Precision Crystal Calorimetry in Particle Physics

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IEEE NPSS Lecture: Precision Calorimetry
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- Crystal Calorimeters in Particle Physics.
- Issues Crucial to Crystal Precision.
  - Light Response Uniformity.
  - Calibration *in situ*.
  - Crystal Radiation Damage.
- Future Crystal Technologies for Particle Physics.

Crystal Calorimeters in Particle Physics (I)

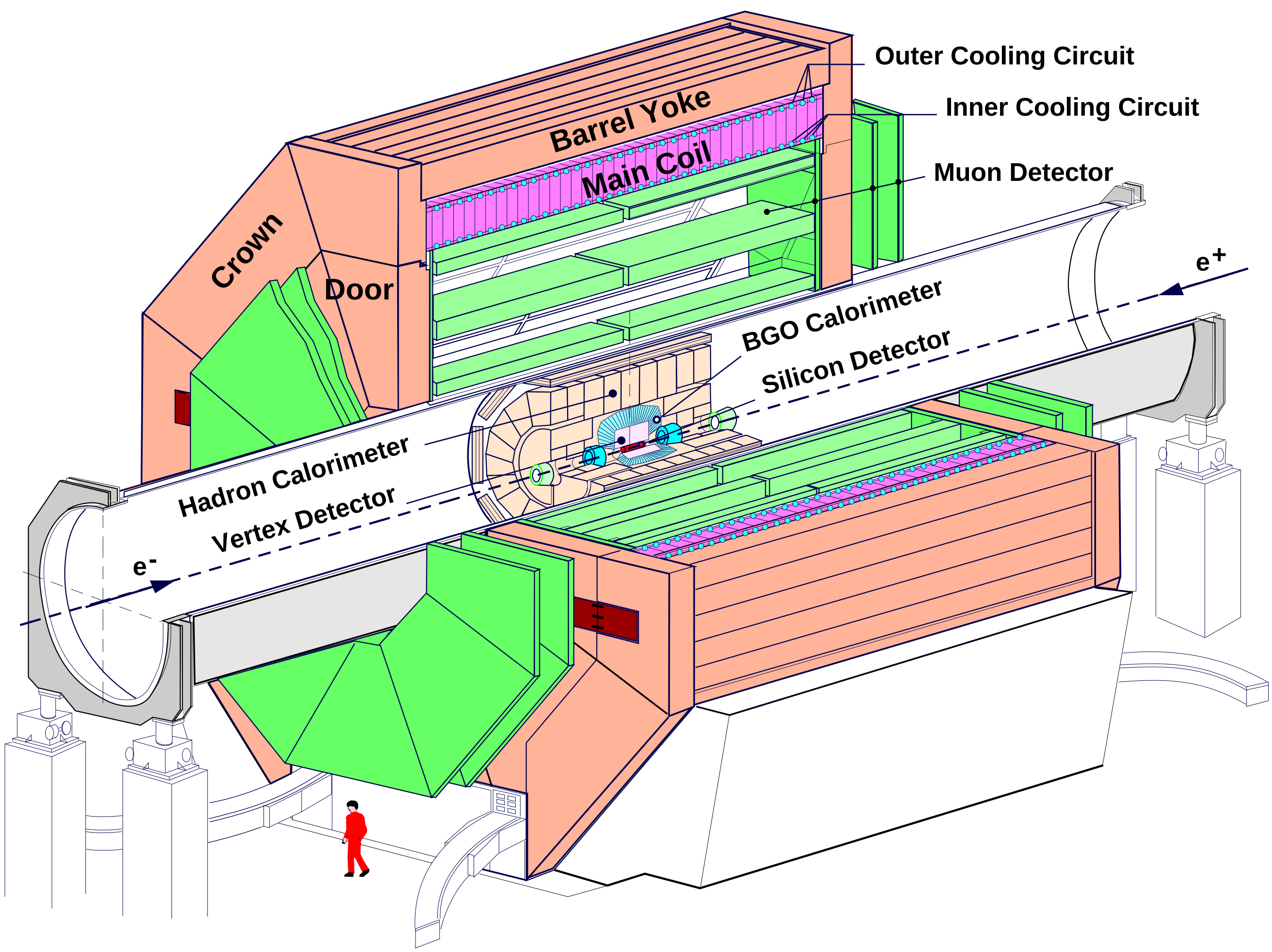
Experiment	C. Ball	L3	CLEO II	C. Barrel
Accelerator	SPEAR	LEP	CESR	LEAR
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)
B-Field (T)	-	0.5	1.5	1.5
r_{inner} (m)	0.254	0.55	1.0	0.27
# of Crystals	672	11,400	7,800	1,400
Depth (X_0)	16	22	16	16
Volume (m^3)	1	1.5	7	1
L.O. (p.e./MeV)	350	1,400	5,000	2,000
Photosensor	PMT	Si PD	Si PD	WS[a]+Si PD
Gain of P.S.	Large	1	1	1
σ_N/Chan. (MeV)	0.05	0.8	0.5	0.2
Dynamic Range	10^4	10^5	10^4	10^4
$\mathbf{a_0}$[b] (%)	0.02	0.3	0.2	0.06
$\mathbf{a_1}$[c] (%)	0.2	0.1	0.05	0.07

a Wavelength Shifter.

b Noise contribution to the energy resolution (at 1 GeV).

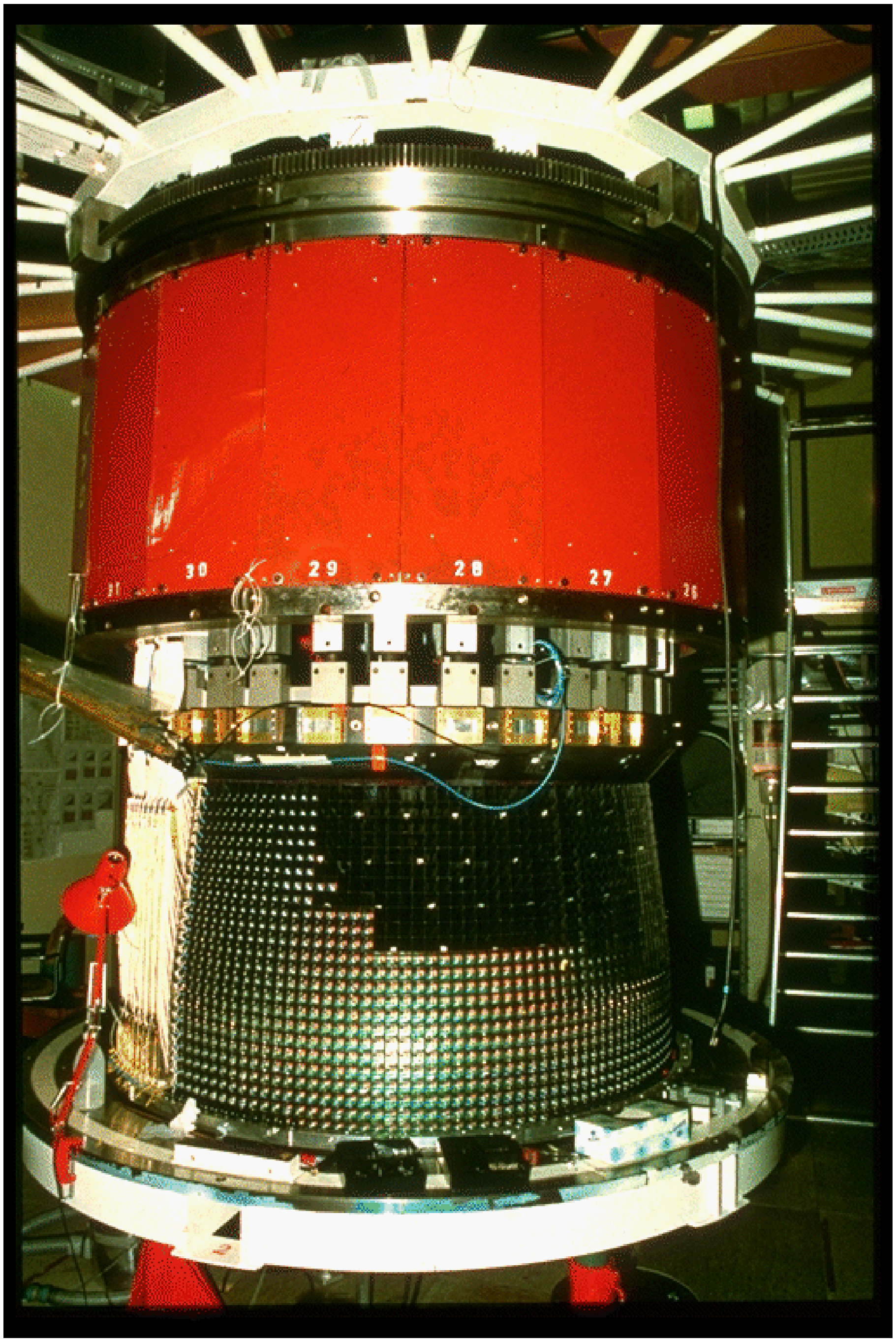
c Photoelectron statistics contribution at 1 GeV.

3D Cut-away View of L3 Detector



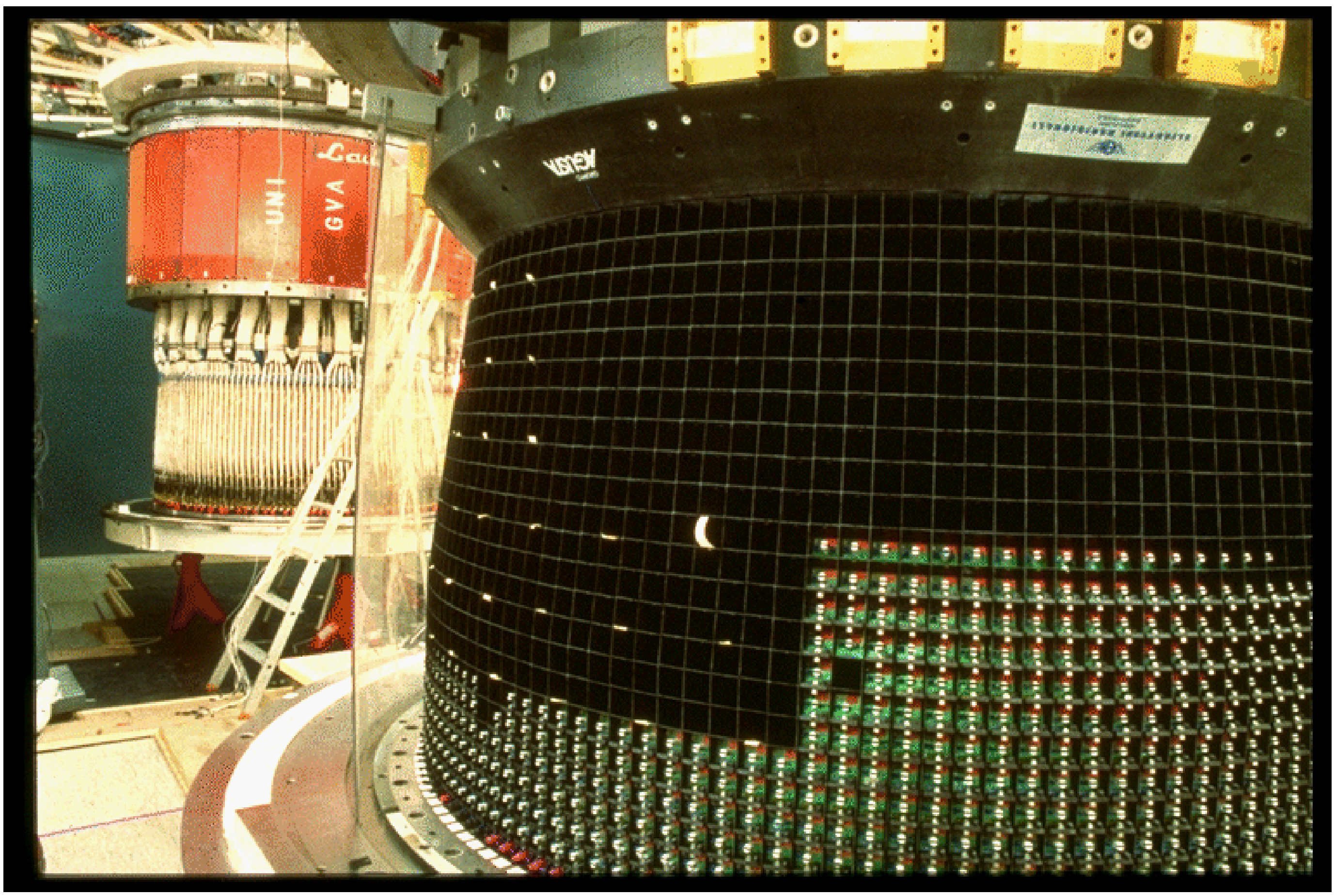
L3 BGO Calorimeter under Construction

First Half Barrel



L3 BGO Calorimeter under Construction

Second Half Barrel



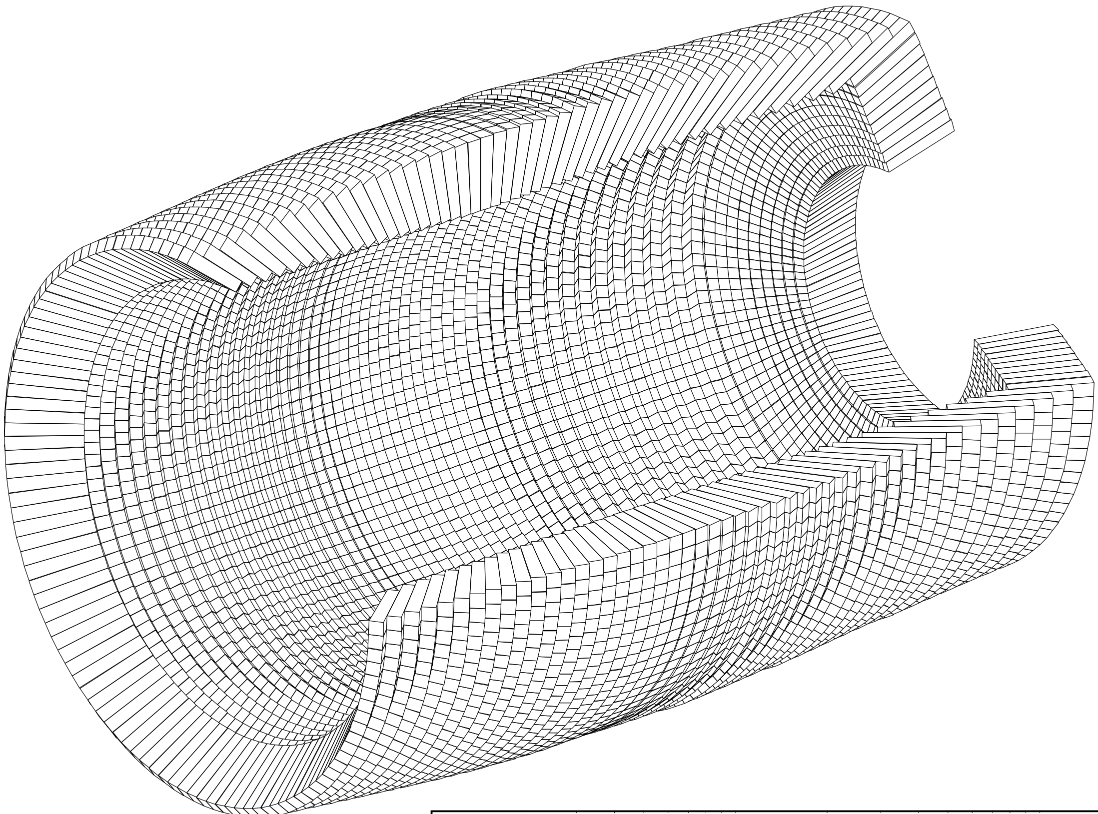
Crystal Calorimeters in Particle Physics (II)

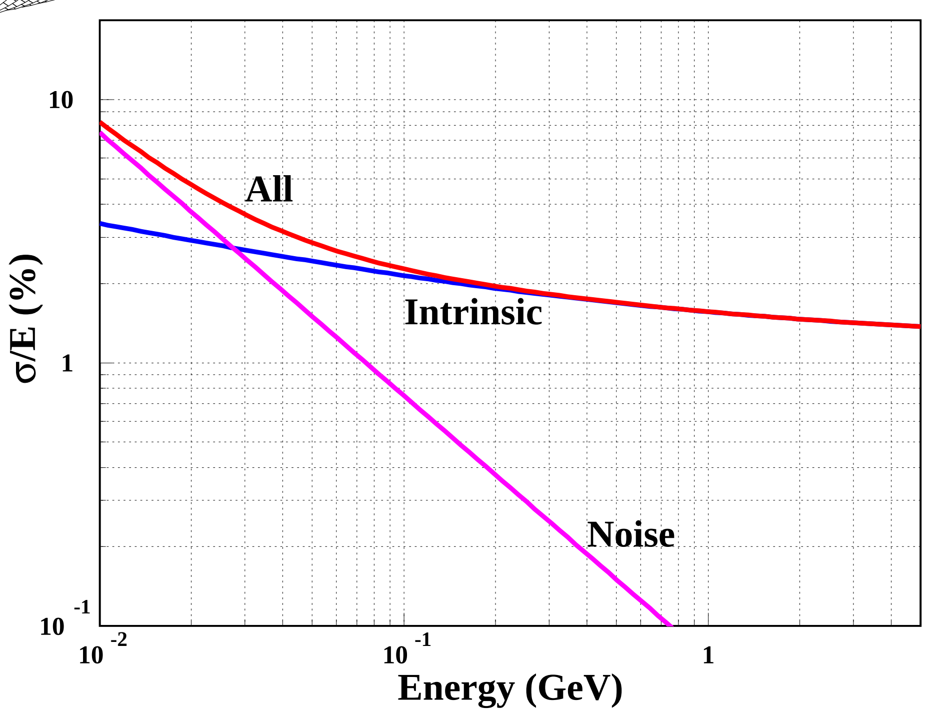
Experiment	KTeV	*BaBar*	BELLE	CMS
Laboratory	FNAL	SLAC	KEK	CERN
Crystal Type	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	1.5	1.0	4.0
Inner Radius (m)	-	1.0	1.25	1.29
Number of Crystals	3,300	6,580	8,800	83,300
Crystal Depth (X_0)	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	2	5.9	9.5	11
Light Yield. (p.e./MeV)	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	4,000	1	1	50
Noise/Channel (MeV)	small	0.15	0.2	30
Dynamic Range	10^4	10^4	10^4	10^5

a Avalanche photodiode.

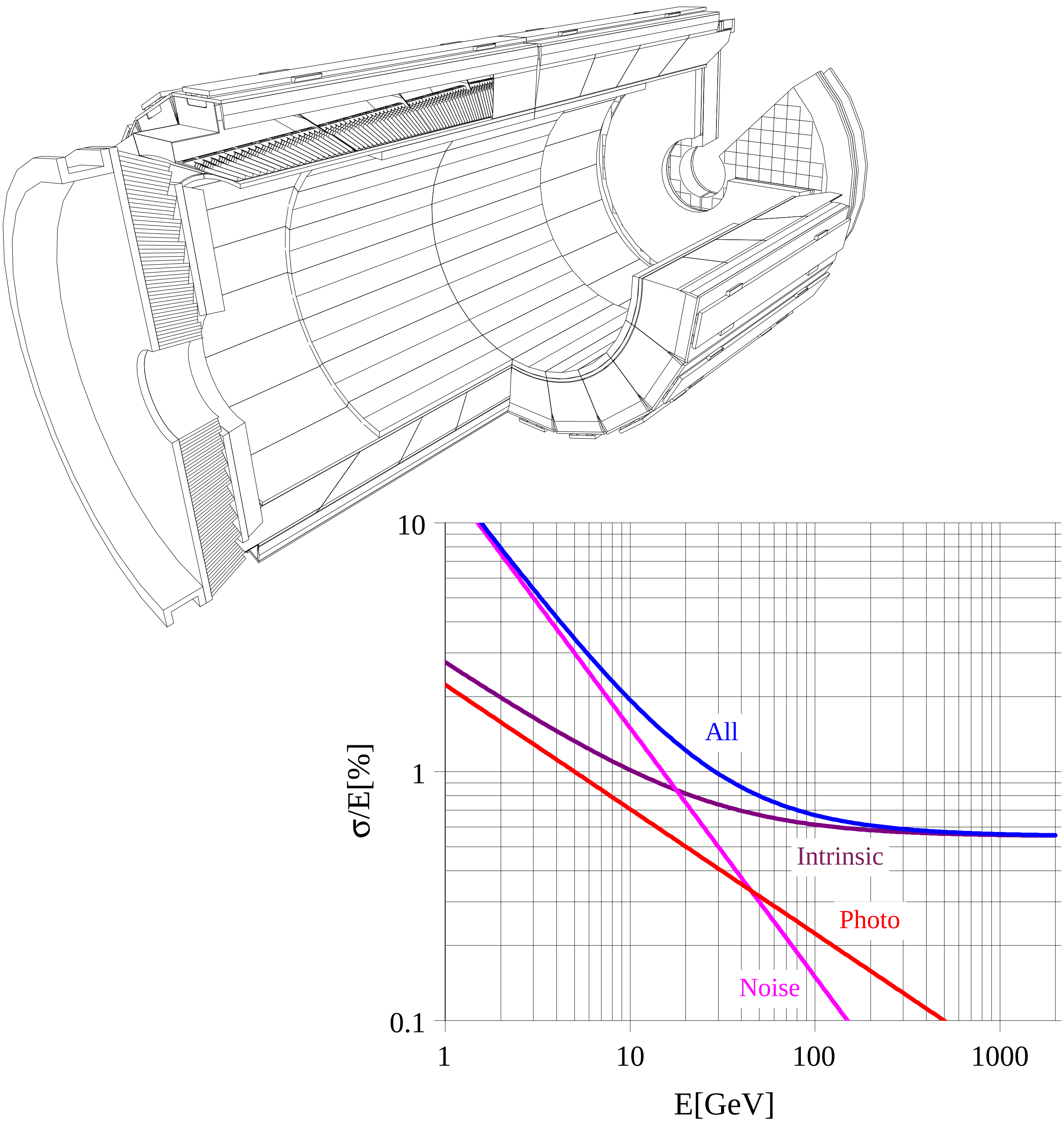
A PWO Crystal ECAL is under Design by BTeV.

BaBar CsI(Tl) ECAL and Resolution

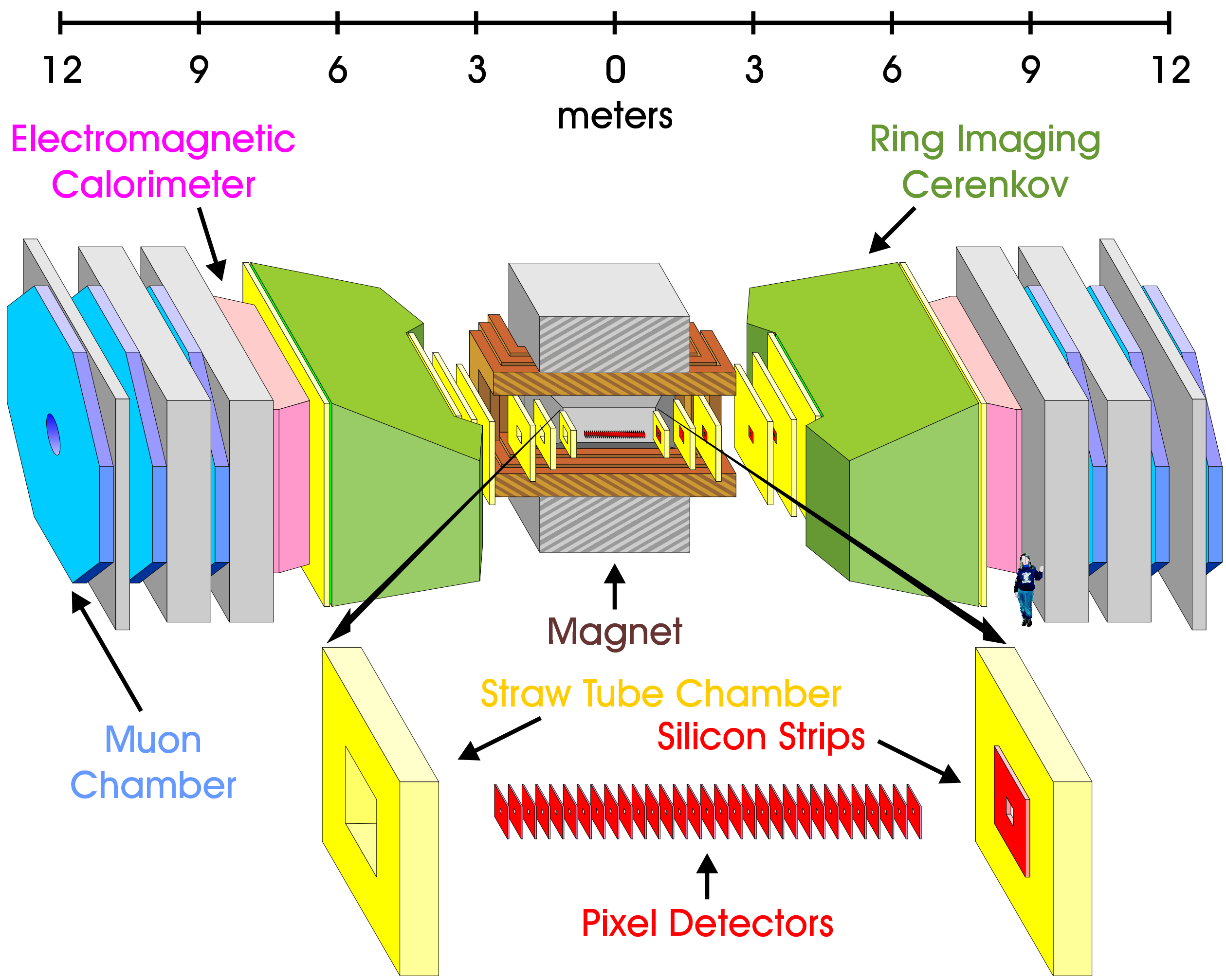




CMS $PbWO_4$ ECAL and Resolution



BTeV Detector Layout



Properties of Crystal Scintillators

	NaI(Tl)	CsI(Tl)	CsI	BaF_2	CeF_3	BGO	$PbWO_4$
ρ (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.13	8.28
$t_{Melting}$ (°C)	651	621	621	1280	1460	1050	1123
X_{rad} (cm)	2.59	1.85	1.85	2.06	1.68	1.12	0.89
$R_{Molière}$ (cm)	4.8	3.5	3.5	3.4	2.6	2.3	2.0
X_{int} (cm)	41.4	37.0	37.0	29.9	26.2	21.8	18
n^a	1.85	1.79	1.95	1.50	1.62	2.15	2.2
Hygroscopic	Yes	slight	slight	No	No	No	No
λ_{Lum} (nm)^b (at Peak)	410	560	420 310	300 220	340 300	480	420/500
τ_{Decay} (ns)^b	230	1250	35 6	630 0.9	30 9	300	$<$30
Relative LY^{b,c}	100	45	5.6 2.3	21 2.7	6.6 2.0	9	1
d(LY)/dT^d (%/°C)	$\sim$0	0.3	-0.6	-2/$\sim$0	0.14	-1.6	-1.9
Price ($/cc)	1–2	2	2.5	2.5	3^e	7	2^f

a At the wavelength of the emission maximum.

b Top line: slow component, bottom line: fast component.

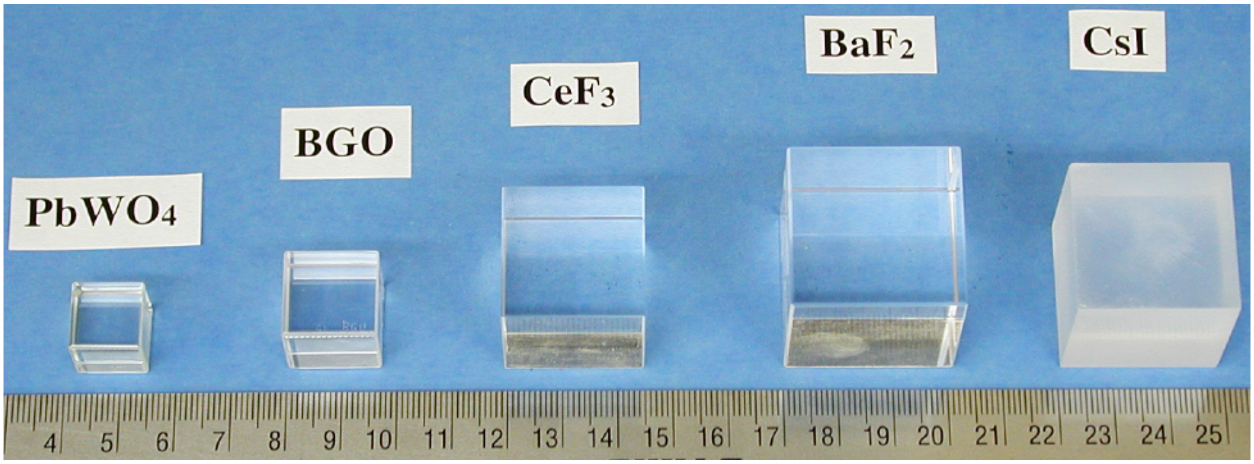
c Measured with a PMT with a bialkali cathode.

d At Room temperature.

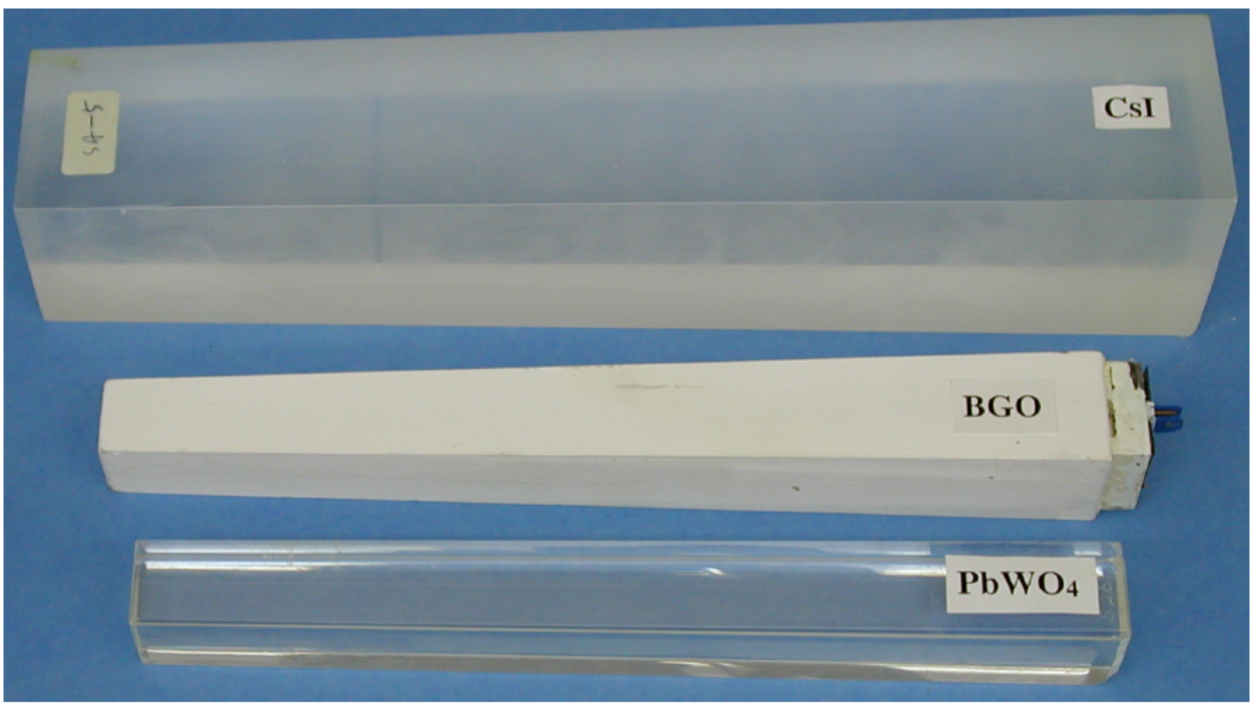
e Not mass produced yet, expected price.

f CMS mass-production price.

Crystal Samples of 1.5 Radiation Length

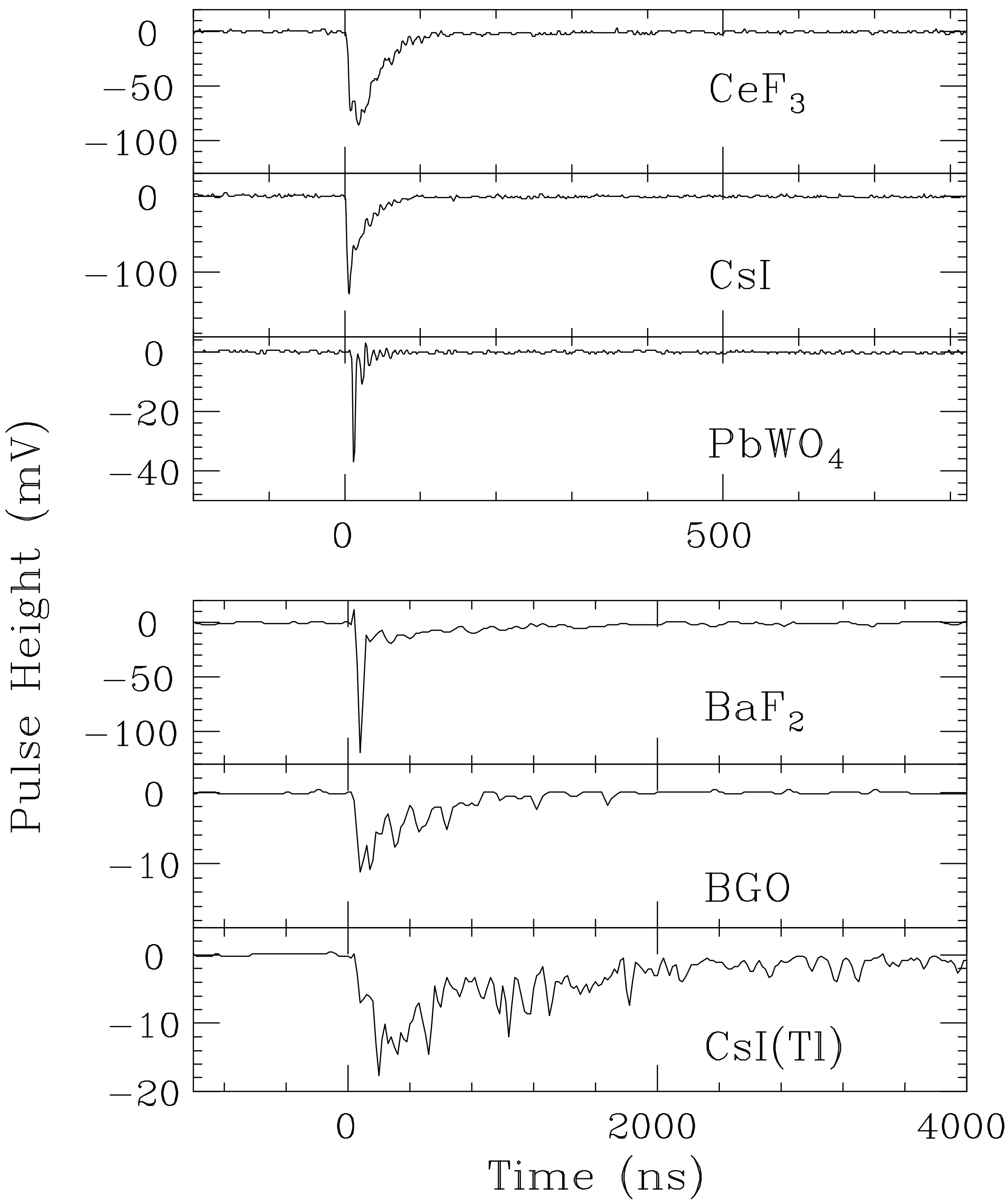


Full Size Samples for $BaBar$, L3 and CMS



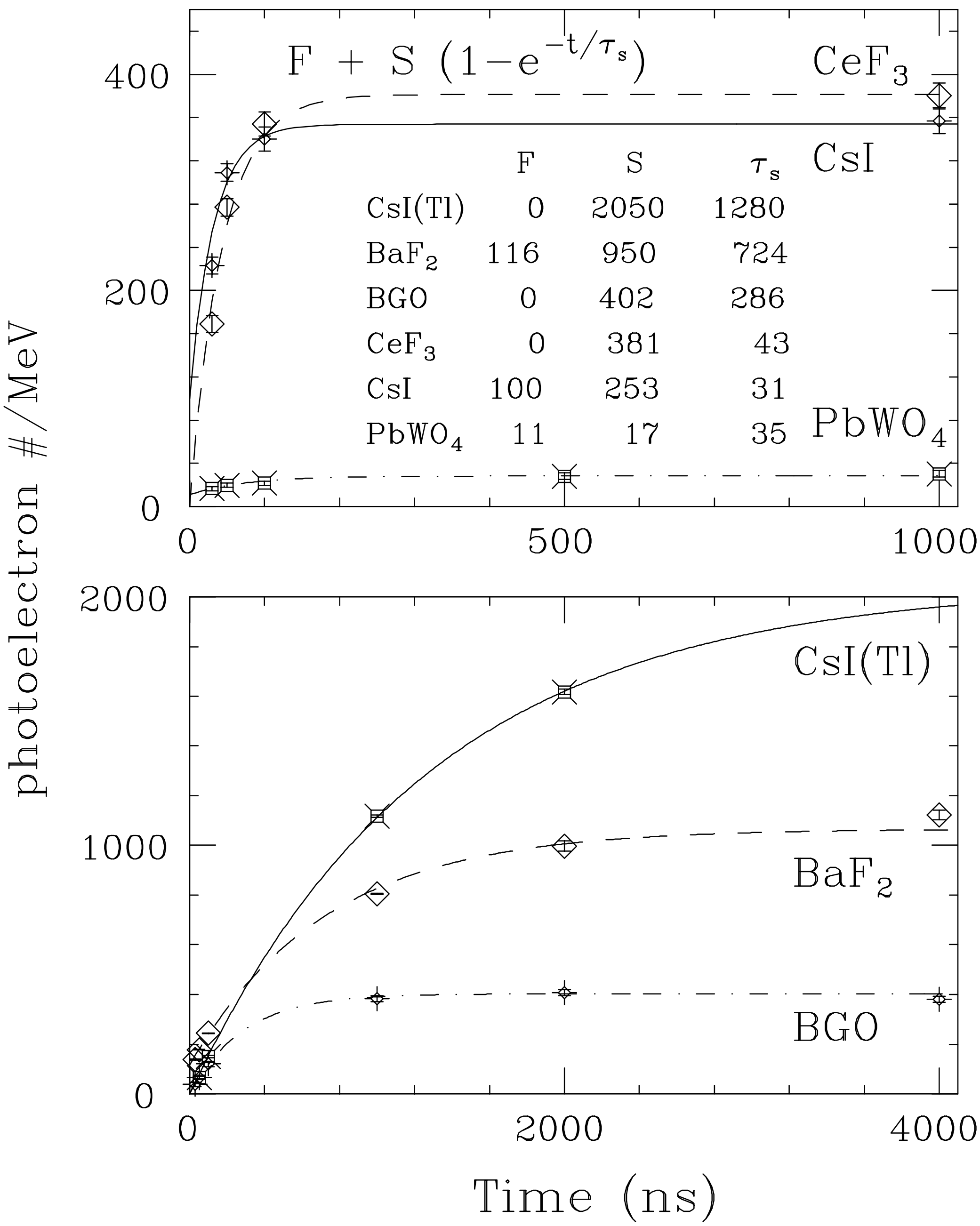
Scintillation Pulse of 6 Crystal Scintillators

Measured with HP54111D DS



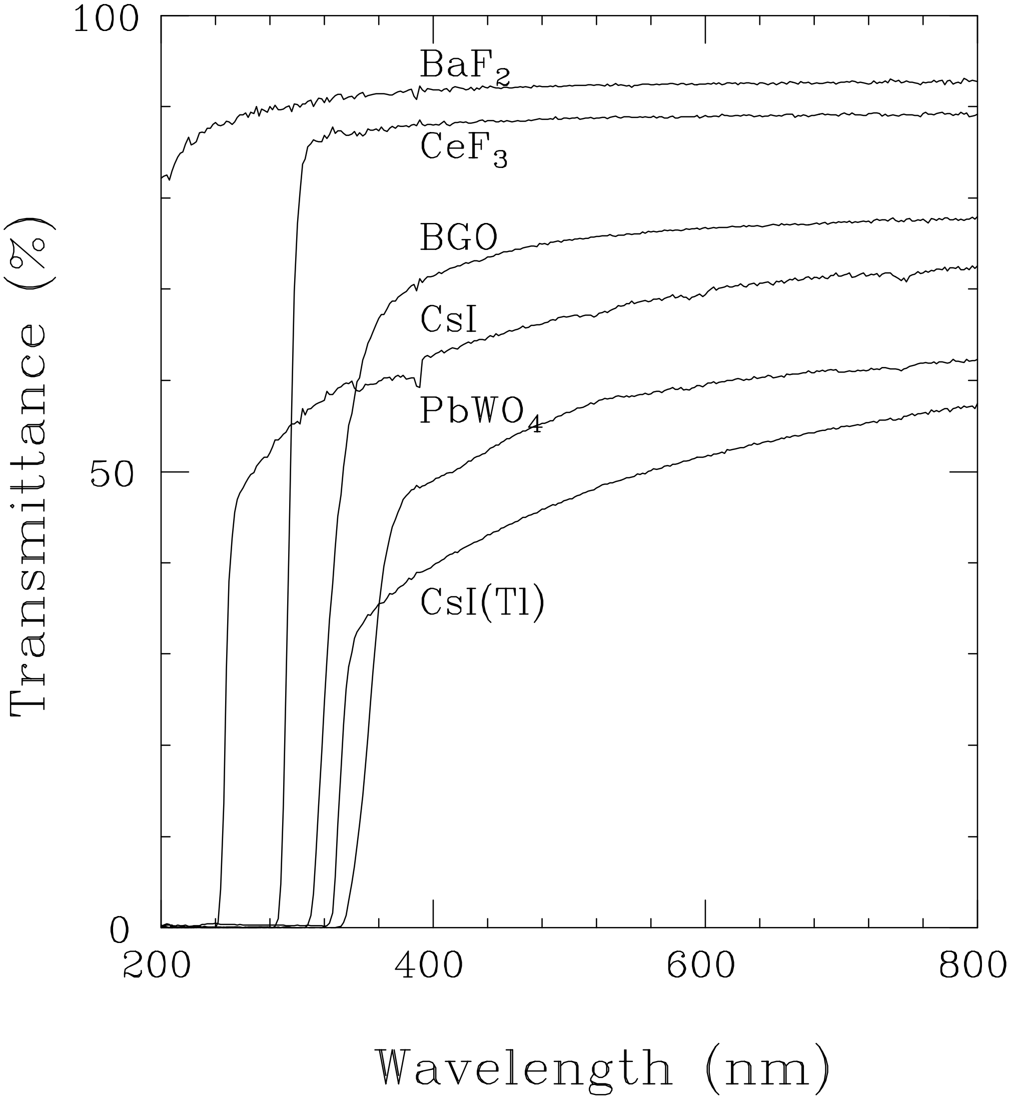
Light Yield of 6 Crystal Scintillators

Measured with Hamamatsu R2059 PMT



Transmittance of 6 Crystal Scintillators

Measured with Hitachi U-3210 SPM



Why Crystal Calorimetry?

- Good **electromagnetic energy resolution** because of total absorption: 0.6% is achievable for isolated e or γ, $\sigma = 2\%/\sqrt{E} \oplus 0.5\% \oplus c/E$.

- Good **position resolution** because of its fine segmentation: 0.3 mm is achievable for cell size and Molière radius of 2 cm, $\sigma = 2/\sqrt{E} \oplus 0.29$ mm.

- Good **photon angular resolution** by using primary event vertex.

- Good **e and γ identification and reconstruction efficiency** because of fine granularity and pointing geometry: e/π discrimination better than 10^{-3} is achievable for e ID efficiency of 95%.

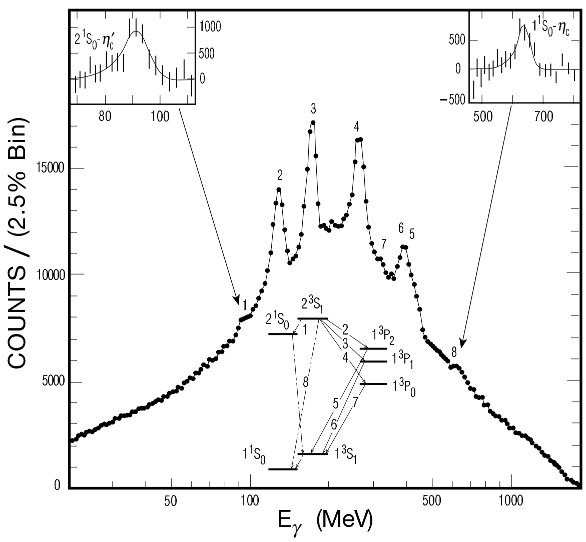
- Good **missing energy resolution** together with HCAL because of hermeticity.

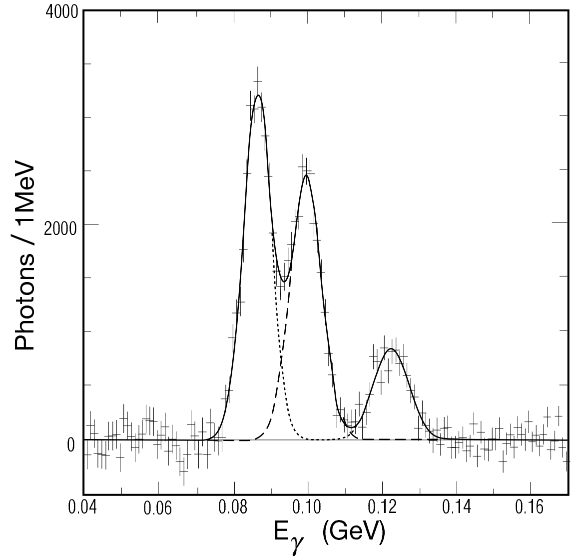
- Good **jet energy resolution** by using information from other detector components: L3 achieved 7% for hadronic Z decays.

- Can be rather **compact** by using heavy crystals of $\sim$1 cm radiation length (BGO and $PbWO_4$).

Discovery Power of Precision e & γ

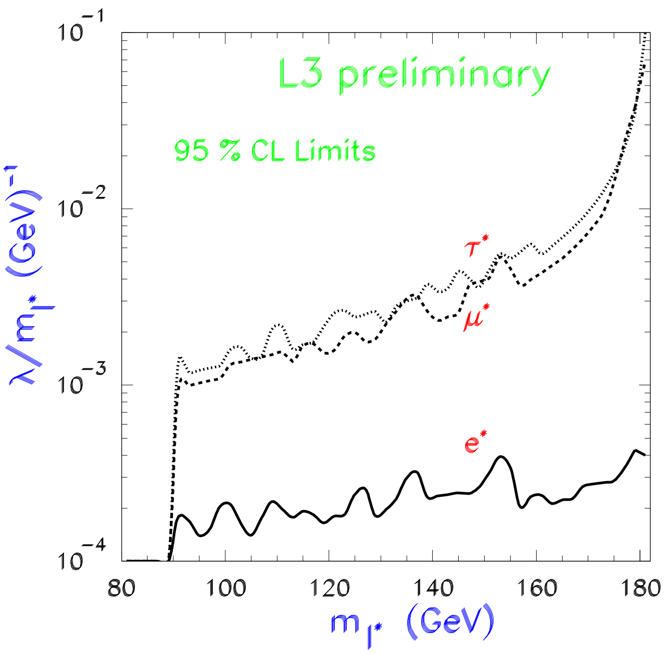
- Study quarkonium system through inclusive photons by Crystal Ball and CLEO.

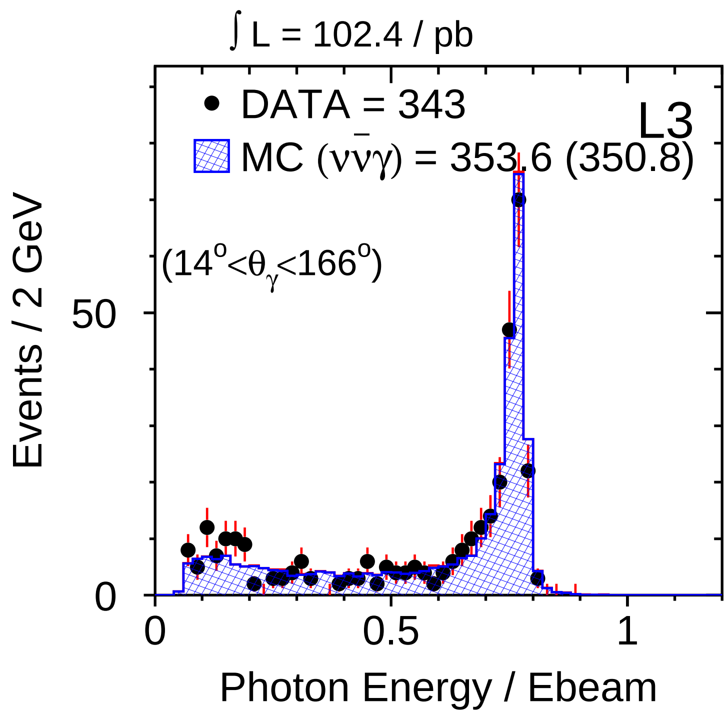




- Searches for excited leptons in composite models and a SUSY breaking model with gravitino $\tilde{G}$ as LSP at LEP II.

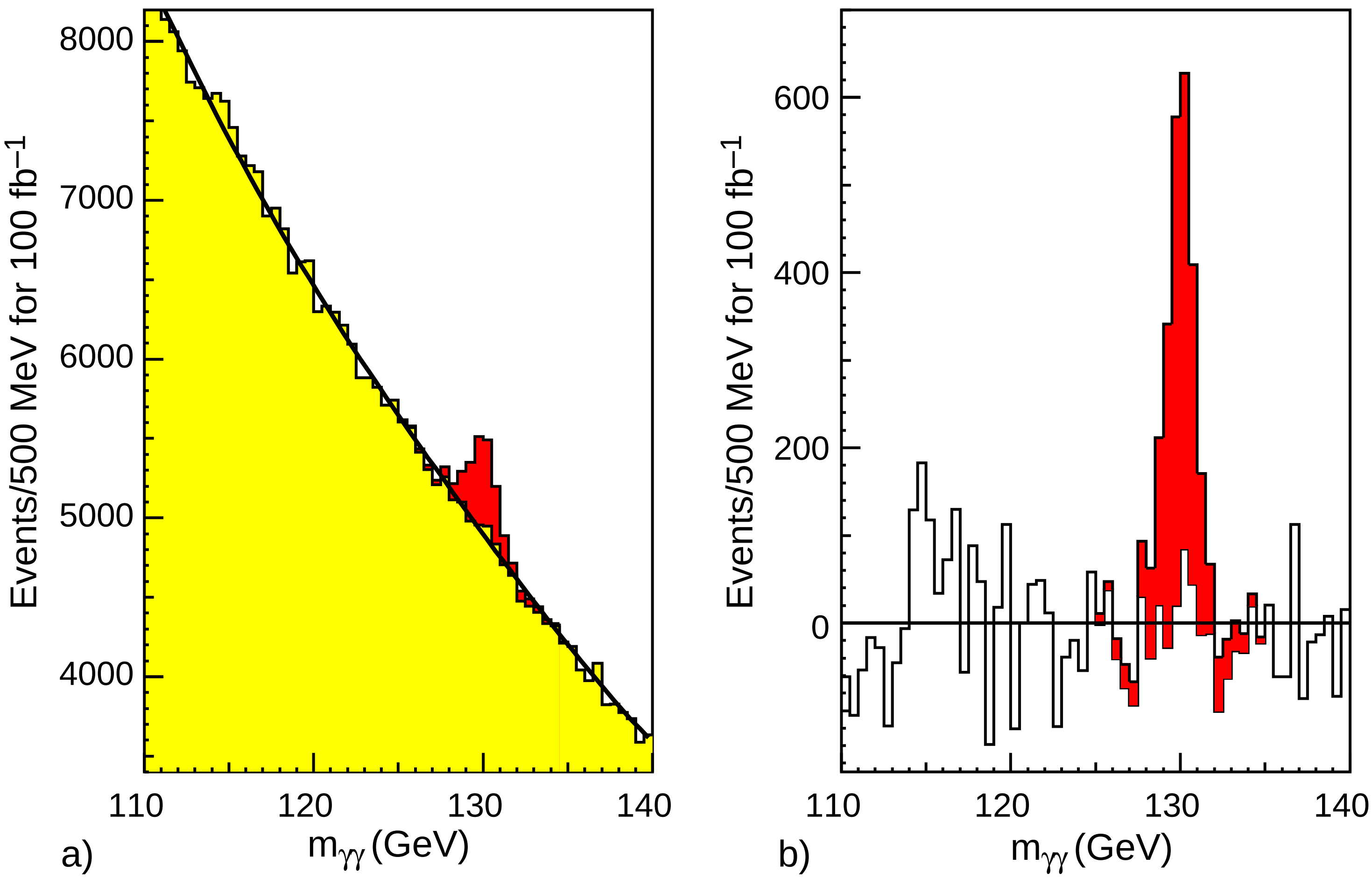
$$\mathrm{e}^+\mathrm{e}^- \to \ell^*\ell^* \; or \; \ell^*\ell, \; \ell^* \to \ell\gamma, \quad \mathrm{e}^+\mathrm{e}^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1 \; or \; \tilde{\chi}^0_1\tilde{G}, \; \tilde{\chi}^0_1 \to \tilde{G}\gamma$$





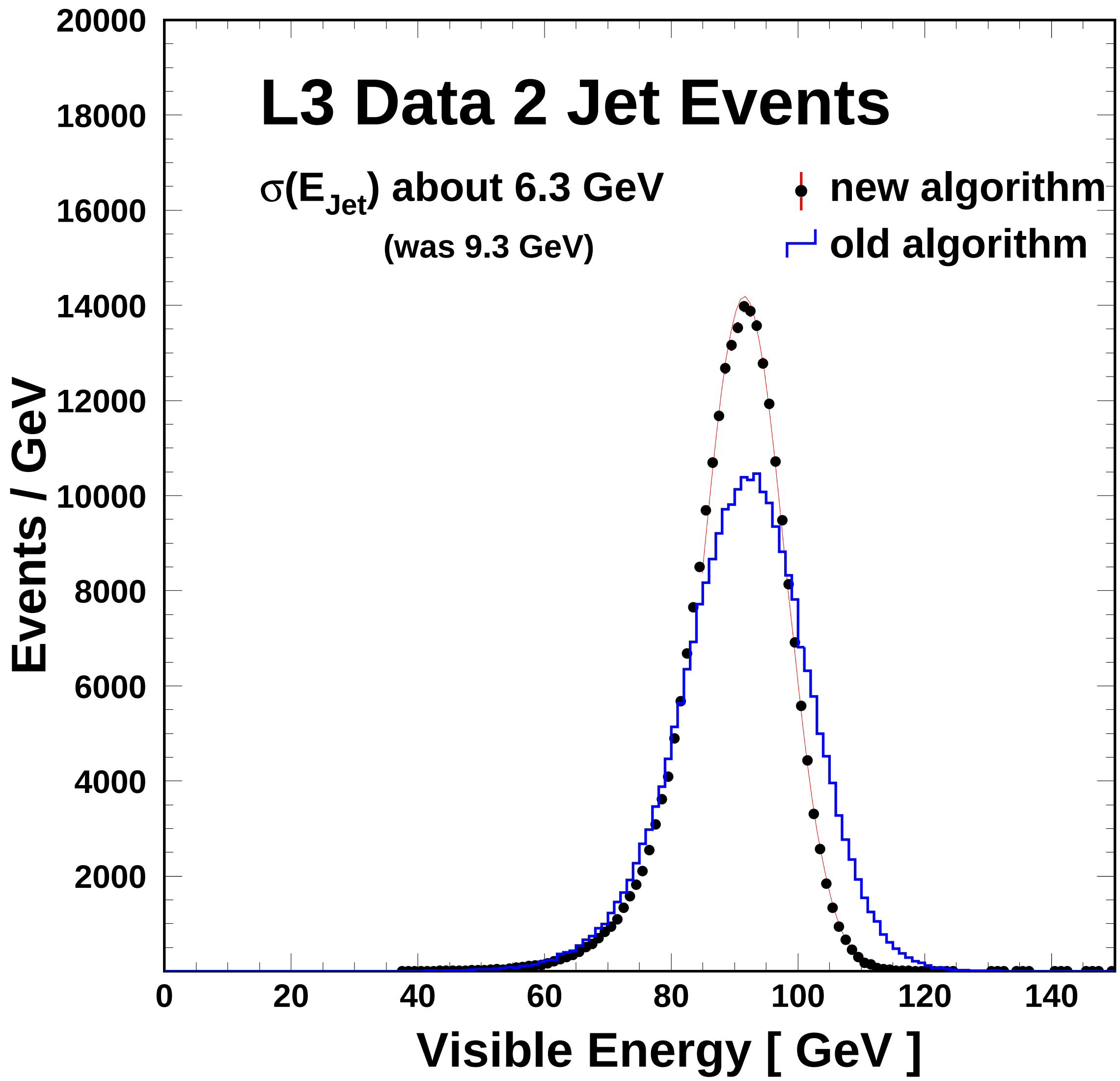
Discovery Power of Precision Photons

H$\rightarrow \gamma\gamma$ Searches with PWO ECAL by CMS at LHC



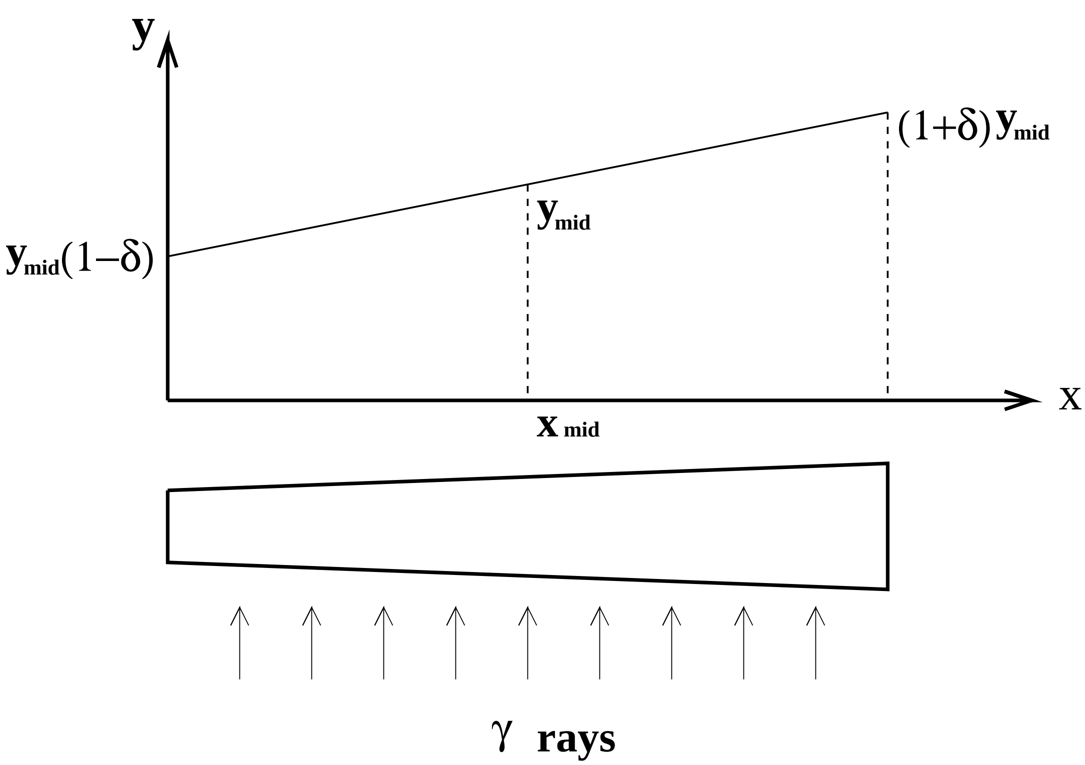
Improvement of L3 Jet Mass Resolution

Using Information from other Detector Components



Definition of Light Response Uniformity

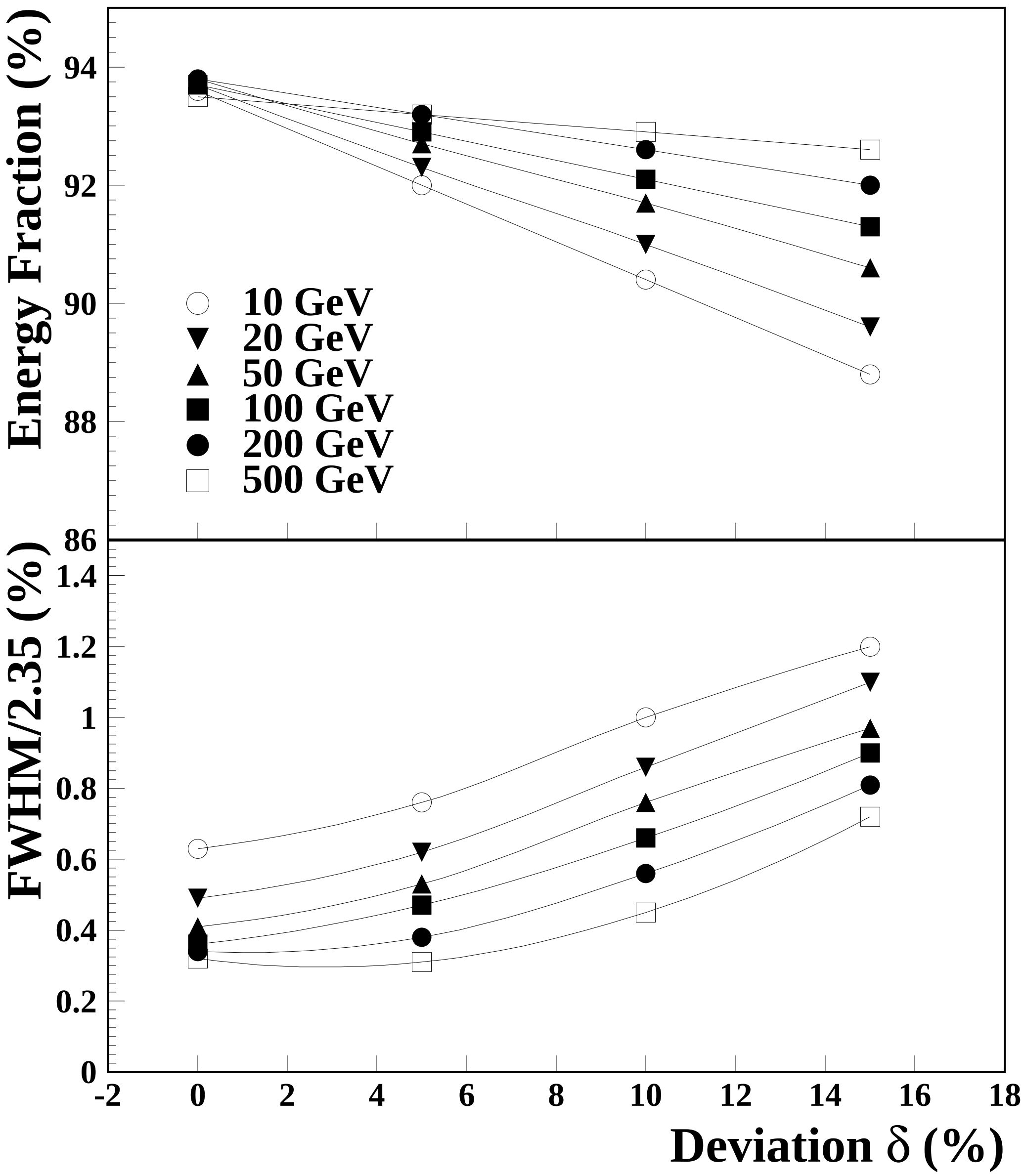
$$Y = Y_{mid}\left[1 + \delta(x/x_{mid} - 1)\right]$$



Effect of Light Response Uniformity

GEANT Simulation: NIM **A340** 442 (1994)

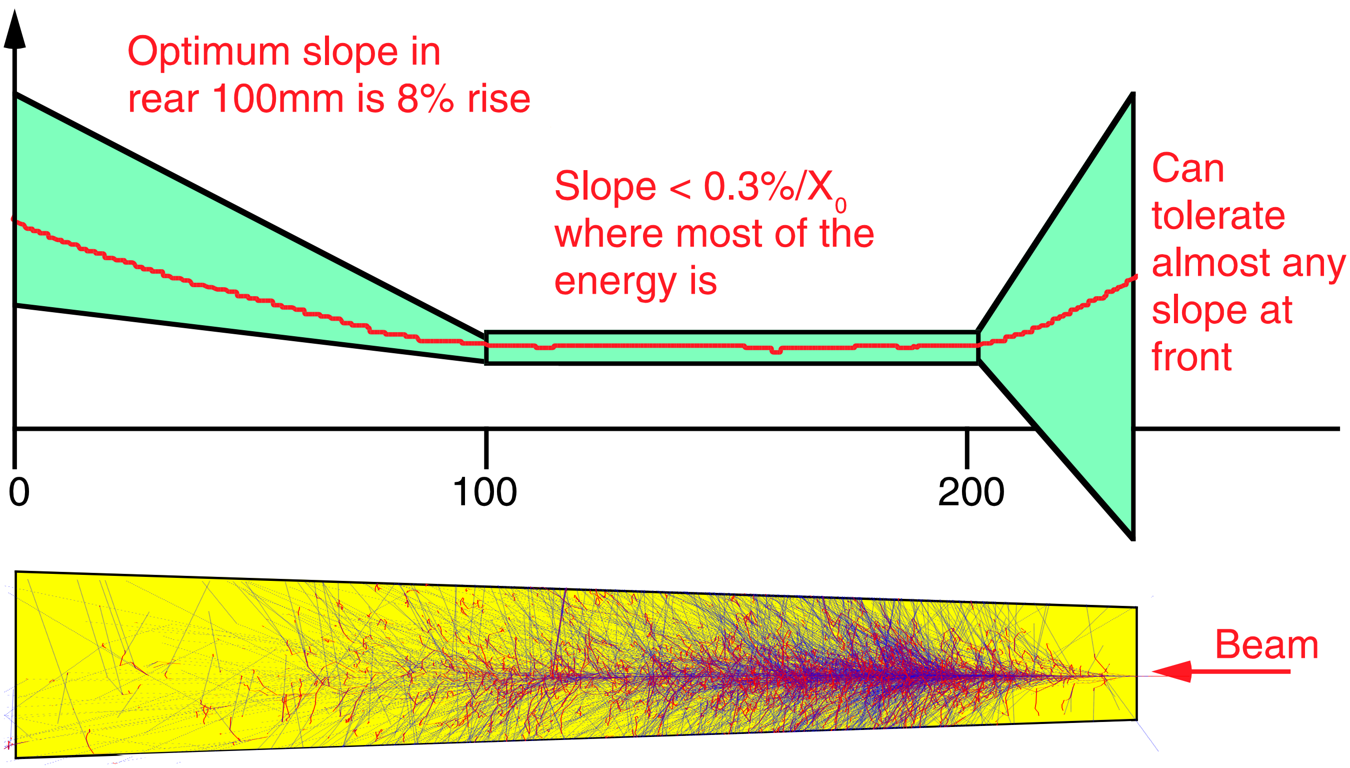
Not Recoverable Resolution Degradation



Effect of Light Response Uniformity

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

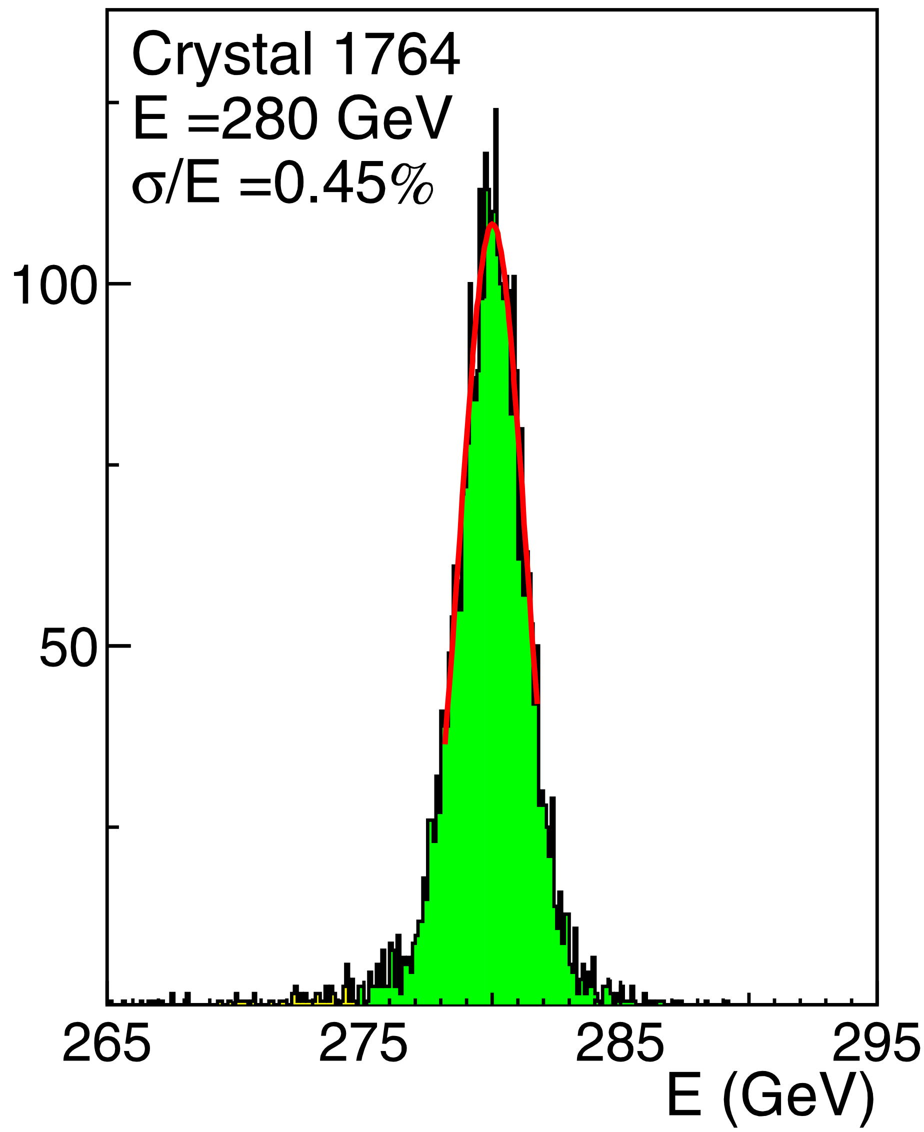
- Minimize contributions to the constant term of energy resolution, caused by light response non-uniformity.



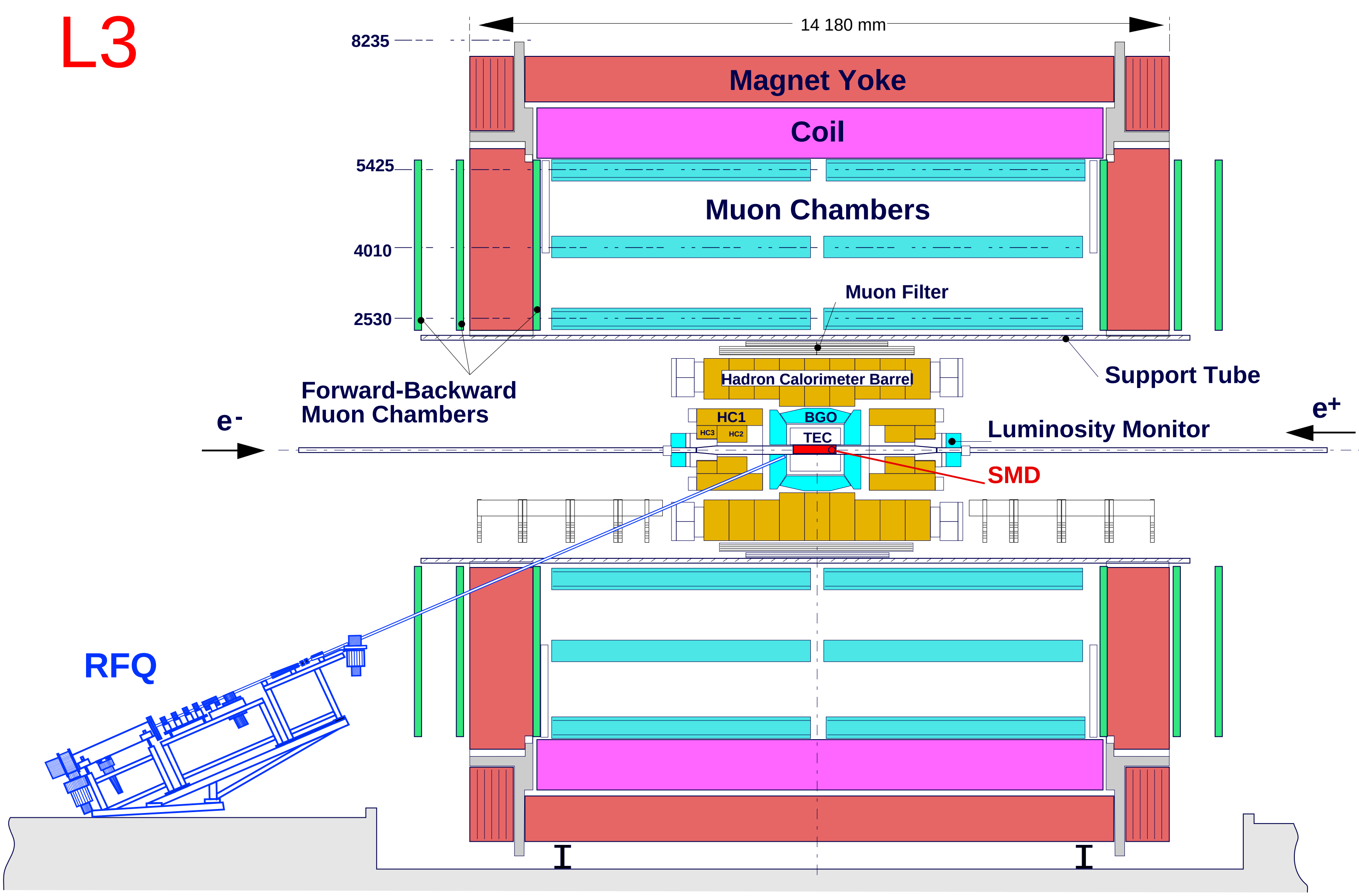
CMS $PbWO_4$ ECAL Beam Test

Resolution of 280 GeV Electrons

$$\frac{\delta E}{E} = \frac{4.1\%}{\sqrt{E}} \oplus \mathbf{0.37\%} \oplus 0.15/E = 0.45\%$$



RFQ Installation in L3 Experiment

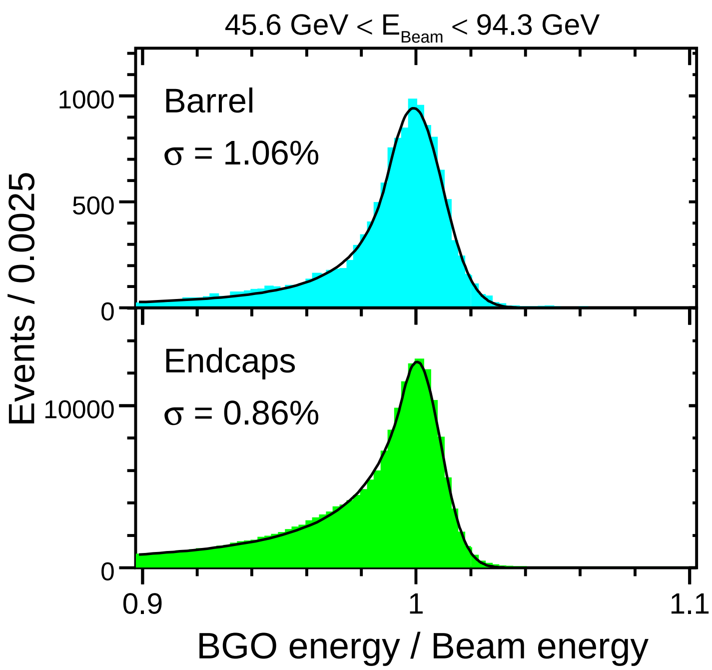


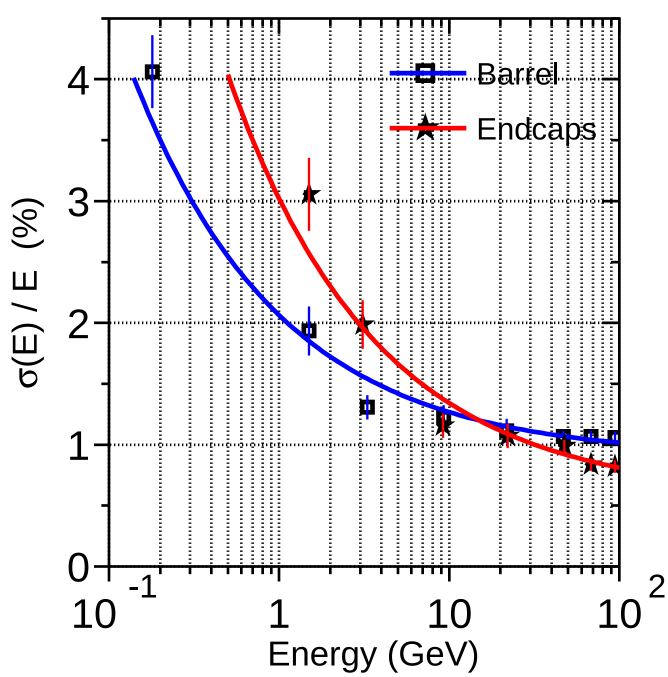
y863col

Bhabha Electron Energy Resolution with L3 BGO

0.5% Calibration Achieved *in situ* with RFQ

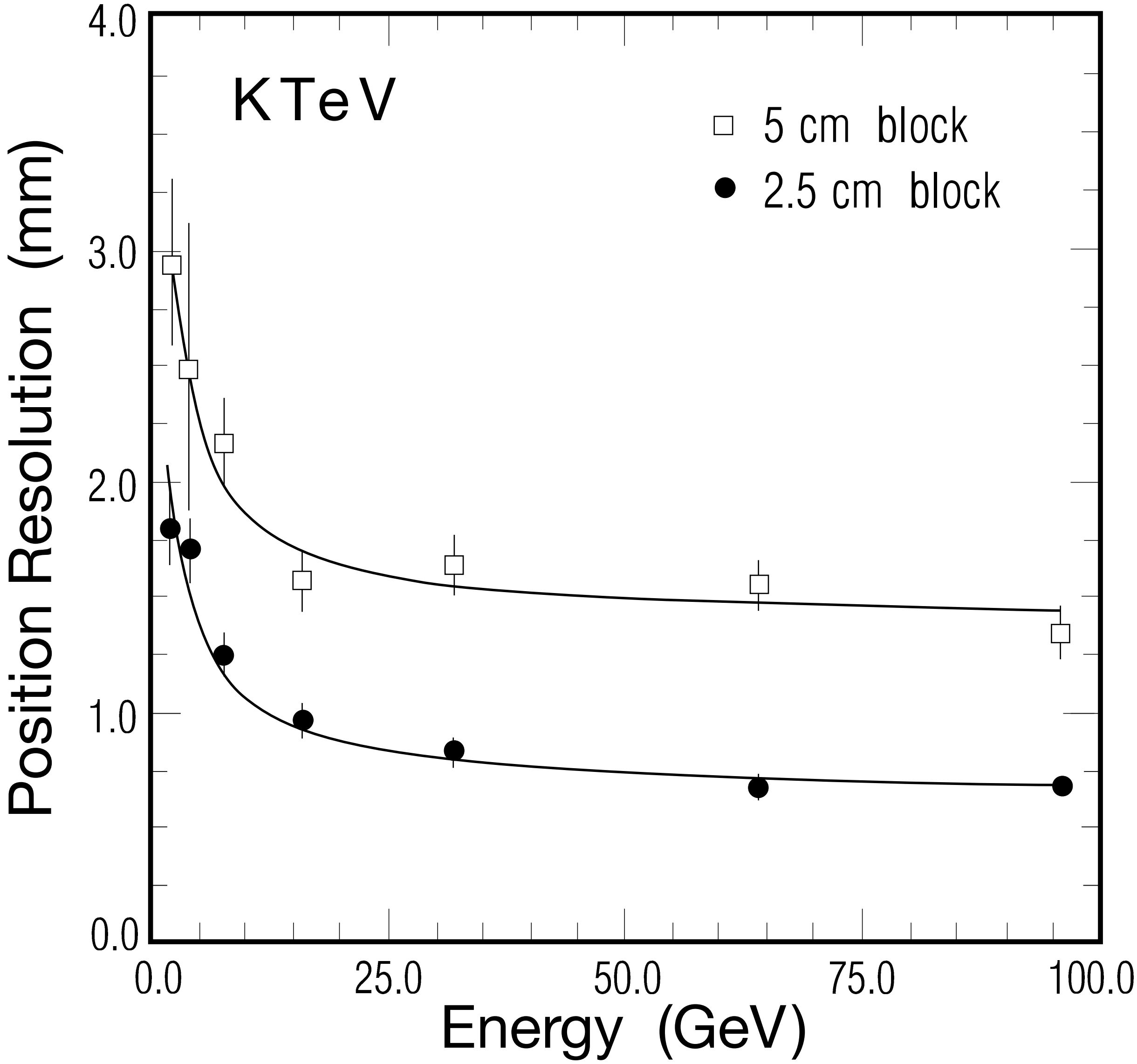
Contribution	"Radiative"+Intrinsic	Temperature	Calibration	Overall
Barrel	0.8%	0.5%	0.5%	1.07%
Endcaps	0.6%	0.5%	0.4%	0.88%



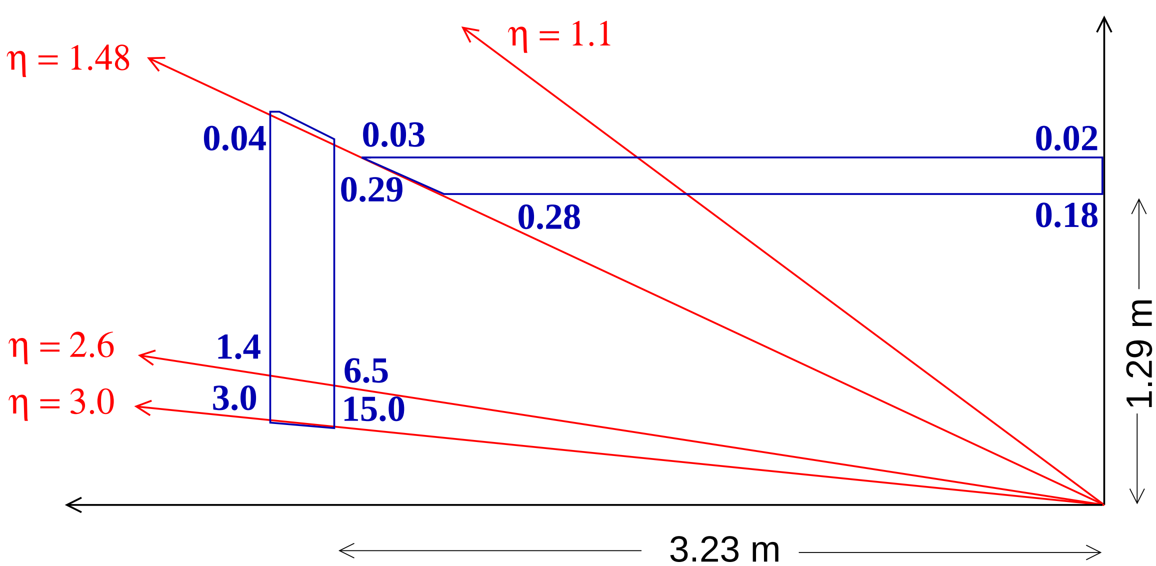


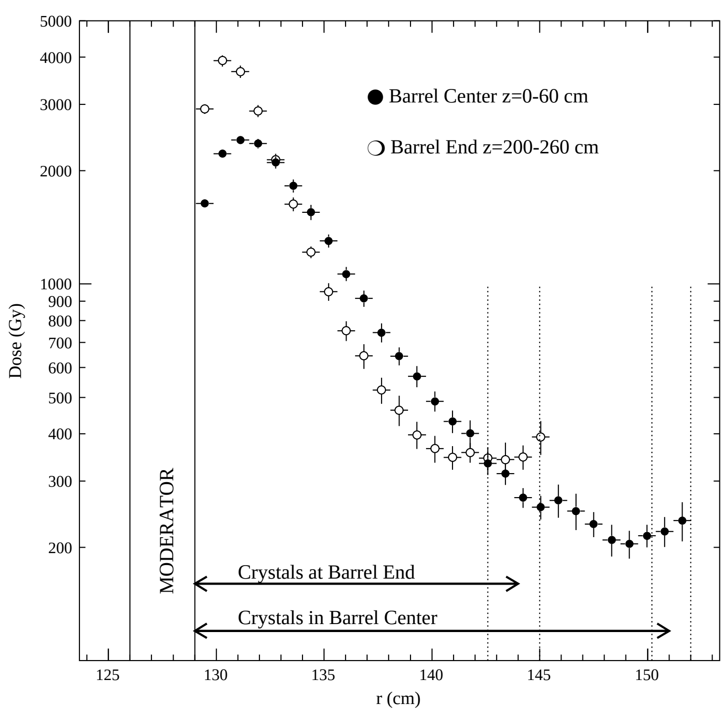
Crystal Position Resolution

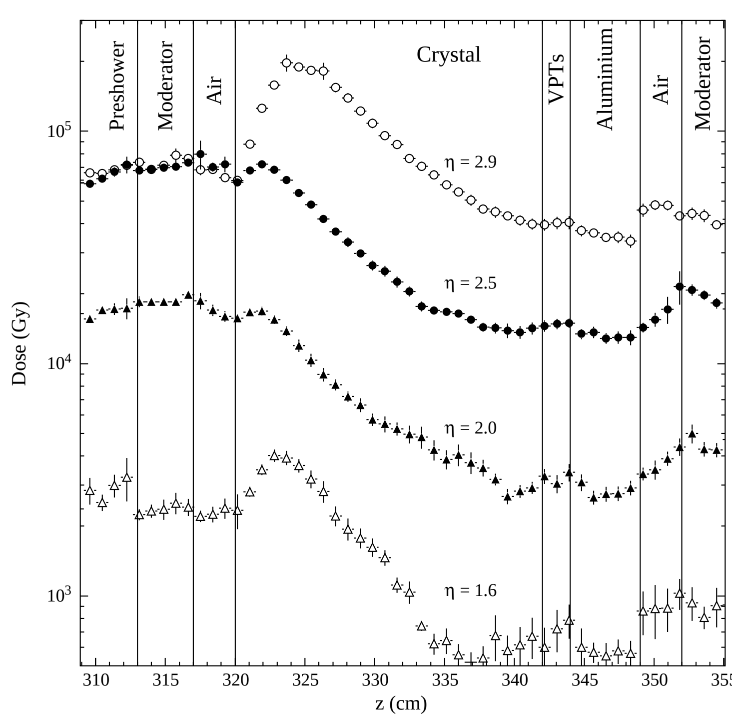
$2/\sqrt{E} \oplus 0.29$ mm for $R_{Moliere}$ = 2 cm



$PbWO_4$ Radiation Environment







Possible Effects of Radiation on Crystals

1. Induced absorption caused by color center formation:
   - Reduce light attenuation length and thus light output, and maybe
   - Degrade of **light response uniformity**.

2. Induced phosphorescence:
   - Increase readout noise.

3. Reduced scintillation light yield:
   - Reduce light output and degrade light response uniformity.

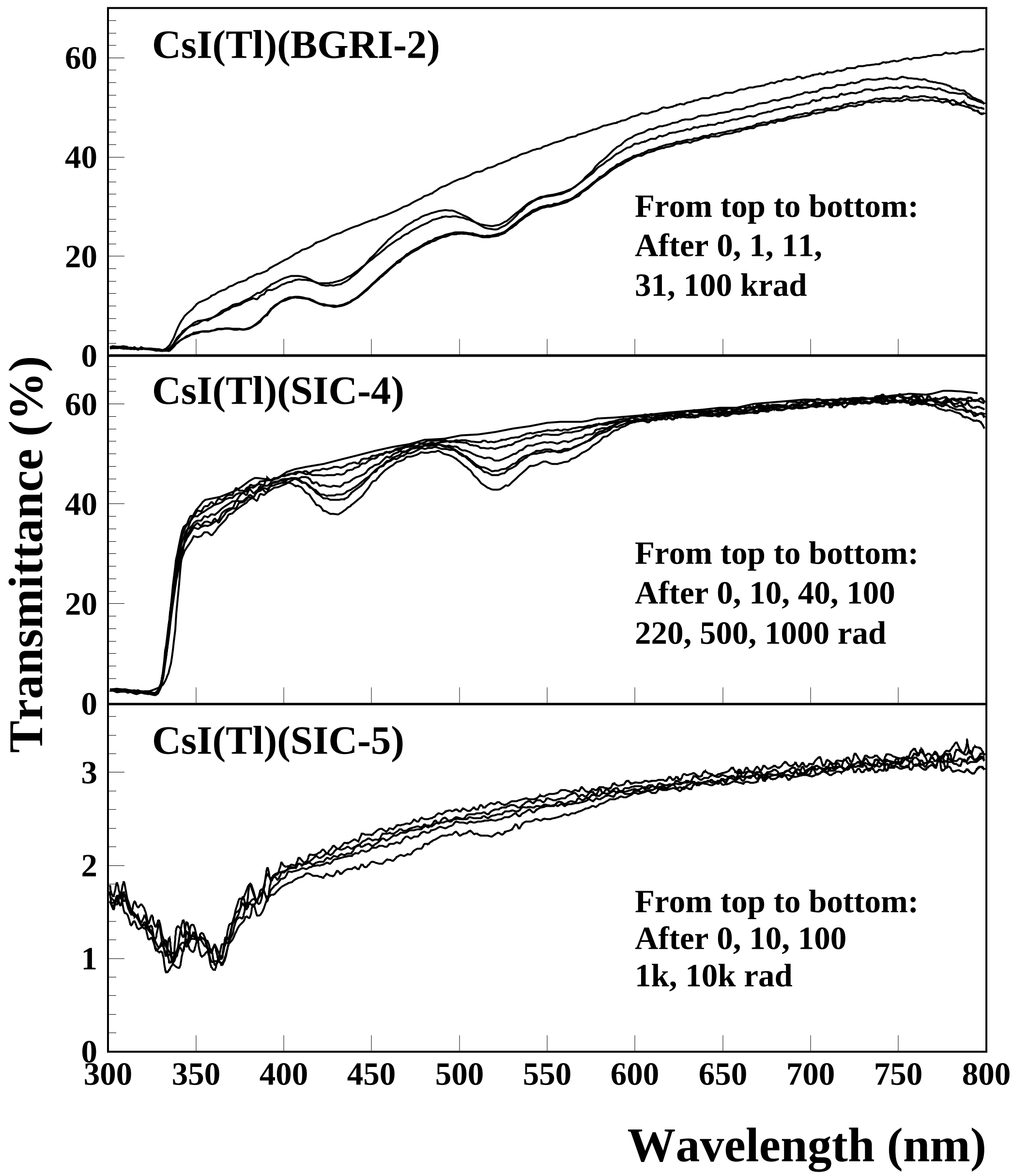
Item	CsI(Tl)	CsI	BaF_2	BGO	$PbWO_4$
Color Centers	Yes	Yes	Yes	Yes	Yes
Fluorescence	Yes	Yes	Yes	Yes	Yes
Scintillation	No	No	No	No	No
Recover @RT	Slow	Slow	No	Yes	Yes
Dose Rate Dependence	No	No	No	Yes	Yes
Thermall Annealing	No/Yes	No/Yes	Yes	Yes	Yes
Optical Bleaching	No/Yes	No/Yes	Yes	Yes	Yes

CsI(Tl) Longitudinal Transmittance

Measured with Hitachi U-3210 Photospectrometer

Three Full Size Samples

Proc. of VI ICCHEP, Frascati Physics Series, (1996) 589

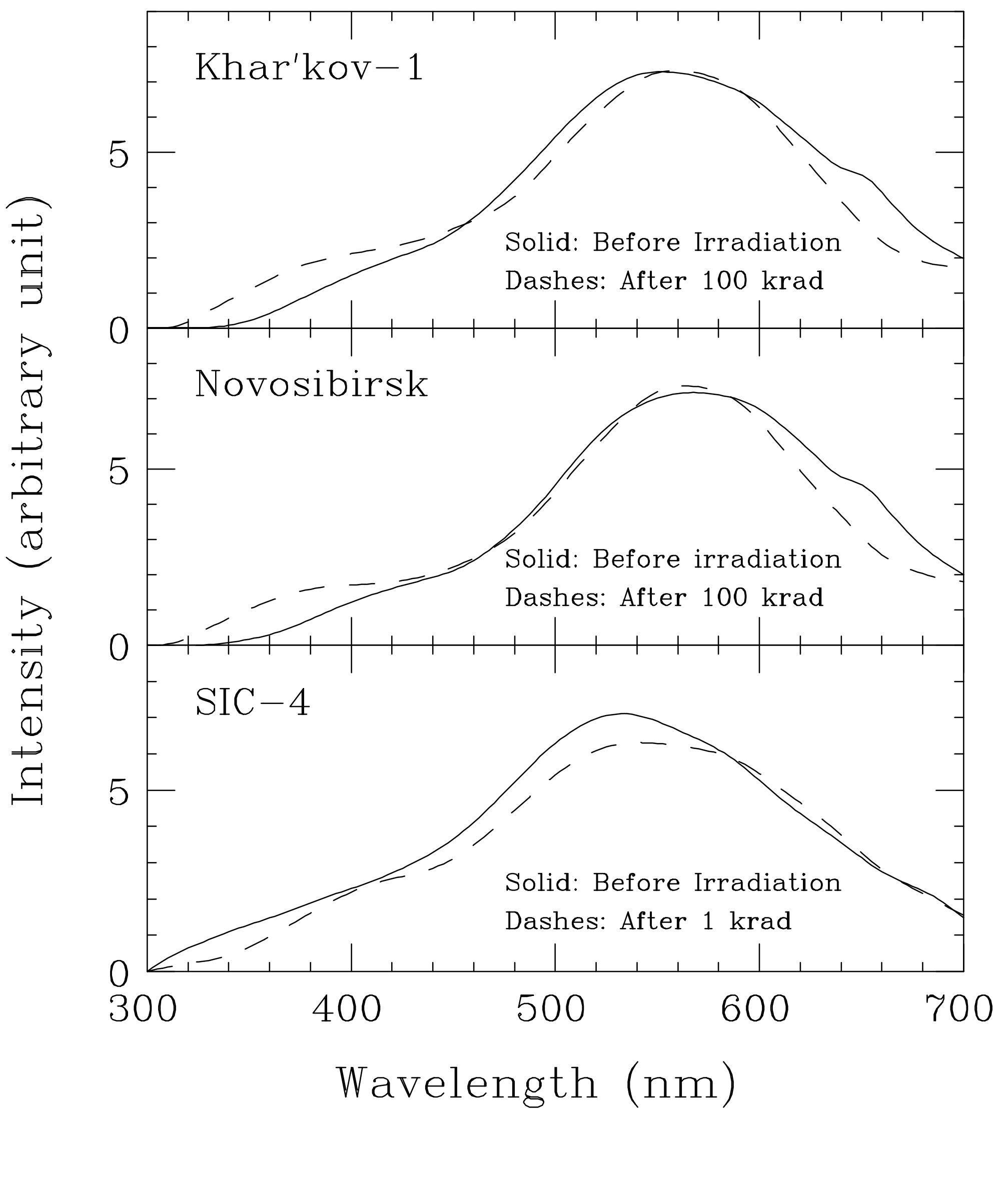


CsI(Tl) Photoluminescence

Measured with ORIEL 77250 Monochromator

Three Full Size Samples

Proc. of VI ICCHEP, Frascati Physics Series, (1996) 589

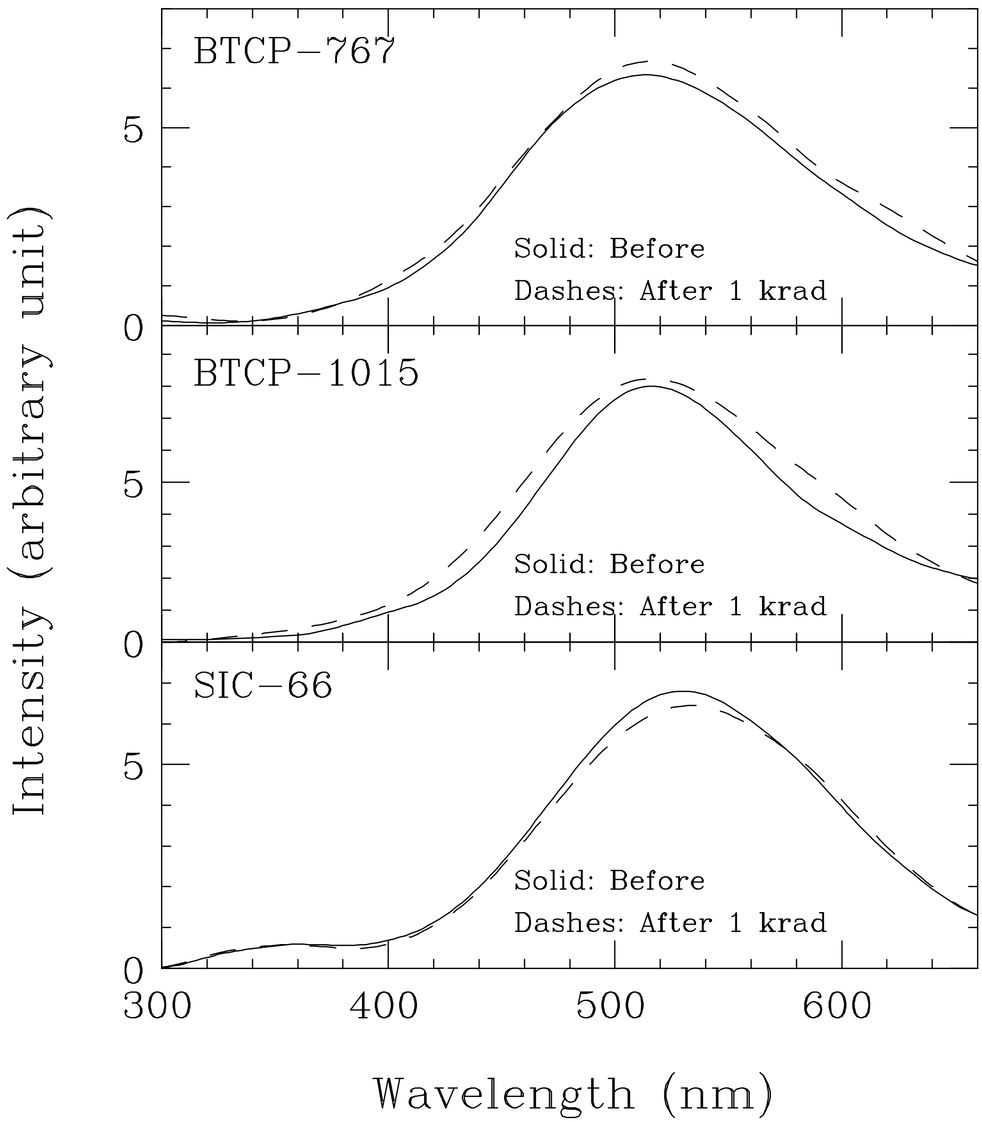


$PbWO_4$ Photoluminescence

Measured with ORIEL 77250 Monochromator

Before (Solid) & After (Dashes) 1 krad

Three Large Samples



Effect of LAL on Light Response Uniformity

Ray-Tracing Simulation for CMS $PbWO_4$ Crystals

No Change in Uniformity with LAL longer 3.5 crystal length

The **light collection efficiency** (η), fit to a linear function of distance to the small end of the crystal (x), was determined with two parameters: η_m — the light collection efficiency at the middle of the crystal (X_m), and δ — the **uniformity**.

$$\eta(x)/\eta_m = 1 + \delta(x - x_m)/x_m$$

LAL (cm)	20	40	60	80	200
Large Area Photo Detector, covering 100% back face					
η_m (%)	9.5±.2	15.7±.4	19.2±.5	21.6±.6	26.9±.7
δ (%)	23±1	-4.6±.8	-11±1	-15±1	-15±1
ϕ5 mm Photo Detector, covering 3.7% back face					
η_m (%)	.38±.04	.74±.08	1.1±.1	1.4±.2	3.0±.3
δ (%)	23±4	–3.5±4	-12±4	-16±4	-17±3
$\frac{\eta_m(\phi 5mm)}{\eta_m(Full)}$ (%)	4.0	4.7	5.7	6.5	11

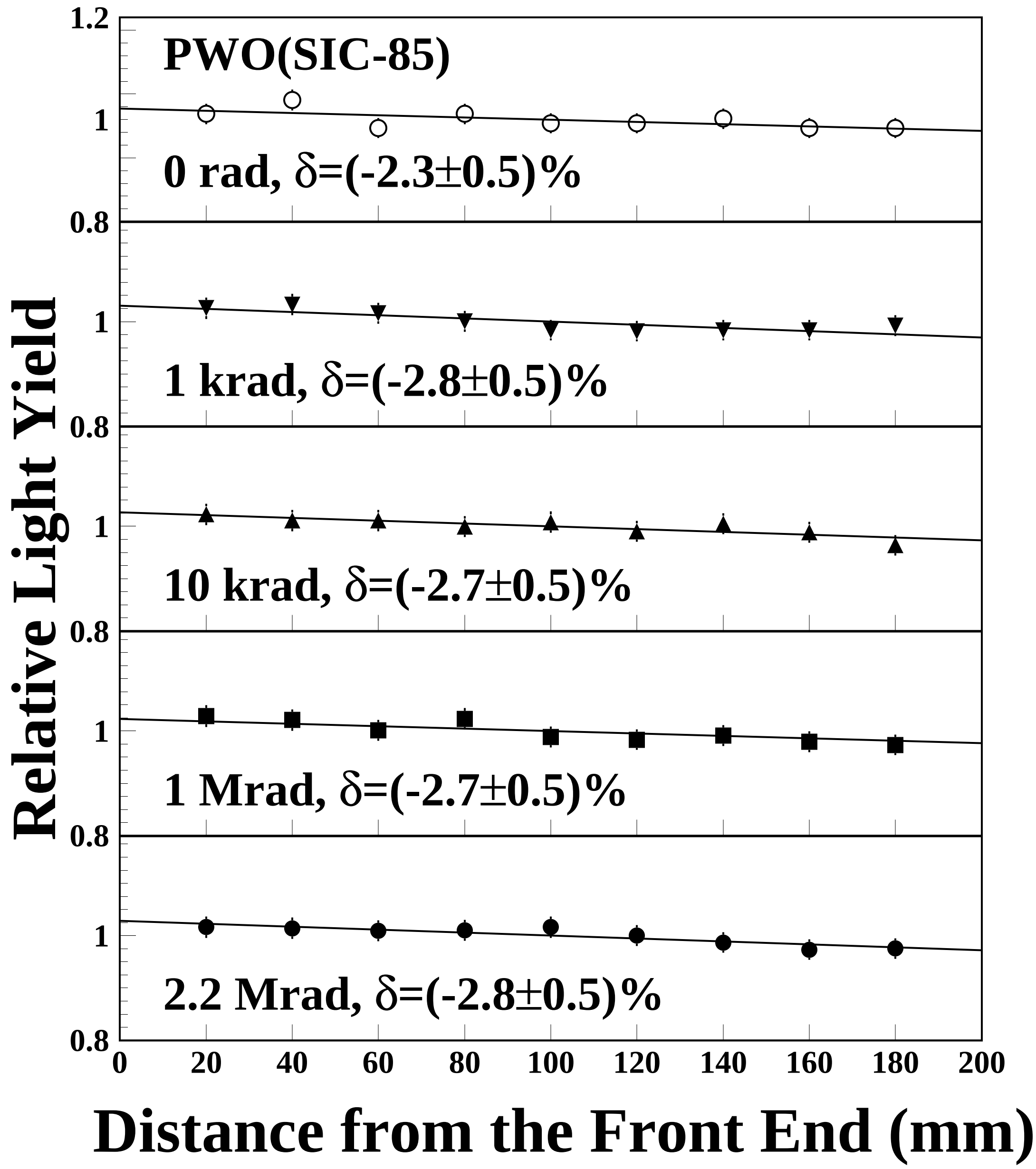
$PbWO_4$ Light Response Uniformity

Measured with R2059 PMT, 200 ns

20 cm SIC-85 under High Rate Lateral Irradiation

$$LY/LY_{mid} = 1 + \delta(x - x_{mid})/x_{mid}$$

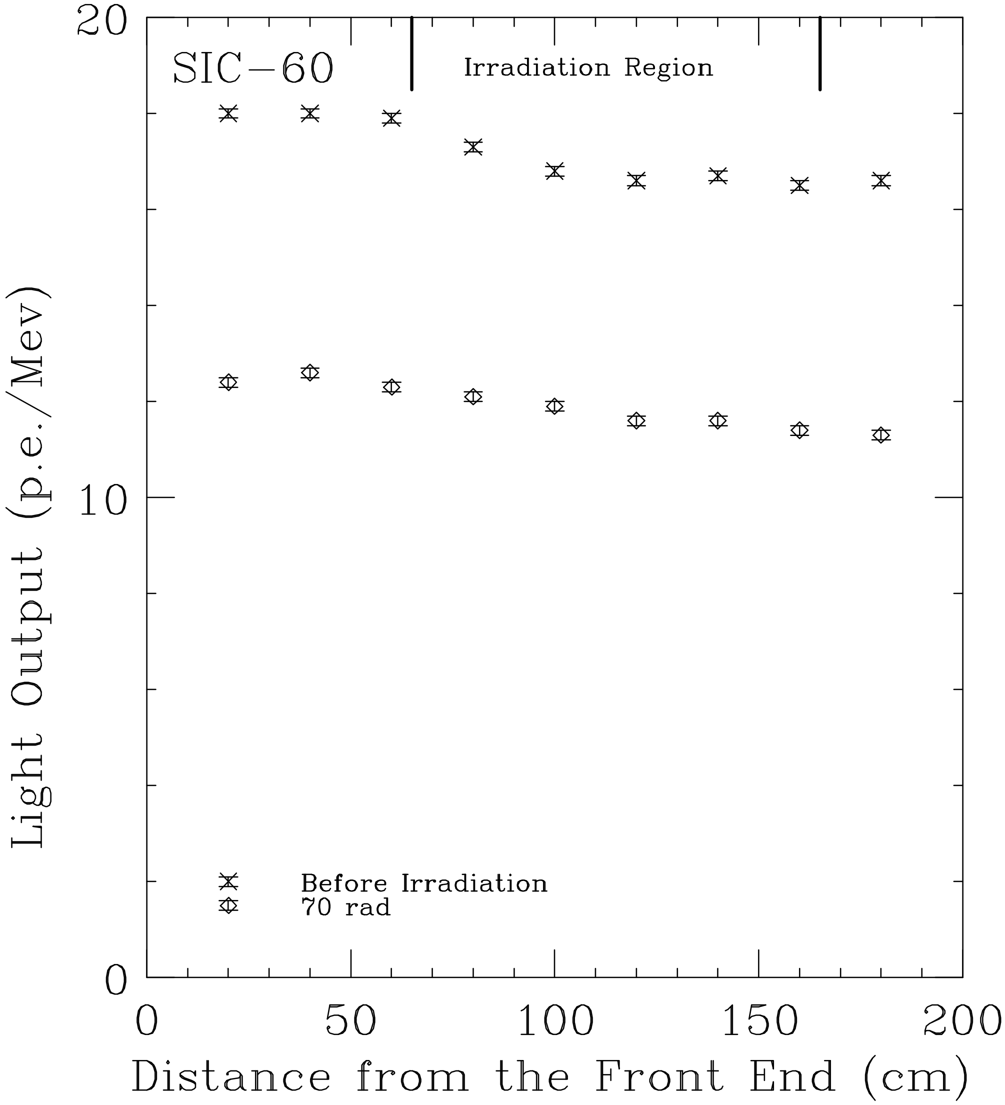
IEEE Trans. Nucl. Sci. **NS-44** 468 (1997)



No Scintillation Damage

Light Response Uniformity

20 cm $PbWO_4$ SIC-60

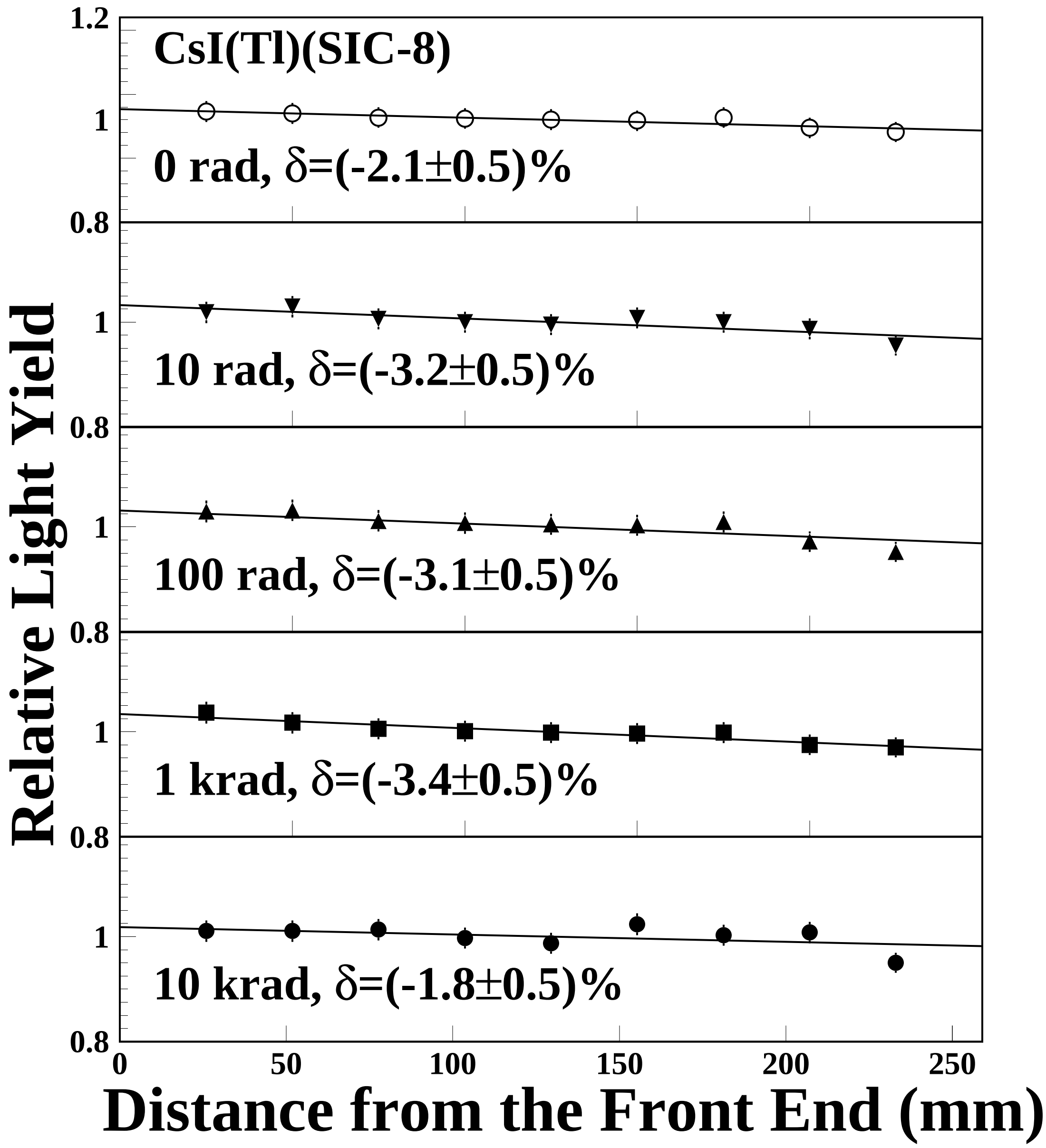


CsI(Tl) Light Response Uniformity

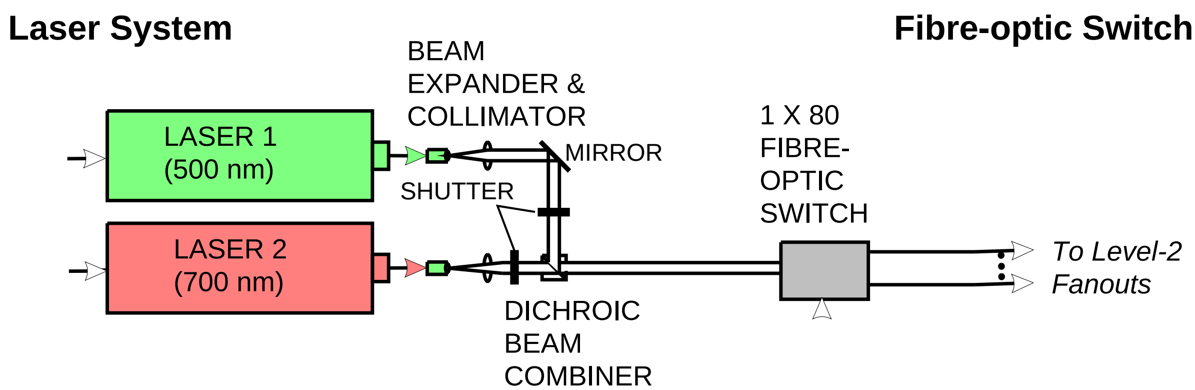
Measured with 2×S2744-08 Si Diode, 2 μs

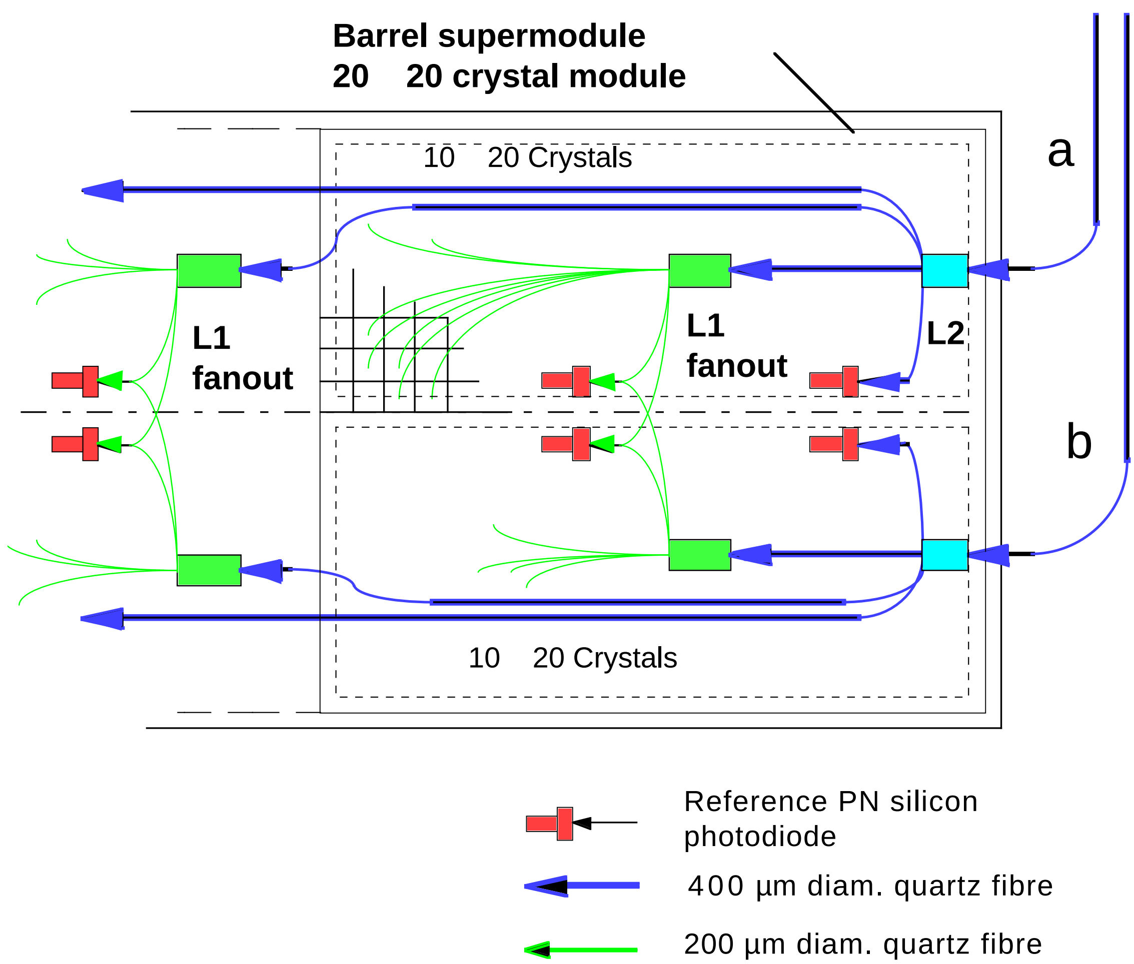
Full Size Sample SIC-8 under Front Irradiation

$$LY/LY_{mid} = 1 + \delta(x - x_{mid})/x_{mid}$$



Monitoring System Design

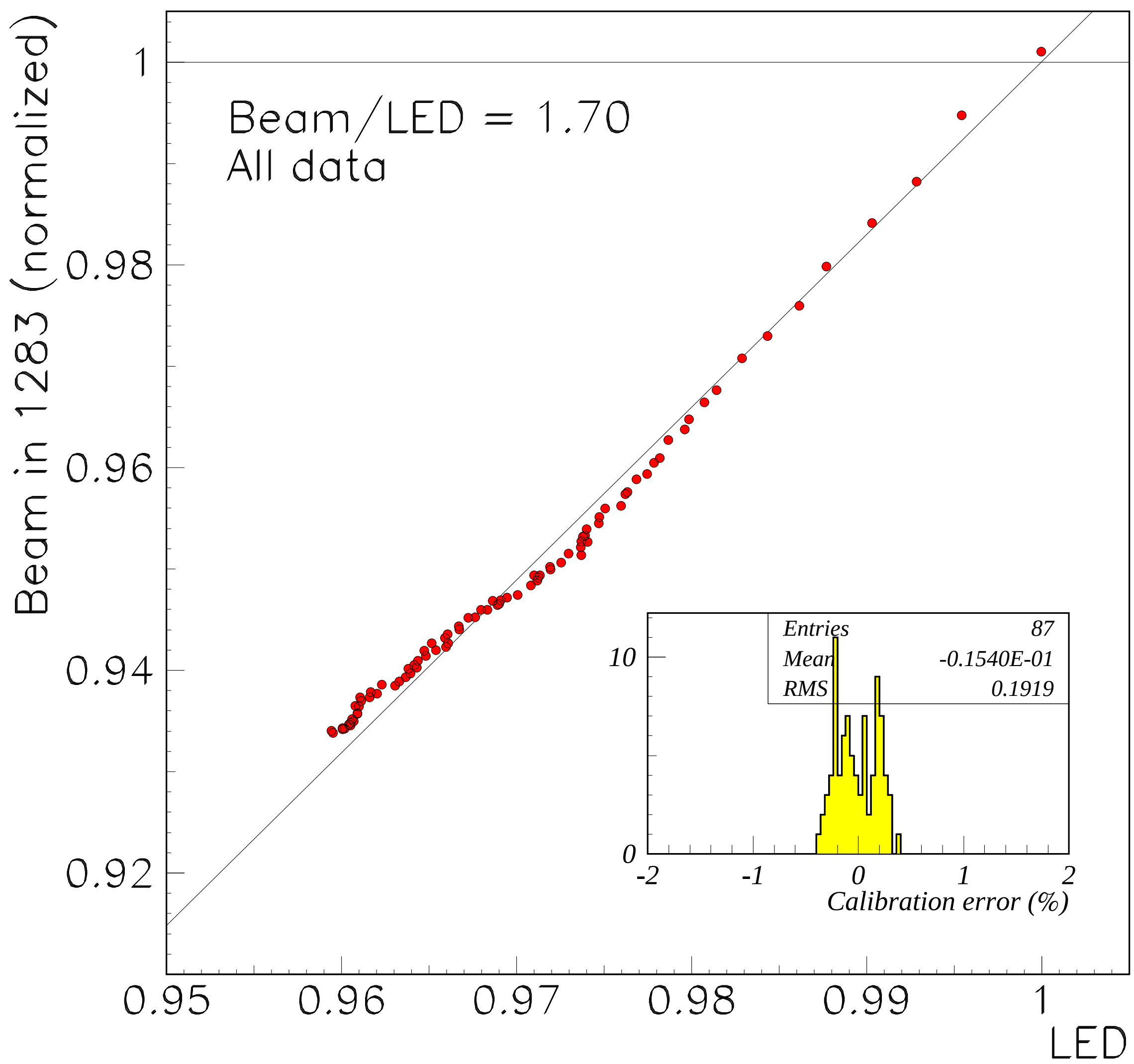




Correlation: Monitoring & Beam Signals

$PbWO_4$ Sample 1283, up to 650 rad

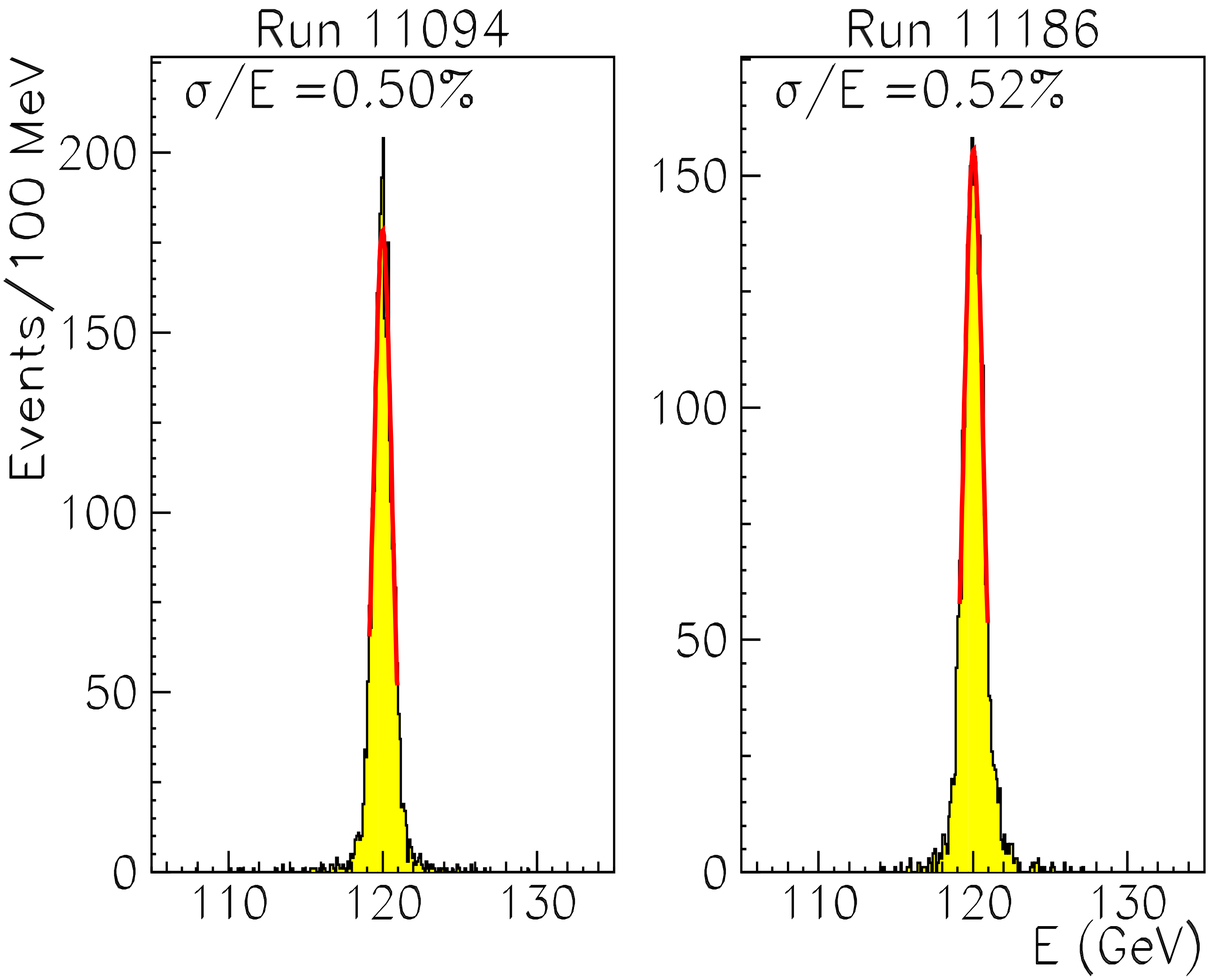
CERN EP/98-020 (1998)



Energy Resolution (Uniformity) Not Damaged

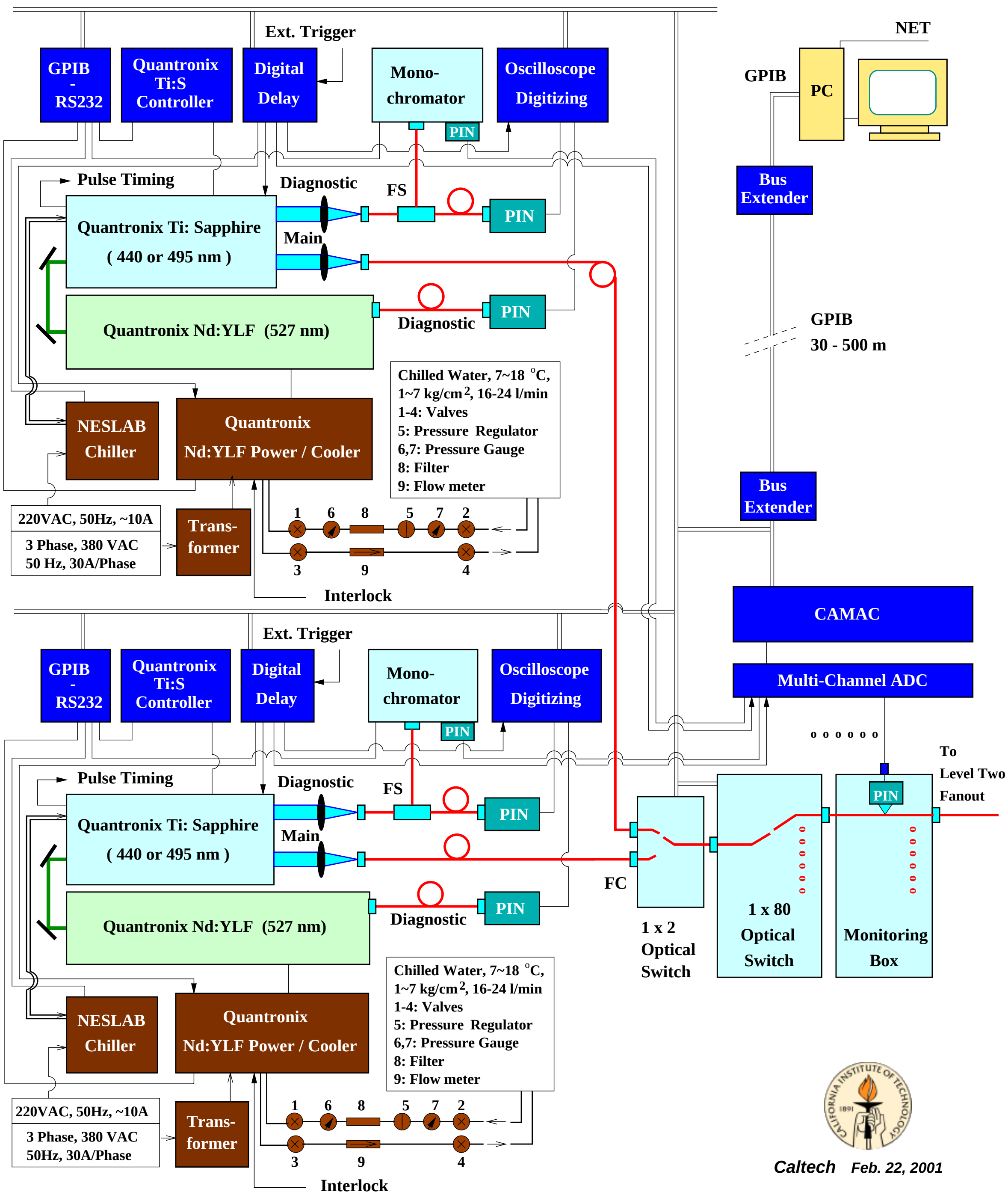
$PbWO_4$ Sample 1283, before & after 650 rad

CERN EP/98-020 (1998)



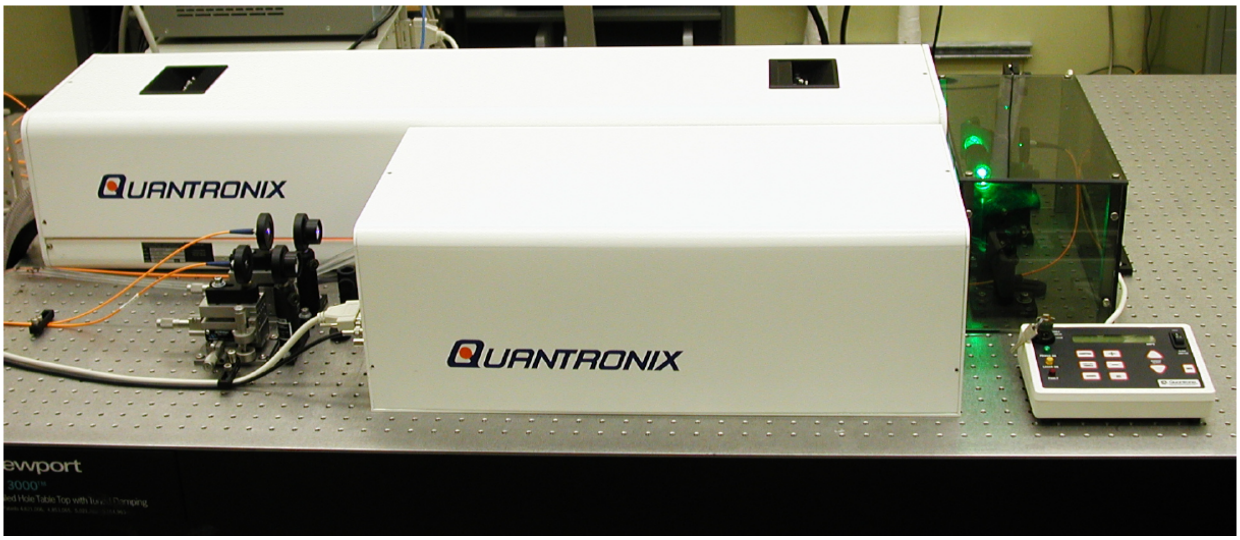
Monitoring Light Source & High Level Distribution

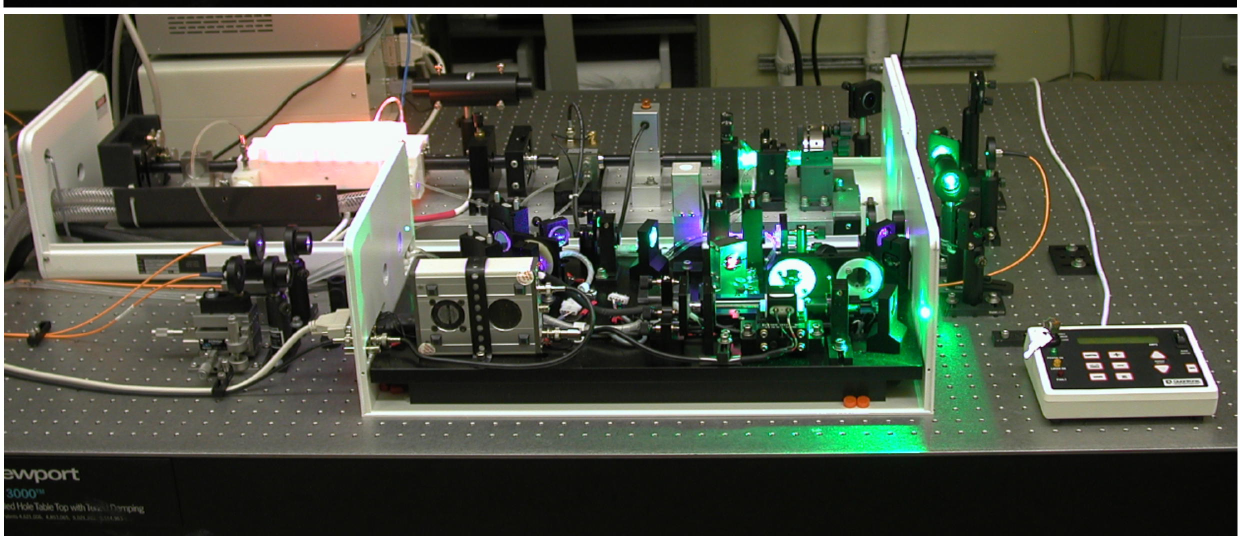
Two Laser Systems, Switch, Monitor and Control



Caltech *Feb. 22, 2001*

Nd:YLF and Ti:S Monitoring Lasers





Color Center Kinetics
Annihilation (Recover) and Creation (Damage)

NIM A332 (1993) 113, NIM A356 (1993) 113

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

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

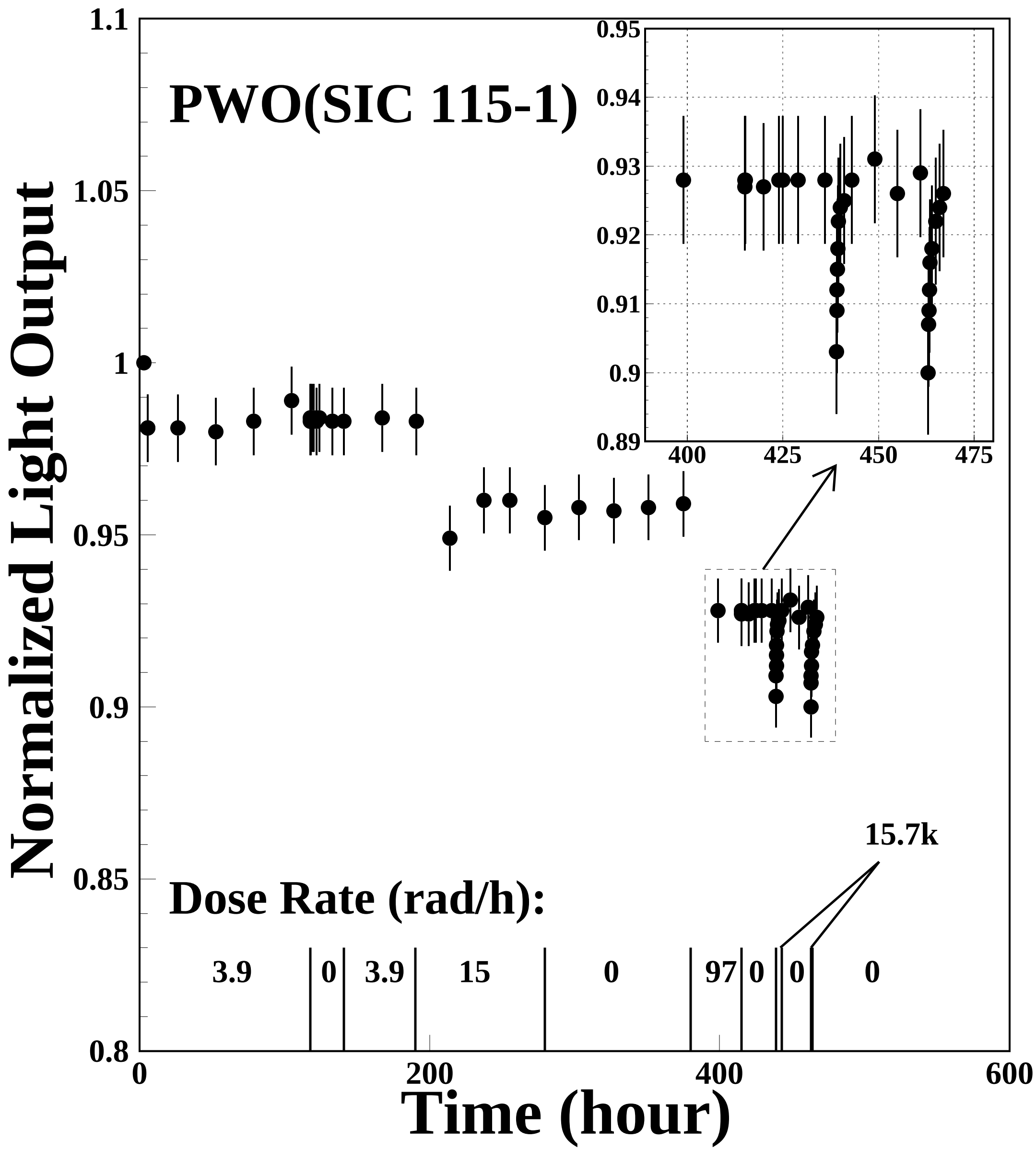
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of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

$$D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R}$$

$PbWO_4$: Dose Rate Dependence

Measured with R2059 PMT

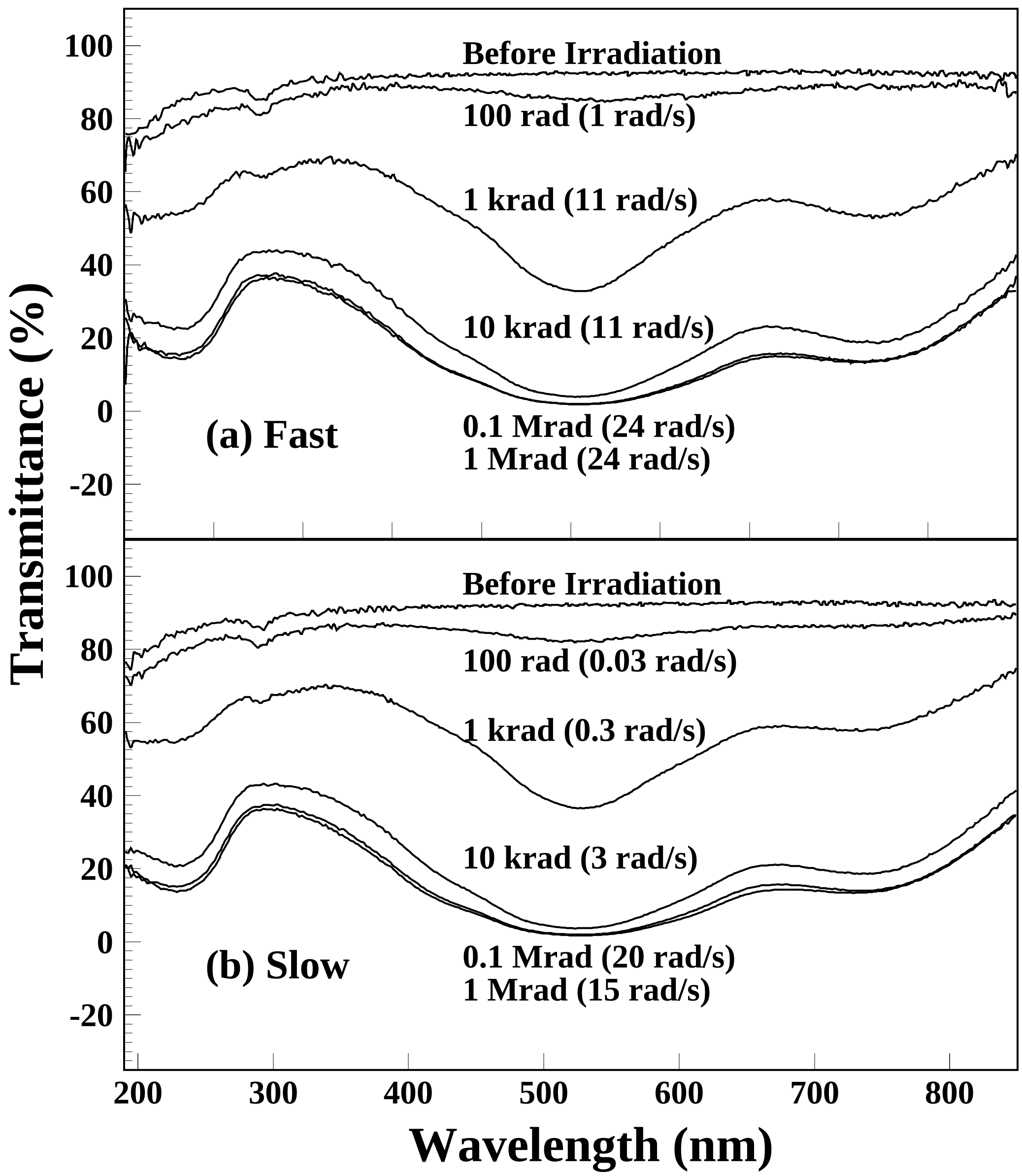
5 cm Sample SIC 115-1



BaF_2: No Dose Rate Dependence

the Same Crystal with Identical Wrapping

Nucl. Instr. and Meth. **A340** (1994) 442



CsI(Tl) Damage Mechanism

Oxygen Contamination is known to cause radiation damage for other alkali halide scintillators. In BaF_2, for example, hydroxyl (OH^-) may be introduced into crystal through a hydrolysis process, and latter decomposed to interstitial and substitutional centers by radiation through a radiolysis process,

$$OH^- \rightarrow H_i^0 + O_s^- \;\; or \;\; H_s^- + O_i^0$$

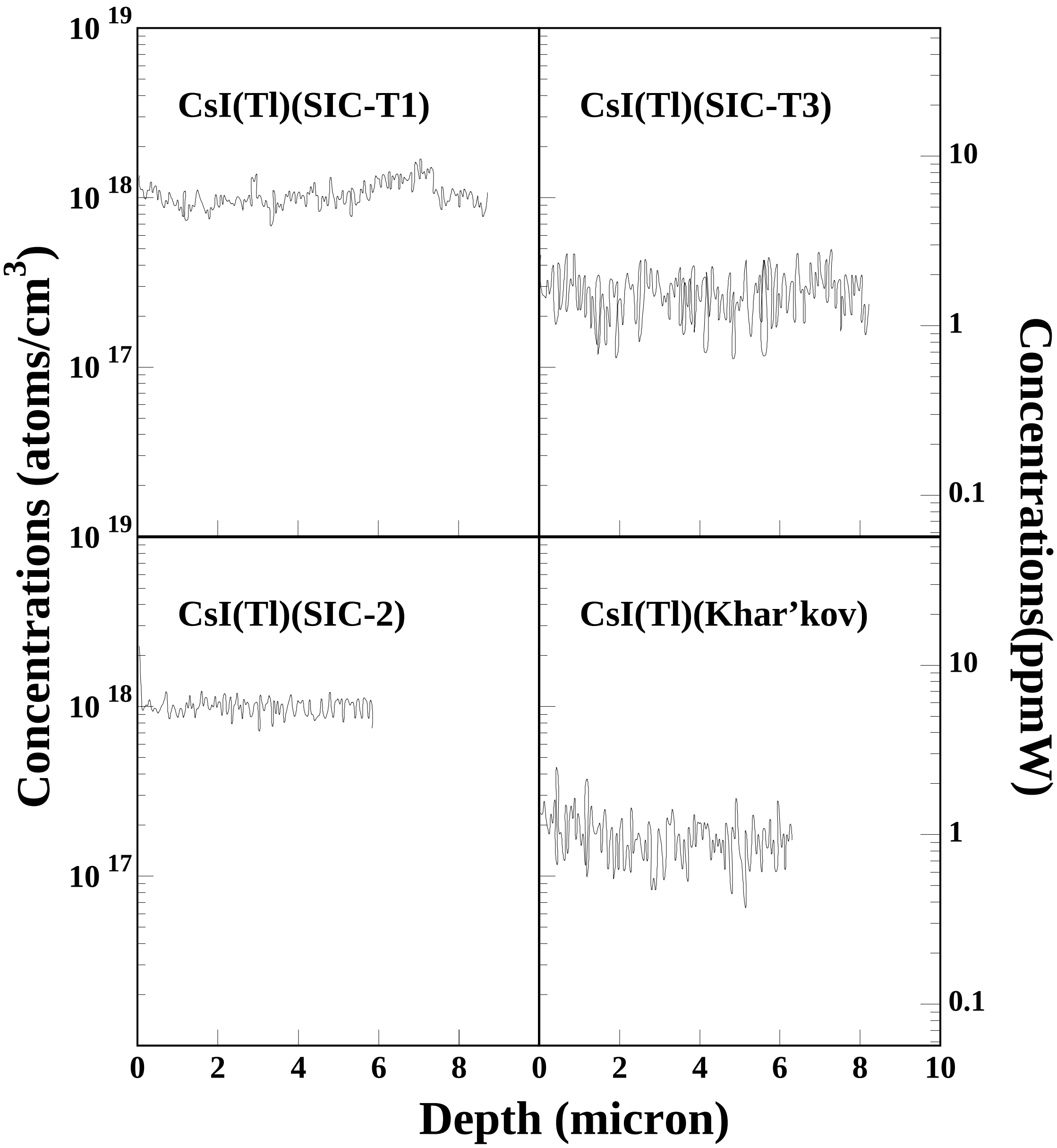
where subscript i and s refer to interstitial and substitutional centers respectively, as discussed in *Nucl. Instr. and Meth.* **A340** 442 (1994).

Possible means for trace oxygen identification: (1) Secondary Ionization Mass Spectroscopy (SIMS); (2) Gas Fusion (LEGO); and (3) Energy Dispersive x-Ray (EDX).

Depth Profile of Oxygen in CsI(Tl)

Secondary Ion Mass Spectrometry Analysis

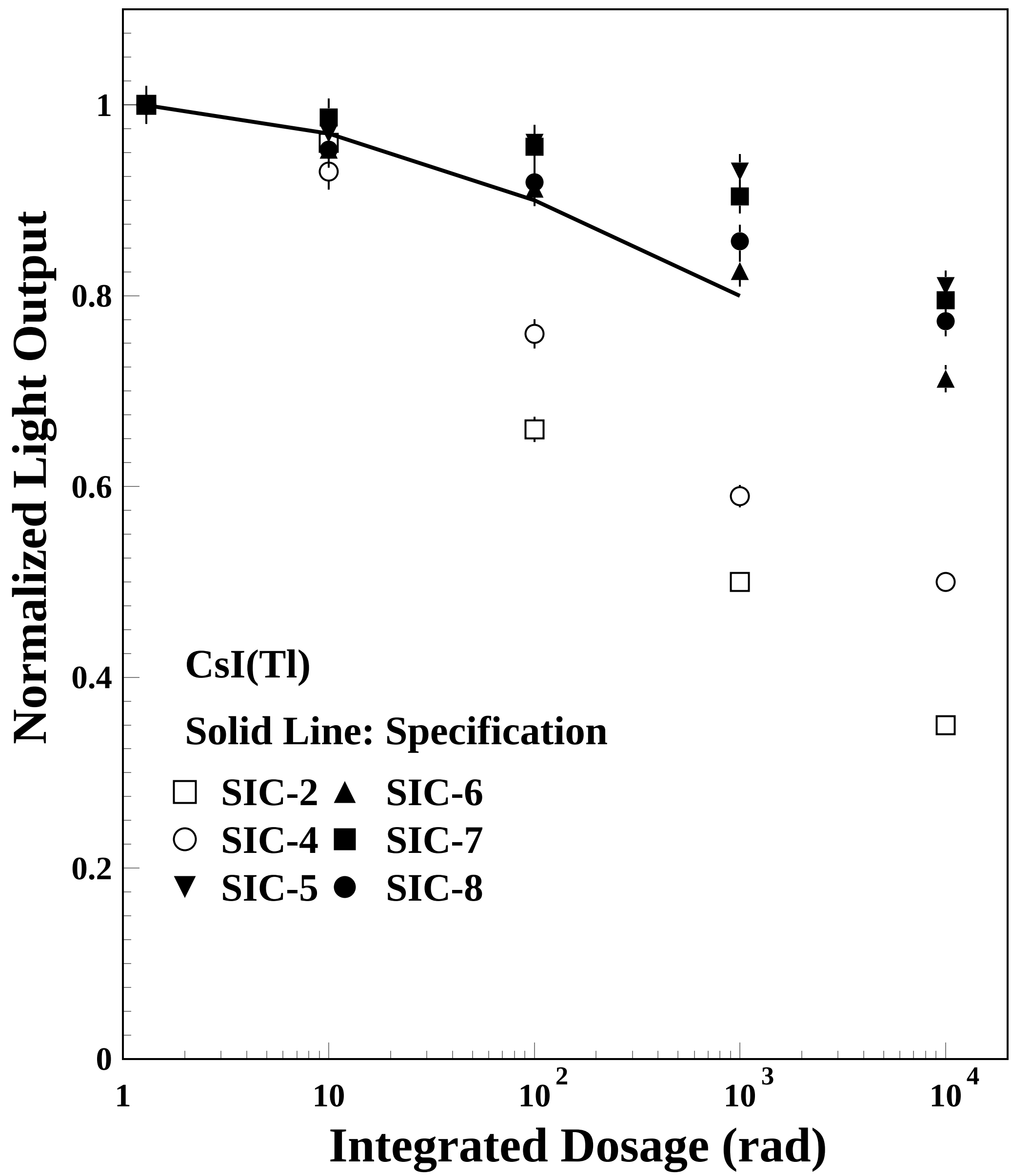
by Charles Evana & Associates



CsI(Tl) Radiation Hardness Progress

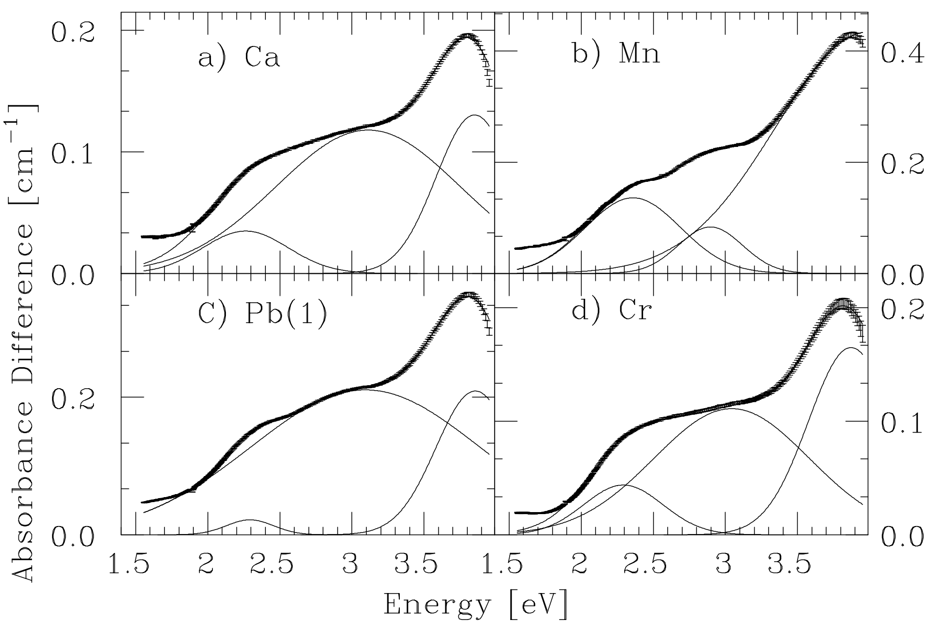
Measured with 2×2744-08 Si PD and 2μs Shaping

Full Size CsI(Tl) Samples from SIC



$PbWO_4$ Damage Mechanism

Crystal defects, such as Oxygen Vacancy, are known to cause radiation damage for other oxide scintillators. In BGO, for example, three common radiation induced absorption bands at 2.3, 3.0 and 3.8 eV were found in a series of 24 doped samples, as discussed in *Nucl. Instr. and Meth.* **A302** 69 (1991), indicating defect-related color centers.



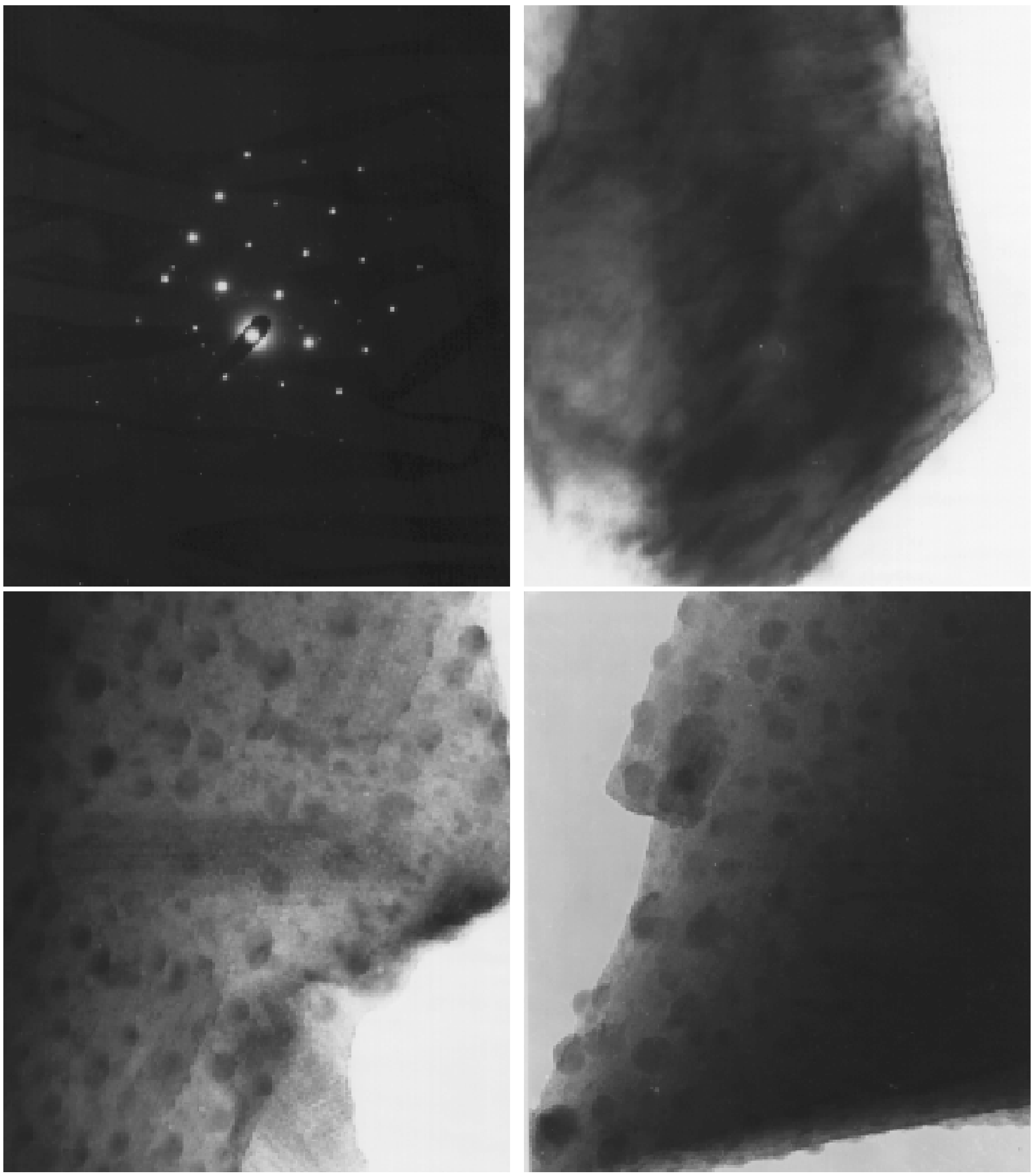
Possible means for oxygen vacancy identification: (1) Electron Paramagnetic Resonance (ESR) and Electron-Nuclear Double Resonance (ENDOR); (2) Transmission Electron Microscopy (TEM)/Energy Dispersion Spectrometry (EDS); and (3) a pragmatic way: Oxygen Compensation by Post-Growing Annealing in Oxygen Rich Atmosphere.

TEM Study on $PbWO_4$ Crystals

TOPCON-002B Scope, 200 kV, 10 μA

Scale: 1 cm (——) $\Rightarrow$ 20 nm

ϕ5–10 nm **Black Spots Identified**



TEM/EDS Study on $PbWO_4$ Crystals

JEOL JEM-2010 Scope and Link ISIS EDS

Localized (ϕ0.5 nm) Stoichiometry Analysis

Z.W. Yin *et al.*, in SCINT97, Shanghai (9/97)

Oxygen Vacancies Identified

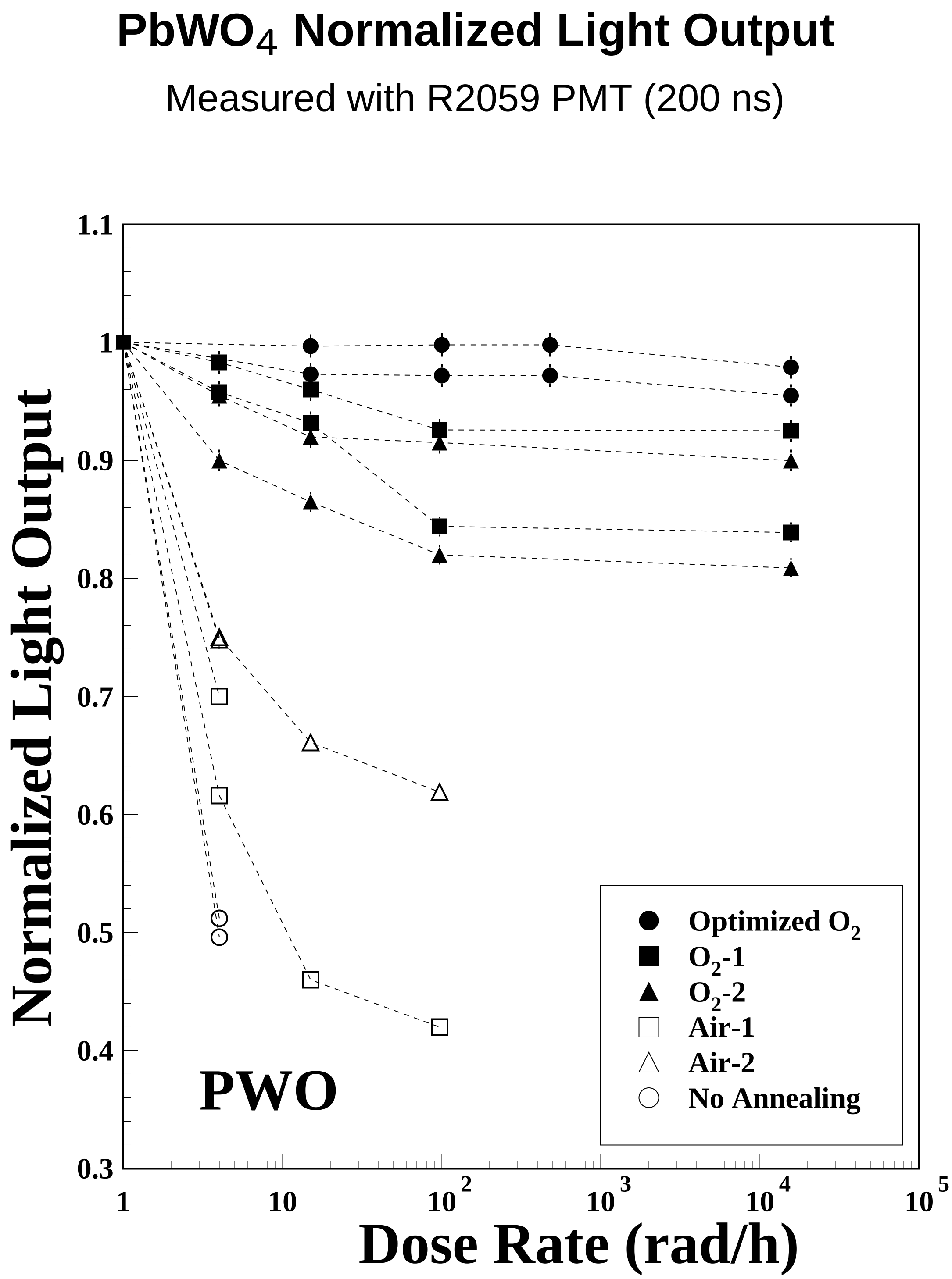
Atomic Fraction (%) in $PbWO_4$

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

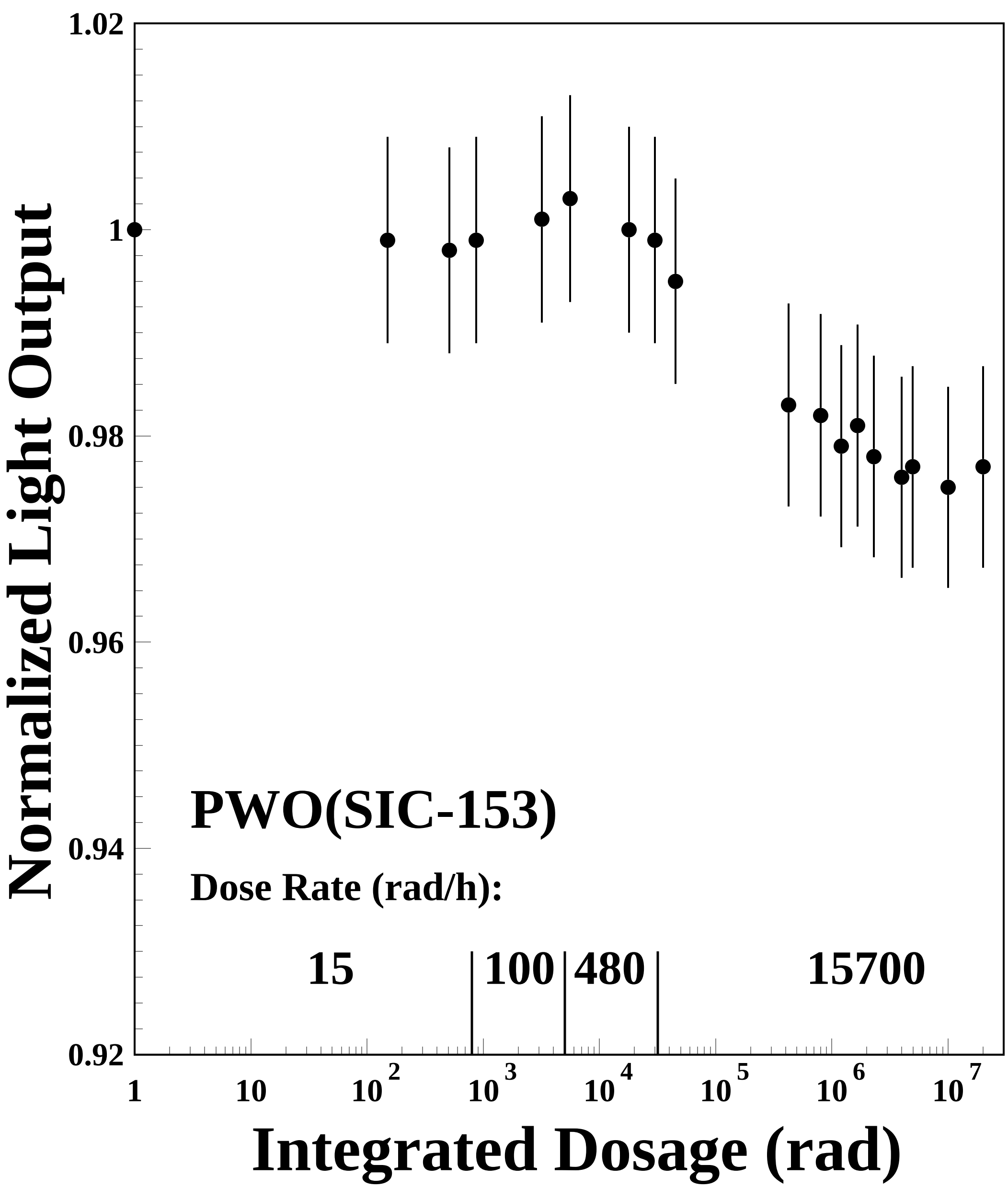


PbWO4 Normalized Light Output
Measured with R2059 PMT (200 ns)
Normalized Light Output
Dose Rate (rad/h)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
10
10 2
10 3
10 4
10 5
Optimized O2
O2-1
O2-2
Air-1
Air-2
No Annealing
PWO

$PbWO_4$ Light Output Degradation

Measured with R2059 PMT (200 ns)

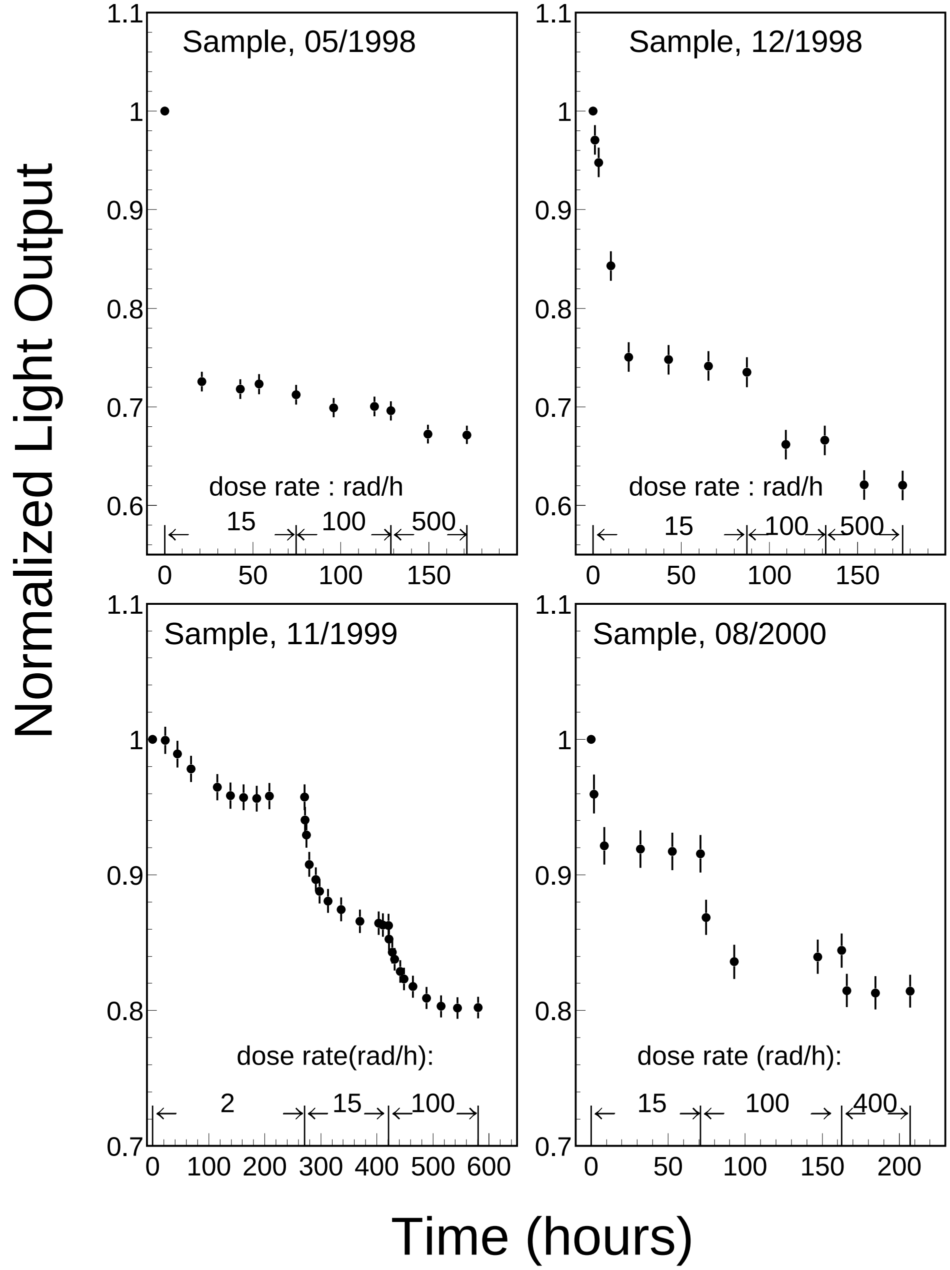
5 cm Sample SIC-153



Progress of $PbWO_4$ Radiation Hardness

Normalized Light Output Measured with R2059 PMT, 200 ns

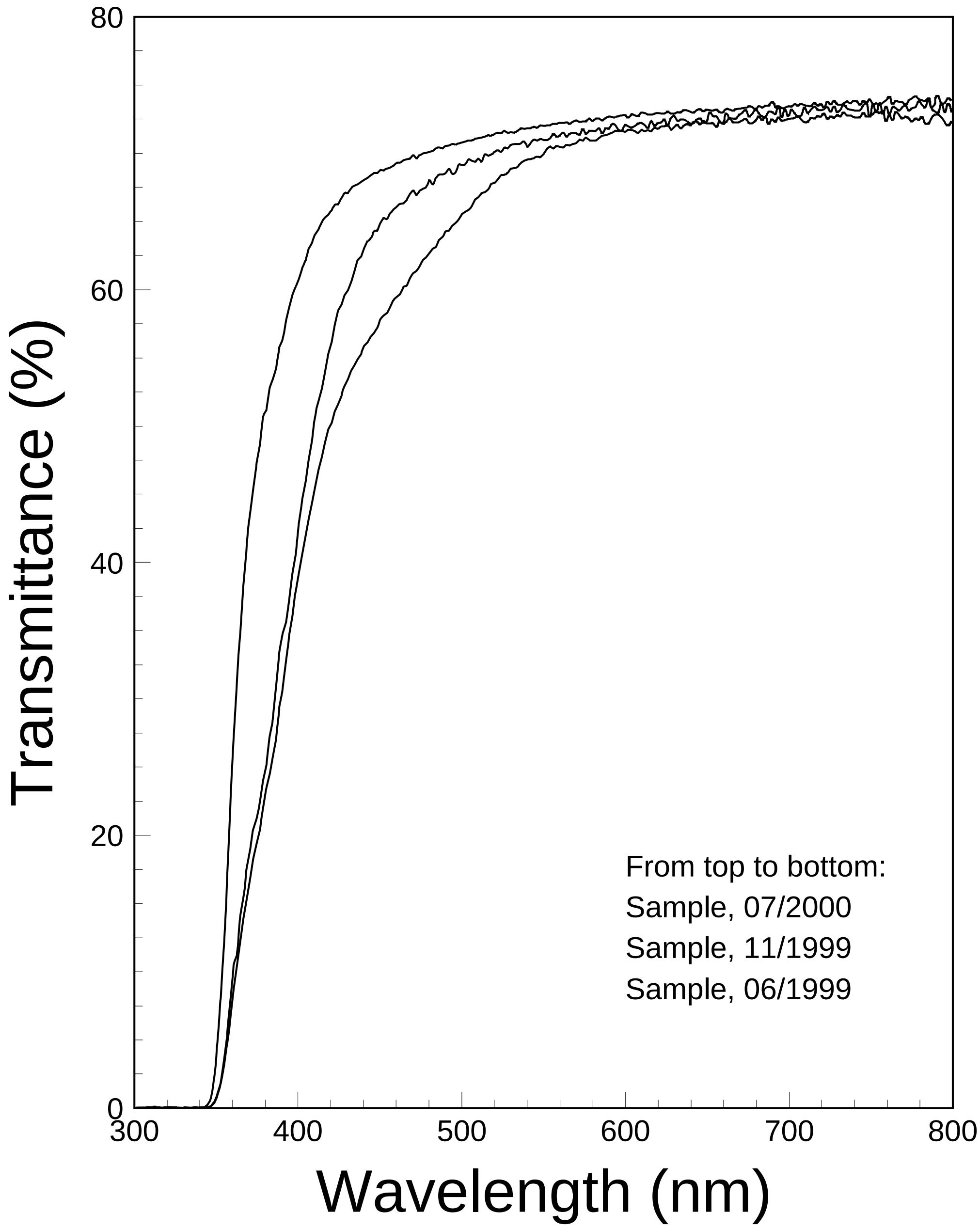
Full Size (23 cm) Samples



Progress of $PbWO_4$ Longitudinal Transmittance

Measured with Hitachi U-3210 SPM

Full Size (23 cm) Samples



Possible Choices of Crystal Technology

- Oxides:
  - BGO is a mature and dense crystal (ρ = 7.13 g/cc, X_0 = 1.12 cm, $R_{Moli\grave{e}re}$ = 2.3 cm), but has a slow scintillation (300 ns) and not cost effective ($7/cc) due to expensive raw material (GeO_2).
  - $PbWO_4$ is a mature and dense crystal (ρ = 8.28 g/cc, X_0 = 0.89 cm, $R_{Moli\grave{e}re}$ = 2.0 cm). It is a fast and cost effective crystal ($2.5/cc). Its low light yield is overcome by using Si avalanche photodiode. $\sigma = 4.1\%/\sqrt{E} \oplus 0.37\% \oplus 0.15/E$ has been achieved with 25 mm^2 APD readout in beam test. It is possible to develop a brighter $PbWO_4$ crystal.

- Halides:
  - CsI is a mature and cost effective crystal ($2/cc), but has low density (ρ = 4.5 g/cc, X_0 = 1.85 cm, $R_{Moli\grave{e}re}$ = 3.5 cm). In addition, CsI(Tl or Na) is too slow ($\sim$1 μs) and CsI is less bright.
  - PbF_2 is a mature and dense crystal (ρ = 7.77 g/cc, X_0 = 0.93 cm, $R_{Moli\grave{e}re}$ = 2.1 cm). It is also cost effective (less than $PbWO_4$). However, it is not yet a scintillator, but being used as a Čerenkov radiator. A scintillating PbF_2 crystal may be developed by selected doping.

Status of PbF_2 Crystal as a Scintillator

- PbF_2 has been studied in details as a Čerenkov material by D. Anderson and C. Woody *et al.*, *NIM* **A290** (1990) 385 and *IEEE Trans. Nucl. Sci.* **NS-40** (1993) 546.

- Attempt has been made to produce scintillating PbF_2 through phase transition (cubic to orthorhomic). Positive result reported by N. Klassen *et al.* in *Crystal 2000* (1992) 587 does not agree with observations by S. Derenzo *et al. IEEE Trans. Nucl.Sci.* **NS-37** (1990) 206 and D. Anderson *et al. NIM* **A342** (1994) 473.

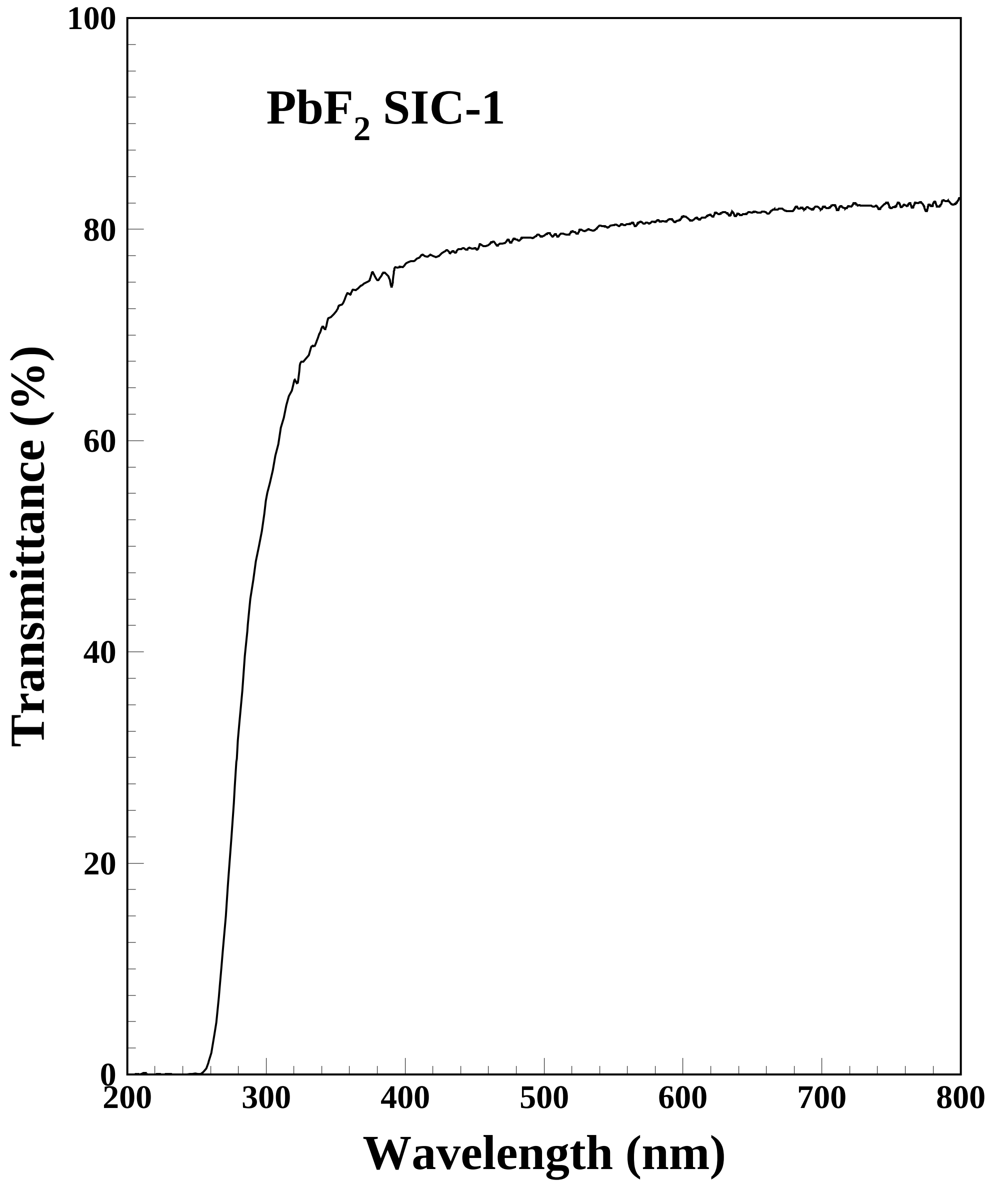
- Observation of fast scintillation in PbF_2(Gd) and PbF_2(Eu) was reported by D. Shen *et al.* (SIC) *Jour. Inor. Mater.* Vol **10**1 (1995) 11. The scintillation emission of PbF_2(Gd) was confirmed by C. Woody *et al.* in *Delft Conference* (1995), and **6.5 p.e./MeV** was observed for a PbF_2(Gd) sample of $\phi 2.1 \times 2.2$ cm from SIC by using R2059 PMT.

- About 1,000 PbF_2 crystals of $3 \times 3 \times 18.6$ cm (a total of 0.167 m^3) are being produced by SIC in 1998 for an experiment at Mainzer Microtron, Germany. They are used as Čerenkov radiator.

Longitudinal Transmittance of PbF_2

Measured with Hitachi U-3210 Photospectrometer

$3 \times 3 \times 18.6$ cm Sample from SIC



X-ray Excited Emission Spectra of PbF_2(Gd)

D. Shen *et al.*, *Jour. Inor. Mater.* **Vol 101 (1995) 11.**

X-ray Excited Emission Spectra of PbF_2(Eu)

D. Shen *et al.*, *Jour. Inor. Mater.* **Vol 101 (1995) 11.**

γ-ray Excited Emission Spectra of PbF_2(Gd)

C. Woody *et al.*, *Delft Conference* **(1995)**

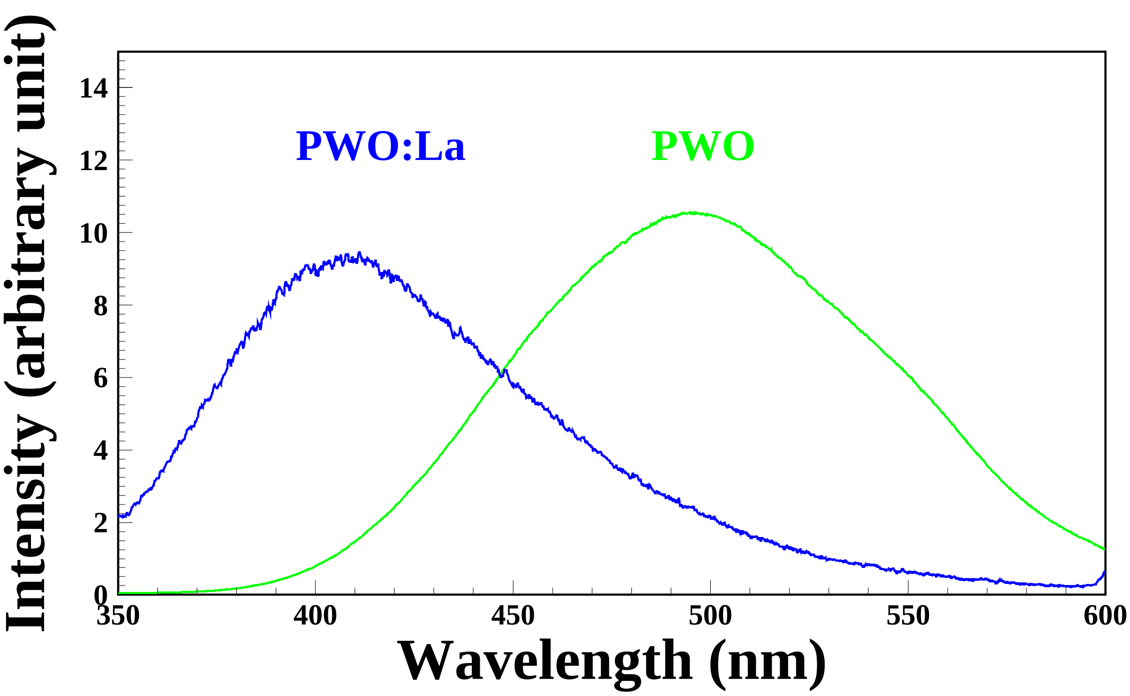
PbF_2(Gd) ($\phi 2.1 \times 2.2$ cm) Pulse Height

Measured at AGS with 1 GeV/c MIPS by C. Woody *et al.*

6.5 p.e./MeV Observed by R2059 PMT

$PbWO_4$ Crystal Properties

- Density: 8.28 g/cm^3
- Radiation/Interaction Length: 0.89/22.4 cm
- Moliere Radius: 2.2 cm
- Index of Refraction: 2.2 — 2.3
- Light Yield: 50 — 100 photons/MeV, -2%/°C
- Decay Time: $>$80% in 50 ns

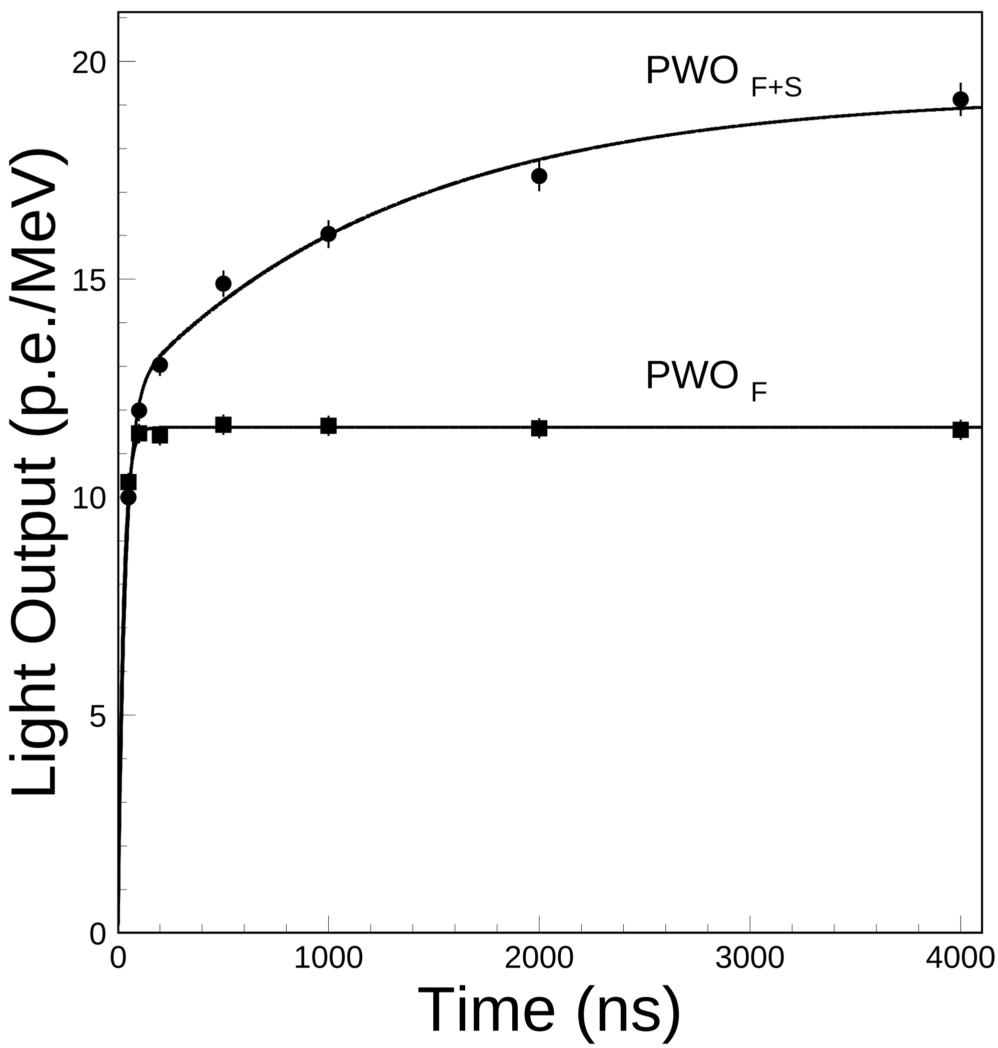


$PbWO_4$ Scintillation Light Output

Measured with R2059 PMT

23 cm $PbWO_4$: SIC-210 & BTCP-1971:La

NLC Detector Workshop, Keystone (1998)



Summary

- Precision crystal calorimetry extends physics reach in experimental nuclear and high energy physics because of its best achievable resolutions for electrons and photons.

- An optimized light response uniformity is the key for crystal energy resolution.

- A precision calibration is the key to maintain crystal precision *in situ*.

- Predominant radiation damage effect in crystal scintillators is the radiation induced absorption, or color center formation, not the loss of scintillation light yield.

- The quality of mass produced crystals can be improved by understanding the mechanism of radiation damage. While oxygen and/or hydroxyl contaminations cause damage in halides, stoichiometry related defects, e.g. oxygen vacancies, cause damage in oxides.

- R&D on dense crystals, such as PbF_2 and $PbWO_4$, may lead to new type of crystal scintillators for crystal calorimetry in future particle physics experiments.