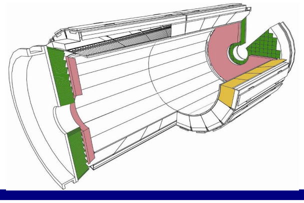
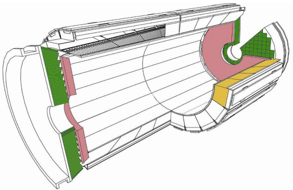


Calibration and performance test of the Very-Front-End electronics for CMS electromagnetic calorimeter

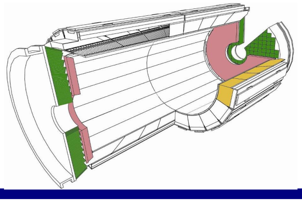
Jan Blaha

26th September 2008

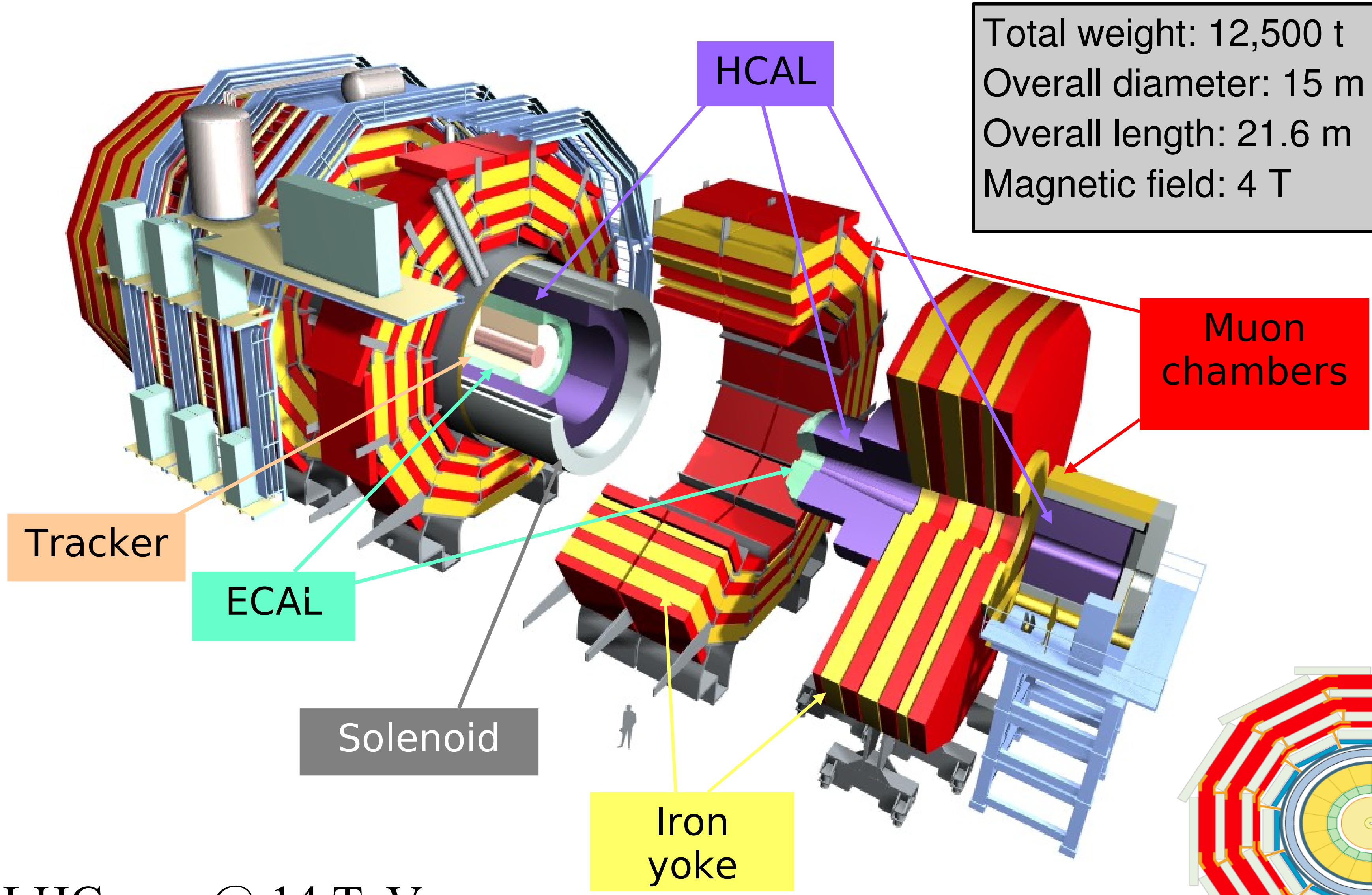


Presentation outline

- CMS and Electromagnetic calorimeter
- Read-out electronics
- Calibration and performance of the VFE electronics
- Electronics performance during test beam
  - Noise, gain ratio, energy resolution
- Conclusion



Compact Muon Solenoid (CMS)



HCAL

Muon chambers

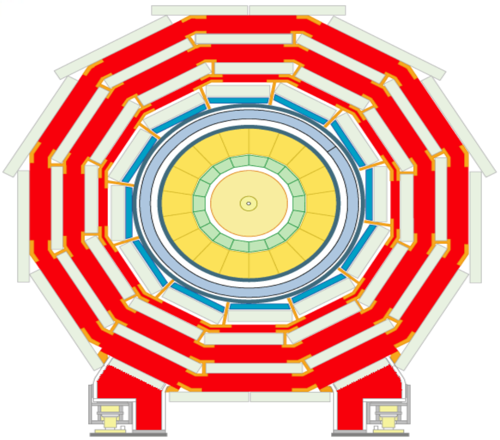
Tracker

ECAL

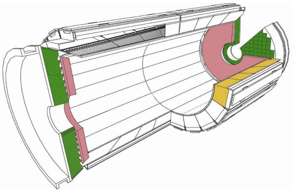
Solenoid

Iron yoke

Total weight: 12,500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 T



LHC: p-p @ 14 TeV
L = 10^{33} - 10^{34} cm^2 s^{-1}



ECAL resolution goal

Main goal: precise energy and position measurement of e, γ

Benchmark for $m_H < 150$ GeV/c^2: H ⇒γ γ

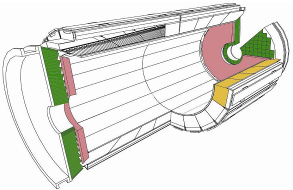
irreducible background ➡ **excellent energy resolution needed!!!**

Energy resolution:

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

a: Stochastic term: photo-statistics, shower fluctuations, ...
b: Noise term (5x5): electronic noise, pile-up noise, ...
c: Constant term: intercalibration, non-uniformities, ...

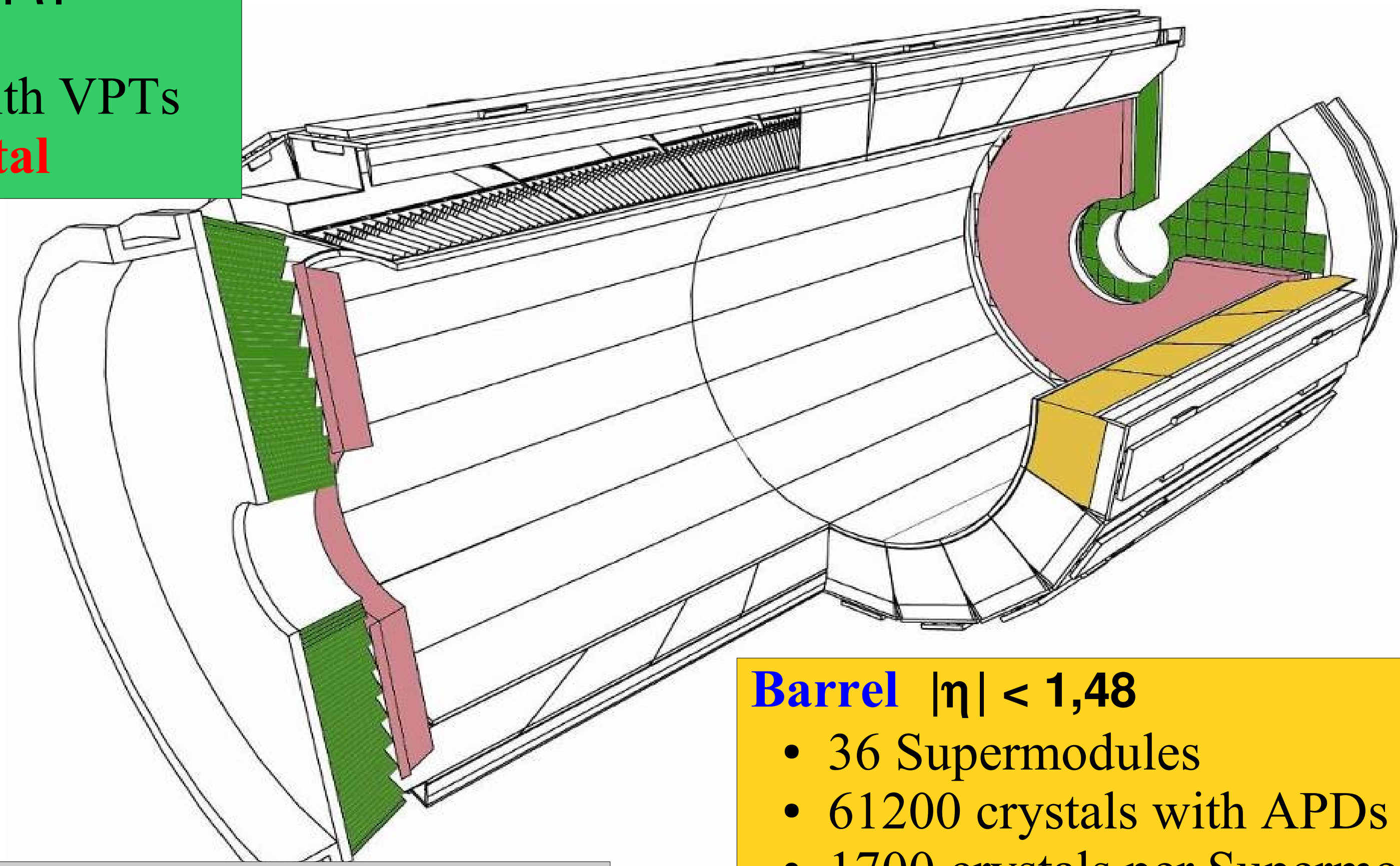
Contribution	Barrel	End-cap
Stochastic term	2.7%/√E	5.7%/√E
Noise term	0.155 GeV/E (0.210 GeV/E)	0.770 GeV/E (0.915 GeV/E)
Constant term	0.55%	0.55%

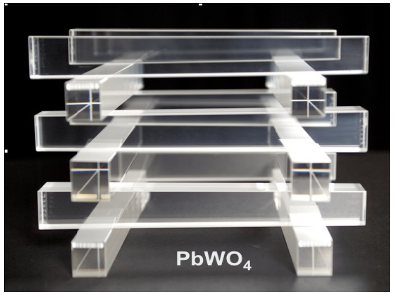


ECAL design

End-Caps **1.48 < |η| < 3.0**

- 4 Dees
- 14648 crystals with VPTs
- 2936 VFEs in total





PbWO$_4$ crystals:

- High density 8.28 g/cm^3
- Short radiation length 0.89 cm
- Small Moliere radius 2.19 cm
- Barrel: ~24 x 24 x 230 mm^3 (25.8 X_0)
- Endcap: 30 x 30 x 220 mm^3 (24.7 X_0)

Barrel **|η| < 1,48**

- 36 Supermodules
- 61200 crystals with APDs
- 1700 crystals per Supermodule
- 12240 VFEs in total

Preshower **1.65 < |η| < 2.6**

- Pb/Si, 2 layers
- 3 X_0

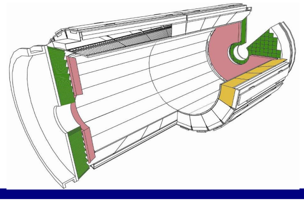


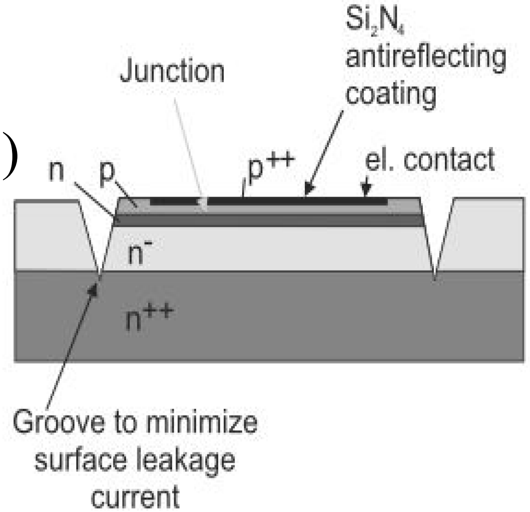
Photo-detectors

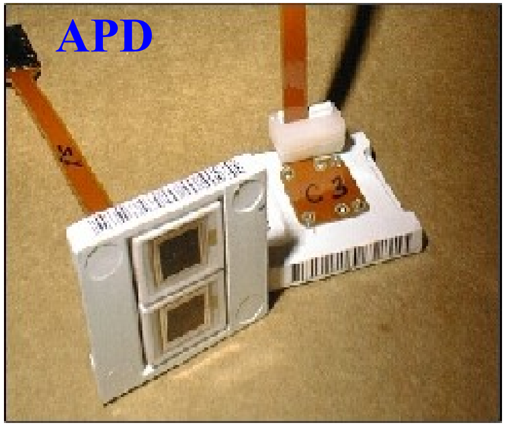
Requirements:

- Intristic amplification
- Fast (< 10 ns)
- Insensitive to 4 T mag field
- Radiation hard

Barrel: APD (S8141 Hamatsu)

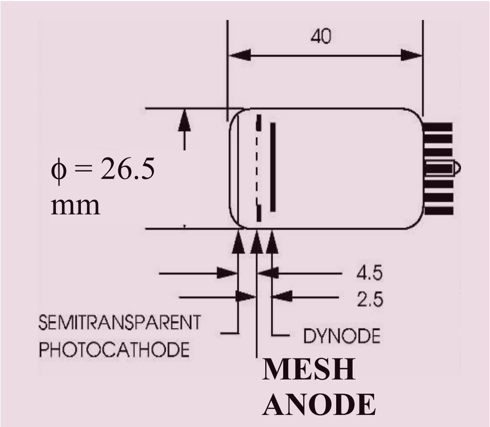
- Two APDs per crystal (total ~125000 pcs)
- Active area: 25 mm^2
- Quantum efficiency: 75 % at 430 nm
- Temperature sensitivity: -2.4 %/°C
- Voltage sensitivity: <3.5 %/V
- Operating gain: 50

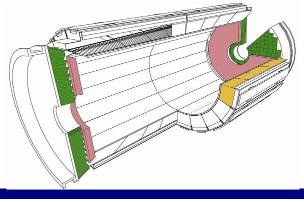




Endcap: VPT (PMT 188 RIE)

- One VPT per crystal (total ~15000 pcs)
- Active area: 280 mm^2
- Quantum efficiency: 22 % at 430 nm
- Temperature sensitivity: <0.1 %/°C
- Voltage sensitivity: <0.1 %/V
- Operating gain: 10

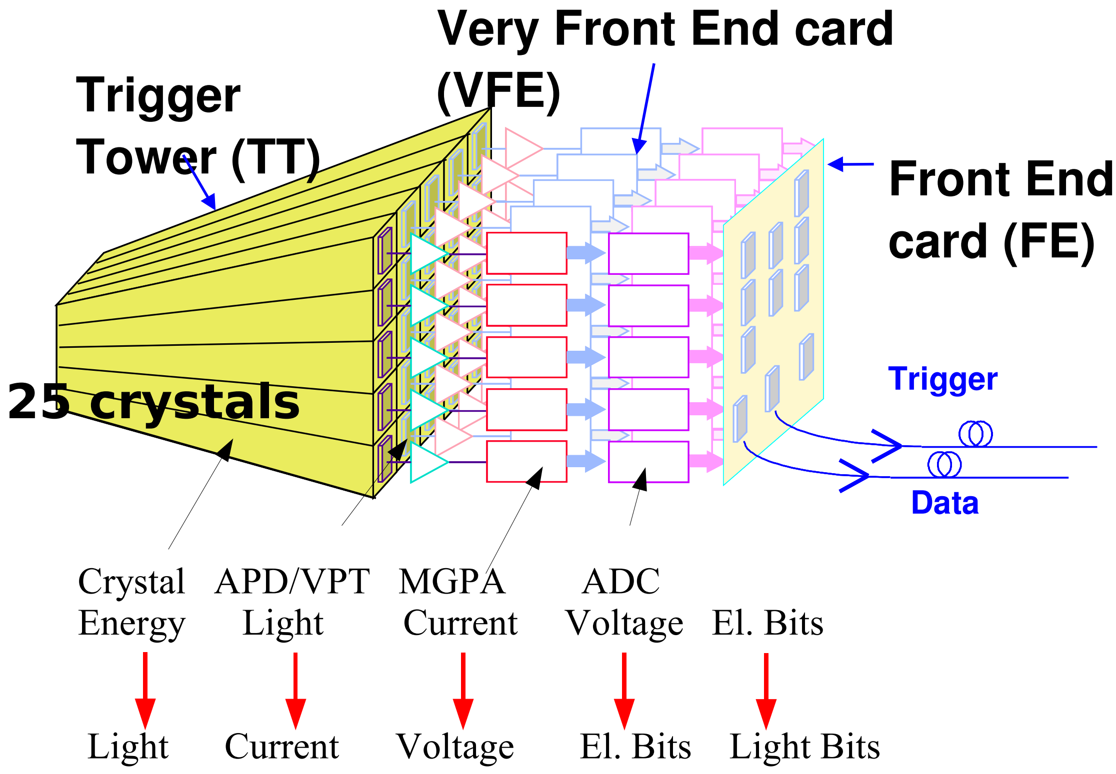


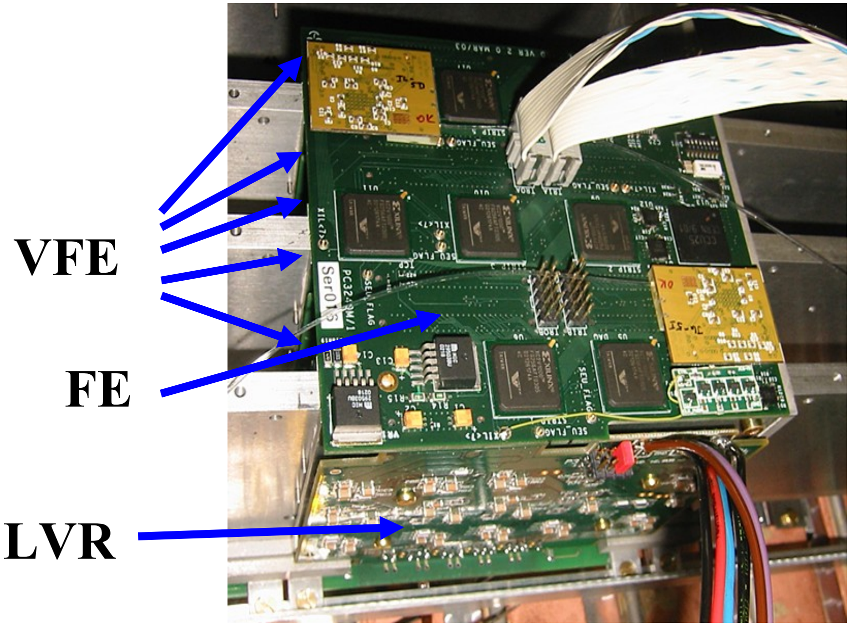


ECAL read-out electronics

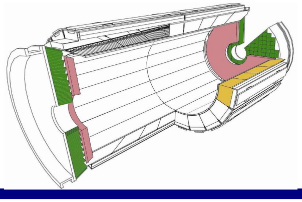
On-detector electronics

- **5 Very Front End cards (VFEs) - each VFE reads 5 crystals**
- 1 Front End card (FE) – sends control signal and receives data from the 5 VFEs
- 1 Low Voltage Regulator card (LVR)
- 1 Mother Board (MB)





Trigger tower in supermodule



Very-Front-End electronics

Requirements:

- Dynamic range from ~ 50 MeV to ~ 1.7 TeV (3 TeV)
  => 16 bits
- Low noise (<~ 50 MeV)
- Linearity ~ 0.1%
- Radiation-hard

Solution:

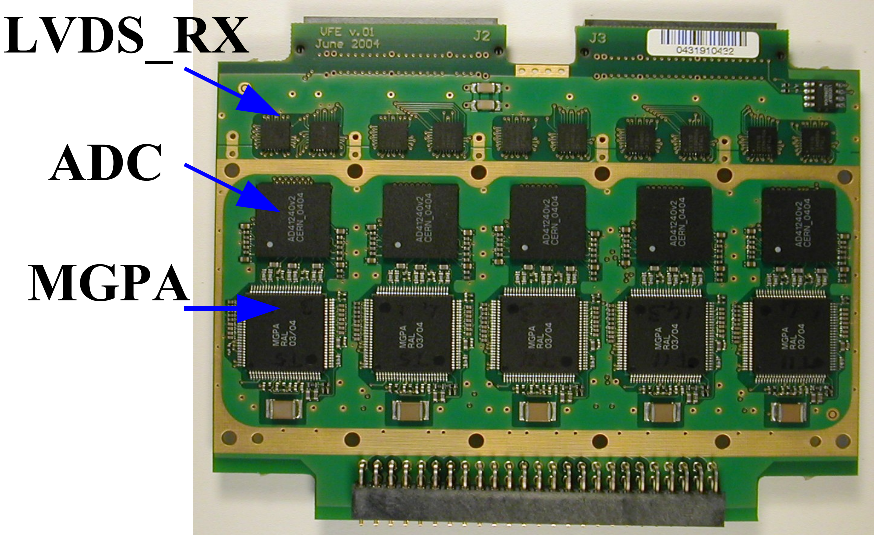
MGPA - Multi Gain Pre-Amplifier:

- Gains 1, 6 and 12.
- Full scale signal: barrel: 60 pc (~1.7 TeV)
  endcap: 16pC (~3 TeV)
- Linearity ~ 0.1 %

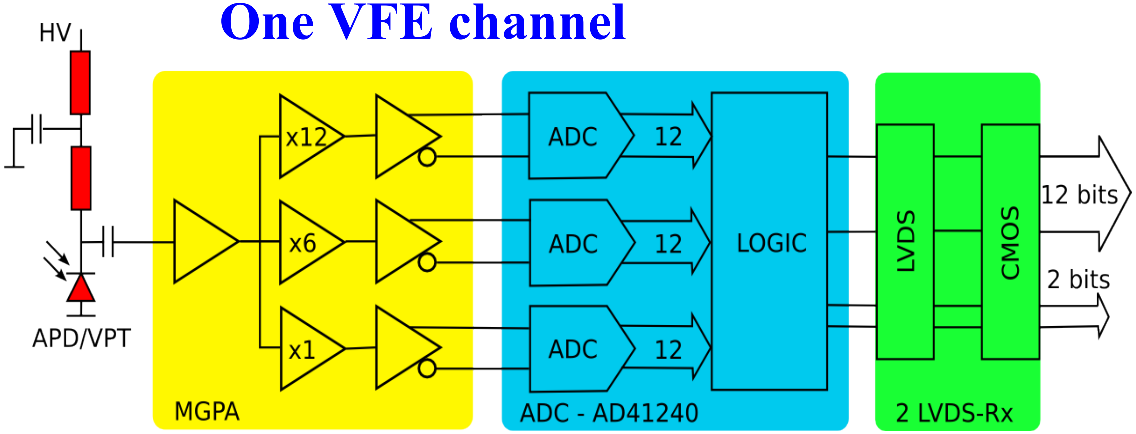
Quad Channel ADC (AD41240):

- 12 bit, 40 MHz
- Digital logic selects the highest unsaturated gain

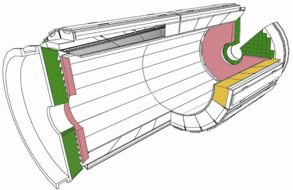
VFE card



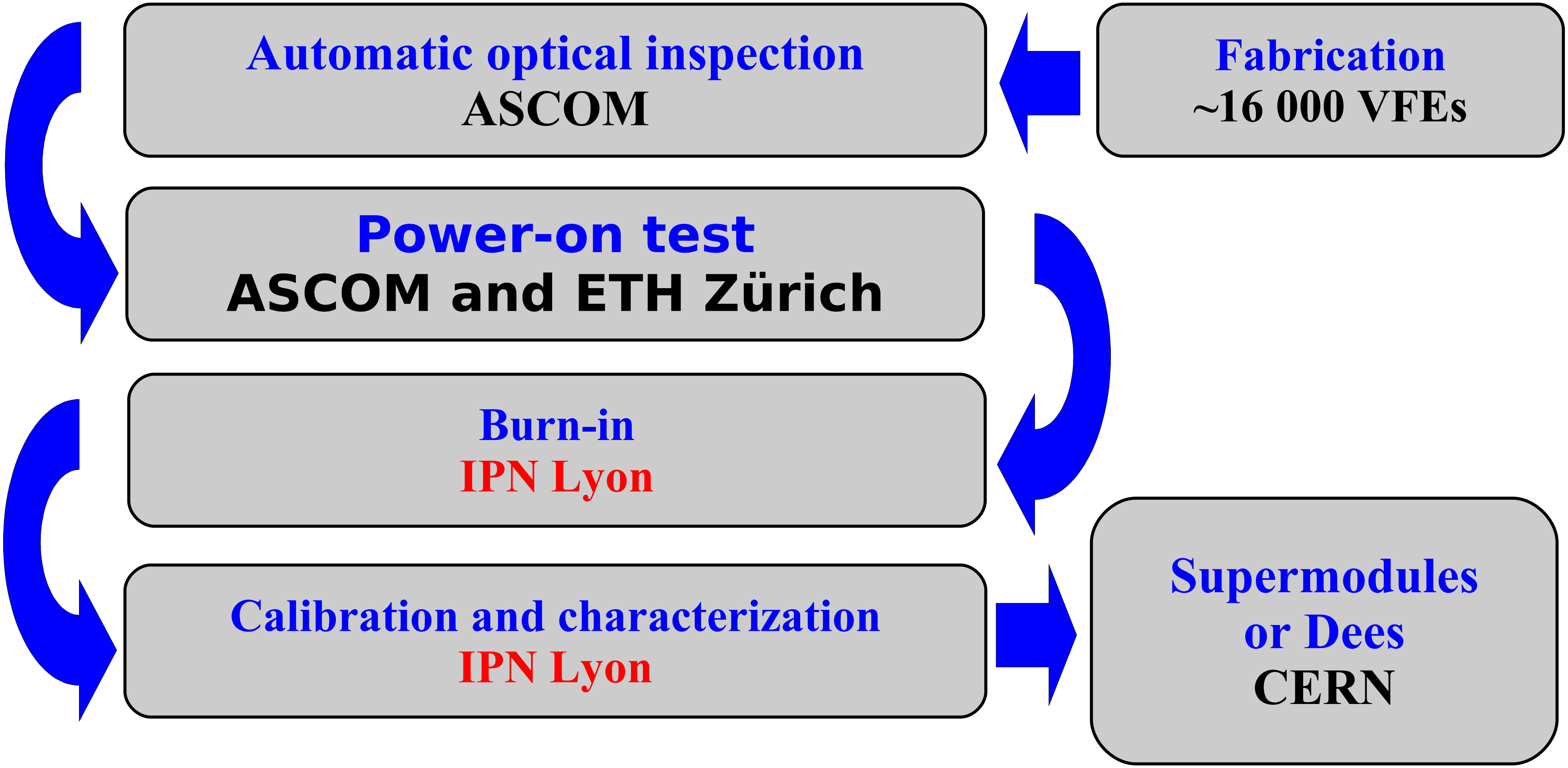
One VFE channel



All chips designed in 0.25 µm CMOS radiation hard technology



Production test program



Automatic optical inspection
ASCOM

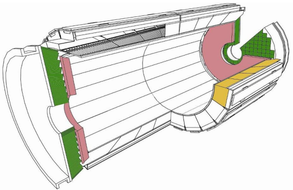
Fabrication
~16 000 VFEs

Power-on test
ASCOM and ETH Zürich

Burn-in
IPN Lyon

Calibration and characterization
IPN Lyon

Supermodules
or Dees
CERN



Calibration of the VFE electronics

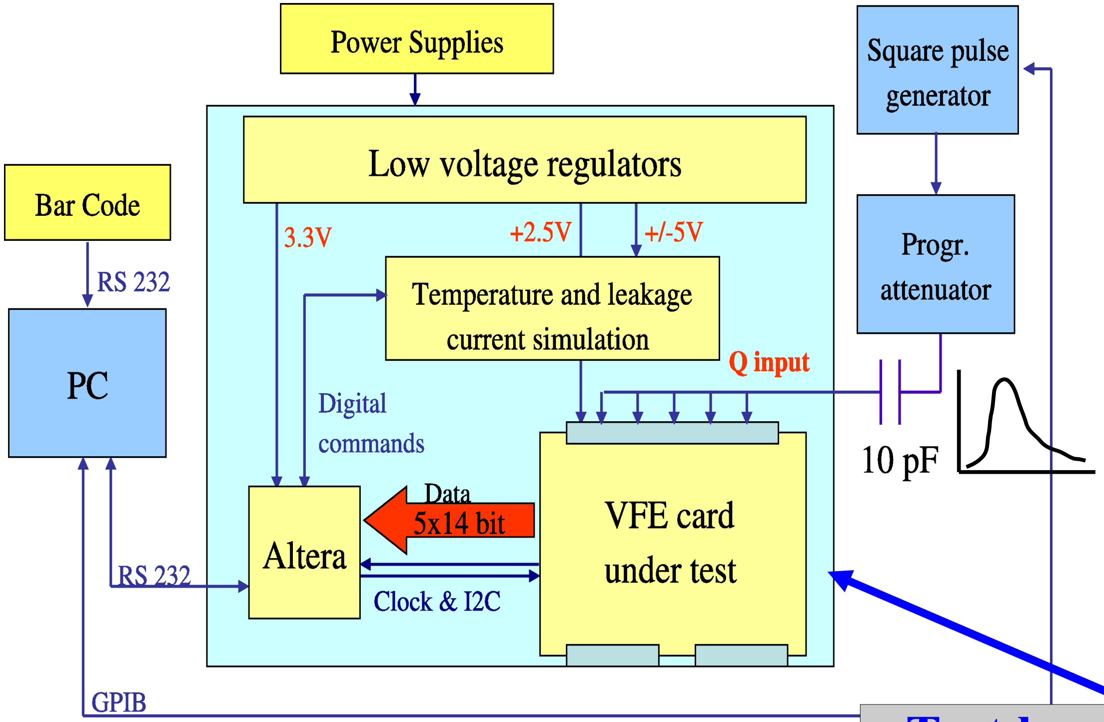
Main calibration goals:

- Absolute calibration of the 3 gains in ADC/pC (< 5%)
- Relative calibration between channels (< 2%)
- Determine gain ratios: G12/G6 and G12/G1(< 2 %)
- Linearity and Noise studies

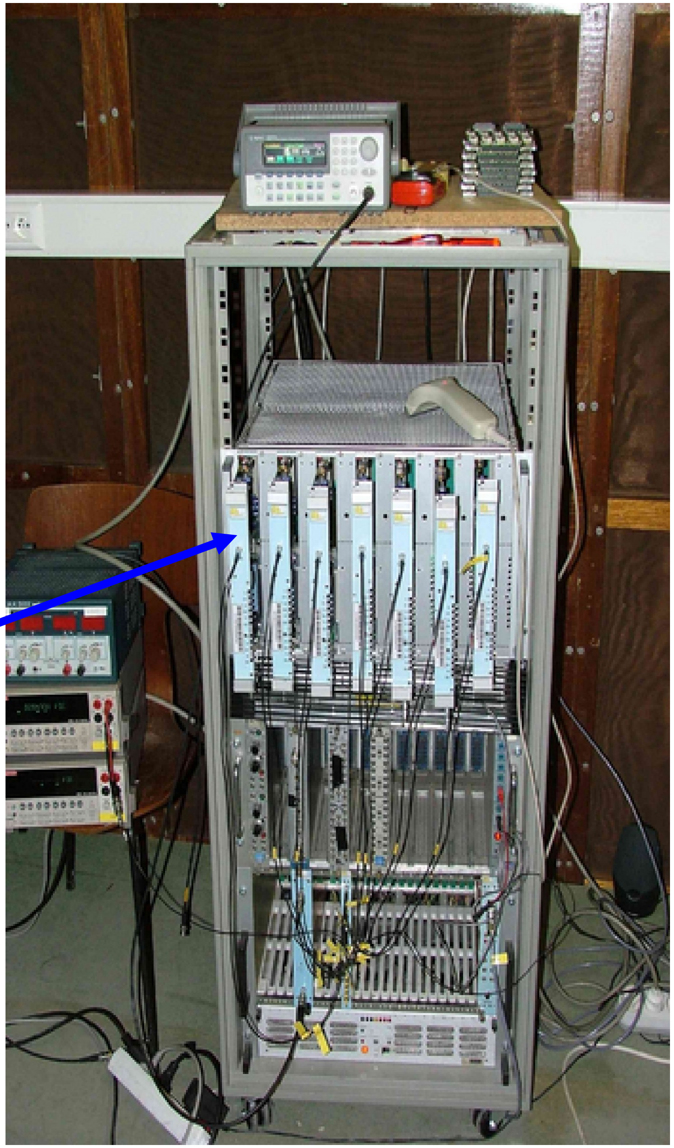
Other characteristic were also measured

- Pedestal setting was checked for each DAC
- Simulation of the APD leakage current and crystal temperature
- Verification of the MGPA test pulse unit functionality
- Check of the power consumption of the analog and digital parts

Calibration bench



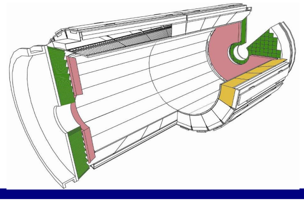
Test board
IPN Lyon



System set-up:

- **Agilent** square pulse generator
- **Attenuator** – range from 0 up to 63 dB
- **Capacitor:** 10 ± 0.01 pF
- **Fanout** – impedance adaptation between attenuator and test cards
- **Test boards** – to test VFEs
- **PC** – to pilot measurements and store data

Temperature-stabilized room(18±0.3) °C



Calibration procedure

Injected charge data range:

- Set of precise charges are injected into each gain
- Charge range: 0 - 40 pC for barrel
  0 – 9 pC for endcap
- Range chosen to remain under saturation
- Overlap points to check a good link between different gains

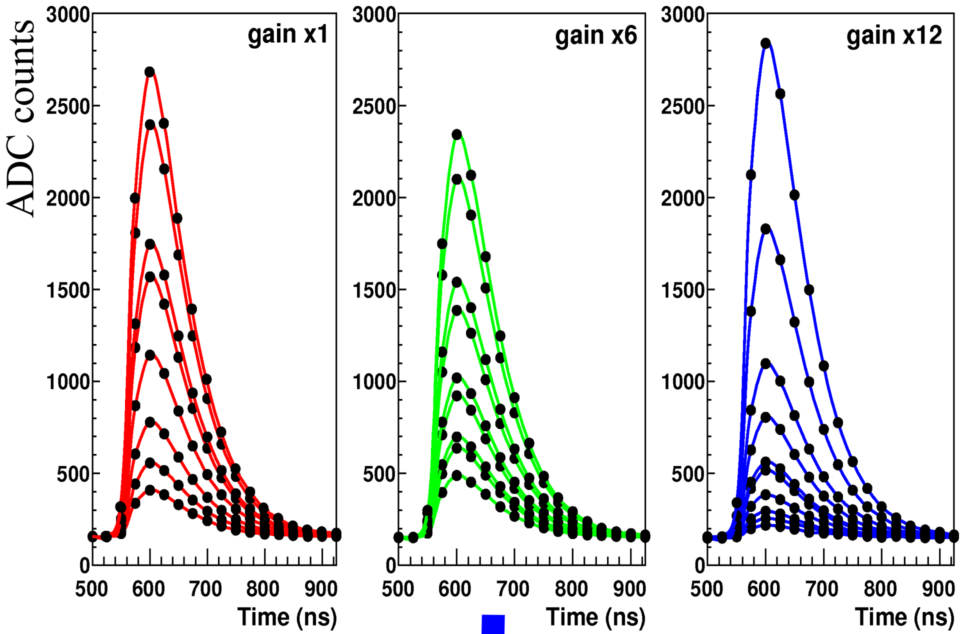
Electronic transfer function:

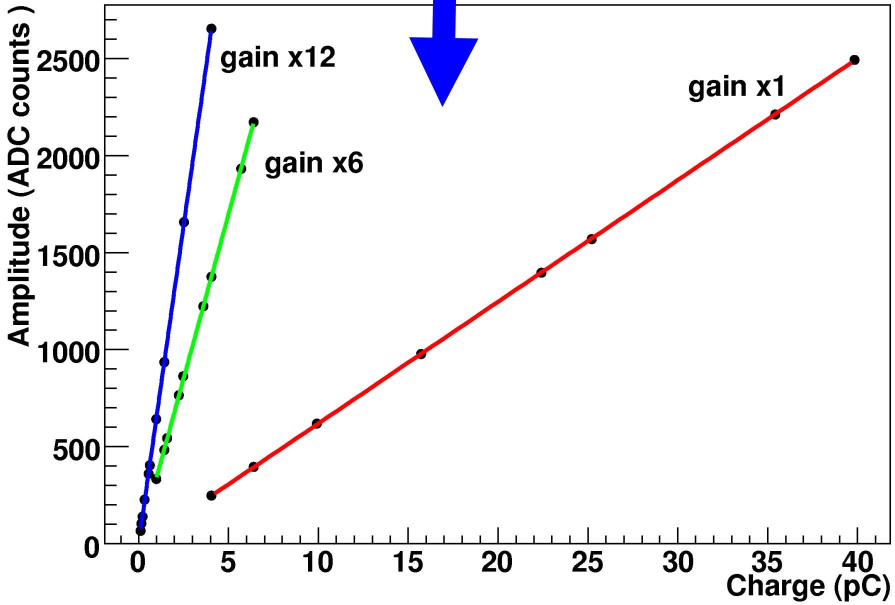
An analytic fit is used to extract an amplitude

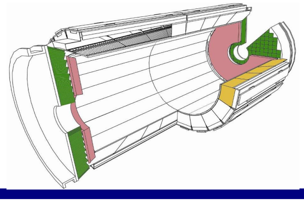
$$f(t)=\left(\frac{t-T_0}{\beta}\right)^{\alpha}\exp\left(-\alpha\frac{t-T_0-\beta}{\beta}\right)$$

Calibration curve:

The VFE gain is described by parameters (slope and intercept) of the linear fit of the extracted amplitudes versus charges







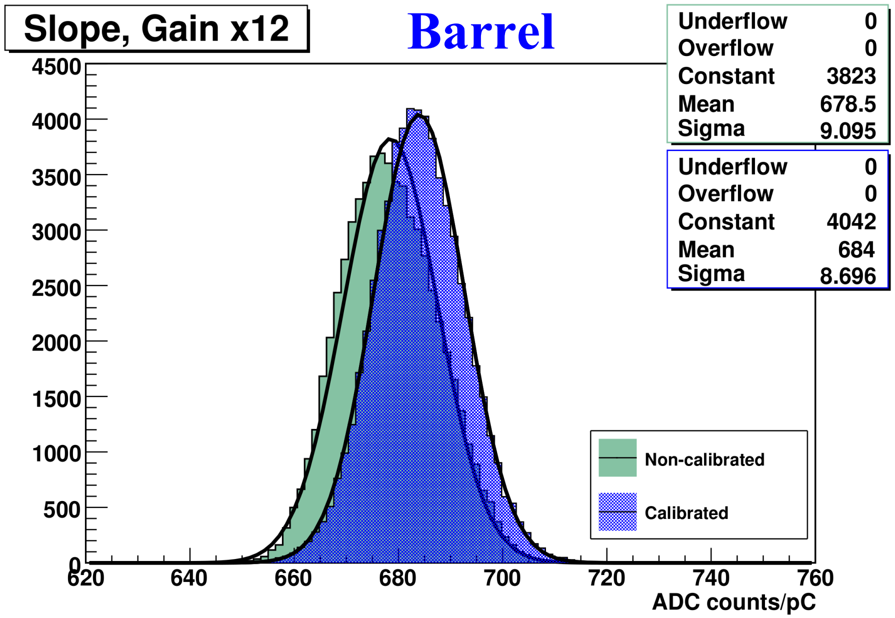
Absolute and intercalibration

Absolute calibration: - Charges measured by precise QADC (LSB 25 fC)

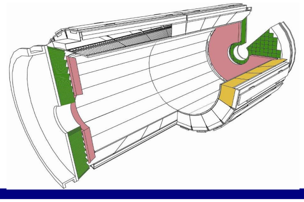
Test board intercalibration: - To suppress differences between the test boards, the VFE response is normalized to a chosen test board

Time intercalibration: - Due to the length of the measurement period, a normalization w.r.t. burn-in group (~300 VFEs) has been performed

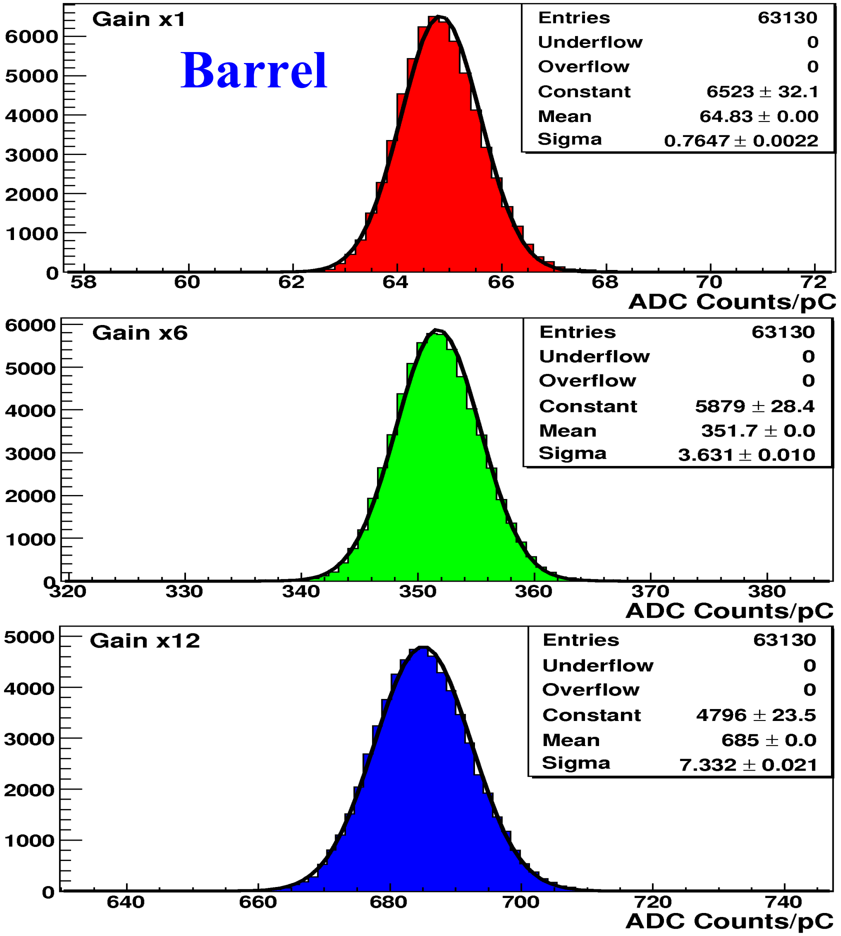
N. B. The stability of the system was monitored periodically by 6 reference VFE cards

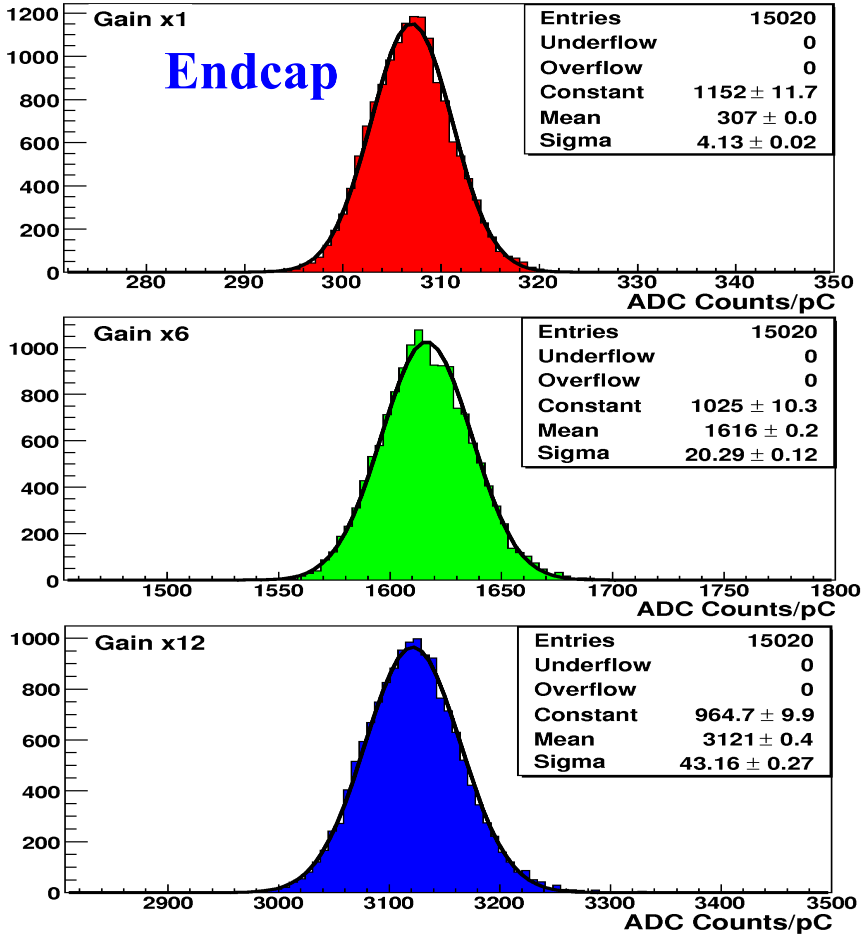


	Improvement (%)	
Gain	Barrel	Endcap
x1	13	5
x6	15	9
x12	18	10

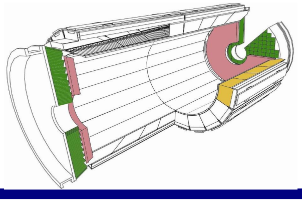


Gain

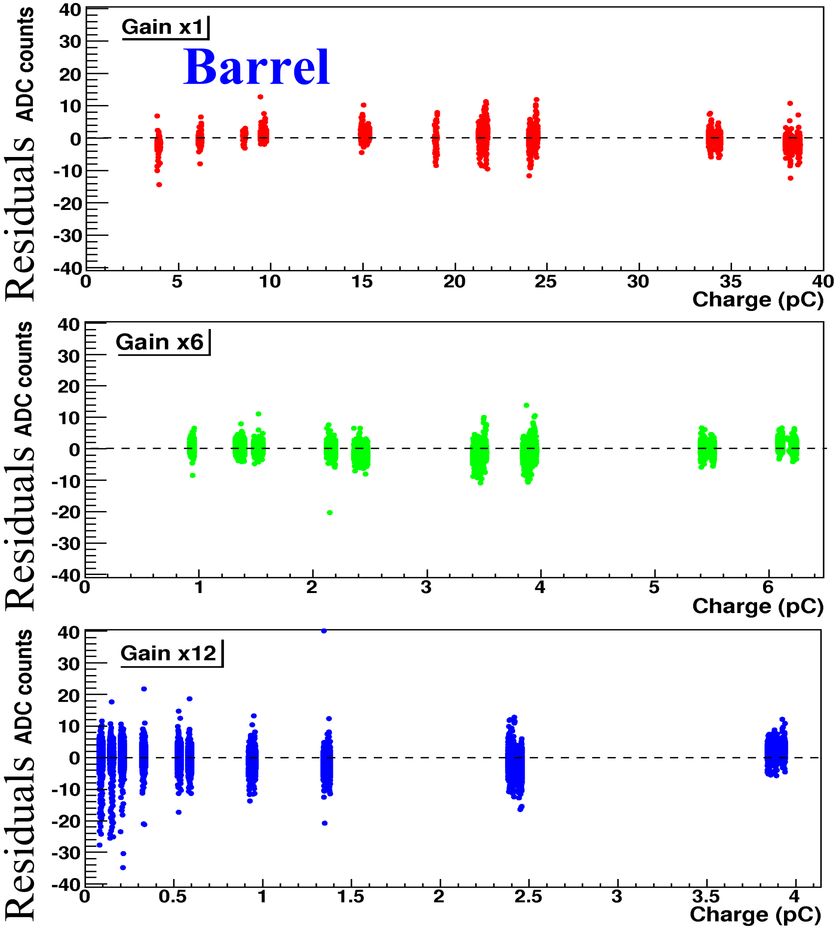


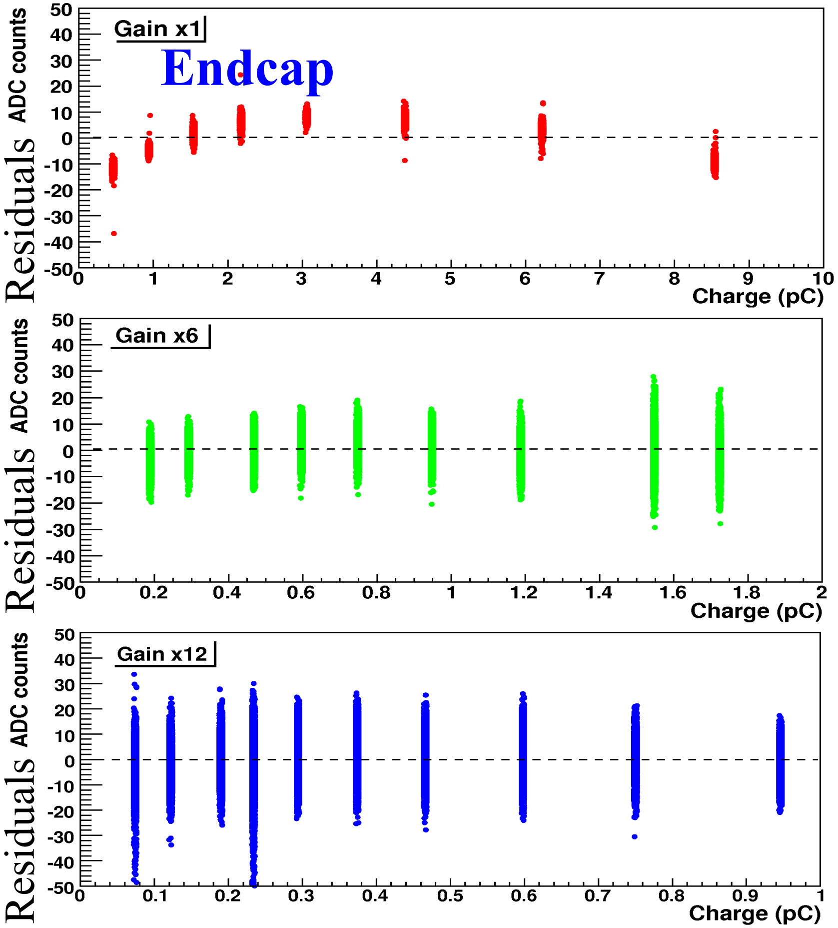


	Barrel		Endcap	
Gain	Mean (ADC counts/pC)	σ/mean (%)	Mean (ADC counts/pC)	σ/mean (%)
x1	64.83	1.18	307	1.35
x6	351.7	1.03	1616	1.26
x12	685	1.07	3121	1.38



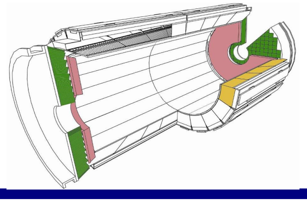
Linearity



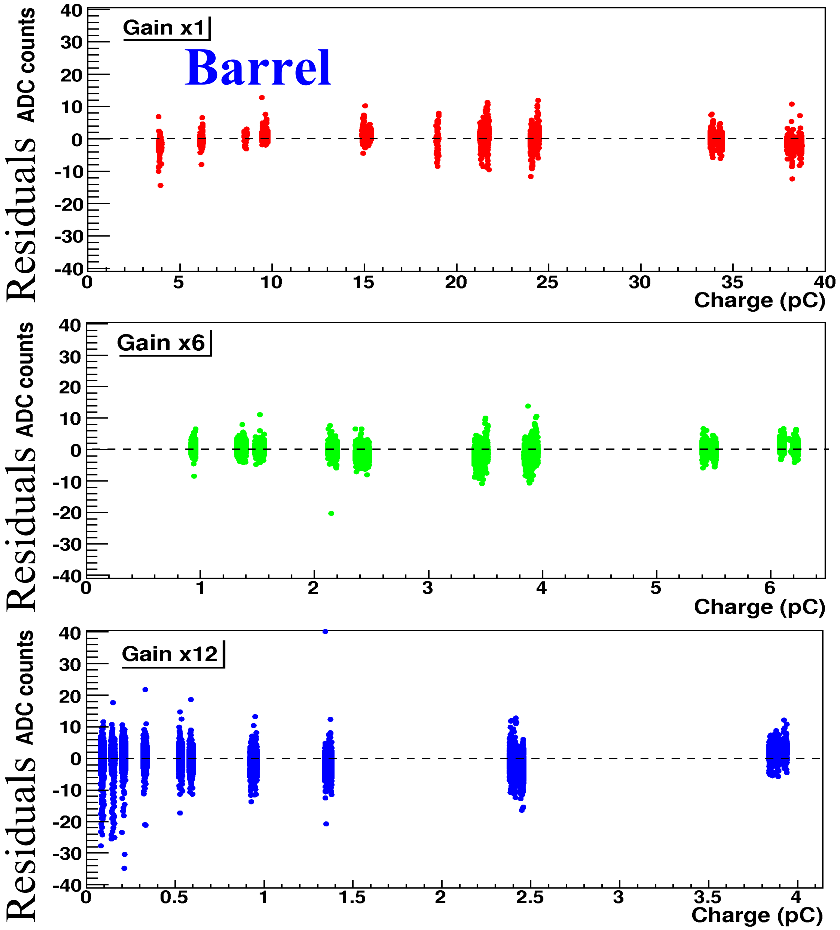


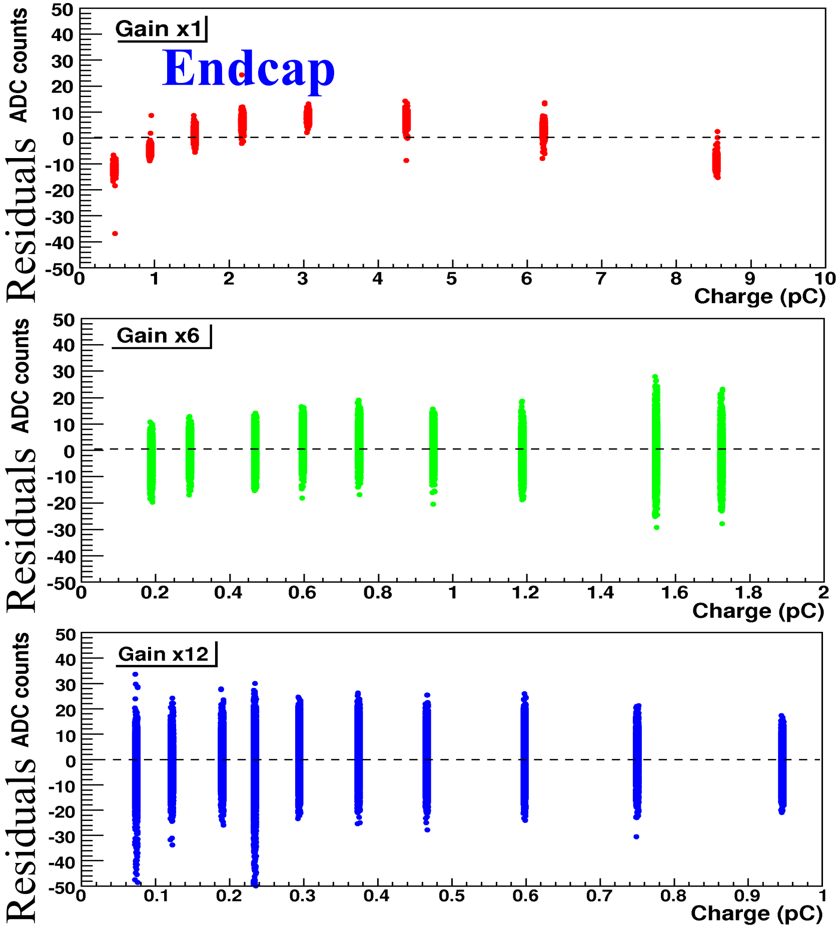
$$Non-linearity[\%]=\frac{A_{exp}-A_{fit}}{A_{fullscale}}$$

	Non-linearity (% fullscale)	
Gain	Barrel	Endcap
x1	0.1	0.45
x6	0.1	0.14
x12	0.12	0.14



Linearity

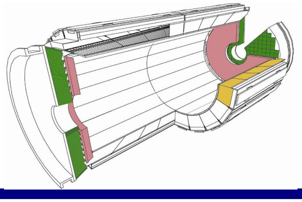




$$Non-linearity[\%] = \frac{A_{\exp} - A_{fit}}{A_{fullscale}}$$

	Non-linearity (% fullscale)	
Gain	Barrel	Endcap
x1	0.1	0.45
x6	0.1	0.14
x12	0.12	0.14

98% of the VFE cards have passed the strict specification criteria

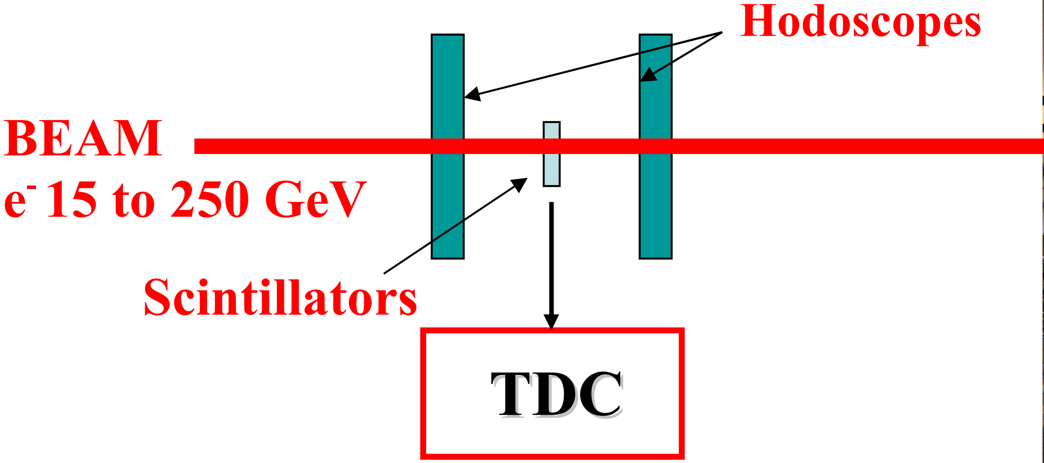


Test beam

Main test beam objectives:

- Intercalibration of supermodules (120 and 90 GeV)
- Amplitude reconstruction procedure
- Electronics noise and gain ratio measurements
- Energy resolution and linearity studies
- Irradiation study
- Service systems validation

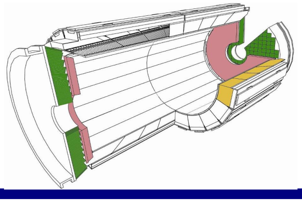
Experimental setup at H4:



TDC: Used to determine the phase between the trigger signal and the readout clock.

Hodoscopes: Scintillating fibers. Allows to determine the beam position In the transverse plane σ (x/y)=150μ m

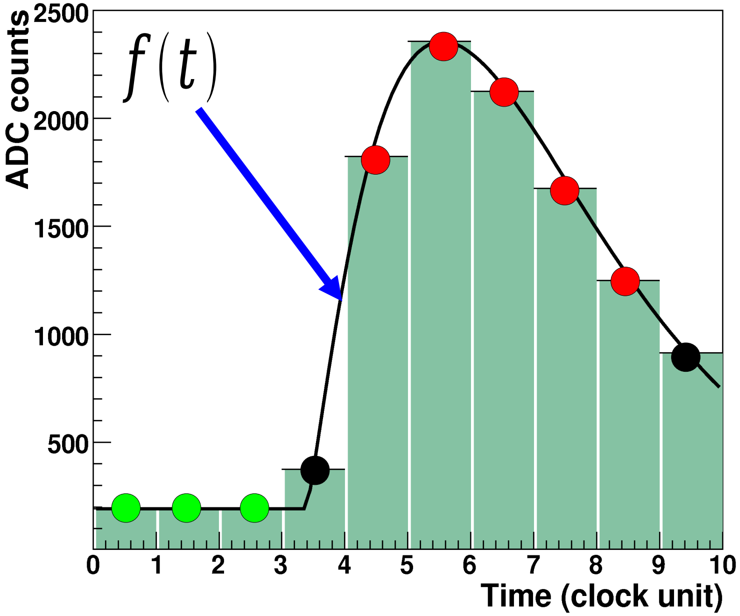
Scintillator: 6 scintillators were used for triggering



Amplitude reconstruction

Weights method: standard digital filtering technique using weights (w_i) to reconstruct the amplitude

$$\hat{A} = \sum_i w_i S_i \qquad w_i \propto f(t_i)$$

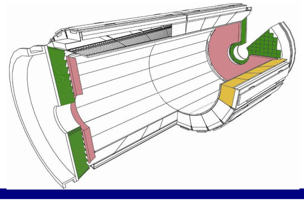


Description of the pulse shape f(t) is needed to determine the weights.

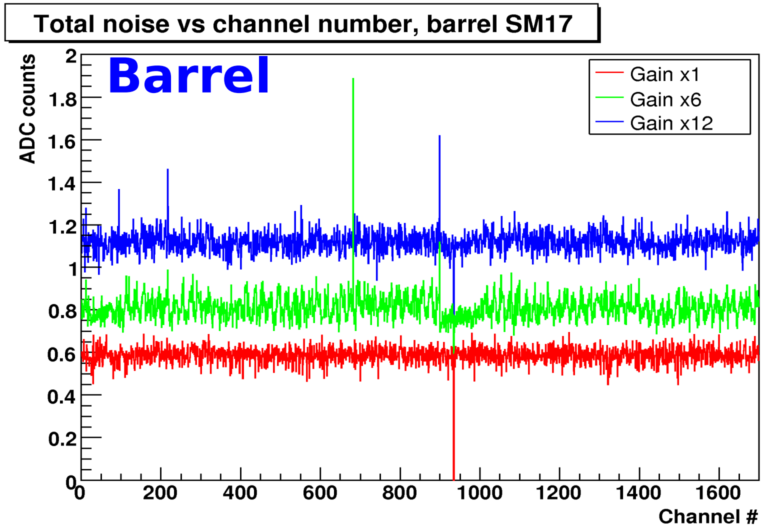
Different implementations:

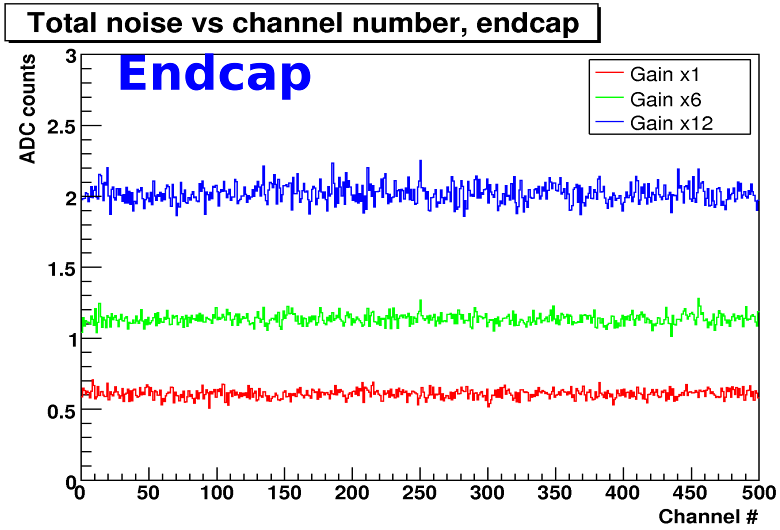
- 5 - weights on the peak, pedestal from database (for gain 6 and 1)
- 3+5 weights: pedestal calculated by use of 3 pre-samples (for gain 12)

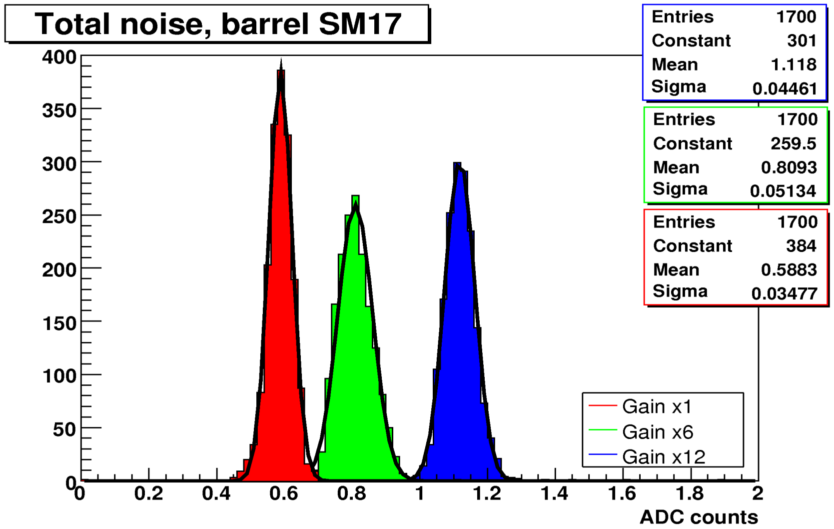
Asynchronous running ➡ 25 sets of weights were used (each ADC clock divided in 25 1ns bin)

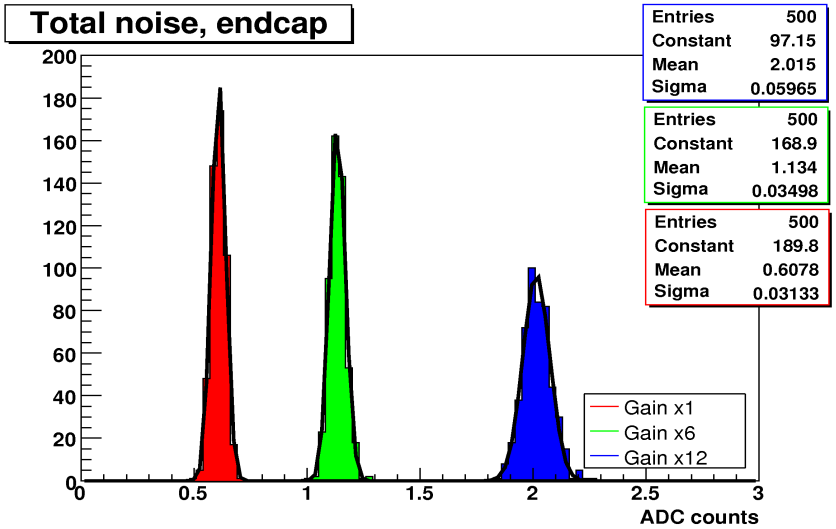


Single channel noise

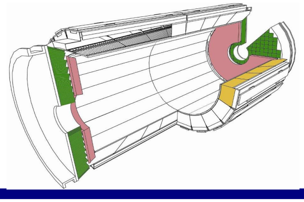

Total noise vs channel number, barrel SM17


Total noise vs channel number, endcap


Total noise, barrel SM17


Total noise, endcap

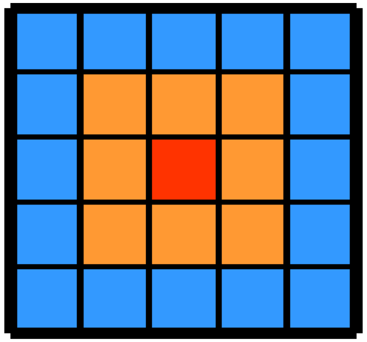
Noise performance: 1.118 ADC counts (~ 40 MeV) for barrel
2.015 ADC counts (~ 124 MeV) for endcap



Noise performance in clusters

Noise studied applying weights amplitude reconstruction method (3x3 and 5x5 crystal arrays) to pedestal events (random trigger)

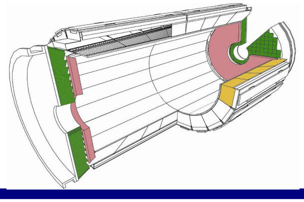
Clustering matrix



Method	Barrel Noise (MeV)		
n + m	1 x 1	3 x 3	5 x 5
1 sample	41.44	124.32	207.94
0 + 5 weights	41.07	126.91	212.75
3 + 5 weights	38.85	116.55	194.63

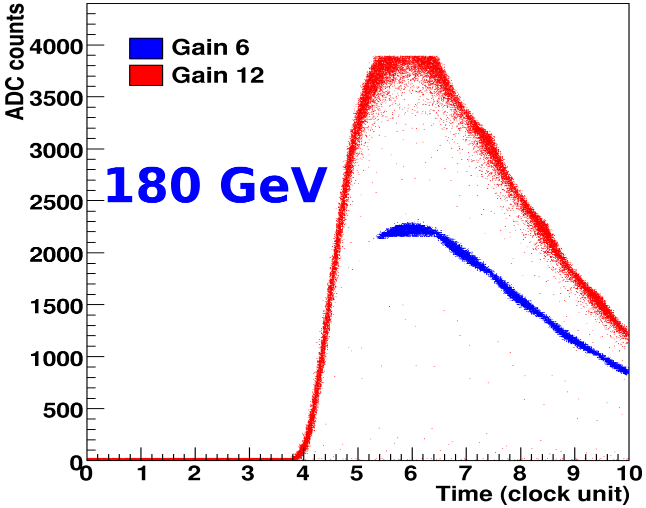
Method	Endcap Noise (MeV)		
n + m	1 x 1	3 x 3	5 x 5
1 sample	123.08	370.46	617.85
0 + 5 weights	117.54	352.61	588.92
3 + 5 weights	147.69	444.31	742.15

- Very good noise performance demonstrated
- Low frequency noise (pick up noise) in the barrel is effectively removed by the dynamic pedestal extraction
- Different behavior of noise in the endcap due to higher high frequency noise
- Very small or no correlated noise (coherent noise) between channels

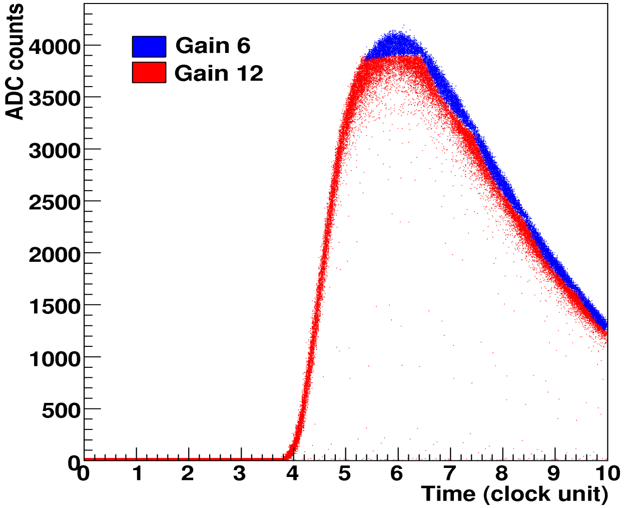


Gain ratio measurement

Motivation: Find a reliable and precise method to determine the gain ratios

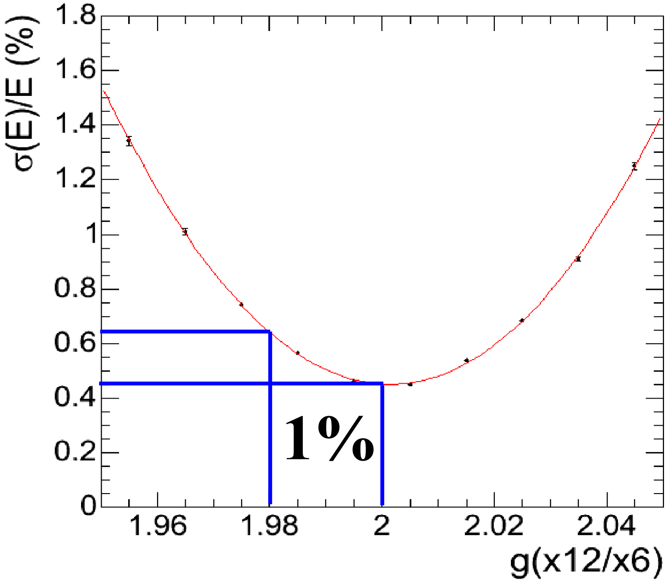


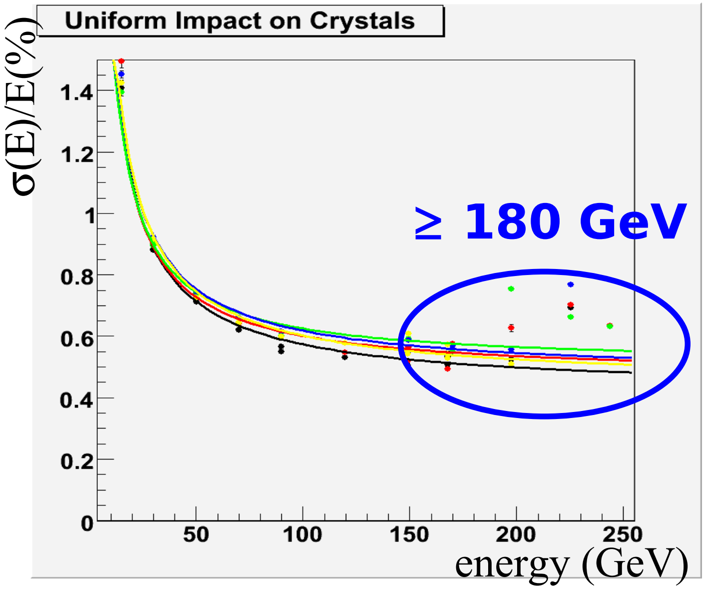
Gain ratio 12/6



P. Jarry

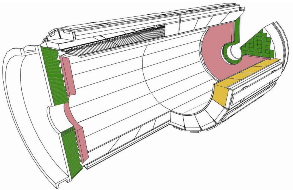
Impact on the energy resolution:





Gain ratio has to be known for each crystal with high precision

P. Jarry TB Workshop Roma 2007



Gain ratio measurement

Several gain ratio determination techniques have been studied:

Test pulse – method using MGPA internal charge on the supermodules during test beam at CERN H4

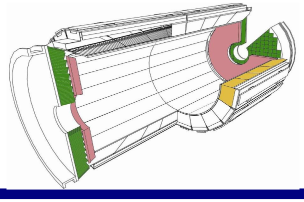
In situ

Laser – method using a laser pulse of fixed intensity distributed by the ECAL laser monitoring system.

In situ

Beam – measurement using electron beam. The beam provides measurements of the gain ratio in real data-taking conditions

The gain ratio is computed as the ratio of the mean value of signal amplitudes reconstructed in different gains for a same input pulse signal below saturation.



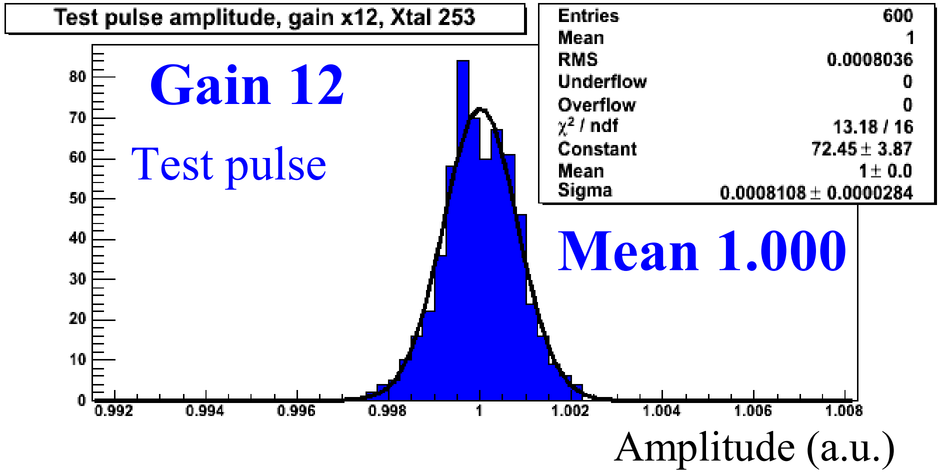
Test pulse and laser gain ratio

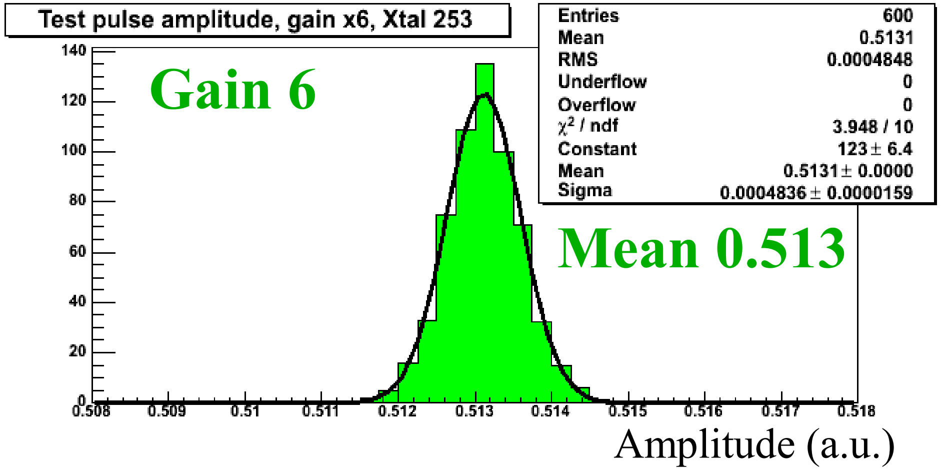
Test pulse and laser:

- 1700 Xtals measured in one run
- 1800 events/run (600 events taken for each gain)

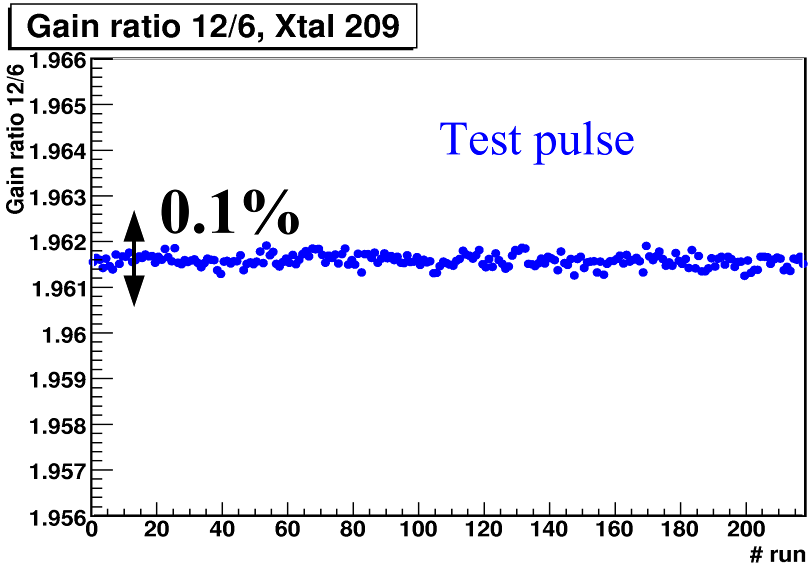
Amplitude reconstruction:

- Weights method
- Analytic function

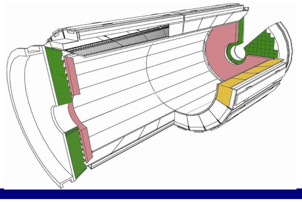




Stability of the gain ratio over time (3 weeks):



The ratio of the reconstructed (1/0.513) amplitudes gives the gain ratio (1.949)



Beam gain ratio

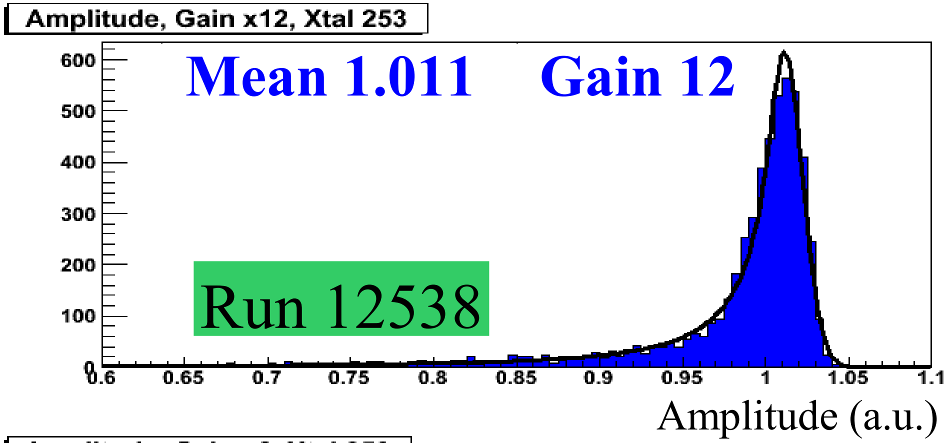
Test beam measurements for a given energy with forced gain.

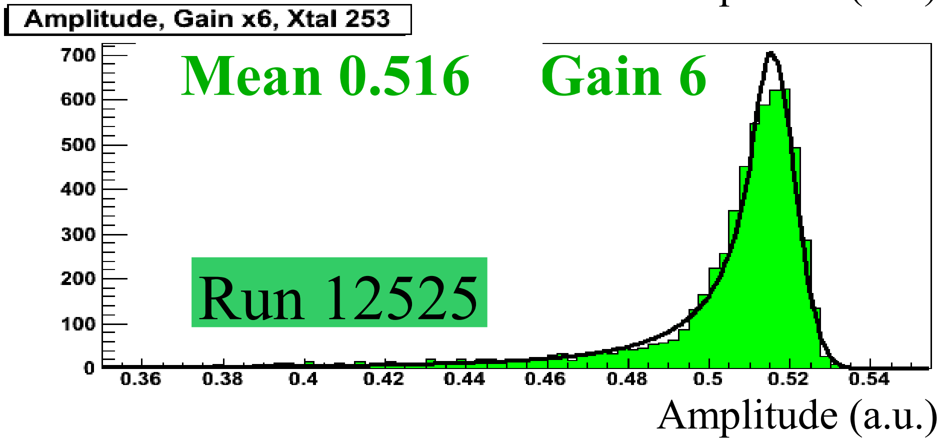
Experimental set-up:

- 5x5 and 9x9 crystal arrays
- 179 measured crystals
- E = 120 GeV, 30k events/crystal
- Beam runs taken for each gain separately

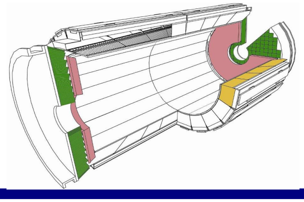
Amplitude reconstruction:

- Reconstructed data
- Hodoscope cut: 9x9 mm^2
- Weights method is used



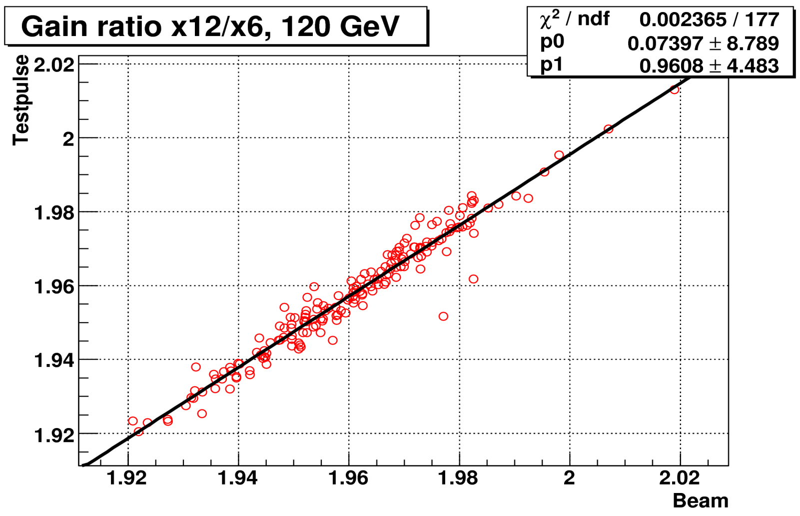


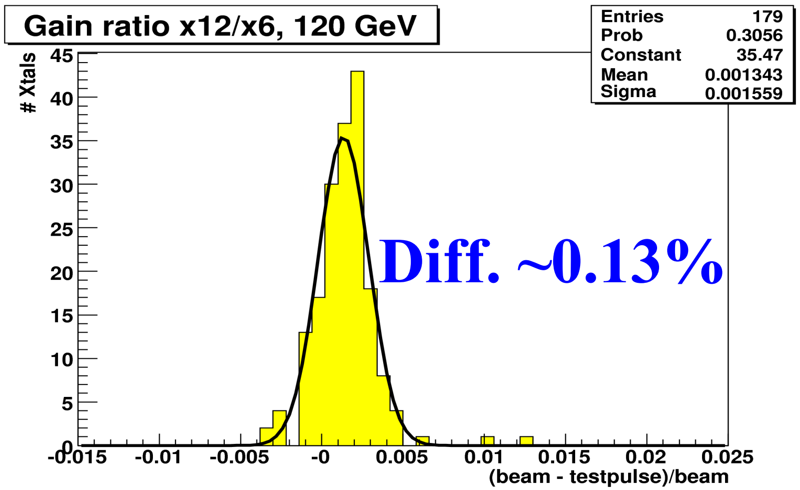
The ratio of the reconstructed (1.011/0.516) amplitudes gives the gain ratio (1.959)



Gain ratio comparison

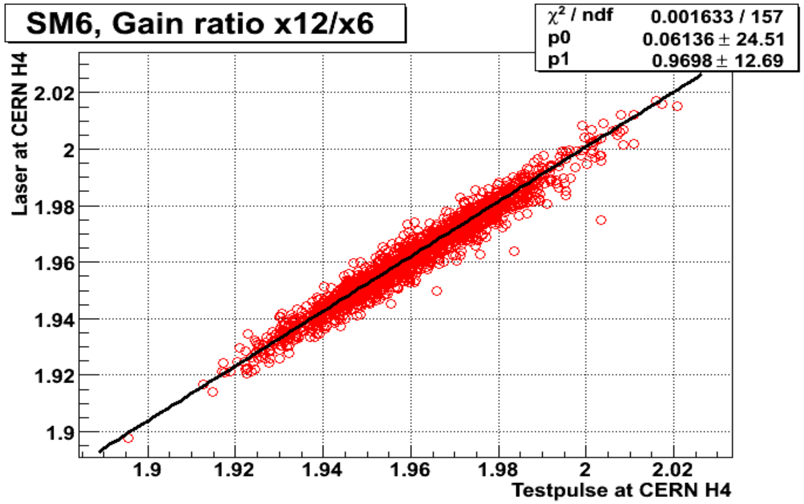
Test pulse vs beam

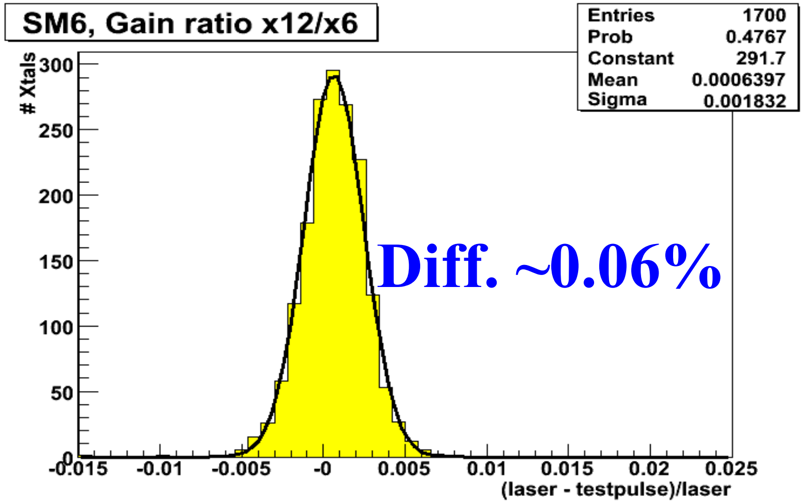




Diff. ~0.13%

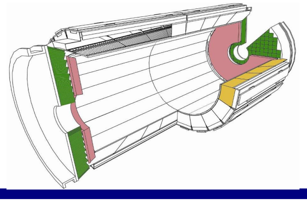
Laser vs test pulse





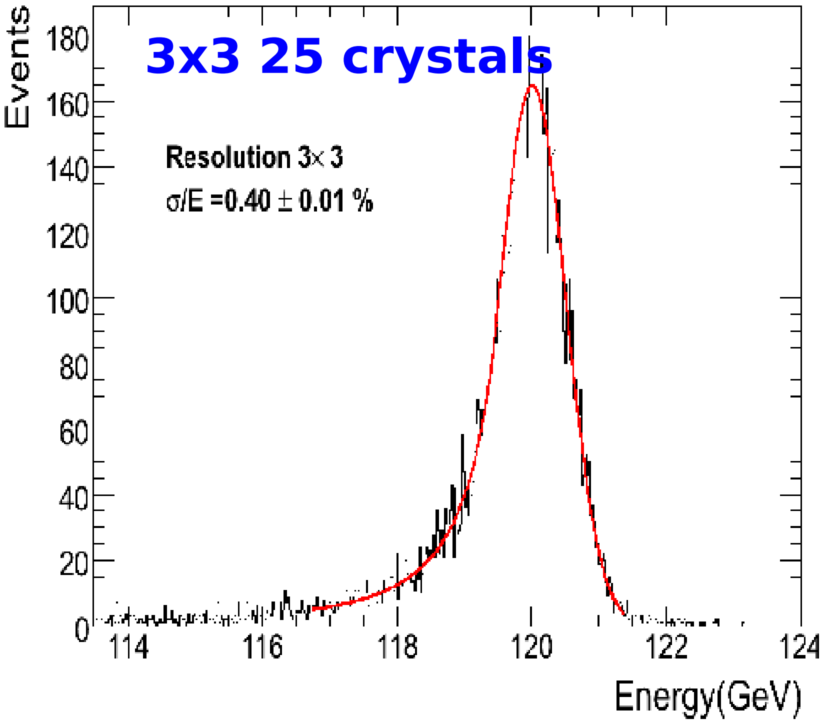
Diff. ~0.06%

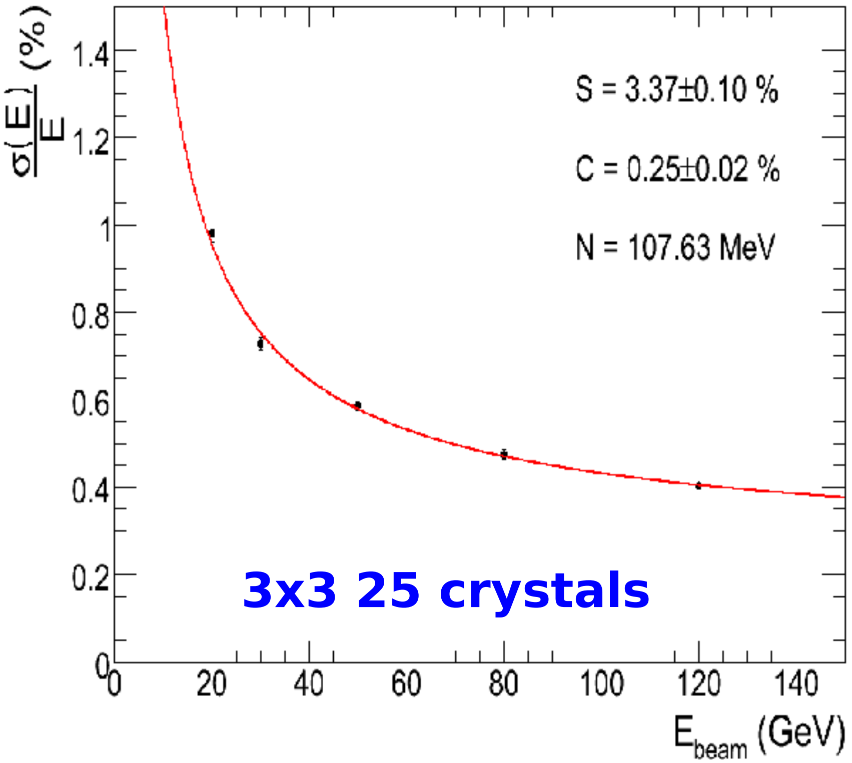
- Measurements of gain ratios with beam have confirmed that the test pulse or laser methods can be used for reliable gain ratio determination in situ
- Advantage of the test pulse is its simplicity, no additional corrections are needed as in the case of the laser



Energy resolution for central impact

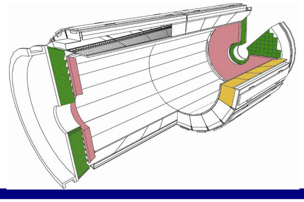
- Energy summed in 3x3 for 25 crystals
- Optimized weights used in reconstruction
- Central point restricted to 4x4 mm^2
- High statistic run (30,000 events per crystal)





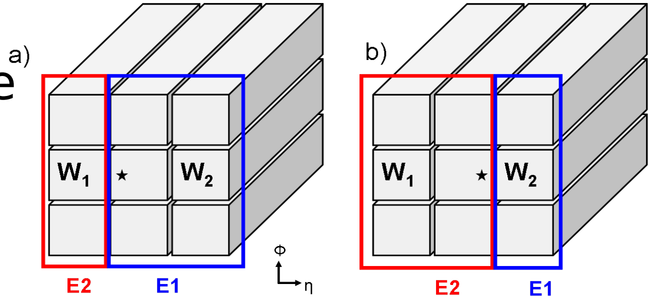
Energy resolution is **0.4% at 120 GeV** (0.48 % at 120 GeV for standard weights)

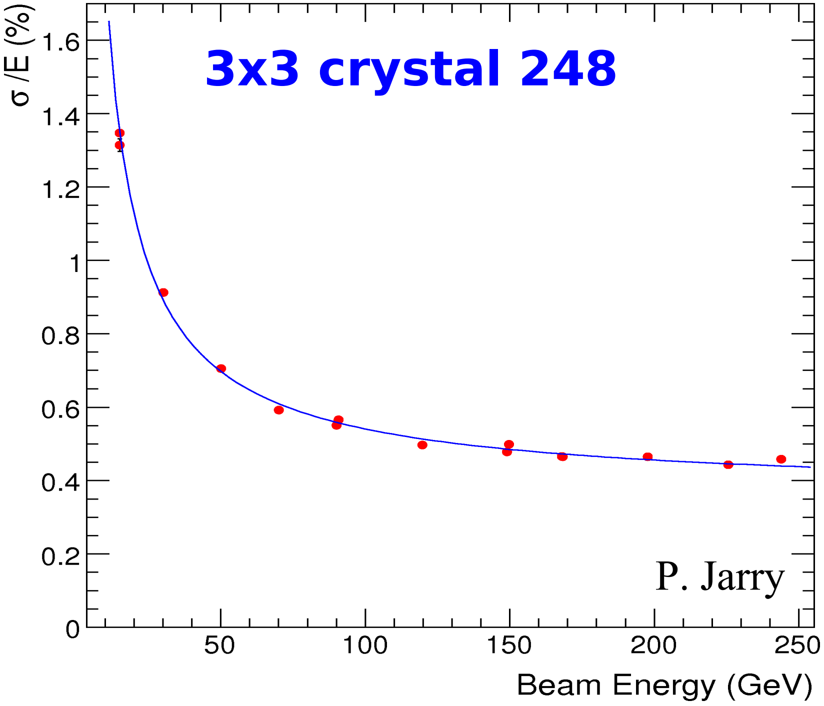
$$\frac{\sigma_E}{E} = \frac{3.37\,\%}{\sqrt{E}} \oplus \frac{0.108\,(GeV)}{E} \oplus 0.25\,\%$$

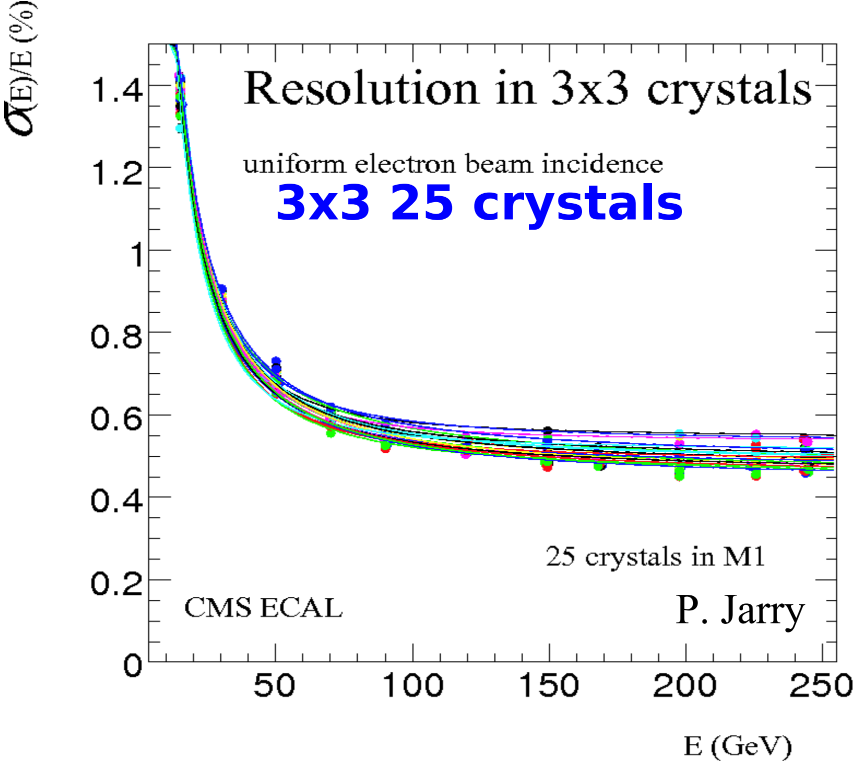


Energy resolution for uniform impact

- Energy scan: 15 – 250 GeV electrons
- Uniform impact – trigger area ≅ crystal front face
- Energy containment correction (lnE2/E1 method)
- For energy > 180 GeV gain ratio used





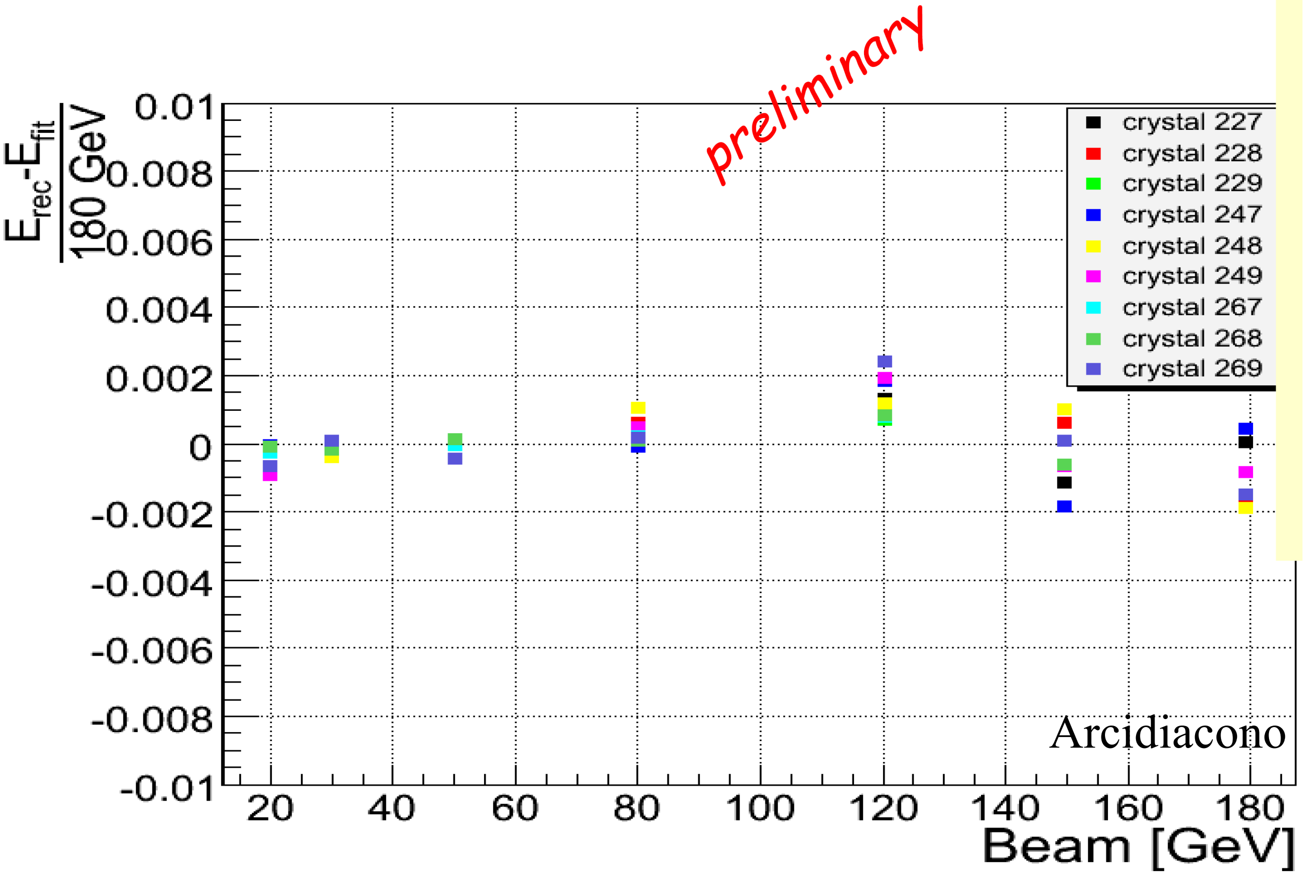


Energy resolution is **< 0.5% for energy higher than 150 GeV** for any electron impact

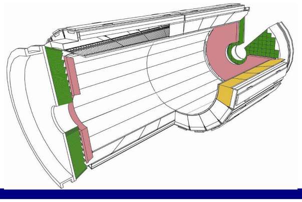
$$\frac{\sigma_E}{E}=\frac{3\%}{\sqrt{E}}\oplus\frac{0.12(GeV)}{E}\oplus 0.4\%$$

Energy linearity

- 9 crystals (5x5 clusters)
- Central point restricted to 1x1 mm^2
- Include beam and intercalibration uncertainly
- For energy > 150 GeV gain ratio used



Differential non linearity in 20 – 180 GeV is **< 2%**

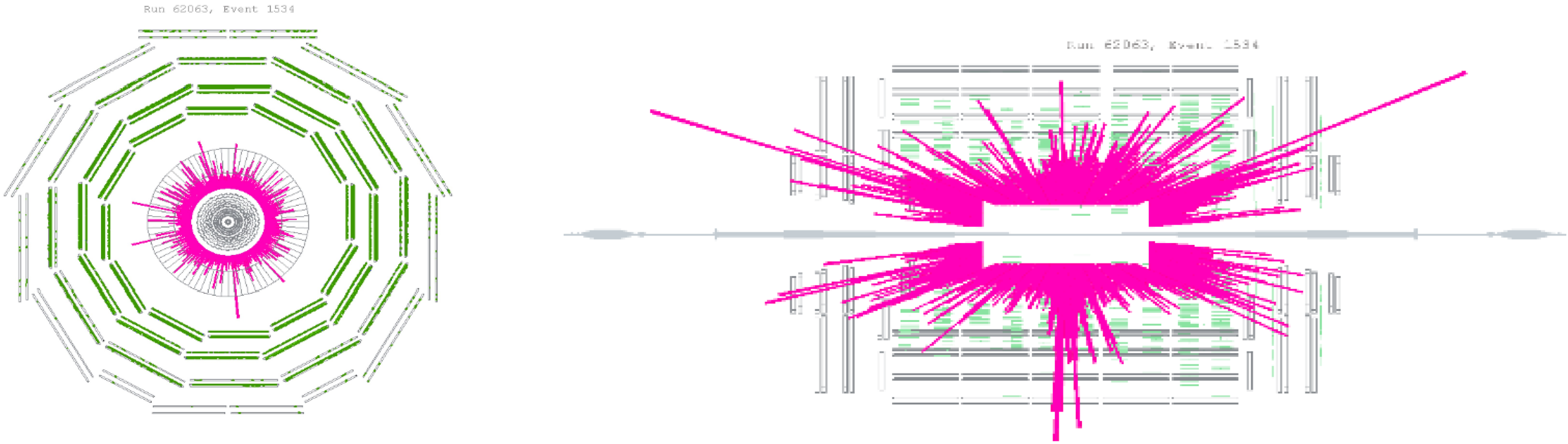


Conclusion

ECAL electronics is calibrated, behaves as expected and its contribution to detector performance is within specifications

Test Beam studies clearly demonstrate that ECAL will meet its ambitious design goals

ECAL barrel and endcaps are installed, commissioned and operational



Splash events observed (2.10^9 protons on collimator 150 m upstream of CMS)