Electronics for calorimeters

Porquerolles 2007

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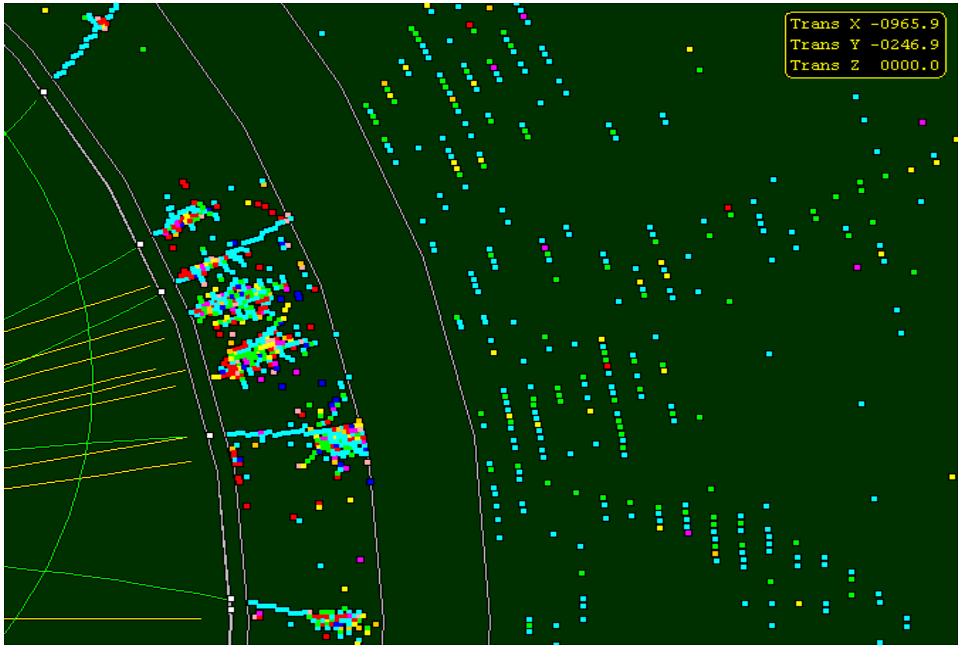

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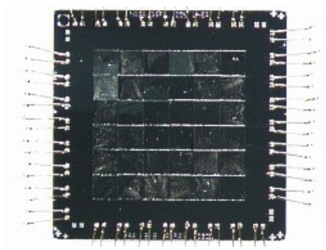
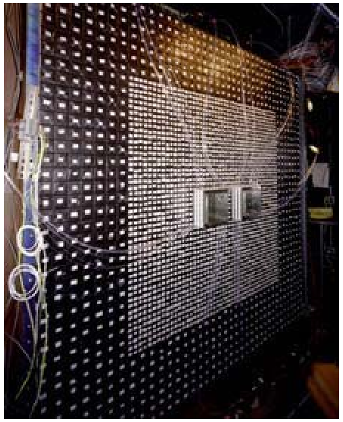
Basics on calorimetry [1]

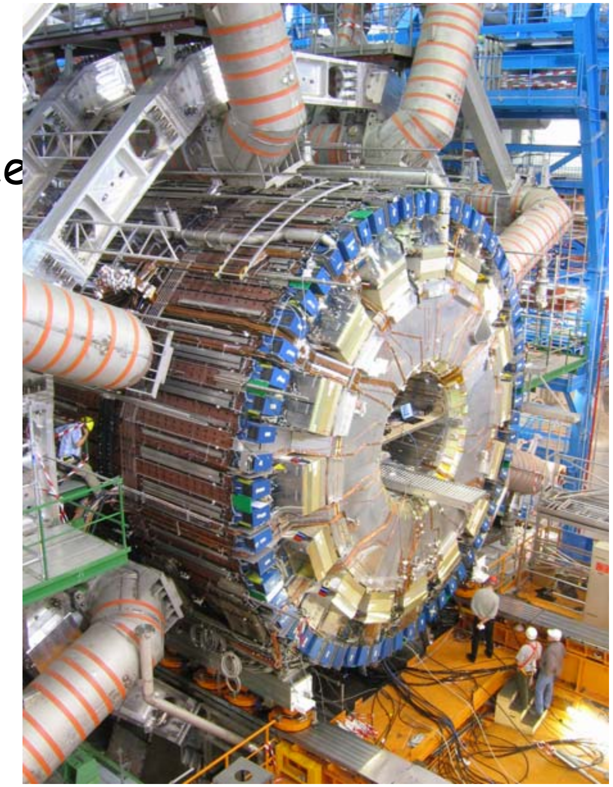
- **Measurement of :** energy, position, time, particle id
- **Calorimeters :** moderate resolution, large, stable
- ≠ **Spectrometers :** high resolution, limited acceptance
- **A large choice of detectors :**



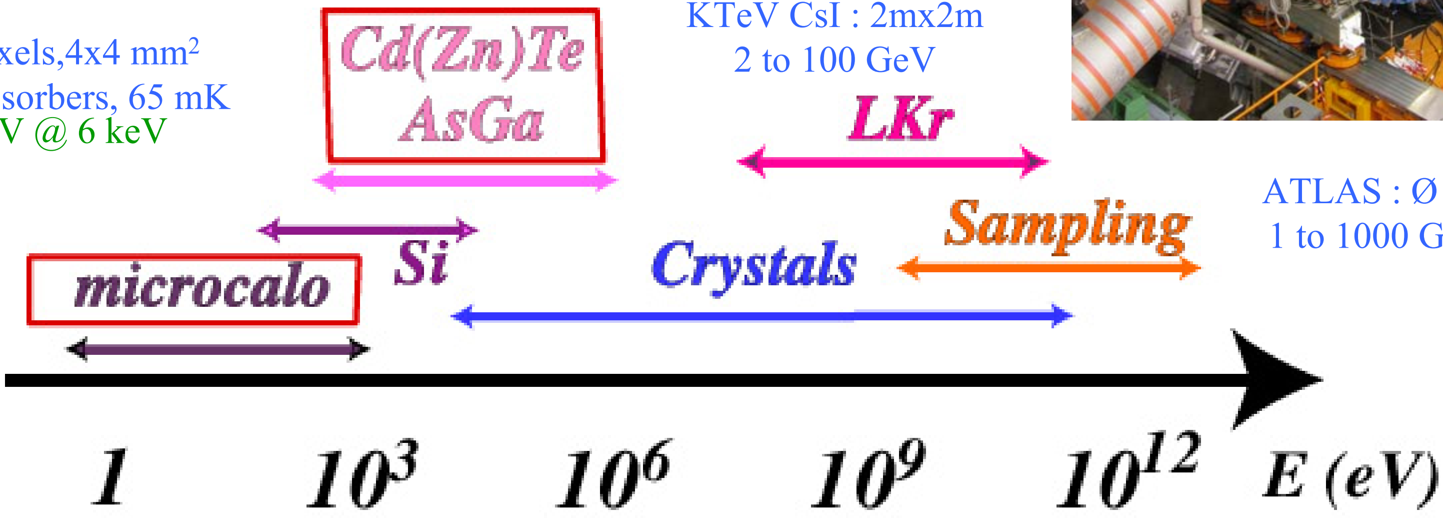
6x6 pixels,4x4 mm^2
HgTe absorbers, 65 mK
12 eV @ 6 keV



KTeV CsI : 2mx2m
2 to 100 GeV

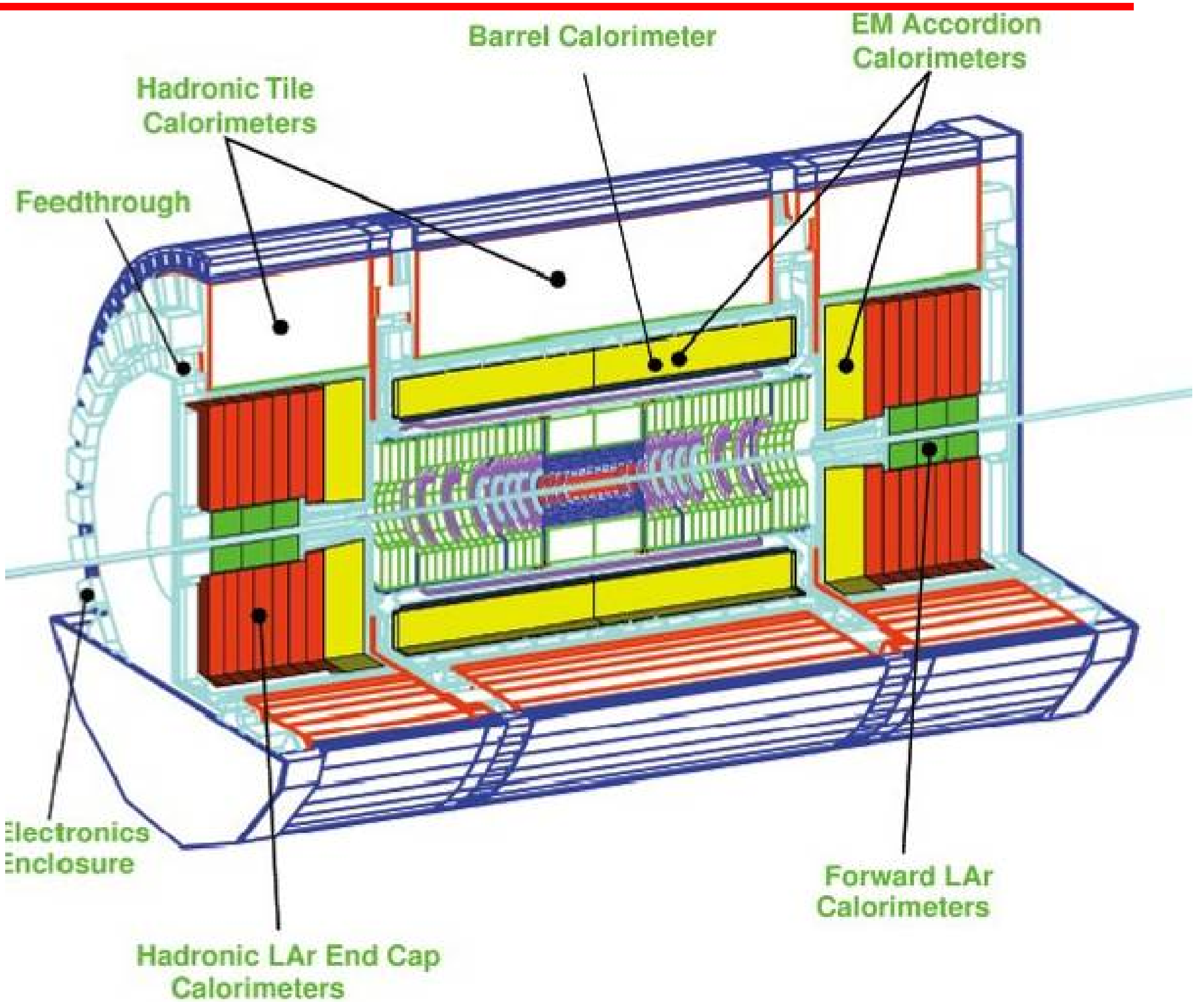


ATLAS : Ø 4m
1 to 1000 GeV



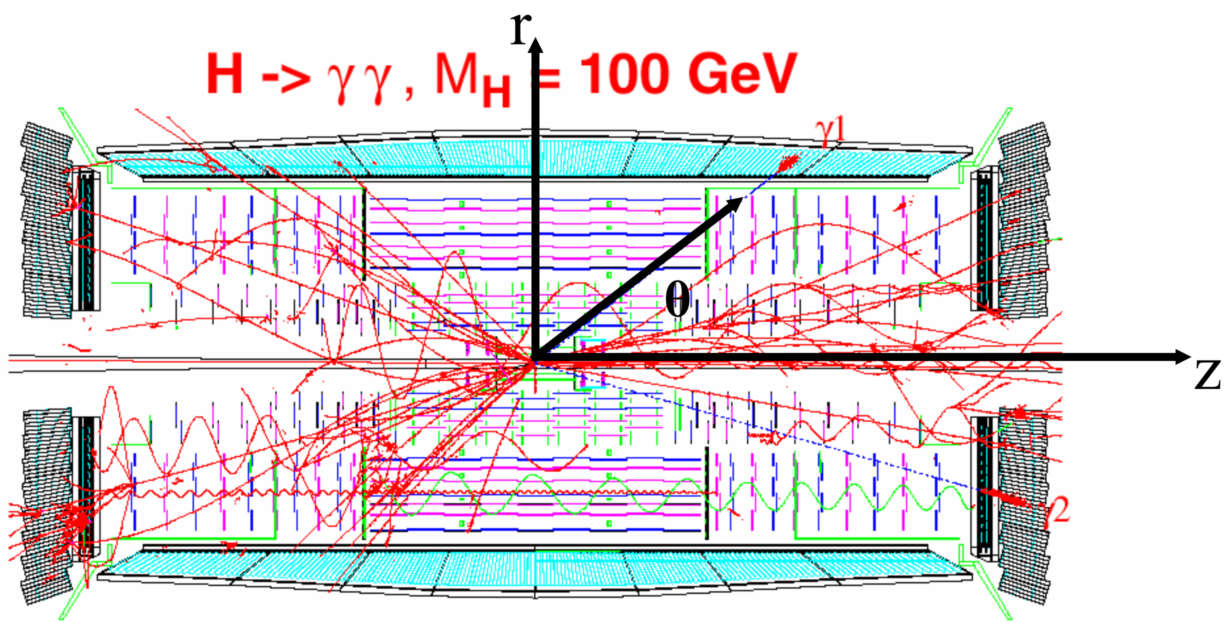
Basics on calorimetry : vocabulary

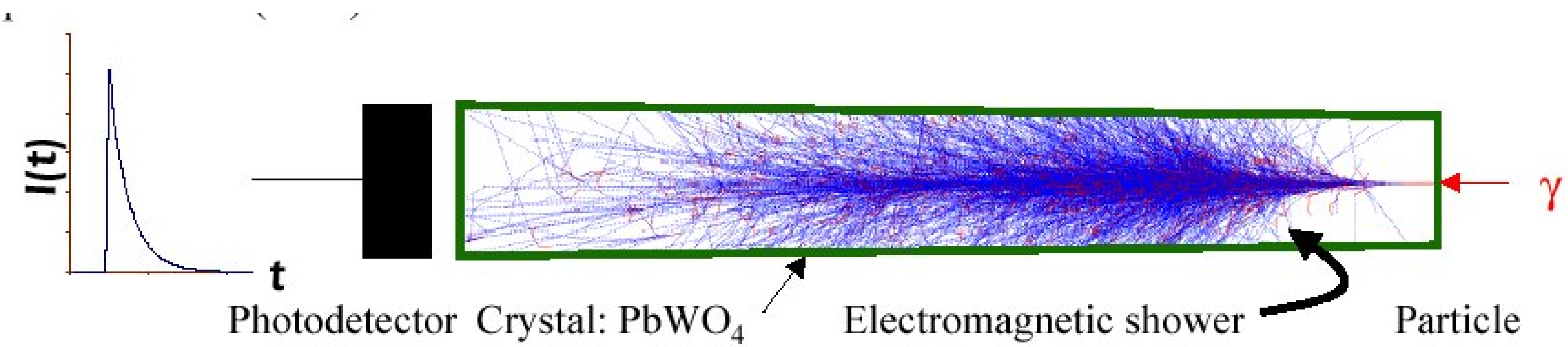
- **Electromagnetic**
  - Electrons, photons
- **Hadronic**
  - Neutrals, jets
- **Missing energy (E_{Tmiss})**
  - Neutrinos
  - Hermeticity
- **Barrel, Endcap, Forward**



Basics on calorimetry : vocabulary

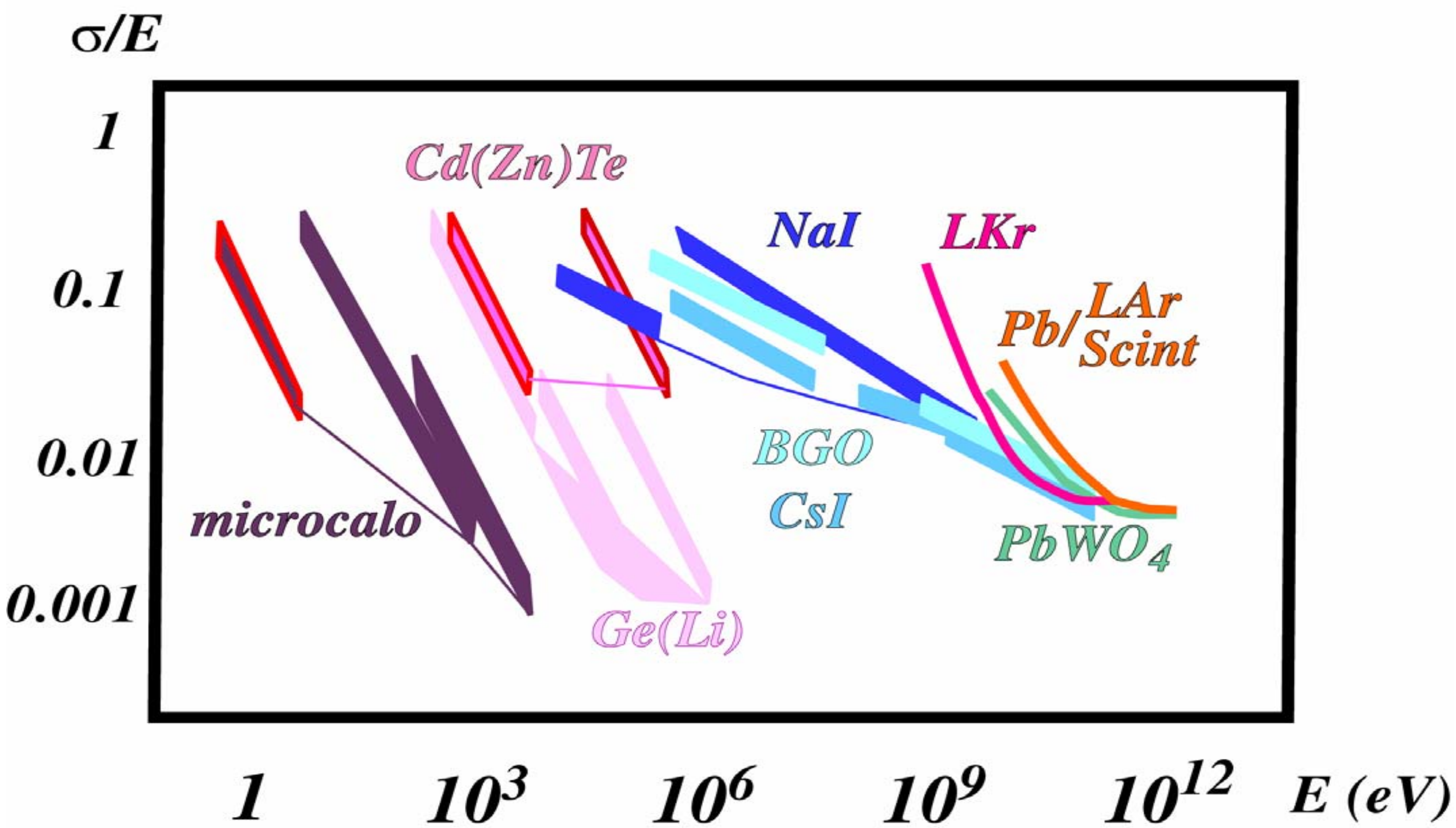
- **Granularity : θ, φ**
- **Rapidity : z,**
  η = -Ln(tg θ/2)
- **Segmentation in depth : r**
- **Shower**





Main features : dynamic range [2]

- **Dynamic range : maximum signal/minimum signal (or noise)**
  - Typically : $10^3 - 10^5$
  - Often specified in dB (=20log Vmax/Vmin) = 60 – 100 dB
  - Also in bits : 2^n = Vmax/vmin = 10 – 18 bits
- **The large dynamic range is a key parameter for calorimeter electronics**

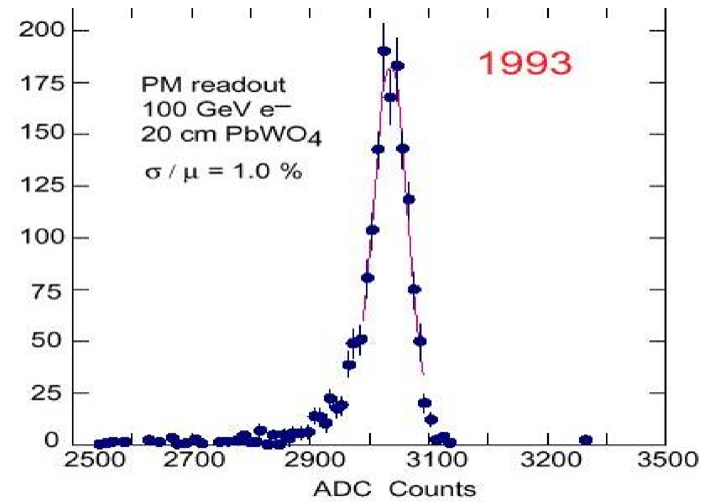


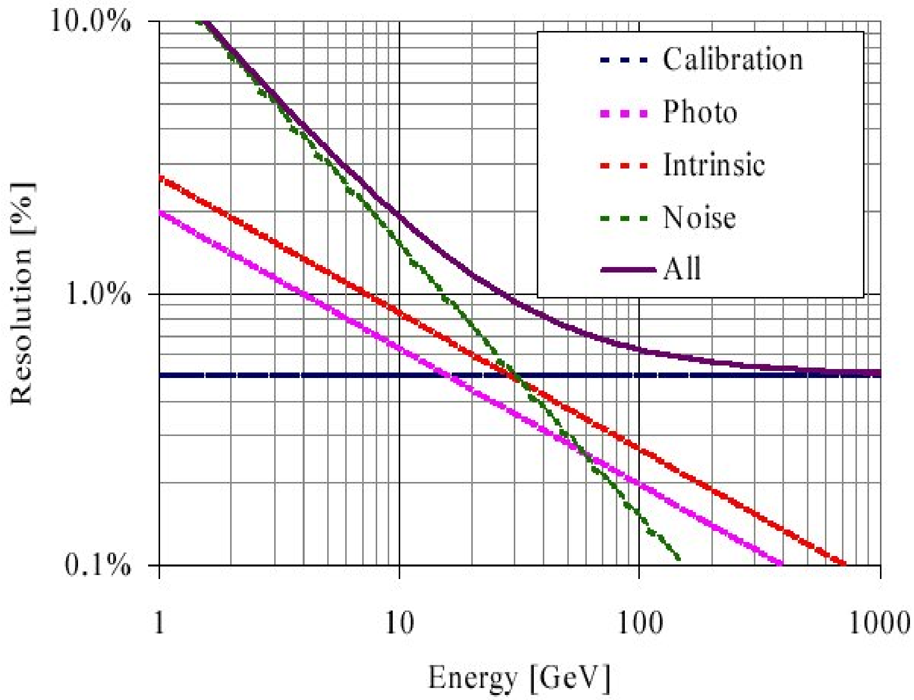
Main features : energy resolution [2]

- **Energy resolution :**

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

  - **a** : electronics noise term
    - Dominates at low energy
    - Coherent noise control essential for summing over large areas (jets, Emiss)
  - **b** : stochastic term
    - Statistical flucutations in detector
  - **c** : constant term
    - Non uniformities
    - Importance of calibration

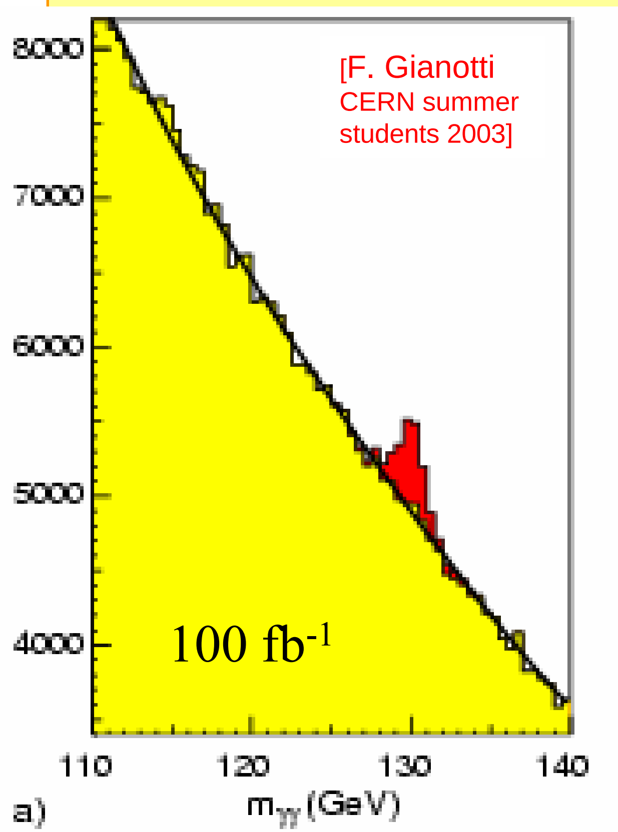


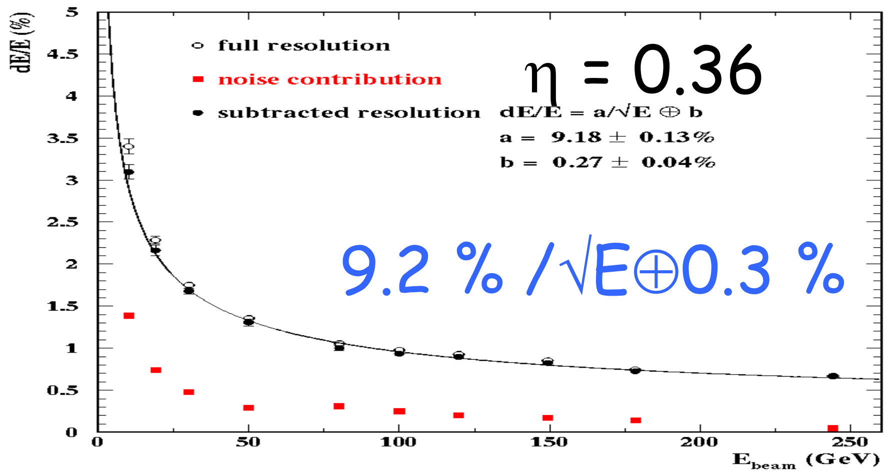


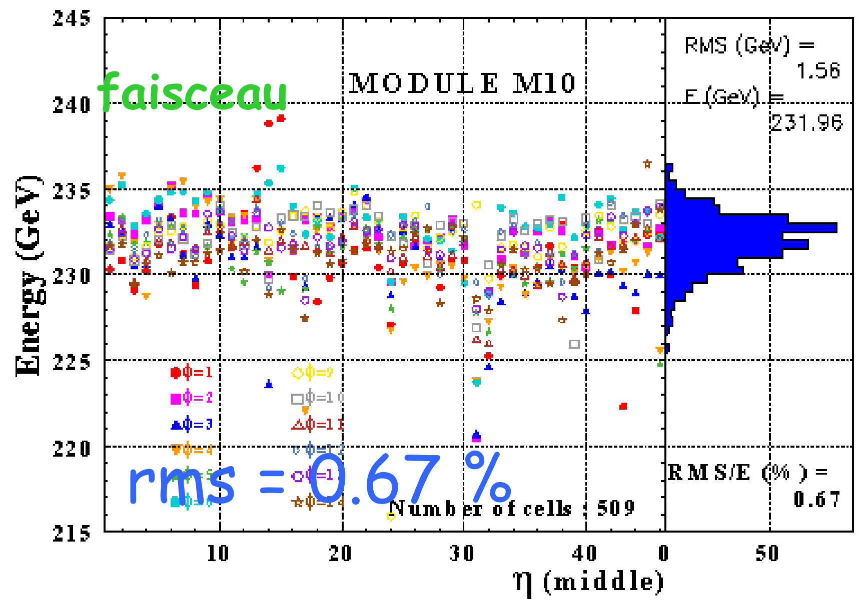
Precision

- **Precision ~1%**
  - Importance of low noise, uniformity, linearity…
  - Importance of calibration

H-> γ γ in CMS calorimeter

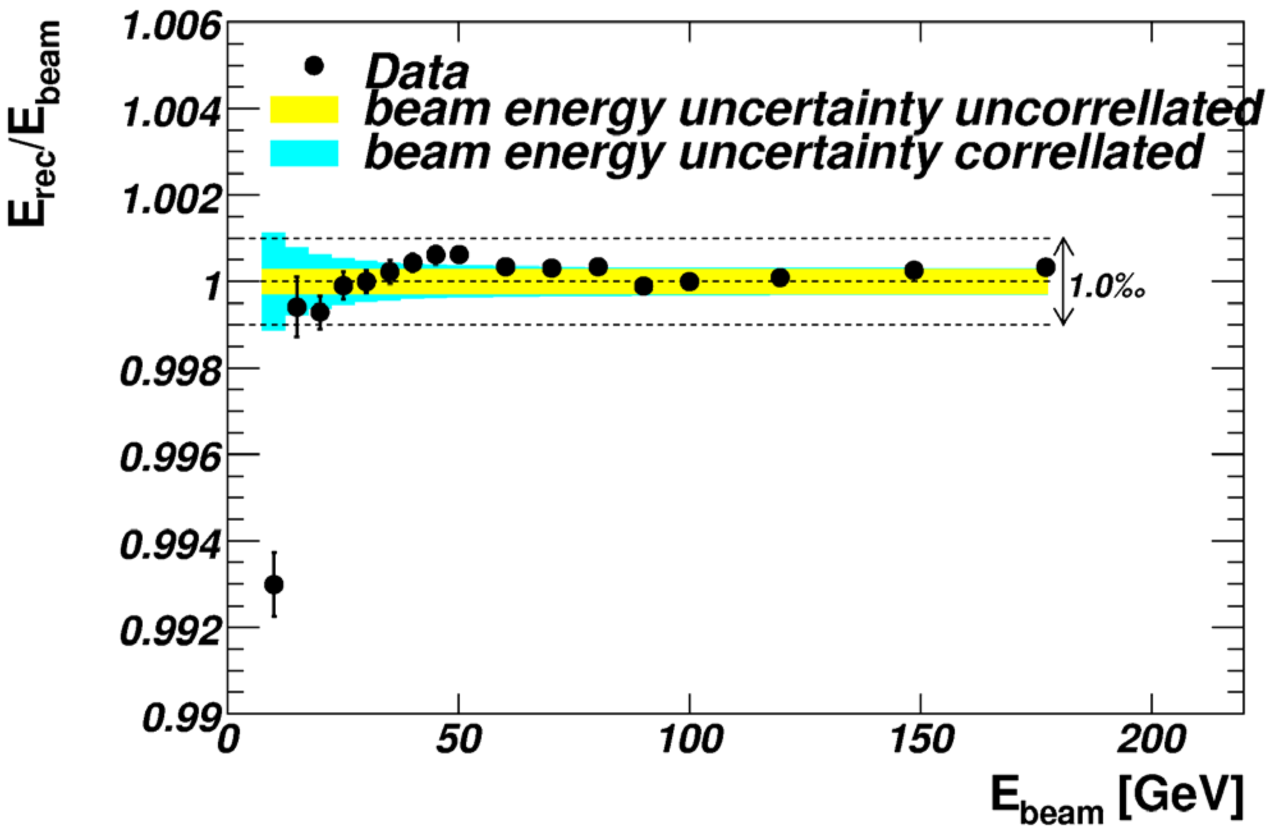






Linearity

- **Good linearity << 1%**
  - To ensure good precision
  - To perform accurate summations



Position measurement

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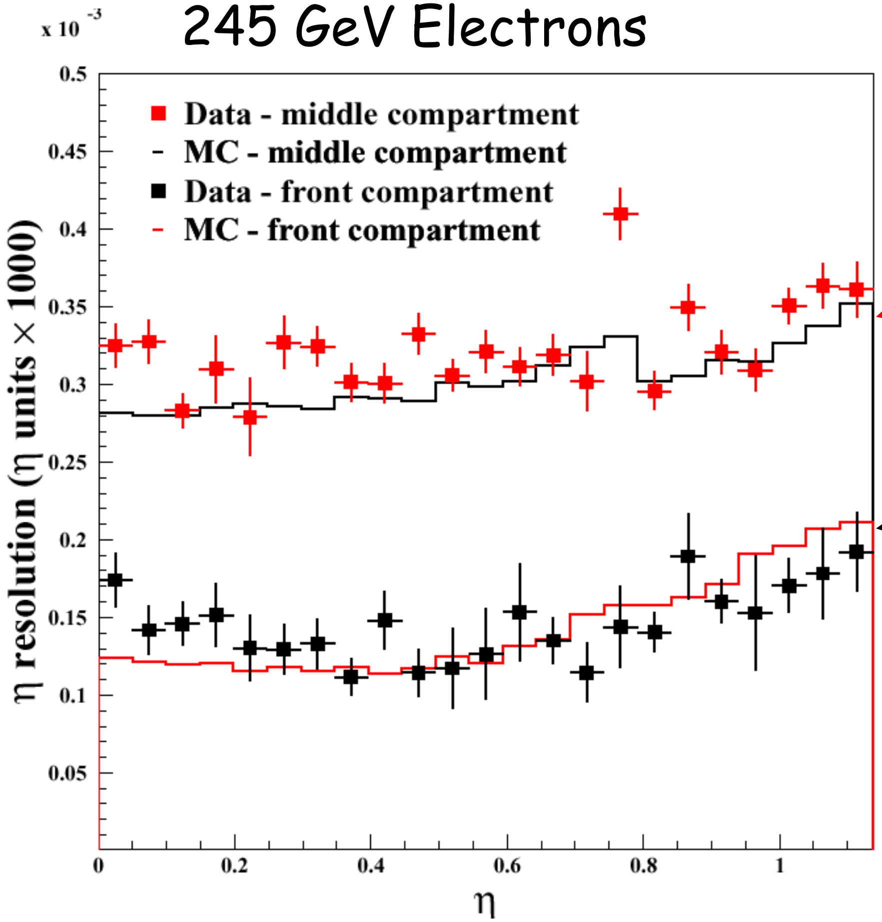
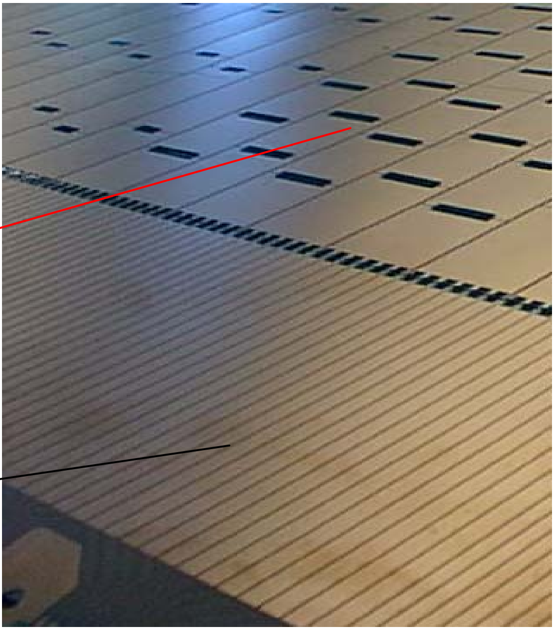
- **Fine segmentation in order to measure position with good accuracy**
  - Large number of channels
  - Measurement by center of gravity

245 GeV Electrons



~550 μm at η=0

~250 μm at η=0



Similar level of performance in endcap

Particle identification

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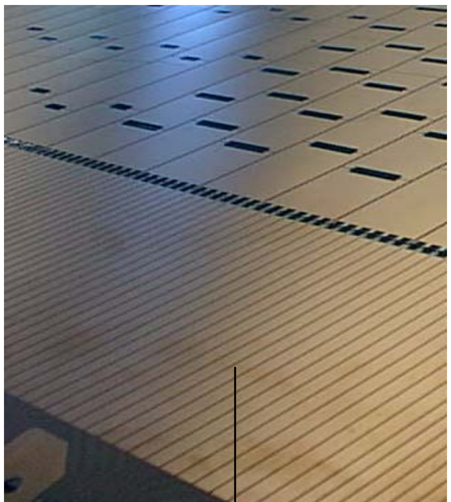
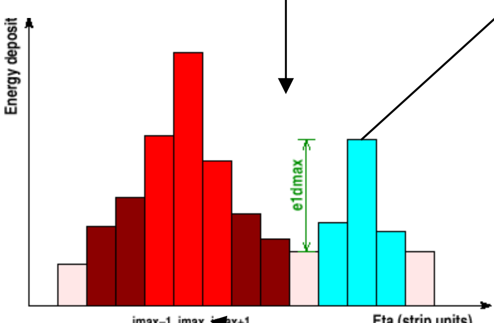
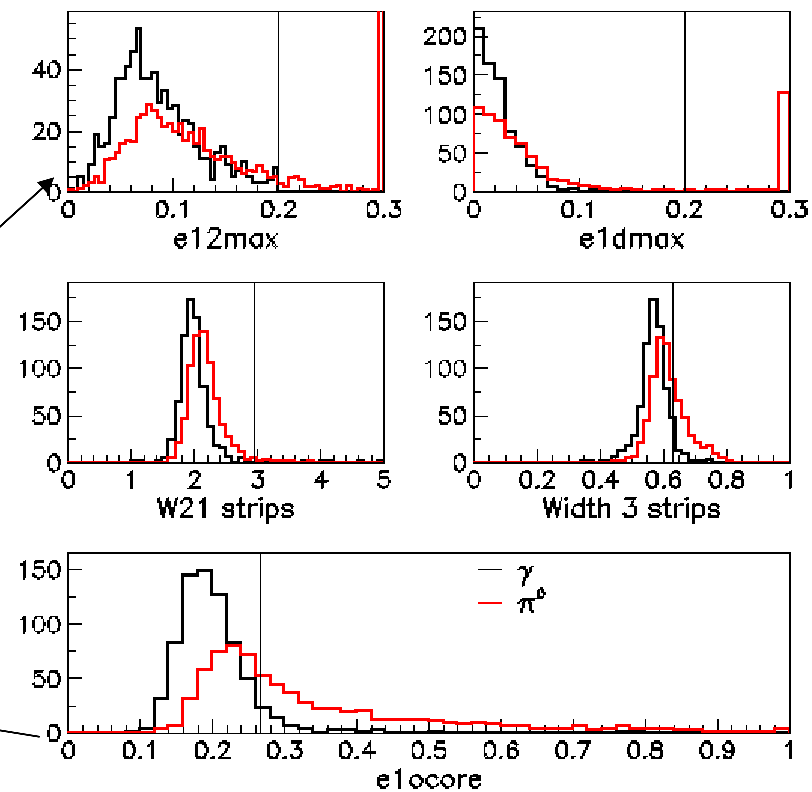
- **Gamma / pi0 rejection**



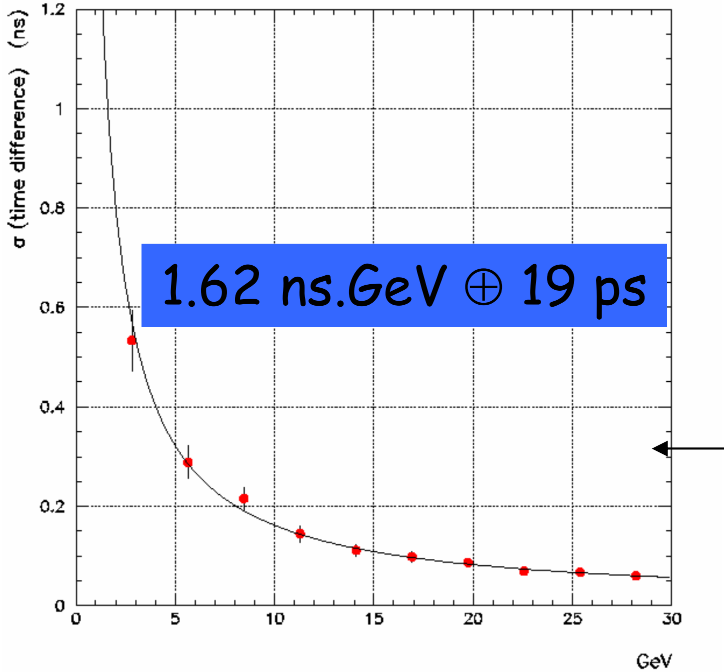


Discriminating variables strongly based on fine strip first layer :



ε= 90 % for 50 GeV photons

- Intrinsically fast signal in Argon →accurate time measurement
- Can be used for Zvertex measurement (endcap events), long lived neutral particles (GMSB photon)…



Front end electronics resolution :
- very low constant term < 20 ps
-Needs to correct for time variation with Switch Capacitor Array (2 ps/capa)

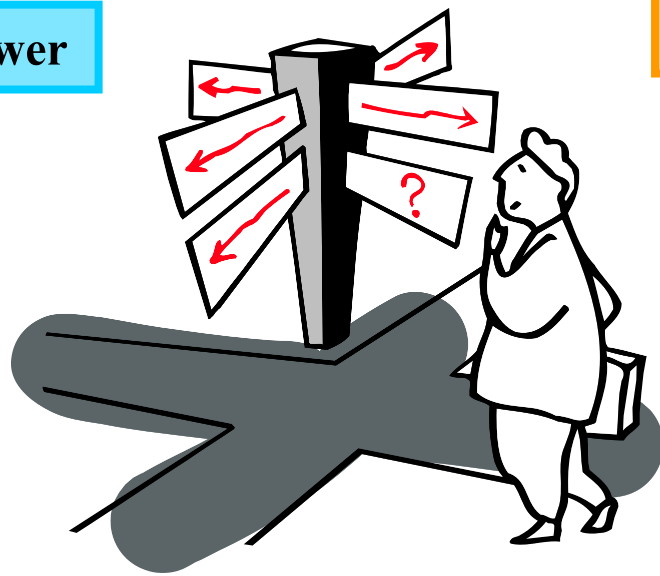
Note : Trigger + clock distribution in beam test not included here

Readout electronics : requirements

Low noise

Low power

High speed



Large dynamic range

High reliability

Radiation hardness

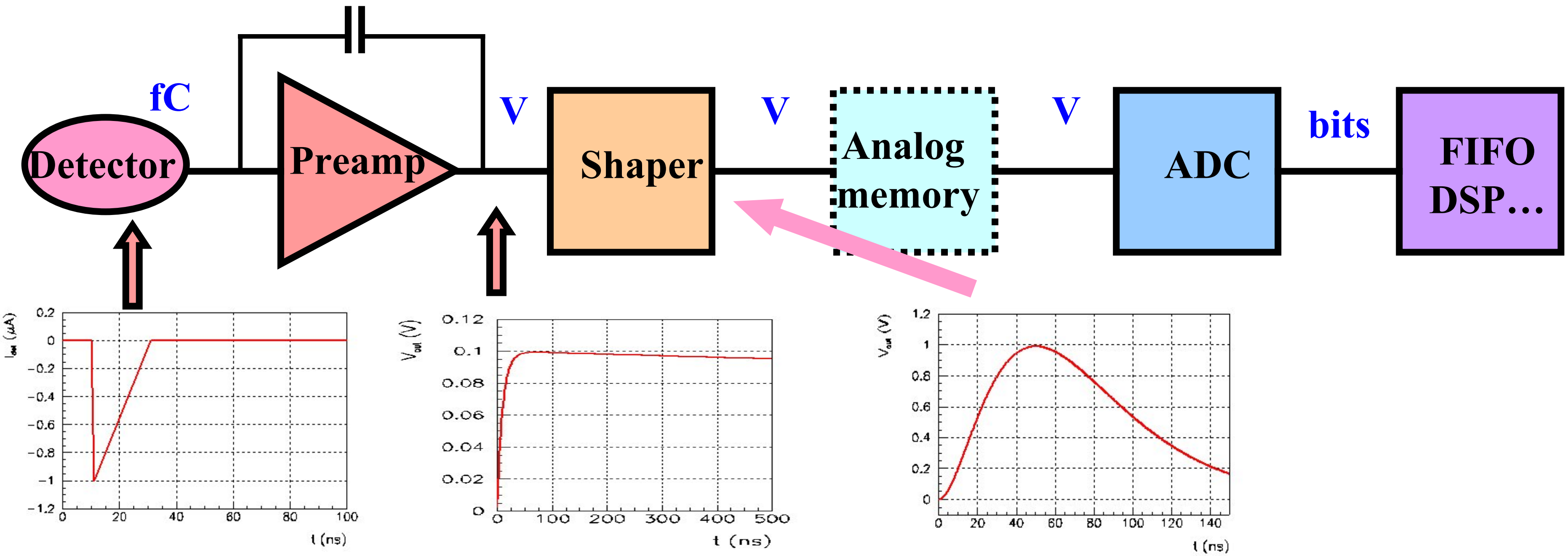
Low material

Low cost !

(and even less)

Overview of readout electronics

- Most front-ends follow a similar architecture



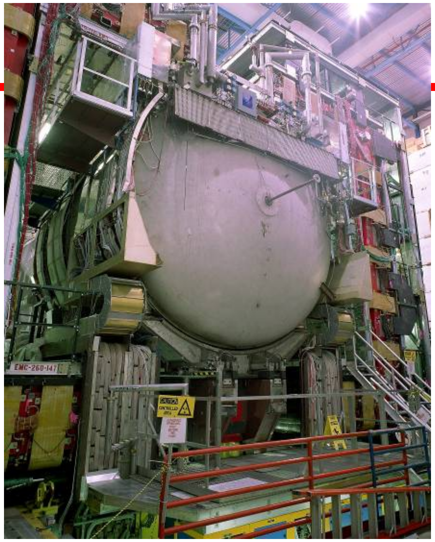
- Very small signals (fC) -> need amplification
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Thousands to millions of channels

Preamps overview [3]

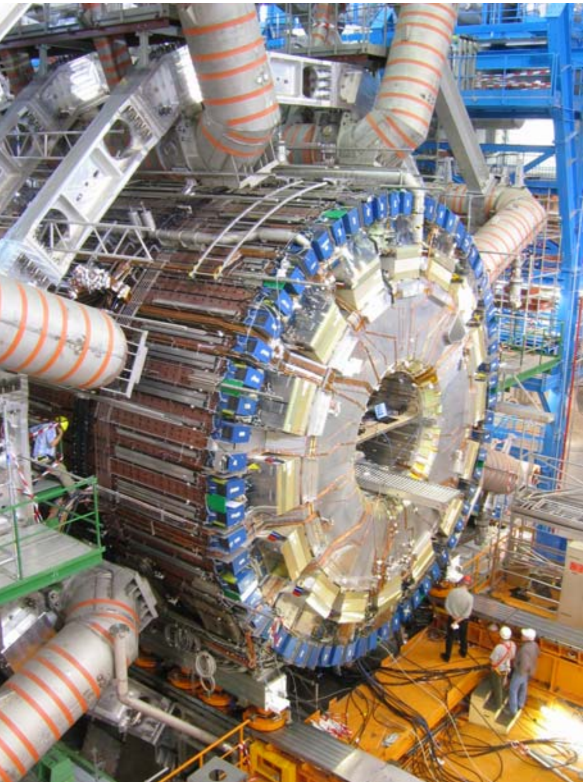
Experiment	Detector	Q/I	Technology		Power	Noise : e_n
ATLAS em	LAr	I	Bipolar	Hybrid	50 mW	0.4 nV/√Hz
ATLAS had	Tiles + PMT	Q	None			
ATLAS HEC	LAr	I	GaAs	ASIC	108mW	0.8 nV/√Hz
BABAR	CsI + PD	Q	JFET	Hybrid	50 mW	0.6 nV/√Hz
CMS em	PbWO4+APD	Q	CMOS	ASIC	50 mW	0.9 nV/√Hz
CMS had	Tiles + HPD	Q	BiCMOS	ASIC		
DØ	LAr	Q/I	JFET	Hybrid	270 mW	0.5 nV/√Hz
FLC	W/Si	Q	BiCMOS		3 mW	1 nV/√Hz
KLOE	CsI + PD	Q	Bipolar	Hybrid	60 mW	
LHCb em	PMT	Q	None			
NA48	LKr	I	JFET	Hybrid	80 mW	0.4 nV/√Hz
Opera TT	PMTMA	Q	BiCMOS	ASIC	5 mW	

Readout overview

Experiment	Shaping	tp	Technology	Dyn. Rge	Gains	ADC
ATLAS em	$CRRC^2$	50 ns	BiCMOS 1.2µ	16 bits	1-10-100	12 bits 5 MHz
ATLAS had	Bessel 9	50 ns	Passive hybrid	16 bits	1-64	
BABAR	$CRRC^2$	400 ns	BiCMOS 1.2µ	18 bits	1-4-32-256	10 bits 4 MHz
CMS em	RC^2	50 ns	CMOS 0.25µ	16 bits	1-6-12	12 bits 40 MHz
CMS had	Gated int	25 ns				
DØ	CR	350 ns	Bipolar hyb	15 bits	1-8	12 bits
FLC	CRRC	150 ns	BiCMOS	16 bits	1-8-64	
KLOE	Bessel 3	200 ns	Bipolar hyb.	12 bits	1	
LHCb em	DLC	50 ns	BiCMOS 0.8µ	12 bits	1	12 bits 40 MHz
NA48	Bessel 8	70 ns	BiCMOS 1.2µ	14 bits	1-2.5-6-18	10 bits 40 MHz
Opera TT	$CRRC^2$	150 ns	BiCMOS 0.8µ		1	



Ionization calorimeters

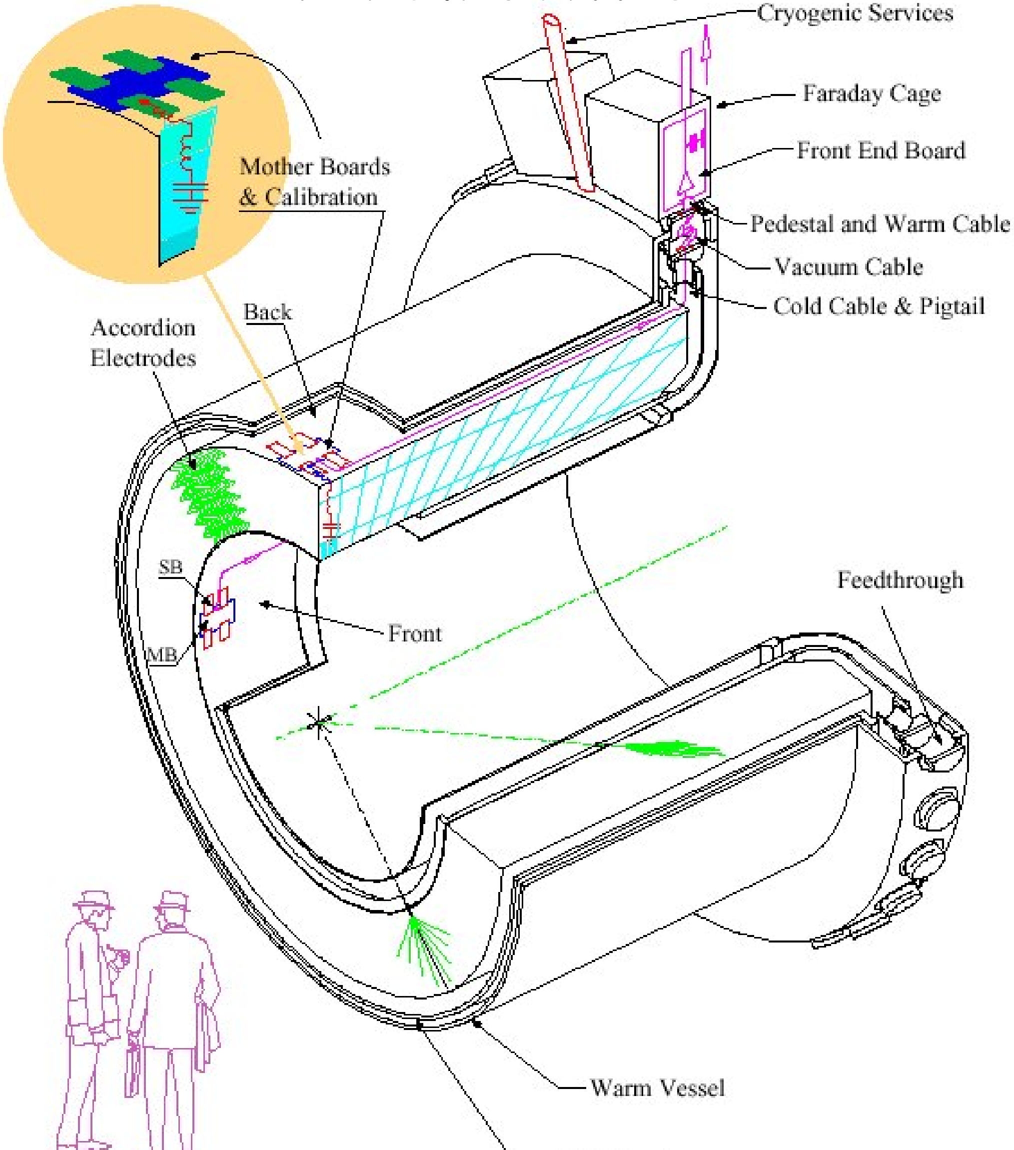


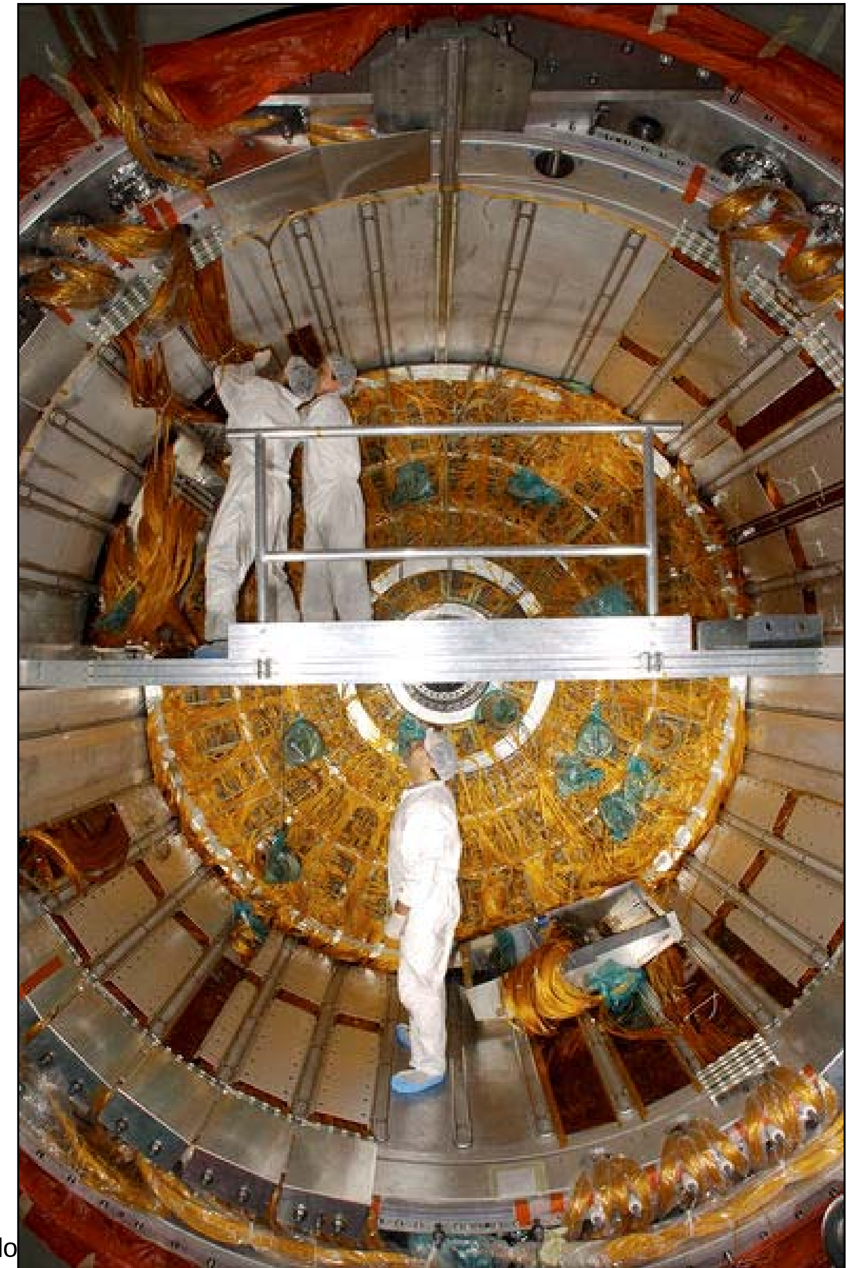
- DØ (LAr)
- NA48 (LKr)
- ATLAS (LAr)
- *H1,*

- Stable, linear
- Easy to calibrate (!)
- Moderate resolution

ATLAS : LAr e.m. calorimeter [11]

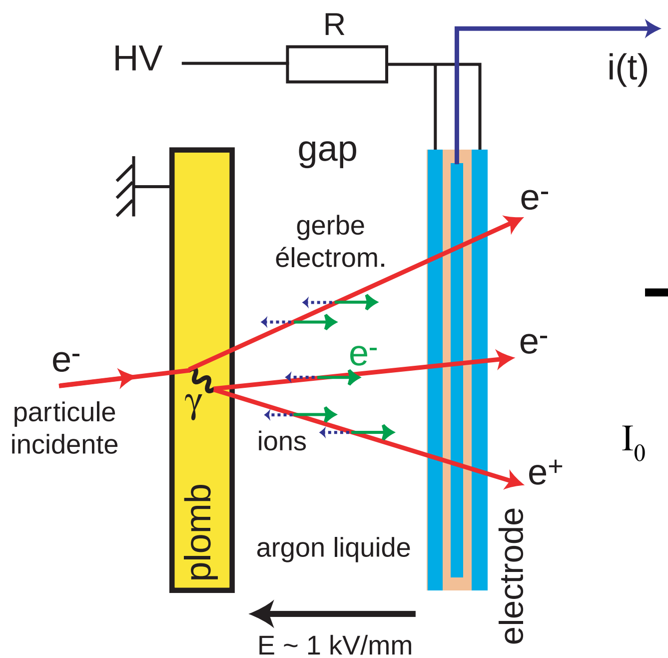
- **200 000 readout channels**

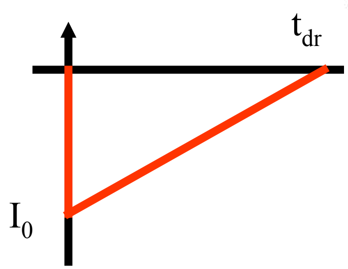


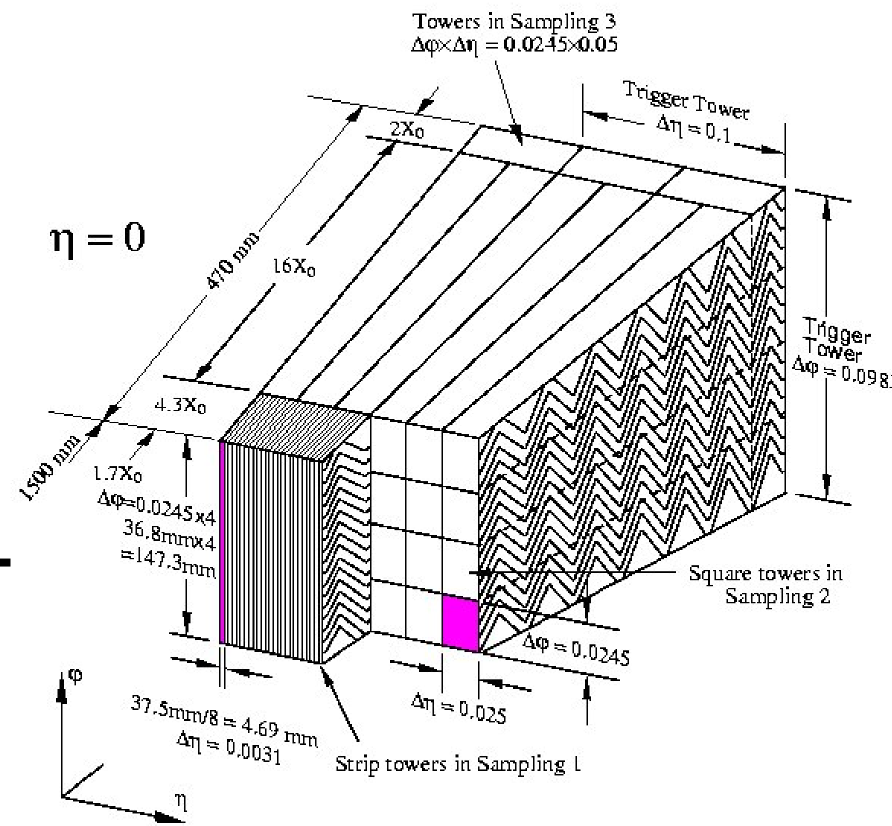


ATLAS : LAr e.m. calorimeter [11]

- **Dynamic range : 16 bits** (50 MeV-3 TeV)
  - Energy resolution : $10\%/\sqrt{E} \oplus 0.7\%$
- **Segmentation : PS, Frt, Mid, Back**
  - Capacitance : 200 pF – 2 nF
- **Traingular ionisation signal**
  - $I_0 = 2.5\ \mu A/GeV \quad t_{dr} = 450$ ns



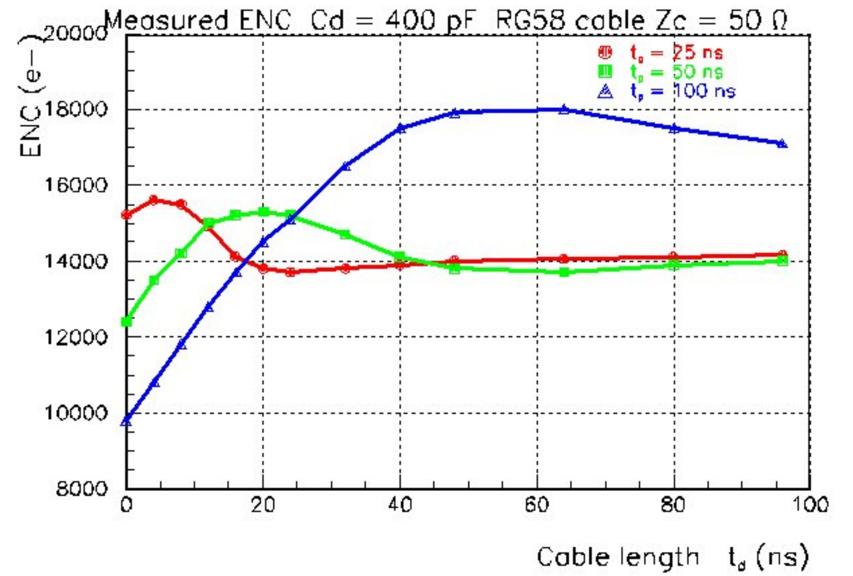


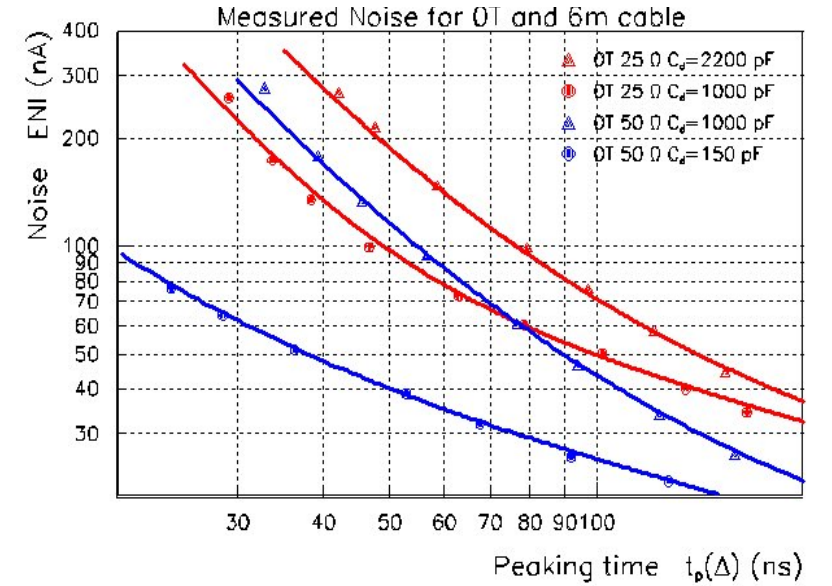


ATLAS : LAr preamplifier [13]

- **Warm preamp**
  - After 2-5m coax cable
  - Noise independent of cable length at fast shaping ($R_0*C_d \sim t_p$)
  - Current sensitive to handle dynamic range with long signals

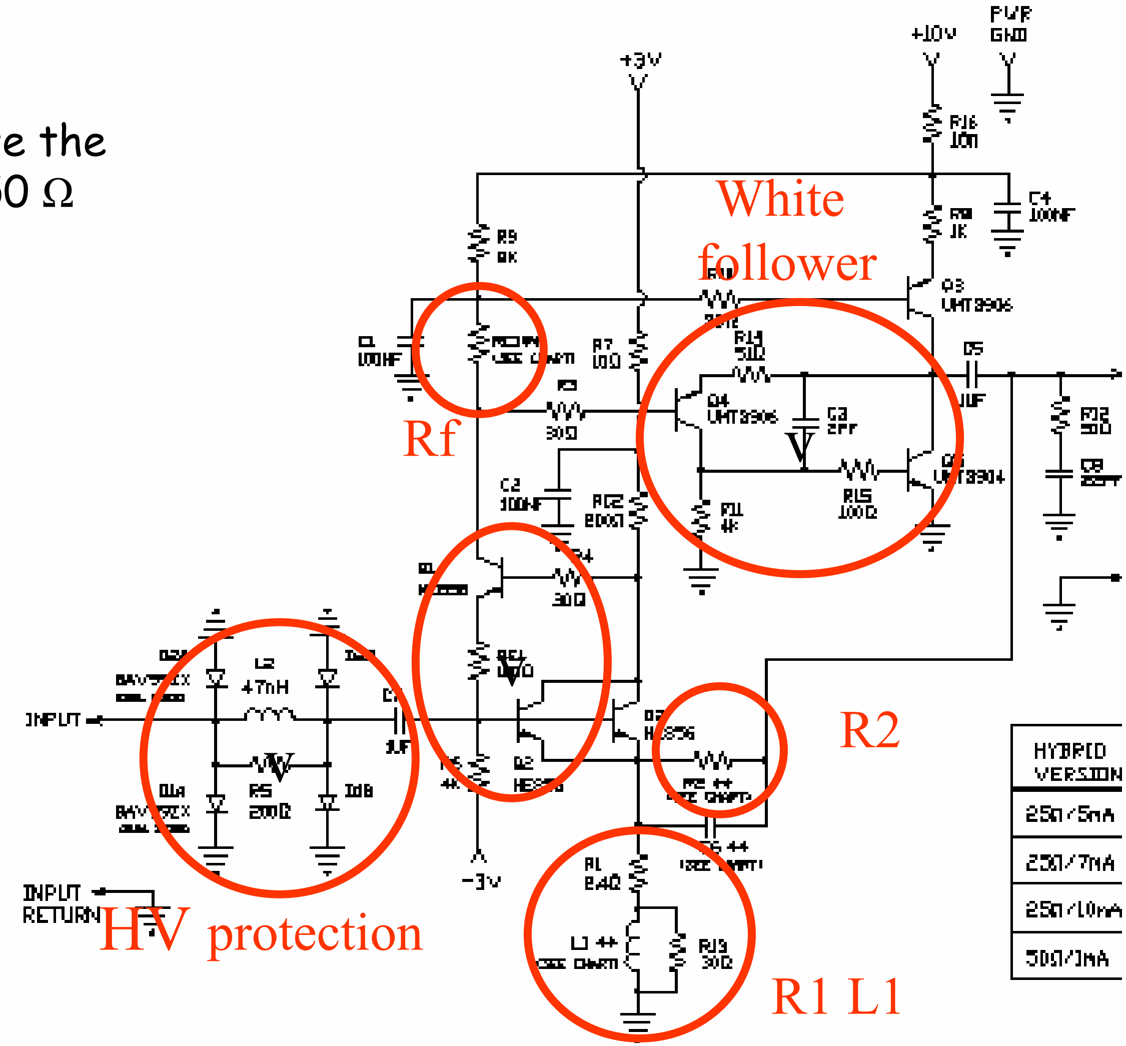
- **Noise :**
  - NE856 Bipolar transistor I_C = 5 mA
  - e_n = 0.4 nV/√Hz
  - i_n = 5 pA/√Hz





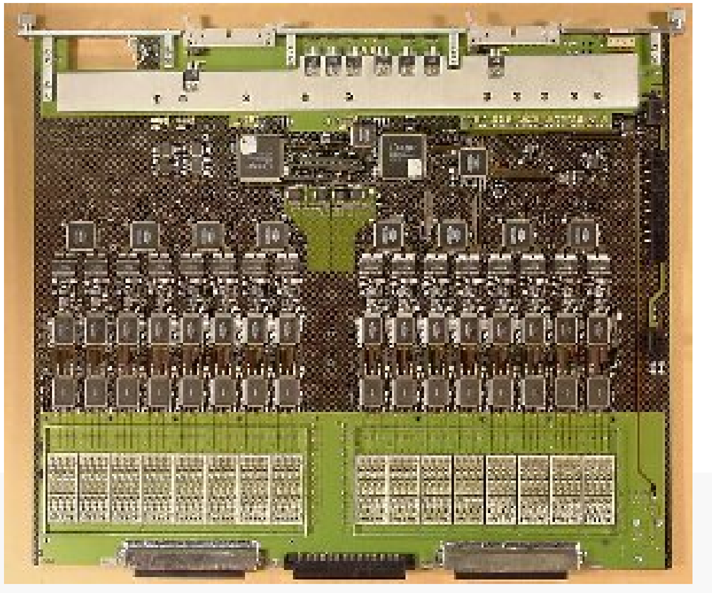
ATLAS : LAr preamplifier [14]

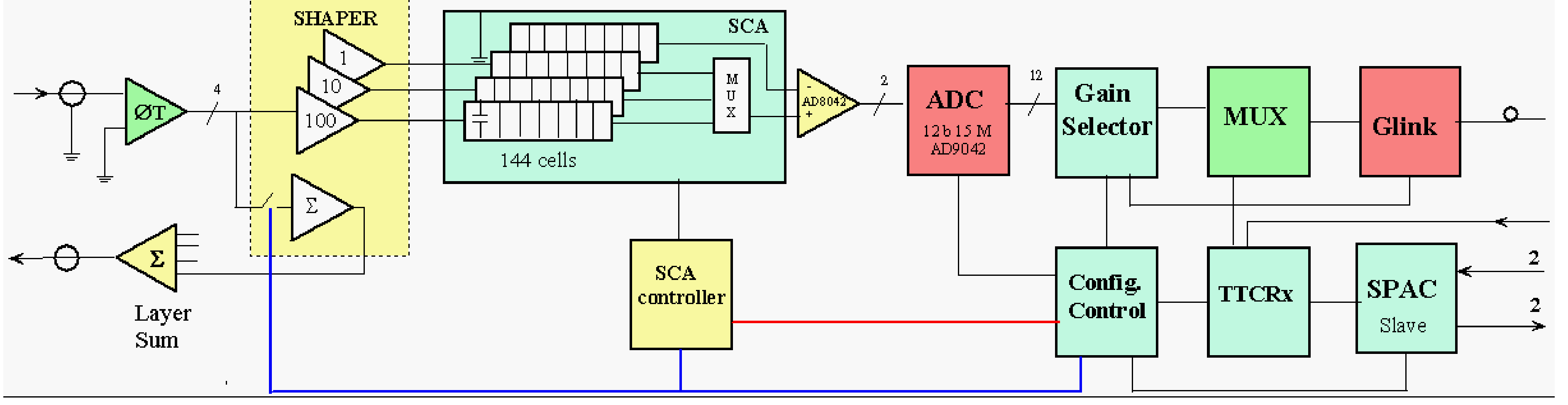
- **Current preamp bipolar hybrid**
  - "super common base" input
  - Feedback on the base to raise the input impedance to 25 Ω or 50 Ω
  - White follower output stage
- **Input impedance :**
  - $Zin = 1/g_m + Rf*R_1/R_2$
  - Inductance to extend BW
- **3 transimpedance (gain) values**
  - 3 kΩ (Front)
  - 1 kΩ
  - 500 Ω



ATLAS LAr : Front End boards

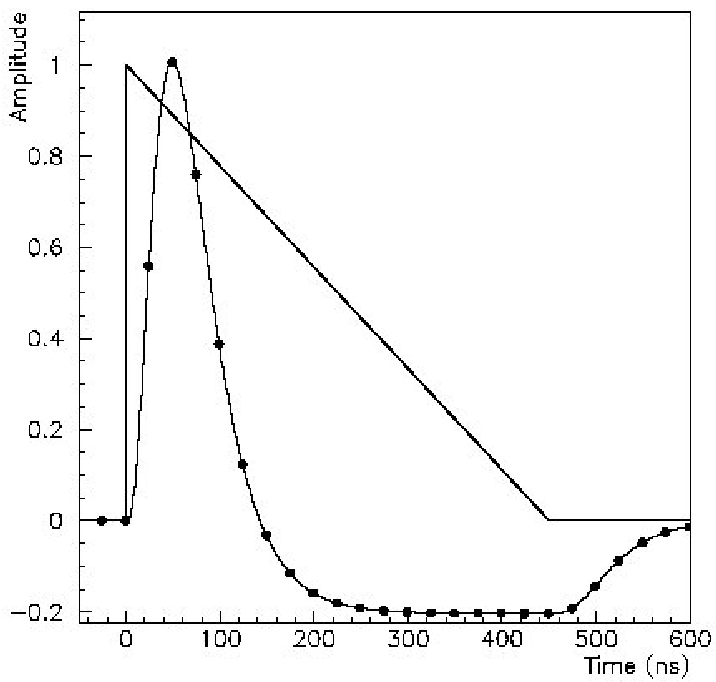
- **Amplify, shape, store and digitize Lar signals**
  - 128 preamps
  - 128 tri-gain shapers
  - 128 quad pipelines
  - 32 ADCs (12bits 5 MHz)
  - 1 optical output (Glink)

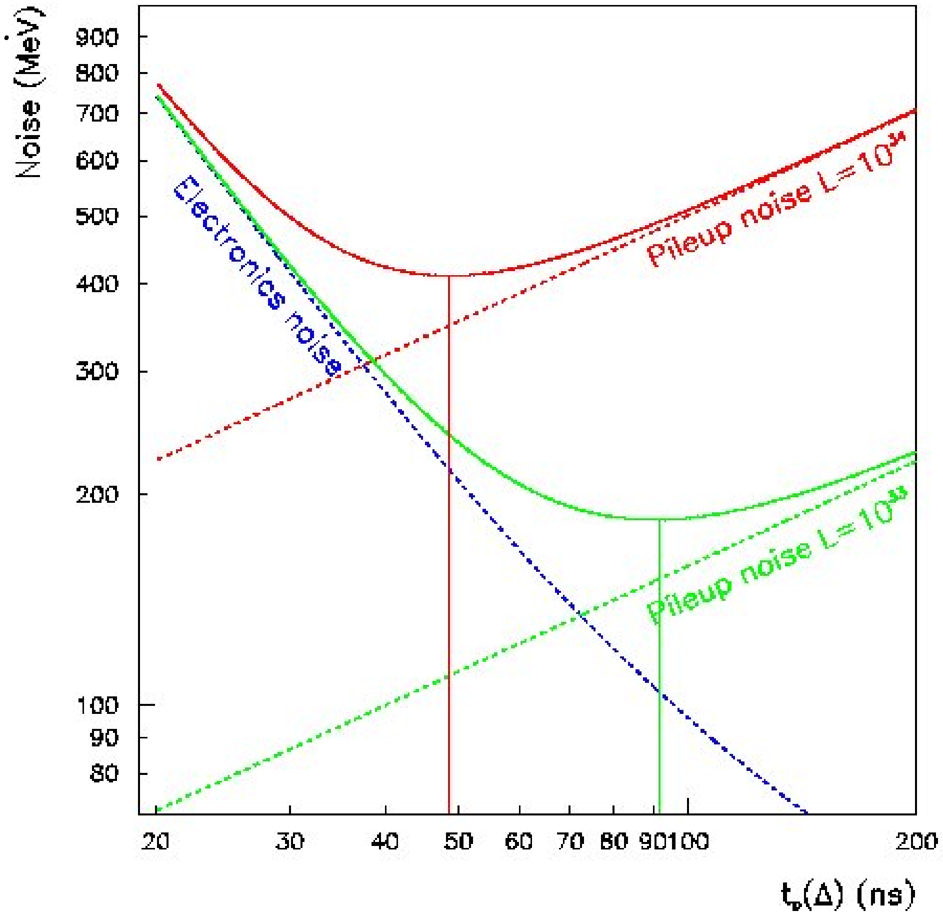




ATLAS : LAr shaper [16]

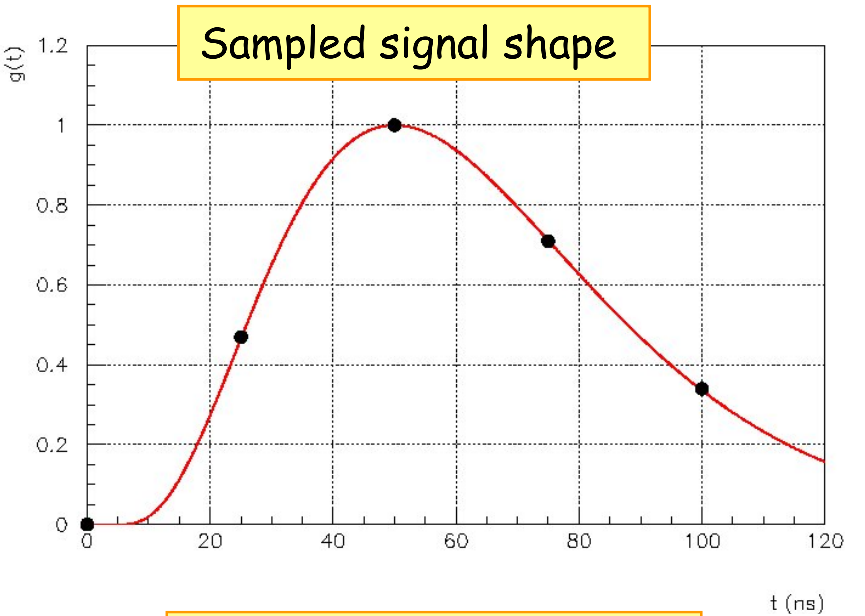
- **Goal : optimize signal to noise ratio between electronics noise and pileup noise**
  - Differentiation to Remove long trailing edge of Lar signal
  - Electronics : $ENI = A/t_p^{3/2} + B/\sqrt{t_p}$
  - Pileup : $ENE = C\sqrt{t_p}$
  - Vary with location and luminosity…

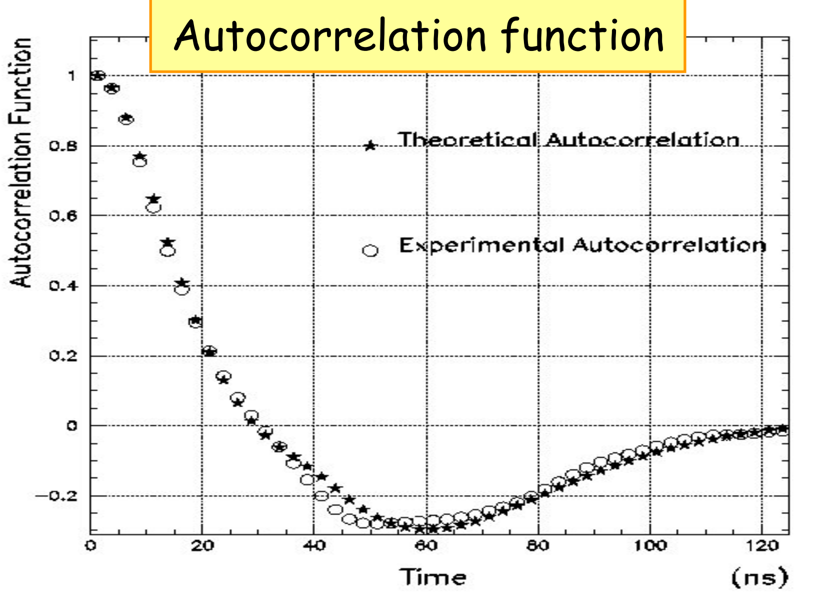




Digital filtering

- **Linear sums of sampled signal**
  - Finite Impulse Respopnse (FIR)
  - **made possible by fast ADCs (or analog memories)…**
- **Signal : s(t)=Ag(t)+b**
  - A : amplitude
  - G(t) : normalised signal shape
  - B : noise
  - Sampled signal : $s_i = Ag_i + b_i$
- **Filter : weighted sum $\Sigma\ a_i\ s_i$**
  - $a_i = \Sigma\ R^{-1}_{ij}\ g_i$
  - R = autocorrelation fonction
  - g_i = signal shape
    (0, 0.63, 1, 0.8, 0.47)
  - $S = \Sigma^n_{i=1}\ a_i s_i$





Exemple : ATLAS "multiple sampling"

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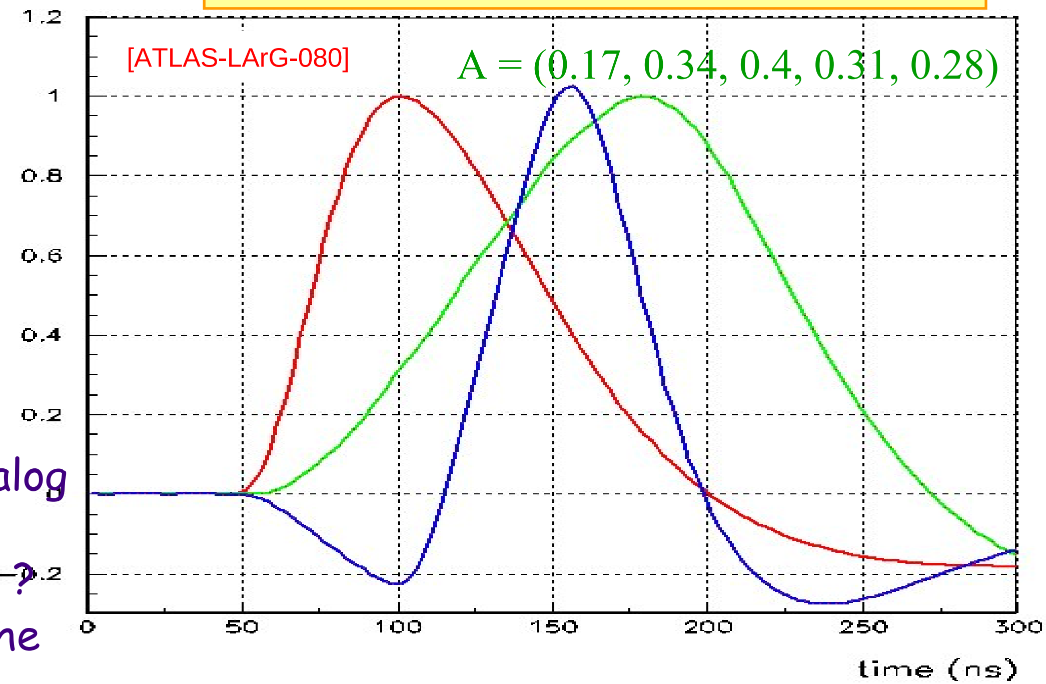
- **Slowing down the signal**
  - Reduction of series noise
  - Similar to a simple integration
- **Accelererating the signal**
  - Reduction of pileup noise
  - Similar to a differentiation
- **Measuring the timing**
- **Some questions**
  - How does-it compare to an analog filter
  - How many samples are needed ?
  - What accuracy is needed on the waveform and on the autocorrelation ?
  - What analog shaping time is needed ?
  - Is the analog filter really useful ?

Signal before and after digital filtering

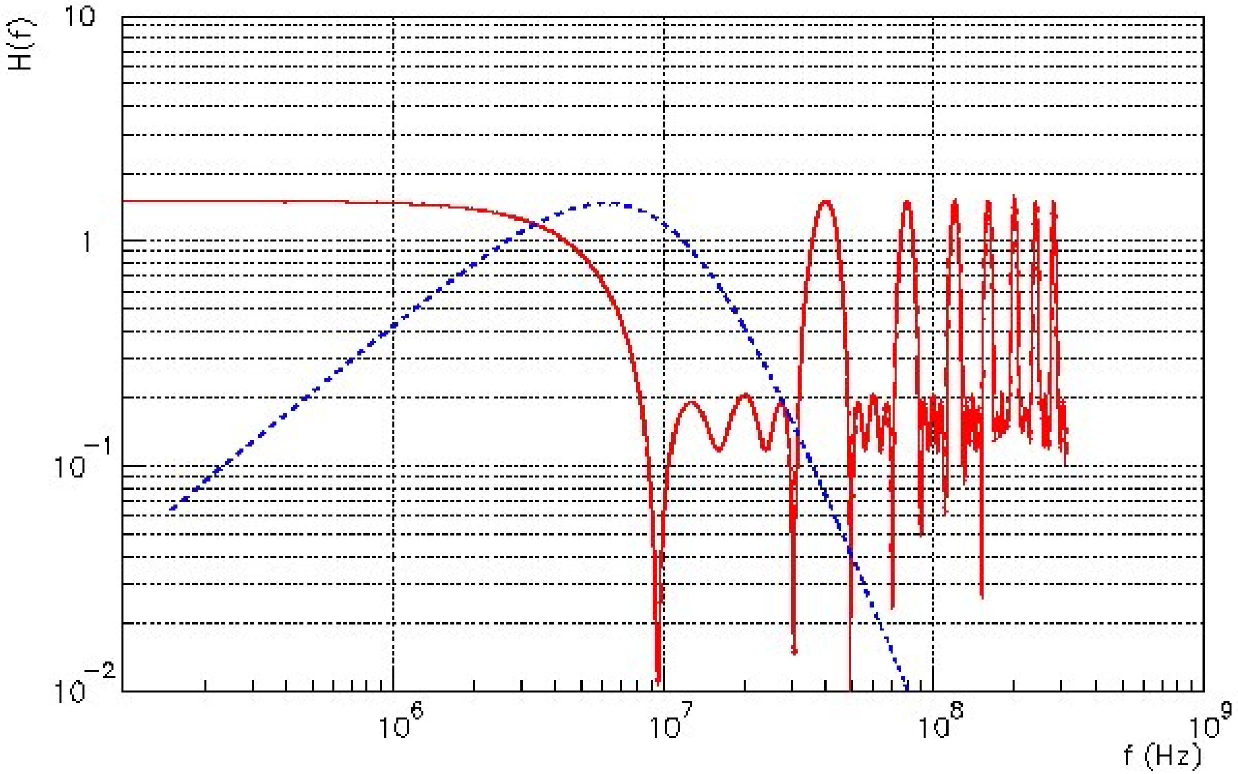


A = (-0.75, 0.47, 0.75, 0.07, -0.19)

Transfer function of digital filter

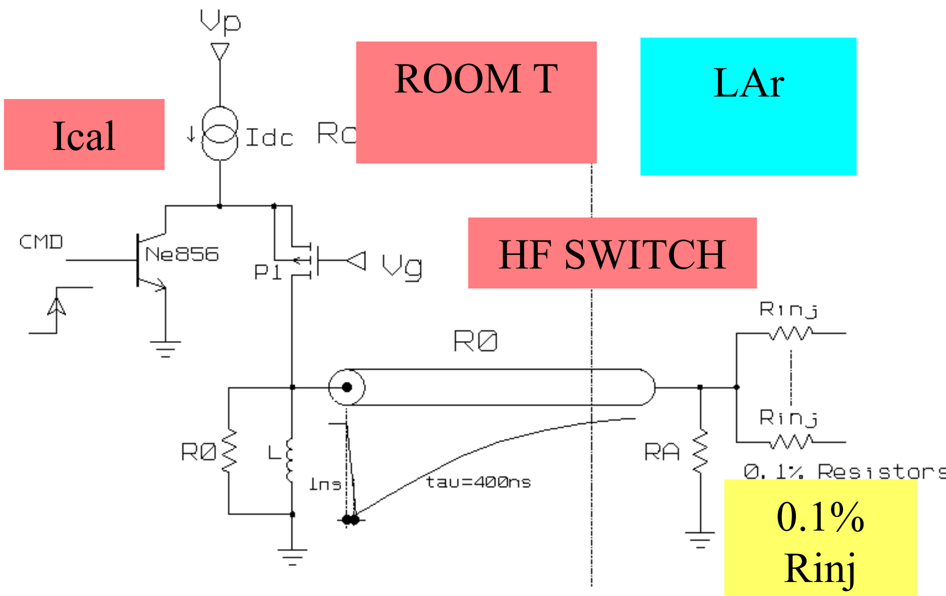
- **Calculation with Z-transform**
  - $H(Z) = a_1 Z^{-4} + a_2 Z^{-3} + a_3 Z^{-2} + a_4 Z^{-5} + a_5$ $Z = \exp(j\omega T_{ech})$ (T_{ech} = 25 ns)
  - Beware of Aliasing !

- **Digital filtering has rendered complex filters obsolete**

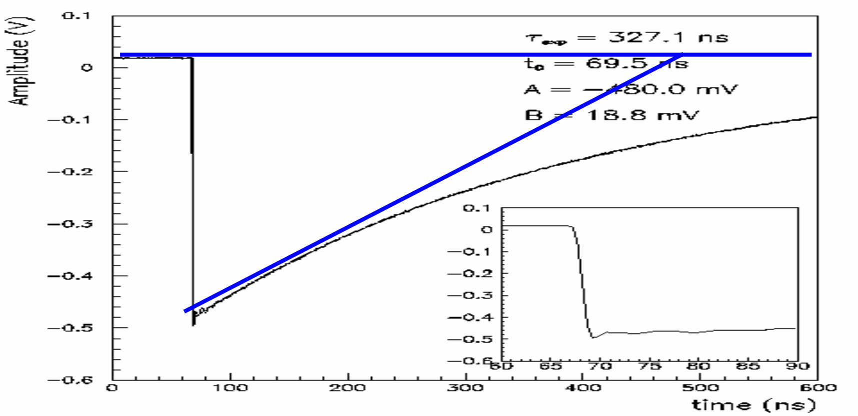


ATLAS Lar : Calibration principle

- **Goal: Inject a precise current pulse as close as possible as the detector pulse**
  - Injection with precision resistors
  - Rise time < 1ns, Decay time ~ 450 ns
  -
- **Dynamic range : 16 bits**
  - Output pulse : 100 µV to 5V in 50Ω
  - Integral non linearity < 0.1%
- **Uniformity between channels < 0.25%**
  - To keep calorimeter constant term below 0.7%)
- **Timing between physics and calibration pulse ±1ns**



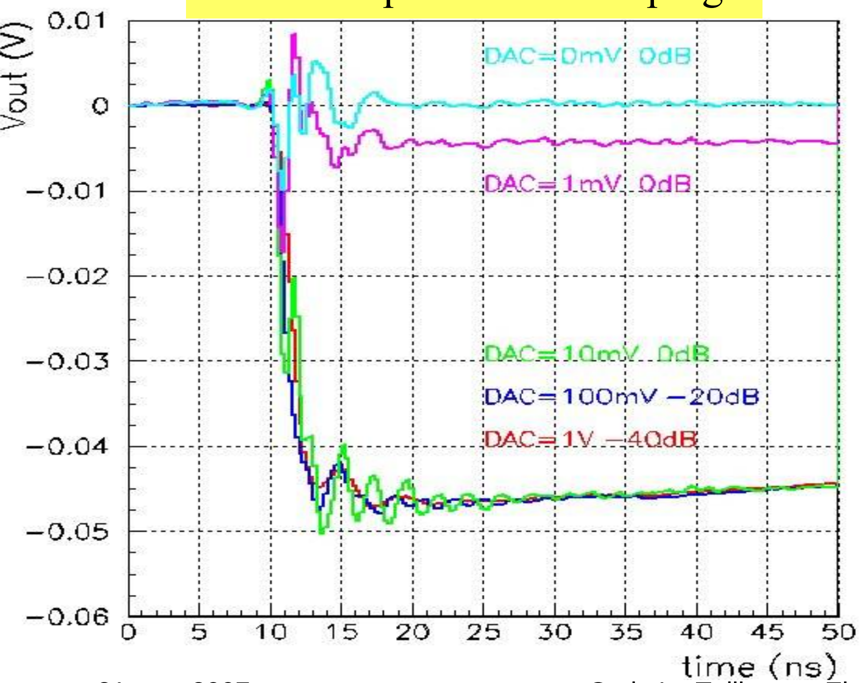
$$Ical = Idc \frac{R0/2}{Rinj} e^{-2R0t/L}$$



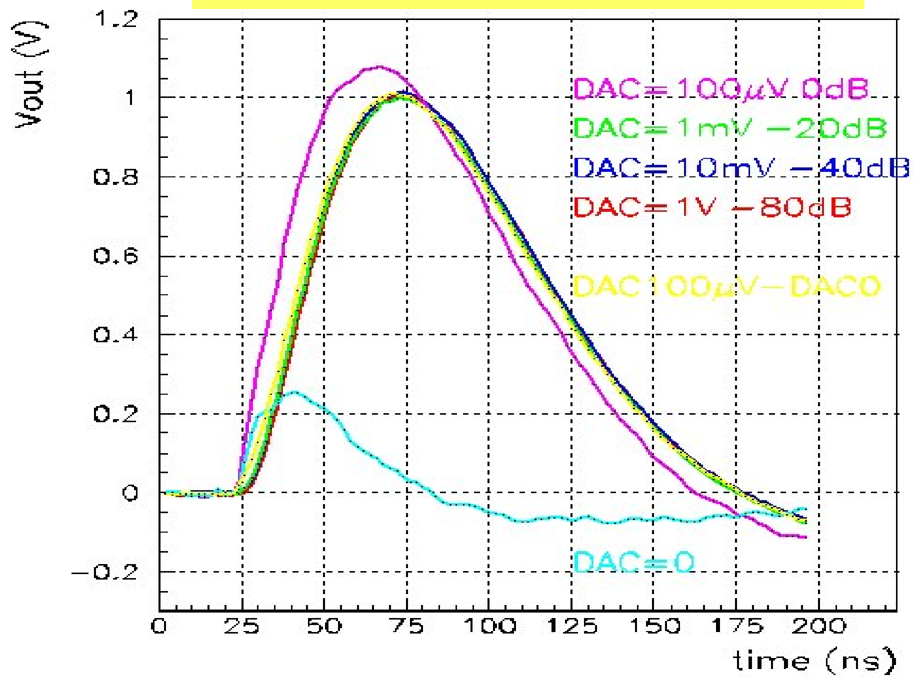
Calibration waveforms

- 0-5 V pulses in 50 2ns rise time
- HF Ringings :
  - At small DAC values, due to parasitic package inductance in HF switch
  - « Parasitic injected charge » (PIC)
  - Peak of Qinj : equivalent to DAC=30 μV (2LSB)
  - At signal peak : PIC < DAC = 15 μV = 1 LSB

Pulse output without shaping



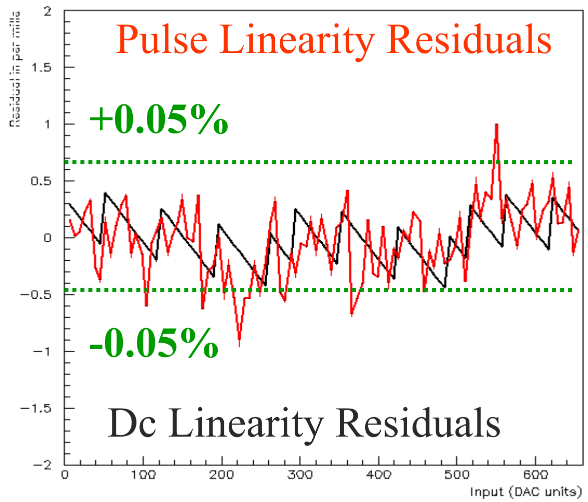
Pulse output after 50 ns shaping



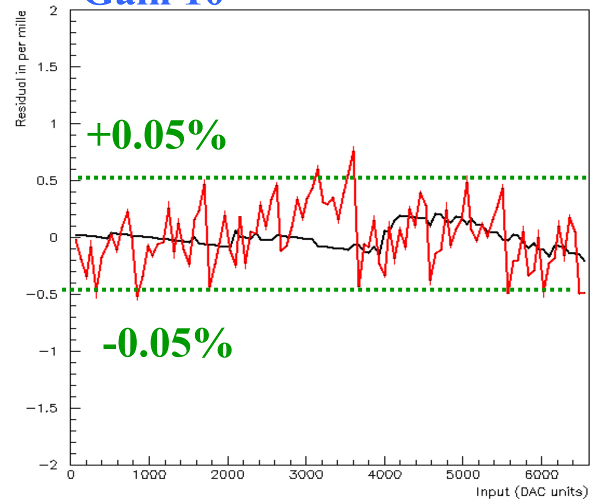
DC and Pulse Linearity

- **Measured on 3 gains 1-10-100**
- **Pulse measurements**
  - In red
  - After shaping (tp=50ns)
- **DC current measur.**
  - In black
  - With Keithley
- **Example of problems**
  - DAC referenced to VP6 by mistake
  - Bad 5Ω resistor brand
- **Dynamic performance at the level to DC performance**

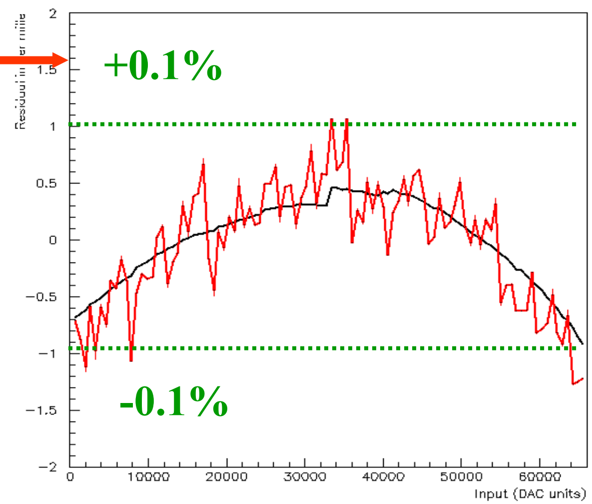
Gain 100



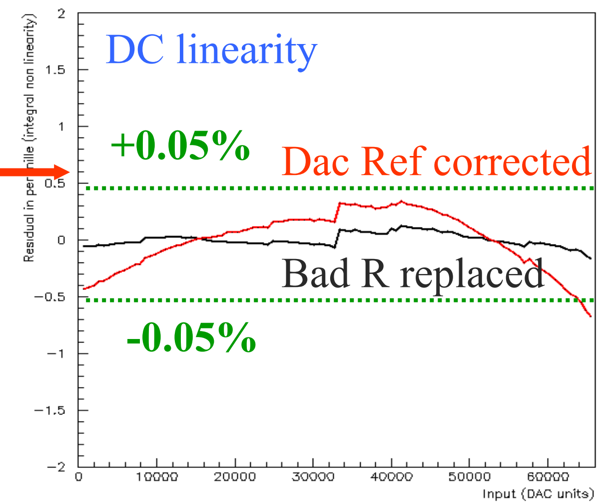
Gain 10



Gain 1

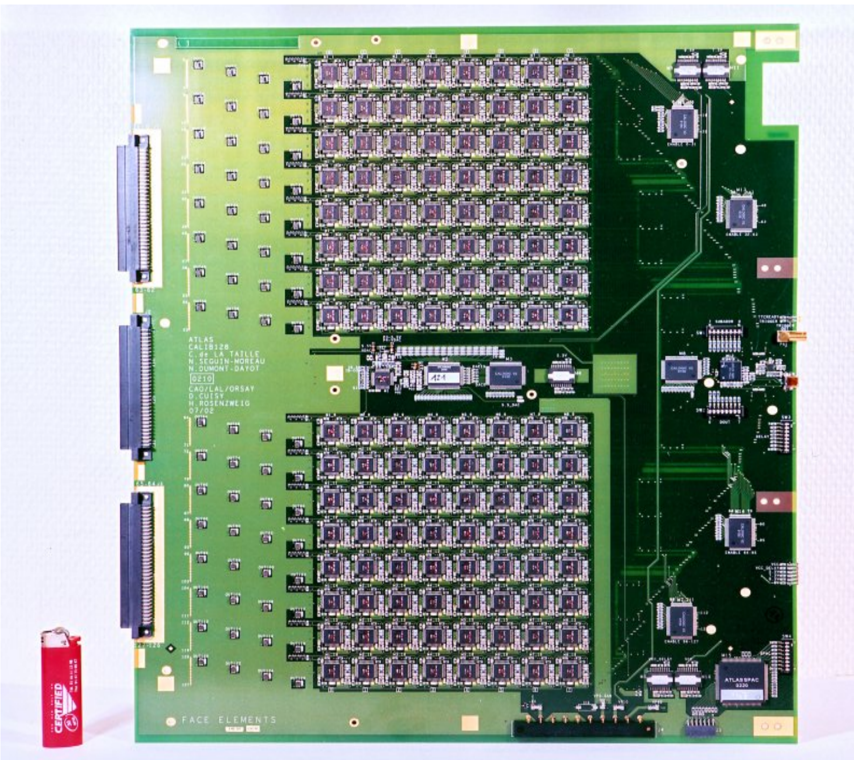


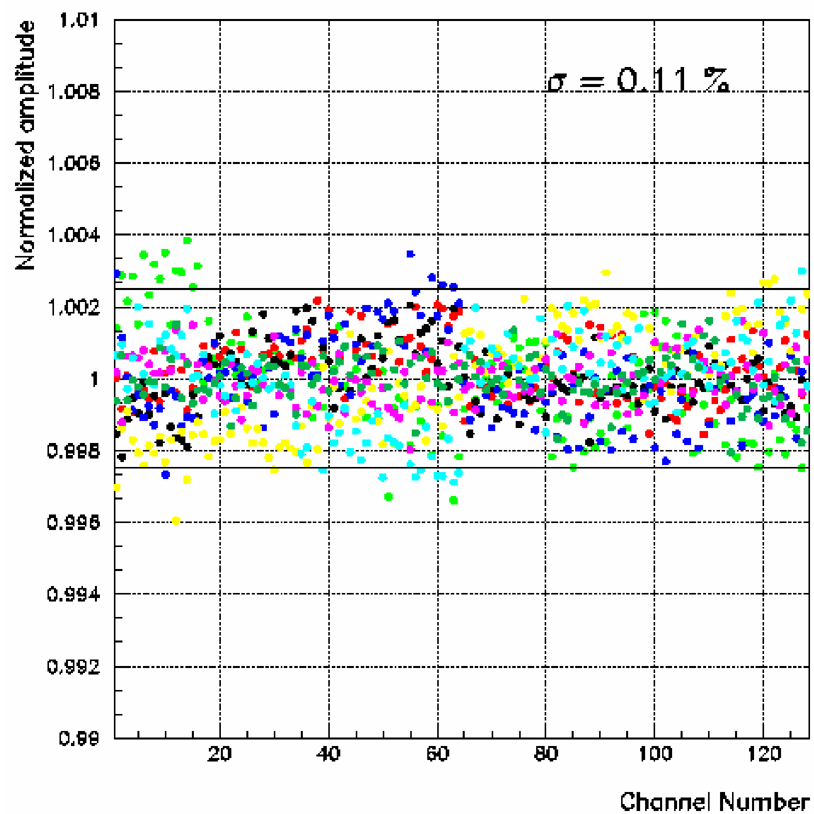
Gain 1

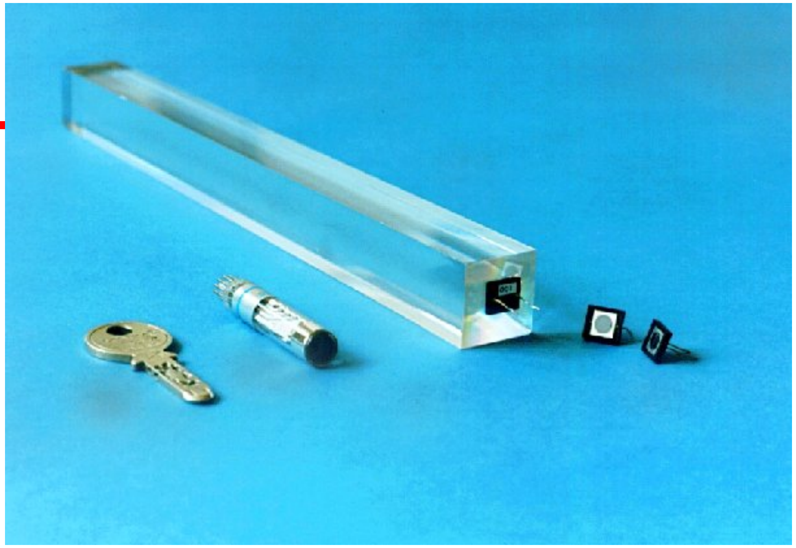


ATLAS Lar : calibration performance

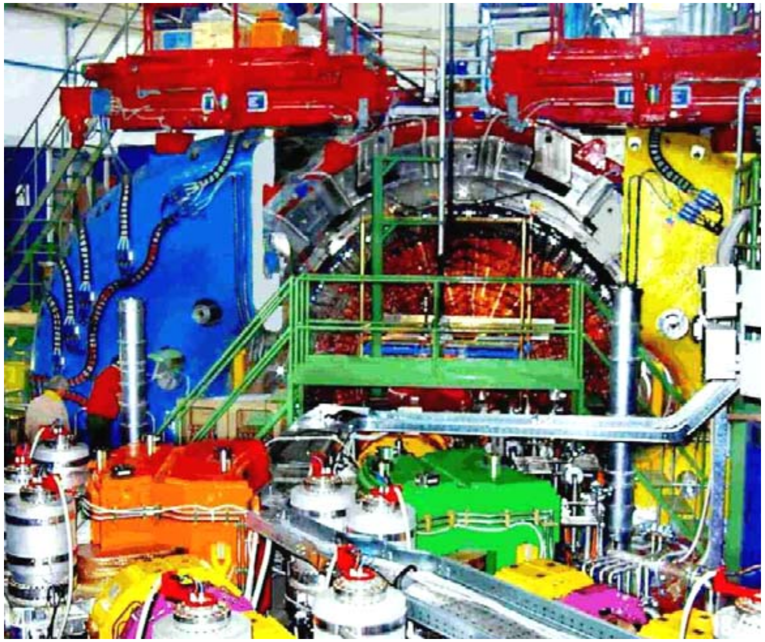
- 128 channels/ board
- Uniformity : 0.1%







Crystal calorimeters

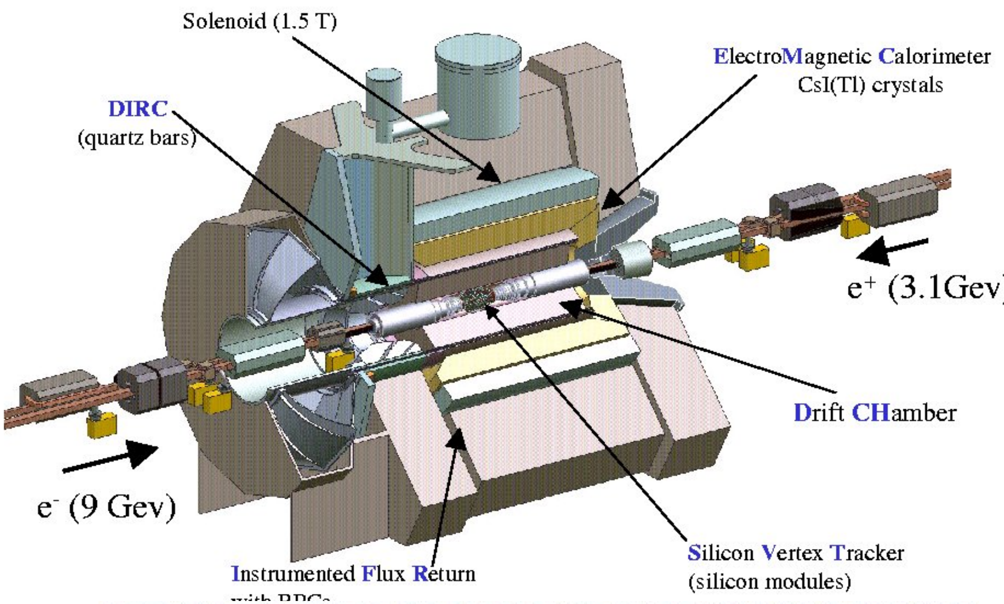


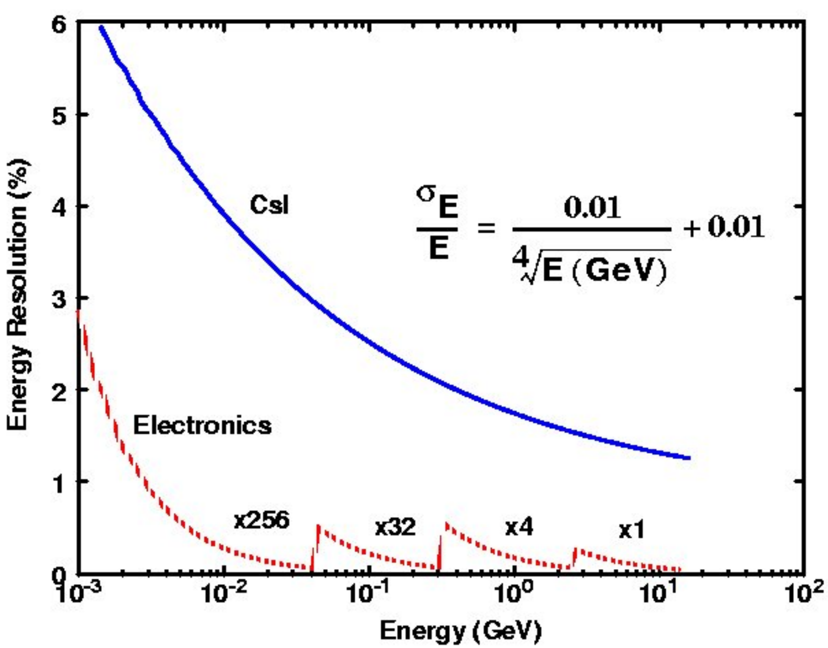
- Babar (CsI)
- Kloe (CsI)
- CMS ($PbWO_4$)
- *L3, CLEO, Belle, ALICE*

- Fast
- Best resolution
- Difficult to calibrate
- expensive

Babar : em CsI calorimeter [25]

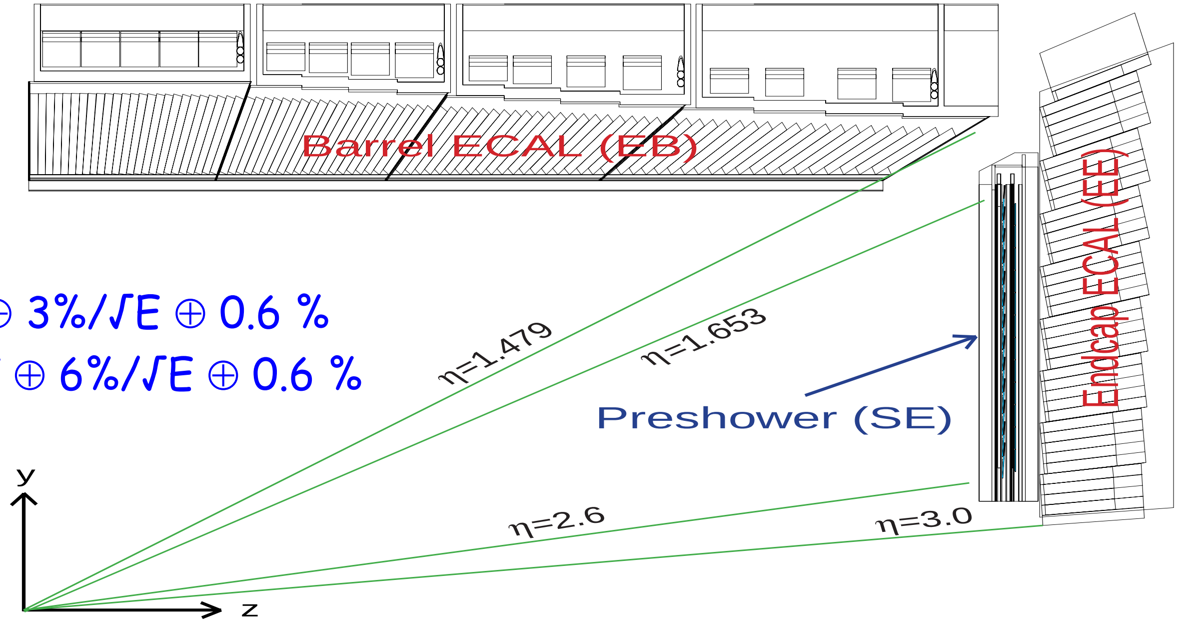
- **Goal : study CP violatio and B physics**
  - Installed at SLAC (1998)
  - Crystal calorimeter with 6500 CsI crystals (5720 Barrel + 820 End-Cap)
  - *very similar to Belle at KEK*
- **18 bits dynamic range** (50 keV -> 10 GeV)
  - 4 gains 1, 4, 32 & 256

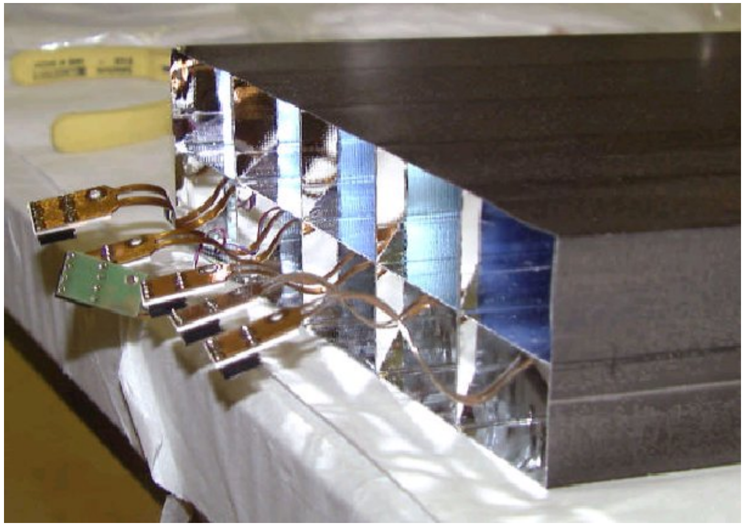


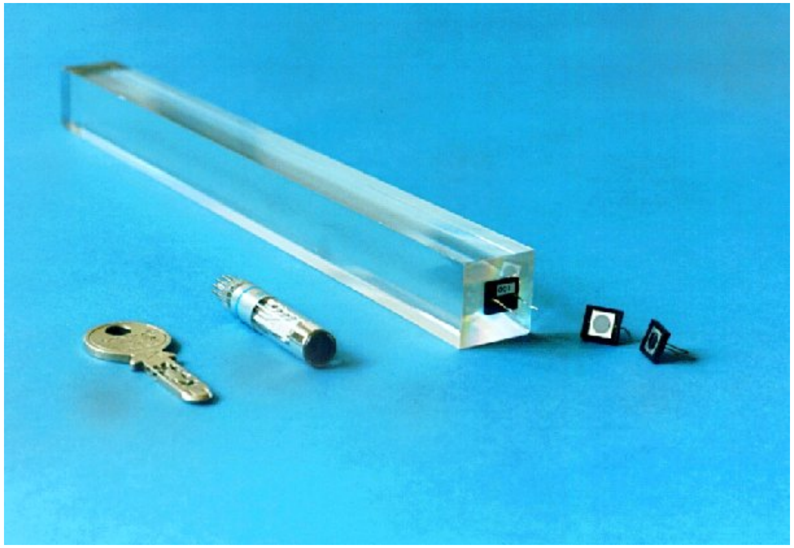


CMS : em PbWO4 calorimeter [30]

- **Lead-Tungstate crystals**
  - light yield 9 p.e. /MeV
- **Dynamic range : 16 bits**
  - 50 MeV-3 TeV
- **Energy resolution : ~ 0.5%**
  - Barrel : $\sigma(E)/E = 200\ MeV \oplus 3\%/\sqrt{E} \oplus 0.6\ \%$
  - End-cap : $\sigma(E)/E = 200\ MeV \oplus 6\%/\sqrt{E} \oplus 0.6\ \%$
- **Granularity : ~ 0.1 x 0.1**
  - Barrel : 61 200 channels
  - End-cap : 16 000 channels

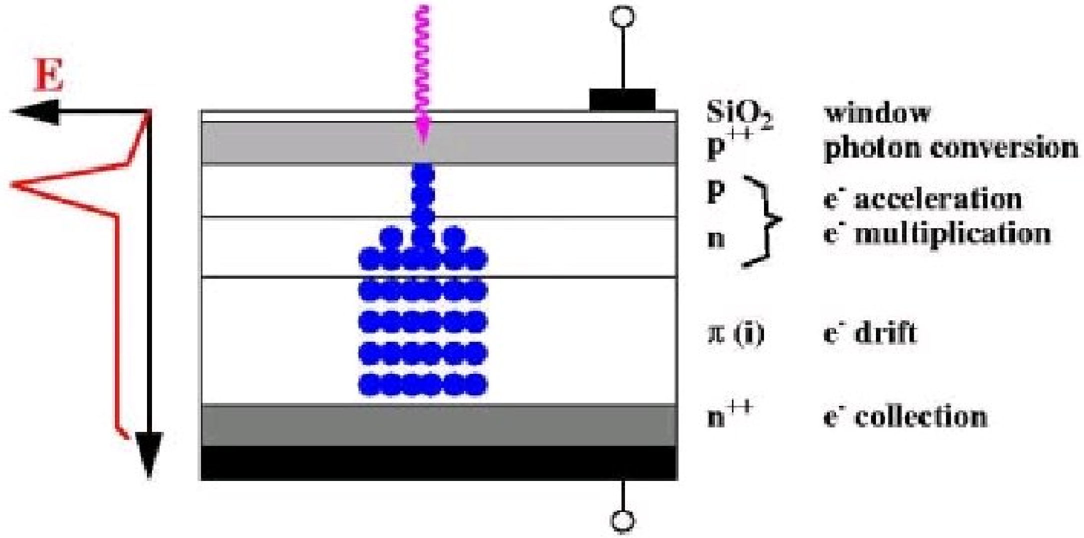


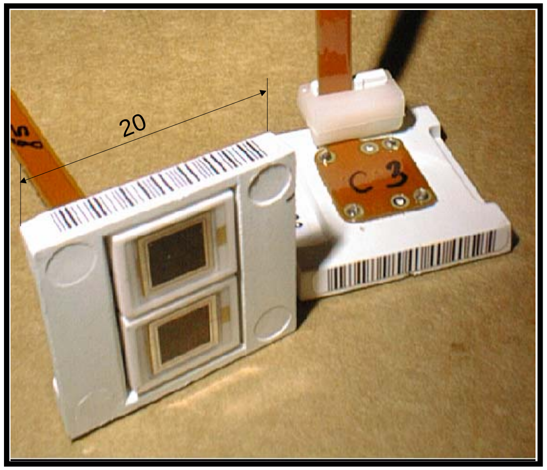


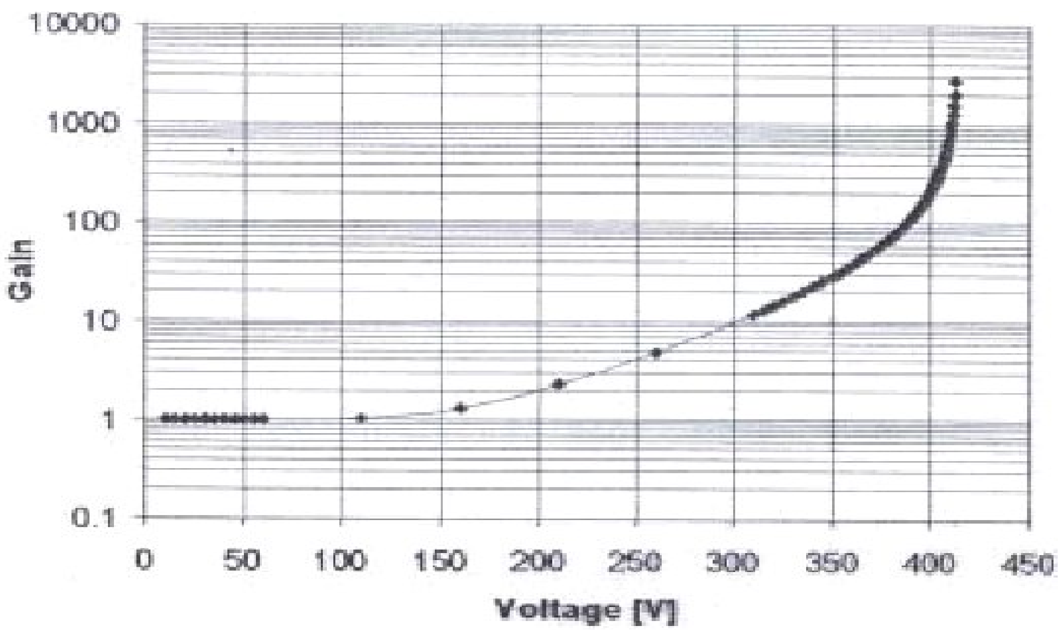


CMS : em photodetector

- **Avalanche photodiodes (APDs)**
  - Area : 25 mm^2, QE = 80%
  - Gain = 50   TC = -2%/K
  - Excess noise factor : 2.2
  - C= 30 pF
  - Bias ~200-300 V







Example : CMS ECAL preamp (MGPA) [45]

1st stage

- $R_F C_F$ = 40 nsec. (avoids pile-up)
- choose $R_F C_F$ for barrel/endcap external components
  - => 1 chip suits both

3 gain channels 1:6:12

- set by resistors (on-chip) for linearity

differential current O/P stages

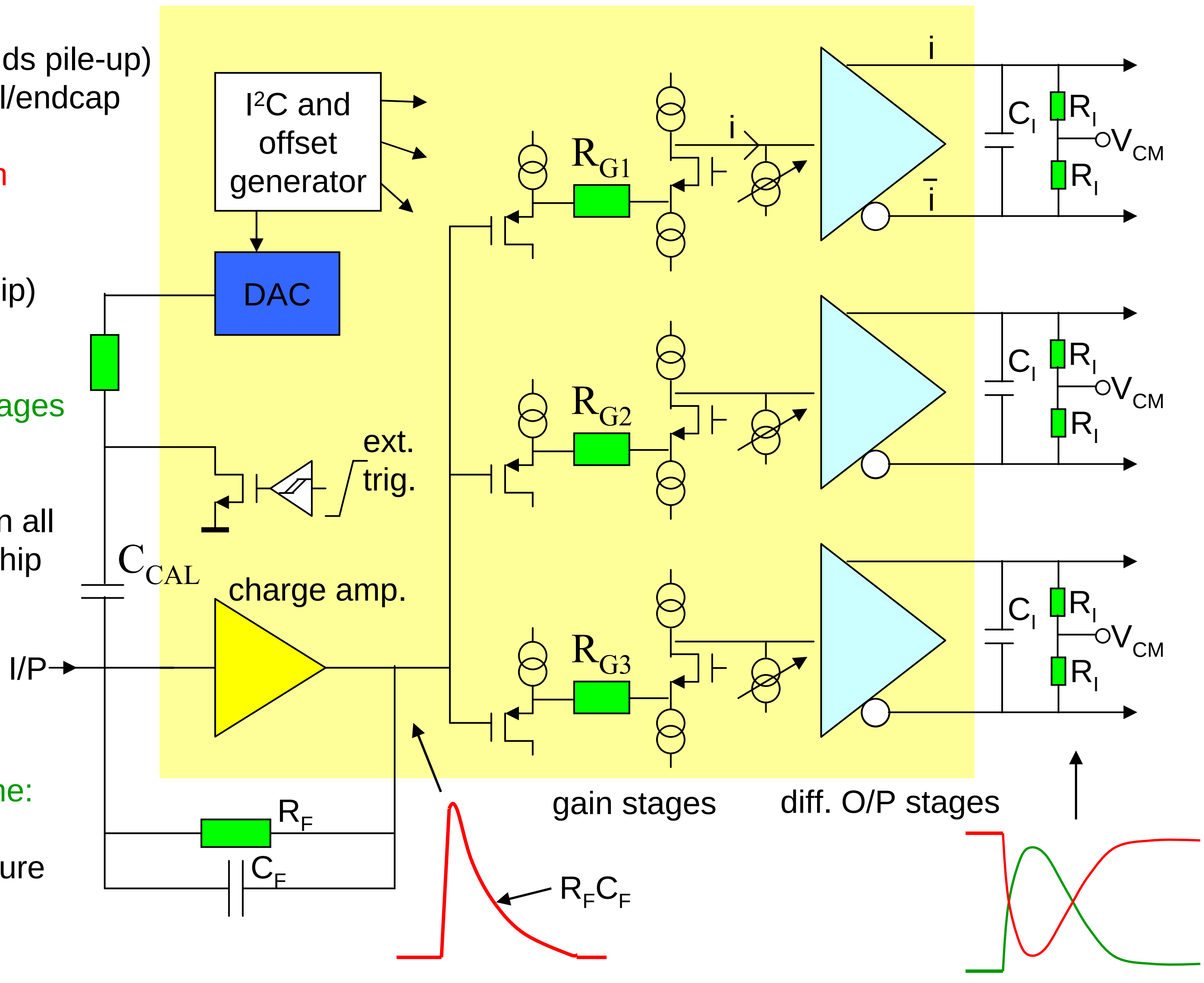
- external termination
- $2R_I C_I$ = 40 nsec.
- => low pass filtering on all noise sources within chip

calibration facility

- prog. amplitude
- needs ext. trigger

I²C interface to programme:

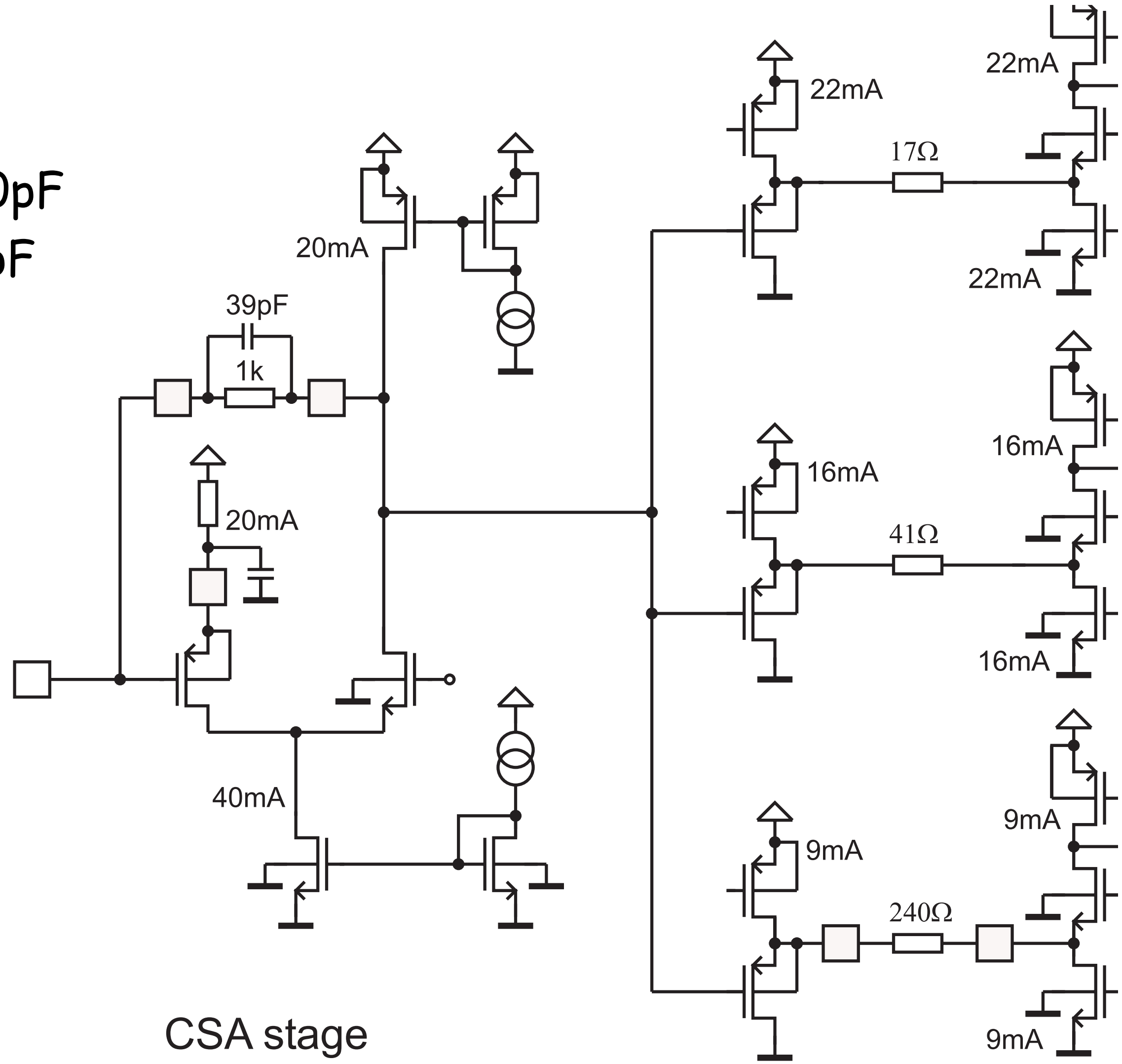
- output pedestal levels
- enable calibration feature
- cal DAC setting

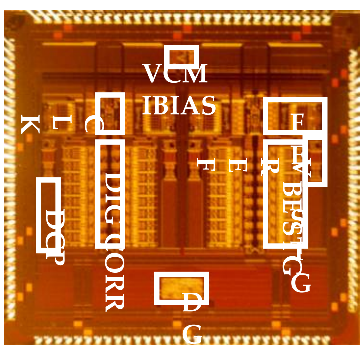


CMS : MGA preamp

©M. Remond

- Techno : CMOS 0.25µm
- Noise
  - ENC=8000 e- @ Cd=200pF
  - ENC=5000 e- @ Cd=56pF
- Power : 600 mW





ECAL Electronics

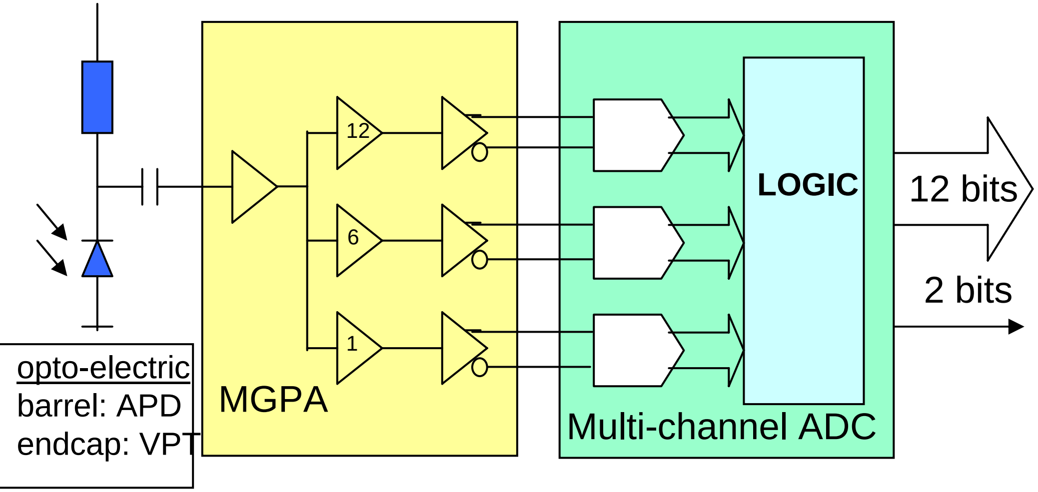
building block :

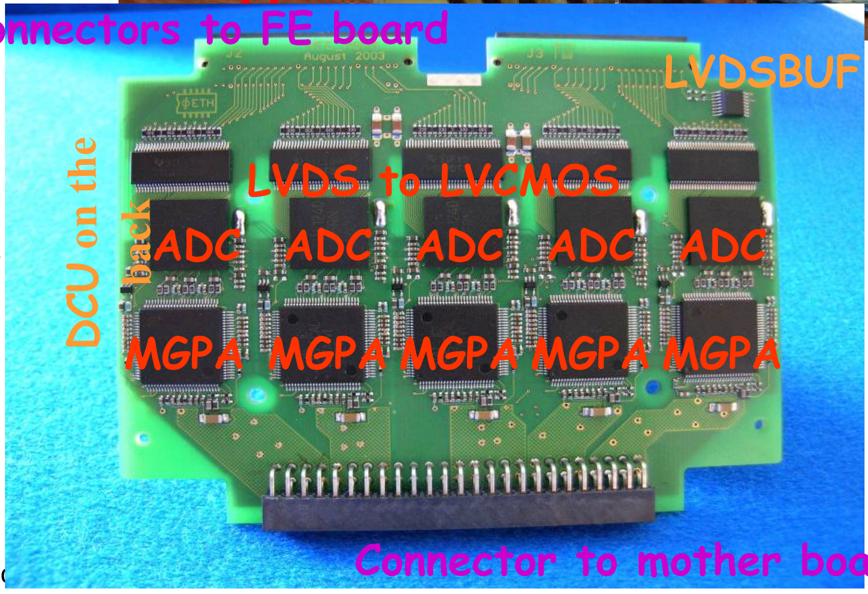
Trigger Tower (25 channels)

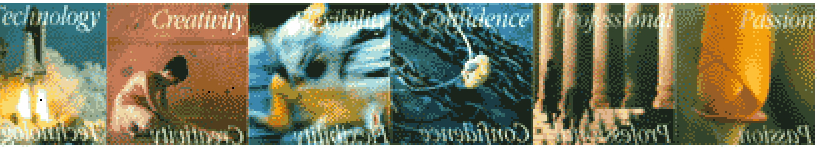
- 1 mother board
- 1 LV regulator board
- 5 VFE boards (5 channels each)
- 1 FE board

• 2 fibres per TT sending

- trigger primitives (every beam crossing)
- data (on level 1 trigger request)

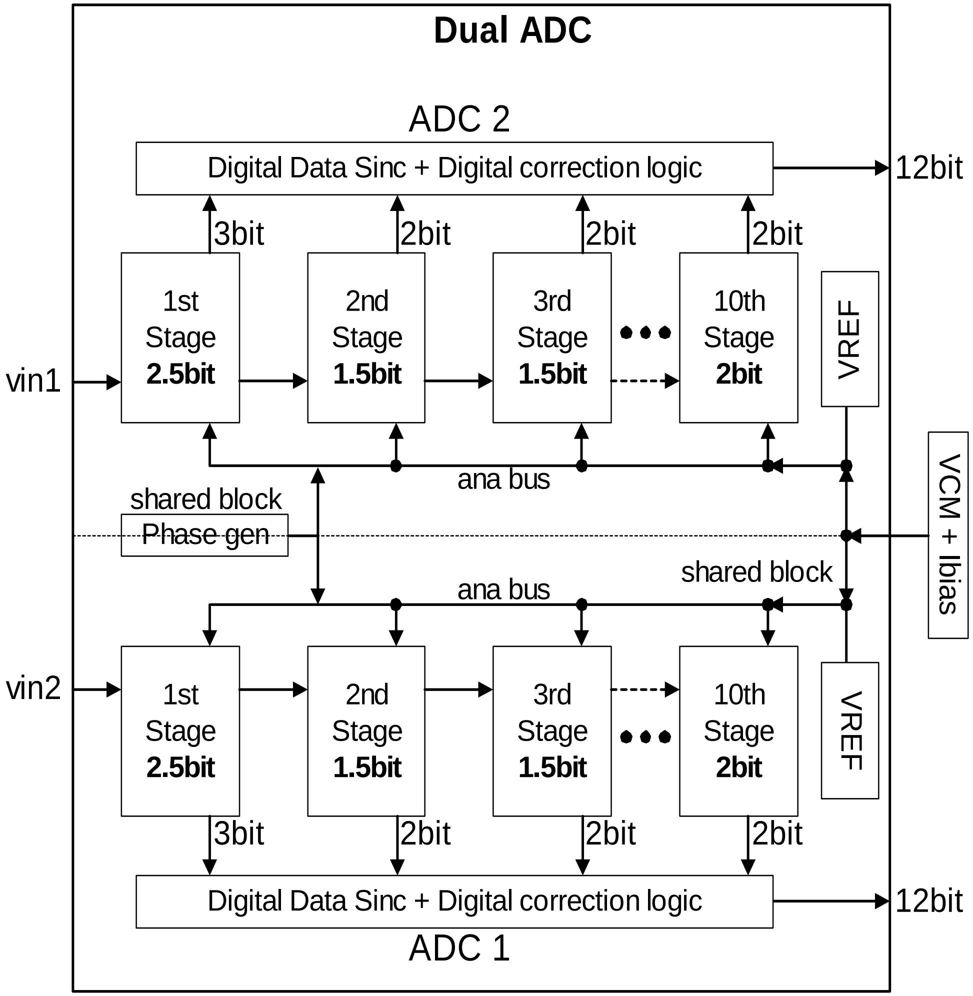






ADC Macro

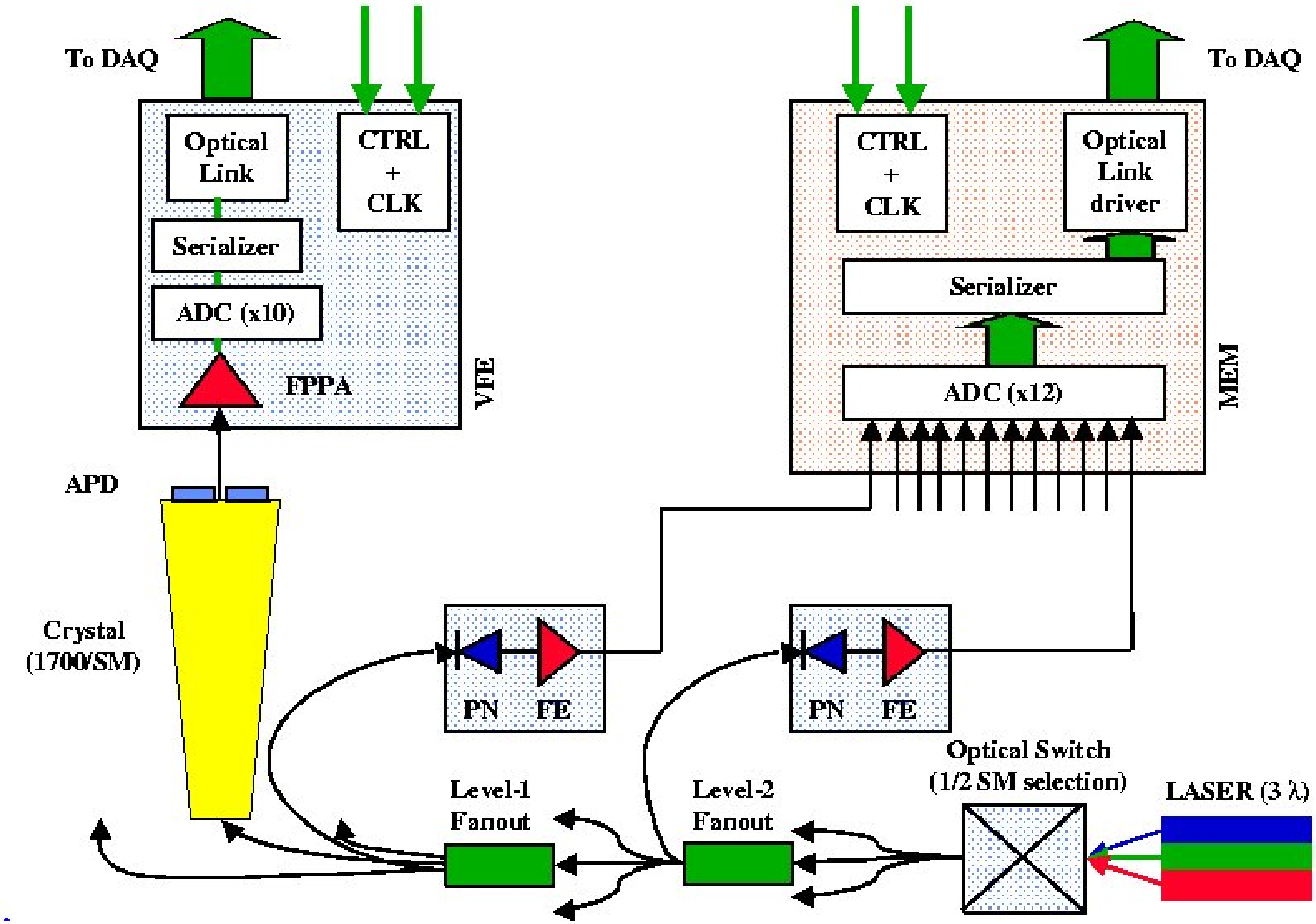
- **Pipeline Architecture**

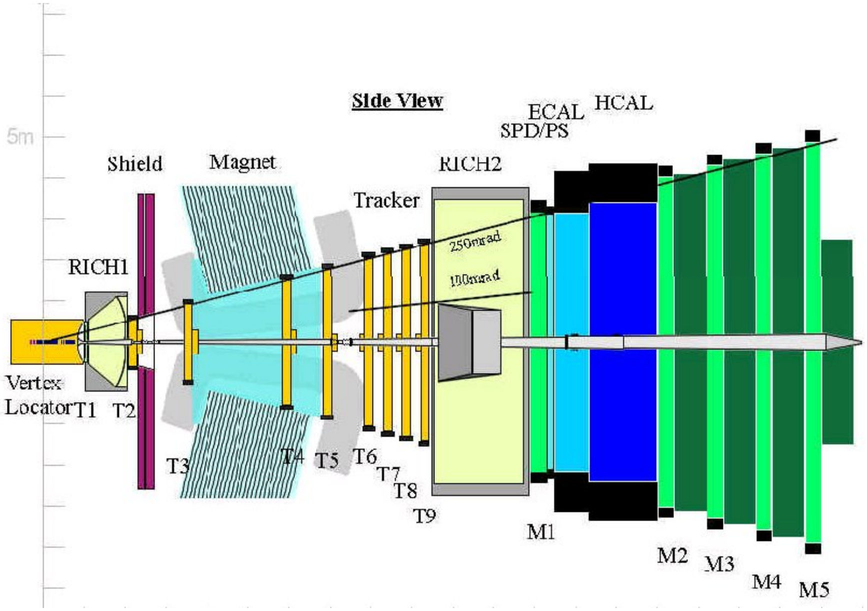


- Stage Resolution Tradeoff
- > Nbit/stage
  - better static linearity
  - more complex blocks
  - Less modularity
- < Nbit/stage
  - fastest time response
  - worst static linearity
  - simple to implement
- FE 2b5 : area=0.38mm^2; power=9.7mW
- BE 1b5 : area=0.095mm2; power=1.9mW

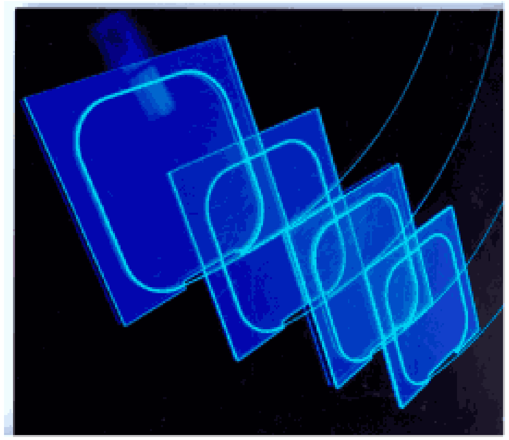
CMS : Ecal calibration

- Optical
- Physics events





Scintillating calorimeters



- CMS hadronic
- LHCb
- OPERA
- *ATLAS hadronic*

- Fast
- Cheap
- Moderate resolution
- Difficult to calibrate

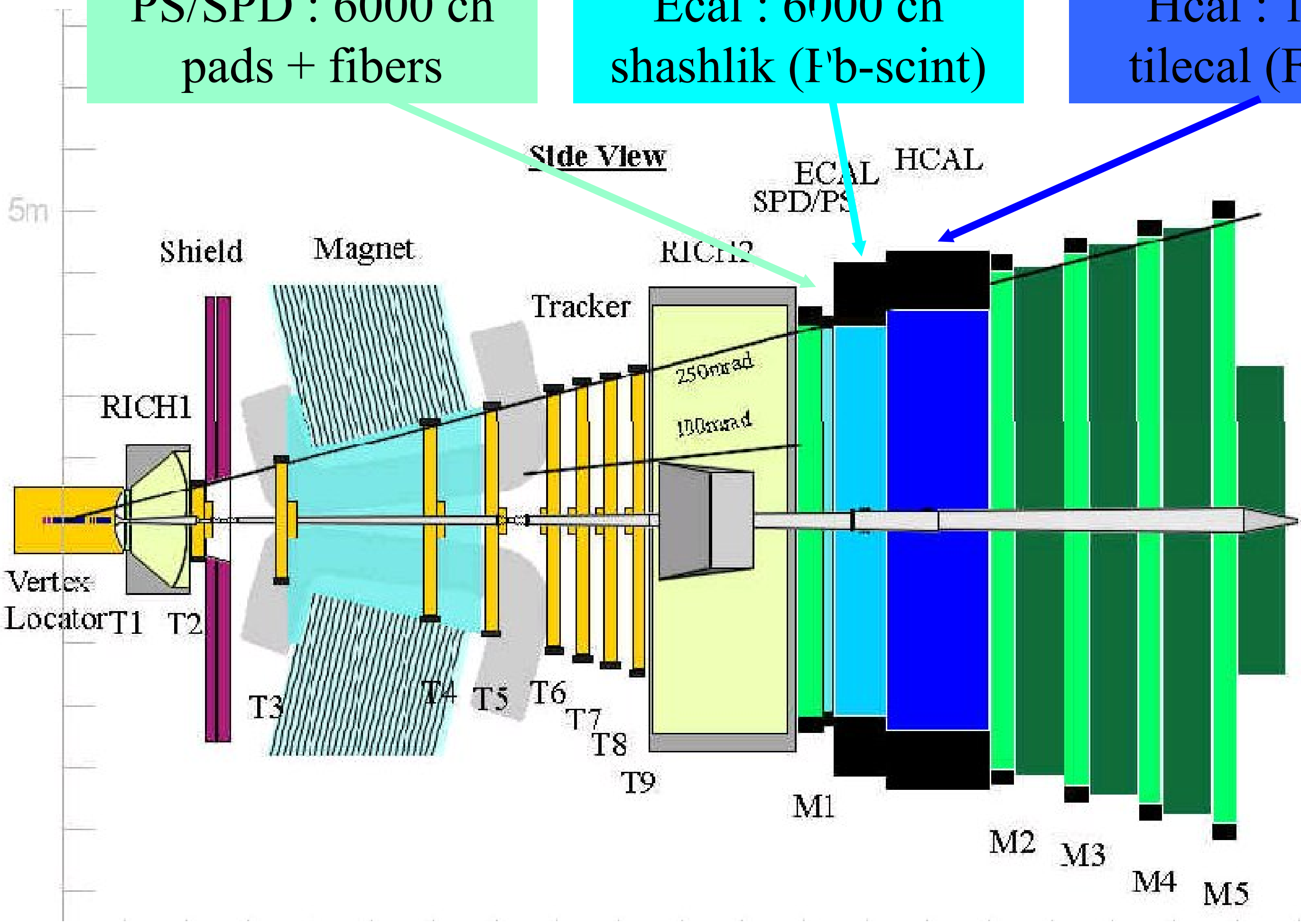
LHCb experiment [33]

- **Goal : study B physics and CP violation**
  - To be installed on LHC at CERN (2007) (*cf.* ATLAS)

PS/SPD : 6000 ch
pads + fibers

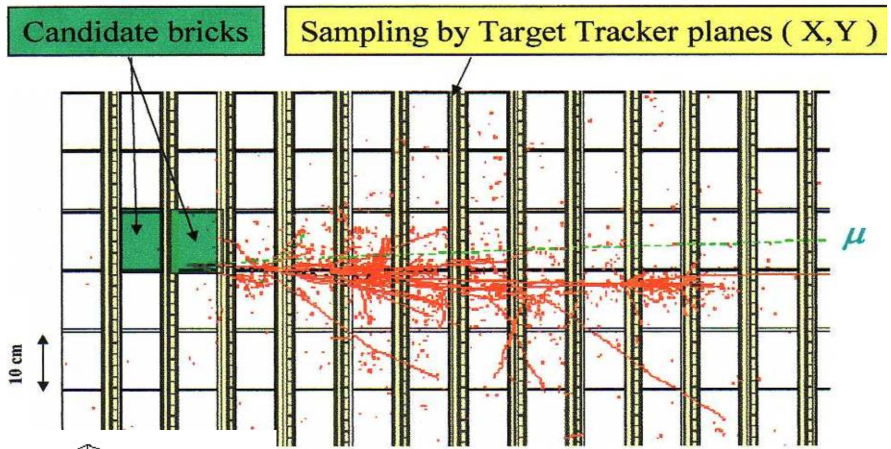
Ecal : 6000 ch
shashlik (Pb-scint)

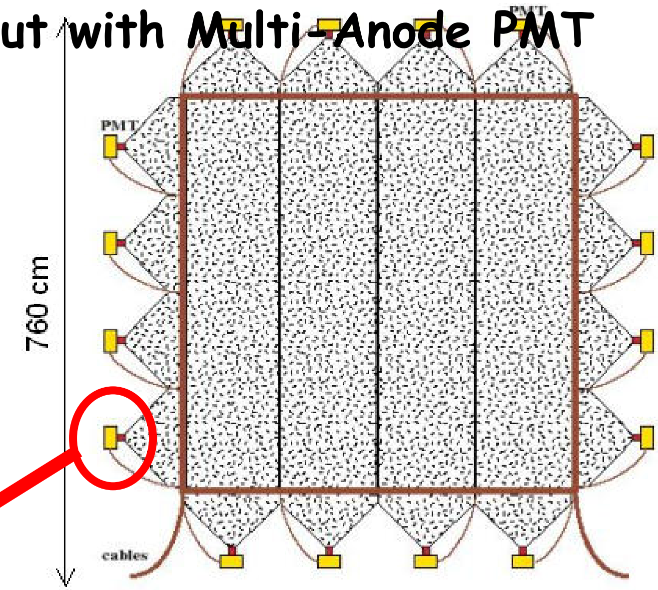
Hcal : 1500 ch
tilecal (Fe-scint)

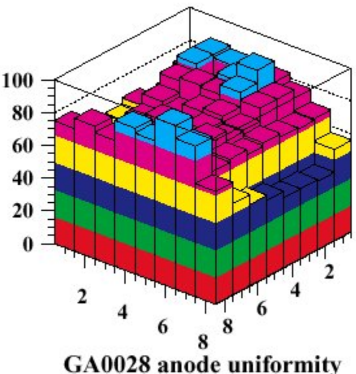


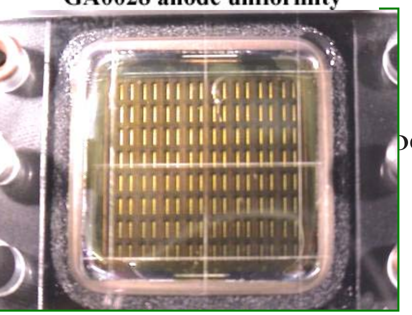
OPERA Target tracker

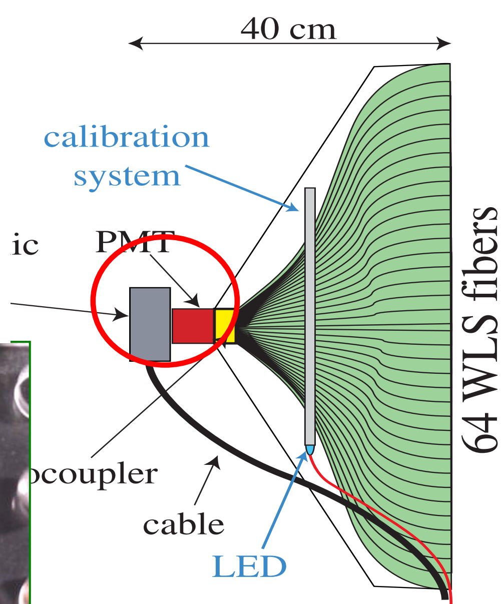
- **Scintillator walls for brick location : readout with Multi-Anode PMT**

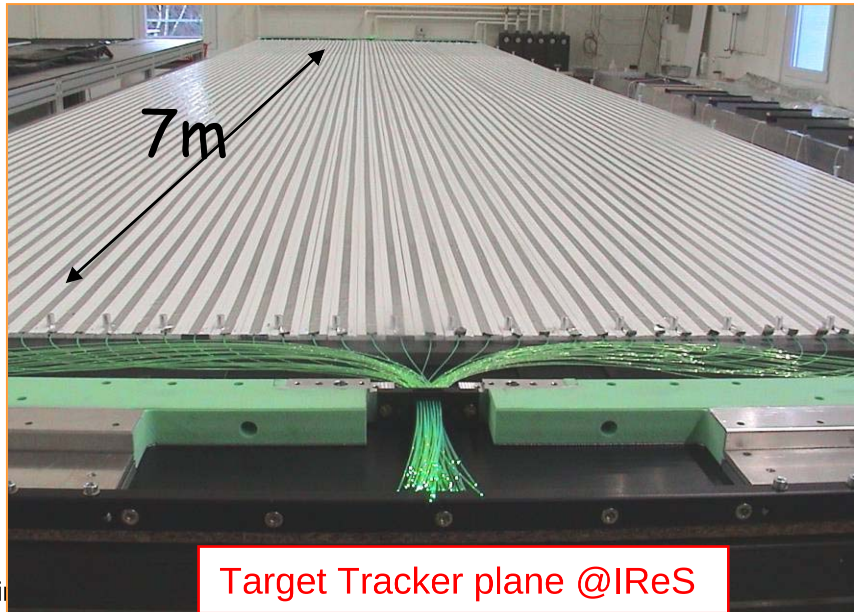






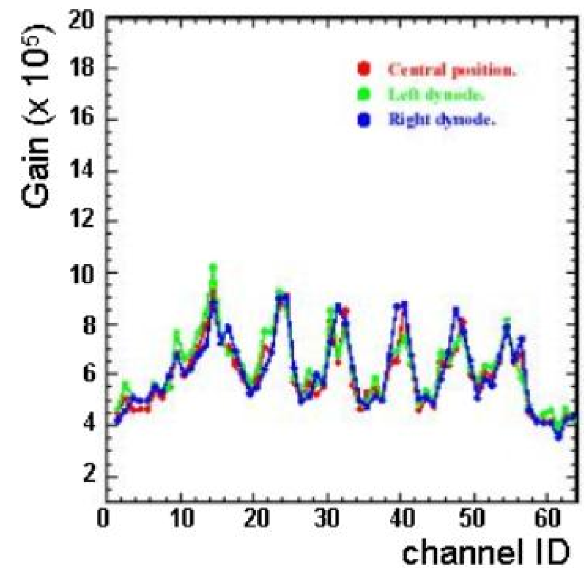


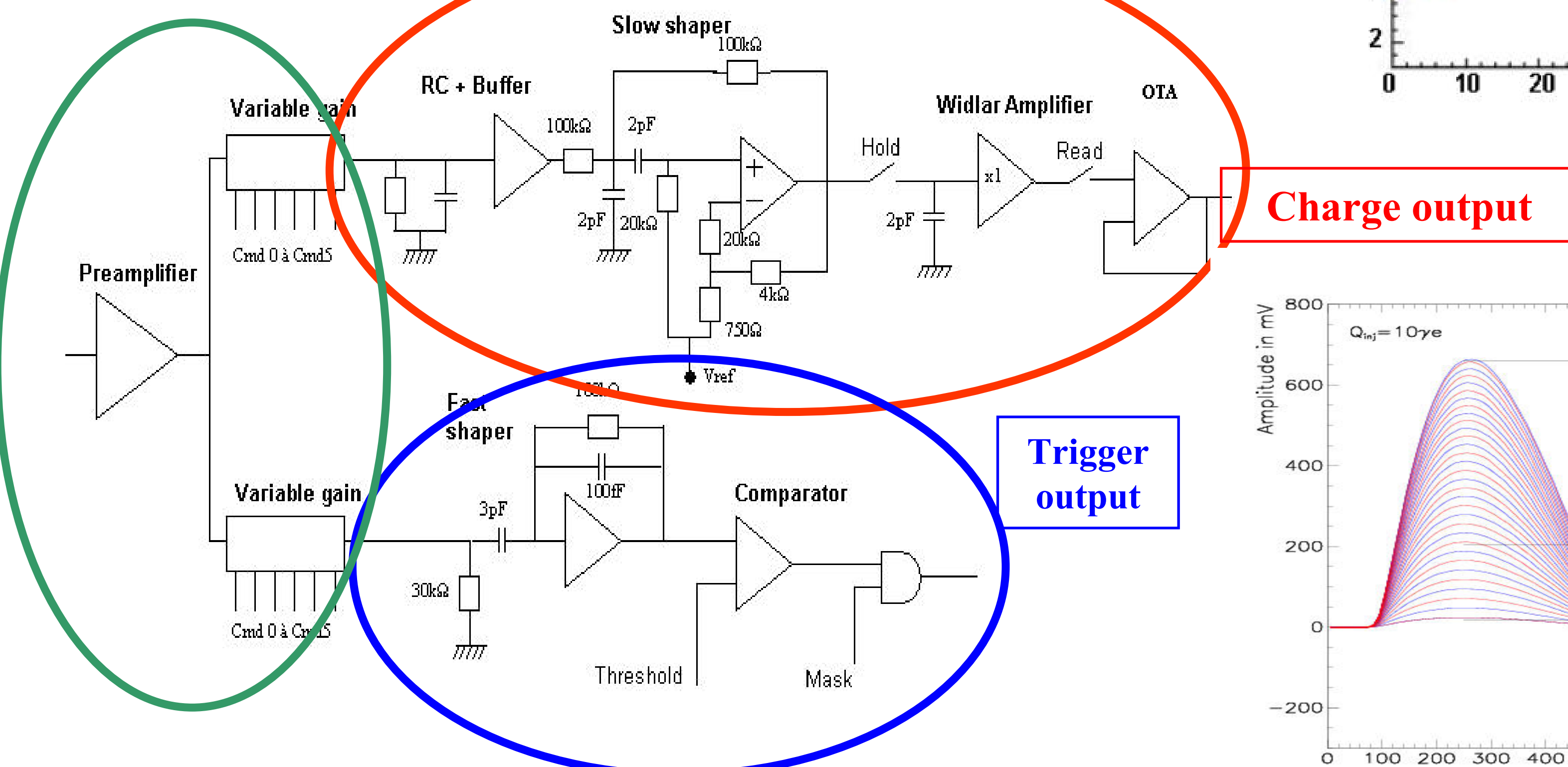


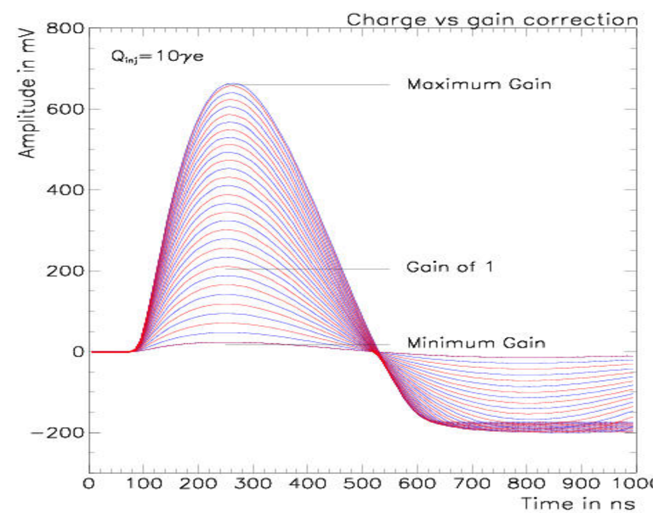


OPERA : Target Tracker chip OPERA_ROC

- **Lecture de PM multi-anodes**
  - Forte variation du gain (1-3) entre voies
  - -> Preampli de courant a gain variable (0-4, 5 bit
  - Lecture de charge multiplexée (0.1-100p.e.)
  - Autotrigger on $\frac{1}{4}$ p.e. in 15 ns
  - 32 channels chip, 180 mW

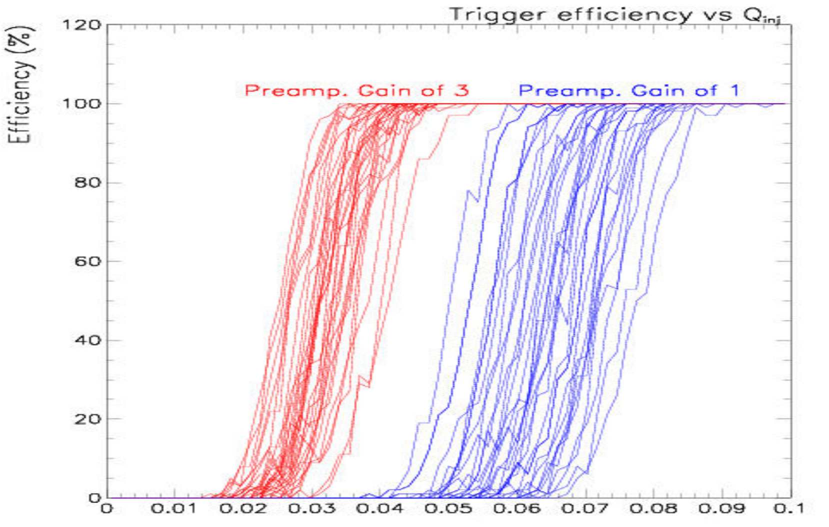


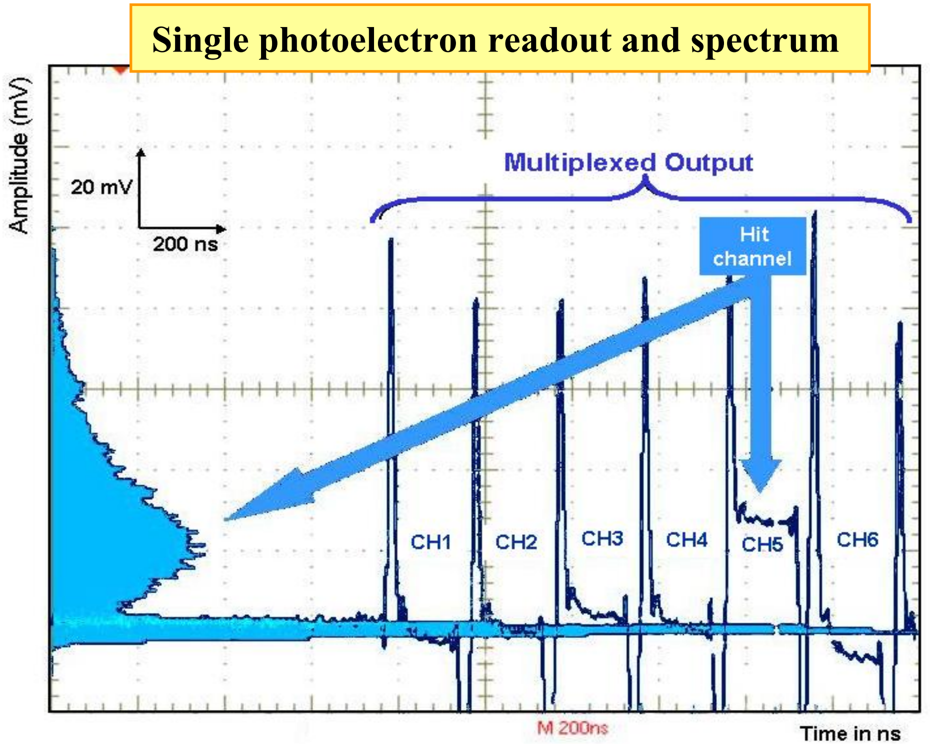


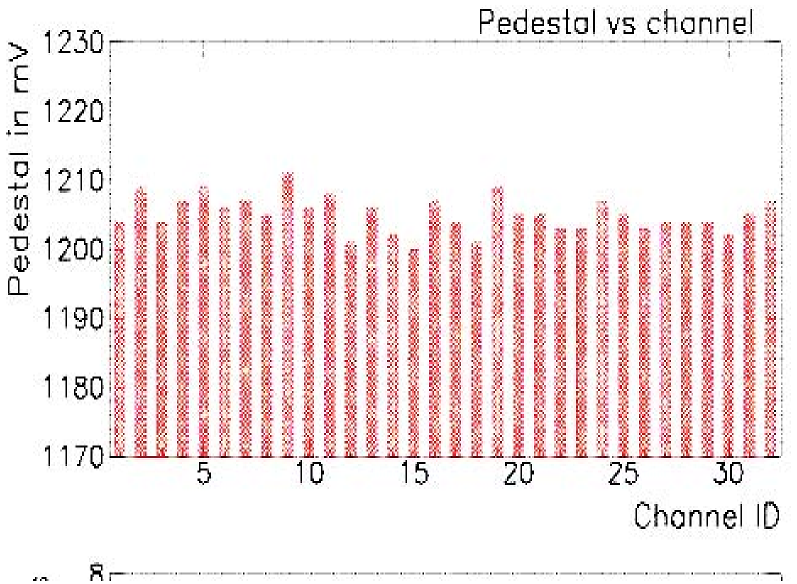


Mesures avec le PMT

- **Efficacité de trigger**
  - « courbes en S »
- **Lecture multiplexée**
  - Dispersion de piedestal, bruit…
- **Spectres**



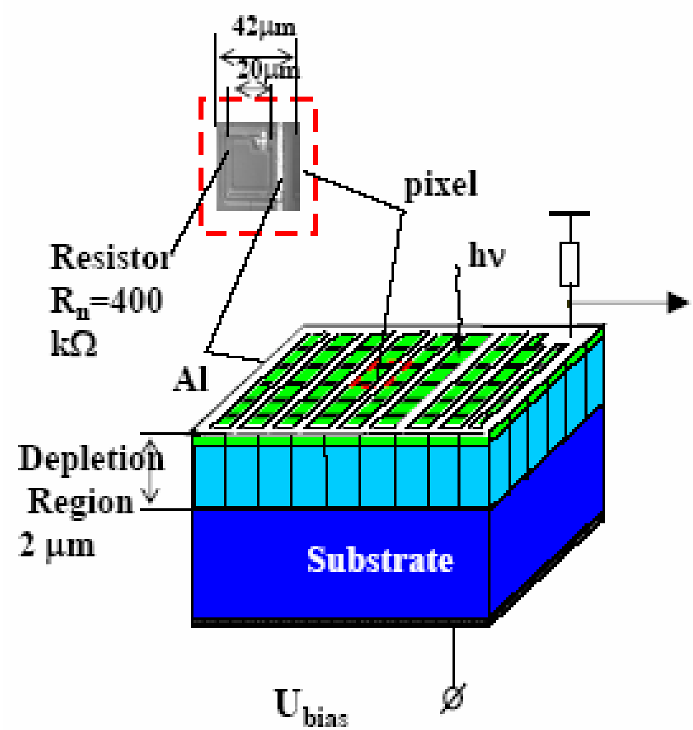


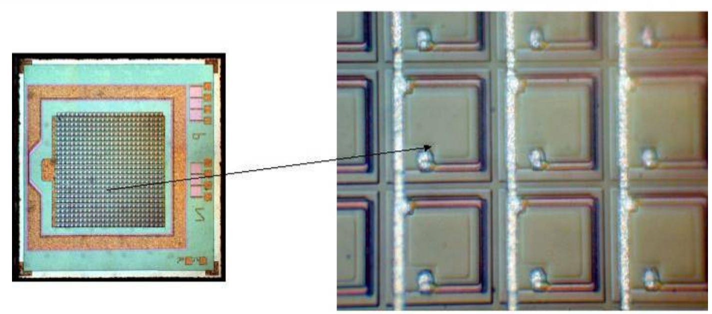


ILC CALICE Analog HCAL

©F. Sefkow

Iron/plastic(tiles) sandwich **Readout: fibres + Silicium PhotoMultiplier**



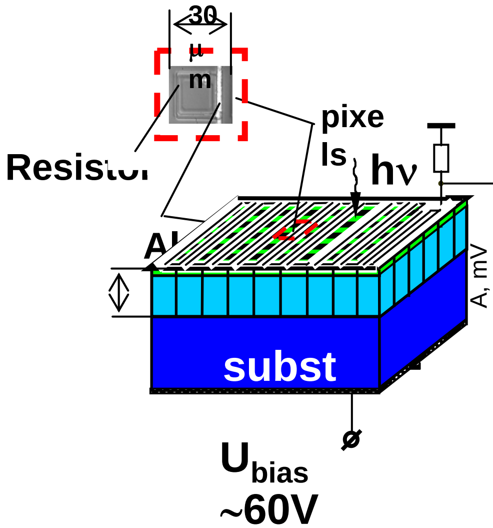


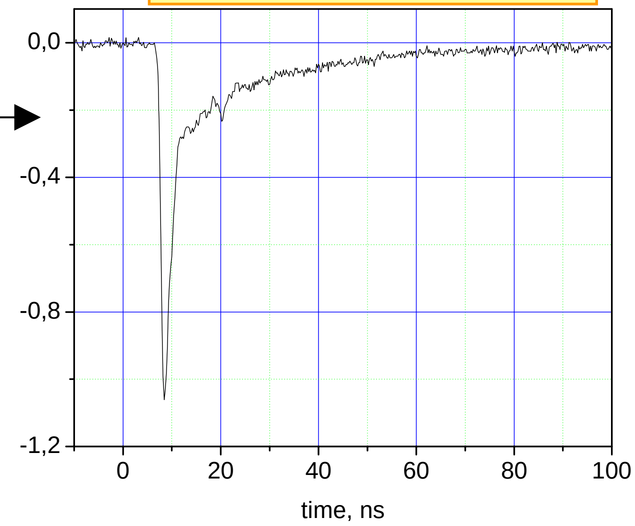
SiPM

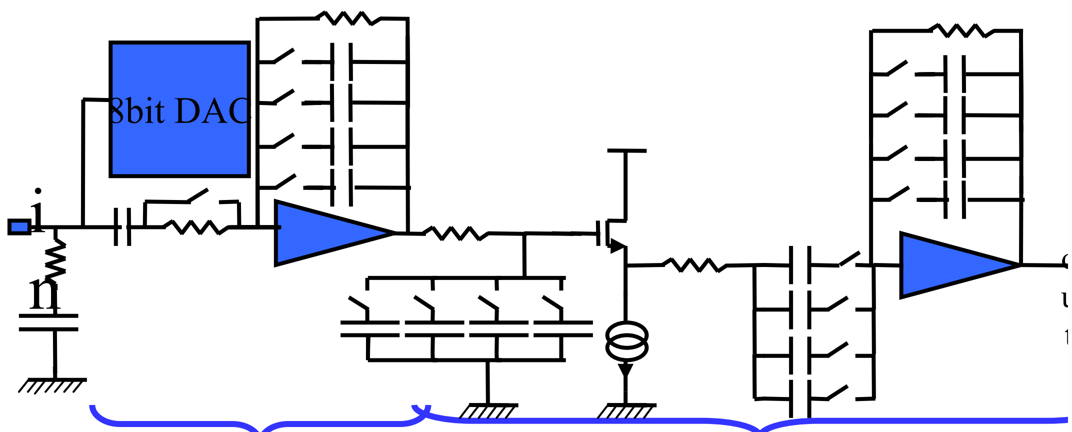
Pixels of the SiPM

SiPM readout ASIC

- **Readout AHCAL (DESY)**
  - SiPM detector (MEPHI)
  - >3000 channels
  - G ~ 10^6 e ~10% HV ~ 50 V
- **FLC_SiPM readout ASIC**
  - 18 channel variable gain preamp and shaper
  - 8 bit DAC for gain adjustment

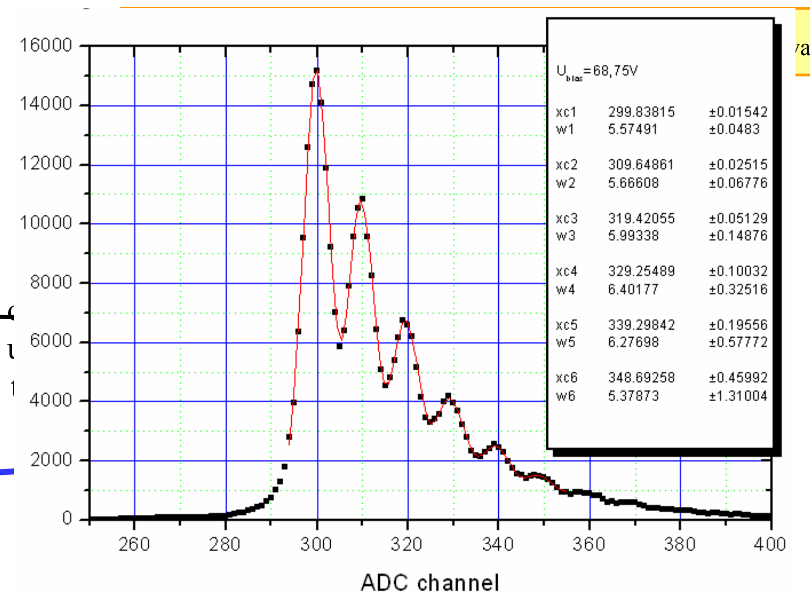


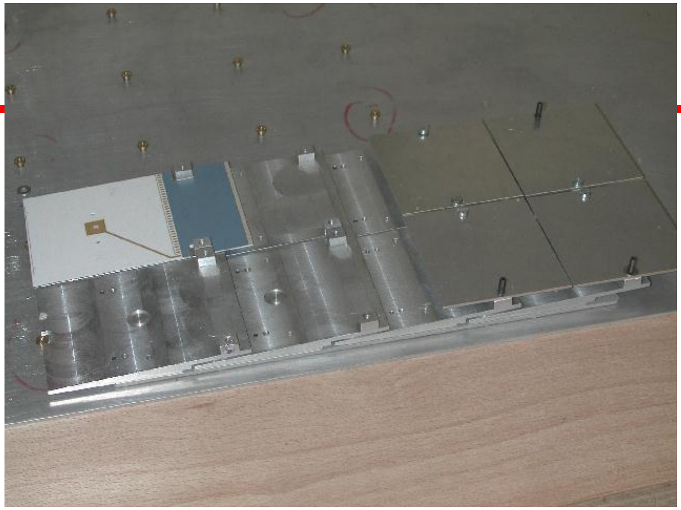




Variable Gain Charge Preamplifier

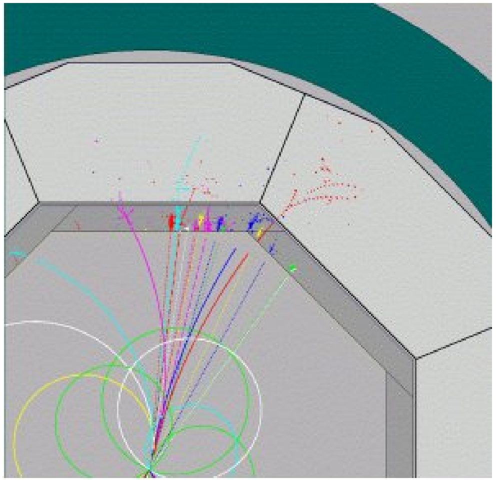
Variable Shaper CR-RC²





Semiconductor calorimeters

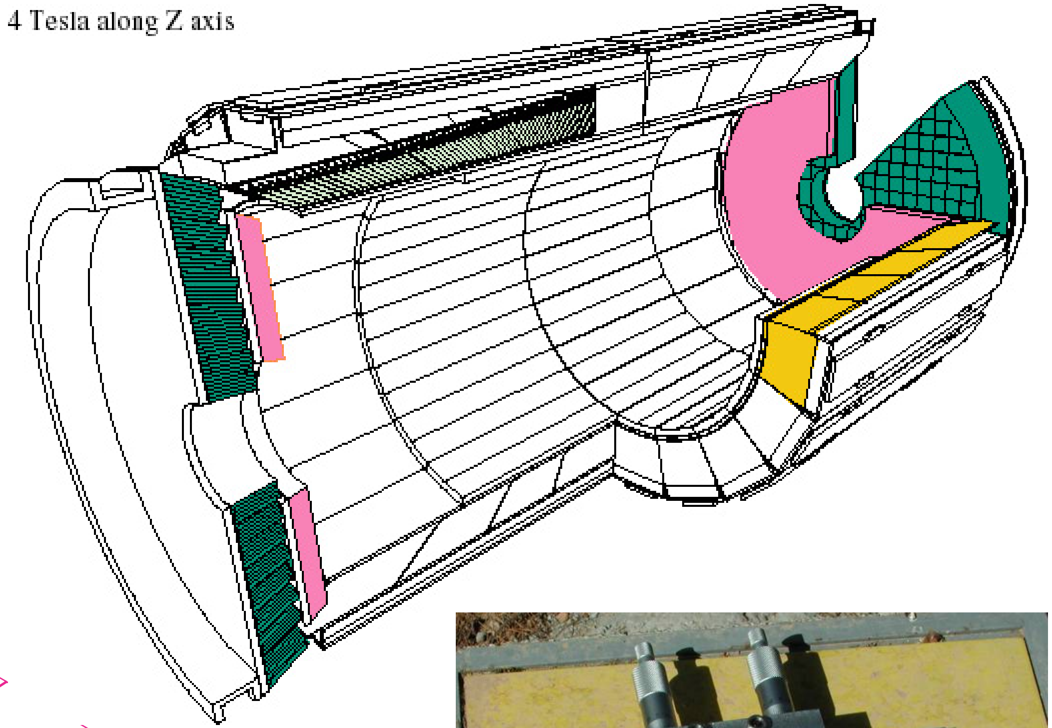
- CMS preshower
- ILC CALICE ECAL

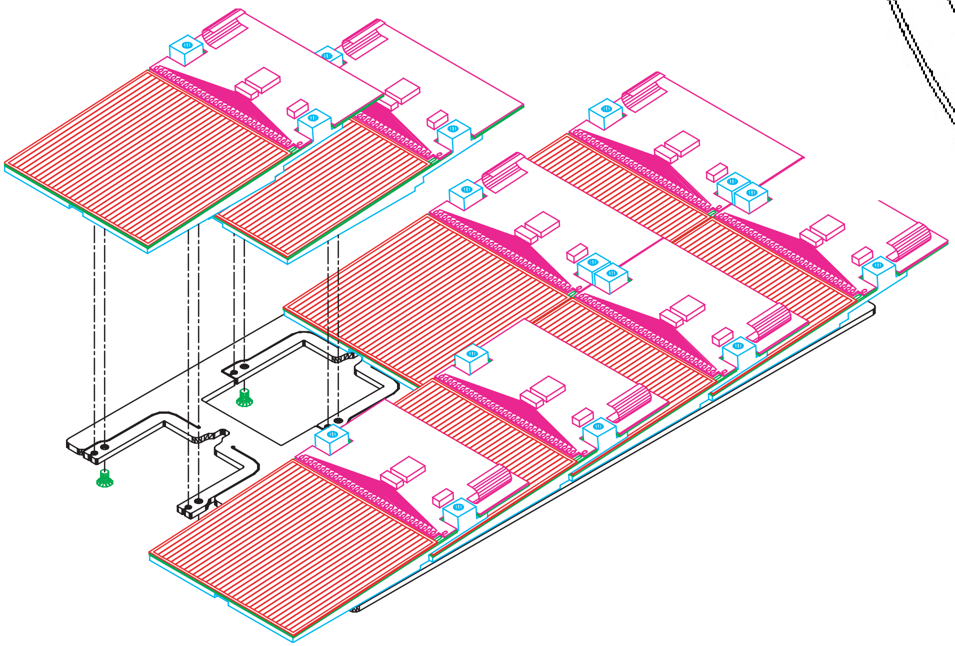


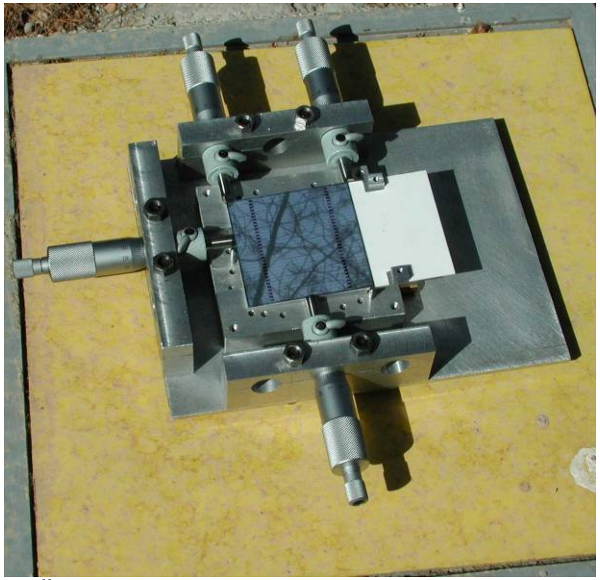
- Highly granular
- Good resolution
- Expensive

CMS : preshower detector [34]

- **Aluminium tiles**
- **Silicon sensor**
  - 1 cm2
  - Vdepl = 60V +/- 5 V
  - Ileak = 100 nA

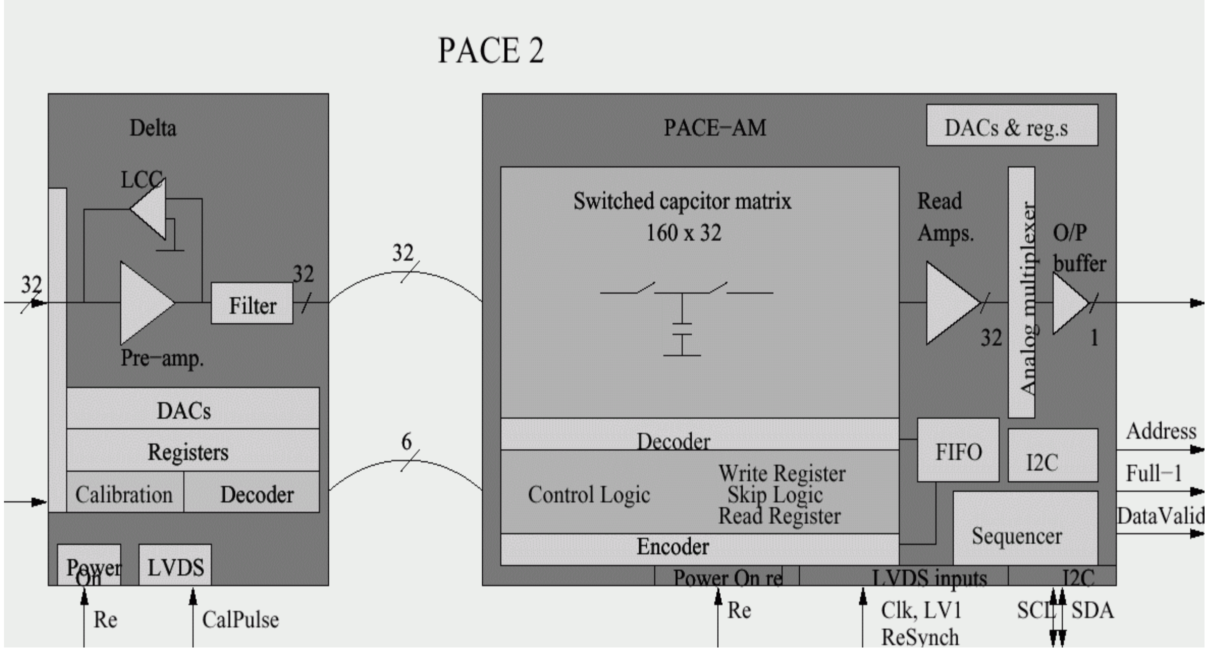


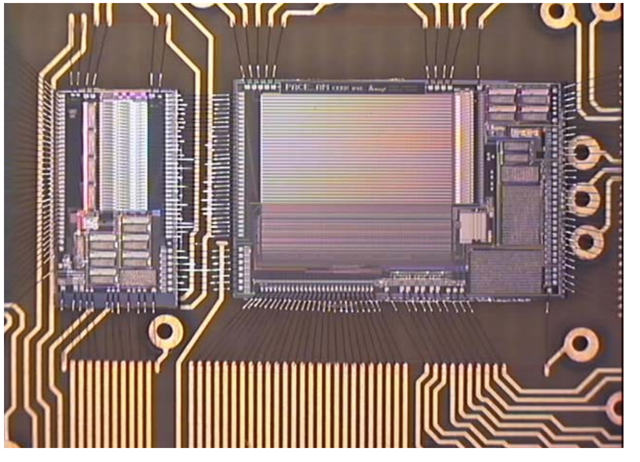




CMS PS : readout chip PACE2

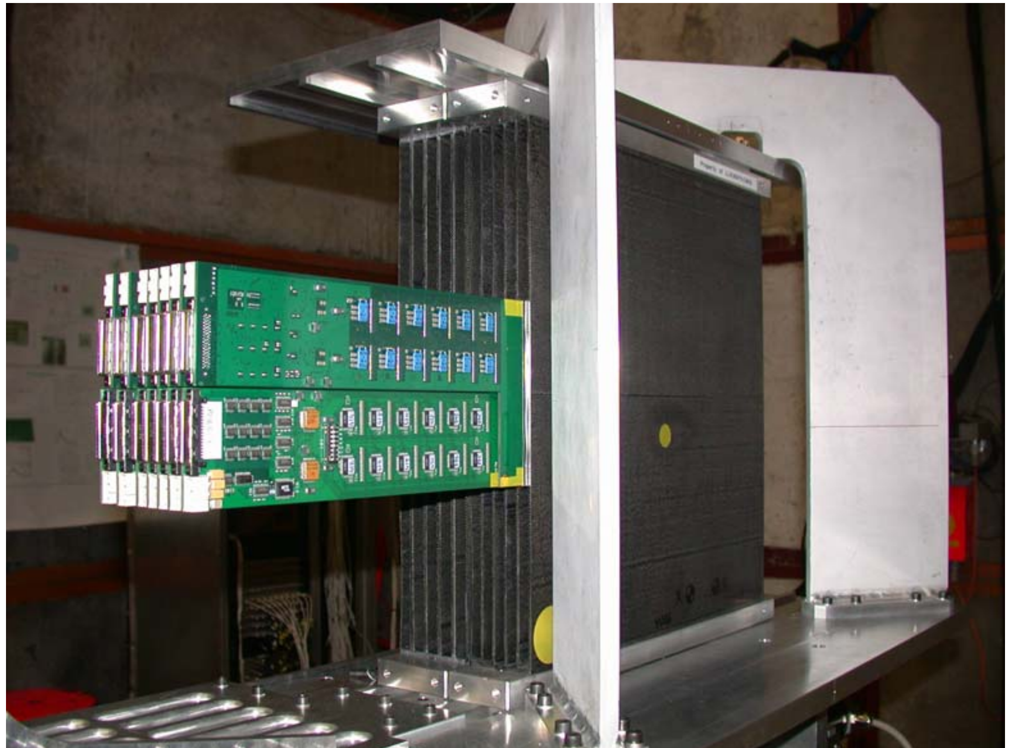
- **Requirements**
  - 10 bit dynamic range
  - Low gain and high gain
  - Leakage current comp
- **MCM**
  - Delta preamp
  - PACE analog memory

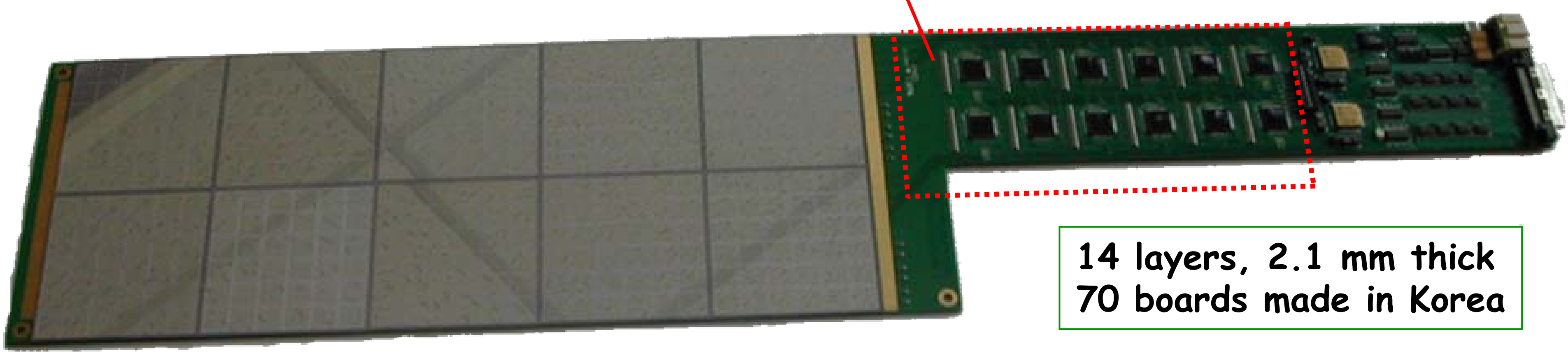




CALICE W-Si calorimeter

- "Imaging calorimeter"
  - 30 layers W-Si
  - 1 cm^2 Si PADS

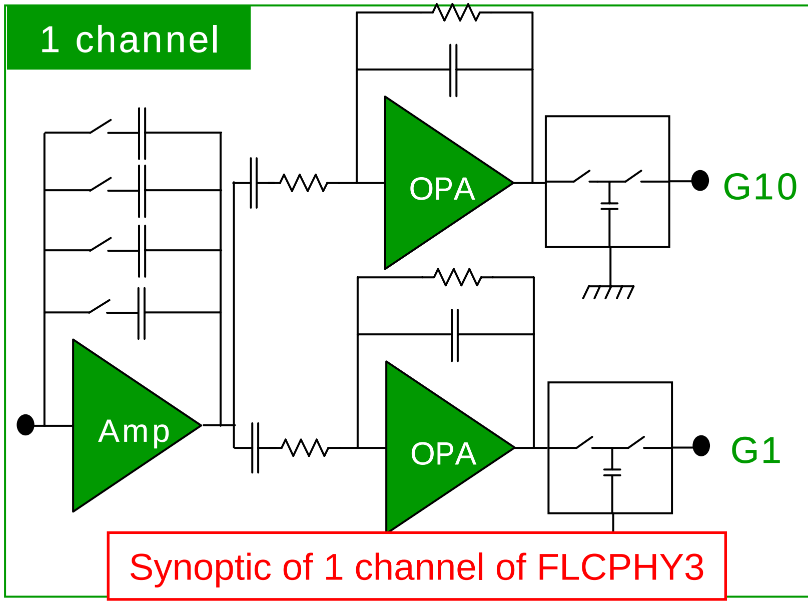




14 layers, 2.1 mm thick
70 boards made in Korea

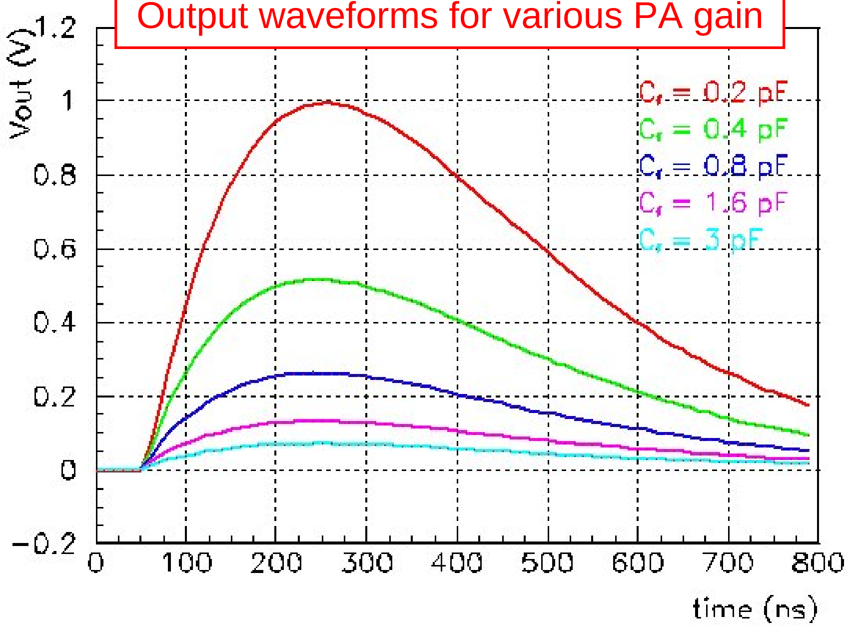
FLCPHY3 front-end ASIC

- **Chip architecture**
  - Low noise charge preamp optimized for Cd=70pF. Variable gain (Cf = 0.2 -> 3 pF)
  - Dual gain shaper (G1-G10) tp = 200 ns splits 15bit dynamic range in 2 x 12 bits
  - Differential shaper and Track&Hold => better pedestal stability and dispersion
  - Multiplexed output : 5 MHz

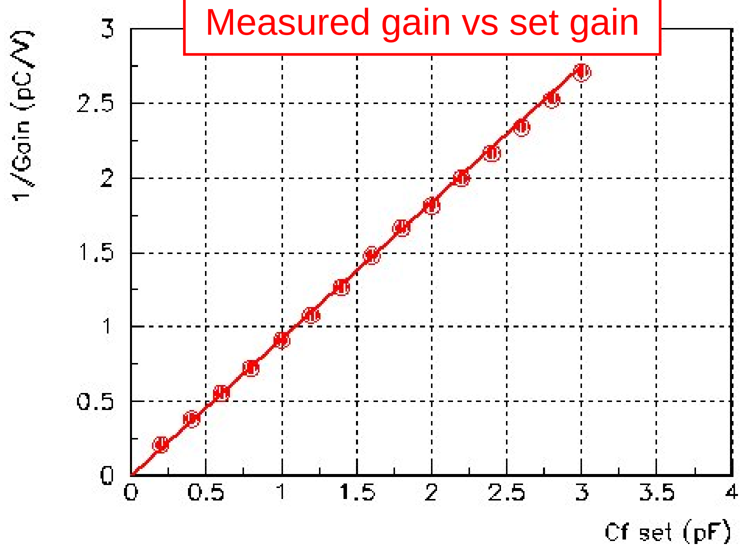


Synoptic of 1 channel of FLCPHY3

Output waveforms for various PA gain



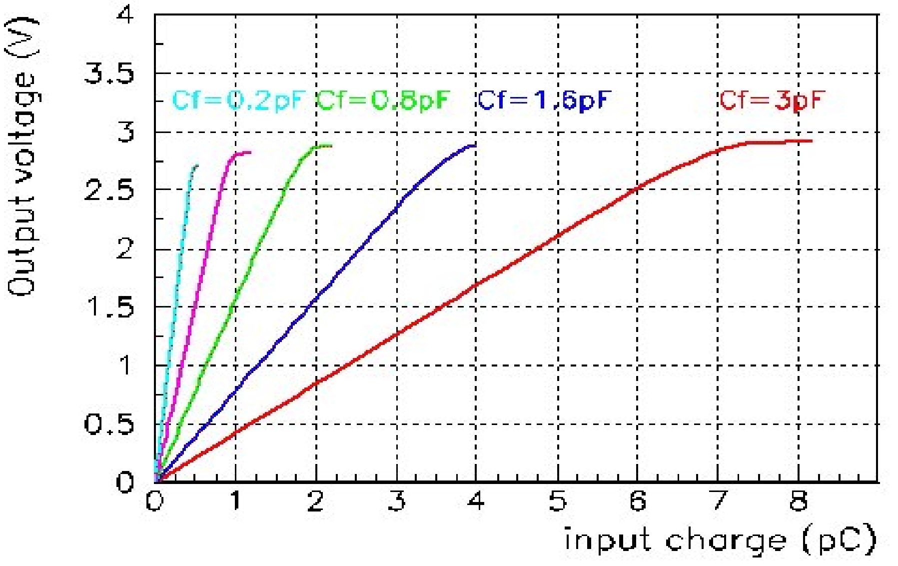
Measured gain vs set gain

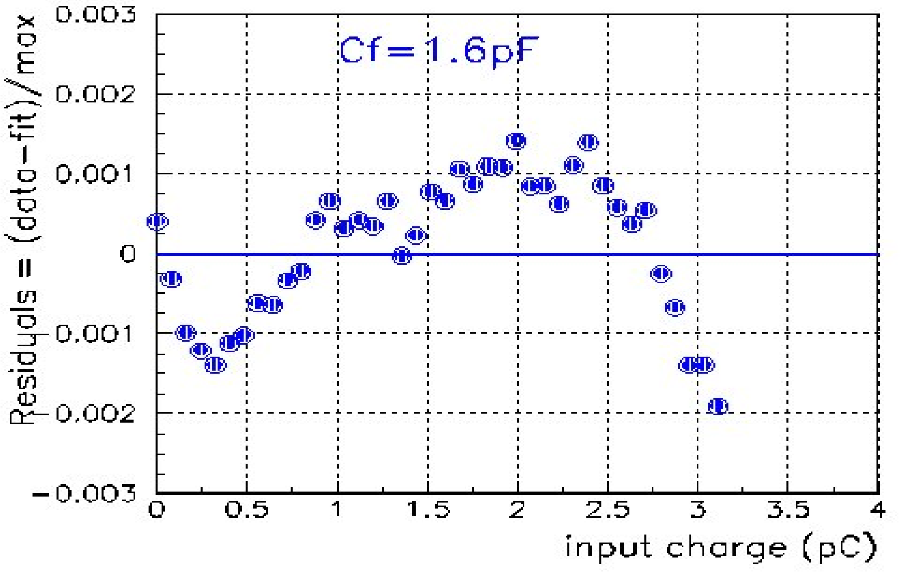


Linearity

- **Measured on all preamp gains**
  - Cf = 0.2, 0.4, 0.8, 1.6, 3 pF
  - Well within ± 0.2 %

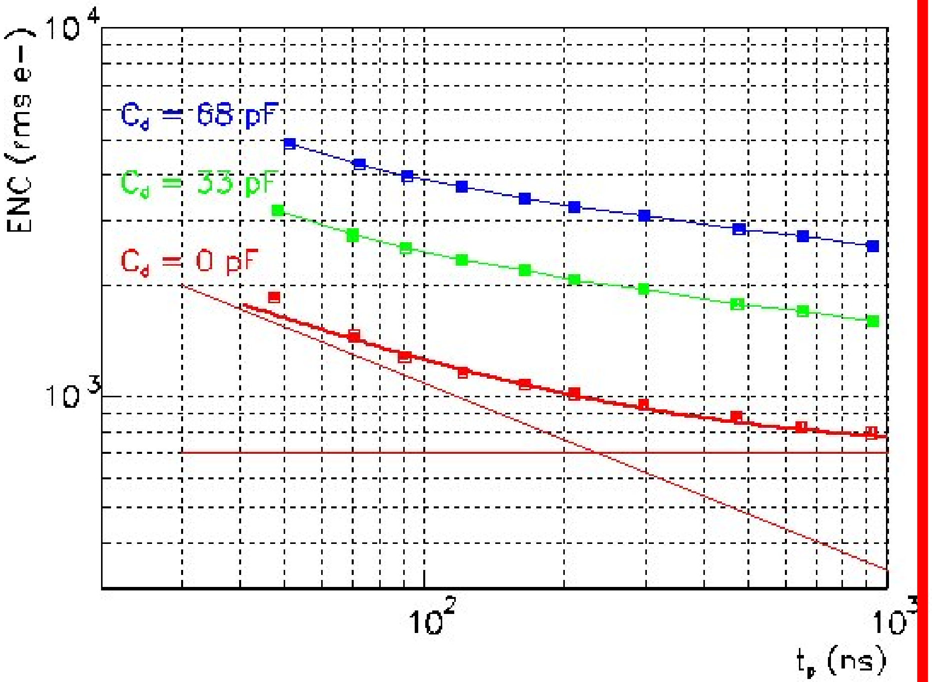
- **Dynamic range** (G1, C_f=1.6pF)
  - Max output : 3 V
  - linear (0.1%) range : 2.5V **= 500 MIPS @ C_f = 1.6 pF**
  - Noise :
    - 200 µV (Cd = 0)
    - 410 µV (Cd = 68pF)
    - **= 0.1 MIP @ C_d = 68 pF**
  - Dynamic range : **> 12 bits**
    - 13 000 (14 bits) @ Cd = 0
    - 6500 (12 bits) @ Cd = 68 pF
  - Can be easily extended by using the bi-gain outputs





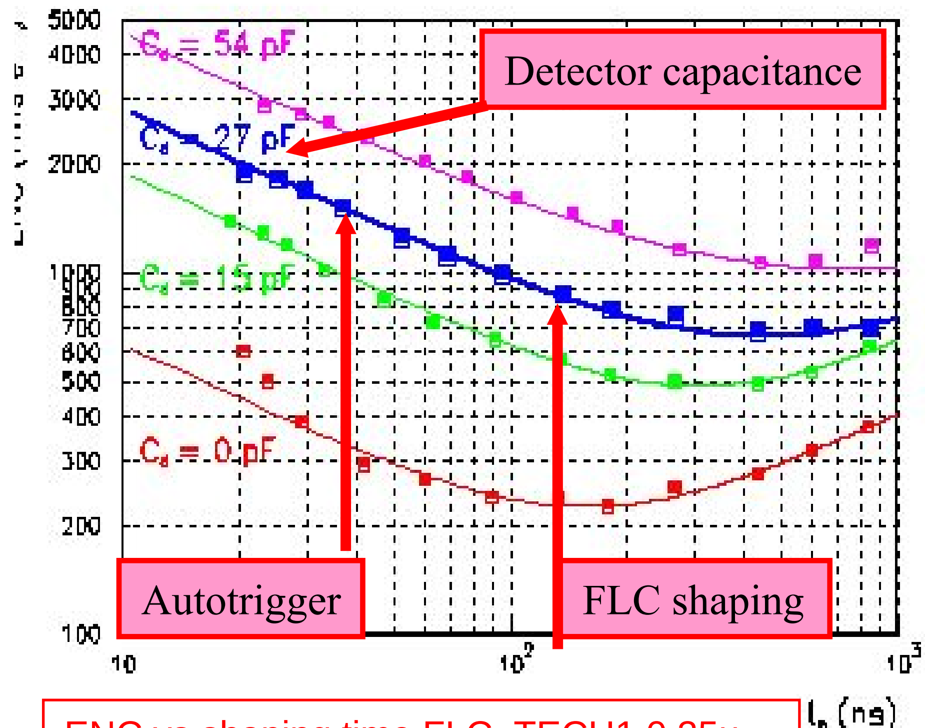
FLC_TECH1 : noise performance

- **FLC_PHY3 : 0.8µm**
  - Series : e_n = 1.6nV/√Hz
  - C_{PA} = 10pF + 15pF test board
  - 1/f noise : 25e-/pF
  - Parallel : i_n = 40 fA/√Hz



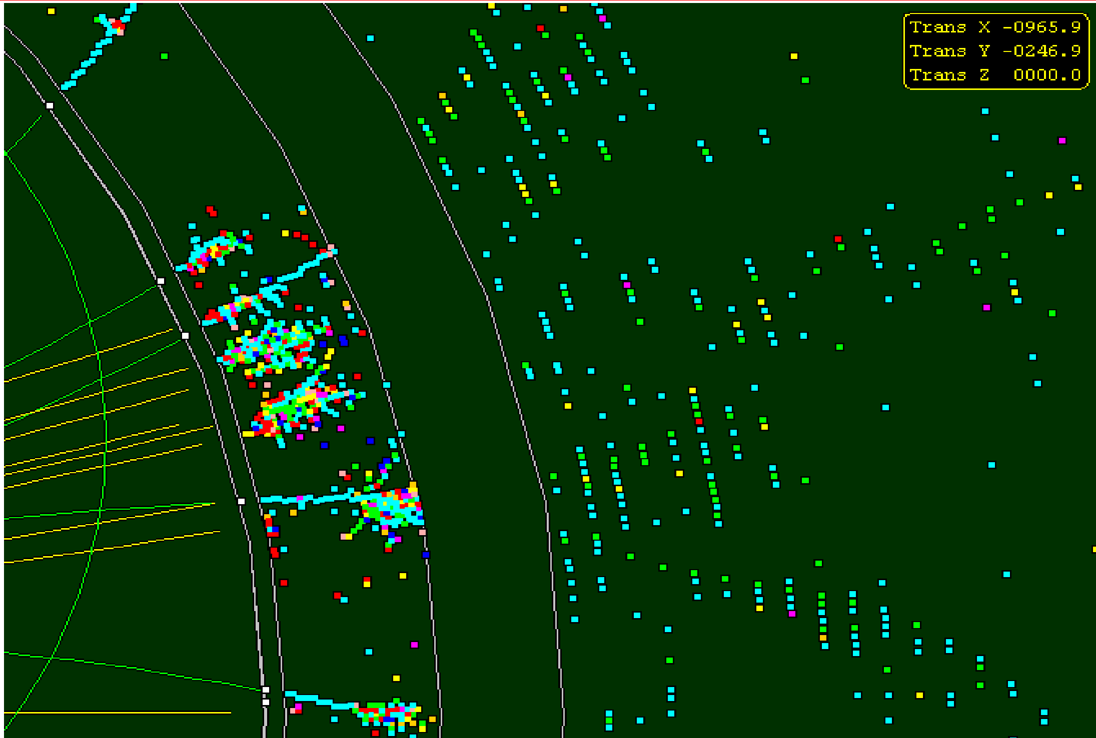
ENC vs shaping time FLC_PHY3 0.8µ

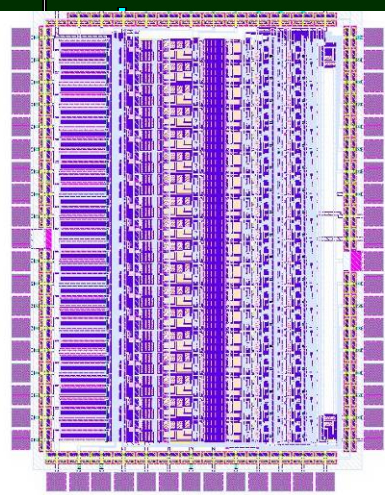
- **FLC_TECH1 : 0.35µm**
  - Series : e_n = 1.4 nV/√Hz
  - C_{PA} = 7 pF
  - 1/f noise : 12 e-/pF
  - Parallel : i_n = 40 fA/√Hz
- **Target noise of ENC < MIP/10 = 4000 e- is (more than) achieved**

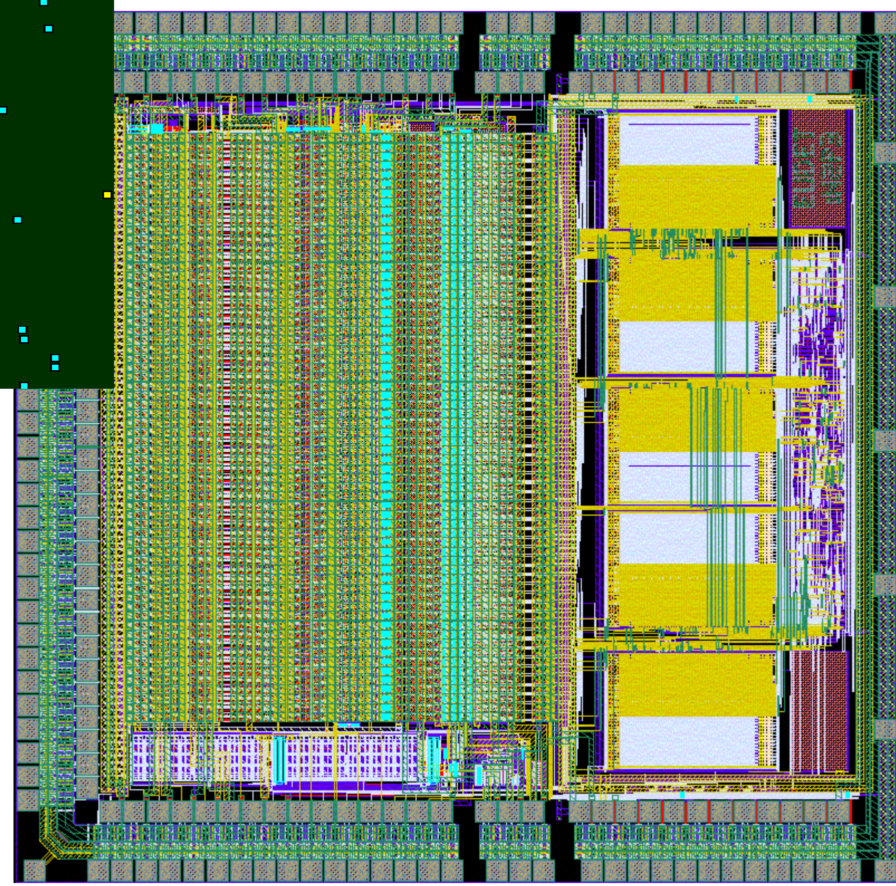


ENC vs shaping time FLC_TECH1 0.35µ

Future

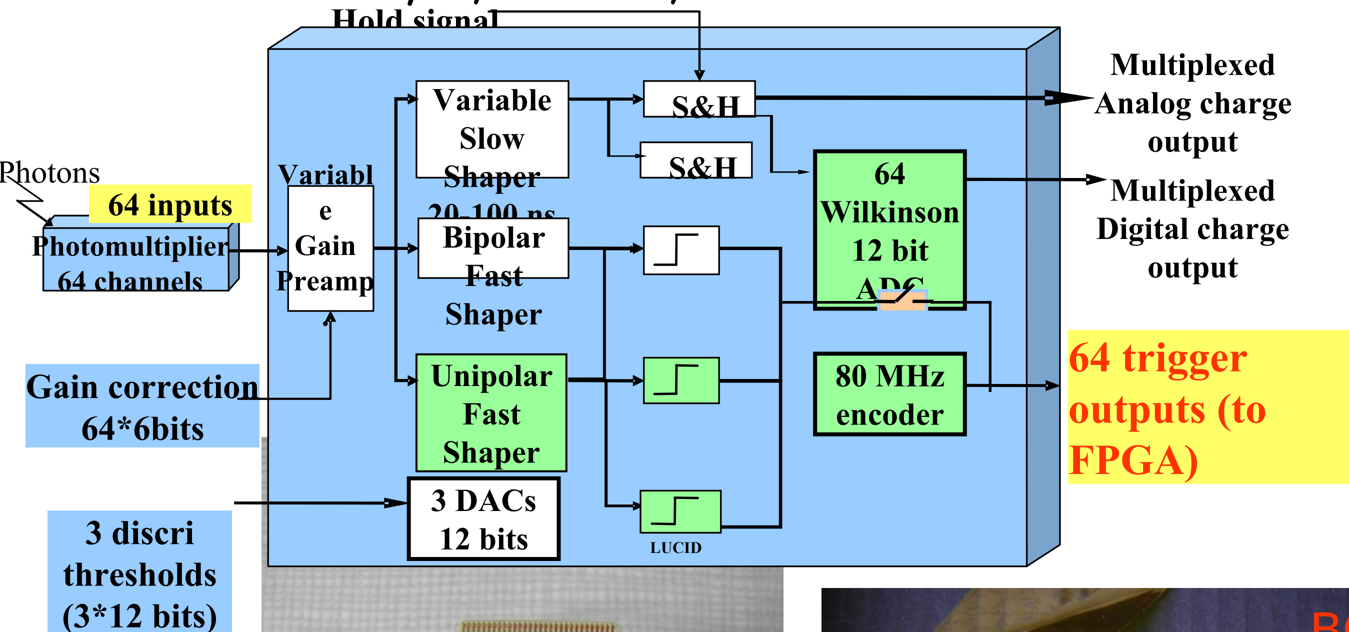


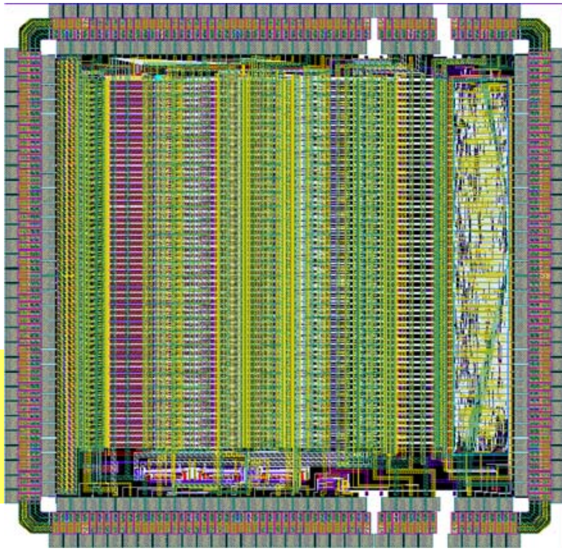


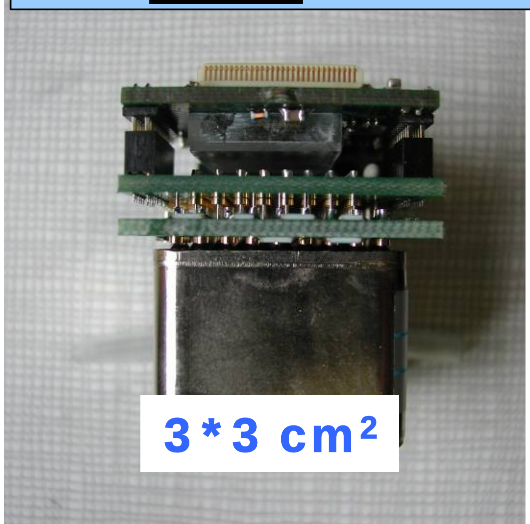


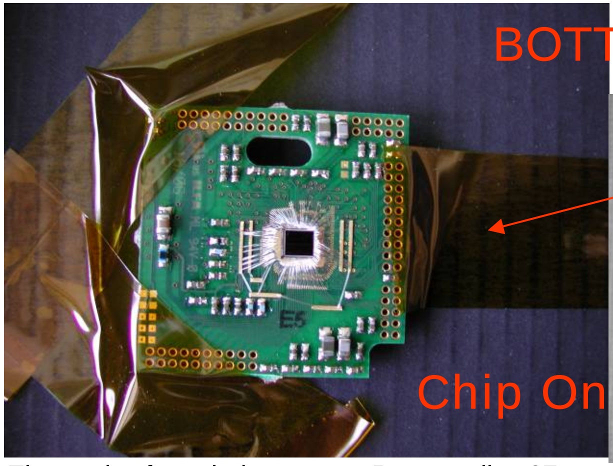
MAROC : 64 ch MAPMT chip for ATLAS lumi

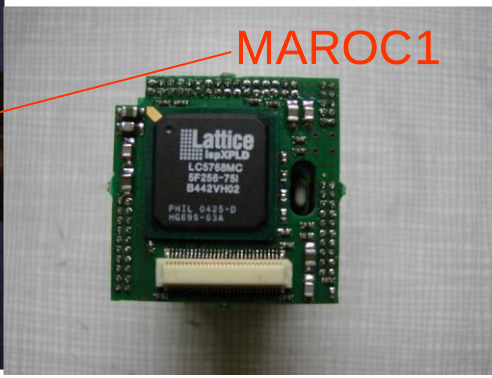
- **Complete front-end chip for 64 channels multi-anode photomultipliers**
  - Auto-trigger on 1/3 p.e. at 10 MHz, 12 bit charge output
  - SiGe 0.35 µm, 12 mm2, Pd = 350mW







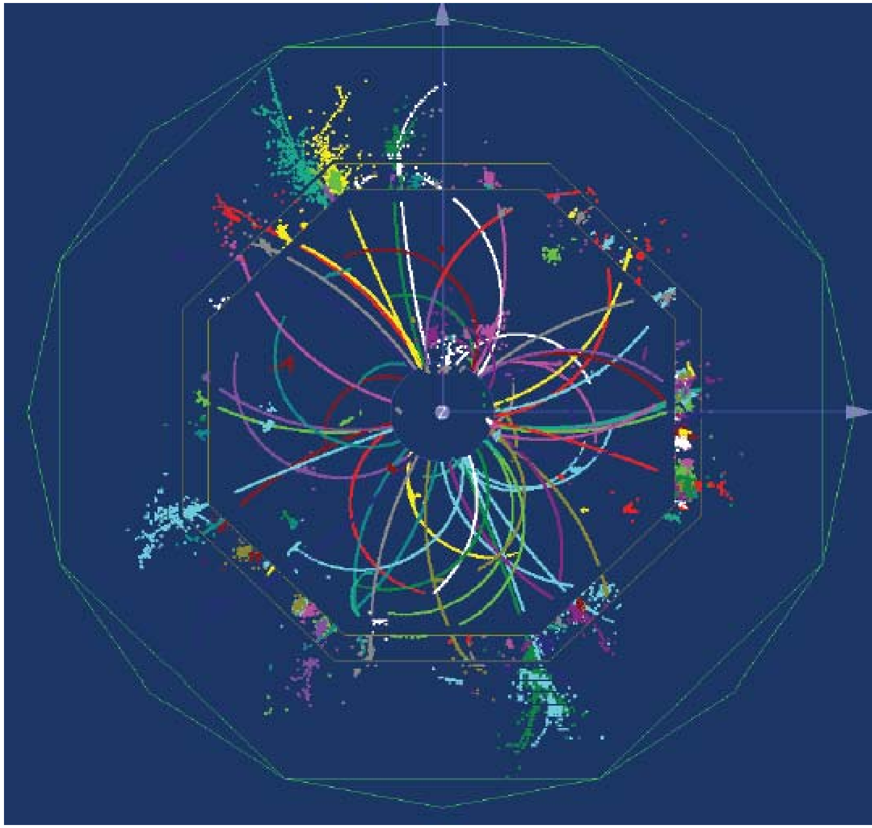




« Imaging calorimetry » at ILC

©J.C Brient (LLR)
F. Sefkow (DESY)

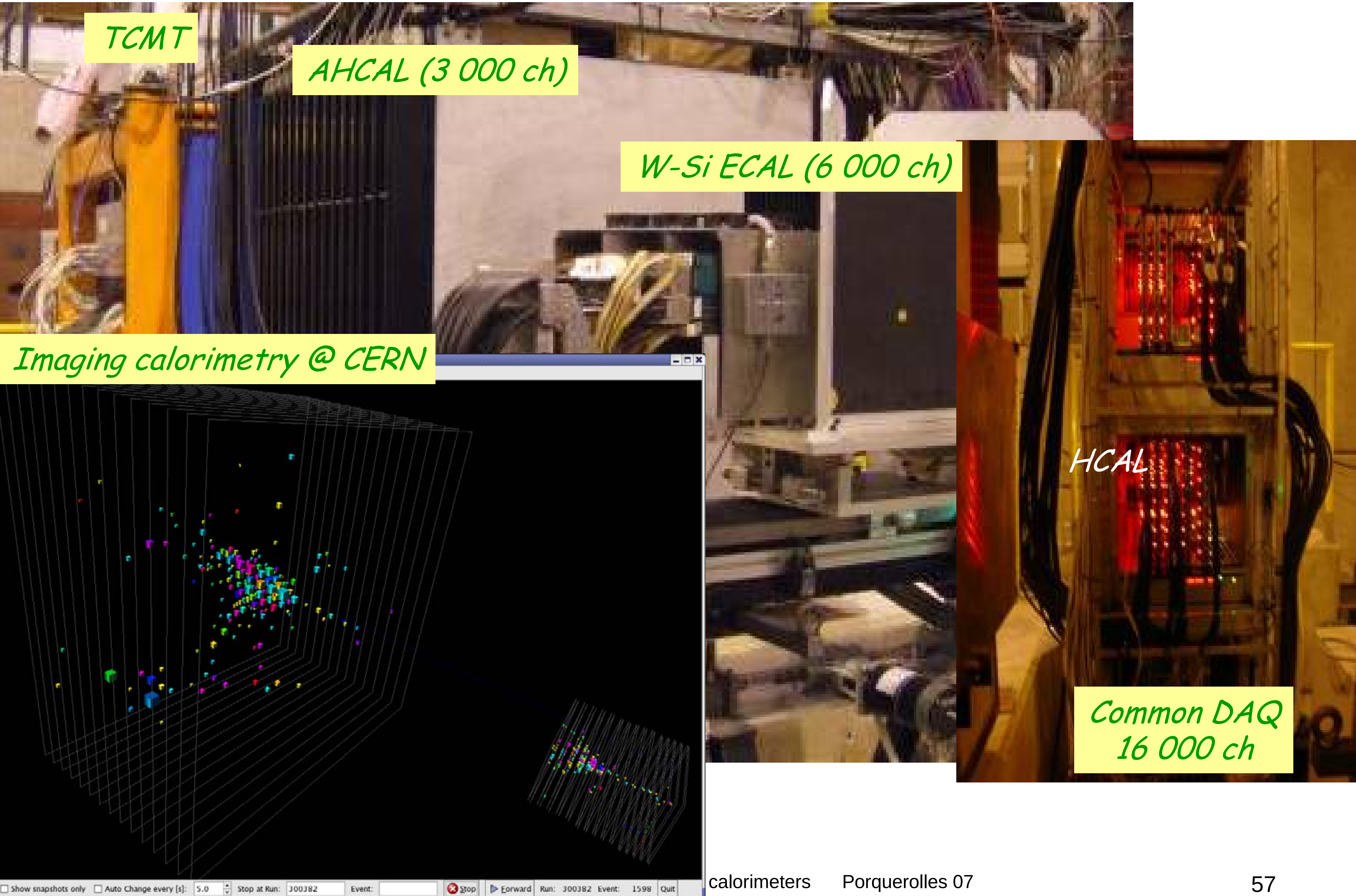
- **Particle flow algorithm**
  - Reconstruct each particle individually
  - Bring jet resolution down to 30%/√E
  - Measure charged particles in tracker
  - Measure photons in ECAL
  - Measure hadrons in ECAL and HCAL
  - Minimize confusion term



- **Calorimeter design**
  - High granularity : typ < 1 cm^2
  - High segmentation : ~30 layers
  - Moderate energy resolution (10%/√E)
  - ECAL : Silicon-Tungsten
  - HCAL : analog vs digital

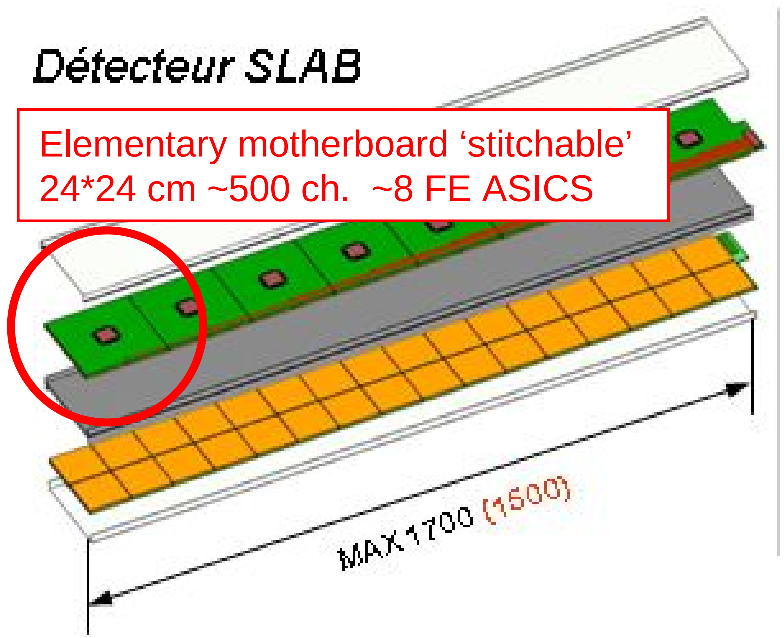
- **CALICE collaboration**
  - « a high granularity calorimeter optimized for particle flow algorithm
  - 190 phys./eng., 9 countries, 3 regions

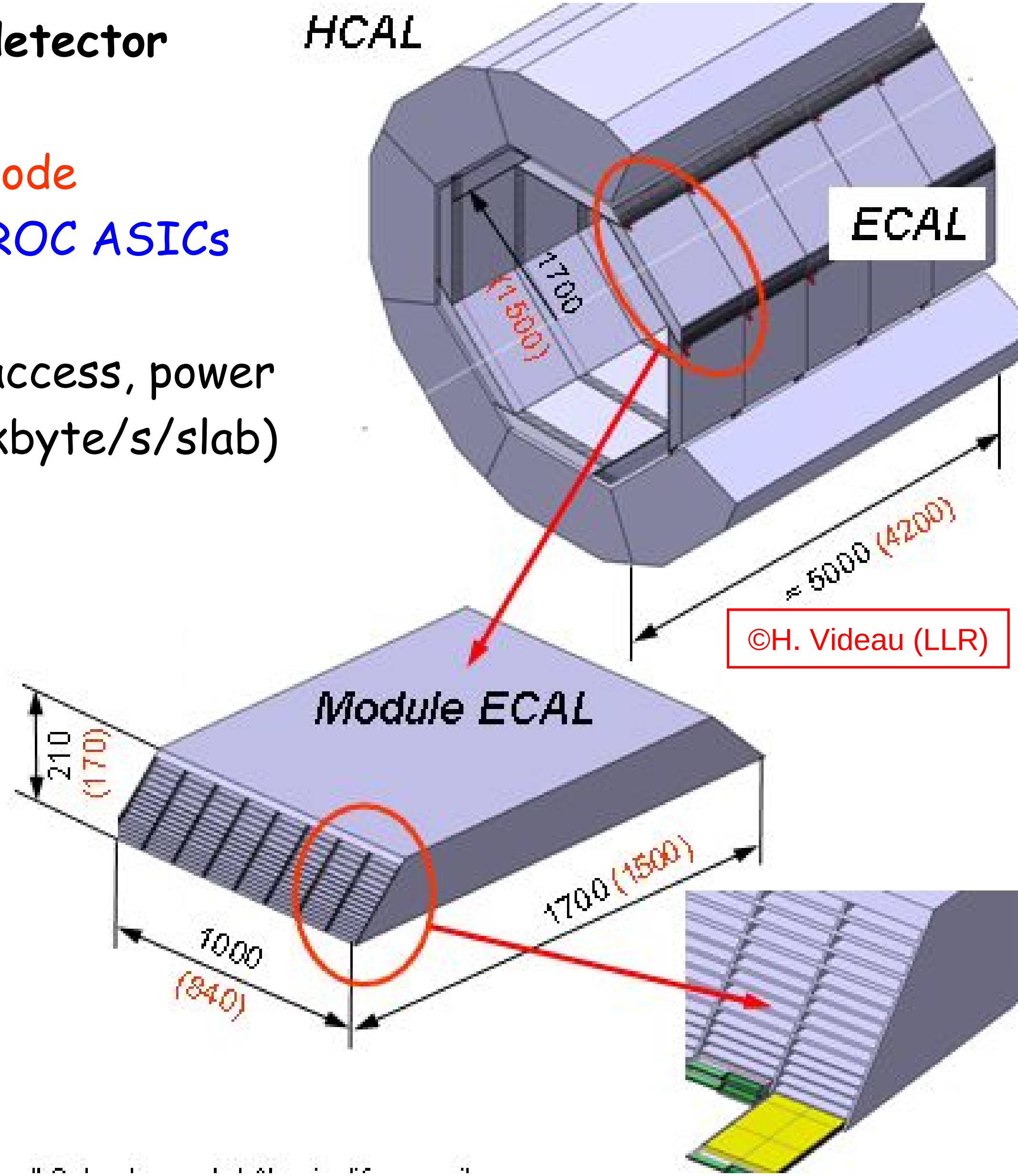
CALICE Testbeam at CERN SPS



Technological prototype : "EUDET module"

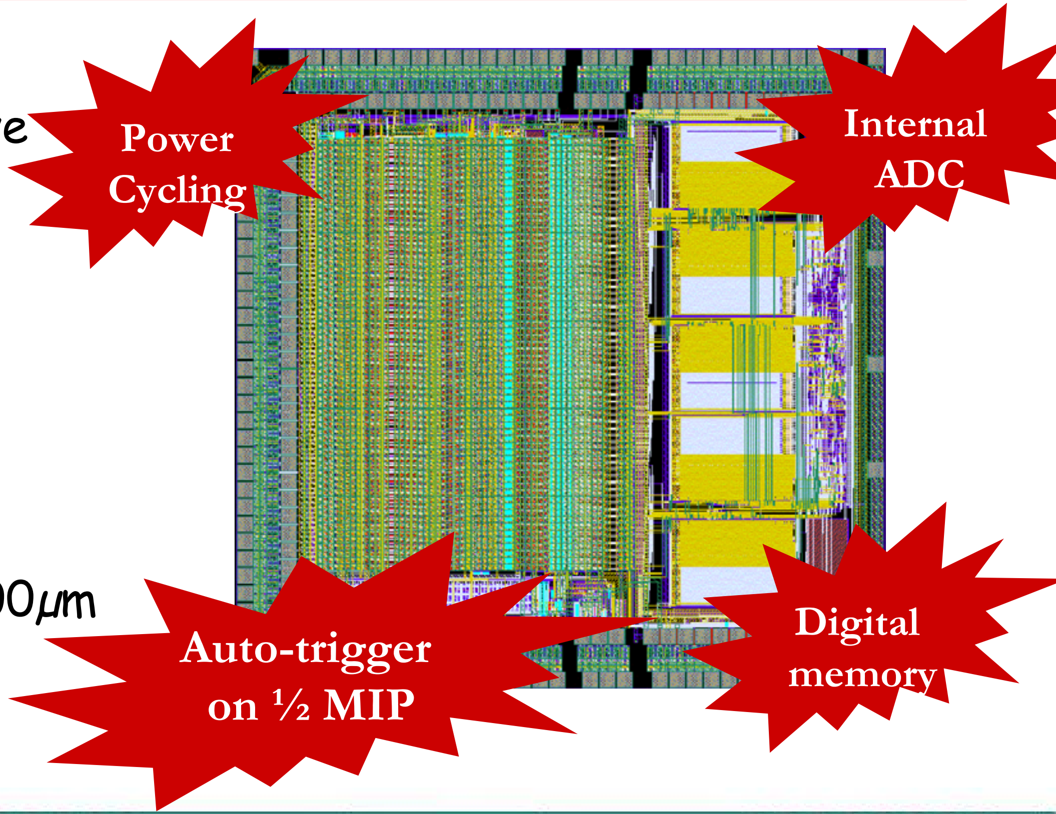
- **Front-end ASICs embedded in detector**
  - Very high level of integration
  - Ultra-low power with pulsed mode
  - HaRDROC, SKIROC and SiPMROC ASICs
- **All communications via edge**
  - 4,000 ch/slab, minimal room, access, power
  - small data volume (~ few 100 kbyte/s/slab)
- **« Stitchable motherboards »**

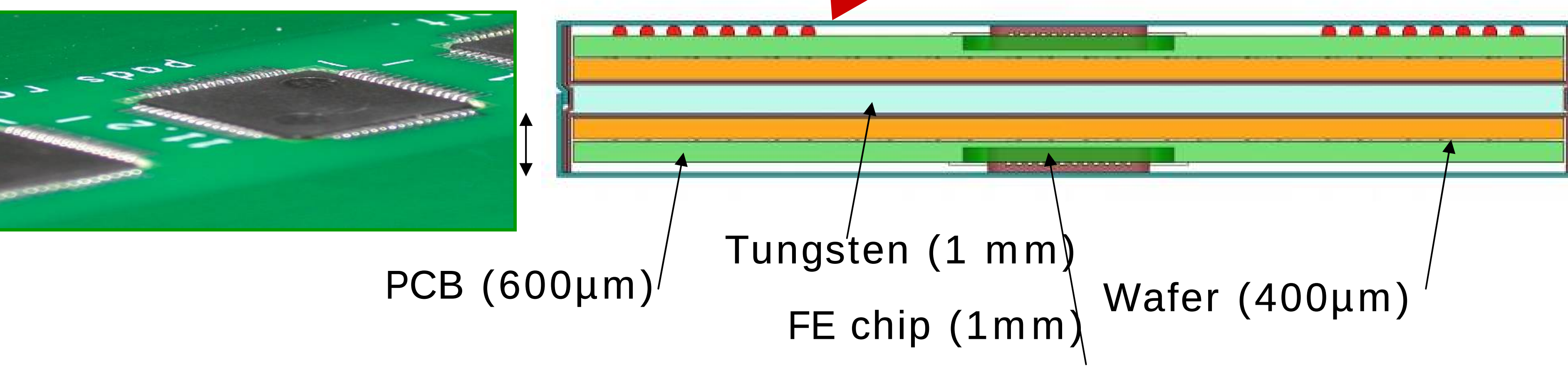




EUDET module FEE : main issues

- **Mixed signal issues**
  - Digital activity with sensistive analog front-end
- **Pulsed power issues**
  - Electronics stability
  - Thermal effects
  - To be tested in beam a.s.a.p.
- **No external components**
  - Reduce PCB thickness to < 800µm
  - Internal supplies decoupling





Conclusion

- **Specific calorimeter features**
  - Large dynamic range (10-16 bits)
  - High precision (%)
  - Good linearity
  - Large size (capacitance)

- **Low noise preamps needed**
  - Impacts energy resolution
  - Coherent noise to be controlled to make large sum

- **Multigain readout**
  - Split dynamic range in several linear ranges
  - Digital filtering optimizes signal to noise ratio

- **Calibration essential for good performance**