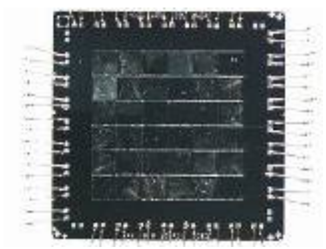
Readout Electronics

the path of the signal
from detection to acquisition

Detector(s)

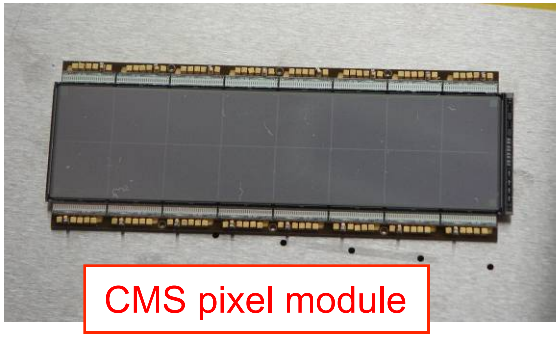
A large variety of detectors

But similar modeling

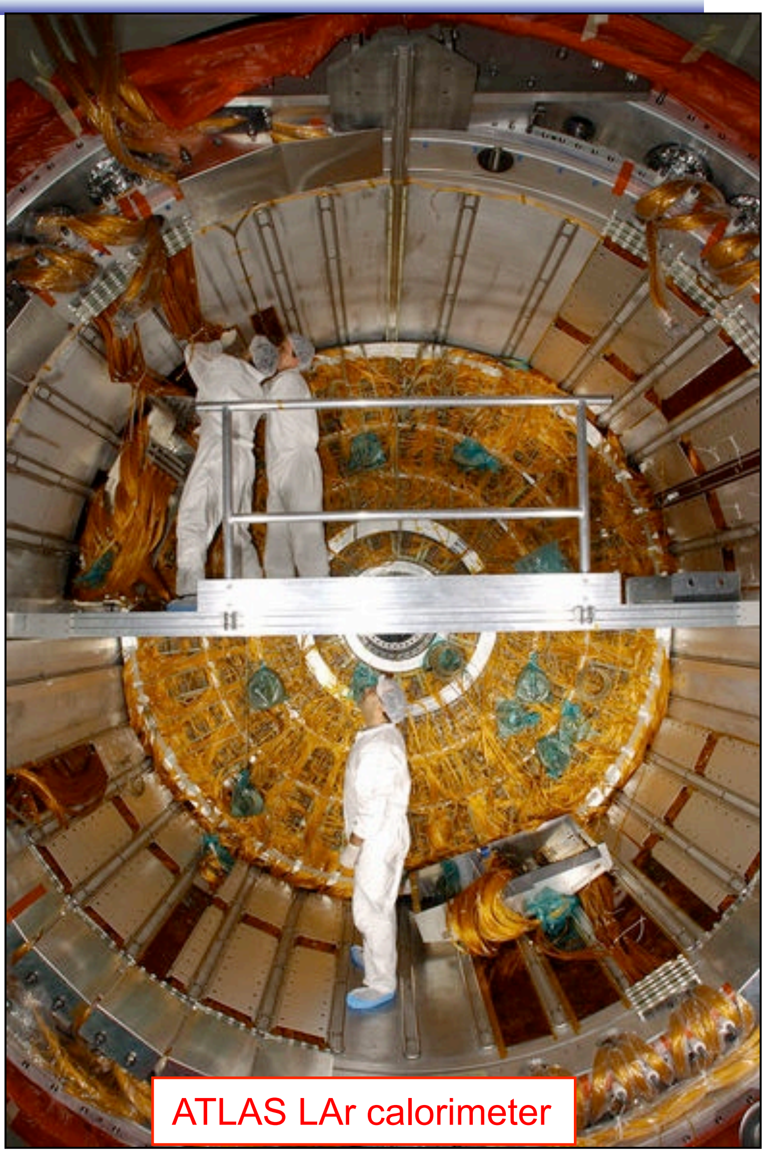


6x6 pixels,4x4 mm^2
HgTe absorbers, 65 mK
12 eV @ 6 keV

PMT in ANTARES



CMS pixel module



ATLAS LAr calorimeter

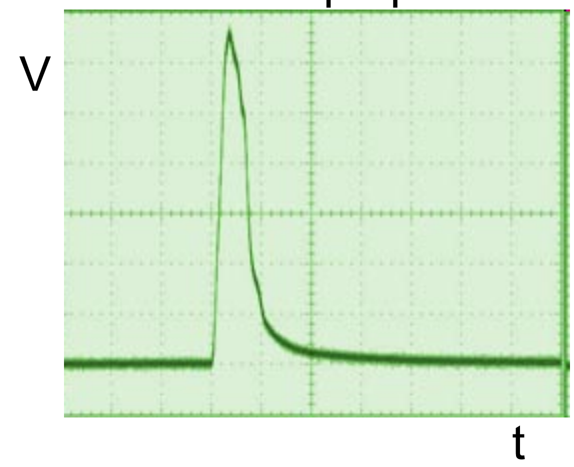
Detector Signal

- Detector signal generally a short current pulse:

  i =V/R (R = 50Ω, oscilloscope termination)

– thin silicon detector (10 –300 μm):	100 ps–30 ns
– thick (~cm) Si or Ge detector:	1 –10 μs
– proportional chamber:	10 ns –10 μs
– Microstrip Gas Chamber:	10 –50 ns
– Scintillator+ PMT/APD:	100 ps–10 μs

oscilloscope picture



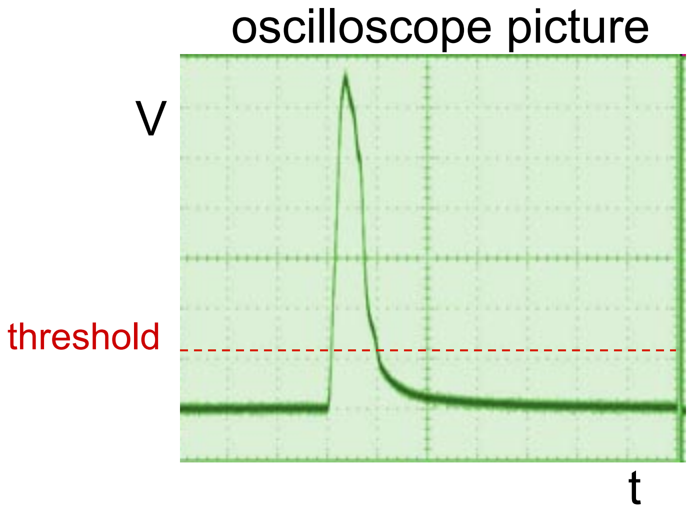
$$E \propto Q_s = \int i_s(t)dt$$

Signal measurements

Various measurements of this signal are possible
Depending on information required:

- Signal above threshold
  digital response / event count
- Integral of current = charge
  ➔ energy deposited
- Time of leading edge
  ➔ time of arrival (ToA) or time of flight (ToF)
- Time of signal above threshold
  ➔ energy deposited by TOT

and many more …



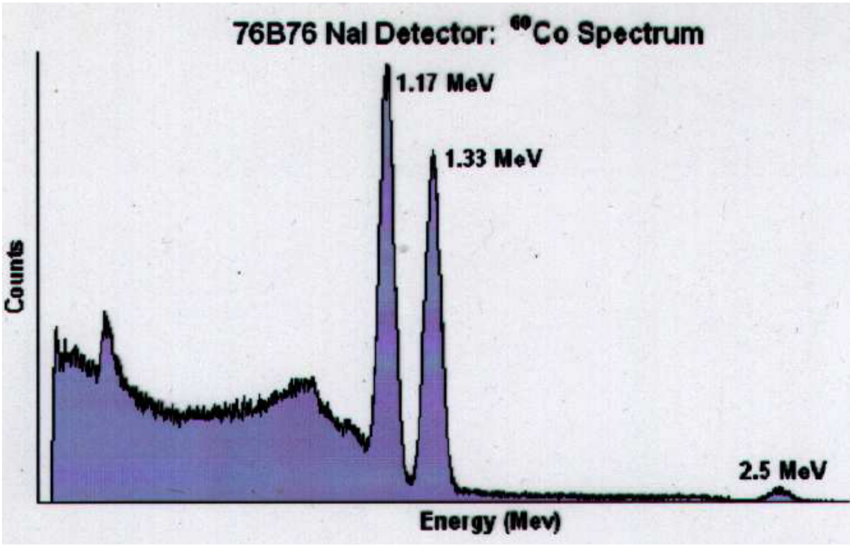
Energy measurement

Determine energy deposited in a detector

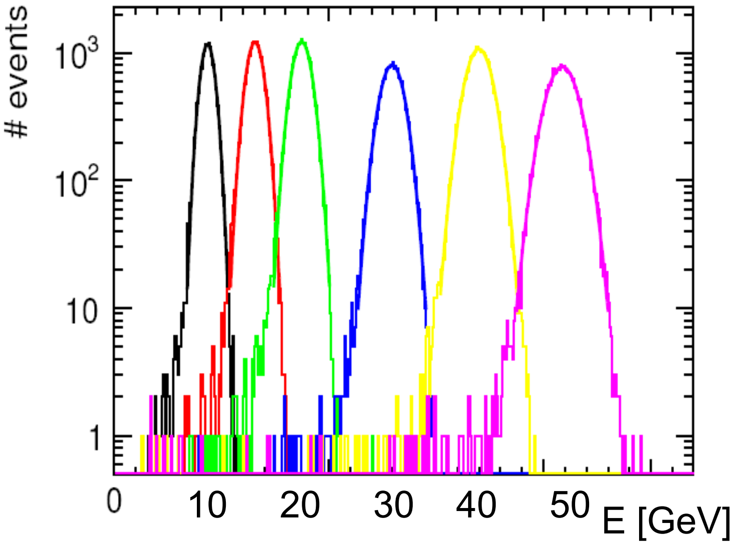
$$E \propto Q_s = \int i_s(t)\,dt$$

• Necessary to integrate detector signal current:
– integrate charge on input capacitance
– use integrating (“charge sensitive”) preamplifier
– amplify current pulse and use integrating ADC (analog to digital converter)

Examples:



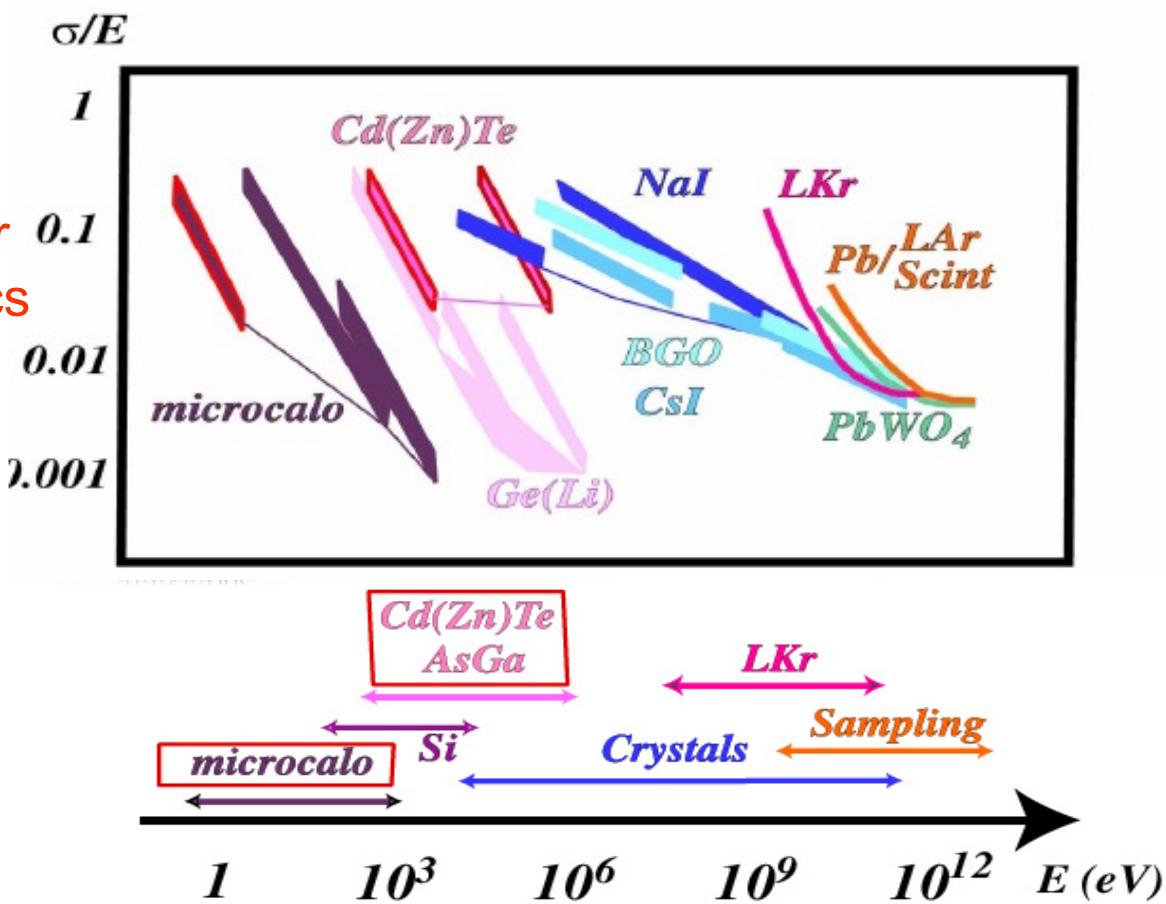
E meas. of e^- in a calorimeter



Electronics requirements for E meas.

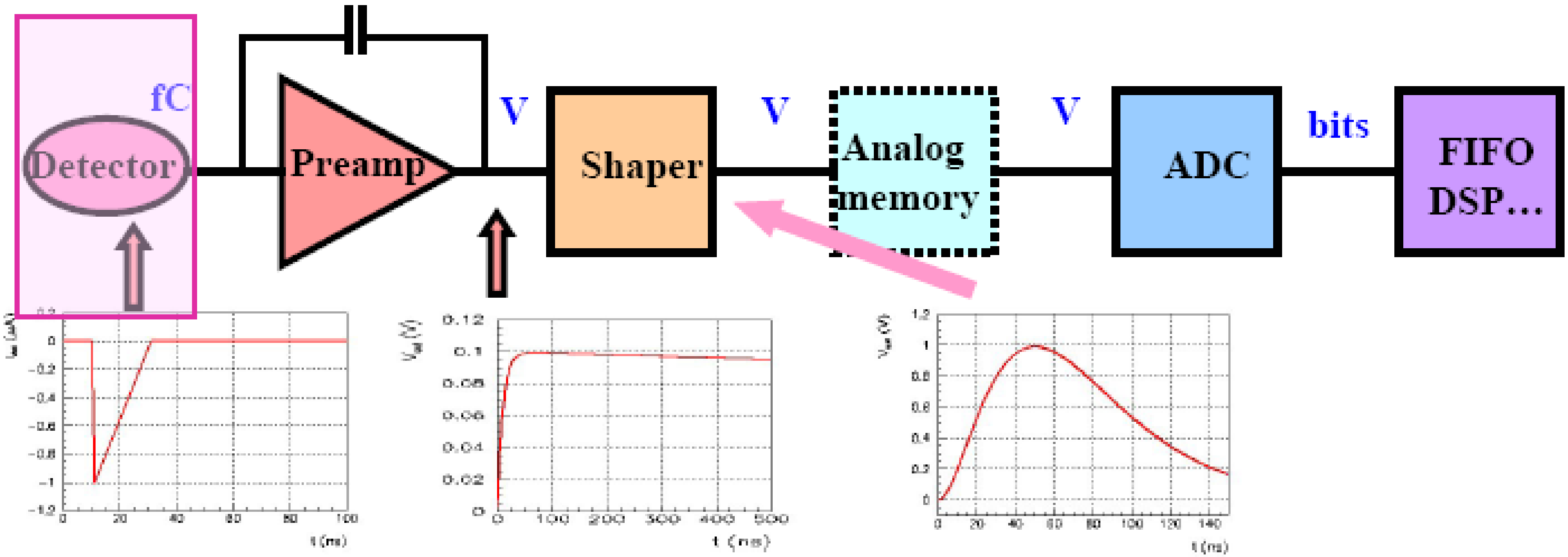
Dynamic range:
maximum signal/minimum signal (or noise) typically: 10^3–10^5
often specified in dB (=20log V_{max}/V_{min}) = 60 –100 dB
also in bits: $2^n = V_{max}/V_{min}$ = 10 –18 bits

The large dynamic range is a key parameter for calorimeter electronics



Readout architecture for E meas.

Most front-ends follow a similar architecture



- Very small signals (fC) -> need amplification
- Measurement of amplitude (ADCs)
- Thousands to millions of channels

Detector modeling (approximation)

Detector = capacitance Cd

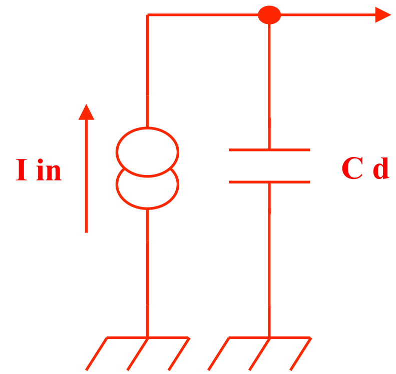
– Pixels : 0.1-10 pF
– PMs : 3-30 pF
– Ionization chambers: 10-1000 pF
– Sometimes effect of transmission line

Signal : current source

– Pixels : ~100 e^-/µm
– PMs : 1 photoelectron -> 10^5-10^7 e^-
– Modeled as an impulse (Dirac) :
$i(t)=Q_0\delta(t)$

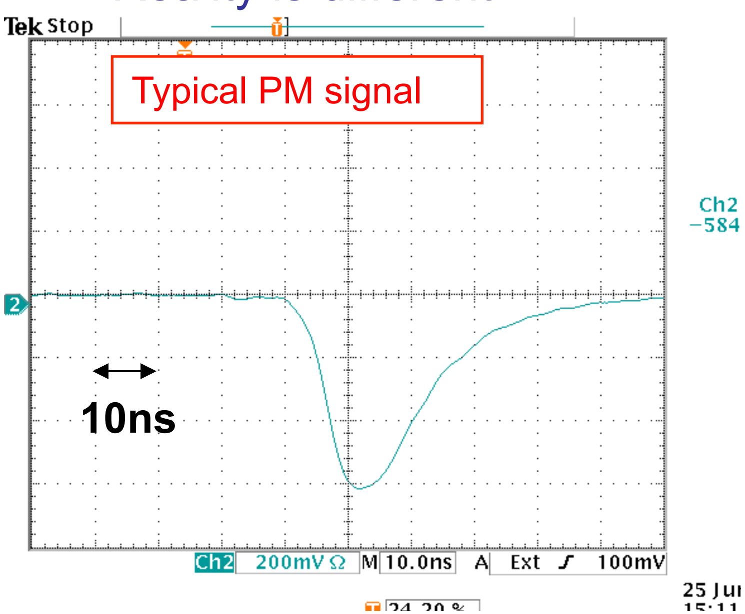
Missing :

– High Voltage, bias
– Connections, grounding
– Neighbors
– Calibration…



Detector model

Reality is different

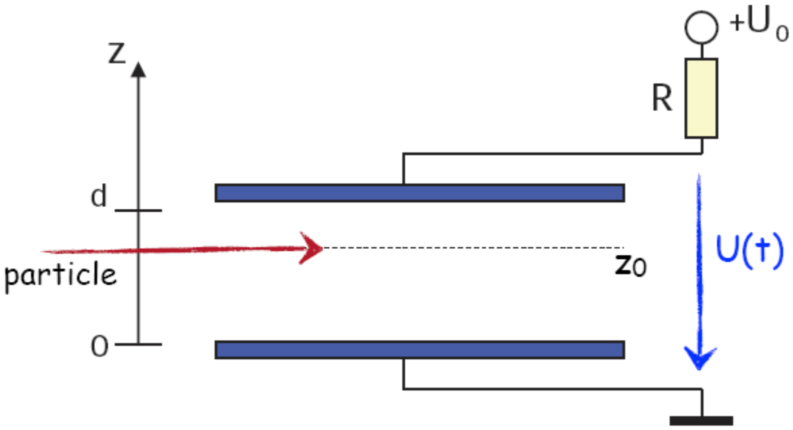


Ionization chamber signal shape

derive signal for single ionizing particle [R = ∞]

$$U = U_0 + \Delta U$$

$$\Delta U = -\frac{N_+ q_+}{Cd}(d - z_0) + \frac{N_- q_-}{Cd}(0 - z_0) = \Delta U_- + \Delta U_+$$
$$= -\frac{N}{Cd}\left[e(d - z_0) - e(0 - z_0)\right] = -\frac{Ne}{C}$$



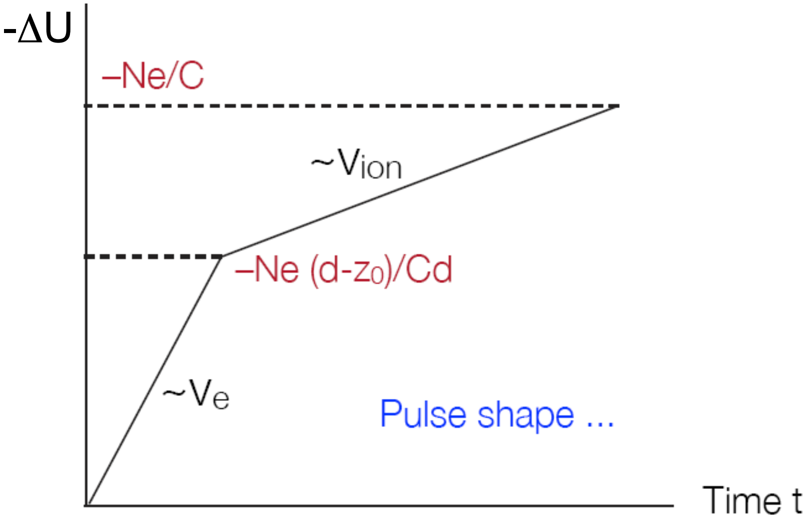
Schematic view
of an ionization chamber

Final signal independent of ionization position and of detector dimension ...
[see also Geiger counter]

Time evolution of pulse height:

$$z(t) = v_D \cdot t$$
$$\Delta U = -\frac{Ne}{Cd}\left(v_D^{\mathrm{e}} + v_D^{\mathrm{ion}}\right) t$$

with:
$$v_D^{\mathrm{e}} \approx 1000 \cdot v_D^{\mathrm{ion}}$$



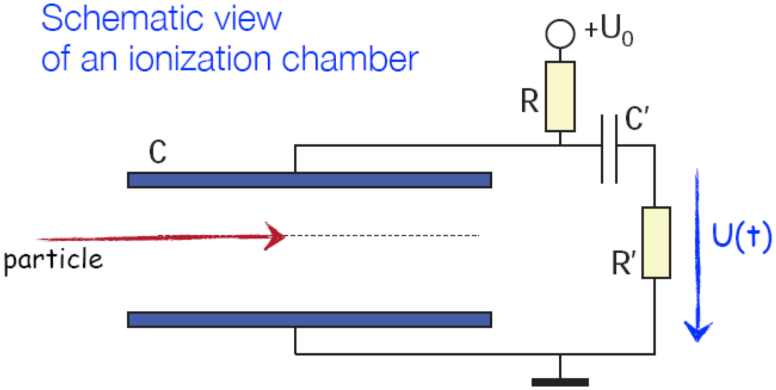
Pulse shape ...

Typical:

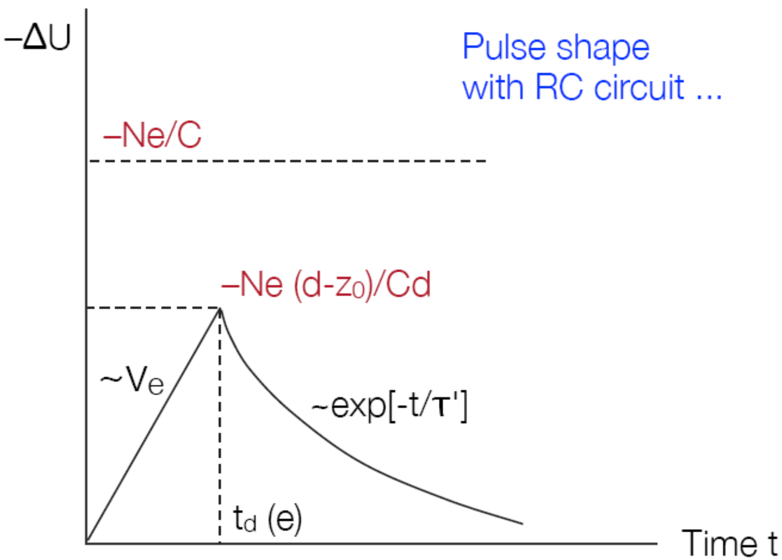
$v_{d,e}$ = 4 cm/μs
$v_{d,ion}$ = 4 cm/ms

Ionization chamber signal shape

Schematic view
of an ionization chamber



Pulse shape
with RC circuit ...



Pulse mode operation
[Use RC circuit; R finite]

Response time of chamber: $\tau = RC$

Must be sufficiently large with respect to t_{signal}

Example: 2 x 2 x 10 cm^3 chamber

Electron drift time: $t^-_{max} = d/v_{d,e} = 2cm/4cm/\mu s = 500$ ns
Ion drift time: $t^+_{max} = d/v_{d,ion} = 500\ \mu s$

Suppress ion signal by C'R' high pass filter
with time constant $\tau' = R'C'$

Chose: $t^-_{max} < \tau' < t^+_{max}$

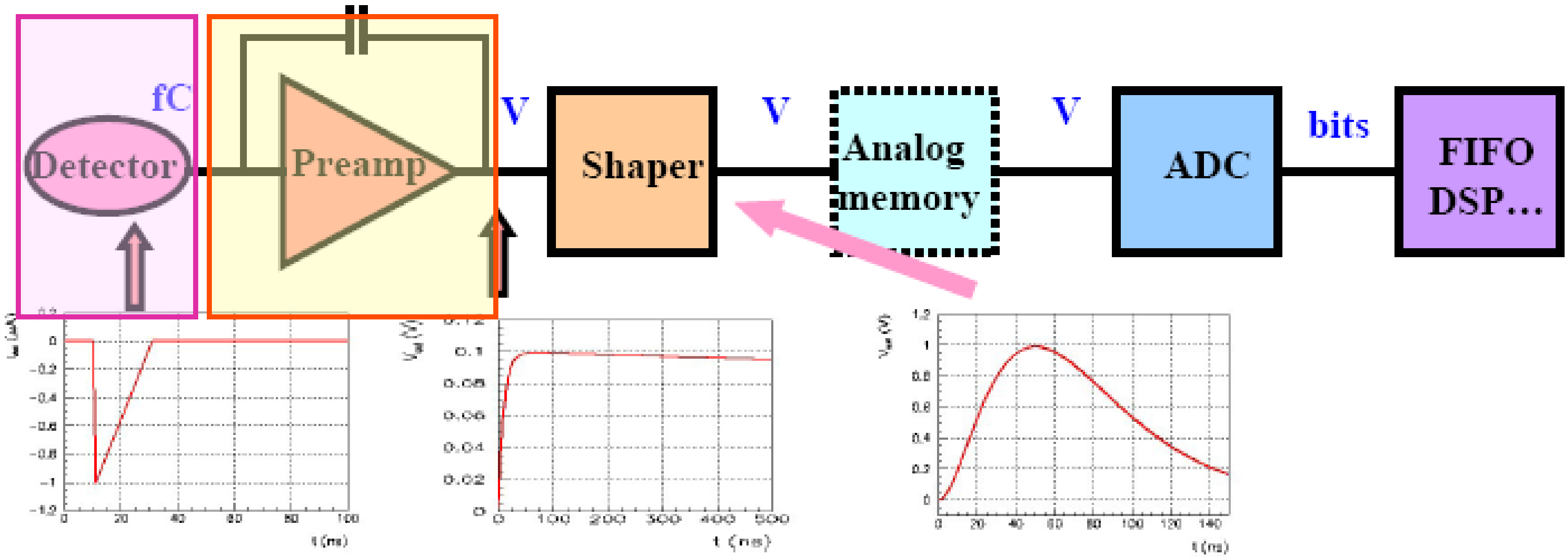
Ex.: τ' = 1μs
C = 1pF, R = 10MΩ
C' = 1pF, $C_{tot} = CC'/(C+C') = 0.5$ pF
R' = τ/C = 1 μs/0.5 pF = 2 MΩ

Features:

- linear rise; exponential fall
- dead time $T_{dead} \approx \tau'$
- position dependent pulse height
- position dependent resolution

Readout architecture for E meas.

Most front-ends follow a similar architecture

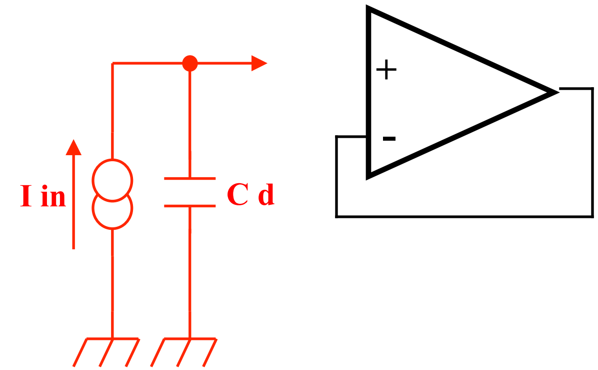


- Very small signals (fC) -> need amplification
- Measurement of amplitude (ADCs)
- Thousands to millions of channels

Reading the signal

Signal

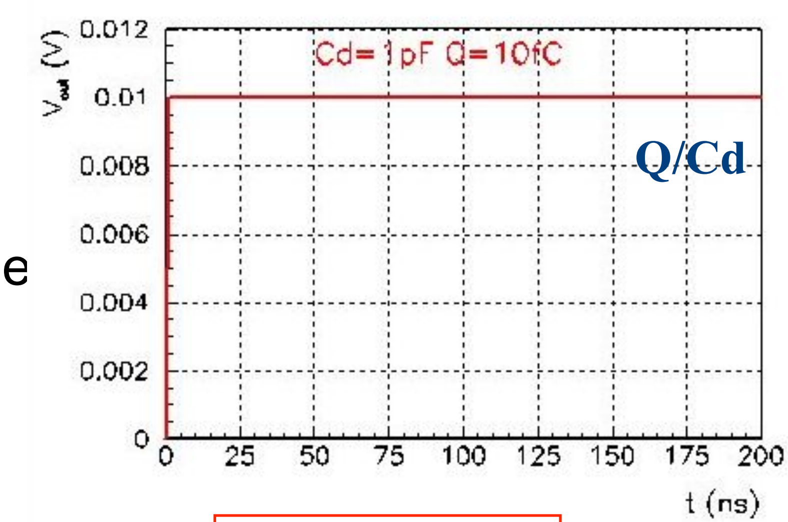
- Signal = current source
- Detector = capacitance C_d
- Quantity to measure
  - Charge ➔ integrator needed
  - Time ➔ discriminator + TDC



Voltage readout

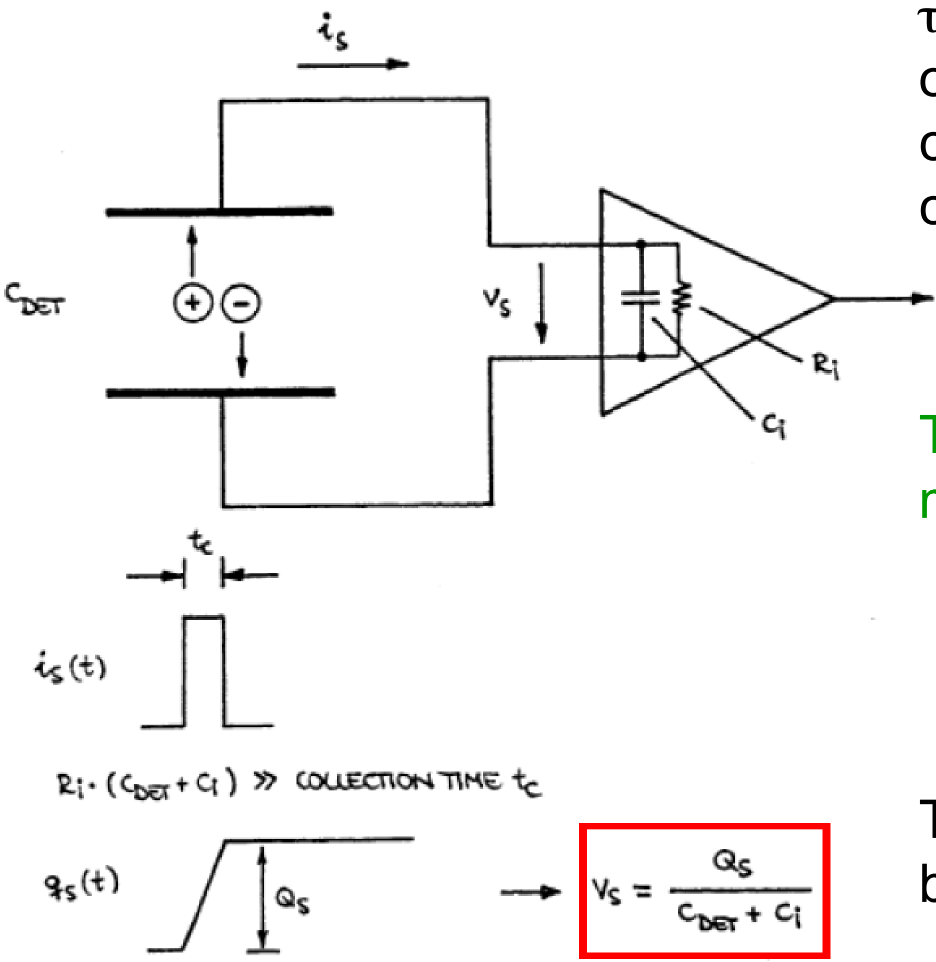
Integrating on C_d

- Simple : $V = Q/C_d$
- « Gain » : $1/C_d$: 1 pF ➔ 1 mV/fC
- Need a follower to buffer the voltage ➔ parasitic capacitance
- Gain loss, possible non-linearity
- crosstalk
- Need to empty C_d…



Impulse response

Reading the signal (II)



If the input time constant of the amplifier, $\tau = C_i R_i$ is large compared to the duration of the current pulse of the detector, t_c the current pulse will be integrated on the capacitance C_i.

The resulting voltage at C_i and R_i is

$$v_i = v_s = Q_s / (C_{det} + C_i)$$

The fraction of the signal charge measured is:

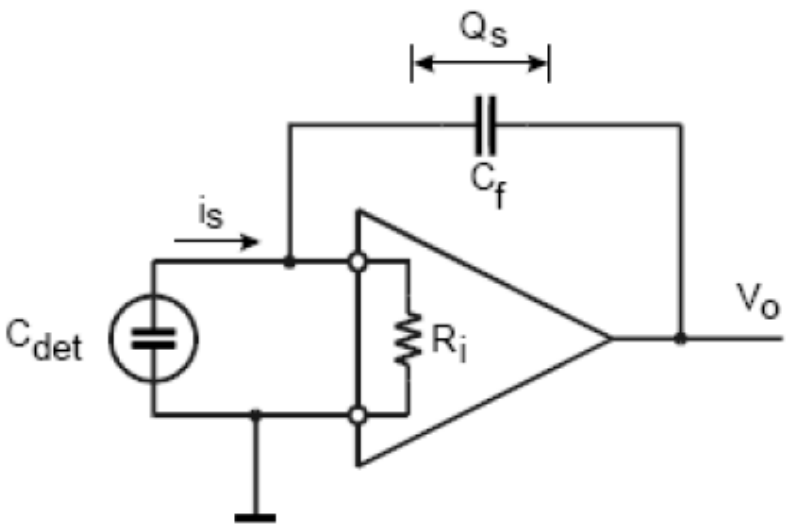
$$\frac{Q_i}{Q_s} = \frac{C_i v_i}{v_i (C_i + C_{det})} = \boxed{\frac{1}{1 + C_{det} / C_i}}$$

The dynamic input capacitance C_i should be >> C_{det} to get a good ratio close to 1

Depends on the detector capacitance

Charge sensitive amplifier

Add feedback capacitor C_f:



Voltage gain dV_o/dV_i=-A ➔ $v_o=-Av_i$
Input impedance = ∞ (no signal current flows into amplifier input)

Voltage diff. across C_f: $v_f=(A+1)v_i$
➔Charge deposited on C_f: $Q_f=C_f v_f$
$Q_i = Q_f$ (since $Z_i= \infty$)
➔Effective input capacitance

$$C_i= Q_i/v_i = C_f(A+1)$$

"dynamic input capacitance"

Amplifier gain:

$$A_Q = \frac{dV_o}{dQ_i} = \frac{A \cdot v_i}{C_i \cdot v_i} = \frac{A}{C_i} = \frac{A}{A+1}\frac{1}{C_f} \approx \frac{1}{C_f} \qquad (A >> 1)$$

Charge sensitive amplifier (II)

So finally the fraction of charge signal measured by the amplifier is:

$$\frac{Q_i}{Q_s} = \frac{C_i v_i}{v_i(C_i + C_{\det})} = \frac{1}{1 + C_{\det}/C_i} \qquad C_f \approx \frac{A}{C_i} \quad (A >> 1)$$

Example: $A = 10^3$

$C_f = 1pF$ ➔ $C_i = 1nF$

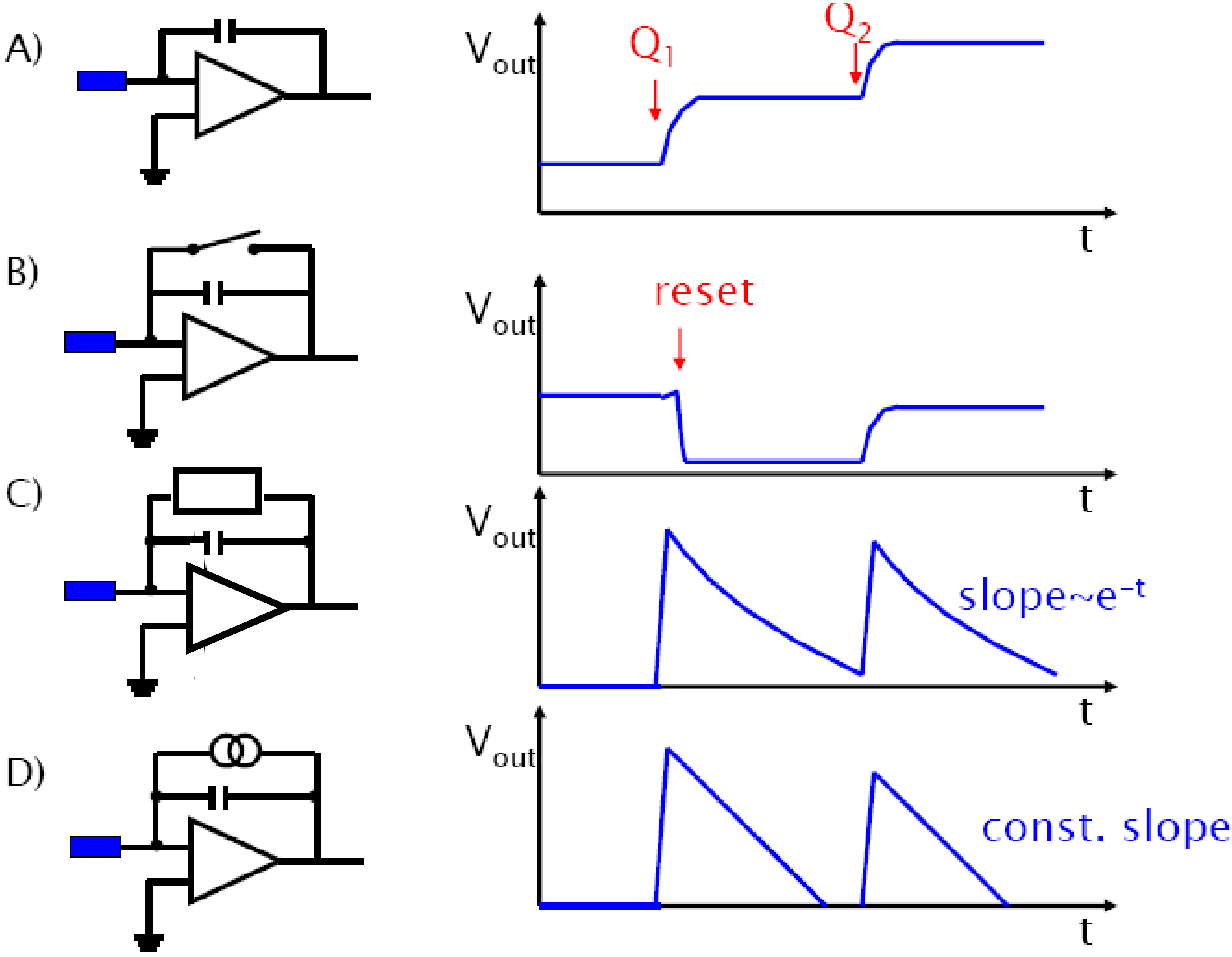
$C_{det} = 10pF$ ➔ $Q_i/Q_s = 0.99$ $(C_i >> C_{det})$

$C_{det} = 500pF$ ➔ $Q_i/Q_s = 0.67$ $(C_i \sim C_{det})$

↑

Si det: 50um thick, 500mm² area

Charge sensitive (pre)-amplifier

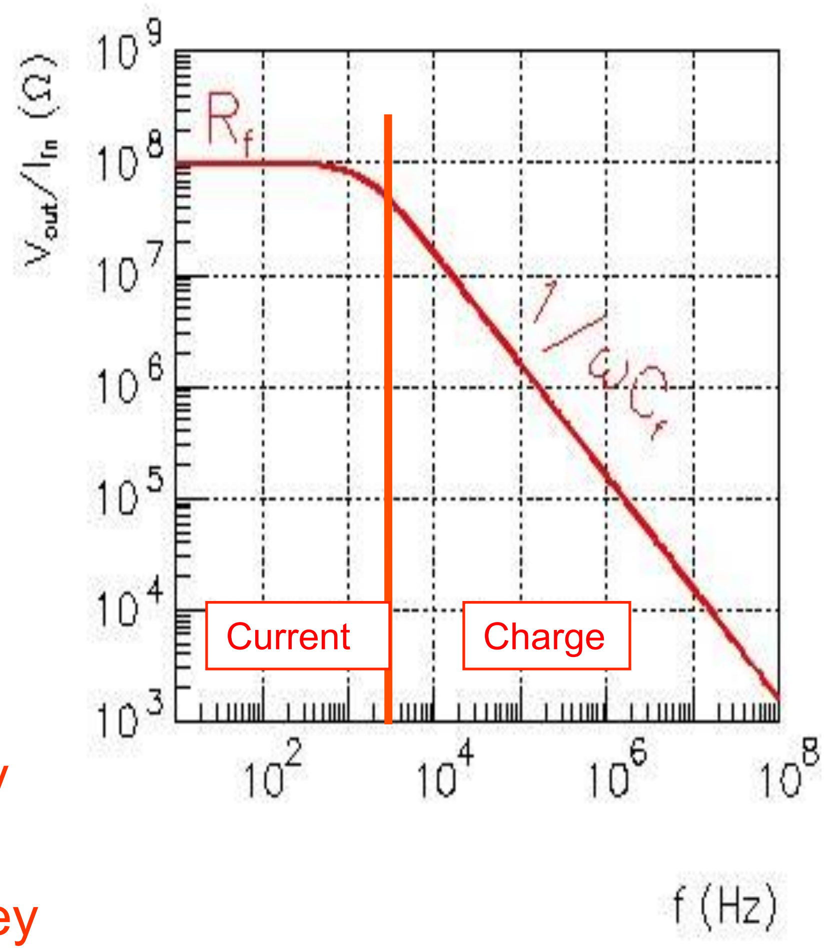


Charge vs Current preamps

- Charge preamps
  - Best noise performance
  - Best with short signals
  - Best with small capacitance

- Current preamps
  - Best for long signals
  - Best for high counting rate
  - Significant parallel noise

- Charge preamps are <u>not slow</u>, they are <u>long</u>
- Current preamps are <u>not faster</u>, they are <u>shorter</u> (but easily unstable)



Readout architecture for E meas.

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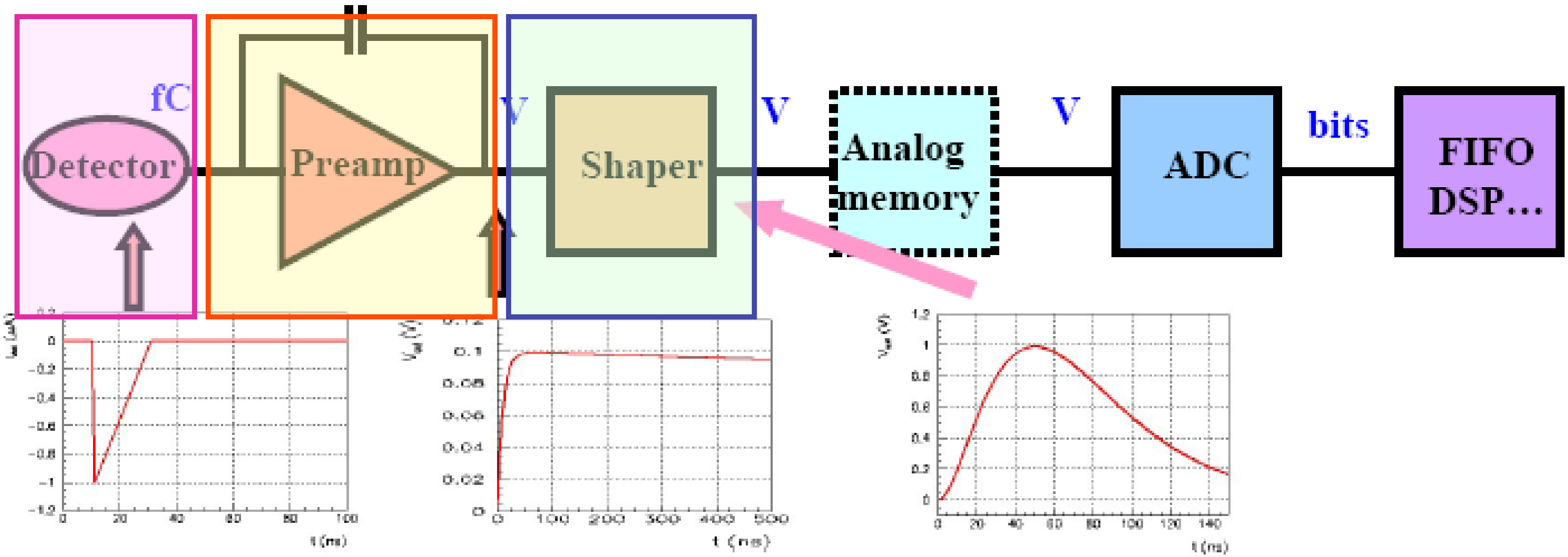


- Very small signals (fC) -> need amplification
- Measurement of amplitude (ADCs)
- Thousands to millions of channels

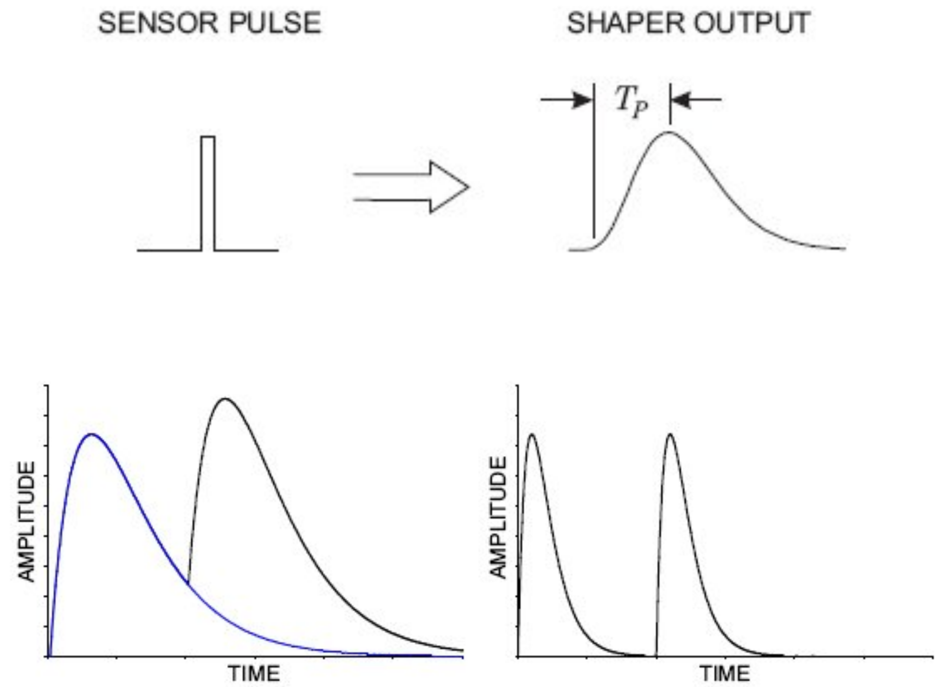
Pulse shaping

Two conflicting objectives:

1) Limit the bandwidth to match the measurement time.
   ➔ too large bandwidth increases the noise

2) Contain the pulse width so that successive signal pulses can be measured without overlap (pile-up)

➔ Short pulse duration increases the allowed signal rate but also noise

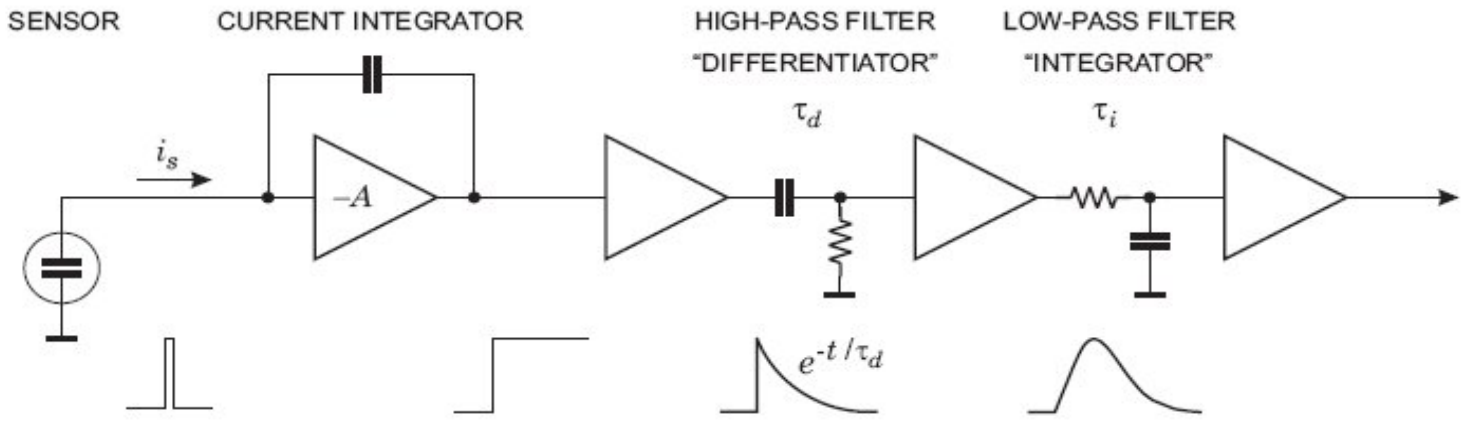


CR-RC shaper

Example of a simple shaper: CR-RC

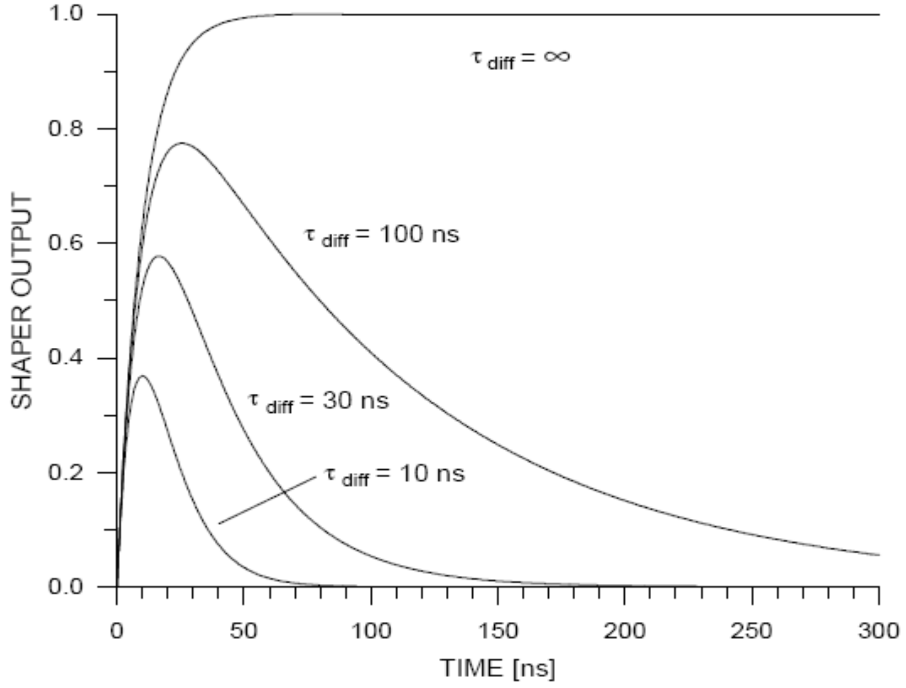
• the high-pass filter sets the duration of the pulse to have a decay time τ_d
• the low-pass filter increases the rise time to limit the noise bandwidth

key design parameter: peaking time ➔ it dominates the noise bandwidth



CR-RC shaper (II)

Effect of a CR-RC shaper with
fix integrator time constant = 10ns
and variable differentiator time constant



readout architecture for E meas.

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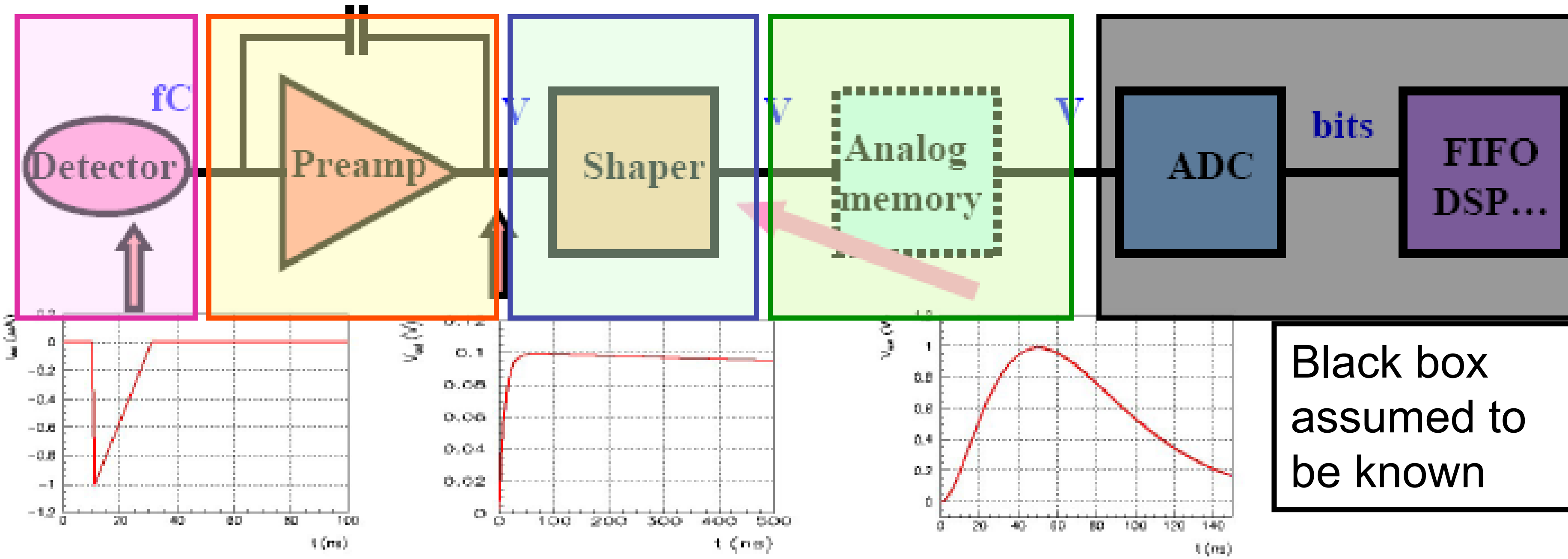
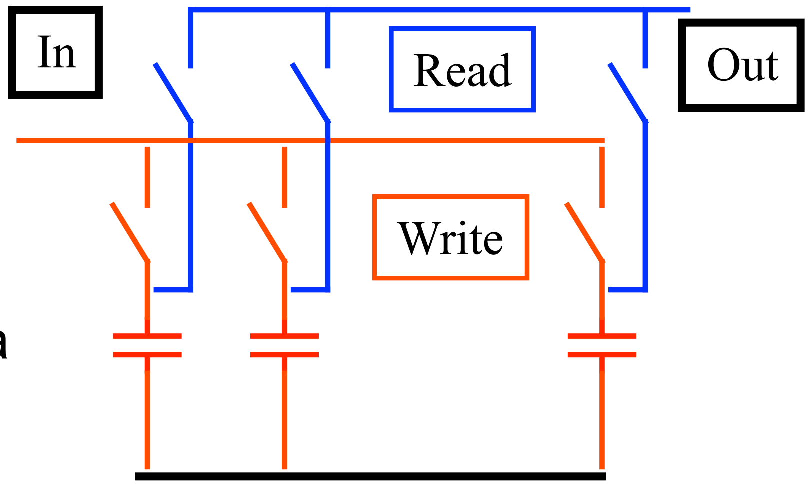


Black box assumed to be known

- Very small signals (fC) -> need amplification
- Measurement of amplitude (ADC)
- Thousands to millions of channels

Analog memories

- Switched Capacitor Arrays (SCAs)
  - Store signal on capacitors (~pF)
  - Fast write (~ GHz)
  - Slower read (~10MHz)
  - Dynamic range : 10-13 bits
  - depth : 100-2000 capacitors
  - Insensitive to absolute value of capa (voltage write, voltage read)
  - Low power
  - Possible loss in signal integrity (droop, leakage current)

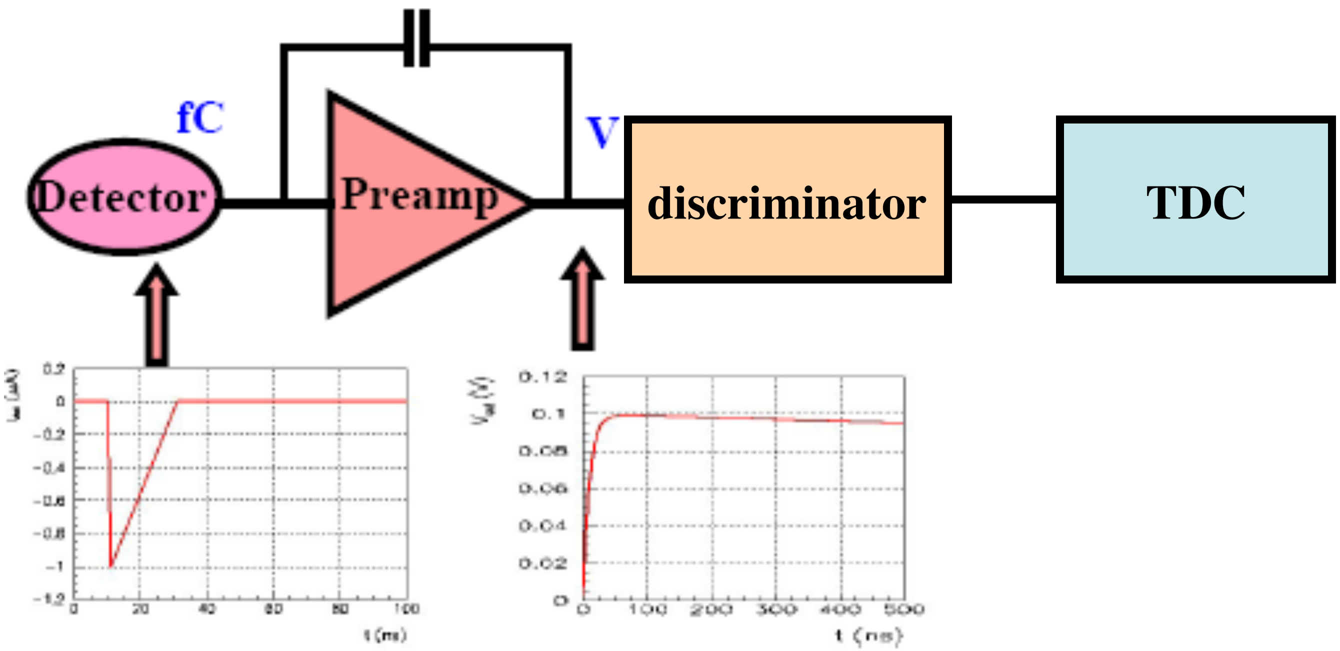


Principle of a « voltage-write, voltage-read » analog memory

- The base of 90% of digital oscilloscopes !

Readout architecture for t meas.

Most front-ends follow a similar architecture

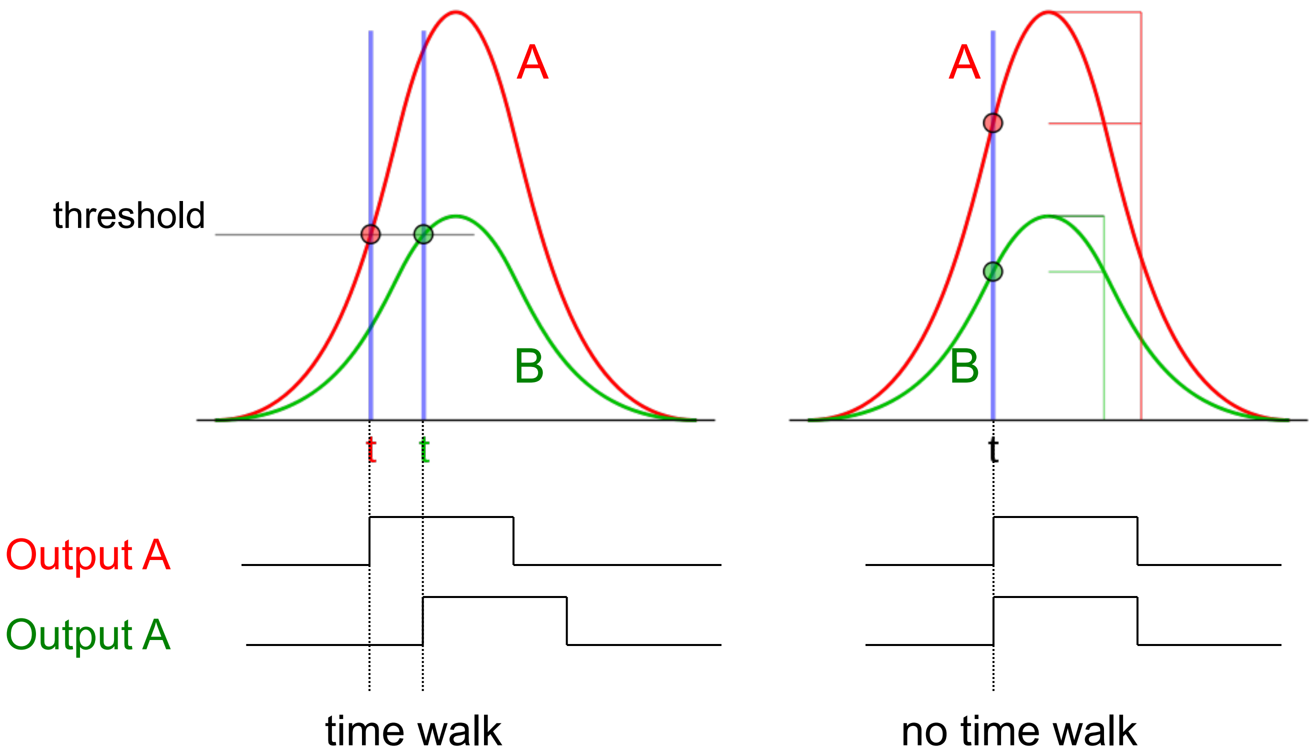


- Very small signals (fC) -> need amplification
- Measurement time (discriminator, TDCs)
- Thousands to millions of channels

Discriminator

Working principle: compare voltage level of signal with fixed voltage level (threshold)
if the signal level exceeds the threshold a standard logic signal is generated

Discriminator techniques: leading edge triggering and constant fraction triggering

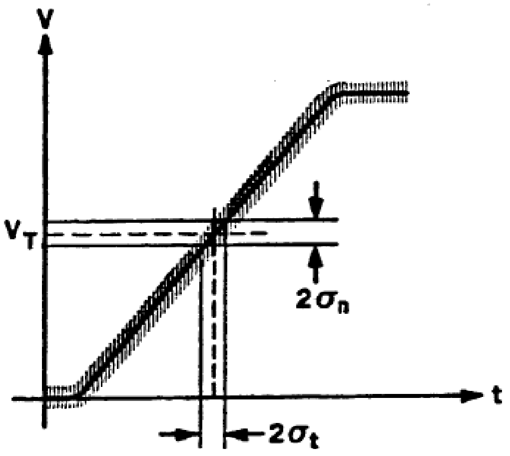


Time measurements

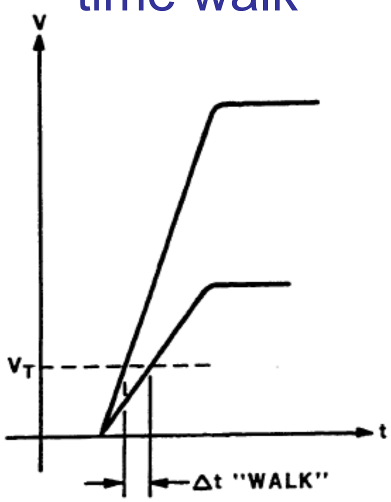
Time measurements are characterized by their slope-to-noise ratio

Two main effects contribute to the deterioration of a time measurement i.e. time of threshold crossing fluctuates due to:

jitter



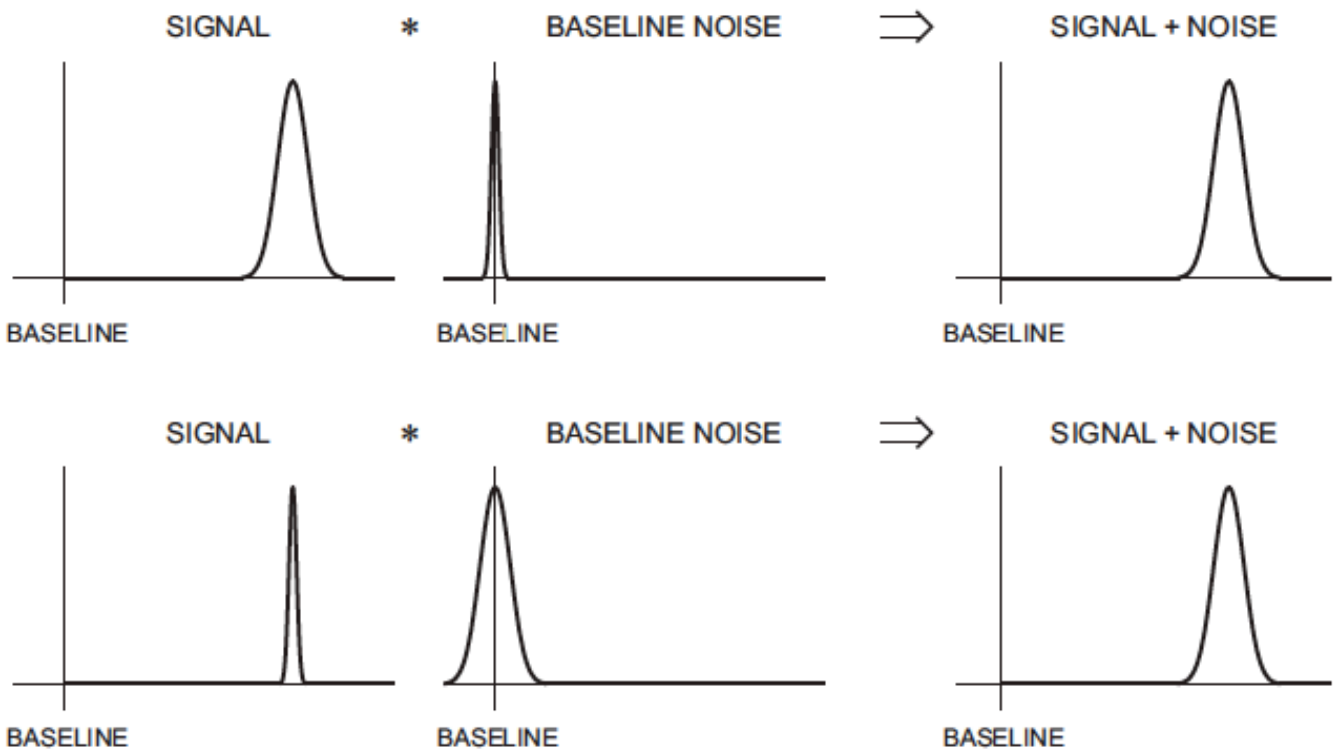
time walk



Often driven by the time constant of the shaper which determines rise time & amplifier bandwidth

From theory to reality

Every signal comes together with noise …

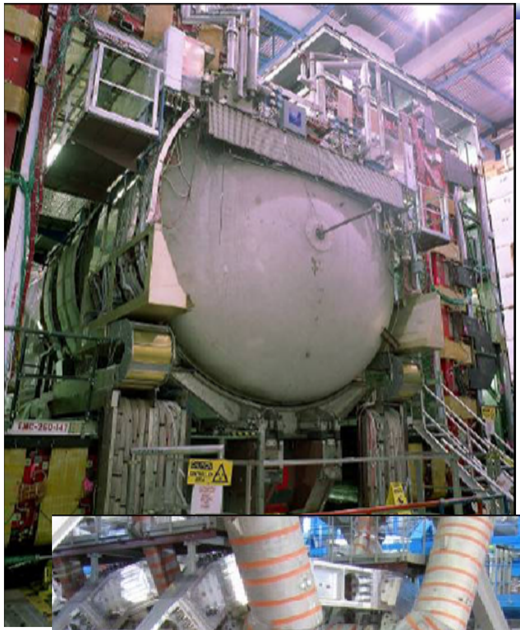


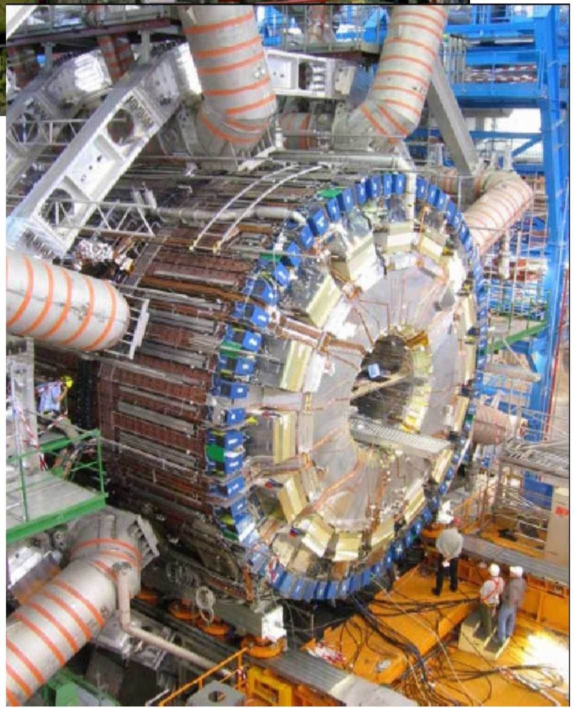
Noise is a quite complex topic (see backup), we do not have time to discuss it. But always remember:

➔ what matters in a detector is S/N

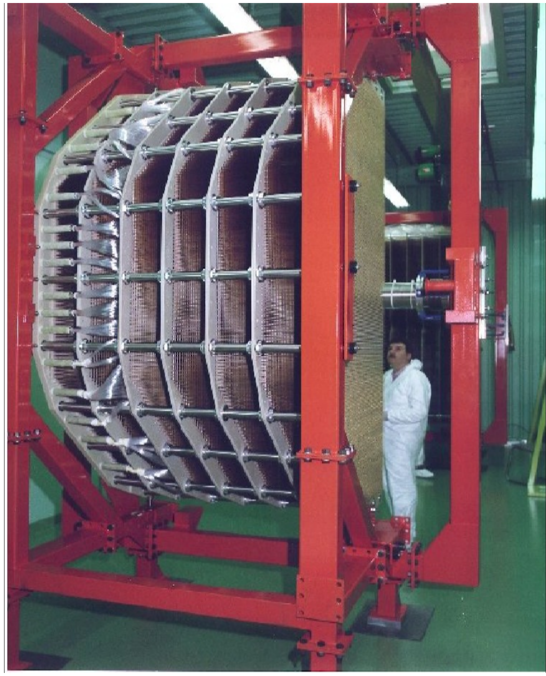
Examples of readout elerctronics

Ionization calorimeters





Examples:
DØ(LAr)
NA48 (LKr)
ATLAS (LAr)
H1

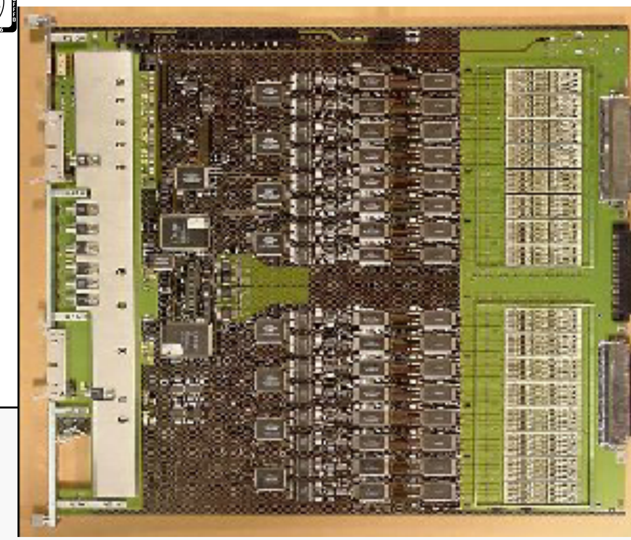


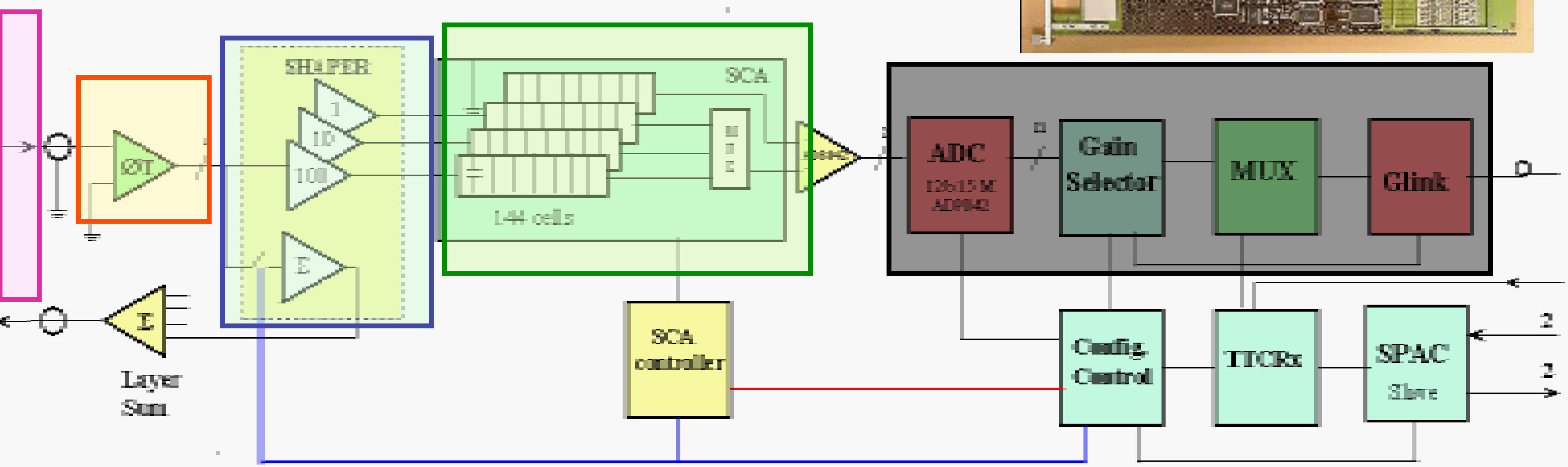
Stable, Linear
Easy to calibrate (!)
Moderate resolution

ATLAS LAr: Front End boards

Amplify, shape, store and digitize Lar signals

128 warm preamps
128 tri-gain shapers
128 quad pipelines
32 ADCs (12bits 5 MHz)
1 optical output (Glink)





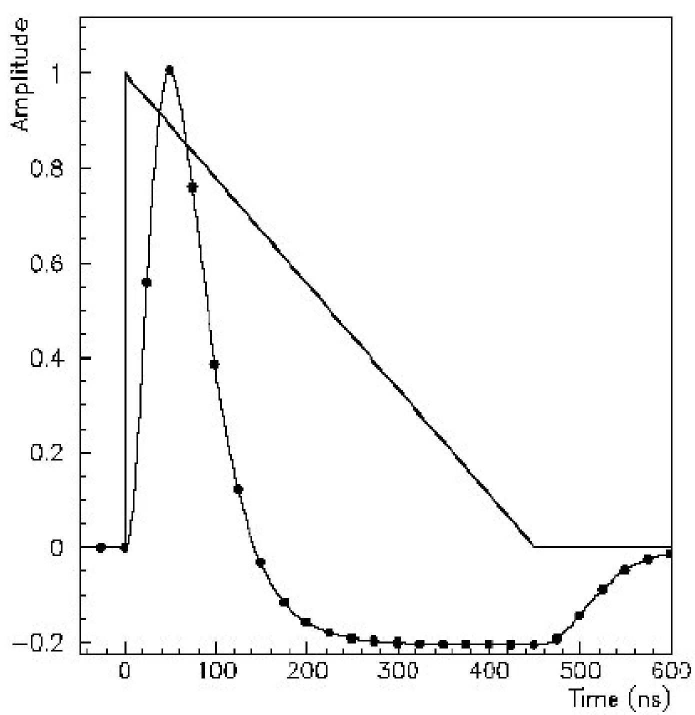
ATLAS : LAr shaper

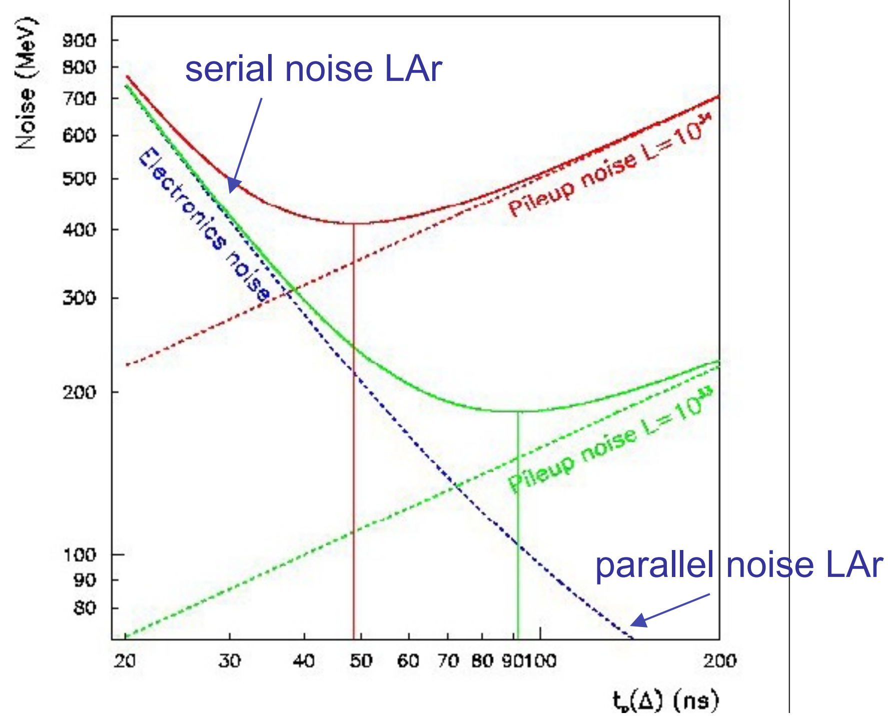
Goal : optimize signal to noise ratio between electronics noise and pileup noise

Ionization signal ~500ns=20 LHC bunch Xings

Reduced to 5 bunch Xings with fast shaper ➔ worse S/N due to loss of charge

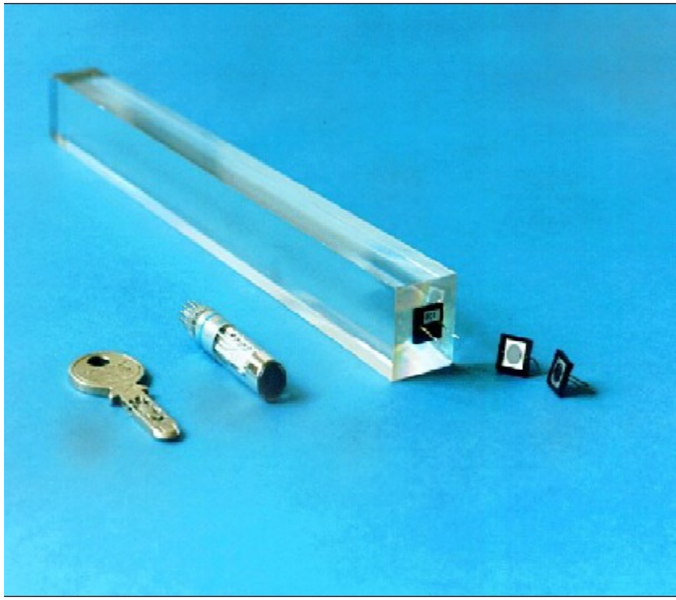
Choice of peak time varies with luminosity ➔ 45ns at L=$10^{34}cm^{-2}s^{-1}$

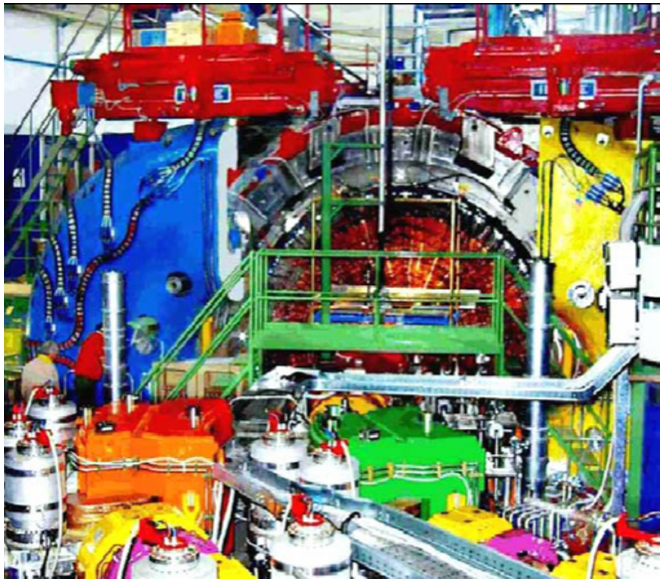




Crystal calorimeters

Babar(CsI)
Kloe(CsI)
CMS (PbWO4)
L3, CLEO, Belle,
ALICE





Fast
Best resolution
Difficult to calibrate
expensive

CMS: ECAL Electronics

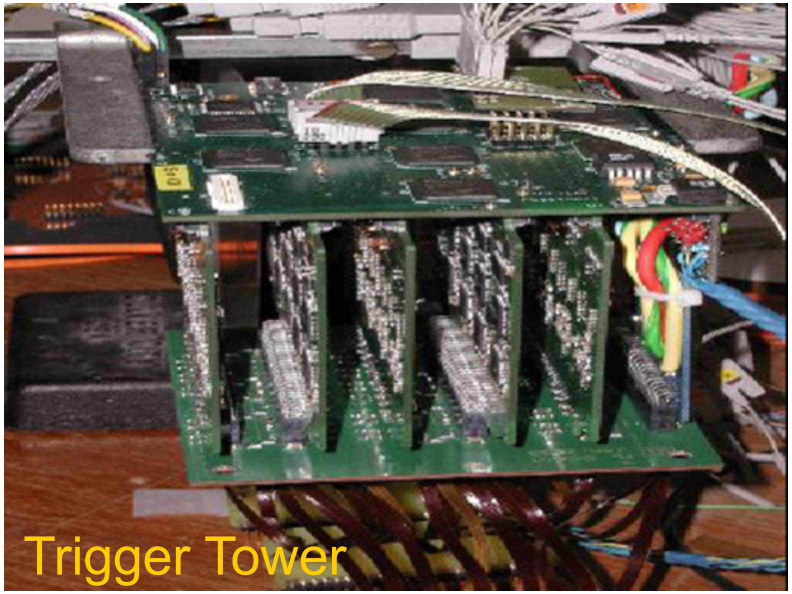
building block :

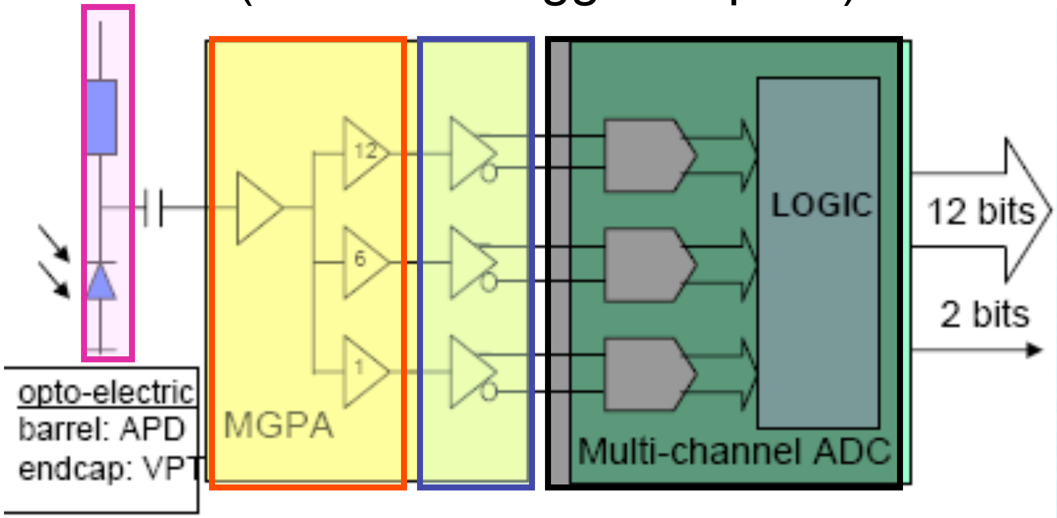
Trigger Tower (25 channels)

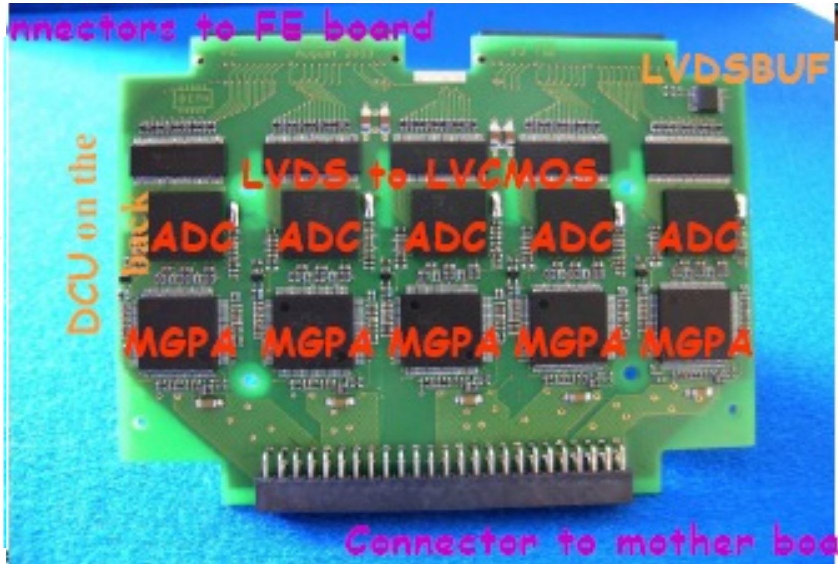
- -1 mother board
- -1 LV regulator board
- -5 VFE boards (5 channels each)
- -1 FE board

2 fibres per TT sending

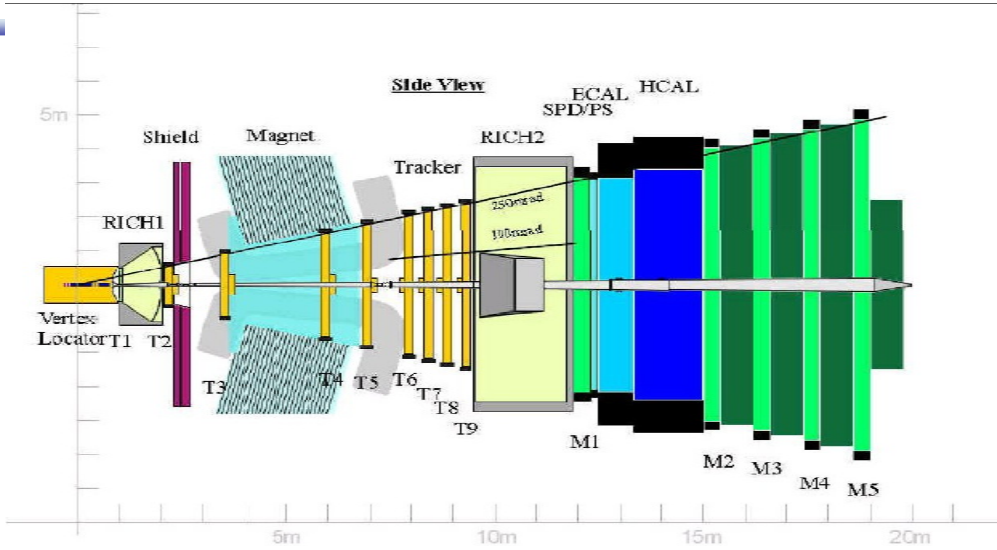
- -trigger primitives (every beam crossing)
- -data (on level 1 trigger request)

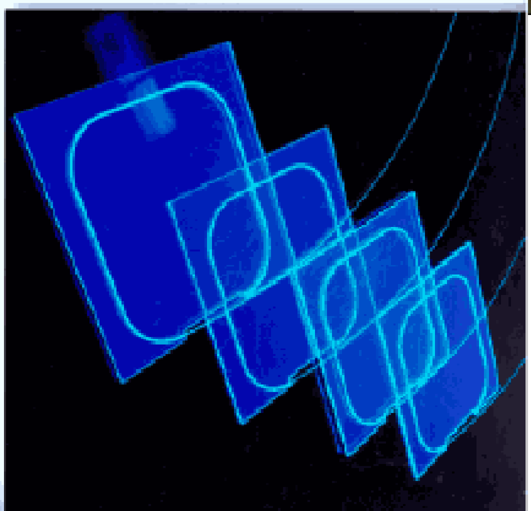






Scintillating calorimeters





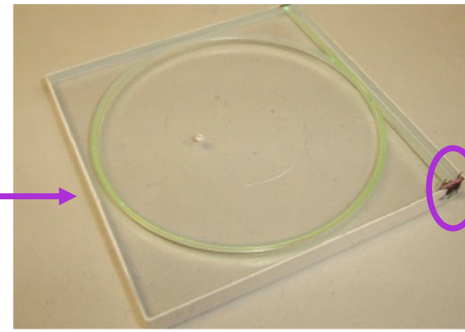
CMS hadronic
LHCb
OPERA
ILC hadronic
ILC em
ATLAS hadronic

Fast
Cheap
Moderate resolution
Difficult to calibrate

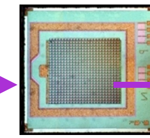
ILC: hadronic calorimeter (CALICE)

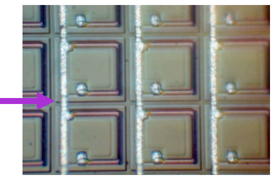
Iron/plastic(tiles) sandwich

Single tile readout with WLS fiber + SiPM:



pixel device operated in Geiger mode



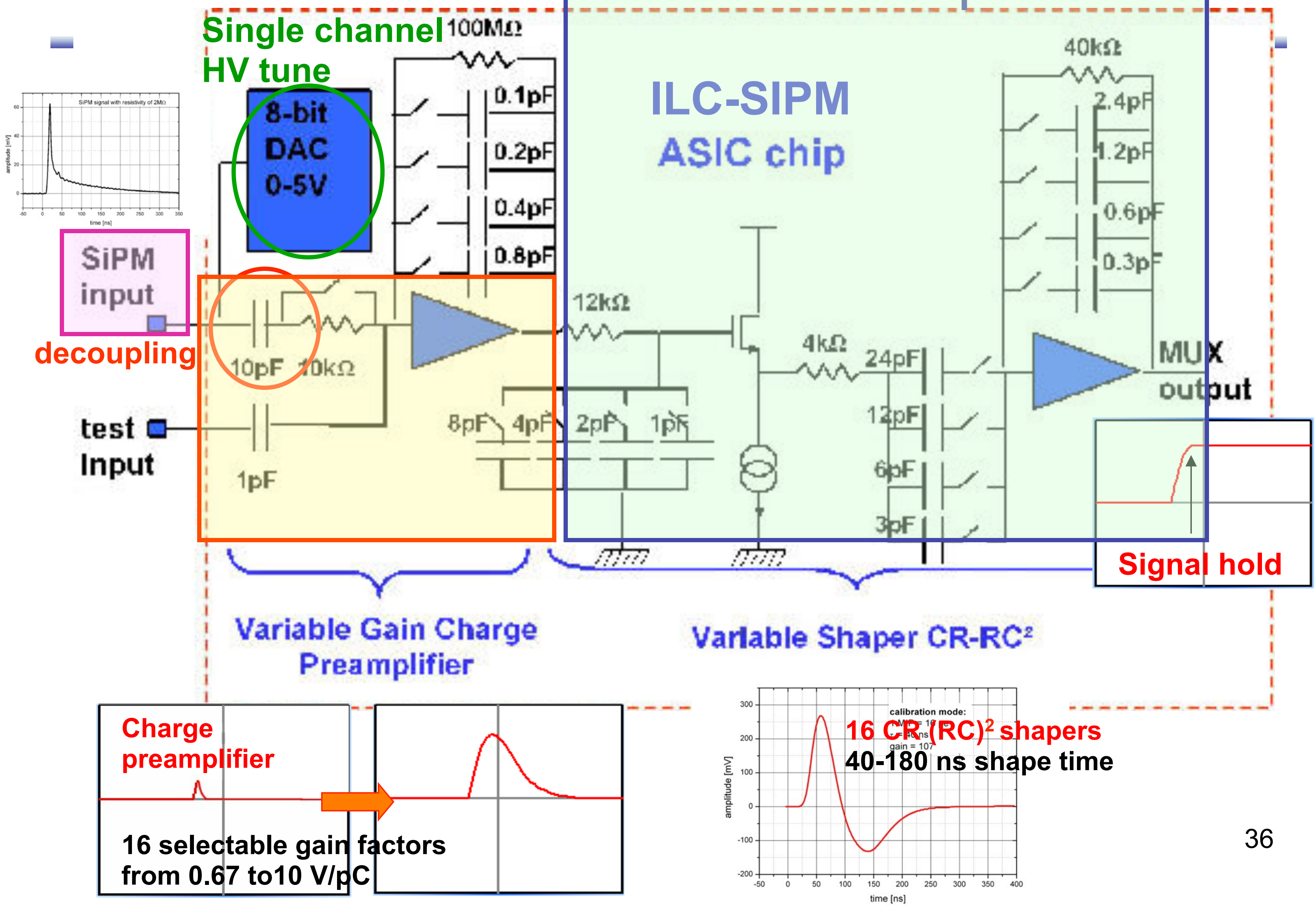


Read out 216 tiles/module
38 sampling layers
~8000 channels

VFE: control board for 12 ASICs / layer connect to SiPMs

ASIC: amplification + shaping + multiplexing (18 ch.)

ILC: HCAL readout chip



Trends & Future

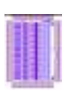
More channels / more functionality in the chip (analog+digital)

➔ more integration

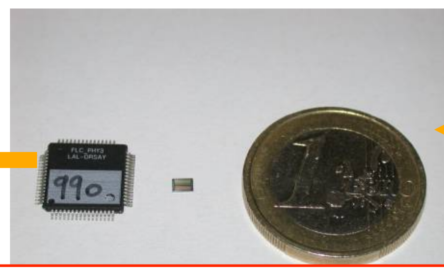
Detector imbedded electronics

➔ reduce cable volume = dead volume

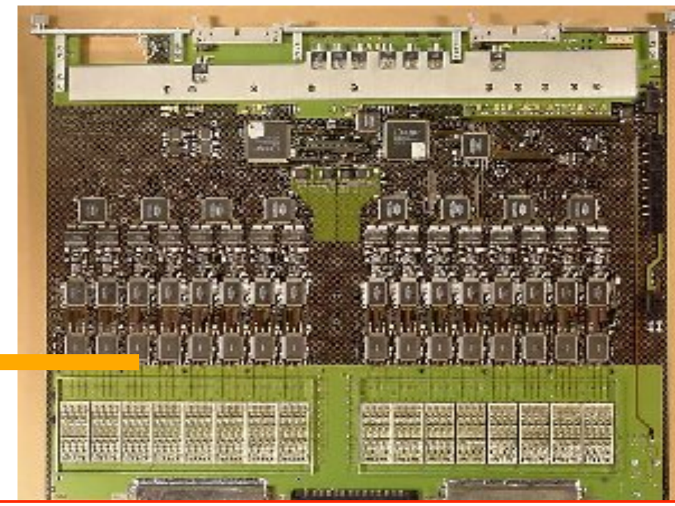
➔ ultra-low power consumption



ILC : **100µW/ch**

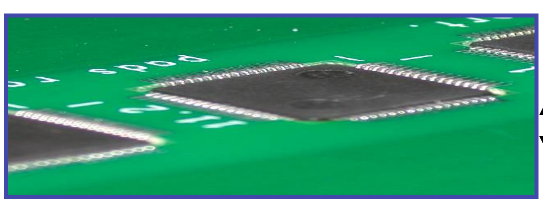


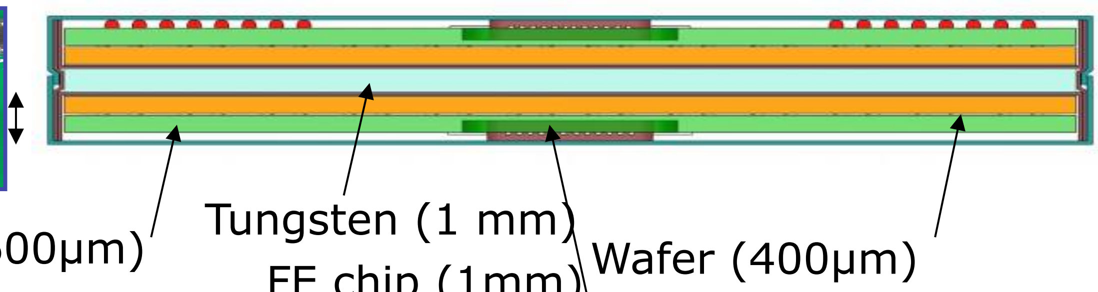
FLC_PHY3 18ch 10*10mm **5mW/ch**



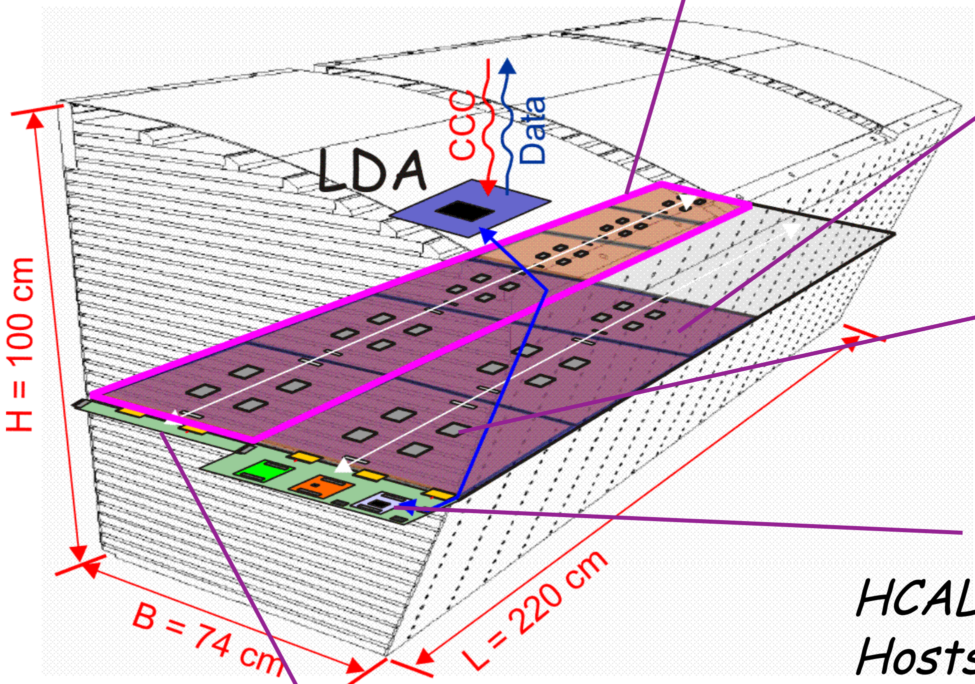
ATLAS LAr FEB 128ch 400*500mm **1 W/ch**

Readout chip integrated in active layer (Si-W ECAL for ILC)





Imbedded electronics (ILC HCAL)



AHCAL Slab
6 HBUs in a row

Front end ASICs embedded
Interfaces accessible

HBU
HCAL Base Unit
12 x 12 tiles

SPIROC
4 on a HBU

Power:
40 µW / channel

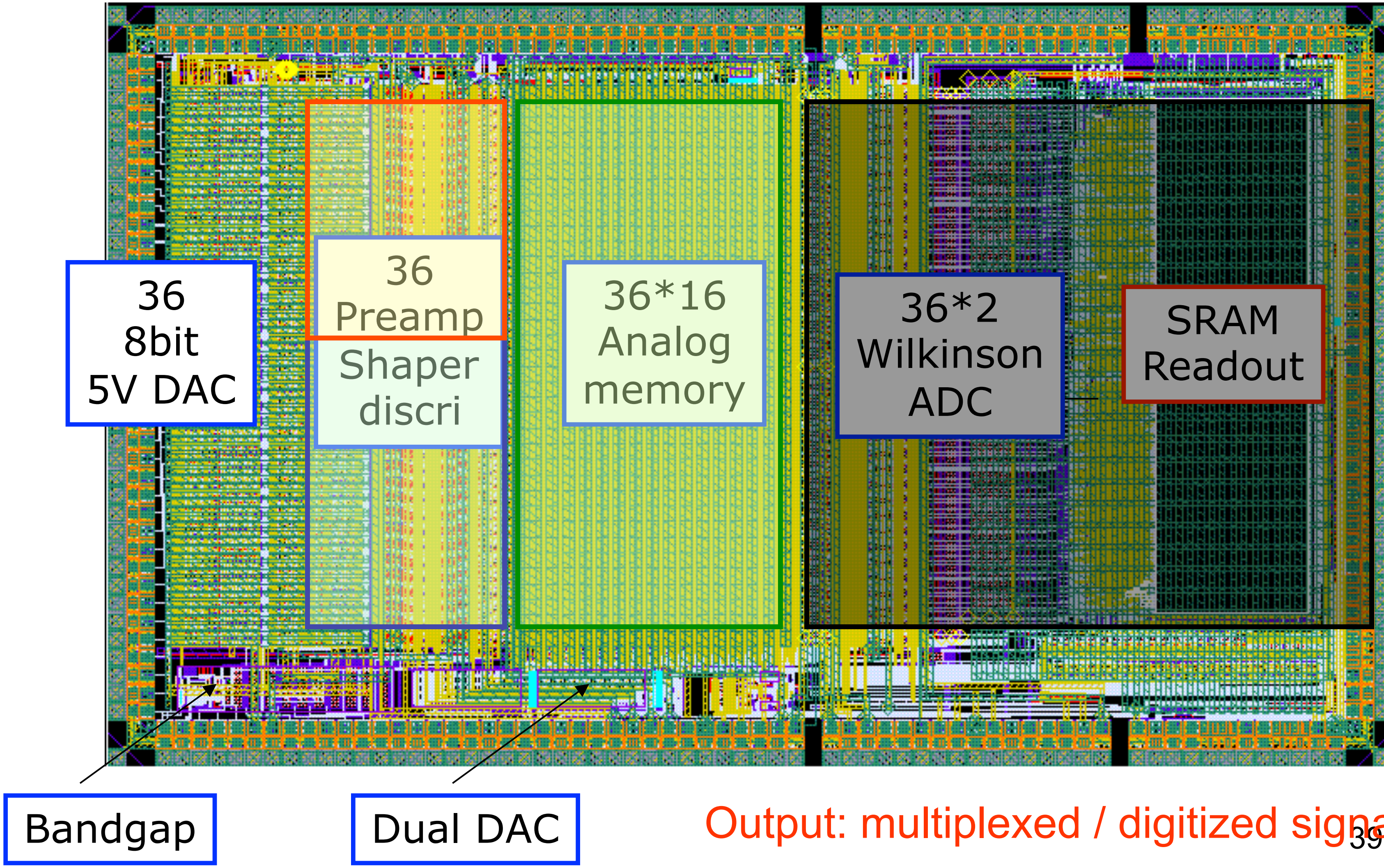
Heat:
T grad. 0.3K/2m
Time constant: 6 d

HEB
HCAL Endcap Board
Hosts mezzanine modules:
DIF, **CALIB** and **POWER**

HLD
HCAL Layer Distributor

More pixels / more functionality

SPIROC layout (CALICE chip for Analog HCAL readout)

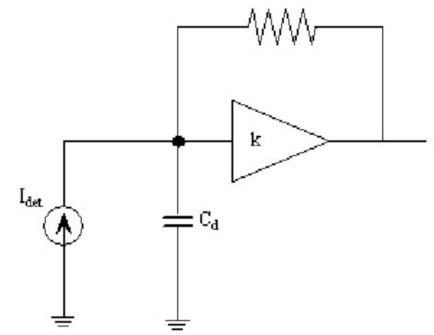


Output: multiplexed / digitized signals

Support material

Current preamplifiers

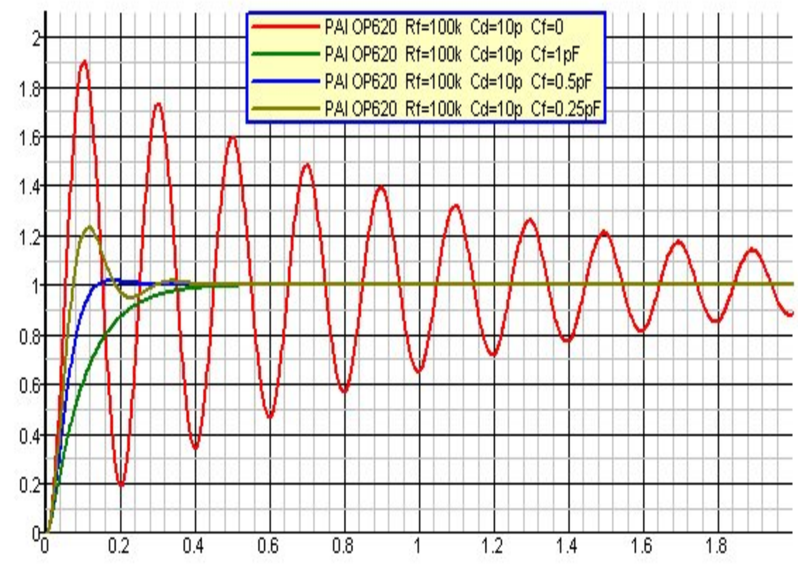
- Transimpedance configuration
  - $V_{out}(\omega)/i_{in}(\omega) = - R_f / (1+Z_f/GZ_d)$
  - Gain = R_f
  - High counting rate
  - Typically optical link receivers



Current sensitive preamp

- Easily oscillatory
  - Unstable with capacitive detector
  - Inductive input impedance

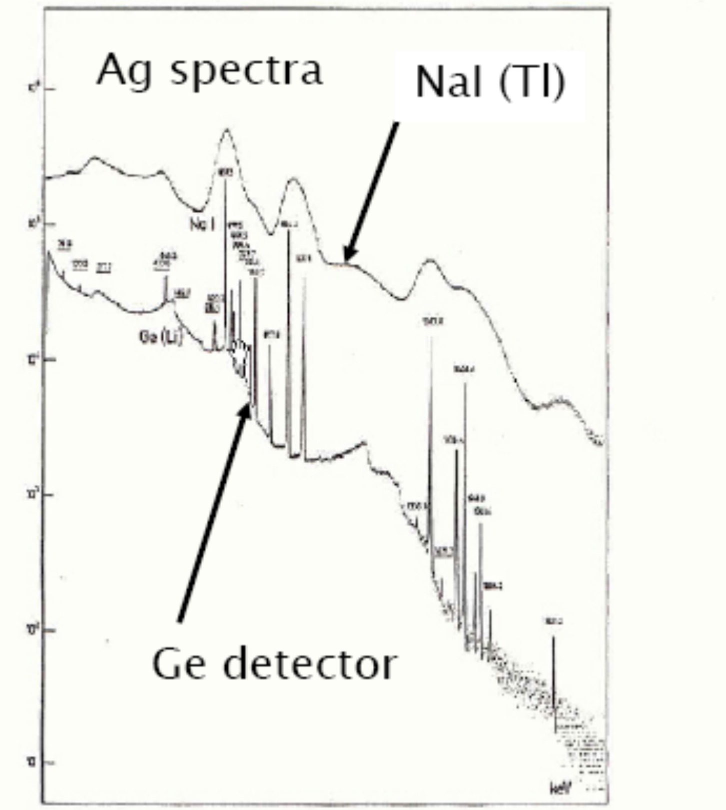
    $L_{eq} = R_f / \omega_C$
  - Resonance at : $f_{res} = 1/2\pi \sqrt{L_{eq} C_d}$
  - Quality factor : $Q = R / \sqrt{L_{eq}/C_d}$
    - $Q > 1/2$ -> ringing
  - Damping with capacitance C_f
    - $C_f = 2 \sqrt{(C_d/R_f G_0 \omega_0)}$
    - Easier with fast amplifiers



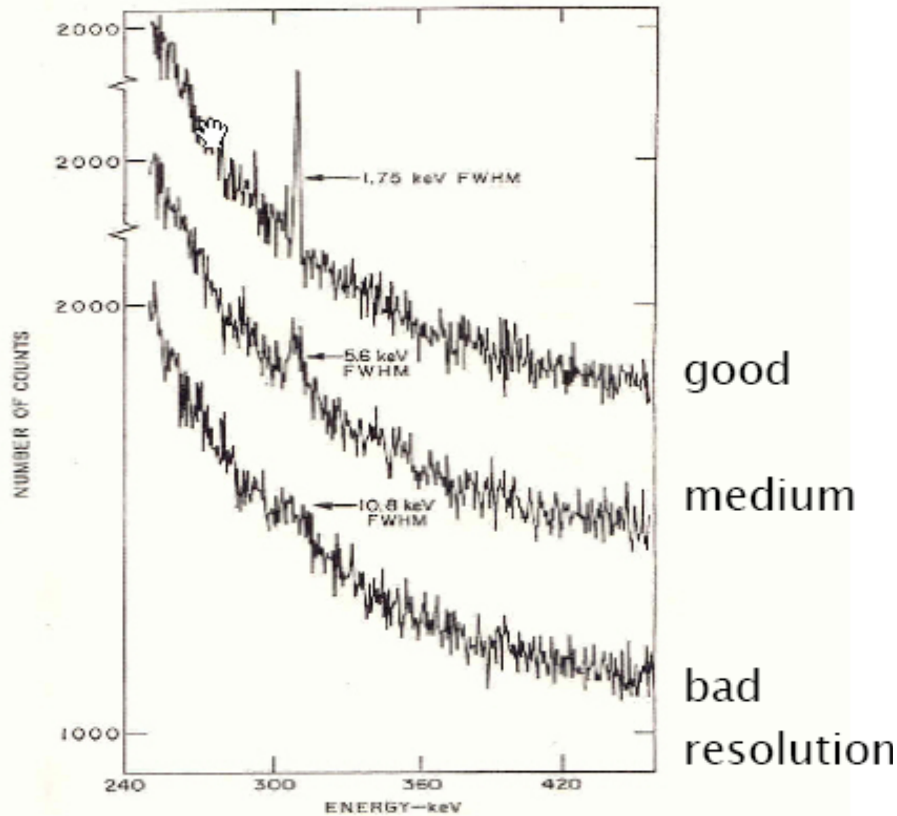
Step response of current sensitive preamp

Resolution and noise

Why bother about resolution and noise?



(J.Cl. Philippot, IEEE Trans. Nucl. Sci. NS-17/3 (1970) 446)



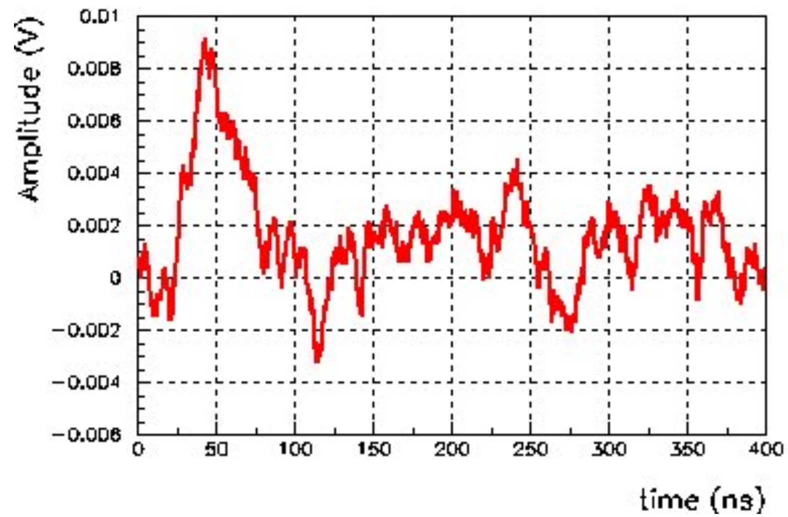
G.A. Armantrout *et al.*, IEEE Trans. Nucl. Sci. NS-19/1 (1972) 107

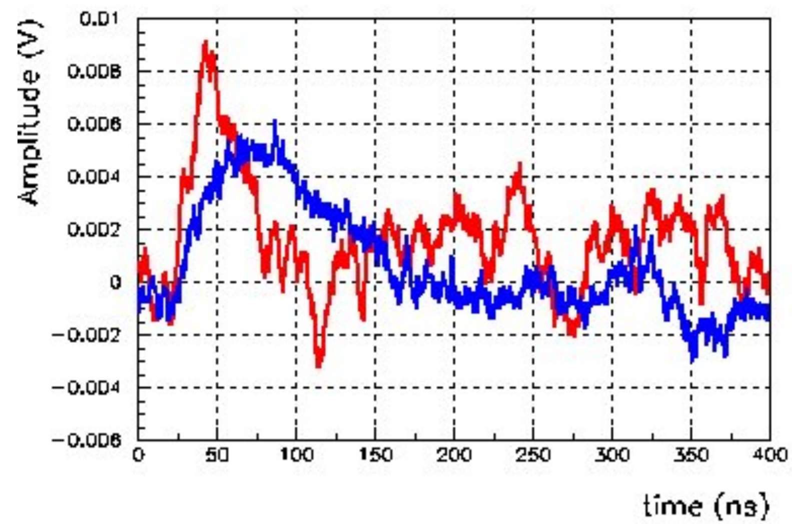
low noise improves the resolution and the ability to distinguish (signal) structures	low noise improves the signal to back-ground ratio (signal counts are in fewer bins and thus compete with fewer background counts)

Electronics noise

- Definition of Noise
  - Random fluctuation superimposed to interesting signal
  - Statistical treatment

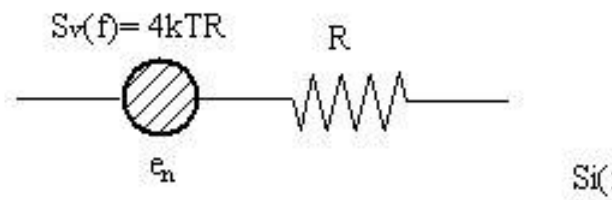
- Three types of noise
  - Fundamental noise (Thermal noise, shot noise)
  - Excess noise (1/f …)
  - Parasitic → EMC/EMI (pickup noise, ground loops…)



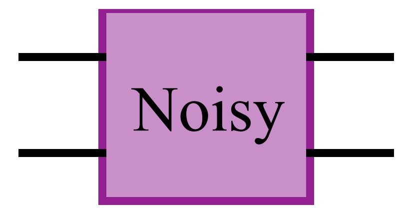


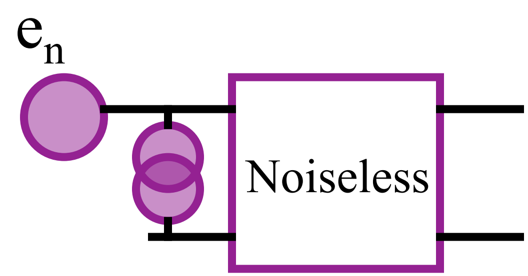
Calculating electronics noise

- Fundamental noise
  - Thermal noise (resistors) : $S_v(f) = 4kTR$
  - Shot noise (junctions) : $S_i(f) = 2qI$



- Noise referred to the input
  - All noise generators can be referred to the input as 2 noise generators :
  - A voltage one e_n in series : series noise
  - A current one i_n in parallel : parallel noise
  - Two generators : no more, no less…





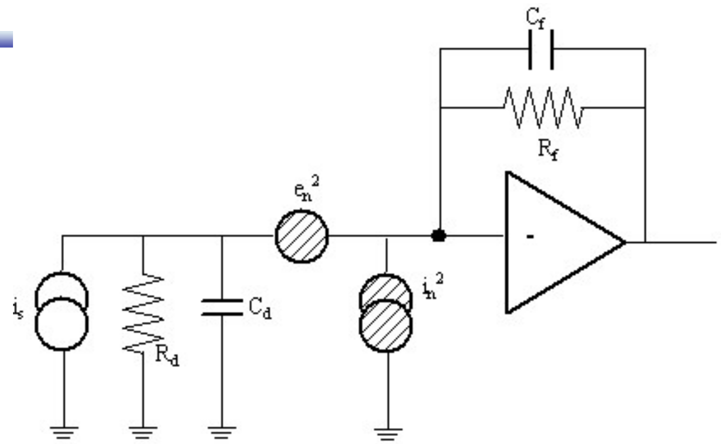
- **To take into account the Source impedance**

Noise generators referred to the input

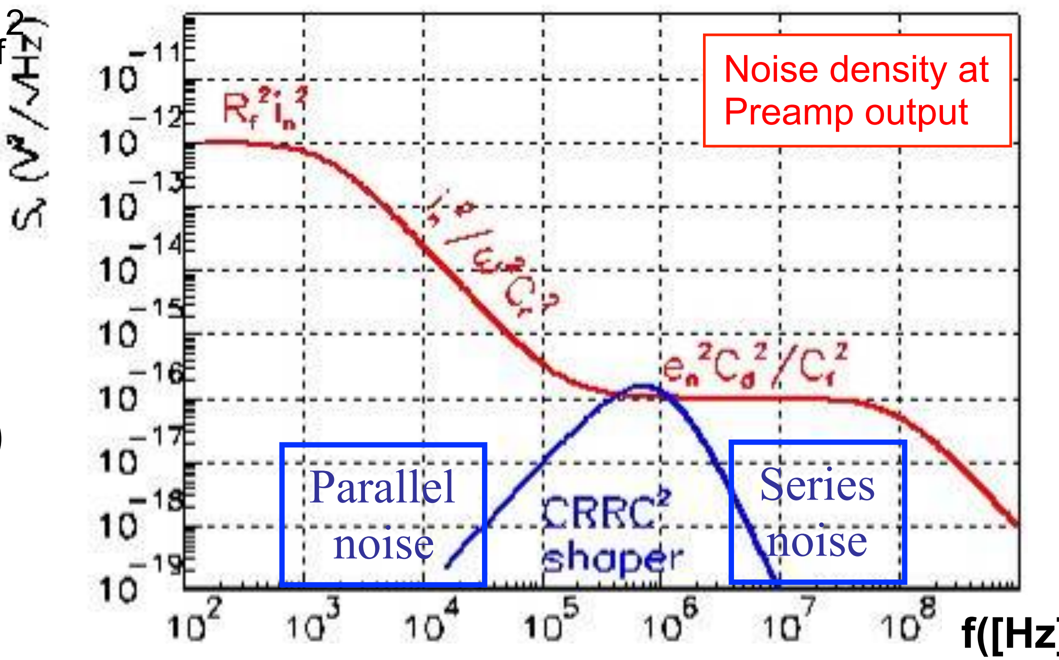
- **Golden rule**
  - **Always calculate the signal before the noise what counts is the signal to noise ratio**

Noise in charge pre-amplifiers

- 2 noise generators at the input
  - Parallel noise : (i_n^2) (leakage currents)
  - Series noise : (e_n^2) (preamp)
- Output noise spectral density :
  - $S_v(\omega) = (i_n^2 + e_n^2/|Z_d|^2) / \omega^2 C_f^2$
    $= i_n^2 /\omega^2 C_f^2 + e_n^2 C_d^2/C_f^2$
  - Parallel noise in $1/\omega^2$
  - Series noise is flat, with a « noise gain » of C_d/C_f
- *rms* noise V_n
  - $V_n^2 = \int Sv(\omega)\, d\omega/2\pi \rightarrow \infty$ (!)
  - Benefit of shaping…



Noise generators in charge preamp



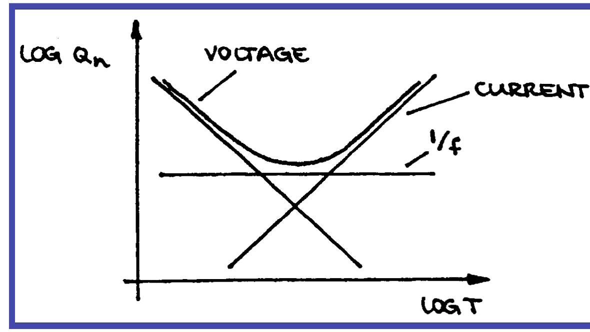
Equivalent Noise Charge (ENC)

Two basic noise mechanisms: input noise current i_n [pA/√Hz]
input noise voltage e_n [nV/√Hz]

Equivalent Noise Charge:

$$Q_n^2 = i_n^2 \, T_s \, F_i + C_i^2 \, v_n^2 \, \frac{F_v}{T_s}$$

from Front End
from Shaper



where T_s = characteristic shaping time (*e.g.* peaking time)
F_i, F_e "Form Factors" that are determined by the shape of the pulse (calculated in the frequency or time domain)
C_i = total capacitance at the input node (detector capacitance + input capacitance of preamplifier + stray capacitance + …)

➔ Current noise contribution increases with *T*
➔ Voltage noise contribution decreases with increasing *T*
only for "white" voltage & current noise sources + capacitive load
"1/*f* " voltage noise contribution constant in *T*

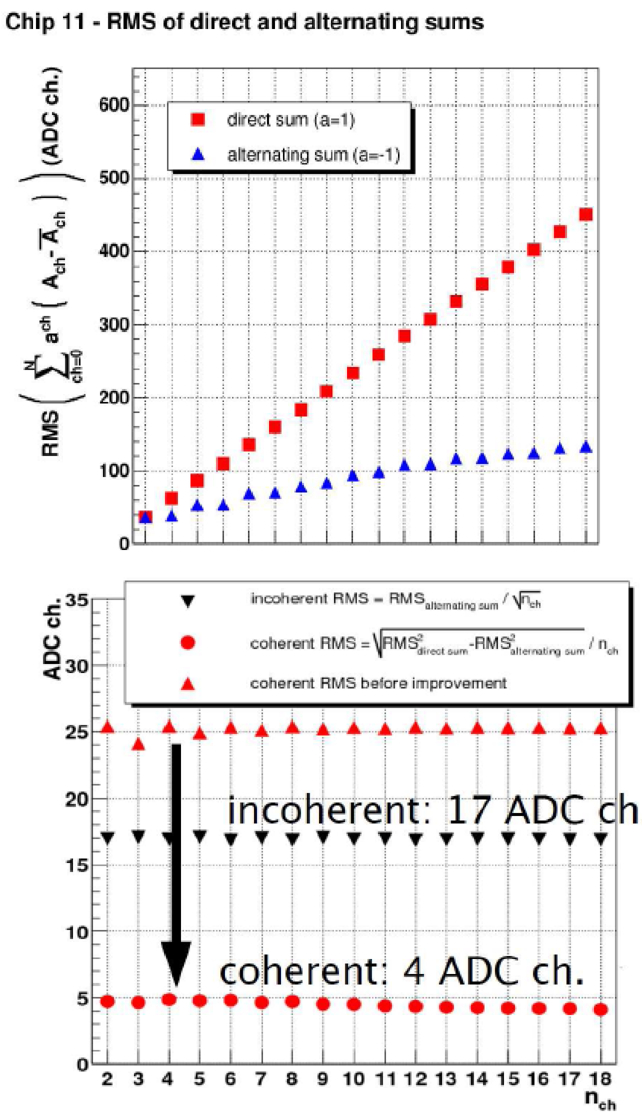
Coherent noise in a multi-channel system

Coherent noise problem :

- Noise adds linearly instead of quadritically
- Particularly sensitive in calorimetry as sums are performed to reconstruct jets or E_t^{miss}
- $\Sigma \ a_i^2 = n \ \sigma^2_{incoh} + n^2 \sigma^2_{coh}$ (i=channels)

Coherent noise estimation

- Perform Direct and Alternate sums to extract coherent noise
- $SD^2 = \Sigma \ a_i^2$
- $SA^2 = \Sigma \ (-1)^i \ a_i^2$
- $SA^2 = n \ \sigma^2_{incoh}$
- Incoherent & coherent noise :
  - $\sigma^2_{incoh} = SA^2/n$
  - $\sigma^2_{coh} = (SD^2-SA^2)/n^2$



Usually σ_{coh} / σ_{incoh} <~ 20 %