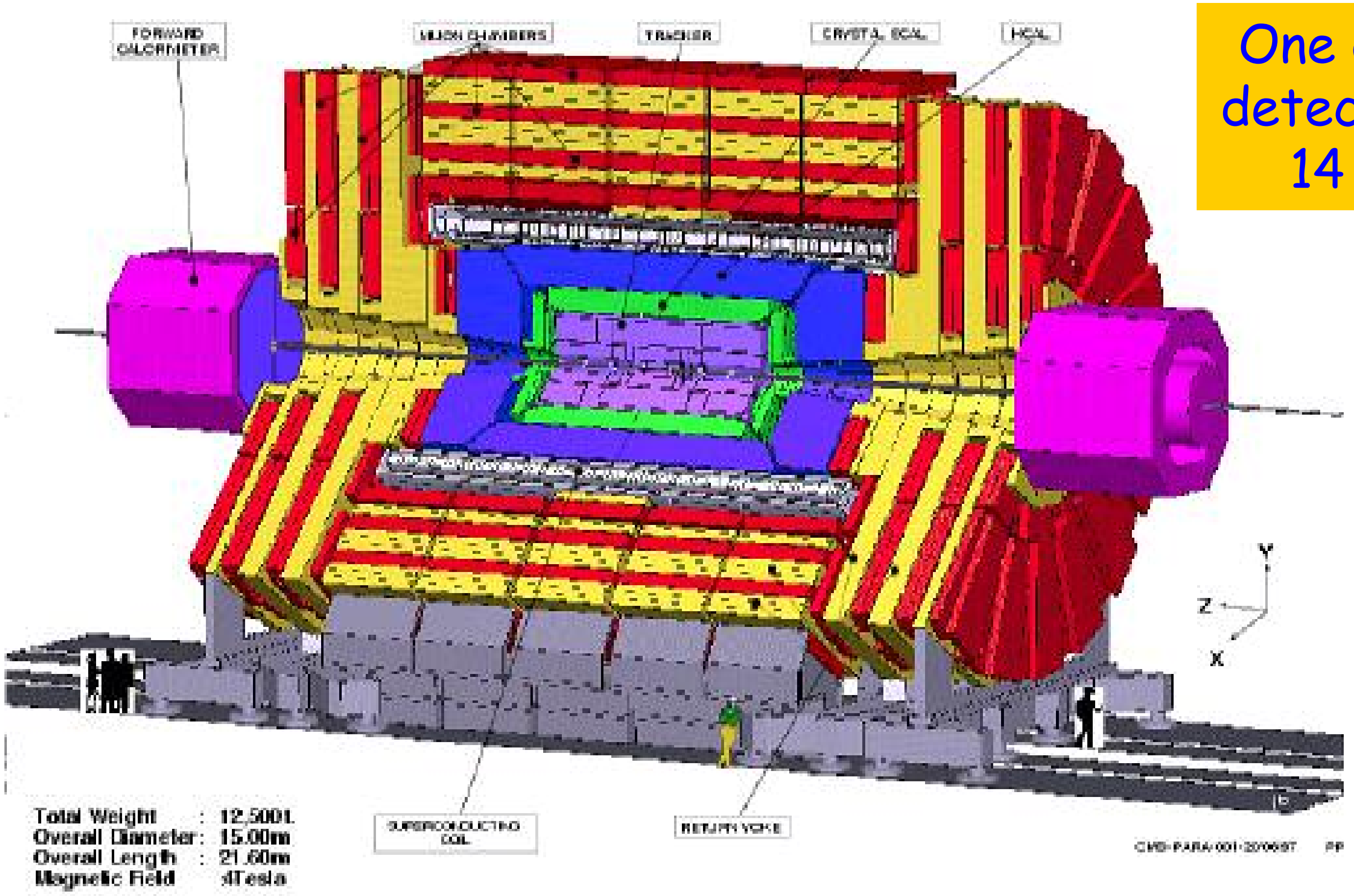
The Electromagnetic Calorimeter of the CMS Experiment

One of the four detectors at the 14 TeV LHC



Main goal:
Higgs, SUSY

8th Topical Seminar on Innovative Particle and Radiation Detectors - Siena 22/10/2002

Outline

- General considerations and motivations
- Physics benchmark
- Crystals
- Photodetectors
- Readout
- Key points in energy resolution
- Regional Centers for assembly and test

LHC experimental conditions

Max Machine Luminosity $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-2}$

$\sigma_{inel} = 100$ mb → 10^{9} events/s

$\sigma_{higgs} = 1$ pb → 10^{-2} events/s

20 events/crossing → 1000 tracks

1 crossing/25ns

Neutrons: $10^{17}\ \mathrm{n/cm}^2$

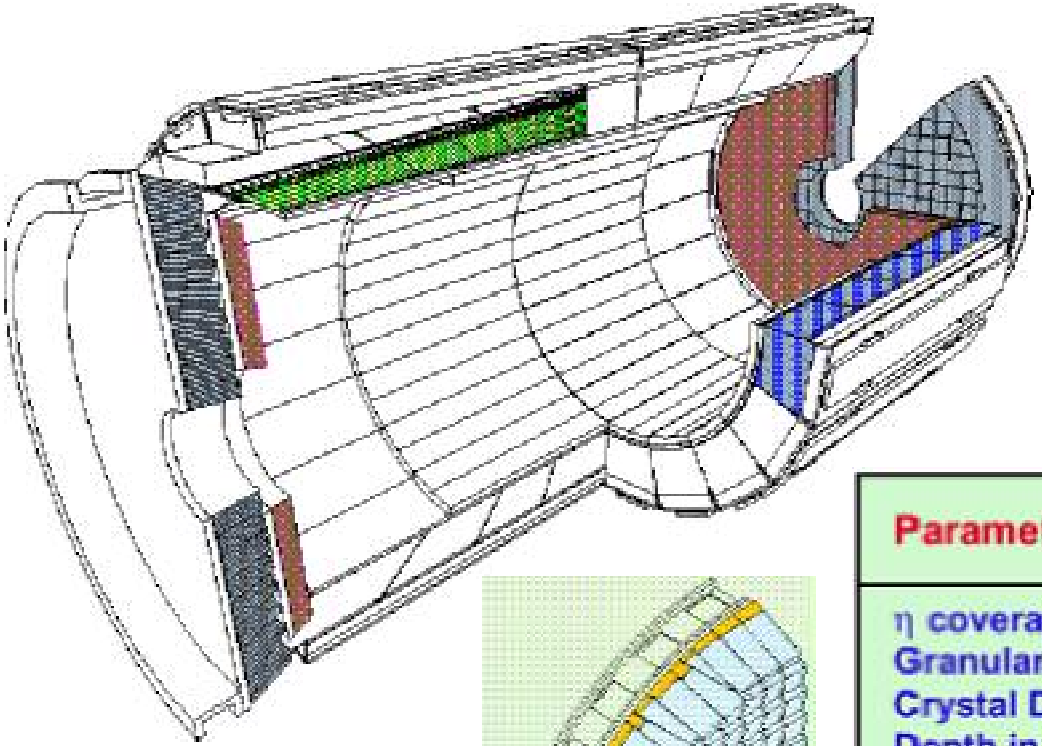
Gammas: 10^{7} Gy

in 10 years

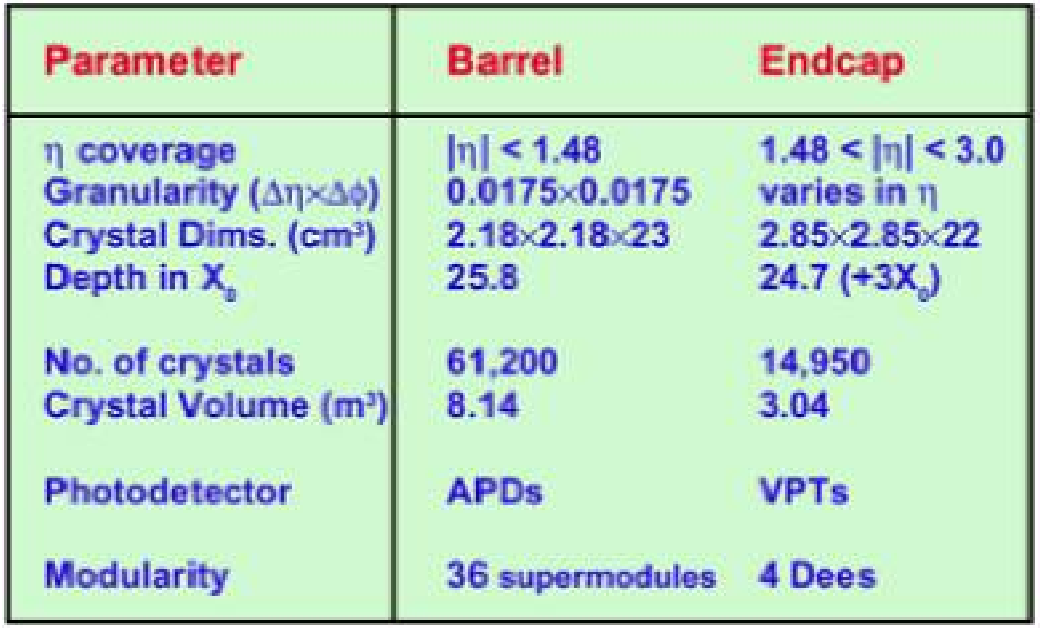
Extreme conditions for detectors

- Granularity ($10^5 \div 10^7$ channels)
- Speed of response
- DAQ + trigger ($10^9 \rightarrow 10^2$ ev/s)
- High radiation resistance

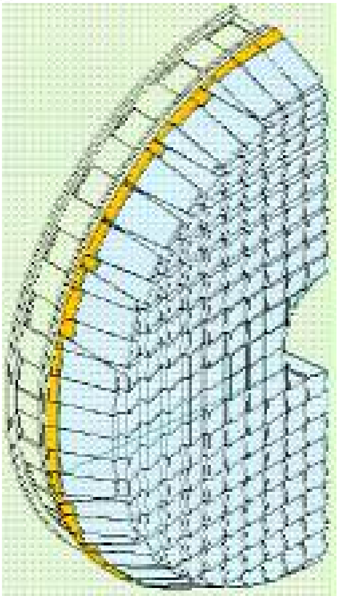
CMS ECAL Structure



≈75000 PWO Crystals
+ Preshower (Endcaps)



Parameter	Barrel	Endcap
η coverage	$\lvert\eta\rvert < 1.48$	$1.48 < \lvert\eta\rvert < 3.0$
Granularity ($\Delta\eta\times\Delta\phi$)	0.0175×0.0175	varies in η
Crystal Dims. (cm^3)	$2.18\times2.18\times23$	$2.85\times2.85\times22$
Depth in X_0	25.8	24.7 ($+3X_0$)
No. of crystals	61,200	14,950
Crystal Volume (m^3)	8.14	3.04
Photodetector	APDs	VPTs
Modularity	36 supermodules	4 Dees



Motivations for Crystals

- Excellent energy resolution (over a wide range)
- High detection efficiency for low energy e and γ
- Structural compactness:
  - simple building blocks allowing easy mechanical assembly
  - hermetic coverage
  - fine transverse granularity
- Tower structure facilitates event reconstruction
  - straightforward cluster algorithms for energy and position
  - electron/photon identification

Instrumental Effects

Precision has a price… a long list to take care:

- Longitudinal and lateral shower containment
- Light production and collection
- Light collection uniformity
- Nuclear counter effect (leakage of particles in PD)
- Photo Detector gain (if any) stability
- Channel to channel intercalibration
- Electronic noise
- Dead material (energy loss and γ conversions)
- Temperature stability and uniformity
- Radiation damage
- Pileup

A question of philosopy…

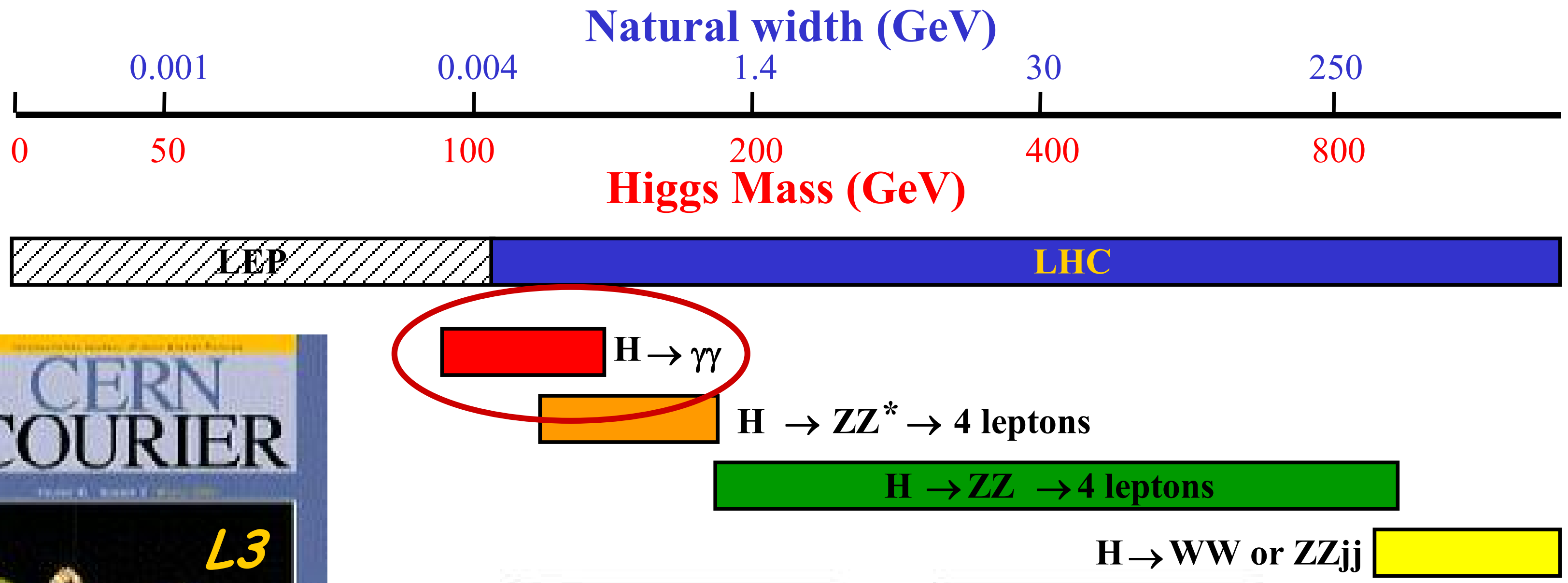
A crystal calorimeter is a very precise instrument that requires a tremendous effort to be finalized

- understand & optimize crystal parameters
- technology for growing crystals
- …..
- extreme resolution very fragile

Is it worth?

If you look for some specific reaction…

Higgs hunt: low mass?



Natural width (GeV)

0.001 0.004 1.4 30 250

0 50 100 200 400 800

Higgs Mass (GeV)

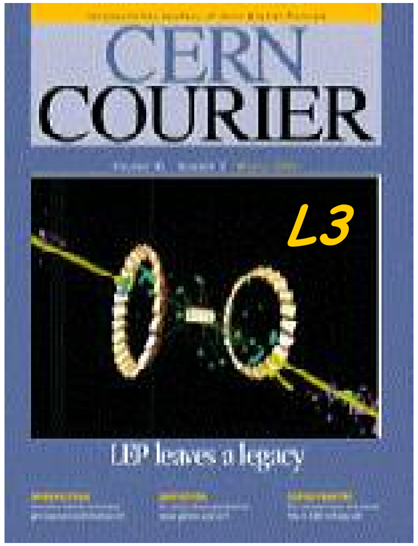
LEP **LHC**

H → γγ

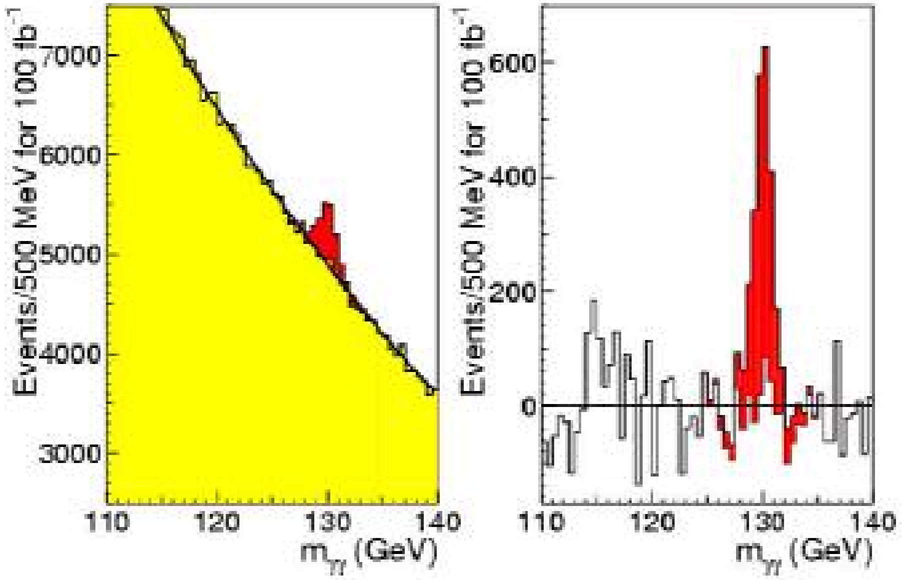
H → ZZ* → 4 leptons

H → ZZ → 4 leptons

H → WW or ZZjj



LEP observed an excess of events around 115 GeV



Evidence of H →γγ signal ECAL CMS @ design resolution

CMS ECAL benchmark

Low mass Higgs discovery:

$\Gamma_H\ (m_H \cong 100\ \text{GeV}) \sim 2 - 100\ \text{MeV} \Rightarrow \Gamma_H / m_H \leq 10^{-3}$

Precision given by experimental resolution

$m_{\gamma\gamma} = 2\ E_1\ E_2\ (1 - \cos\theta)$

$$\frac{\sigma_m}{m} = \frac{1}{2}\left[\left(\frac{\sigma_1}{E_1}\right)^2 + \left(\frac{\sigma_2}{E_2}\right)^2 + \left(\frac{\sigma_\theta}{\mathrm{tg}\theta/2}\right)^2\right]^{1/2}$$

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Target →

$a \sim 0.025\ \text{GeV}^{1/2}$

$b < 200\ \text{MeV}$

$c \sim 0.005$

and an angular resolution

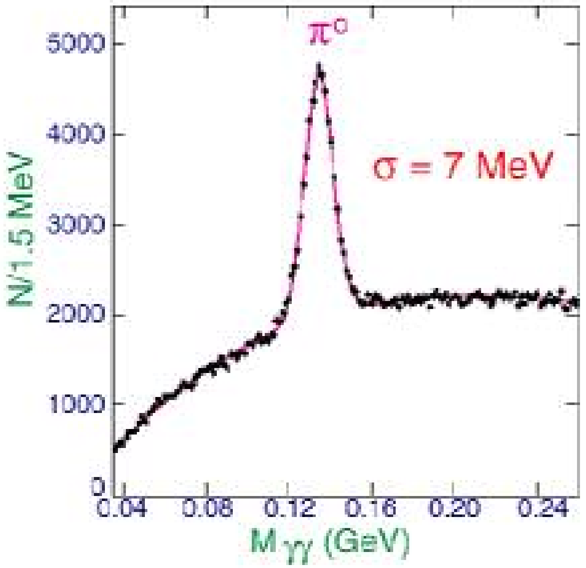
$\sigma_\theta \sim 50\ \text{mrad}/\sqrt{E}$

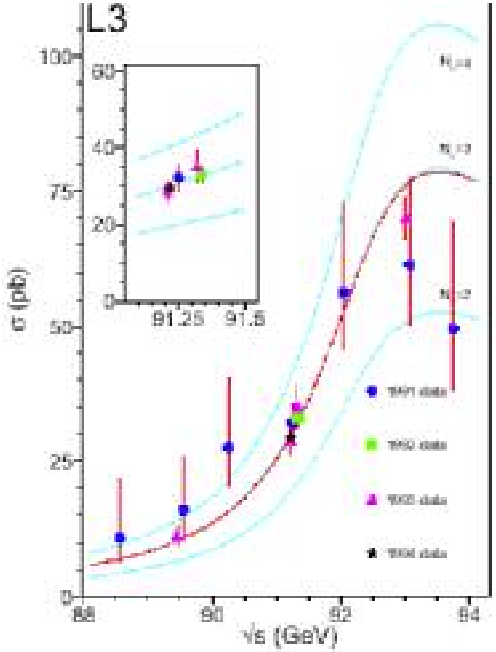
L3 photon measurements

Beautiful instrument & excellent physics results

π mass reconstruction $\Rightarrow$

single gamma
neutrino counting $\Downarrow$





N_ν=2.98±0.07±0.07

most accurate
model independent
measurement

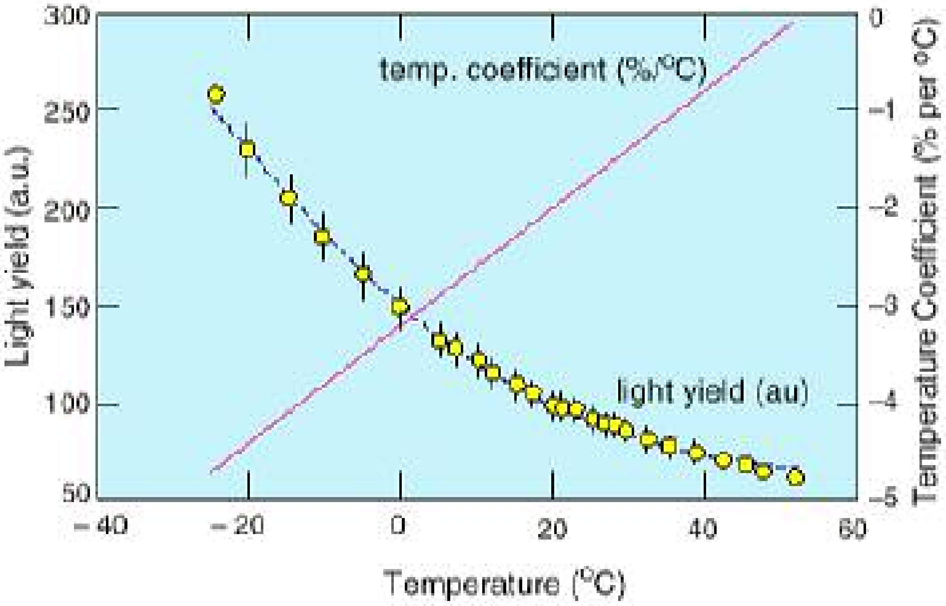
Which crystal?

	NaI(Tl)	BaF_2	CsI(Tl)	CsI	CeF_3	BGO	PWO	
ρ	3.67	4.88	4.53	4.53	6.16	7.13	8.26	g/cm^3
X0	2.59	2.05	1.85	1.85	1.68	1.12	0.89	cm
RM	4.5	3.4	3.8	3.8	2.6	2.4	2.2	cm
τ	250	0.8/620	1000	20	30	300	15	ns
λp	410	220/310	565	310	310/340	480	420	nm
n (λp)	1.85	1.56	1.80	1.80	1.68	2.15	2.29	
LY	100%	15%	85%	7%	5%	10%	0.2%	%NaI

Typical light yield of NaI ~ 40000 γ/MeV

The choice of Lead Tungstate

Parameter		Value
Radiation length	cm	0.89
Moliere radius	cm	2.2
Hardness	Moh	4
Refractive index		2.3
Peak emission	nm	440
% of light in 25 ns		80%
Light yield (23 cm)	γ/MeV	100



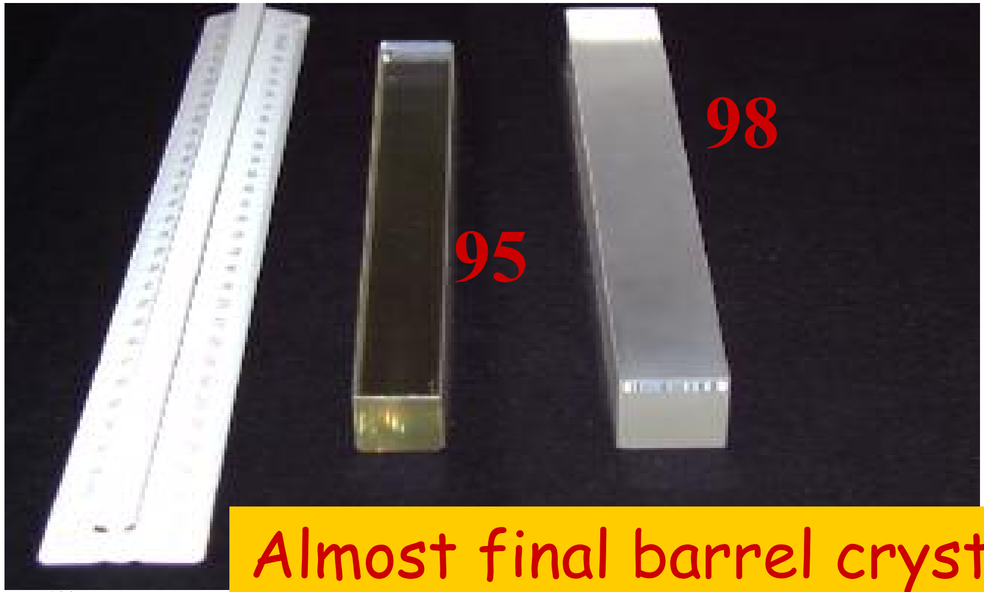
- Fast scintillation
- Small X_0 and R_m
- Intrinsic radiation hardness
- Relatively easy to grow
- Massive production capability

- Low Light Yield
- High index of refraction
- Strong LY dependance on T

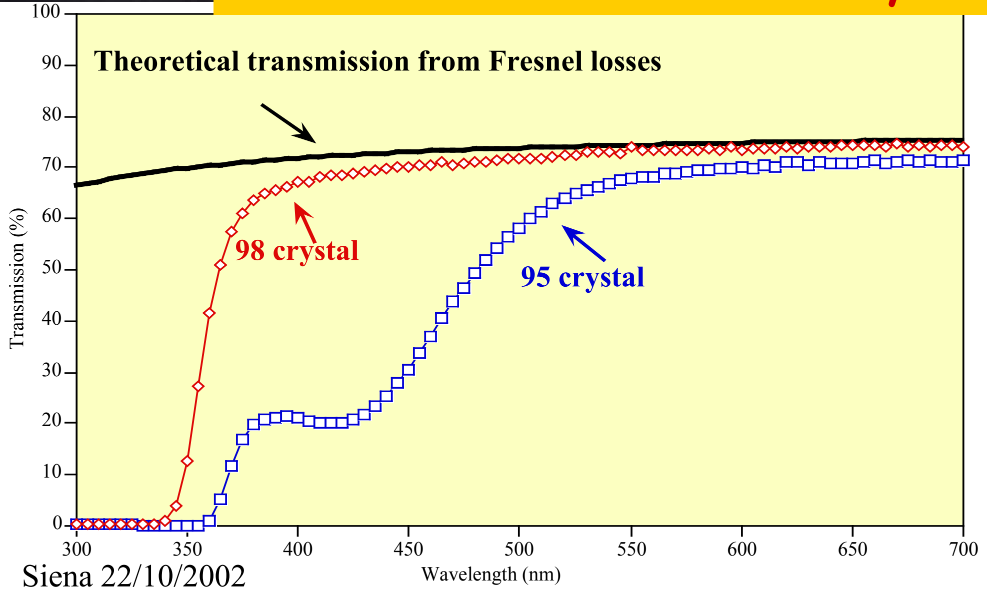
Main CMS ECAL challenges

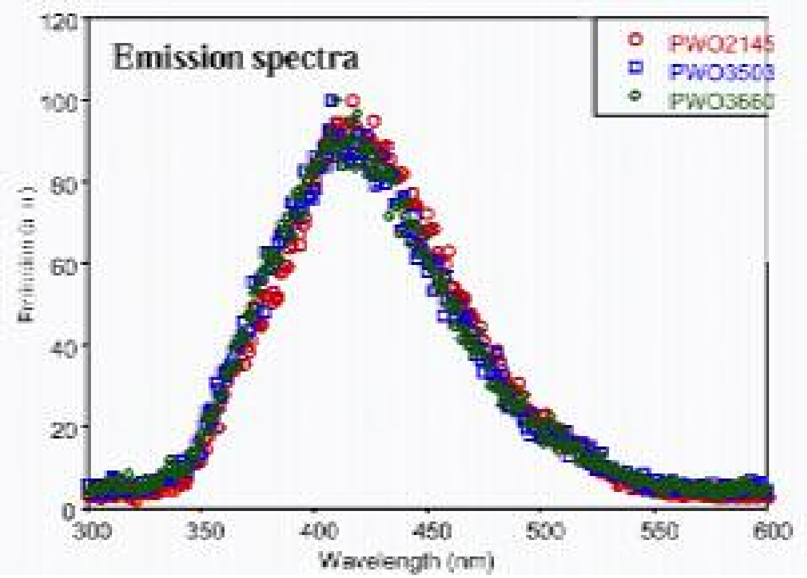
- Improve the low level of light yield of crystals
- Keep fast response (understand decay kinetics)
- Insure radiation resistance
- Improve growing and production techniques
- Achieve longitudinal response uniformity
- Develop solid state photodtector with gain (APD)
- Develop suitable radiation hard electronics
- Control effects below few permill
- Design low-Z support structure
- Test and assembly ~ 75000 crystals

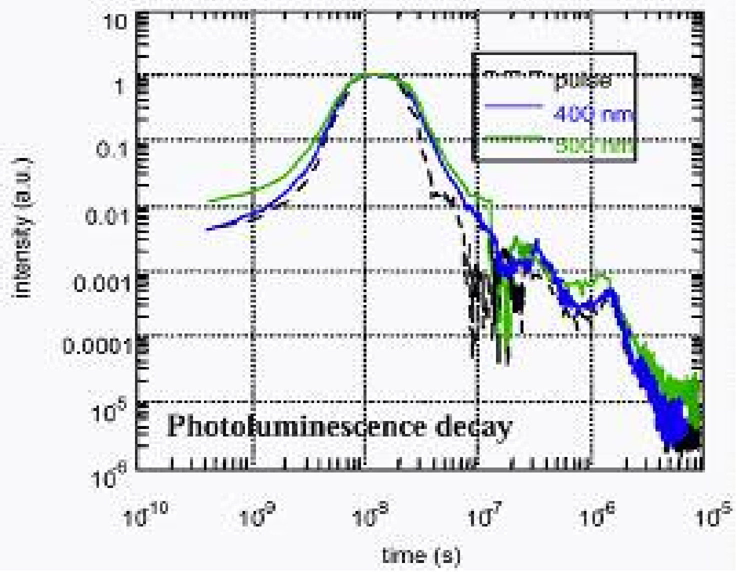
Crystals R&D 1995 - 1998



Almost final barrel crystals

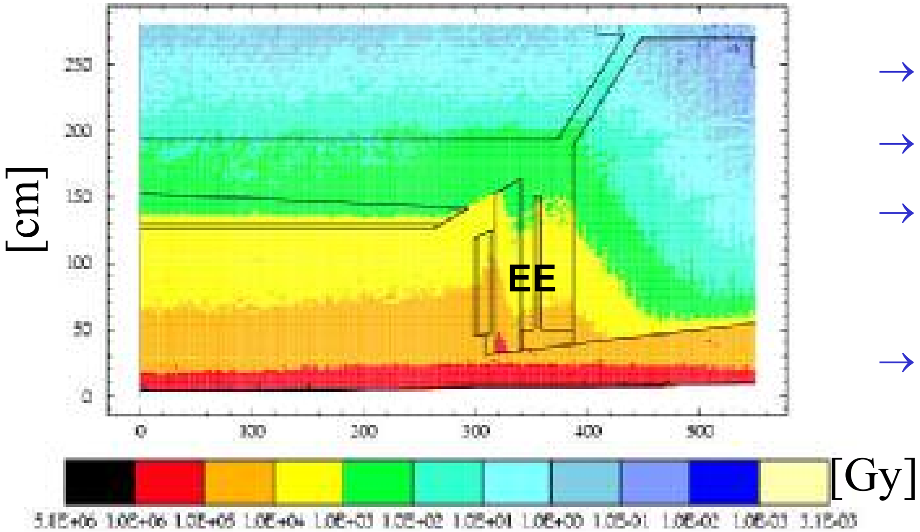


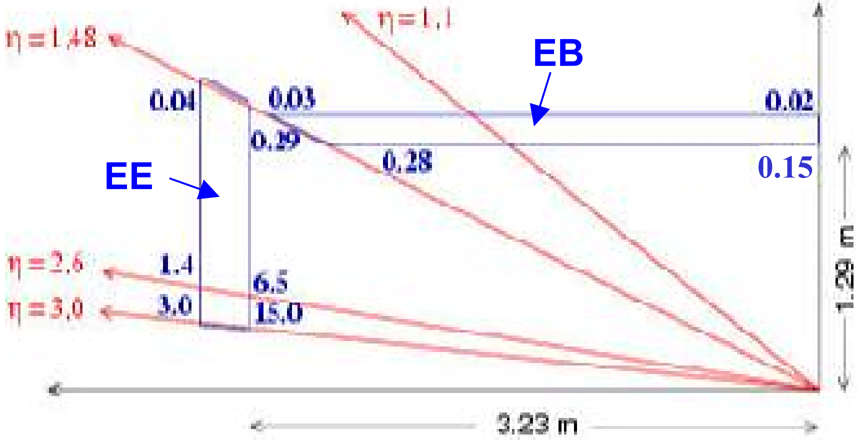




Facts on Radiation Damage

Total dose after 10 years of running ($5x10^5$ pb^{-1})





Dose rates [Gy/h] in ECAL at luminosity $L=10^{34}cm^{-2}s^{-1}$

Major R&D problem

→ Only e.m. radiation produces a damage

→ Scintillation mechanism is not affected

→ Only crystal transparency is reduced

creation of color centers

→ Damage level depends on dose rate

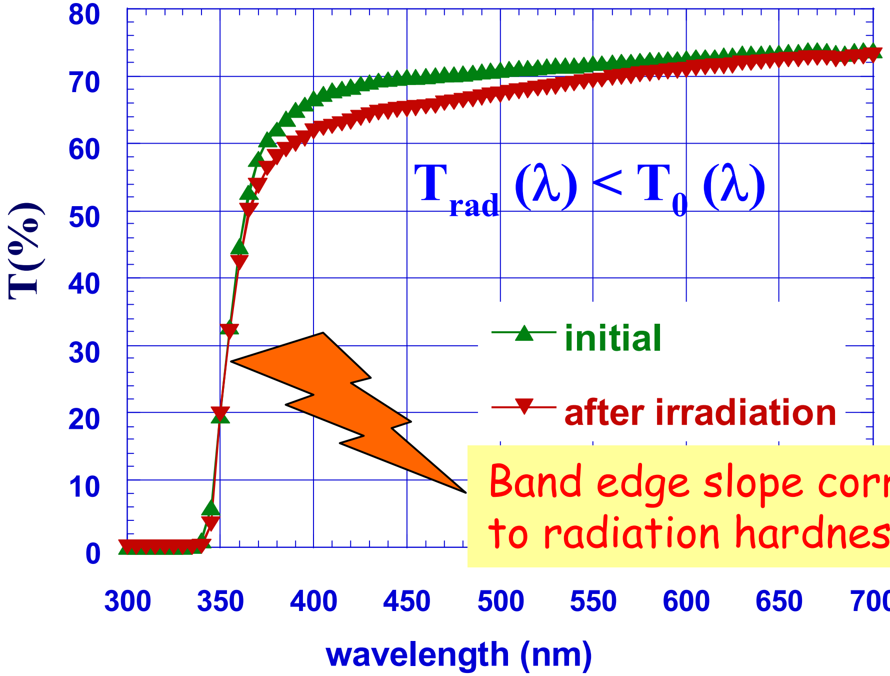
creation and annealing of color centers at room temperature

→ Damage level reaches an equilibrium after a small administered dose

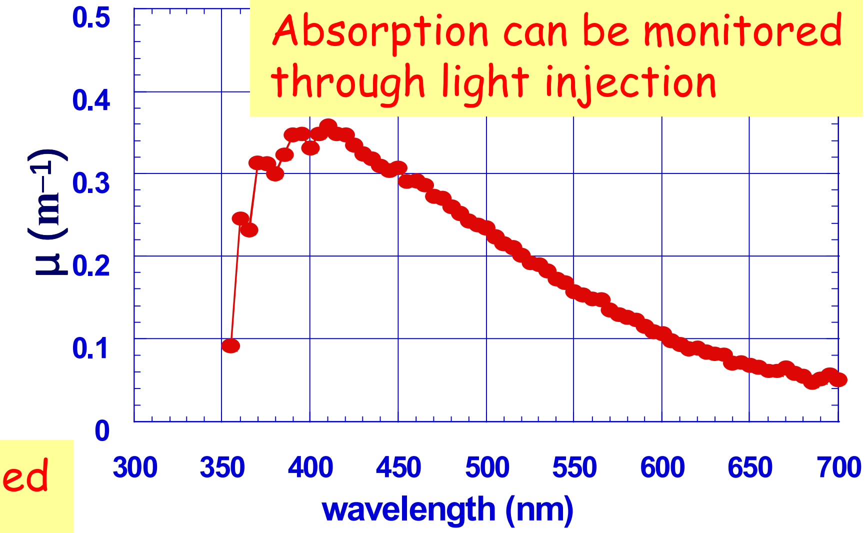
→ Partial damage recovery in few hours

→ Loss in extracted light of few % is tolerable and can be followed with a monitor system

γ induced radiation damage



Band edge slope correlated to radiation hardness!!

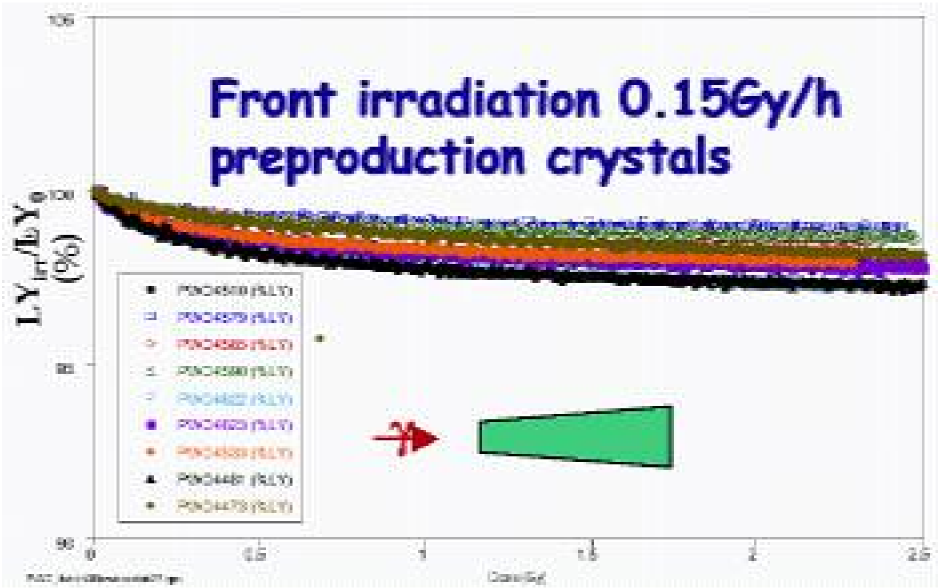


Absorption can be monitored through light injection

Can be quantified by:

$$\mu(\lambda) = \frac{1}{L_{xtl}} \ln\left[\frac{T_0(\lambda)}{T_{rad}(\lambda)}\right]$$

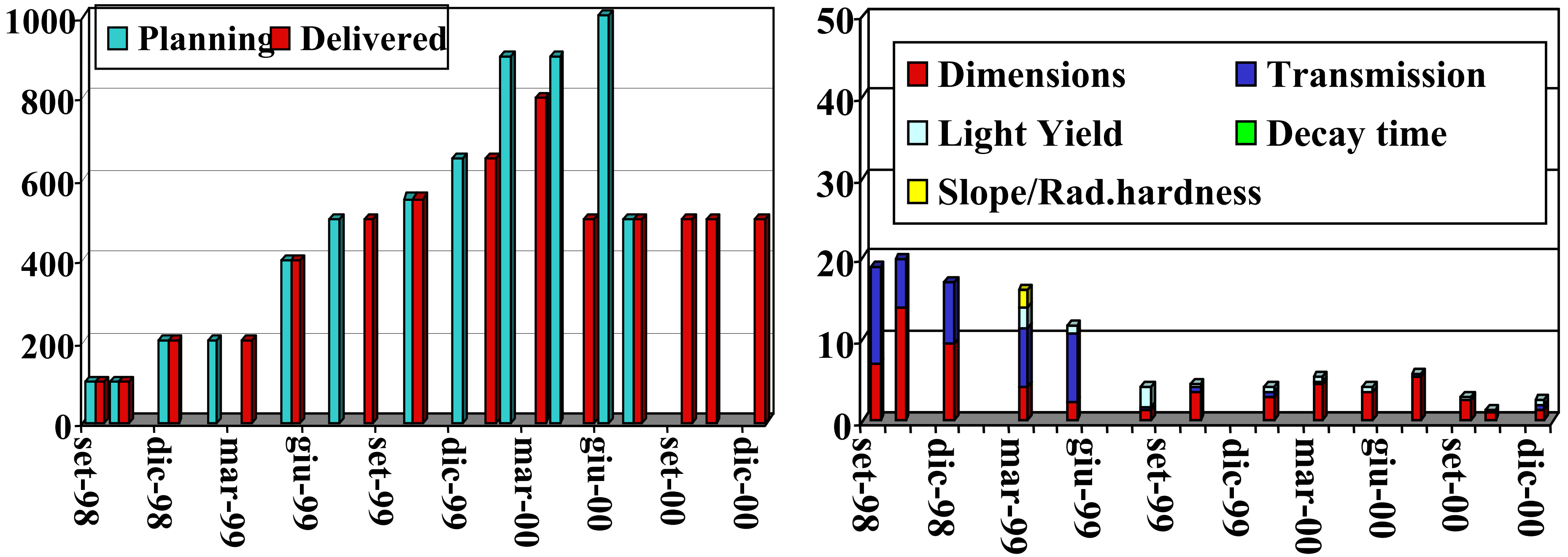
$$LY_{loss} = LY_{rad}/LY_0$$



Crystals Preproduction

Sept. 1998 to Dec. 2000

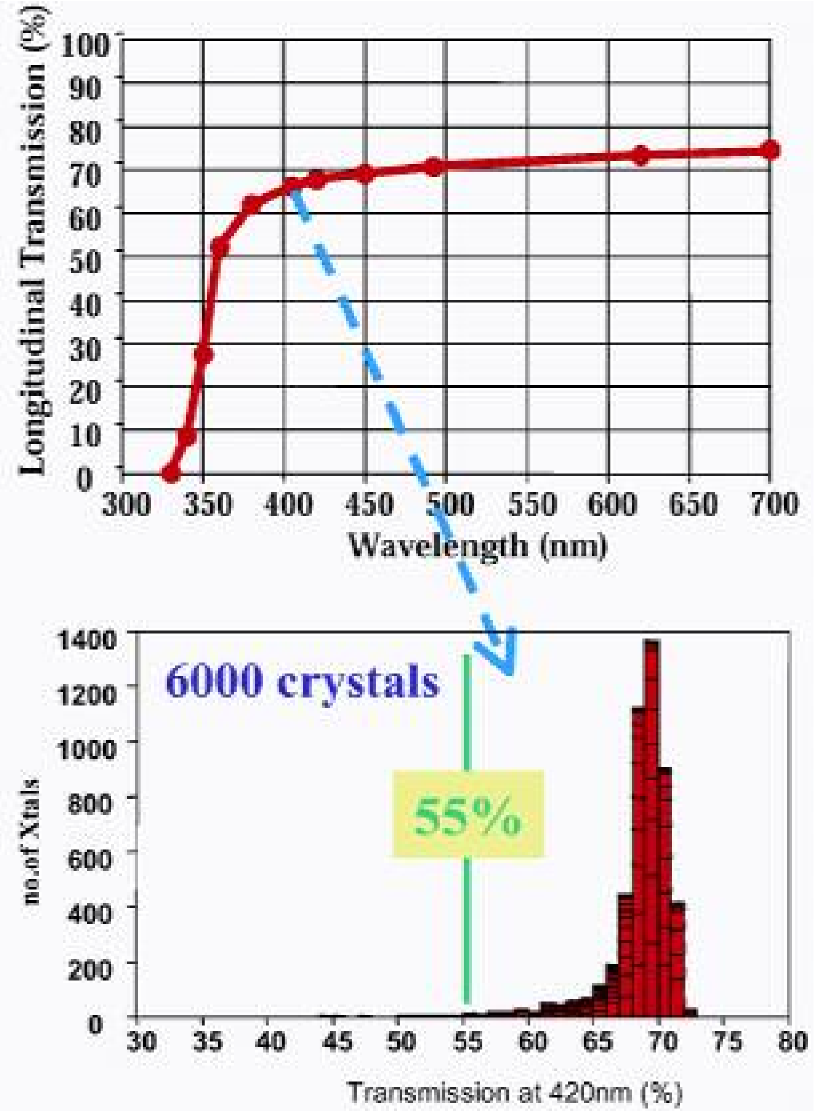
6000 crystals produced by BTCP

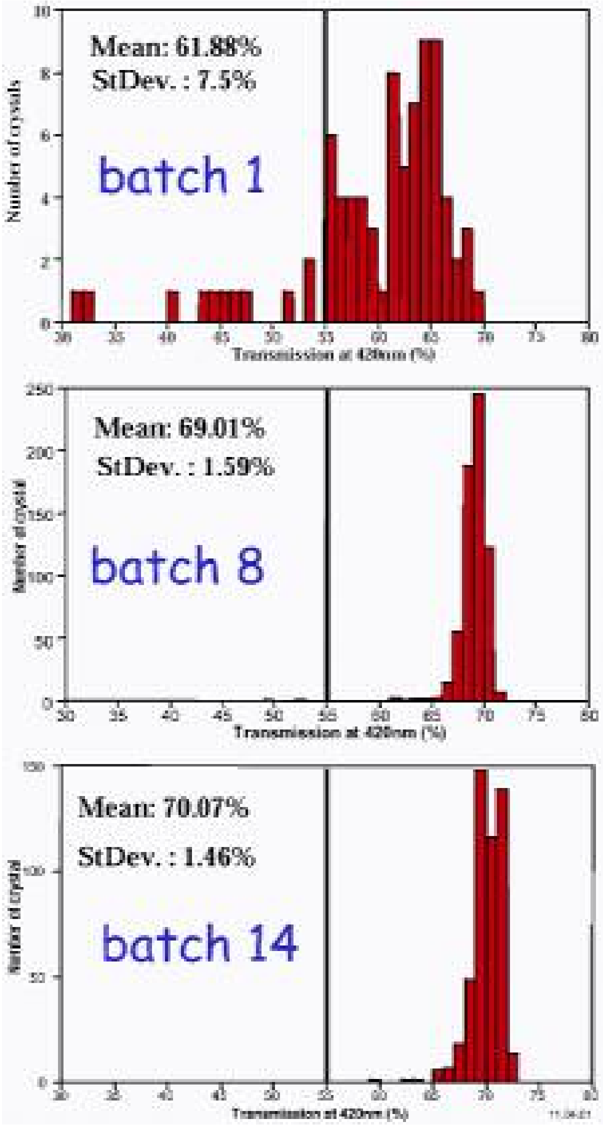


- Production yield
- Production rate
- Crystals quality
- Stability of parameters

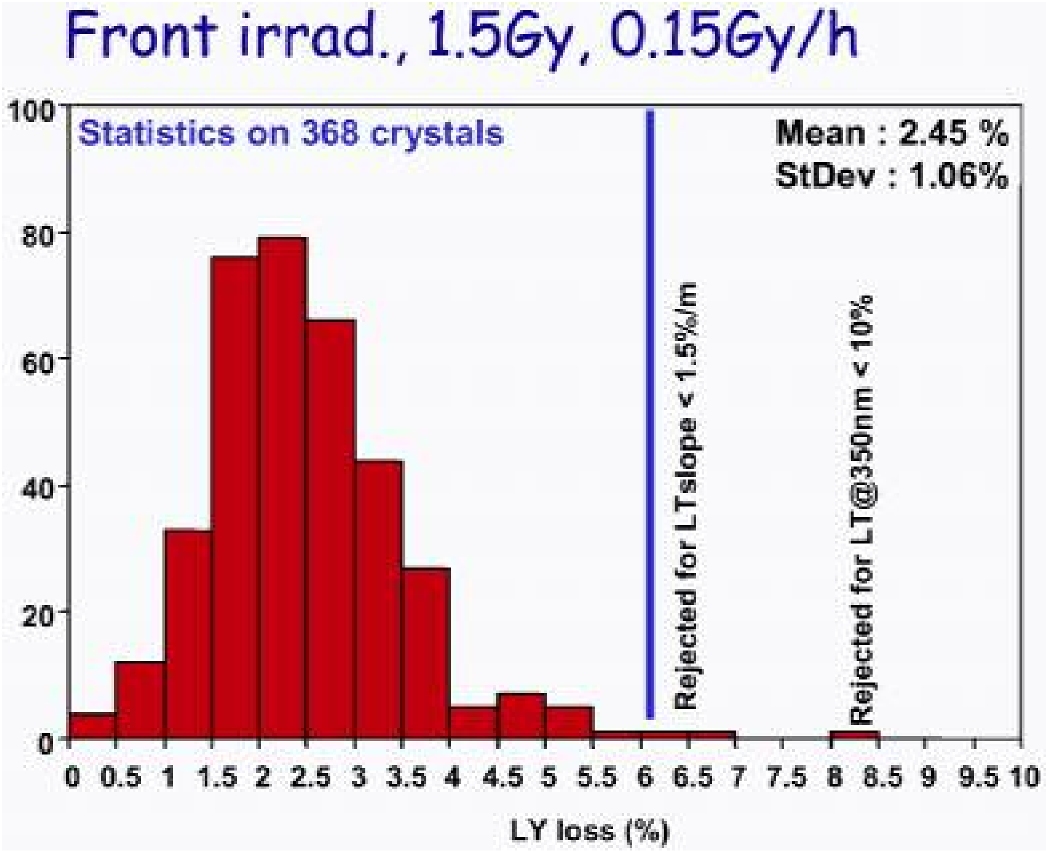
Goals successfully achieved!

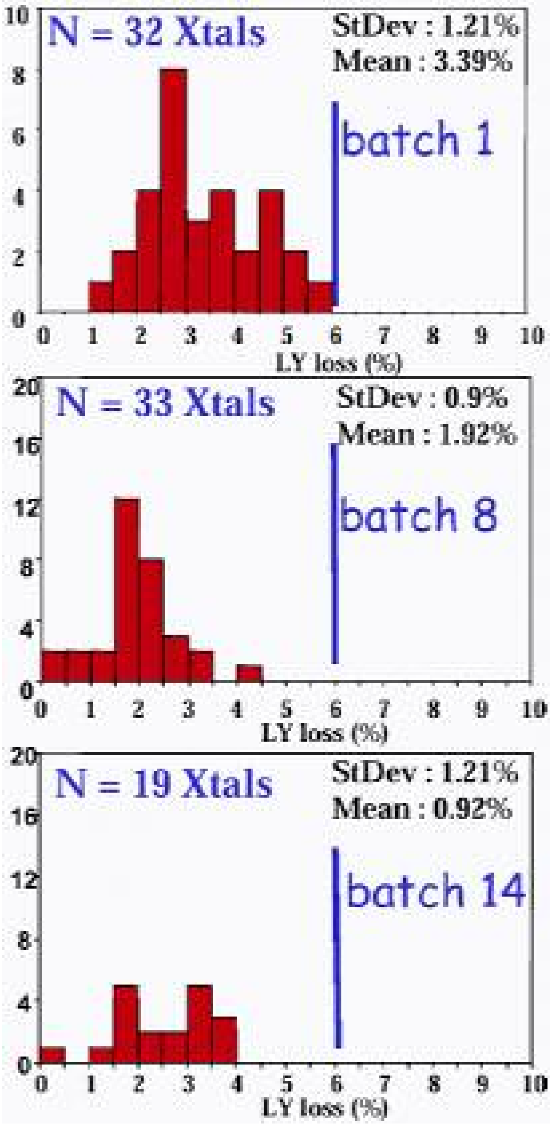
Preproduction Goals





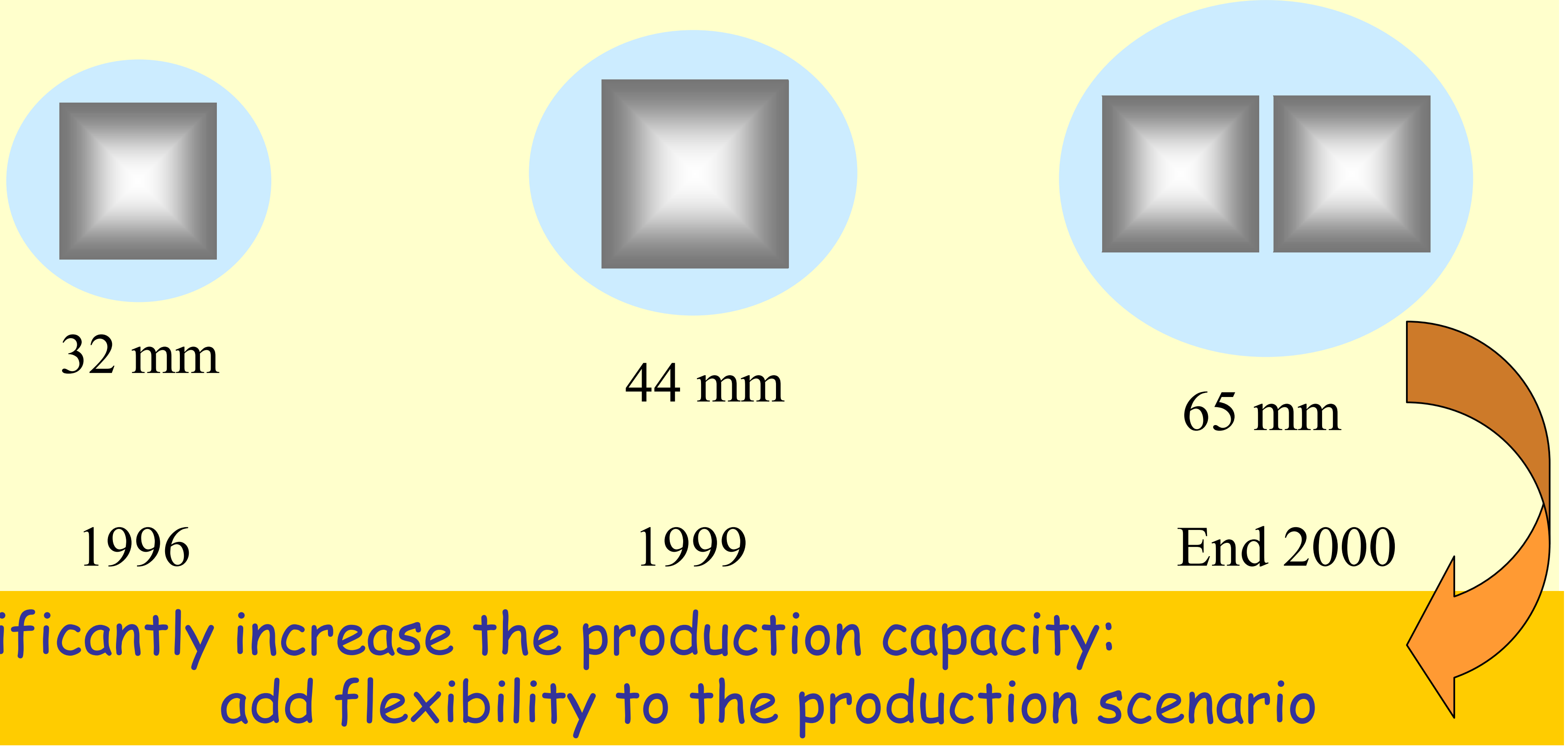
Preproduction Goals





2001: Crystals New Technology

Technology steps in Bogoroditsk



Barrel	Endcap	Barrel
32 mm	44 mm	65 mm
1996	1999	End 2000

Significantly increase the production capacity:
add flexibility to the production scenario

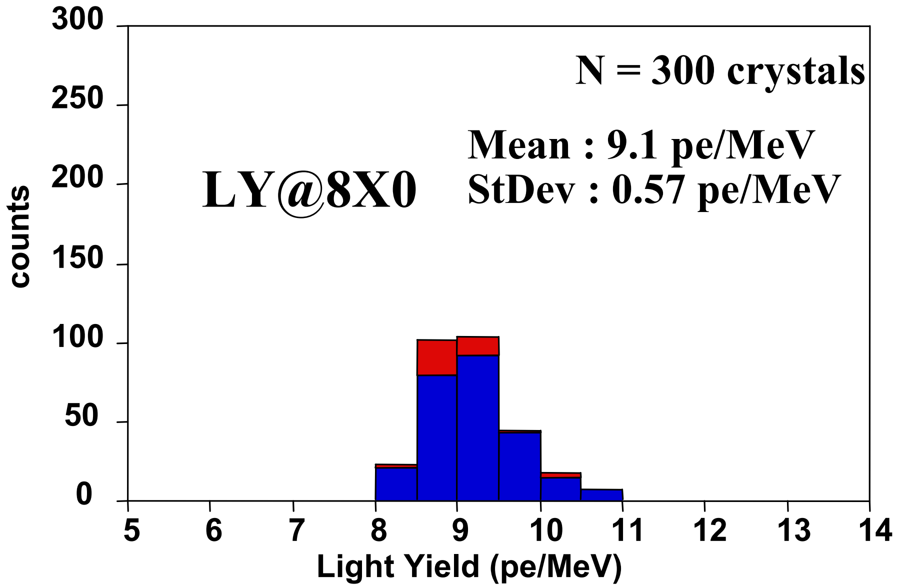
PWO as grown

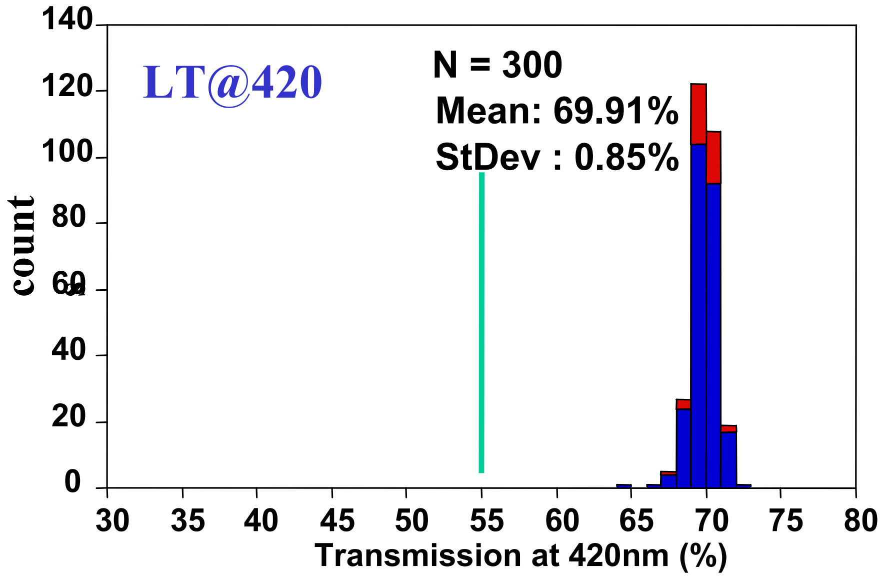
BARREL ingot

ENDCAP ingots

Production of barrel crystals started in 2001: 5700 crystals delivered
In parallel R&D to increase productivity (driven by endcap ingot success)

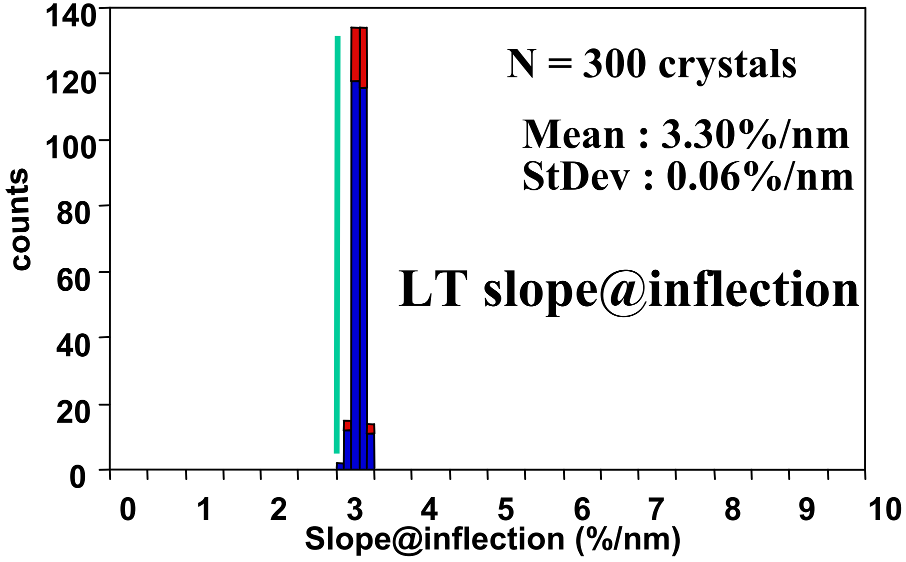
New Technology: Quality





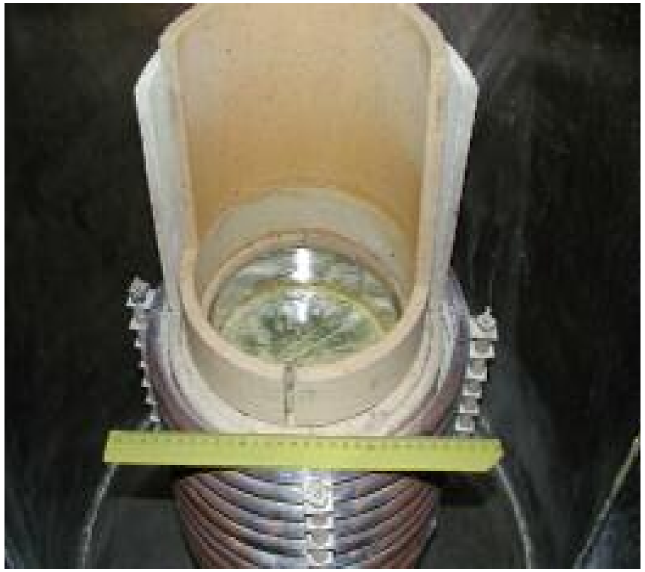
COMPARE:

- 260 barrel xl produced with the standard technology 🟦
- 40 barrel xl produced with the new technology

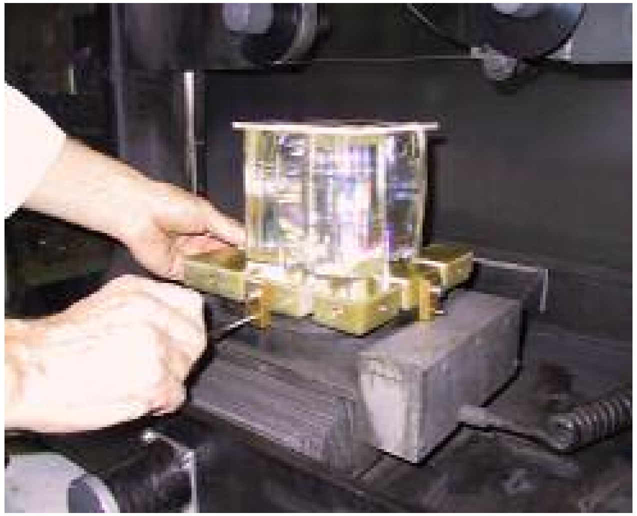


New Technology: Production

- 138 ovens upgraded for up to 85mm

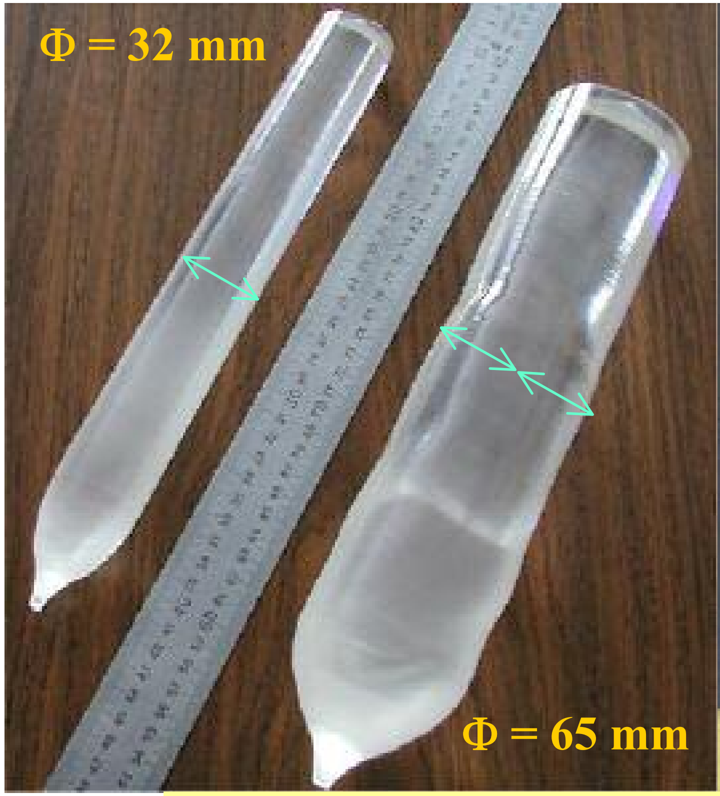


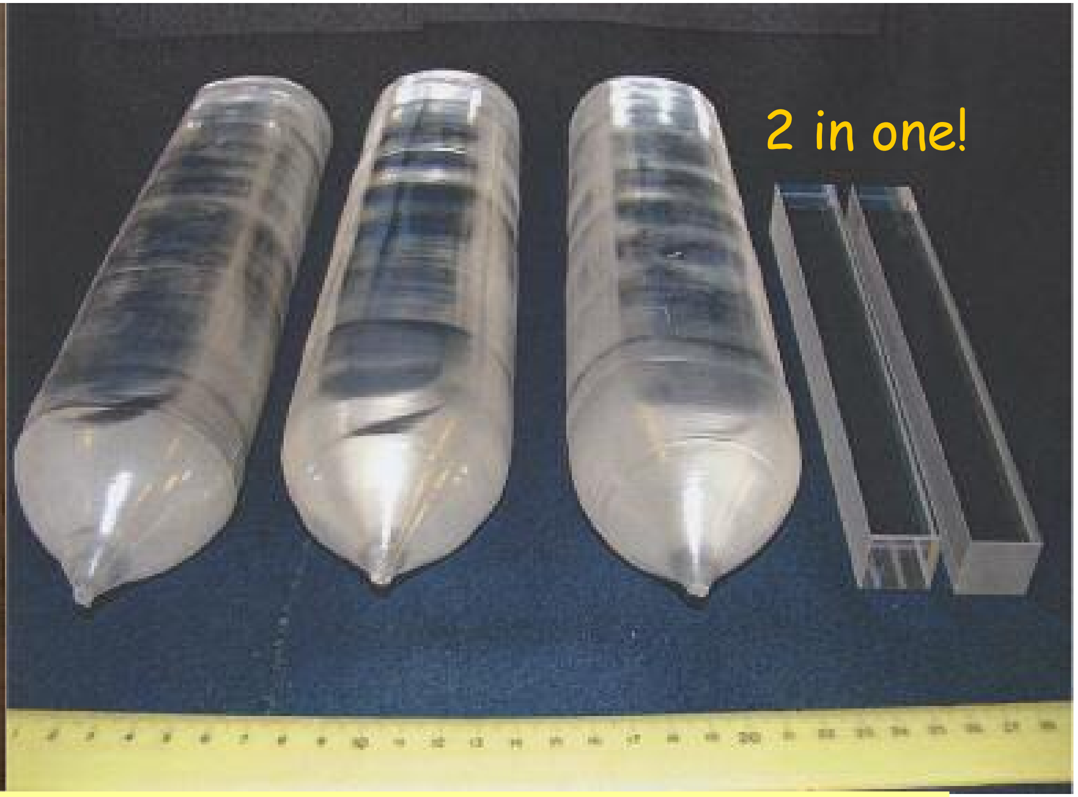
- New cutting technology: yield!



Crystals New Technology

Technology for 65mm ingots under control:
quality comparable with “standard crystals”





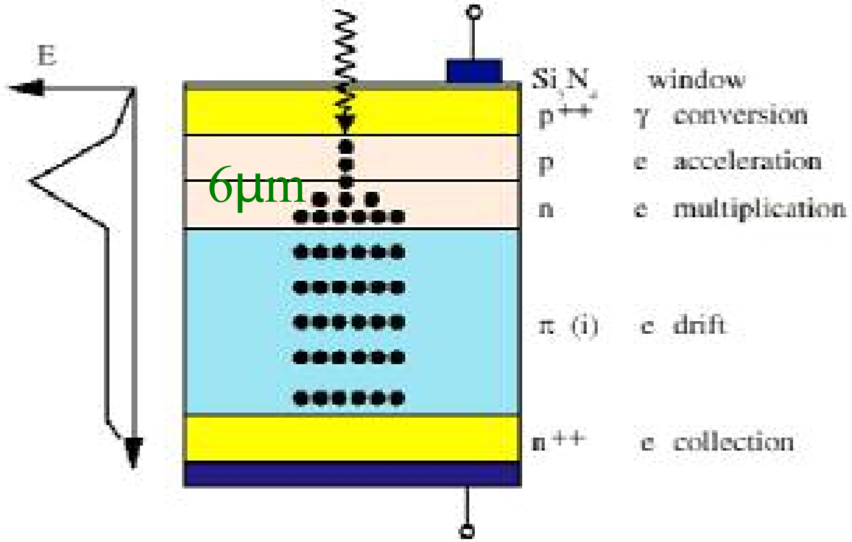
Further increase of the PWO ingot diameter under study:
2Endcap or 4Barrel crystals in one ingot is feasible

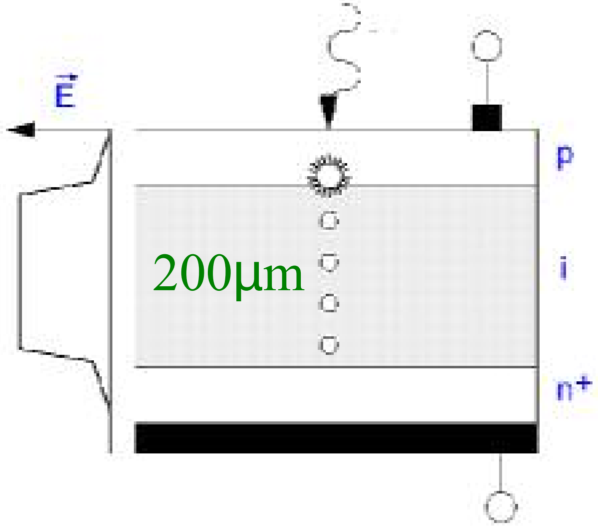
Crystal production schedule

Years	2001				2002				2003				2004				2005	
Quarters	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q
CERN/ISTC #354b- 6Õ000 barrel																		
Delivered	6000																	
CERN/ISTC #1718- 30Õ000 barrel																		
Schedule Sept 2001		1500	1200	2100	2500	2600	1800	2600	2900	2900	2900	2900	2900	1200				
New.sched	1500		500	500	200	200	200	400	2500	4000	4000	4000	4000	4000	3200	800		
Delivered	1500		500	500	200	200	200											
CERN/ETHZ Contract 26Õ000 barrel																		
Contract SCIONIX							2600	2600	2600	2600	2600	2600	2600	2600	2600	2600		
Delivered							2600											
Additionnal order for Barrel (37th SM + spares)																		
Potential product.																*2150*		
EndCap crystals production in Russia																		
Potential EE production										*200*	*400*	*400*	*400*	*400*	*1200*	*1450*	*7000*	*3550*
Barrel Total Cumulative	7500		8000	8500	8700	8900	11.7 K	14.7 K	19.8 K	26.4 K	33.0 K	39.6 K	46.2 K	52.8 K	58.6 K	64.15 K		
EE Total Cumulative										*200*	*600*	*1000*	*1400*	*1800*	*3000*	*4450*	*11.45 K*	*15.0K*

Assumes 2 crystals per ingot for barrel and endcap

Avalanche Photo Diodes - Barrel



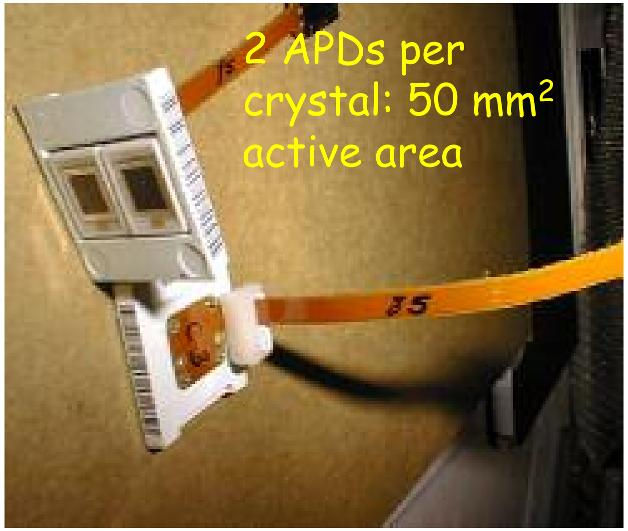


- Insensitive to B-field (4T)
- Internal gain (needed for PWO, M=50 used, $V_{M50} \approx 380V$)
- Good match to PWO scintillation spectrum (Q.E.~80%)

Avalanche Photo Diodes - Barrel

Critical points

- Contributions to all $\sigma(E)/E$ terms
  - C & Idark ⇒ b (1/E)
  - excess noise factor ⇒ a $(1/\sqrt{E})$
  - Gain stability ⇒ c
- Nuclear counter effect
- Radiation hardness


2 APDs per crystal: 50 mm^2 active area

APDs optimized with an extensive R&D program are now in production

Capacitance 75 pF & Idark few nA ⇒ b =150 MeV (Σ5x5 τ_S=40ns)

F=2.2 (→ fluctuations in multiplication) ⇒ a increase 1.6% → 2.3%

dM/dV = 3%/V and dM/dT = -2.3%/°C ⇒ c ~ 0.5% develop very stable systems

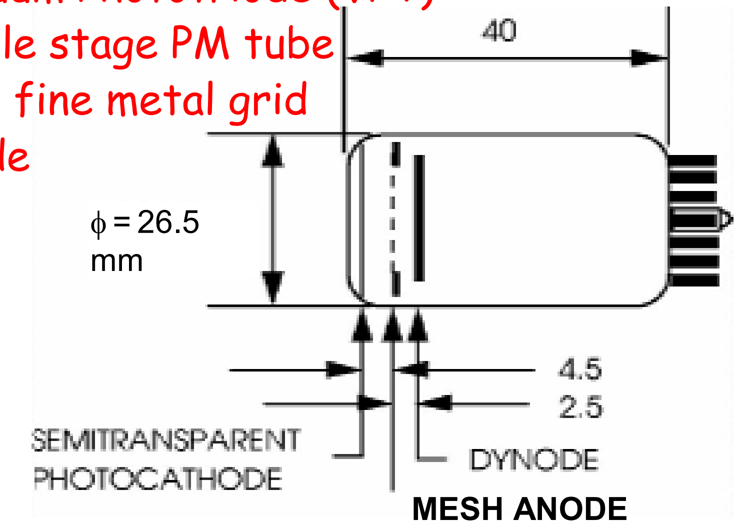
$d_{eff} \cong 6\ \mu m$ (→ acceptable response to ionizing radiation)

Idark increases with neutron irradiation:
$\sqrt{2}$ contribution to noise of single channel
after 10 years running

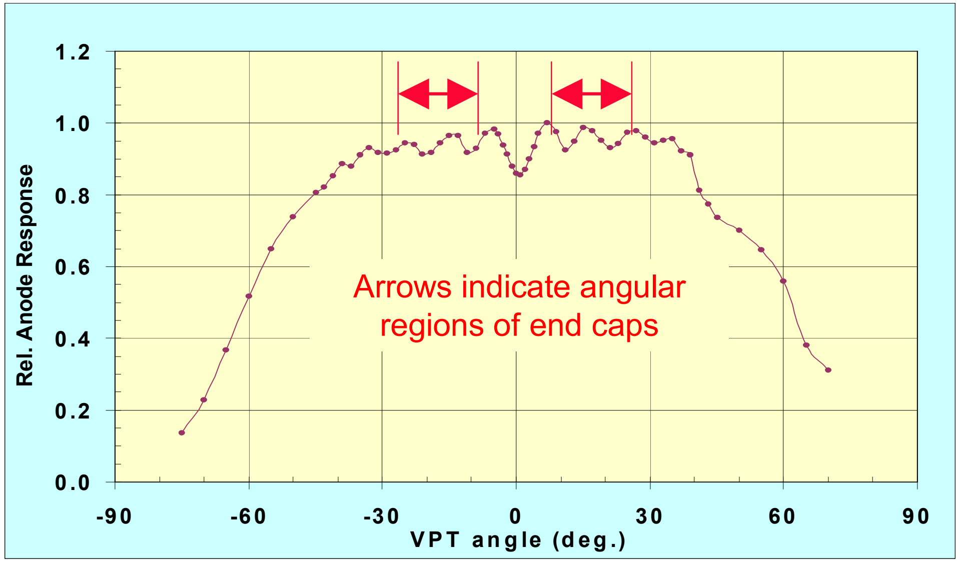
ok

Vacuum Phototriodes - Endcaps

Vacuum Phototriode (VPT):
Single stage PM tube
with fine metal grid
anode



- B-field orientation favourable for VPTs ($\text{Axes: } 8.5^{o} < |\theta| < 25.5^{o}$ wrt to field)
- More radiation hard than Si diodes (with UV glass window)
- Gain 8 -10 at B = 4 T
- Active area of ~ 280 mm^2/crystal
- Q.E. ~ 20% at 420 nm



Arrows indicate angular regions of end caps

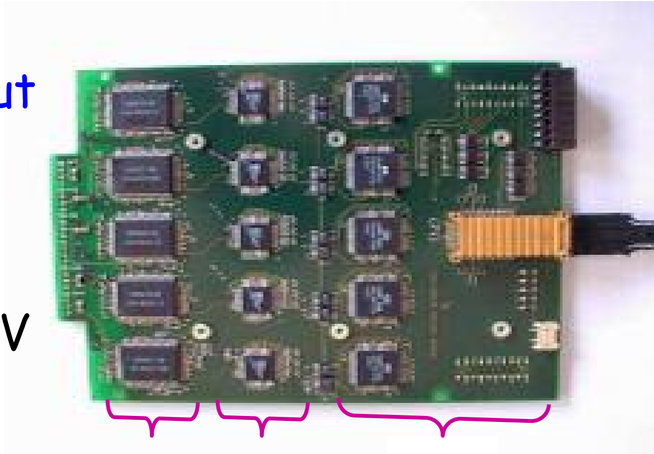
Read out chain/old

On-detector Light-to-Light readout

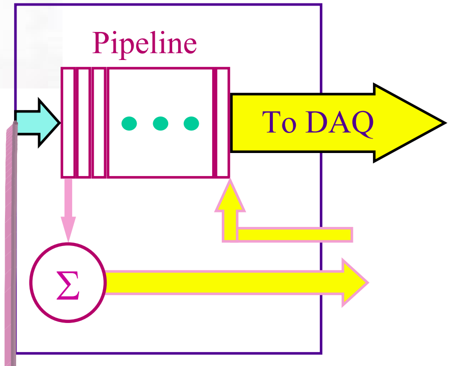
- 40 MHz clock
- High dynamic range to measure an energy interval 50MeV →2TeV

ALL RADIATION HARD

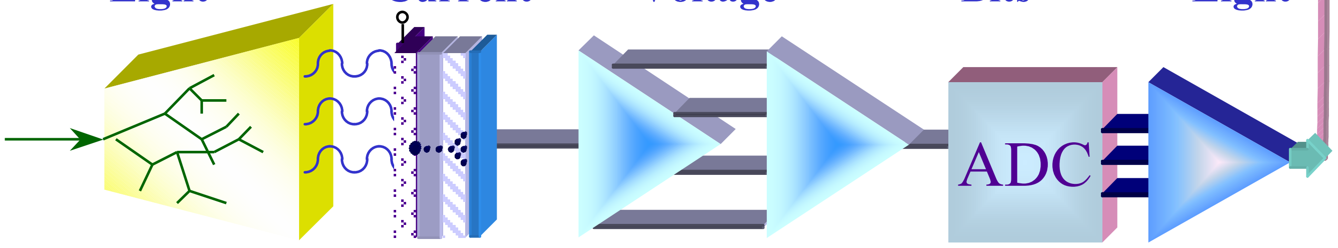
A difficult and costly project!



Upper-Level VME Readout Card (in Counting Room)



Digital Trigger Σ



$PbWO_4$ Crystal

APD VPT

Floating-Point Preamplifier

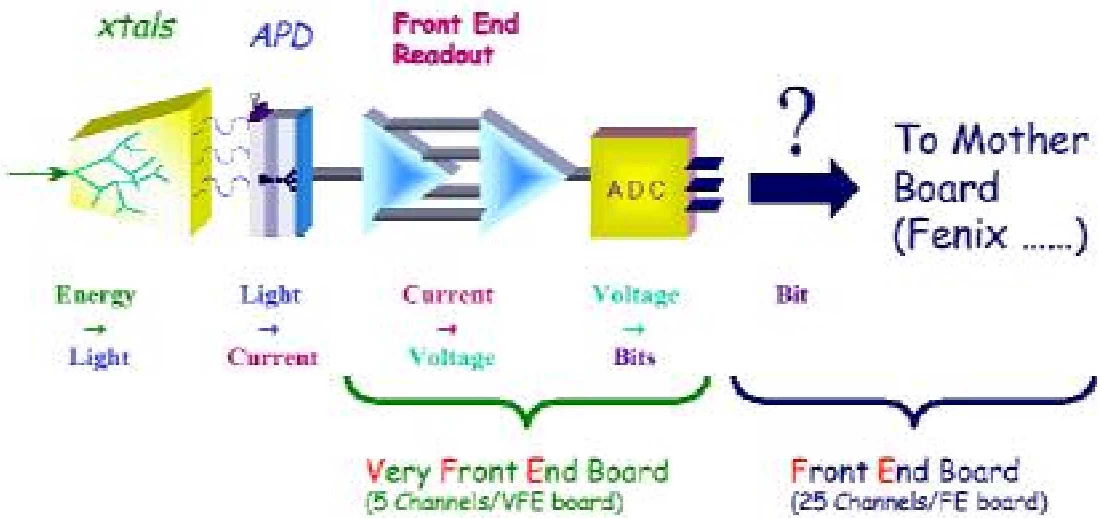
ADC

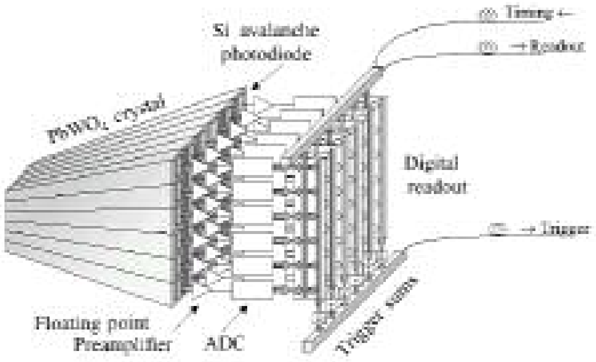
Fiber Readout

Read out chain/new

- Major revision of the project imposed by budget and possible thanks to 0.25μm CMOS rad hard technology:
  - Σ trigger e data storage on detector
  - read out of data only if L1 OK
  - three links each trigger tower (25 xl)

Same scheme of TP (1994)

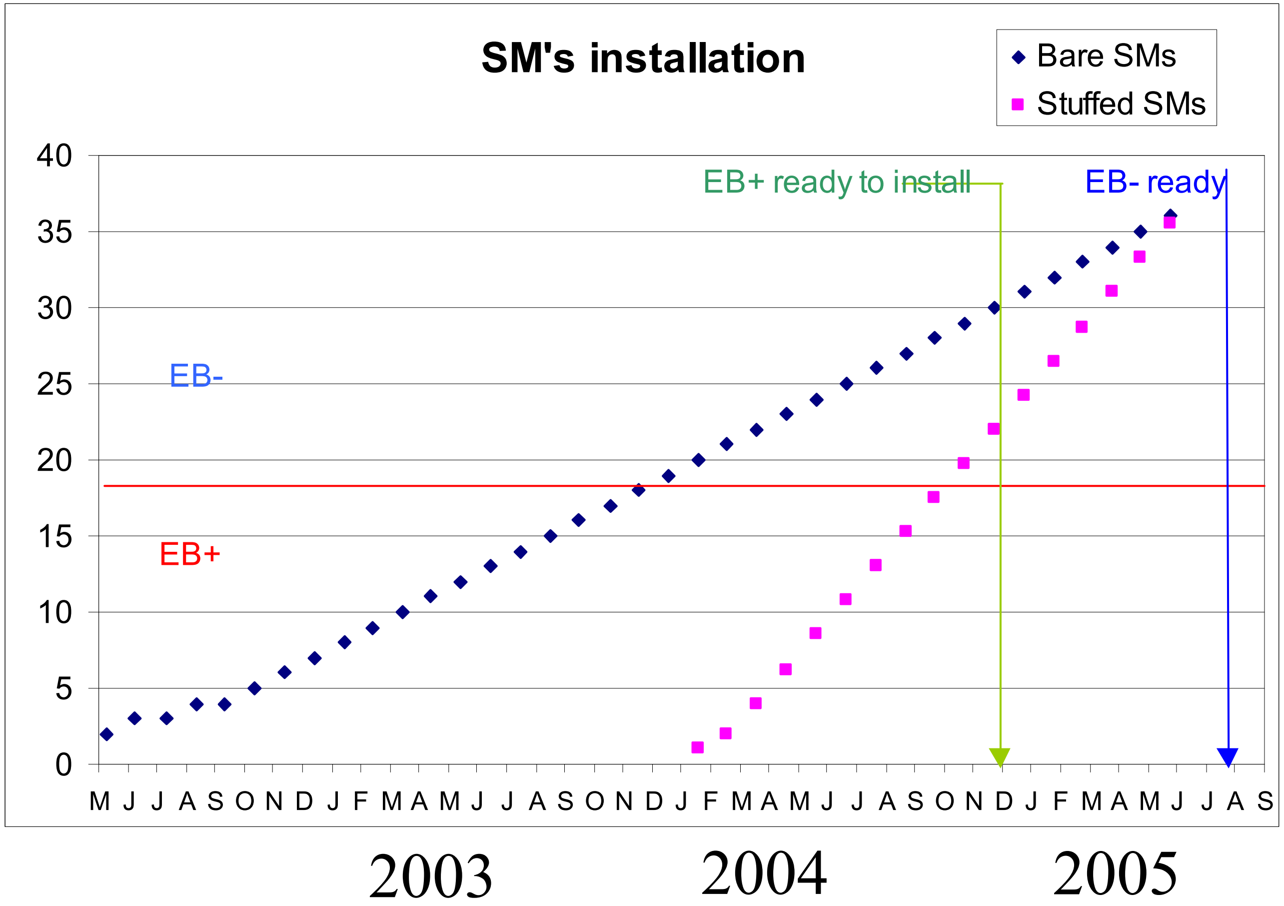




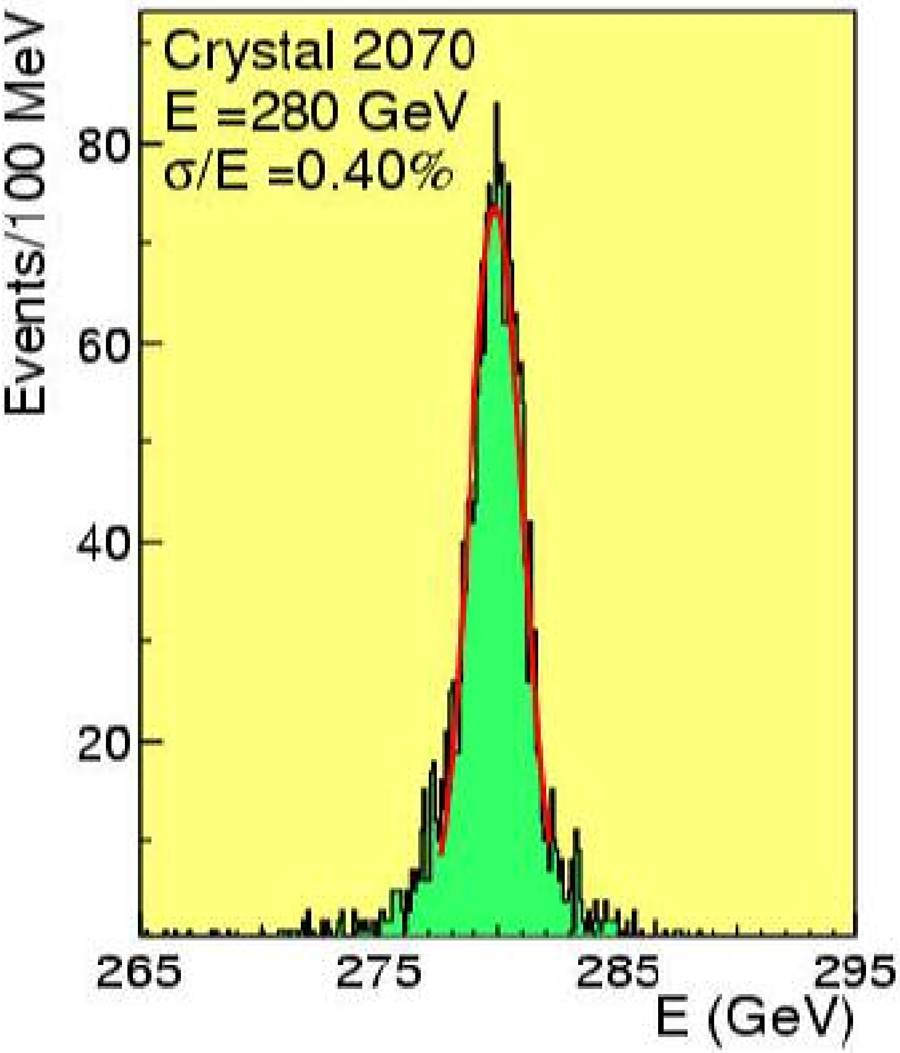
- Reduction of about a factor 8 in the number of data links
- Simplification of off-detector electronics
- Equivalent performances

New construction scheme

Bare/Dressed Super Modules



Design Resolution is achievable



280 GeV electrons:

- no sign of rear leakage, which could cause direct signal in APD

Resolution as a function of energy:

- on 1999 prototype, matrix with 30 preproduction crystals and APDs

$$\frac{\sigma}{E} = \frac{2.74\%}{\sqrt{E}} \oplus 0.40\% \oplus \frac{142\mathrm{MeV}}{E}$$

Energy resolution

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Standard parametrization:

- a: stochastic term from Poisson-like fluctuations
  - sampling contribution (natural advantage of omogeneous calorimeters)
  - intrinsic contribution from photostatistics (⇒ L.Y.)
  - other contributions often important
- b: noise contribution, relevant at low energy
  - electronic noise converted in energy units through N_{pe}/MeV ⇒ b depends on Light Yield too
- c: constant contribution, dominated by stability
  - dangerous limitation to high energy resolution
  - important contribution from calibration constants

Resolution: stocastic term a

- photostatistics contribution, including
  - LY
  - light collection efficiency
  - geometrical efficiency of the photodetector
  - photocatode quantum efficiency

  N_{pe}/GeV = 4000 for 0.5 cm^2 APD → 1.6%
- electron current multiplication in APD, contributing a square root of excess noise factor, F = 2

  1.6×1.4 = 2.25%
- Lateral containment (5×5 matrix) → 1.5%

Total stochastic term a = 2.7 %

Resolution: noise term b

40 ns shaping time, summed over 5x5 channels

- Serial noise (p.d. capacitance) ∝ 1/√t
  - 150 MeV
- Parallel noise (dark current) ∝ √t, mostly radiation induced
  - negligible at the start of the experiment
  - 30 MeV after one year at low luminosity
  - 100 MeV after one year at high luminosity
- Physics pile-up (simulated, with big uncertainties)
  - low luminosity 30 MeV
  - high luminosity 100 MeV

Total contribution

- low luminosity 155 MeV
- high luminosity 210 MeV

Resolution: constant term c

Most dangerous at high energy

- leakage (front, rear, dead material)

  CMS full shower simulation < 0.2 %

- system instabilities designed to be at the permill level $t \sim 3t_{cal}$
  - temperature stabilization < 0.1 °C

    (dLY/dT = -2.0%/°C @ 18°C ; dM/dT ~ -2.3 %/°C)
  - APD bias stable at ±20 mV

    (dM/dV = 3%/V)

Key issues to keep c ~ 0.5 % :

•light collection uniformity

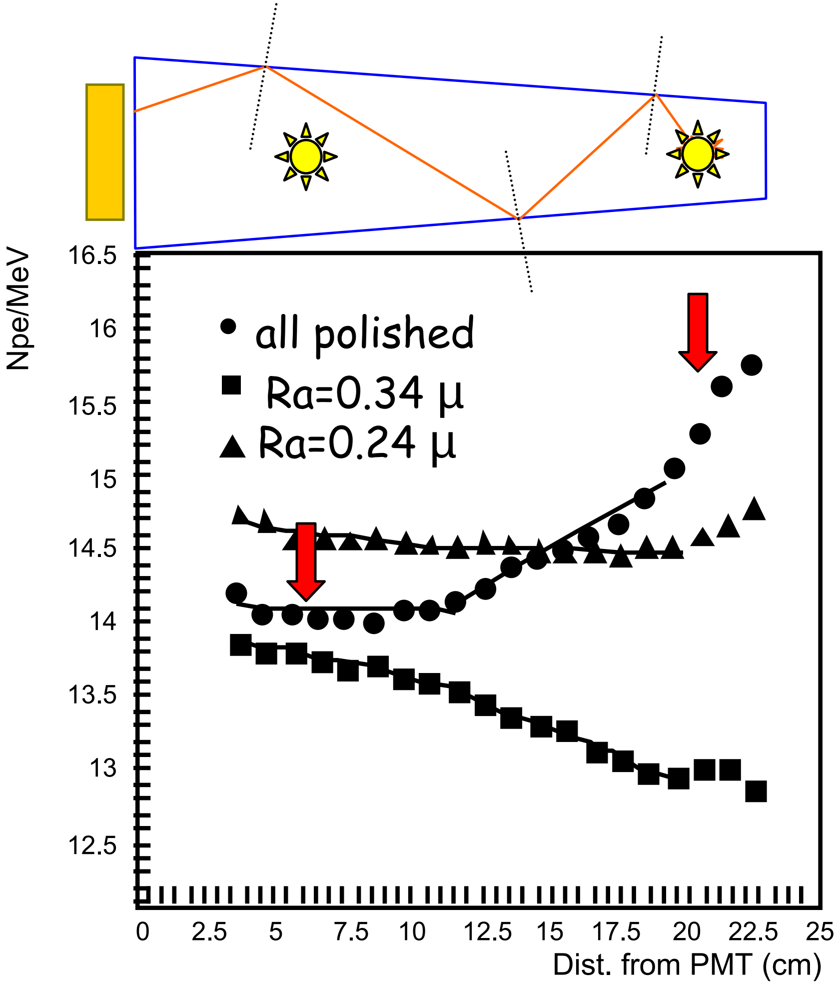
•intercalibration by monitor and physics signals at 0.5 % including the radiation damage effect

Uniformity of light collection

- Focusing effect due to tapered shape of crystals (first seen and studied in L3)
- High index of refraction ($n=2.3$) enhance the effect: $\theta_c \approx 26^o$

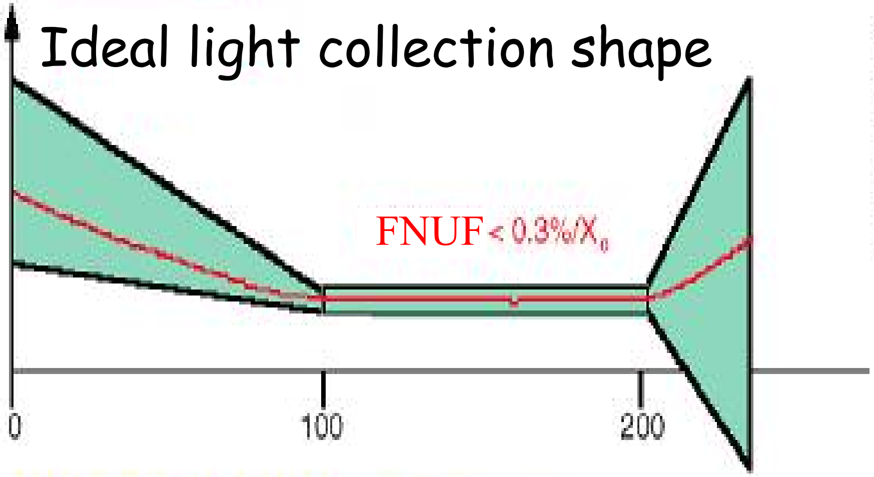
Uniformity can be controlled by depolishing one lateral face with a given roughness

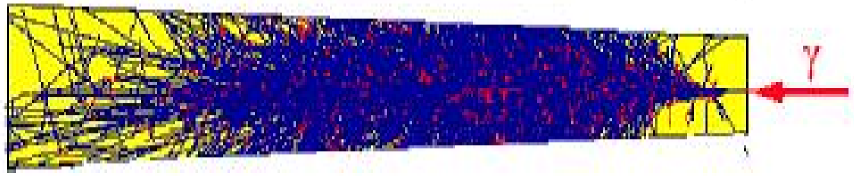
PAY A LOSS IN LY

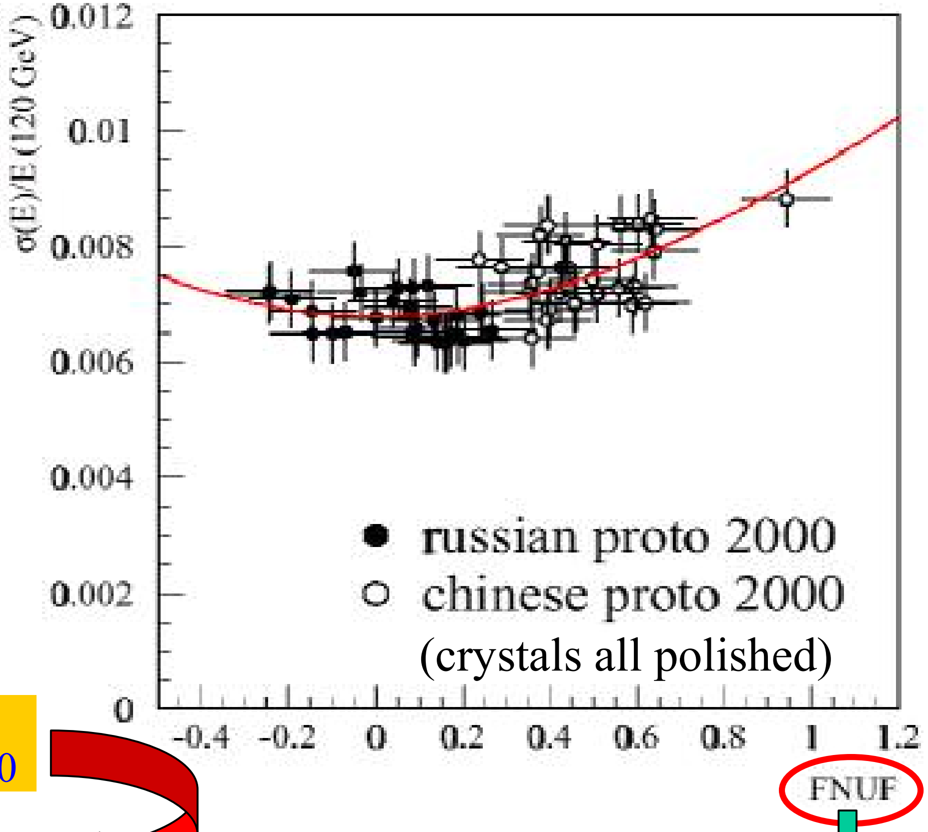


Effect of non uniformity

- A non uniformity of the light collection in the shower max region may significantly contribute to the constant term in the energy resolution







Max Front $d(LY)/dX_0 = \pm 0.35\%/X_0$

$C_{fnuf} < 0.3\%$

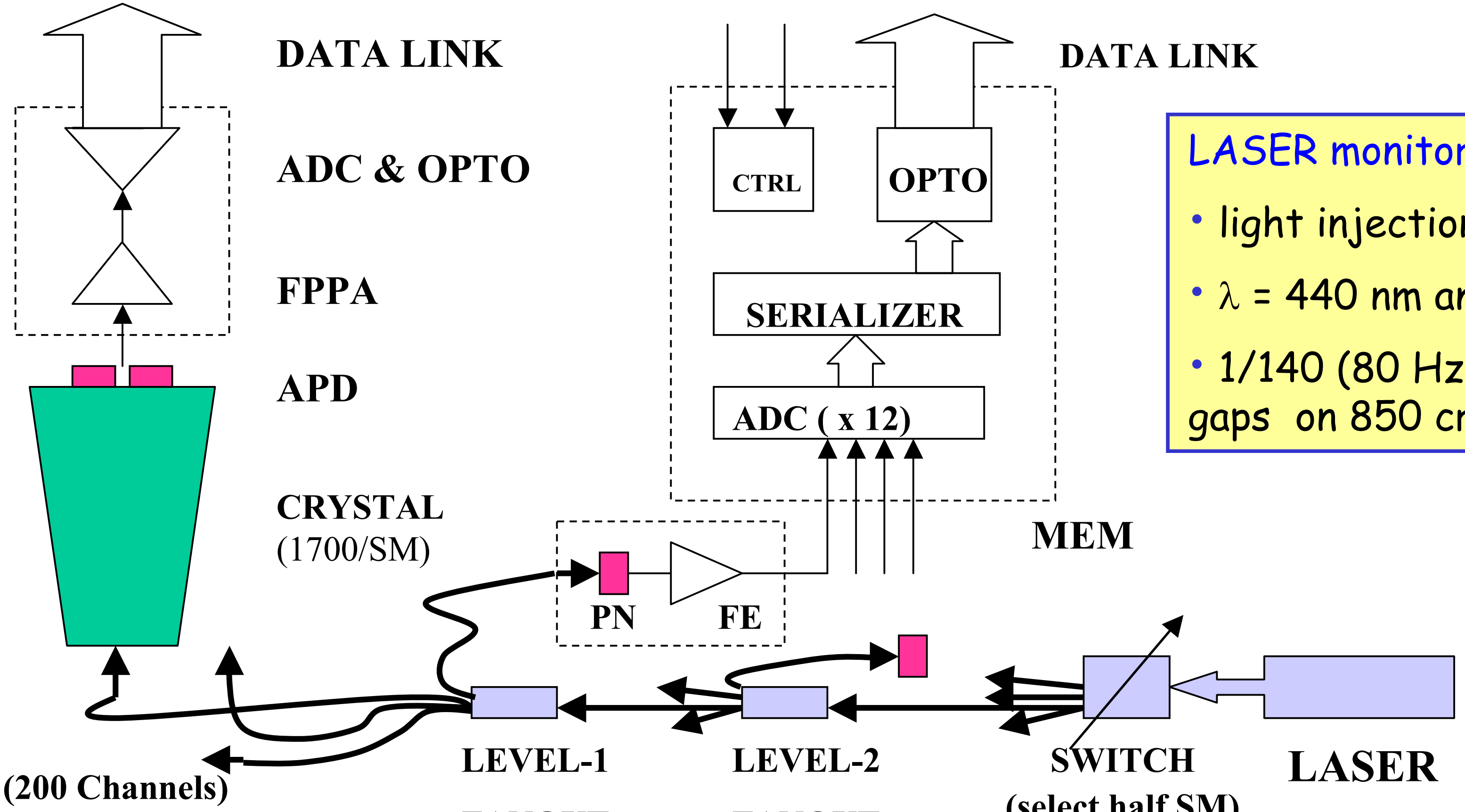
Lab measurement

Calibration & Monitoring system

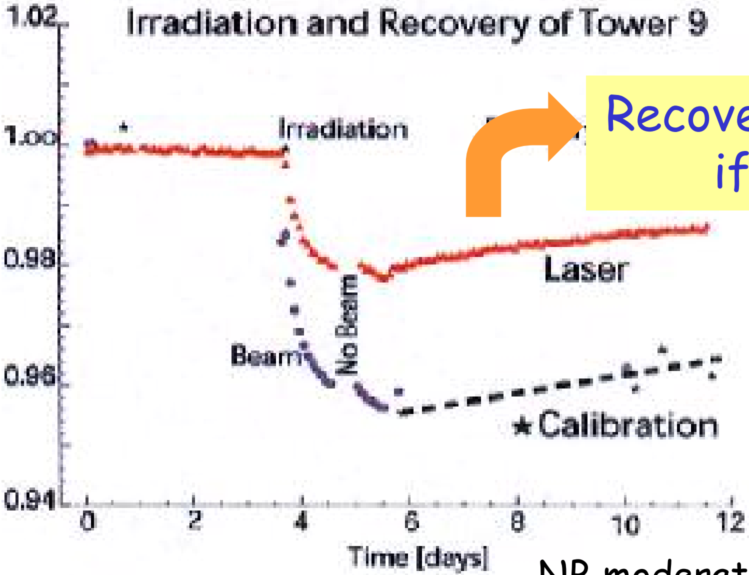
- Initial calibration on test beam (as much crystals as possible)
- In situ calibration with physics events ($W \rightarrow e^+\nu$, $Z \rightarrow e^+e^-$) using E/p from tracker allows at low luminosity in 35 days an intercalibration (single crystal) better than 0.3%.
- Monitoring of response evolution by light injection system

LASER monitoring

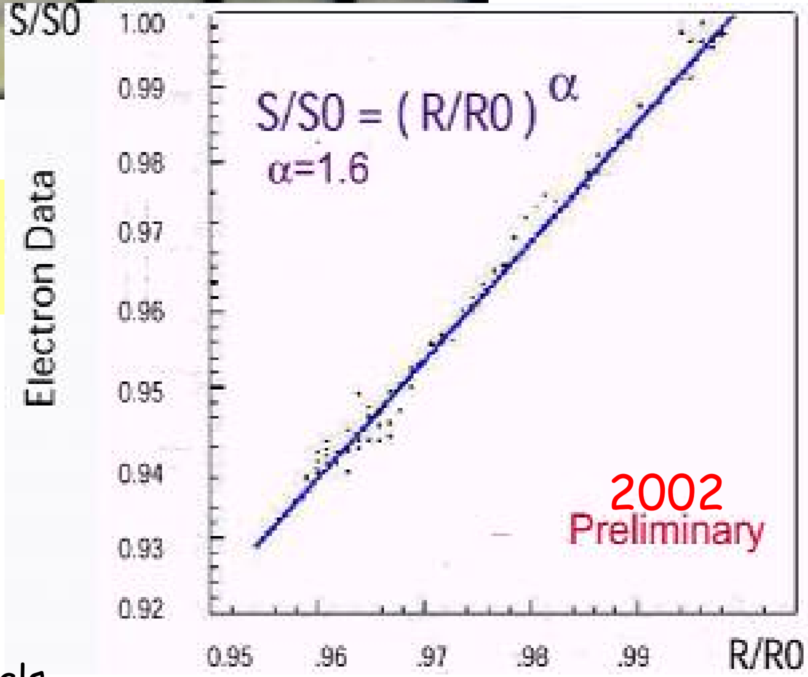
- light injection
- λ = 440 nm and 500 nm
- 1/140 (80 Hz) beam gaps on 850 crystals



Electron vs Light signal



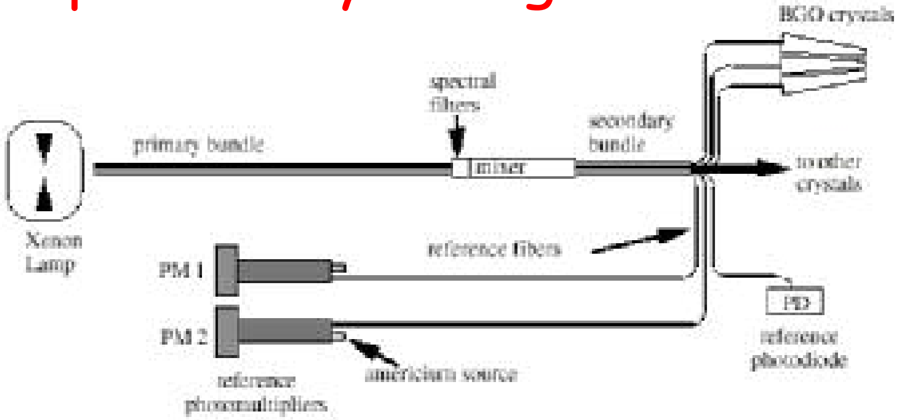
Recovery of damage
if no beam

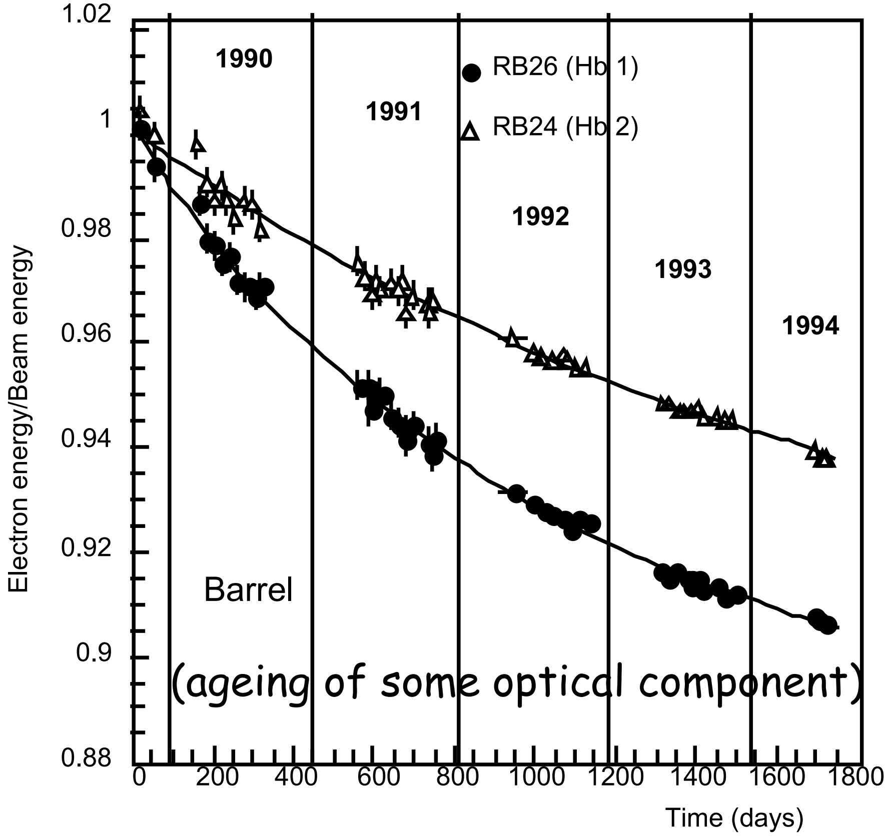


NB moderately rad hard crystals
most suitable for monitoring studies

Monitor: L3 10 years of follow-up

Response may change! Even if not foreseen





(ageing of some optical component)

- system able to track the BGO response decrease (few %/year)
- porting of previous year calibration: 1.3%
- spread after Xe+Bhabha corrections: 0.8% from calibration in 1991

In 1999 0.5% from calibration after refinements of methods

Calibration on test beam

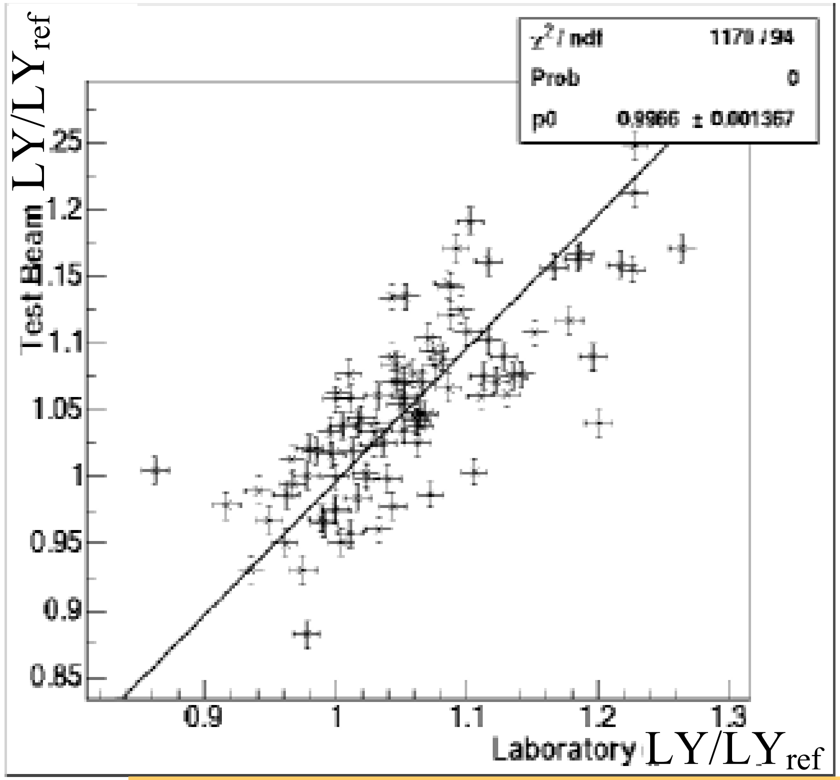
Why pre-calibration of each single channel is desirable?

- Full system test
- Be ready as soon as possible for precision measurement independently from other CMS sub-detectors (precision on intercalibration has a direct impact on the constant term of the energy resolution)

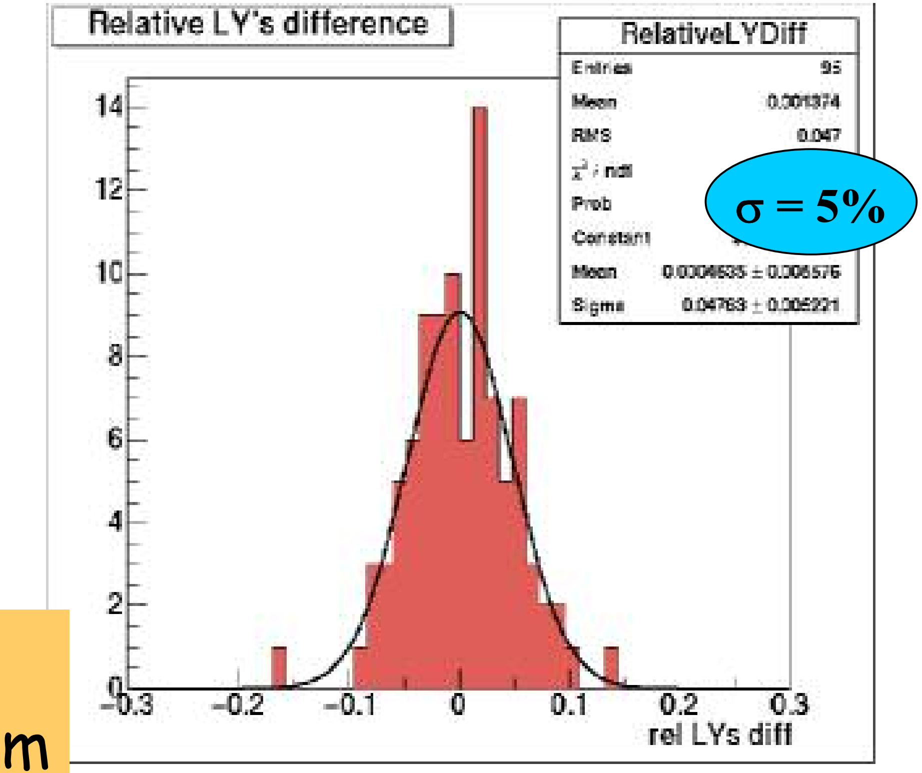
A partial calibration is anyway mandatory to understand

- Geometrical effects (energy deposition depends on η)
- Effects of gaps between crystals, modules
- Thermal stability
- Gain stability in electronics chain
- Monitoring system
- MC simulation in all its aspects
- In situ calibration through reference regions

Compare Intercalibration



Preliminary results on 95 crystals - test beam 2002

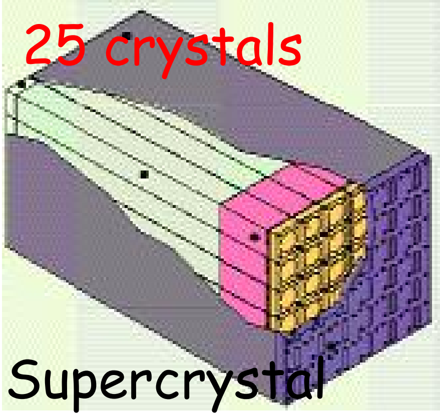


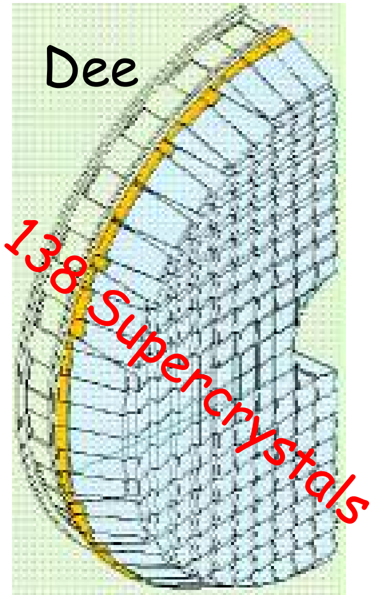
σ = 5%

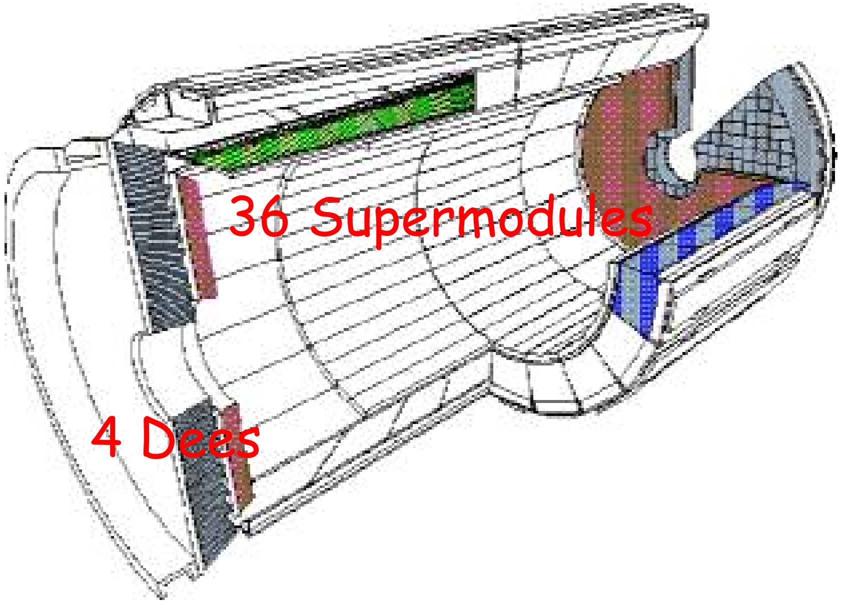
SM not pre-calibrated: intercalibration @ t=0 from RC measurements @ 1MeV with different read-out

ECAL distributed construction

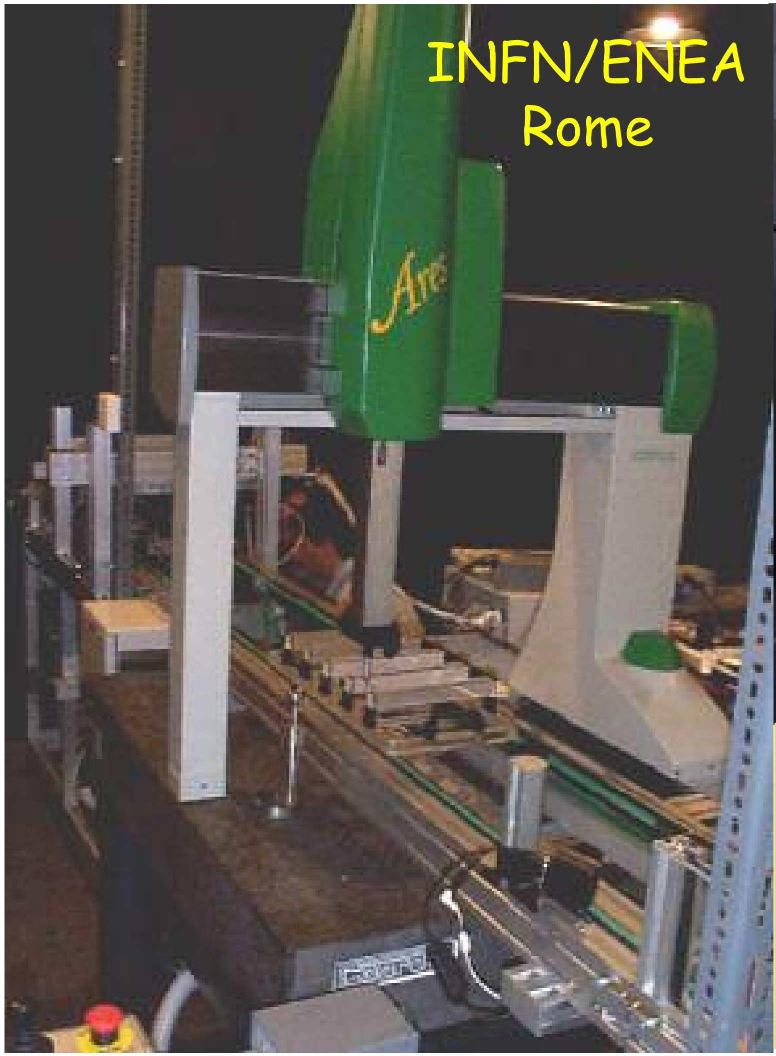
ECAL Regional Centers







Crystal quality insurance



Automatic control of:

- Dimensions
- Transmission (radiation hardness)
- Light yield and uniformity

Module assembly and test

Assemblaggio sottomoduli

Il primo sottomodulo!

Sottomoduli assemblati

Inizio assemblaggio modulo

Il primo modulo!

M. Diemoz – INFN Roma

Transport of modules to CERN

Conclusions

- A challanging project
- Intense and rewording R&D effort performed
- Now in the construction phase
- Few years of construction (→ 2005)
- Few years to understand in detail the system behaviour
- Aiming to outstanding physics results