The Lead Tungstate Calorimeter for CMS

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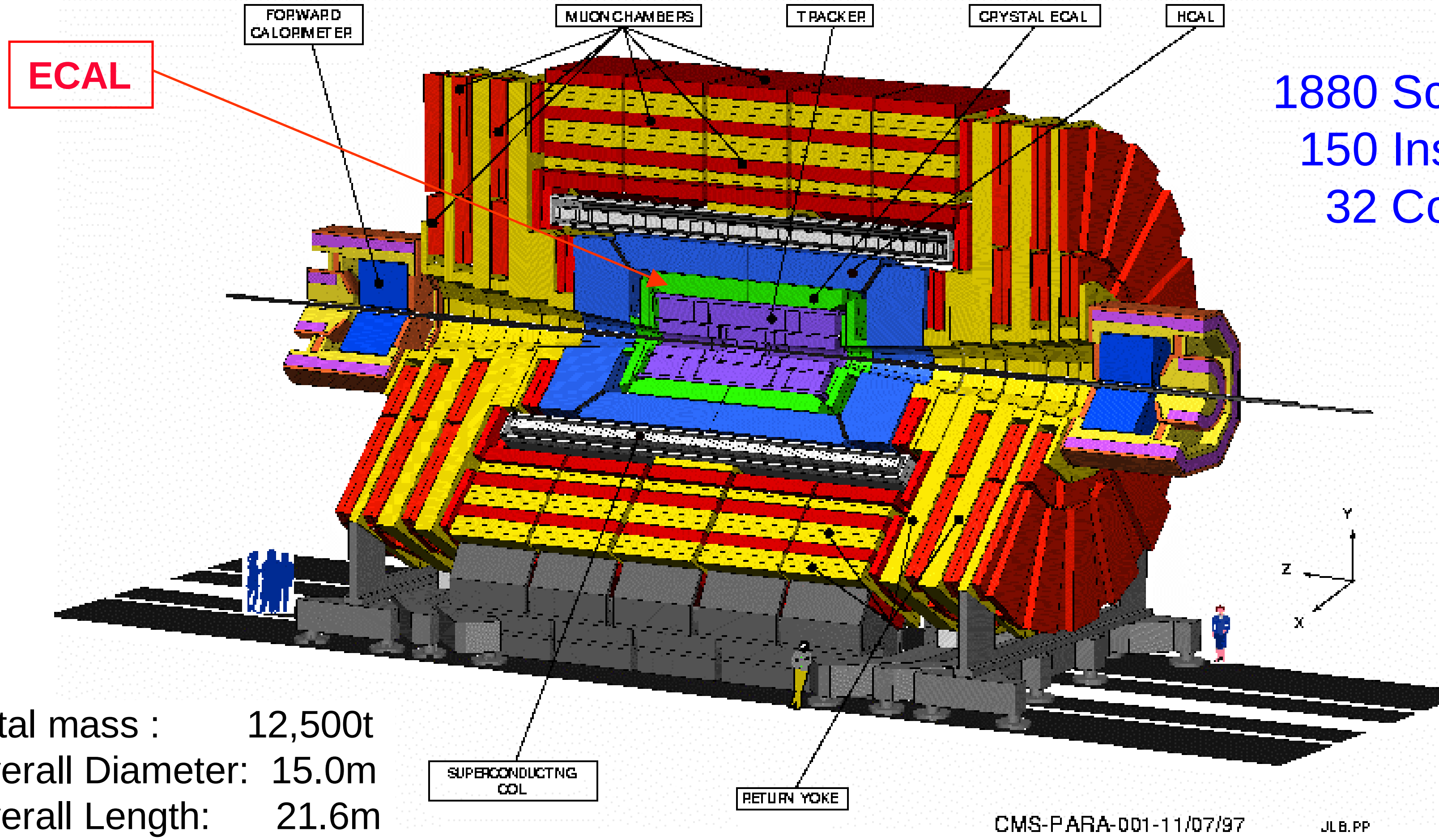
Outline of Talk

- Overview of CMS
- Parameters of the ECAL
- Properties of Lead Tungstate
- Radiation levels
- Crystal production
- Photodetectors: APD, VPT
- Mechanical design
- Preshower detector
- Prototype performance
- Monitoring system
- Electronic readout system
- Status summary

The Compact Muon Solenoid Detector for LHC

Physics goals: SUSY, Higgs, Heavy flavours, heavy ions



1880 Scientists
150 Institutes
32 Countries

Total mass : 12,500t
Overall Diameter: 15.0m
Overall Length: 21.6m
Magnetic field: 4T

ECAL design objectives

High resolution electromagnetic calorimetry is a basic design objective of CMS

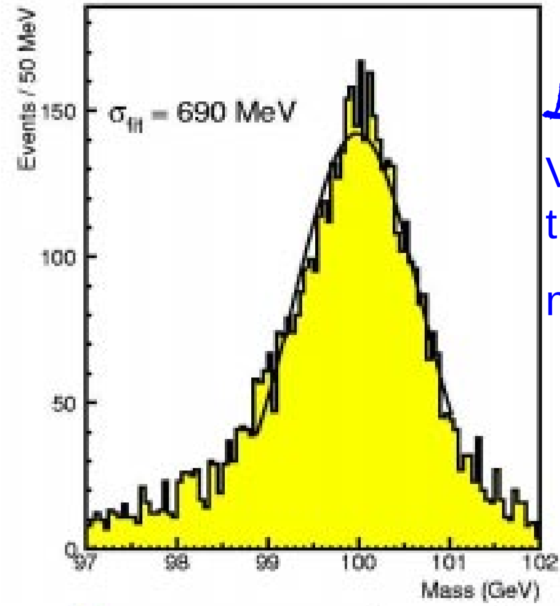
Benchmark physics process:
Sensitivity to a low mass Higgs via $H \rightarrow \gamma\gamma$

$$\sigma_m / m = 0.5 \left[\sigma_{E_1}/E_1 \oplus \sigma_{E_2}/E_2 \oplus \sigma_\theta / \tan(\theta/2) \right]$$

Where $\sigma_E/E = a/\sqrt{E} \oplus b \oplus c/E$

Aim:		Barrel	End cap
Stochastic term:	a =	2.7%	5.7%
(photoelectron statistics/shower fluctuations)			
Constant term:	b =	0.55%	0.55%
(non-uniformities, shower leakage)			
Noise term: Low $\mathcal{L}$	c =	155 MeV	205 MeV
High $\mathcal{L}$		210 MeV	245 MeV

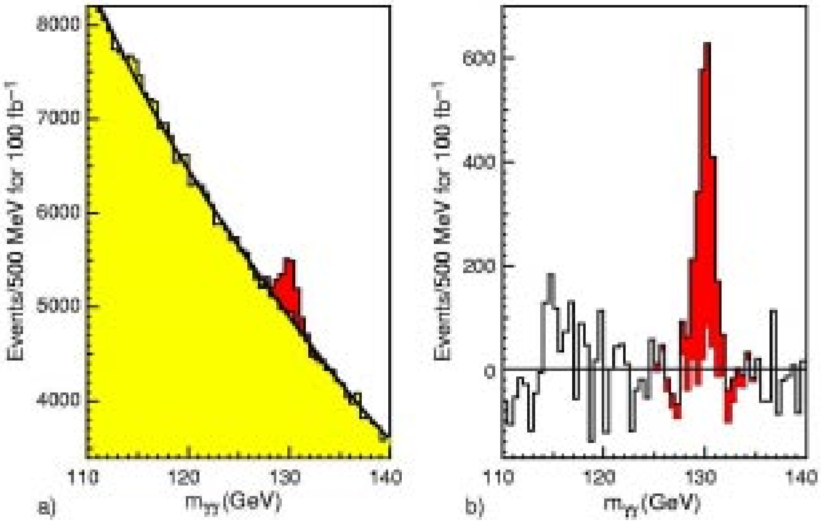
(Angular resolution limited by uncertainty in position of interaction vertex)



$\mathcal{L} = 10^{34}\, cm^2 s^{-1}$

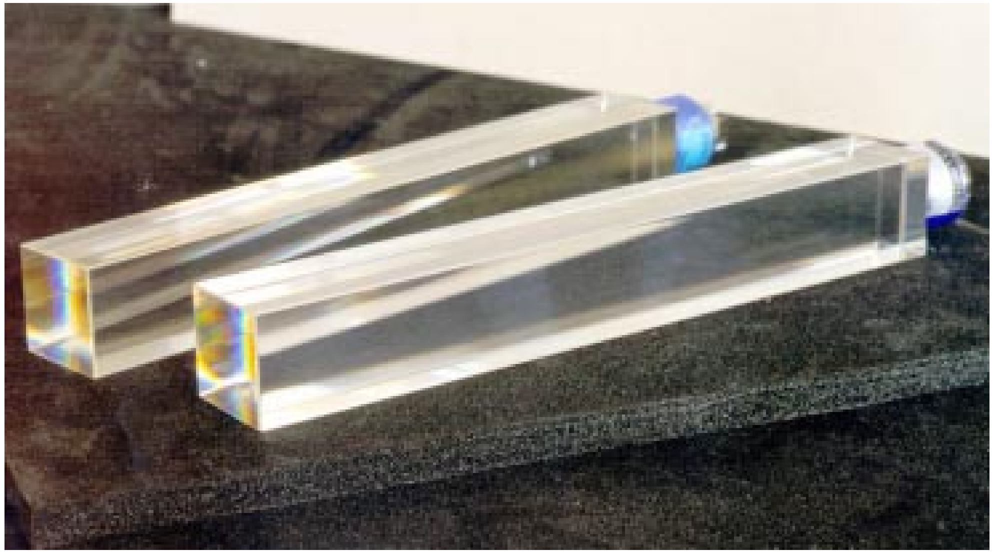
Vertex by track finding

$m_H = 100$ GeV



ECAL design choices

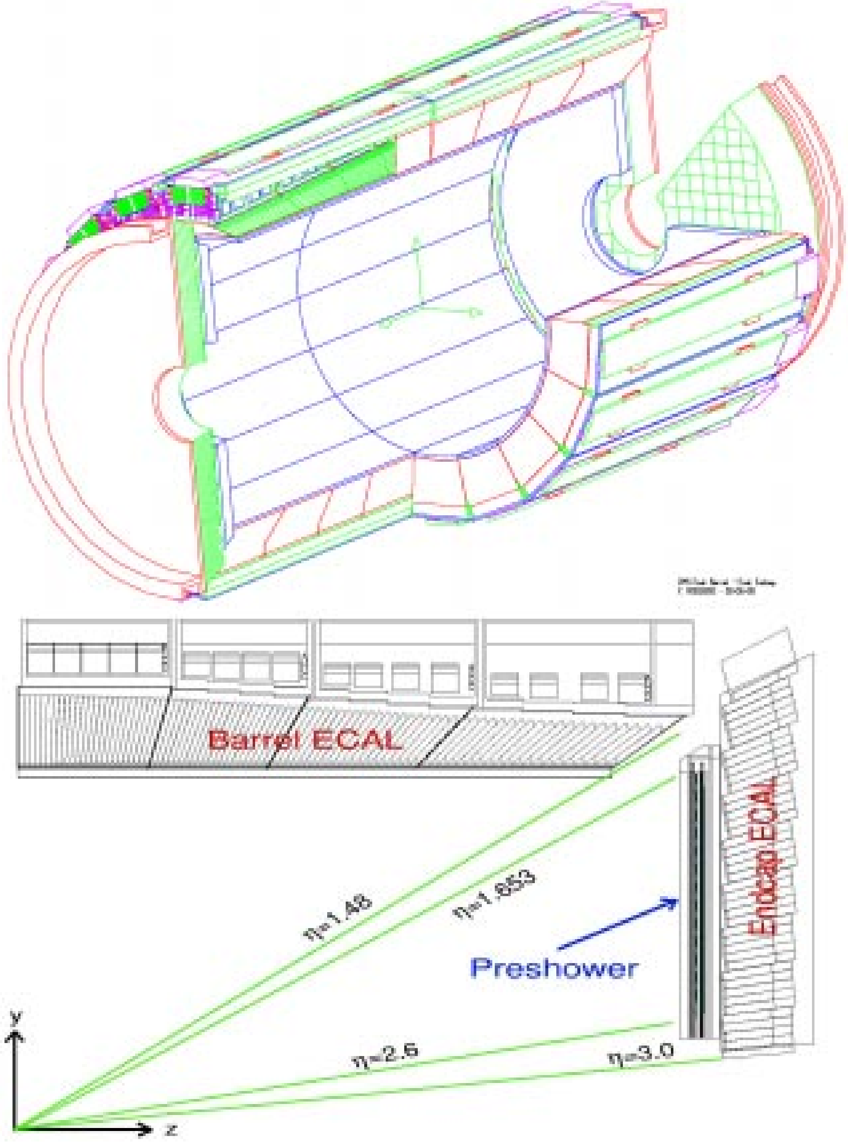
- ECAL (and HCAL) within magnetic vol
- Homogenous active medium ($PbWO_4$)
- Magnetic field-tolerant photodetectors with gain:
  - Avalanche photodiode (APD) for barrel
  - Vacuum phototriode (VPT) for end caps
- Pb/Si Preshower detector in end caps



Properties of dense inorganic scintillators

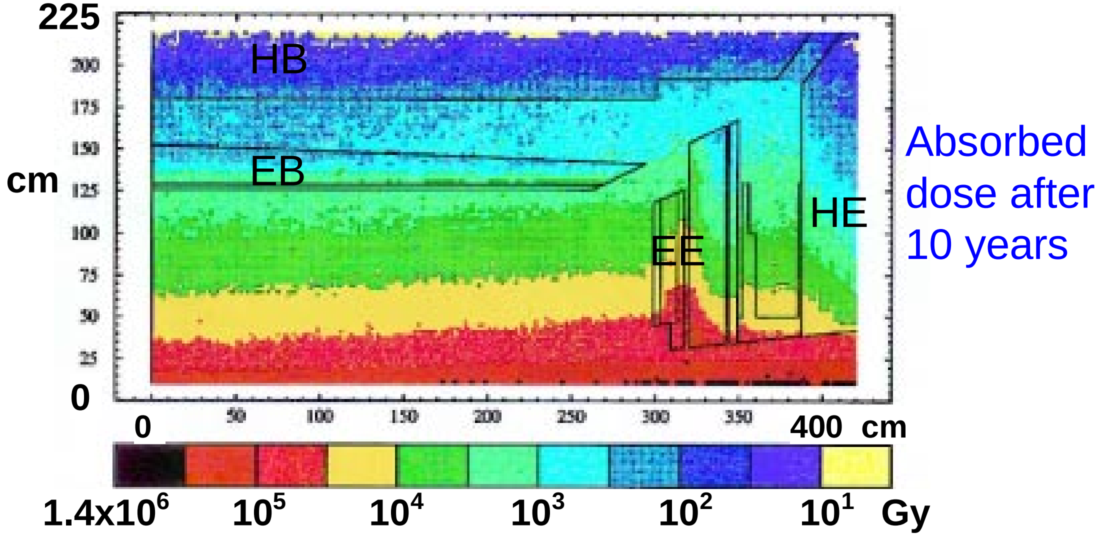
Property	BGO	BaF_2	CeF_3	$PbWO_4$
Density [g/cm^3]	7.13	4.88	6.16	8.28
Rad length [cm]	1.12	2.06	1.68	0.89
Int length [cm]	21.8	29.9	26.2	22.4
Molière rad [cm]	2.33	3.39	2.63	2.19
Decay time [ns]	60 300	0.9 630	8 25	5(39%) 15(60%) 100(1%)
Refractive index	2.15	1.49	1.62	2.30
Max emiss [nm]	480	210 310	300 340	420
Temp coef [%/ºC]	-1.6	0 -2	0.14	-2
Rel light yield	18	4 20	8	1.3

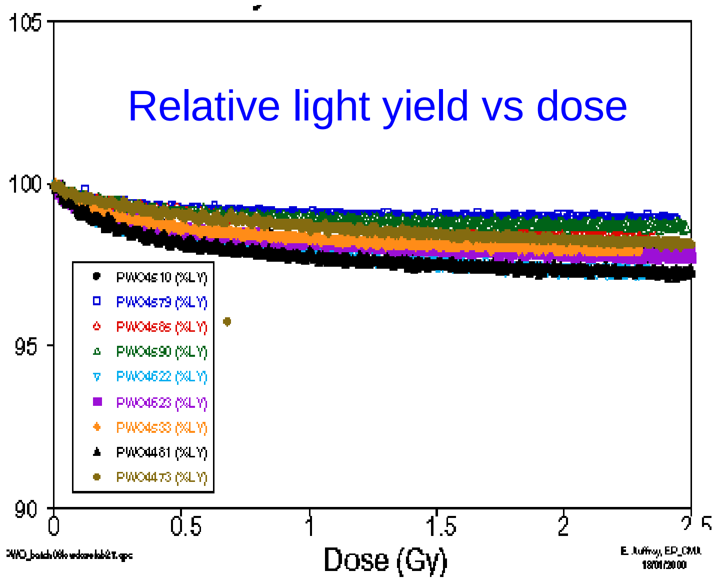
ECAL Parameters

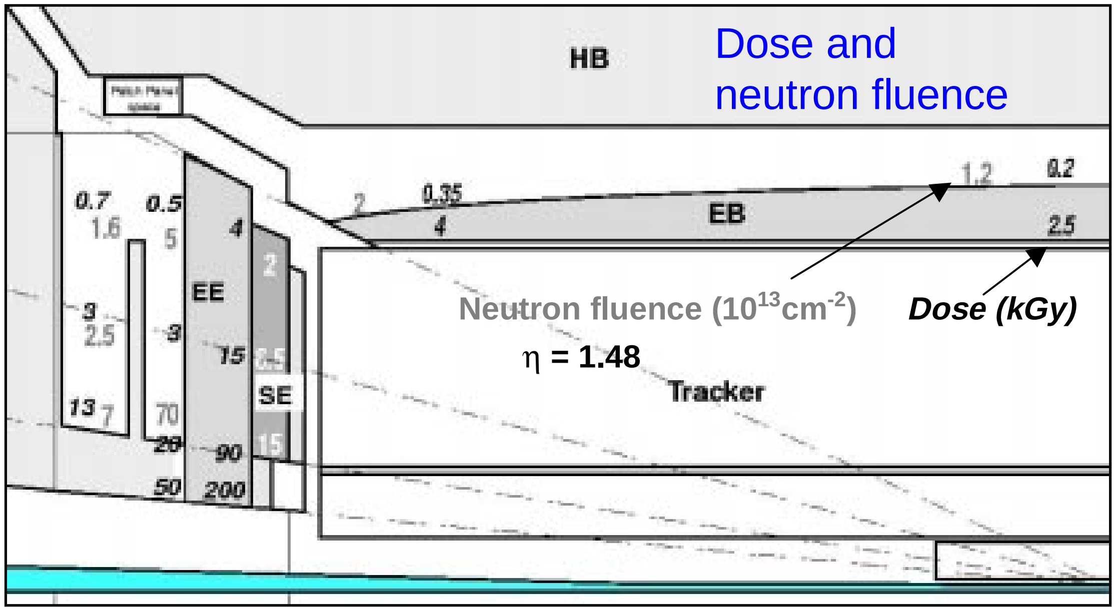


Parameter	Barrel	End caps
Coverage	$\lvert\eta\rvert < 1.48$	$1.48 < \lvert\eta\rvert < 3.0$
R_1, R_0 (mm)	1238, 1750	316, 1711
z_1, z_0 (mm)	0, ± 3045	± 3170, ± 3900
$\Delta\varphi$ x $\Delta\eta$	0.0175 × 0.0175	0.0175 × 0.0175 to 0.05 × 0.05
Xtal size (mm^3)	21.8 × 21.8 × 230	30.0 × 30.0 × 220
Depth in X_0	25.8	24.7
Off-pointing	3^{O}	3^{O}
N. crystals	61200	16000
Volume (m^3)	8.14	3.02
Xtal mass (t)	67.4	25.0
Modularity	36 supermodules	4 Dees
Crystals	1700/supermodule 20 in φ 85 in η	4000 per Dee

Radiation levels in ECAL



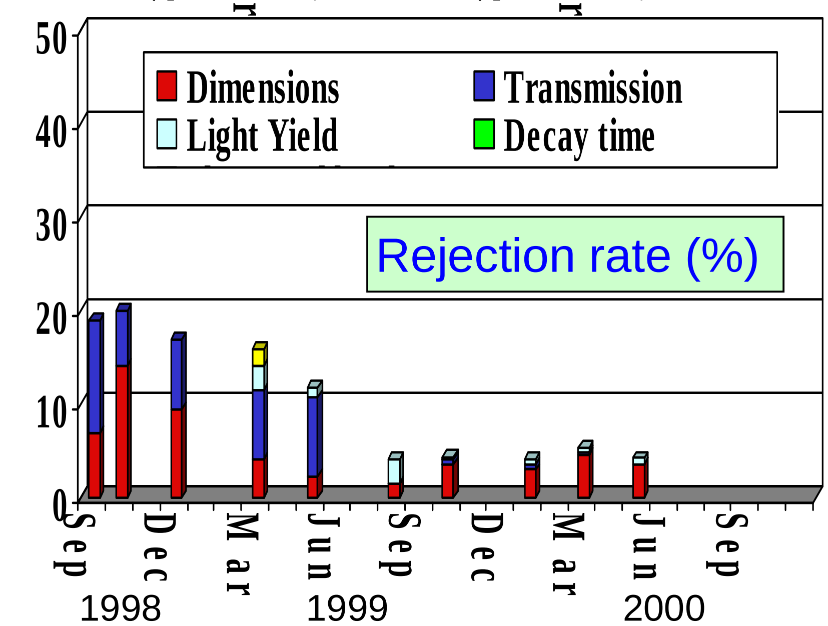




Effect of radiation on $PbWO_4$
(after intense R&D)

- No change in scintillation properties
- Small loss in transmission through formation of colour centres
- Damage saturates
- Slow self-annealing occurs
- Loss in light yield of a few percent corrected with monitoring system
- No damage observed with neutrons

Crystal production



Russia (Czochralski)

Preproduction (6 000): 5000 delivered so far

Production (30 000): Order placed
Delivery starts this year

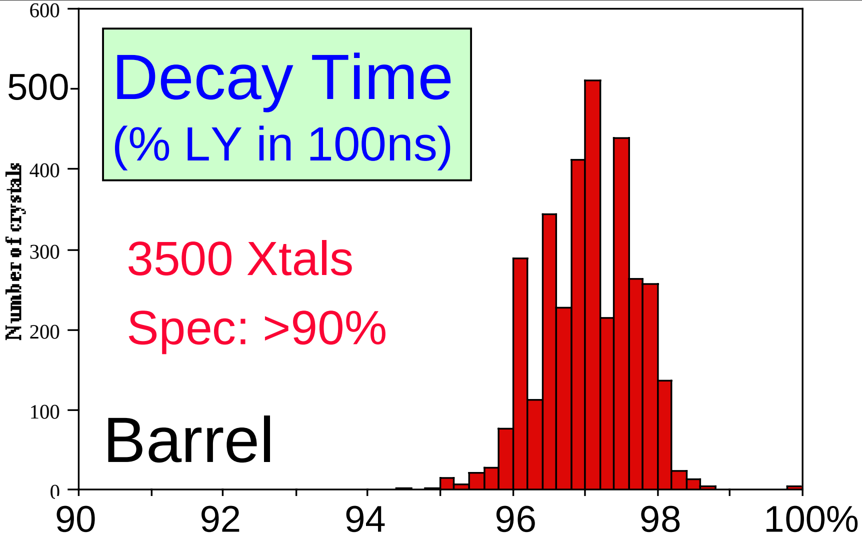
China (modified Bridgman-Stockbarger)

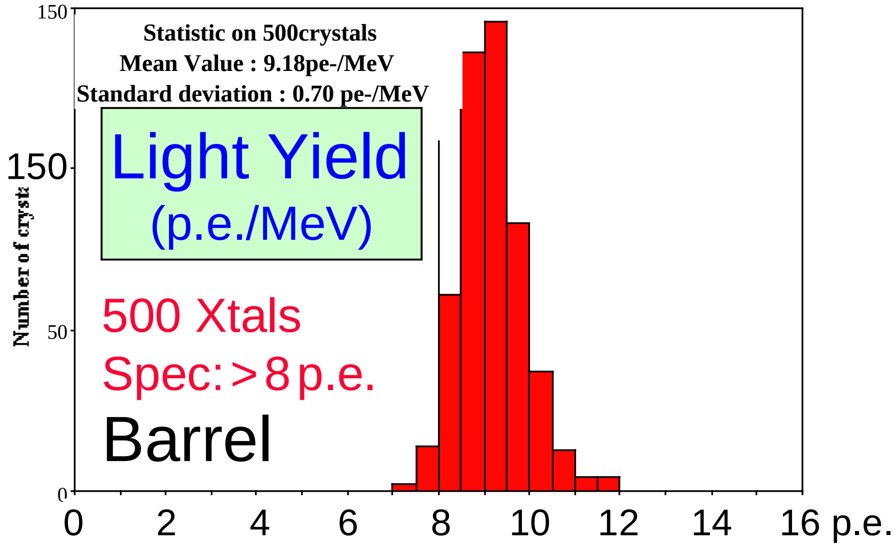
R&D phase advanced

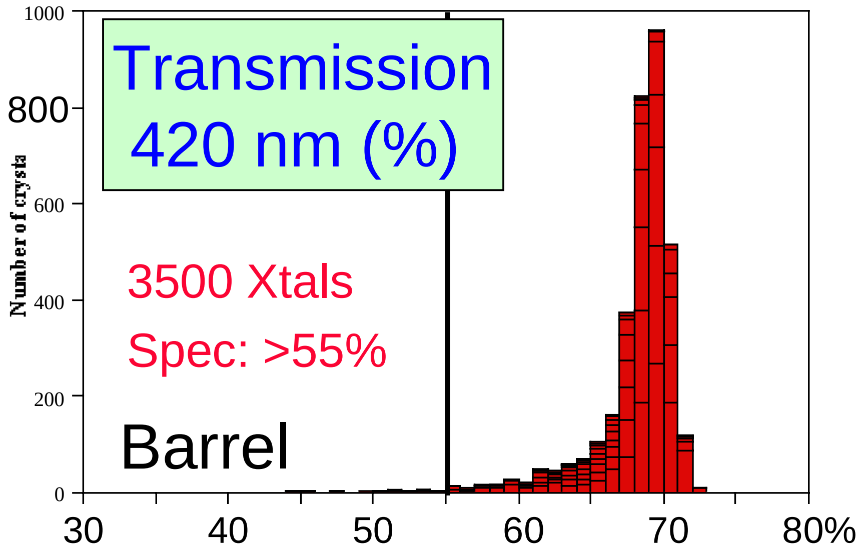
Preproduction: Planned start at end of 2000

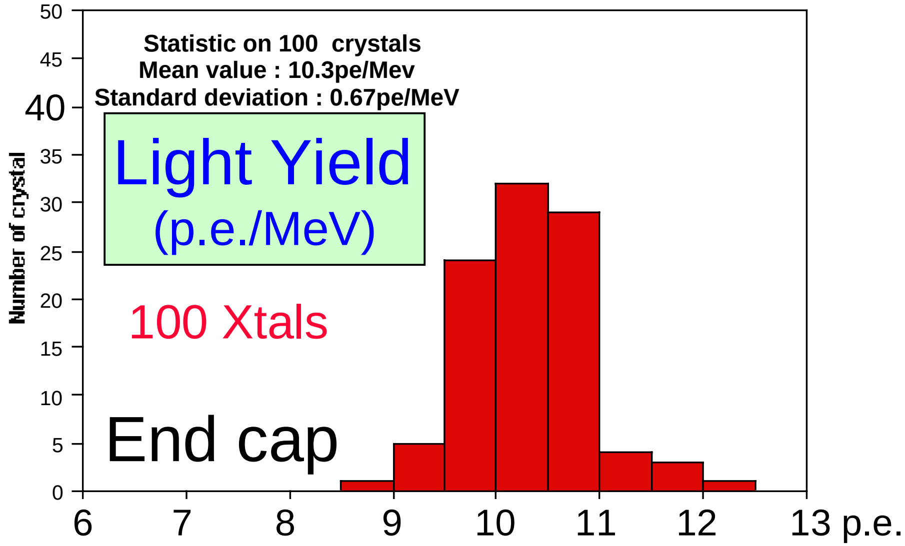
Production: Planned start in 2001

Distributions of Crystal properties







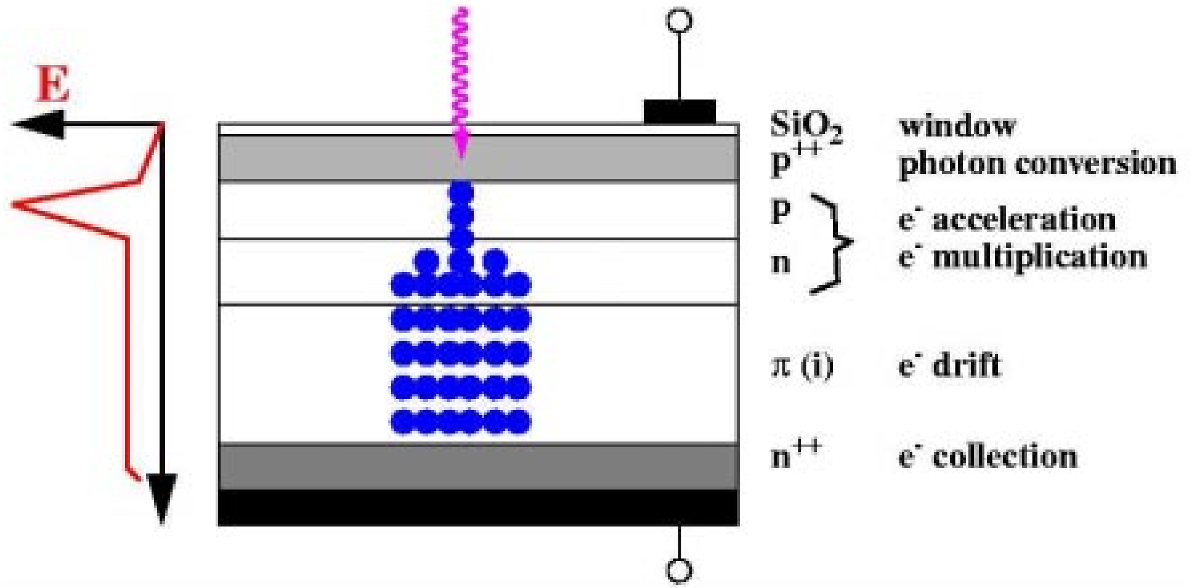


Photodetectors: barrel

Avalanche photodiodes (APD)

- Operated at a gain of 50
- Active area of 2 x 25mm^2/crystal
- Q.E. ~ 80% for $PbWO_4$ emission
- Excess noise factor is F = 2.2
- Insensitive to shower leakage particles (d_{eff} ~ 6 μm)
- Irradiation causes bulk leakage current to increase

➔ electronic noise doubles after 10 yrs - **acceptable**



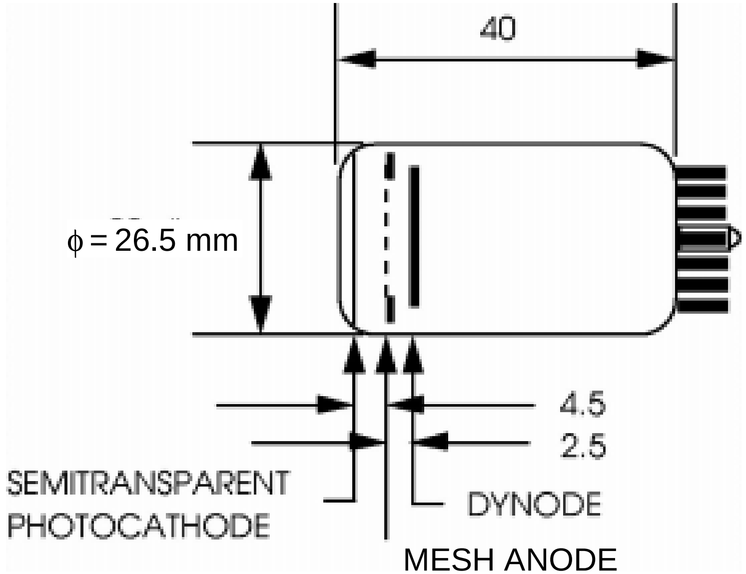
Delivery from Hamamatsu starts this year

Photodetectors: end caps

Vacuum Phototriodes (VPT)

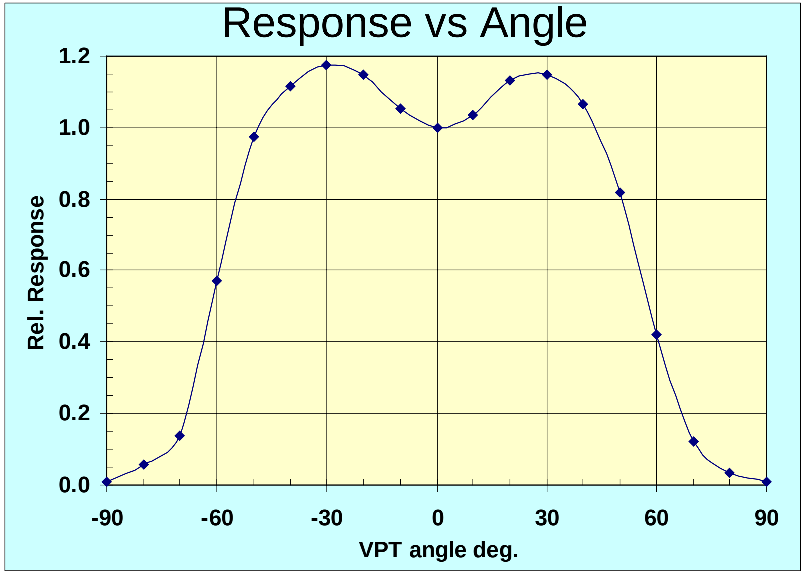
B-field orientation in end caps favourable for VPTs (Tube axes $8.5^o < |\theta| < 25.5^o$ with respect to field)
Vacuum devices offer greater radiation hardness than Si diodes

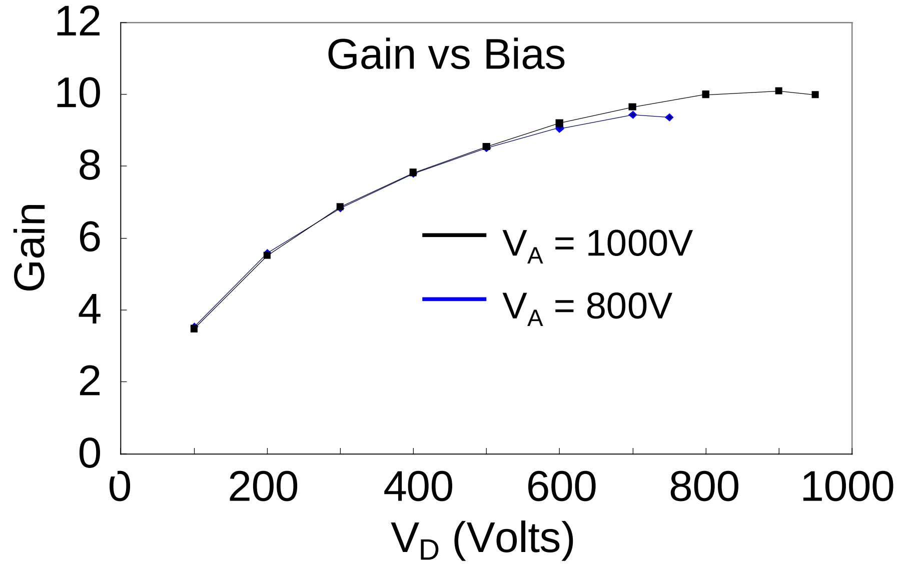
- Gain 8 - 10 at B = 4 T
- Active area of ~ 280 mm^2/crystal
- Q.E. ~ 20% at 420 nm
- Excess noise factor is F ~ 3
- Insensitive to shower leakage particles
- UV glass window - less expensive than ‘quartz’
  - more radiation resistant than borosilicate glass
- Irradiation causes darkening of window
  ➔ Loss in response < 20% after 10 yrs - **acceptable**

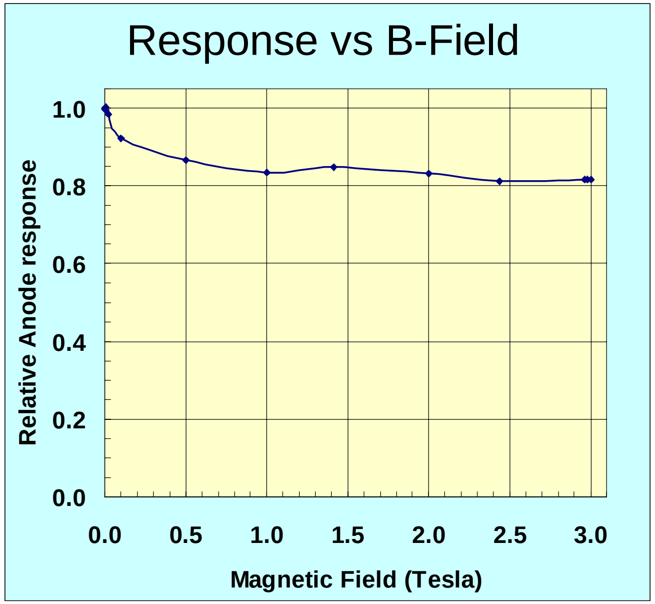


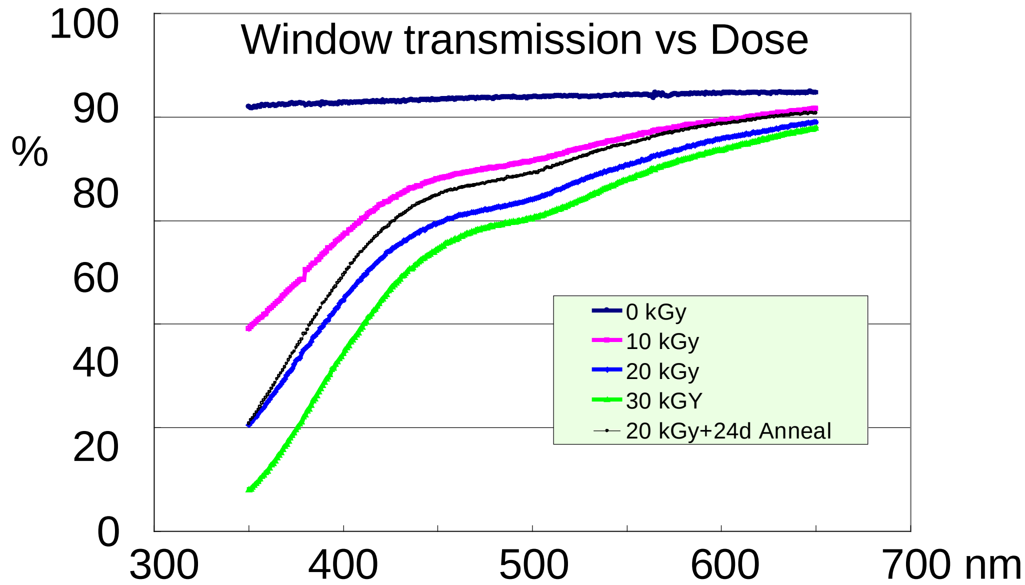
Pilot order placed with RIE (St Petersburg):
100 devices delivered so far and under test

VPT Characteristics





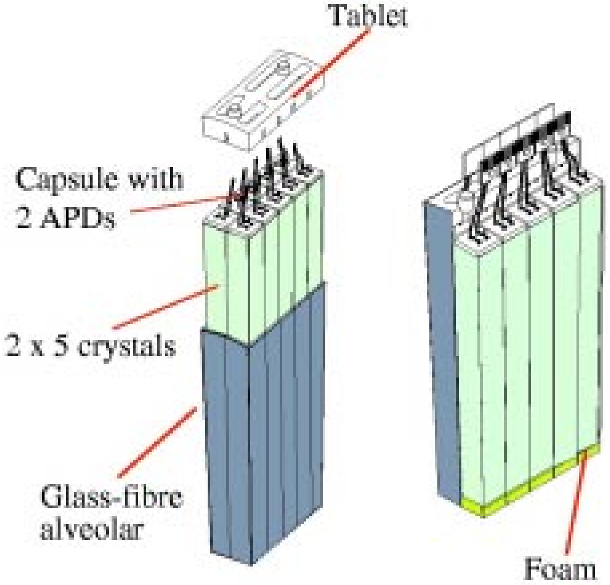


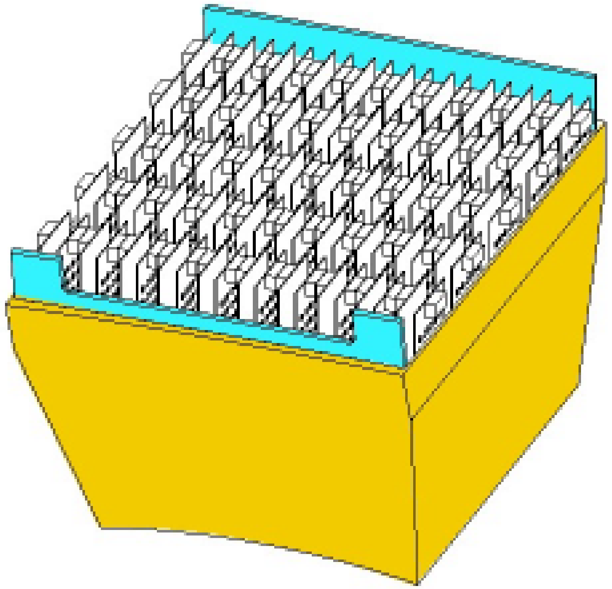


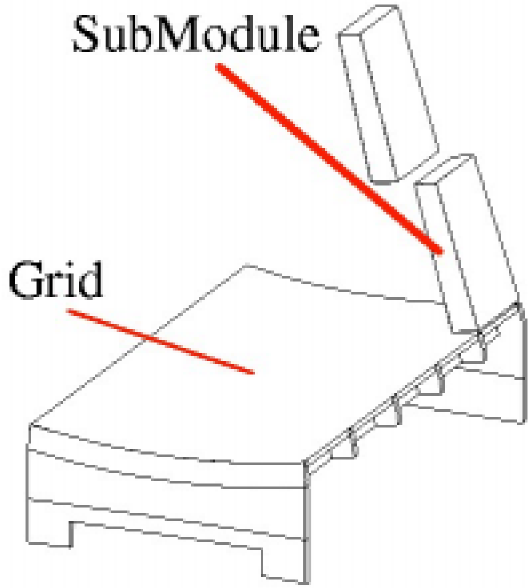
Construction: barrel

Submodule: 2x5 Xtals with APD and FE electronics in 200µm glass fibre alveola

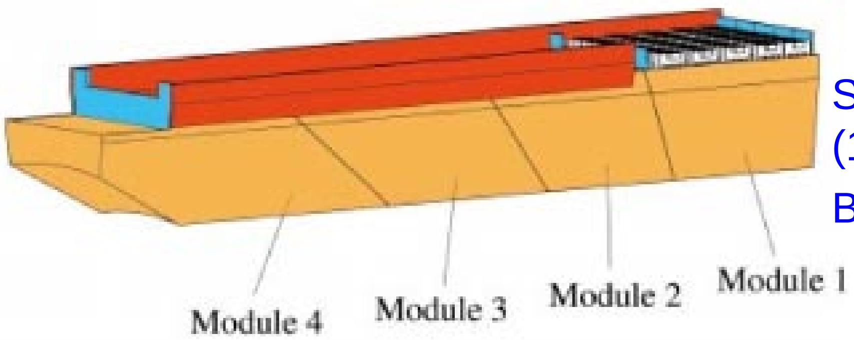
Module: 10x4 or 10x5 submodules mounted on a 'Grid', inside a 'basket'







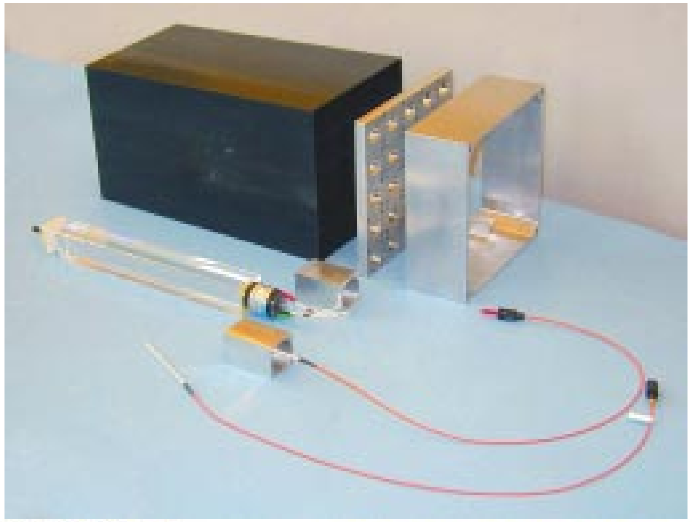
Assembled Submodules



Supermodule: 4 Modules (1700 Xtals)

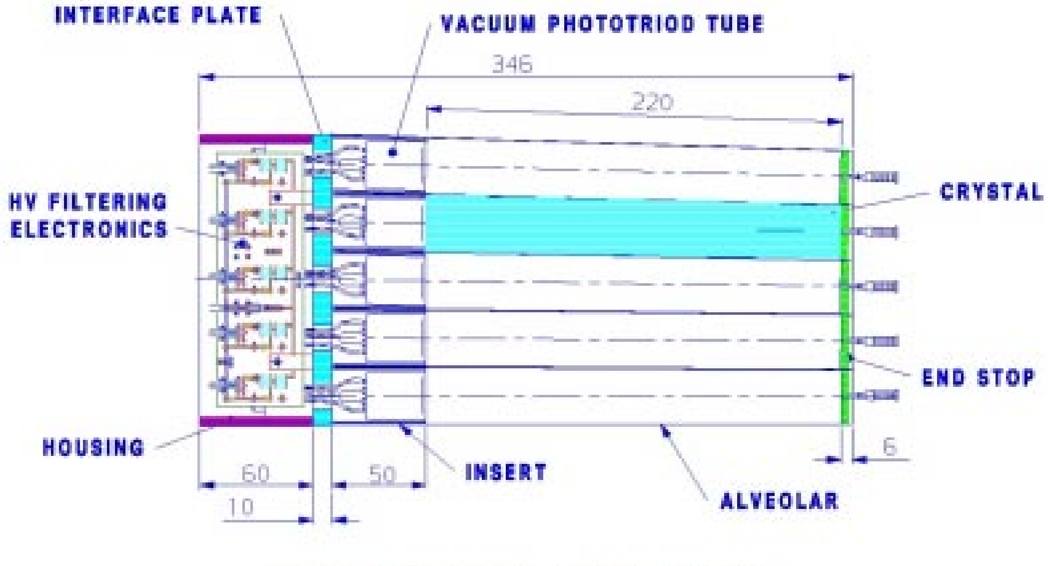
Barrel = 36 Supermodules

Construction: end caps

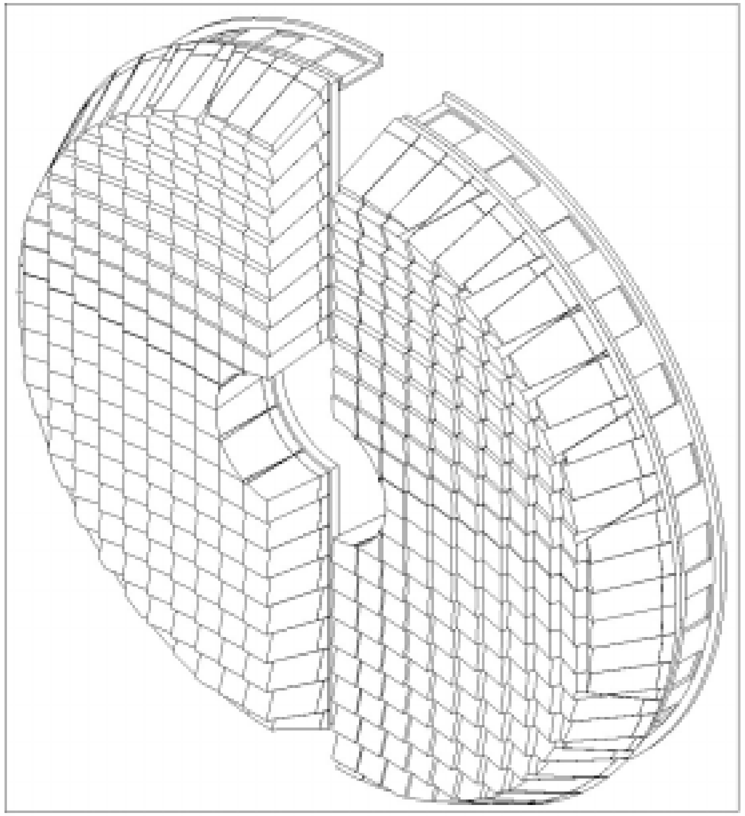


‘**Supercrystal**’: carbon-fibre alveola containing 5x5 tapered crystals + VPTs + HV filter

- 160 Supercrystals per **Dee**
- All crystals have identical dimensions
- All Supercrystals are identical (apart from inner and outer circumference)



SUPER CRYSTAL SIDE VIEW



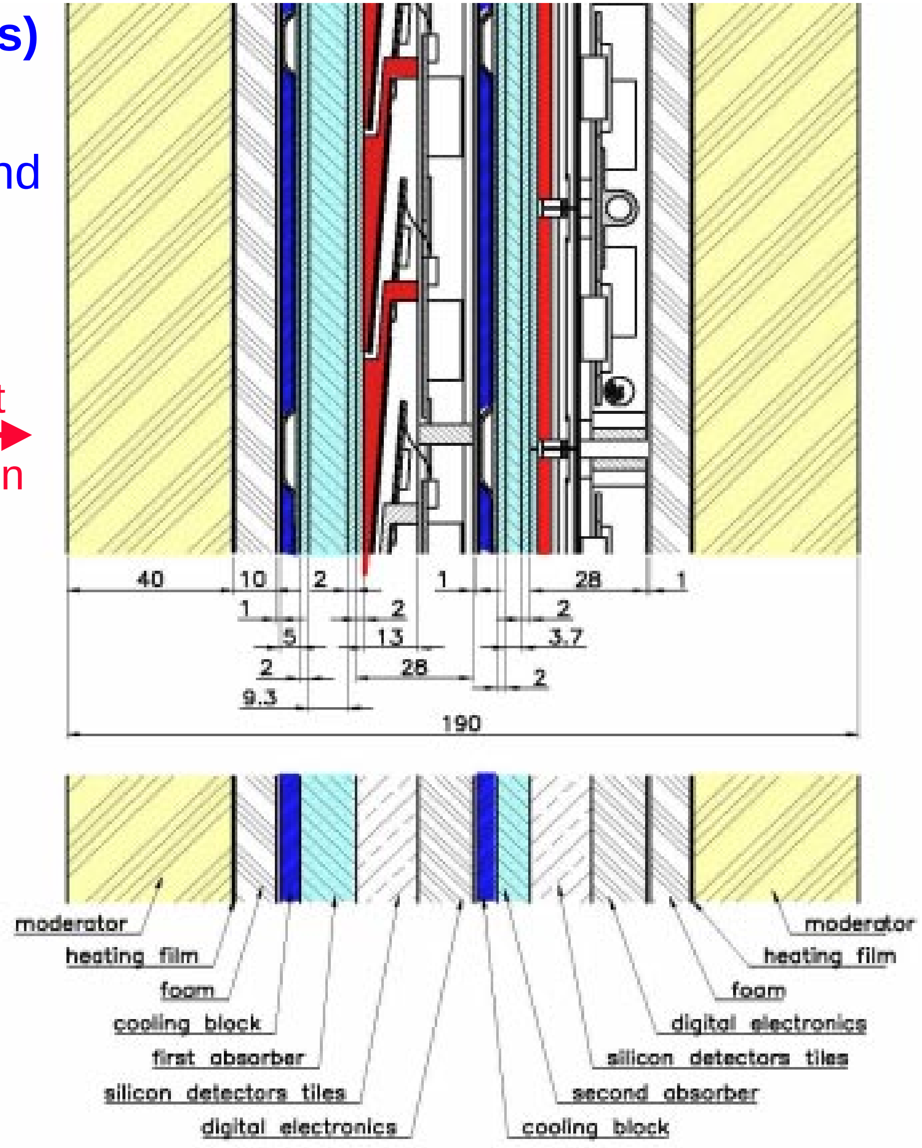
Preshower detector

Rapidity coverage: $1.65 < |\eta| < 2.6$ (End caps)

Motivation: Improved π^0/γ discrimination

- 2 orthogonal planes of Si strip detectors behind 2 X_0 and 1 X_0 Pb respectively
- Strip pitch: 1.9 mm (60 mm long)
- Area: 16.5 m^2 (4300 detectors, 1.4×10^5 channels)

Incident → Direction



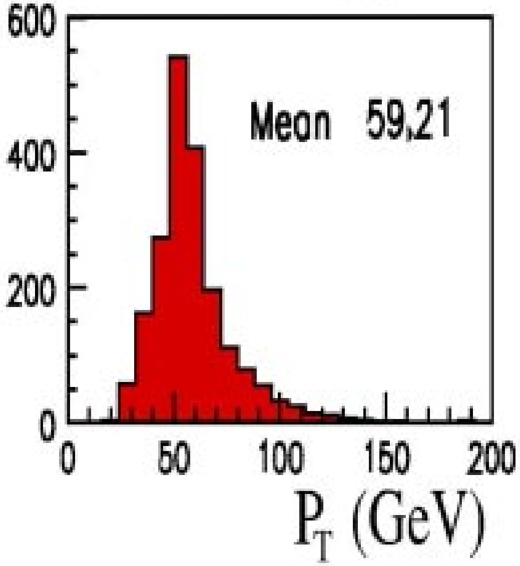
High radiation levels - Dose after 10 years:

- ~ 2×10^{14} n/cm^2
- ~ 60 kGy

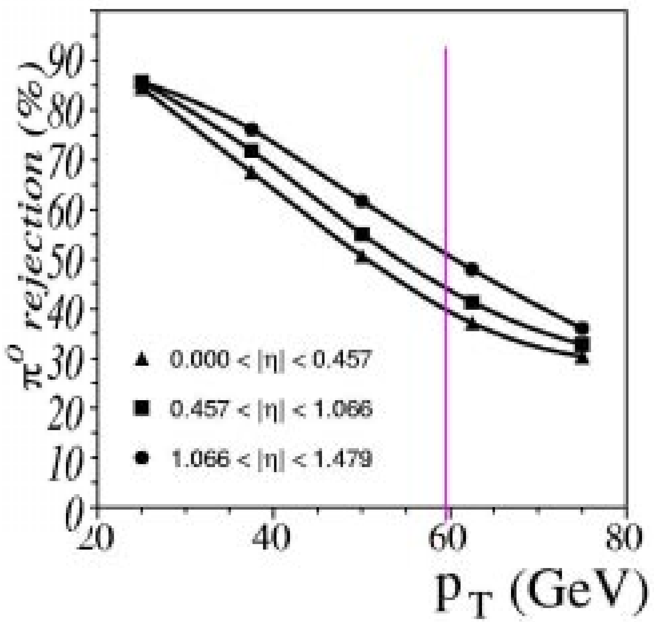
➔ **Operate at -10^{o}C**

π^0/γ Discrimination

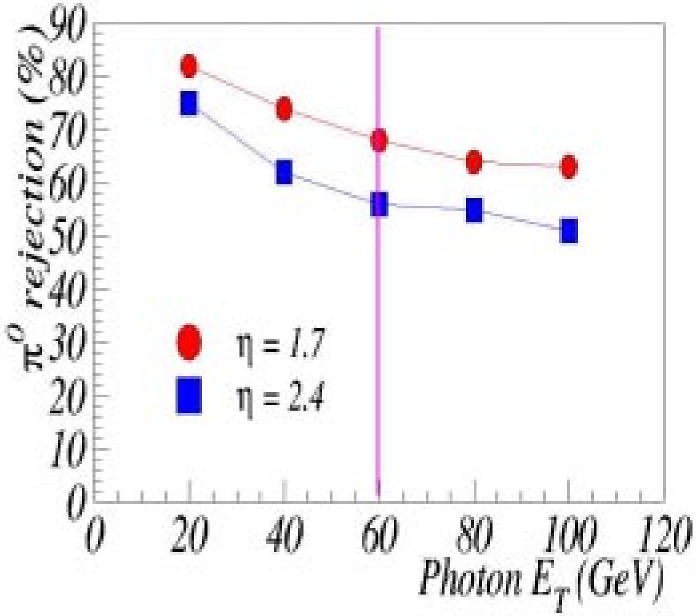
Photon P_T from 110 GeV Higgs



Barrel - use Crystals



Endcaps - use Preshower



(γ-jet) is potentially the most serious background to $H \rightarrow \gamma\gamma$

Track isolation cut reduces (γ-jet) to ≈ 50% of the intrinsic (γ-γ) background (p_T cut = 2GeV/c)

Use π^0/γ discrimination in the ECAL to gain an extra margin of safety

Barrel: Lateral shower shape in crystals (limited by crystal size at high E_{π^0})

End cap: Cluster separation in preshower (limited by shower fluctuations at $3X_0$)

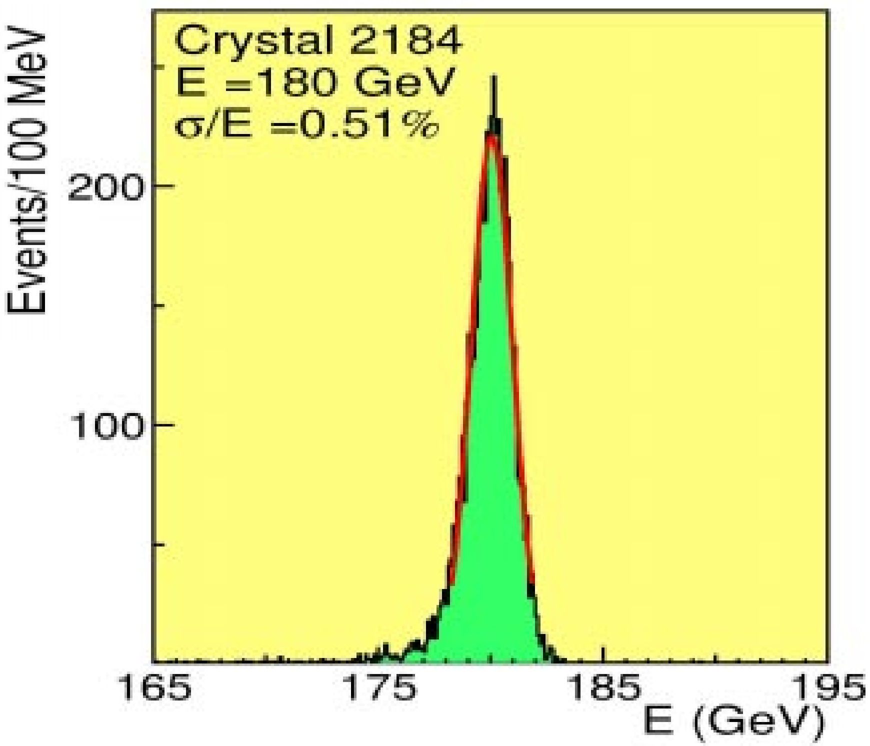
Test beam:Energy Resolution

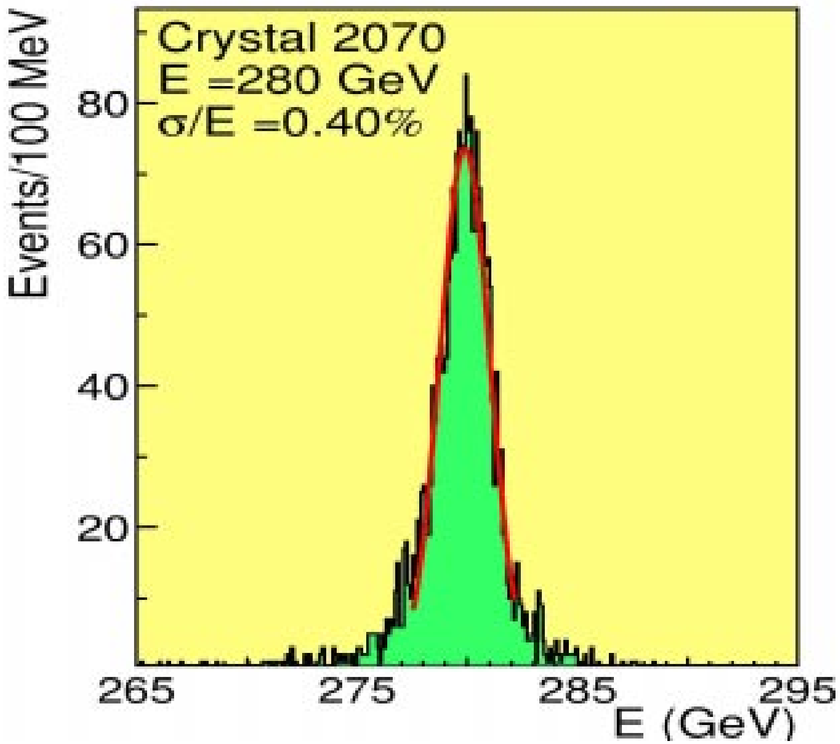
Barrel - 3x3 crystals

$$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus \frac{140\ \mathrm{MeV}}{E} \oplus 0.4\%$$

Endcap - 3x3 crystals

$$\frac{\sigma_E}{E} = \frac{4.1\%}{\sqrt{E}} \oplus \frac{140\ \mathrm{MeV}}{E} \oplus 0.25\%$$

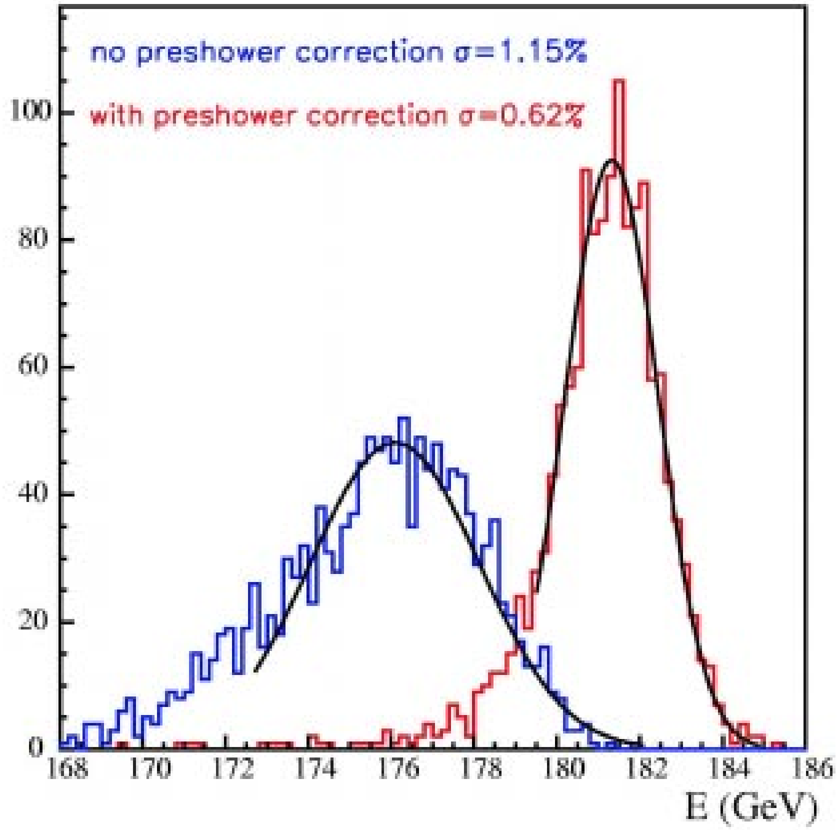


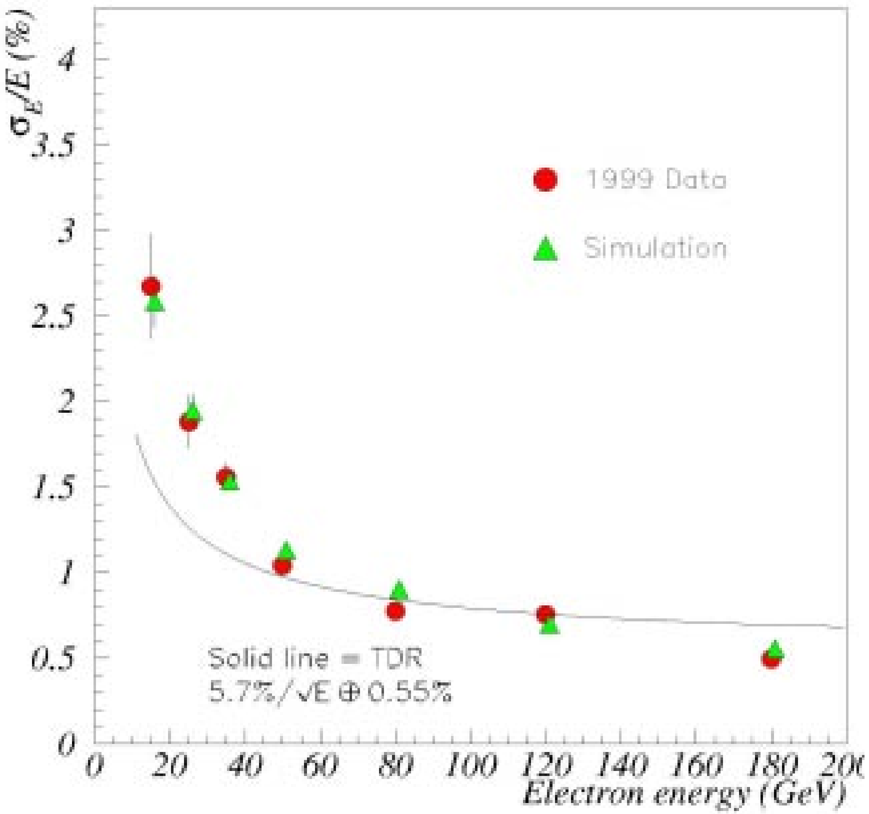


Barrel specifications: $\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus \frac{155\ \mathrm{MeV}}{E} \oplus 0.55\%$

No preshower detector

Energy resolution with preshower





Energy resolution degraded by Pb absorber

- partially restored using Si p.h. information

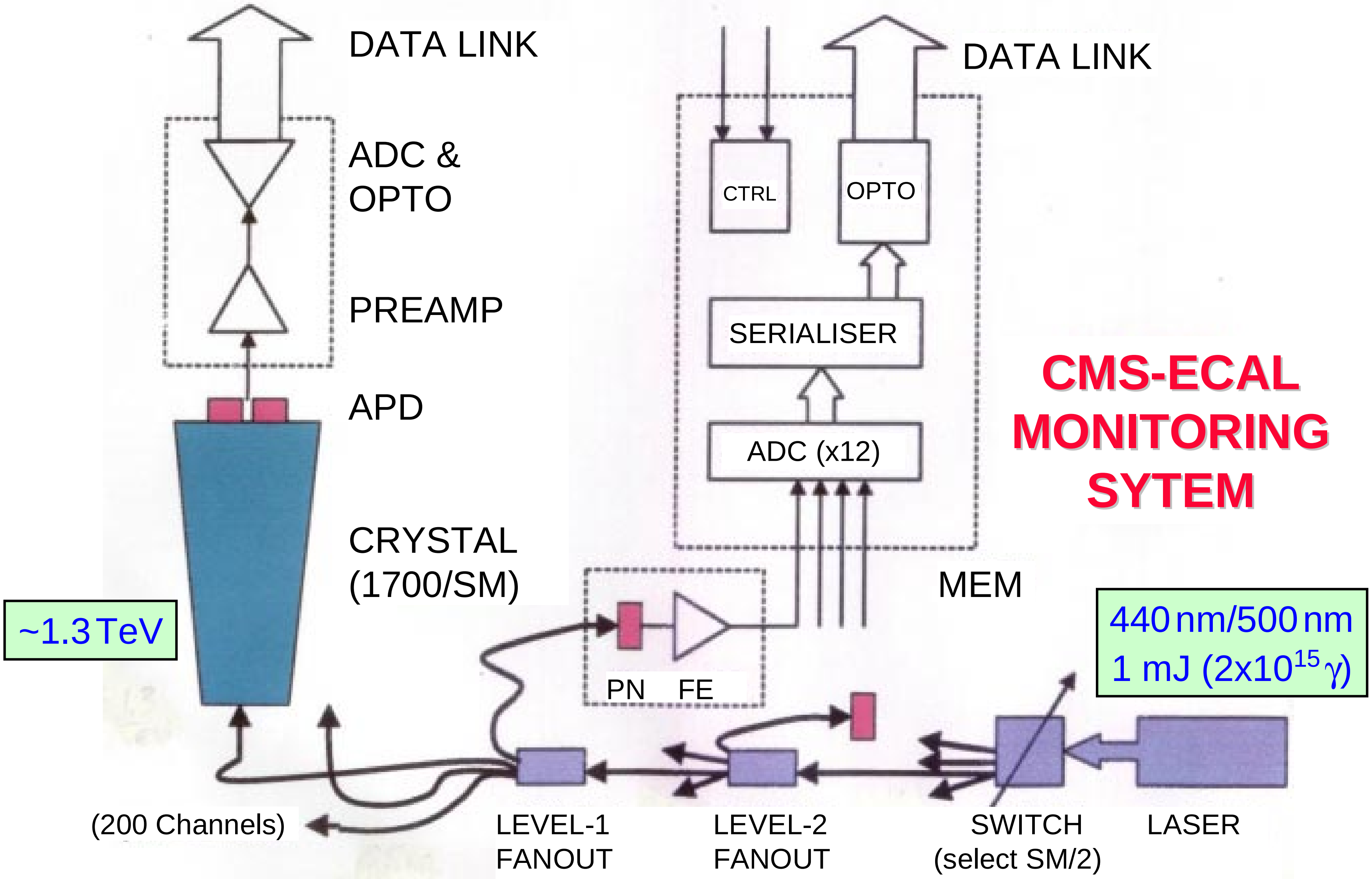
Excellent agreement between MC and data

TDR performance achieved for E > 80 GeV

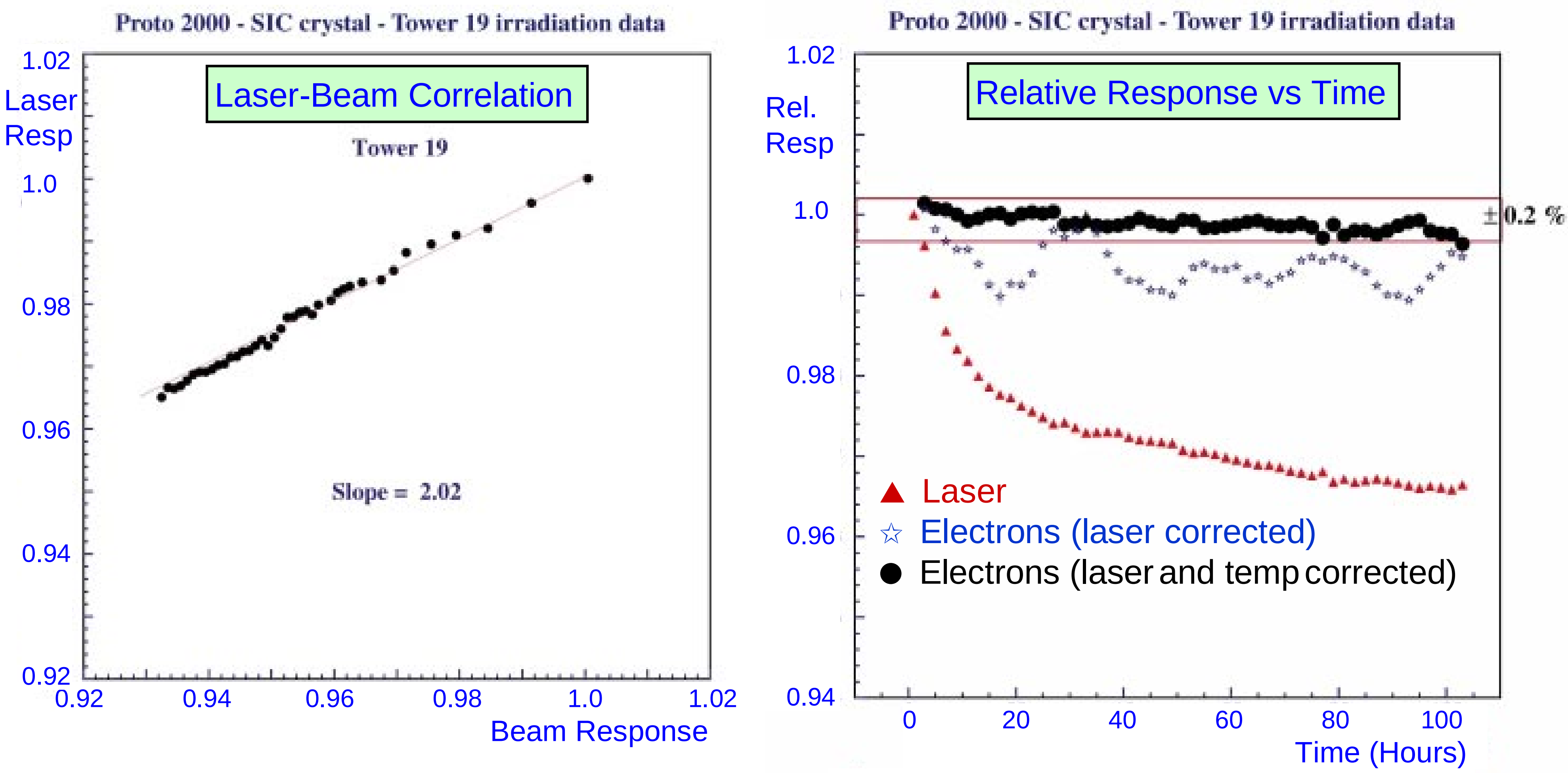
(➔ $E_T > 30$ GeV - OK for H $\rightarrow \gamma\gamma$)

(even though Pb 10% too thick in this test!)

Laser Monitoring System

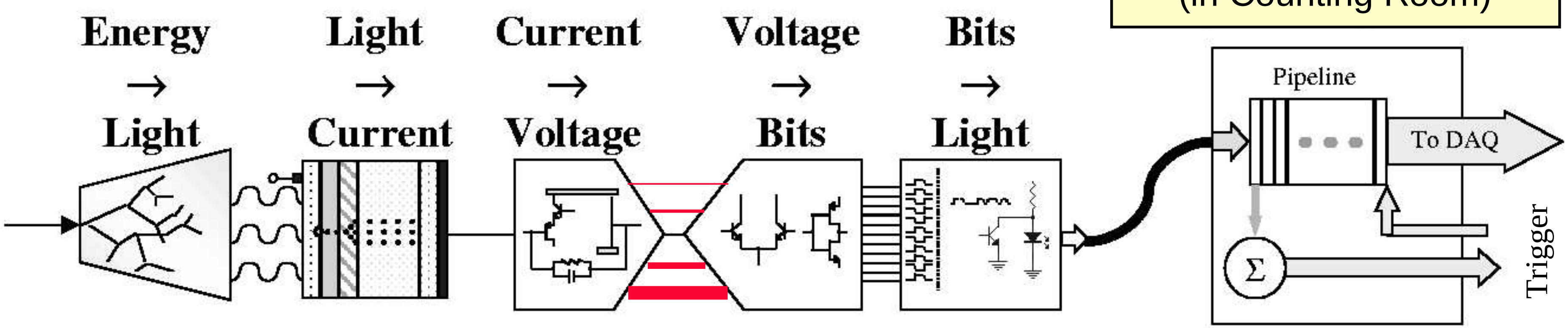


Laser Correction for Effect of Radiation Damage



Readout architecture

Upper-level VME readout
(in Counting Room)



$PbWO_4$ Crystal | APD VPT | Preamp | Gain select | ADC | Serialiser +VCSEL | Optical link | Pipeline control, Interface → DAQ, Interface → Trigger

On-detector *light-to-light* readout

- 40 MHz Clock
- 12 bit precision
- 4 different gains ➔ >17 bit dynamic range

Status summary

Crystals	Russia:	Preproduction of 6 000 Xtals on schedule
		Order for placed 30 000 Xtals placed, delivery starts in 2001
	China:	Preproduction in 2000/1, full production in 2002
Photodetectors	APD:	Preproduction completed, main production imminent
	VPT:	Pilot order placed, delivery started
Mechanics	Barrel:	Submodule parts in production
		Module: some design changes to achieve cost/performance target
	End cap:	Procurement of supercrystal parts starts after EDR in November
Electronics	Full readout chain tested in beam in 2000 - performance OK	
	Some problems with manufacturing yields	
Monitoring	Components ordered and delivery on schedule	
Preshower	Preproduction of Si detectors started	
	Preamplifier prototype tested: radiation harness + performance OK	
	Mechanics progressing well.	
Summary	Some delays in mechanics/electronics/APD ➔ Absorb by rescheduling	
	Critical path defined by crystal delivery and precalibration in an electron beam	