Calibration and Monitoring PWO Crystal ECAL

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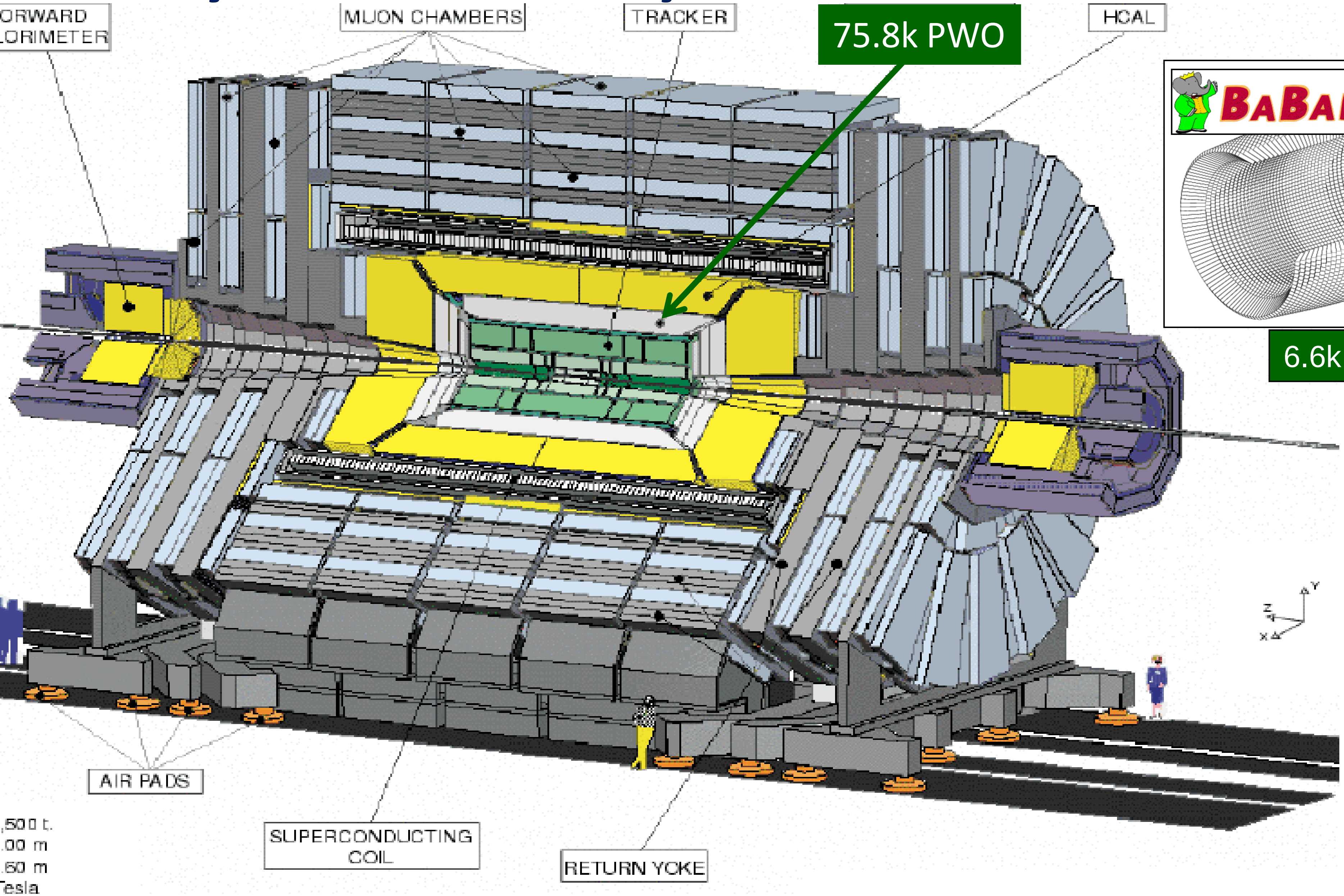
Crystals Used in HEP Calorimeters

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 (ºC)	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] (photons/MeV)	38,000	63,000	1,400 420	13,680 1,560	8,000	32,000	114 40	-
d(LY)/dT[b] (%/ ºC)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	-
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV Mu2e S. BELLE	TAPS Mu2e-II	L3 BELLE	COMET CMS BTL PIONEER	CMS ALICE PANDA EIC	A4 G-2

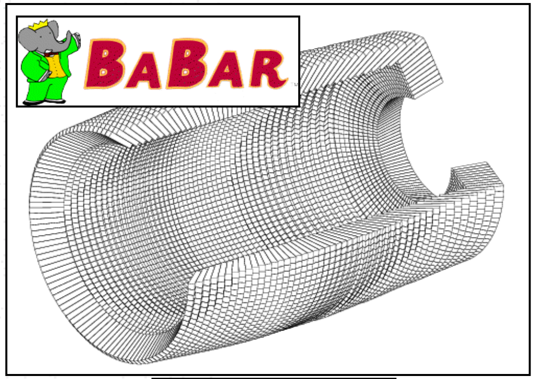
a. at emission peak; b. up/low row: slow/fast component; c. with QE of readout device taken out.

L3 BGO, BaBar CsI, CMS PWO ECAL

11.4k BGO

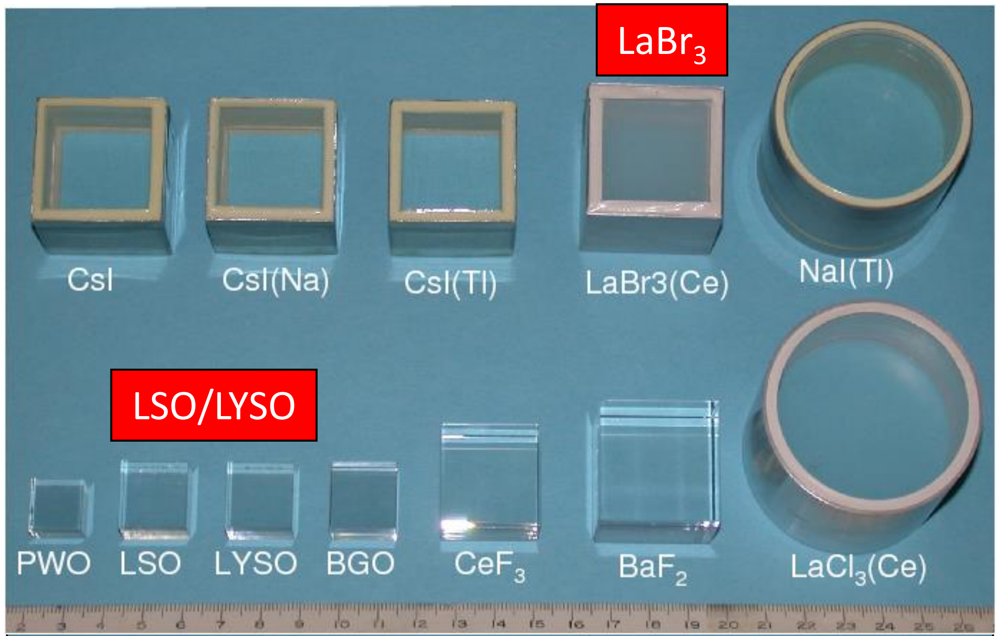


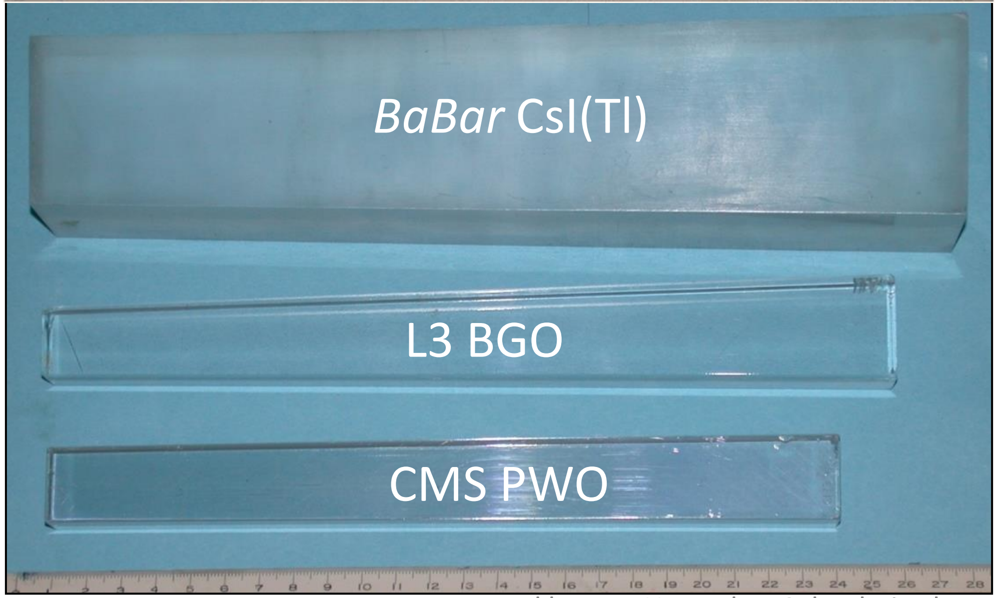
75.8k PWO



6.6k CsI:Tl

Crystal Samples for Calorimetry





1.5 X_0 Samples:

Hygroscopic: Sealed

Surfaces: Polished

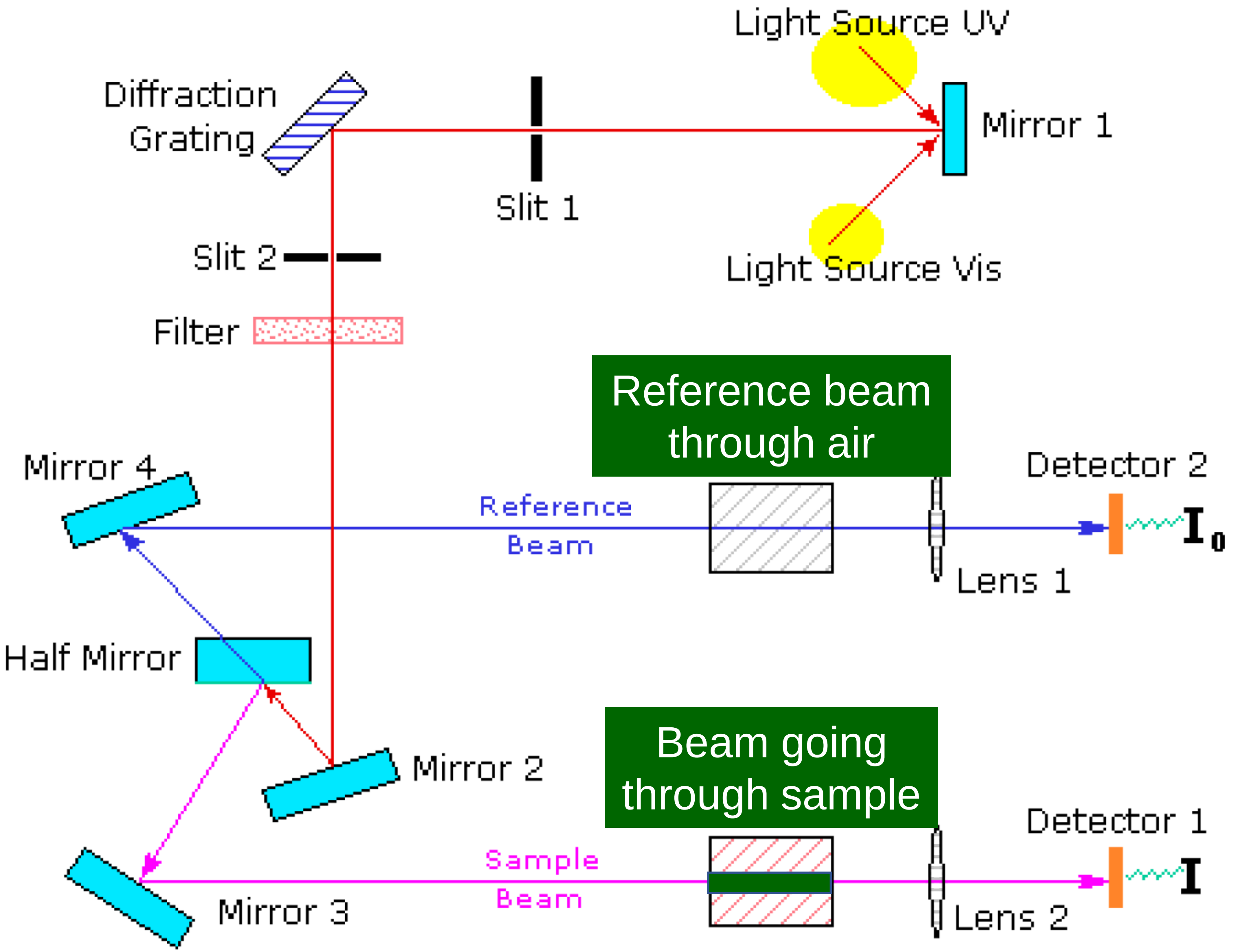
ECAL Crystals:

BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

CMS PWO(Y): 25 X_0

Transmittance and Absorption



HITACHI U3210 UV/VIS and PerkinElmer Lambda 950 UV/VIS/NIR spectrophotometer with large sample compartment to measure transmittance and absorption

Typical Precision: 0.2 to 0.3%

Watch out: Birefringence, sample surface and scattering centers

LAL and Birefringence

Light attenuation length (LAL), or inverse of its light absorption coefficient, extracted from transmittance

$$LAL(\lambda) = \frac{l}{\ln\left\{\left[T(\lambda)\left(1-T_s(\lambda)\right)^2\right] / \left[\sqrt{4T_s^4(\lambda)+T^2(\lambda)\left(1-T_s^2(\lambda)\right)^2}-2T_s^2(\lambda)\right]\right\}} \quad (2)$$

where T(λ) is the longitudinal transmittance measured along crystal length l, and $T_s(\lambda)$ is the theoretical transmittance assuming multiple bouncings between two crystal ends and without internal absorption:

$$T_s(\lambda) = (1-R(\lambda))^2 + R^2(\lambda)(1-R(\lambda))^2 + \cdots = (1-R(\lambda))/(1+R(\lambda)) \quad (3)$$

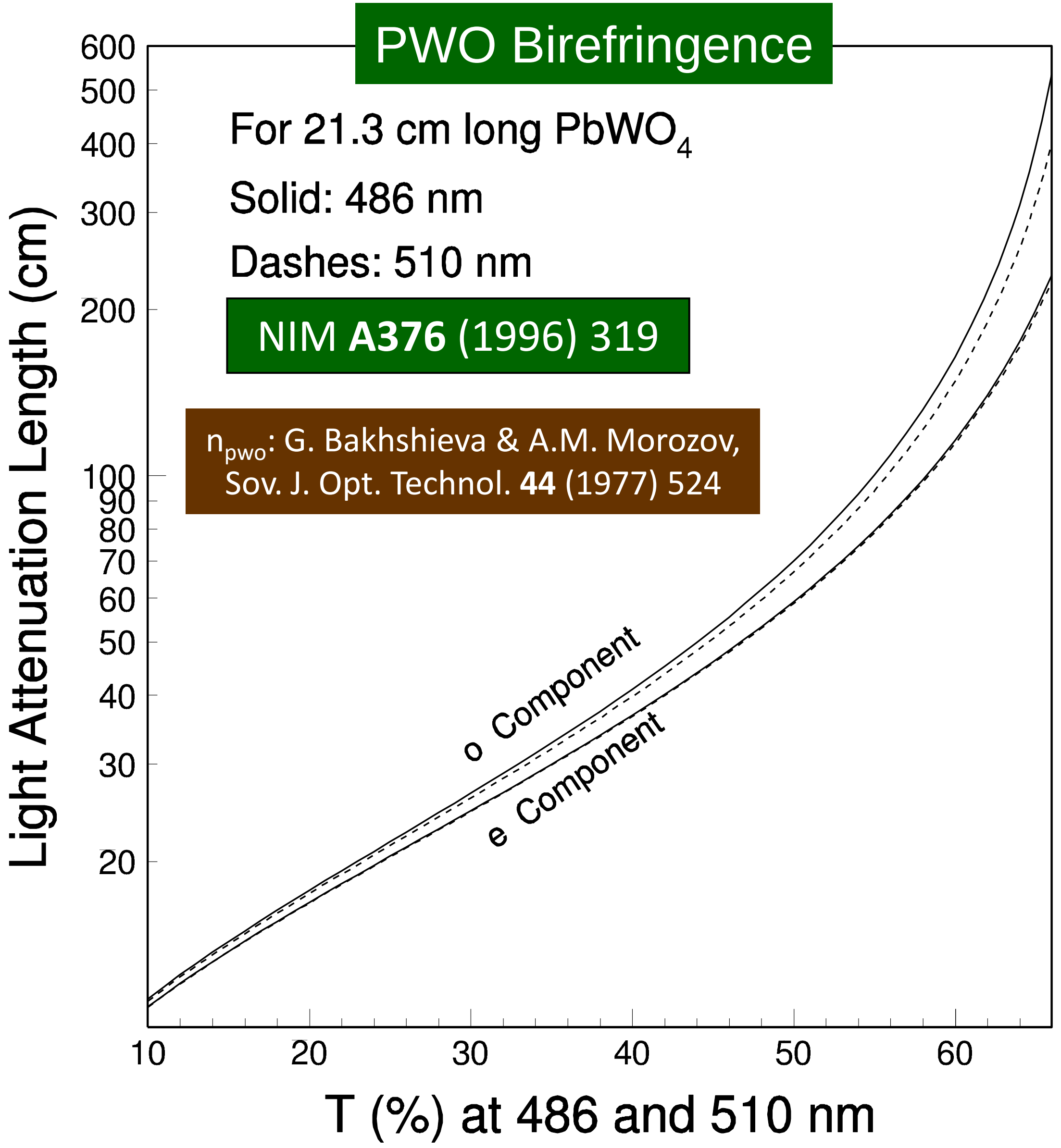
and

NIM **A333** (1993) 422

$$R(\lambda) = \frac{(n_{\mathrm{crystal}}(\lambda) - n_{\mathrm{air}}(\lambda))^2}{(n_{\mathrm{crystal}}(\lambda) + n_{\mathrm{air}}(\lambda))^2} \quad (4)$$

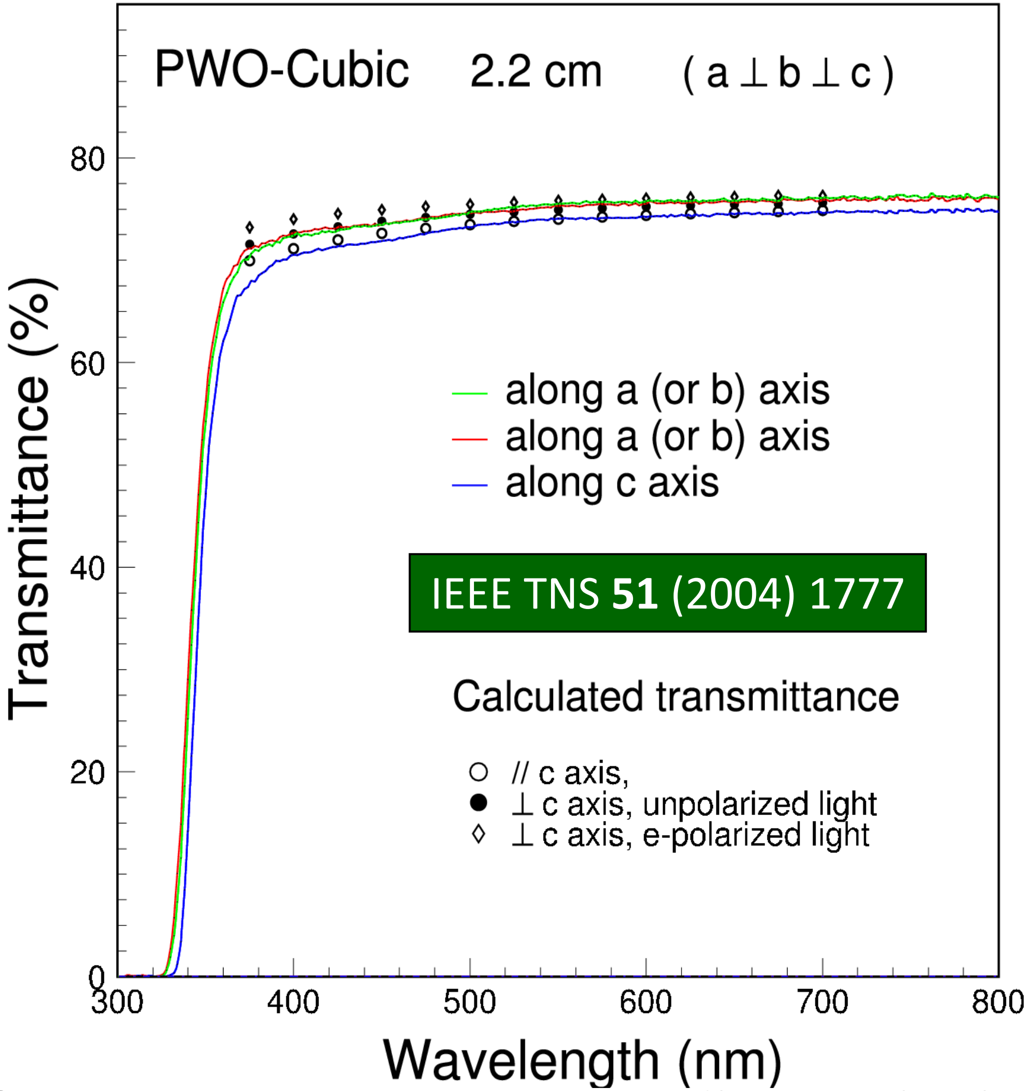
where $n_{\mathrm{crystal}}(\lambda)$ and $n_{\mathrm{air}}(\lambda)$ are the refractive indices for crystal and air, respectively.

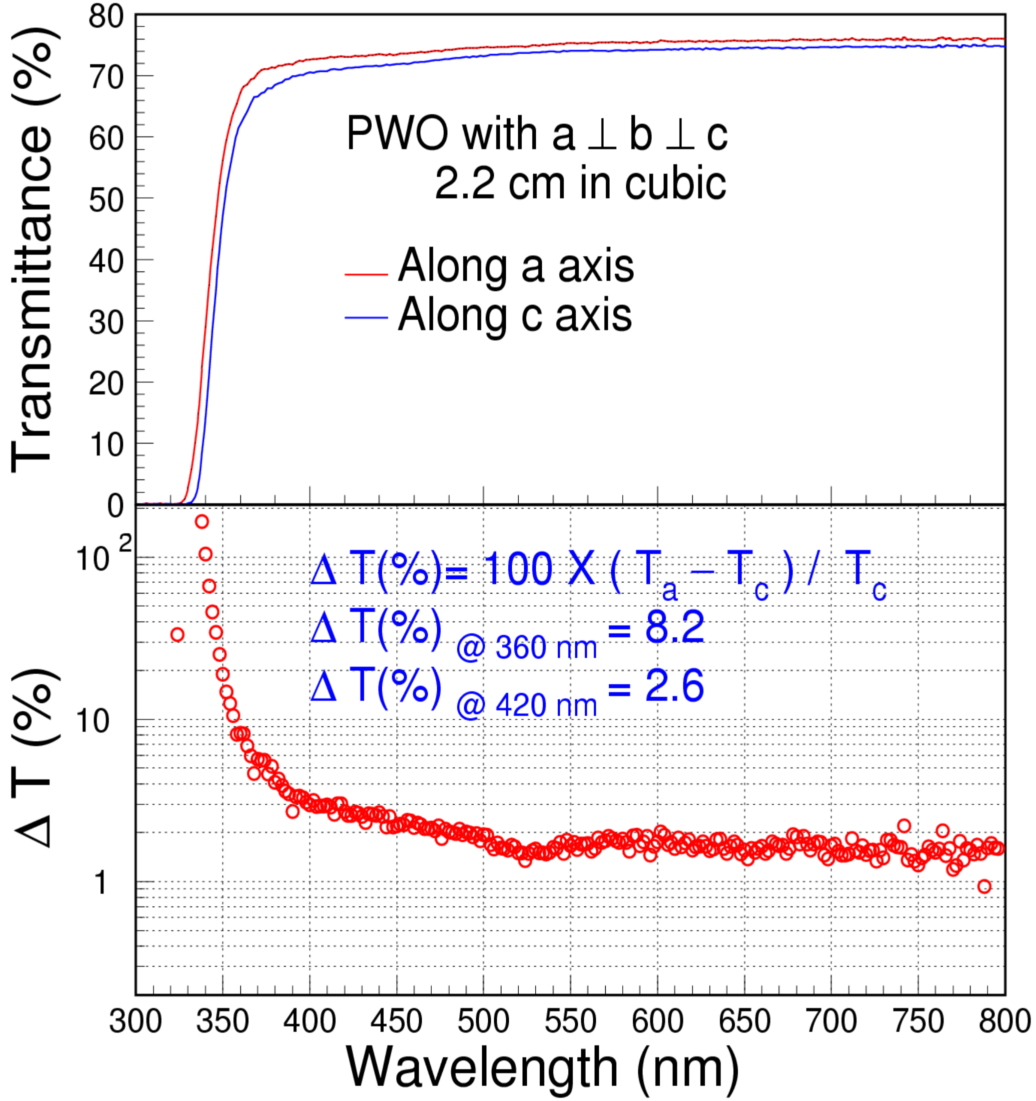
PWO Birefringence



PWO Birefringence

Attention to be paid to the crystal orientation vs. optical axis





LY, LO, LCE and LRU

Crystal light yield (LY) in photons/MeV energy deposition: βE_g is the energy required for an e-h pair, S is energy transferred to the luminescence center and Q is its quantum efficiency.

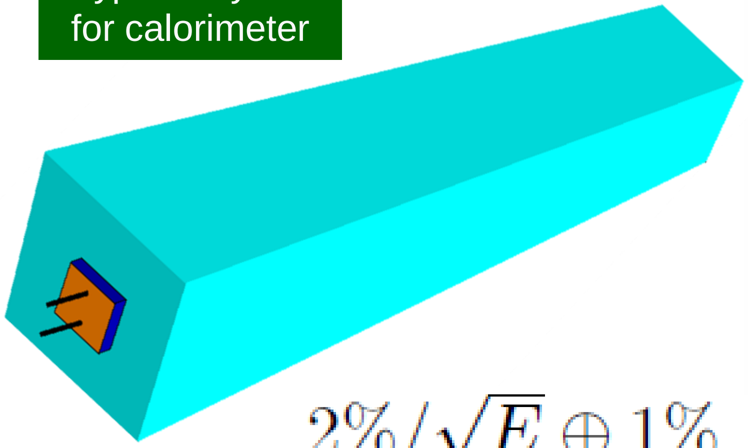
Measured light output (LO) in photoelectrons/MeV depends on crystal LY, light collection efficiency (LCE) and the quantum efficiency of the photodetector used for the measurement.

LCE is sample dependent

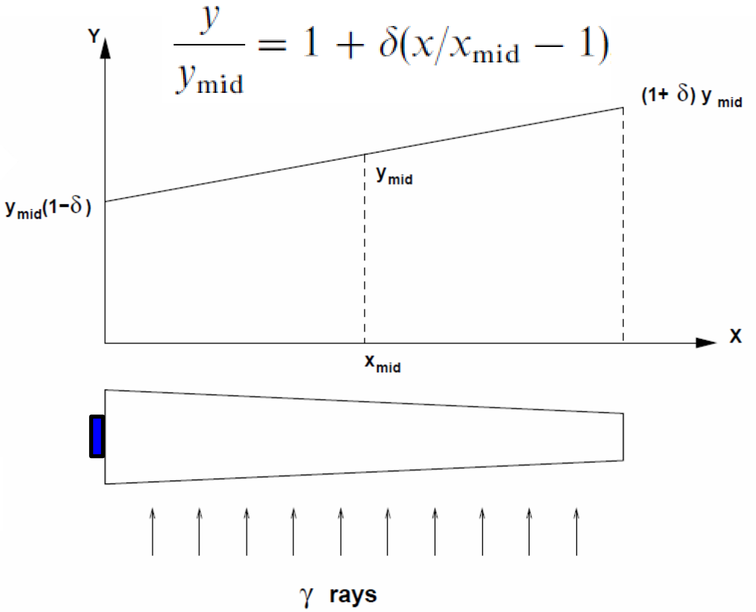
$$LY = 10^6\ S \cdot Q/(\beta \cdot E_g)$$

$$LO = LY \cdot LCE \cdot QE$$

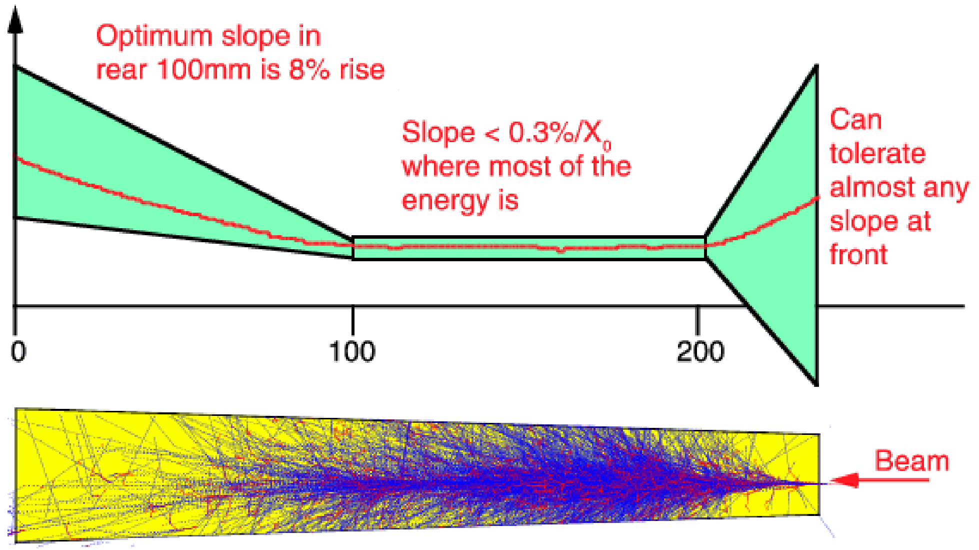
Typical crystal for calorimeter



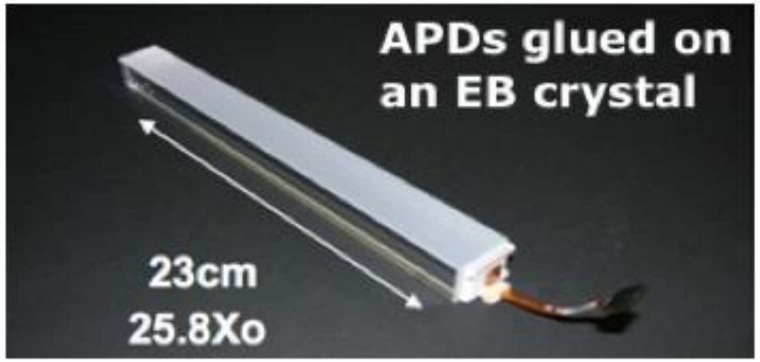
$$2\%/\sqrt{E} \oplus 1\%$$

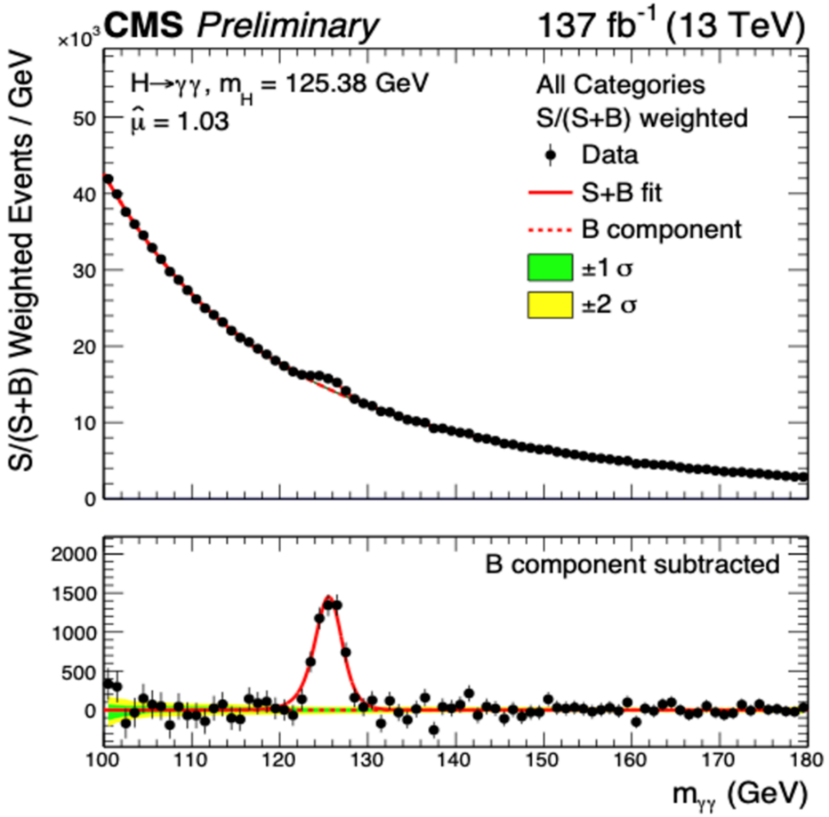


Light Response Uniformity (LRU) CMS Specification

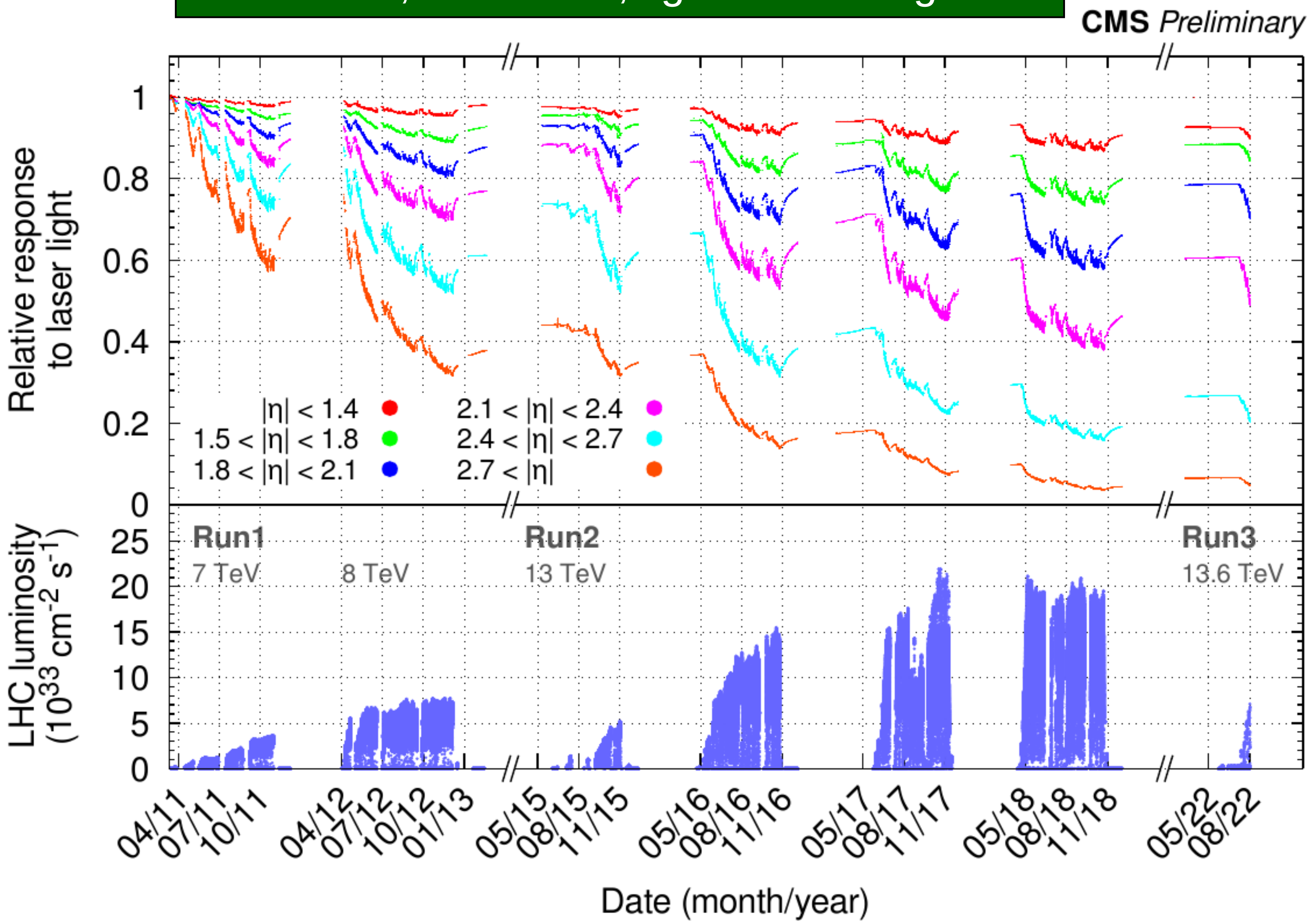


CMS H -> $\gamma\gamma$ and PWO Damage





T. Dimova, TIPP2023, light monitoring data



Resolution maintained by calibration and continuous monitoring

CMS ECAL Calibration and Monitoring

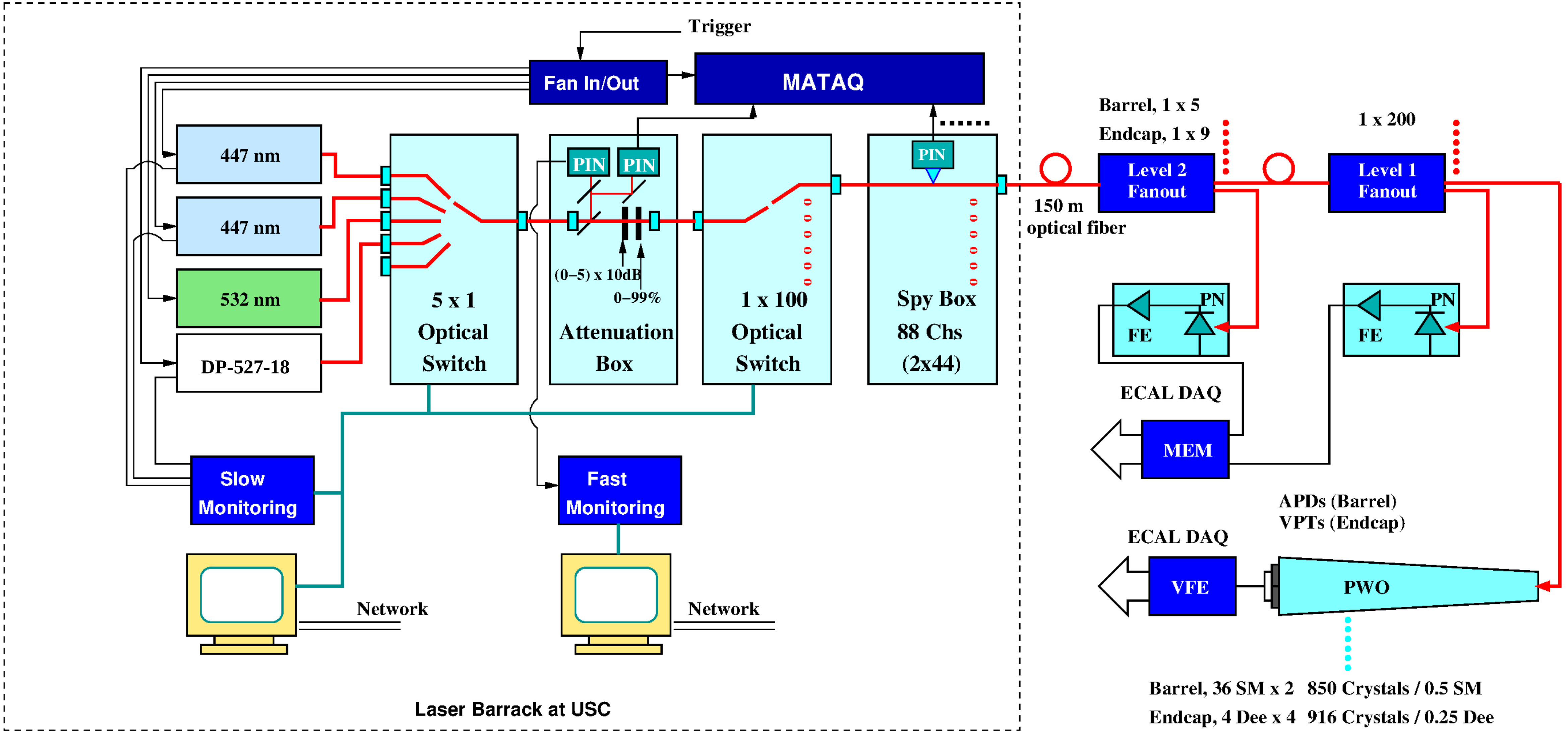
Calibration *in situ* at LHC by combining the following processes:

- Equalizing response of crystals in the same η ring.
- **$\pi^0/\eta \to \gamma\gamma$**: Equalizing measured π^0/η peaks for individual crystals.
- **E/p ratio:** Isolated electrons from W measured in tracker and ECAL.
- **$Z \to e^+e^-$**: invariant mass measured in ECAL for global scale corrections.
- **A laser-based light monitoring system** injects 600 pulses at 100 Hz to each crystal every 30 minutes in 3 μs beam abort gaps in 89 μs beam cycle to correct PWO radiation damage at 0.1%. Correction data are delivered within 48 h.

The combination of ionization dose and hadron-induced damage in PWO crystals complicates the overall correction precision.

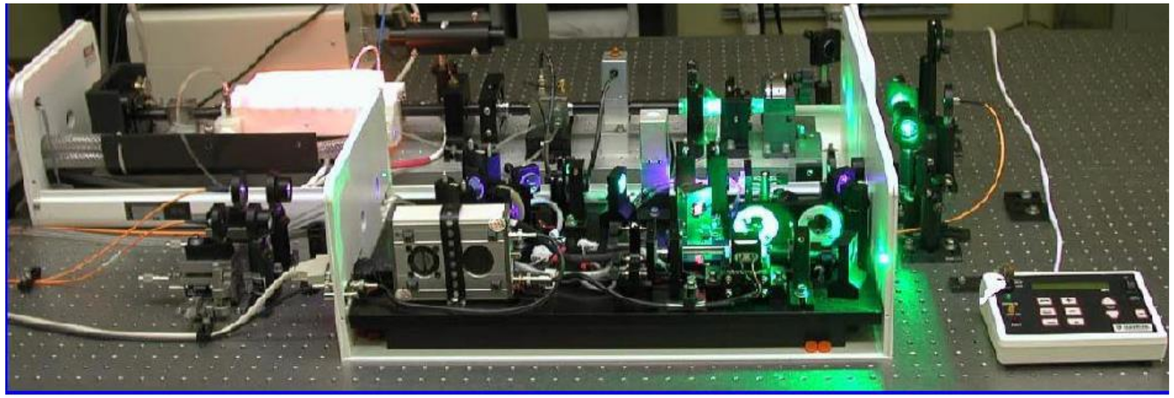
CMS PWO ECAL Laser Monitoring

Runs 24/7 providing 600 laser pulses/crystal at 100 Hz every 30 min

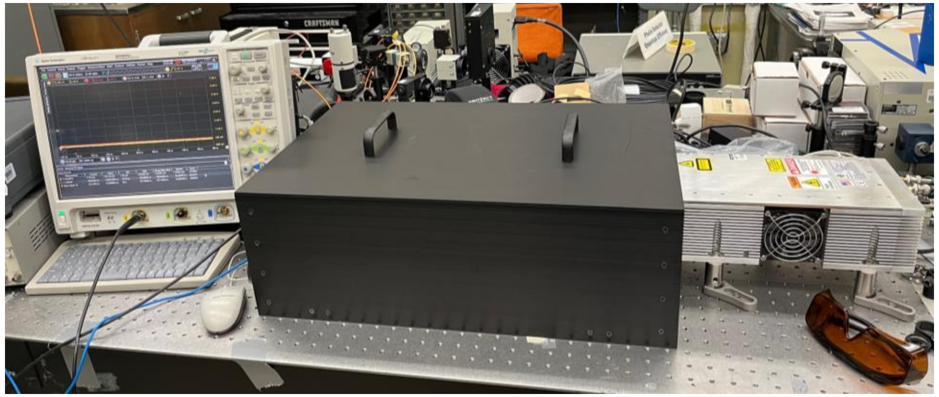


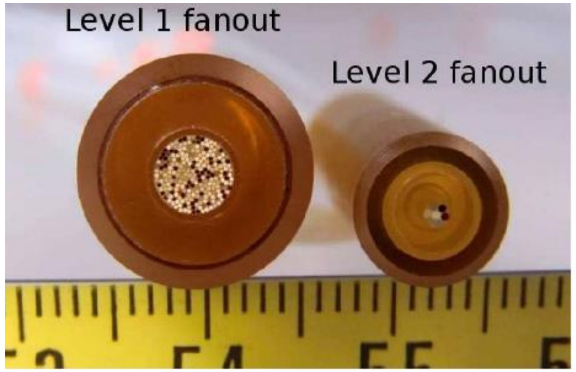
CMS Laser Monitoring Hardware

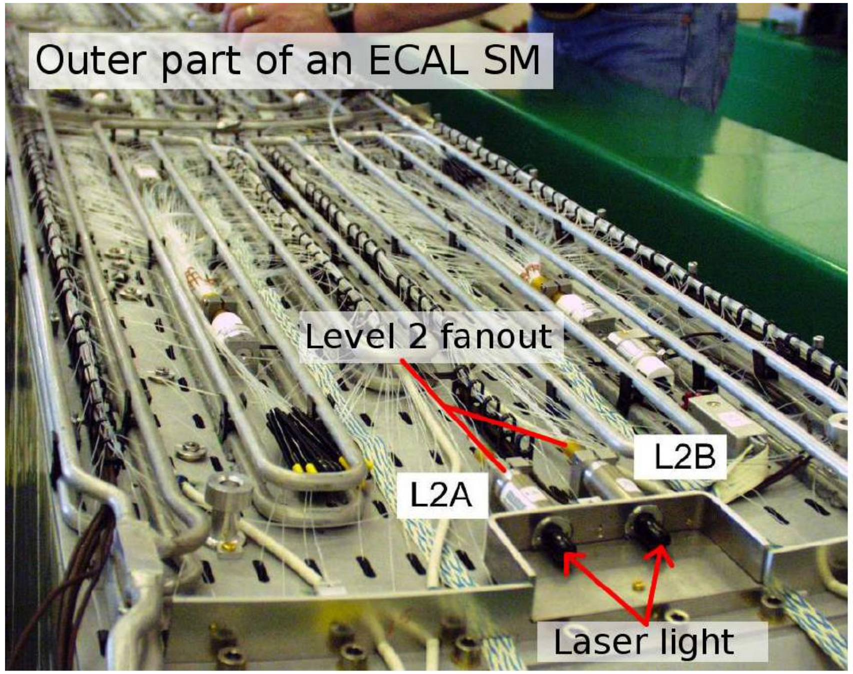
Lamp Pumped Lases: 2002 to 2012

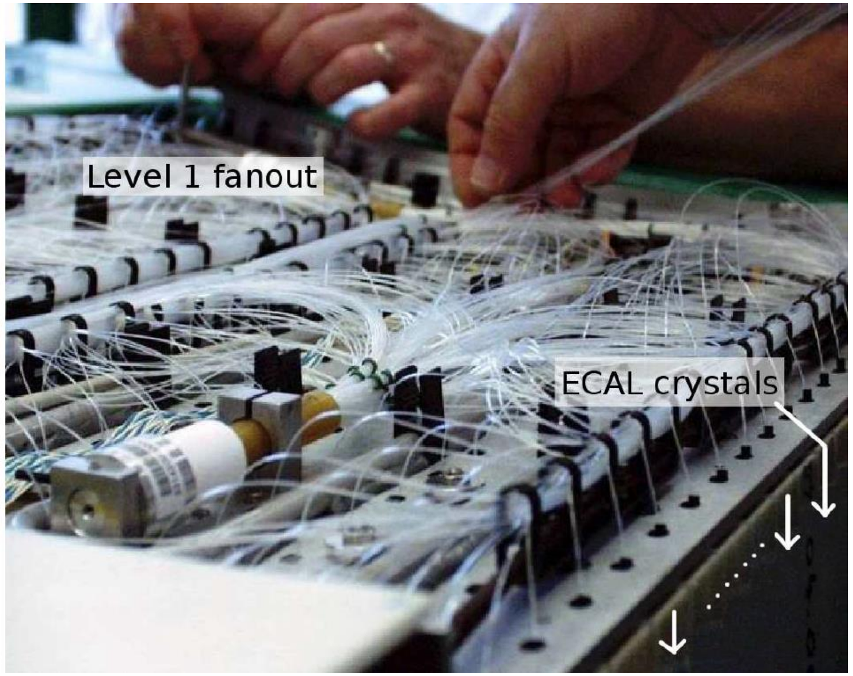


Diode Pumped Lases: since 2012





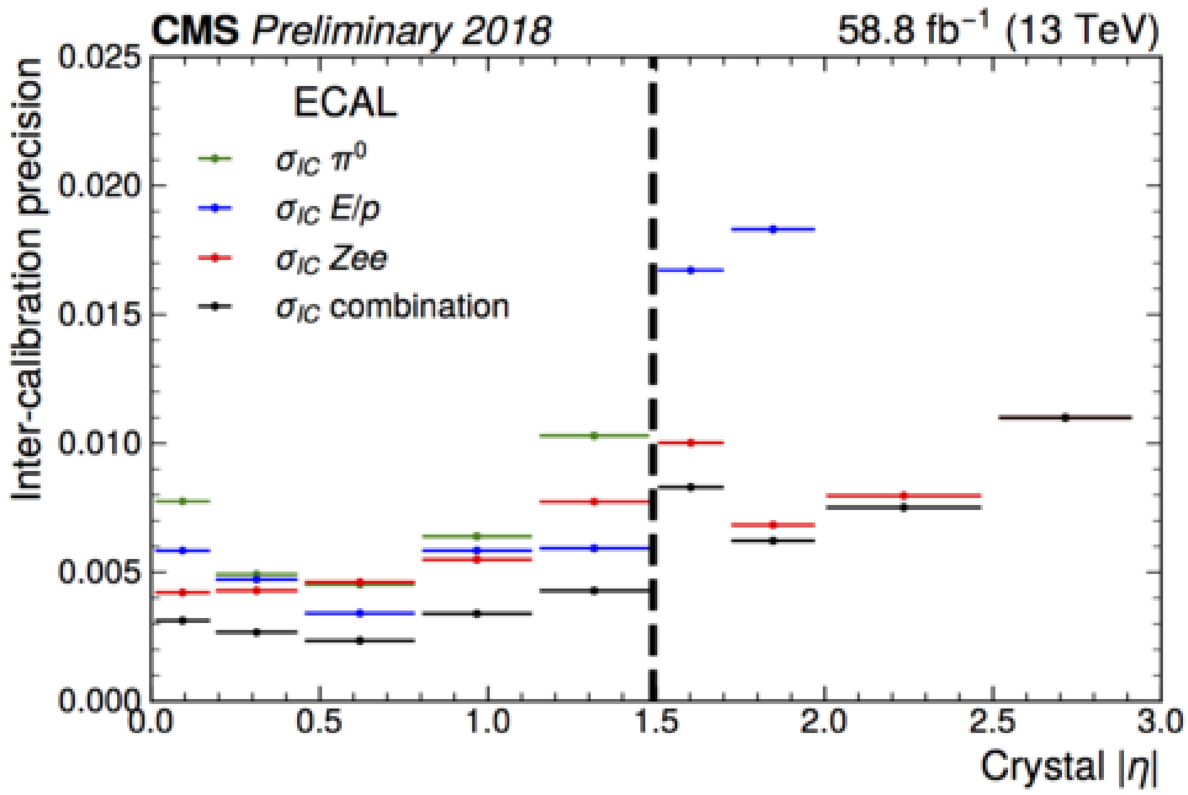


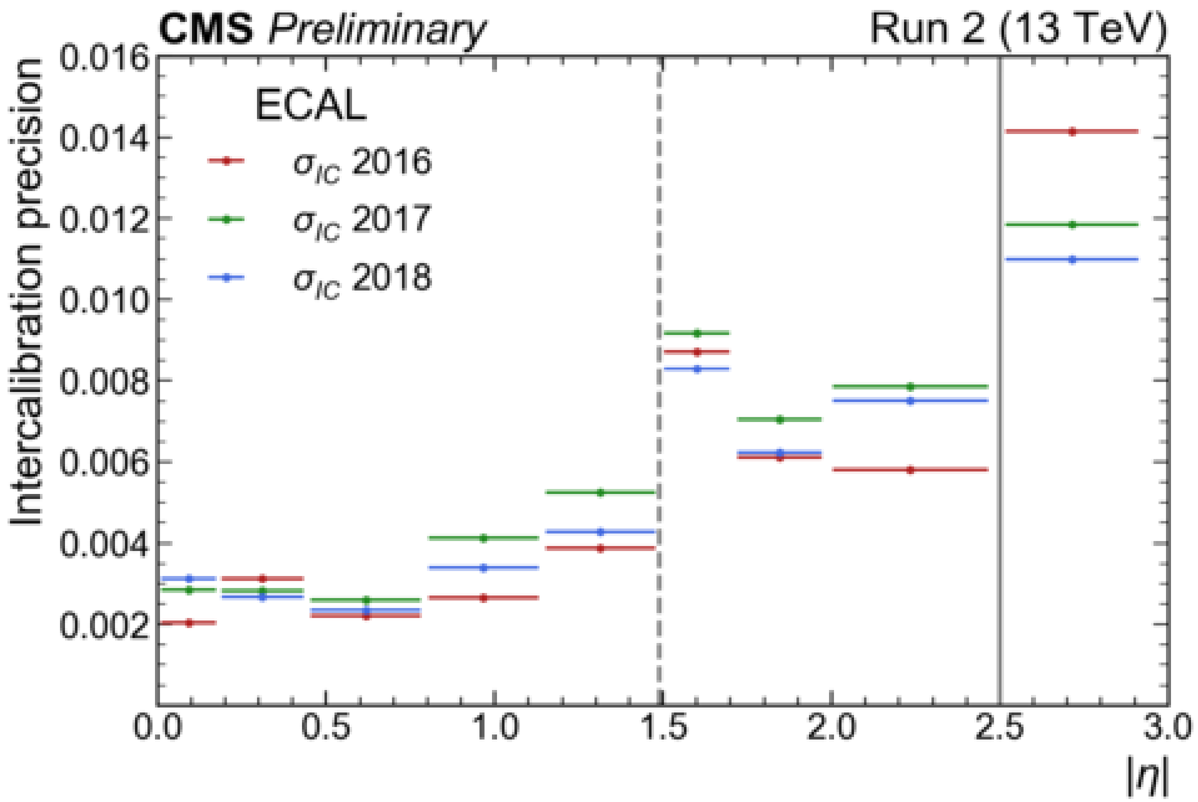


CMS ECAL Intercalibration Precision

T. Dimova, TIPP2023

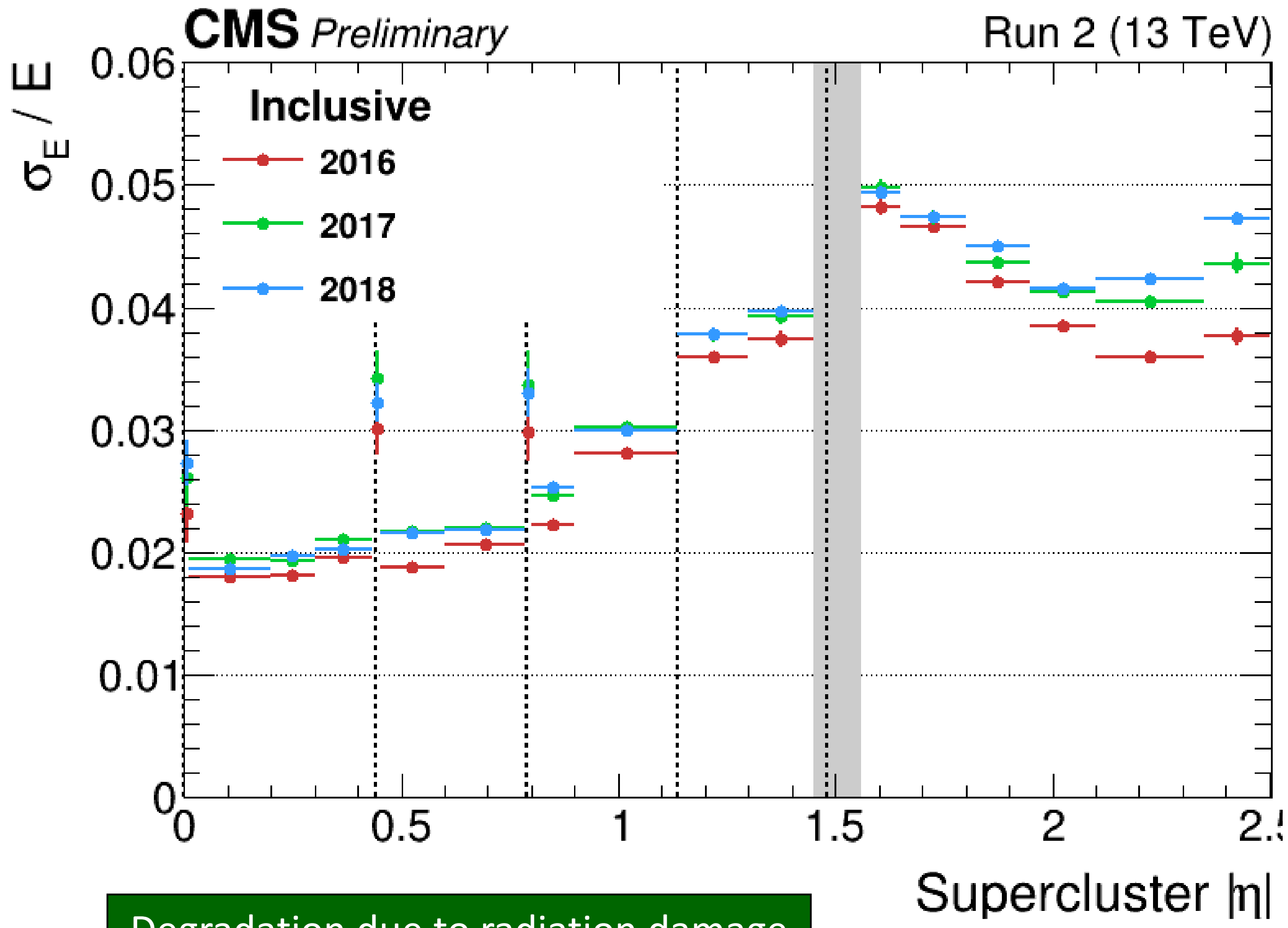
Precision of 0.5% in barrel and 1% in endcaps achieved
by combining monitoring and all physics calibration channels

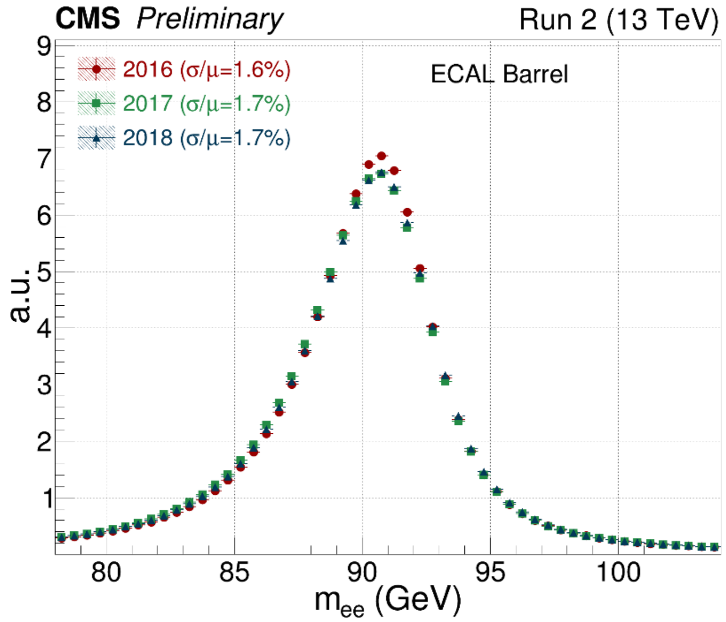


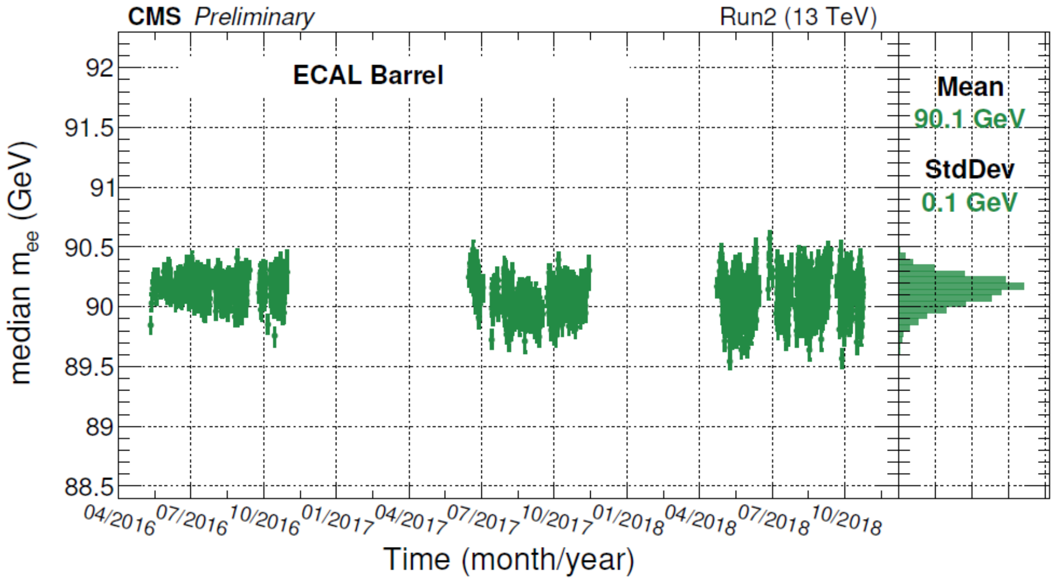


CMS ECAL Performance in Run 2

T. Dimova, TIPP2023







Degradation due to radiation damage

Radiation Damage Effects

NIM A413 (1998) 297, https://doi.org/10.1007/978-3-319-47999-6_22-2

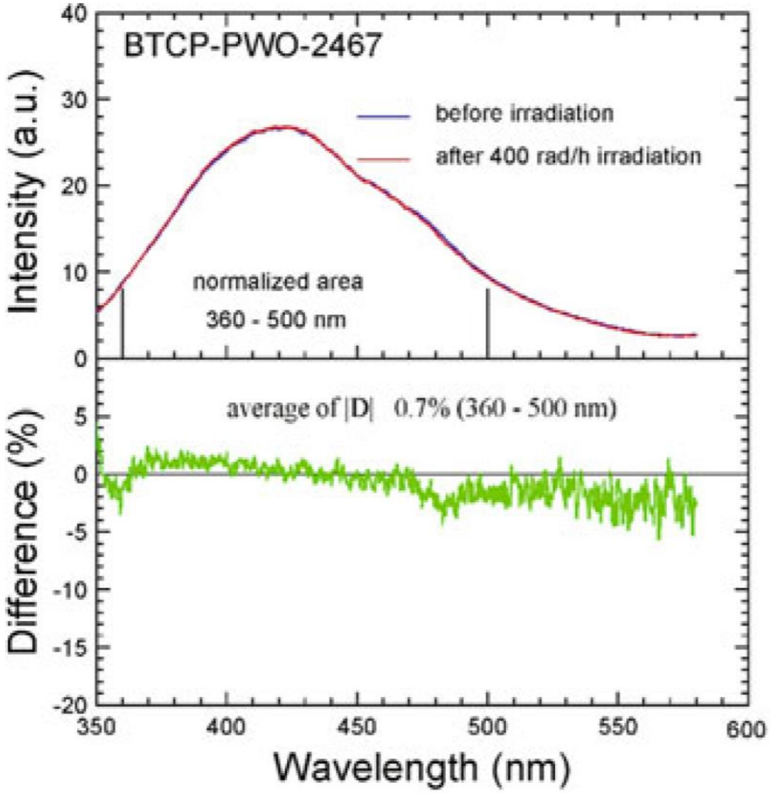
- **Scintillation mechanism damage: reduced LY and LO and maybe also LRU;**
- **Radiation-induced phosphorescence (afterglow): increase dark current, dark counting rate and readout noise;**
- **Radiation-induced absorption (color centers): reduced light attenuation length, LO and maybe also LRU.**

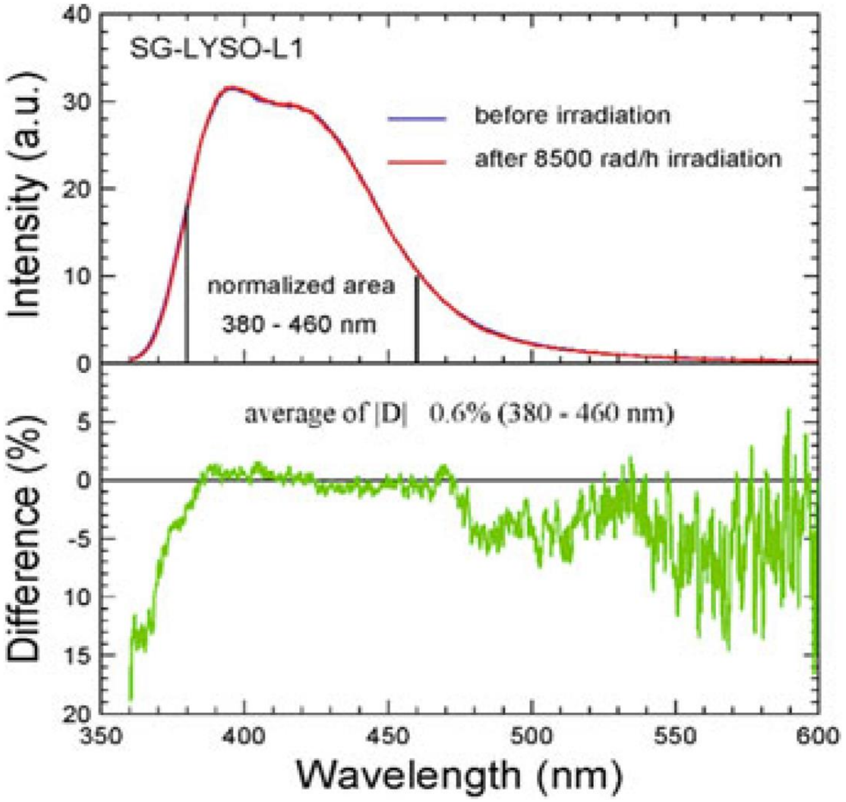
	CsI:Tl	CsI	BaF_2	BGO	PWO	LSO/LYSO
Scintillation mechanism	No	No	No	No	No	No
Phosphorescence (afterglow)	Yes	Yes	Yes	Yes	Yes	Yes
Absorption (color centers)	Yes	Yes	Yes	Yes	Yes	Yes
Recovery	slow	No	No	Yes	Yes	No
Dose rate dependence	No	No	No	No	No	No
Thermal Annealing	No	No	Yes	Yes	Yes	Yes
Optical Bleaching	No	No	Yes	Yes	Yes	Yes

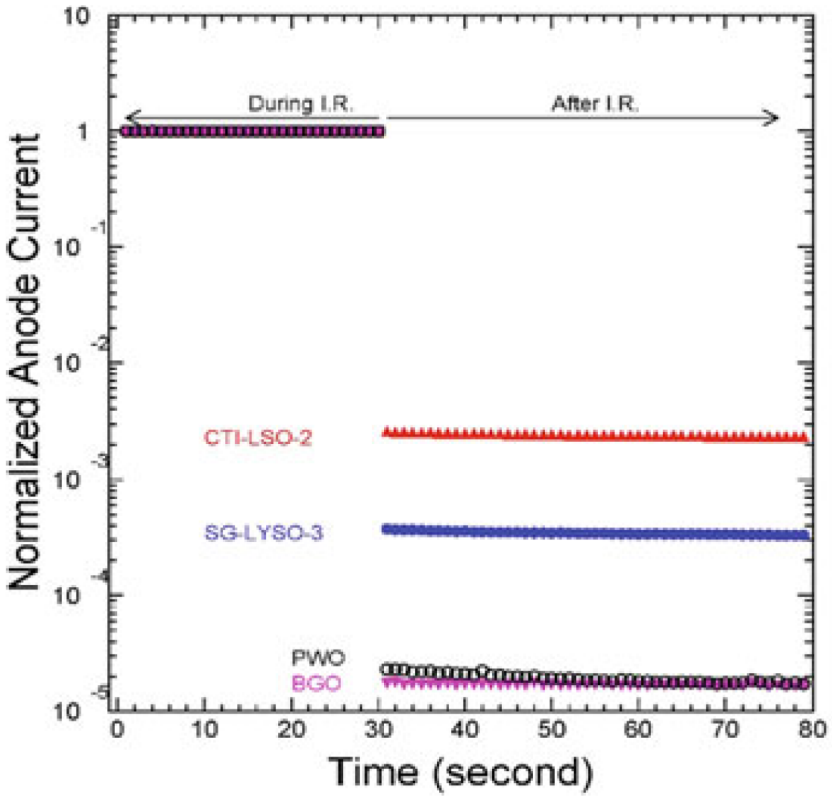
Scintillation Mechanism and Afterglow

https://doi.org/10.1007/978-3-319-47999-6_22-2

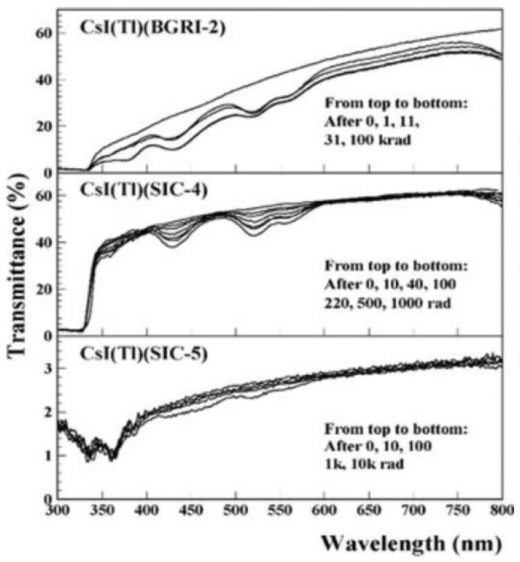
Crystal's scintillation mechanism is not damaged by γ -rays, neutrons and charged hadrons, as shown in no variation in the emission spectra measured before and after irradiations. Radiation-induced phosphorescence is measured as the photo-current after radiation, which is at a level of 10^{-5} for BGO and PWO and 3×10^{-4} for LYSO, and 2×10^{-3} for LSO.

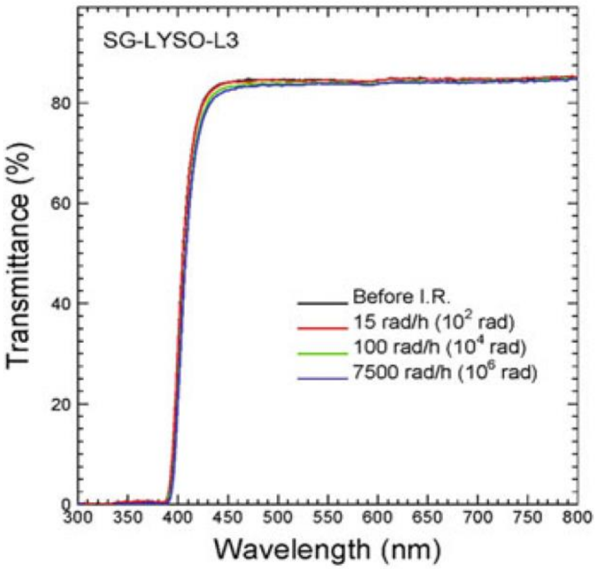


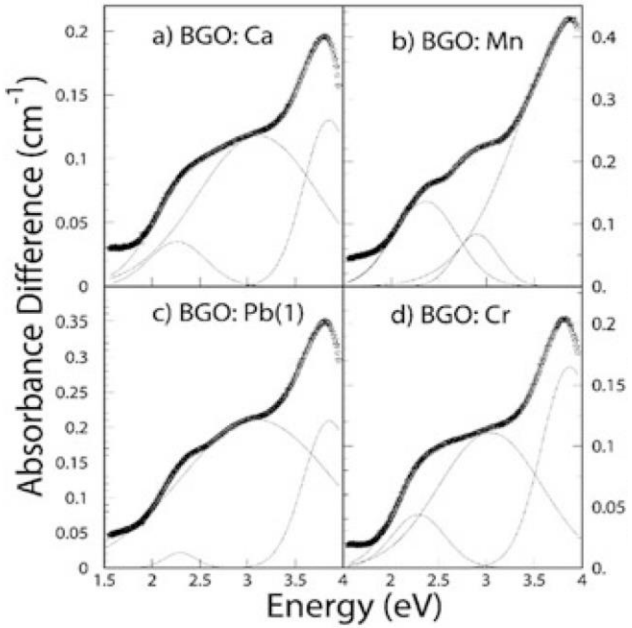


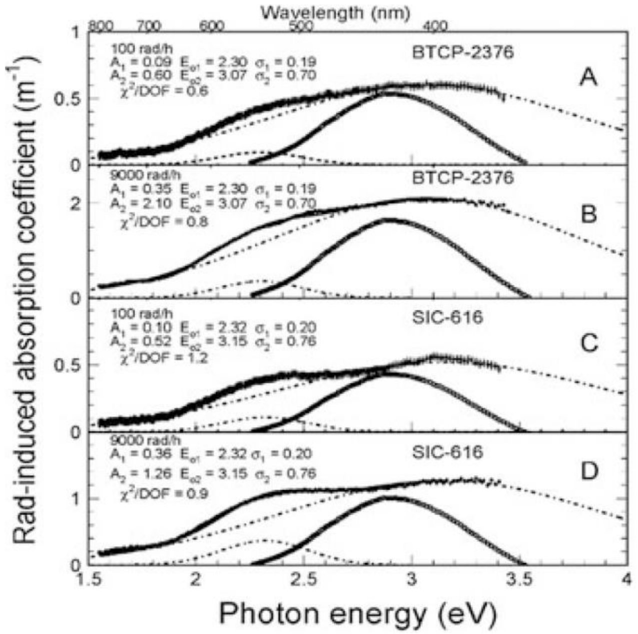


Radiation-Induced Color Centers









https://doi.org/10.1007/978-3-319-47999-6_22-2

$$EWLT = \frac{\int LT(\lambda)\, Em(\lambda)\, d\lambda}{\int Em(\lambda)\, d\lambda}$$

$$RIAC(\lambda)\ \ or\ \ D(\lambda) = 1/LAL_{\text{after}}(\lambda) - 1/LAL_{\text{before}}(\lambda)$$

$$RIAC(\lambda) = \frac{1}{l}\ln\frac{T_0(\lambda)}{T(\lambda)}$$

$$EWRIAC = \frac{\int RIAC(\lambda)\, Em(\lambda)\, d\lambda}{\int Em(\lambda)\, d\lambda}$$

$$RIAC(\lambda) = \sum_{i=1}^{n} A_i e^{-\frac{(E(\lambda)-E_i)^2}{2\sigma_i^2}}$$

NIM A**302** (1991) 69, NIM A**376** (1996) 319

Dose Rate Dependent Damage in PWO

PWO light reached an equilibrium under a dose rate, showing a dose rate dependent damage
Damage/recovery requires continuous light monitoring to maintain PWO energy resolution

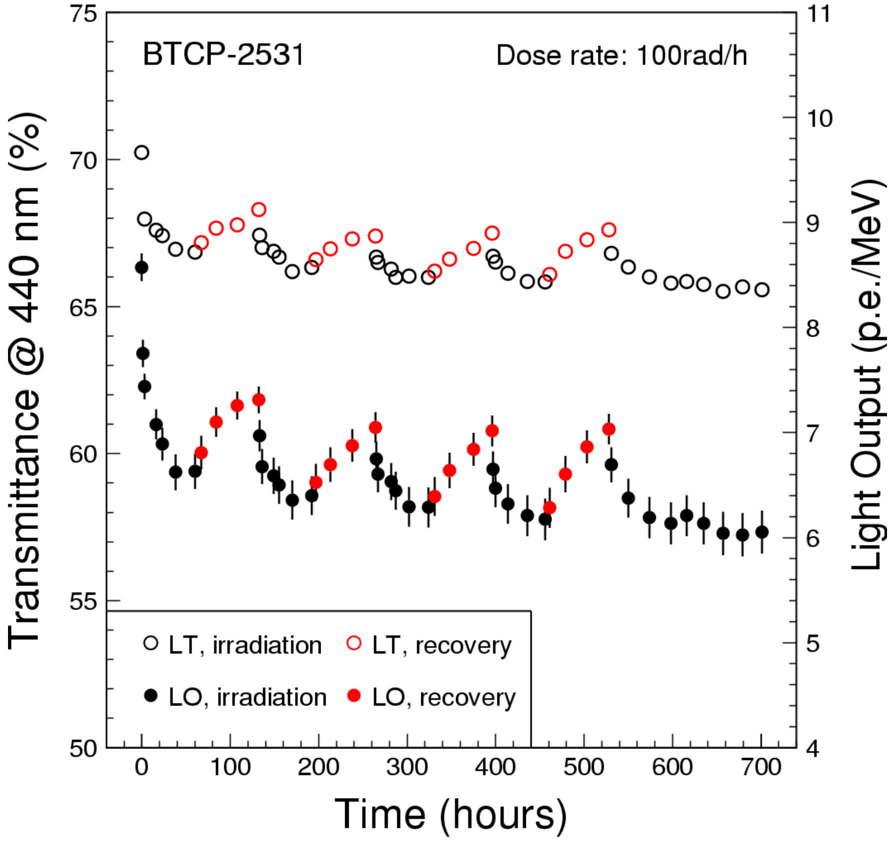
Damage/recovery observed in early lab investigation:
IEEE Trans. Nucl. Sci., Vol. 44 (1997) 458-476

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

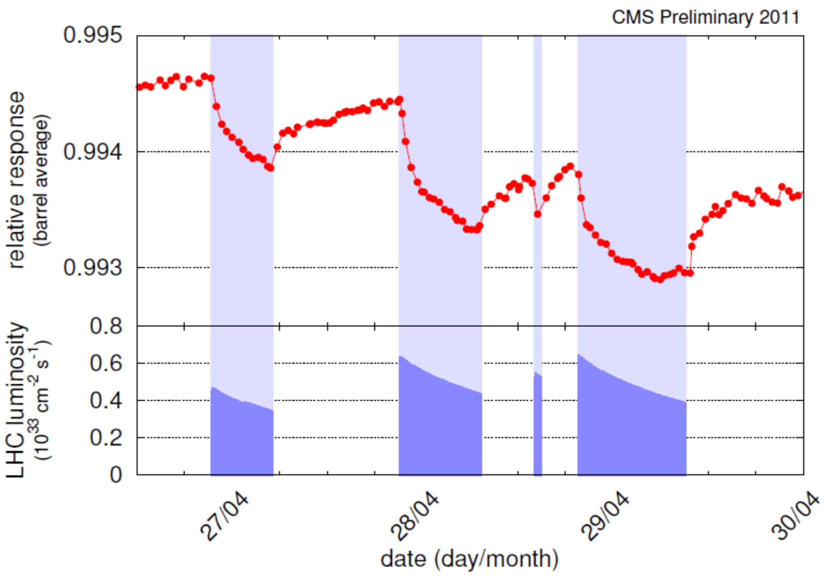
$$D = \sum_{i=1}^{n} \{\frac{b_i R D_i^{all}}{a_i + b_i R} [1 - e^{-(a_i + b_i R)t}] + D_i^0 e^{-(a_i + b_i R)t}\}$$

- 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.

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



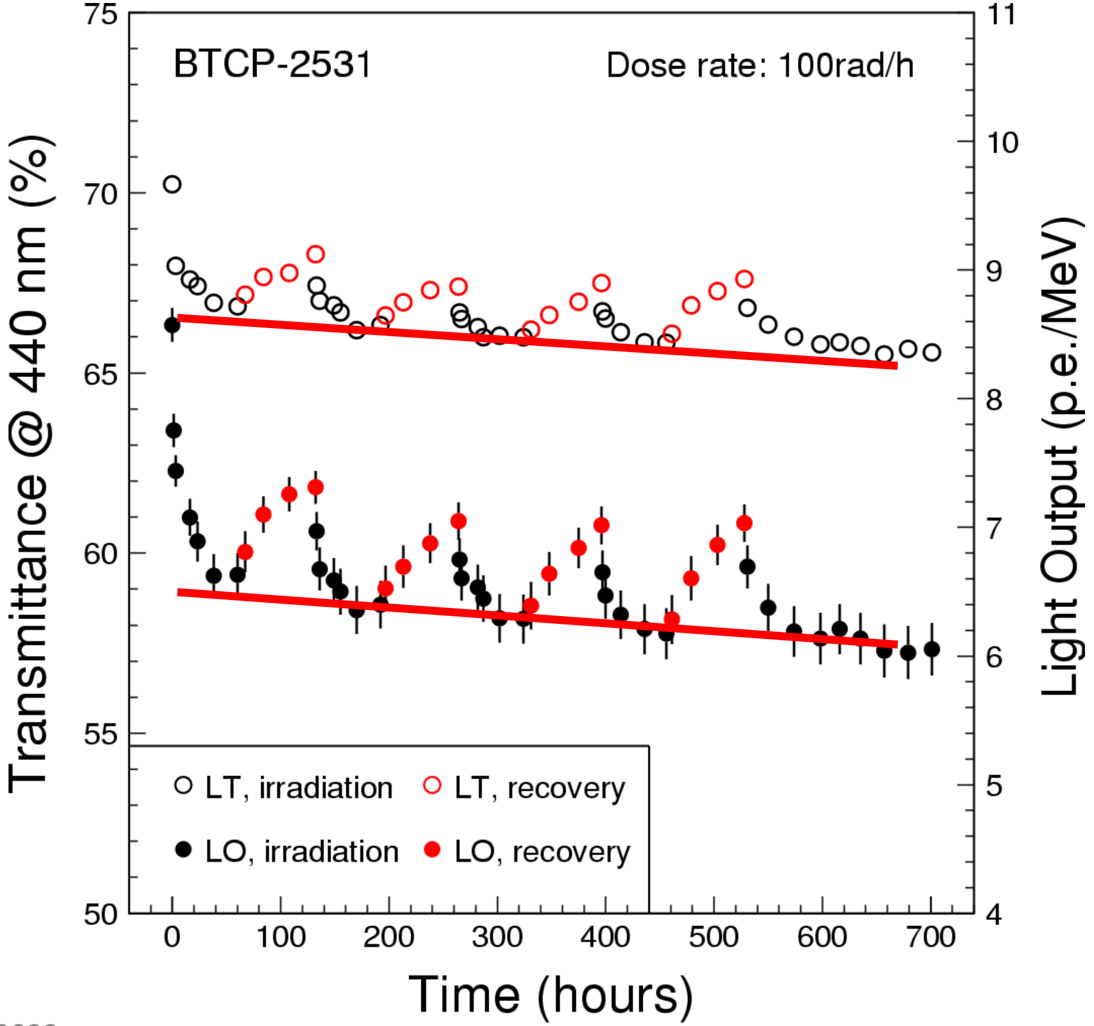
Damage and recovery observed *in situ* at the LHC by the CMS light monitoring system

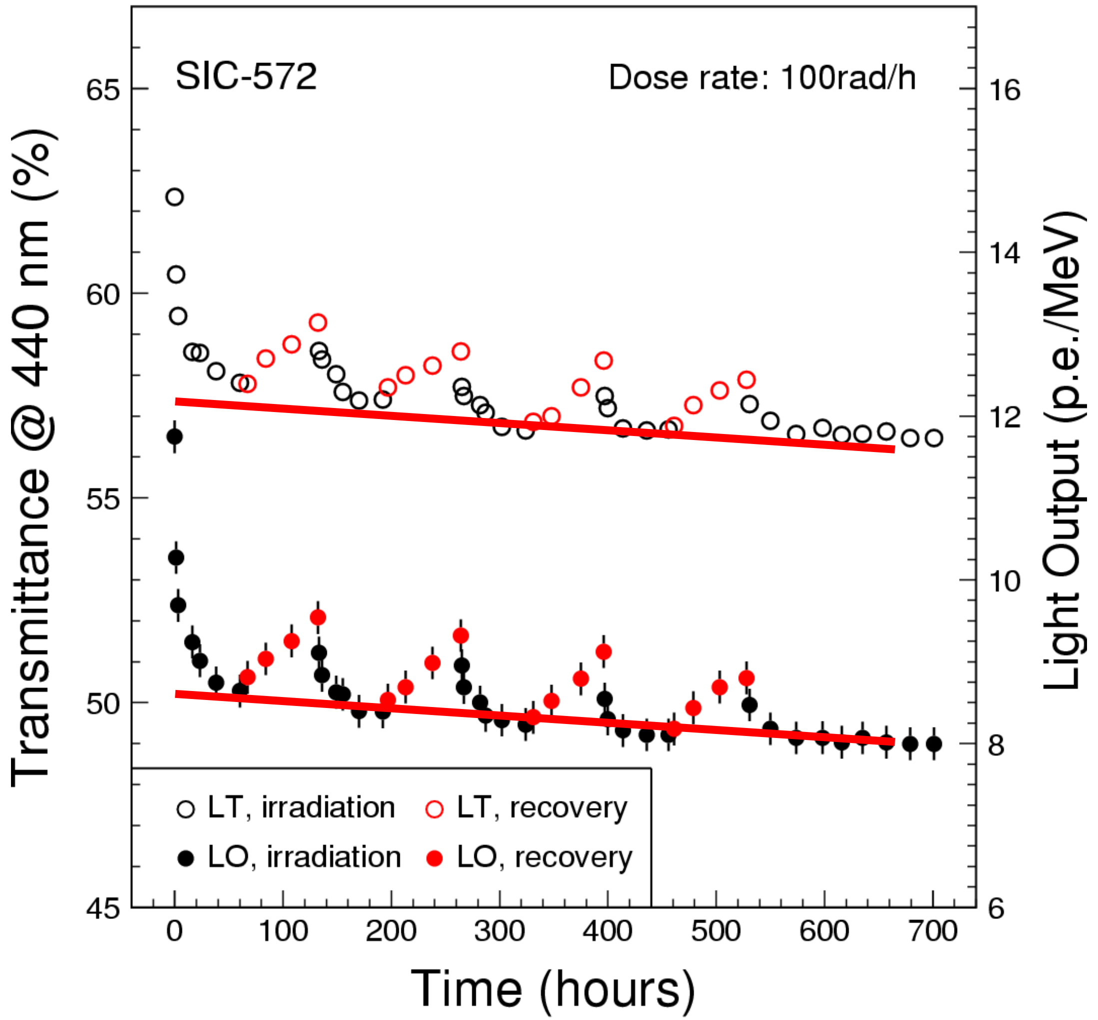


Effect of Multiple Color Centers

BTCP & SIC PWO @ 100 rad/h and recovery

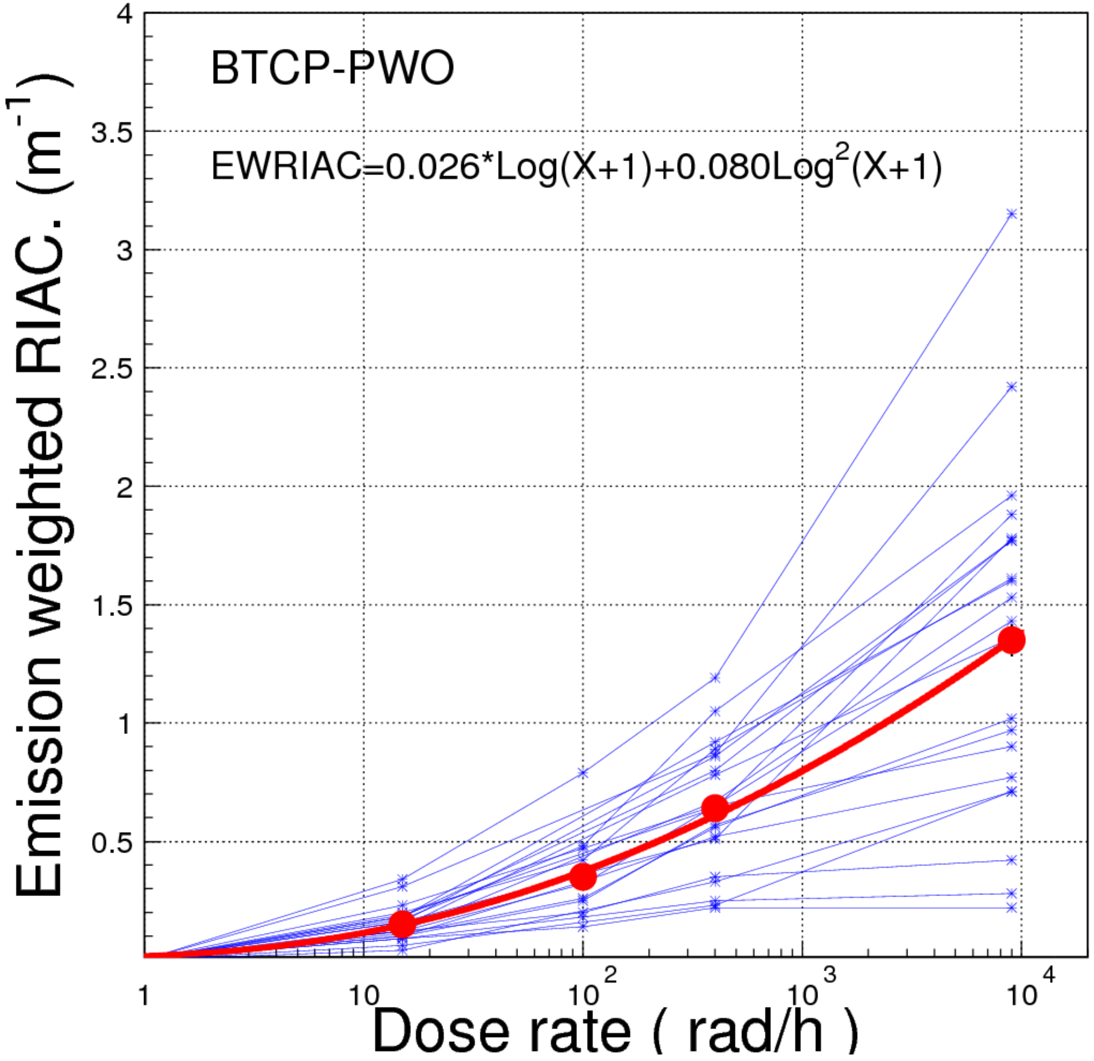
AIP Conference Proceedings 867 (2006) 252

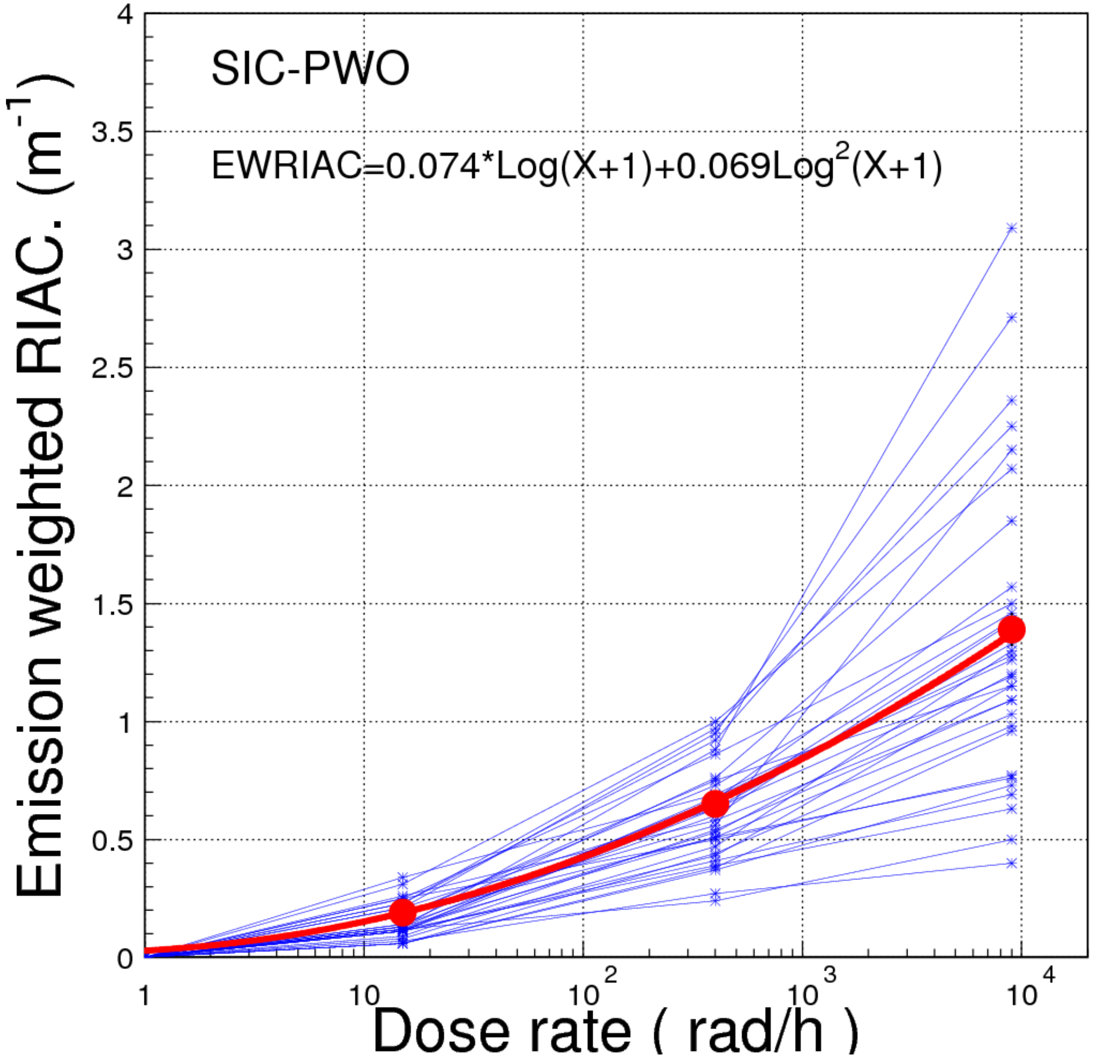




EWRIAC vs. Ionization Dose Rate

Large spread observed for both BTCP and SIC PWO with EWRIAC fit to 2^{nd} order polynomials of dose rate. IEEE Trans. Nucl. Sci. NS-51 (2004) 1777





Ionization Dose Induced Damage in PWO

Dose rate from CMS BRIL Simulation

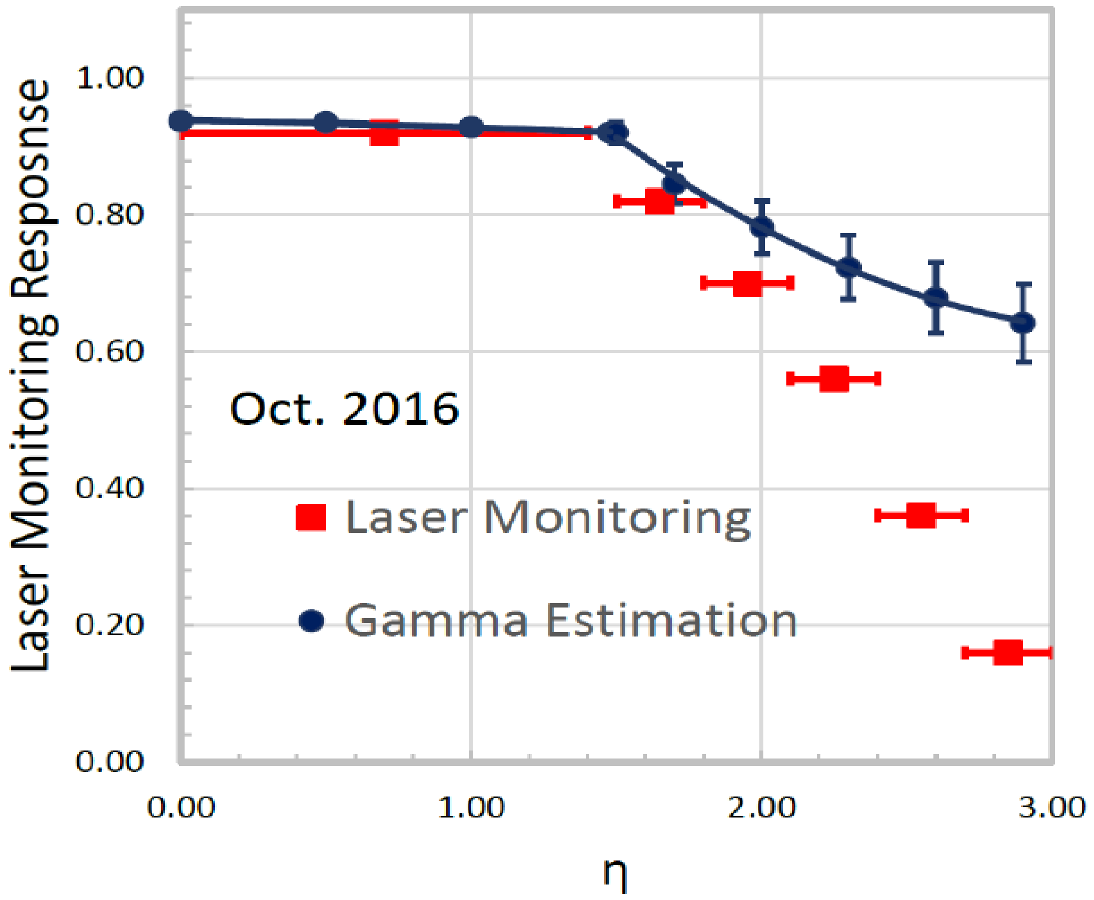
https://cms-project-fluka-flux-map.web.cern.ch/cms-project-fluka-flux-map/

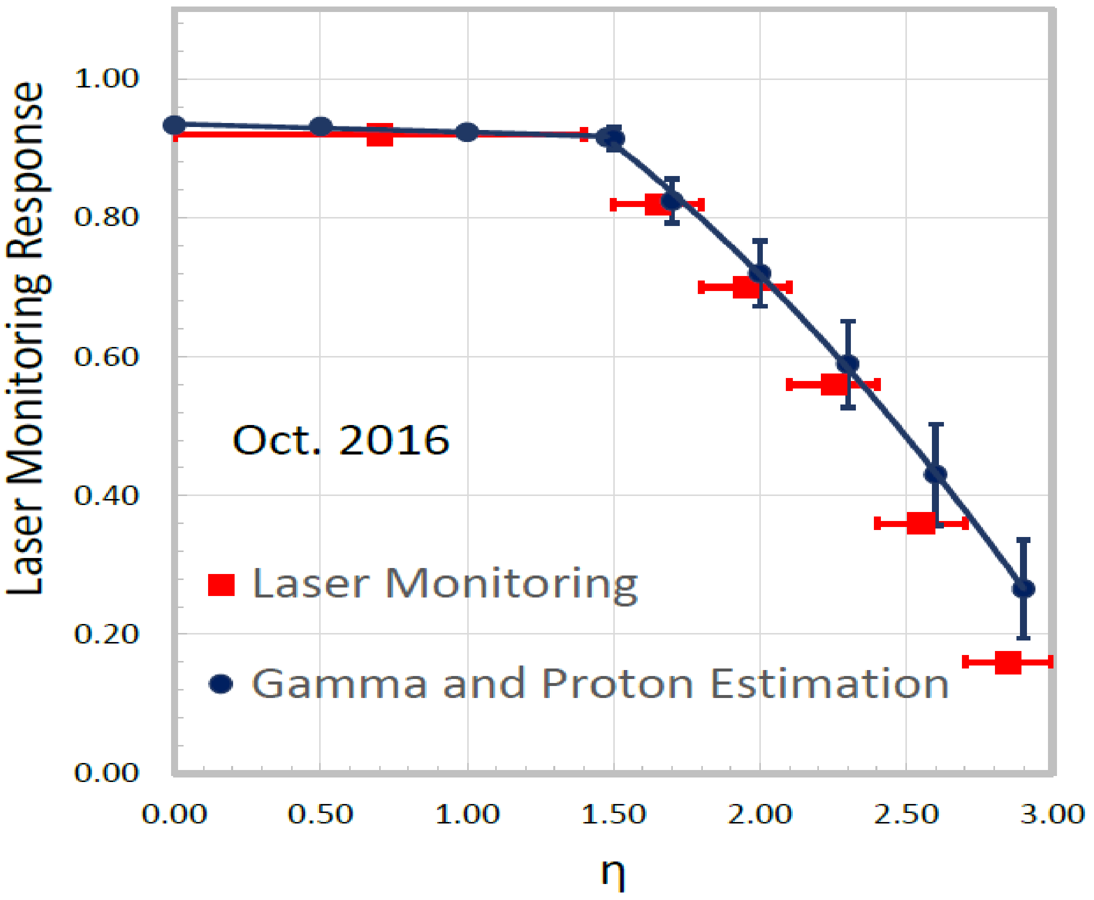
Run I: CMS_pp_4.0TeV_2012_FLUKA, Run II: CMS_pp_7TeV_v3.0.0.0_FLUKA

CMS ECAL	η=0	η=0.5	η=1.0	η=1.478	η=1.5	η=1.7	η=2.0	η=2.3	η=2.6	η=2.9
Run I Dose rate (rad/hr)	10	11	14	17	6	35	86	211	329	433
Run I μ_{440nm} (m^{-1})	0.125	0.133	0.152	0.175	0.089	0.254	0.378	0.527	0.610	0.664
Run II Dose rate (rad/hr)	25	27	34	42	16	63	167	385	706	1170
Run II μ_{440nm} (m^{-1})	0.216	0.223	0.250	0.276	0.165	0.332	0.486	0.640	0.765	0.877

Hadron-Induced Damage in PWO

γ-ray induced absorption alone can not explain monitoring loss,
Charged and neutral hadrons also damage PWO crystals
http://www.its.caltech.edu/~rzhu/talks/ryz_161028_PWO_mon.pdf

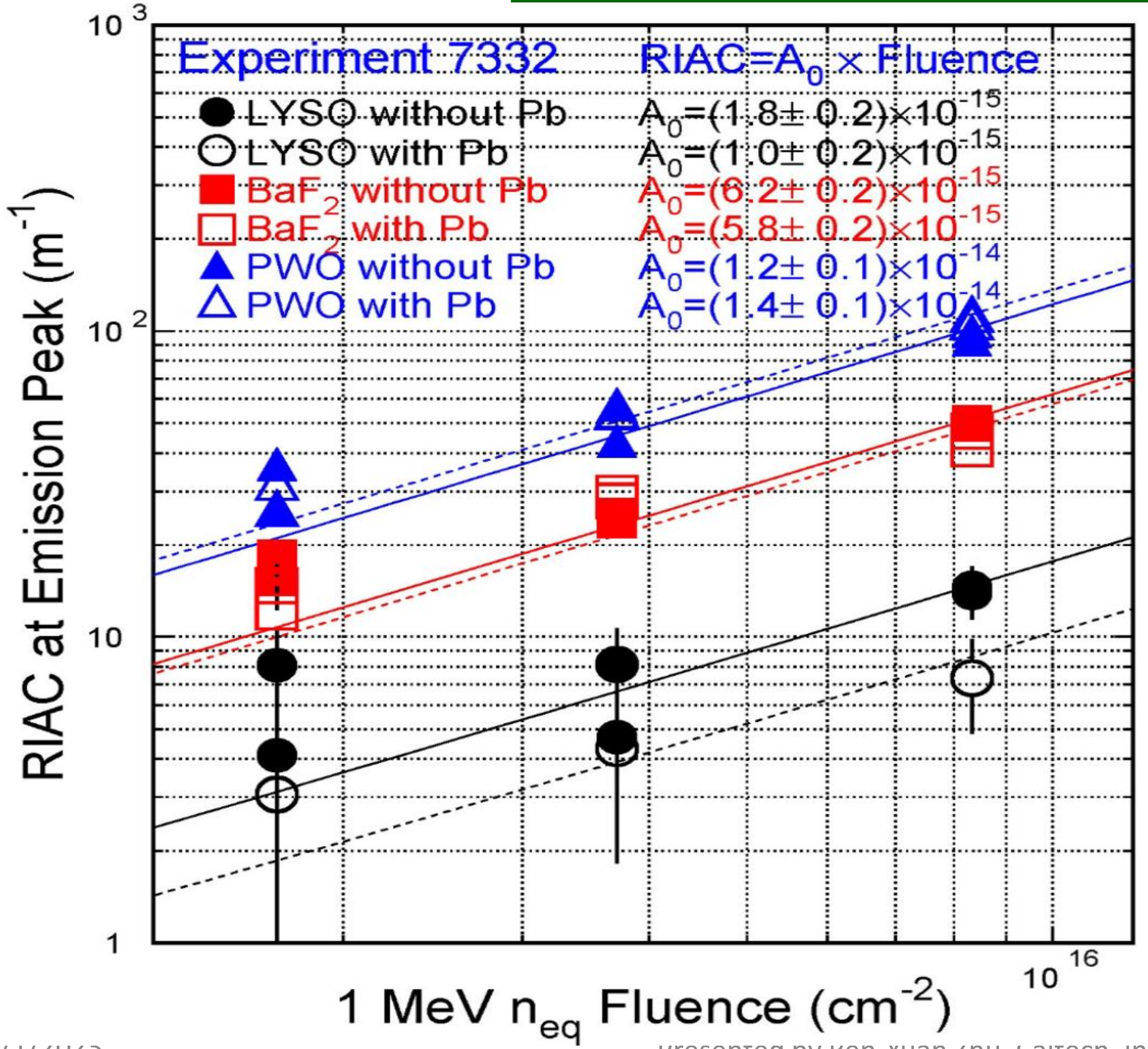


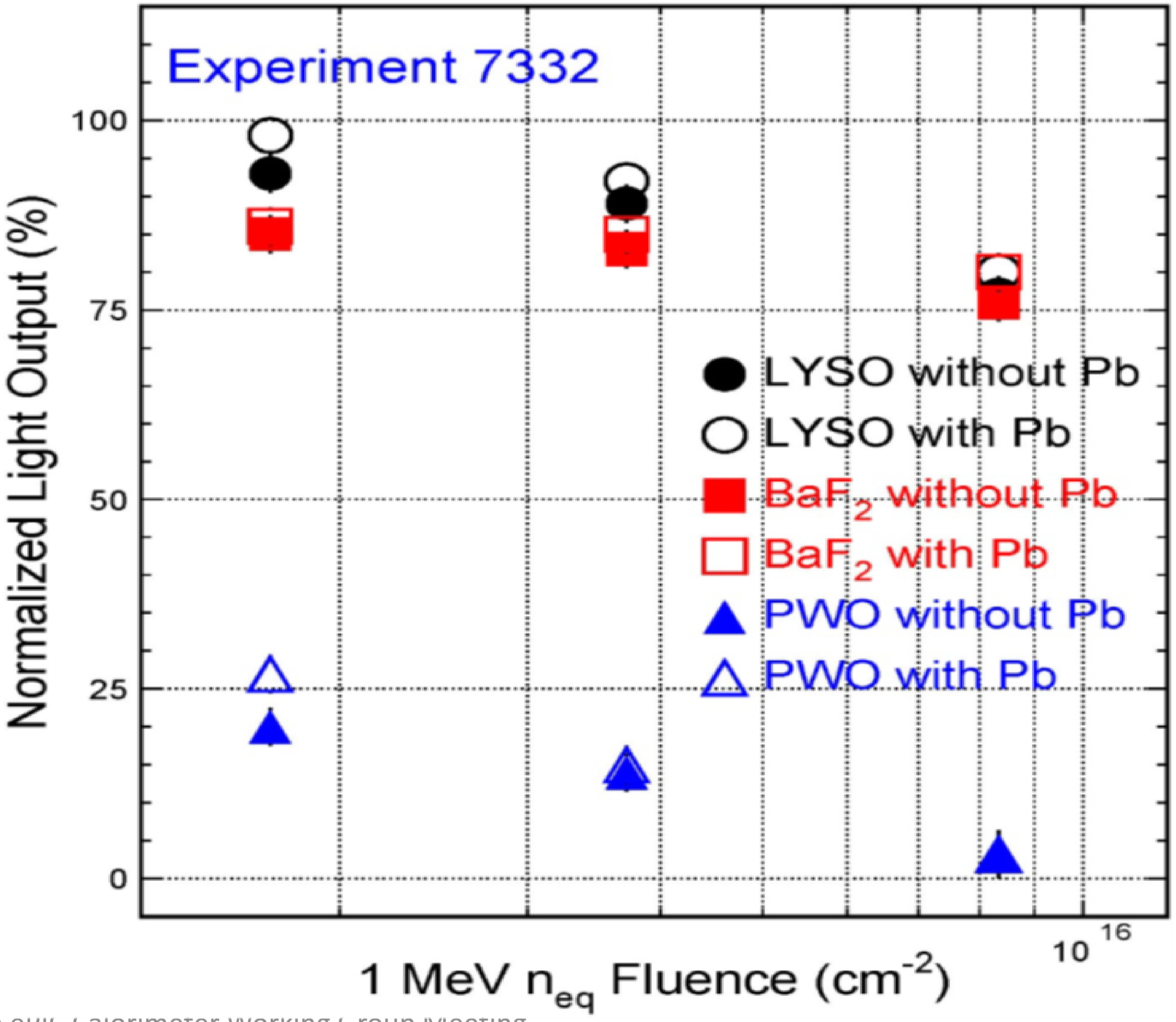


RIAC vs. Neutron Fluence (LANSCE 7332)

RIAC in PWO = $1.4 \times 10^{-14} \times 1$ MeV n_{eq} Fluence

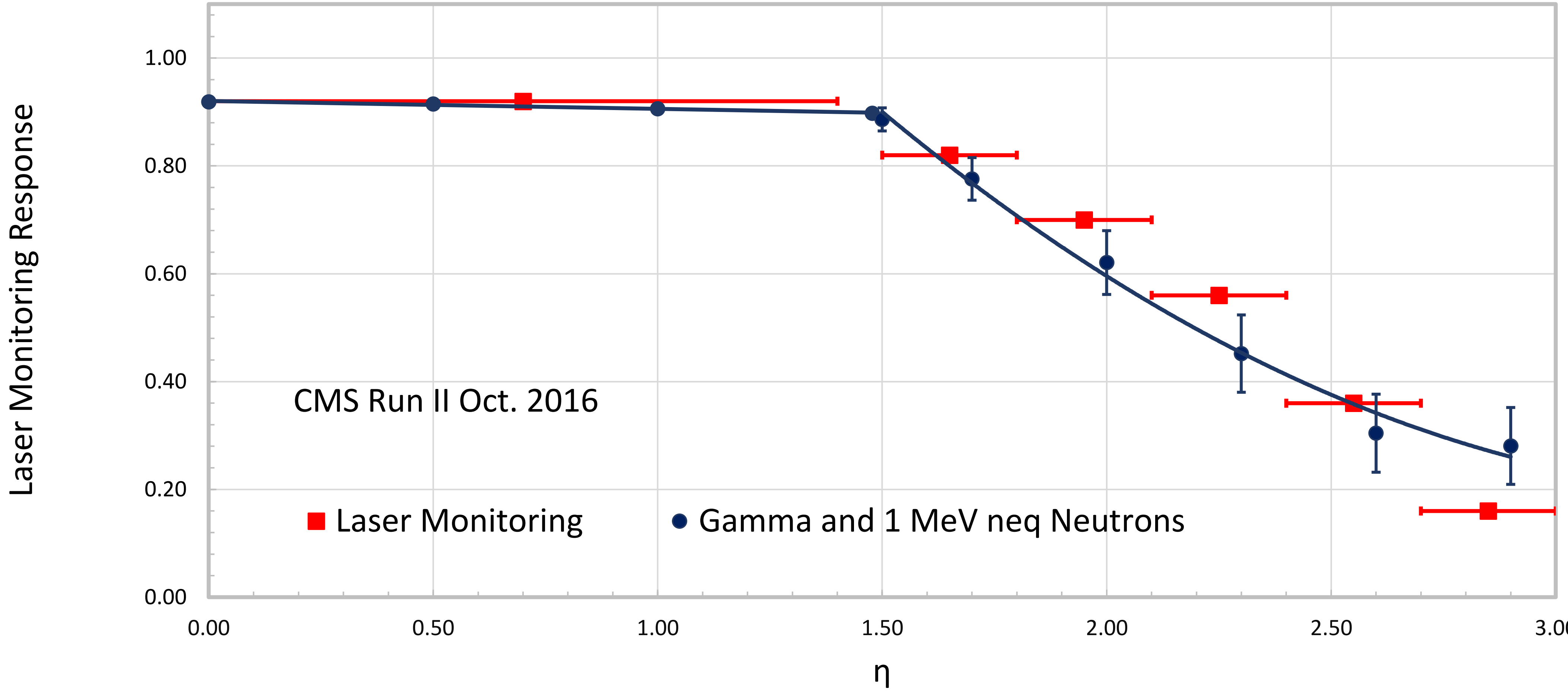
IEEE Trans. Nucl. Sci., Vol. 67 (2020) 1086-1092





Hadron-Induced Damage in PWO

Monitoring data explained by damage induced by ionization and neutrons
Ionization dose includes charged hadrons of 10% of neutron fluence



Comparison: ePIC and BTL at HL-LHC

The ionization dose rate and neutron flux of the ePIC PWO ECAL are two to three orders of magnitude lower than that of the CMS BTL (LYSO:Ce+SiPM) at the HL-LHC
The expected RIAC values are small. QC is needed for mass-produced PWO crystals

Radiation	EIC / Year	EIC*	CMS BTL** / 4000 fb-1 (η= 0-1.45)	CMS BTL** (η= 0-1.45)
Ionization Dose	3 Krad	1.3 rad/h	2.7-4.8 Mrad	110-190 rad/h
1 MeV eq. Neutrons	10^{10} /cm^2	1.2×10^3 /cm^2/s	$(2.5\sim2.9)\times10^{14}$ /cm^2	$(2.8\sim3.2)\times10^6$ /cm^2/s
Charged Hadrons			$(2.2\sim2.5)\times10^{13}$ /cm^2	$(2.4\sim2.8)\times10^5$ /cm^2/s

*Estimated by assuming 100 days operation per year.
** IEEE Trans. Nucl. Sci. NS-68 (2021) 1244-1250

Summary

Total absorption crystal ECAL provides the best energy resolution for HEP experiments. Radiation damage induced by ionization dose and hadrons presents a serious challenge for maintaining crystal precision *in situ*.

PWO crystals suffer from damage recovery *in situ.* Continuous monitoring in 24/7 is crucial for maintaining calibration precision. Use crystals without recovery, such as BaF_2, CsI and LYSO:Ce, would reduce the workload.

The expected ePIC ionization dose of up to 3 krad/year and neutron flux of up to $10^{10}/cm^2/year$ are several orders of magnitudes smaller than CMS. Rigorous QC is required because of the diverse radiation hardness of mass-produced PWO crystals.

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