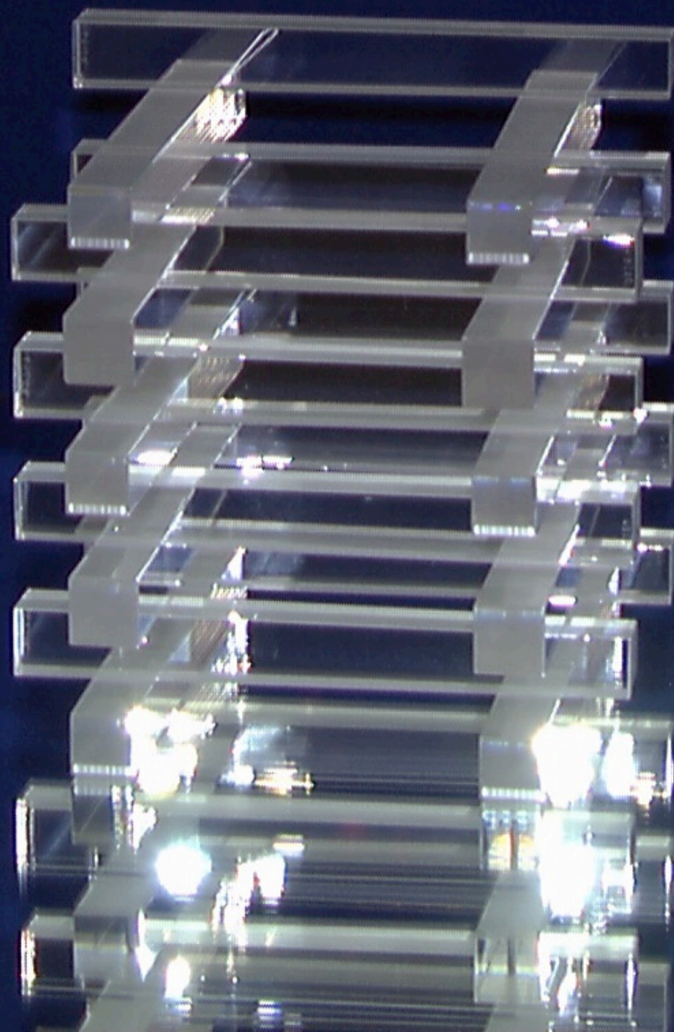
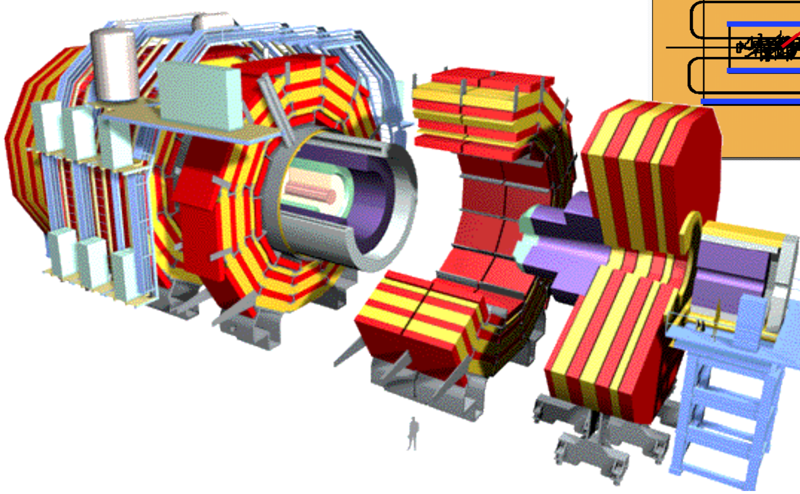
Radiation damage studies on Lead Tungstate crystals from initial R&D to in-situ results with the CMS ECAL



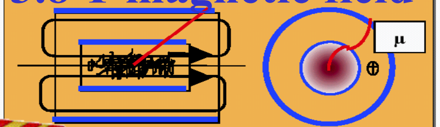
Etiennette Auffray,
CERN PH-CMX
On behalf of CMS ECAL

6th Detector Workshop of the Helmhotz Alliance
Mainz, Germany, Feb 28 2013

CMS : Compact Muon Solenoid @LHC

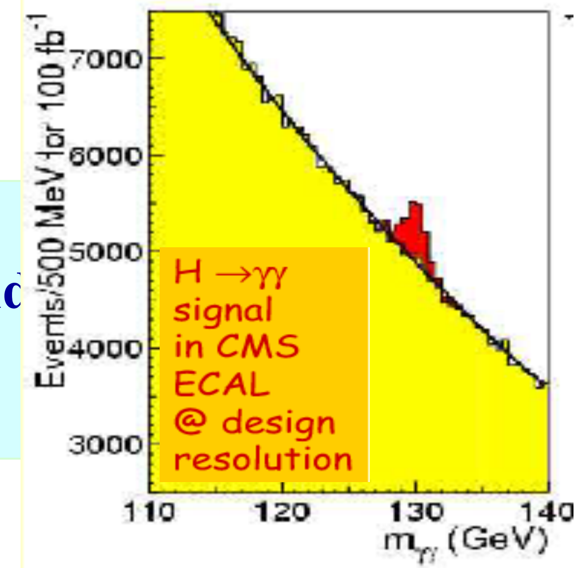


3.8 T magnetic field



Length ~ 22 m
Diameter ~ 15 m
Weight ~ 14000 t

ECAL TDR 94



For a light Higgs
H→γγ best channel. Narrow width, but irreducible background
Electromagnetic calorimeter (ECAL) resolution crucial !
=>Choice of homogeneous crystal calorimeter

Challenges & Choices for ECAL

Challenges:

- Fast response (25ns between bunch crossings at LHC)
- High radiation doses and neutron fluences
  $500fb^{-1}$: 0.3 Gy/h & 4.10^{11} p/cm^2 at $|\eta| < 1.48$;
  6.5 Gy/h & 3.10^{13} p/cm^2 at $|\eta| = 2.6$
- Strong magnetic field (3.8 teslas)
- Long term stability monitoring capability

Choices:

- Lead tungstate crystals ($PbWO_4$, PWO)
- Photo detectors :
  Avalanche photodiodes (APD) in Barrel
  Vacuum phototriodes (VPT) in Endcaps
- Laser light monitoring system for following the evolution of crystal transparency and photo-detector response

INTERNATIONAL WORKSHOP ON HEAVY SCINTILLAT[ORS] FOR SCIENTIFIC AND INDUSTRIAL APPLICATIONS

CRYSTAL 2000

CHAMONIX, France, September 22-26, 1992

4 first papers on PWO for High Energy Physics applications at first conference on inorganic scintillators (SCINT conf)

STUDY OF CHARACTERISTICS OF REAL-SIZE PbWO4 CRYSTAL CELLS FOR PRECISE EM-CALORIMETERS TO BE USED AT LHC ENERGIES

V.A. Kachanov IHEP Protvino, CIS

Y.D. Prokoshkin V.G. Vasilchenko L.L. Nagornaya

M.V. Korzhik

FAST SCINTILLATORS BASED ON LARGE "HEAVY" TUNGSTATE SINGLE CRYSTALS.

L.Nagornaya, V.Ryzhikov, ISC, Kharkov, Ukraine

$PbWO_4$ SCINTILLATOR AT ROOM TEMPERATURE

Masaaki KOBAYASHI[a], Mitsuru ISHII[b], Yoshiyuki USUKI[c] and Hiroshi YAHAGI[d]

a) KEK, National Laboratory for High Energy Physics, Tsukuba 305, Japan,
b) SIT, Shonan Institute of Technology, Fujisawa 251, Japan,
c) Furukawa Co., Kamiyoshima, Yoshima, Iwaki 970-11, Japan,
d) Fujitok Co., Kamijyujyo 1-9-16, Kitaku, Tokyo 114, Japan.

$PbWO_4$: A HEAVY, FAST AND RADIATION RESISTANT SCINTILLATOR FOR EM CALORIMETRY

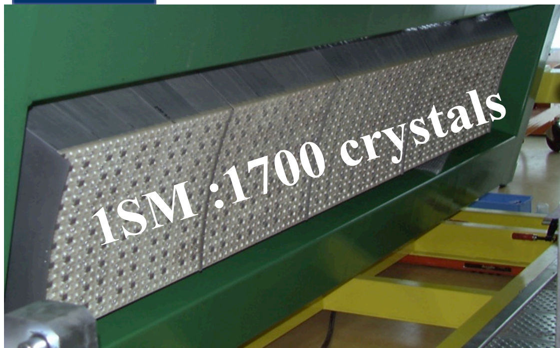
L.V.Miassoedov, V.I.Selivanov, I.V.Sinitsin, V.D.Torokhov
Kurchatov National Center, Moscow 123182, Russia
L.L.Nagornaya, Y.Ia.Vostresov, I.A.Tupitsina
Monocrystal Institute, Kharkov, Ukraine

R&D on new scintillators for LHC

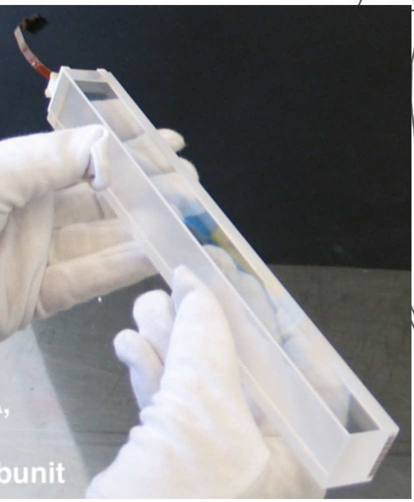
	Before 1990			Developed for LHC Crystal Clear/CMS		
	NaI(Tl)	CsI(Tl)	BGO $Bi_4Ge_3O_{12}$	CeF_3	**PWO** **$PbWO_4$**	HFG Glass
Xo [cm]	2.59	1.86	1.12	1.66	**0.89**	1.6
ρ [g/cm^3]	3.67	4.53	7.13	6.16	**8.2**	6
τ [ns]	230	1050	340	30	**15**	25
λ [nm]	415	550	480	310 340	**420**	320
Ref index n@λ_{max}	1.85	1.80	2.15	1.68	**2.3**	1.5
LY [%NaI]	100	85	10	5	**0.5**	0.5

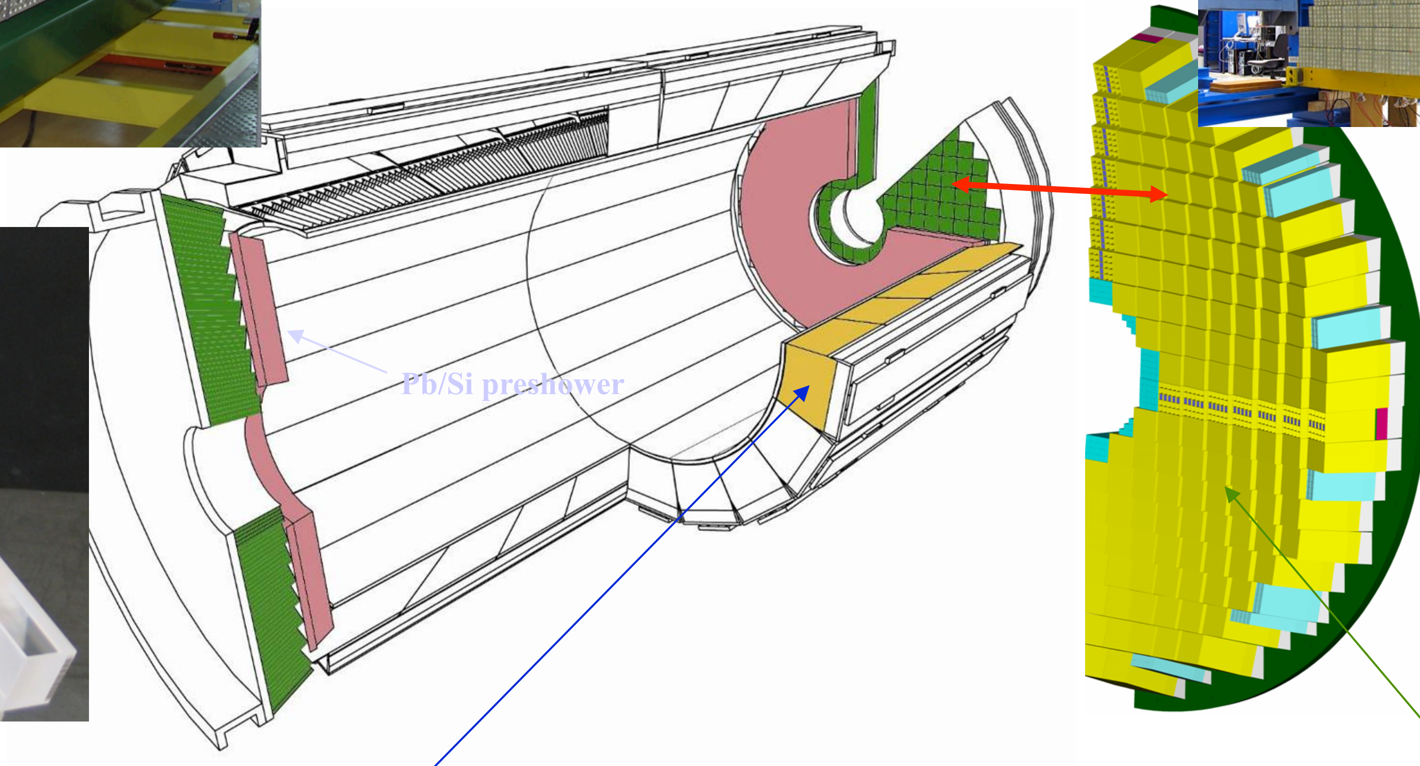
=> Choice by CMS of PWO in 1994

ECAL Design



75848 PWO crystals
about 10 m³, 90 t

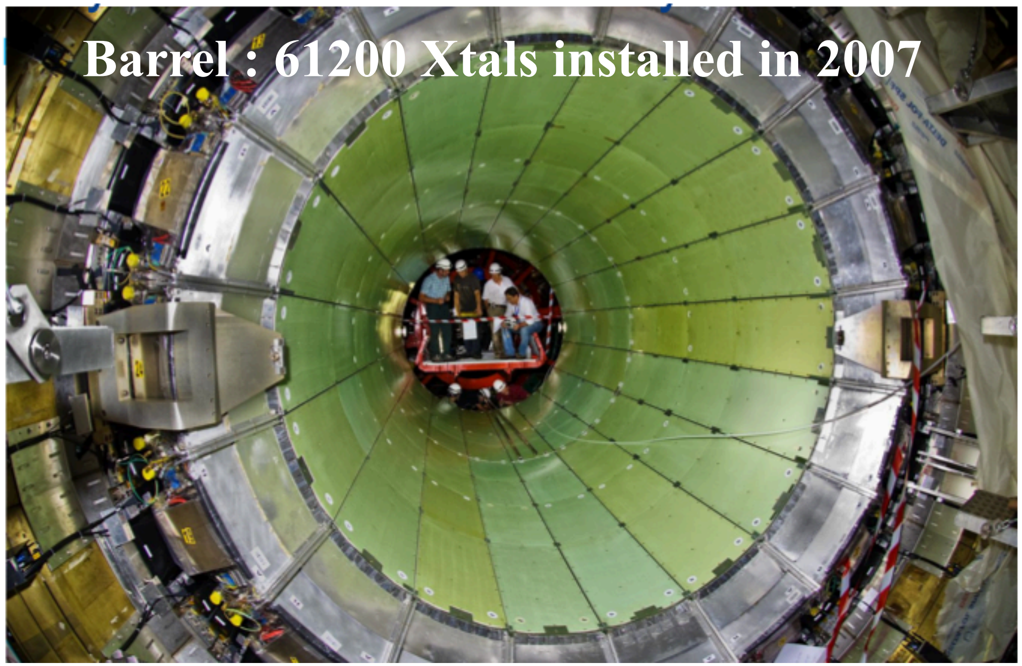


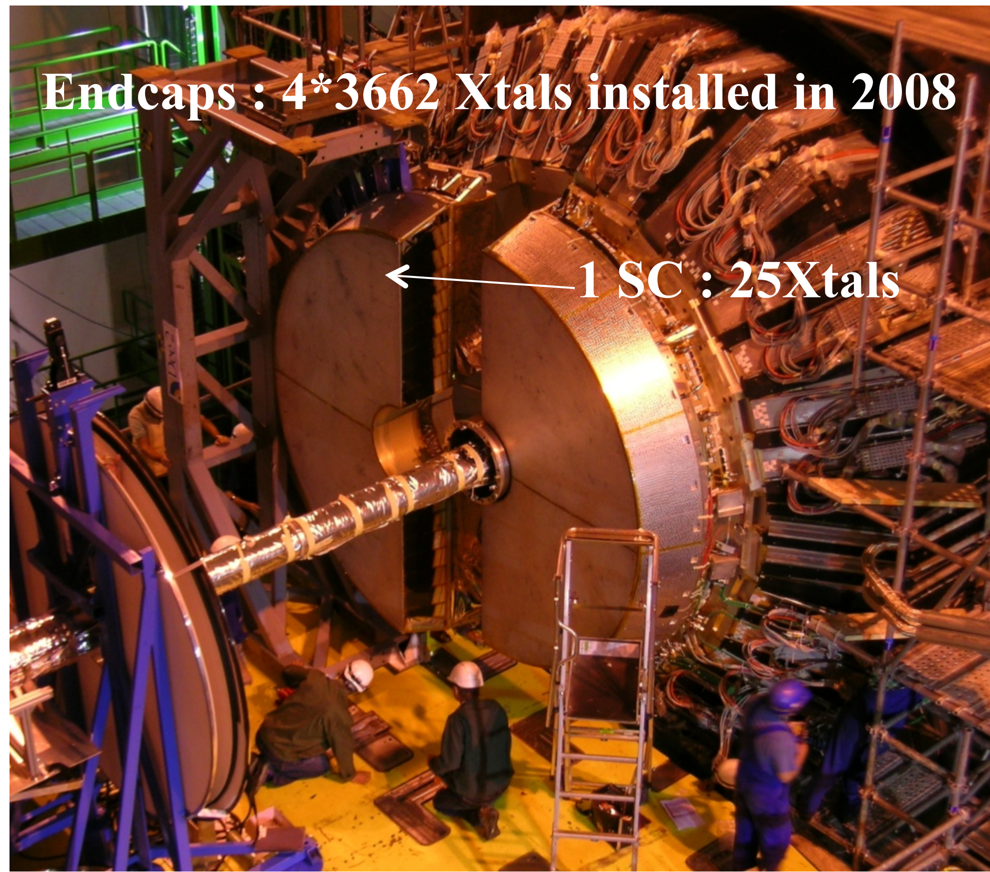


Barrel: $|\eta| < 1.48$
36 Super Modules (SM)
61200 crystals (2.2x2.2x23 cm³)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3x3x22 cm³)

ECAL in CMS at P5 Cessy



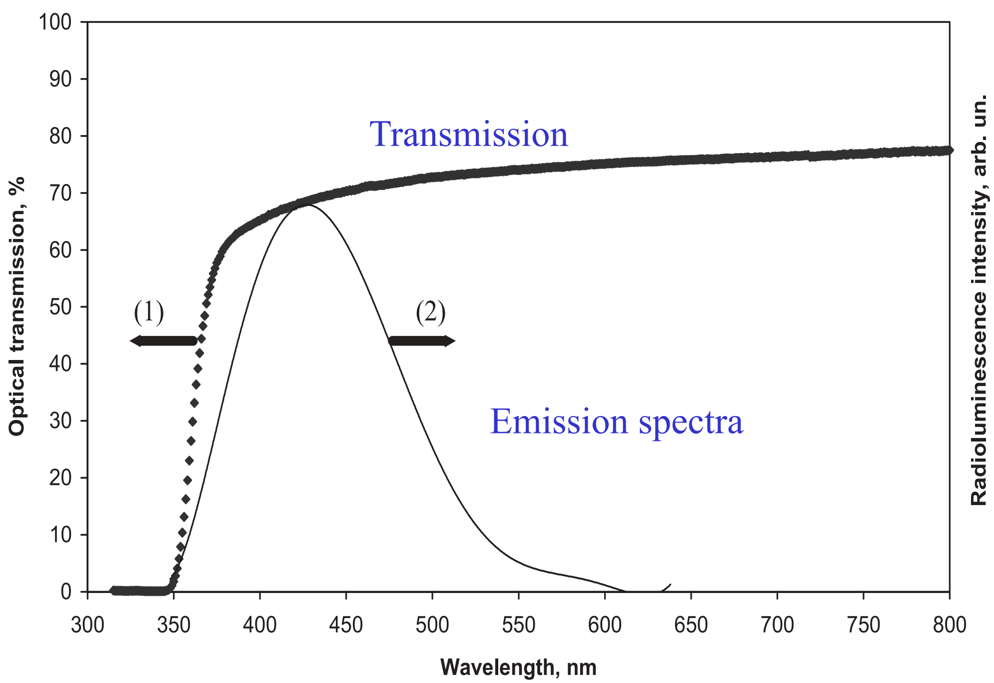


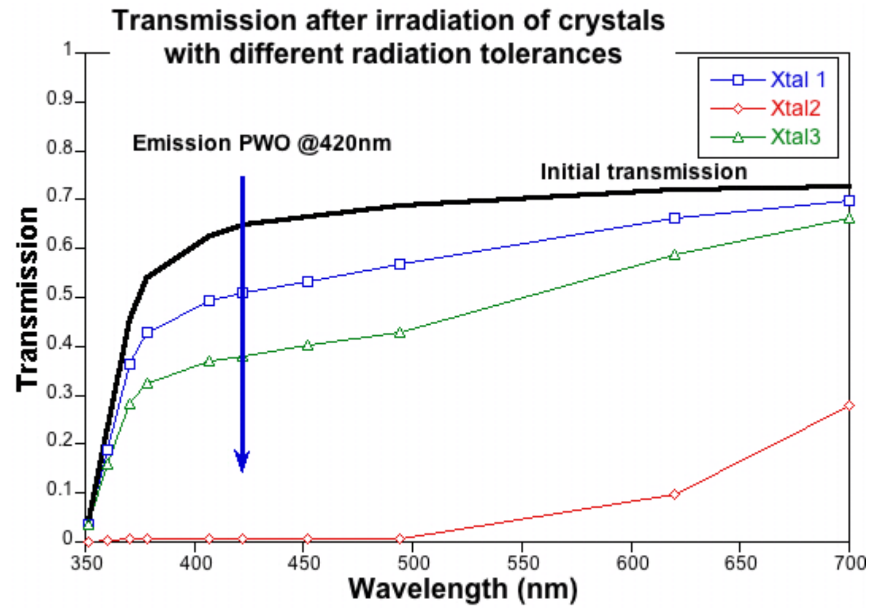
15 years of CMS ECAL construction

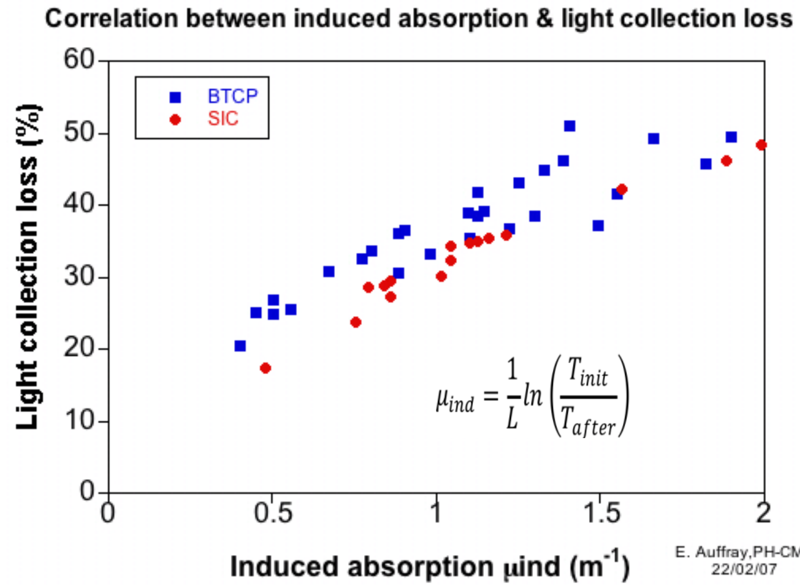
- 1992 Crystal2000 : PWO attracts attention
- 1994 : Choice of PWO for CMS electromagnetic calorimeter
- 1994-1998 : extensive R&D on PWO

- 1998-2000 : Preproduction of 6000 crystals in BTCP
  - Increase production rate
  - Make crystal quality consistent over a large amount of crystals
- 2001 : Start of the Production in BTCP, Russia
- 2005 : Start of the Production in SIC, China
- 2007 : Barrel installation in CMS
- 2008 : Endcaps installation in CMS
- 2009 : First data taken in LHC

The importance of radiation hardness:







E. Auffray, PH-CMA
22/02/07

Under irradiation creation of color centers (light absorption)
=>Degradation of transmission

- ➔ Reduction of light collection ot photodetector
- ➔ Degradation of energy resolution

R&D phase :
to improve crystal quality and radiation hardness
1994-1998

Main results on radiation hardness improvement

Radiation damage mainly due to host structure defects :

Primary defects :
- **Lead vacancy $V_k(Pb)$**
- **Oxygen vacancy V(O)**

Secondary defects created for charge compensation
- **for $V_k(Pb)$: O^{--} + h, Pb^{2+} + h**
- **for V(O) : F and F^+ centres**

Optimisation of

growth conditions, stoichiometry

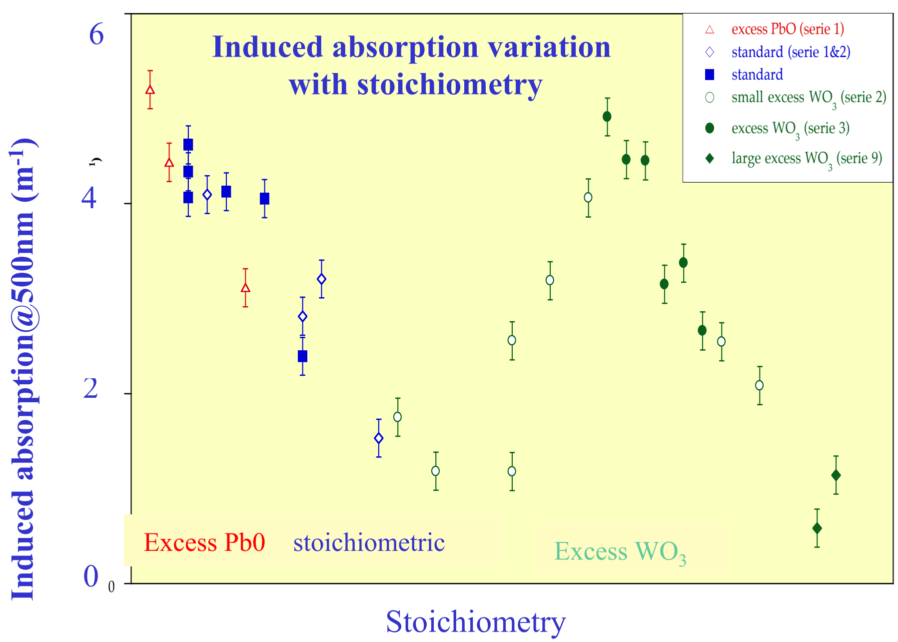
A.Annenkov et al., Rad. Measurements Vol29, p27
E. Auffray et al, proceedings of SCINT2007

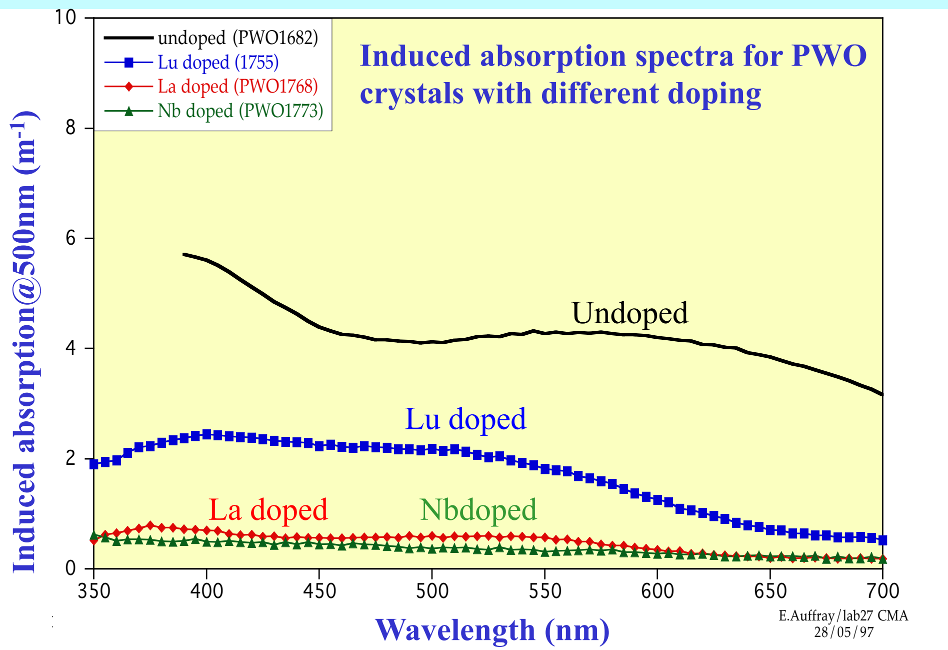
Compensation by

doping :Y, La, Lu, Nb, Sb

optimum codoping Y-Nb

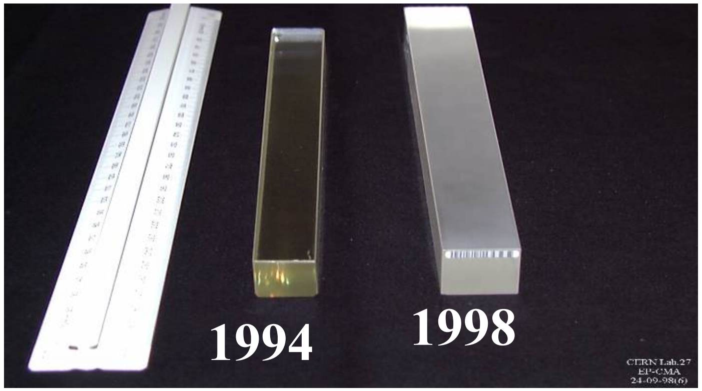
S. Baccaro et al, phys. stat. sol. (a) 160, R5 (1997) /A.Annenkov et al., NIM A426 (1999) 486
M. Kobayashi et al., NIM A404 (1998) 149. / X. Qu et al., NIM 486 (2002) 102
P. Lecoq et al., NIM A402(1998) p75



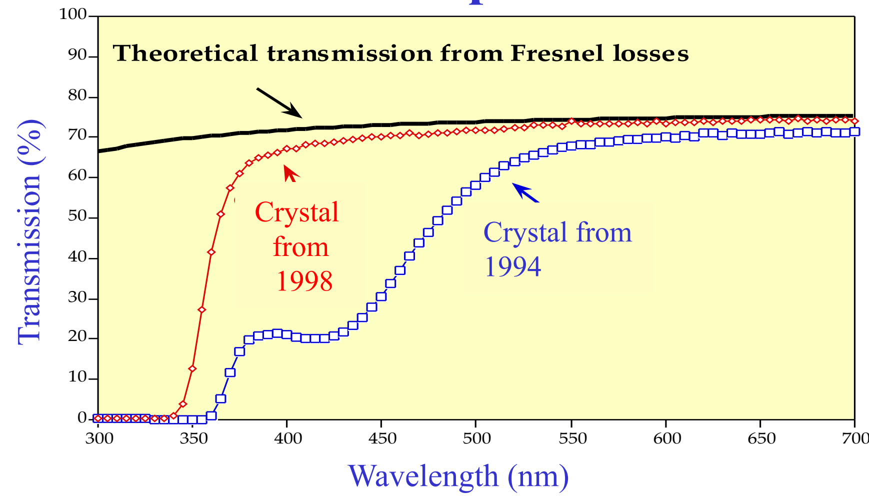


From R&D to Production

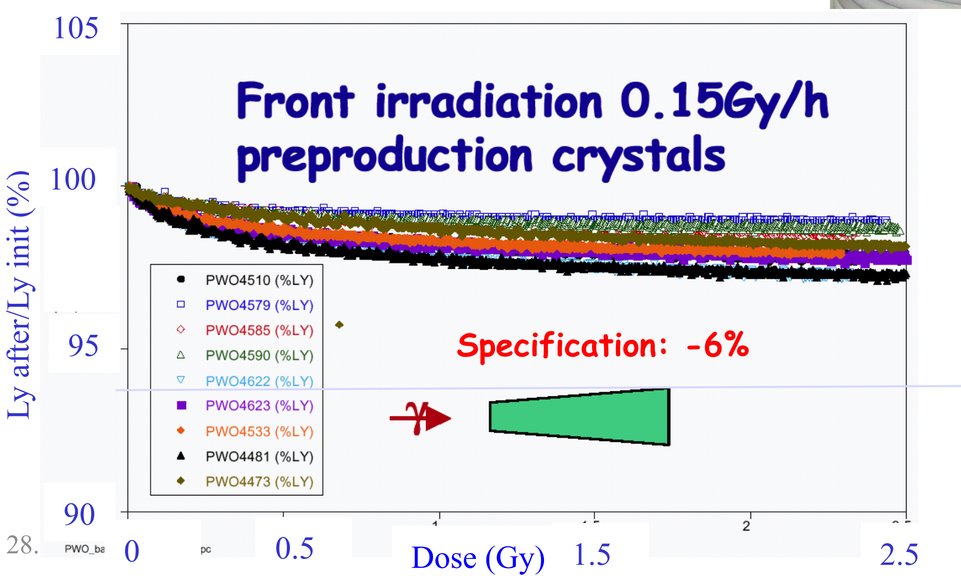
Optical properties improvement



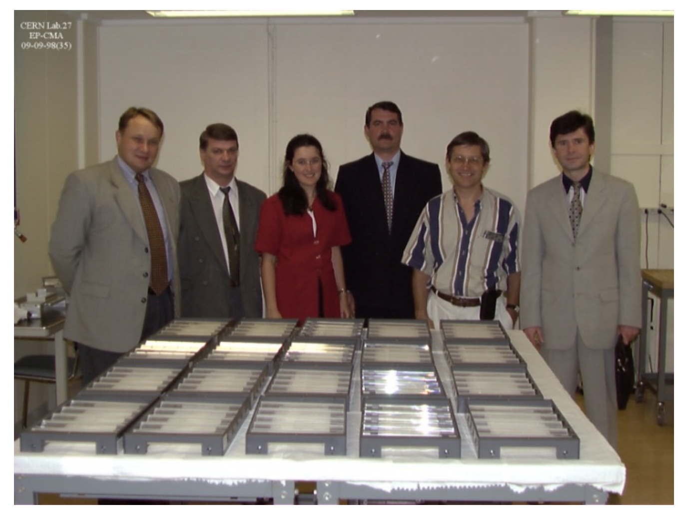
Transmission improvement



Radiation hardness improvement

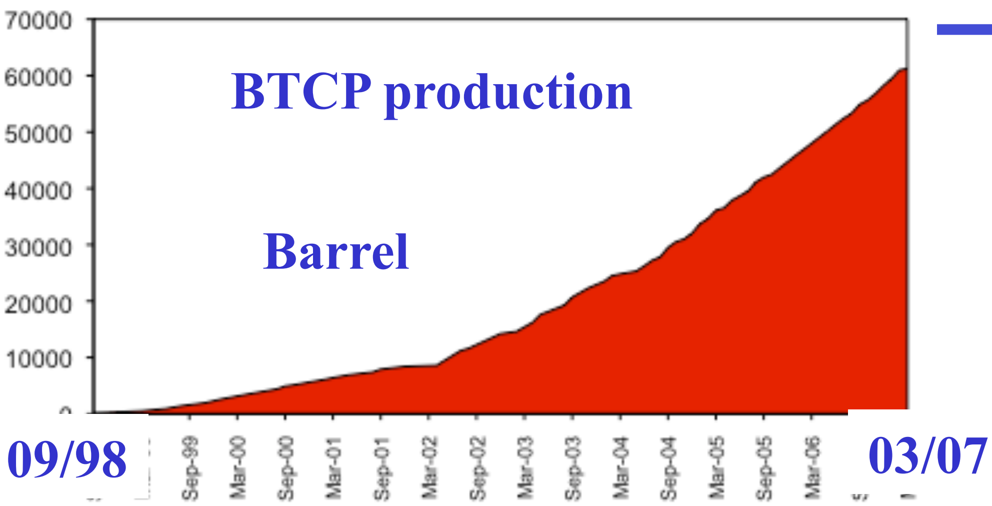


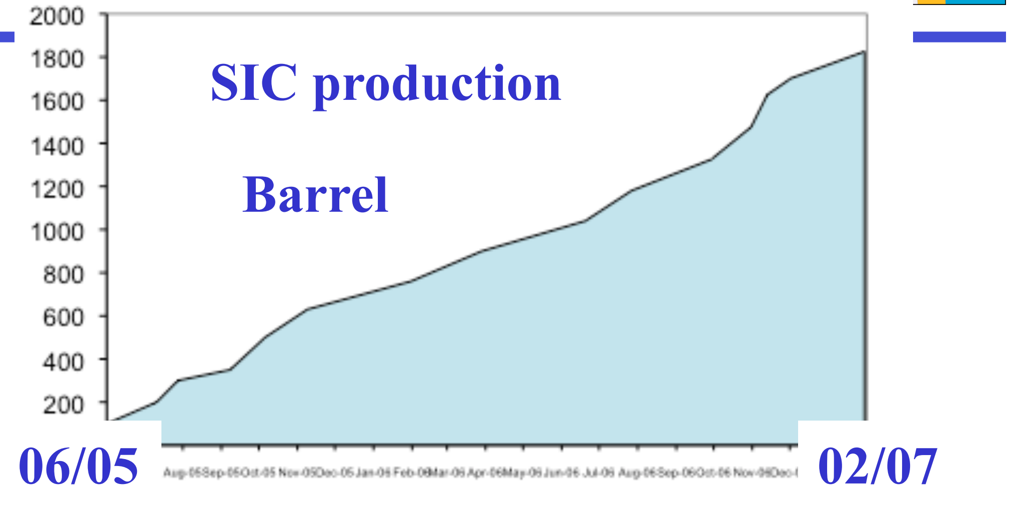
Delivery of the first 100 PWO Crystals Sept 98

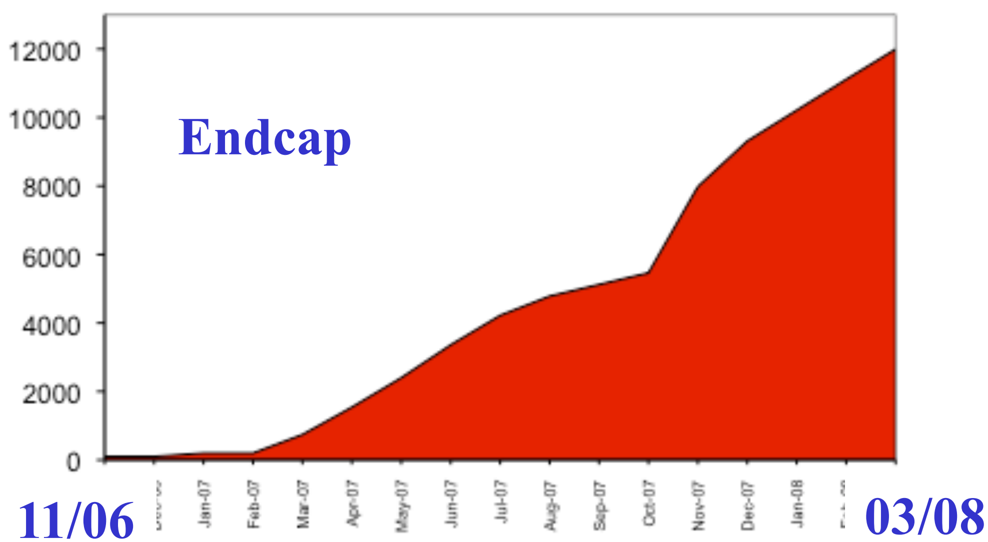


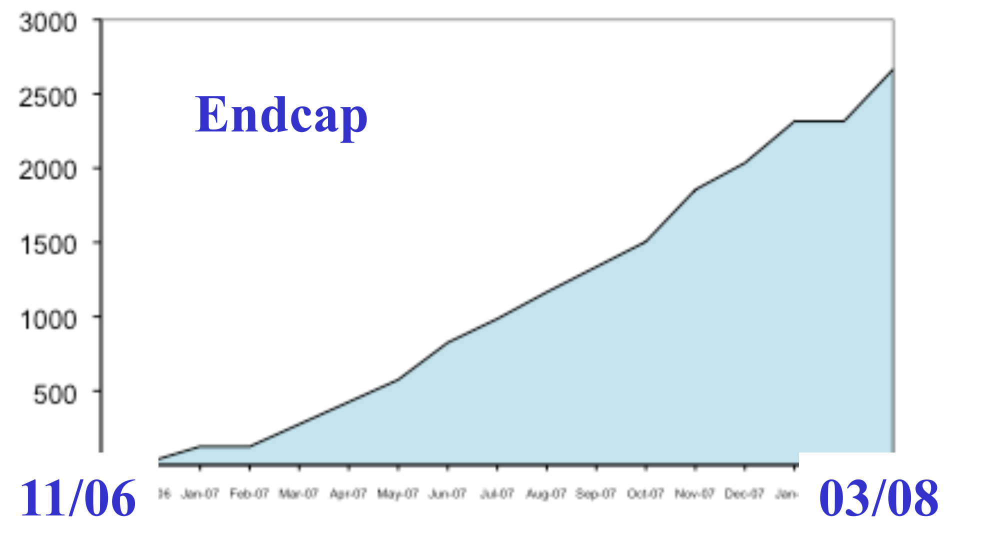
Production phase :
Quality control of PWO production
1999-2008

Crystal production : 10 years



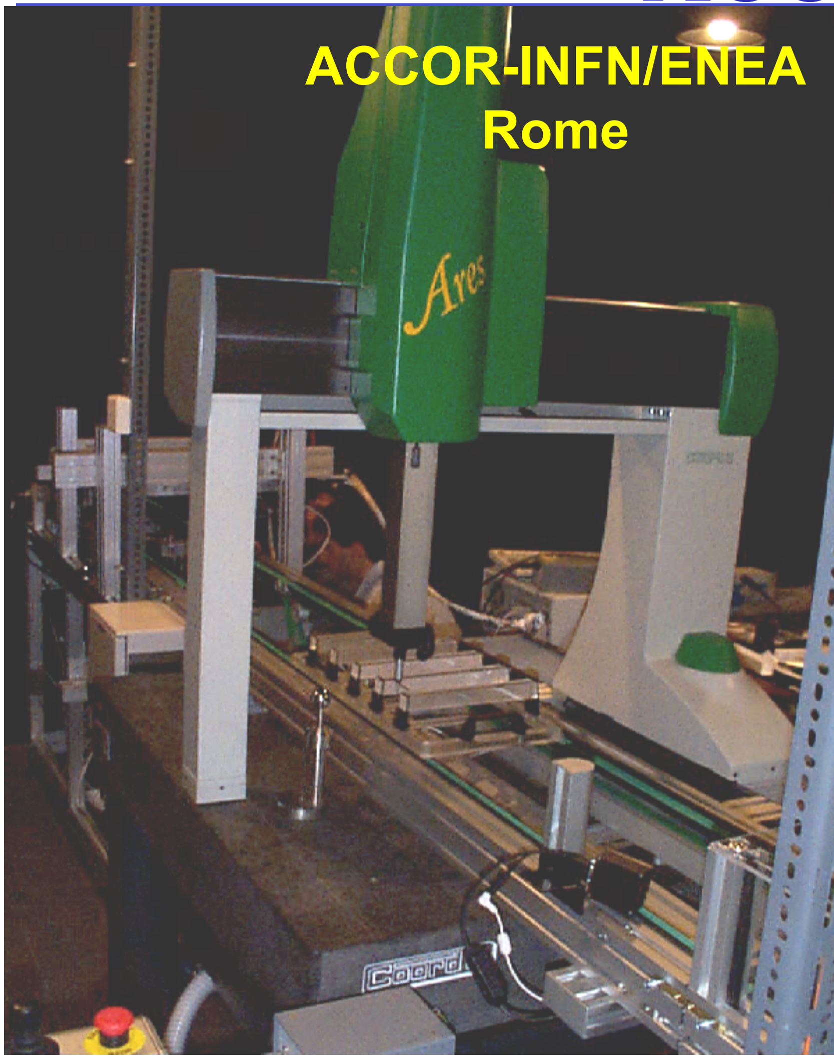






All produced crystals (>76000) fully characterised at CERN or at Rome

Crystal quality control : ACCOS machines



Capacity of 60 crystals/day on each machine

E. Auffray et al, NIMA 456 3 (2001) 325
S. Baccaro et al., NIMAA459 (2001) 278
E. Auffray et al, NIMA 523 3 (2004) 355

Automatic control of:

- Dimensions
- Transmission
- Light yield and uniformity

has been performed on each crystal installed in ECAL (75848!!)

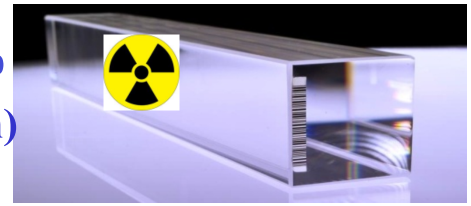
All data stored in database

Radiation hardness control

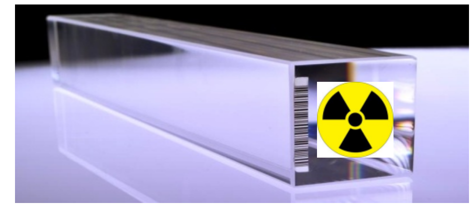
CMS specifications

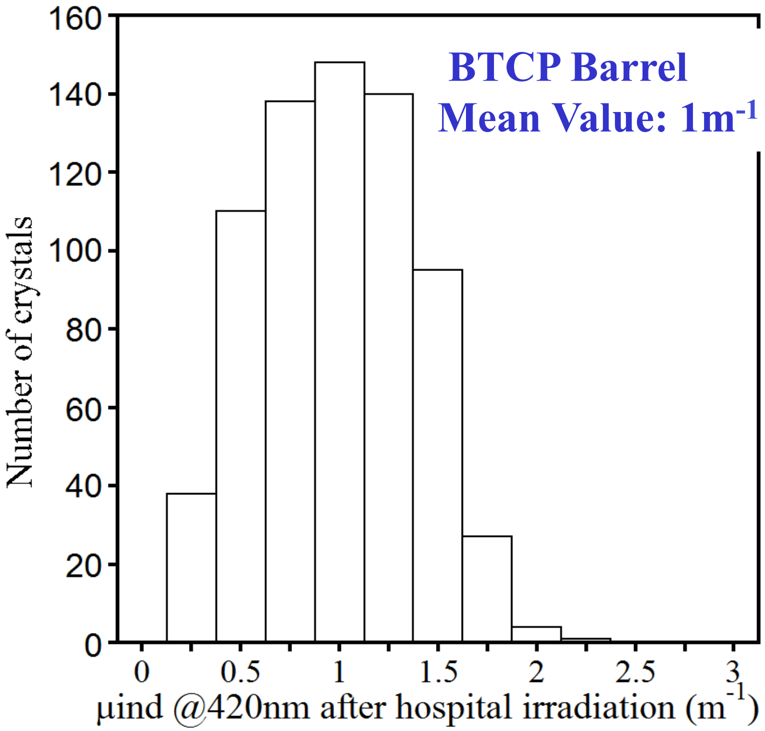
- Saturation of damage at high dose rate (filling of all the defects) $\mu_{420} < 1.5\ m^{-1}$
- Under LHC-like conditions (0.15 Gy/h, $0< |\eta| <1.45$, L_{max}, $10^{34}\ cm^{-2}s^{-1}$), light yield loss $\leq 6\%$

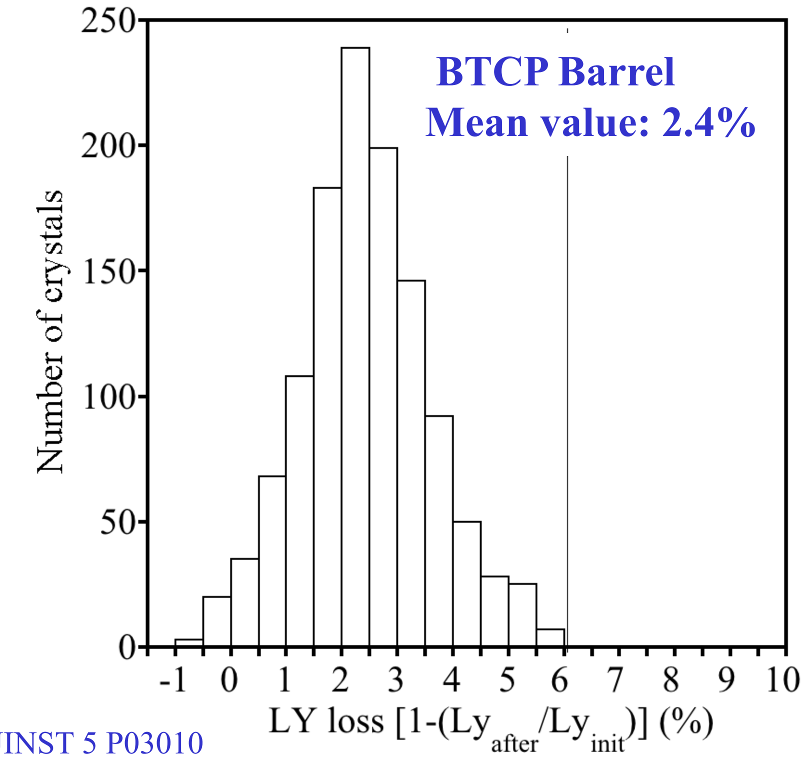
Lateral irradiation Co^{60} (high dose rate > 30Gy/h)



Front irradiation Co^{60} (low dose rate 0.15 Gy/h)



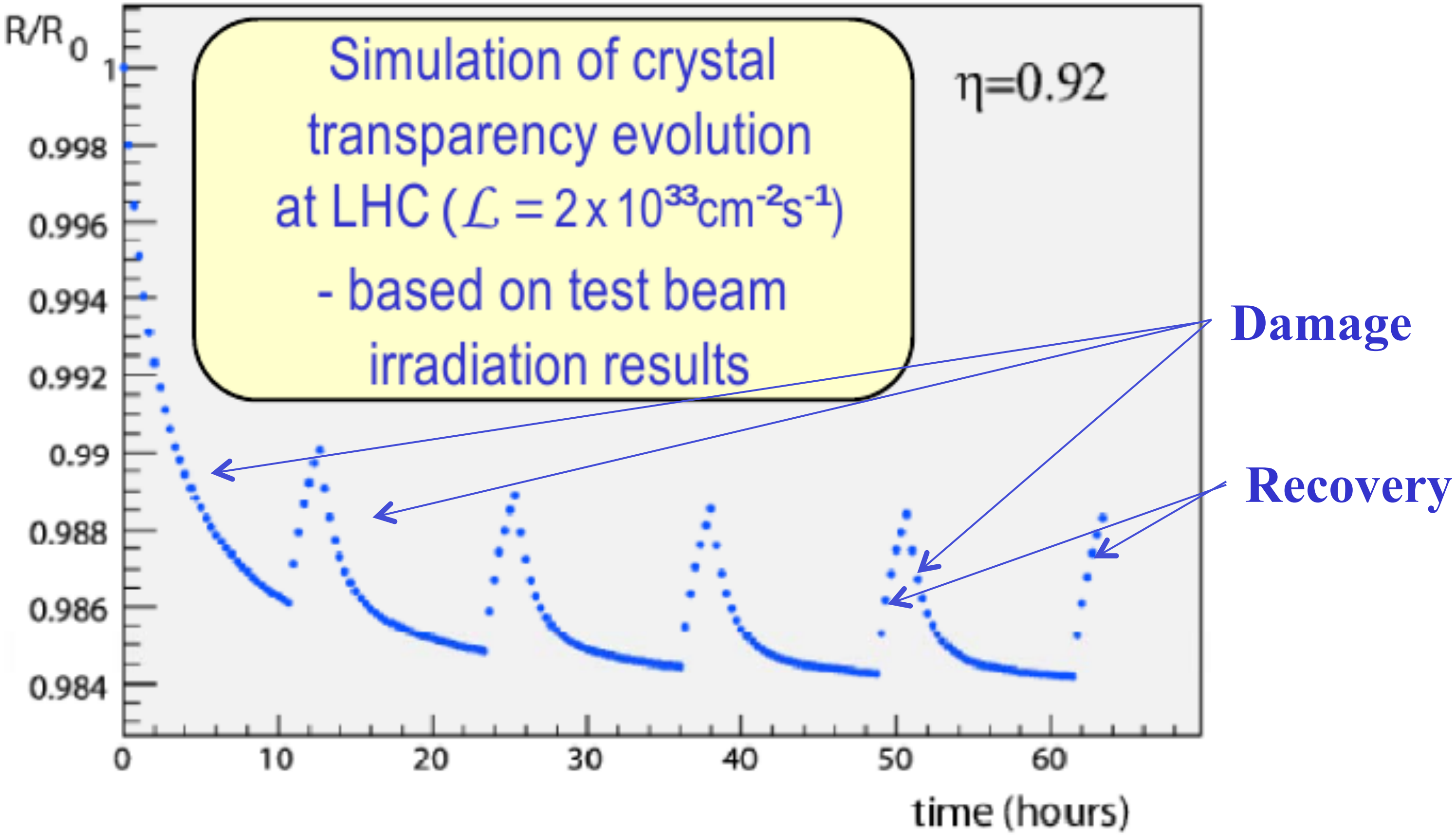




P. Adzic et al., 2010 JINST 5 P03010

Radiation damage dynamics

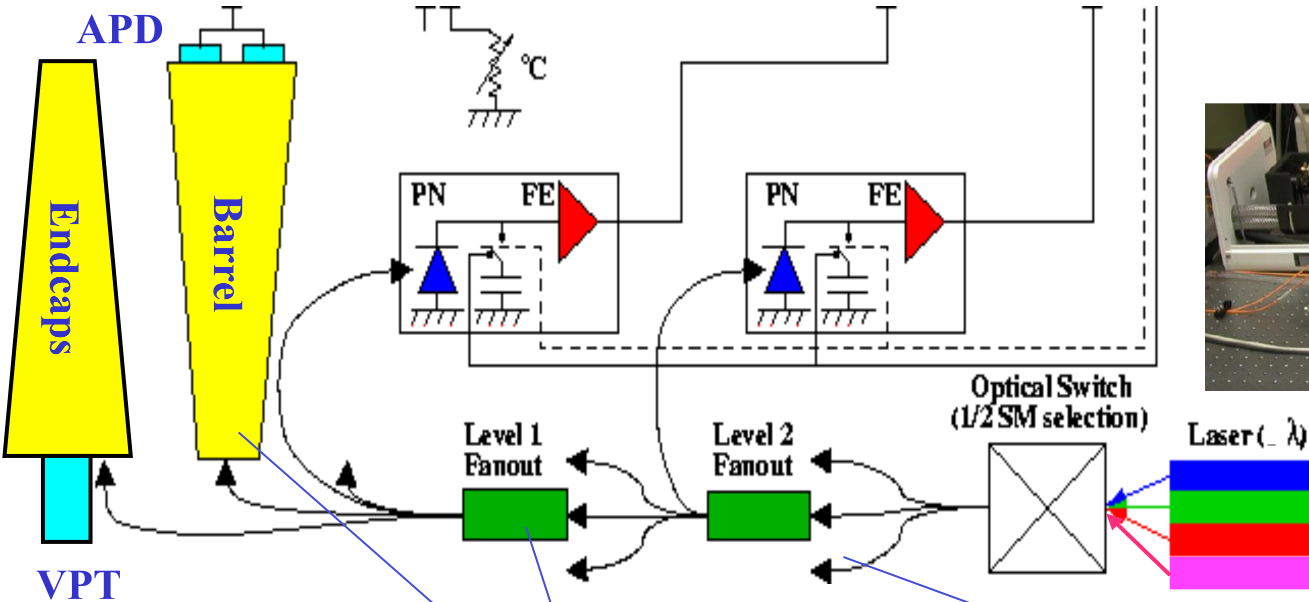
- **Under gamma irradiation :**
  - Dynamic equilibrium between formation and annealing of color centres



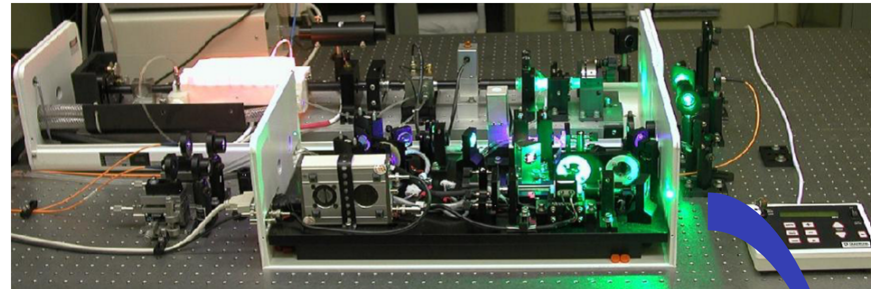
➔ **Need to follow in situ the transparency change**

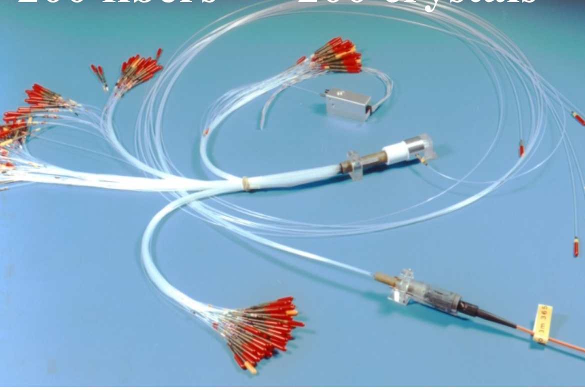
➔ **Need for an accurate monitoring system**

Monitoring System : to follow in situ the Xtal transparency



Laser System

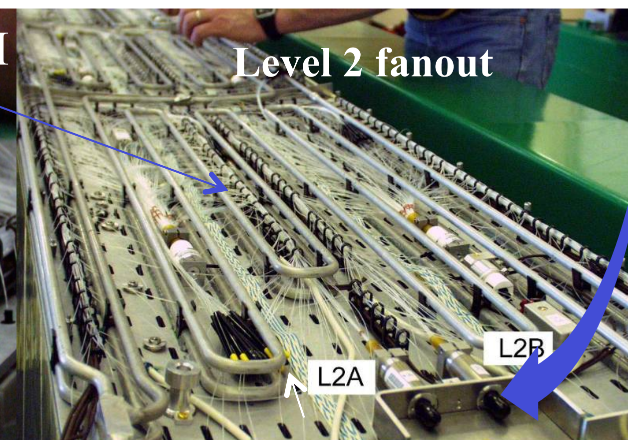




Optical fiber harness :
200 fibers => 200 crystals

Installation inside a SM

Level 1 fanout

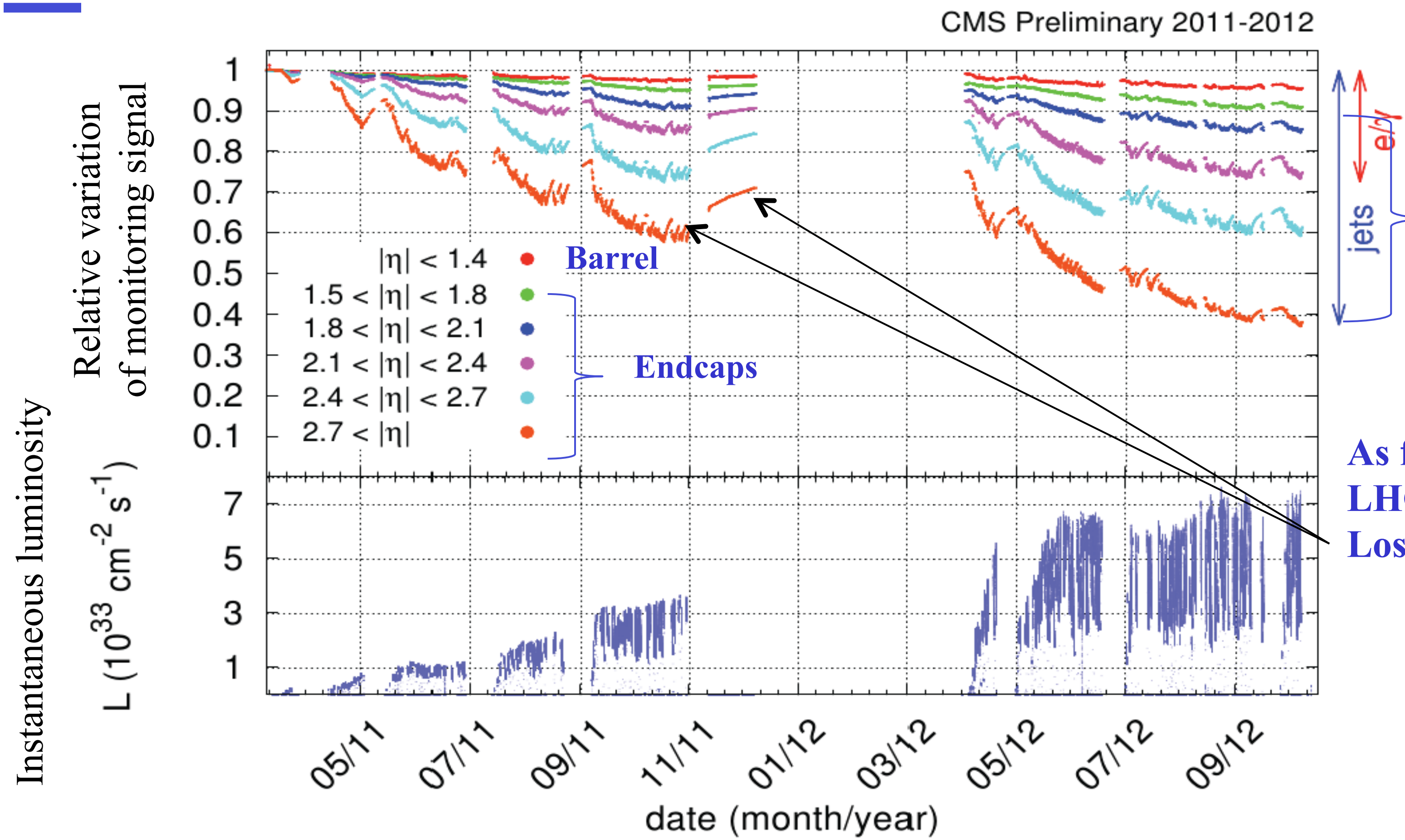


Level 2 fanout

Laser light entrance

CMS operation phase 2009-2012

ECAL evolution in 2011-2012



Barrel : Loss <6%

Endcaps :
Higher irradiation levels
Variation of dose & dose rates with |η|

As foreseen
LHC Cycle visible in the signal
Loss and recovery observed

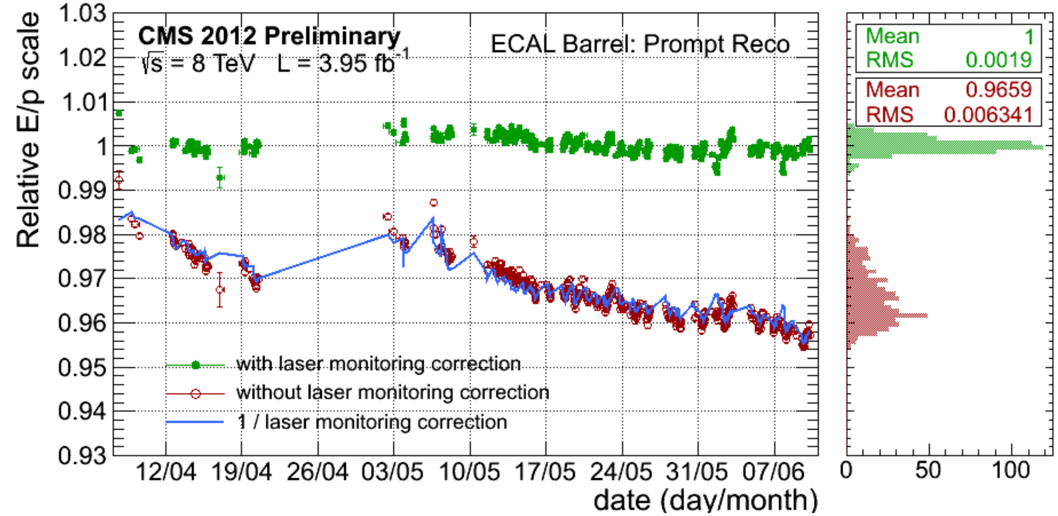
Radiation effects observed in situ are consistent with tests done during crystal production

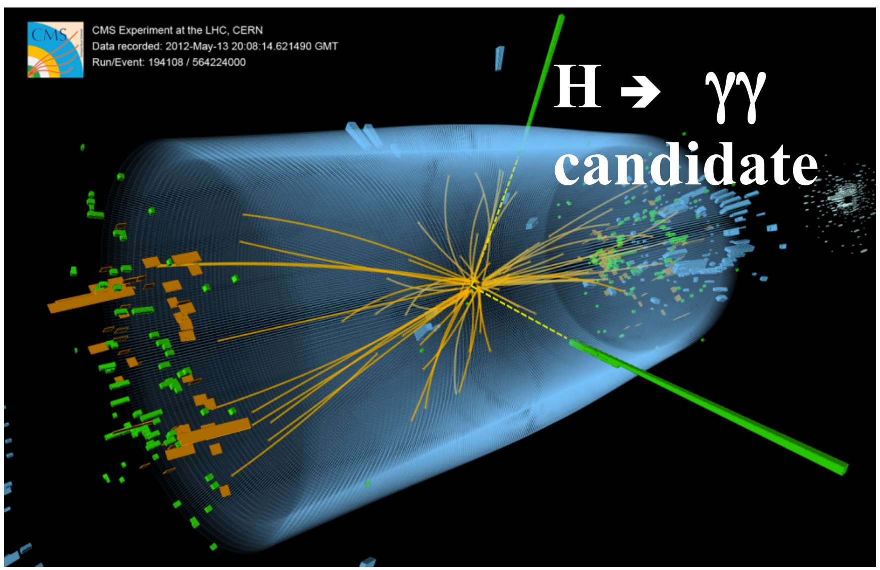
No significant damage in barrel,

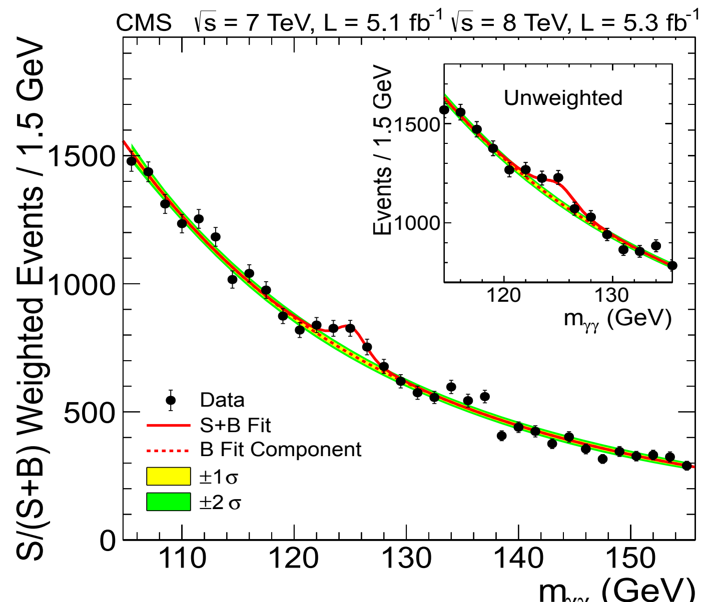
Higher damage for the endcaps due to higher dose and dose rate and VPT response loss

ECAL Results

Thanks to laser monitoring
good correction of signal response achieved







CMS Collab., Phys. Lett. B716 (2012) 30-61

Future phase High Luminosity LHC (HL-LHC) >2023

New PWO R&D in ECAL

CMS ECAL operating conditions assumed in 1994 :

- Instantaneous luminosity of max 10^{34} $cm^{-2}s^{-1}$
- An integrated luminosity of 500 fb^{-1} by 2020
- Radiation damage mainly due to electromagnetic component

=>Intense R&D on radiation damage of PWO under gamma irradiation from 1994 to 1998

=> gamma radiation tolerant PWO crystals

⇒ Results confirmed in situ 2009-2012

At HL-LHC after 2022

- **Significant increase of LHC instantaneous & integrated luminosity**
  - Instantaneous luminosity of $5 10^{34}$ $cm^{-2}s^{-1}$
  - 3000 fb^{-1} by 2033 (300 fb^{-1}/y) (end 2012 the luminosity reached ~30 fb^{-1})

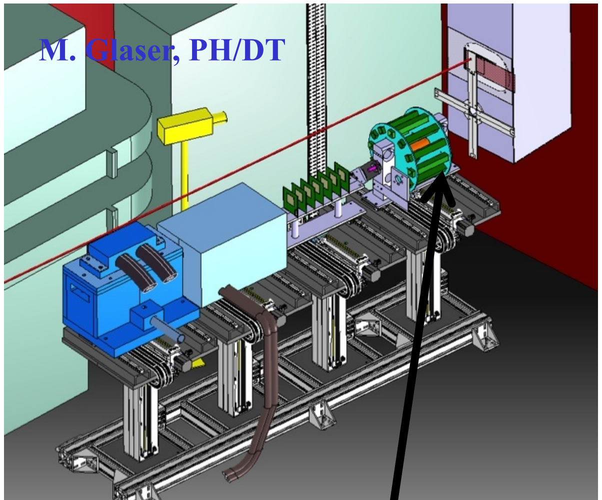
=>Need to understand CMS detector component behavior under higher radiation levels and in particular the effects of hadron damage

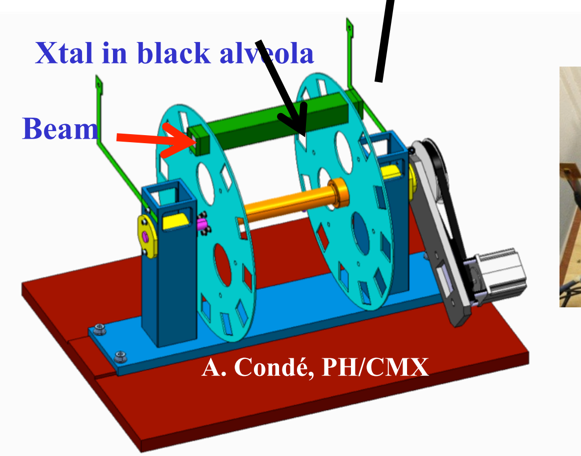
=>New R&D program on PWO to study:

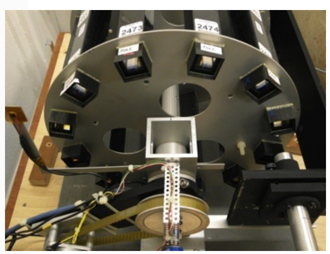
- the crystal behavior after proton irradiation
- hadron damage properties
- the impact on the detector performance

Proton irradiation facilities @ CERN

Irradiation facilities PS-T7 East hall @CERN







Proton beam characteristics :

- 24 GeV
- Flux of 10^9 p/scm^2
- Beam size : Xtal section (3x3cm^2)

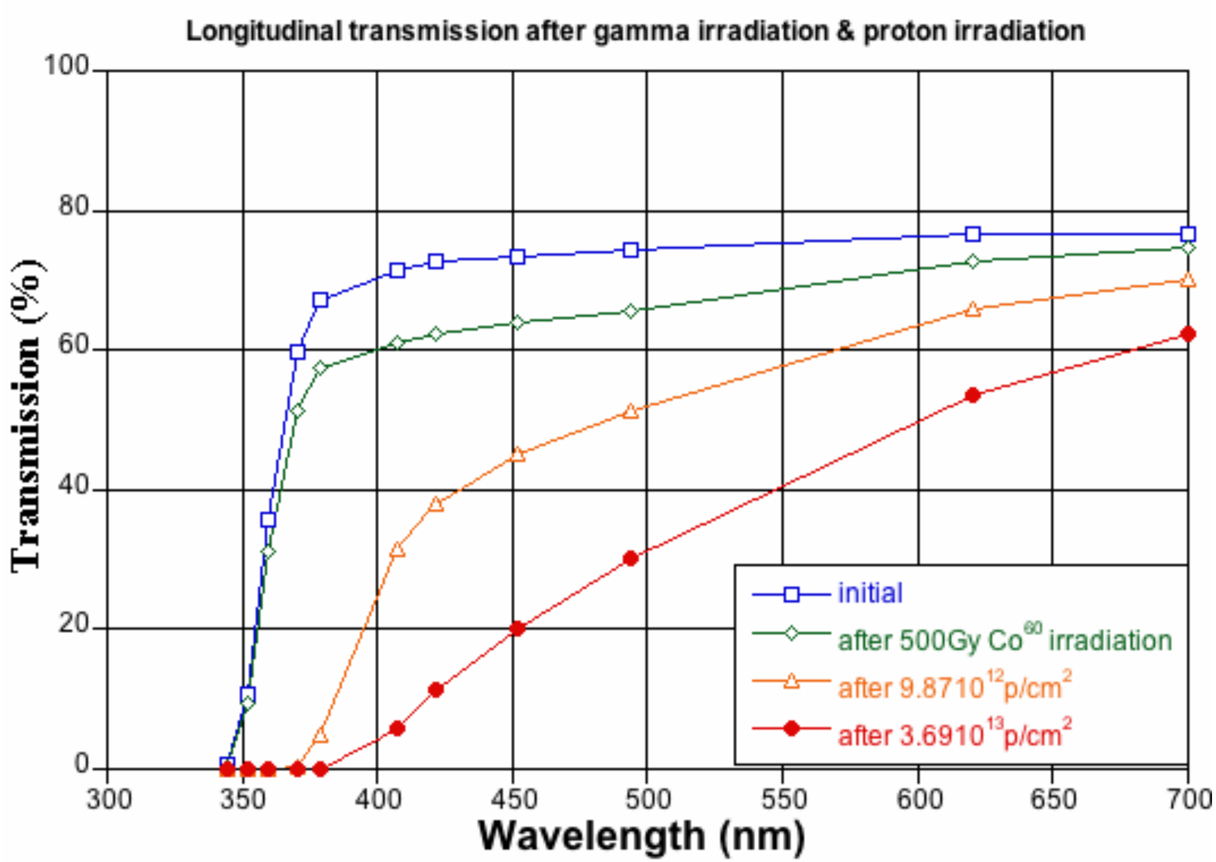
Crystal irradiation conditions

- Accumulated fluence from 1 to 10^{14} p/cm^2 in 10h (500 higher than at LHC)
- After irradiation Xtal activated
- Safety regulations prohibit the manual handling of these crystals for 3-4 months.

Design of a dedicated automated test setup for 12 crystals to be able to irradiate several crystals during the same test period

E. Auffray et al, Proc. SCINT 2011 conference,
A. Singovski et al, paper N29-4, IEEE/NSS 2011 Conference Record.

Comparison of gamma and proton irradiations

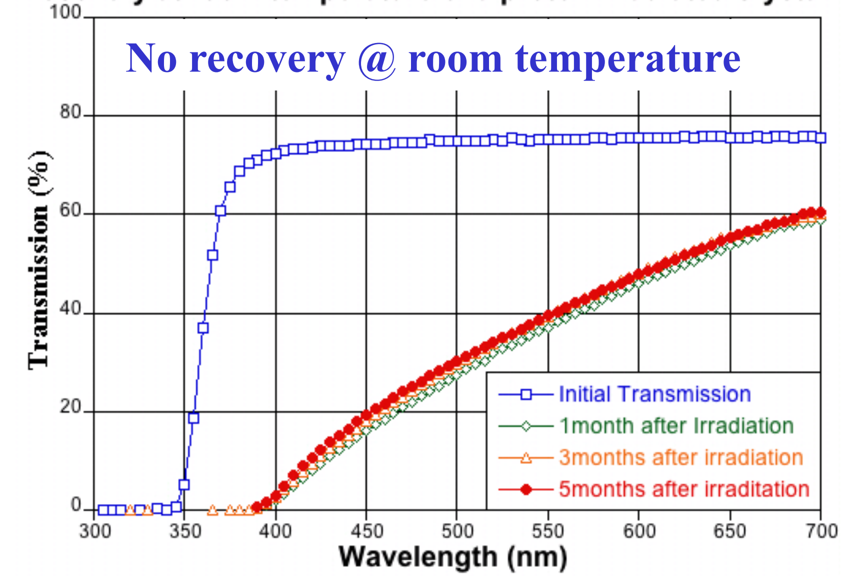


Strong absorption in the band-edge region

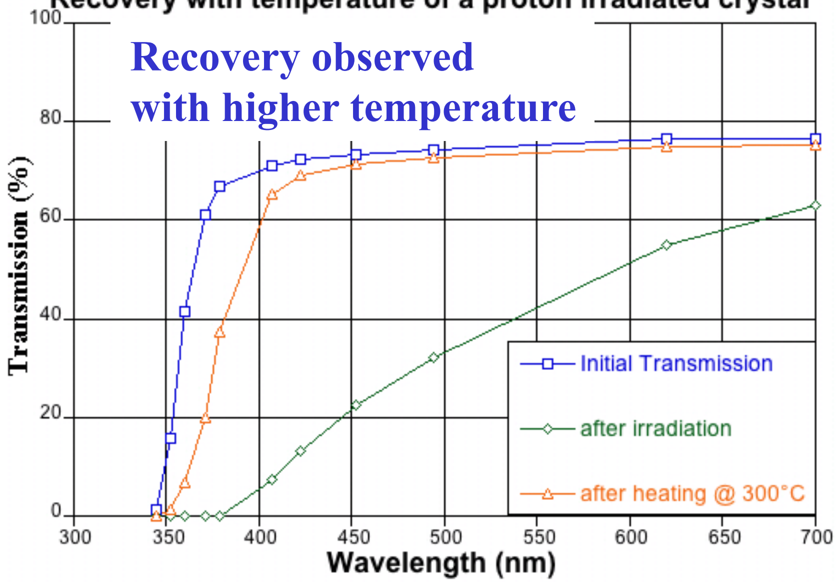
M.Huhtinen et al., NIM. A 545 (2005) 63-87
P. Lecomte et al. NIMA 564 (2006) 164-168, P. Lecomte et al. NIM. A 587 (2008) 266 – 271
E. Auffray et al, Proc. SCINT 2011 conference

Hadron damage dynamics

Recovery at room temperature of a proton irradiated crystal



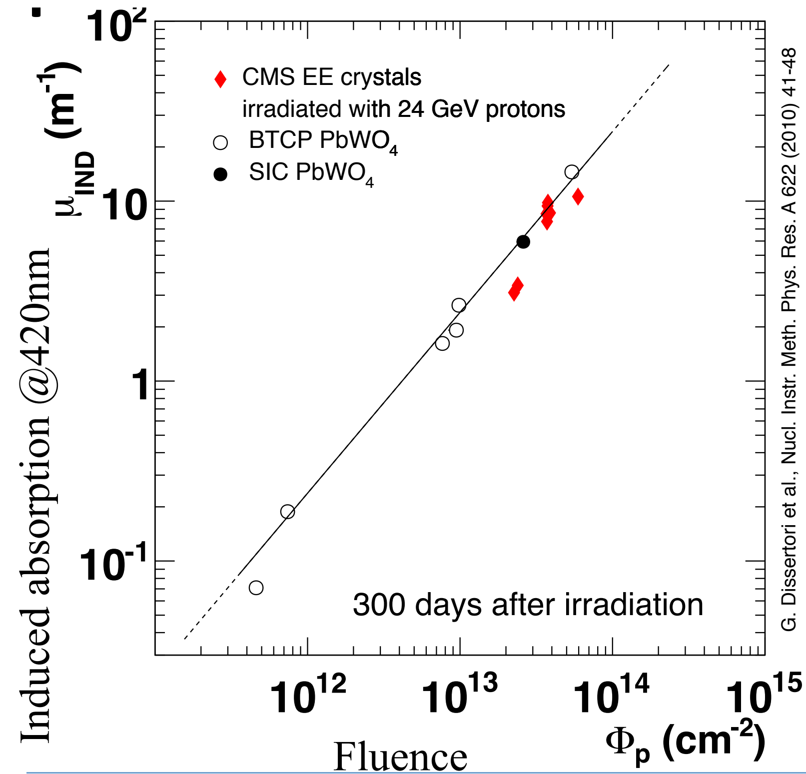
Recovery with temperature of a proton irradiated crystal



No recovery at room temperature

=> cumulative damage

=> No saturation observed



F. Nessi, conference record IEEE NSS/MIC 2012, CMS CR 2012/296

Test beam for future performance assessment

Energy resolution measured at the CERN H4 e-beam
for a 5*5 crystal matrix with non irradiated and proton irradiated crystals
at different fluences from 10^{13} p/cm2 to 10^{14} p/cm^2
to assess the future performance of current Endcap detectors

Data Analysis currently ongoing

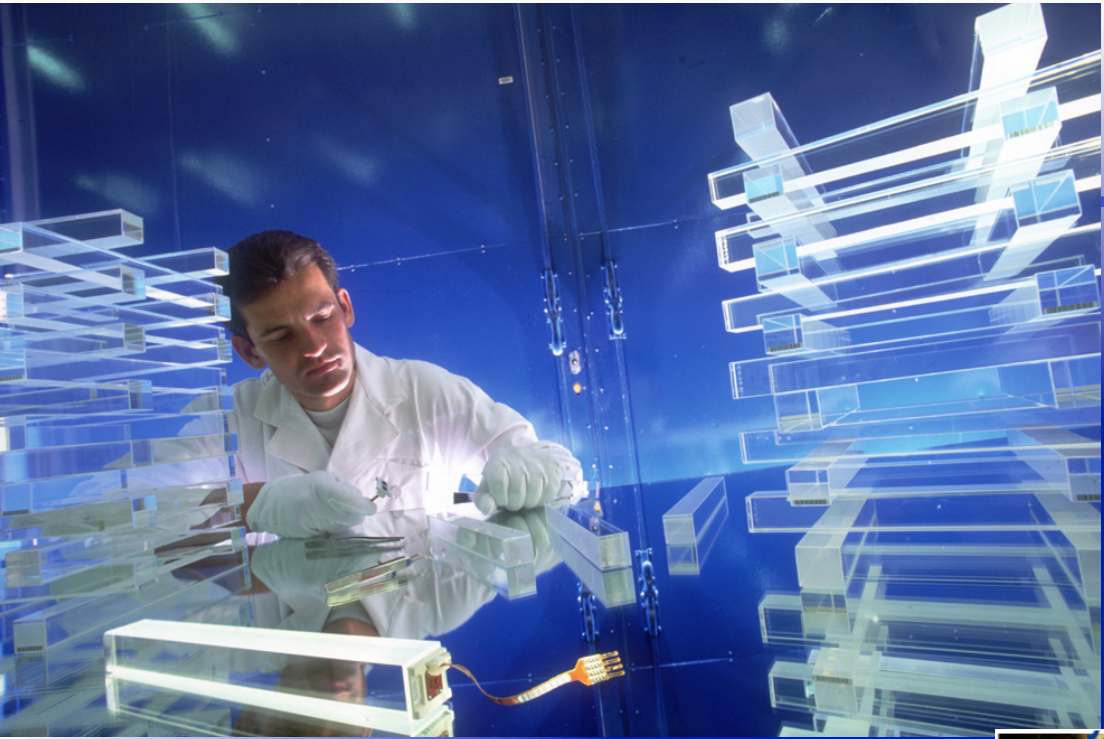
Conclusions

- **From conceptual design to realization : a long journey**
  - ✓ 17 years
  - ✓ Participation and commitment of many people from many institutes

- **Quality control, feedback to producers and book keeping are crucial**

- **Excellent in situ ECAL performance**

- **A new area of R&D opened for High Luminosity LHC**



Thank you