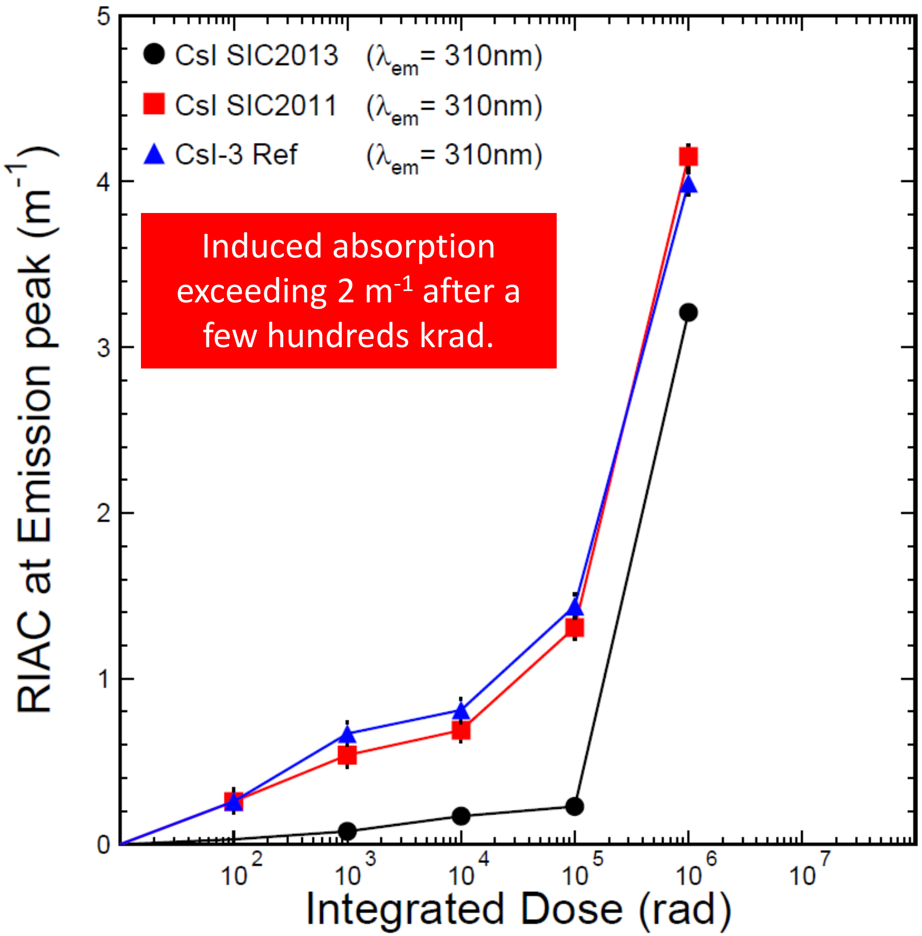


RIAC of mass produced BaF_2 may be controlled to less than 1.6 m^{-1}

Damage in Long Pure CsI Crystals

Consistent damage between 30/20 cm long pure CsI from SIC/Kharkov

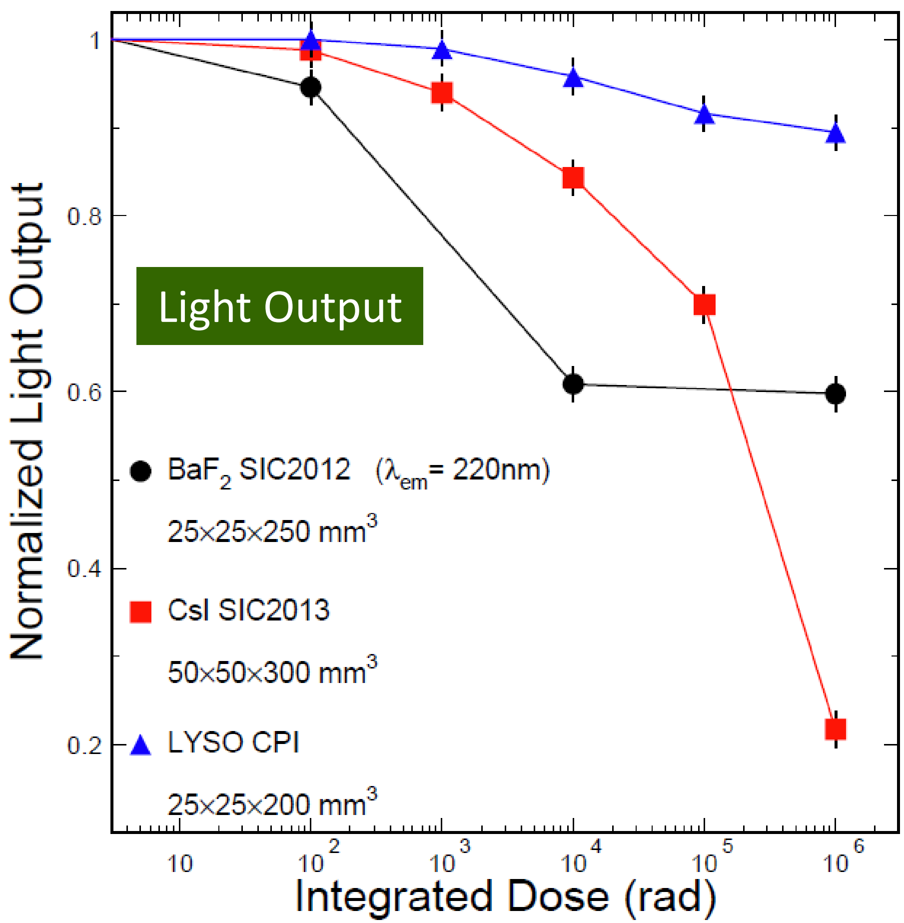


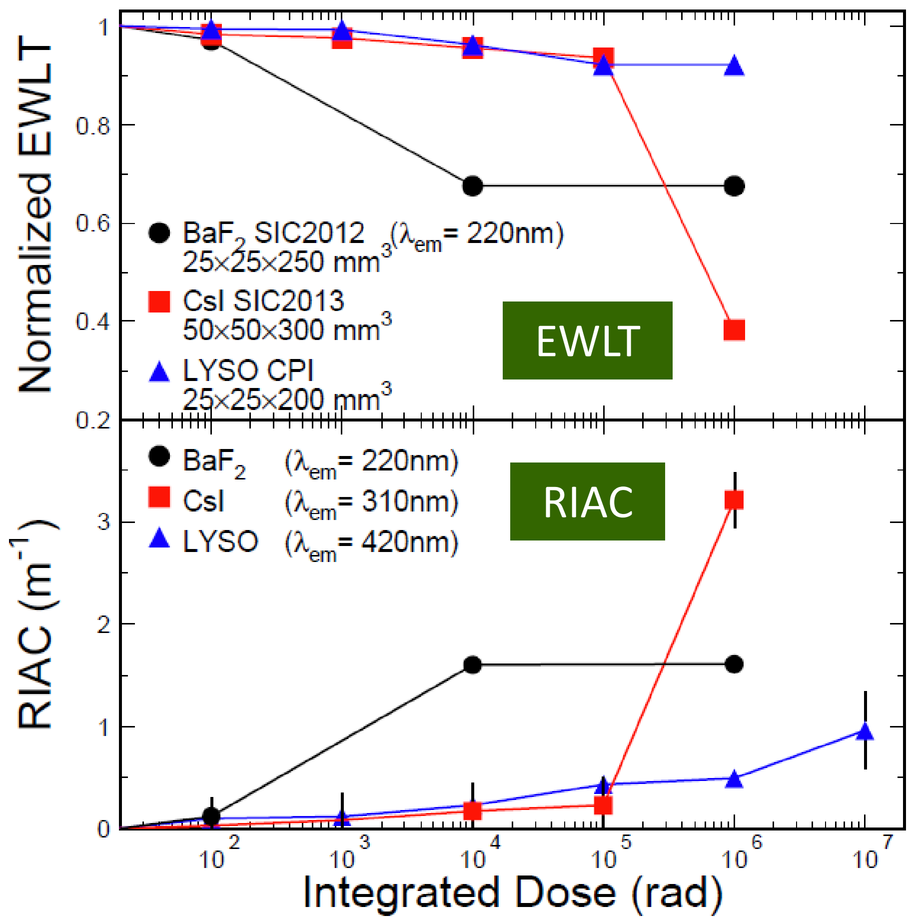


Data of Kharkov crystals: *Nucl. Ins. Meth. A* 326 (1993) 508-512

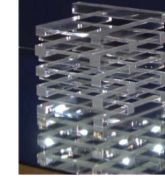
Comparison of Radiation Hardness

LYSO is the best in radiation hardness. BaF_2/CsI is good at high/low dose

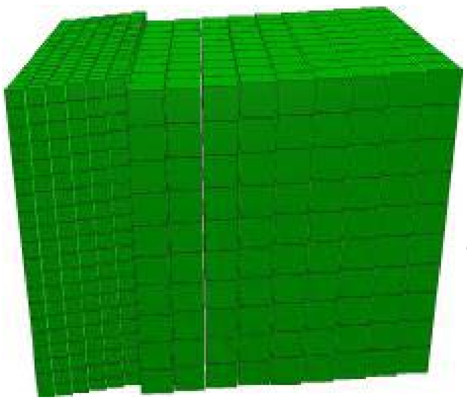


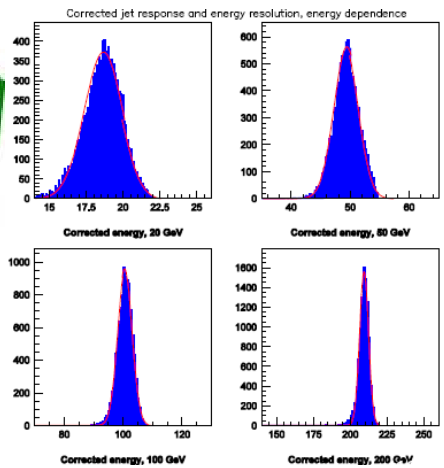


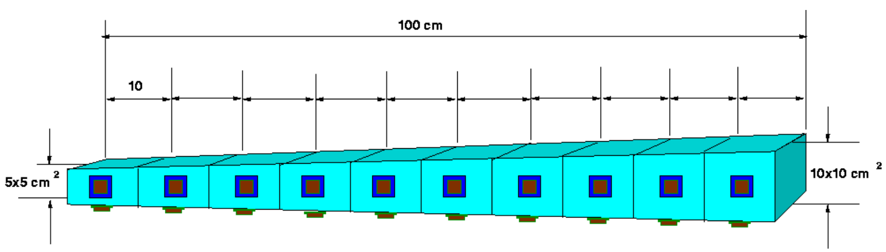
Homogeneous Hadronic Calorimeter



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.

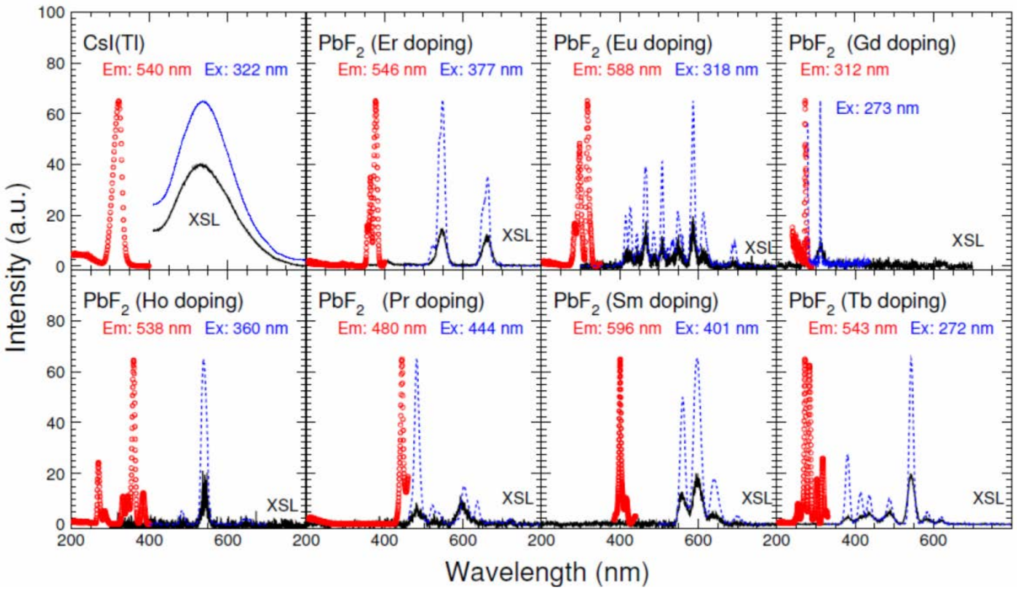
Candidate Crystals for HHCAL

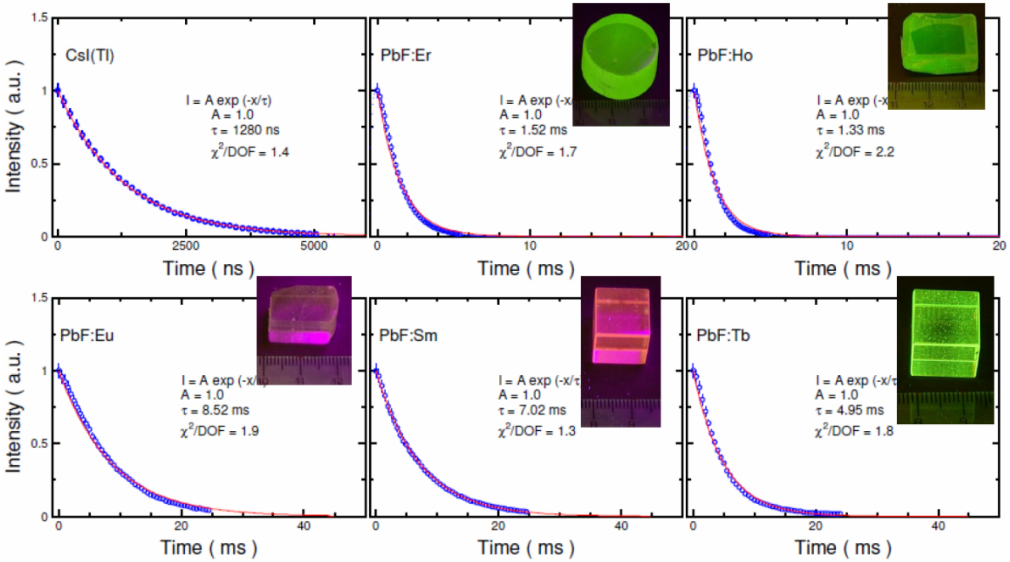
Cost-effective, UV transparent crystals with both scintillation and Cherenkov light

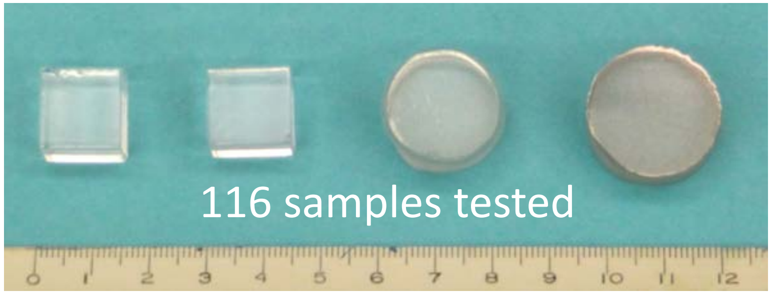
Parameters	$Bi_4Ge_3O_{12}$ (BGO)	$PbWO_4$ (PWO)	PbF_2	PbClF	$Bi_4Si_3O_{12}$ (BSO)
ρ (g/cm^3)	7.13	**8.29**	**7.77**	7.11	6.8
λ_I (cm)	22.8	**20.7**	**21.0**	24.3	23.1
n @ λ_{max}	2.15	2.20	1.82	2.15	2.06
τ_{decay} (ns)	300	30/10	**?**	30	100
λ_{max} (nm)	480	425/420	**?**	420	470
Cut-off λ (nm)	**310**	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

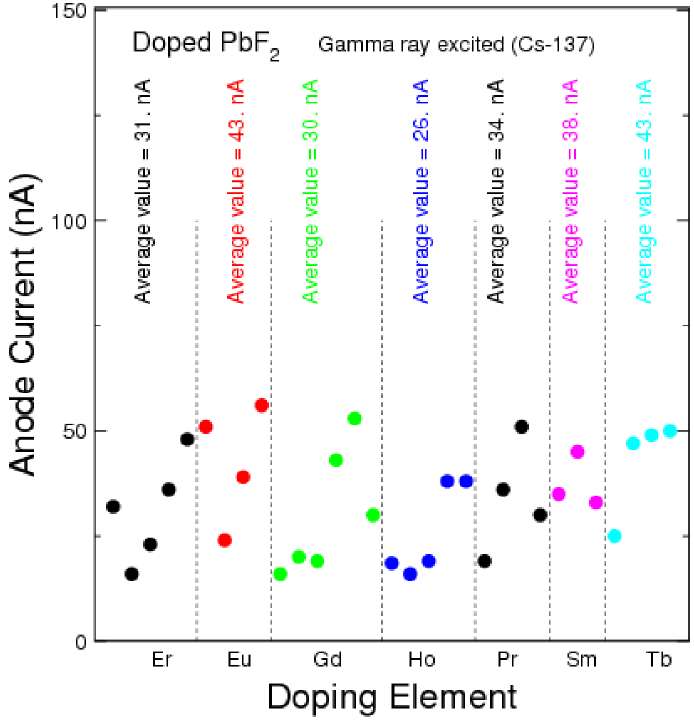
IEEE Trans. Nucl. Sci. **59** *(2012) 2229-2236*

Search for Scintillation in Doped PbF_2



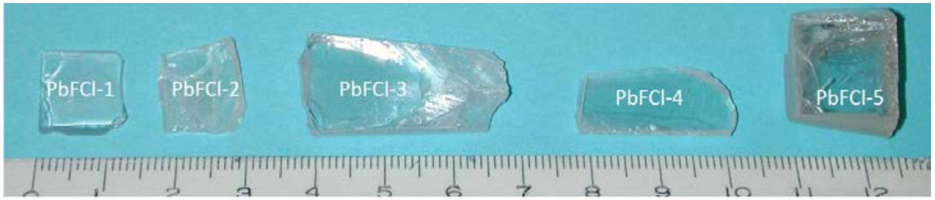


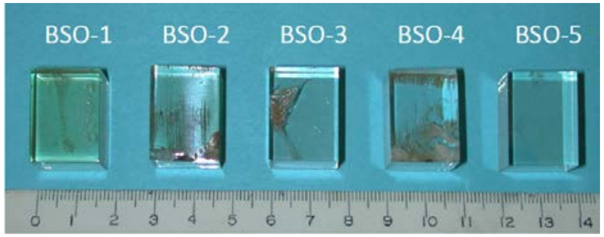




Will look performance at low temperature with the FLS920 fluorescence lifetime spectrometer

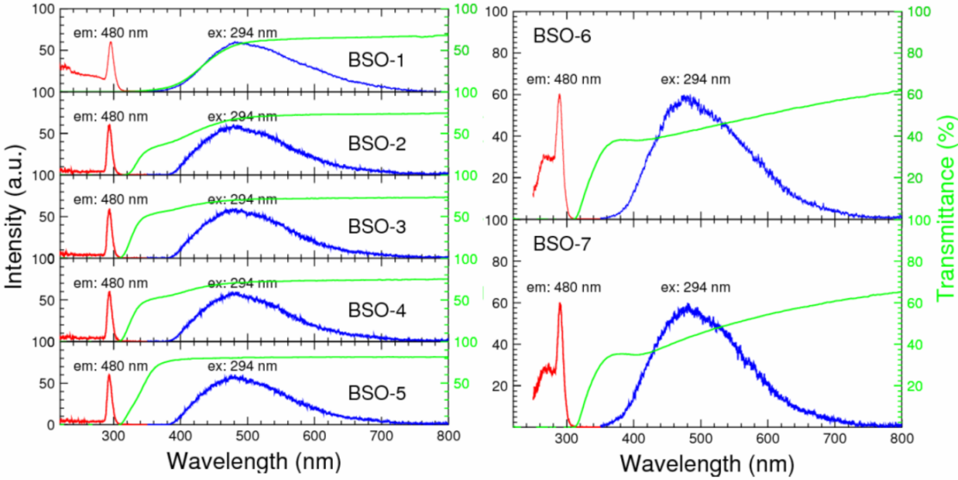
Other Materials: PbFCl & BSO

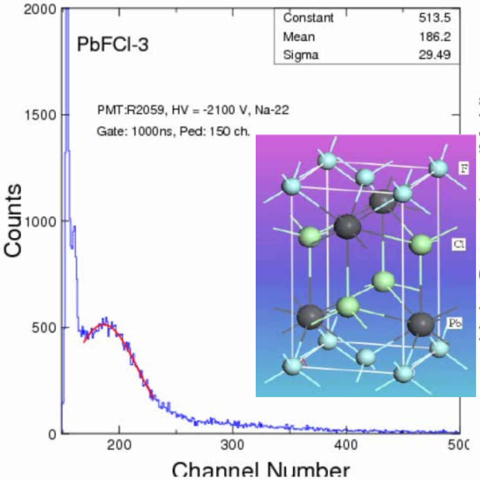


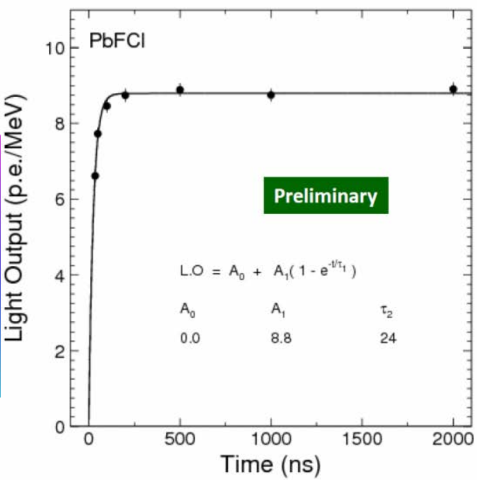


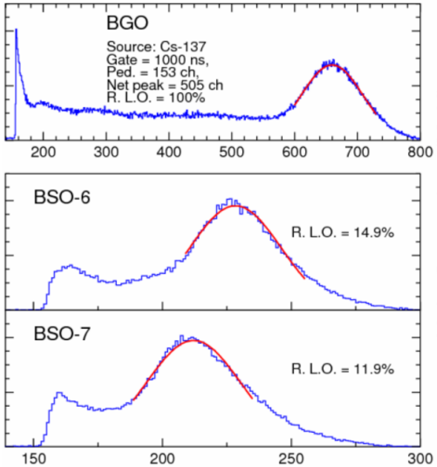
ID	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
Doping	--	Na 0.5at%	--	--	
Dimension (mm)	10x10x2	10x10x2	30x10x5	20x10x3	~10x10x9

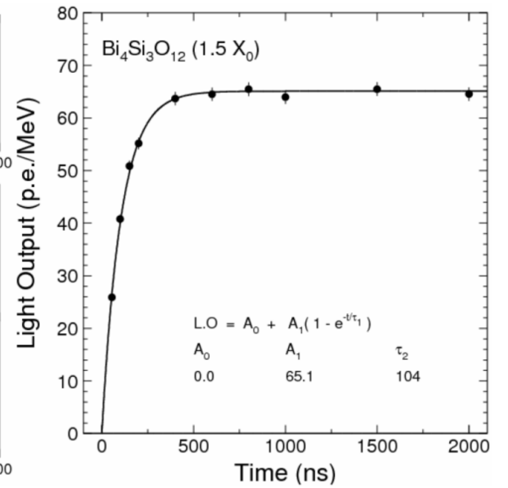
ID	PWO	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
X-luminescence		Peaked @ 420 nm				
L.O. (% PWO)	100	14	64	33	35	31
L.O. (% BGO)	1.8	0.25	1.1	0.59	0.63	0.56







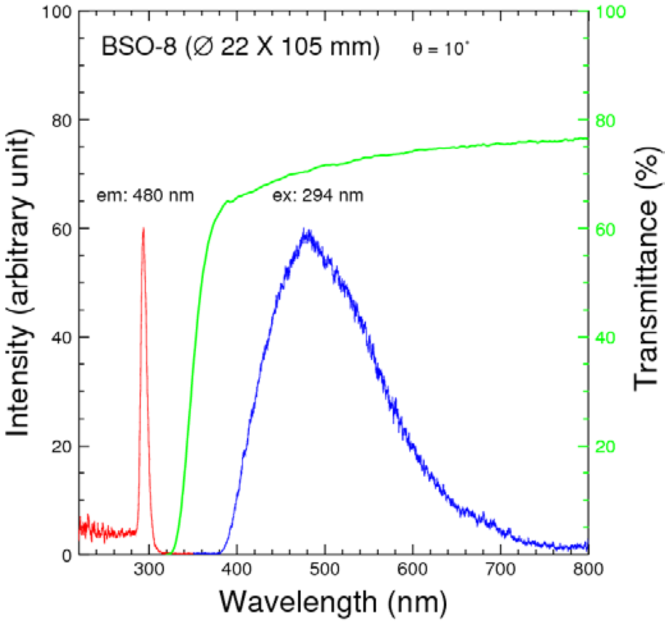


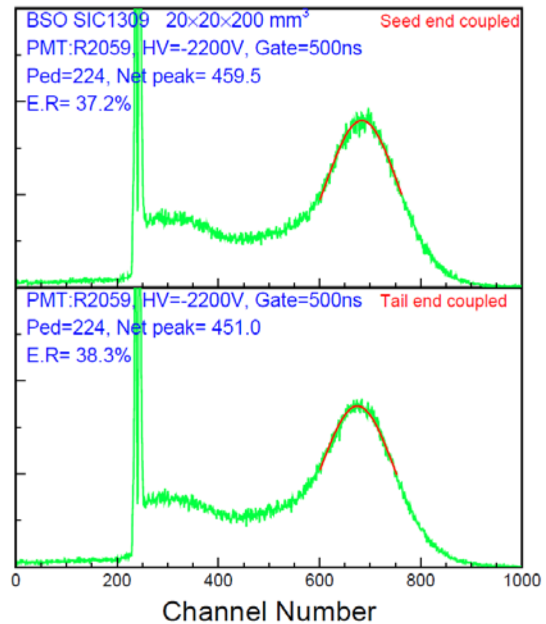


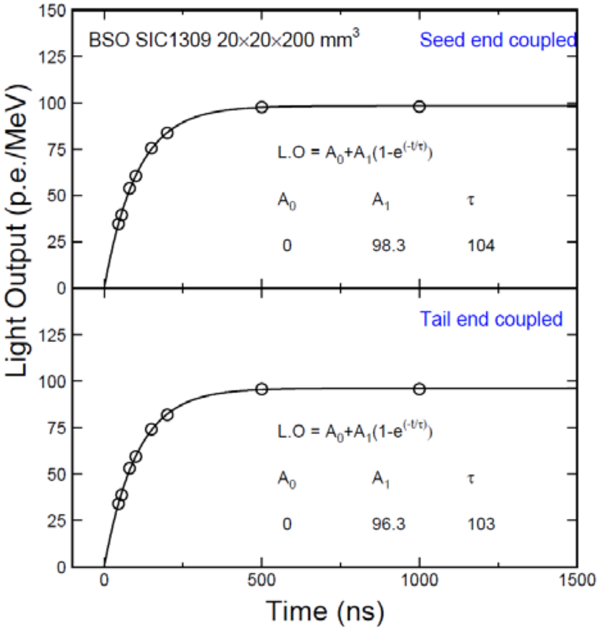
Large Size BSO Sample

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

Presented in SORMA2014.





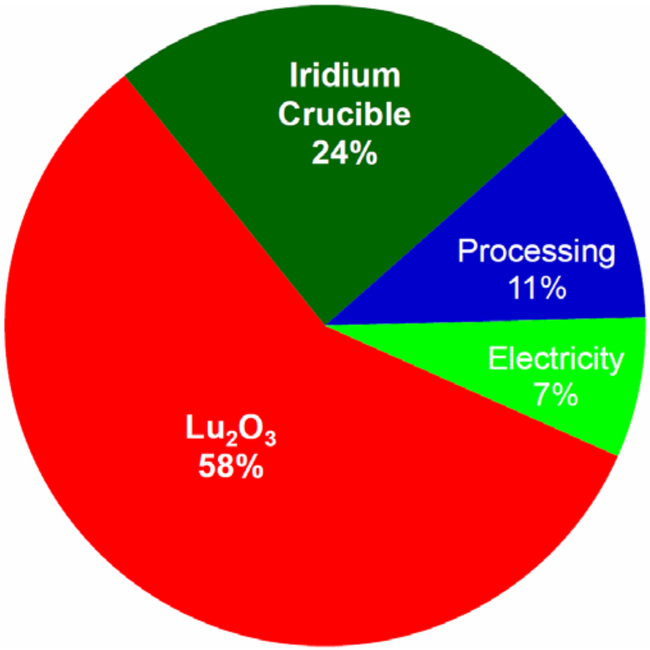


Summary

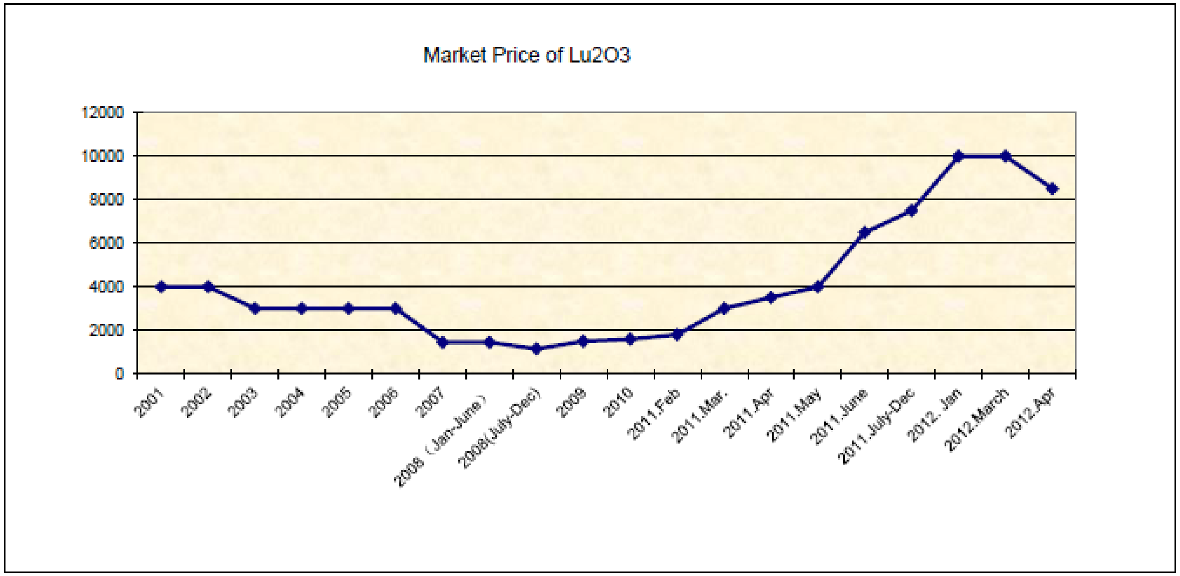
- Bright, fast and radiation hard LSO/LYSO crystals are base-lined for a total absorption ECAL for COMET at J-PARC. LYSO/W Shashlik calorimeter is one of two options for CMS FCAL upgrade for the HL-LHC.
- Future crystal calorimeters with more than ten times faster rate/timing capability require very 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.

LSO/LYSO Crystal Cost

Crystal Cost Breakdown



The Lu_2O_3 price fluctuates up a lot recently, showing a strong influence of market speculation.



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

What is the long term Lu_2O_3 price ?