



The Lead Tungstate Calorimeter for CMS

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CALOR 2000
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Outline of Talk



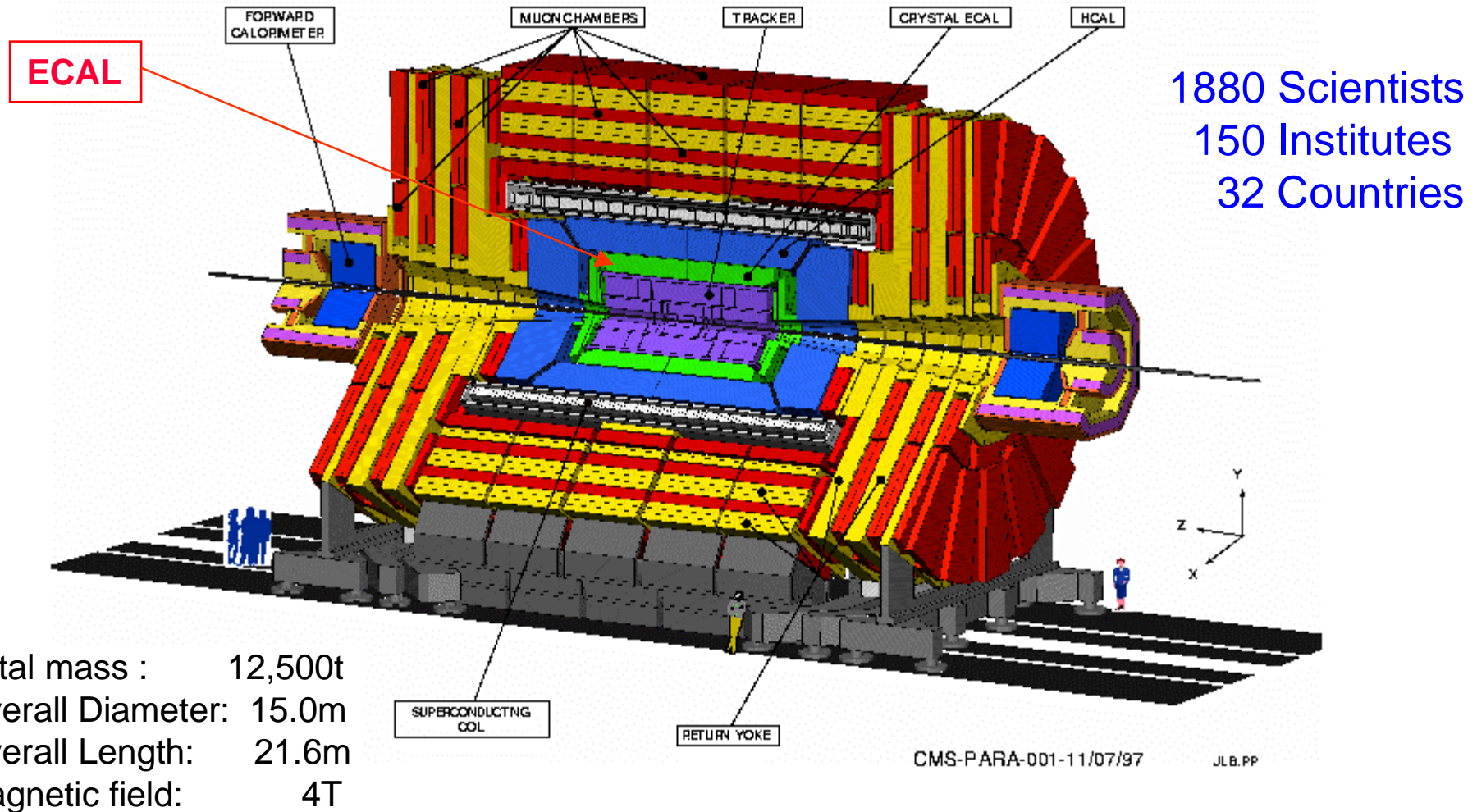
- ▶ Overview of CMS
- ▶ Parameters of the ECAL
- ▶ Properties of Lead Tungstate
- ▶ Radiation levels
- ▶ Crystal production
- ▶ Photodetectors: APD, VPT
- ▶ Mechanical design
- ▶ Preshower detector
- ▶ Prototype performance
- ▶ Monitoring system
- ▶ Electronic readout system
- ▶ Status summary



The Compact Muon Solenoid Detector for LHC



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





ECAL design objectives



High resolution electromagnetic calorimetry is a basic design objective of CMS

Benchmark physics process:

Sensitivity to a low mass Higgs via $H \rightarrow \gamma\gamma$

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

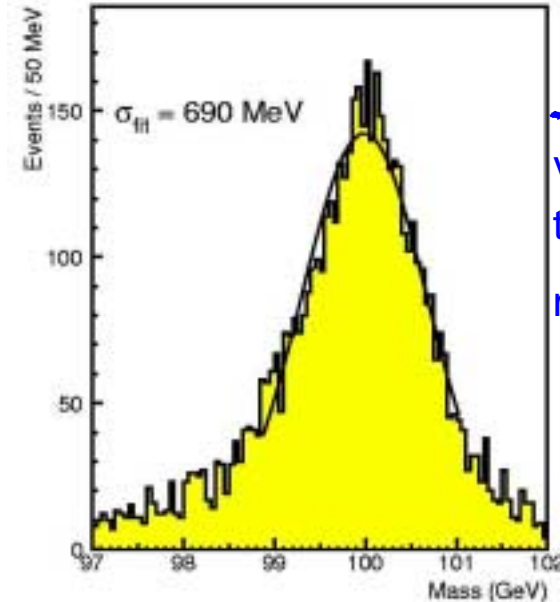
Where $\sigma_E/E = a/\sqrt{E} \oplus b \oplus c/E$

Aim: Barrel End cap
 Stochastic term: $a = 2.7\%$ 5.7%
 (photoelectron statistics/shower fluctuations)

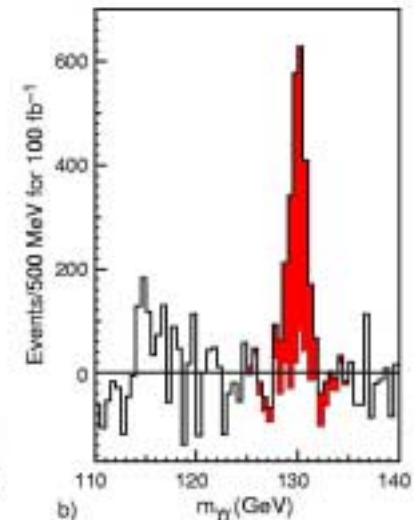
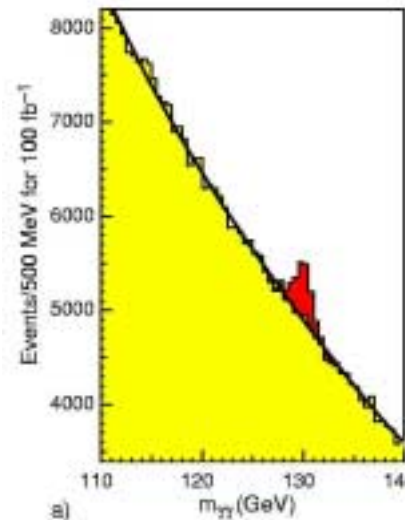
Constant term: $b = 0.55\%$ 0.55%
 (non-uniformities, shower leakage)

Noise term: Low \mathcal{L} $c = 155 \text{ MeV}$ 205 MeV
 High \mathcal{L} 210 MeV 245 MeV

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



$\mathcal{L} = 10^{34} \text{ cm}^2\text{s}^{-1}$
 Vertex by track finding
 $m_H = 100 \text{ GeV}$

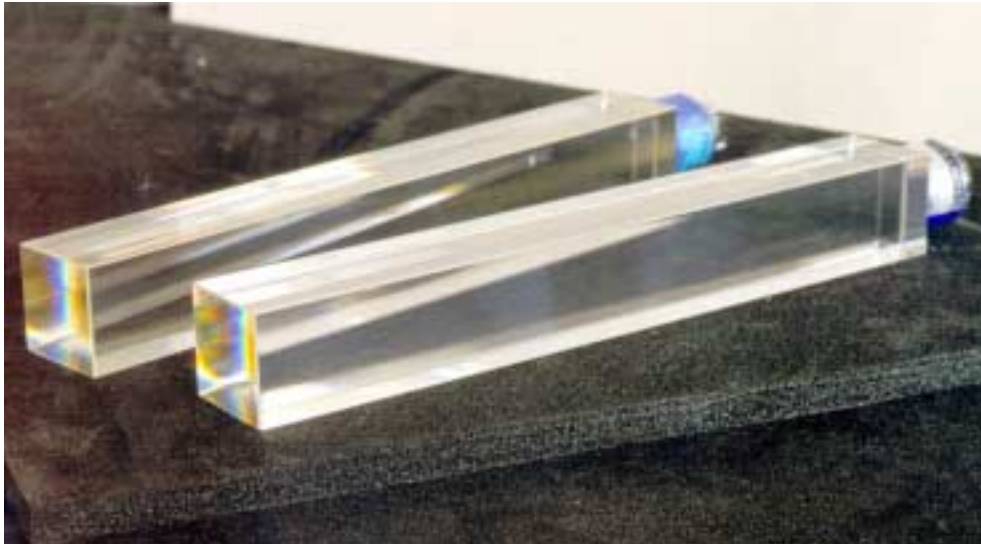




ECAL design choices



- 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

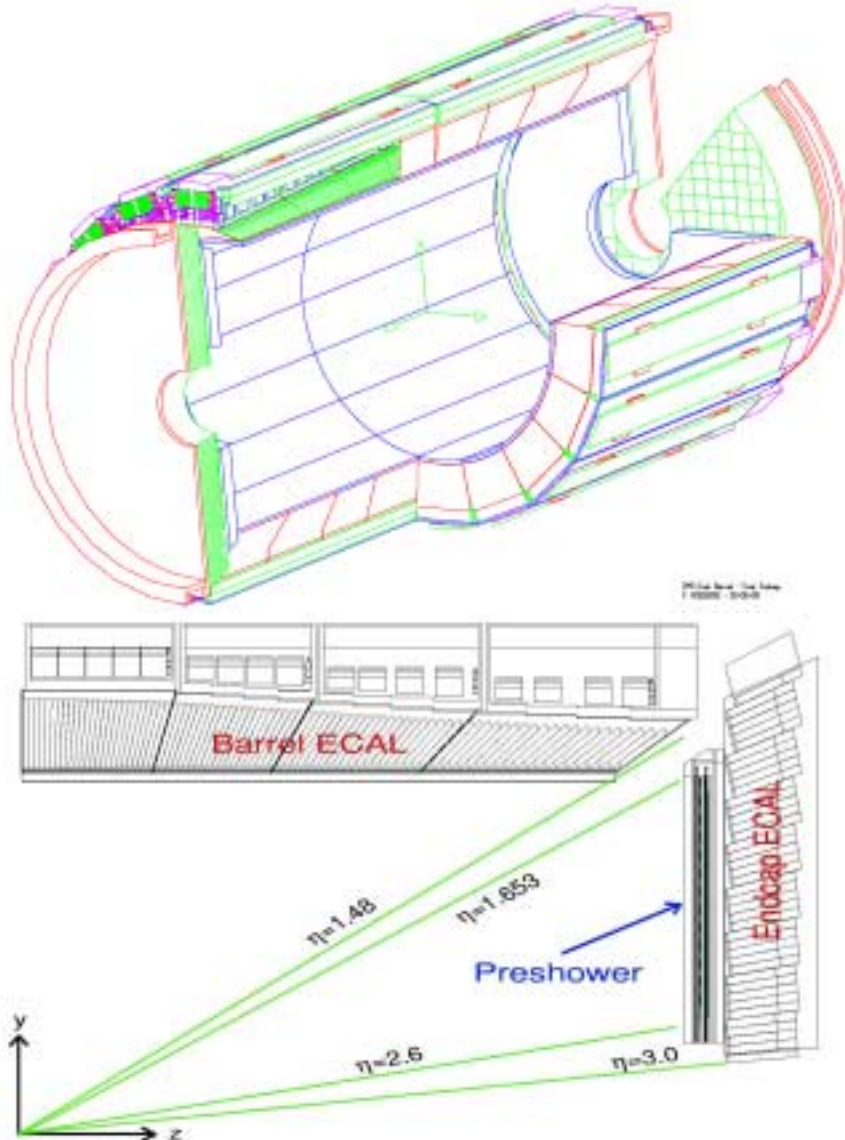


Properties of dense inorganic scintillators

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 [%/°C]	-1.6	0 -2	0.14	-2
Rel light yield	18	4 20	8	1.3



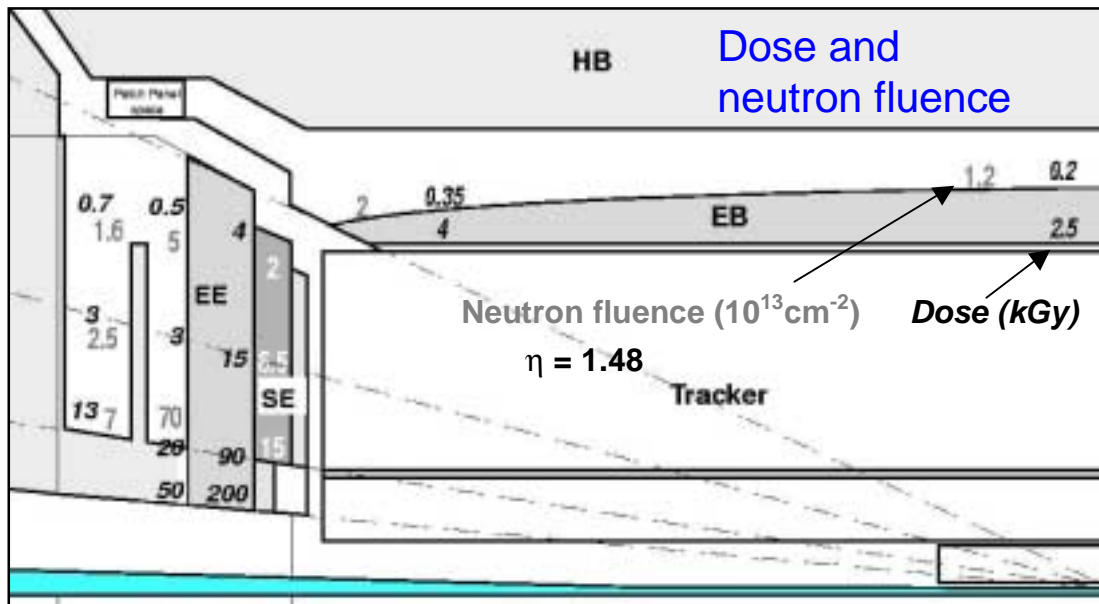
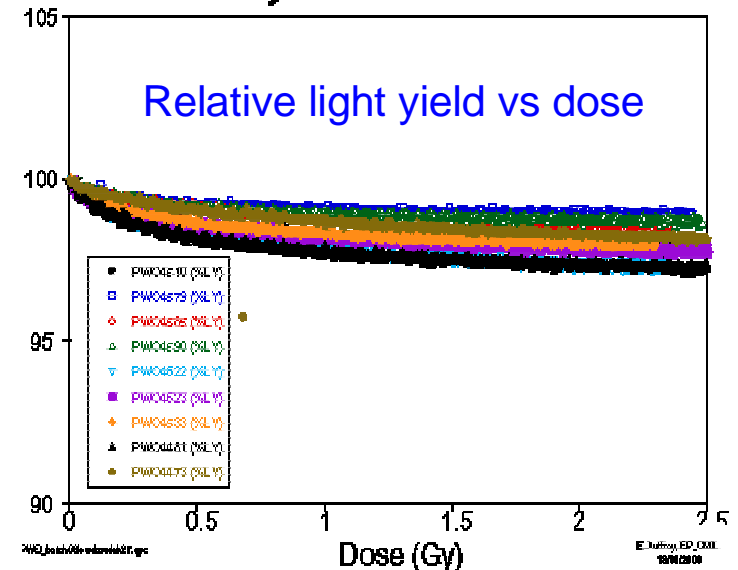
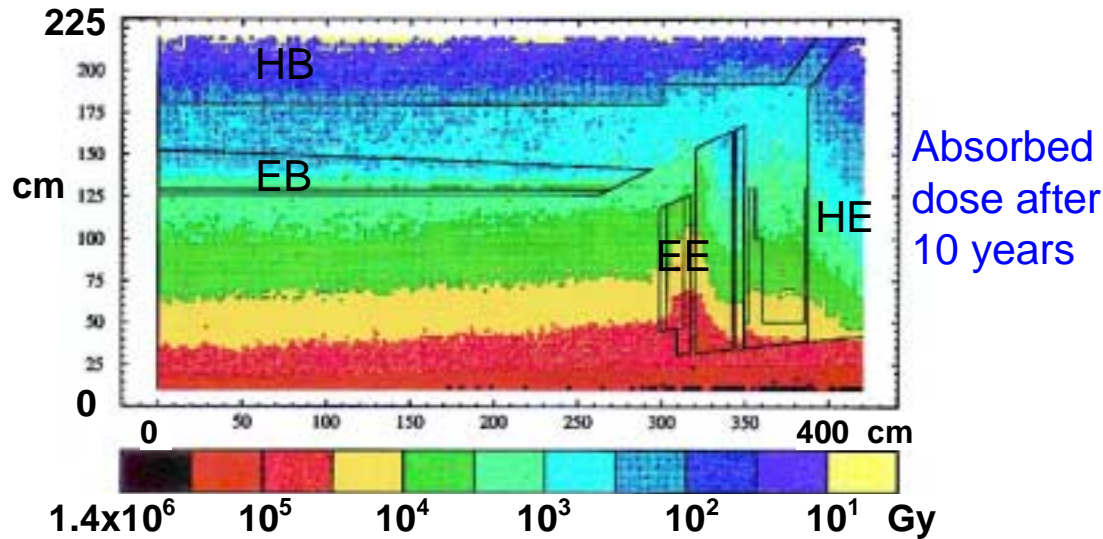
ECAL Parameters



Parameter	Barrel	End caps
Coverage	$ \eta < 1.48$	$1.48 < \eta < 3.0$
R_1, R_0 (mm)	1238, 1750	316, 1711
z_1, z_0 (mm)	$0, \pm 3045$	$\pm 3170, \pm 3900$
$\Delta\phi \times \Delta\eta$	0.0175×0.0175	0.0175×0.0175 to 0.05×0.05
Xtal size (mm^3)	$21.8 \times 21.8 \times 230$	$30.0 \times 30.0 \times 220$
Depth in X_0	25.8	24.7
Off-pointing	3°	3°
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



CLRC

Crystal production



Russia (Czochralski)

Preproduction (6 000): 5000 delivered so far

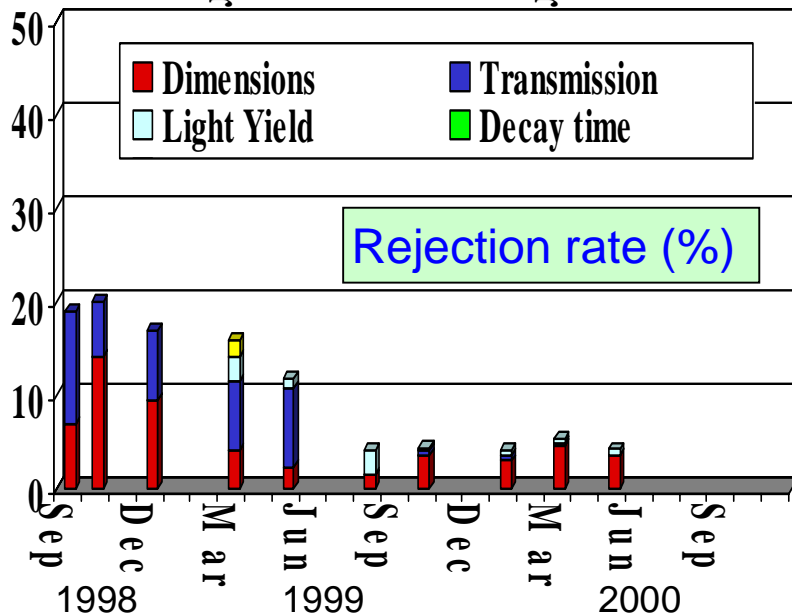
Production (30 000): Order placed
Delivery starts this year

China (modified Bridgman-Stockbarger)

R&D phase advanced

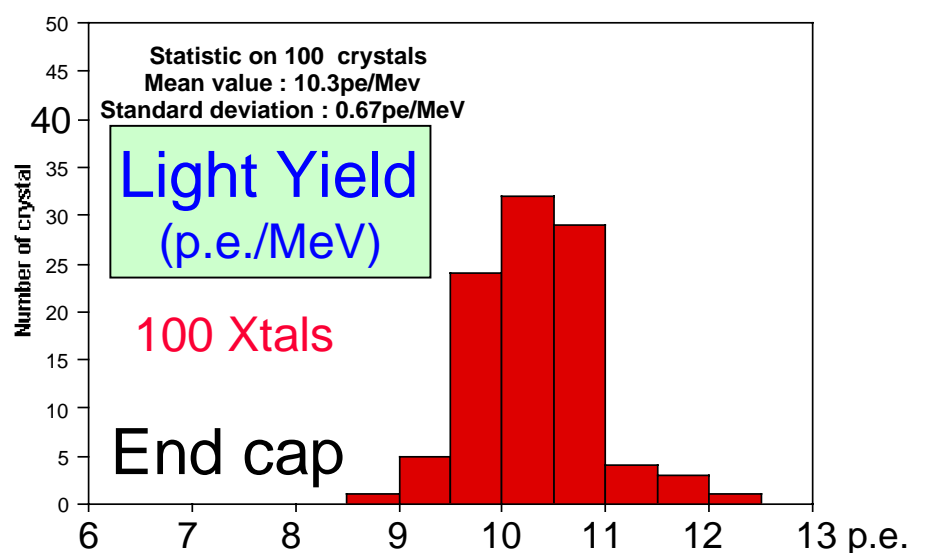
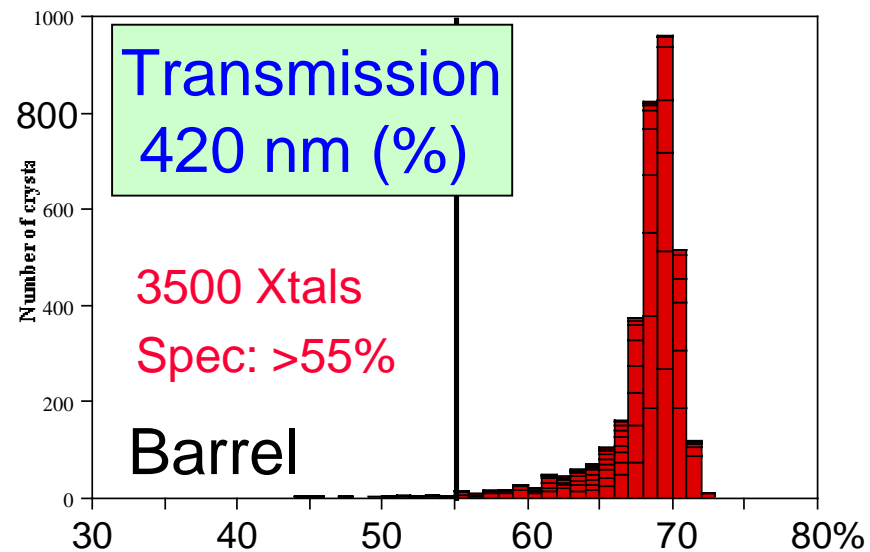
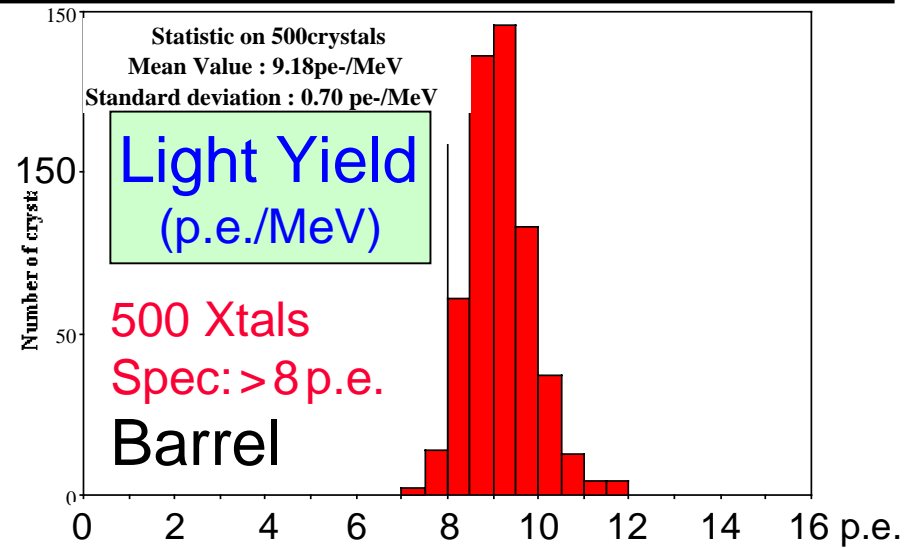
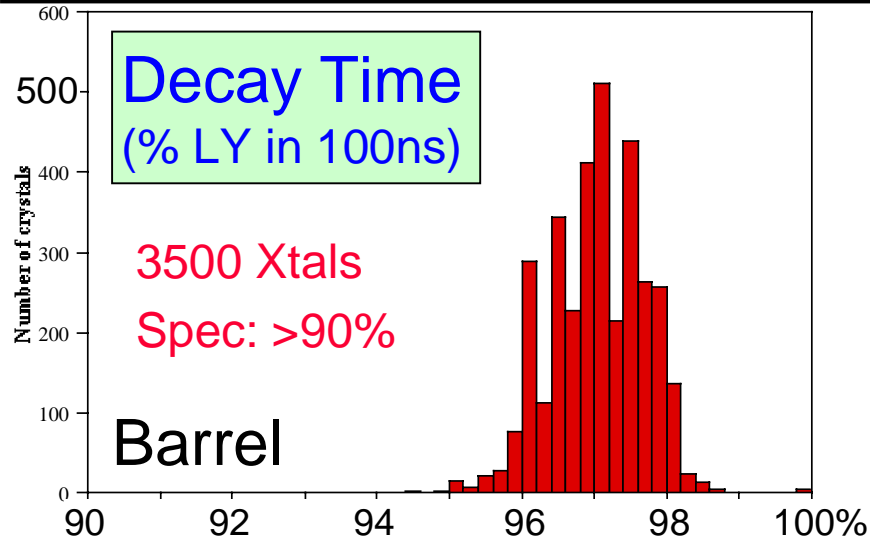
Preproduction: Planned start at end of 2000

Production: Planned start in 2001





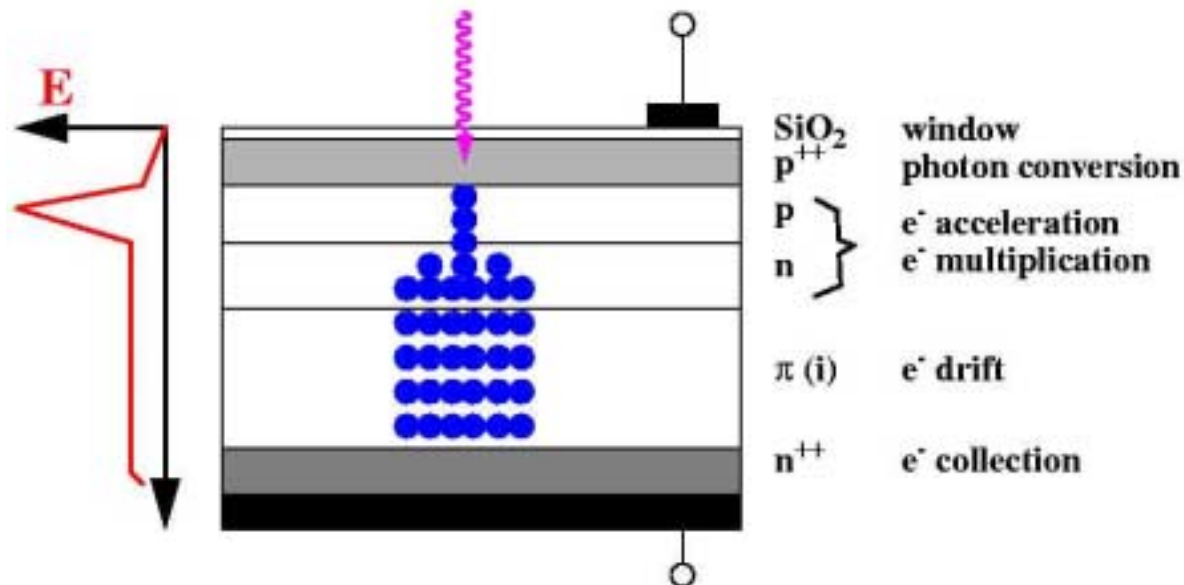
Distributions of Crystal properties



Avalanche photodiodes (APD)

- Operated at a gain of 50
- Active area of $2 \times 25\text{mm}^2/\text{crystal}$
- Q.E. $\sim 80\%$ for PbWO_4 emission
- Excess noise factor is $F = 2.2$
- Insensitive to shower leakage particles ($d_{\text{eff}} \sim 6\mu\text{m}$)
- Irradiation causes bulk leakage current to increase
 → electronic noise doubles after 10 yrs - **acceptable**

Delivery from Hamamatsu starts this year

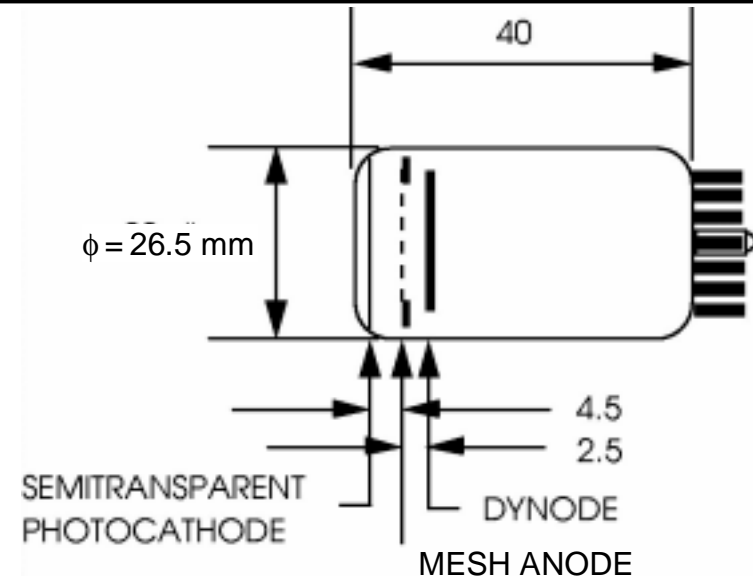


Vacuum Phototriodes (VPT)

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

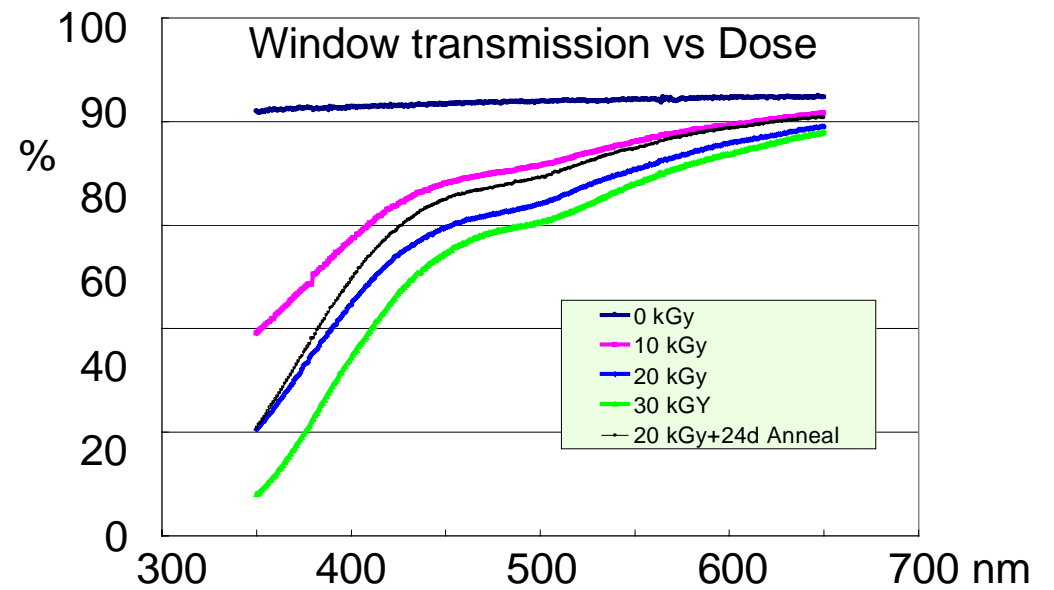
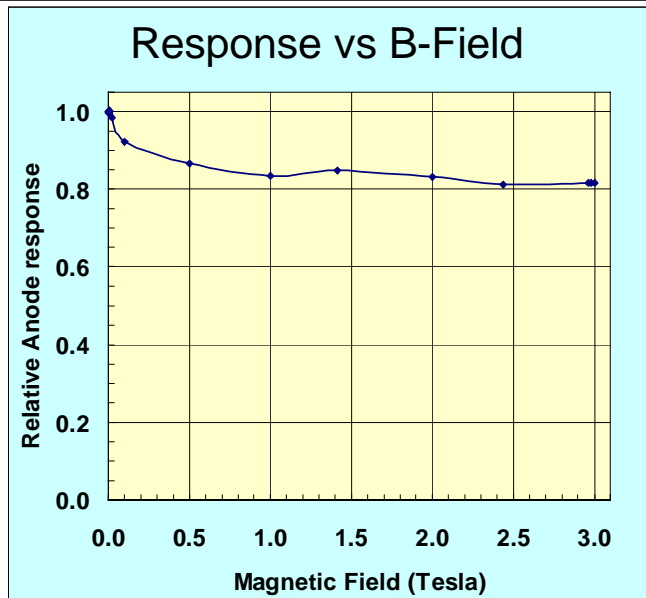
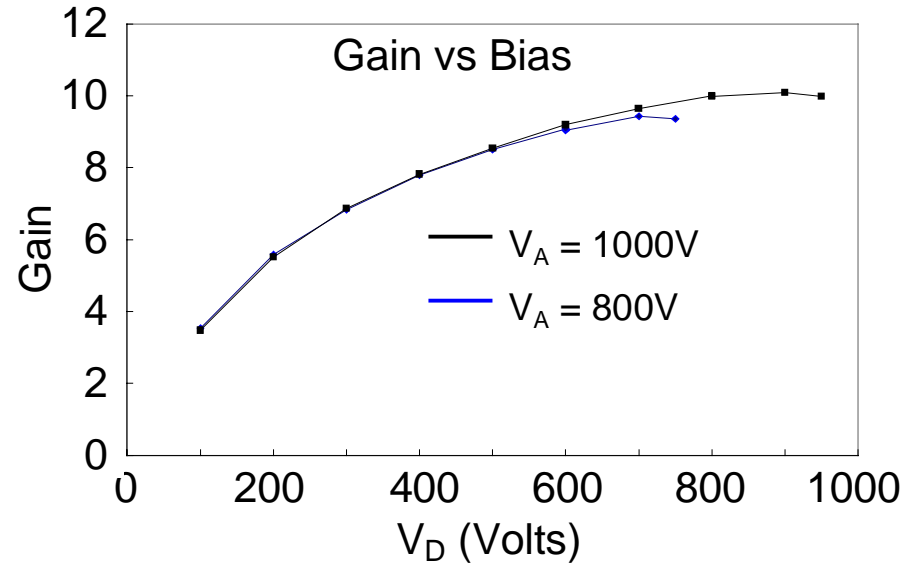
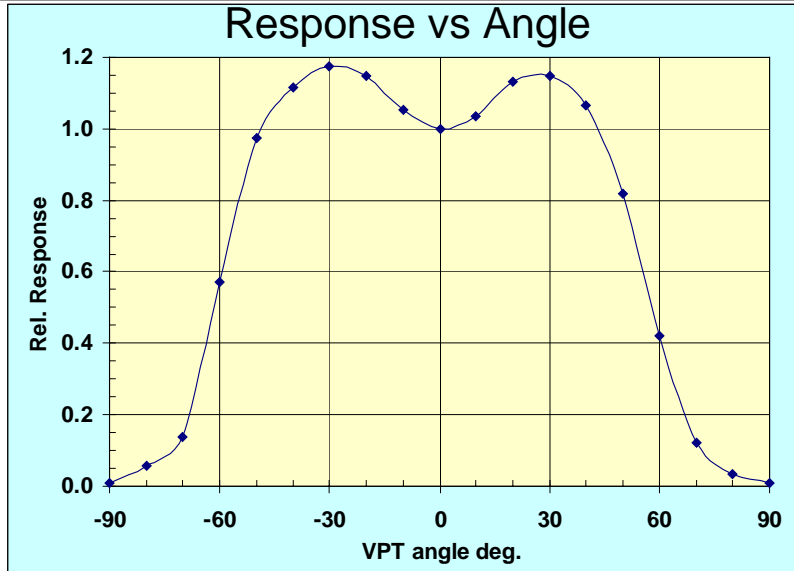
- Gain 8-10 at $B = 4\text{ T}$
- Active area of $\sim 280\text{ mm}^2/\text{crystal}$
- Q.E. $\sim 20\%$ at 420 nm
- Excess noise factor is $F \sim 3$
- Insensitive to shower leakage particles
- UV glass window - less expensive than 'quartz'
 - more radiation resistant than borosilicate glass
- Irradiation 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





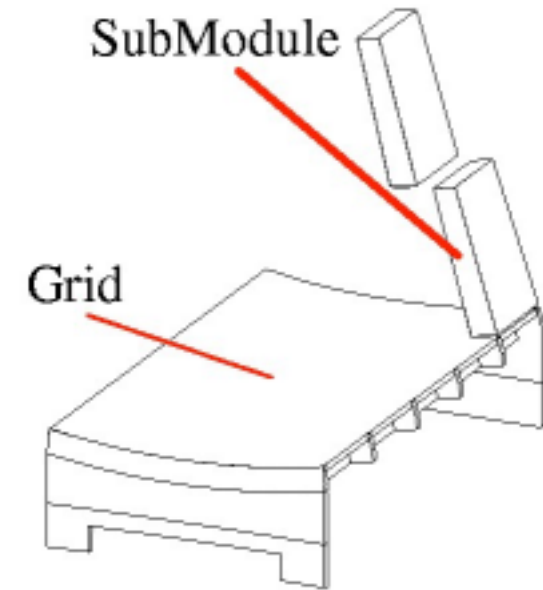
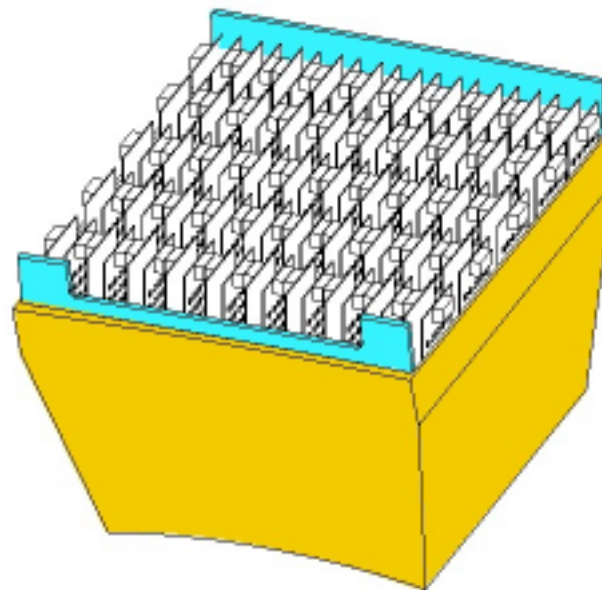
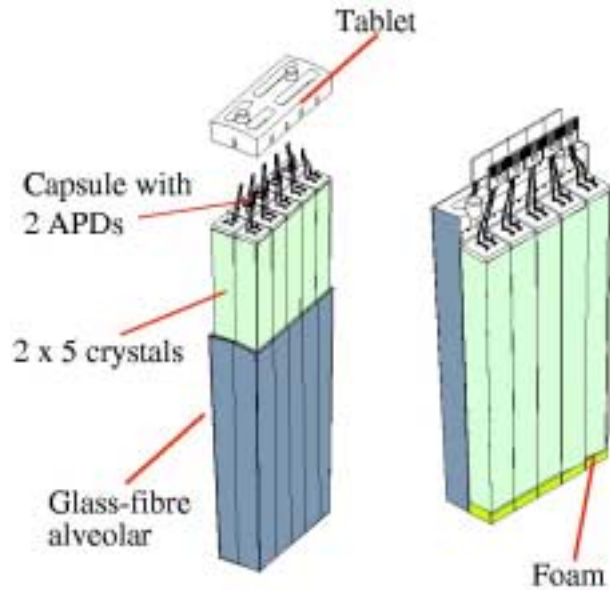
CLRC

Construction: barrel

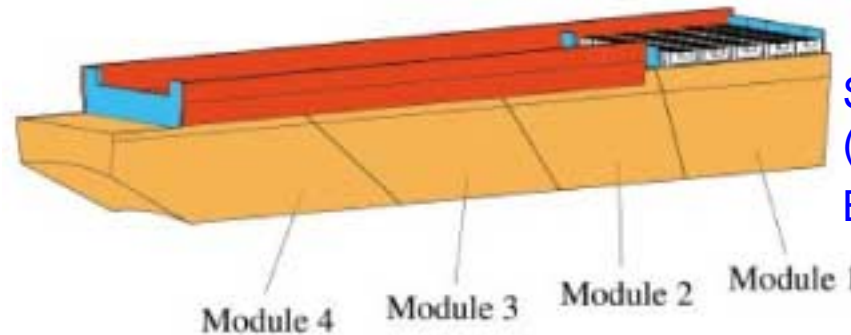


Submodule: 2x5 Xtals with APD and FE electronics in 200µm glass fibre alveola

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

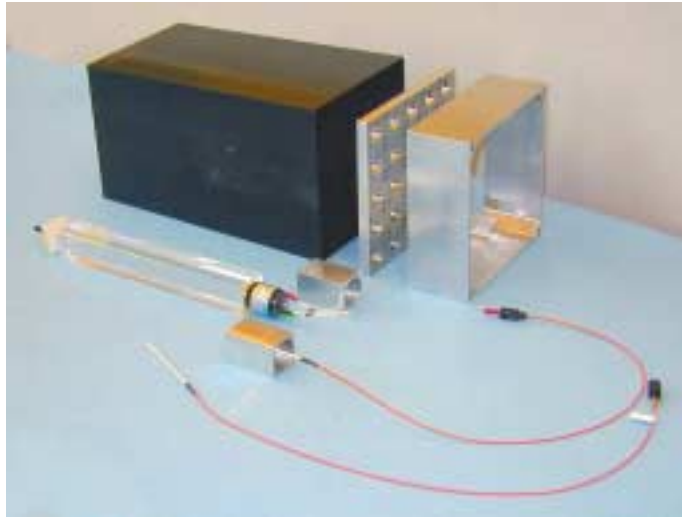


Assembled Submodules



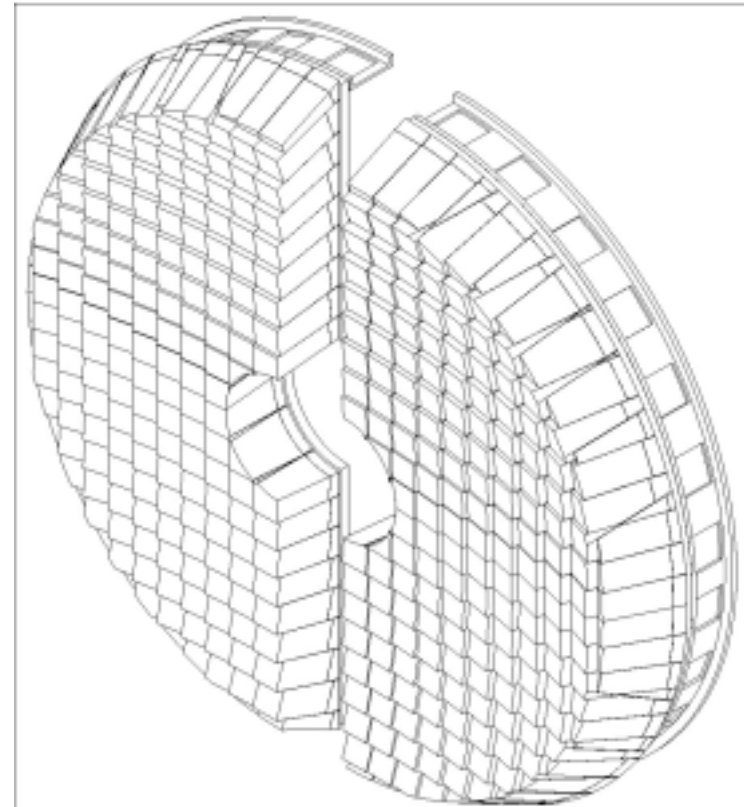
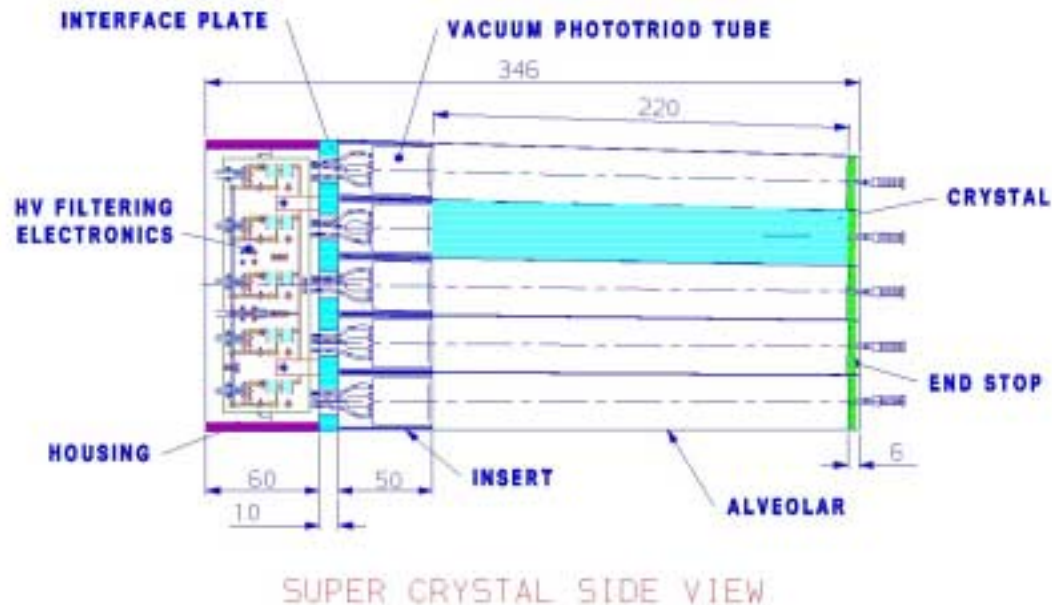
Supermodule: 4 Modules (1700 Xtals)
Barrel = 36 Supermodules

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)



Preshower detector

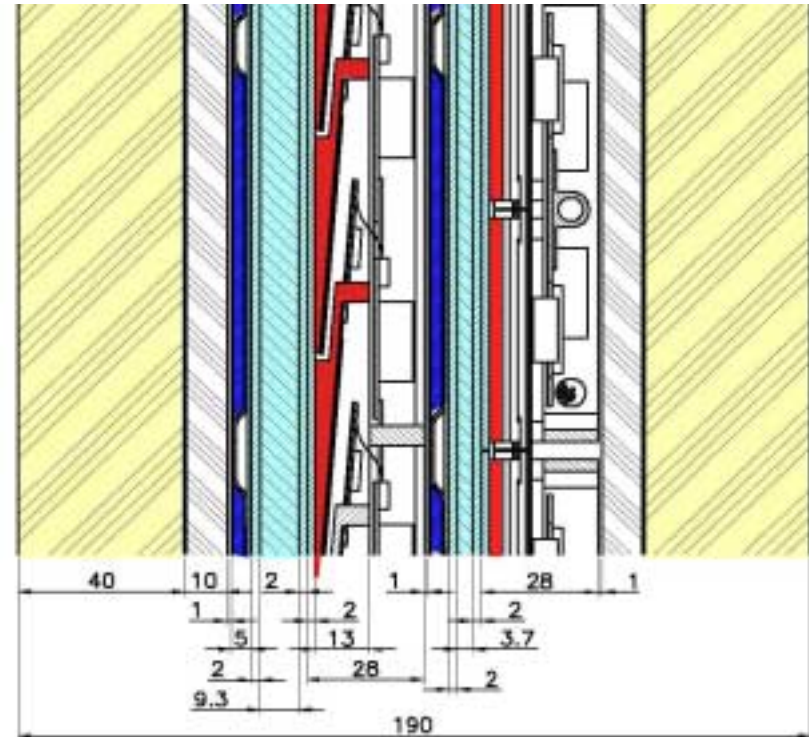
Rapidity coverage: $1.65 < |\eta| < 2.6$ (End caps)

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 m²

(4300 detectors, 1.4×10^5 channels)

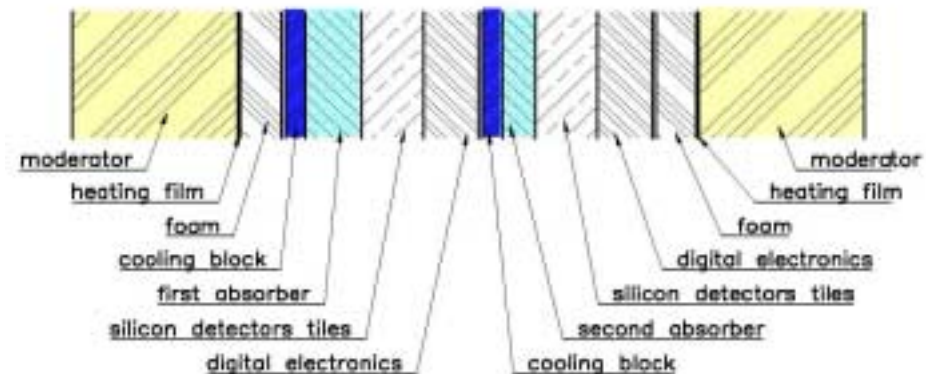
Incident
Direction →



High radiation levels - Dose after 10 years:

- $\sim 2 \times 10^{14}$ n/cm²
- ~ 60 kGy

→ Operate at -10°C

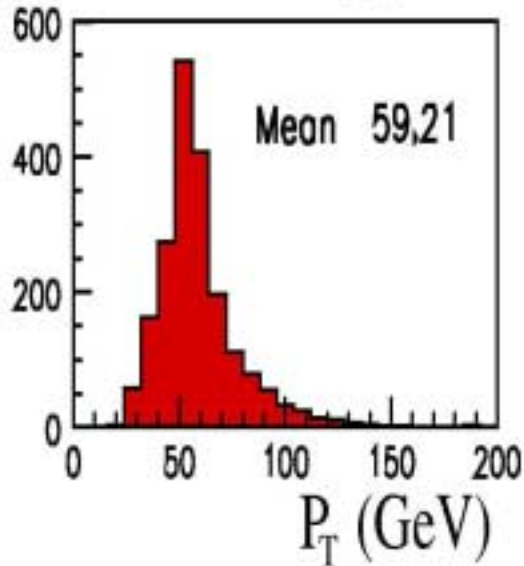




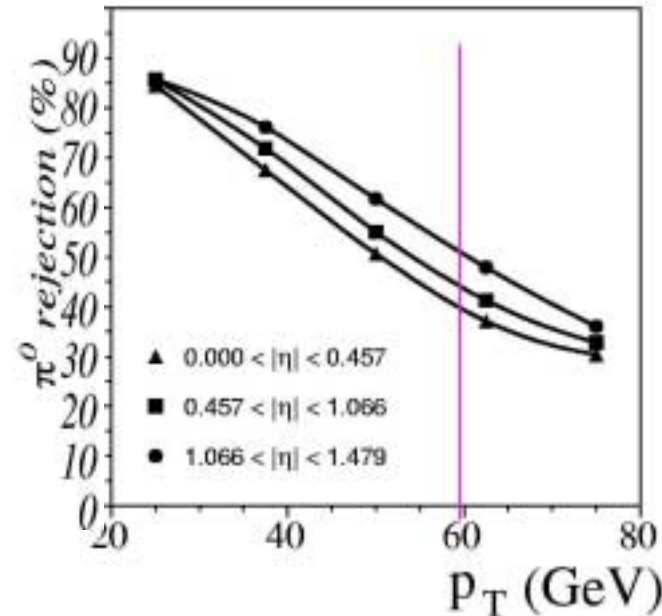
π^0/γ Discrimination



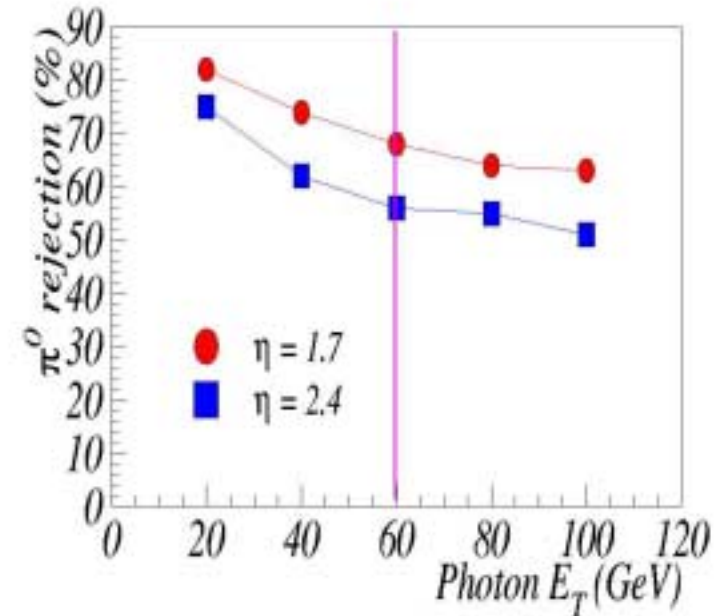
Photon P_T from
110 GeV Higgs



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 $\approx 50\%$ of the intrinsic (γ - γ) background (p_T cut = 2 GeV/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

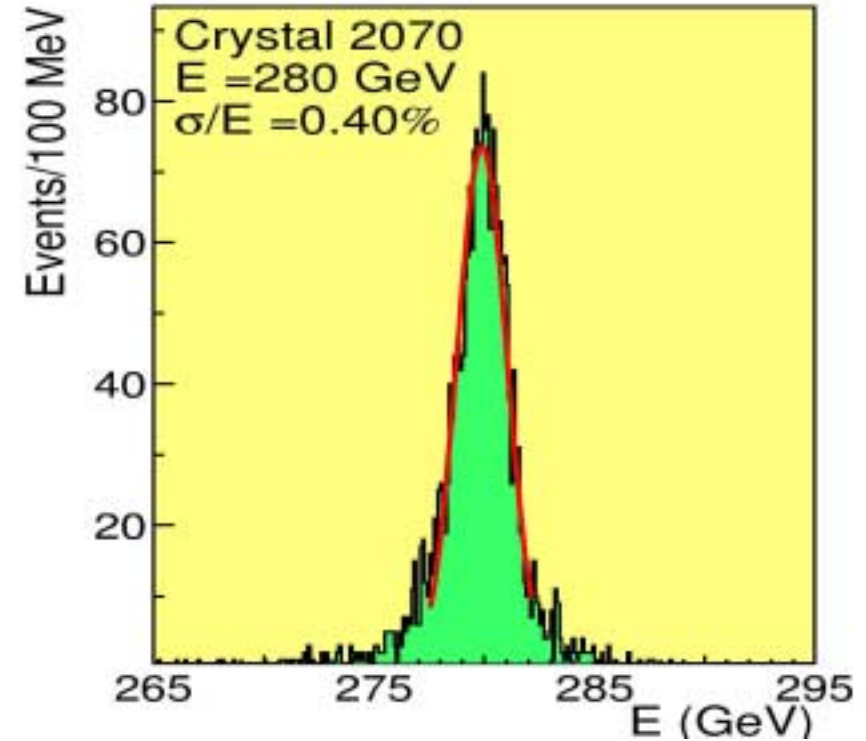
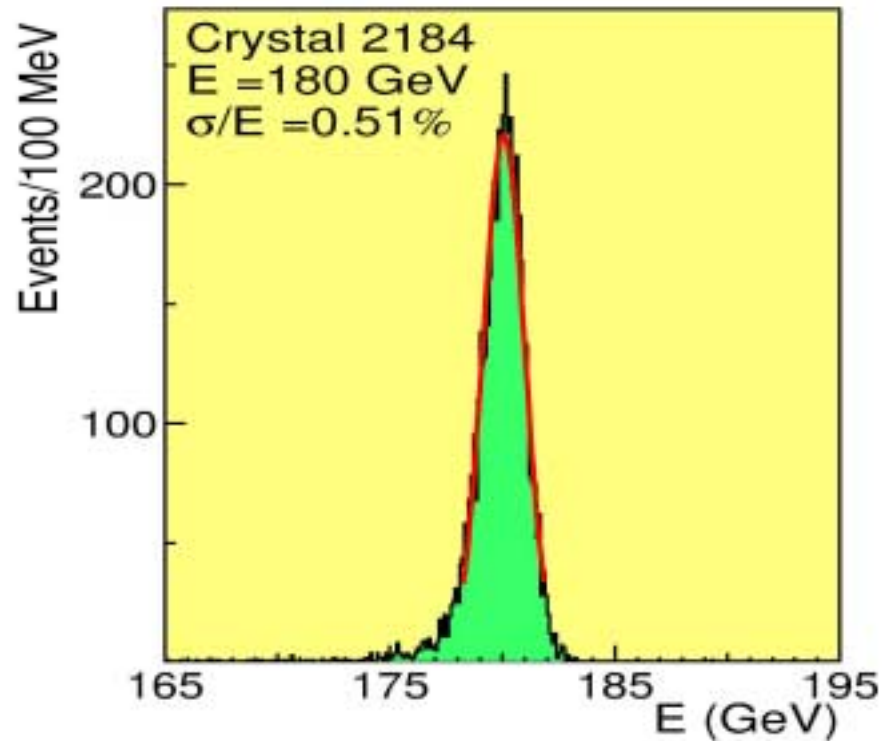


Barrel - 3x3 crystals

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

Endcap - 3x3 crystals

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

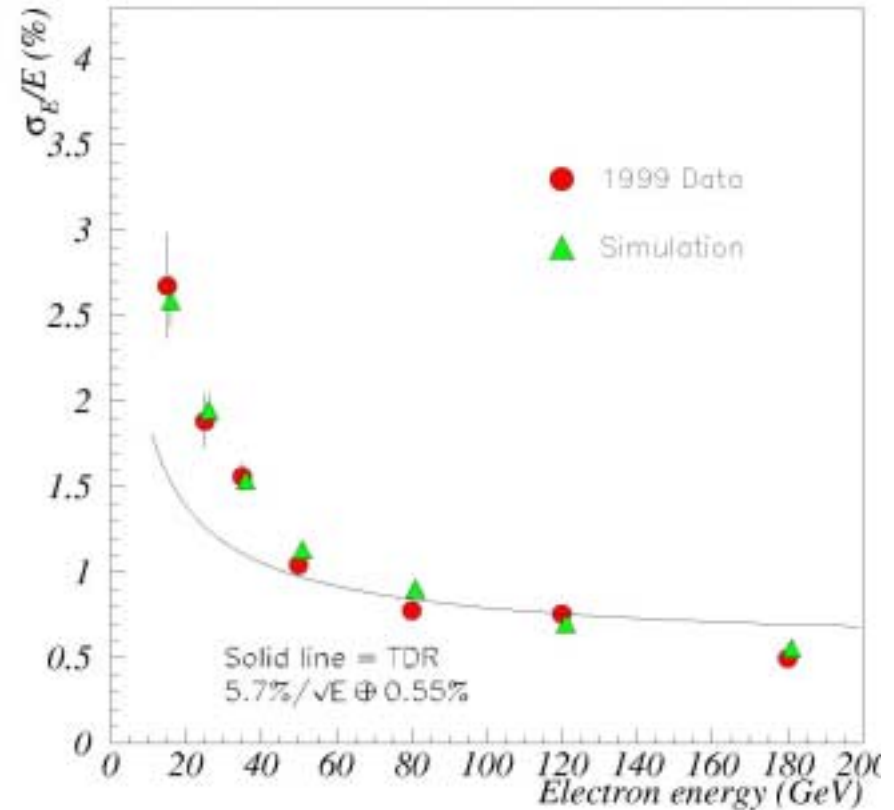
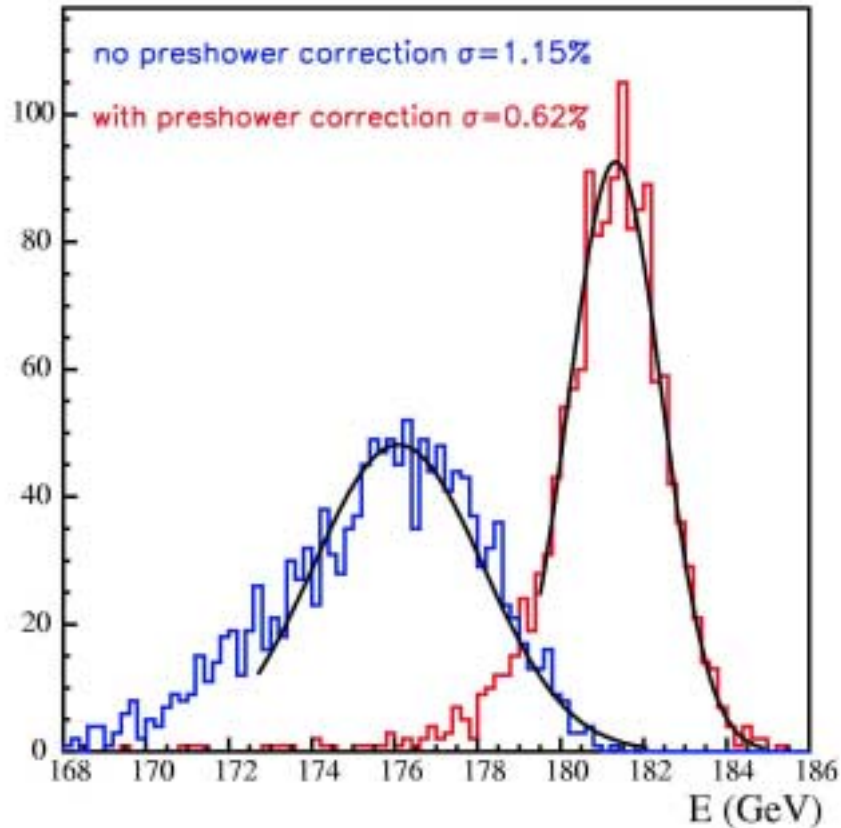


Barrel specifications: $\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus \frac{155 \text{ MeV}}{E} \oplus 0.55\%$

No preshower detector



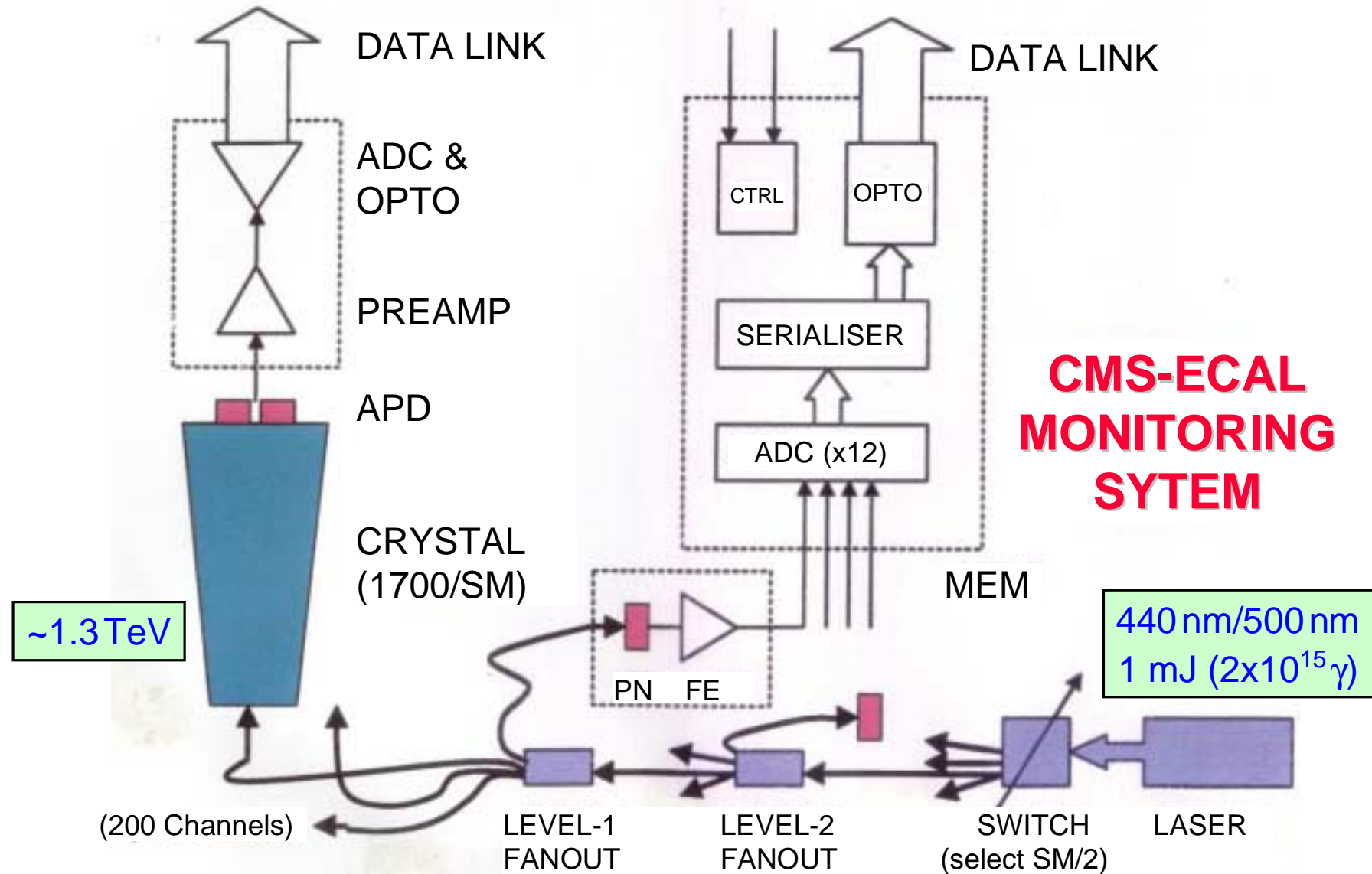
Energy resolution with preshower



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
($\rightarrow E_T > 30$ GeV - OK for $H \rightarrow \gamma\gamma$)
(even though Pb 10% too thick in this test!)

Laser Monitoring System

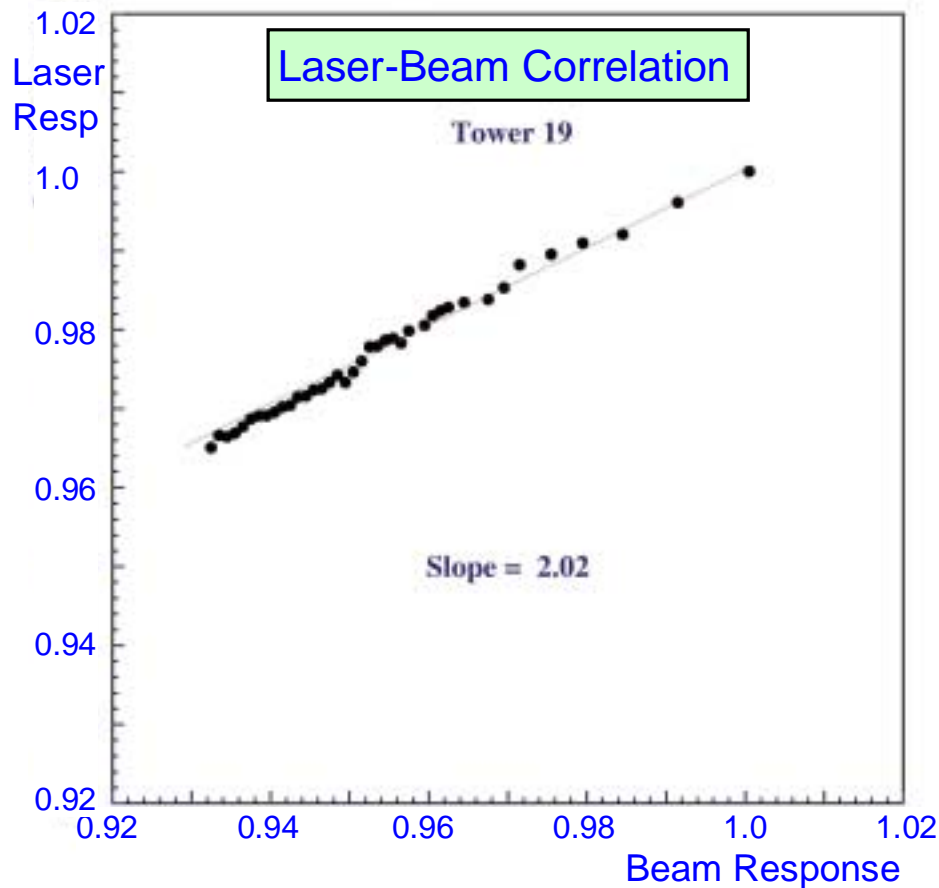




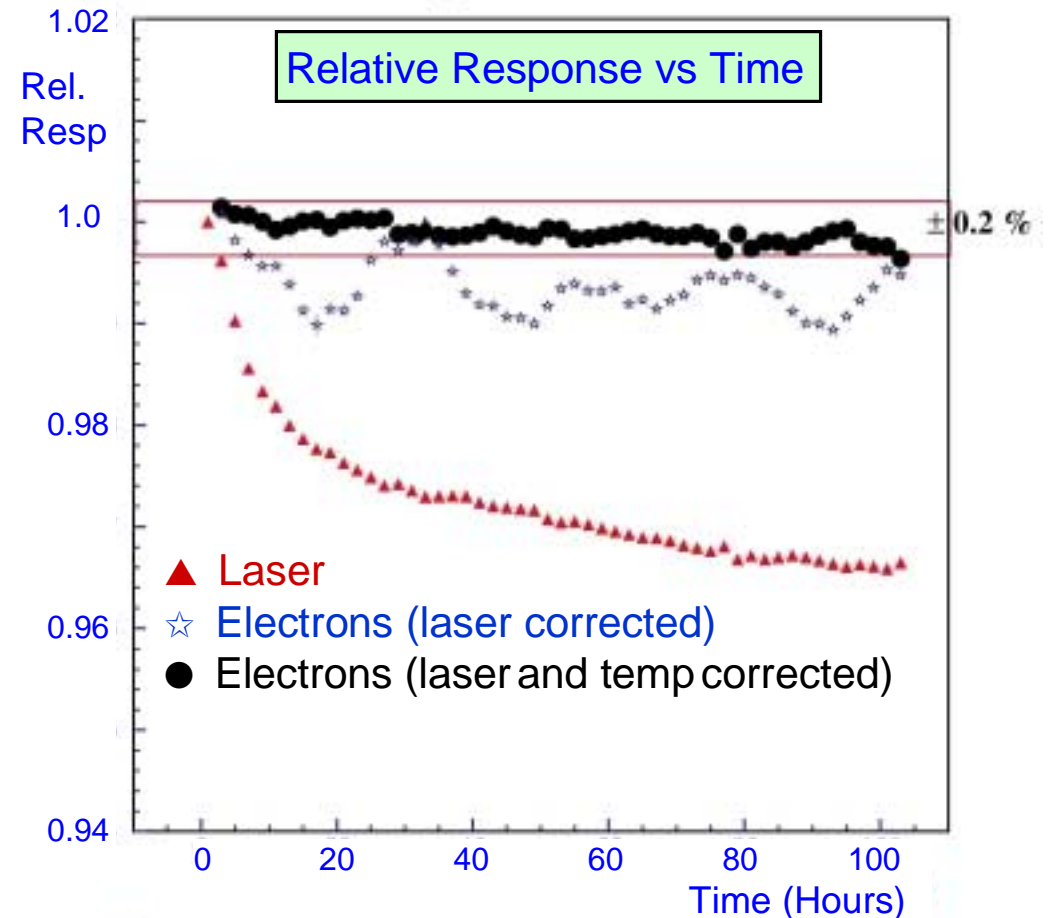
Laser Correction for Effect of Radiation Damage

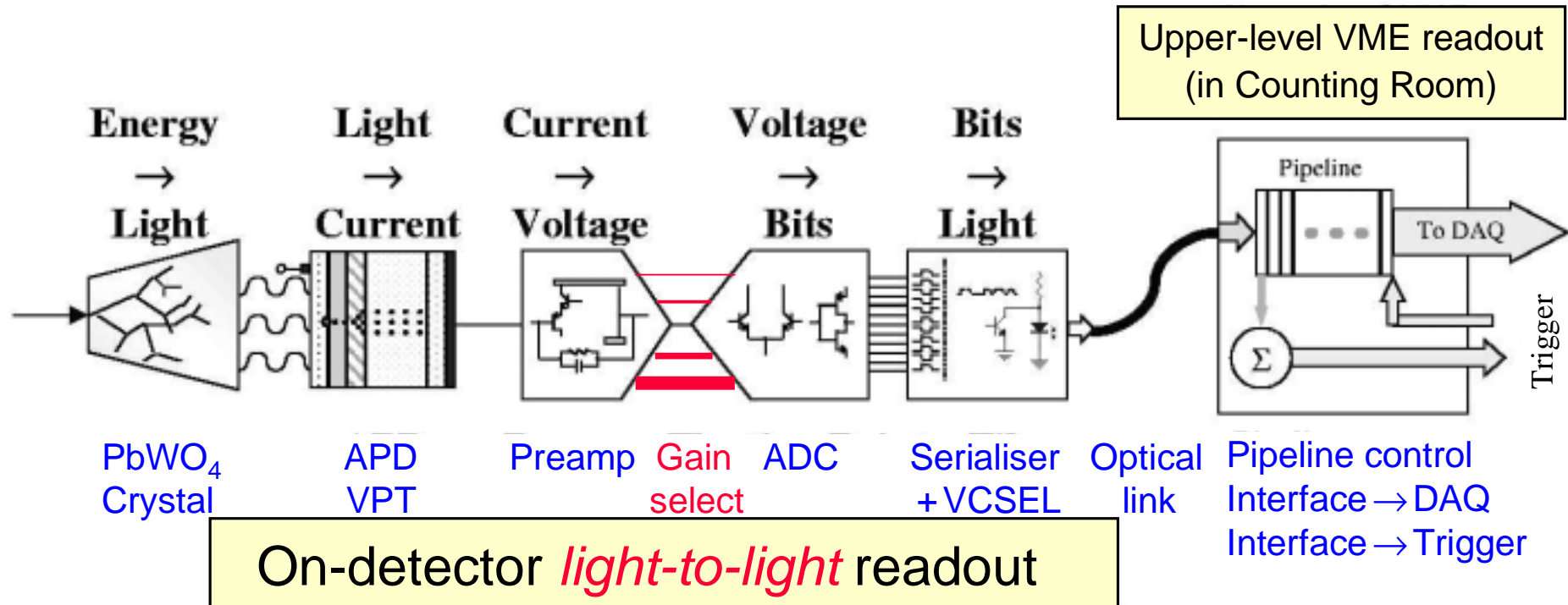


Proto 2000 - SIC crystal - Tower 19 irradiation data



Proto 2000 - SIC crystal - Tower 19 irradiation data





- 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