Fast Crystals for Forward Calorimeter Upgrade at HL-LHC

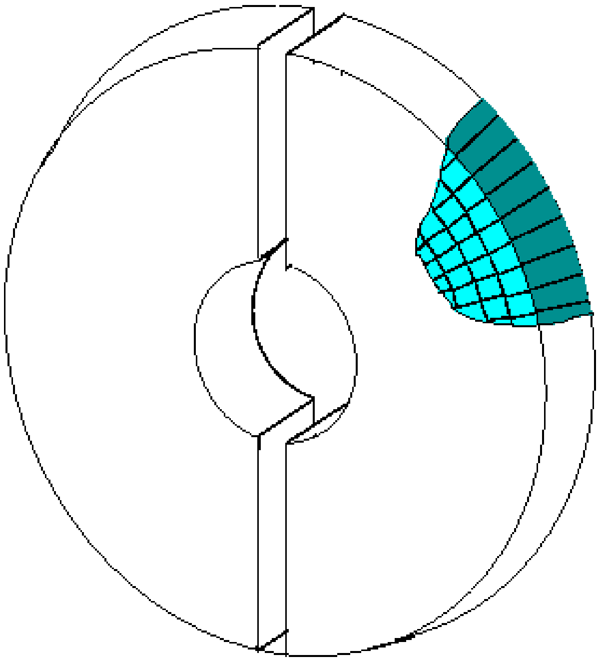
Ren-Yuan Zhu

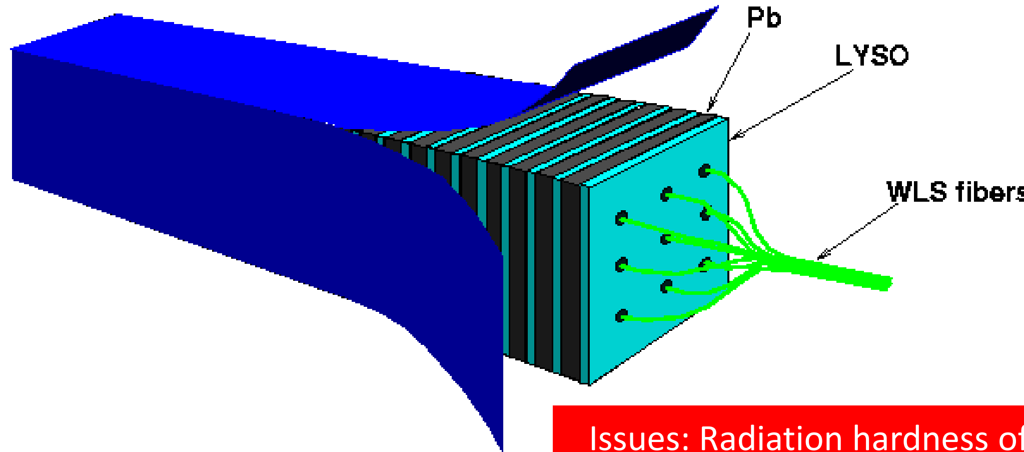
California Institute of Technology

June 27, 2012

Talk given at CMS Forward Calorimetry Taskforce Meeting, CERN

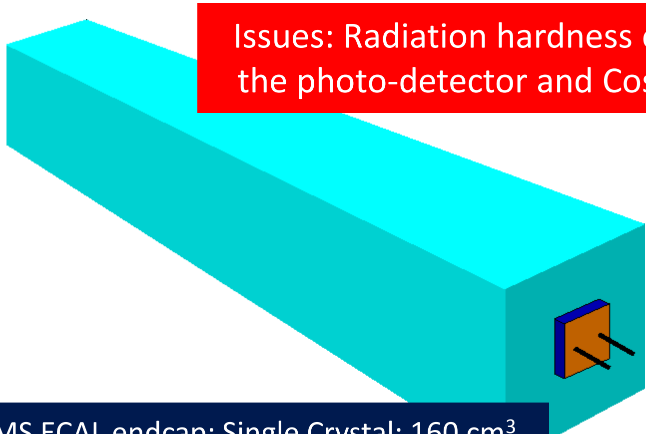
Forward Calorimeter Upgrade Options

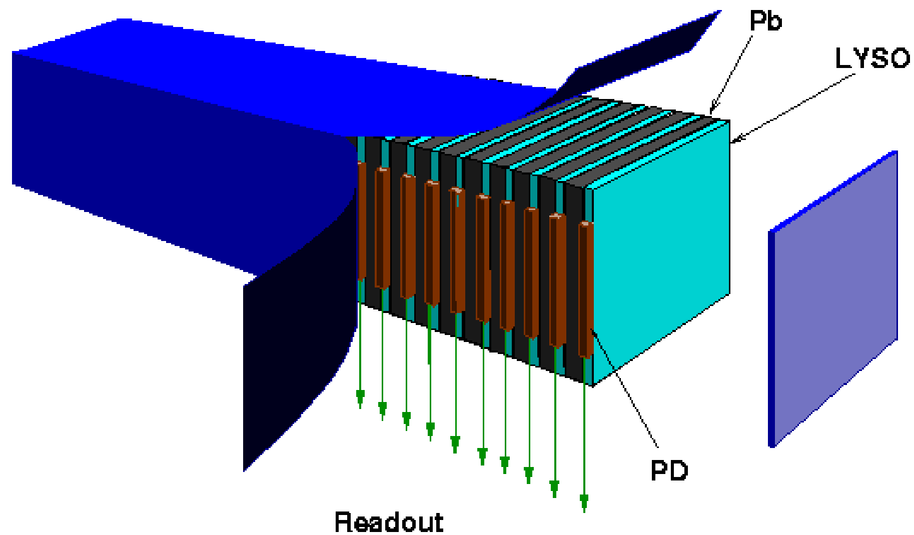




Issues: Radiation hardness of photo-detector and WLS fiber

Issues: Radiation hardness of the photo-detector and Cost





CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 2.5 m^3
Expected Crystal Cost: ~$60M@$25/cc

Crystal Cost: <$10M

Issue: Radiation hardness of the photo-detector

Why LSO/LYSO?

LSO/LYSO is a heavy (7.4 g/cm^3) crystal with bright (200 times light of PWO) and fast (40 ns) scintillation light. It has been widely used in the medical industry. Its good mechanical characteristics allow it to be used in various forms for different calorimeter designs.

Supported by DOE ADR and US CMS Upgrade Effort the Caltech Crystal Lab has been investigating this material for HEP applications starting 2005. Findings:

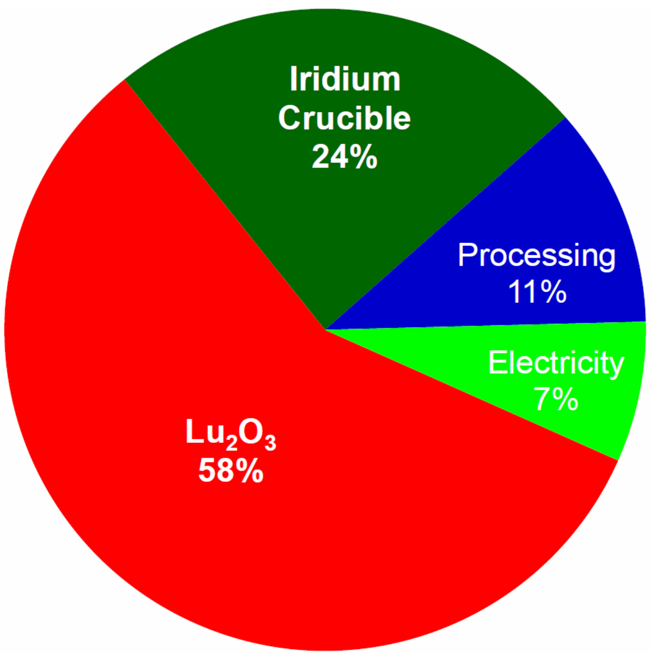
- Its radiation hardness is excellent against γ–ray, neutrons and high energy protons (ETH data). There is no recovery, so calibration is relatively easy. See previous talks in the task force meetings.
- The longitudinal non-uniformity issue caused by tapered crystal geometry, self-absorption and cerium segregation can be addressed by roughening one side surface as demonstrated by the work of Caltech crystal lab for the SuperB experiment. See talk in Calor 2012.
- As a result, LYSO ECAL is base-lined for Mu2e and SuperB.

References: *IEEE Trans. Nucl. Sci.* NS-52 (2005) 3133-3140, *Nucl. Instrum. Meth.* A572 (2007) 218-224, *IEEE Trans. Nucl. Sci.* NS-54 (2007) 718-724, *IEEE Trans. Nucl. Sci.* NS-54 (2007) 1319-1326, *IEEE Trans. Nucl. Sci.* NS-55 (2008) 1759-1766 and *IEEE Trans. Nucl. Sci.* NS-55 (2008) 2425-2341, N32-4 & N32-5 @ NSS09, Orlando, N38-2 @ NSS10, Knoxville, N29-6 @ NSS11, Valencia.

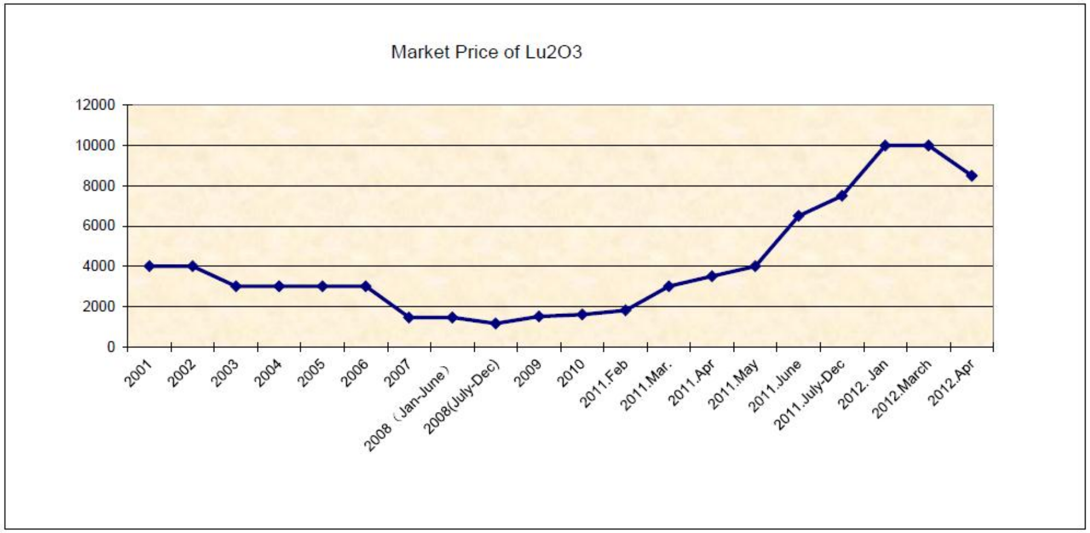
LSO/LYSO Crystal Cost

R.-Y. Zhu, Talk given in Caltech DOE review, June 12, 2012

LSO/LYSO Crystal Cost Breakdown



The Lu_2O_3 price fluctuates up in 2011 and down since 2012, showing market speculation on the rare earth control policy of the Chinese government.

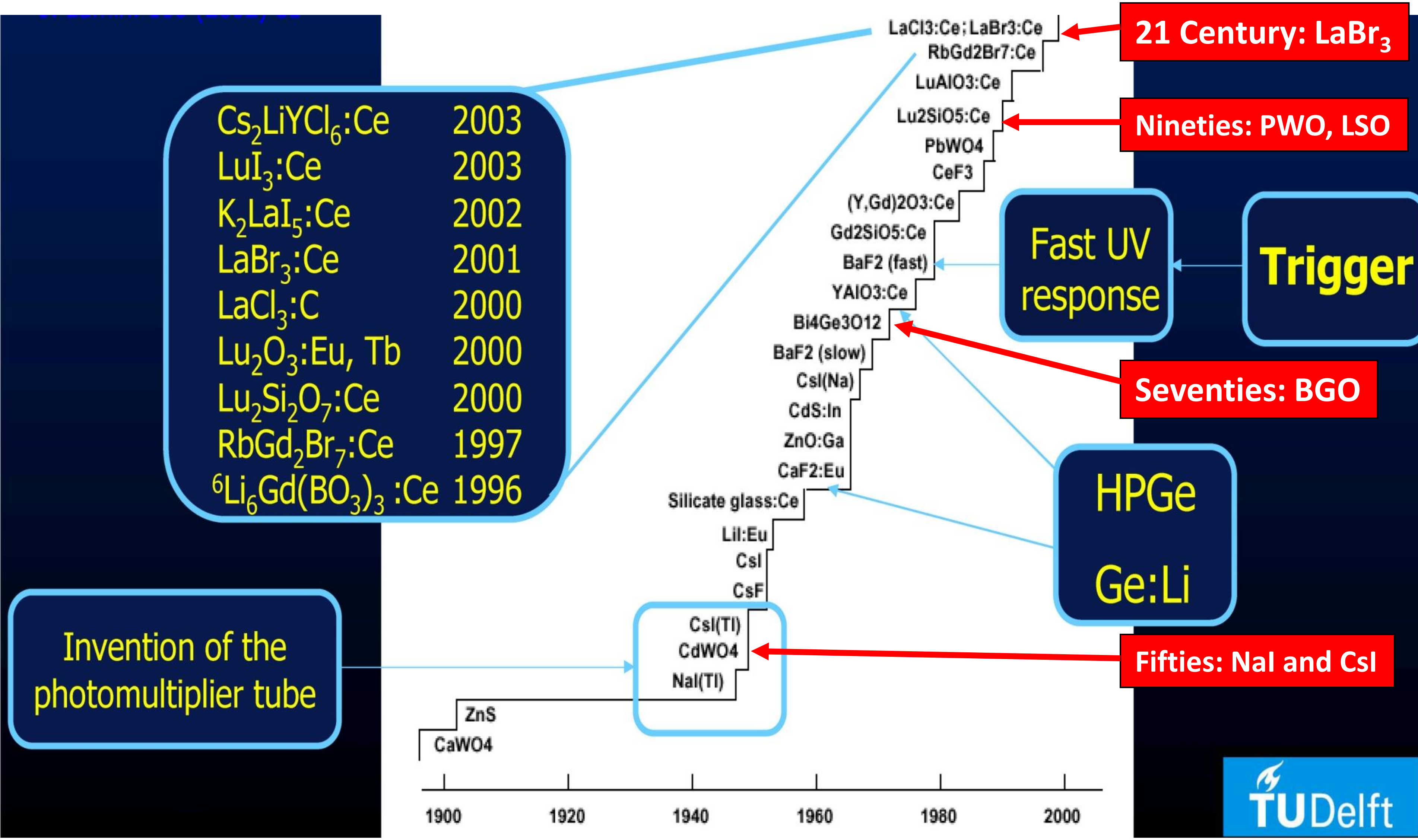


Assuming Lu_2O_3 at \$400/kg and 33% yield the cost is about \$18/cc. Quotations received at \$22-25/cc.

For the sampling calorimeter options it seems worthwhile to look into alternative fast crystals not necessary very heavy but with adequate radiation hardness and lower cost.

History of Scintillating Crystals

M.J. Weber, J. Lumin. 100 (2002) 35



Crystals for HEP Calorimeters

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	Mu2e SuperB HL-LHC?	CMS ALICE PANDA	HHCAL?

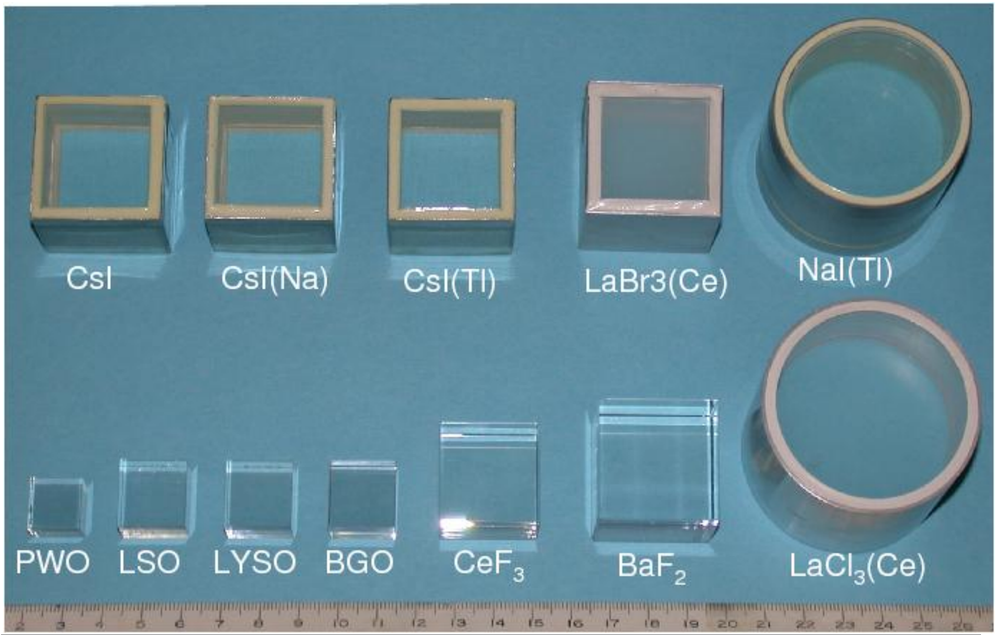
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

Crystals for Homeland Security

Crystal	NaI(Tl)	CsI(Tl)	CsI(Na)	$LaCl_3(Ce)$	SrI_2 (Eu)	$LaBr_3(Ce)$	$CeBr_3$
Density (g/cm³)	3.67	4.51	4.51	3.86	4.59	5.29	5.10
Melting Point (ºC)	651	621	621	859	538	788	722
Radiation Length (cm)	2.59	1.86	1.86	2.81	1.95	1.88	1.96
Molière Radius (cm)	4.13	3.57	3.57	3.71	3.40	2.85	2.97
Interaction Length (cm)	42.9	39.3	39.3	37.6	37.0	30.4	31.5
Refractive Index [a]	1.85	1.79	1.95	1.9	?	1.9	2.3
Hygroscopicity	Yes	Slight	Slight	Yes	Yes	Yes	Yes
Luminescence [b] (nm) (at peak)	410	550	420	335	435	356	371
Decay Time [b] (ns)	245	1220	690	570 24	1100	20	17
Light Yield [b,c] (%)	100	165	88	13 42	221	130	122
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	0.4	0.1	?	0.2	-0.1

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

Crystals Measured at Caltech



1.5 X_0 Cubic Samples:

Hygroscopic: Sealed

Non-hygro: Polished

Full Size Crystals:

***BaBar* CsI(Tl): 16 X_0**

L3 BGO: 22 X_0

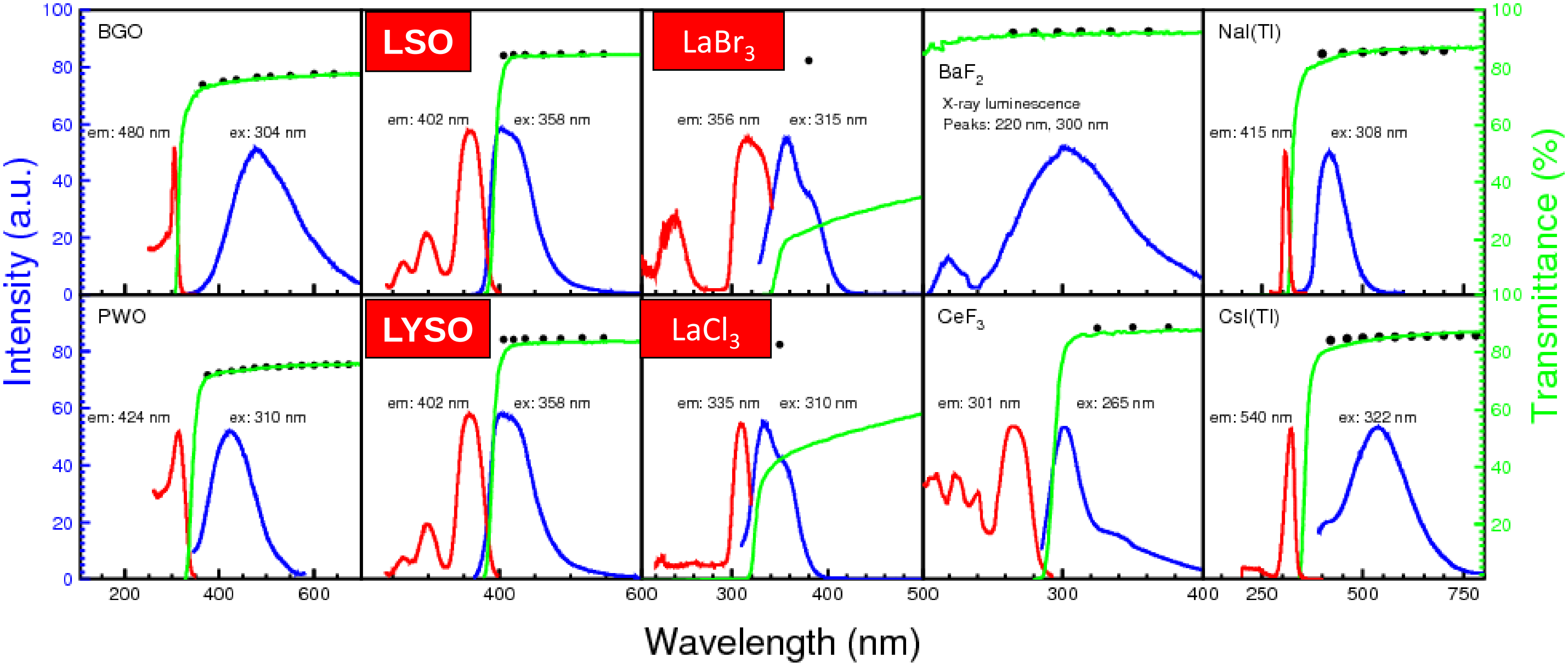
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

$$T_s = (1 - R)^2 + R^2(1 - R)^2 + \ldots = (1 - R)/(1 + R), \text{ with}$$

$$R = \frac{(n_{crystal} - n_{air})^2}{(n_{crystal} + n_{air})^2}.$$

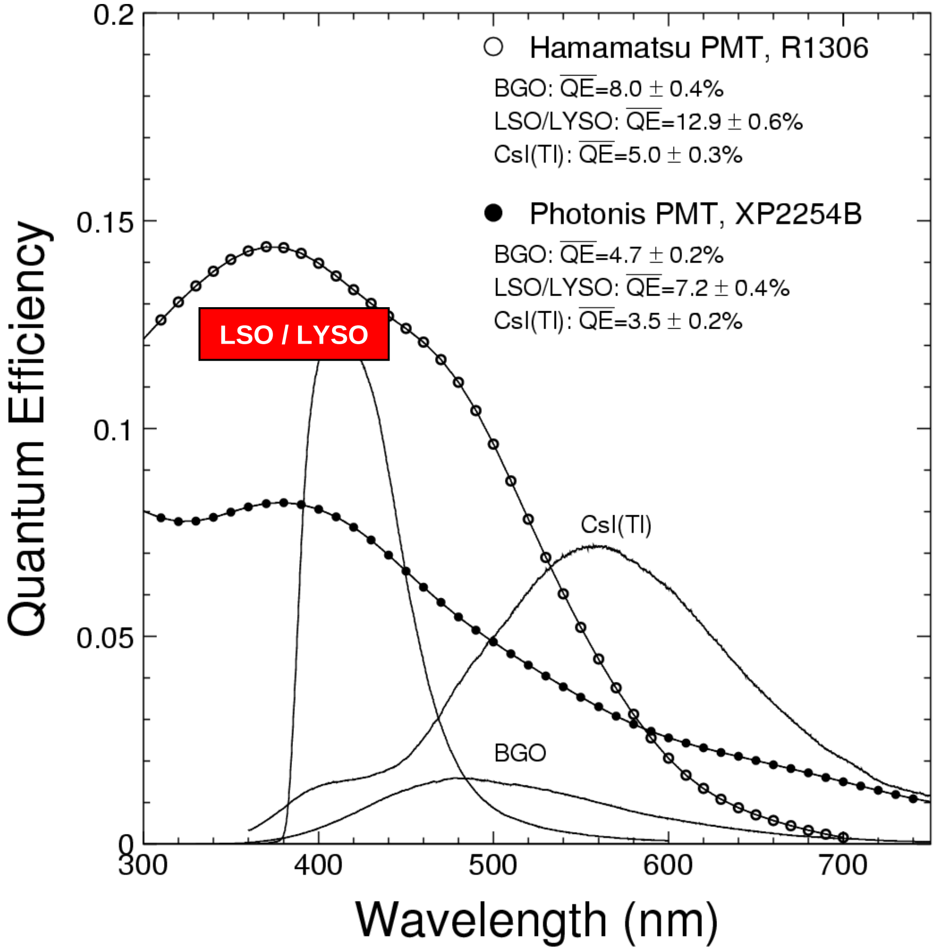
Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422

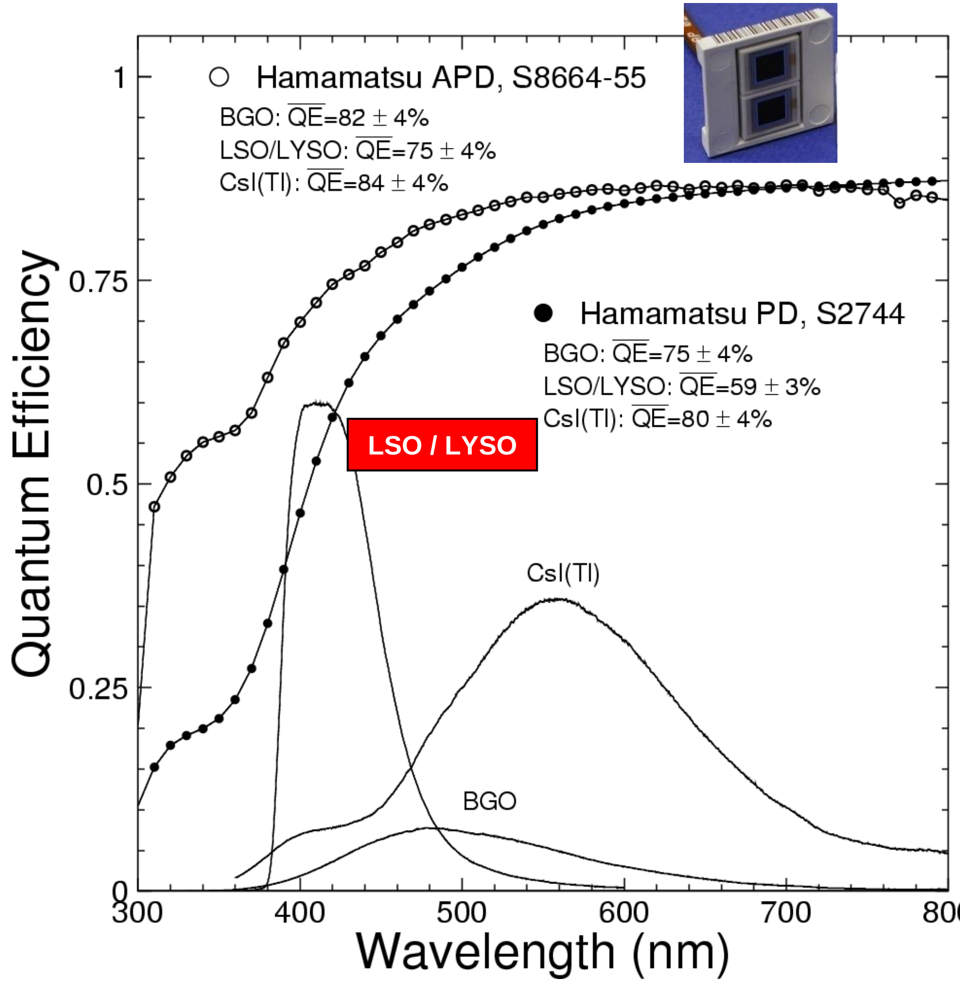


No Self-absorption: BGO, PWO, BaF_2, NaI(Tl) and CsI(Tl)

Emission Weighted QE

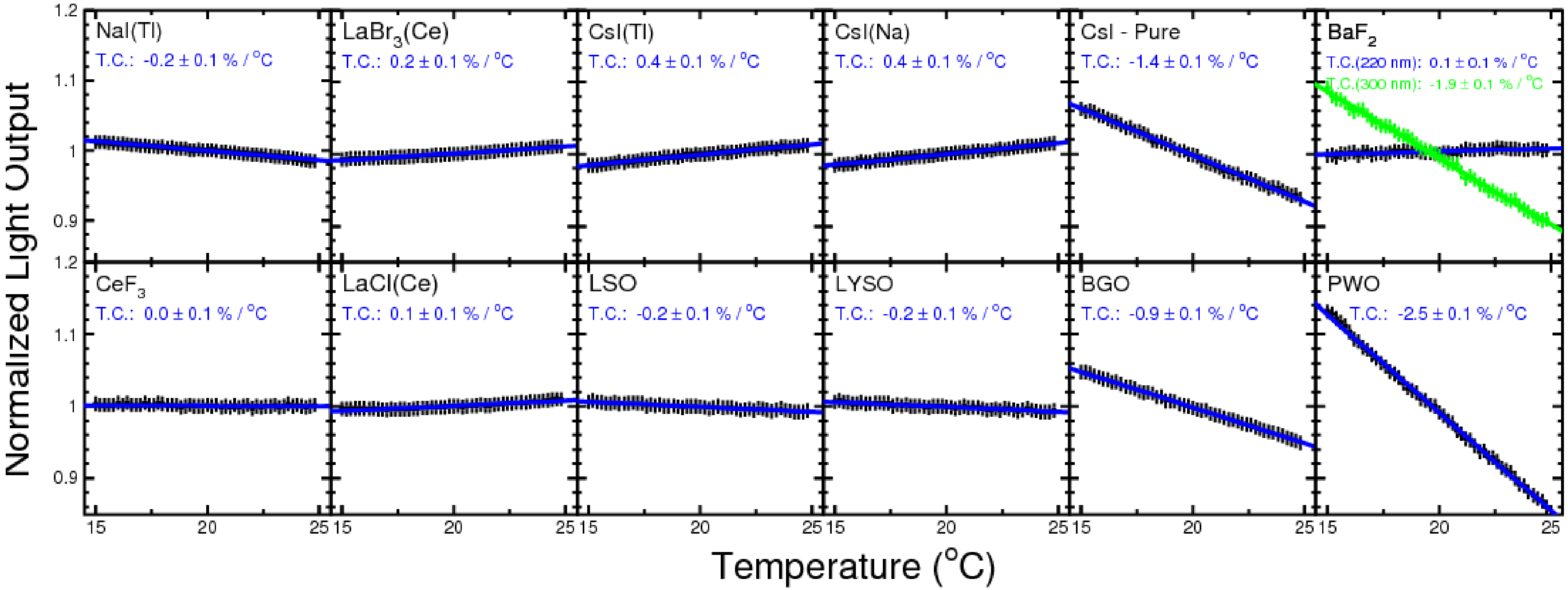
Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO





L.O. Temperature Coefficient

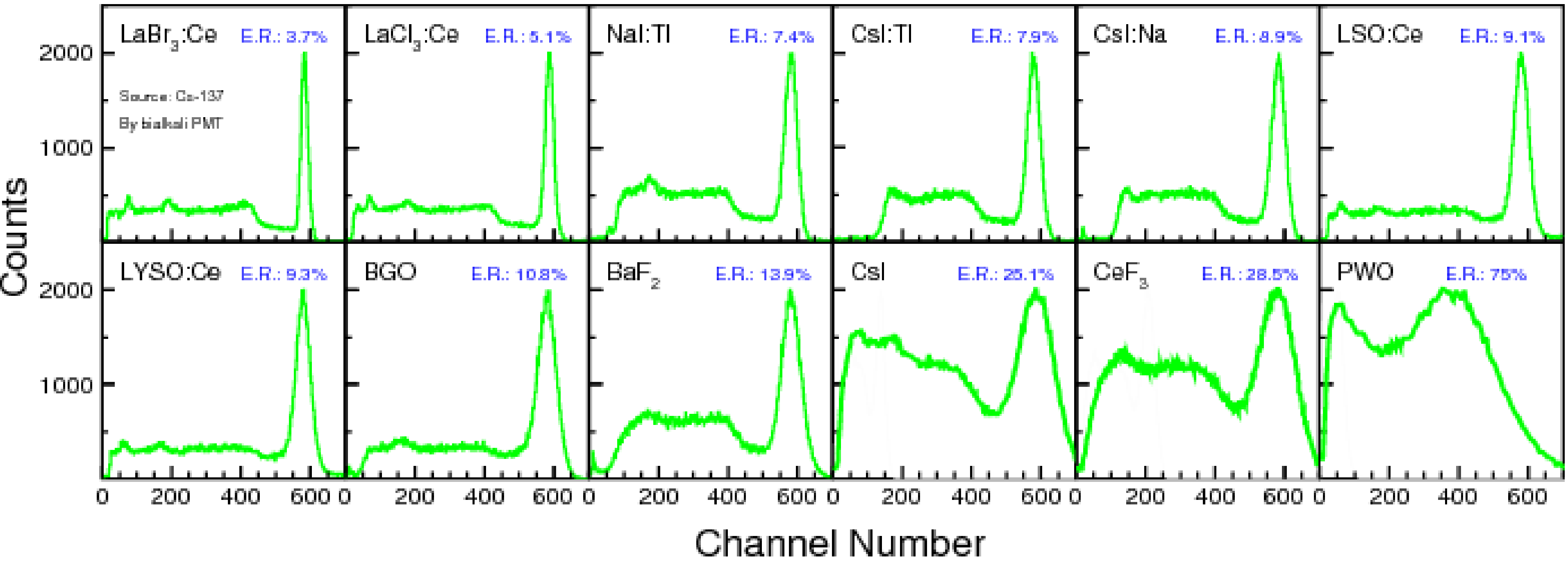
Temperature Range: 15 - 25ºC



Large temperature coefficient: CsI, BGO, BaF_2 and PWO

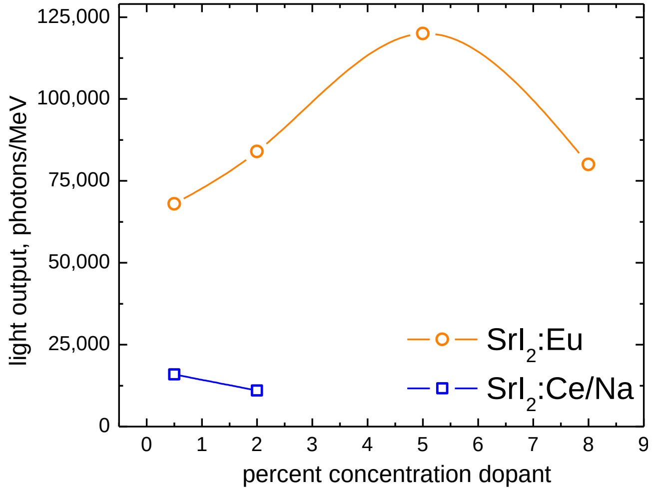
^{137}Cs FWHM Energy Resolution

3% to 80% measured with Hamamatsu R1306 PMT with bi-alkali cathode

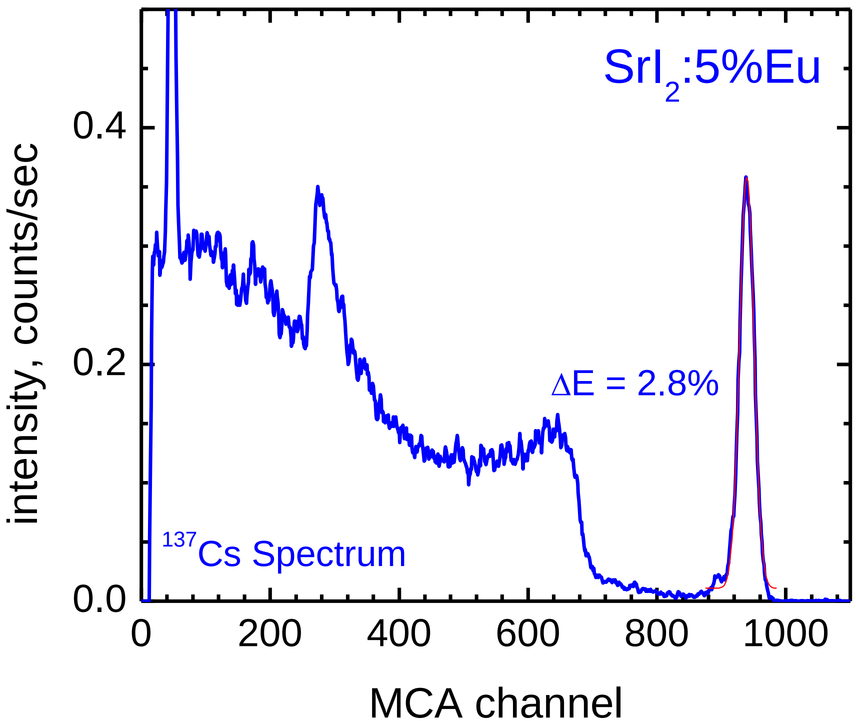


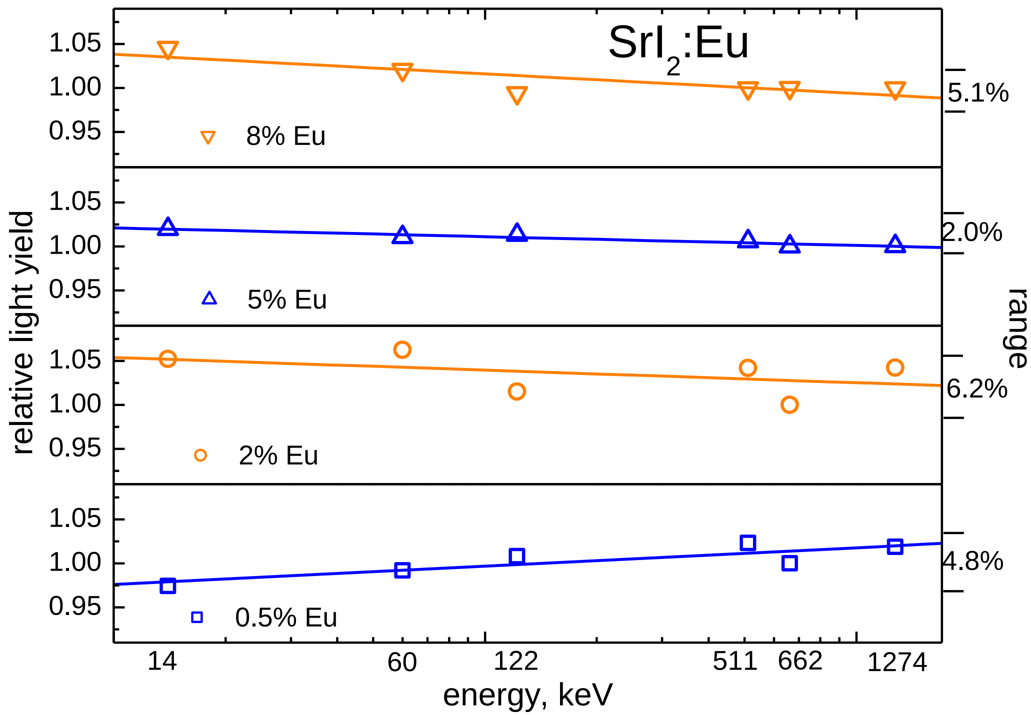
2% resolution and proportionality are important for γ–ray spectroscopy between 10 keV to 2 MeV

$SrI_2(Eu)$ Development



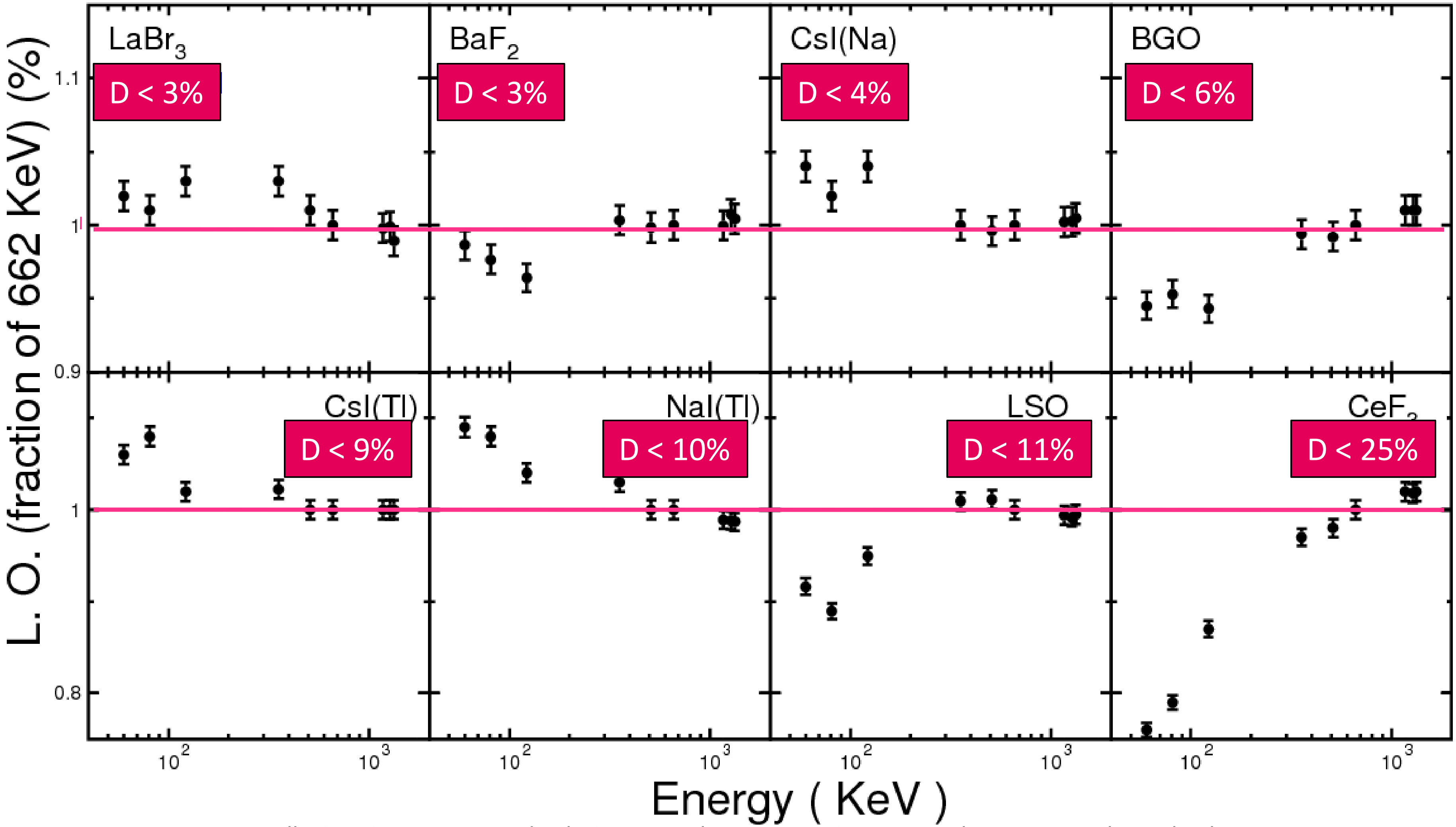
C. Wilson, RMD
ϕ10 X 24 mm ingot
Best Eu doping at 5%
Energy resolution (< 3%)
Linearity (~2%)
Patent (1968) expired





Low Energy Non Proportionality

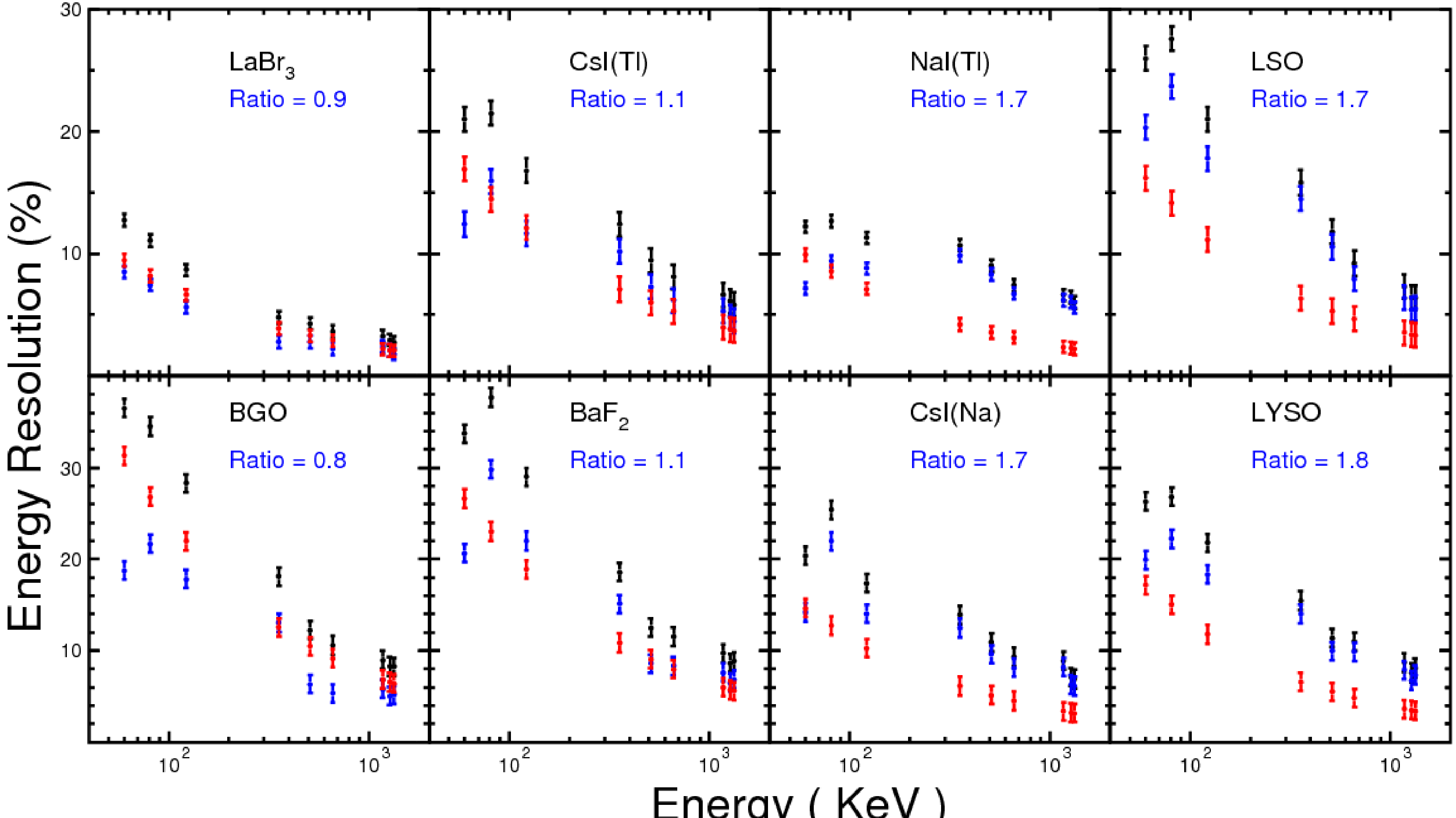
D: deviation from linearity: 60 keV to 1.3 MeV
Good Crystals: $LaBr_3$, BaF_2, CsI(Na) and BGO



Statistical & Intrinsic Resolutions

$\sigma^2 = \sigma^2_{intrinsic} + \sigma^2_{statistical}$, ratio = $\sigma_{intrinsic} / \sigma_{statistical}$

Good crystals: BGO and $LaBr_3$

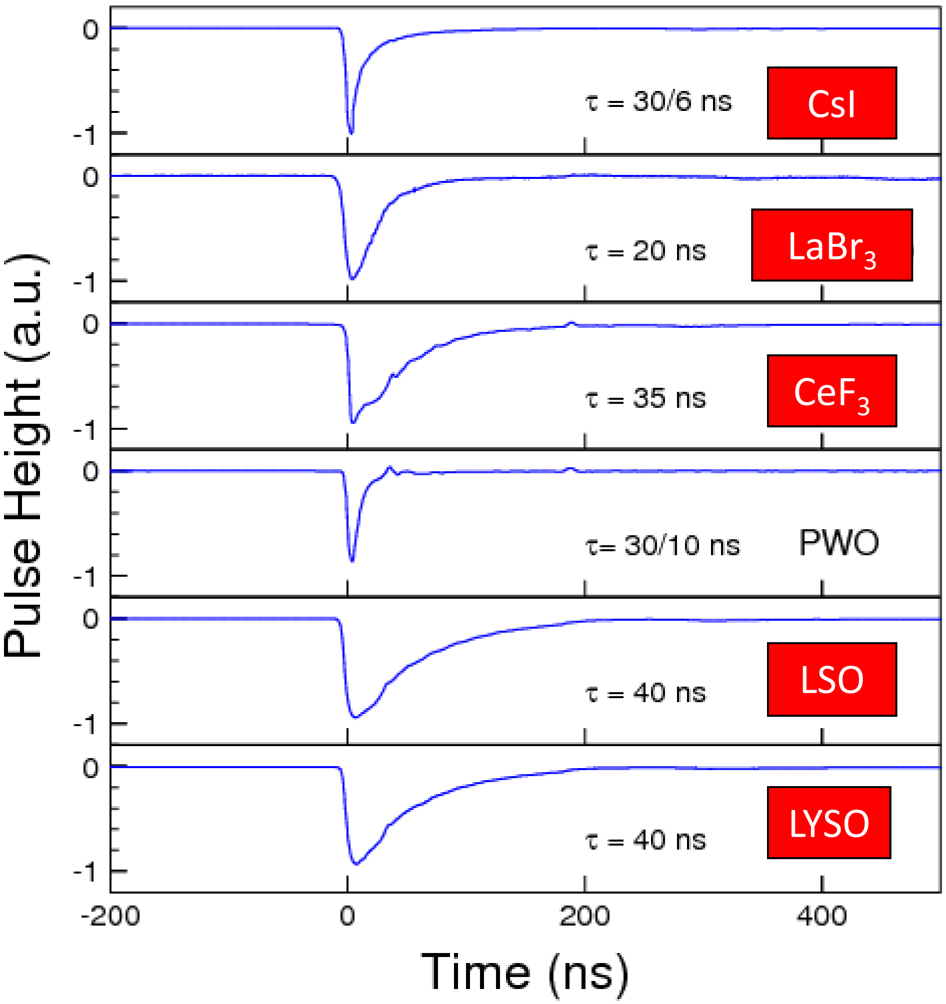


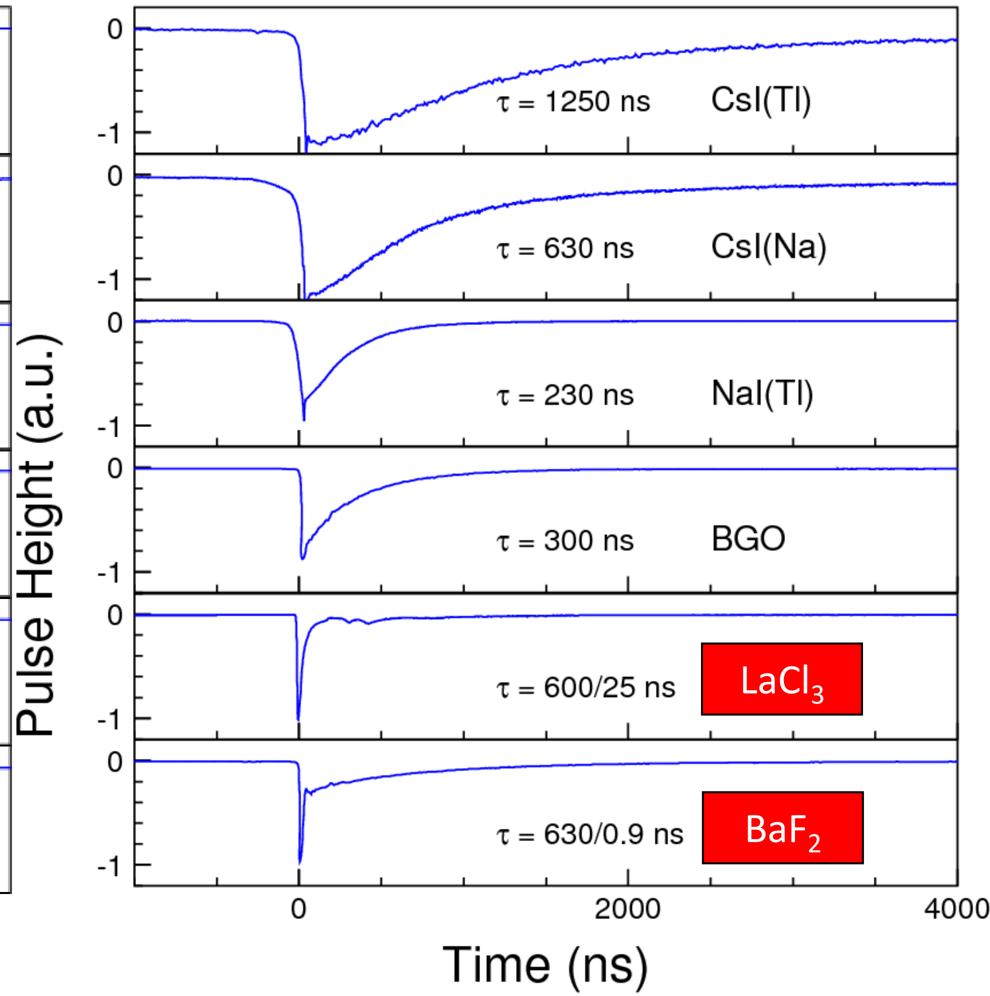
Scintillation Light Decay Time

Recorded with an Agilent 6052A digital scope

Fast Scintillators

Slow Scintillators

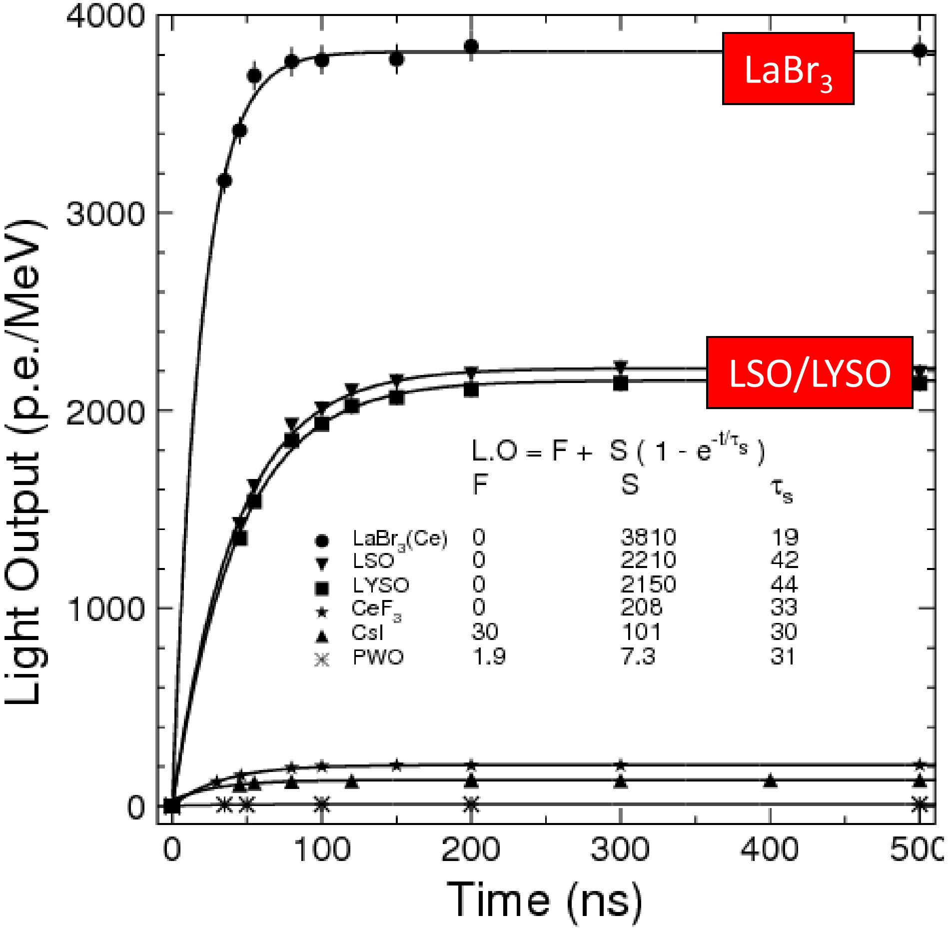




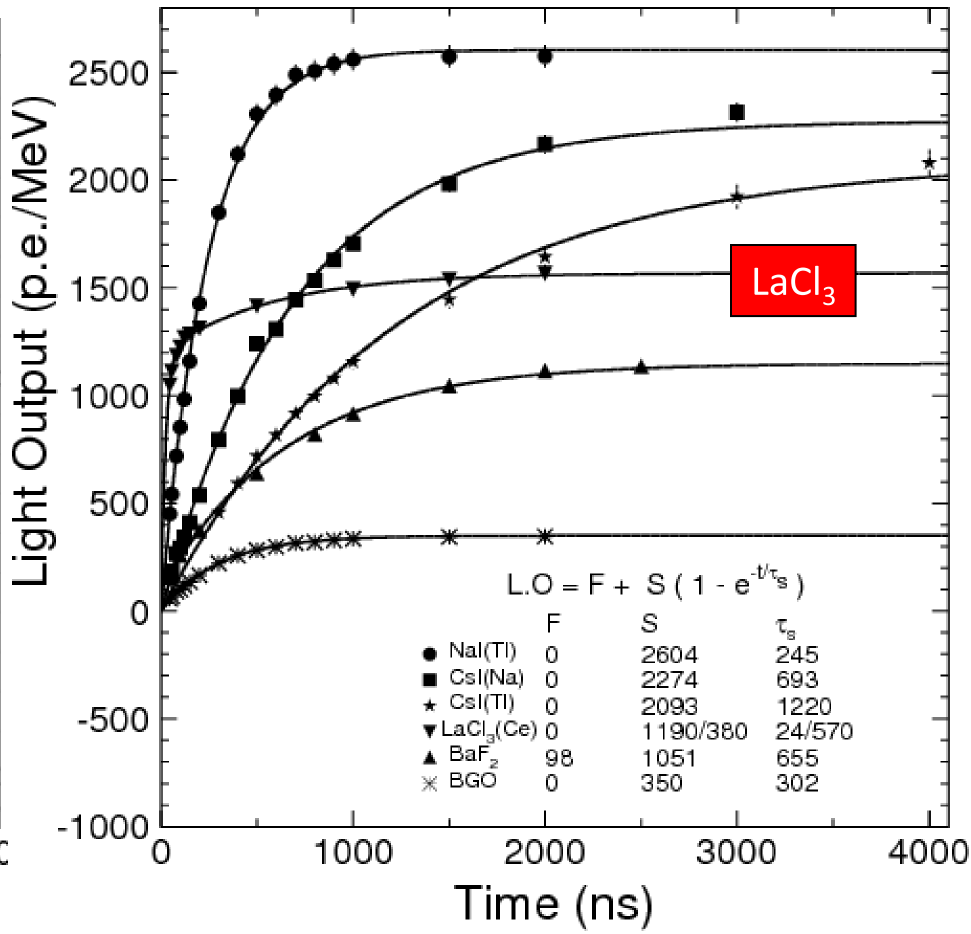
Light Output & Decay Kinetics

Measured with Philips XP2254B PMT (multi-alkali cathode)
$LaBr_3$, $LaCl_3$ and LSO/LYSO are blight and fast crystals

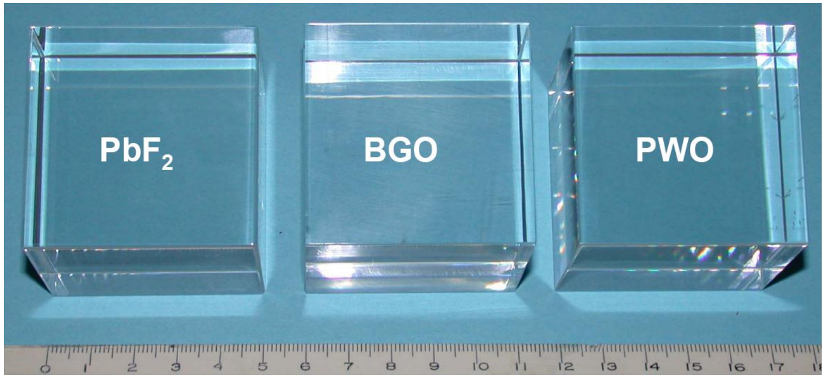
Fast Crystal Scintillators

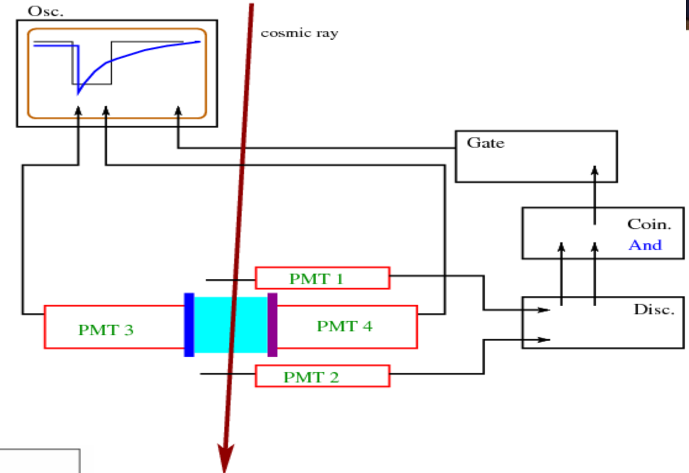


Slow Crystal Scintillators

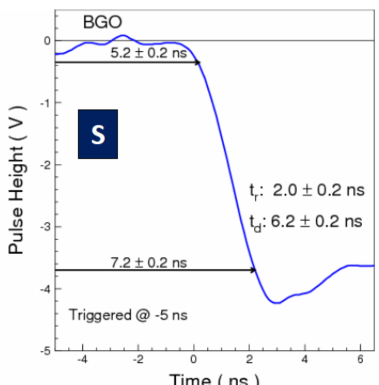


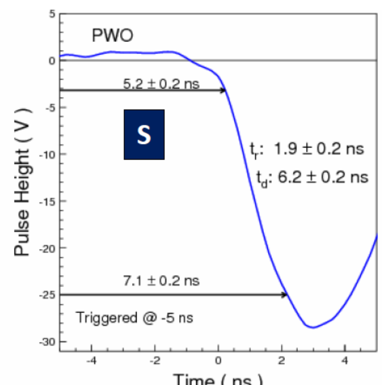
Rising Time of Cherenkov & Scintillation

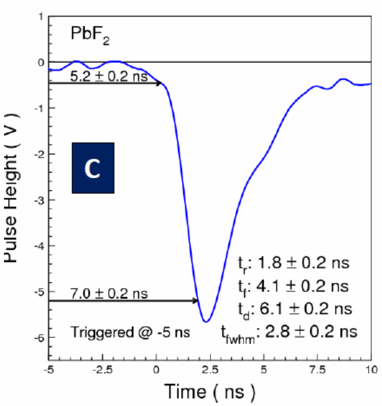


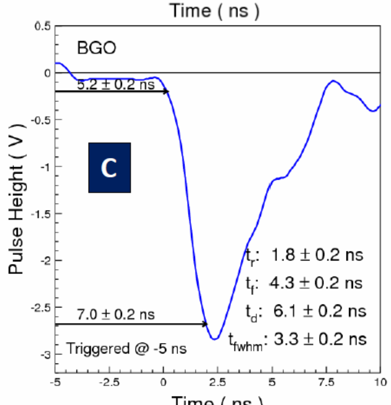


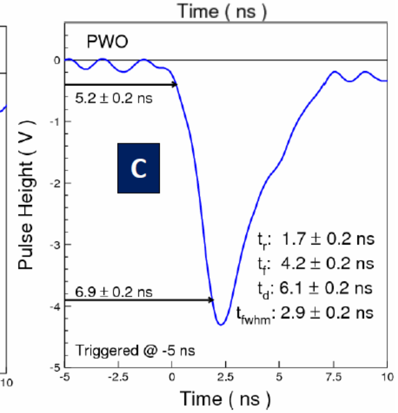
Consistent timing and rise time for all Cherenkov and scintillation light pulses observed.

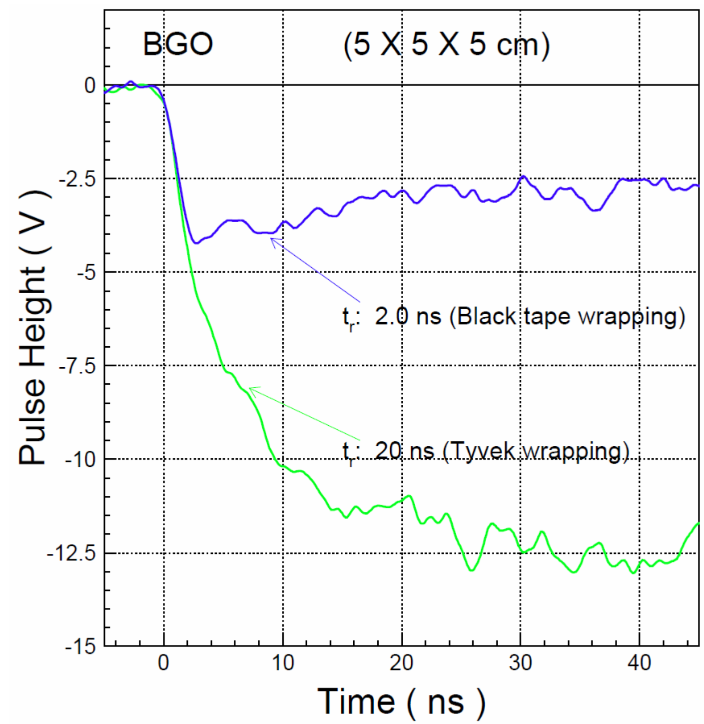






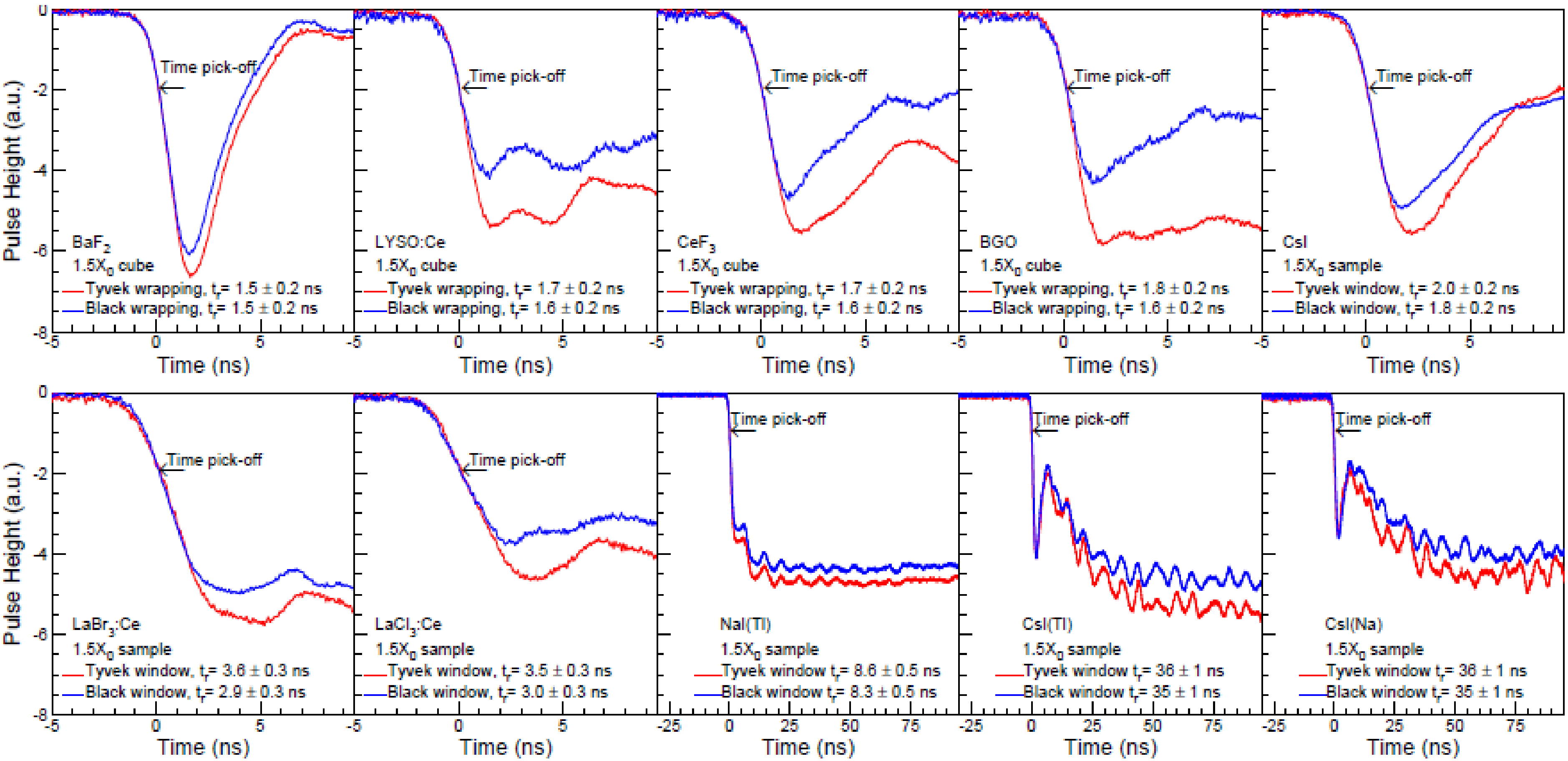






Rising Time for 1.5 X_0 Samples

Reported in the time resolution workshop at U. Chicago: 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 Crystals

R.-Y. Zhu, Talk given in Time Resolution Workshop, April, 2011

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 time resolution is BaF_2 and LSO/LYSO: Ce/Ca. $LaBr_3$ is a material with high potential.

Summary of Fast Scintillators

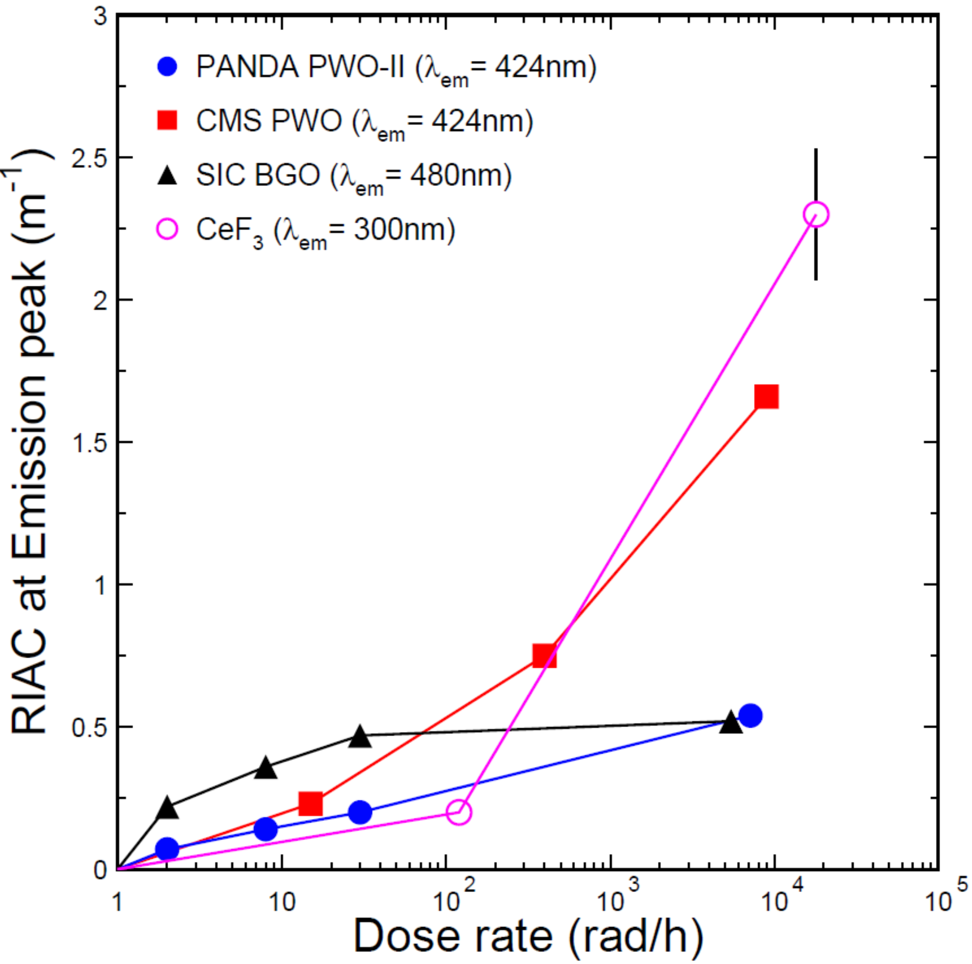
	LSO/LYSO	GSO [1]	YSO [1]	CsI	BaF_2	CeF_3	$CeBr_3$ [2]	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404) [3]
Density (g/cm³)	7.40	6.71	4.54	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70[#]
Radiation Length (cm)	1.14	1.38	3.04	1.86	2.03	1.70	1.96	2.81	1.88	42.54
Molière Radius (cm)	2.07	2.23	2.87	3.57	3.10	2.41	2.97	3.71	2.85	9.59
Interaction Length (cm)	20.9	22.2	27.3	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	6.70	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	35	40	4.2 1.3	42 4.8	8.6	141	15 49	153	35
Decay Time[a] (ns)	40	65	70	30 6	650 0.9	30	17	570 24	20	1.8
d(LY)/dT[d] (%/°C)	-0.2	-0.7	-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

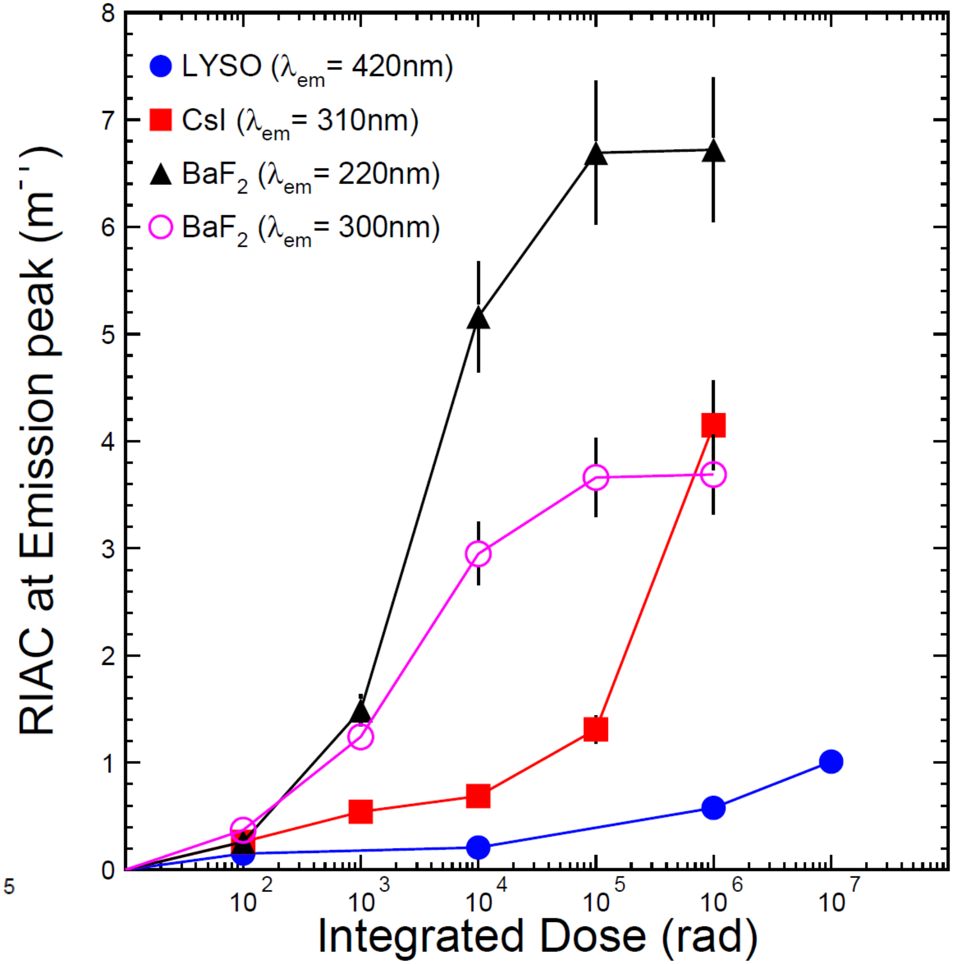
1. N. Tsuchida et al ***Nucl. Instrum. Methods Phys. Res. A,*** 385 (1997) 290-298
http://www.hitachi-chem.co.jp/english/products/cc/017.html
2. W. Drozdowski et al. ***IEEE TRANS. NUCL. SCI***, VOL.55, NO.3 (2008) 1391-1396
Chenliang Li et al, ***Solid State Commun***, Volume 144, Issues 5–6 (2007),220–224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

Comparison of Radiation Hardness

Dose Rate Dependent Damage



Dose Rate Independent Damage



CeF_3 data: E. Auffray et al, *Nucl. Instrum. Methods Phys. Res. A,* 383 (1996) 367-390, CERN-PPE-96-064
CsI data: Zong-ying Wei et al, *Nucl. Instrum. Methods Phys. Res. A,* 326 (1993) 508-512
BaF_2 data : Ren-yuan Zhu, *Nucl. Instrum. Methods Phys. Res. A,* 340 (1994) 442-457

Summary

- Blight crystals are **Eu:SrI$_2$, Ce:LaBr$_3$, CeBr$_3$, Ce:LaCl$_3$ and LSO/LYSO.**
- Fast crystals are available in three groups:
  - A traditional group: **BaF$_2$, pure CsI and CeF$_3$**.
  - A blight and hygroscopic group with patent: **Ce:LaBr$_3$, Ce:LaCl$_3$ and CeBr$_3$**. Mechanically, they are difficult to be used for the sampling option.
  - An expansive group: **LSO/LYSO/YSO and GSO**.
- A R&D program is needed to develop cost effective crystals for CMS forward calorimeter upgrade. While the LSO/LYSO seems the only choice for the total absorption option, the game is wide open for the sampling options.