Avalanche Photodiodes and Vacuum Phototriodes for the Electromagnetic Calorimeter of the CMS experiment at the Large Hadron Collider

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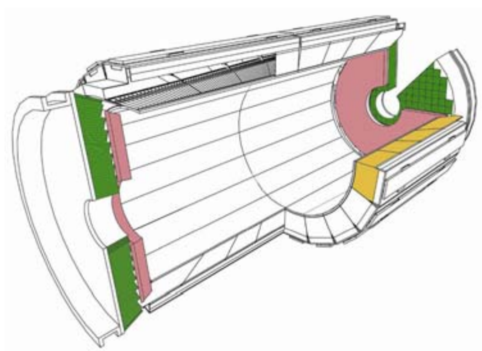
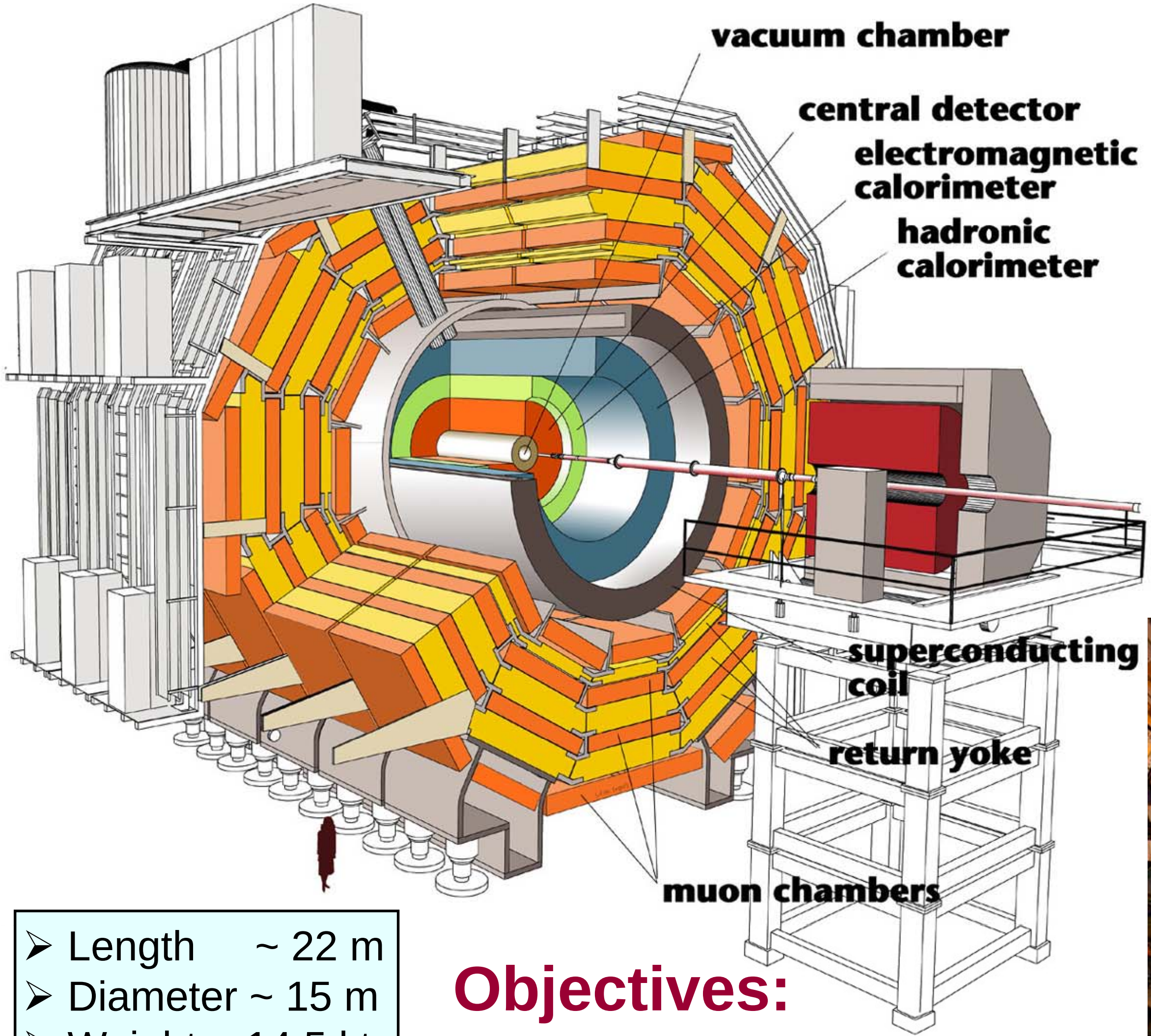
on behalf of the CMS ECAL Group

- Overview
- CMS Electromagnetic Calorimeter
- Avalanche Photodiodes
- Vacuum Phototriodes
- Summary



Compact Muon Solenoid

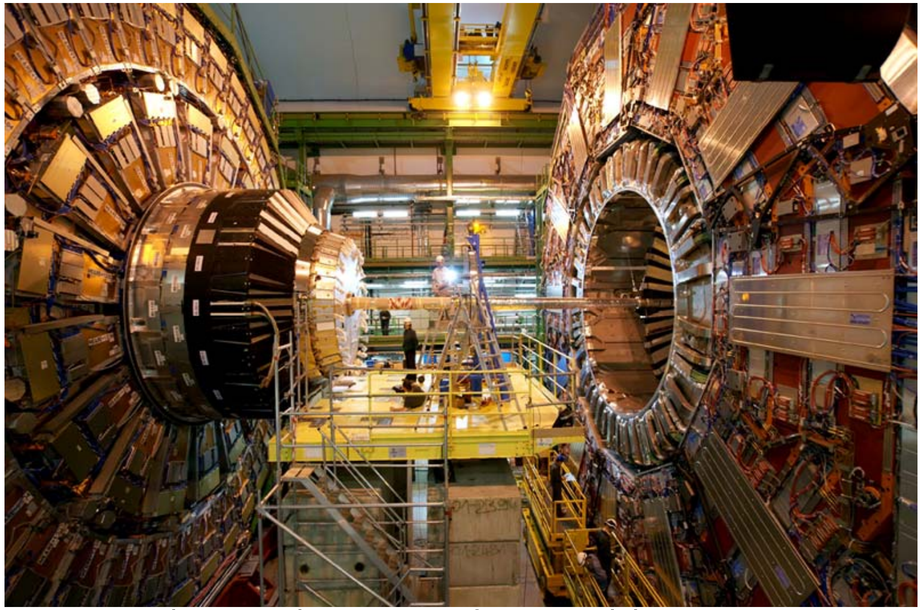


Now fully installed at the Large Hadron Collider, CERN, which is a 7+7 TeV proton-proton collider.

- Length ~ 22 m
- Diameter ~ 15 m
- Weight ~ 14.5 kt

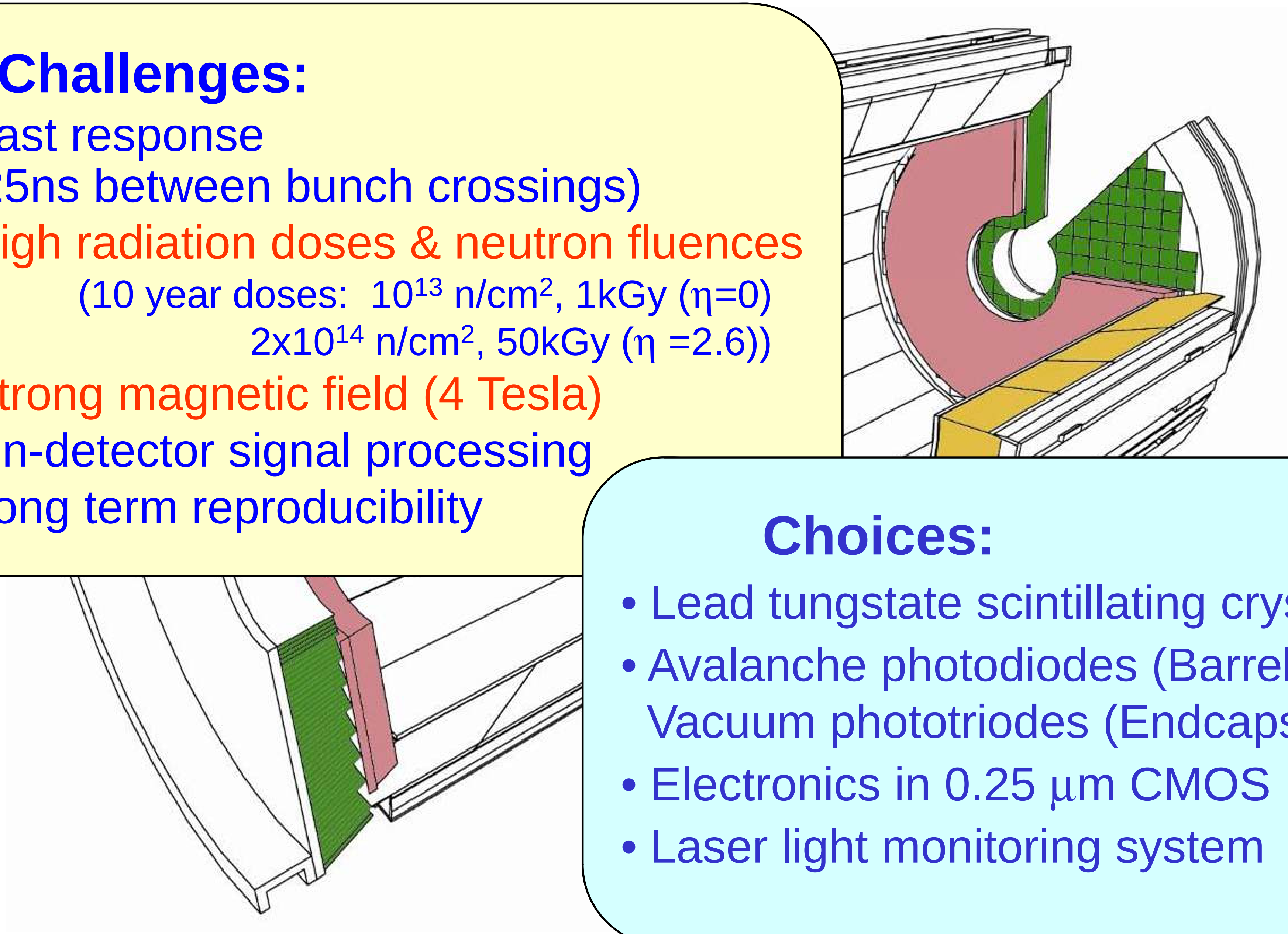
Objectives:

- Higgs discovery
- Physics beyond the Standard Model



Photograph courtesy of ETH Zurich

Electromagnetic Calorimeter



Challenges:

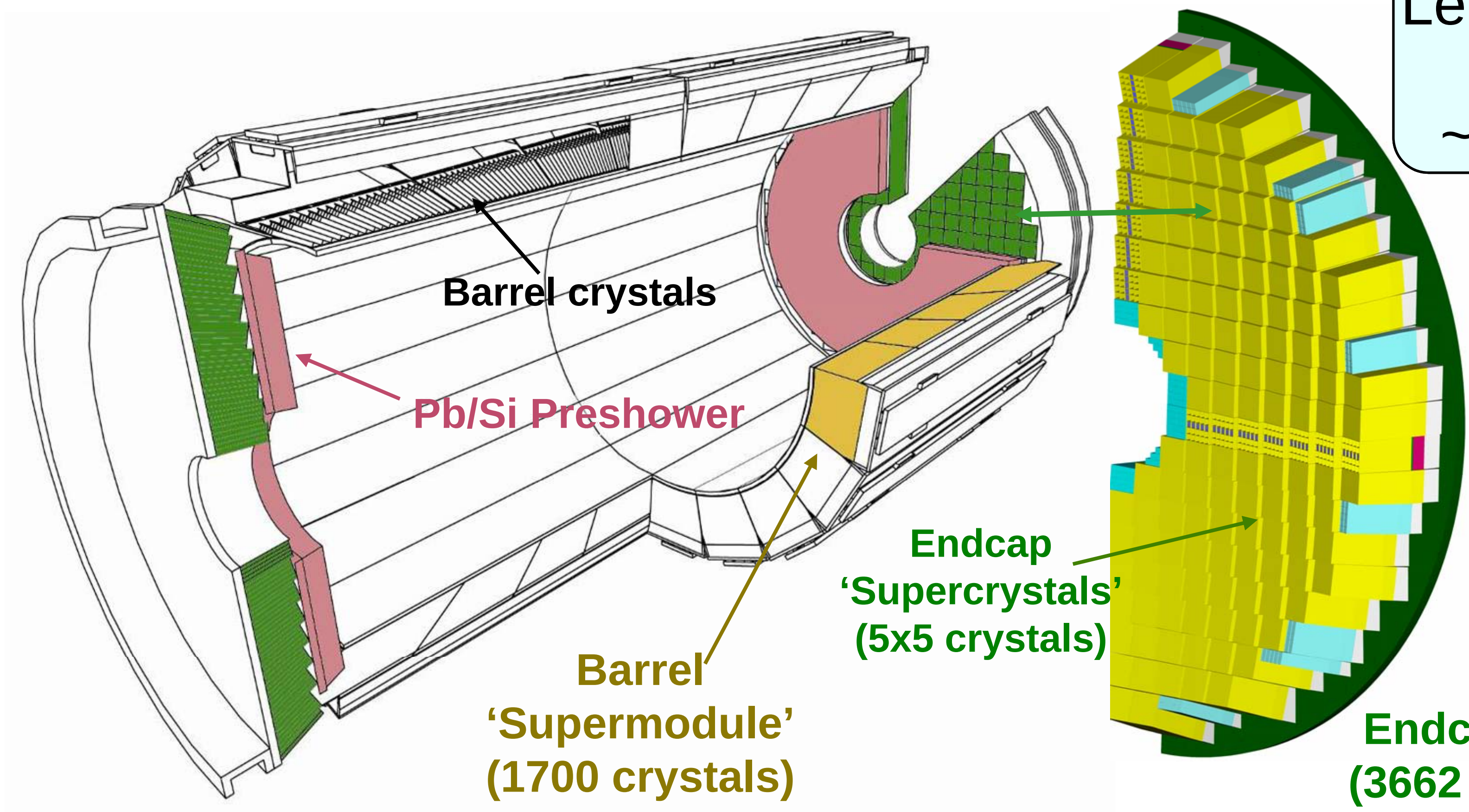
- Fast response (25ns between bunch crossings)
- High radiation doses & neutron fluences
  (10 year doses: 10^{13} n/cm^2, 1kGy (η=0)
  $2\text{x}10^{14}$ n/cm^2, 50kGy (η =2.6))
- Strong magnetic field (4 Tesla)
- On-detector signal processing
- Long term reproducibility

Choices:

- Lead tungstate scintillating crystals
- Avalanche photodiodes (Barrel), Vacuum phototriodes (Endcaps)
- Electronics in 0.25 μm CMOS
- Laser light monitoring system

ECAL layout

Lead tungstate
($PbWO_4$)
~ 11 m^3, 90 t



Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2 x 2 x 23 cm^3)

Endcaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3 x 3 x 22 cm^3)

Lead tungstate properties

Fast light emission: ~80% in 25 ns

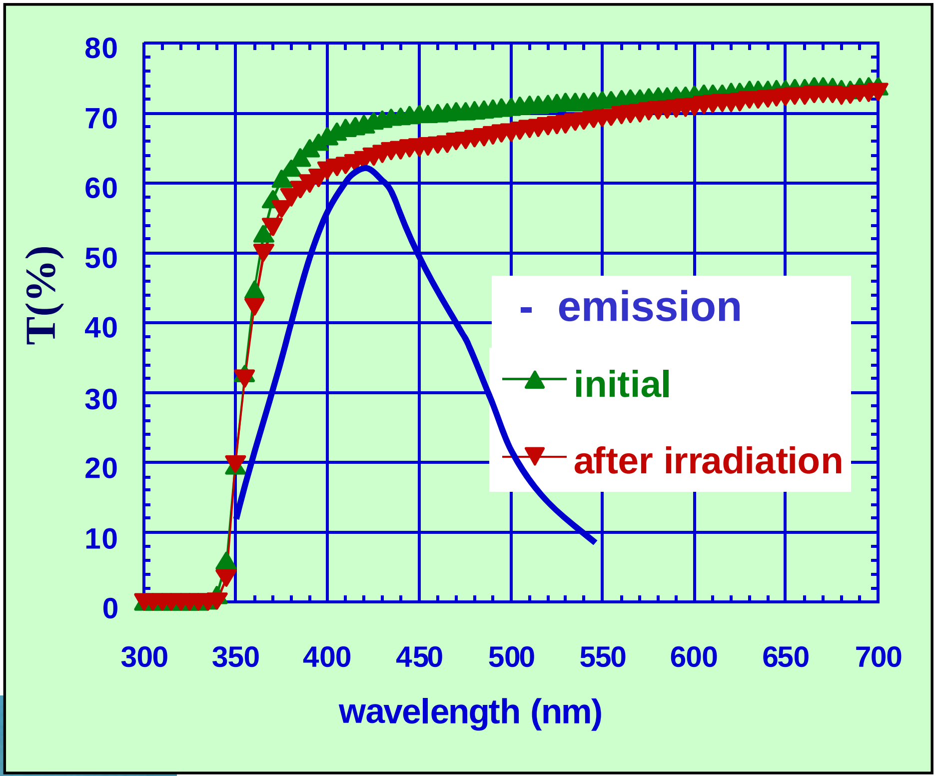
Peak emission ~425 nm (visible region)

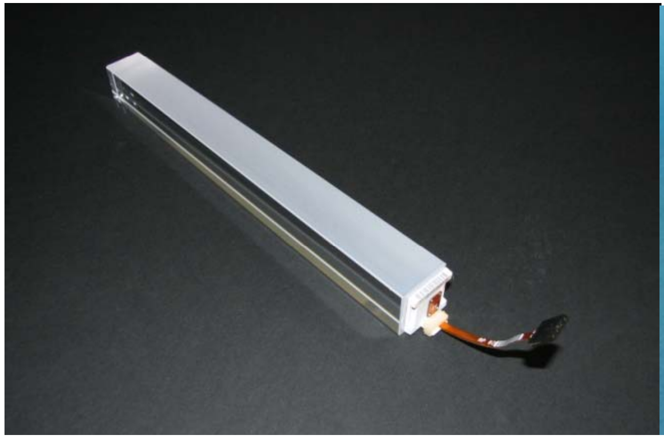
Short radiation length: X_0 = 0.89 cm

Small Molière radius: R_M = 2.10 cm

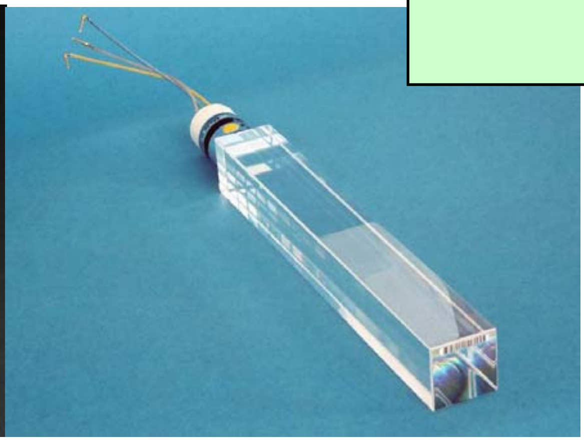
Low Light yield: 1.3% NaI(Tl)

⇒ **Photodetectors with gain at 4T field**



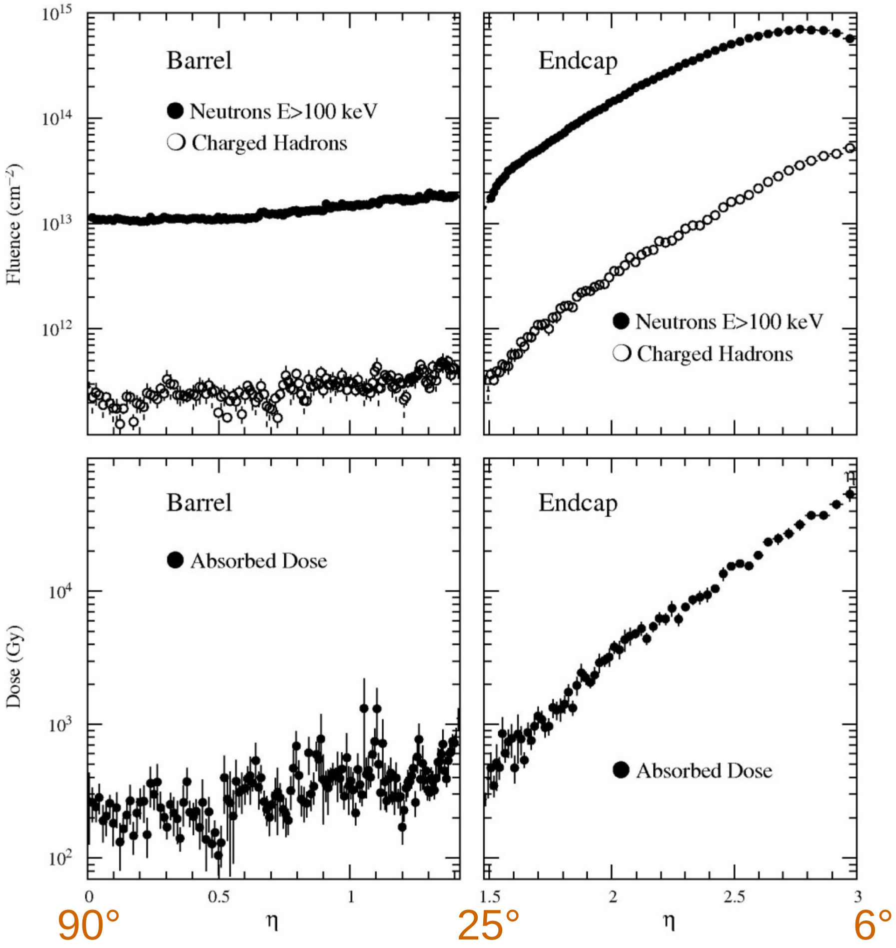


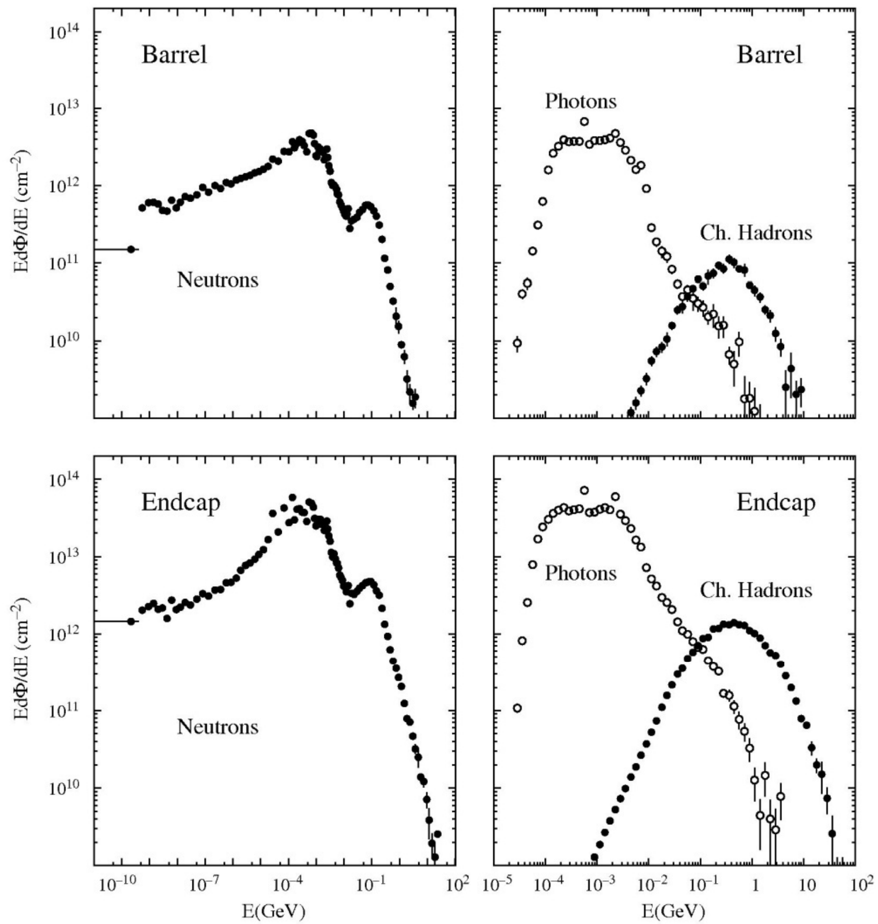
Barrel crystal, tapered
34 types, ~2.6x2.6 cm^2 at rear



Endcap crystal, tapered
1 type, 3x3 cm^2 at rear

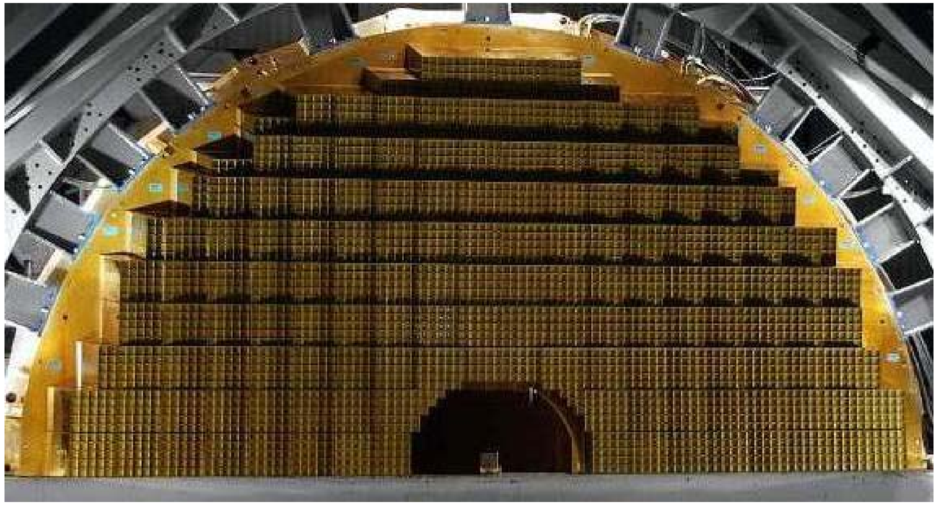
ECAL Radiation Environment



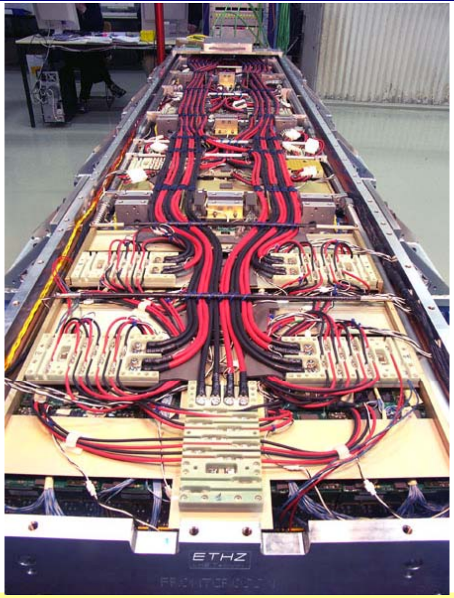


LHC 10 year normal operation assumed

ECAL Construction



A completed Endcap with all Supercrystals



Barrel “Supermodule” (1700 crystals) with cooling, electronics & readout installed

Very complex multilayer structure for both the Barrel “supermodules” and the Endcaps.

Almost impossible to disassemble without damage.
At the LHC we will get significant activation of components due to intense hadron fluence.
Treat component parts of modules as if they were on a satellite!
⇒ **Need very good QA on every component**

Avalanche Photodiodes

Barrel: Avalanche photodiodes (APD)

Two 5 x 5 mm^2 APDs/crystal

- Gain: 50 QE: ~75% @ λ_{peak}= 420 nm
- Temperature dependence: -2.4 %/°C
- Gain dependence on bias: 3 %/V
- Capacitance 80 pF

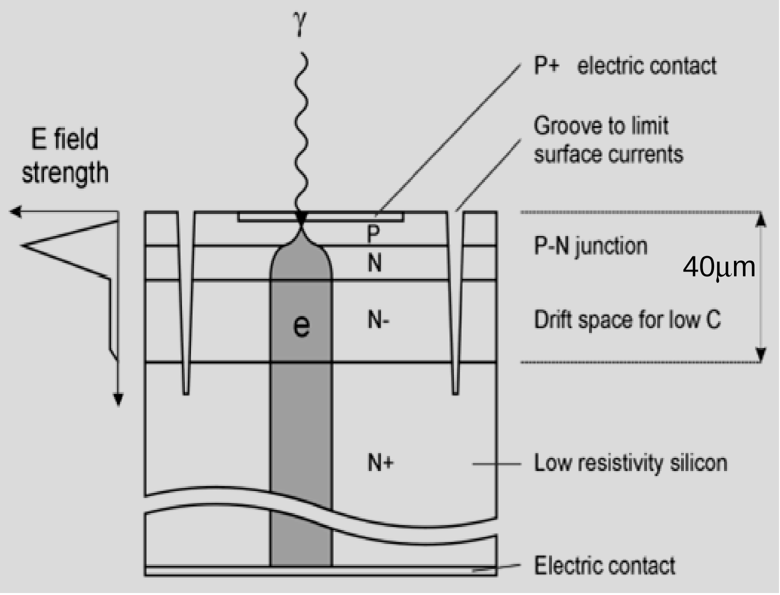
•Hamamatsu type S8148

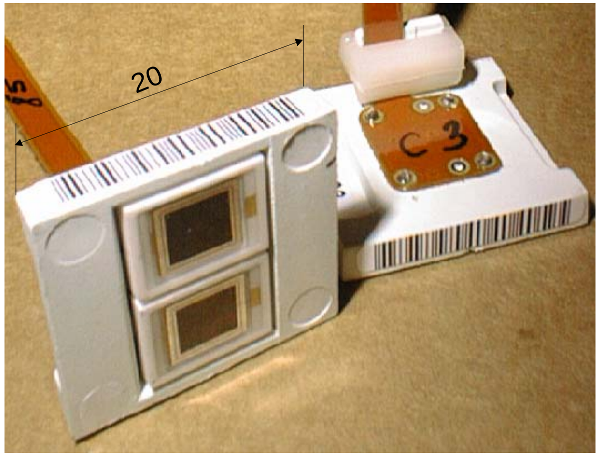
•Silicon: p^+, p, n, n^- and n^+- type structure

•The n^- layer increases the thickness of the depletion region.

This decreases both the capacitance and the dependence of the gain on the applied bias voltage.

d_{eff} ~6μm

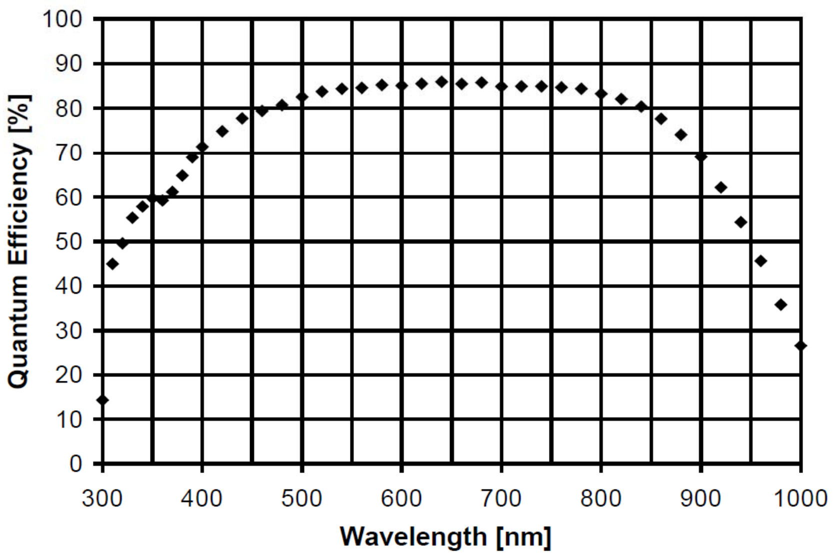


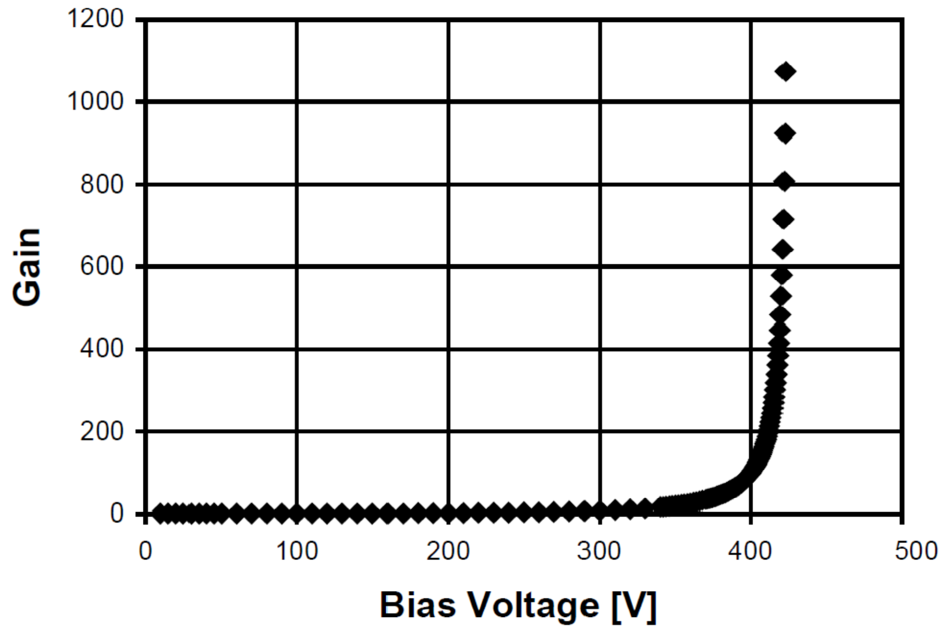


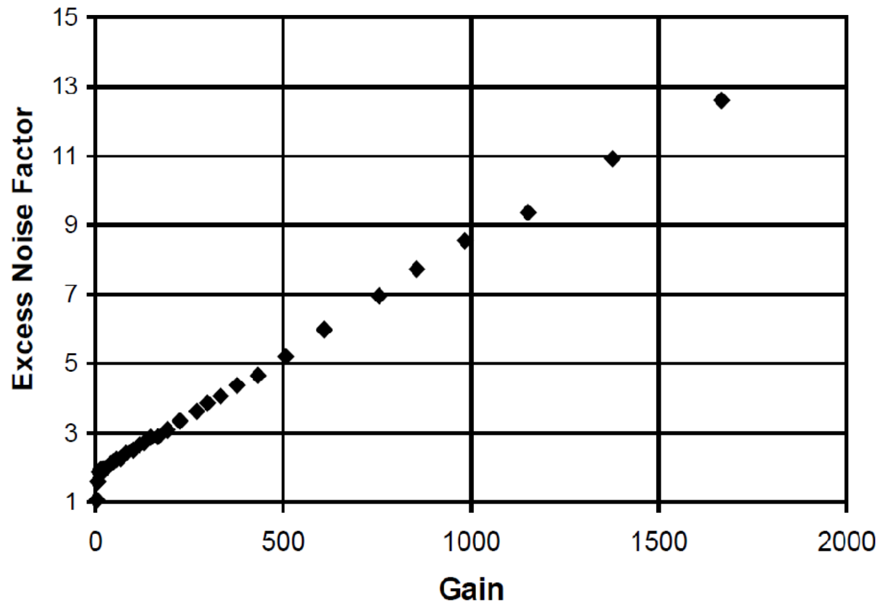
Avalanche Photodiodes

Hamamatsu type S8148

QE, Gain *vs* applied bias voltage, Excess Noise Factor





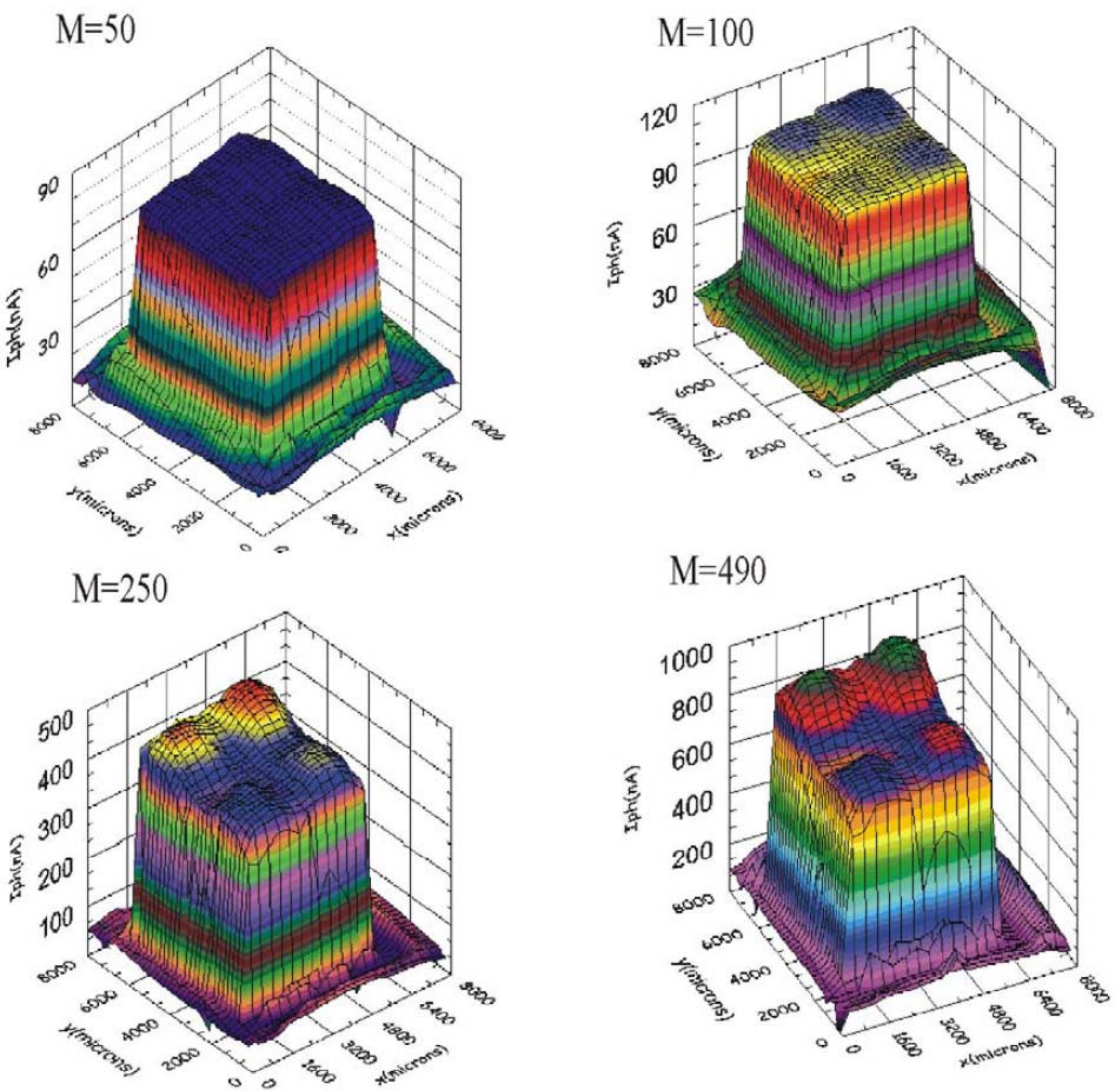


See D Renker, *NIM A* **486** (2002) 164

Avalanche Photodiodes

Uniformity of response to light depends on the operating gain (M). Spot diameter of blue light was 0.2 mm, area scanned was 8×8 mm^2.

Excellent uniformity at M =50 and M = 100 indicates excellent control of the doping and few lattice defects over the very large active area of the APD.



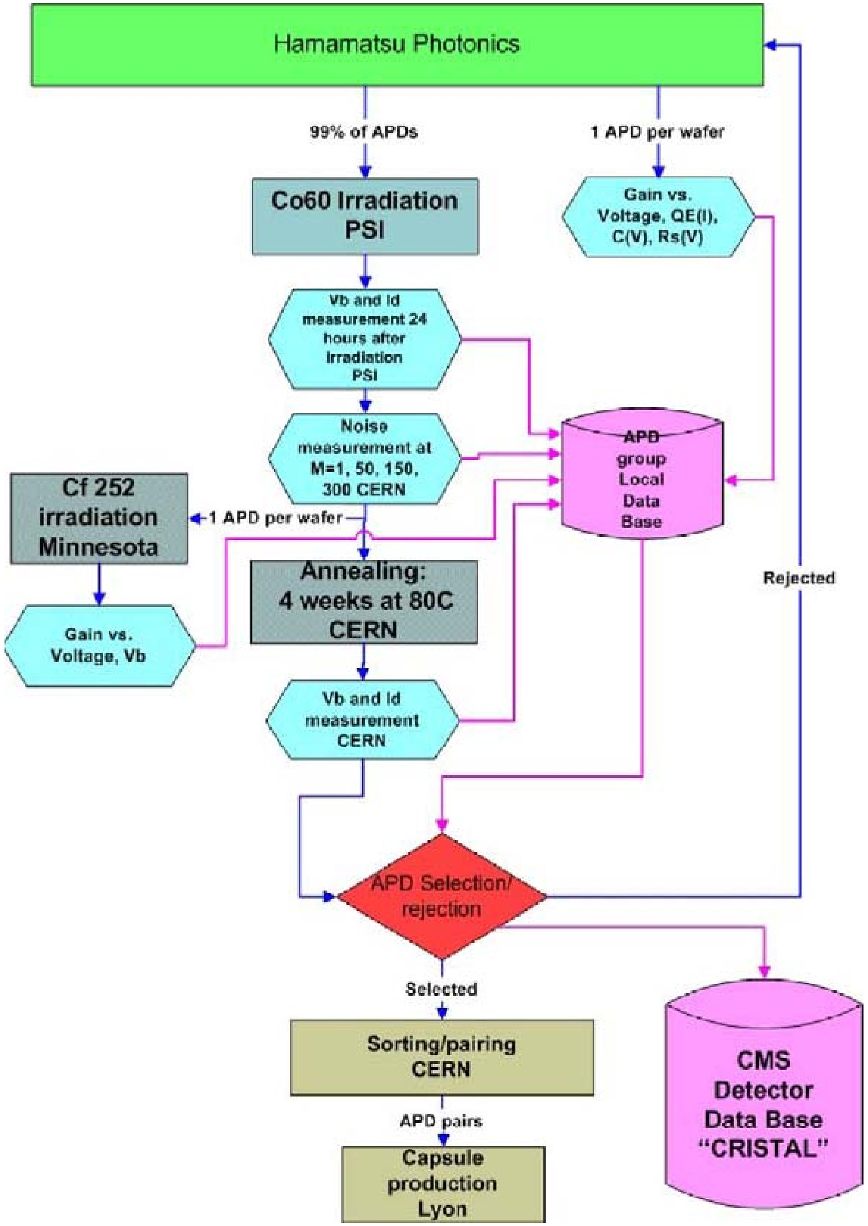
From CMS Note 2004/008

Avalanche Photodiodes QA

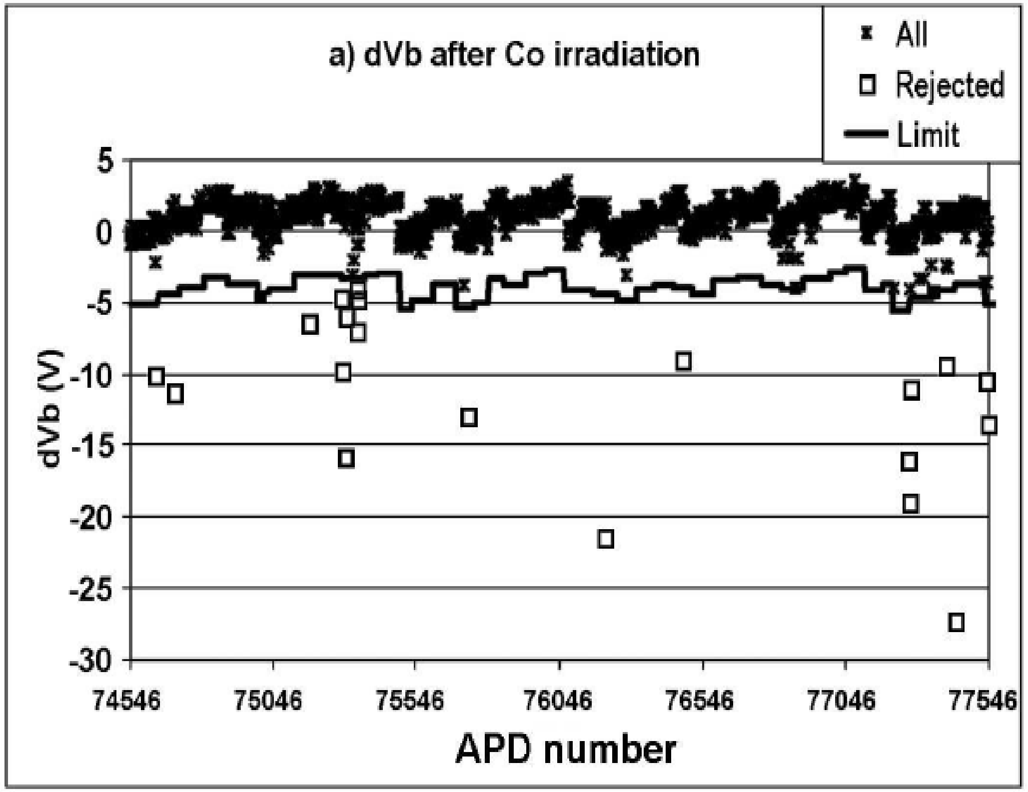
Procedure for all APD (~123 thousand)

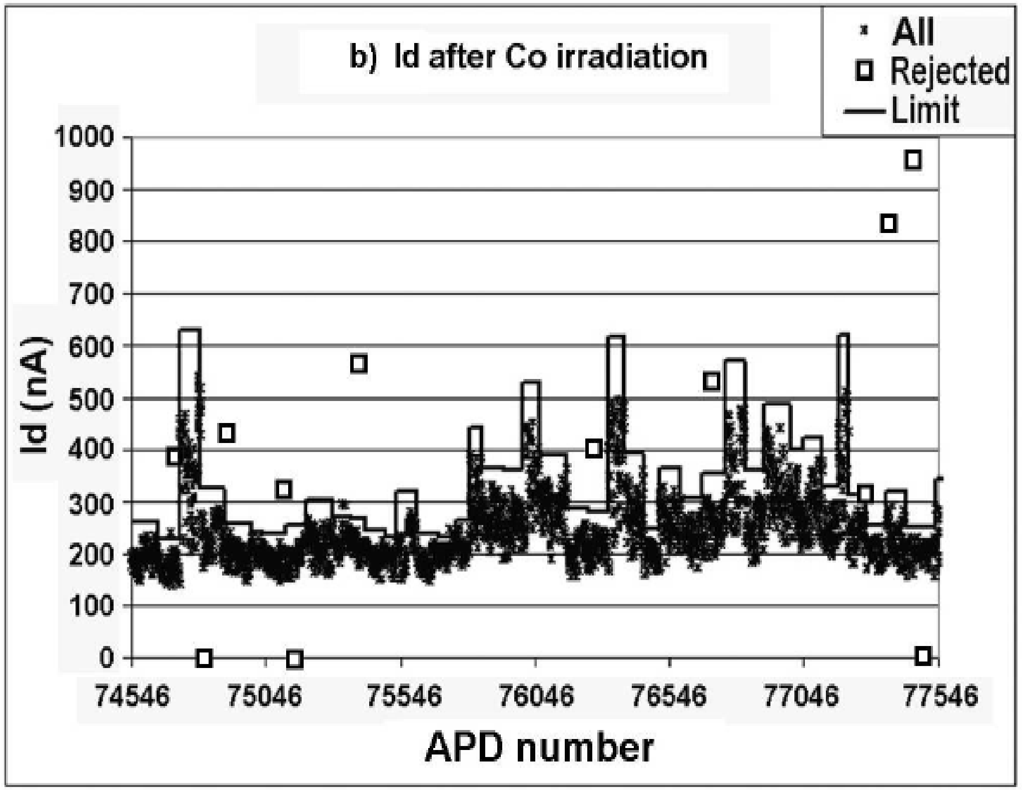
- Irradiate each APD mounted in conducting foam inside an isotropic ^{60}Co source (5 kGy in 2 h.)
- After one day measure I_{dark} to breakdown.
- After one week measure the noise at gains of 1, 50, 150 and 300.
- Run the APDs under bias at ~350V for 4 weeks at 80 C
- Measure I_{dark} to breakdown.
- Reject if breakdown voltage changed by > 5V, or if I_{dark} or noise anomalously high

APD: Workflow for QA



Avalanche Photodiodes QA





3000 production APD evaluated at a gain of 50

From CMS Note 2004/008 (also *NIM* **A537** (2005) 379-382)

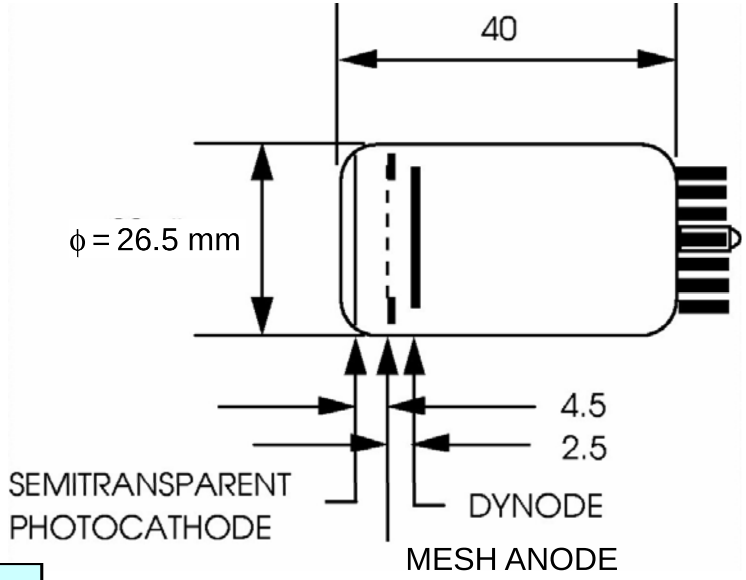
Vacuum Phototriode

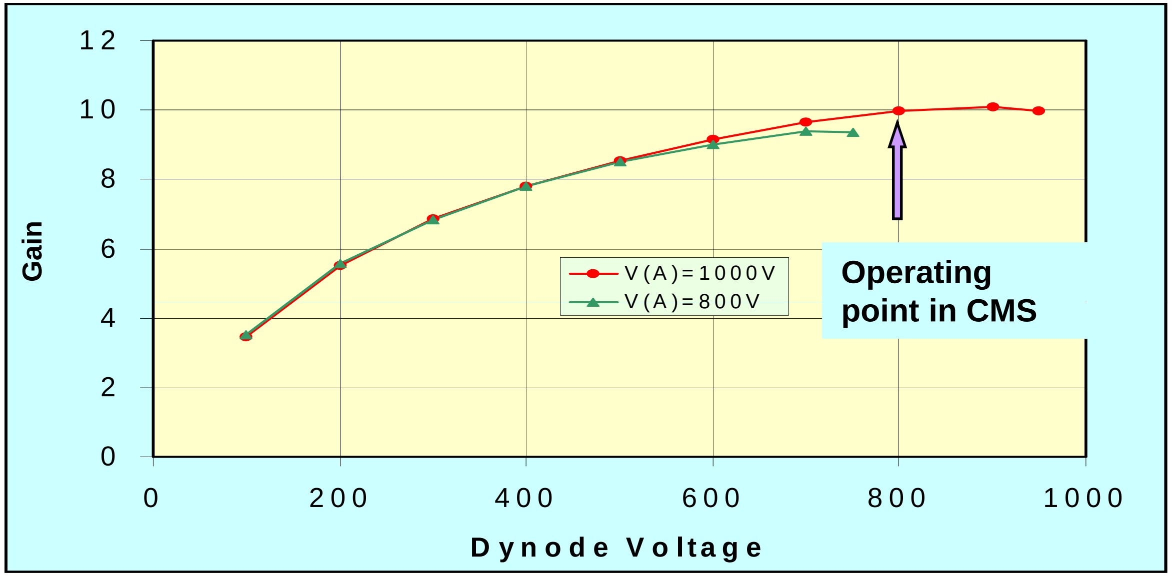
Endcaps: Vacuum phototriodes (VPT)

Produced by RIE, St Petersburg, Russia

More radiation resistant than Si diodes (with UV glass window)

- Active area ~ 280 mm^2
- Gain ~10 (B=4T) Q.E.~ 20% (420 nm)
- Fast devices (simple planar structure)



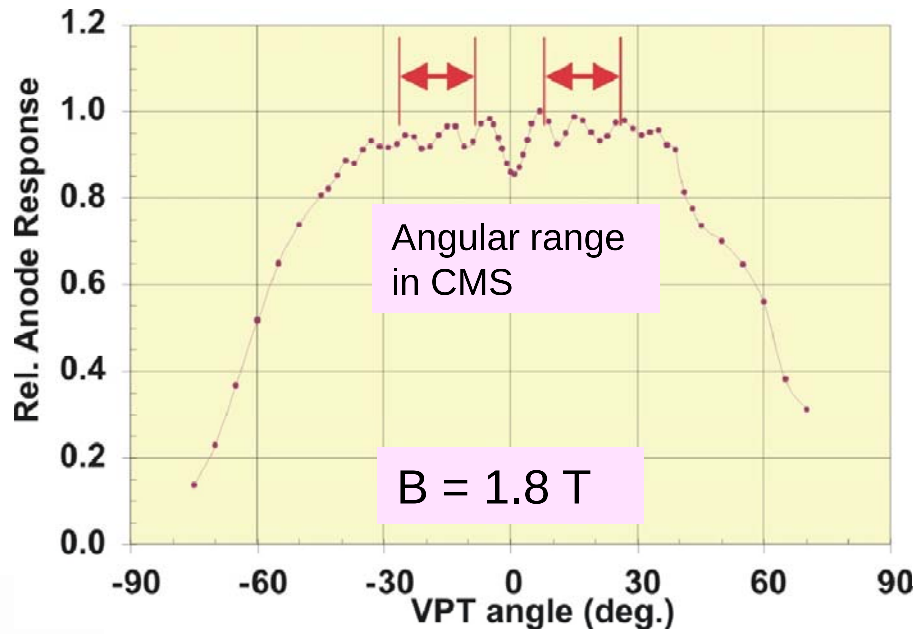


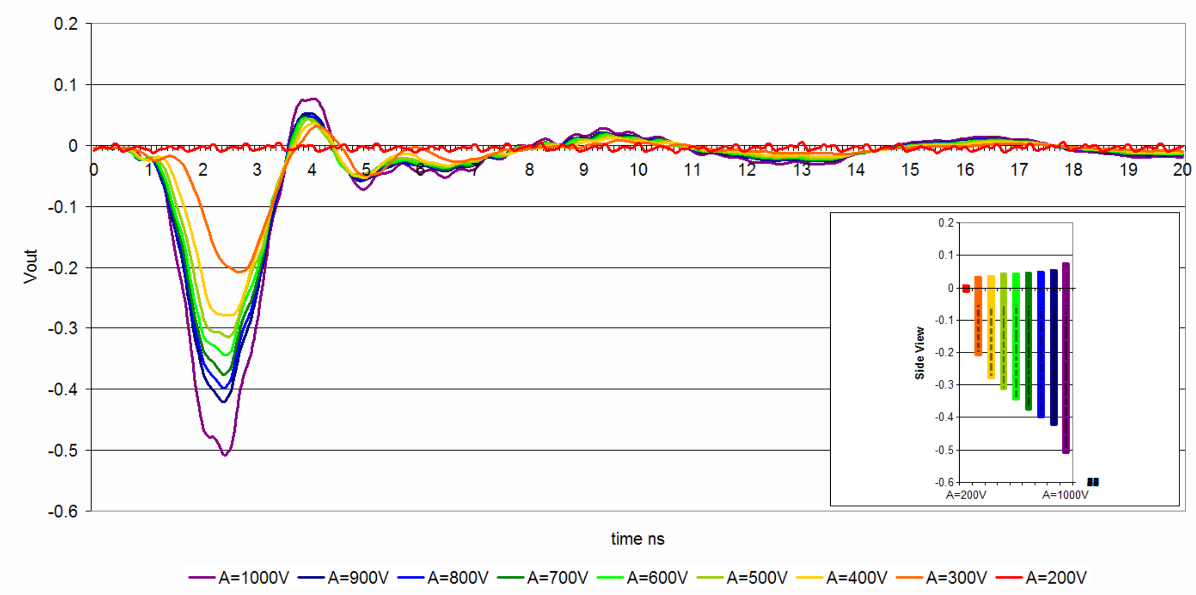
Vacuum Phototriode

Magnetic Field Response

Response drops off with angle to field outside central 30 degrees region.

Oscillations are feature of square mesh anode, reproduced across all VPT





Fast Pulse Response

Response to 80 ps laser pulses at 435 nm wavelength.

Rise and fall times are of order 1 ns (limited by non-optimised connection of anode to the exterior pins).

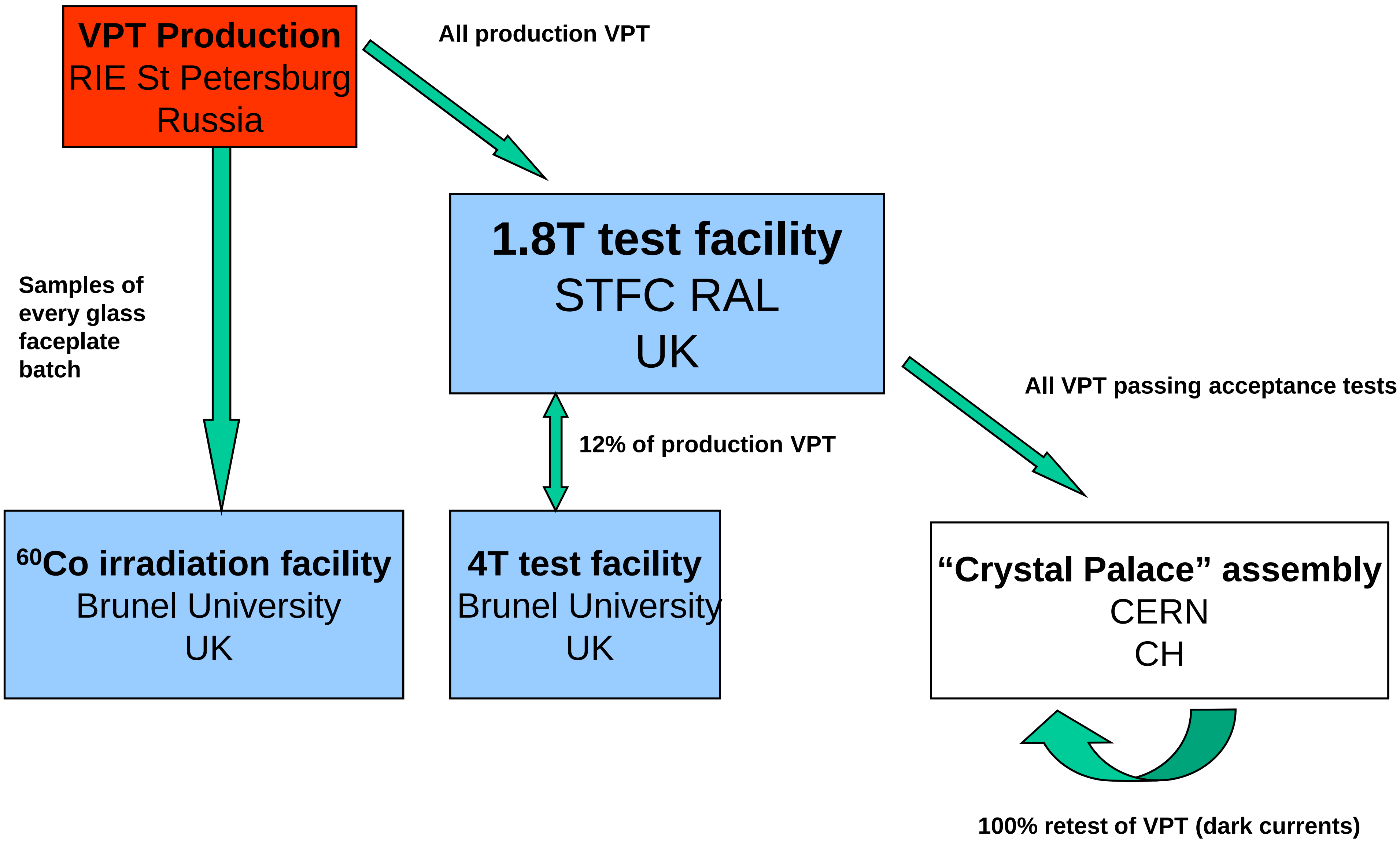
VPT QA

Procedure for all VPT (~17 thousand)

- All VPT evaluated at 0T and 1.8T and at angles ± 30°
- 12% batch sampled also tested at 15° at 4T
- All glass batches for faceplates evaluated for ^{60}Co radiation tolerance (to 20kGy) **before** production
- All dark currents re-checked after VPT shipped from UK to CERN

⇐ 1.8T facility
4T facility ⇒

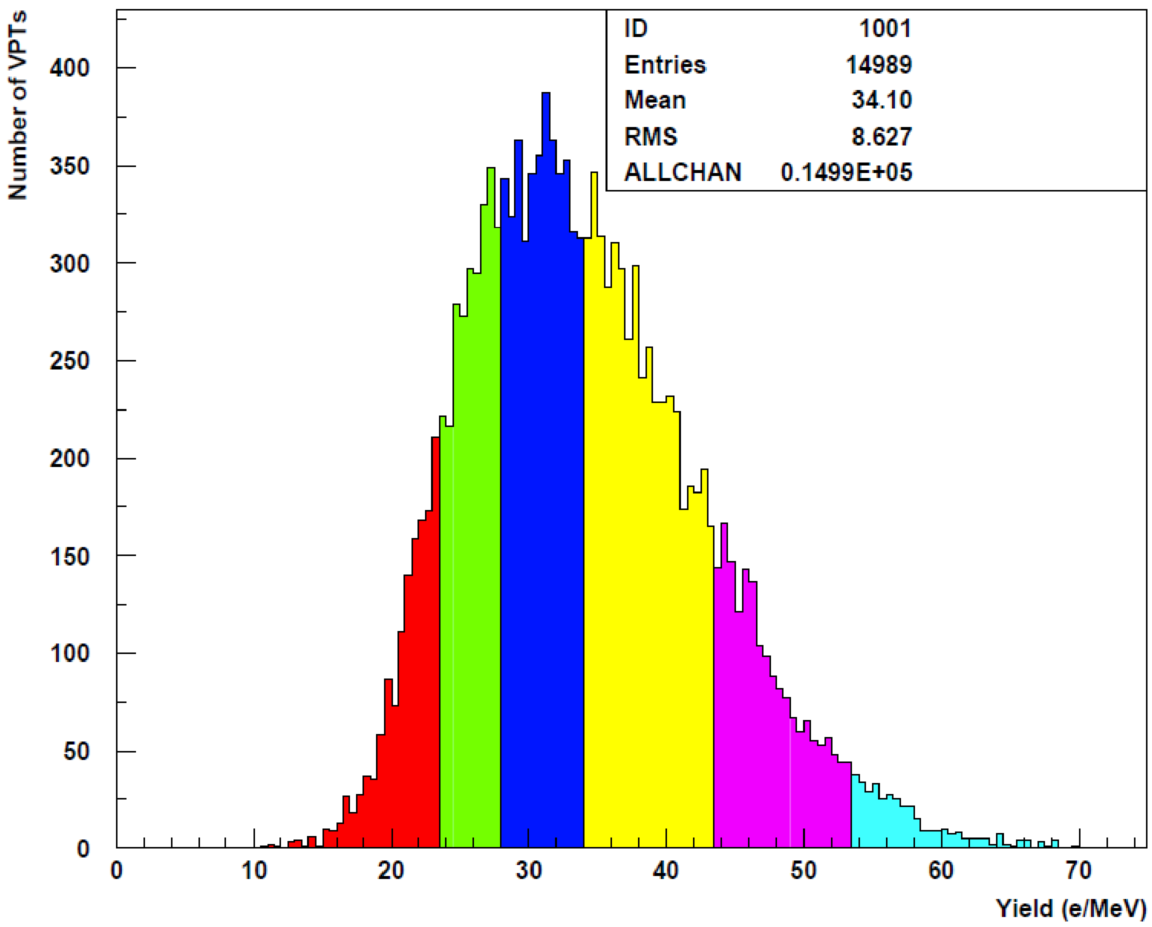
VPT QA workflow



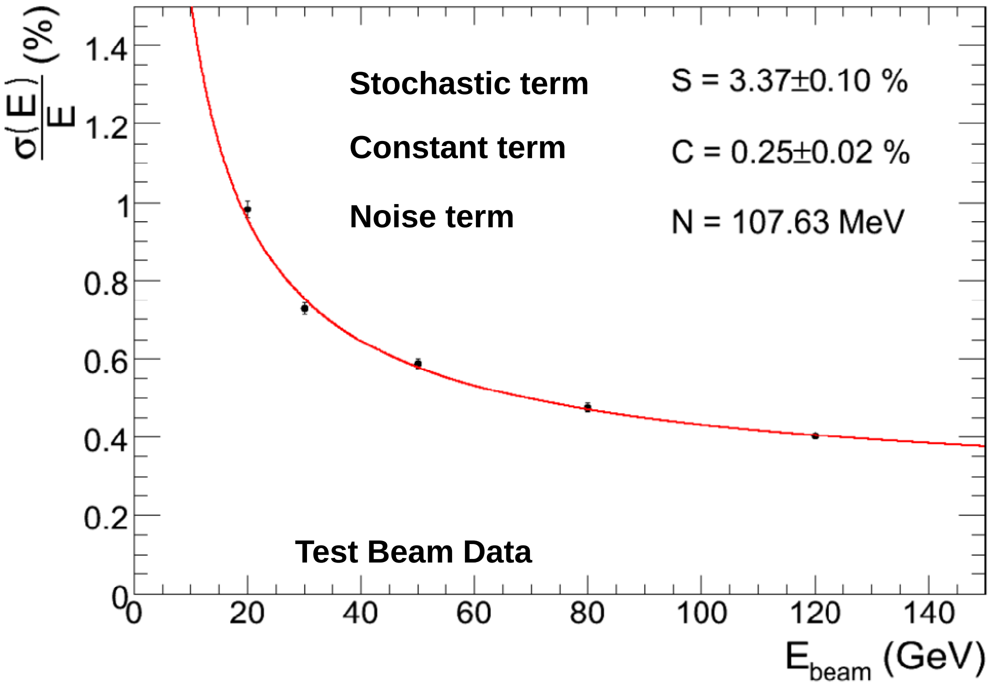
VPT QA

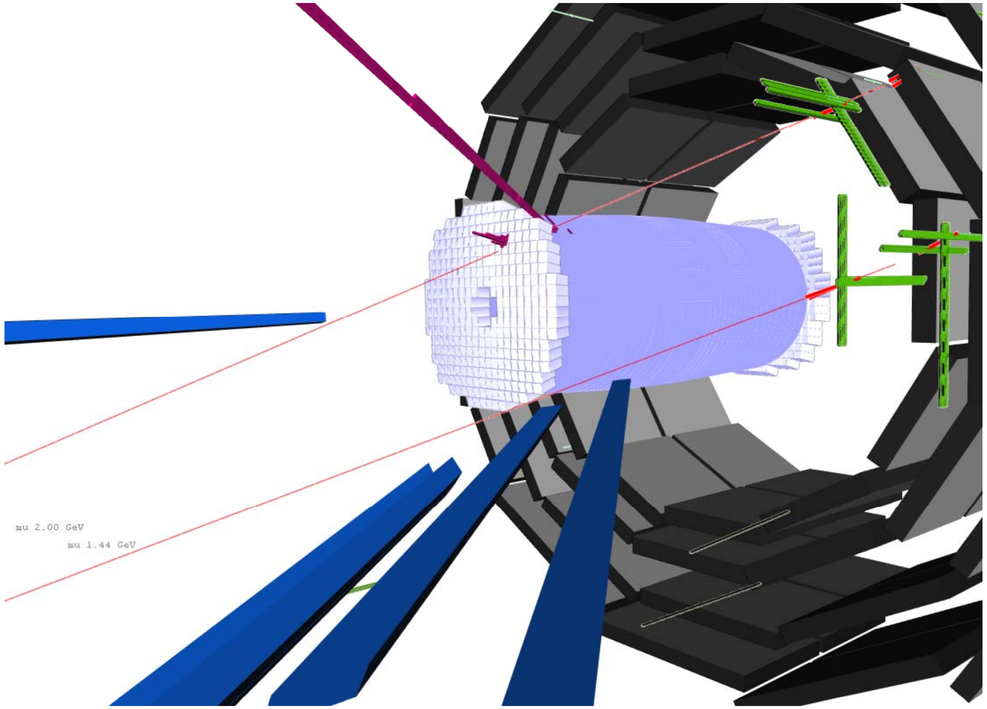
Yield (Gain*QE) variation for the production VPT.

Data shown are the average yield from 8 to 25 degrees and at a fixed field of 1.8T



ECAL Operation





Energy resolution for electrons as a function of energy

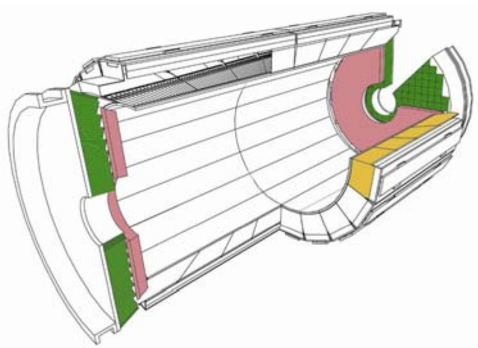
Data folded in from 25 3x3 arrays from a trigger tower of 25 crystals.

Electrons centrally (4mm x 4mm) incident on the crystals

This cosmic ray event was recorded in late August 2008 during the Global Run (CMS magnetic field at 0T).

Summary

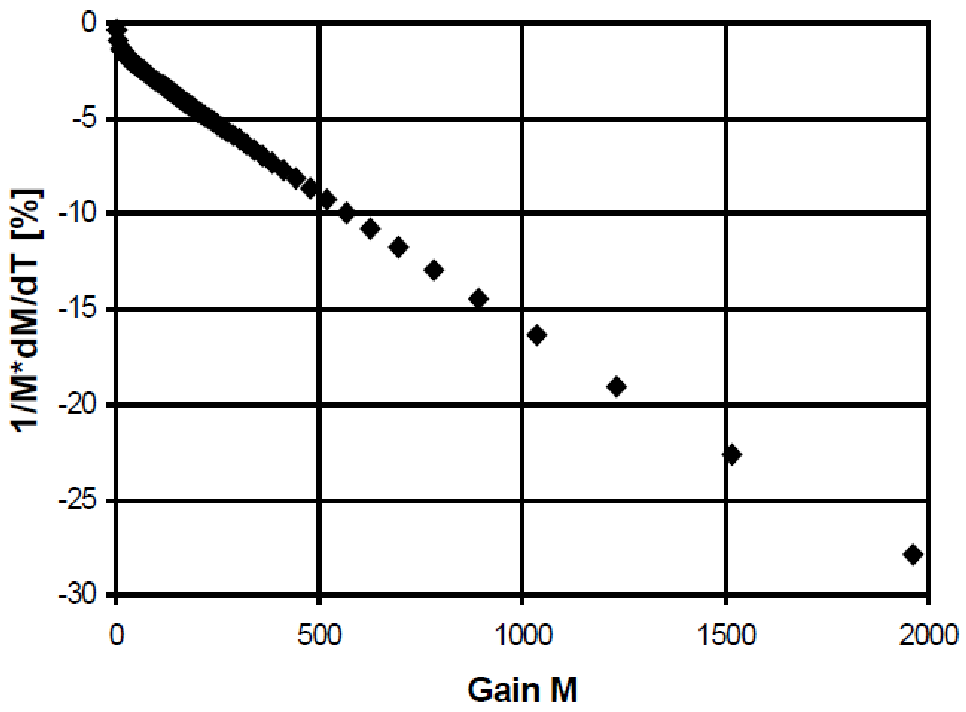
- A hallmark feature of CMS is the high resolution crystal ECAL.
- Two different technologies for the photodetectors used.
- Very extensive QA was performed on all component parts.
- 123 thousand APD and 17 thousand VPT **fully** tested before assembly.
- Extensive test beam studies demonstrate the CMS ECAL will meet its ambitious design goals.
- The whole ECAL is now complete, pre-commissioned and fully installed in CMS.
- **We eagerly await the first p-p collisions at the LHC!**

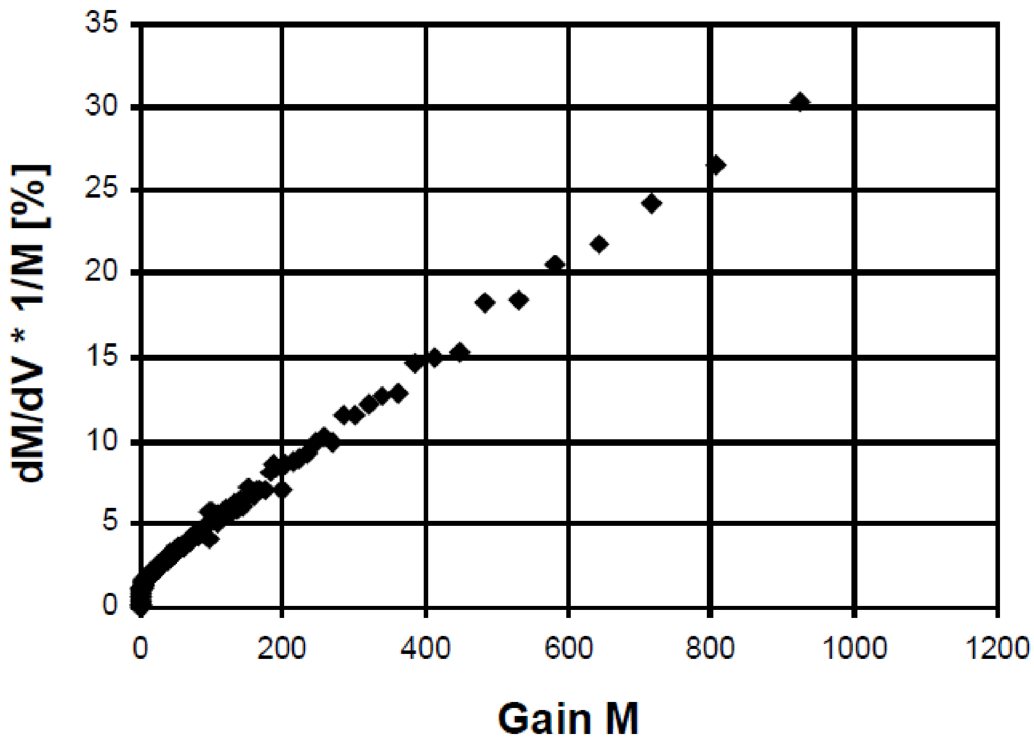


Spares

Hamamatsu type S8148

Sensitivity to Temperature and Bias Voltage Variation





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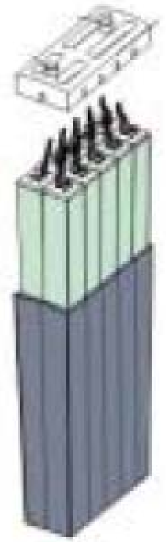
ECAL Construction: Barrel

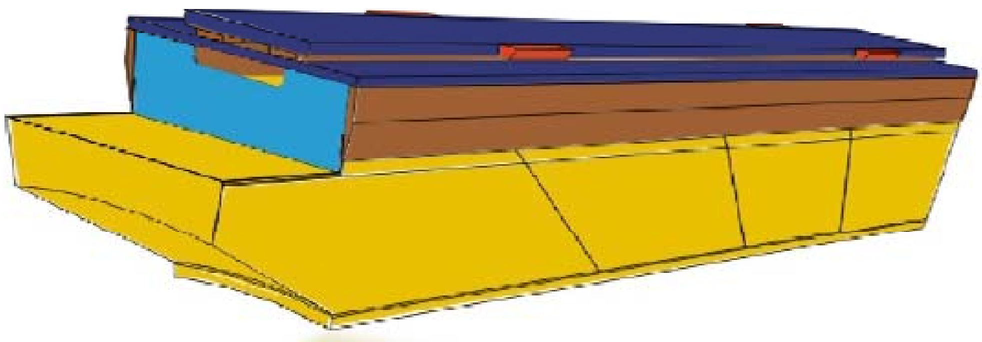
Sub-module assembly (10 crystals)



bare supermodule

Cooling circuits installed

Super module (4 modules, 1700 crystal)



Completed and fully cabled