State of the Art Crystal Calorimetry for High Rate Intensity Frontier Experiments

Ren-Yuan Zhu

California Institute of Technology

August 2, 2013

Why Crystal Calorimeter in HEP?

- 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 and γ-pointing at the intensity frontier;**
  - Good jet mass resolution for future 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

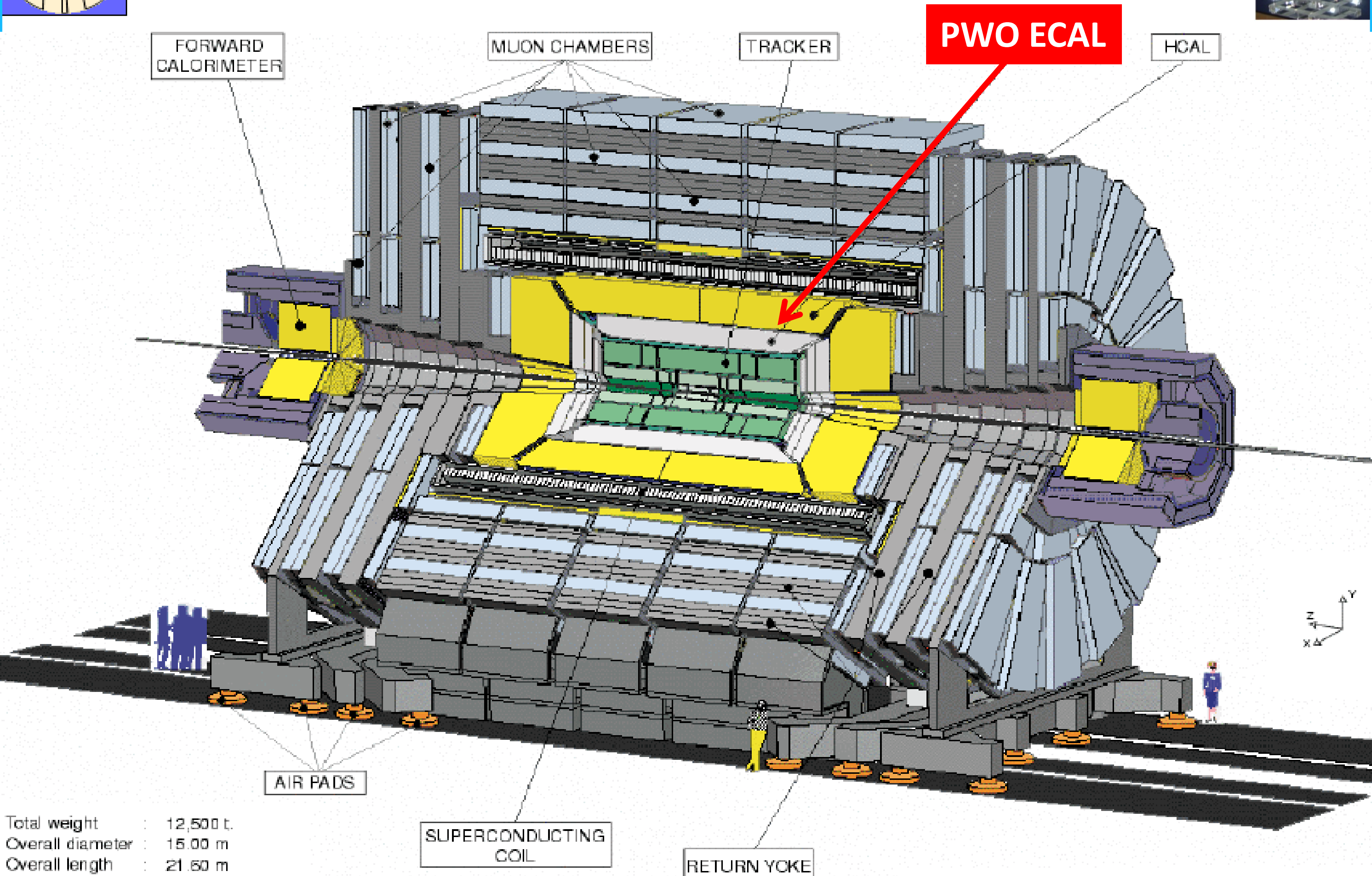
Future crystal calorimeters in HEP:

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

BaF_2 for fast calorimeters at the intensity frontier

PbF_2, PbFCl, BSO for Homogeneous HCAL

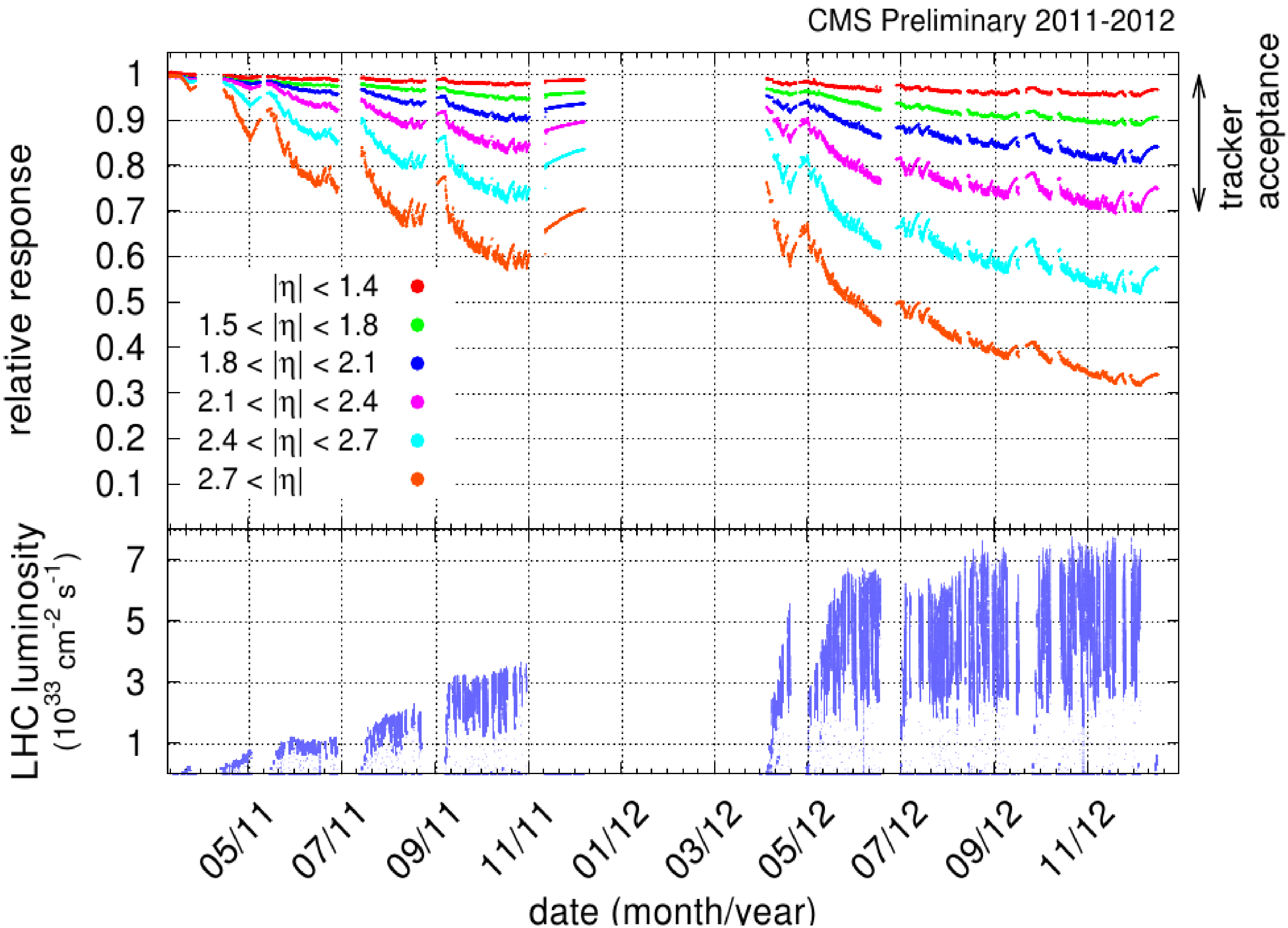
CMS Experiment at LHC



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 EM Damage

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

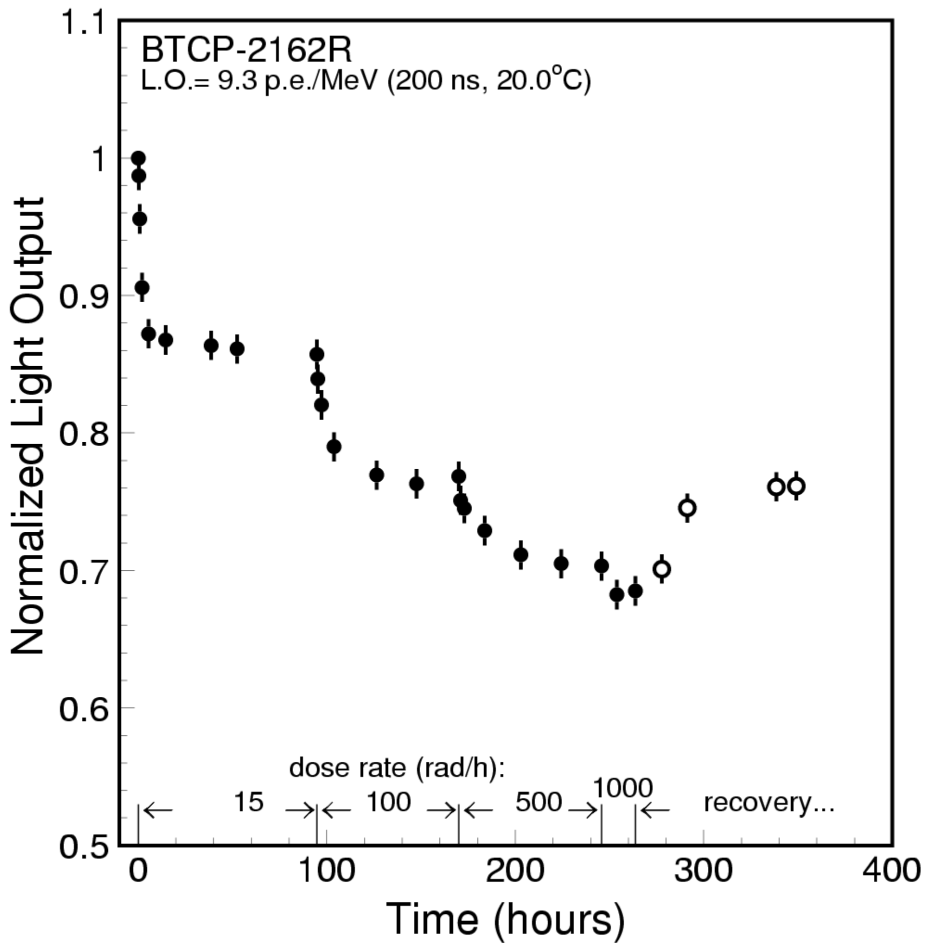
The LO reached equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

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

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

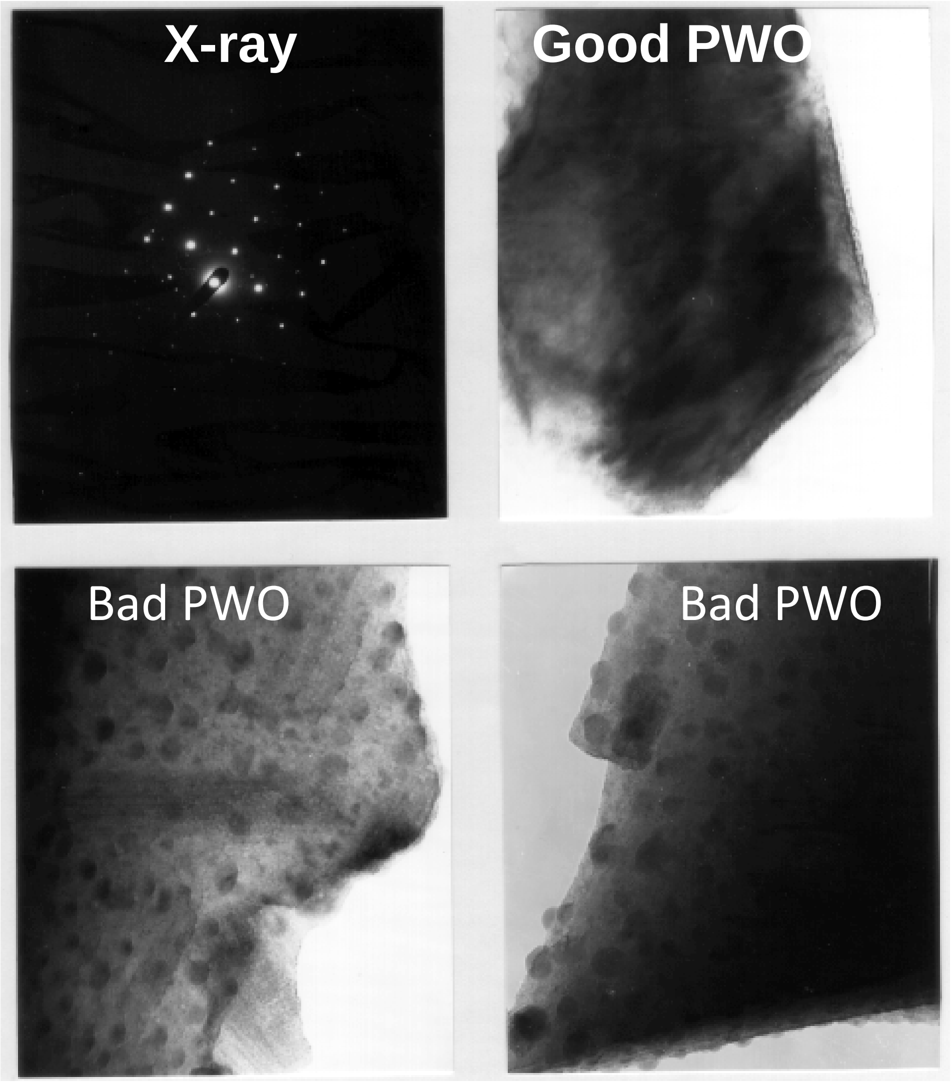
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of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

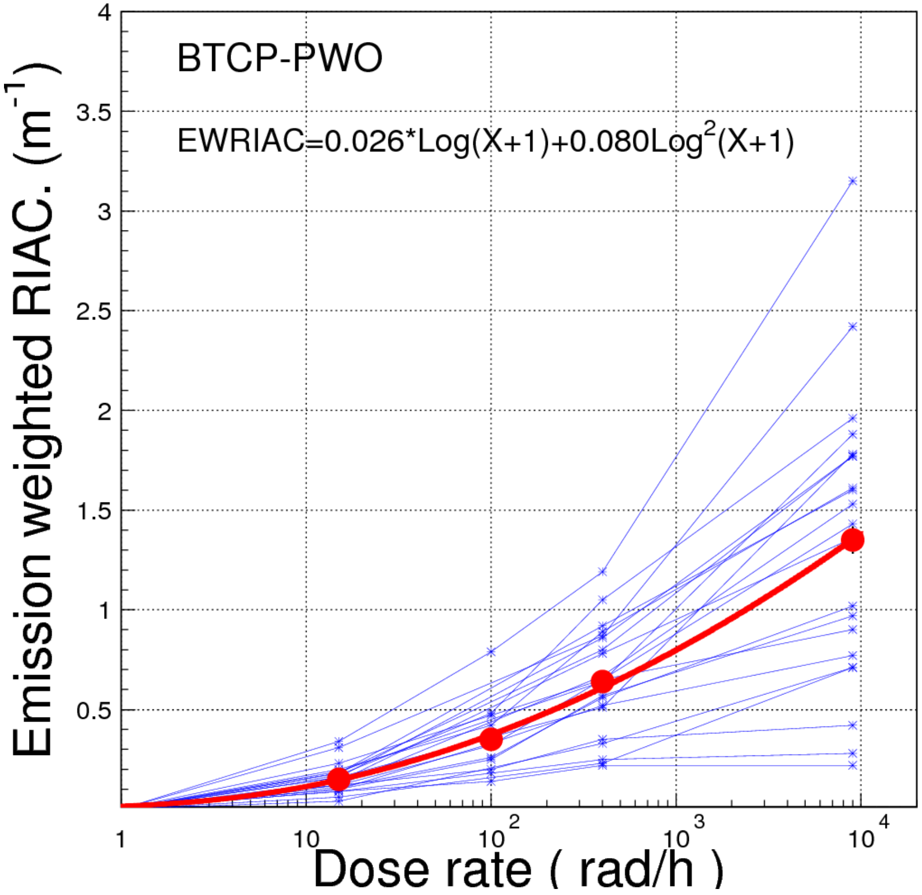
Element	Black Spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

The Same Sample after Oxygen Compensation

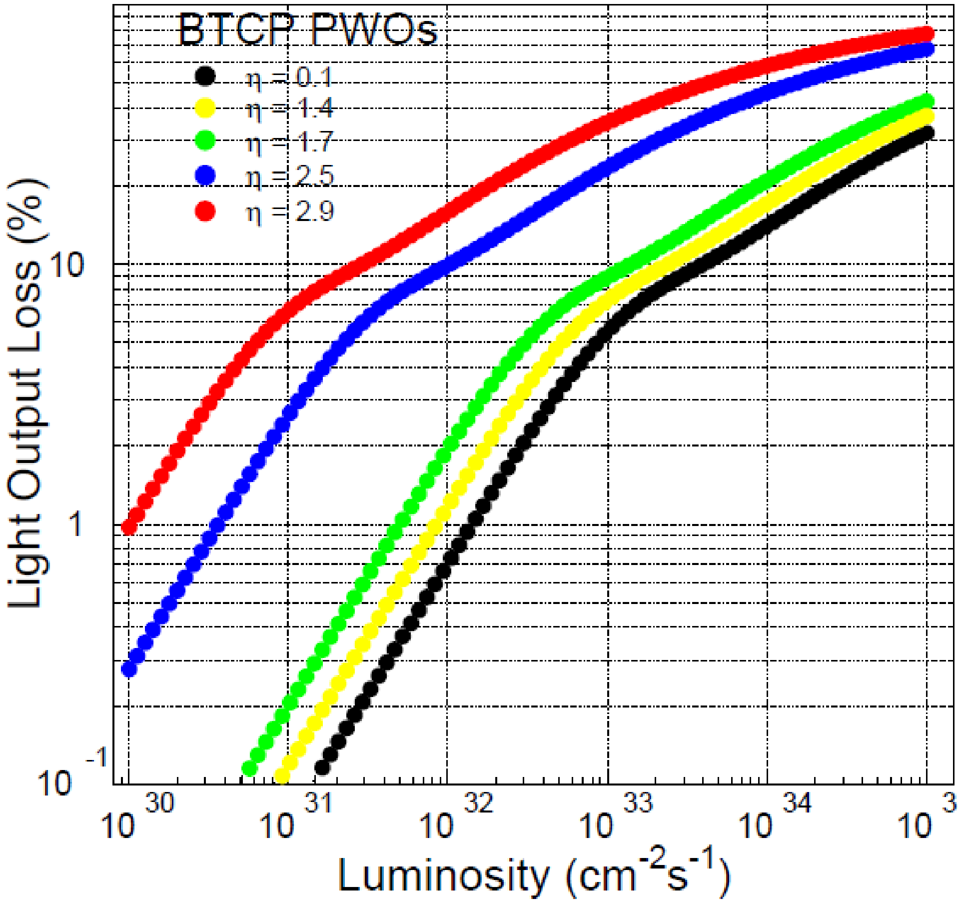
Element	$Point_1$	$Point_2$	$Point_3$	$Point_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

Prediction of PWO Radiation Damage

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



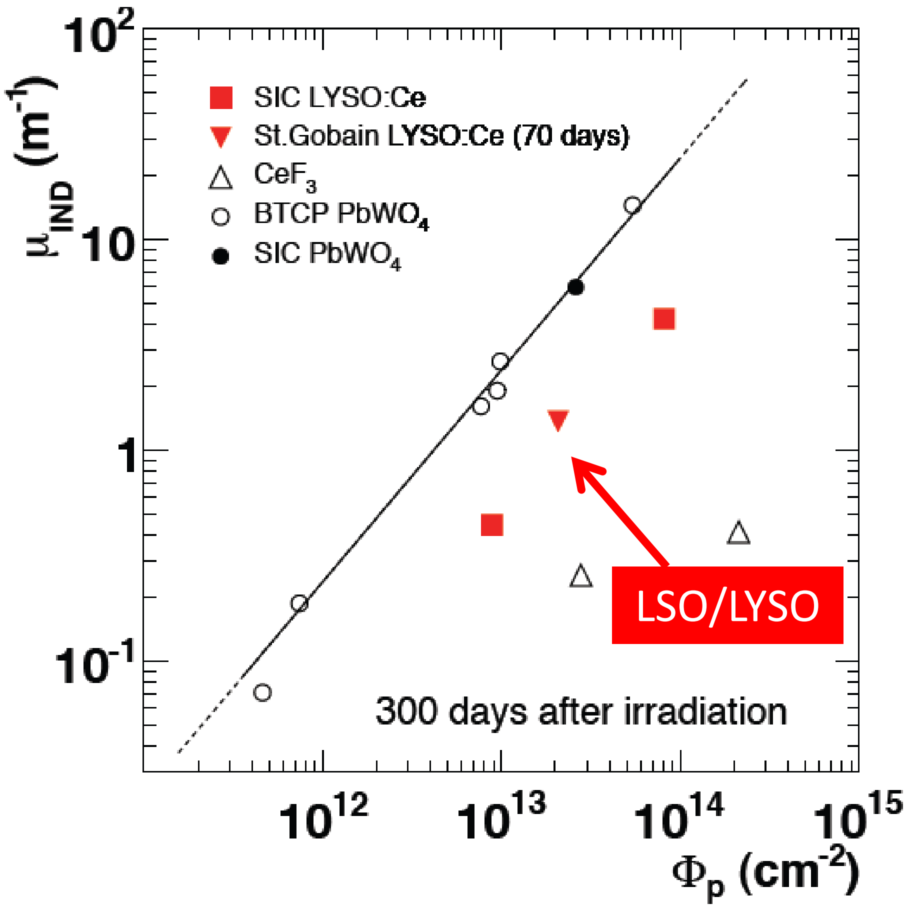
Talk in CMS Forward Calorimeter Taskforce Meeting, CERN, 12/10/2010



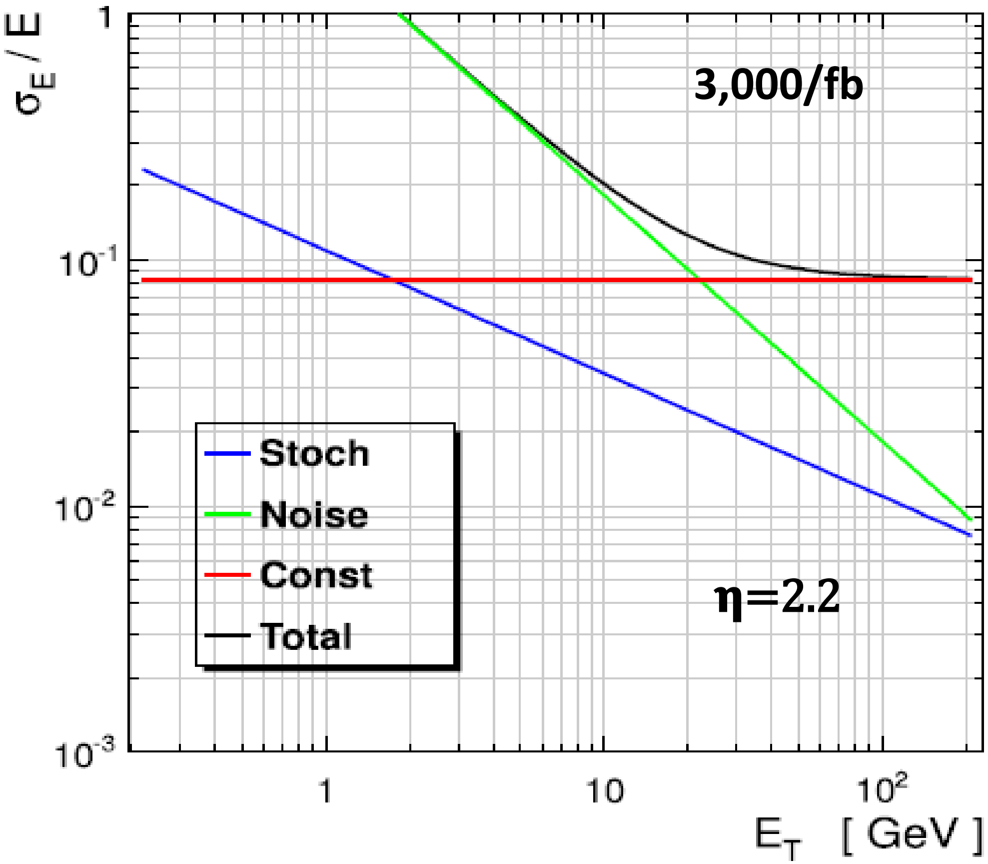
Predicted EM dose induced damage agrees well with the LHC data
In addition, there is cumulative hadron induced damage in PWO

Proton Induced Damage

G. Dissertori et al., IEEE NSS11, NP-5 S-228



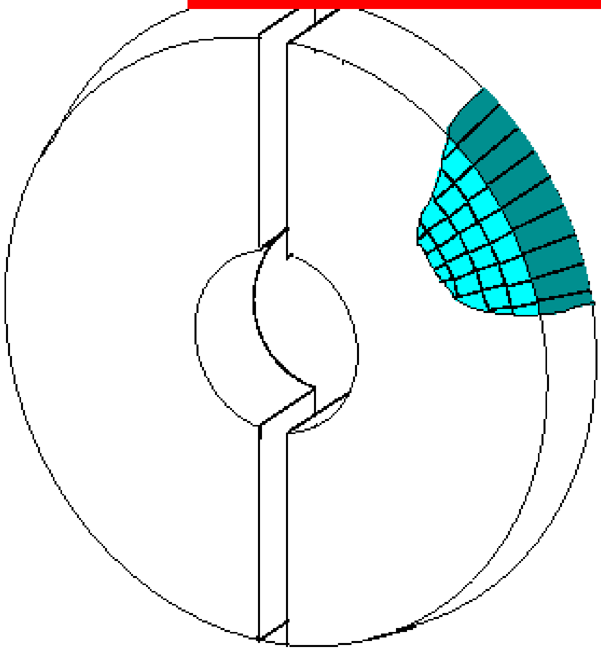
Expected resolution @ η = 2.2

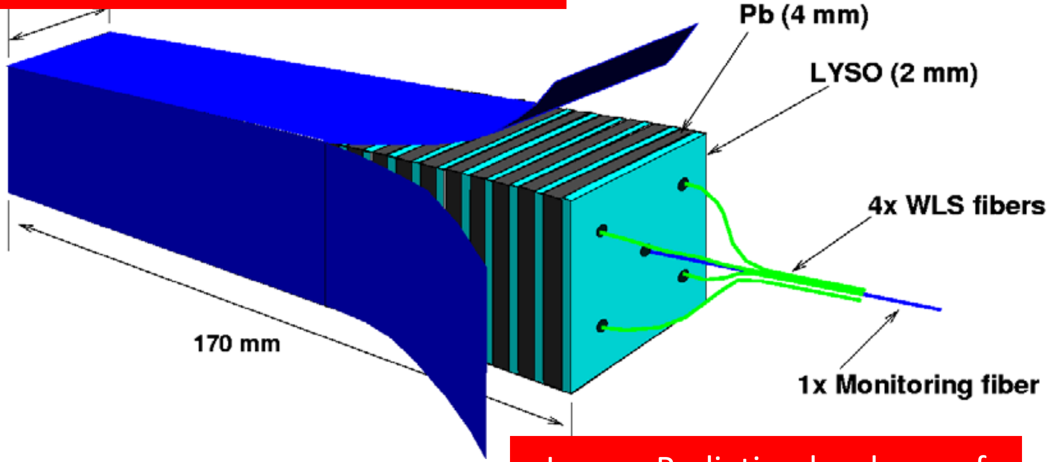


The proton induced absorption in LYSO is 1/5 of PWO
Radiation damage effect reduced by short light path

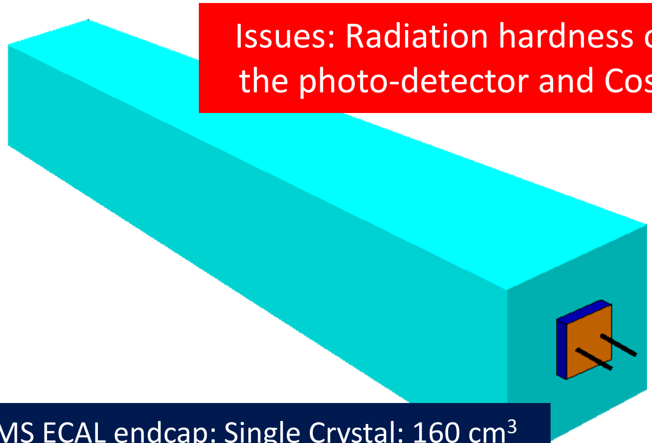
CMS Forward Calorimeter Upgrade

Talk in CMS FCAL Taskforce Meeting at CERN, 6/30/2011

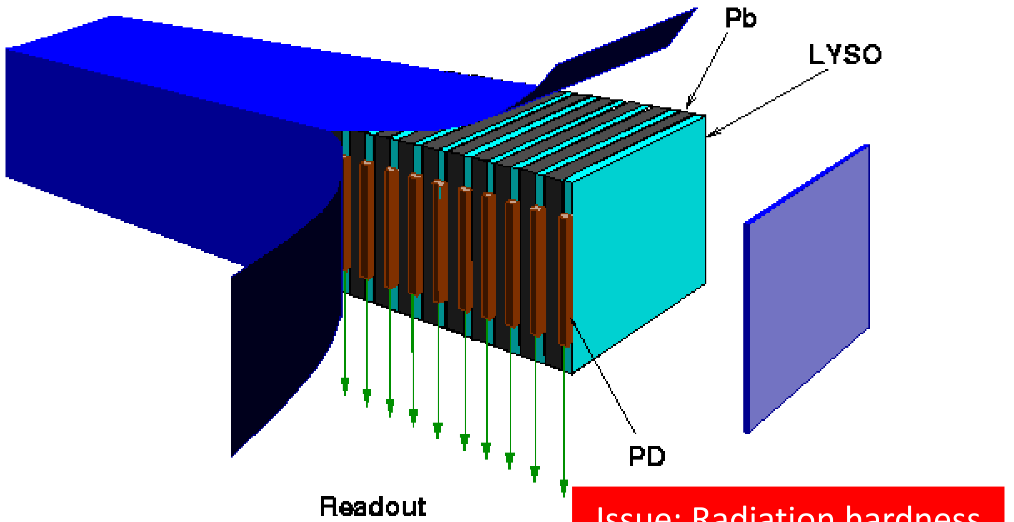




Issues: Radiation hardness of photo-detector and WLS fiber



Issues: Radiation hardness of the photo-detector and Cost

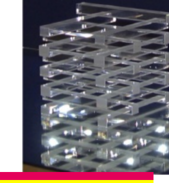


CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 3 m^3
Expected Crystal Cost: ~$90M@$30/cc

Crystal Cost: ~$18M@$30/cc

Issue: Radiation hardness of the photo-detector

LSO/LYSO: Mass Produced Crystals



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	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	Mu2e (SuperB) HL-LHC?	CMS ALICE PANDA	HHCAL?

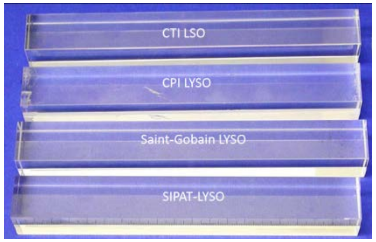
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

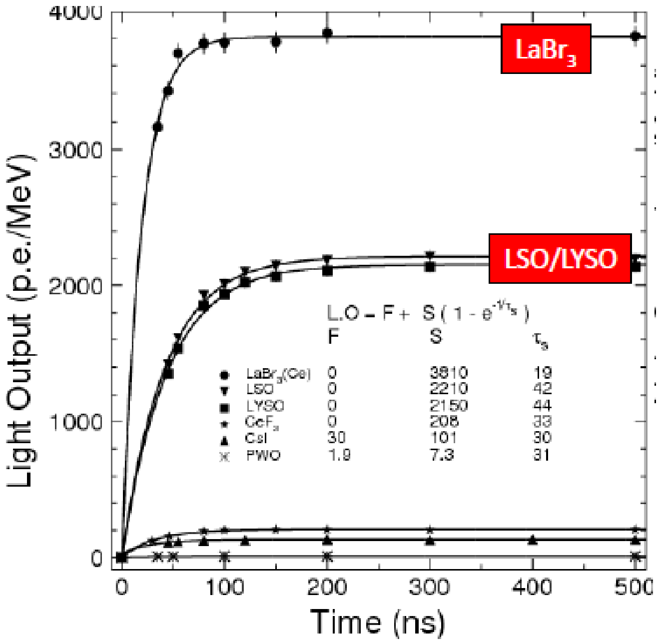
Bright, Fast & Rad Hard LSO/LYSO

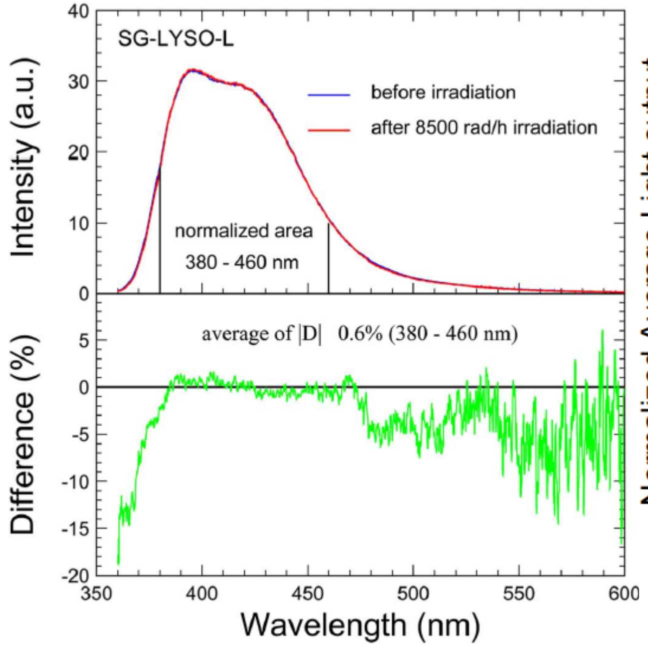
LSO/LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator. The longitudinal non-uniformity issue caused by tapered crystal geometry, self-absorption and cerium segregation can be addressed by roughening one side surface. The material is widely used in the medical industry.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

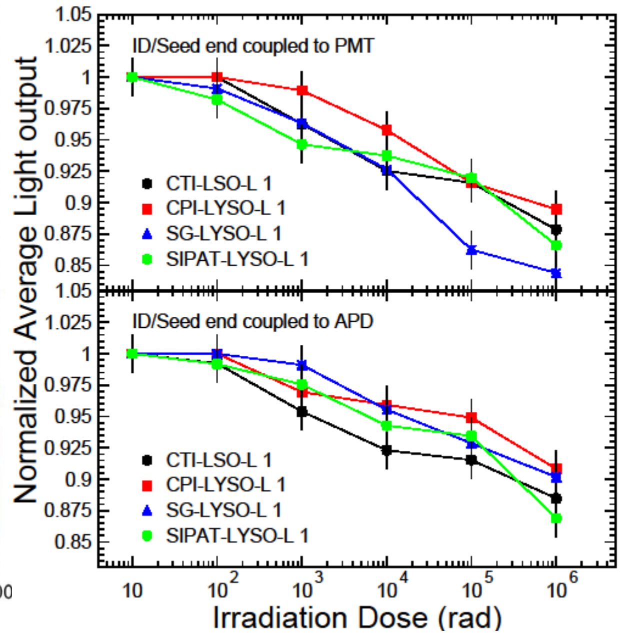
Bright & Fast

No scintillation damage from γ-rays
10% LO loss for 20 cm crystals@ 1 Mrad

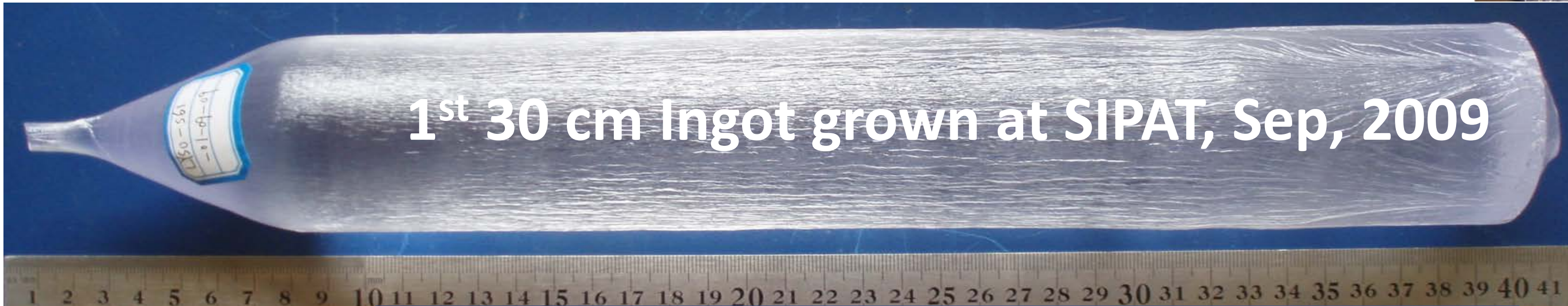


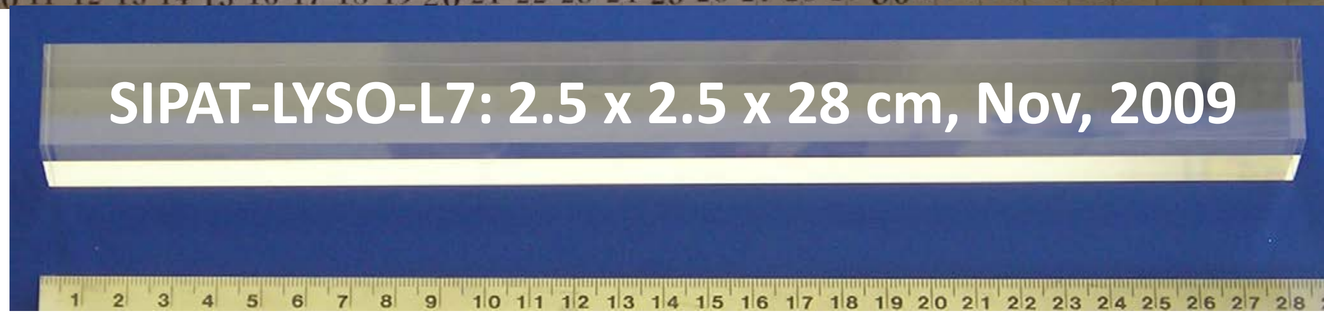


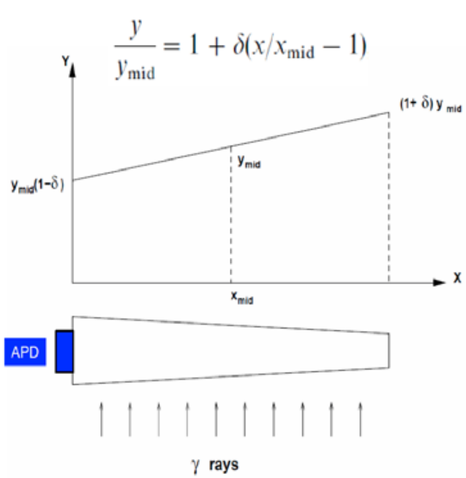


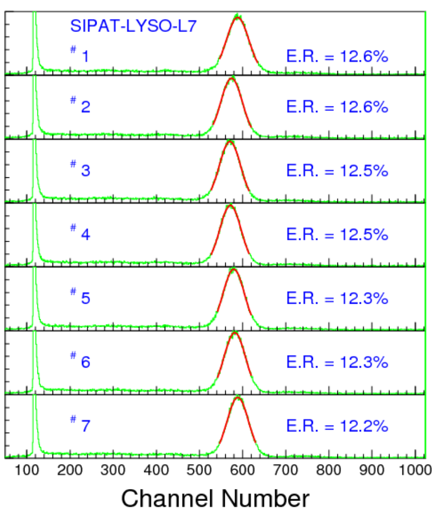


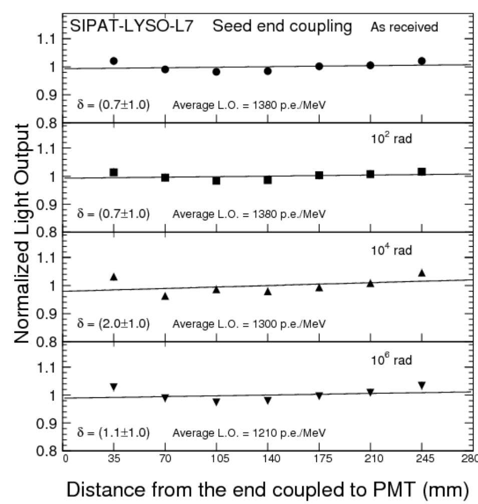
28 cm Long LYSO Under γ-Rays

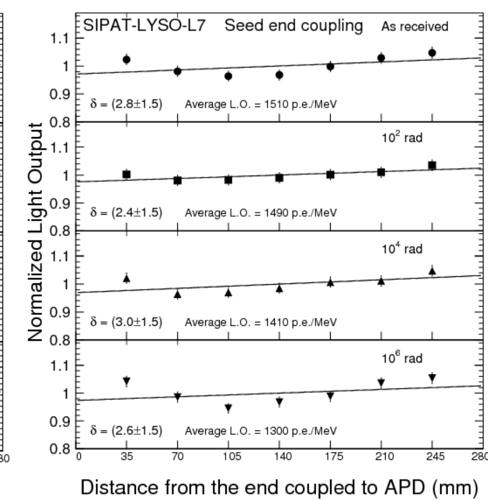




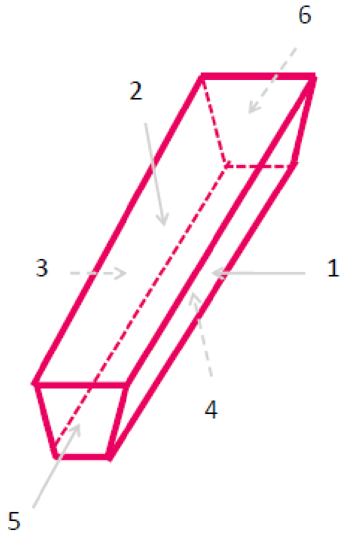


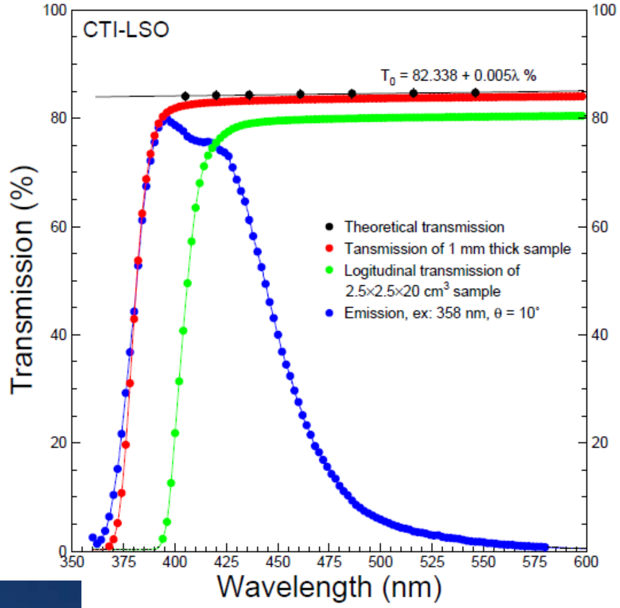


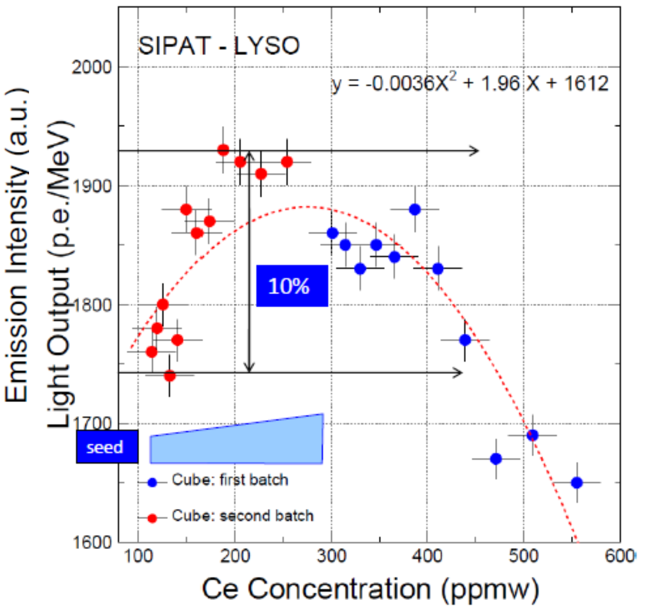


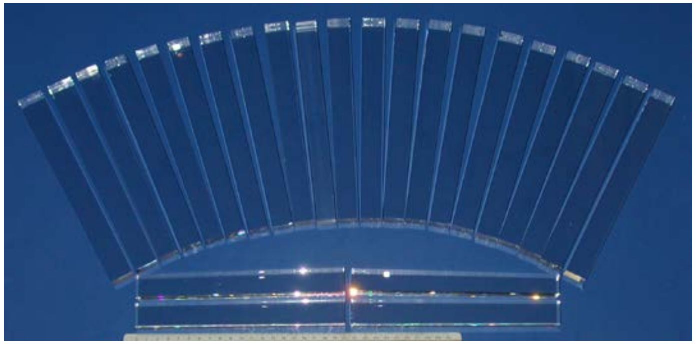


LYSO Light Response Uniformization

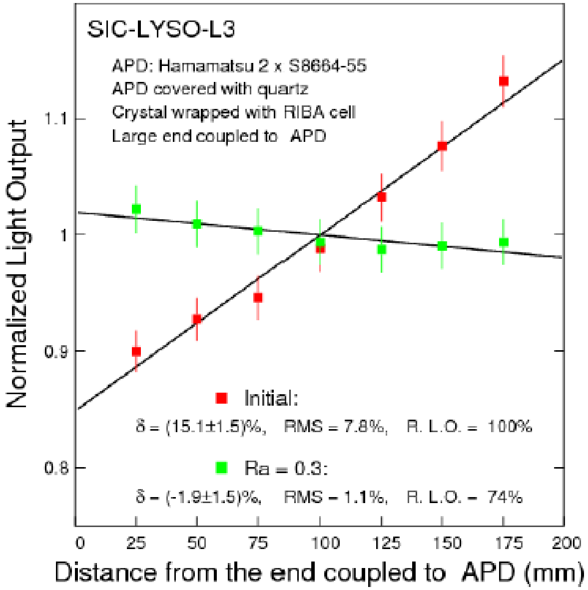


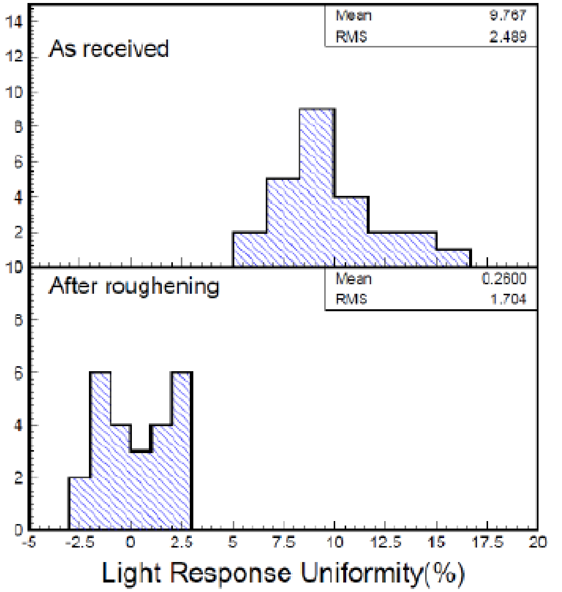






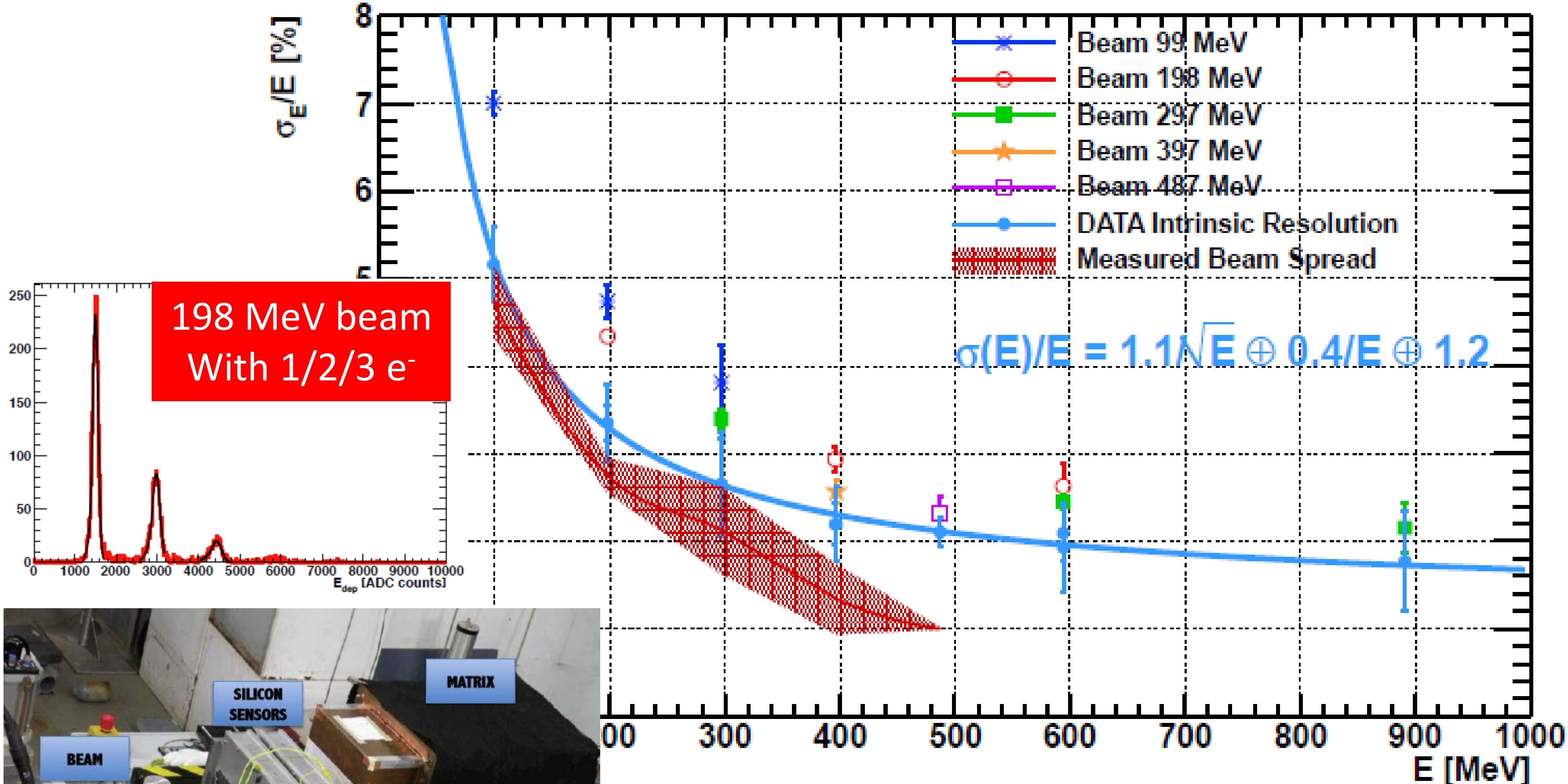
25 LYSO test beam crystals are uniformized to |δ| < 3% by roughening the smallest side surface.

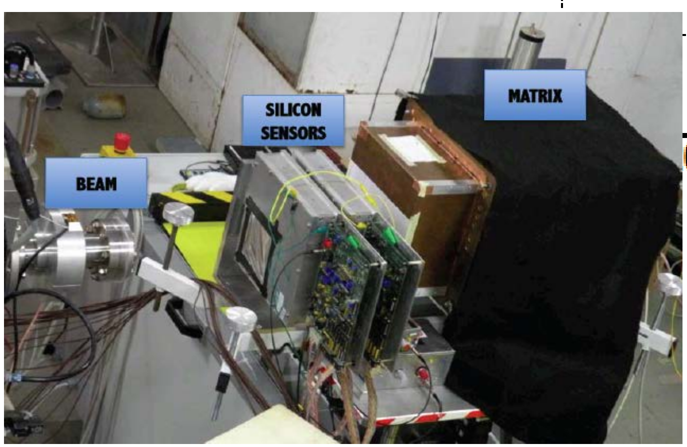




LYSO Test Beam Result

http://iopscience.iop.org/1742-6596/404/1/012065/pdf/1742-6596_404_1_012065.pdf

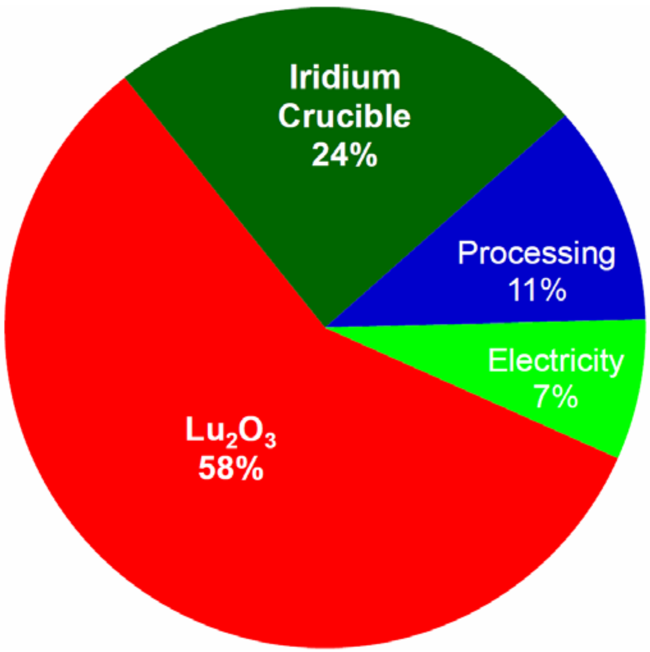




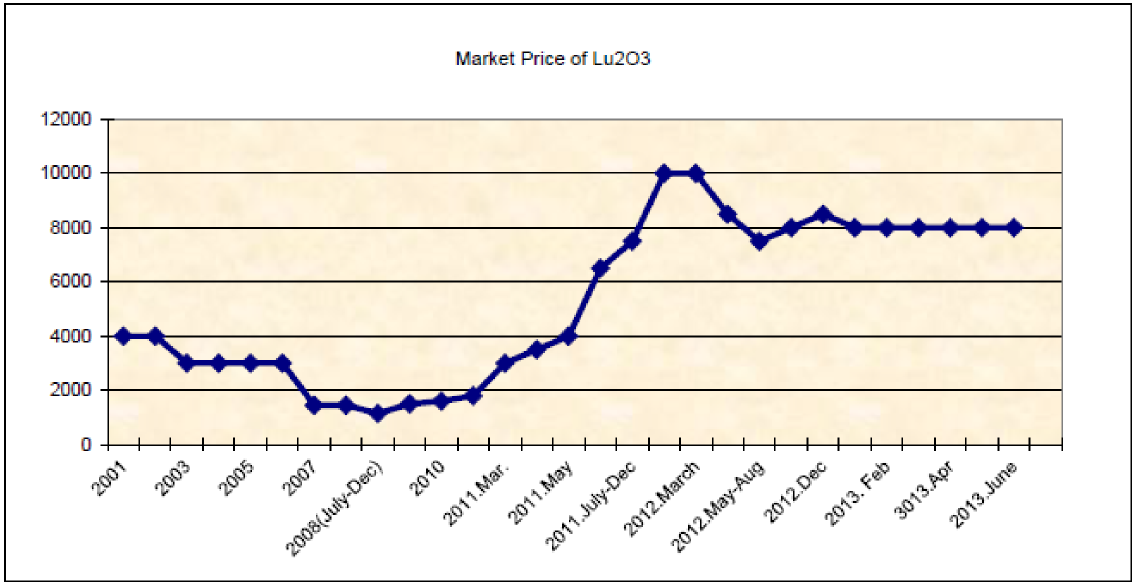
$$\frac{\sigma(E)}{E} = \frac{1.1}{\sqrt{E[GeV]}} \oplus \frac{0.4}{E[GeV]} \oplus 1.2\ \%$$

LSO/LYSO Crystal Cost

Crystal Cost Breakdown
For SuperB LYSO crystals
with $400/kg Lu_2O_3 price



The Lu_2O_3 price fluctuates up a lot since 2011, 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 in 2011 for SuperB crystals at $22-25/cc.

Long term Lu_2O_3 price is expected to go down when other vendors entering market. Mass production cost at $30/cc is expected.

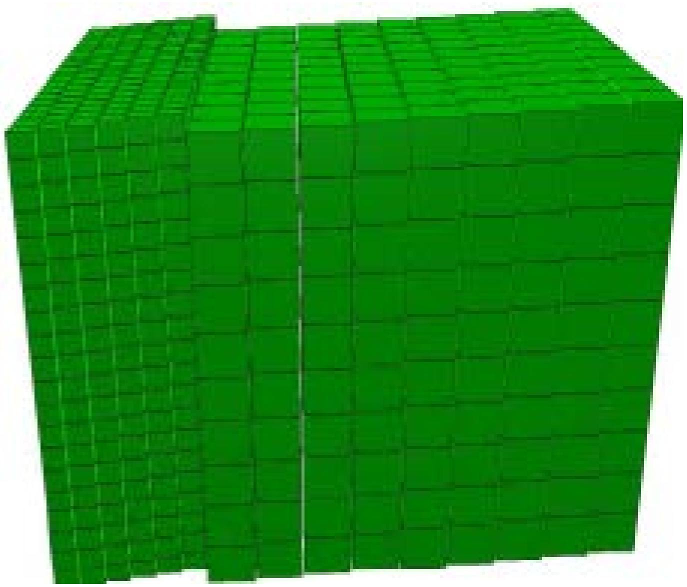
Intensity Frontier Calorimeter

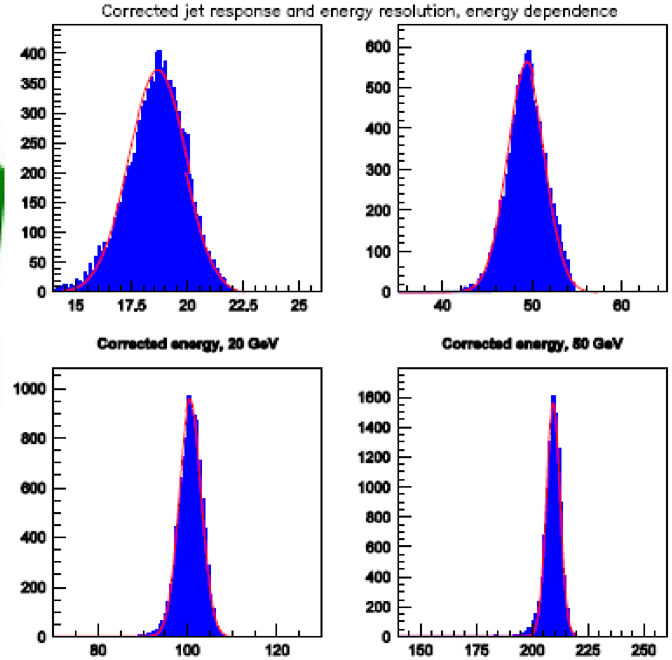
Excellent energy resolution: a total absorption crystal calorimeter.

Good photon pointing for π^0 reconstruction: a longitudinally segmented crystal calorimeter.

A fast calorimeter with ten times rate capability as compared to existing calorimeters: crystals with sub nanosecond scintillation decay time. The figure of merit is the light in the 1^{st} ns.

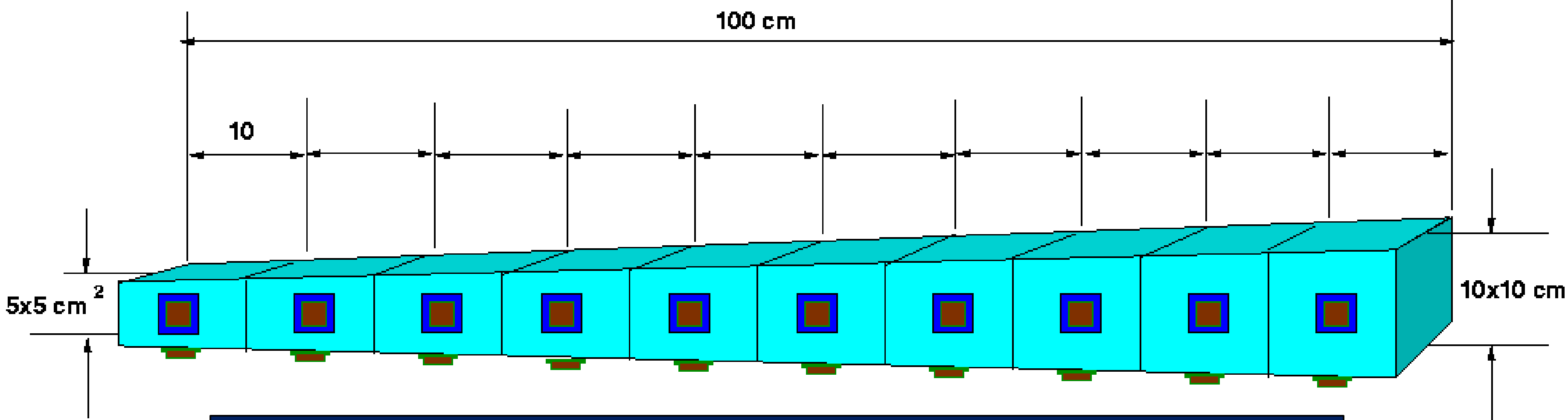
The HHCAL Detector Concept





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

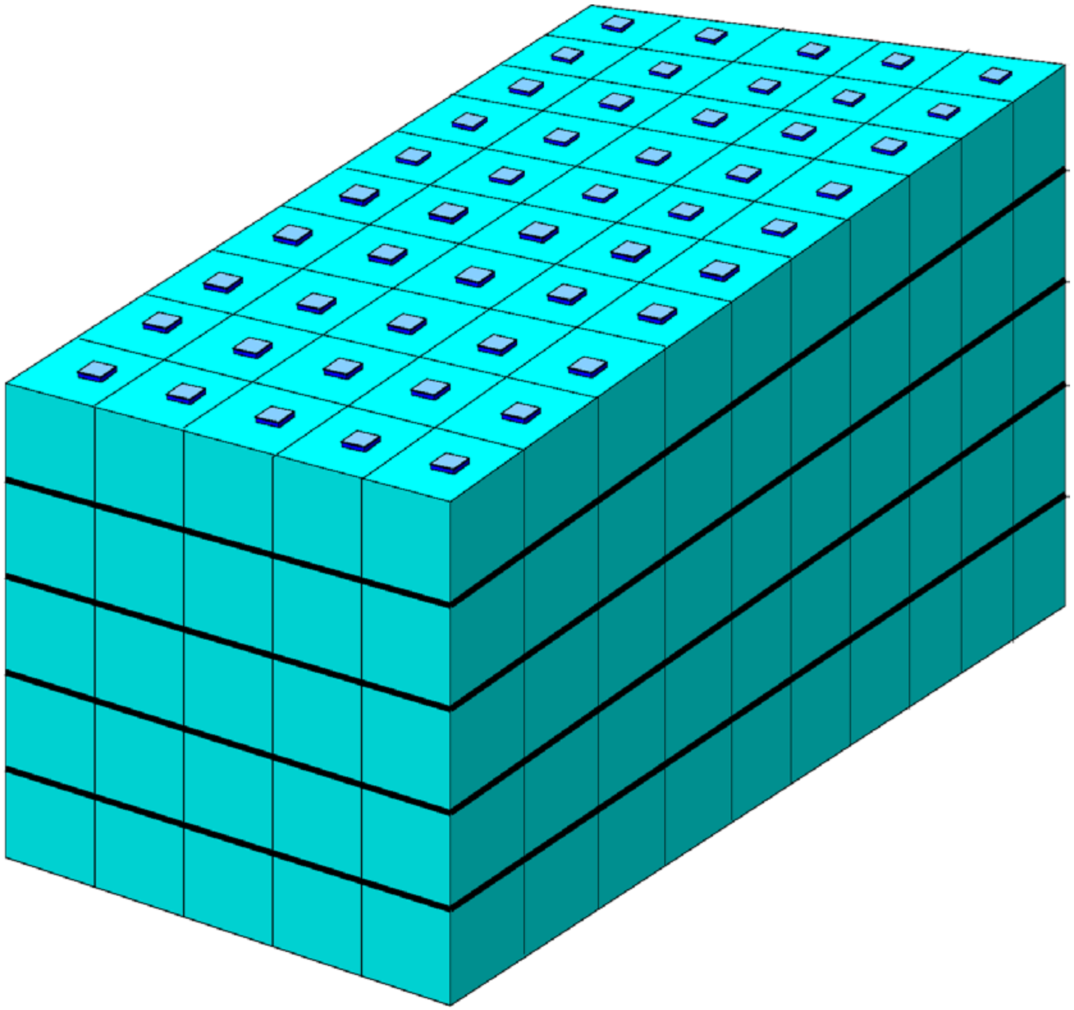
Cost !



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

A Long. Segmented Crystal ECAL

With compact readout devices embedded in the detector



May provide needed resolutions for energy, position and photon angle

Fast Crystal Scintillators

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

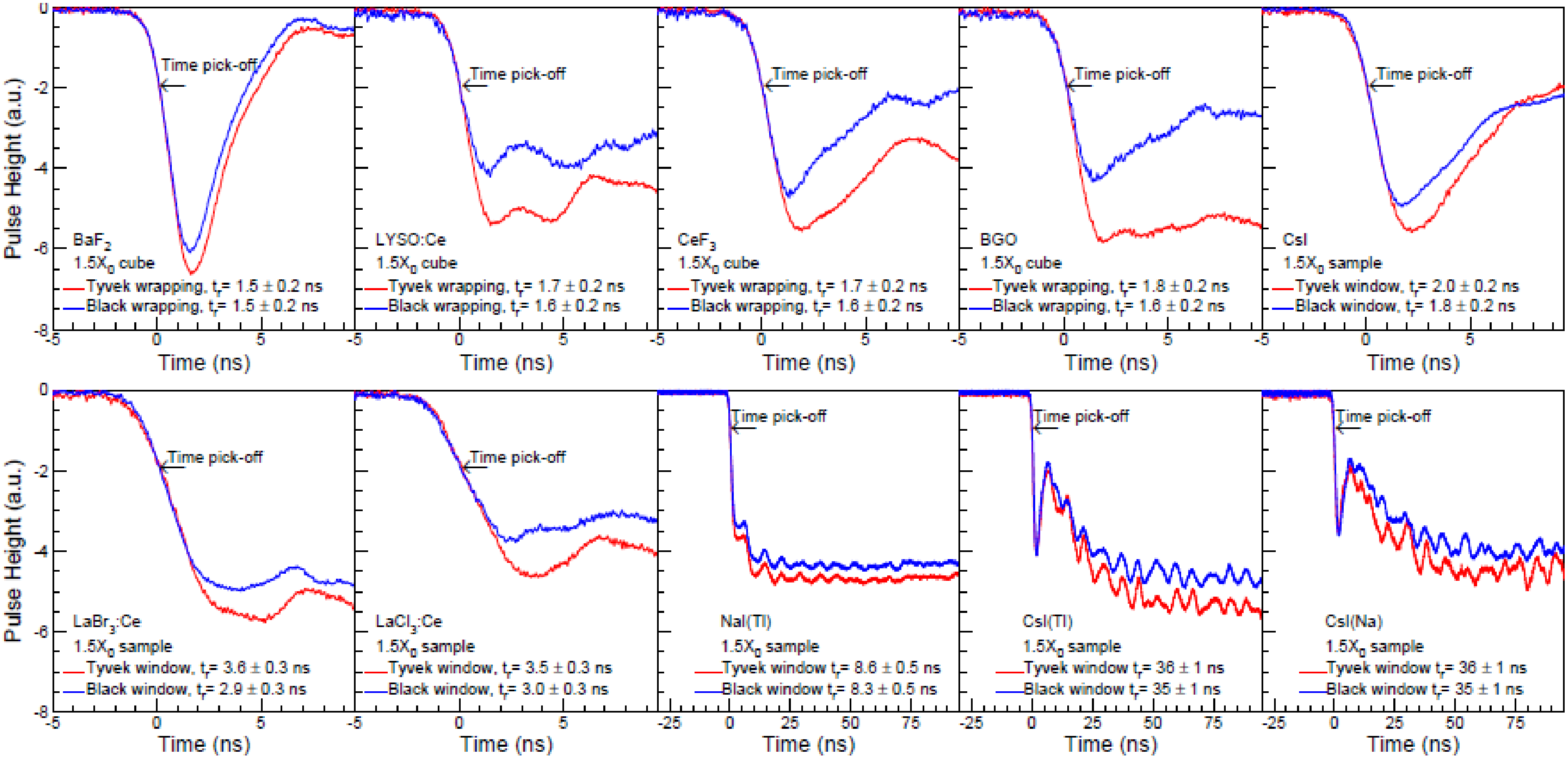
	LSO/LYSO	GSO	YSO[1]	CsI	BaF_2	CeF_3	$CeBr_3$[2]	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404)[3]
Density (g/cm^3)	7.40	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70#
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.70	1.96	2.81	1.88	42.54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

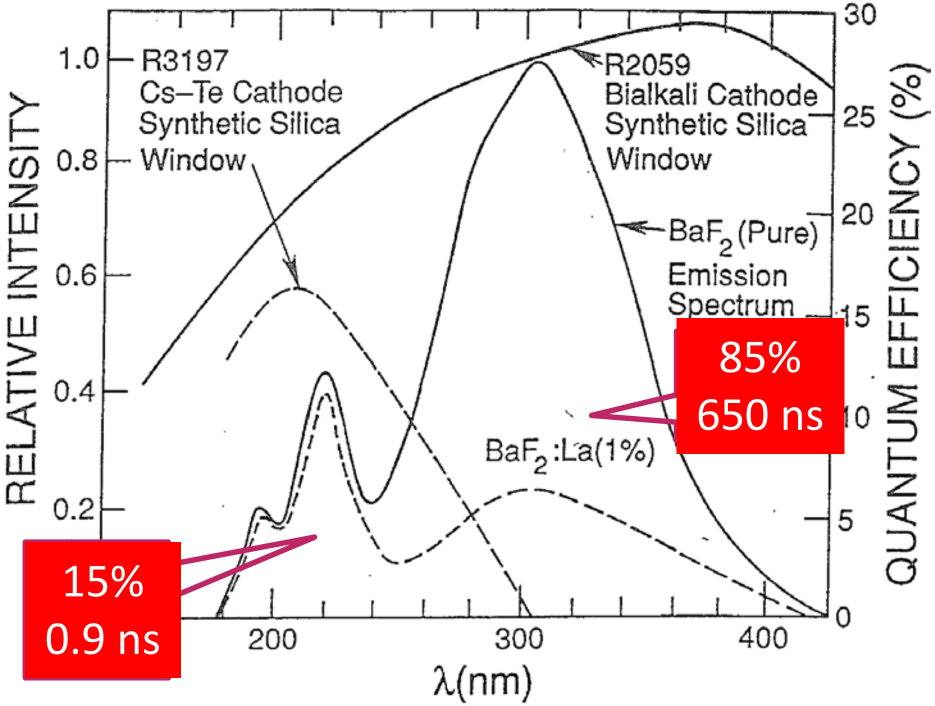
The best crystal scintillator for ultra-fast timing is BaF_2 and LSO(Ce/Ca) and LYSO(Ce). $LaBr_3$ is a material with high potential.

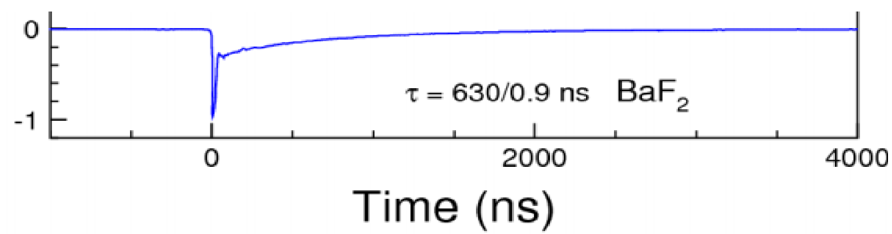
BaF_2 for Very Fast Calorimeter

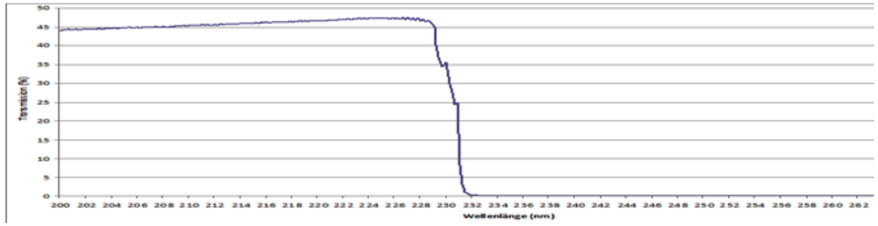
The fast component of BaF_2 crystals at 220 nm has a sub-ns decay time.

The slow component at 300 nm may be reduced by selective doping, such as La.

Spectroscopic selection of fast component may be achieved with solar blind photocathodes or filters.



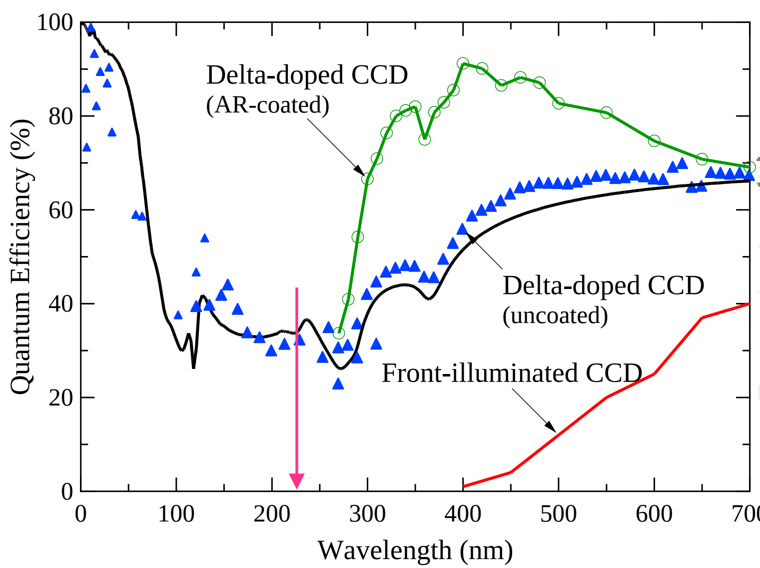




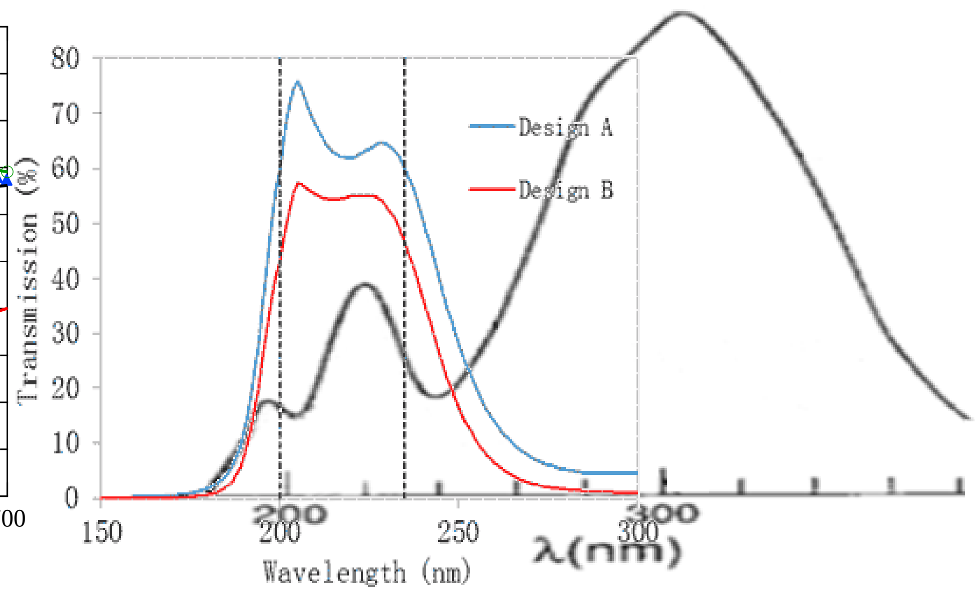
Development of a Novel Photo-sensor

Caltech/JPL are collaborating on development of a large area (10x10mm) APD with 40-50% QE at 220 nm that includes an integrated band-pass interference filter to reduce 330 nm response by orders of magnitude

~~CCD~~ APD spectral response

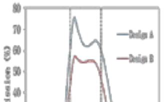


Interference filter response



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

David Hitlin



Development Status

– ADR proposal to DOE for work on BaF_2/APDs in 2012 was not funded

– Work on the APD initiated at JPL with internal seed funding

- Two stage development
  - » Phase I: Demonstrate extended UV response of APD
  - » Phase II: Integrate the interference filter

– Restart BaF_2 studies (depends on funding)

- Radiation hardness of modern samples against γ-rays, neutrons and charged hadrons.
- Selective doping , e.g. La, to reduce the slow component

Crystal Calorimeter Summary

- **Stable crystal calorimeter with good e/γ resolution may be achieved for CMS forward calorimeter upgrade at the HL-LHC by using blight, fast and radiation hard LSO/LYSO crystals.**
- **Longitudinal segmented crystal calorimeters with more than ten times faster rate/timing capability may be achieved for HEP experiments at the intensity frontier by using the sub-ns decay time of BaF_2.**
- **Homogeneous hadron calorimeter with good jet mass resolution may be achieved at future lepton colliders by reading both Cherenkov and scintillation light for PbF_2, PbFCl and BSO.**
- **Novel materials, such as crystals, ceramics and glasses, may play important role in future HEP experiments.**

$YAlO_3$:Yb

Fast (0.87/2.2 ns) scintillation found in YAP:Yb with low light output

M. Nikl et al, Appl. Phys. Lett., Vol. 84, No. 6,

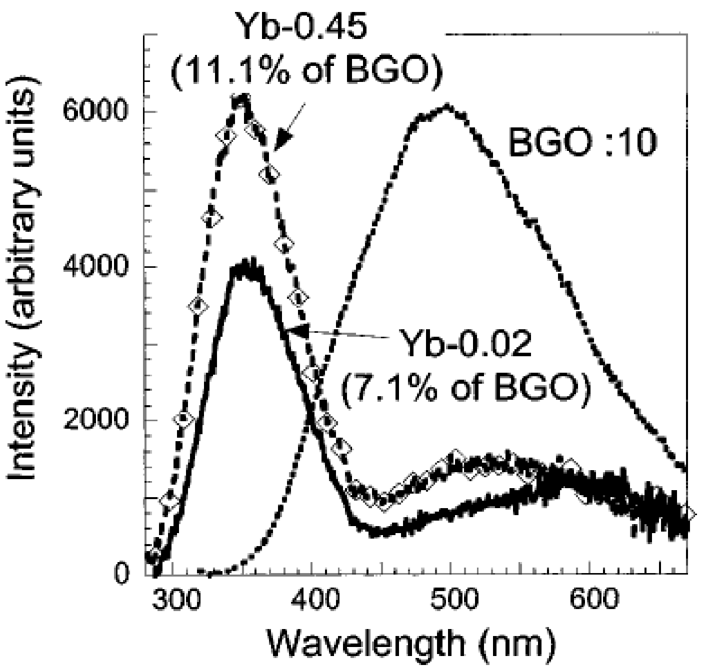


FIG. 1. Radioluminescence of Yb:YAP and BGO at RT. Excitation by x-ray tube, 35 kV, 15 mA. Quantitative comparison with respect to BGO is provided by the calculation of spectra integrals.

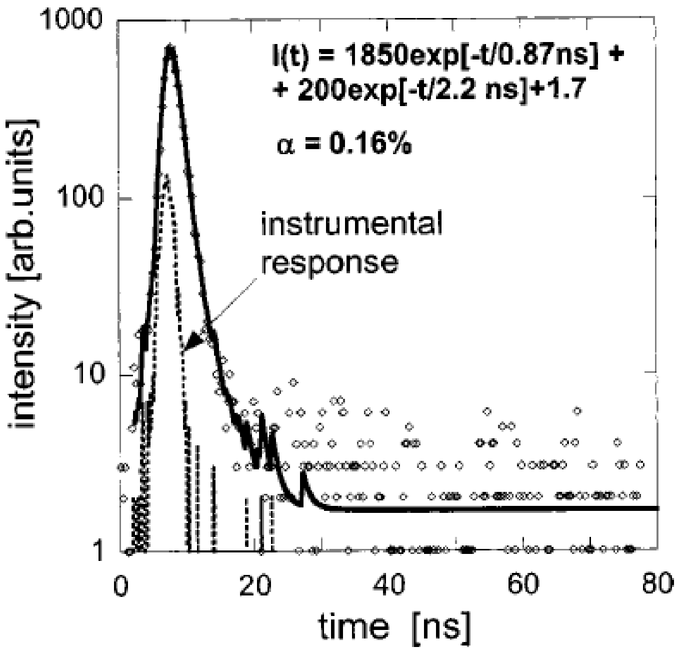


FIG. 3. Scintillation decay of Yb-0.45 at room temperature. Excitation by 511 keV photons of ^{22}Na radioisotope, spectrally unresolved. The two-exponential approximation is given by a solid line: convolution of the two-exponential function in the figure with the instrumental response given by a dashed line. The coefficient alpha related to the relative amplitude of the superslow components calculated according Ref. 12 is also given.