



Performance of Lead Tungstate Crystals for the CMS Electromagnetic Calorimeter

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(on behalf of CMS ECAL Collaboration)



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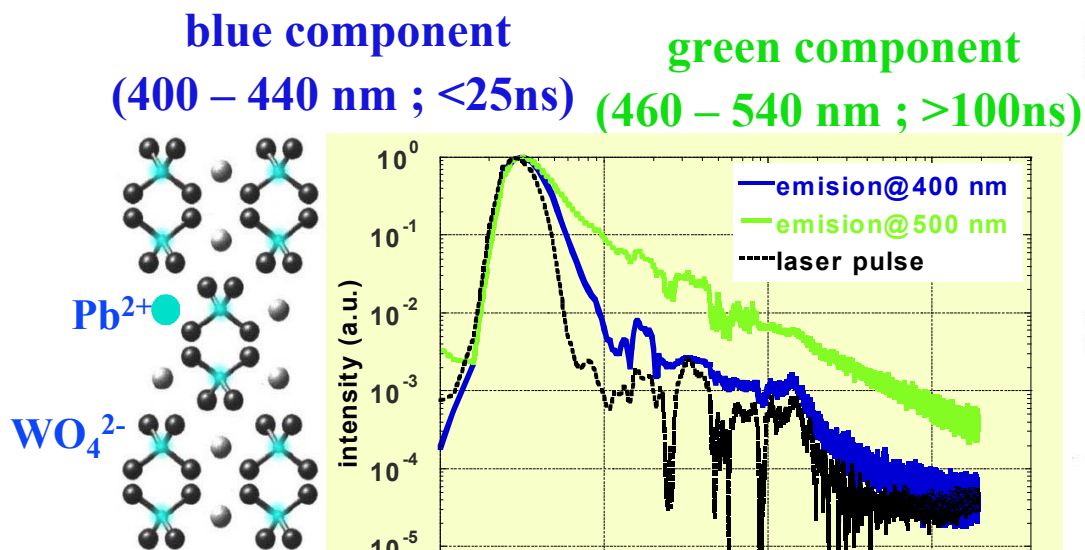
- 1. PWO general properties**
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Luminescence

PbWO₄ (PWO)

- studied as phosphor since 1979
- promoted scintillator early nineties

ρ	g/cm ³	8.26
X_0	cm	0.89
R_m	cm	2.2
τ	ns	15
$\lambda_{\text{emission}}$	nm	420
$n@ \lambda_{\text{emission}}$	-	2.29
LY	% of BGO	5
α_{LY}	%/°C	-2



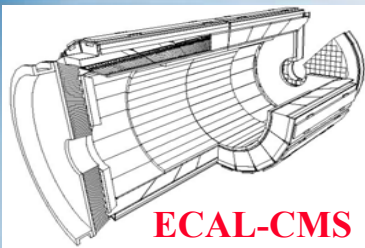
ECAL PWO crystals supplier
Bogoroditsk Techo Chemical Plant
 Russia



♥ suppressed green component
 ♥ improved radiation hardness



PWO properties vs ECAL-CMS requirements



ECAL-CMS

high stopping power

small X_0

high granularity

small R_m

high density and high Z

high energy resolution

large LY



BGO	PWO	CeF3
1.11	0.89	1.68
2.33	2.2	2.63

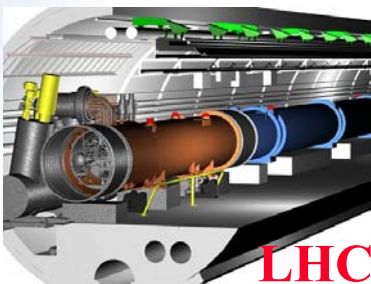
high refractive index !

emission spectrum overlapping with spectral sensitivity of APD and VPT

(see Q. Ingram's talk)

160±20GeV

APD and VPT



LHC

Bunch separation 25 ns

fast

Luminosity $10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$

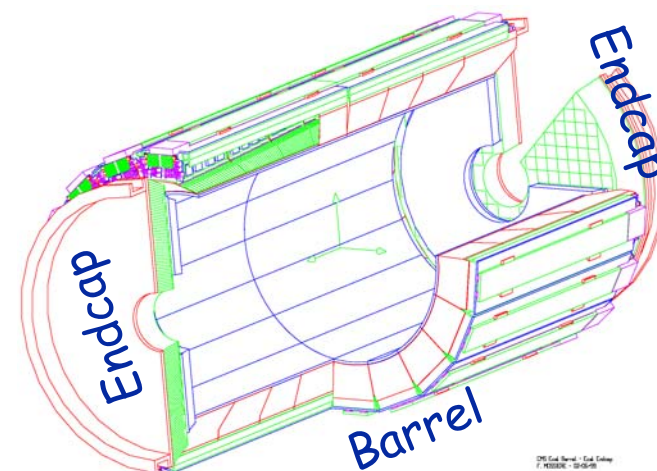
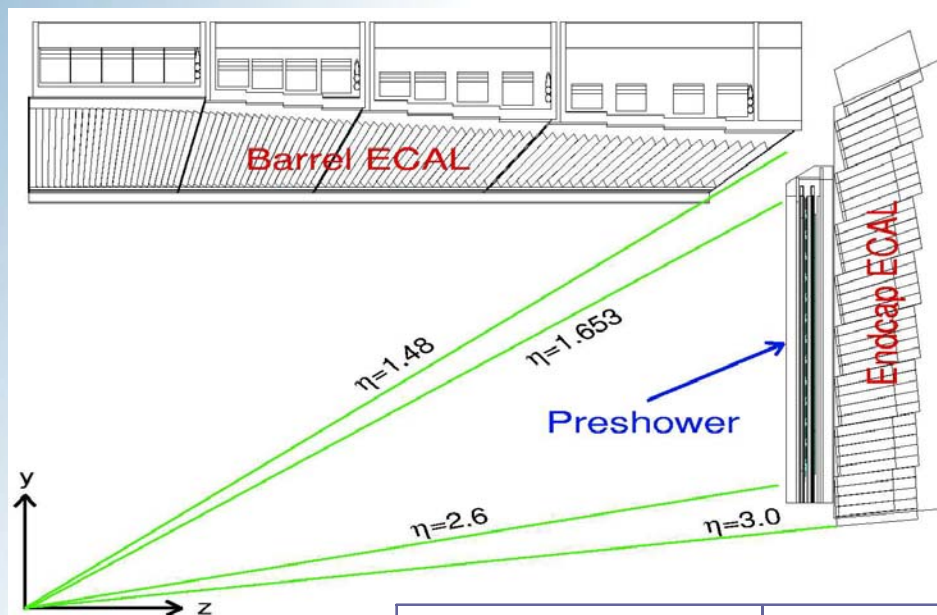
radiation hard

BGO	PWO	CeF3
300	15	30

- light production is not affected
- creation of color centers is quenched by appropriate doping



PWO crystals needed for ECAL-CMS

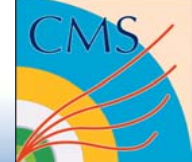


**Xtals point 3°
away from vertex**

		Barrel	Endcap
No.of Xtals		61200 (34 types)	14648 (1 type)
Xtal size (cm)	transv:	2.2 - 2.5 (Rm)	3
	long:	23 (25.8X0)	22 (24.7X0)
Total weight		67.4 tons	22.9 tons
Photosensor		Avalanche Photo-Diode (Si)	Vacuum Photo-Triode



PWO survey during the ECAL construction phase



premise

*at present (ECAL construction phase), the PWO crystal is taken “as it is”
i.e. no spectacular modifications of its scintillation properties are expected*

*keep the qualification
parameters inside the limits
defined by ECAL Collaboration*

**very strict crystal
quality control**

**parallel radiation
hardness tests**

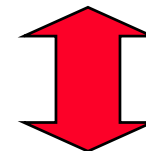
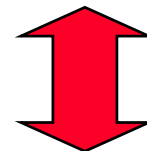
(see P.S.Roldan's talk)

**QC measurements for the LY are seen by the ECAL
Collaboration not as routine check but as a first
crucial step in the frame of calibration activities**

*find the ways to get the best possible
performance from the ECAL
modules built with this PWO*

**LY
characteristics**

**radiation
damage**



calibration

monitoring



PWO survey during the ECAL construction phase



premise

(see R-Y.Zhu talk on calibration and monitoring)

calibration

- defines the ultimate performance of the ECAL
- is influenced by a very large number of factors (electronics gain, APD amplification factor, containment efficiency, etc) besides scintillation characteristics of PWO

monitoring

the change of PWO crystals transparency during ECAL exploitation phase will be monitored in situ with a laser and a correction to particles signal will be applied:

$$R = \frac{\Delta_{BeamSignal}}{\Delta_{MonitorSignal}}$$

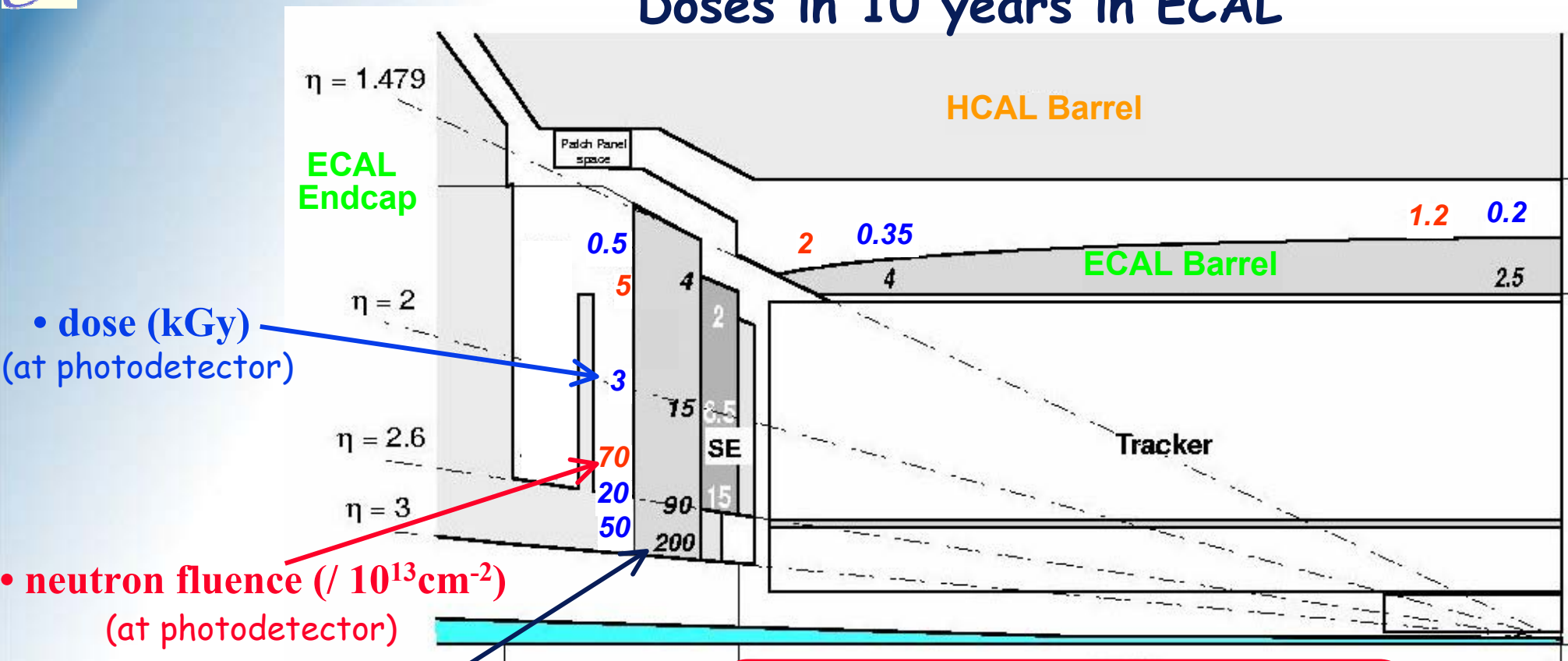
where:

$\Delta_{BeamSignal}$: the fractional decrease in the beam signal

$\Delta_{MonitorSignal}$: the fractional decrease in the light monitoring signal

premise

Doses in 10 years in ECAL



• dose (kGy)
(at photodetector)

• neutron fluence ($/ 10^{13} \text{cm}^{-2}$)
(at photodetector)

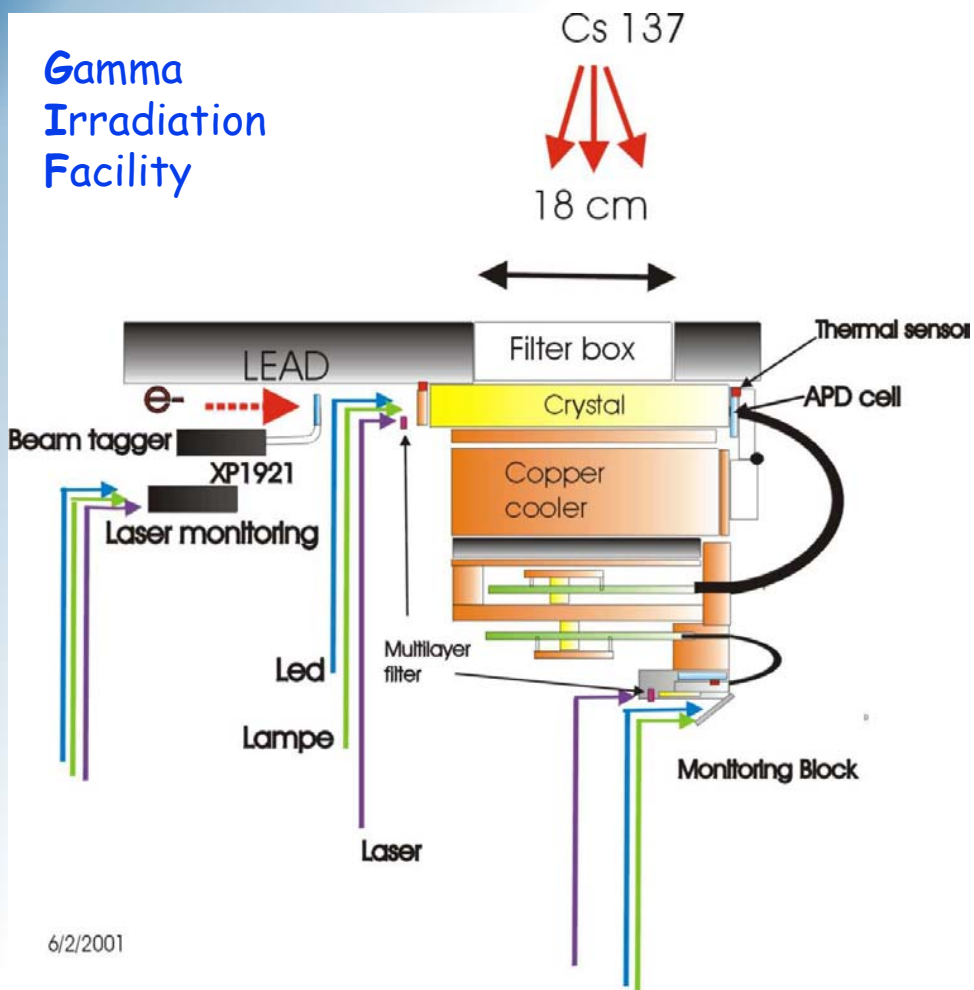
• dose (kGy)
(at shower maximum in crystal)

tests made in:

- CERN (l'Hopital de Genève)
- CERN GIF and H4
- Rome ENEA Casaccia
- California Institute of Technology

PWO crystals tests at GIF

Gamma
Irradiation
Facility



6/2/2001

<http://cmsdoc.cern.ch/cms/ECAL/GIF/www/>



- Irradiation (transversally):

Cs^{137} (0.662 MeV) ; doses rates close to LHC conditions

- Crystal 1: 20 rad/h
- Crystal 2: 26 rad/h
- Crystal 3: 30 rad/h
- Crystal 4: 26 rad/h
- Crystal 5: 20 rad/h

- Excitation

scintillation: SPS e^- beam (50 GeV)

luminescence: UV laser ($\lambda=337\pm 10$ nm, 1.55mJ/pulse, $t=600$ ps)

- Monitor

longitudinal transmission (LED)

$\lambda=450\pm 50$ nm, $t=500$ ns



PWO crystals tests at GIF

Measure the coefficient R defined as:

$$R(t) = \frac{S_A(t) - S_A(t=0)}{S_B(t) - S_B(t=0)} \quad \Big|_{t=0 \text{ (irradiation start)}}$$

where A and B correspond to different ways to produce the light measured by the APD:

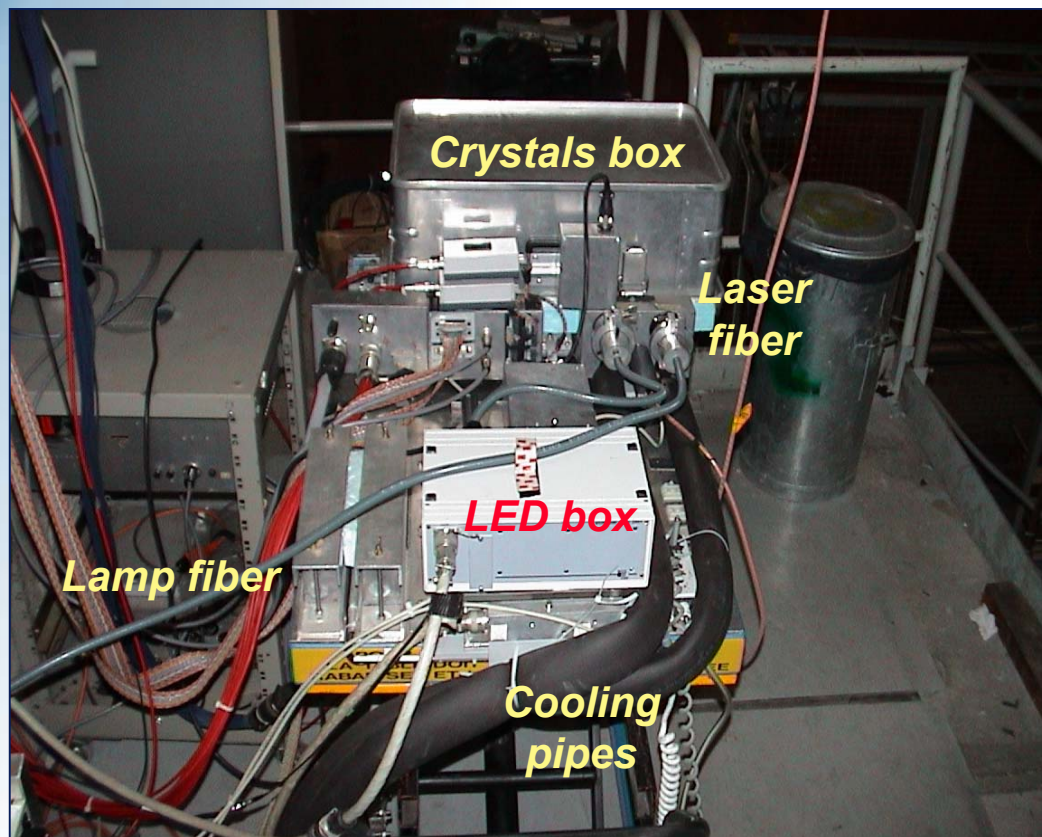
BEAM (scintillation under e beam excitation)

LASER (luminescence under UV laser excitation)

LED (transmitted light along the crystal)

For small radiation doses, in ideal measuring conditions, $R(t)$ has to be constant. $R(t) = R$

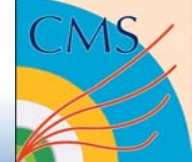
PWO crystals tests at GIF



- Crystals are tested in batches of 5
- The detectors for scintillation light are standard ECAL-CMS APDs
- The monitoring of different light sources is made by a PM coupled to a 6th crystal
- The monitoring of the laser pulse is made by a PIN diode
- The gain is periodically monitored with a constant charge injected to the amplifiers

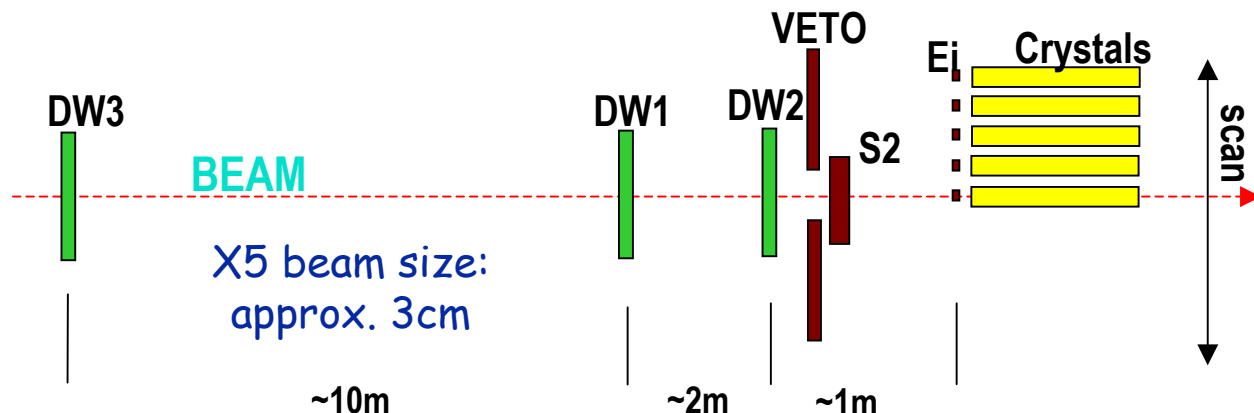
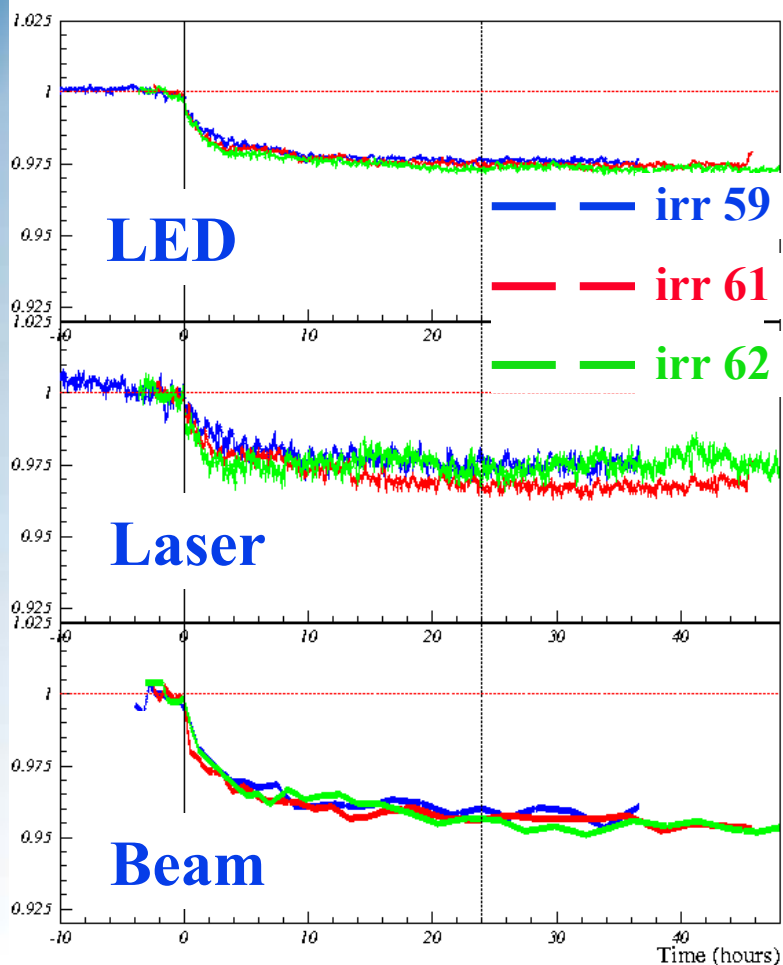


PWO survey during the ECAL construction phase



PWO crystals tests at GIF

Signal reduction cry_7467



Data analysis includes: test pulse correction, temperature correction, normalization with the monitor, signal cleaning using simple algorithms, normalization to 1 based on 3h data collection before the start of the effective run, computation of $R_{\text{BEAM/LED}}$, $R_{\text{BEAM/LASER}}$, $R_{\text{LASER/LED}}$ and using 1D gaussian fit method

PWO crystals tests at GIF

$$R_{\text{BEAM/LED}} = 1.9 \pm 4.2\%$$

$$R_{\text{BEAM/LASER}} = 1.6 \pm 8.4\%$$

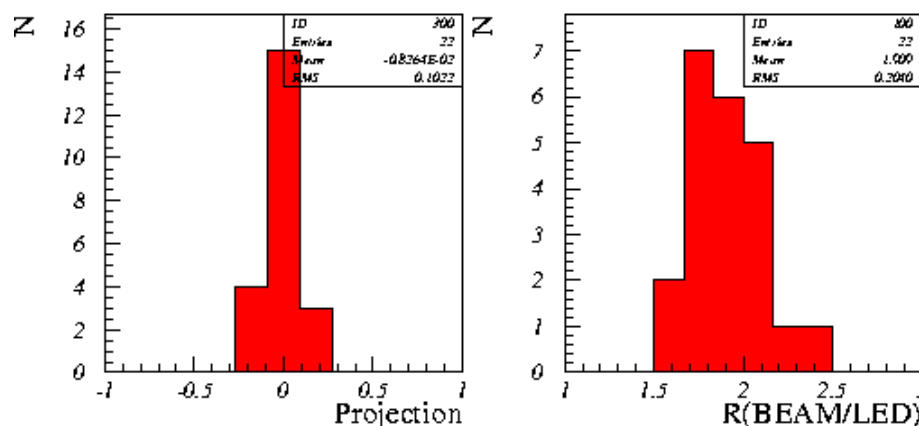
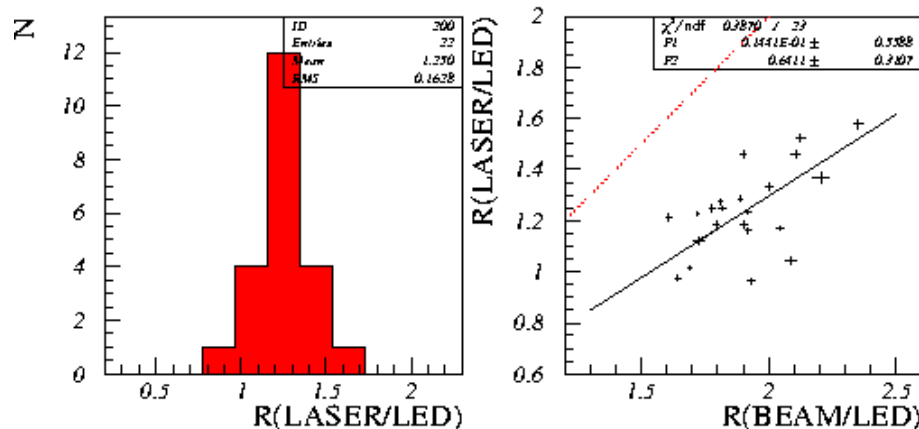
$$R_{\text{LASER/LED}} = 1.2 \pm 9.6\%$$

- Crystal to crystal dispersion of R is not significant (inside the errors)
- Good reproducibility of measurements
- Good correlation $R_{\text{LASER/LED}}$ vs $R_{\text{BEAM/LED}}$

$$\sigma_{R_{\text{LASER/LED}}} = 9\%$$

$$\sigma_{R_{\text{BEAM/LED}}} = 5\%$$

rfit1 correlation distribution



PWO crystals tests at Caltech



Caltech γ -ray Irradiation Facilities



Co⁶⁰

$\Lambda = 50$ Curie
15, 100, 400 rad/h



Cs¹³⁷

$\Lambda = 2000$ Curie
up to 36 Krad/h

(see rad.hard dedicated talk of R-Y. Zhu)

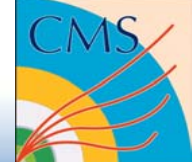
studies:

- UV-excited photo luminescence.
- Longitudinal transmittance.
- Radiation induced color centers.
- Emission weighted radiation induced absorption coefficient.
- Recovery speed and time constant of transmittance.
- Light output and decay kinetics.
- Damage speed and time constant of light output under 15 rad/h.

steps:

- (1) thermal annealing at 200°C
- (2) γ -irradiations: 15, 100, 400 and 9k rad/h (until equilibrium)
- (3) recovery

Crystals are kept in dark at 18°C after annealing. Minimum time between annealing and 1st measurement is 48 hours.



PWO crystals tests at Caltech

Caltech results generally confirm those obtained on PWO during the R&D and pre-production phase

no variations in either light output or longitudinal transmittance observed 8h after the thermal annealing

STABLE

no modification under γ -ray exposure of either excitation or emission spectra

RELIABLE

no very short time recovery components

MONITORING OK

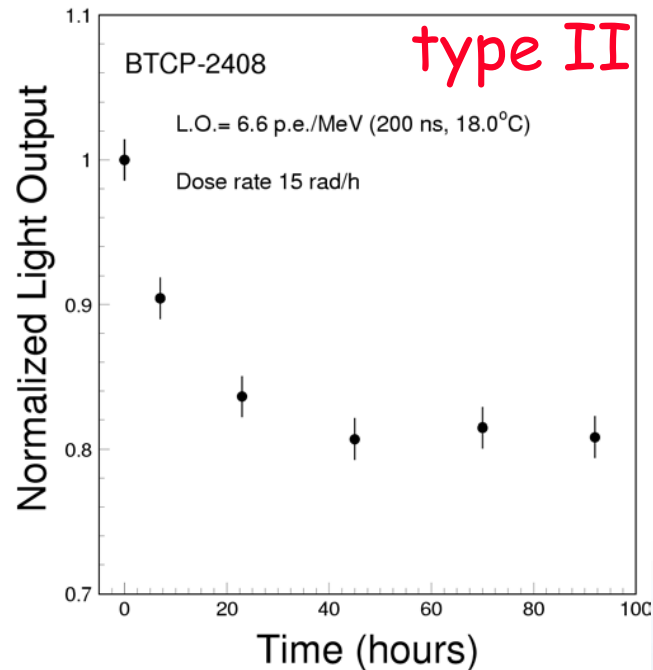
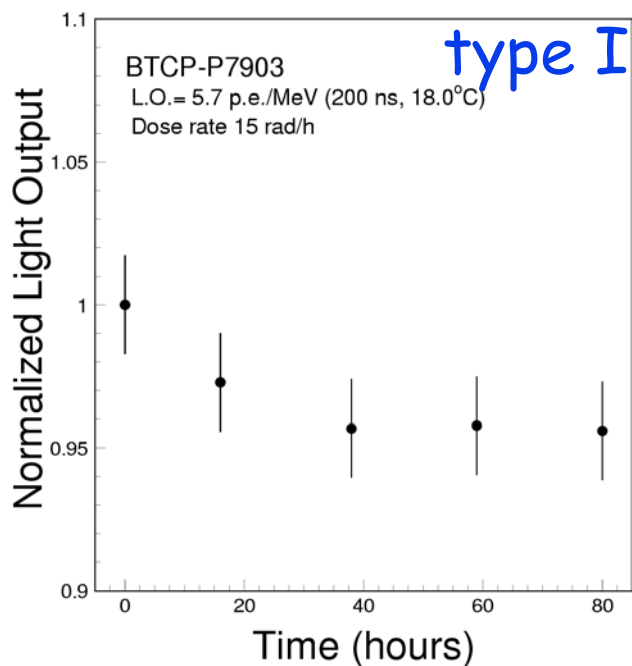
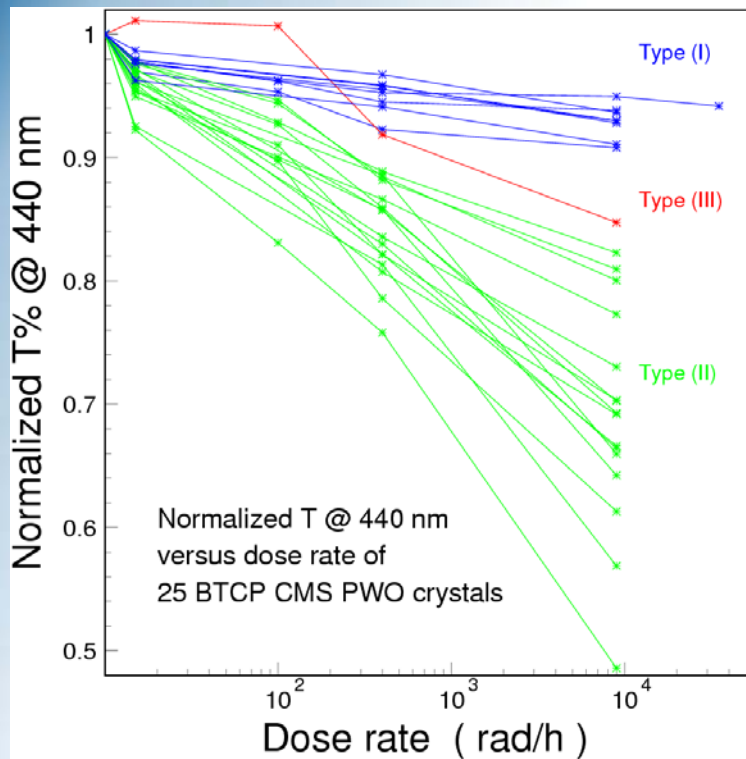
samples can be divided into 3 types from radiation hardness point of view



PWO survey during the ECAL construction phase



INFN PWO crystals tests at Caltech

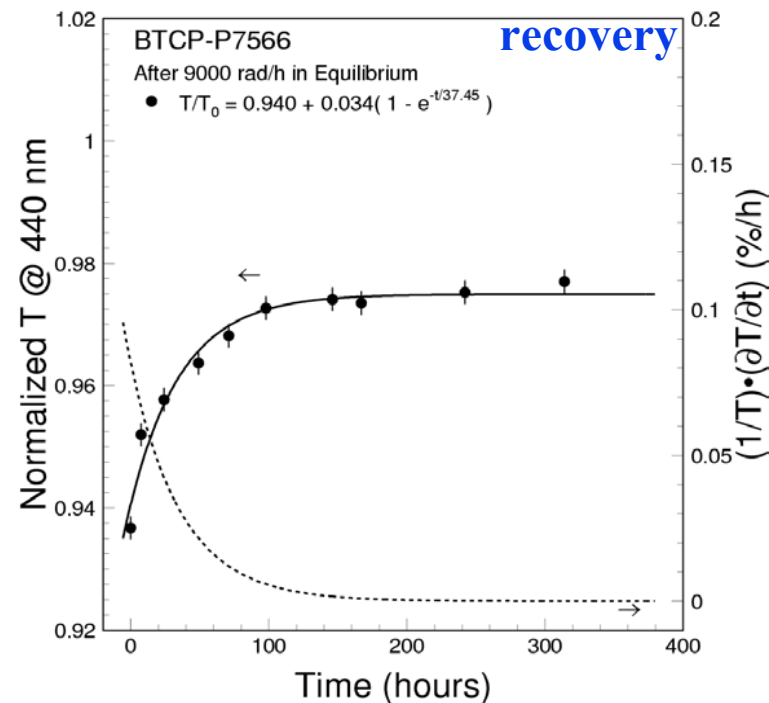
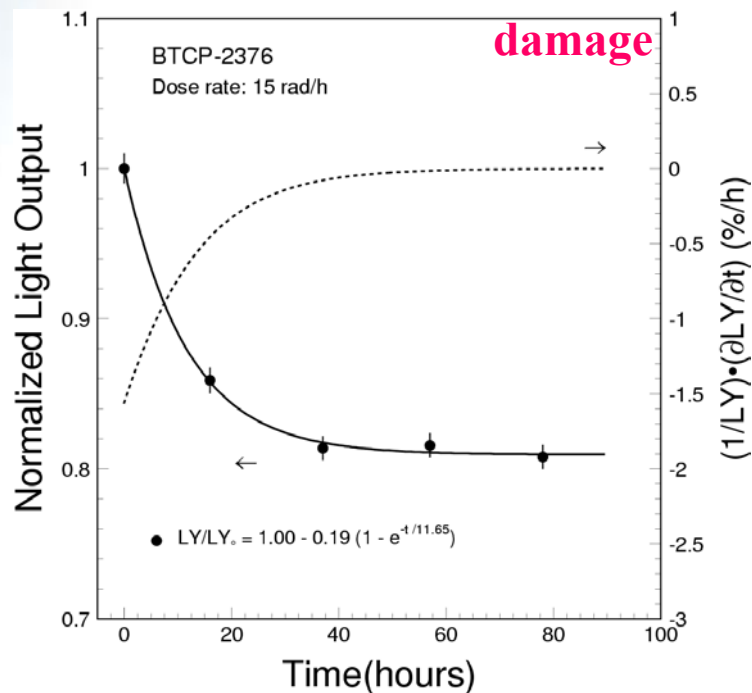


type III crystals are hopefully discarded by ECAL rejection criteria (see P.S.Roldan's talk)

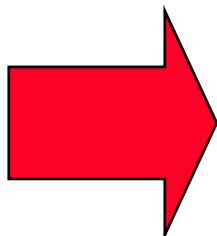
PWO crystals tests at CIT damage and recovery kinetics studies

particularly
interesting for
monitoring

(see dedicated
talk of R-Y.Zhu)



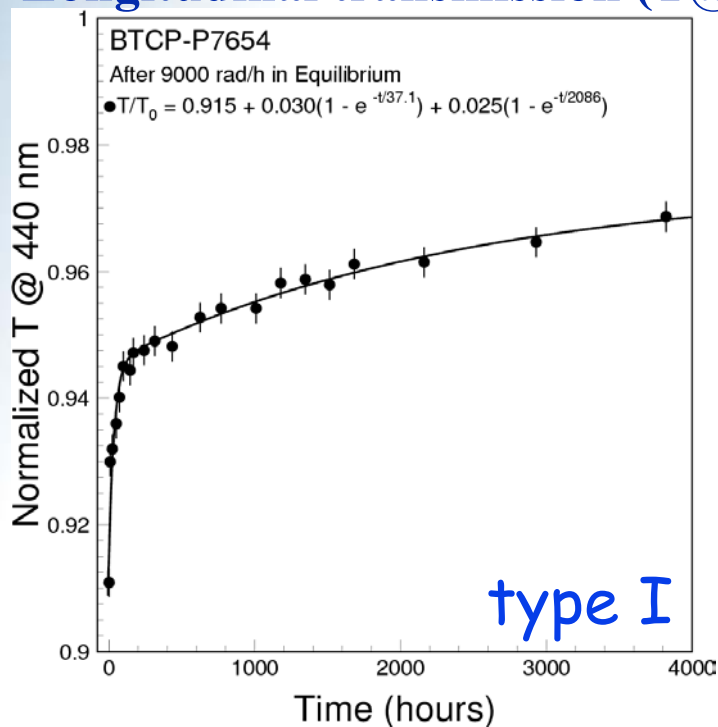
ECAL monitoring takes
30 minutes to cover
entire calorimeter *in situ*.



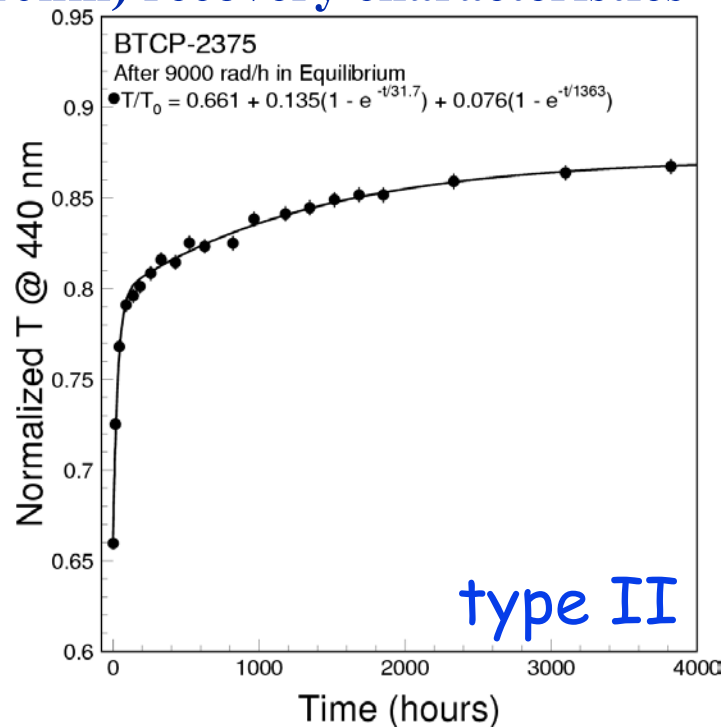
Damage and recovery time constants decide
whether the monitoring system can adequately
track the changes in light yield

INFN PWO crystals tests at Caltech

Longitudinal transmission ($T@440\text{nm}$) recovery characteristics



Small Damage and 2 Time Constants: ~40 h and ~1,950 h



Large Damage and 2 Time Constants: ~30 h and ~1,300 h

In both cases the fastest component is slower than monitoring time



PWO survey during the ECAL construction phase



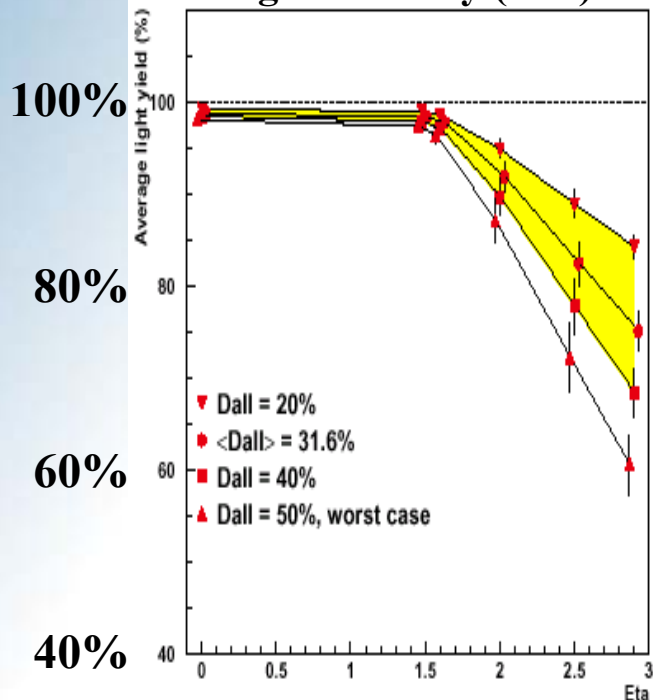
studies on PWO crystals for EE

Detector Performance Group

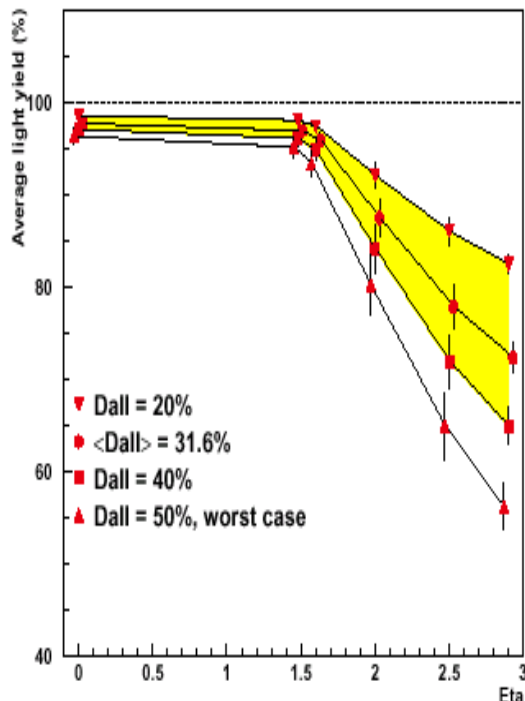
<http://agenda.cern.ch/displayLevel.php?fid=4150>

Average light yield at LHC, versus Eta

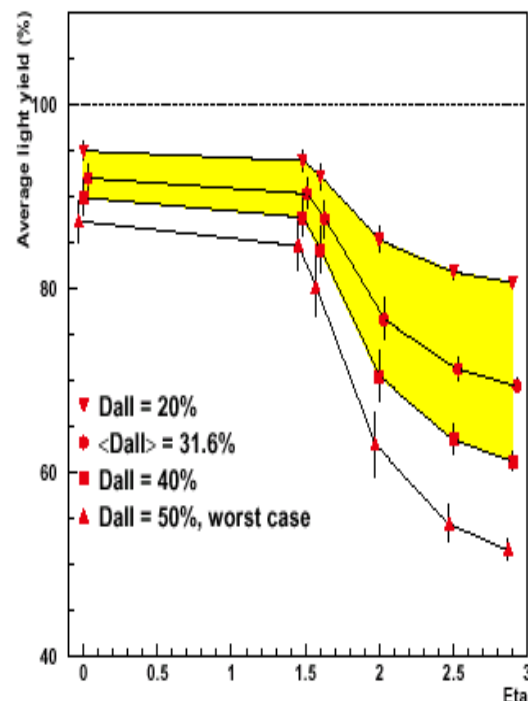
Starting luminosity (10^{33})



Low luminosity ($2 \cdot 10^{33}$)



High luminosity (10^{34})



D_{all} : total density of the potential color centers
(for a given crystal, can be evaluated from GIF measurements)

Improved radiation tolerance for EE crystals would be of benefit



PWO survey during the ECAL construction phase

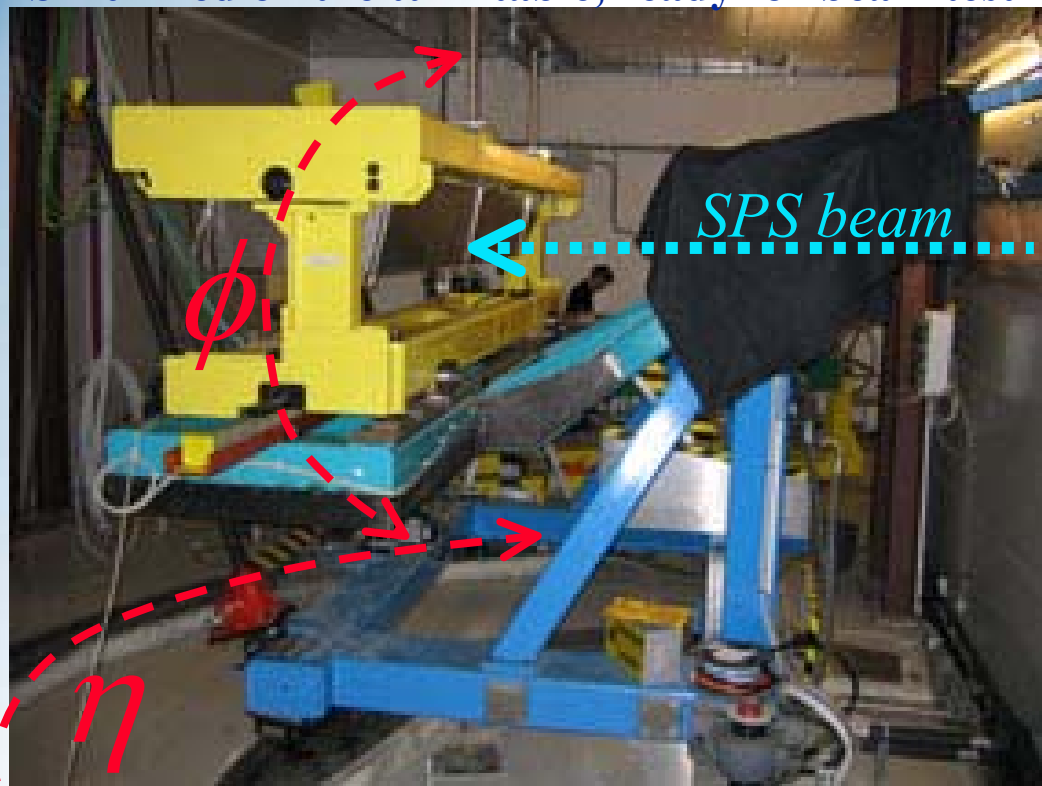


beam tests at CERN

<http://cms-project-h4-testbeam-2003.web.cern.ch>

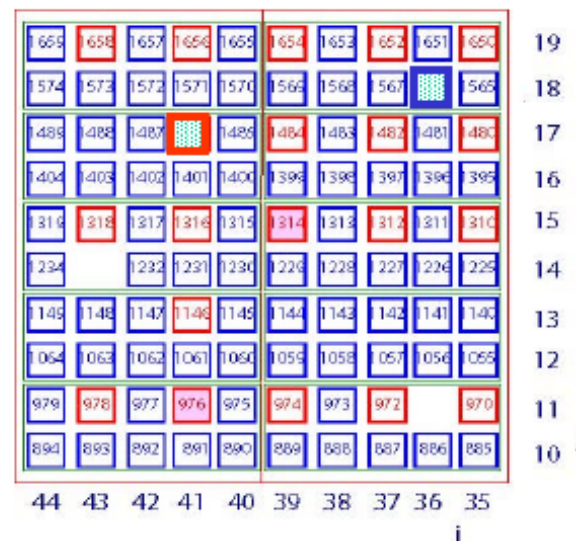


SM0 fixed on the turn table, ready for beam test



2002 preliminary results

<http://polywww.in2p3.fr/actualites/congres/wach4-2002/>



- Irradiated Crystals
- Pion irradiation
- LHC cycle

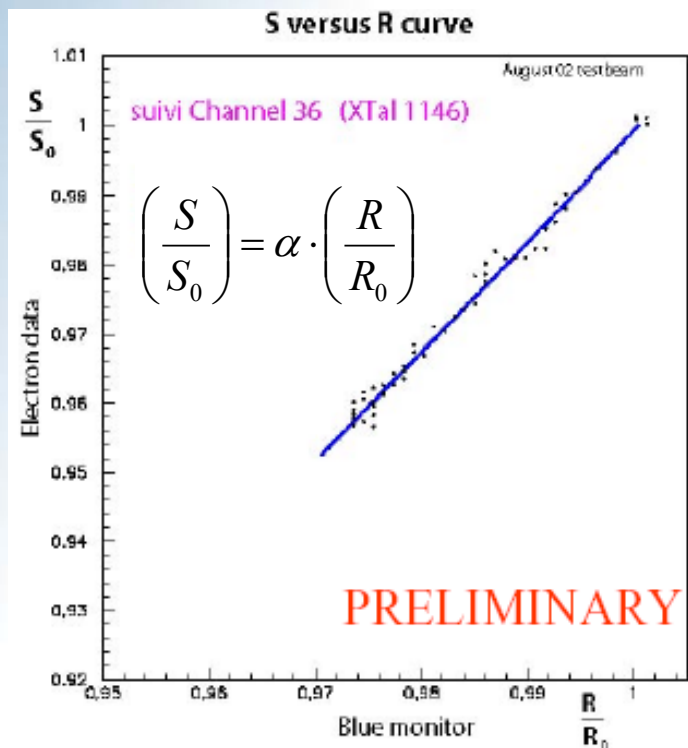


PWO survey during the ECAL construction phase

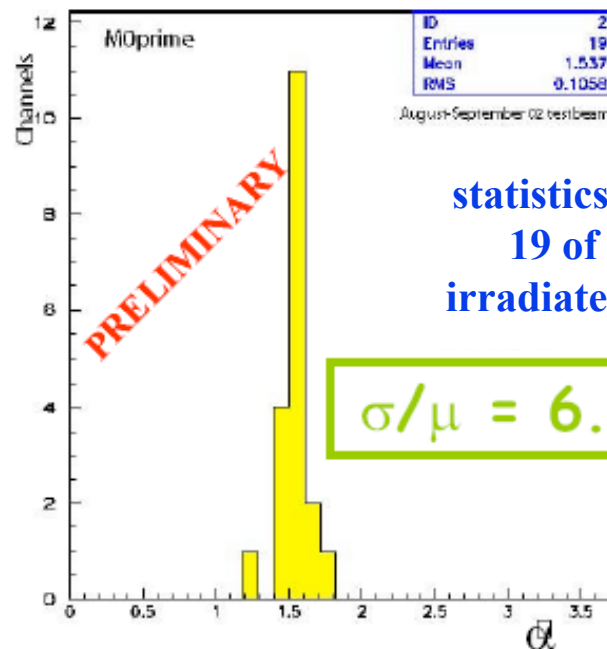


beam tests at CERN

electron beams irradiation: cumulated doses between 2 and 8 Gray



S: scintillation light signal
 R: monitoring light signal
 α determined with 3% precision



statistics made on
 19 of the 20
 irradiated crystals

universality of
 irradiation slope α
 (inside 6.8%)



PWO survey during the ECAL construction phase



beam tests at CERN

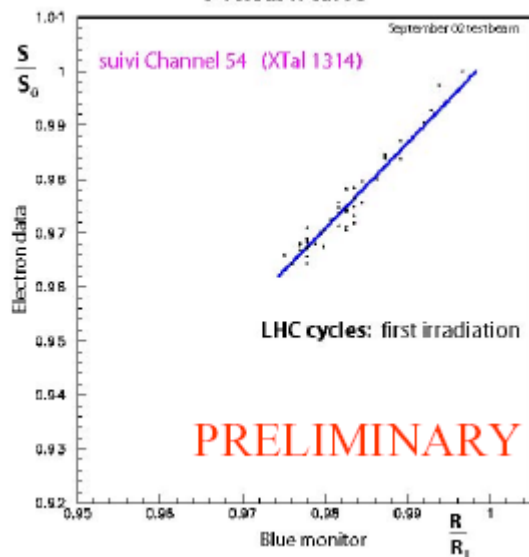
Behavior under LHC cycle conditions

1st irradiation

dose rate: 0.25Gray/h

cum.dose: 2.5Gray

S versus R curve

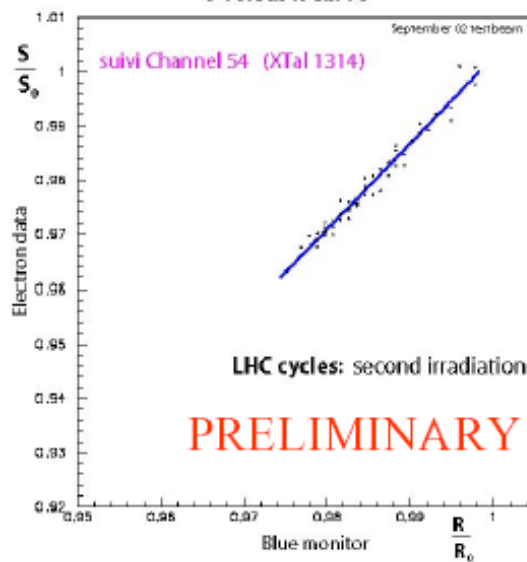


2nd irradiation

dose rate: 0.18Gray/h

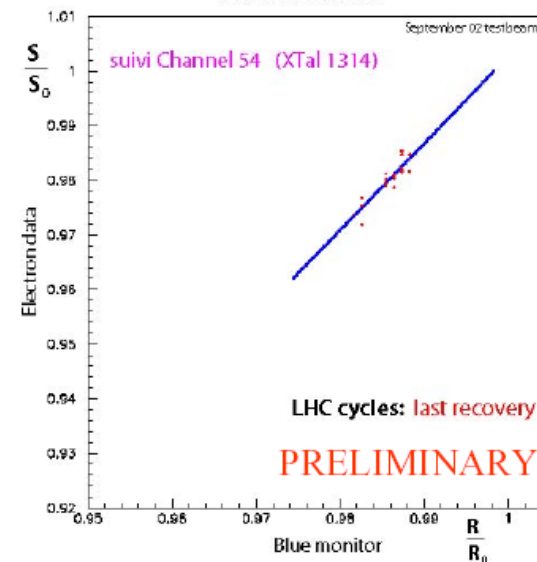
cum.dose: 1.8Gray

S versus R curve



recovery

S versus R curve



P
O
W
E
R
C
U
T

same slope for different irradiations

same slope for irradiation and recovery

good reproducibility during multiple irradiations and recoveries (LHC cycle)



Conclusion (1)



PWO crystals presently produced at industrial level and used for ECAL modules construction:

- ♥ have optical characteristics (scintillation and transmission) stable enough to guarantee a stability of the final monitoring system at the level of 1.4‰ after correction for laser pulse width variation**
- ♥ have the same irradiation slope α at the level of 6.8‰ reproducibility during multiple irradiations and recoveries (LHC cycle)**
- ♥ allow for a good reproducibility of relative intercalibration**
- ♥ allow a relative inter-calibration at the level of 4.5% from routine quality control data (ACCOS machines)**



Conclusion (2)



- ♣ Several techniques were put in place aimed at predicting the Lead Tungstate (PWO) crystal performance at the future CMS experiment
- ♣ They converge to the conclusion that the PWO choice for ECAL-CMS was the good one