Crystal Calorimeters for Future HEP Experiments

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Talk at the Joint CPAD and Instrumentation Frontier Community Meeting, ANL

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).

Existing Crystal Calorimeters in HEP

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

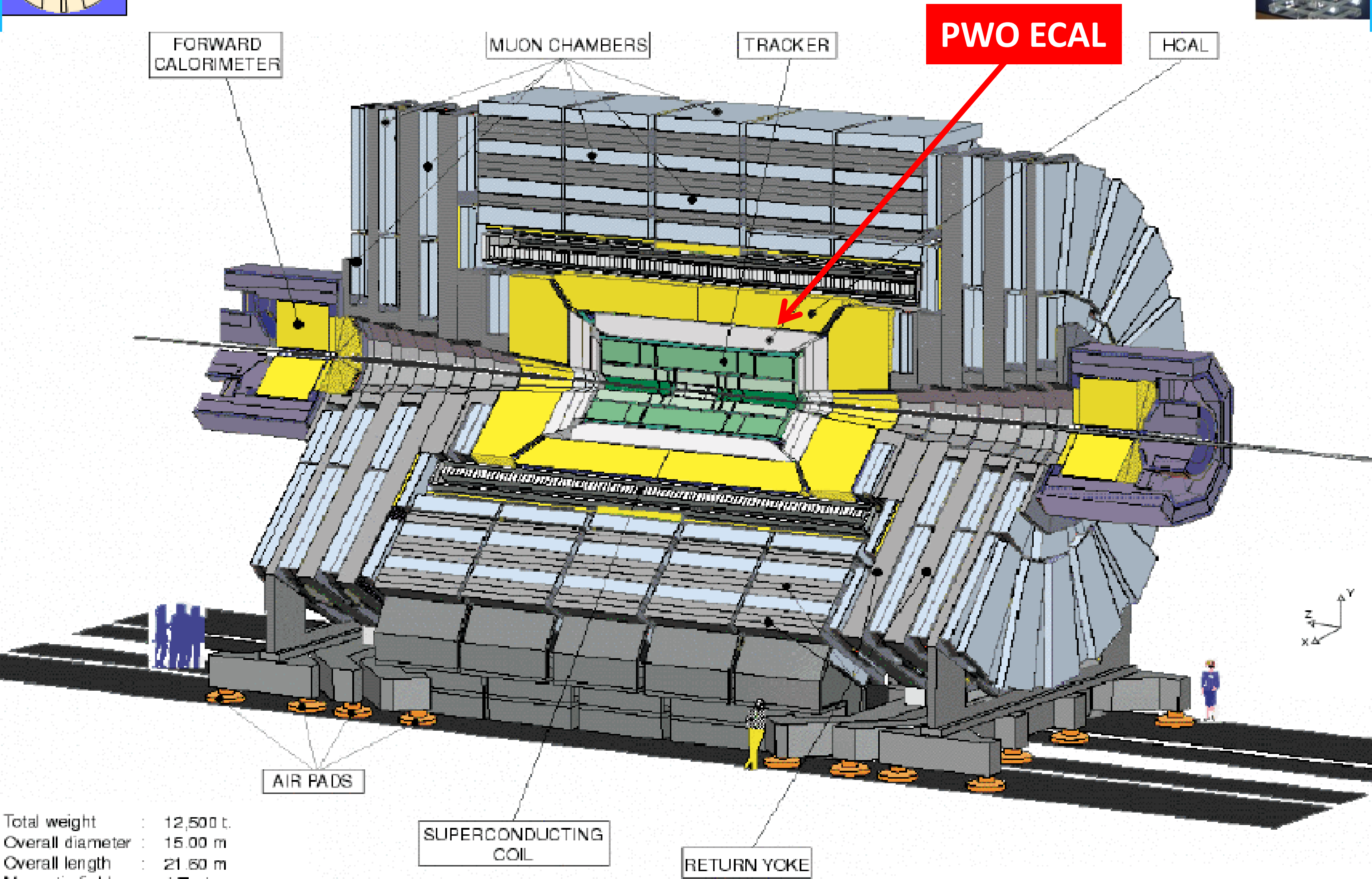
Future crystal calorimeters in HEP:

LSO/LYSO for Mu2e, (Super B) and HL-LHC (Sampling)

BaF_2 for fast calorimeter for project X

PbF_2, PbFCl, BSO for Homogeneous HCAL

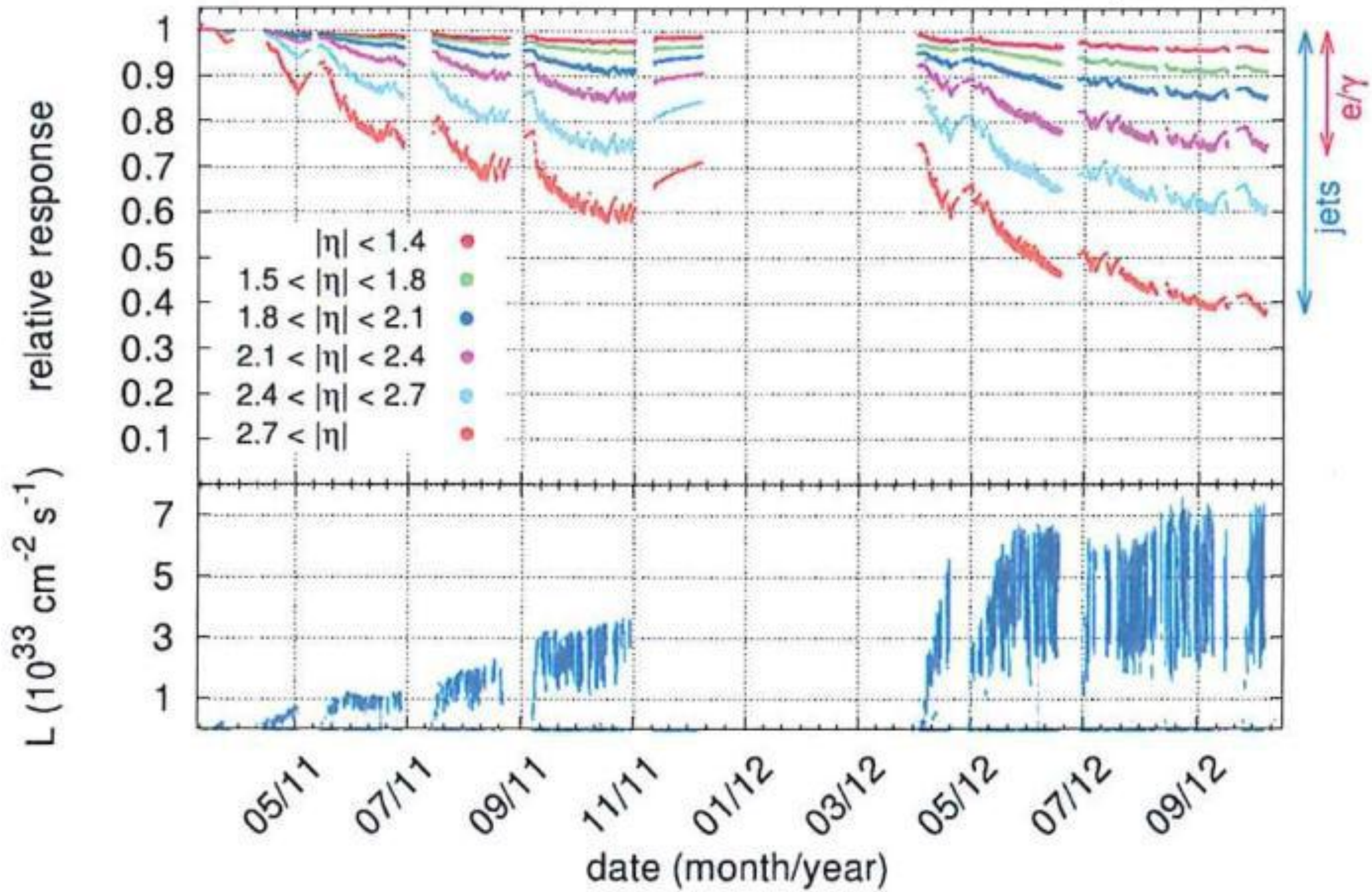
CMS Experiment at LHC



Total weight	: 12,500 t.
Overall diameter	: 15.00 m
Overall length	: 21.60 m
Magnetic field	: 4 Tesla

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

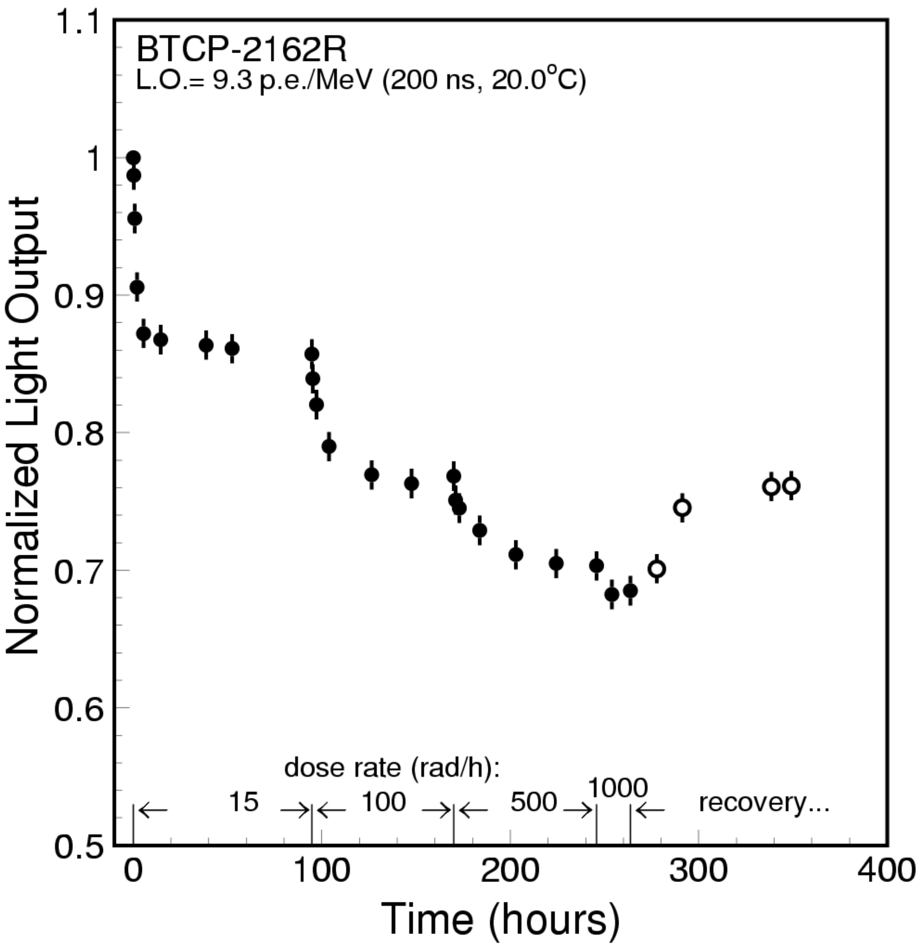
The LO reached equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

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

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

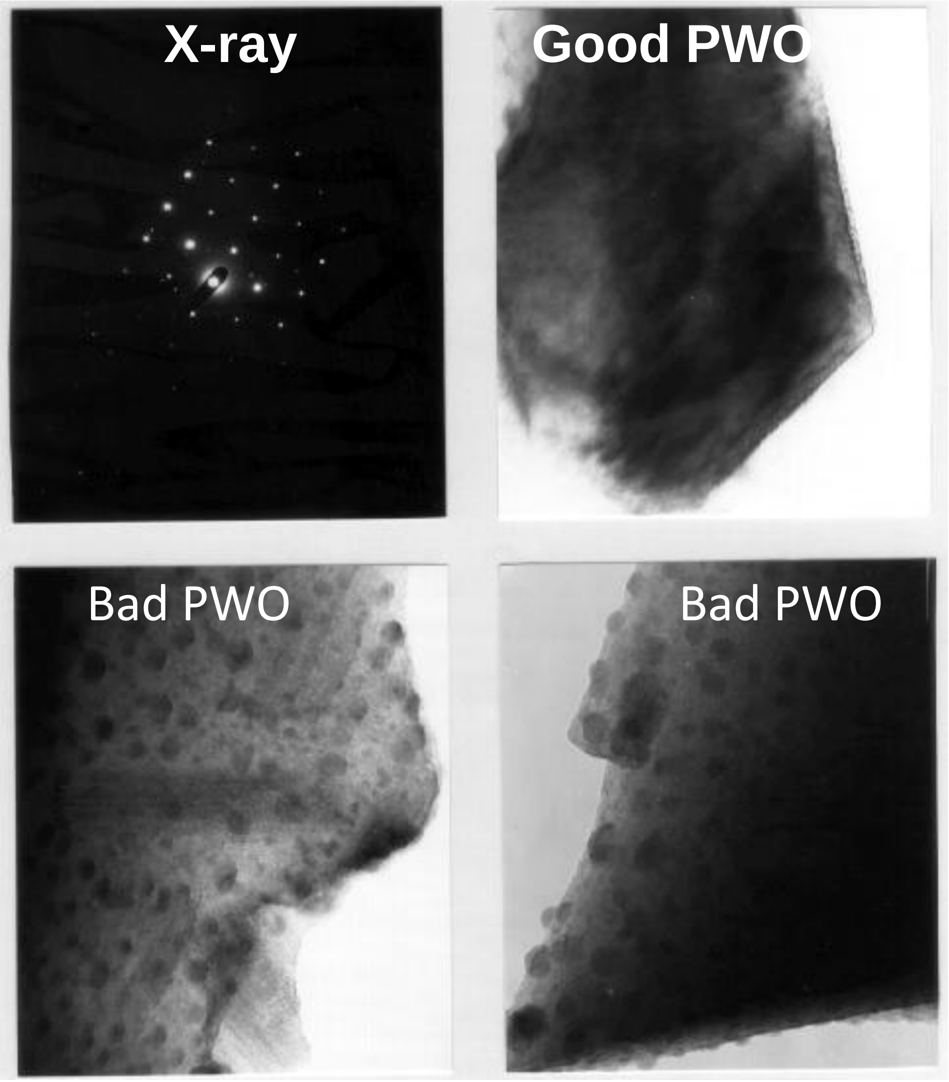
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of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

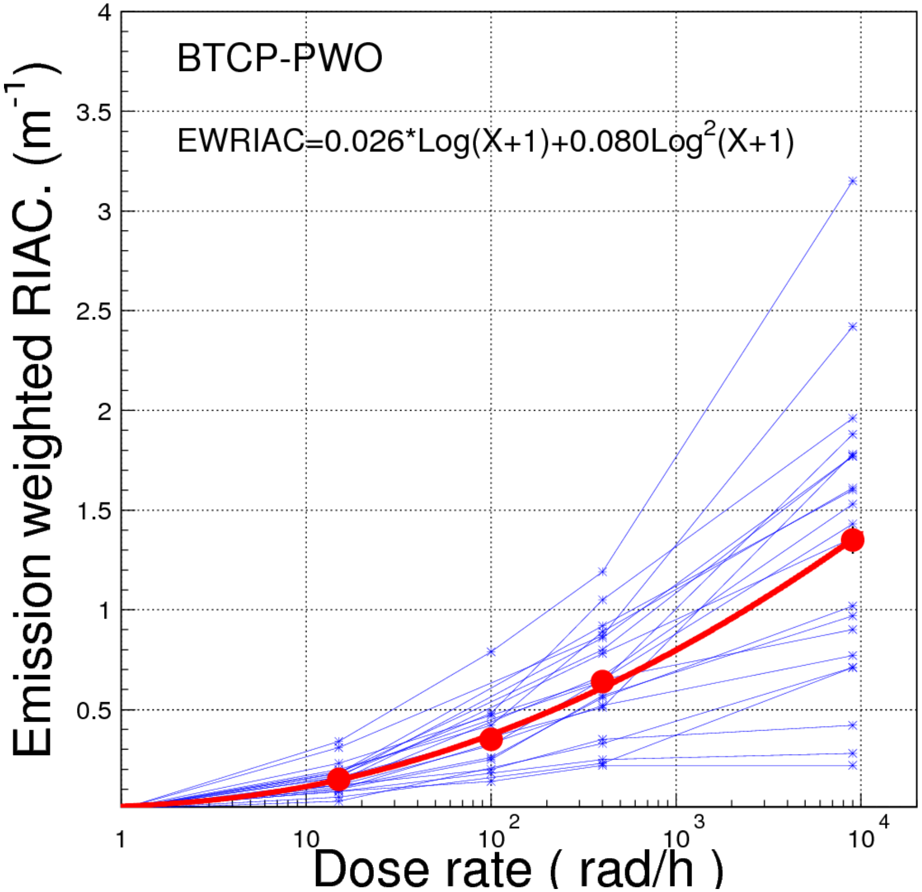
Element	Black Spot	Peripheral	Matrix$_1$	Matrix$_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

The Same Sample after Oxygen Compensation

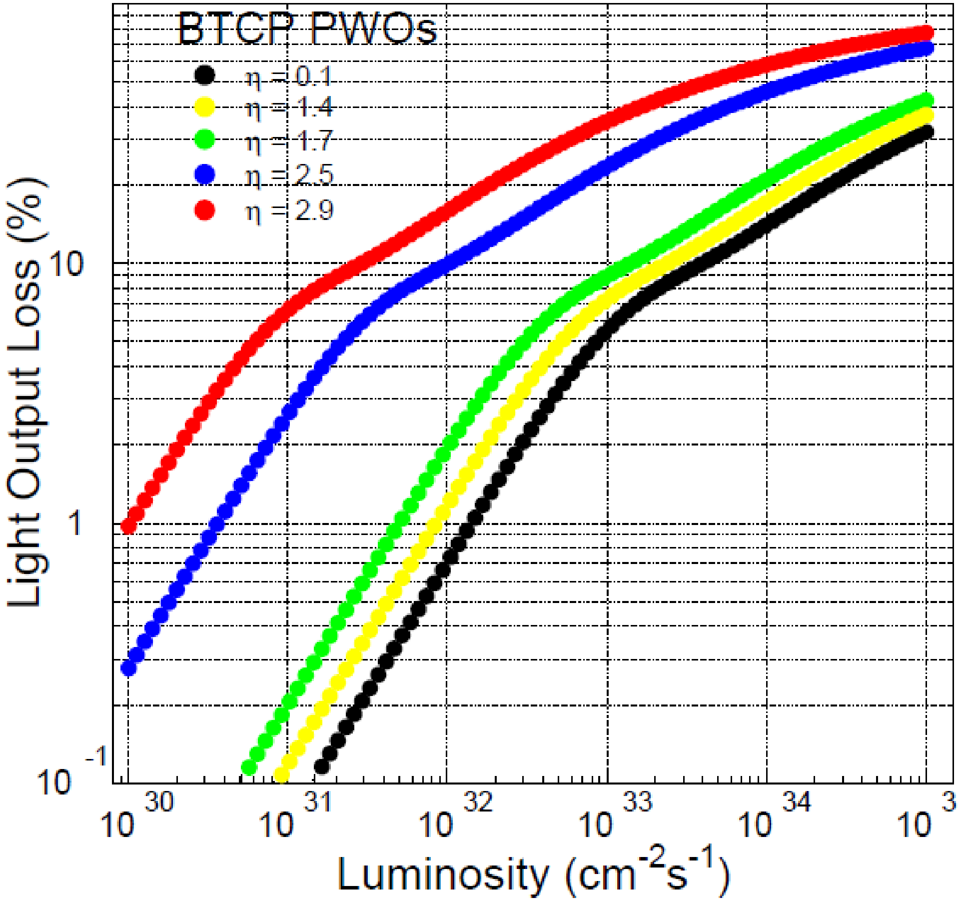
Element	Point$_1$	Point$_2$	Point$_3$	Point$_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

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

Bright, Fast Scintillator: LSO/LYSO

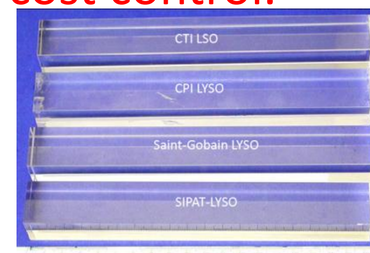
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm³)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (°C)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction 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	420 310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	30 6	650 0.9	300	40	30 10	?
Light Yield [b,c] (%)	100	165	3.6 1.1	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	(L*) (GEM) TAPS	L3 BELLE	KLOE-2 (SuperB) SLHC?	CMS ALICE PANDA	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

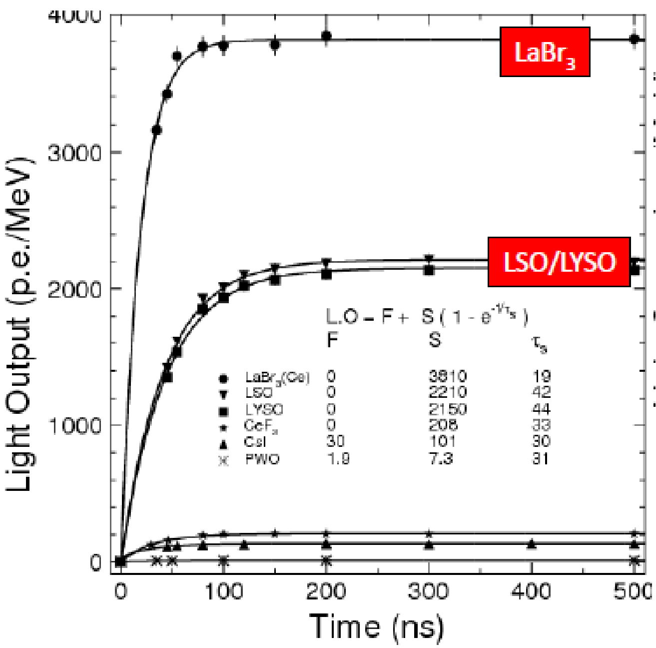
See Talk in Session B for the Details

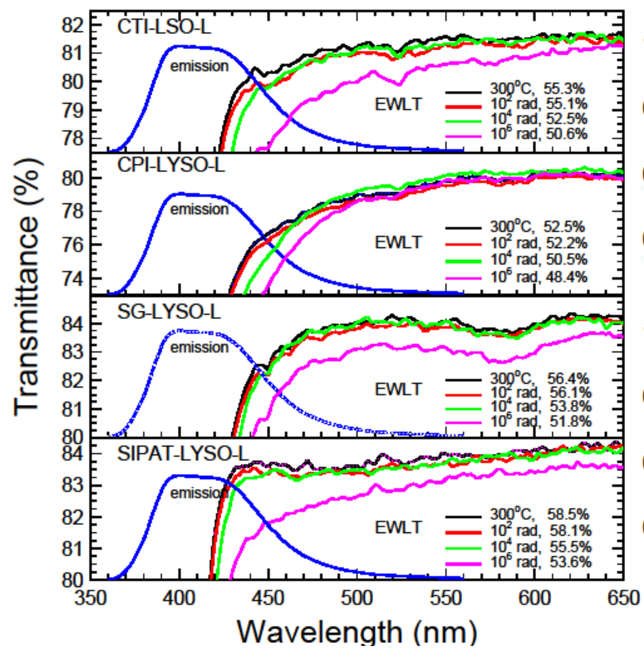
LSO/LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator. The longitudinal non-uniformity issue caused by tapered crystal geometry, self-absorption and cerium segregation can be addressed by roughening one side surface. The material is widely used in the medical industry.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

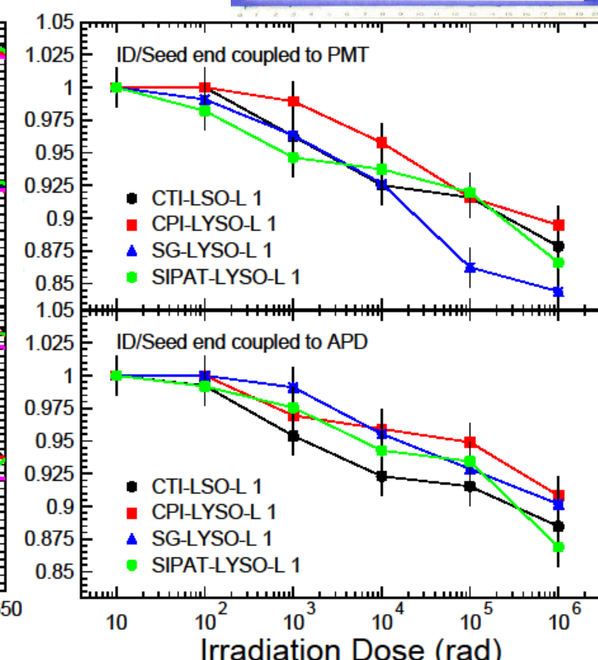


Bright & Fast

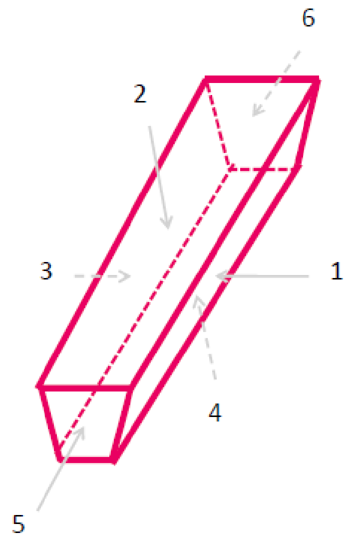
EWLT/LO damage: 8%/10% @ 1 Mrad
For 20 cm long LSO/LYSO crystals

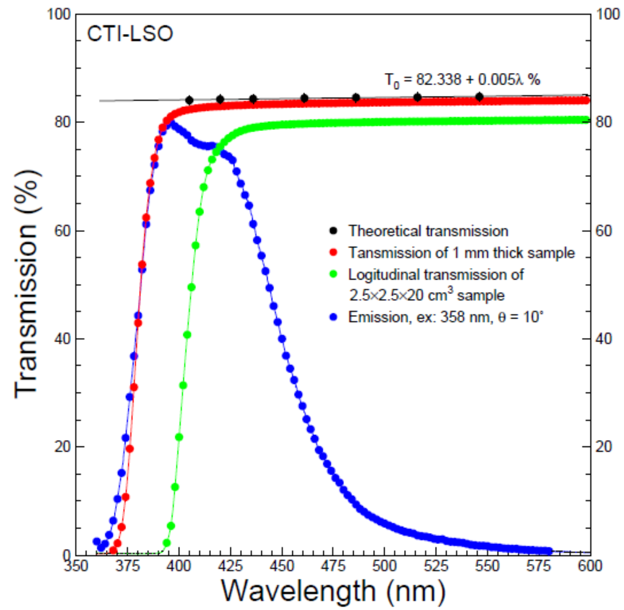


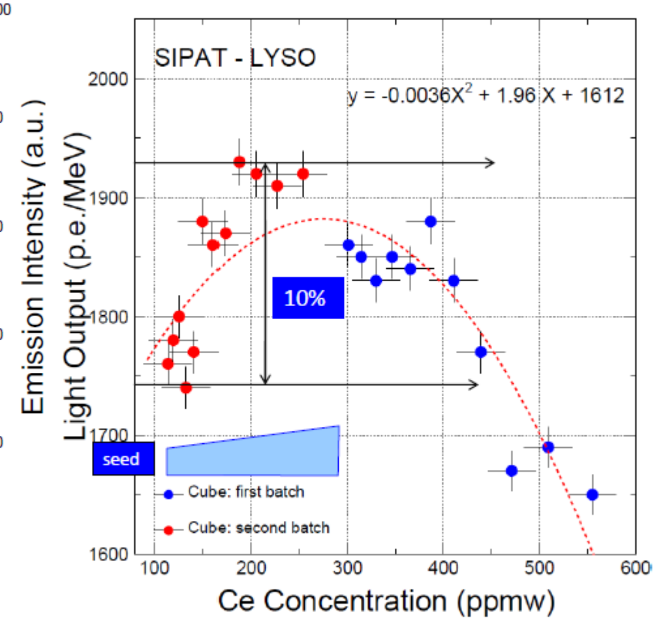




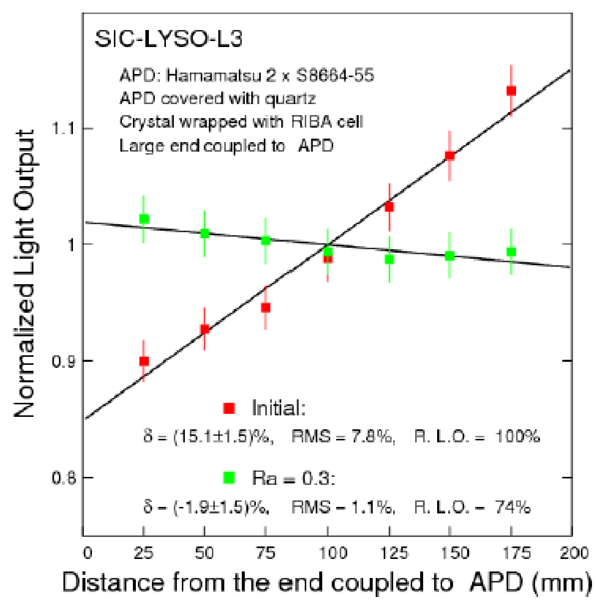
LYSO Light Response Uniformization

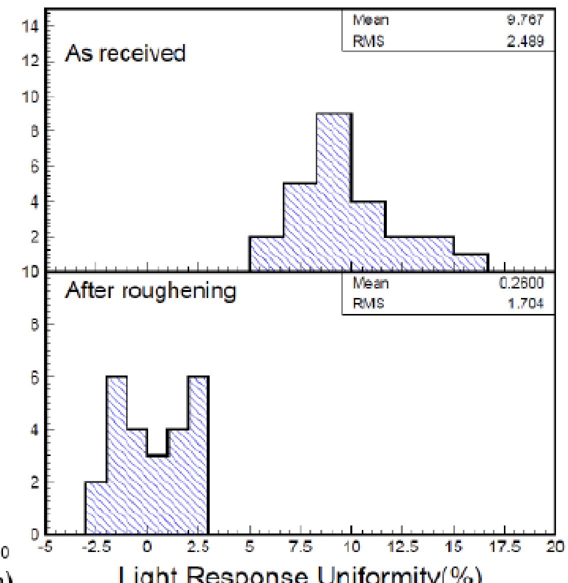






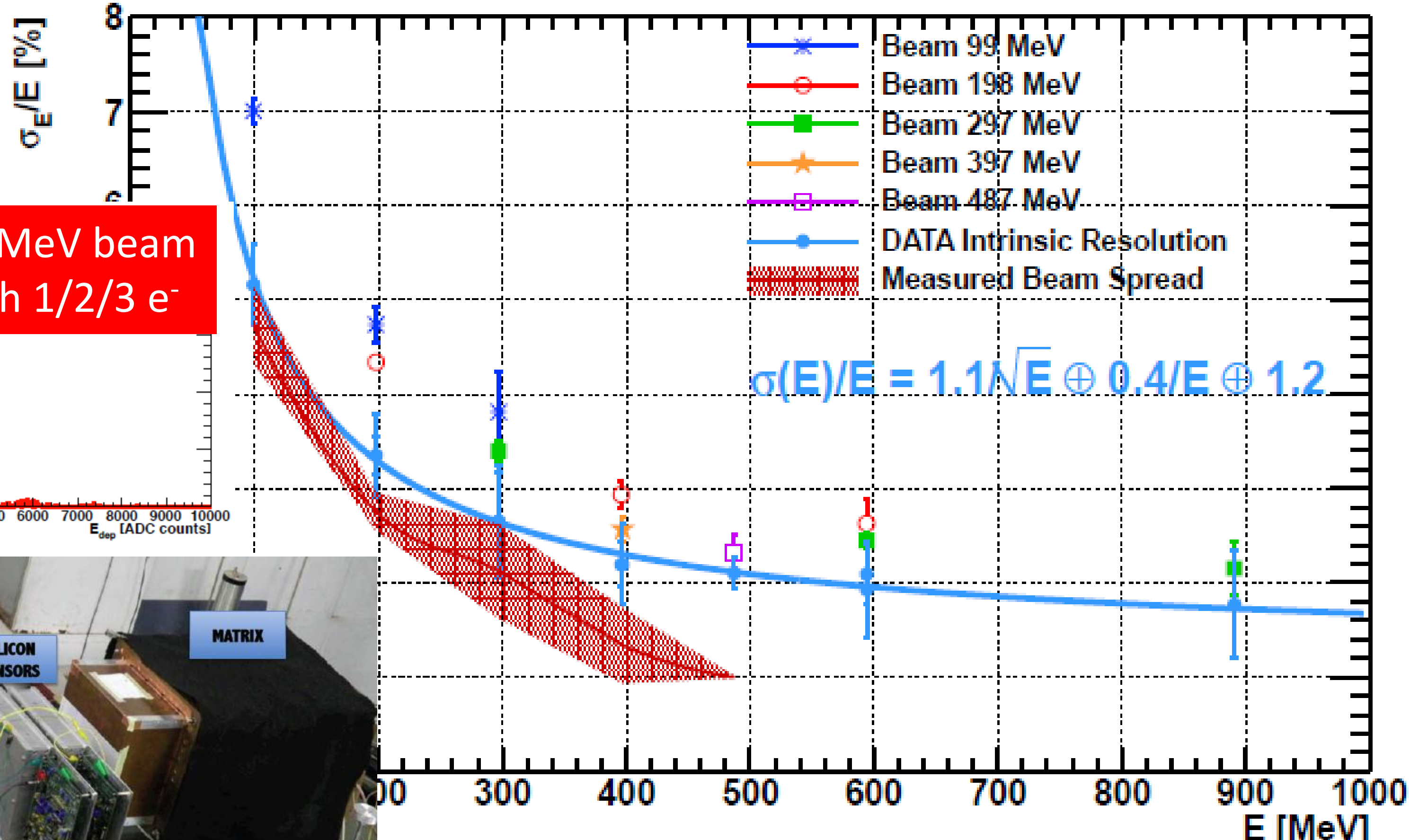
25 LYSO test beam crystals are uniformized to |δ| < 3% by roughening the smallest side surface.

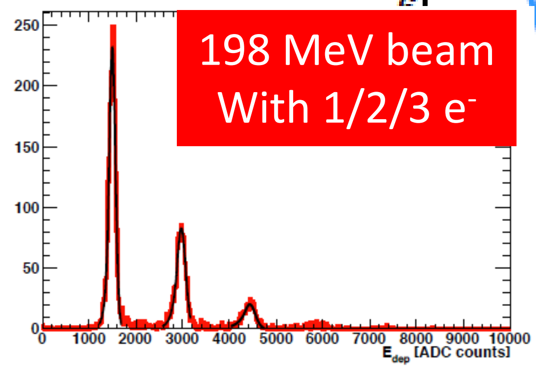


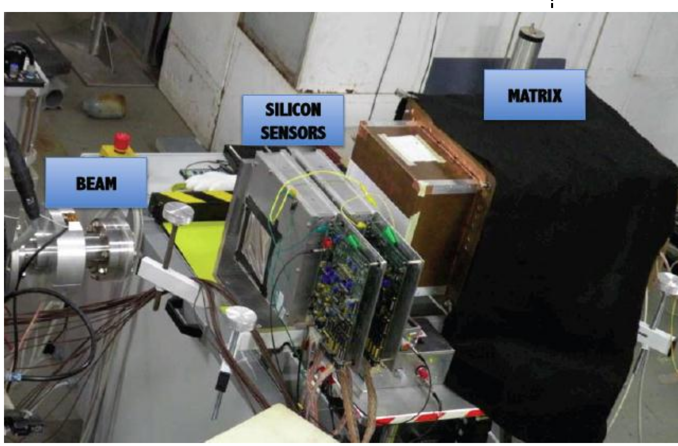


LYSO Test Beam Result

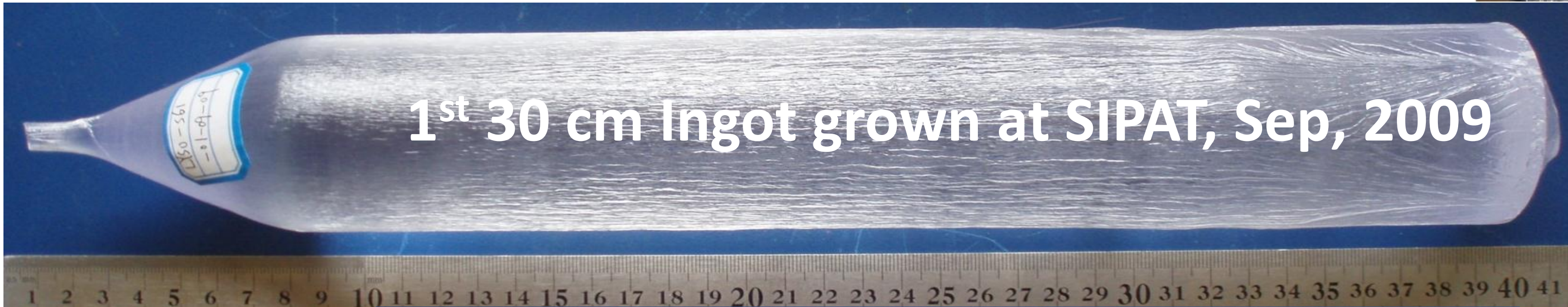
$$\frac{\sigma(E)}{E} = \frac{1.1}{\sqrt{E[GeV]}} \oplus \frac{0.4}{E[GeV]} \oplus 1.2\ \%$$

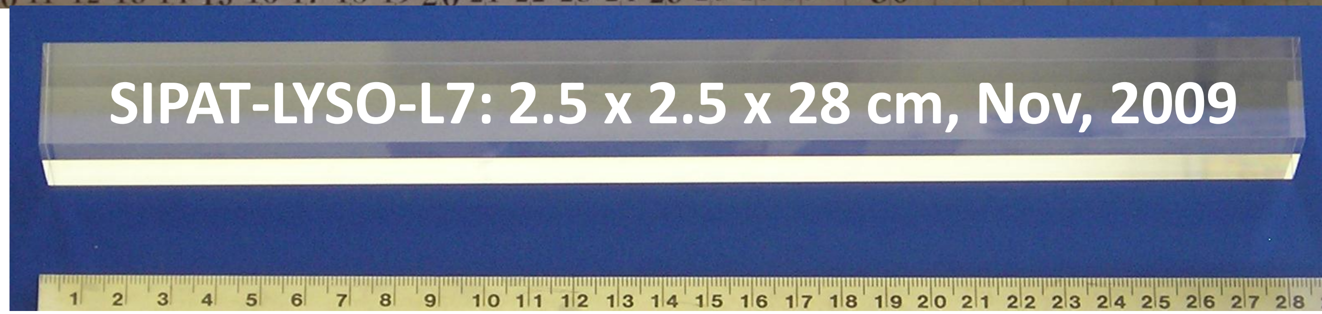


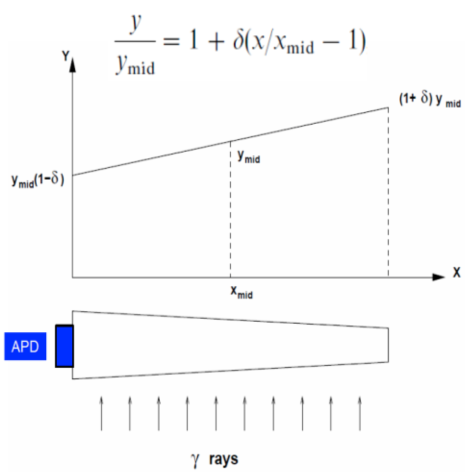


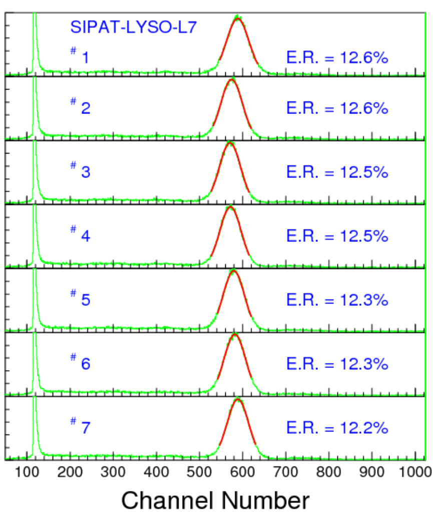


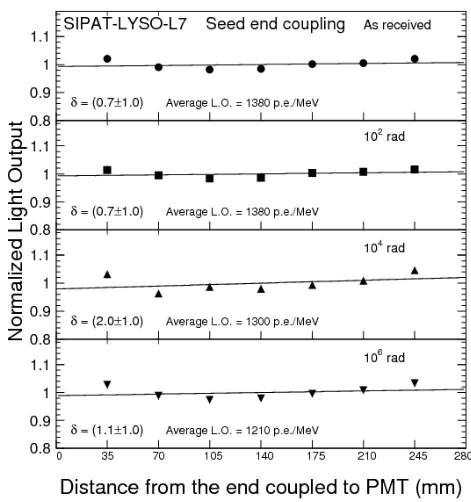
28 cm Long LYSO Under γ-Rays

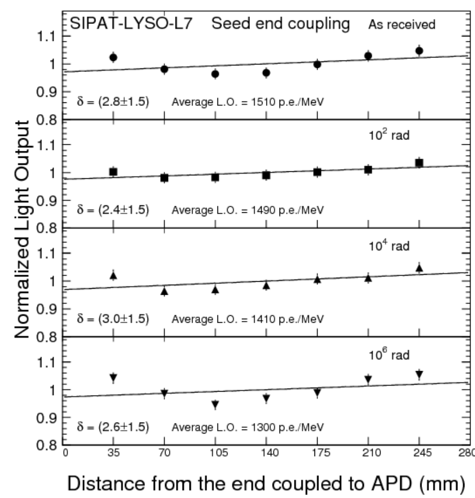






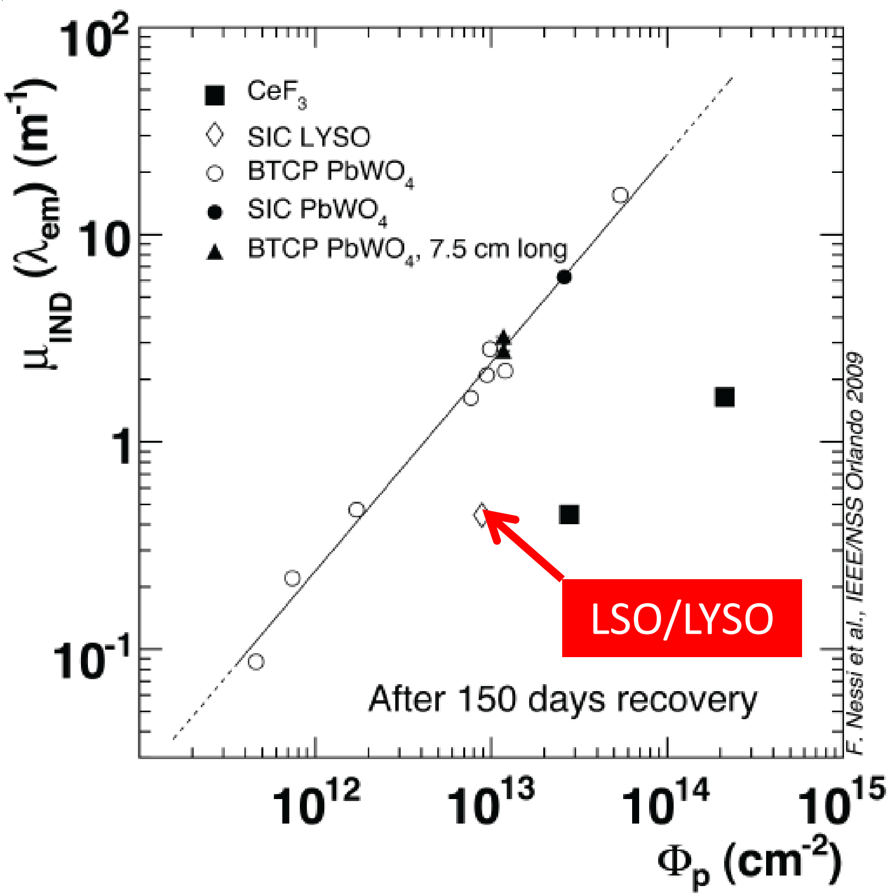




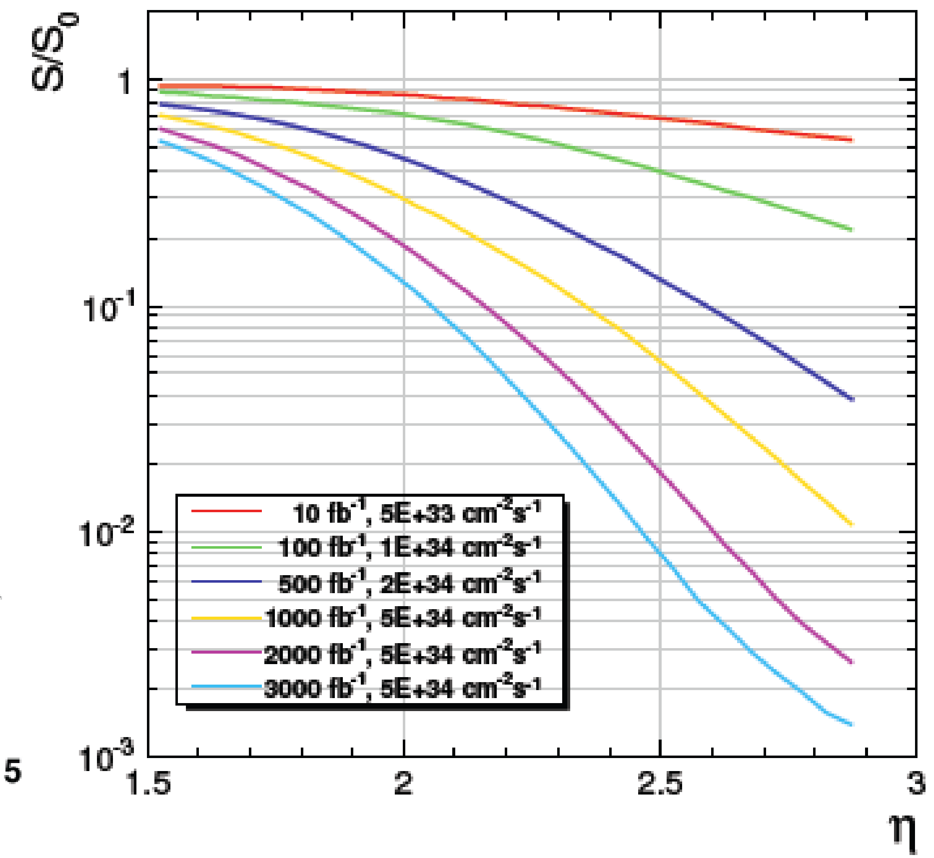


Proton Induced Damage

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



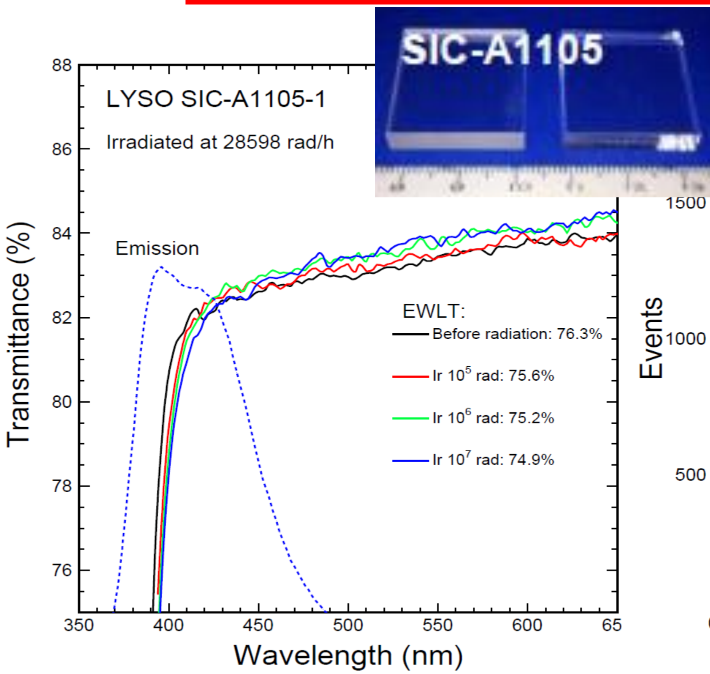
Expected LO loss for CMS endcap PWO

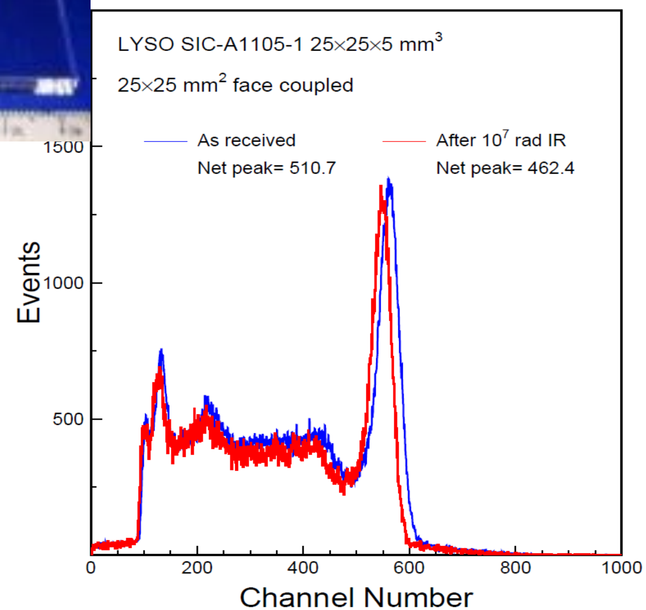


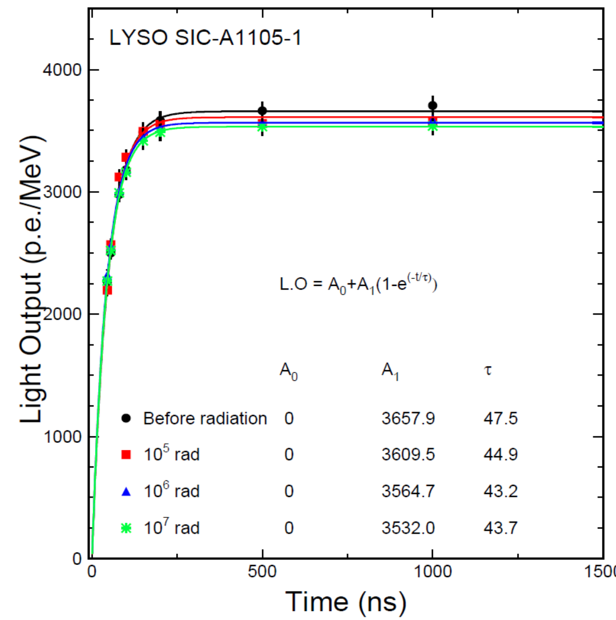
The proton induced absorption in LYSO is 1/5 of PWO
Net effect of damage is smaller for short light path

Damage in 5 mm LYSO Plates

Two 5 mm thick LYSO plates went through γ-ray irradiation to 10 Mrad with degradation in both EWLT and LO less than 10%.
Since damage does not recover, so is easy to be monitored.

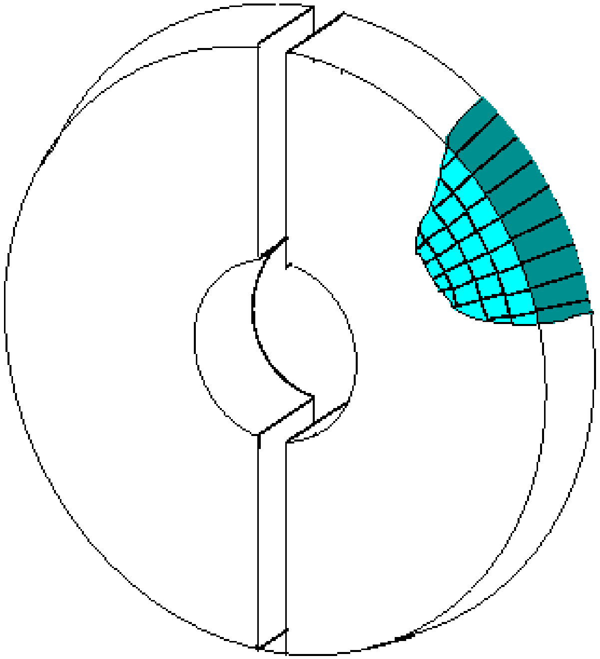


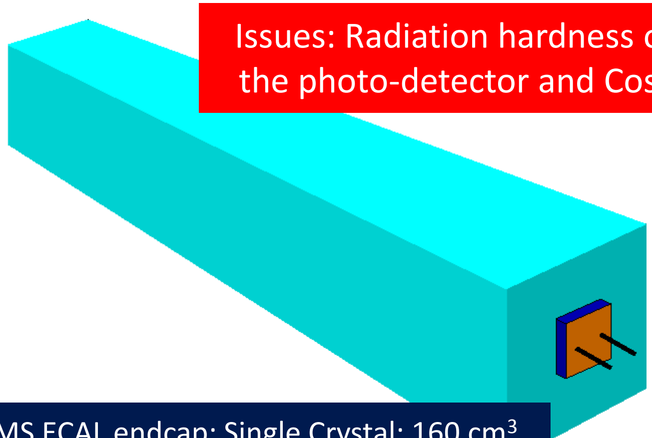




Samples	EWLT (%)	L.O. (p.e./MeV)	EWLT loss (%)			L.O. loss (%)		
			10^5 rad	10^6 rad	10^7 rad	10^5 rad	10^6 rad	10^7 rad
SIC-A1105-1	76.3	3657.9	0.9	1.4	1.8	1.3	2.5	3.4
SIC-A1105-2	77.2	3846.1	2.3	2.5	2.6	4.4	7.7	9.1

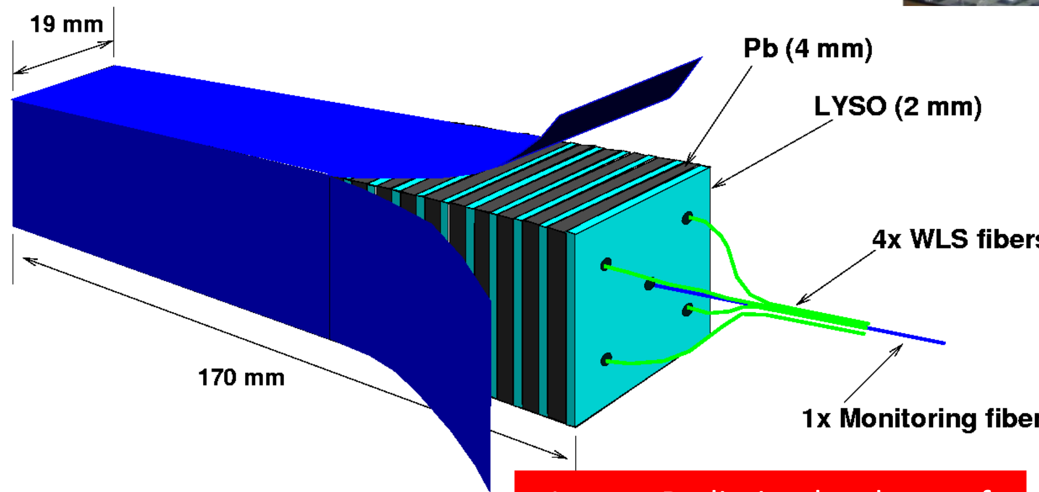
CMS Forward Calorimeter Upgrade



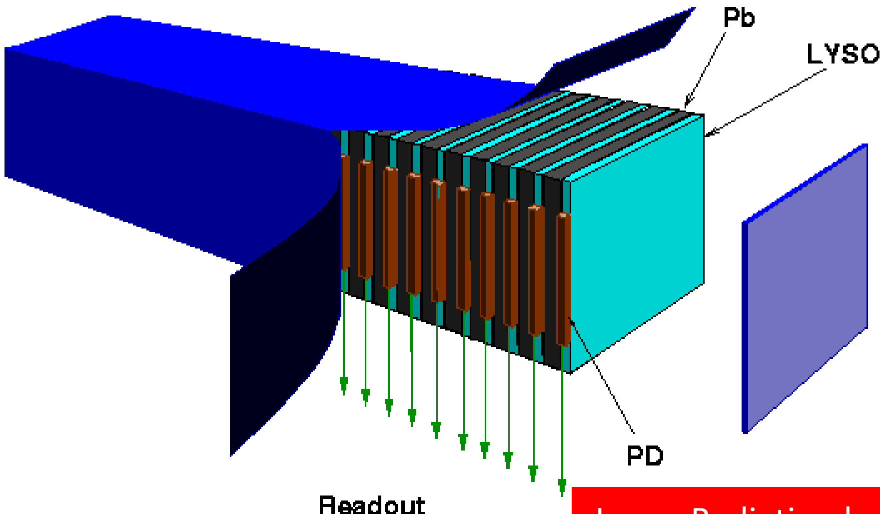


Issues: Radiation hardness of the photo-detector and Cost

CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 3 m^3
Expected Crystal Cost: ~$75M@$25/cc



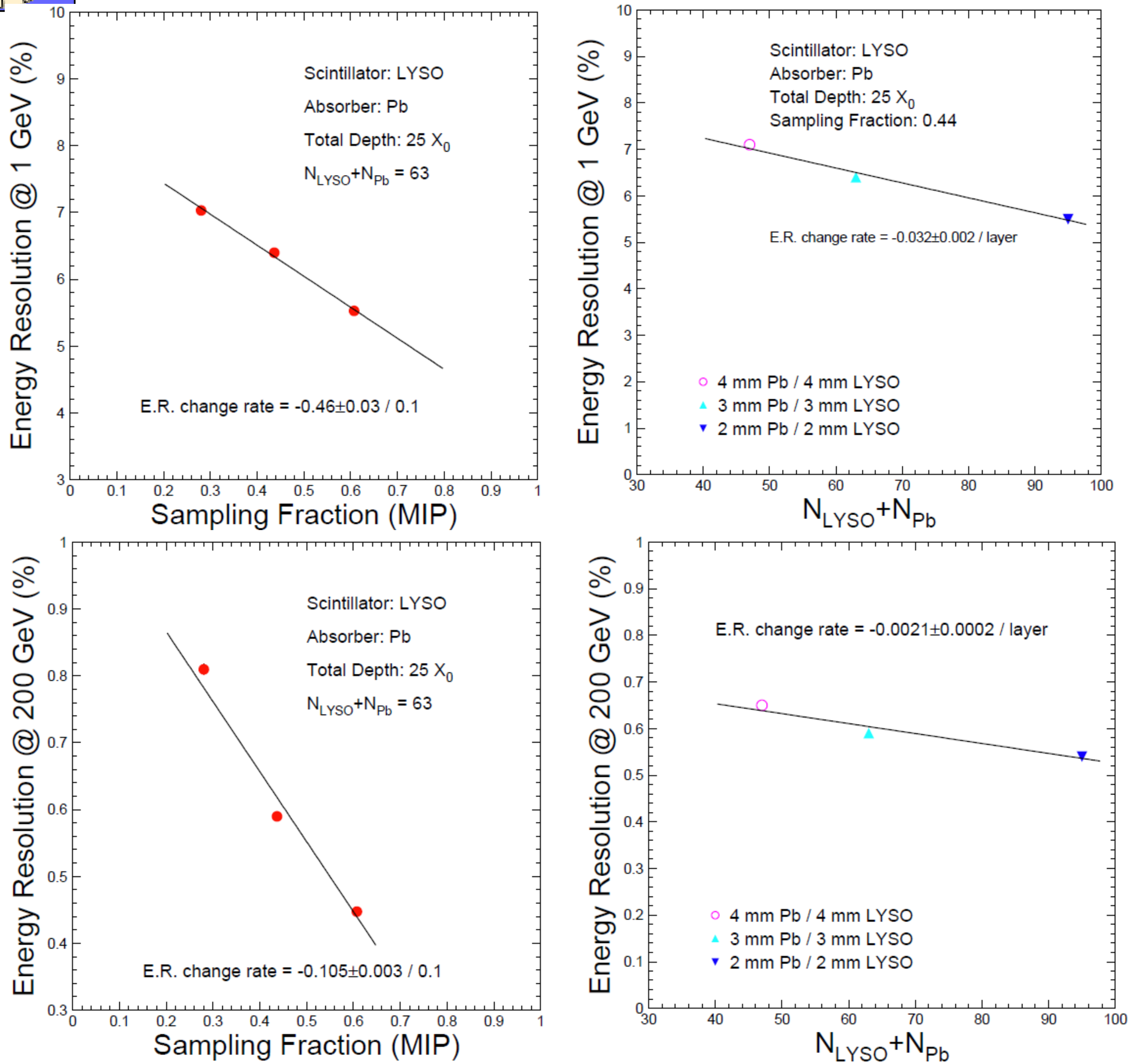
Issues: Radiation hardness of photo-detector and WLS fiber



Crystal Cost: ~$15M

Issue: Radiation hardness of the photo-detector

Optimization of Sampling Design



GEANT simulation points to larger sampling fraction and frequency. Other limitations, such as pile-up noise and crystal cost etc., apply.

Knowing Higgs mass it is important to optimize resolution for H->γγ physics

Alternative Fast Crystals

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

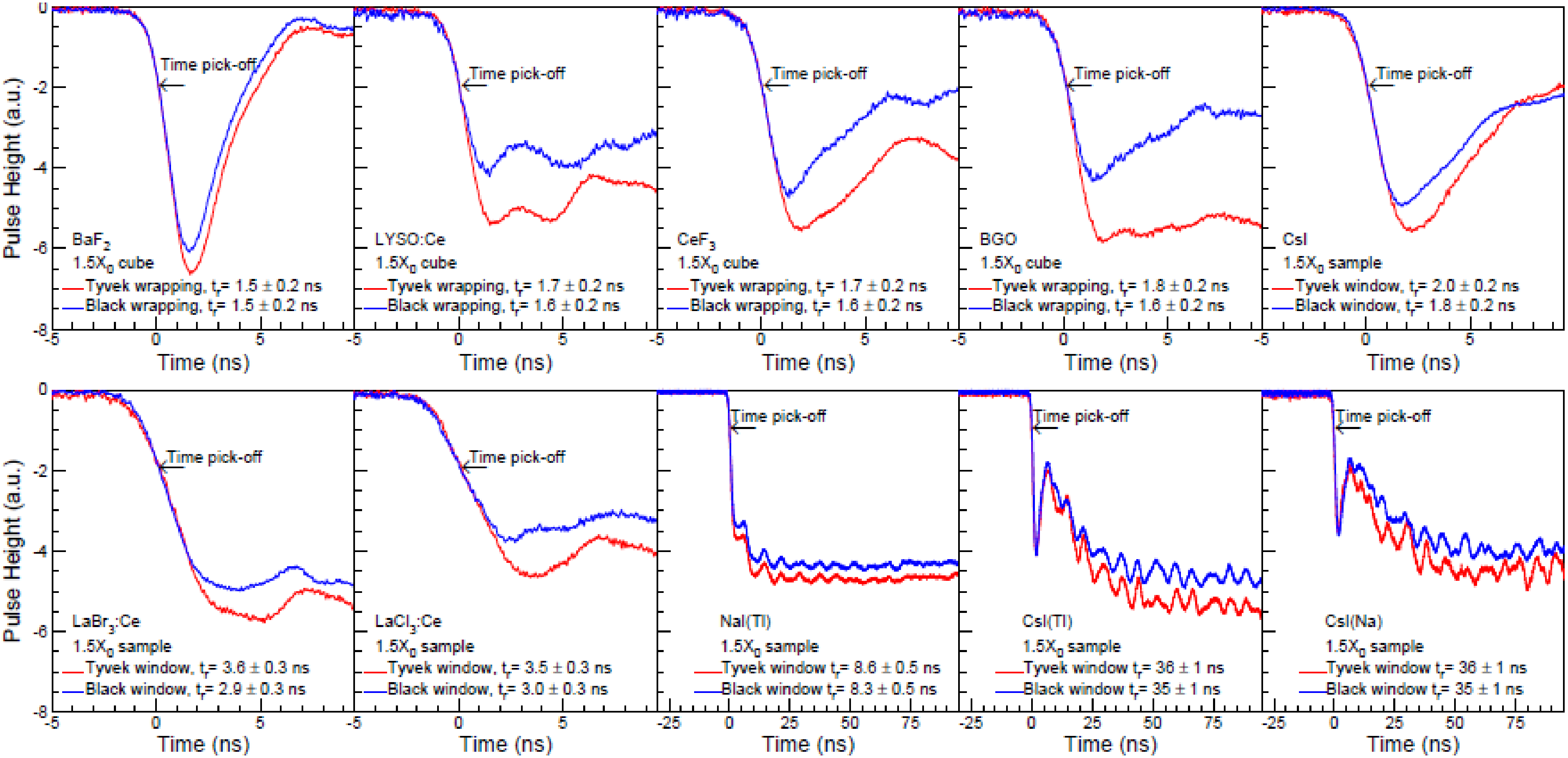
	LSO/LYSO	GSO	YSO [1]	CsI	BaF_2	CeF_3	$CeBr_3$ [2]	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404) [3]
Density (g/cm^3)	7.40	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70#
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.70	1.96	2.81	1.88	42.54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

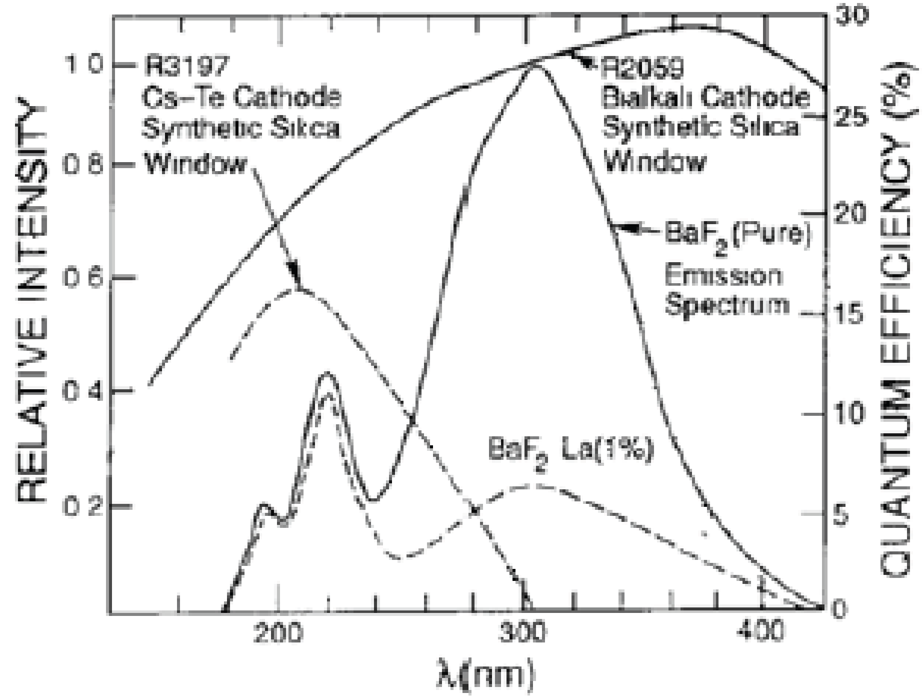
The best crystal scintillator for ultra-fast timing is BaF_2 and LSO(Ce/Ca) and LYSO(Ce). $LaBr_3$ is a material with high potential.

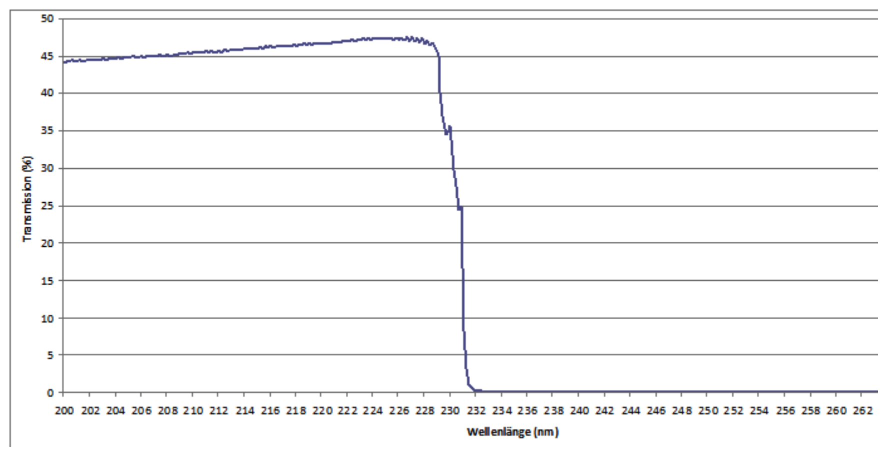
BaF_2 for Very Fast Calorimeter

D. Hitlin, Talk in Session B

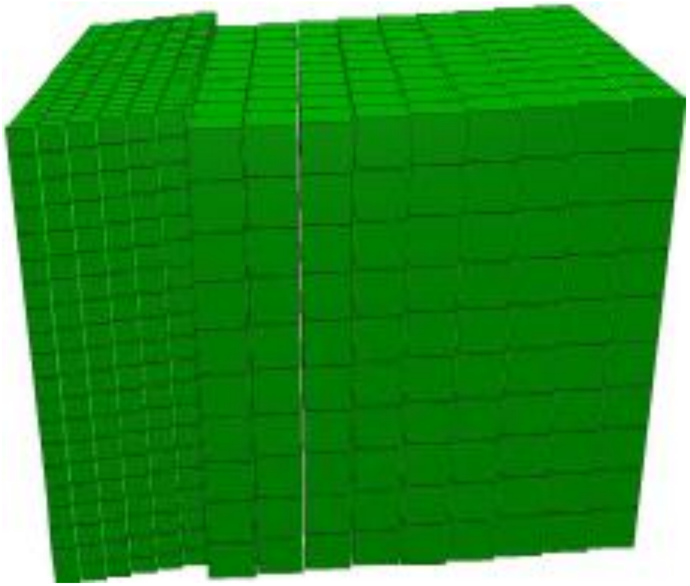
The fast component of BaF_2 crystals at 220 nm has a similar light output as pure CsI and sub-ns decay time.

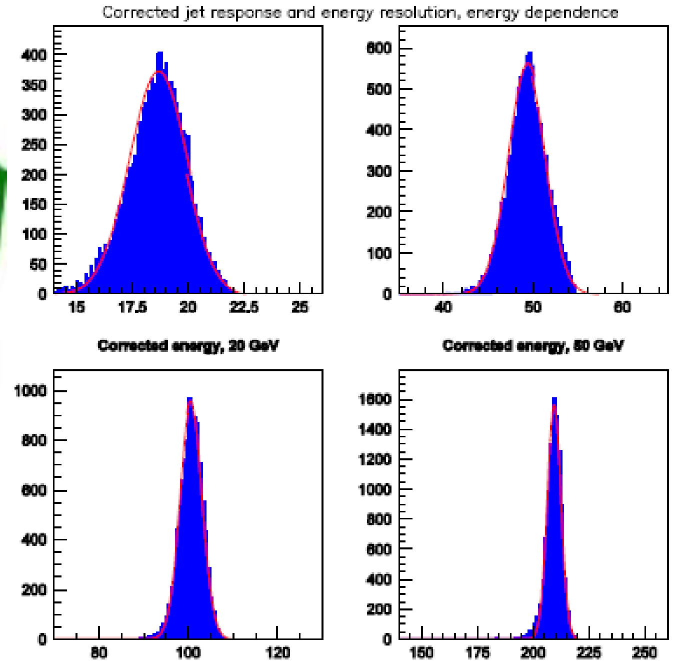
Spectroscopic selection of fast component may be achieved with solar blind photocathode or short pass filter.





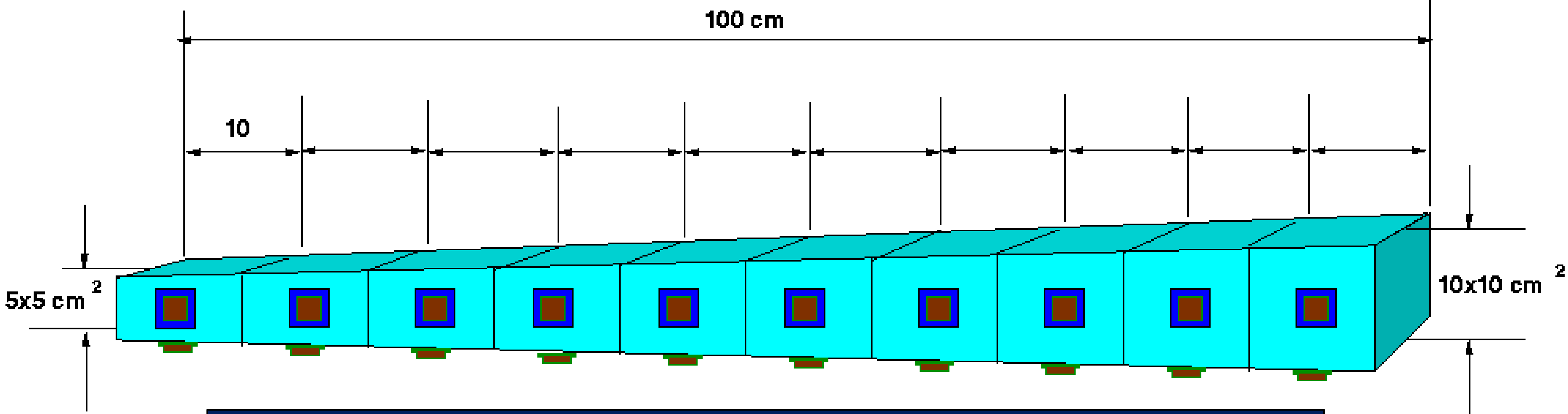
The HHCAL Detector Concept





See S. McGill, H. Wenzel, Callor2012: GEANT simulations show a jet energy resolution at a level of 20%/√E after corrections.

Cost < $2/cc!

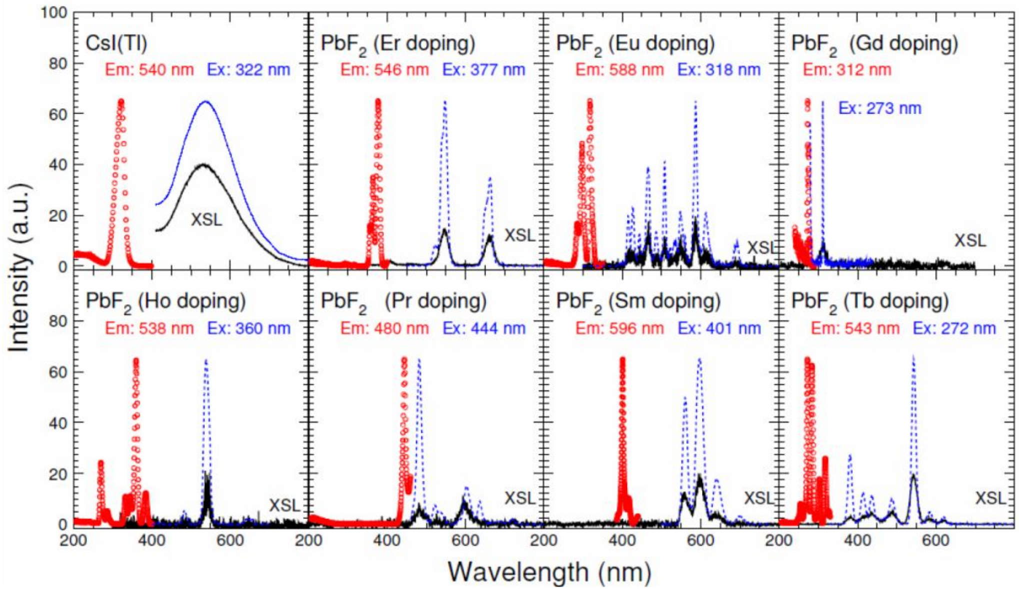


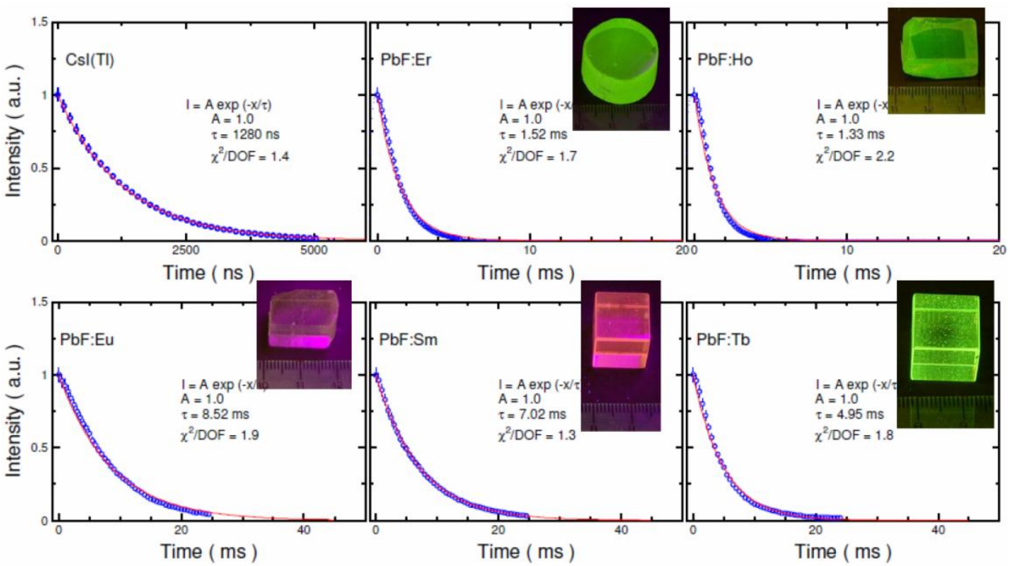
R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

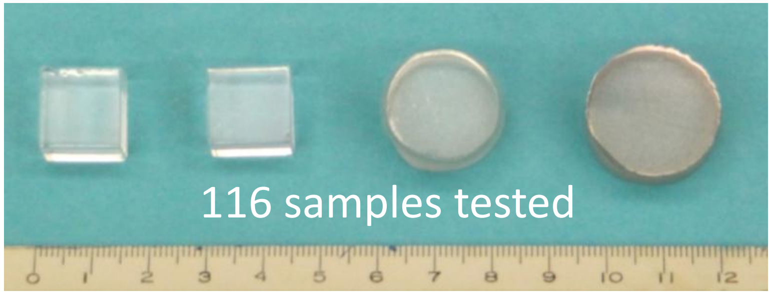
Candidate Crystals for HHCAL

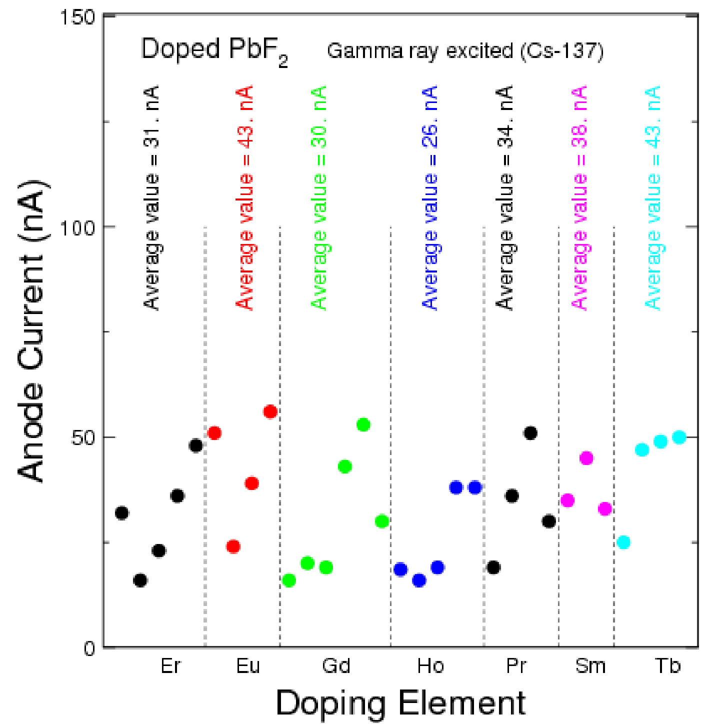
Parameters	$Bi_4Ge_3O_{12}$ (BGO)	$PbWO_4$ (PWO)	PbF_2	PbClF	$Bi_4Si_3O_{12}$ (BSO)
ρ (g/cm^3)	7.13	**8.29**	**7.77**	7.11	6.8?
λ_I (cm)	22.8	**20.7**	**21.0**	24.3	23.1
n @ λ_{max}	2.15	2.20	1.82	2.15	2.06
τ_{decay} (ns)	300	30/10	**?**	30	100
λ_{max} (nm)	480	425/420	**?**	420	470
Cut-off λ (nm)	**310**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

Search for Scintillation in Doped PbF_2



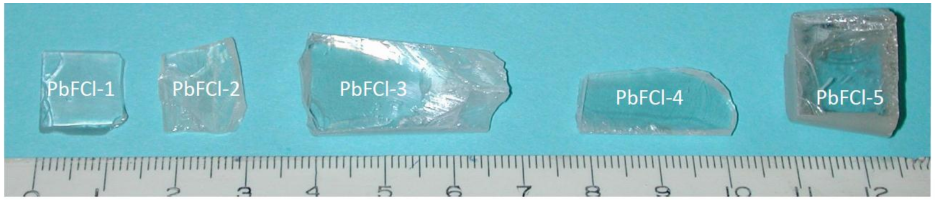


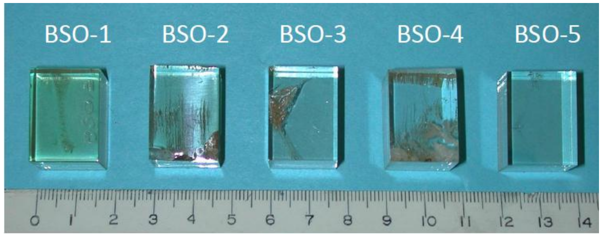




Will look performance at low temperature with the FLS920 fluorescence lifetime spectrometer

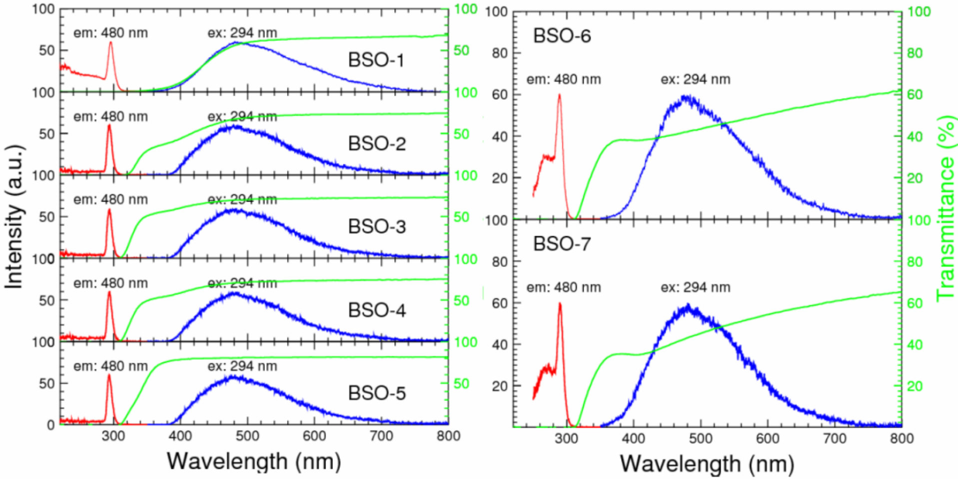
Other Materials: PbFCl & BSO

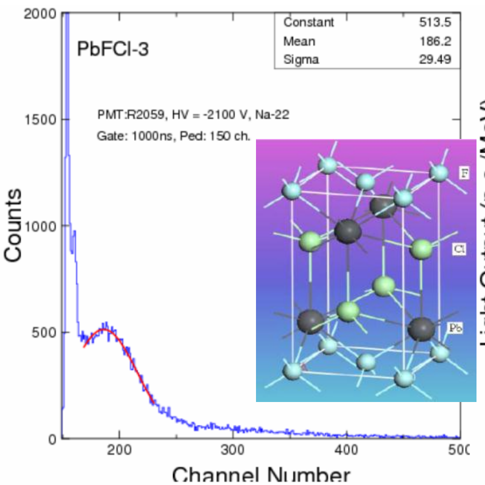


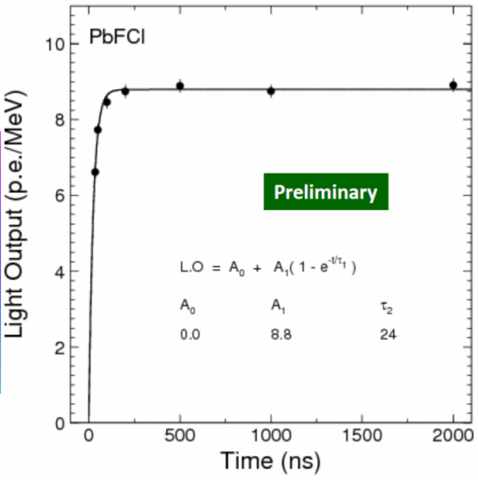


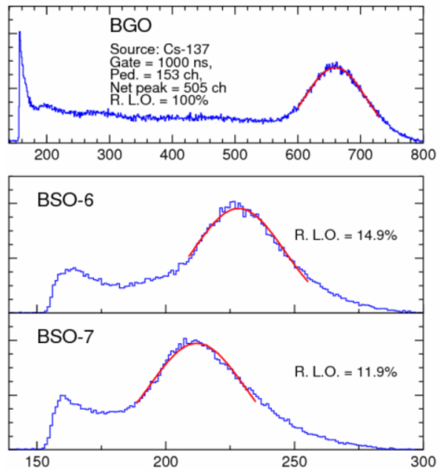
ID	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
Doping	--	Na 0.5at%	--	--	
Dimension (mm)	10x10x2	10x10x2	30x10x5	20x10x3	~10x10x9

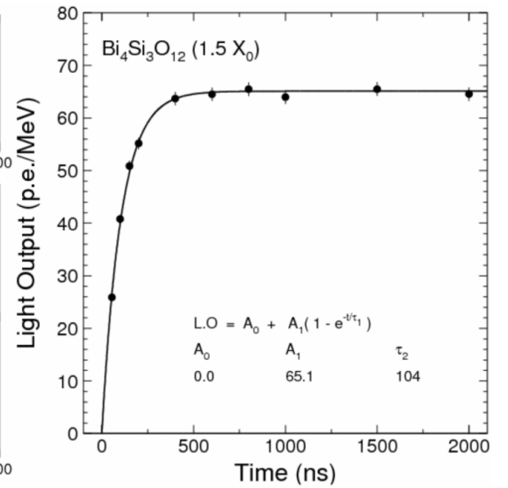
ID	PWO	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
X-luminescence		Peaked @ 420 nm				
L.O. (% PWO)	100	14	64	33	35	31
L.O. (% BGO)	1.8	0.25	1.1	0.59	0.63	0.56



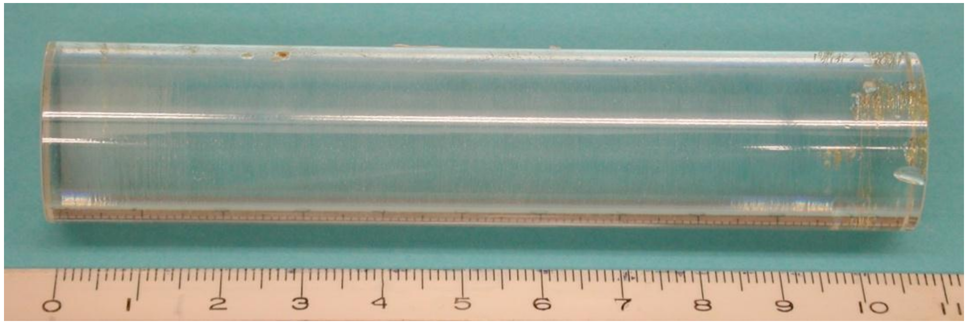




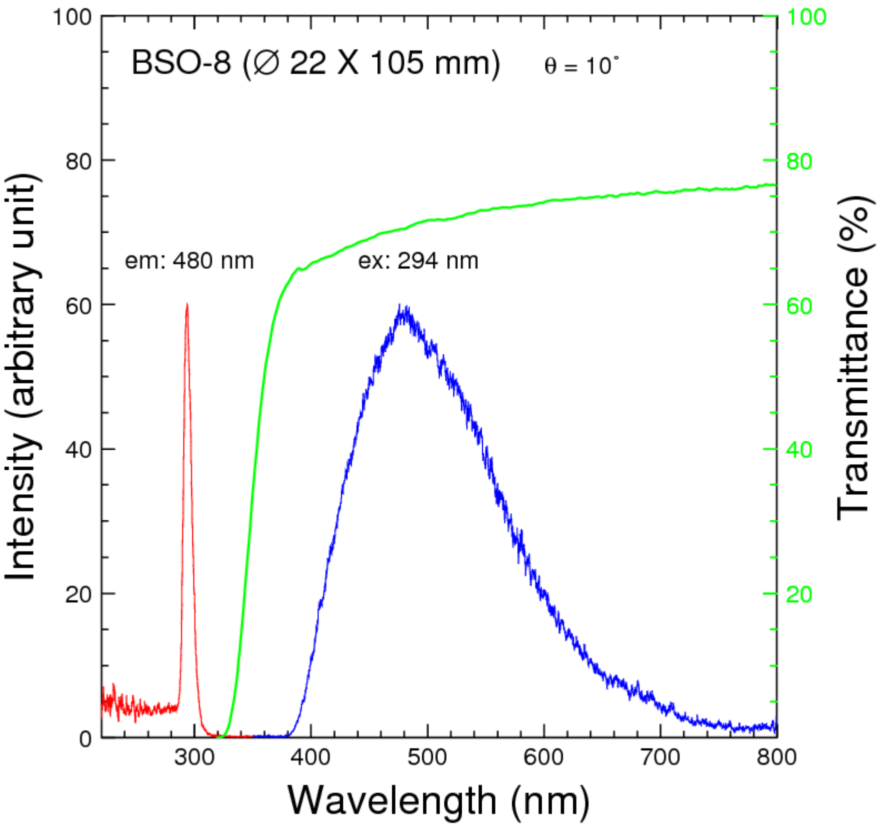


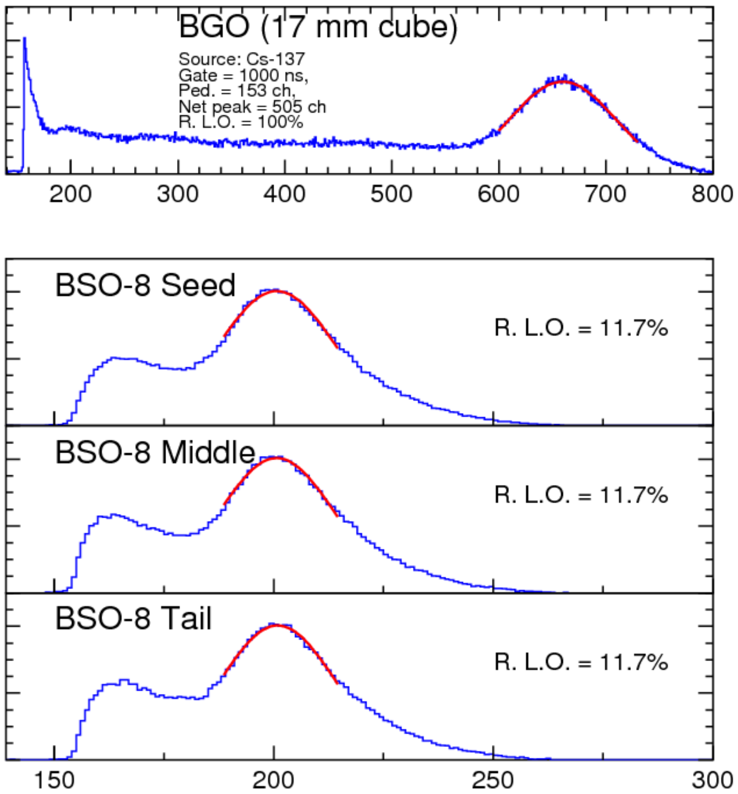


Large Size BSO Sample



A Φ22 X 105 mm BSO crystal from Yuan Hui, SIC, shows good transparency and longitudinal uniformity.





Crystal Calorimeter Summary

- Bright, fast and radiation hard LSO/LYSO crystals may be used for a total absorption ECAL, as well as a sampling ECAL where resolution at low energies is less crucial, such as the CMS forward calorimeter at HL-LHC
- Crystal calorimeters with more than ten times faster rate/timing capability may be achieved at the project X by using the sub-ns decay time of the BaF_2 fast scintillation component.
- 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 materials, such as crystals, ceramics and glasses, may play important role in future HEP experiments.

Transparent Ceramic Scintillators for LHC Calorimetry

January 2013

N.J. Cherepy, Z.M. Seeley, S.A. Payne

Lawrence Livermore National Laboratory, Livermore, CA 94550

Thanks for discussions: Ren-Yuan Zhu, Roger Rusack, Sarah Eno, Erik Ramberg, Francesca Nessi-Tedaldi

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Transparent Ceramics: A route to high-melting point oxide polycrystalline optical materials for a range of applications

Lenses

"Lumicera" -Ba/Sr titanate (Murata)

Fig. (2). Transparent ceramic lenses from Murata Manufacturing Co., Ltd (LUMICERA™) (courtesy of Murata Manufacturing Co., Ltd.) [31].

Laser Media

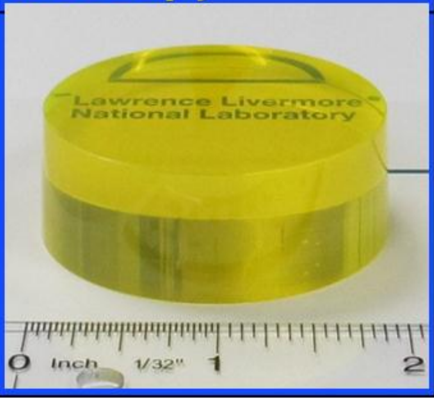
Nd:YAG, Yb:Sc_2O_3, Yb:Y_2O_3 (Baikowski / Konoshima)

Transparent Armor

Spinel, AlON (Surmet and others)

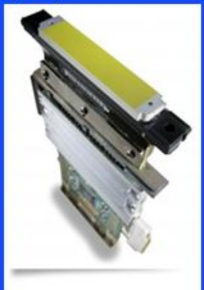
Gamma Spectroscopy

Garnets -
Ce-doped GYGAG and GYSAG
(discovered & fabricated at LLNL)

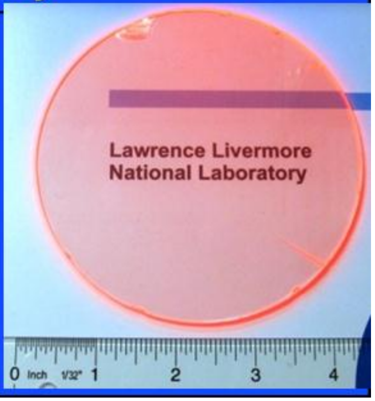


Radiography

Garnets- "Gemstone" (GE)
Bixbyites-
"GLO" (LLNL)



GE's new garnet-based CT scintillator



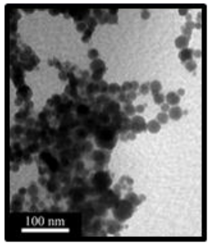
Advantages

- WIDE RANGE OF STRUCTURES POSSIBLE - Polycrystalline transparent ceramics are *sintered*, never melted, providing access to a wide range of oxide crystal structures that are not growable as single crystals
- NEAR NET SHAPE FABRICATION - Ability to form large plates, long rods, etc.
- LOW COST - Furnace costs low since sintering complete in <24 hrs

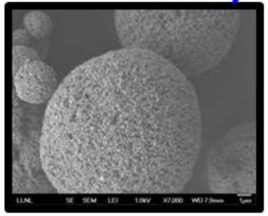
LLNL transparent ceramics fabrication facility is unique for high-throughput sample production and optics fabrication up to 10” diameter

Powder Formulation

Flame Spray Pyrolysis reactor for powder production



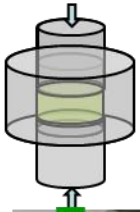
Nanoparticles



Powder-organic dispersion utilizing spray dryer methods

Densification

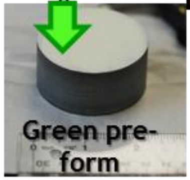
Pressing



Green pre-form

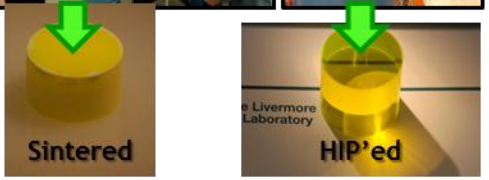
Sintering

Vacuum



Sintered

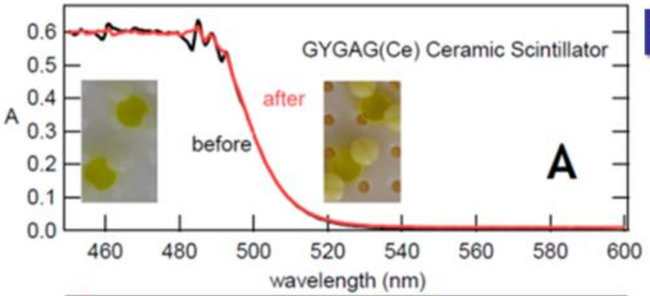
Hot Isostatic Pressing

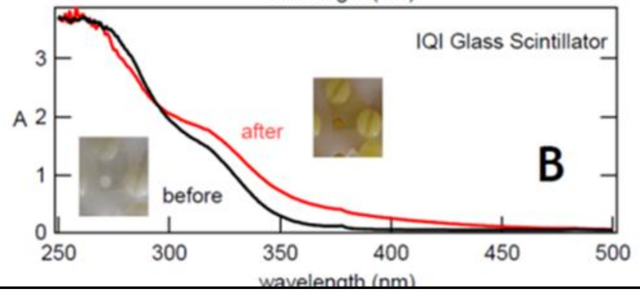


HIP’ed

Industrial Hot Isostatic Press, 66” diameter

Radiation Hardness





Initial study shows
(A) GYGAG(Ce) transparent ceramic more resistant to darkening than
(B) Standard glass scintillator

Many options for *dense* transparent ceramics with *fast* decay, *high* radiation damage threshold, *low* n_o activation, and *formable* in large size at low cost

Crystal structure	Scintillator	ρ (g/cm3)	Z_{max}	λ_{max} (nm)	Decay (ns)	Light Yield (Ph/MeV)	511 keV Rad. Length (cm)
Must be cubic	Ideal	>8	<72	~450	<25	>8,000	0.9
	Acceptable	>5	<72	>340	<50	>400	<2.5
GARNET	$A_3B_5O_{12}$(Ce) : A = Gd, Lu, Y B = Al, Ga, Sc	5.8 - 6.8	71	530	20-80	up to 60,000	1 -2
PEROVSKITE	ABO_3(Ce) : A = Sr, Ba B = Ti, Zr, Hf	6 - 8	72	400	50	up to 10,000	0.7-2
BIXBYITE	A_2O_3 (undoped) : A = Gd, La, Y, Lu, Ce	5 - 9.4	71	400-600	30	up to 20,000	0.73-2.3
FLUORITE	AO_2 (undoped) : A = Zr, Hf, Ce	5.7 - 8	72	400-600	30	no data available	0.7-2

Proposed project plan for transparent ceramic calorimetry materials:

- **Analyze neutron activation & fission cross-sections of elements; identify cubic oxide candidate structures**
- **Fabricate small <0.1 cm^3 samples - identify those formable with high transparency**
- **Test optical and scintillation properties; radiation hardness**
- **Optimize fabrication methods**
- **Scale up best candidates, send to partners for testing**
- **Identify and fine-tune the processing of best candidate**
- **Transfer technology to industrial partner for production**

2nd Workshop for the HHCAL

May 9, 2010, Beijing: http://indico.ihep.ac.cn/conferenceTimeTable.py?confId=1470

1) **HHCAL and General Requirement:**

Gene Fisk, FNAL: "Fermilab's History in the Development of Crystals, Glasses and Si Detector Readout for Calorimetry"
Adam Para, FNAL: "Scintillating Materials for Homogeneous Hadron Calorimetry"
Steve Derenzo, LBL: "Search for Scintillating Glasses and Crystals for Hadron Calorimetry"
Paul Lecoq, CERN: "A CERN Contribution to the Dual Readout Calorimeter Concept"

2) **Materials for HHCAL (I) :**

Alex Gektin, SCI: "Crystal Development for HHCAL: Physics and Technological Limits"
Liyuan Zhang, Caltech: "Search for Scintillation in Doped Lead Fluoride for the HHCAL Detector Concept"
Guohao Ren, SIC: "Development of Halide Scintillation Crystals for the HHCAL Detector Concept "
Hui Yuan, SIC: "BSO Crystals Development with the Modified Multi-crucible Bridgman Method for the HHCAL Detector Concept"

3) **Materials for the HHCAL (II) followed by discussions**

Mingrong Zhang, BGRI: "R&D on Scintillation Crystals and Special Glasses at BGRI"
Tiachi Zhao, U Washington/IHEP and Ningbo University: " Study of Dense Scintillating Glass Samples"
Jing Tai Zhao, SIC: "Status of Scintillating Ceramics and Glasses at SIC and Their Potential Applications for the HHCAL Detector Concept"
Richard, Wigmans, Texas Tech University: "Some thoughts about homogeneous dual-readout calorimeters"

3rd Workshop for the HHCAL

October 31, 2010, Knoxville: http://www.nss-mic.org/2010/program/ListProgram.asp?session=HC1,2,3,4

1. **A. Para,** Prospects for High Resolution Hadron Calorimetry
2. **G. Mavromanolakis ,** Studies on Dual Readout Calorimetry with Meta-Crystals
3. **D. Groom,** Degradation of resolution in a homogeneous dual readout hadronic calorimeter
4. **S. Derenzo,** High-Throughput Synthesis and Measurement of Candidate Detector Materials for Homogeneous Hadronic Calorimeters
5. **M. Poulain,** Fluoride Glasses: State of Art and Prospects
6. **I. Dafinei,** High Density Fluoride Glasses, Possible Candidates for Homogeneous Hadron Calorimetry
7. **P. Hobson,** Prospects for Dense Glass Scintillators for Homogeneous Calorimeters
8. **G. Dosovitski,** Potential of Crystalline, Glass and Ceramic Scintillation Materials for Future Hadron Calorimetry
9. **Tianchi Zhao,** Study on Dense Scintillating Glasses
10. **Jin-tai Zhao,** BSO-Based Crystal and Glass Scintillators for Homogeneous Hadronic Calorimeter
11. **Guohao Ren,** Development of RE-Doped Cubic PbF2 and PbClF Crystals for HHCAL
12. **12, N. Cherepy,** Transparent Ceramic Scintillators for Hadron Calorimetry
13. **J. Dong,** Experimental Study of Large Area GEM
14. **H. Frisch,** The Development of Large-Area Flat-Panel Photodetectors with Correlated Space and Time Resolution