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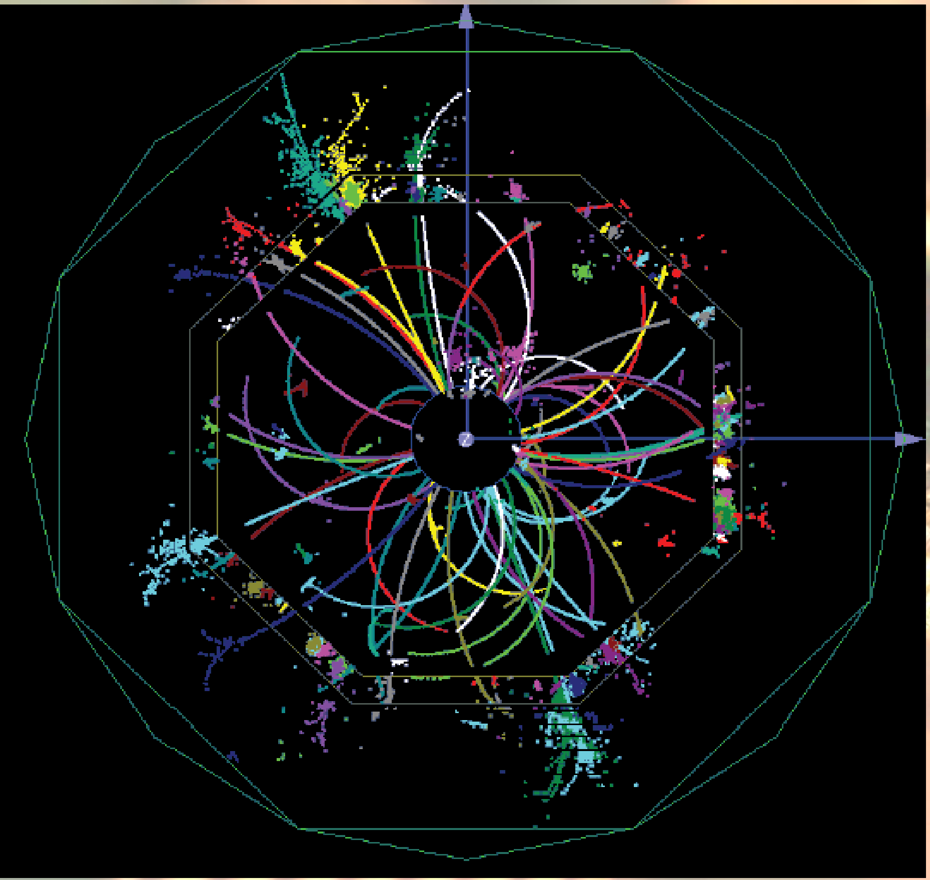

Front-End electronics in particle physics

EDIT school 2020

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Outline

1. Low noise charge preamps : pixel readout
2. Large dynamic range : calorimeters
3. High speed designs : sipm readout
4. Trends and future

Lectures for physicists, not electronics engineers => will concentrate on front-end and performance of detector, not on detailed engineering

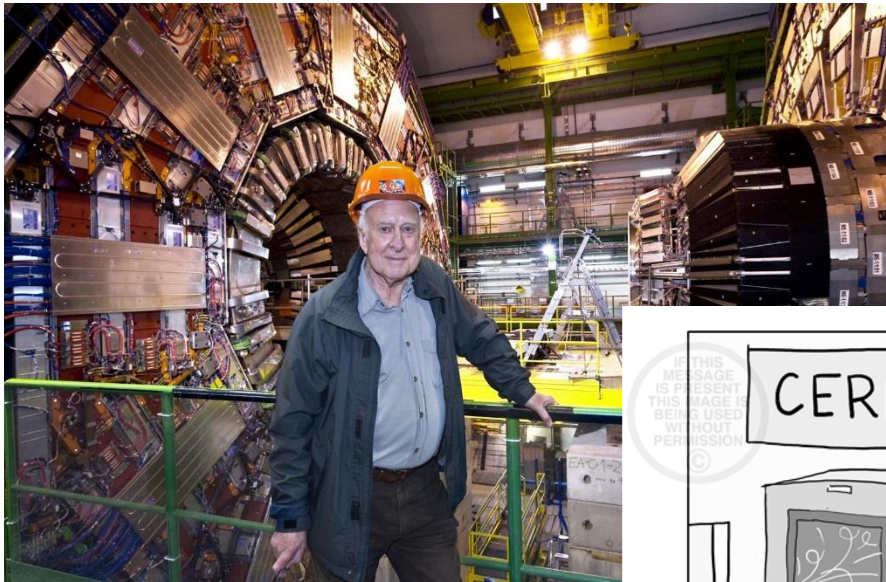
Many more slides than allocated time : don't be afraid !

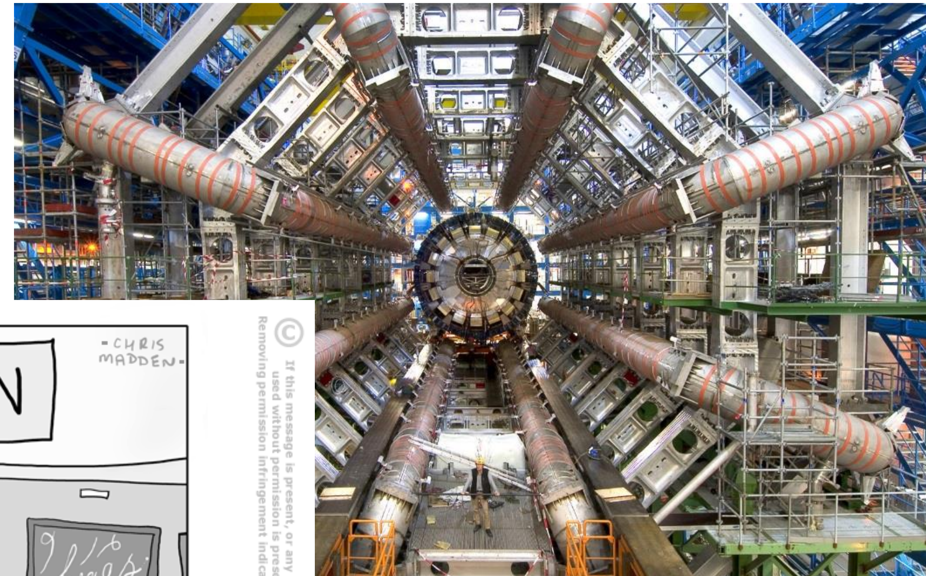
I will skip many details : they are for further reference

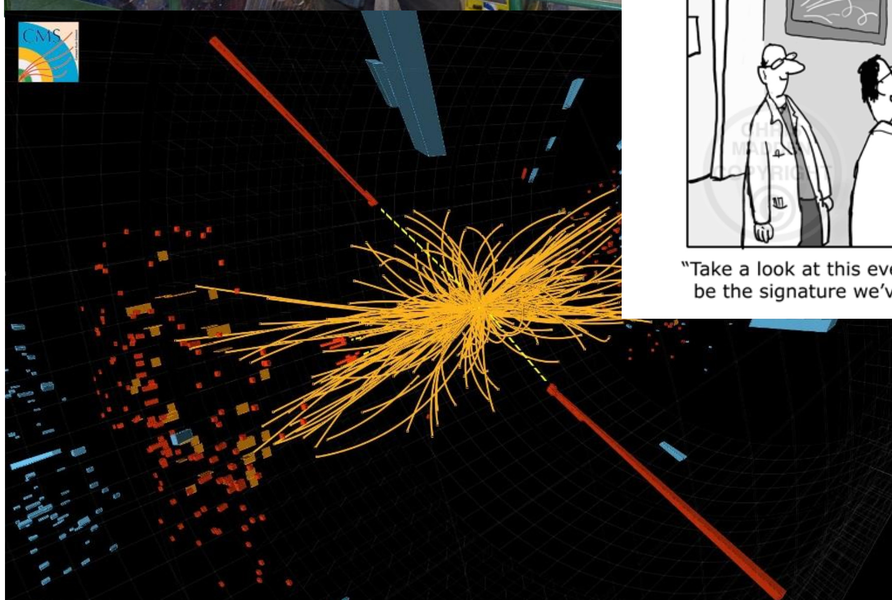
No prerequisites needed (apart from U = Z*I)

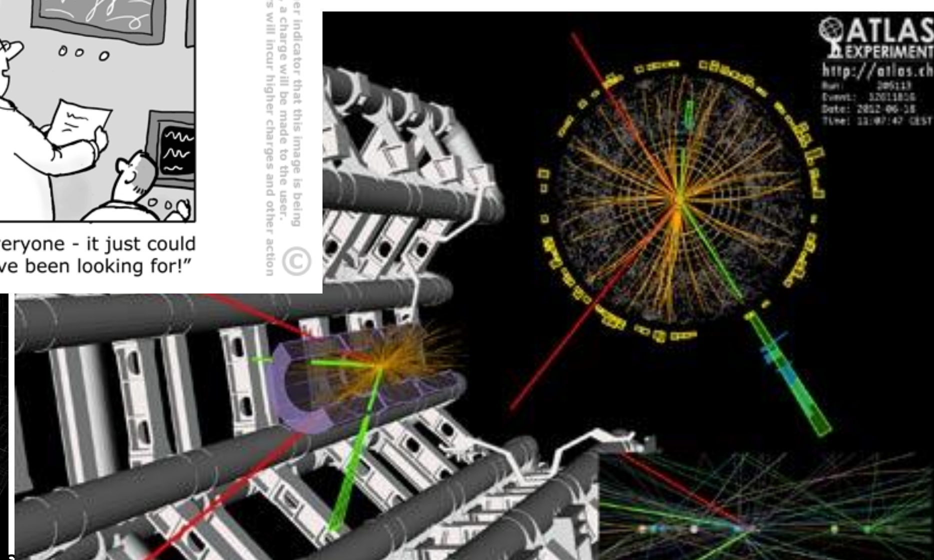
Electronics in experiments

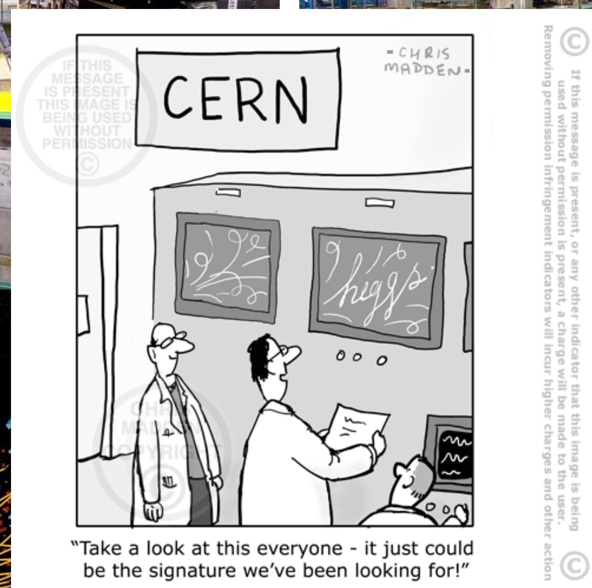
- A lot of electronics in the experiments…which impacts the detectors





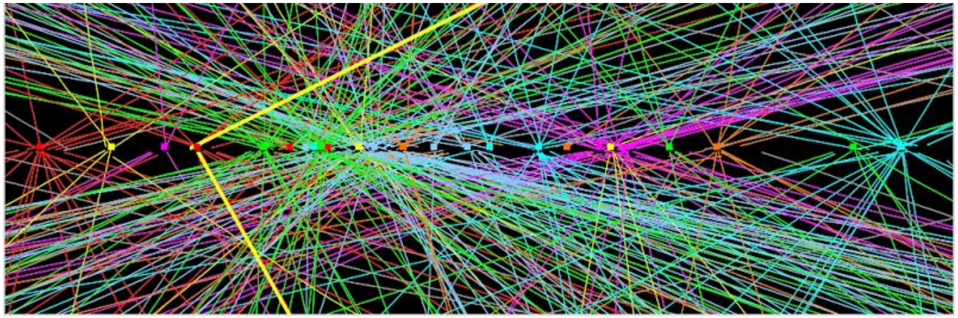


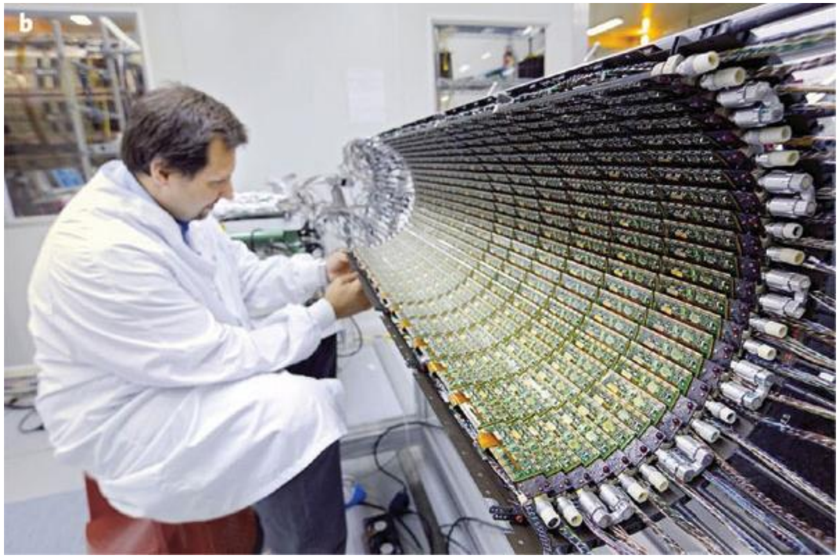


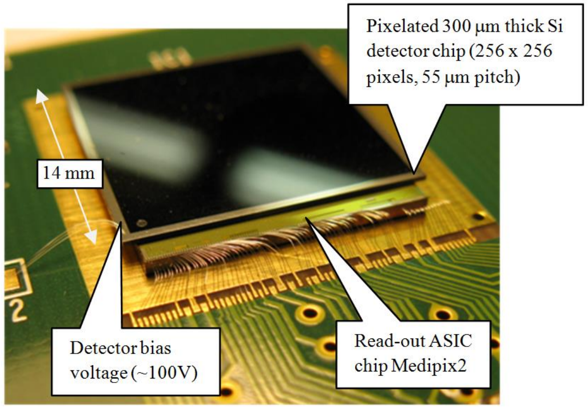


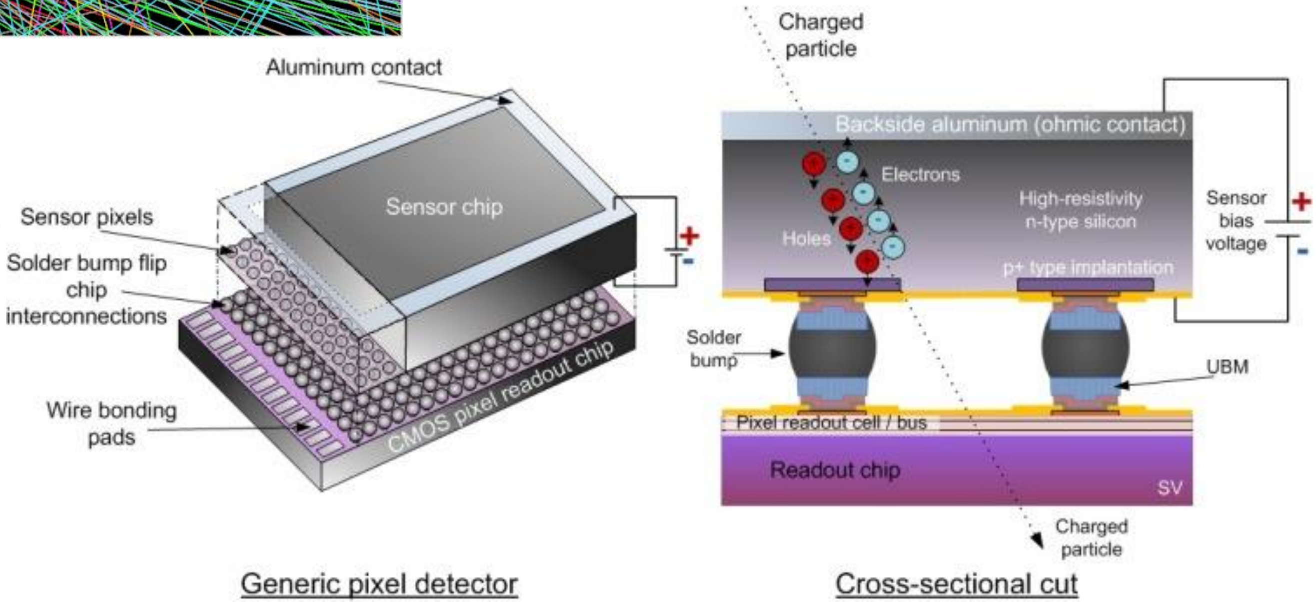
Electronics enabling new detectors : trackers

- Measurement of (charged) particle tracks
  - millions of pixels (~100 µm)
  - binary readout at 40 MHz
  - High radiation levels
  - Made possible by ASICs



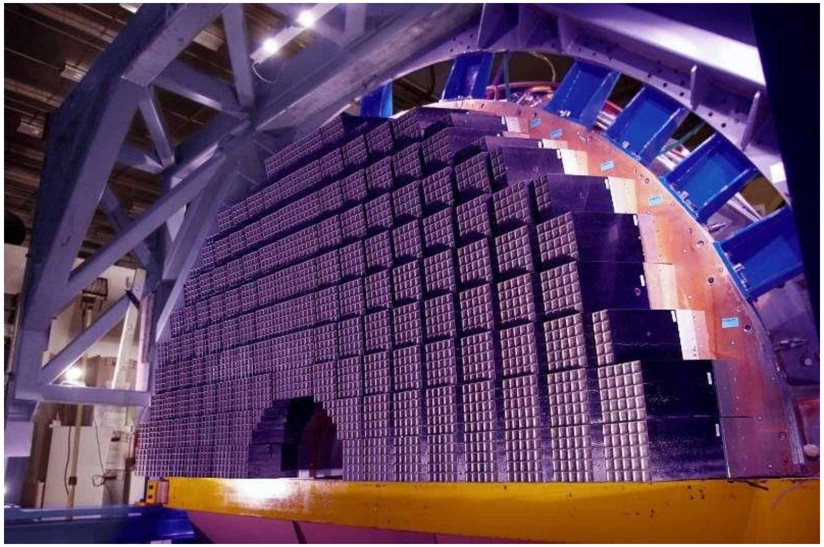




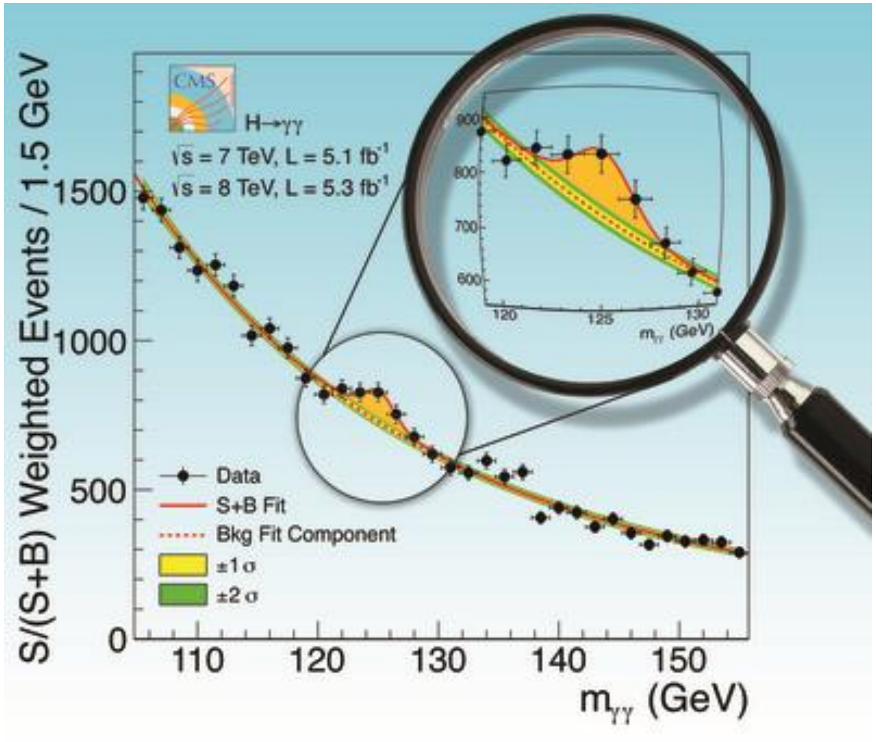


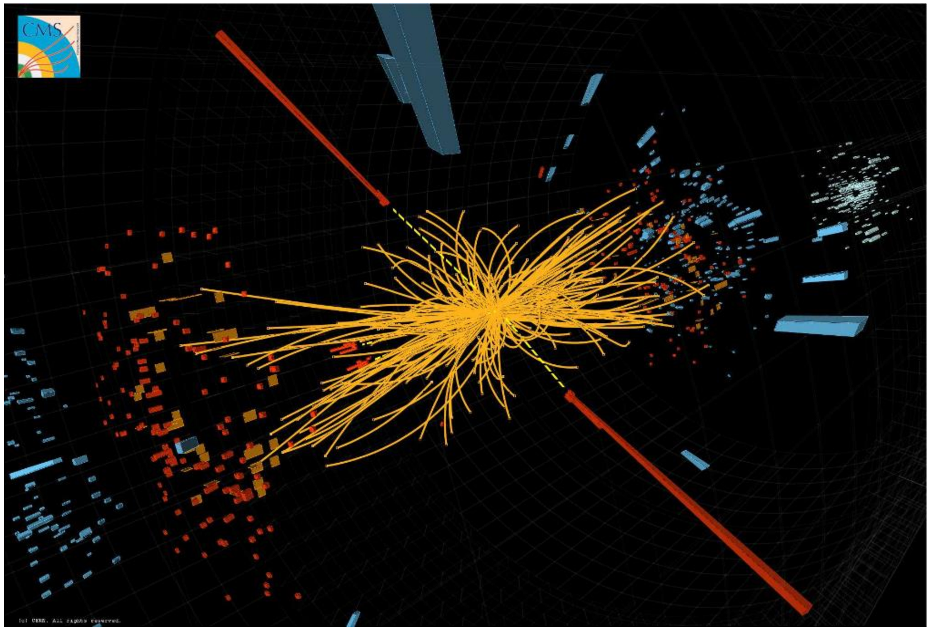
Importance of electronics : calorimeters

- Large dynamic range (10^4-10^5)
- High Precision ~1%
  - Importance of low noise, uniformity, linearity…
  - Importance of calibration



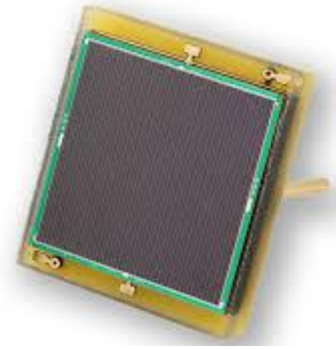
H -> γ γ in CMS calorimeter

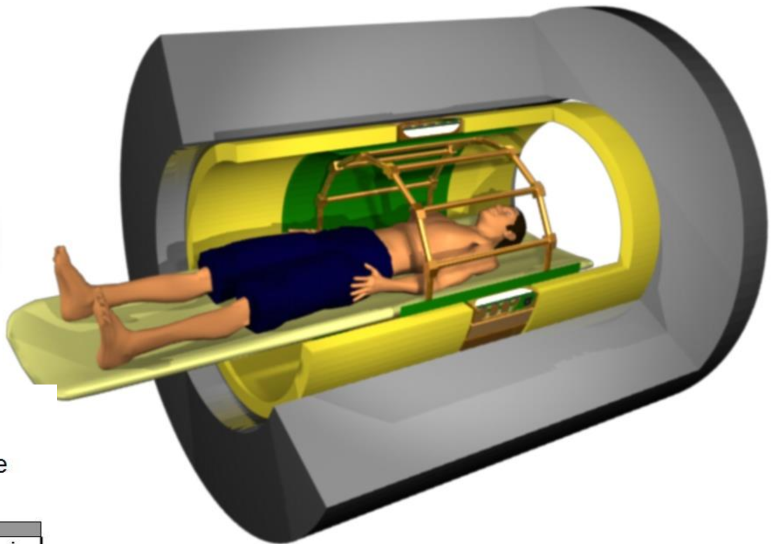


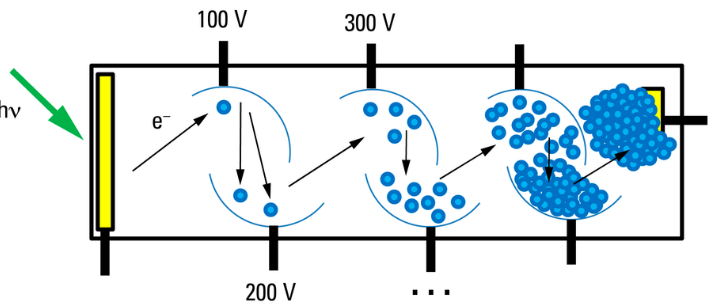


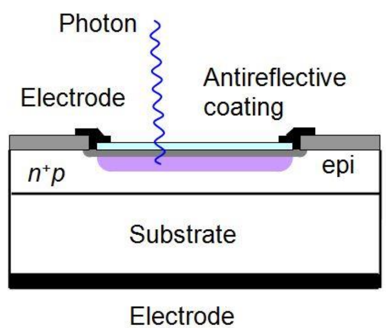
Single photon sensors & timing information

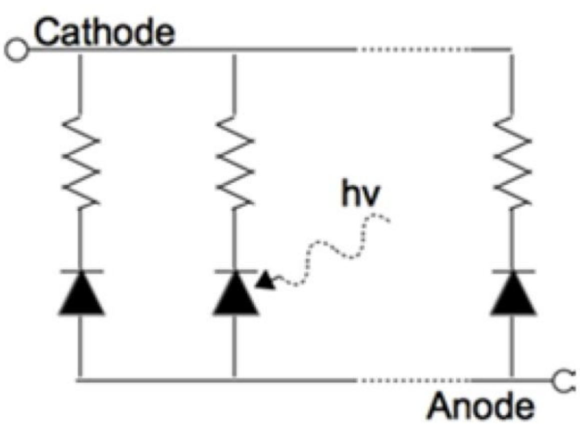
- Photomultipliers, silicon photomultipliers

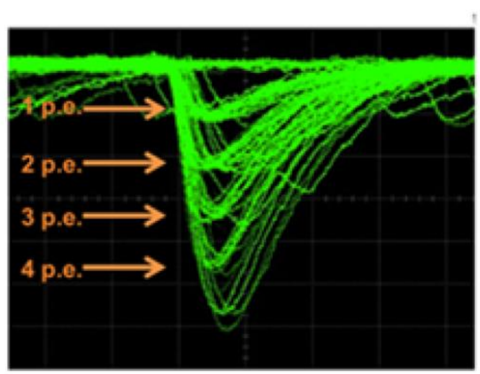


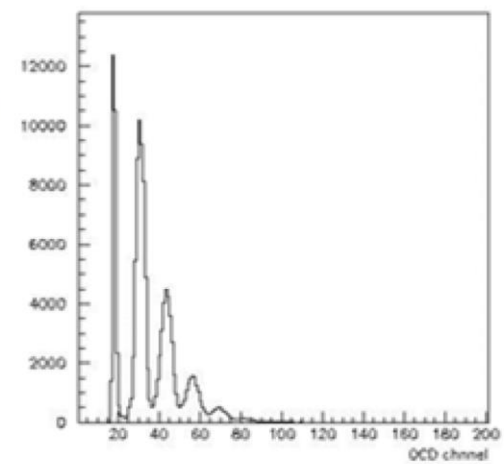






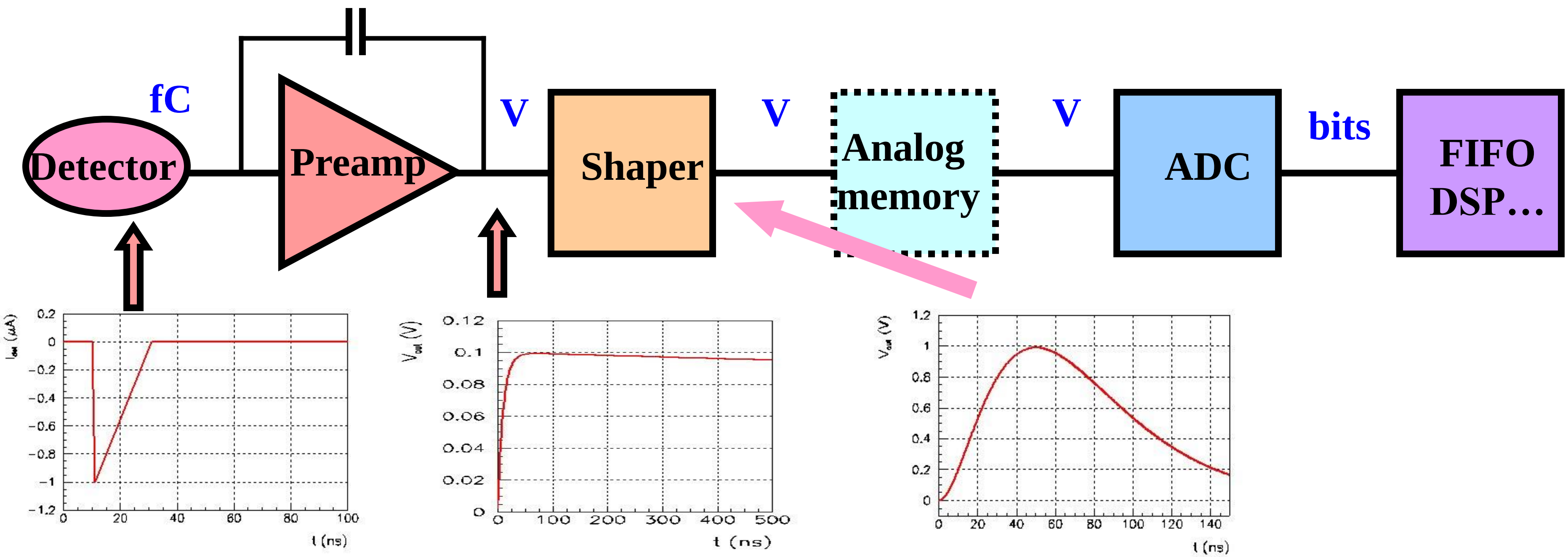






Overview of readout electronics

- Most front-ends follow a similar architecture



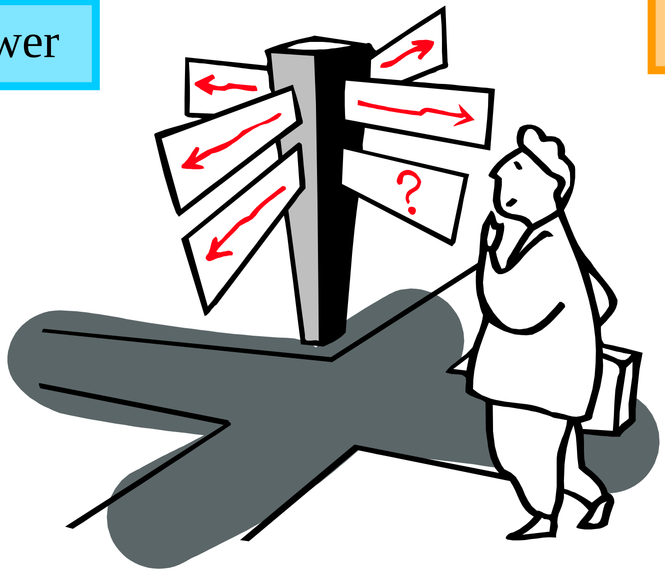
- Very small signals (fC) -> need amplification
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Several thousands to millions of channels
- Trends : high speed, low power

Ωmega

Low noise

Low power

High speed



Large dynamic range

High reliability

Radiation hardness

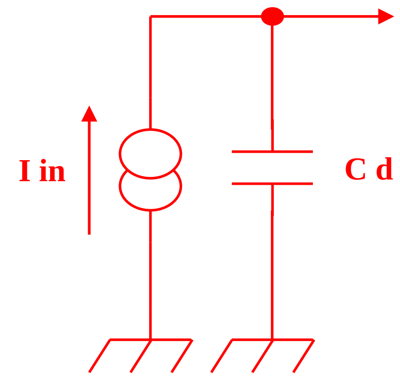
<u>Low cost !</u>

<u>(and even less)</u>

Low material

Detector modelization

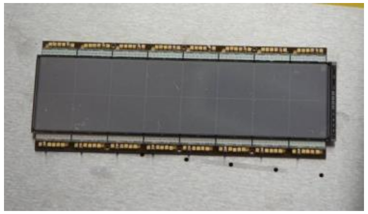
- Detector = capacitance Cd
  - Pixels/strips : 0.1-10 pF
  - PMs/SiPMs : 3-300 pF
  - Ionization chambers 10-1000 pF
  - Sometimes effect of transmission line



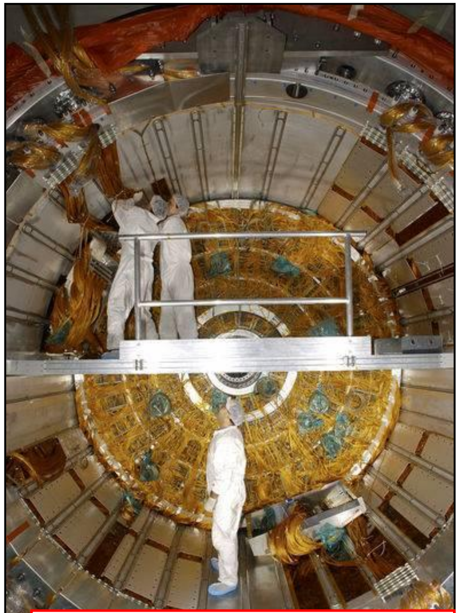
Detector modeilization

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

- Missing :
  - High Voltage bias
  - Connections, grounding
  - Neighbours
  - Calibration…



CMS pixel module



ATLAS LAr calorimeter

Vacuum Photomultipliers

$G = 10^5 - 10^7$

Cd ~ 10 pF

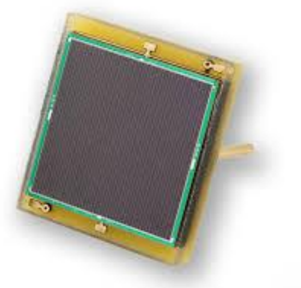
L ~ 10 nH

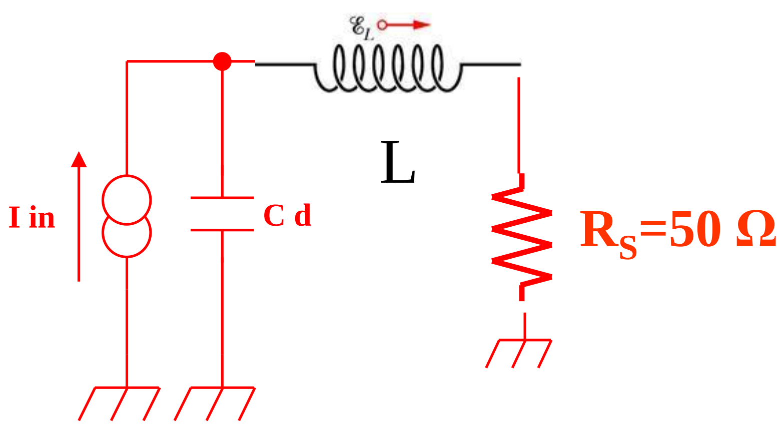
Silicon Photomultipliers

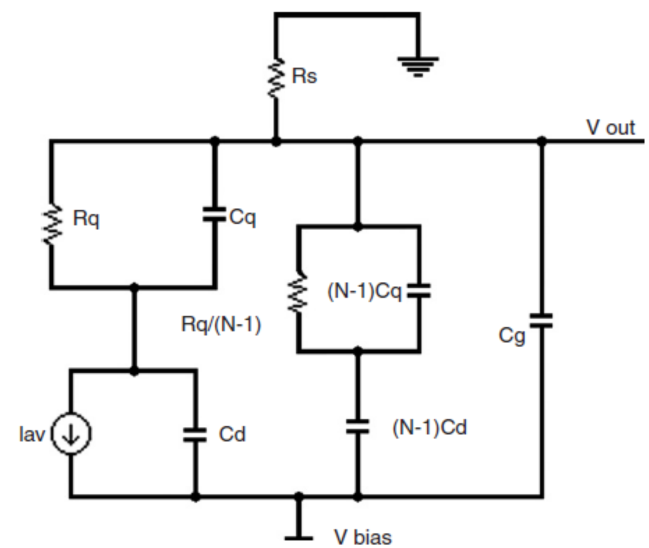
$G = 10^5 - 10^7$

C = 10 - 400 pF

L = 1 – 10 nH







Optimizing signal shape for timing

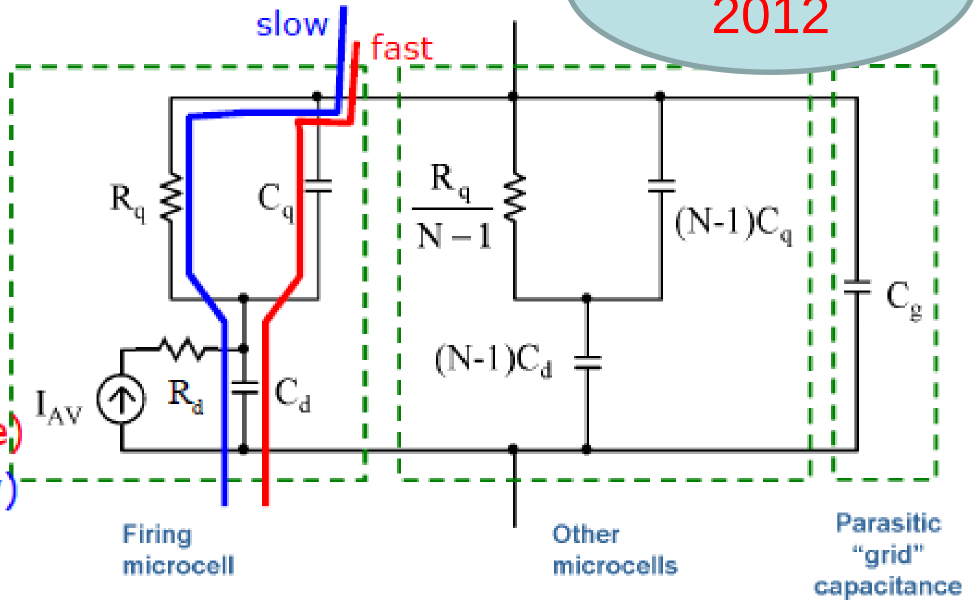
Collazuol 2012

Single cell model → $(R_d||C_d)+(R_q||C_q)$

SiPM + load → $(||Z_{cell})||C_{grid} + Z_{load}$

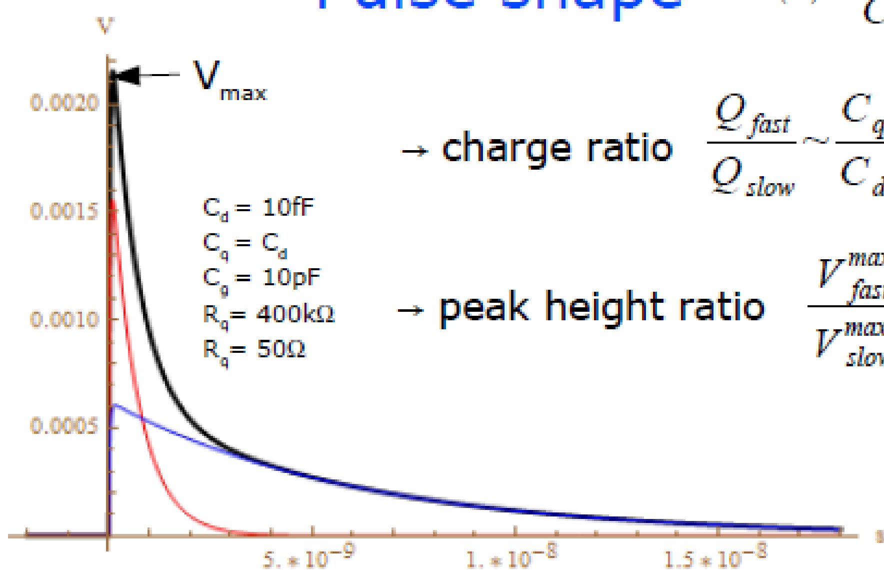
Signal = slow pulse ($\tau_{d\,(rise)}, \tau_{q\text{-}slow\,(fall)}$) +
+ fast pulse ($\tau_{d\,(rise)}, \tau_{q\text{-}fast\,(fall)}$)

- $\tau_{d\,(rise)} \sim R_d(C_q+C_d)$
- $\tau_{q\text{-}fast\,(fall)} = R_{load}\ C_{tot}$ (fast; parasitic spike)
- $\tau_{q\text{-}slow\,(fall)} = R_q\,(C_q+C_d)$ (slow; cell recovery)



Pulse shape

$$V(t) \simeq \frac{Q}{C_q+C_d}\left(\frac{C_q}{C_{tot}} e^{\frac{-t}{\tau_{FAST}}} + \frac{R_{load}}{R_q}\frac{C_d}{C_q+C_d} e^{\frac{-t}{\tau_{SLOW}}}\right)$$



→ charge ratio $\frac{Q_{fast}}{Q_{slow}} \sim \frac{C_q}{C_d}$

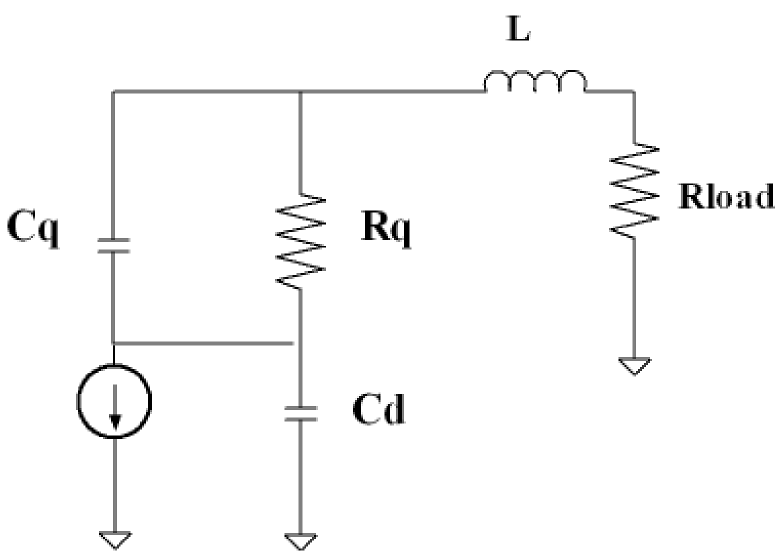
→ peak height ratio $\frac{V_{fast}^{max}}{V_{slow}^{max}} \sim \frac{C_q^2 R_q}{C_d C_{tot} R_{load}}$

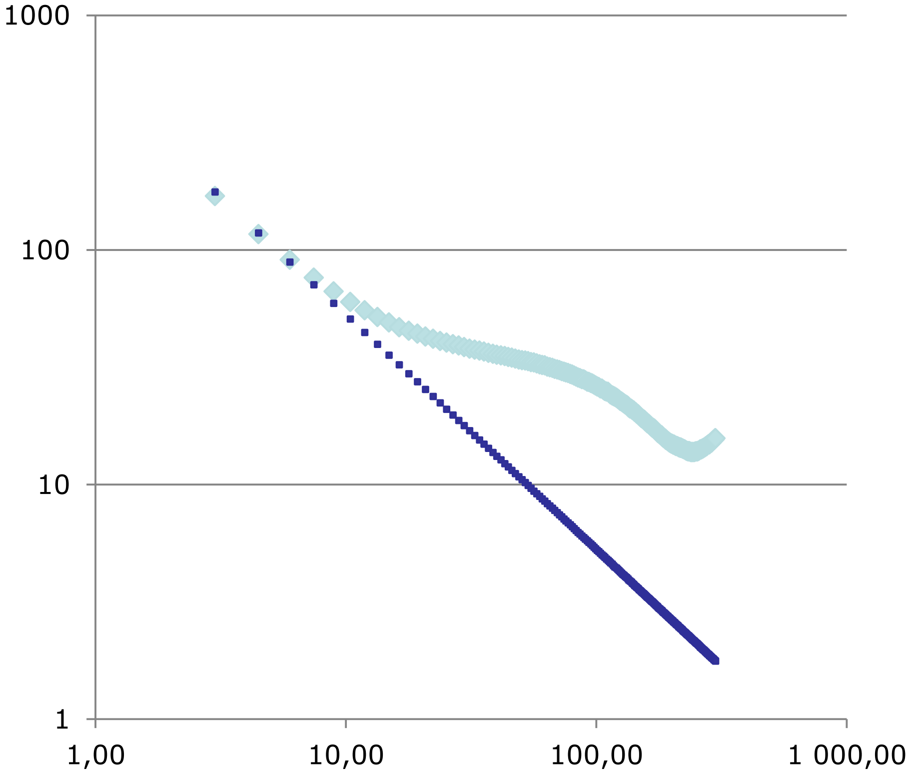
increasing with Rq and $1/R_{load}$
(and Cq of course)

Increasing C_q/C_d or/and R_q/R_{load}
→ spike enhancement
→ better timing

G.Collazuol - PhotoDet 2012

- RLC too simple, inaccurate at high frequency
- CdRqCqLR OK
  - May better explain HF noise behaviour

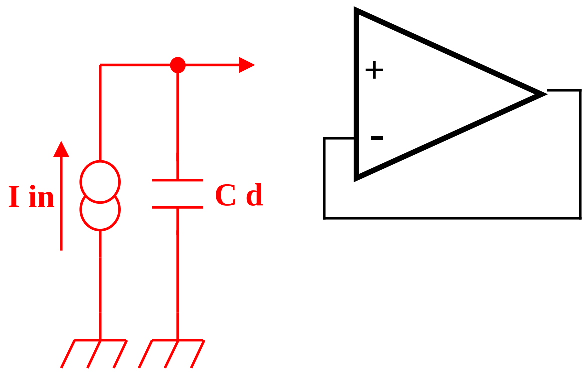




Measured impedance
MPPC HPK 3x3 mm
Line : C = 320 pF

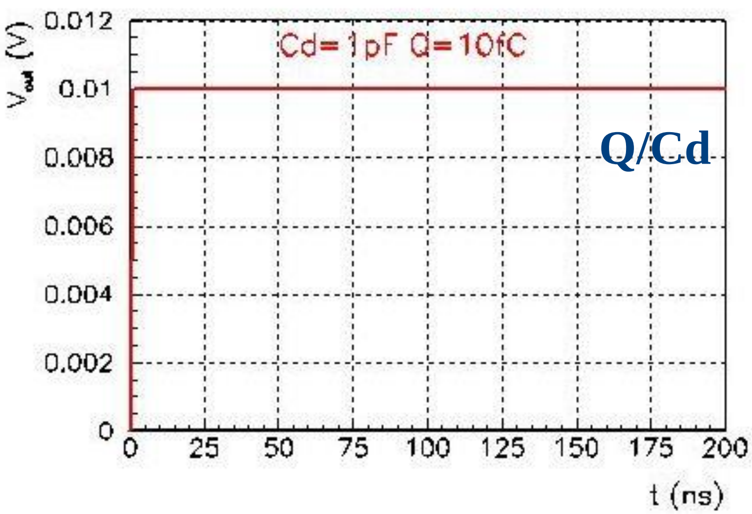
Reading the signal

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



- Integrating on Cd
  - 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-linearities
  - crosstalk
  - Need to empty Cd…

Voltage readout

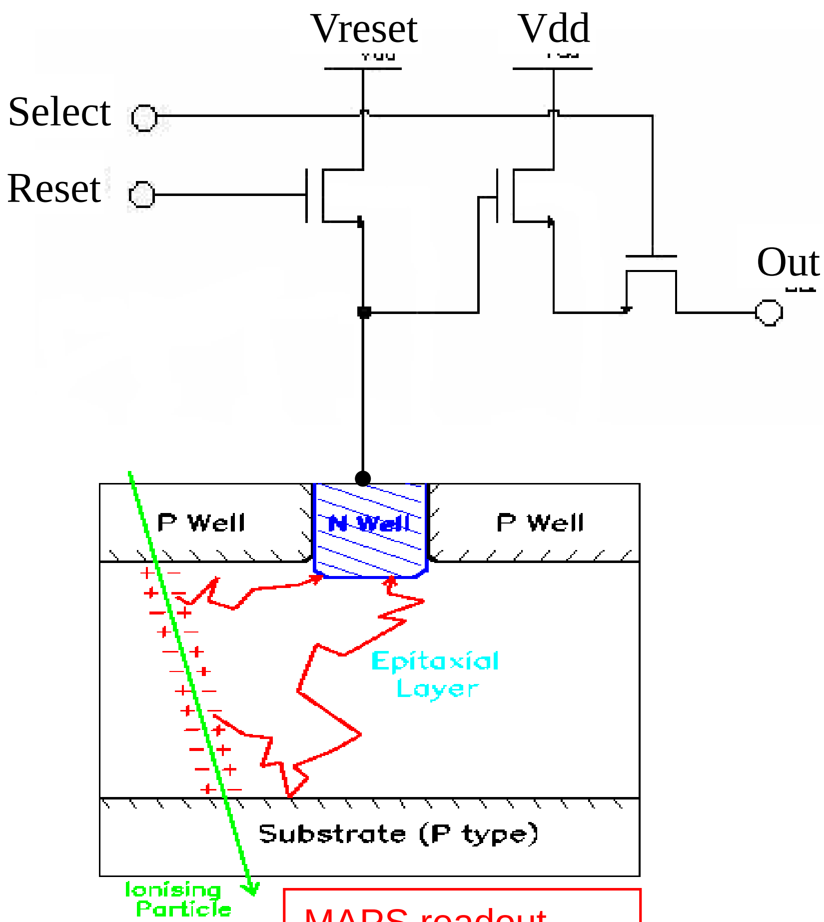


Impulse response

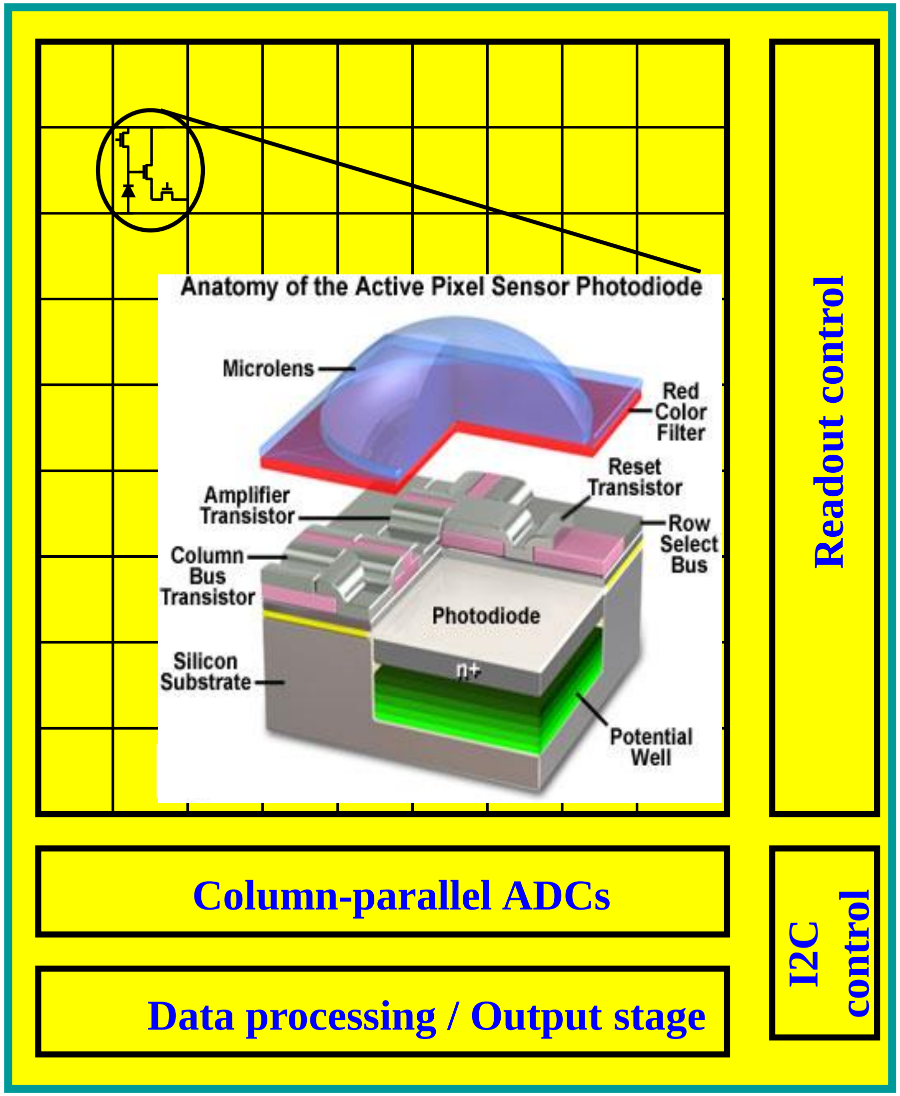
Example : Monolithic active pixels

© R Turchetta RAL

- Epitaxial layer forms sensitive volume (2-20μm)
- Charge collection by diffusion
- Read ~100 e- on Cd~10fF = few mV

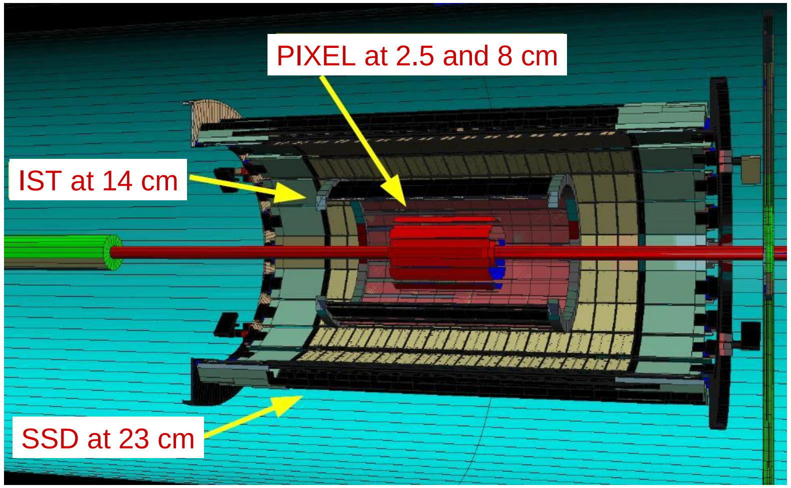


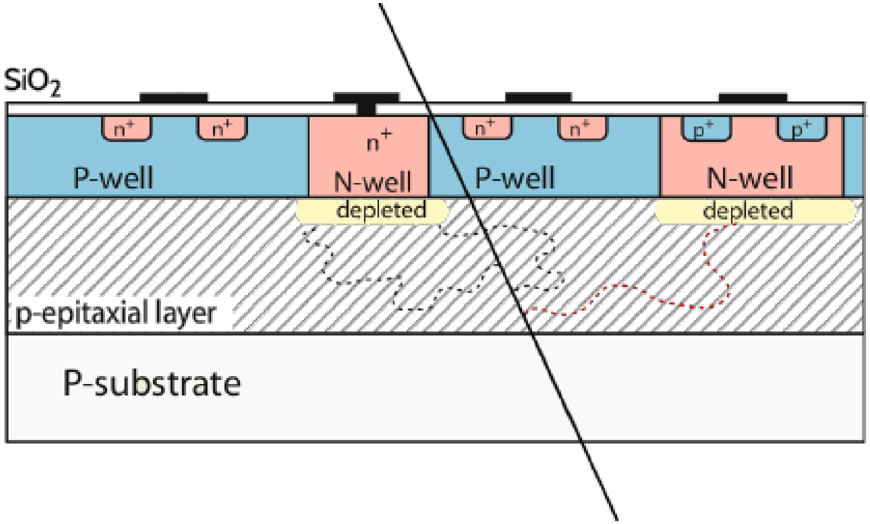
MAPS readout

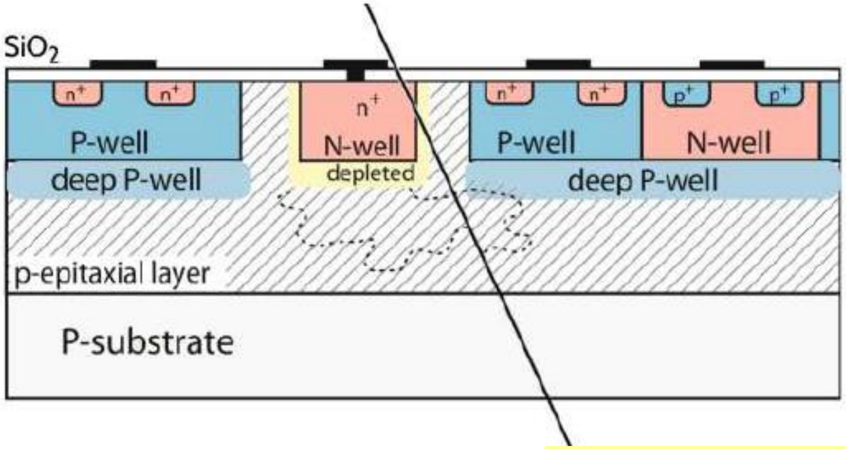


- MIMOSTAR [ÏPHC strasbourg et al.]
  - First use in HEP : STAR detector 2014
  - 2 cm² ASIC with21x21 um pixels

- ALPIDE for ALICE upgrade [CERN et al.]
  - Several process and design improvements
  - Deep pwell to allow CMOS
  - In-pixel preamp and comparator
  - P = 40 nW/pixel (5 mW/cm²)

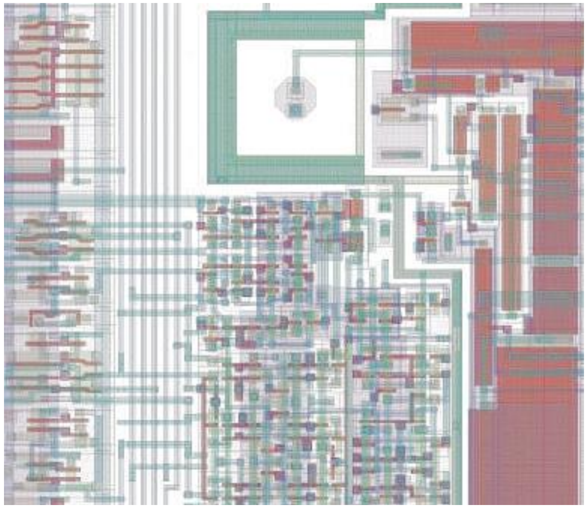


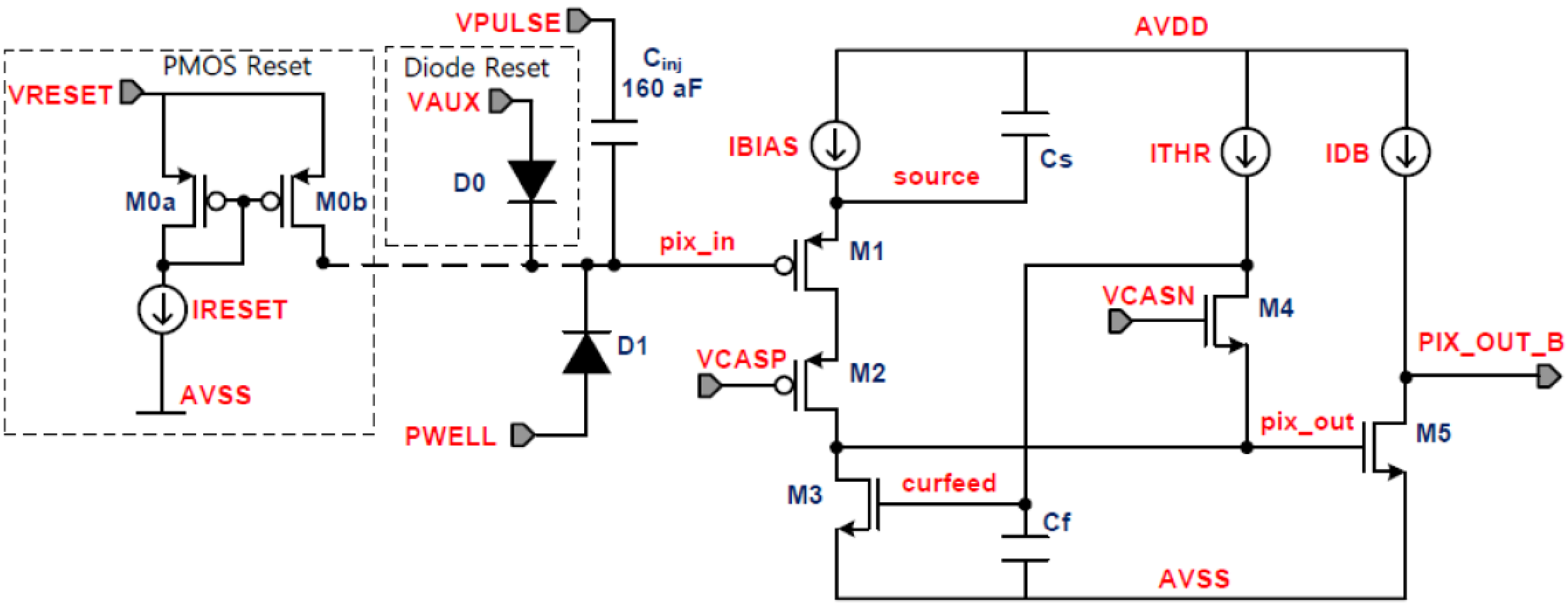




ALPIDE preamplifier

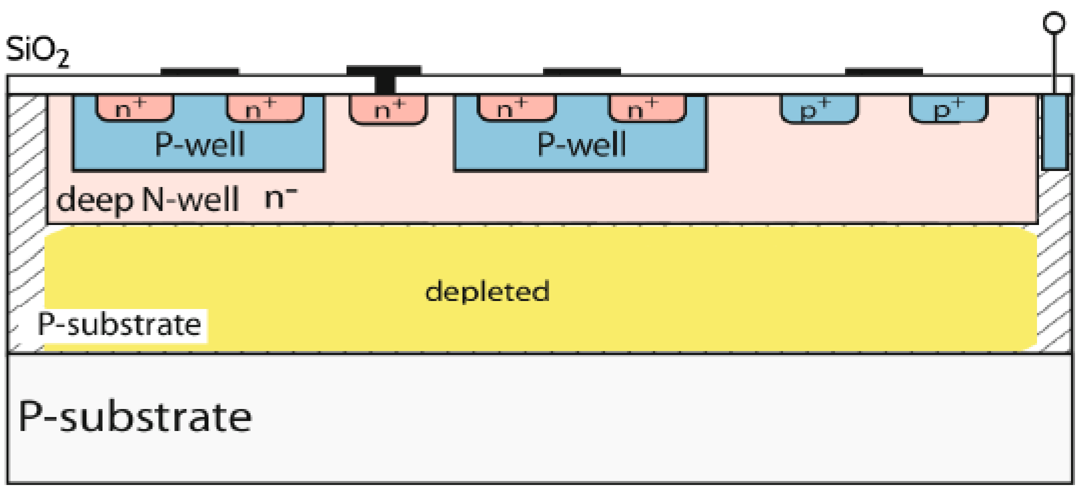
- Far from the 3T design…





Evolution of MAPs

- Going to HV-MAPS [I. Peric U. Bonn]
  - HV CMOS process => partial/full sensor depletion
  - Collection by drift and not diffustion => fast signal ~ns
  - Better radiation tolerance
  - Nanosecond timing capability
  - Proposed for ATLAS upgrade and μ3e

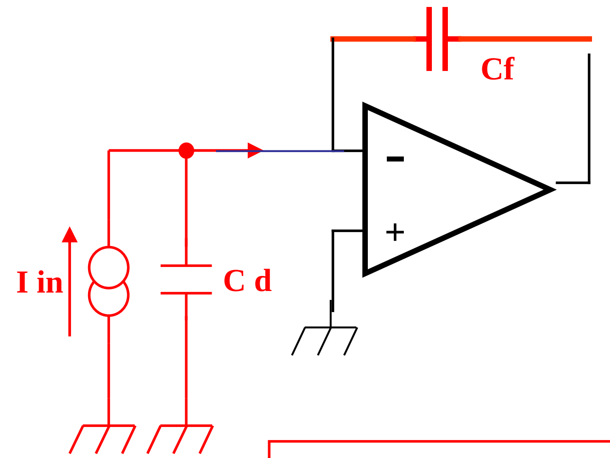


Ideal charge preamplifier

- ideal opamp in transimpedance ($C_f << C_d$)
  - Shunt-shunt feedback : low Z_{in}, low Z_{out}
    - $i_{in}(\omega) = j\omega C_d V_{in}(\omega) + j\omega\, C_f\, (V_{in}(\omega) - V_{out}(\omega))$
    - $V_{out}(\omega) = -\,G\, V_{in}\omega)$ (opamp gain)
  - => $V_{out}(\omega)/i_{in}(\omega) = -\,1/j\omega C_f\,(1 + C_d\,/\,GC_f)$
  - Ideal opamp : $G \to \infty$
  - $V_{out}(\omega)/i_{in}(\omega) = -\,1/j\omega C_f$
  - Integrator : $v_{out}(t) = -1/C_f \int i_{in}(t)dt$

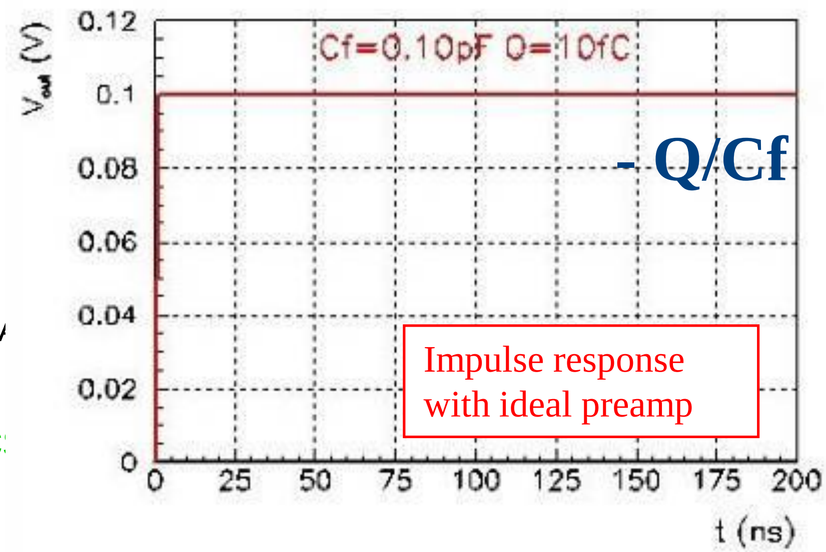
$$v_{out}(t) = -\,Q/C_f$$

  - « Gain » : $1/C_f$: 0.1 pF -> 10 mV/fC
  - C_f determined by maximum signal



Charge sensitive preamp

- Integration on Cf
  - Simple : $V = -\,Q/C_f$
  - Unsensitive to preamp capacitance C_{PA}
  - Turns a short signal into a long one
  - The front-end of 90% of particle physic
  - But always built with custom circuits…

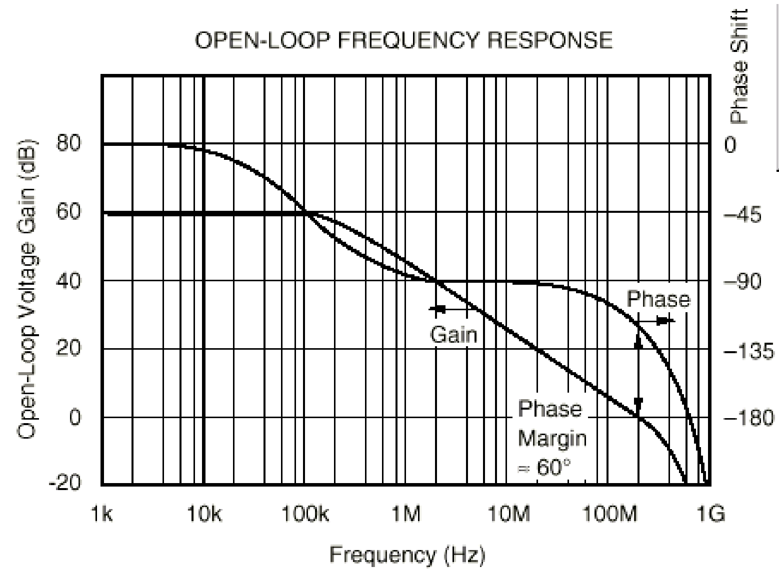


Preamp speed

- Finite opamp gain
  - $V_{out}(\omega)/i_{in}(\omega) = - Z_f / (1 + C_d / G_0 C_f)$
  - Small signal loss in $C_d/G_0C_f << 1$ (ballistic deficit)

- Finite opamp bandwidth
  - First order open-loop gain
  - $G(\omega) = G_0/(1 + j\ \omega/\omega_0)$
    - G_0 : low frequency gain
    - $G_0\omega_0$: gain bandwidth product
  - $V_{out}(\omega)/i_{in}(\omega) = - 1/j\omega C_f\ (1+j\omega C_d/G_0\omega_0 C_f)$

- Preamp risetime
  - Time constant : τ *(tau)*
  - $\tau = C_d/G_0\omega_0 C_f$
  - Rise-time : $t_{10-90\%} = 2.2\ \tau$
  - Rise-time optimised with w_{C} or C_f

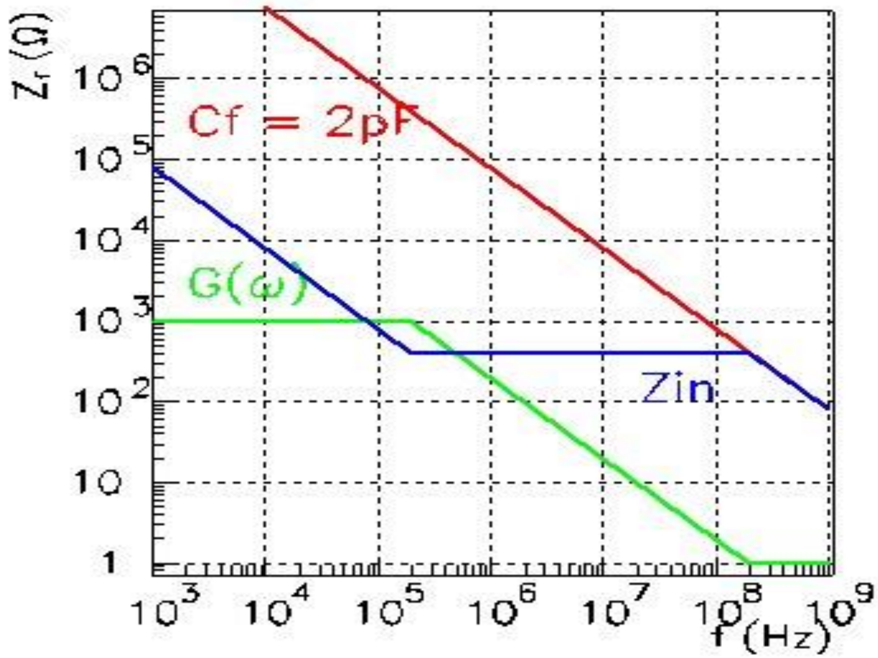


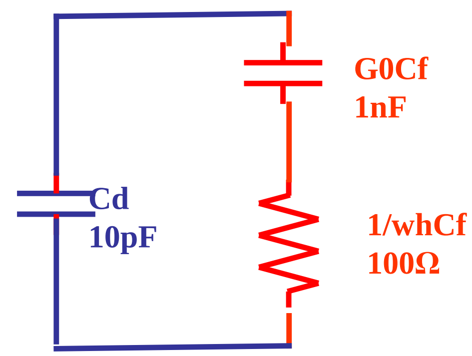
Impulse response with non-ideal preamp

Charge preamp seen from the input

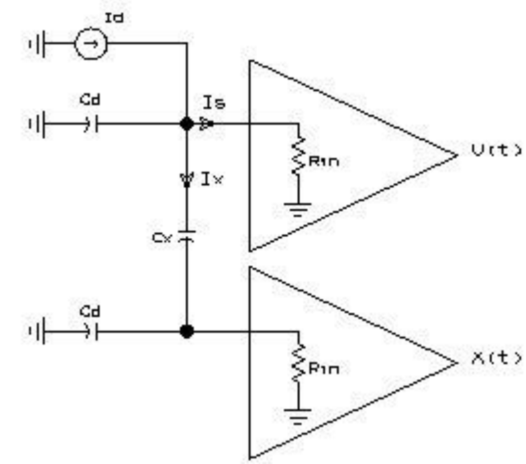
- Input impedance with ideal opamp
  - Zin = Zf / G+1
  - Zin->0 for ideal opmap
  - « Virtual ground » : Vin = 0
  - Minimizes sensitivity to detector impedance
  - Minimizes crostalk
- Input impedance with real opamp
  - Zin = $1/j\omega G_0 C_f + 1/ G_0 \omega_0 C_f$
  - Resistive term : Rin = $1/ G_0 \omega_0 C_f$
    - Exemple : $w_C = 10^{10}$ rad/s C_f= 1 pF => Rin = 100 Ω
  - Determines the input time constant : $t = R_{eq} C_d$
  - Good stability= (…!)
  - Equivalent circuit :

Input impedance or charge preamp



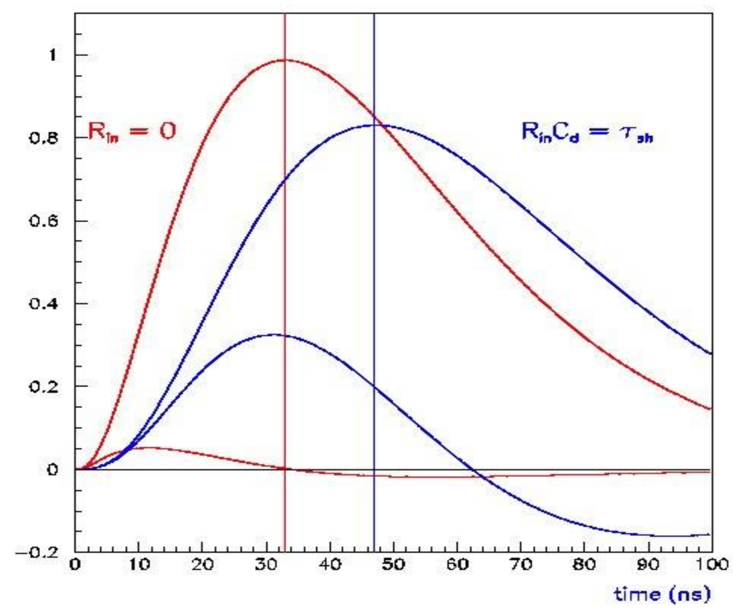


- Capacitive coupling between neighbours
  – Crosstalk signal is differentiated and with same polarity
  – Small contribution at signal peak
  – Proportionnal to Cx/Cd and preamp input impedance
  – Slowed derivative if RinCd ~ tp => non-zero at peak



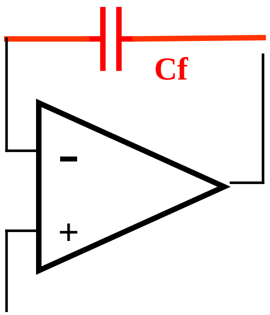
Crosstalk electrical modelization

- Long distance crosstalk
  – Inductive/resistive common ground return
  – References impedance
  – Connectors : mutual inductance

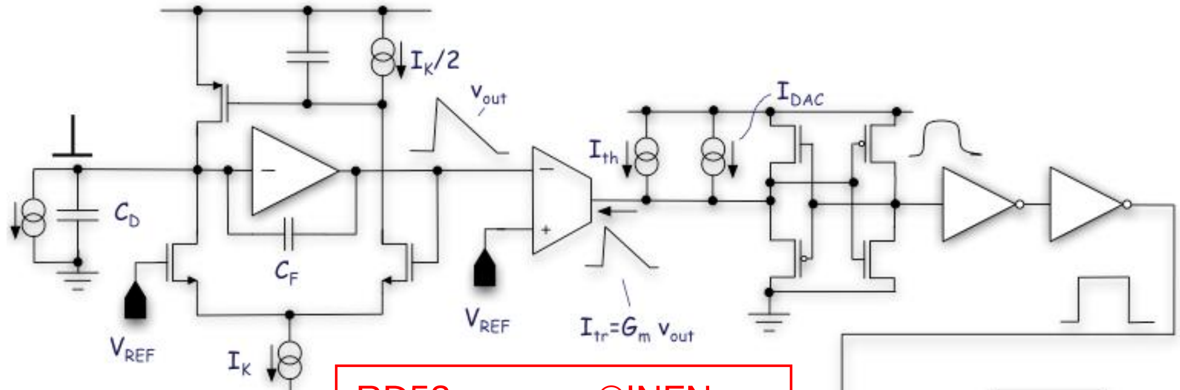


Charge preamplifier schematics

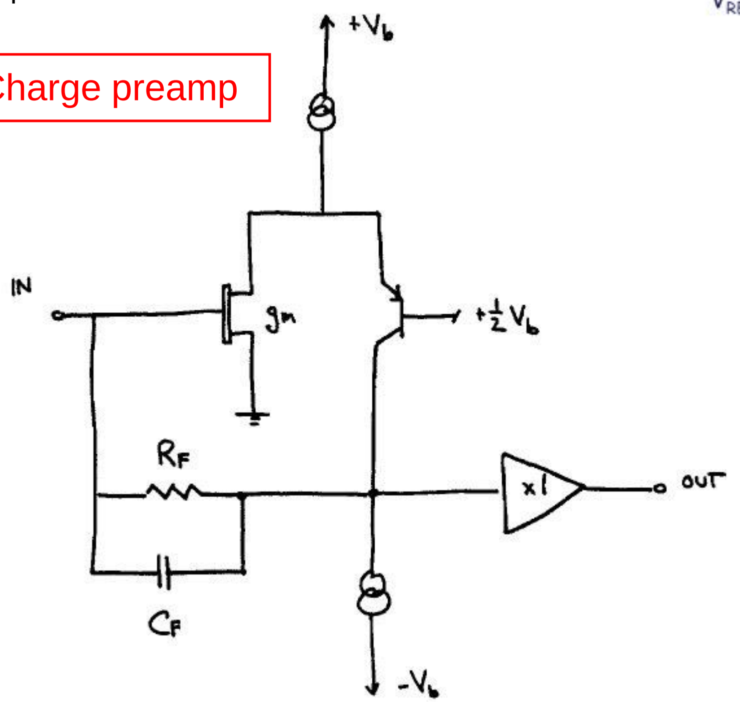
- More details after the section on noise



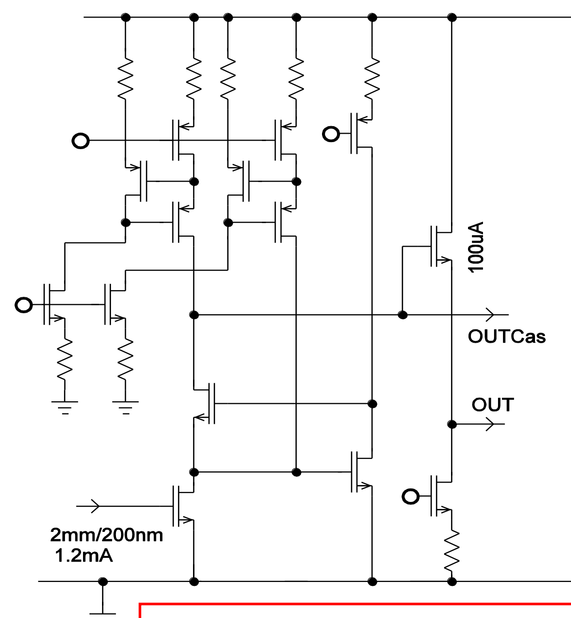
Charge preamp



RD53 preamp ©INFN



Charge preamp ©Radeka 68

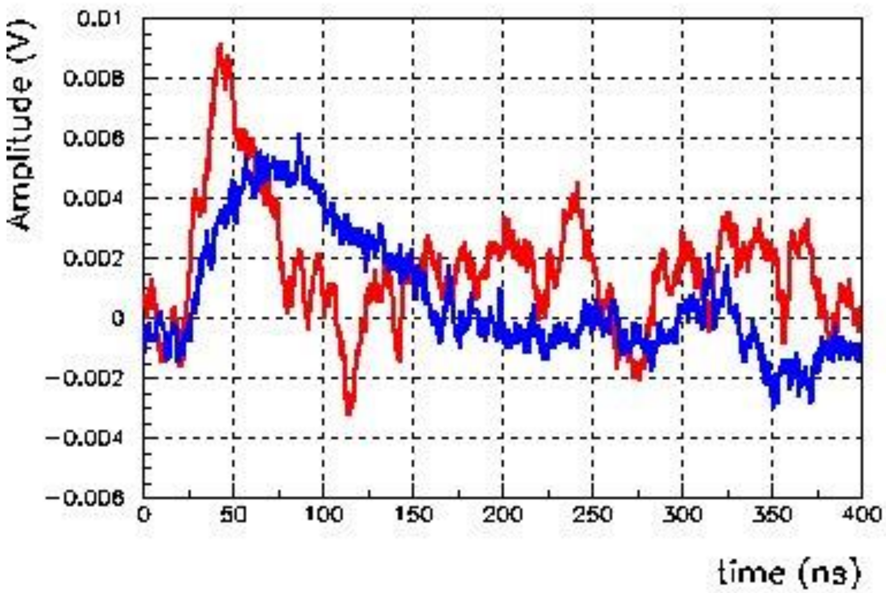


HGCAL preamp ©J. Kaplon

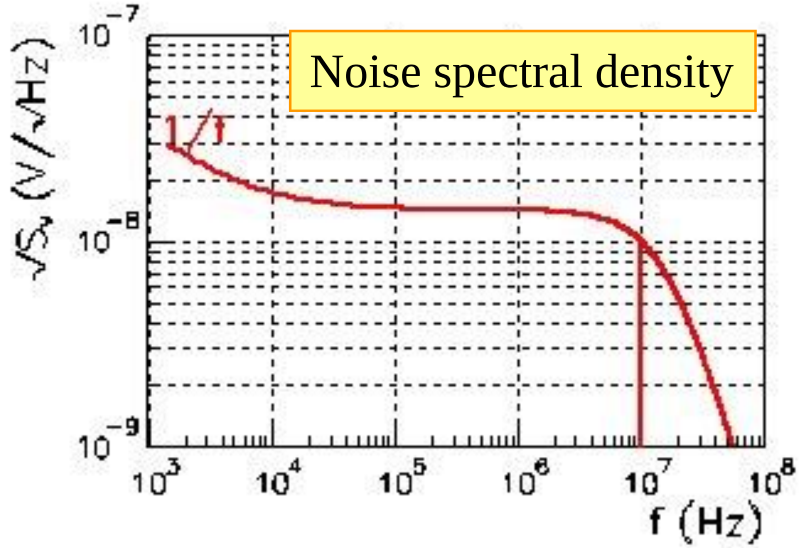
Electronics noise

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

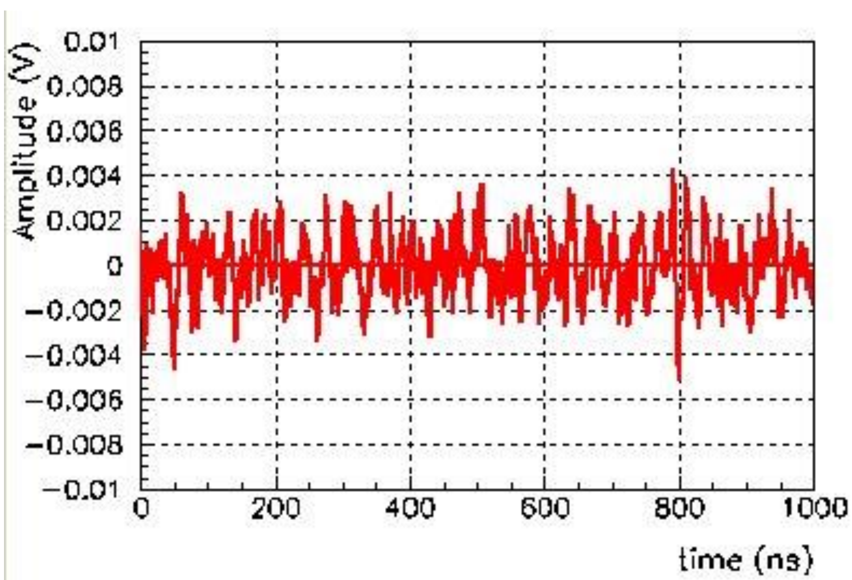
- Three types of noise
  - Fundamental noise (Thermal noise, shot noise)
  - Excess noise (1/f …)
  - Parasitics -> EMC/EMI (pickup noise, ground loops…)

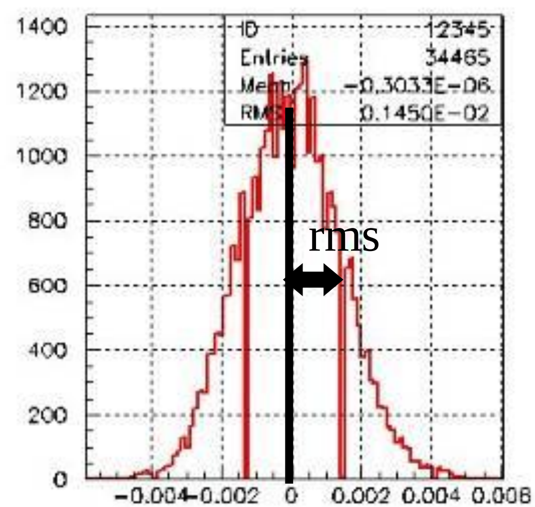


- Modelization
  - Noise generators : e_n, i_n,
  - Noise spectral density of e_n & i_n : S_v(f
  - $Sv(f) = | \mathcal{F}(e_n) |^2 \ (V^2/Hz)$



- *Rms* noise Vn
  - $V_n^2 = \int e_n^2(t)\, dt = \int Sv(f)\, df$
  - White noise (e_n) : $v_n = e_n \sqrt{\frac{1}{2}\pi f_{-3dB}}$

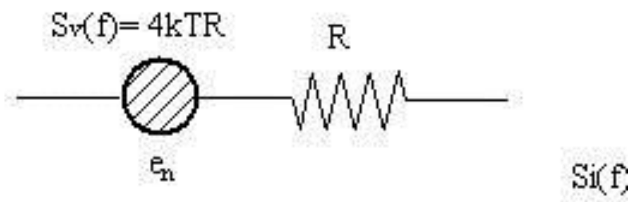




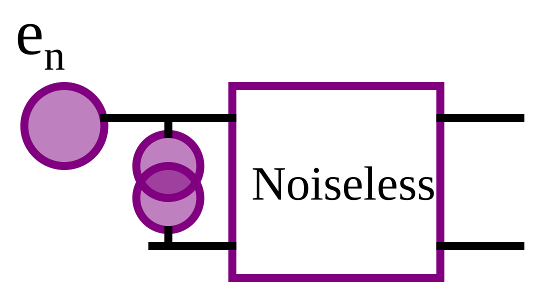
Rms noise vn

Calculating electronics noise

- Fundamental noise
  - Thermal noise (resistors) : Sv(f) = 4kTR
  - Shot noise (junctions) : Si(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…

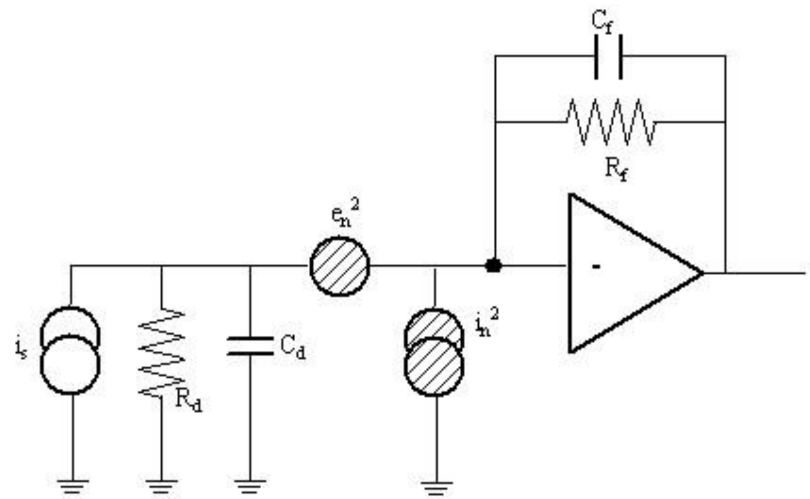


Noise generators referred to the input

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

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

Noise in transimpedance amplifiers



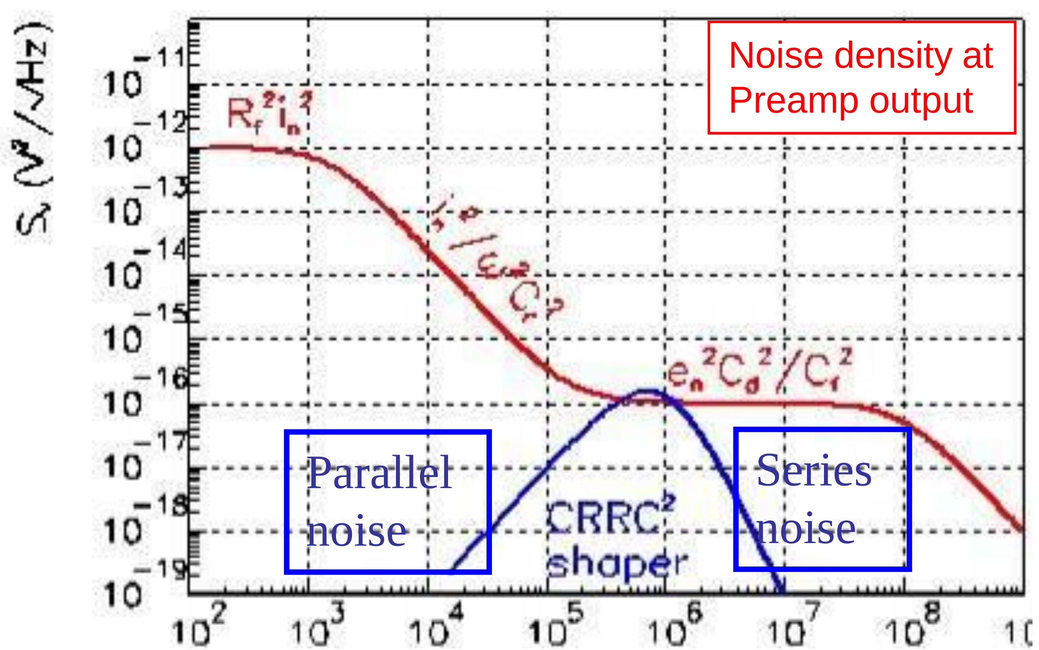
Noise generators in charge preamp

- 2 noise generators at the input
  - Parallel noise : (i_n^2) (leakage)
  - Series nosie : (e_n^2) (preamp)

- Output noise spectral density :
  - $Sv(\omega) = (i_n^2 + e_n^2/|Z_d|^2) * |Z_f|^2$

- For charge preamps
  - $Sv(\omega) = i_n^2 /\omega^2 C_f^2 + e_n^2 C_d^2/C_f^2$
  - Parallel noise in $1/\omega^2$
  - Series noise is flat, with a « noise gain » of C_d/C_f

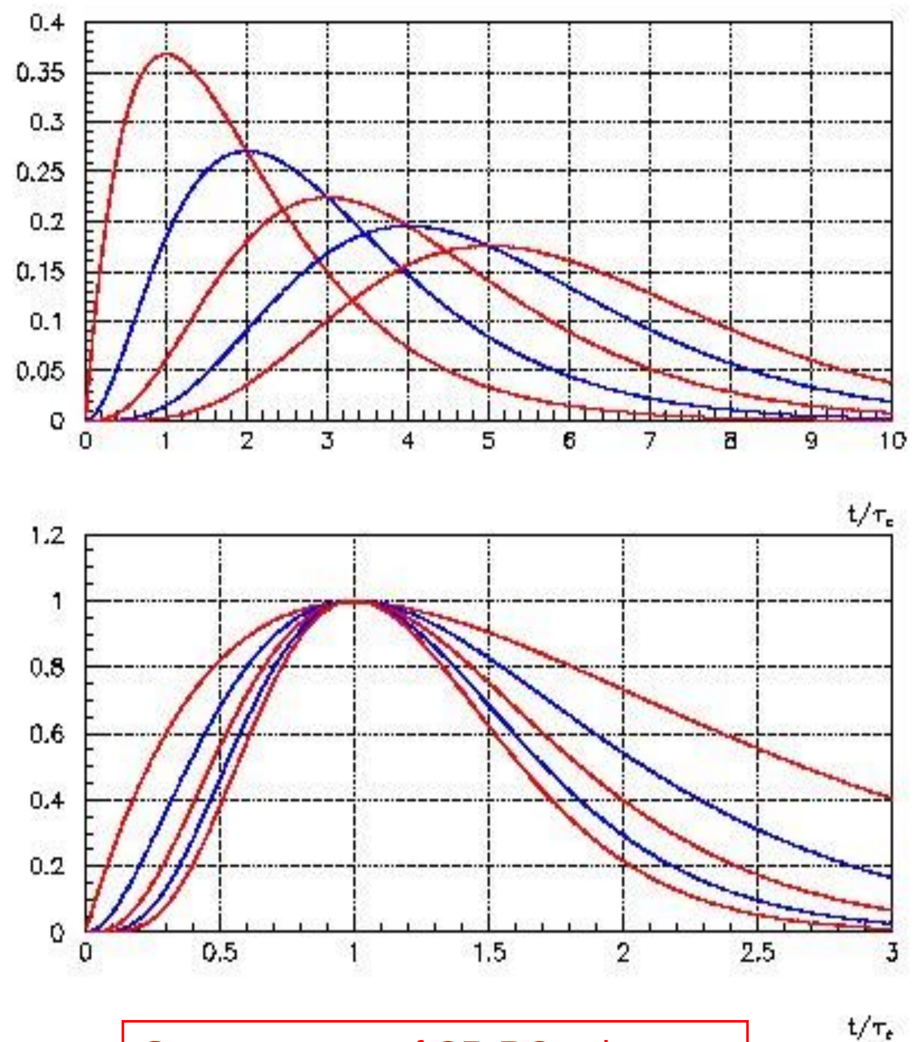
- *rms* noise V_n
  - $V_n^2 = \int Sv(\omega)\, d\omega/2\pi \rightarrow \infty$
  - Benefit of shaping…



Equivalent Noise Charge (ENC) after CRRC^n

- Noise reduction by optimising useful bandwidth
  - Low-pass filters (**RC^n**) to cut-off high frequency noise
  - High-pass filter (**CR**) to cut-off parallel noise
  - -> pass-band filter CRRC^n

- Equivalent Noise Charge : ENC
  - Noise referred to the input in electrons
  - $ENC = Ia(n)\, e_n C_t/\sqrt{\tau}$
    $\oplus\ Ib(n)\, i_n^*\, \sqrt{\tau}$
  - Series noise in $1/\sqrt{\tau}$
  - Paralle noise in $\sqrt{\tau}$
  - 1/f noise independant of τ
  - Optimum shaping time $\tau_{opt} = \tau_c/\sqrt{2n-1}$

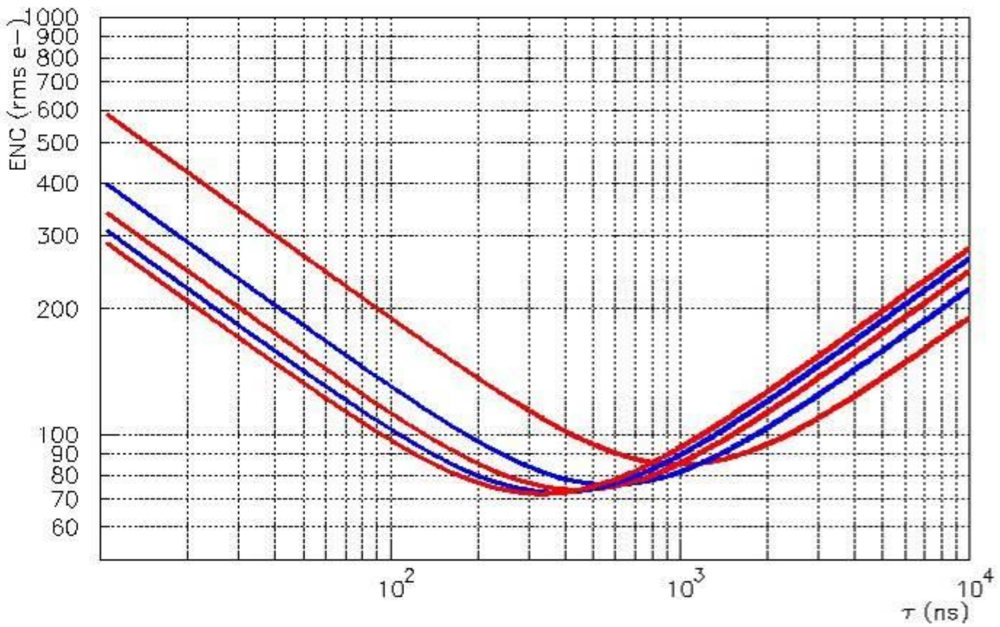


Step response of CR RCn shapers

Equivalent Noise Charge (ENC) after CRRC^n

- Peaking time tp (5-100%)
  - ENC(**tp**) independent of n
  - Also includes preamp risetime

- Complex shapers are getting obsolete :
  - Power of digital filtering
  - Analog filter = CRRC ou CRRC^2
  - antialiasing



ENC vs tau for CR RCn shapers

Equivalent Noise Charge (ENC) after CRRC^n

Omega

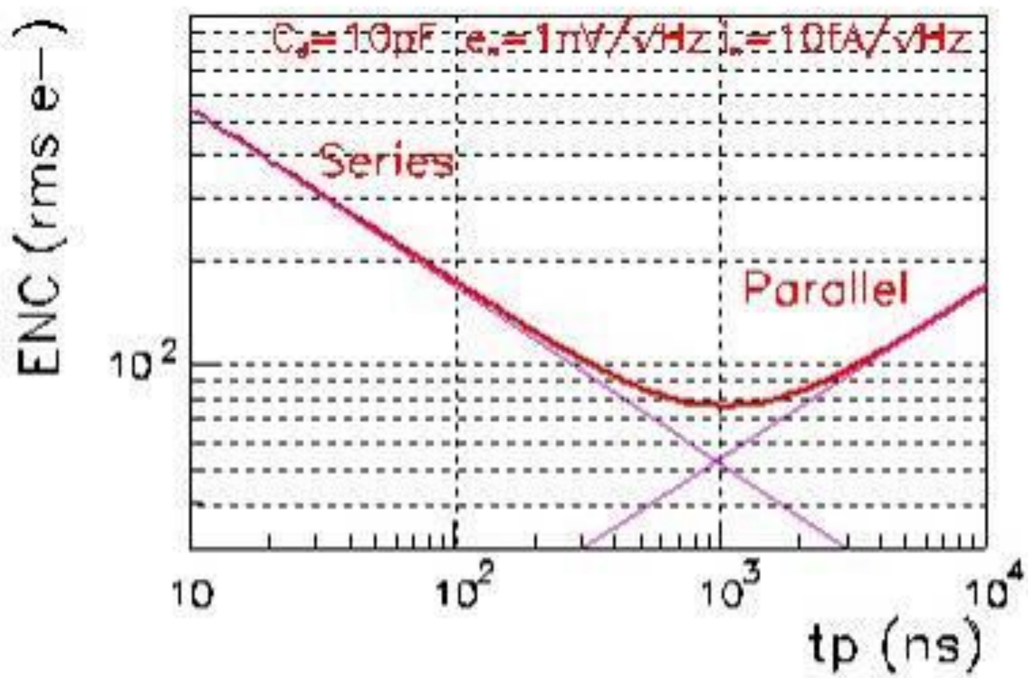
- A useful formula : **ENC (e- rms) after a CRRC^2 shaper :**

$$ENC = 174\ e_n C_{tot}/\sqrt{t_p}\ (\delta) \oplus 166\ i_n \sqrt{t_p}\ (\delta)$$

  - e_n in nV/ √Hz, i_n in pA/ √Hz are the preamp noise spectral densities
  - C_{tot} (in pF) is dominated by the detector (C_d) + input preamp capacitance (C_{PA})
  - t_p (in ns) is the shaper peaking time (5-100%)

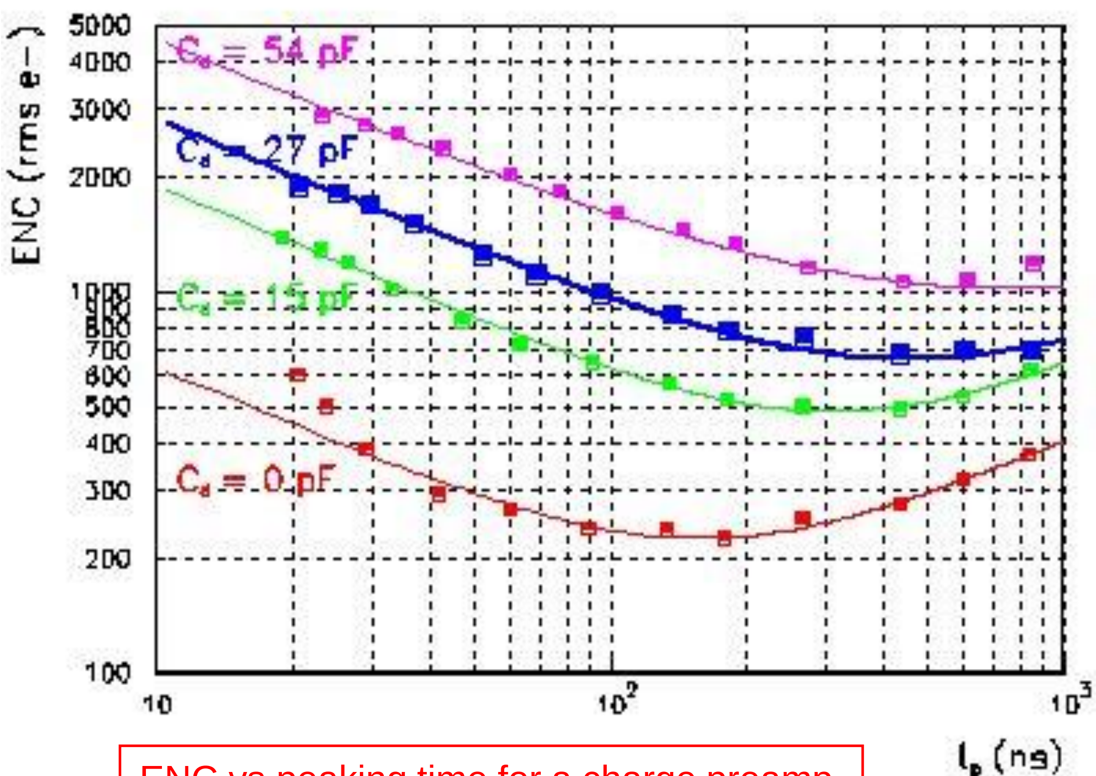
- **Noise minimization**
  - Minimize source capacitance
  - Operate at optimum shaping time
  - Preamp series noise (en) best with high trans-conductance (g_m) in input transistor

    => large current, optimal size

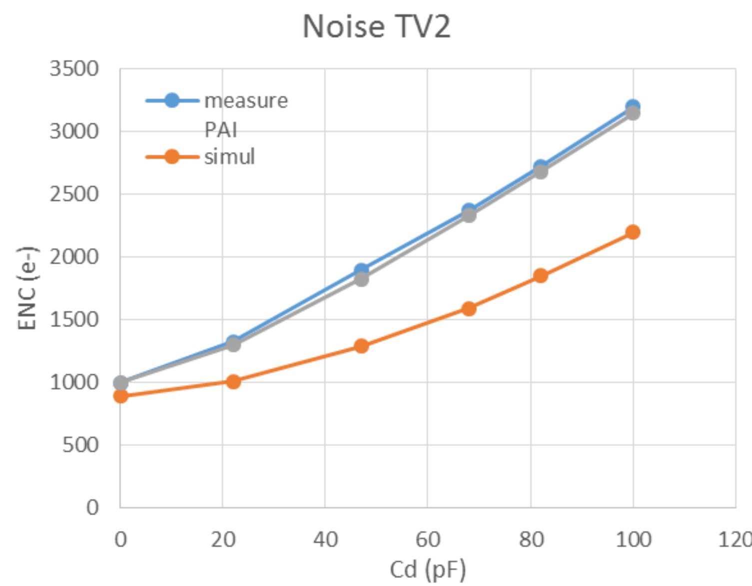


Example of ENC measurement

- 2000/0.35 PMOS 0.35µm SiGe Id=500 µA
  - Series : e_n = 1.4 nV/√Hz, C_{PA} = 7 pF , 1/f noise : 12 e-/pF, Parallel : in = 40 fA/√Hz
  - Series noise e_n and Preamp capacitance extraction fitting ENC(Cd)
  - NB : linear fit wrong for e_n and C_{PA}, use quadratic fit :
    - $ENC^2(Cd) = 3^e4\ e_n{}^2(Cd+Cpa)^2/tp + 3^e4\ i_n{}^2\ tp +$ 2nd stage
    - $ENC^2(Cd) - ENC^2(0) = 3^e4\ e_n{}^2/\ tp\ (Cd^2 + 2\ Cd{*}Cpa) = \alpha Cd^2+\beta Cd \Rightarrow Cpa = \beta/2\alpha$



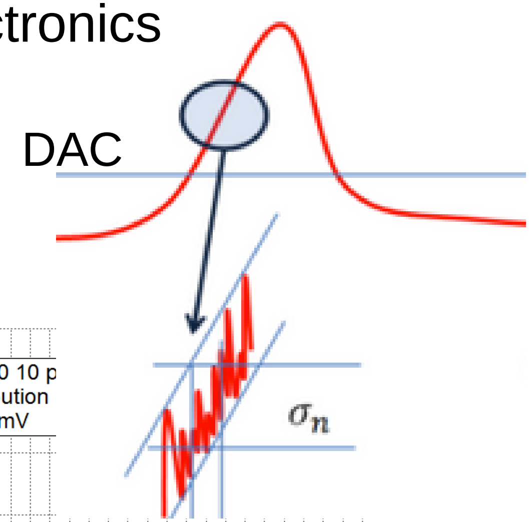
ENC vs peaking time for a charge preamp

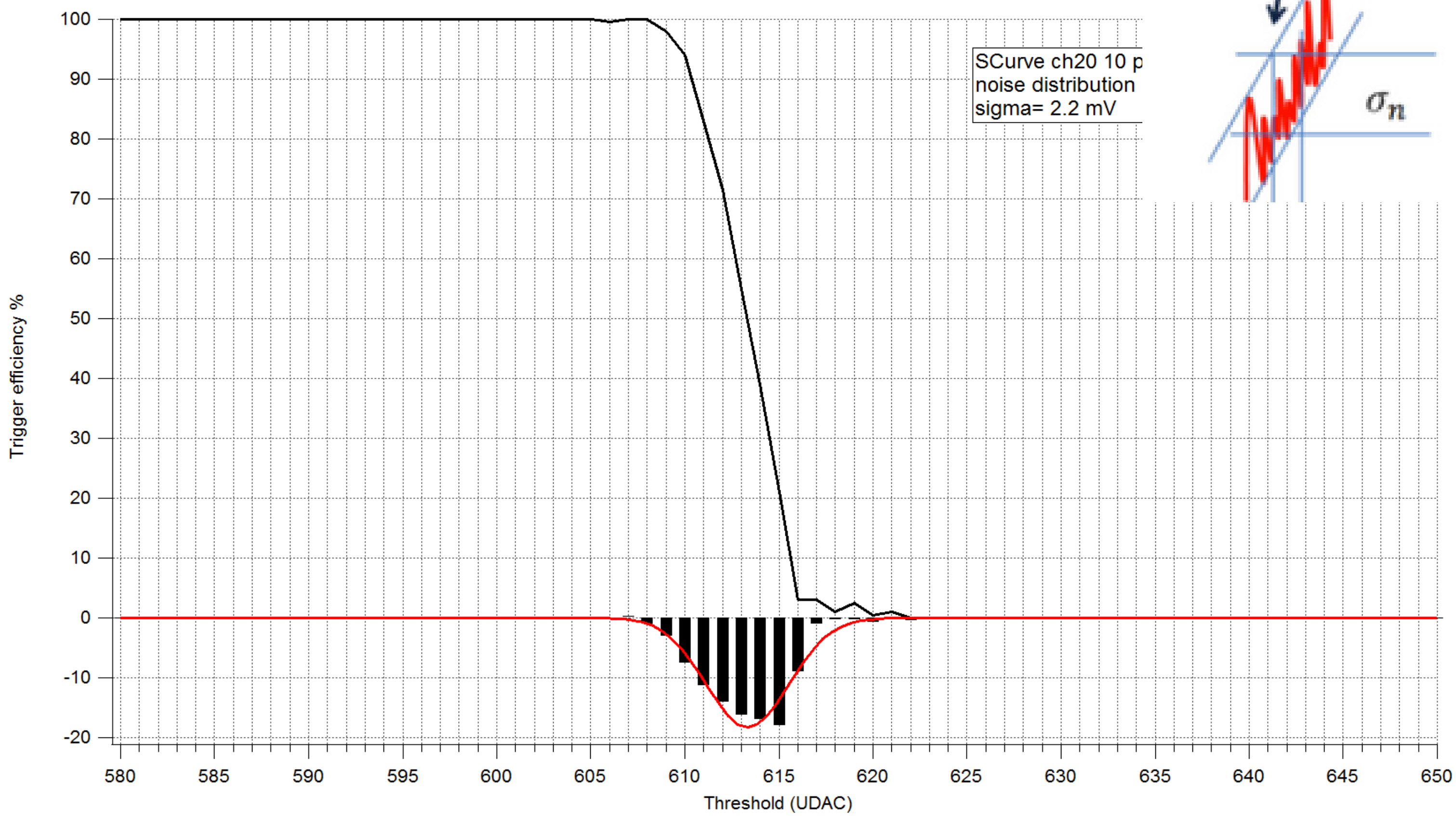


ENC vs Capacitance (other preamp)

Trigger efficiency

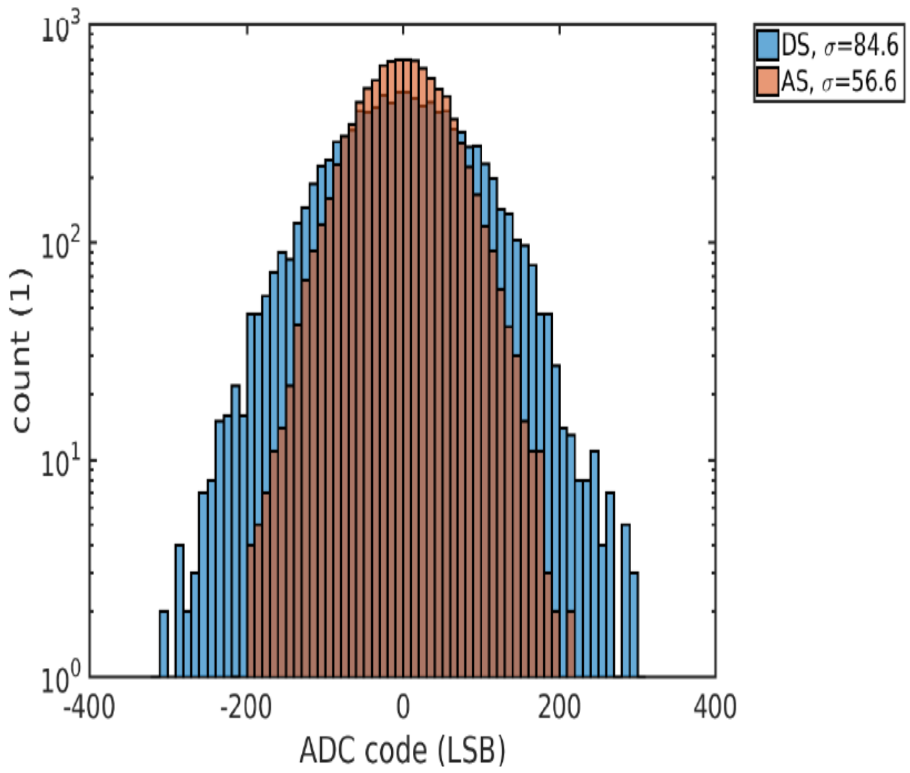
- Preamp + discriminator front-end = tracker electronics
- scanning the DAC produces « s-curves »
- Derivative gives the noise

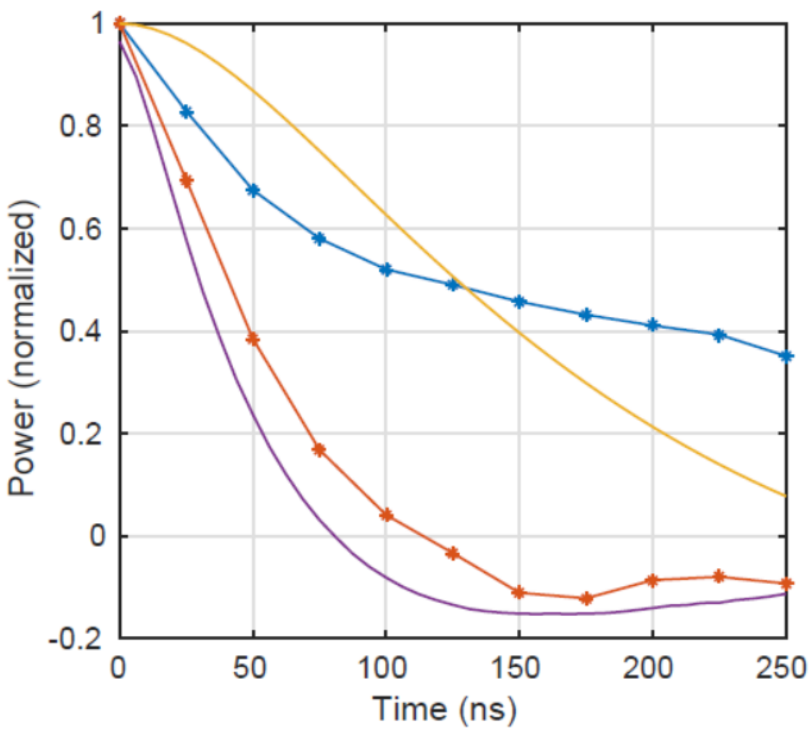




Coherent and incoherent noise

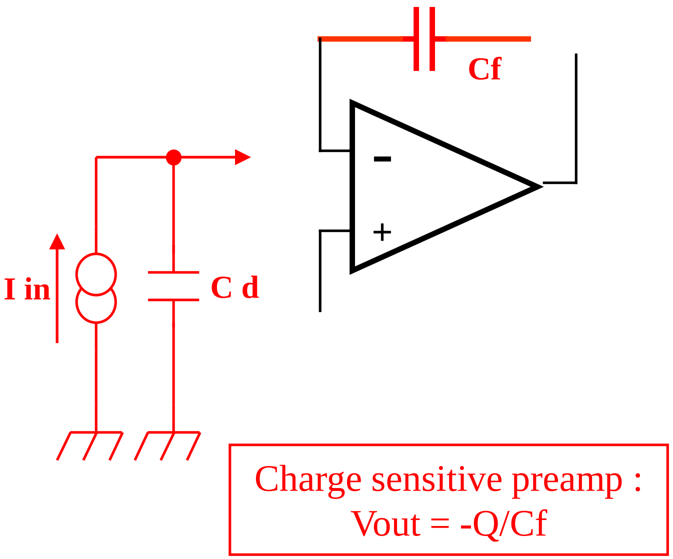
- A constant concern in calorimetry
  - Coherent noise extracted by comparing direct and alternate sums on n channels (n=64) : DS = $\sum$ ped[i] ; AS = $\sum (-1)^i$ ped[i]
  - Incoherent noise IN = rms(AS) / $\sqrt{n}$
  - Coherent noise : CN = $\sqrt{var(DS) - var(AS)}$ / n
- Need to show that CN / IN ~ 10% can be obtained at system level



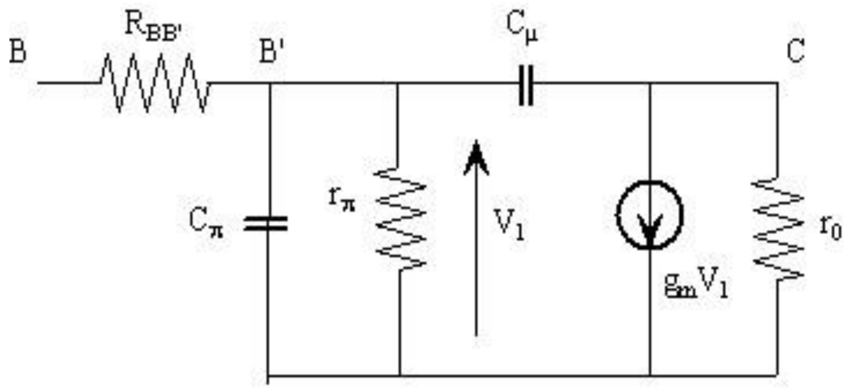


Summary of part 1

- Importance of front-end on electronics on physics performance
- Benefits of charge preamplifiers : low noise, low crosstalk
  - The front-end of 90% of particle physics detectors…
  - But always built with custom circuits…

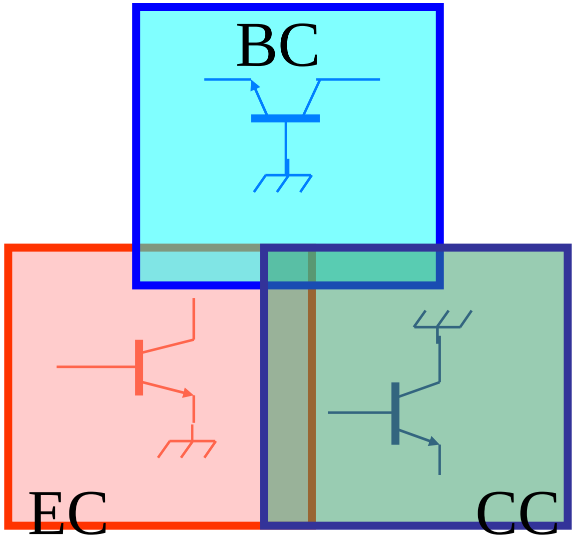


- Performant design is at transistor level
- Simple models
  - hybrid π model
  - Similar for bipolar and MOS
  - Essential for design



High frequency hybrid model of bipolar

- **Three basic configurations**
  - Common emitter (CE) = V to I (transconductance)
  - Common collector (CC) = V to V (voltage buffer)
  - Common base (BC) = I to I (current conveyor)
- **See backup slides**

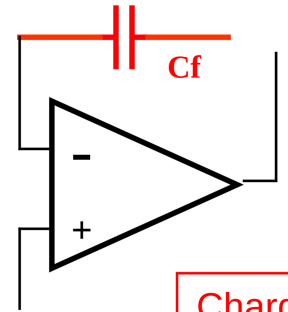


The *Art* of electronics design

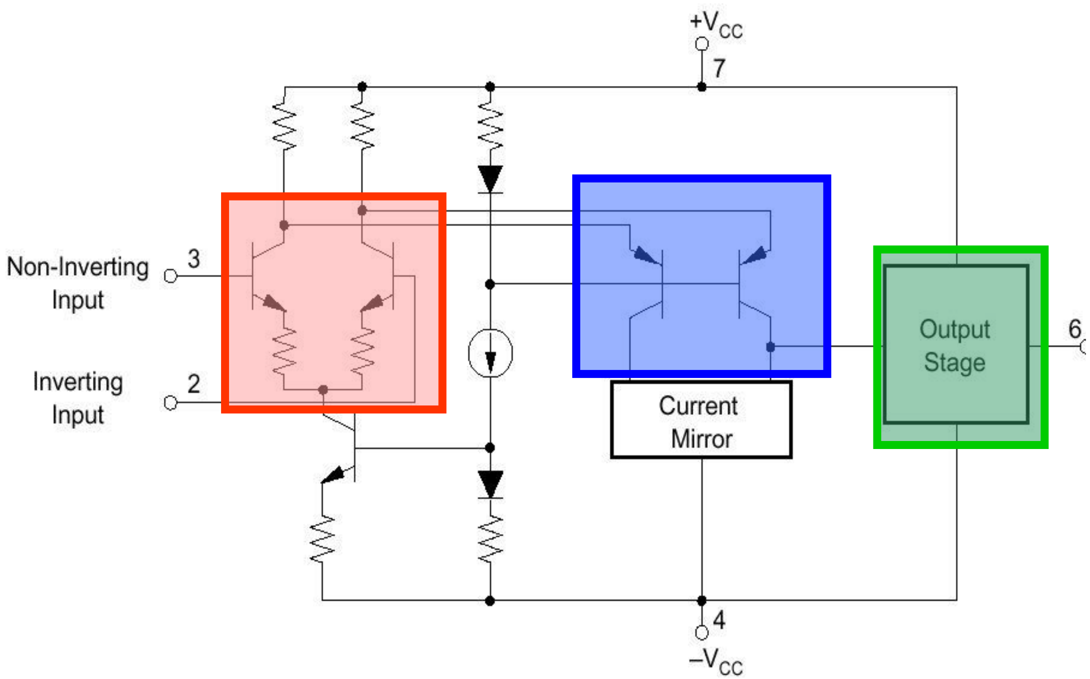
- Numerous « composites »
  - Darlington, Paraphase, Cascode, Mirrors…

Designing a charge preamp…

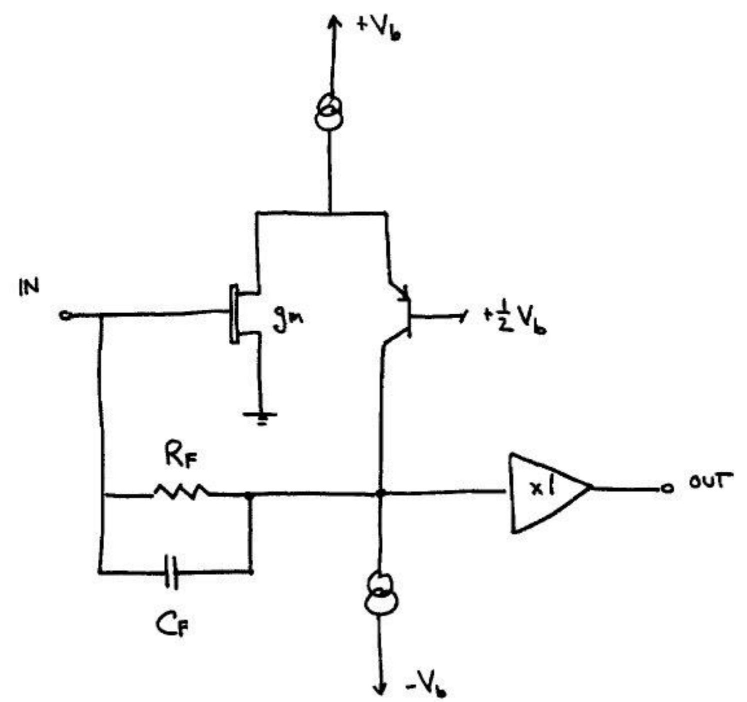
- From the schematic of principle
  - Using of a fast opamp (OP620)
  - Removing unnecessary components…
  - Similar to the traditionnal schematic «Radeka 68 »
  - Optimising transistors and currents



Charge preamp



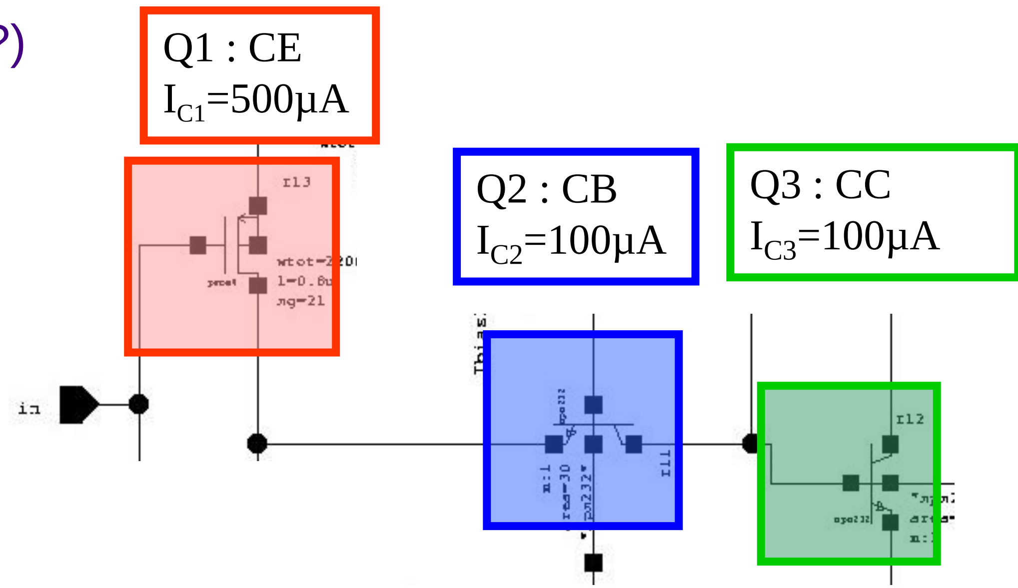
Schematic of a OP620 opamp ©BurrBrown



Charge preamp ©Radeka 68

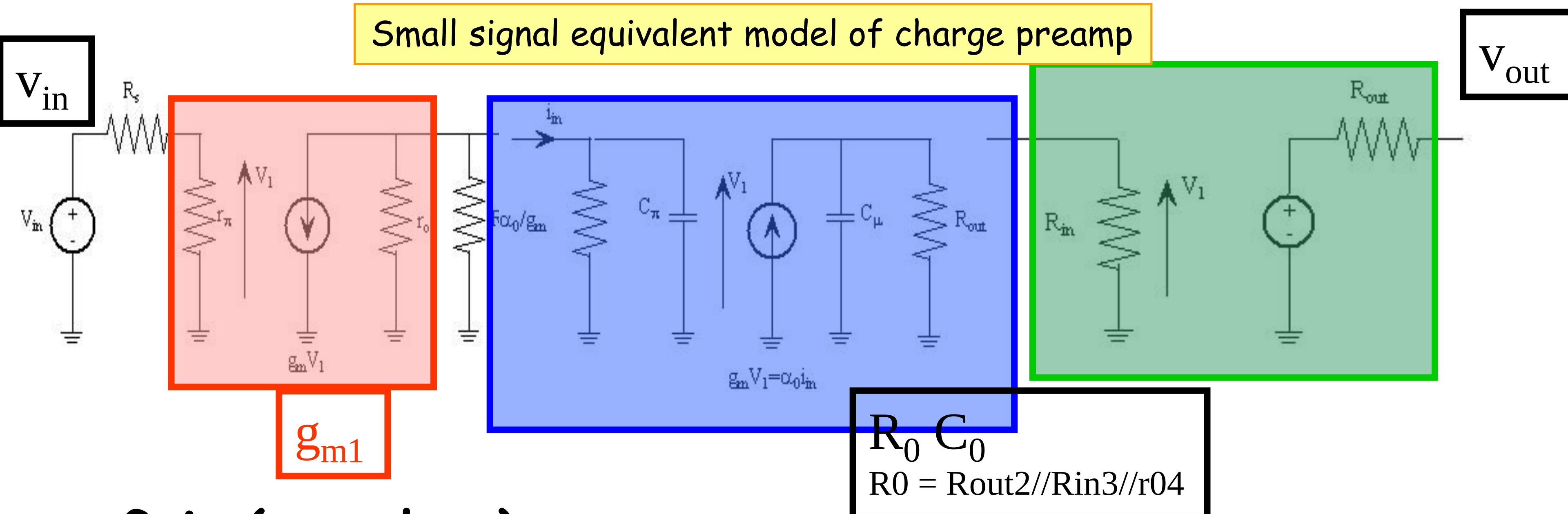
Example : designing a charge preamp (2)

- Simplified schematic
- Optimising components
  - What transistors (PMOS, NPN ?)
  - What bias current ?
  - What transistor size ?
  - What is the noise contribution of each component ?
  - how to minimize it ?
  - What parameters determine the stability ?
  - Waht is the saturation behaviour
  - How vary signal and noise with input capacitance ?
  - How to maximise the output voltage swing ?
  - What is the sensitivity to power supplies, temperature…



Simplified schematic of Charge preamp

- Small signal equivalent model
  - Transistors are replaced by hybrid π model
  - Allows to calculate open loop gain

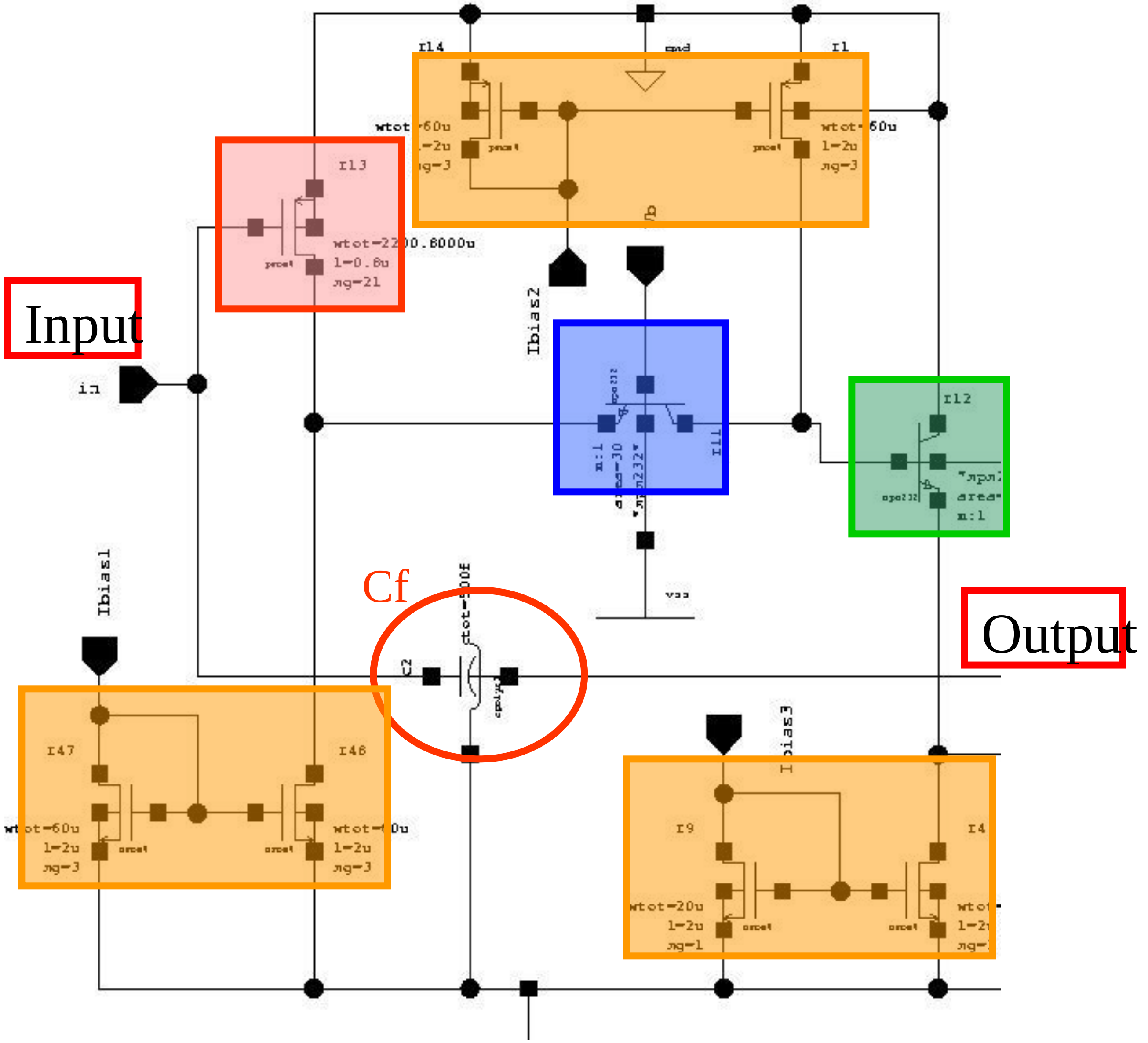


- **Gain (open loop) :**

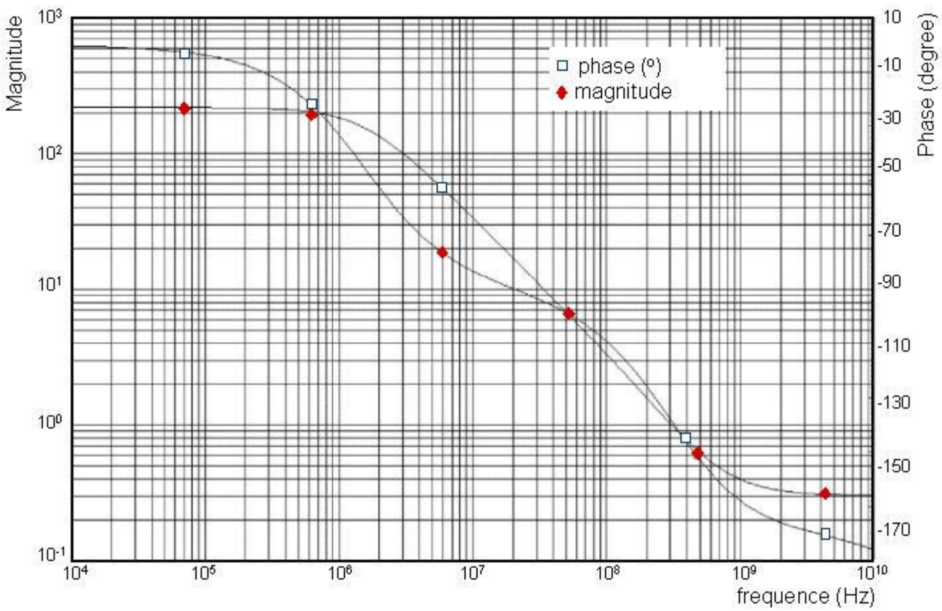
$$v_{out}/v_{in} = - g_{m1} R_0 /(1 + j\omega\ R_0 C_0)$$

- *Ex : g_{m1}=20mA/V , R_0=500kΩ, C_0=1pF => $G_0=10^4$ $\omega_0=2 10^6$ $G_0\omega_0=2\ 10^{10}$ = 3 GHz !*

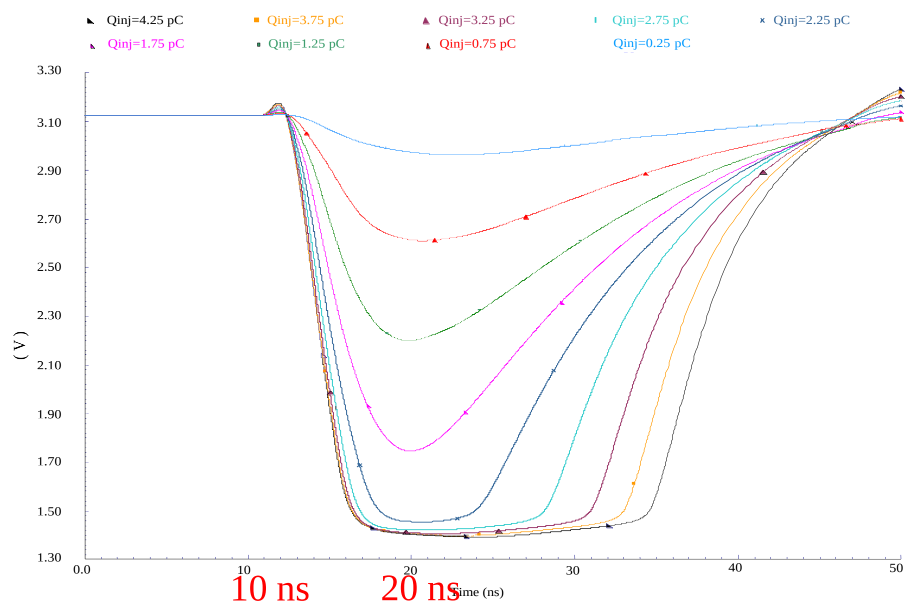
- Complete schematic
  - Adding bias elements



- Complete simulation
  – Checking hand calculations against 2nd order effects
  – Testing extreme process parameters (« corner simulations »)
  – Testing robustness (to power supplies, temperature…)



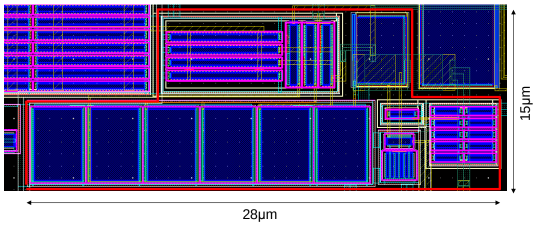
Simulated open loop gain



Saturation behaviour

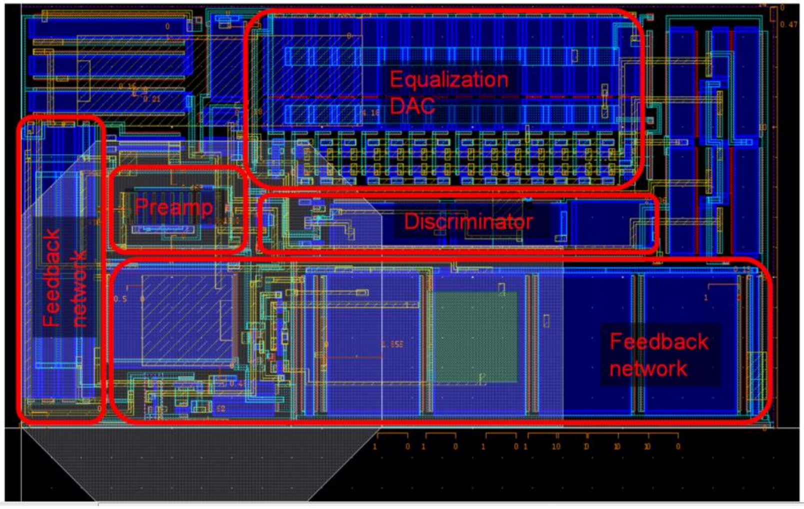
Example : designing a charge preamp (6)

- Layout
  - Each component is drawn
  - They are interconnected by metal layers



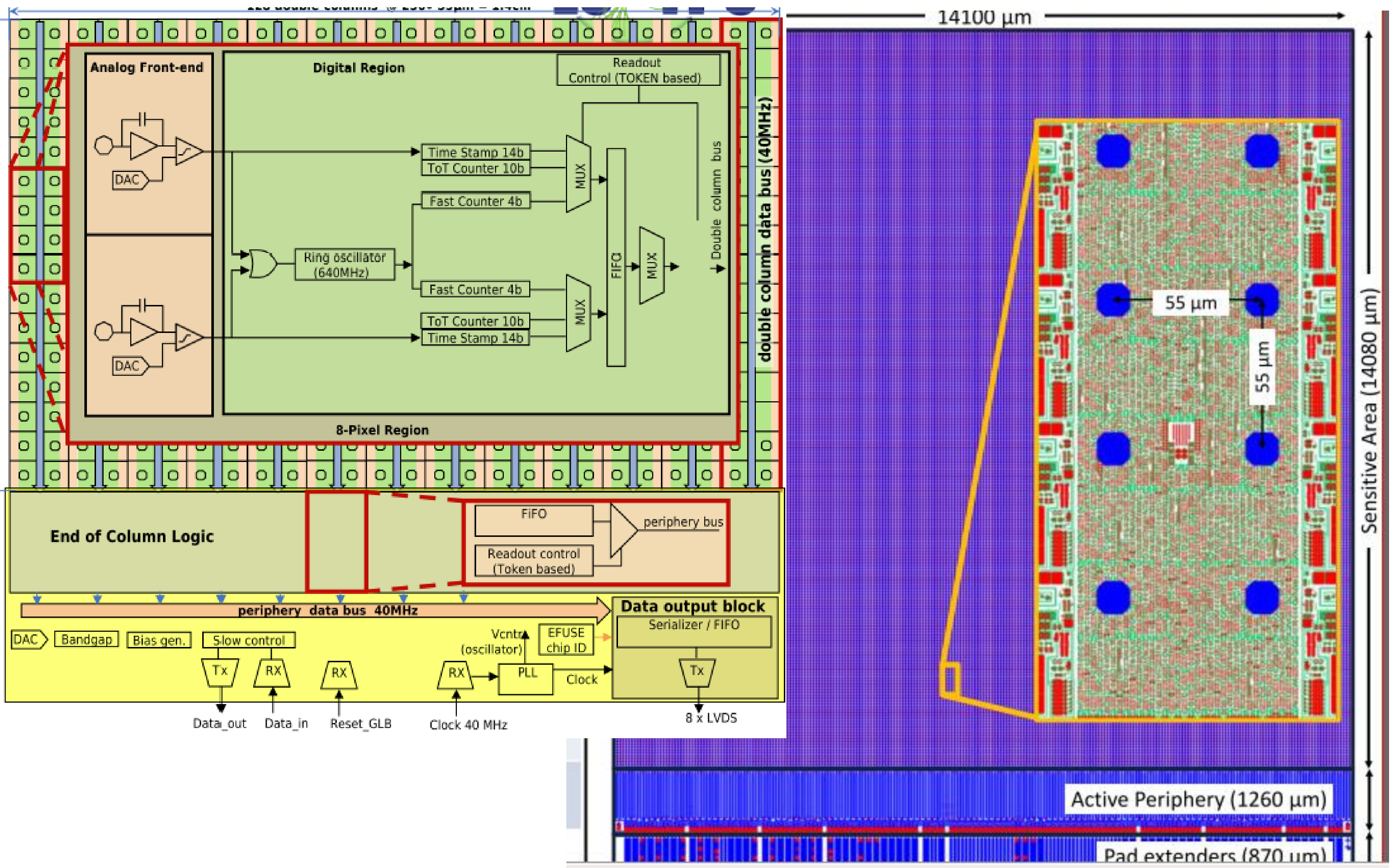
Charge preamp in 65nm
Clicpix P. Valerio (CERN 2013)

- Checks
  - DRC : checking drawing rules (isolation, minimal dimensions…)
  - ERC : extracting the corresponding electrical schematic
  - LVS (layout vs schematic) : comparing extracted schematic and original design
  - Simulating extracted schematic with parasitic elements



- Generating GDS2 file
  - Fabrication masks : « reticule »

From preamp to chip : Timepix 3…

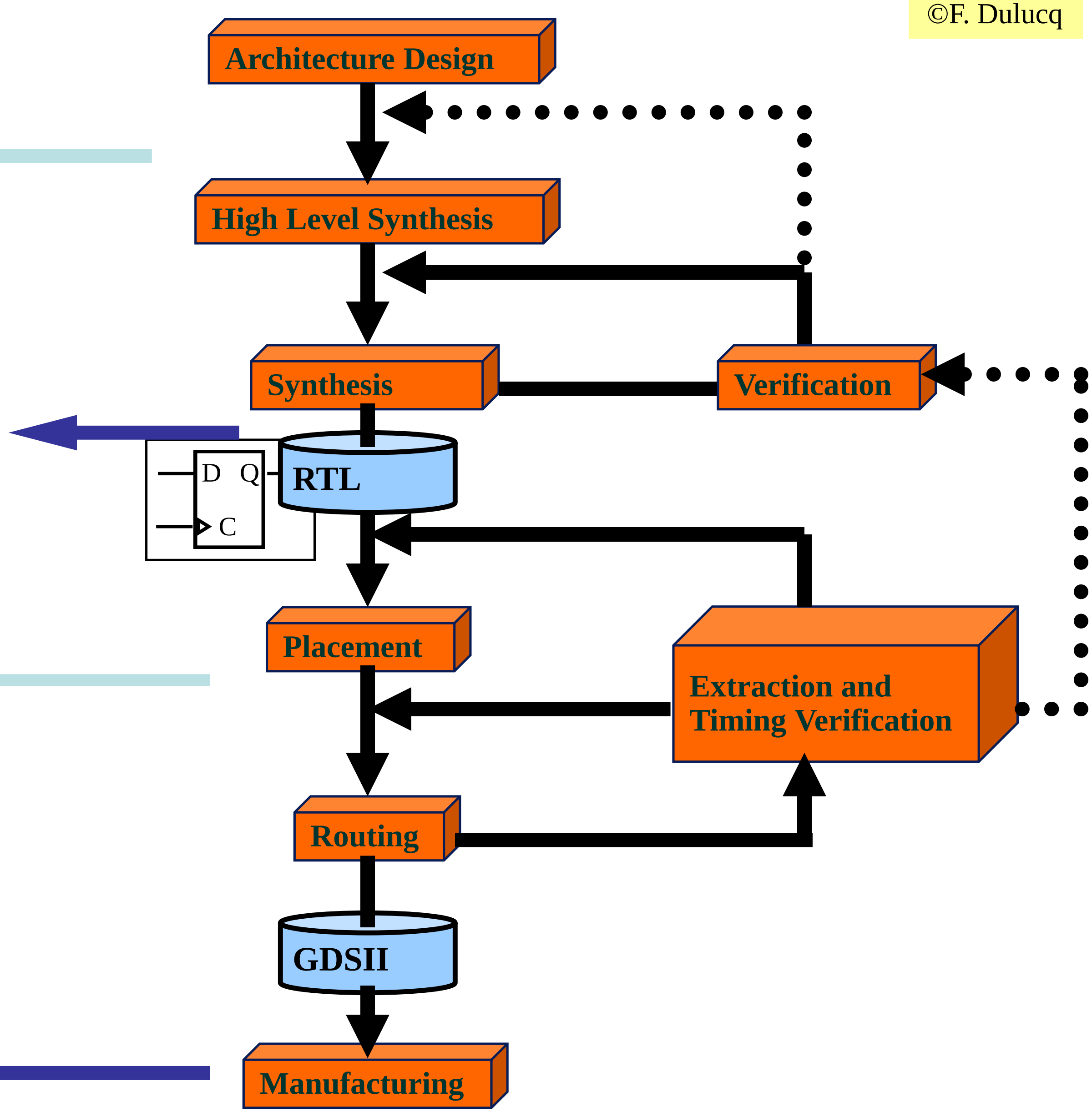


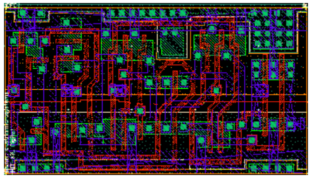
Digital implementation global Flow

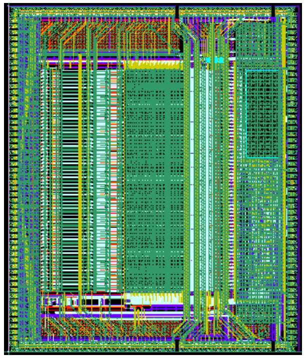
Ωmega

©F. Dulucq

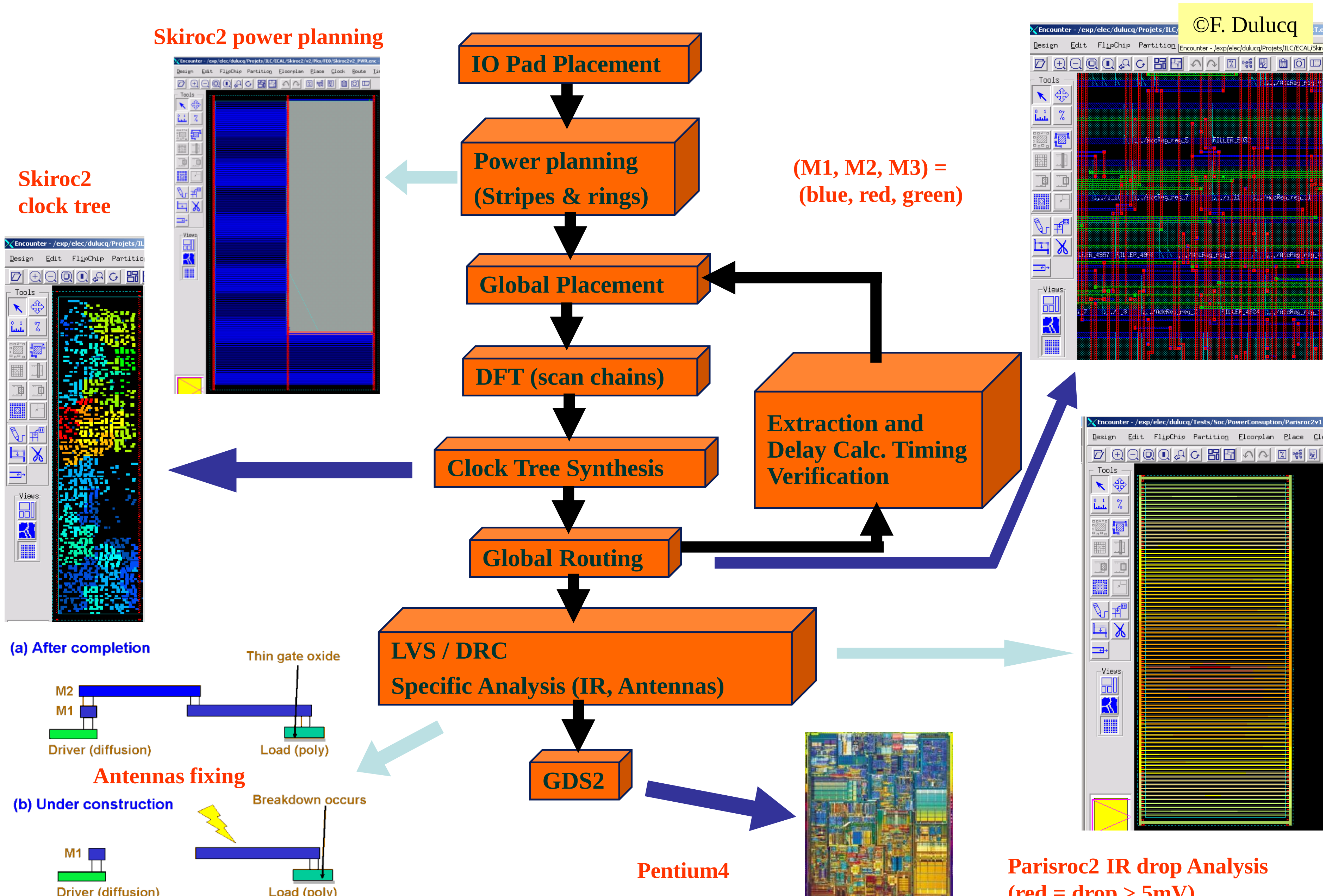
```
process(Rstb, Clk)
begin
   if Rstb ='0' then
      Q <= '0';
   elsif rising_edge Clk then
      Q <= D;
   end if;
end process;
```







ASIC specific flow for digital routing

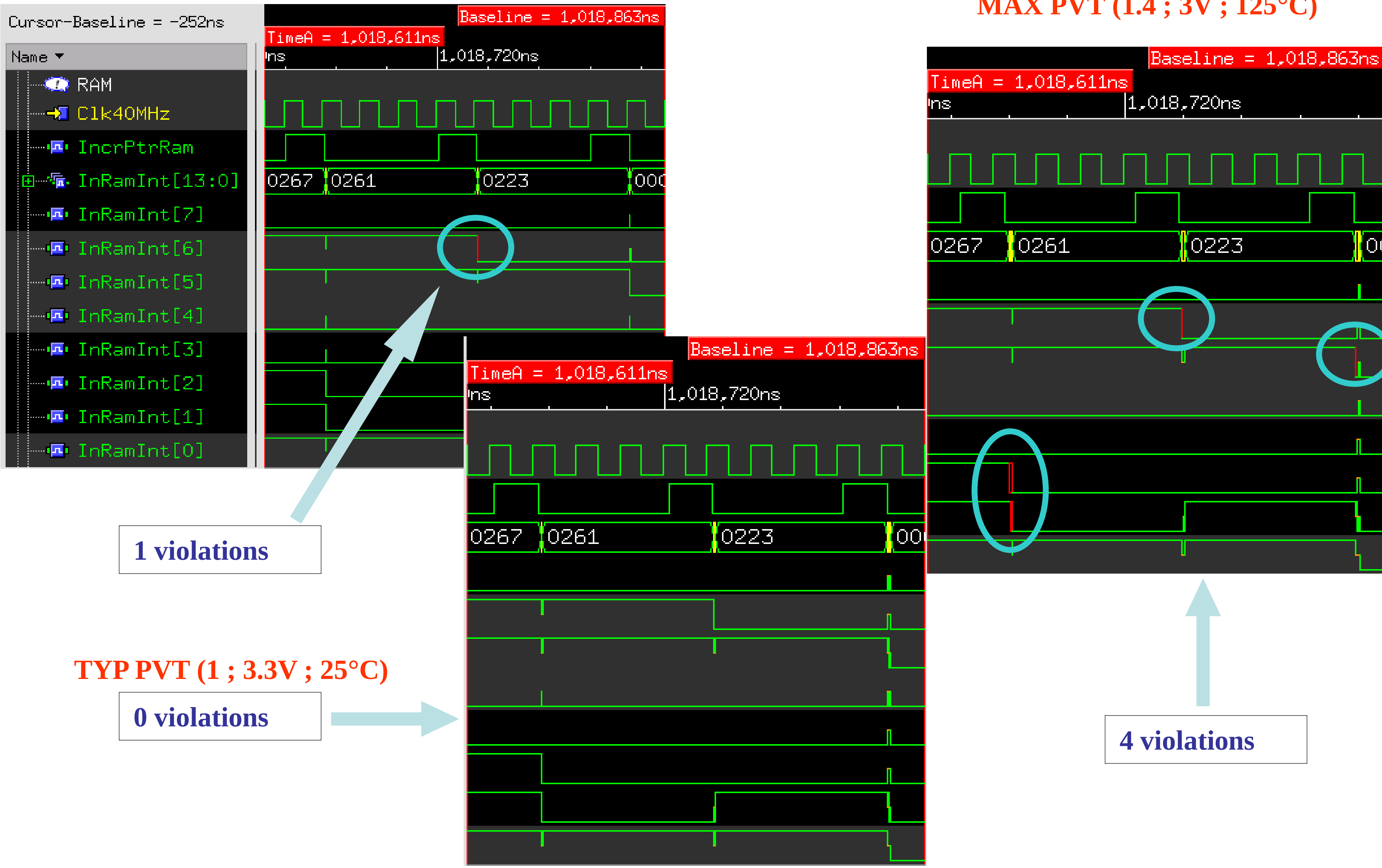


Post layout simulation (extracted RC)

©F. Dulucq

MIN PVT (1.6 ; 3.6V ; -50°C)

MAX PVT (1.4 ; 3V ; 125°C)



1 violations

TYP PVT (1 ; 3.3V ; 25°C)

0 violations

4 violations

Electromagnetic compatibility (EMC-EMI)

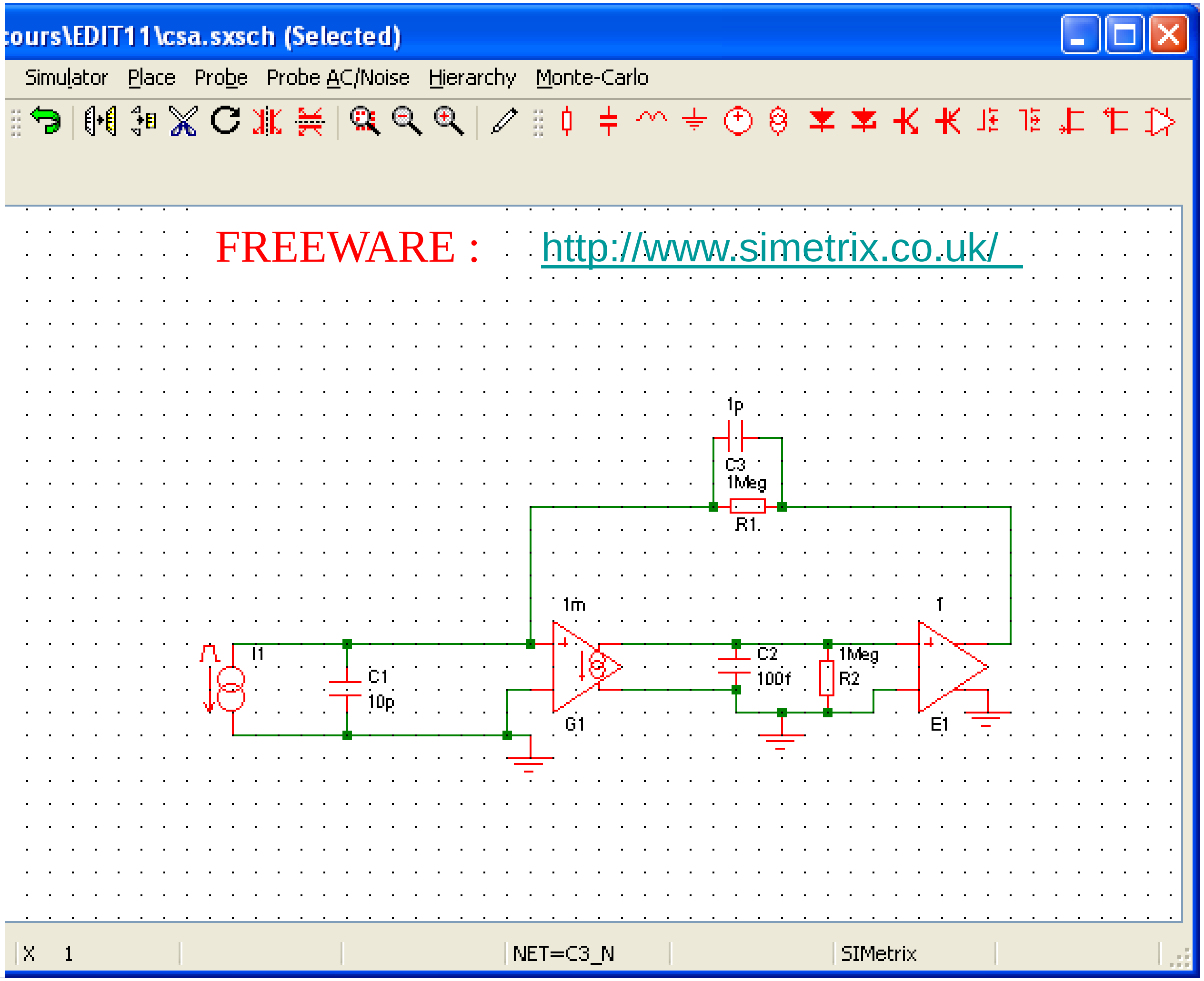
- Coexistence analog-digital
  - Capacitive, inductive and common-impedance couplings
  - A full lecture !
  - A good summary : there is no such thing as « ground », pay attention to current return

Simple simulations : Simetrix freeware

Ωmega

Example : bandwidth and EMC of simple charge preamp

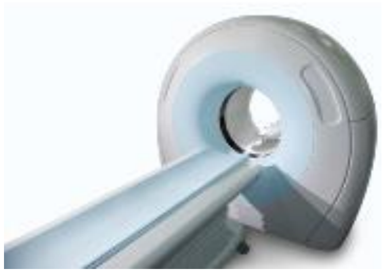
- **Simulate impulse response**
- **Frequency response**
- **Input impedance**
- **Ballistic deficit**
- **Effect of amplifier gain**
- **Effect of resistive feedback**
- **Test pulse injection**
- **Effect of input capacitance**
- **Parasitic inductance**
- **Capacitive crosstalk**
- **Resistive/Inductive ground return**



Need for timing

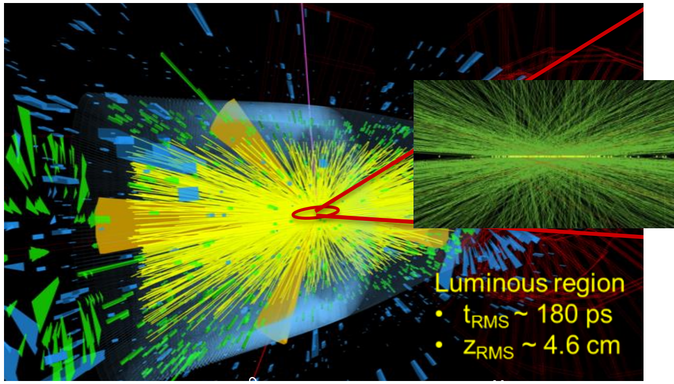
Omega

- Time resolution <50ps required by many experiments/applications keeping low power, large dynamic range ….



- **PET/ Time of Flight** measurements (SiPM)
  - Dynamic range : 1 pe (100fC) up to 3000 pe (300 pC)
  - Time resolution <100ps

- **CMS High Granularity CALorimeter**: (Si pin diodes)
  - Large dynamic range : few fC up to ~10 pC
  - Calorimetry => Precision /linearity < 1%
  - Fast timing ability ~50ps (for > 10 mips desirable)
  - Peaking time 15-20 ns (minimize noise, minimise Out of Time pileup)
  - Power on detector < ~10 mW/channel all included

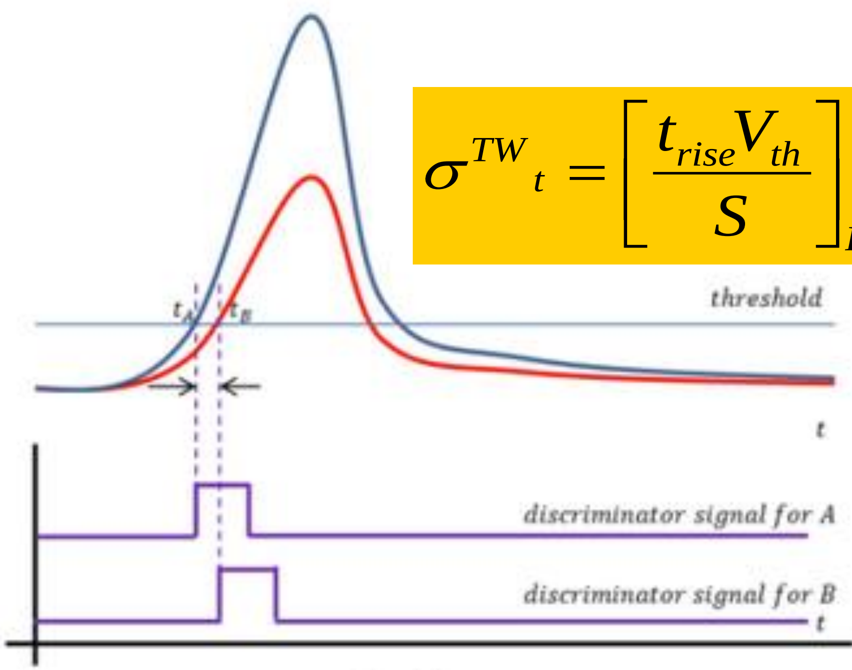


- **ATLAS High Granularity Timing Detector** (LGAD)
  - Time performance ~30 ps : To reject Time Pile up events => better particle identification

Time walk and time jitter

Time walk: the voltage value Vo is reached at different time for signal of different amplitudes

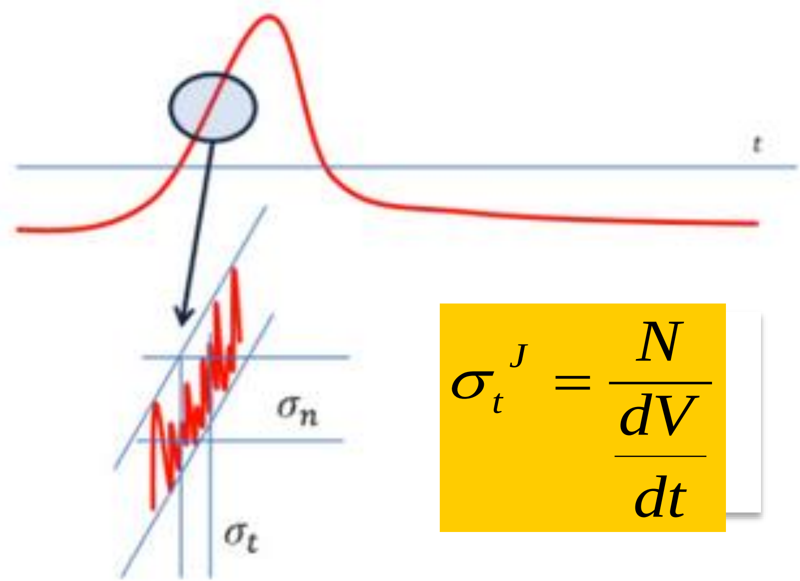
$$\sigma^{TW}_t = \left[\frac{t_{rise} V_{th}}{S} \right]_{RMS}$$



Time walk effect

Jitter: the noise is summed to the signal, causing amplitude variations

$$\sigma_t^J = \frac{N}{\frac{dV}{dt}}$$



Jitter effect

Due to the physics of signal formation

Mostly due to electronic noise

$$\sigma_t^2 = \left(\frac{t_{rise}}{S/N} \right)^2 + \left(\left[\frac{t_{rise} V_{th}}{S} \right]_{RMS} \right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}} \right)^2$$

Jitter

Time Walk

TDC

© N. Cartiglia Trento workshop 2016

https://indico.cern.ch/event/485239/overview/

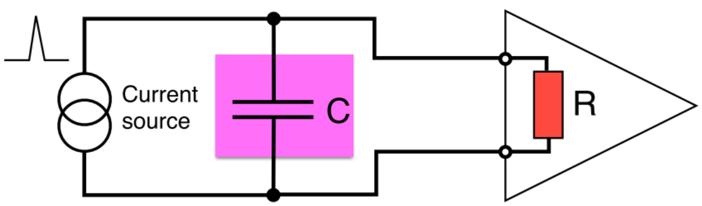
Omega

$$\sigma_t^{J} = \frac{N}{\frac{dV}{dt}}$$

- Jitter due to electronics noise:
- also presented as j = tr / (S/N)
- dV/dt prop to BW, N prop to √ BW => jitter prop to 1/√BW

⇒ « the faster the amplifier the better the jitter ? »

⇒ « High speed preamps need to be low impedance (50 Ω or less) »



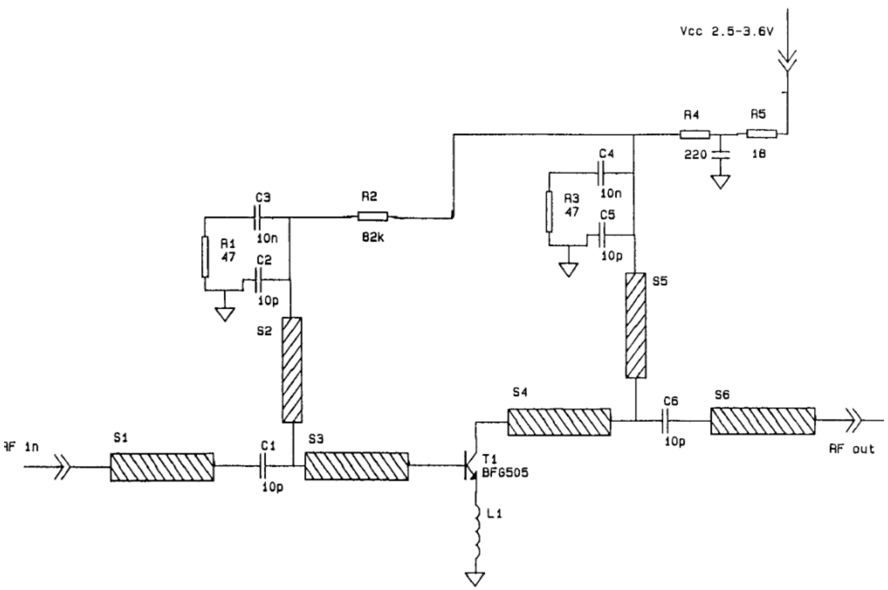
NB : tr = $t_{10\text{-}90\%}$ = 2.2 tau.

f_{-3dB} = 1/2πtau = 0. 35 / $t_{10\text{-}90}$

f_{-3dB} = 1 GHz <-> $t_{10\text{-}90\%}$ = 300 ps

1 ps = 300 µm in vaccum


2120 LNA
1.6 TO 1.8 GHz
Research Communications Ltd.


Vcc 2.5-3.6V
R4
R5
220
18
C4
10n
R3
47
C5
10p
C3
R2
82k
R1
47
10n
C2
10p
S2
S5
S4
C6
10p
S6
RF out
S1
C1
10p
S3
T1
BFG505
L1

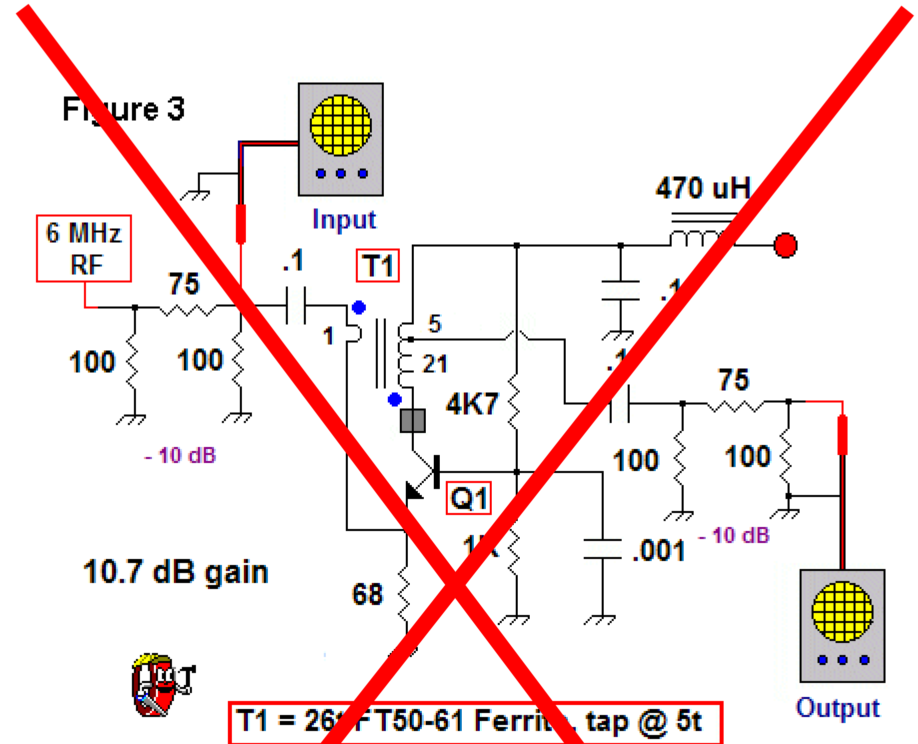
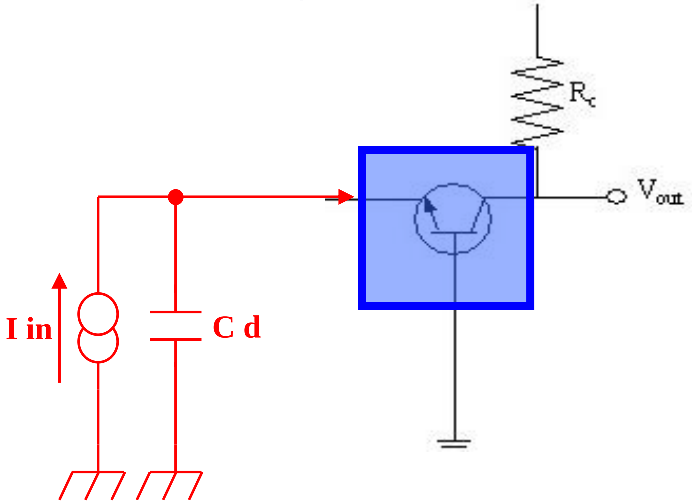


Figure 3
Input
6 MHz RF
75
.1
T1
470 uH
100
100
5
1
21
4K7
75
- 10 dB
Q1
100
100
- 10 dB
.001
10.7 dB gain
68
Output
T1 = 26t FT50-61 Ferrite, tap @ 5t

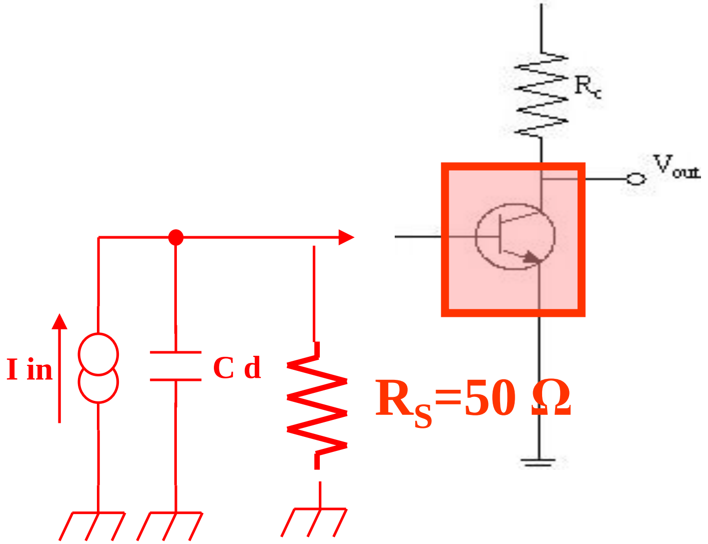
High speed configurations

- Open loop configurations : current conveyors, RF amplifiers
- Usually designed at transistor level MOS or SiGe

- **Current conveyors**
- Small Zin : current sensitive input
- Large Zout : current driven output
- Unity gain current conveyor
- E.g. : (super) common-base configuration
- Low input impedance : Rin=1/gm
- Transimpedance : Rc
- Bandwitdth : 1/2πRcCu > 1 GHz



- **RF amplifiers**
- Large Zin : voltage sensitive input
- Large Zout : current driven output
- Current conversion with resistor R_S
- E.g. common-emitter configuration
- Transimpedance : -gmRcRs
- Bandwitdth : 1/2πRsCt

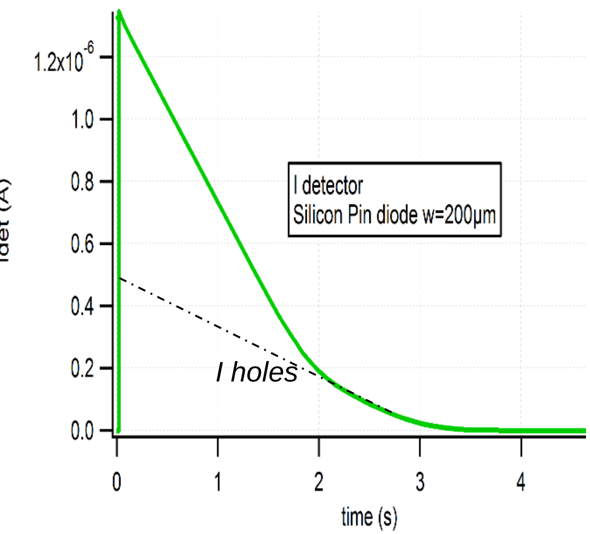


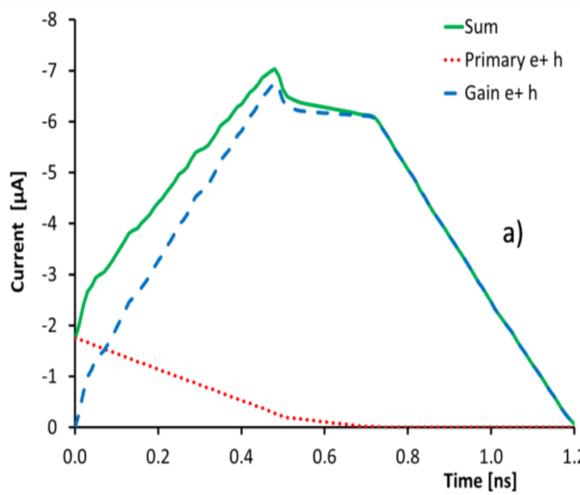
Signal : detector current

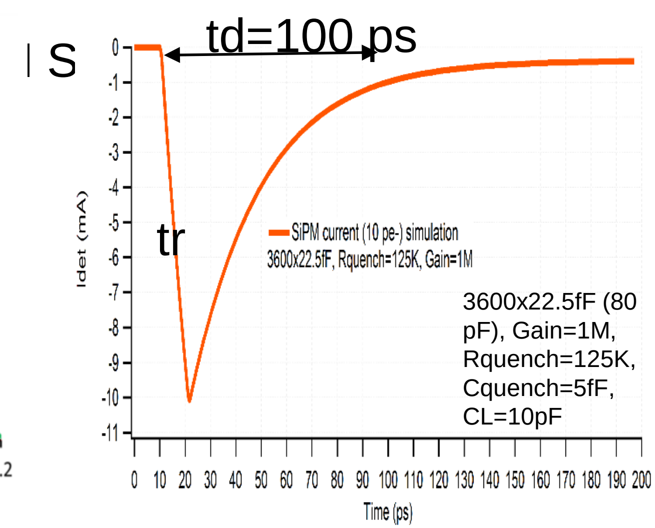
- PN diode w =200µm
- Very short rise time : tr~10ps
- Relatively long «drift time» : td~2ns

- LGAD sensor w =50µm
- rise time : tr~500ps
- Decay time» : td~700ps

- SiPM detector (10pe-)
- very short rise time : tr~10 ps
- Short duration : td~100ps),



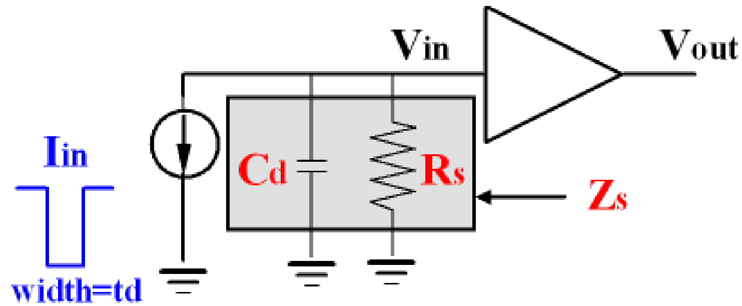




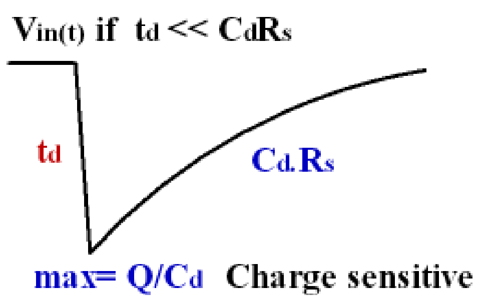
© Harmut Sadrozinski (Santa Cruz) "the beautiful risetime of the detector is spoilt by the electronics"

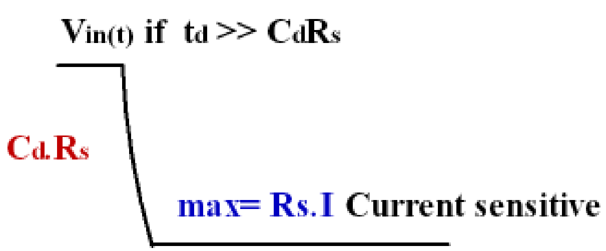
Detector impedance and input voltage

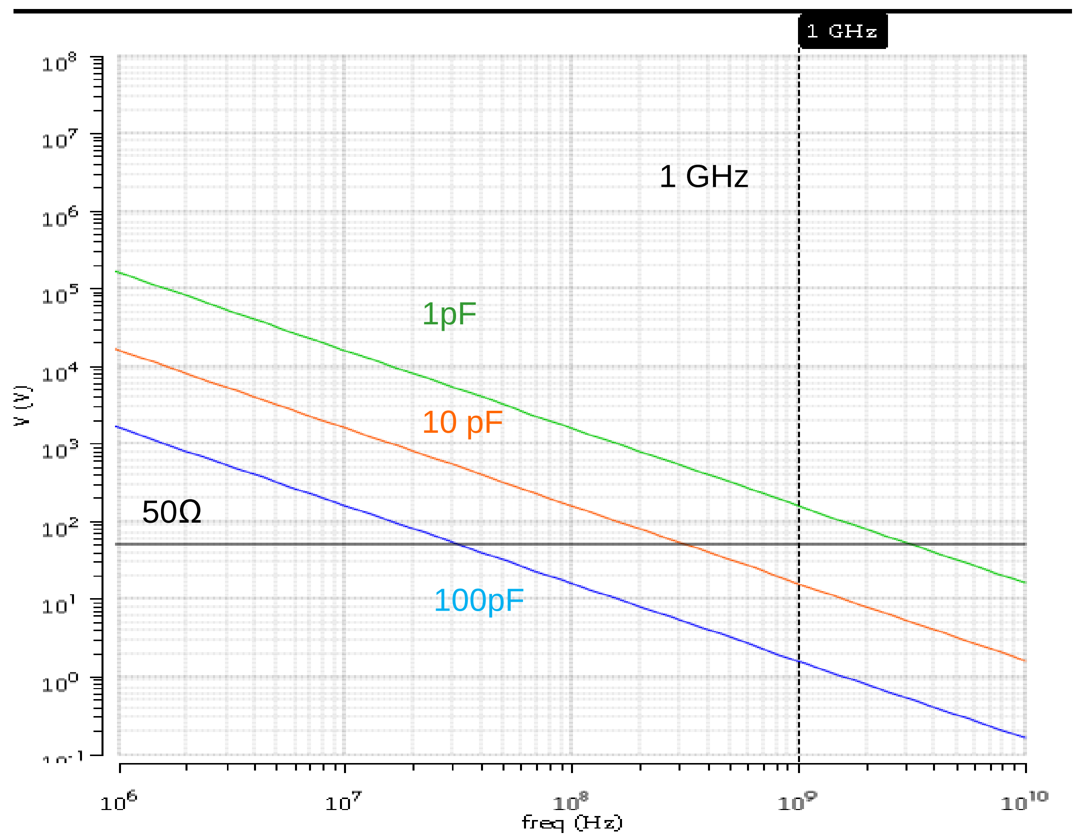
- 1 GHz, Cd=few tens of pF, input signal width <1ns
- Cd>1 pF, Zs@1GHz dominated by Cd
- Rise time: tr= td when td<< $R_S C_d$ and tr= $R_S C_d$ when td>> $R_S C_d$



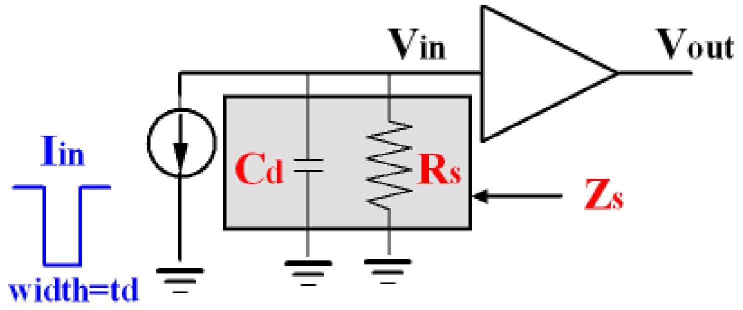
At HF : difficult to beat the capacitance => signal integrated on Cd

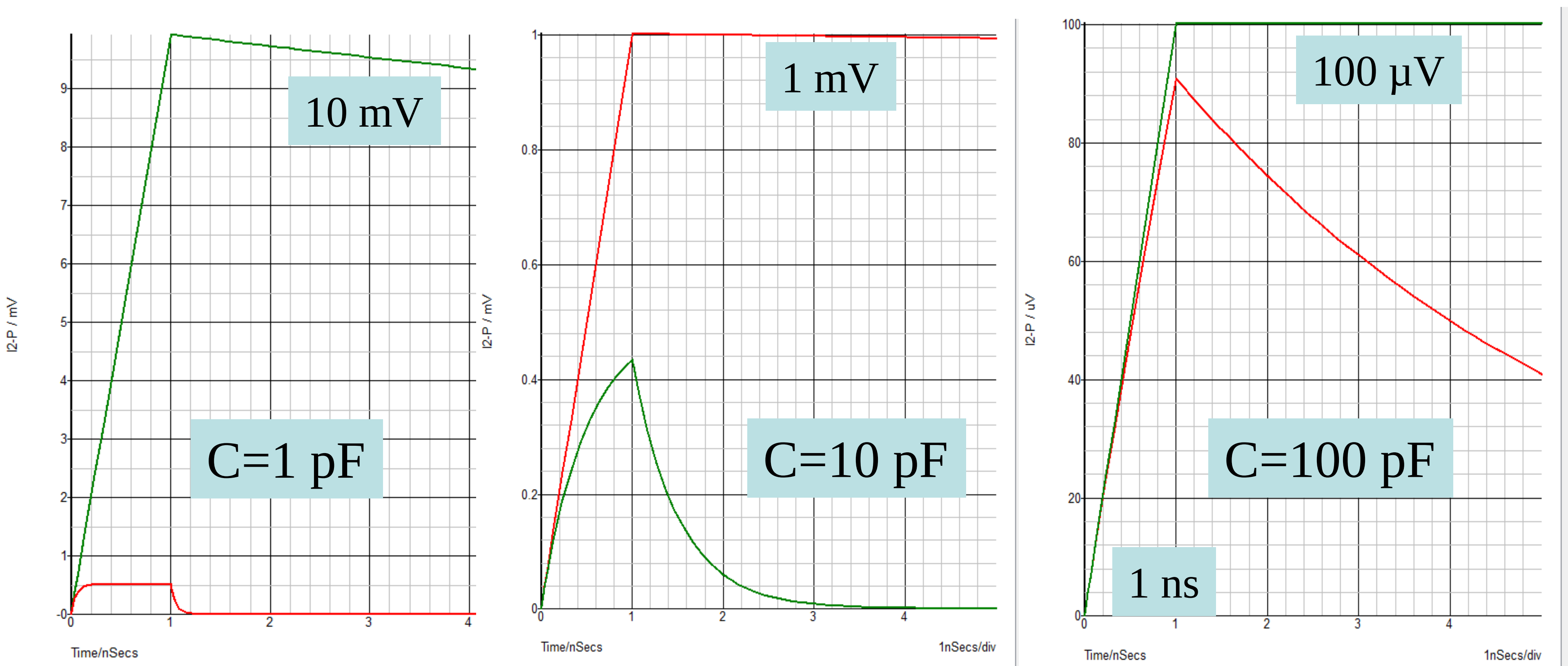






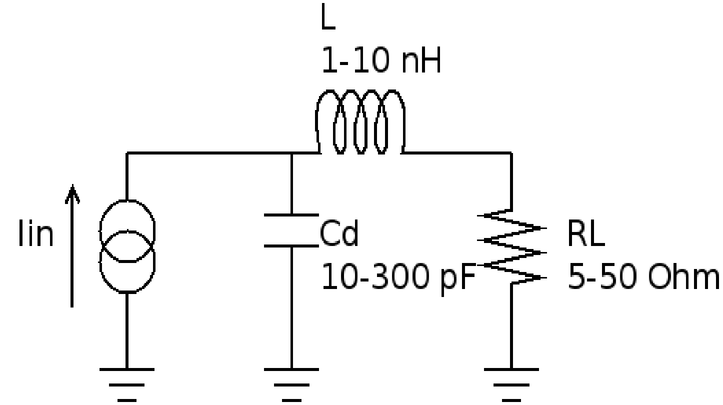
- *Example* : 10 fC – 1 ns signal from 1-10-100 pF sensors into 50 Ω (current) or 50k (voltage) preamp

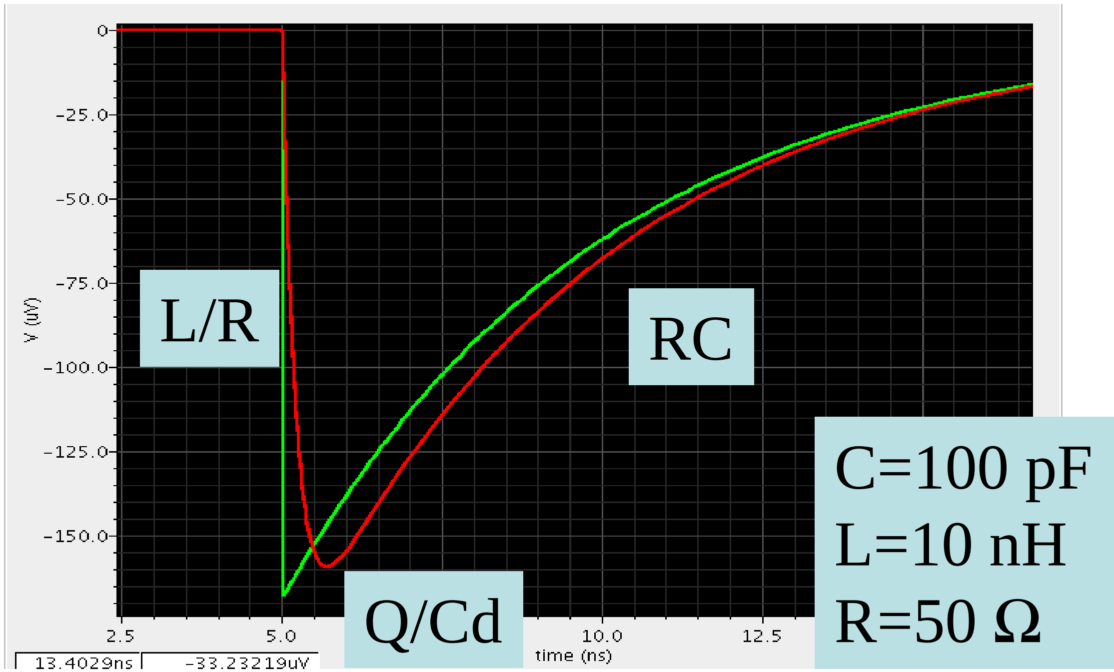


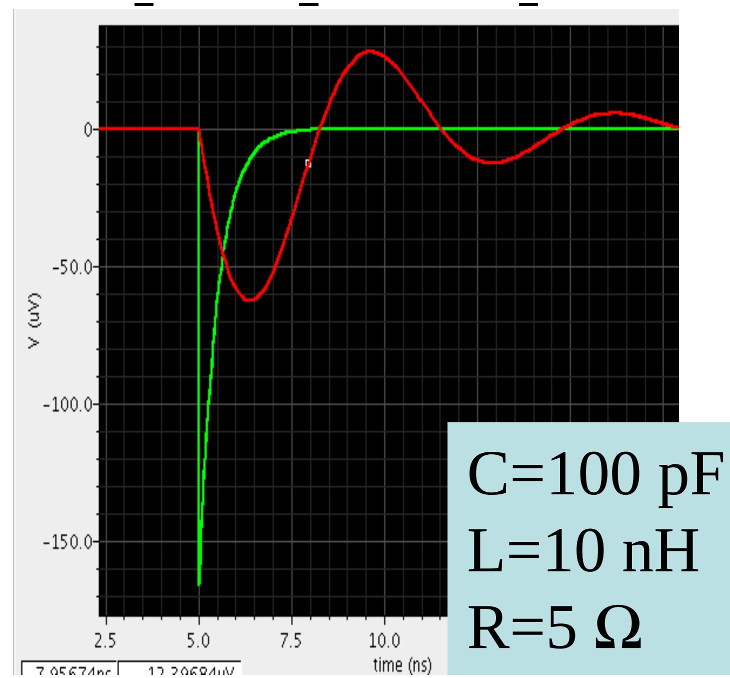


Omega

- SiPM pulse : Q=160 fC, Cd=100 pF, L=0-10 nH, R_{PA}=5-50 Ω
- Sensitivity to parasitic inductance
- Choice of R_{PA} : decay time, stability
- Small R_{PA} not necessarily the fastest
- Convolve with current shape… (here delta)

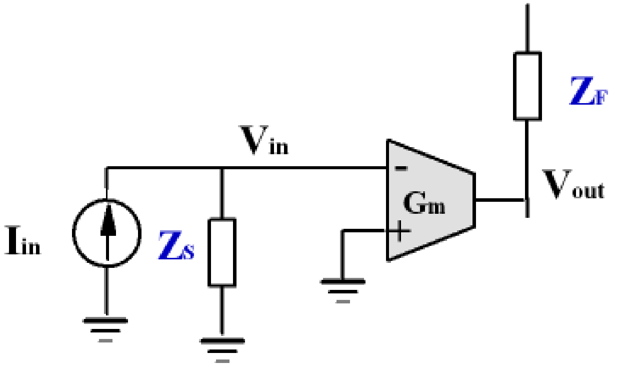




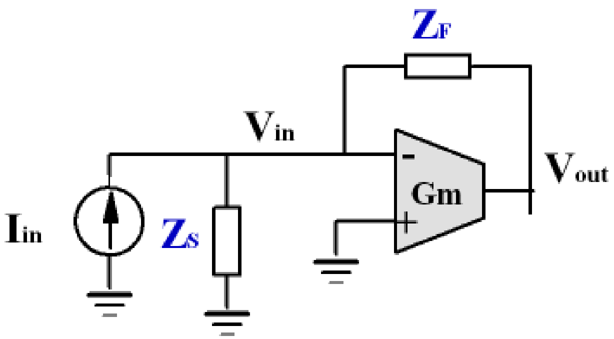


- Response to very short pulse

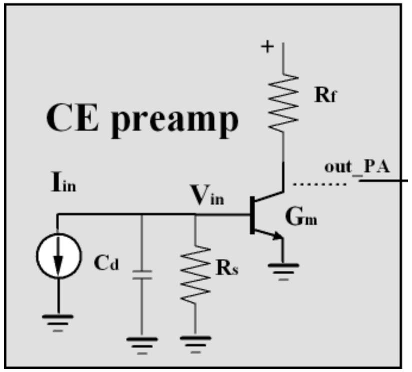
- Broadband
  - Zin=Rs (50 Ohm)
  - Vin = Q/Cin
  - $V_{OUT} = -G_m R_F \frac{Q_{IN}}{C_d}$



- Transimpedance
  - Zin ~ Zf/G ~ 1/gm
  - $V_{OUT} = \frac{\frac{1}{G_m} - R_F}{1 + j\omega\frac{C_d}{G_m}} I_{IN} \approx -G_m R_F \frac{Q_{IN}}{C_d}$



- Same response at High Frequency
- For highest speed : go to broadband. Faster, less stability issues



- Jitter is given by [details in backup] :

$$\sigma_t^J = \frac{N}{dV/dt} = \frac{e_n}{\sqrt{2t_{10-90\_PA}}} \frac{C_d \sqrt{t_{10-90\_PA}^2 + t_d^2}}{Q_{in}} = \frac{e_n C_d}{Q_{in}} \sqrt{\frac{t_{10-90\_PA}^2 + t_d^2}{2t_{10-90\_PA}}}$$

- Optimum value: $t_{10-90\_PA} = t_d$ (current duration)

$$\sigma_t^J = \frac{e_n C_d}{Q_{in}} \sqrt{t_d}$$

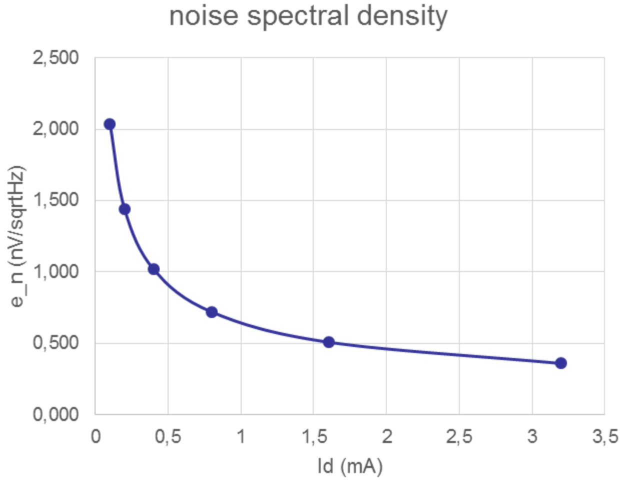
Cd: detector capacitance
$t_{10\_10\_PA}$: rise time of the PA
t_d= drift time of the detector
e_n preamp noise density

Dominated by sensor
Electronics only gives the spectral density of the input transistor e_n

- Gives ps/fC as scales with 1/Qin

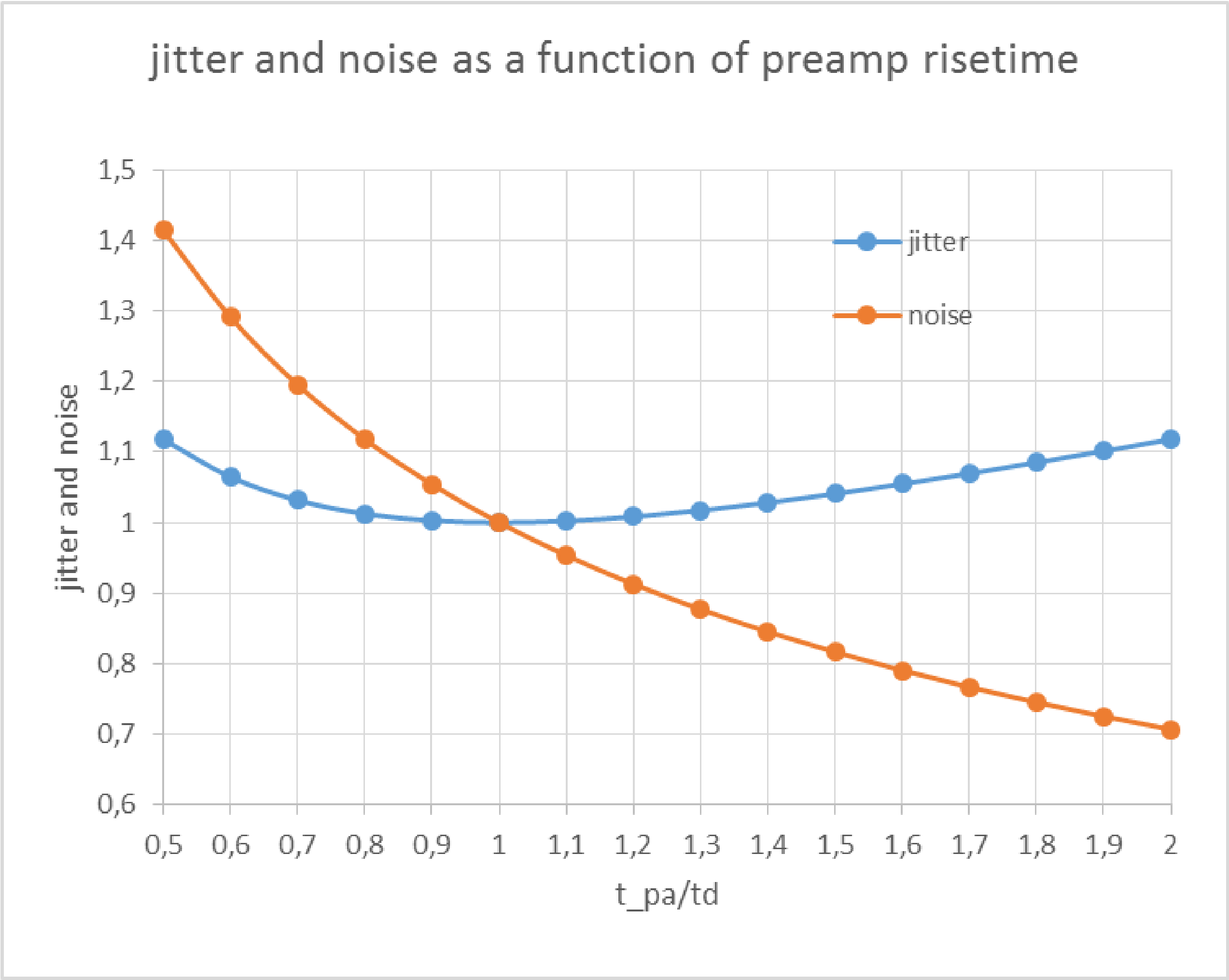
- Electronics noise e_n given by the input transistor transconductance g_m:

$$e_n = \sqrt{\frac{2kT}{g_m}} \approx \frac{2kT}{\sqrt{qI_D}}$$



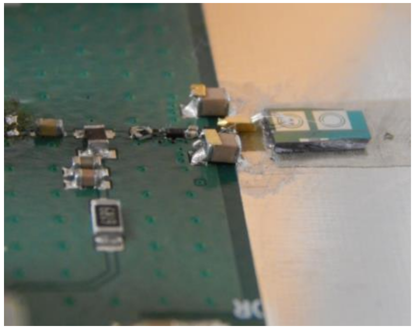
Jitter and minimum threshold

- Jitter optimum is rather shallow with preamp risetime
- But noise and minimum threshold goes up quickly with speed (as sqrt)



$$\sigma_t^J = \frac{e_n C_d}{Q_{in}} \sqrt{t_d}$$

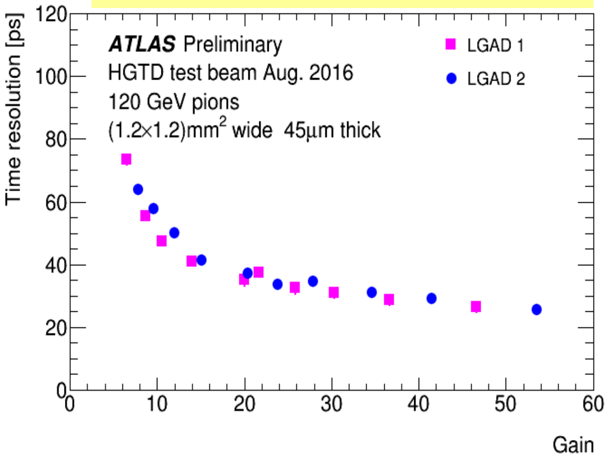
- NA62 tracker : PIN diode thickness 300 µm A=0.09 mm²
  - C_d = 0.1 pF e_n = 11 nV/√Hz t_d = 3 ns σ = 60 ps/Q(fC)
  - 1 MIP = 3 fC => σ = 20 ps/#MIP (~60-200 ps measured)



- CMS HGCAL : PIN diode thickness 300 µm A=25 mm²
  - C_d = 8 pF e_n = 1 nV/√Hz t_d = 3 ns σ = 420 ps/Q(fC)
  - 1 MIP = 3.8 fC => σ = 110 ps/#MIP (~200 ps measured)

- ATLAS HGTD : LGAD diode thickness 50 µm A= 2 mm² G = 10
  - C_d = 2 pF e_n = 2 nV/√Hz t_d = 0.5 ns σ = 50 ps/Q(fC)
  - 1 MIP = 5 fC (G=10) => σ = 10 ps/#MIP (~40 ps measured

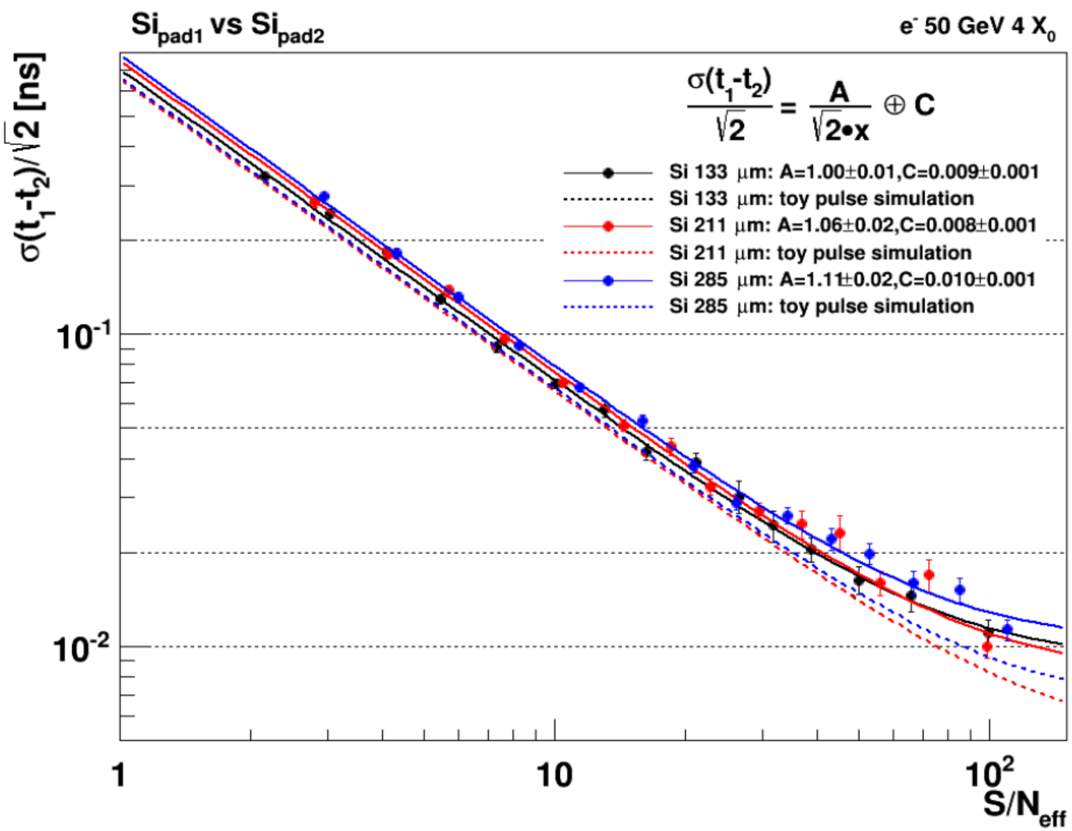
SiGe preamp © N. Spencer (UCSC)

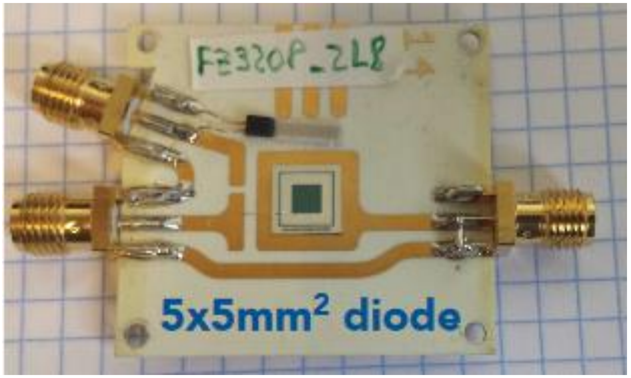


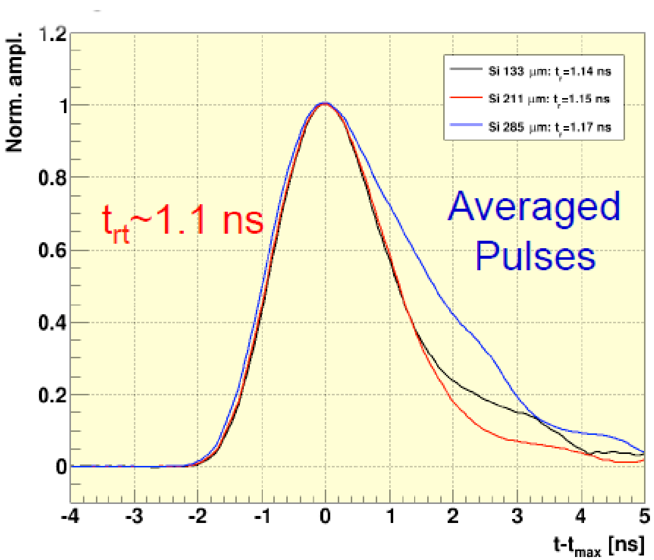
- SiPM G = 1E6
  - C_d = 300 pF e_n = 1 nV/√Hz t_d = 100 ps σ = 3 ns/Q(fC)
  - 1 pe = 160 fC => σ = 20 ps/#pe (~60 ps measured)

HGCAL timing performance

- CMS HGCAL testbeam measurements
- Jitter : j ~1 ns / S/N
  - But S and N depend on BW…
  - Parts come from detector and from electronics

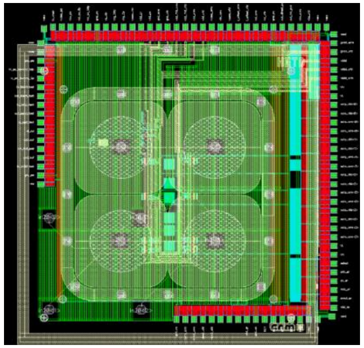






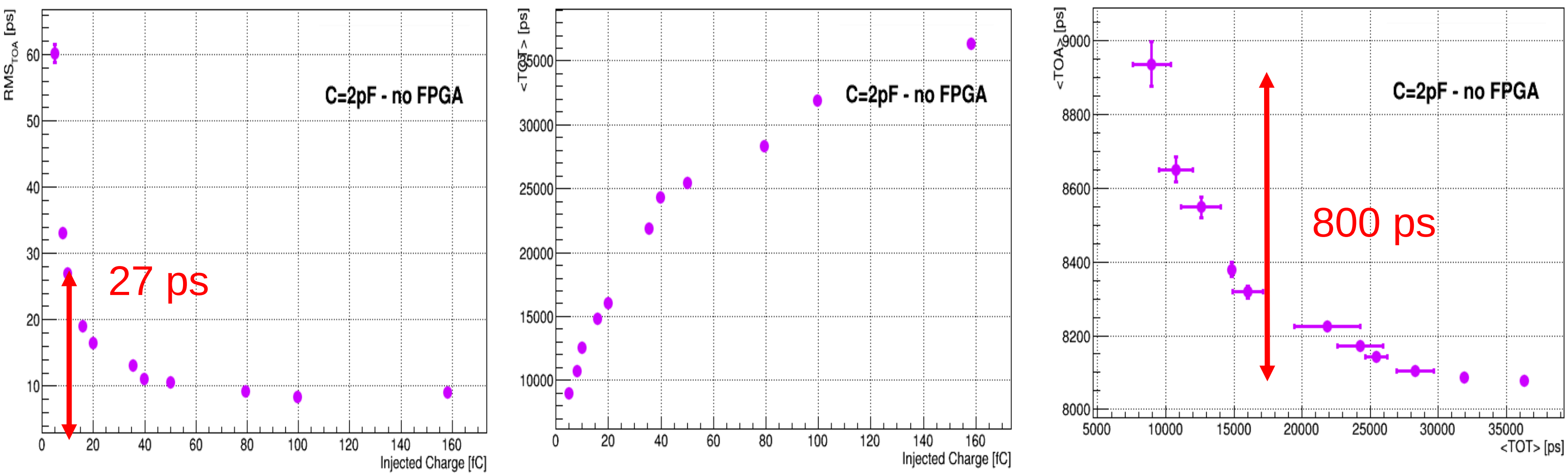
Example : HGTD measurements

Ωmega



- ALTIROC ASIC designed for HGTD (Atlas LGAD Timing Read-Out Chip)
  - Broadband amplifier + high speed discriminator Pd = 1 mW
  - Optimized for 1 mm² 50 µm LGAD (Cd=2 pF)
- TOA and TOT vs injected charge with additionnal Cd= 2 pF
- Preamp and testboard capacitance : ~1.3 pF
- Jitter = 27 ps @ 10 fC
- Time walk = 800 ps

© C. Agapopoulou LAL

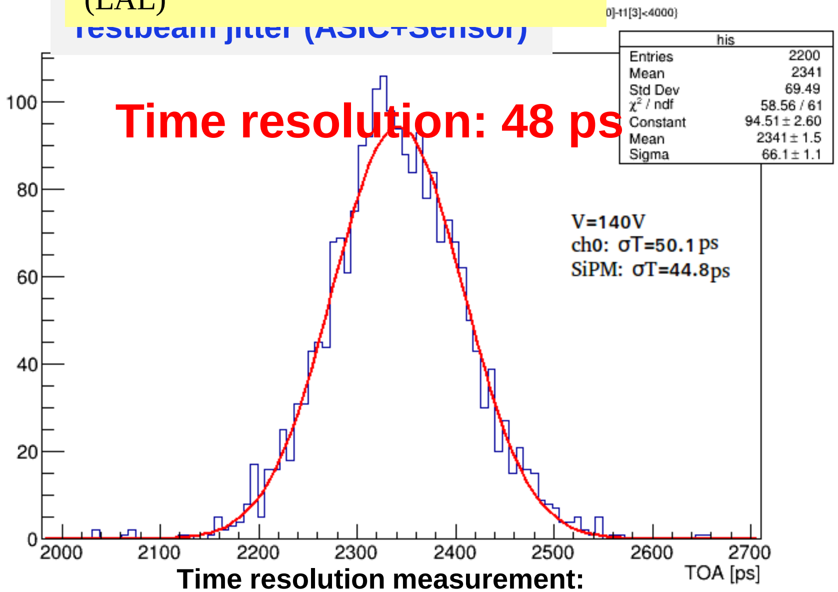


Testbeam with ASIC + sensor (Sept 2017)

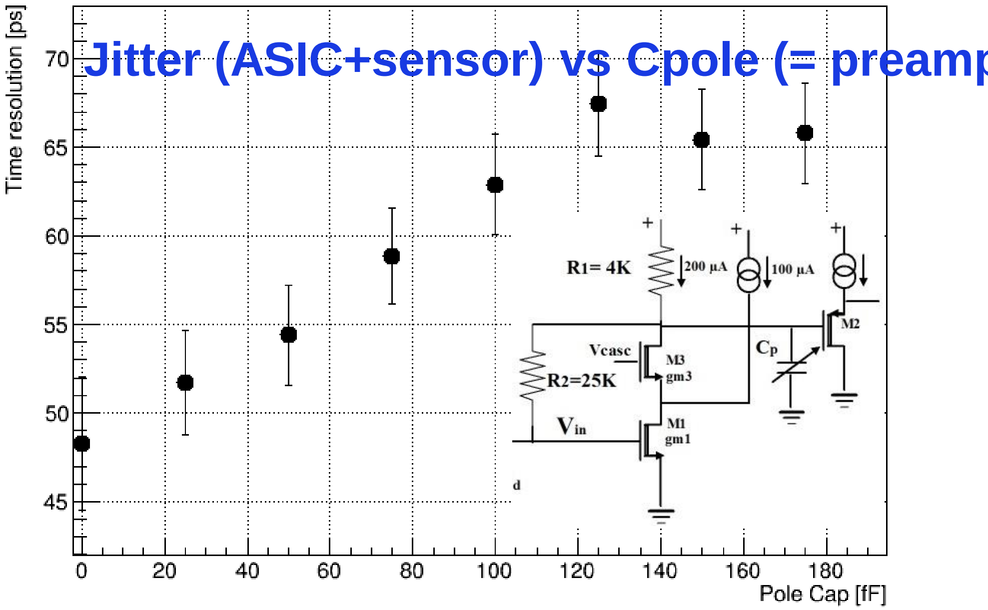
Ωmega

- 1x1 mm² sensors fabricated by CNM/IFAE Barcelona
- Bump-bonded to ALTIROC0 at Barcelona
- Sensor biased at - 80 V
- **Testbeam** measurement **ASIC+Sensor (LGAD signal)**= **48 ps**

© C. Agapopoulou N. Makovec (LAL)



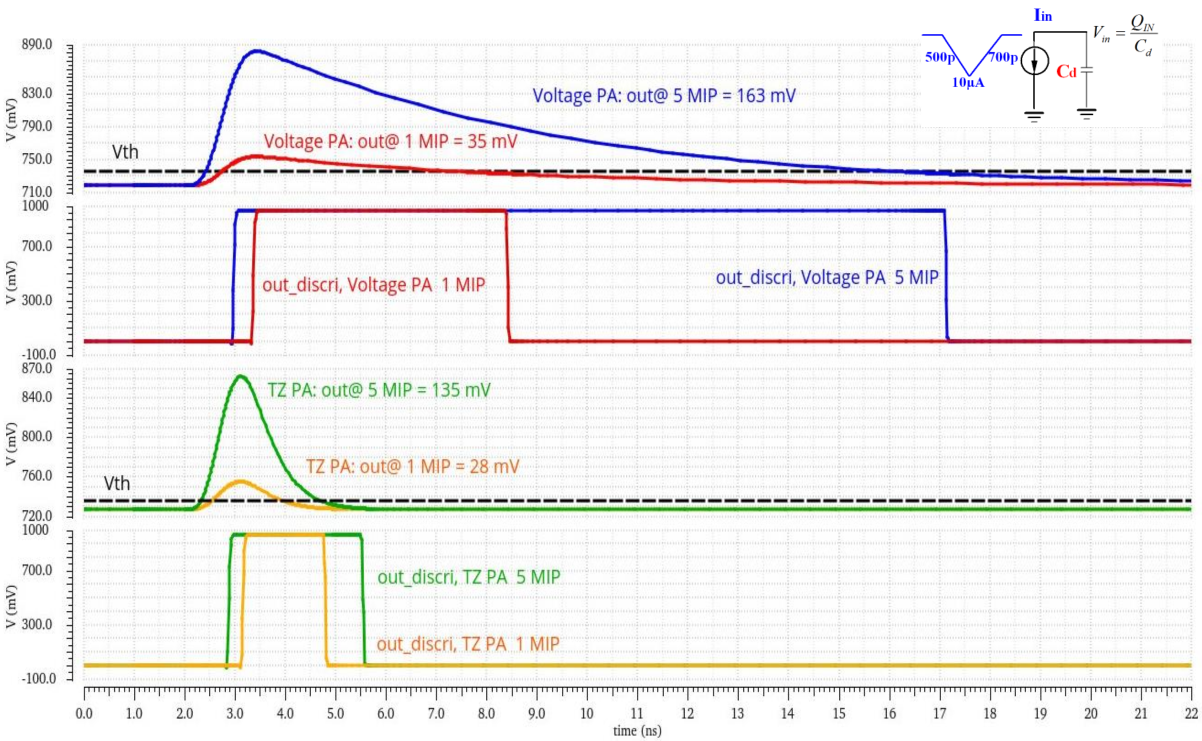
Time resolution measurement:
σ^{fit} of $t_{ASIC} - t_{SiPM}$ distribution

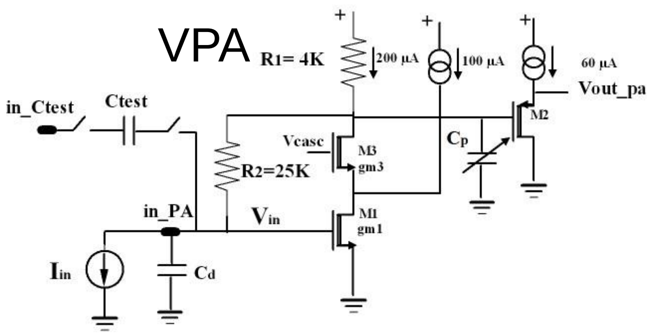


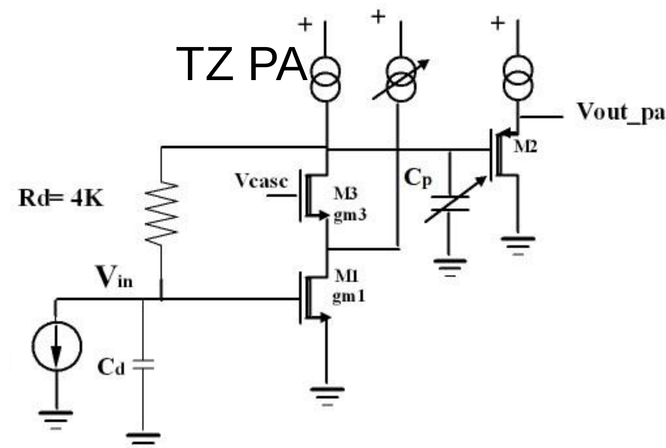
- Jitter: calculation gives the same result for VPA and TZ

- Fall time given by 2.2* Rin_pa * Cd
Rin_TZ pa =150 Ω whereas Rin_Voltage PA ~ 1.5 KΩ
=> **TOT_TZ (few ns) very different from TOT_VPA**

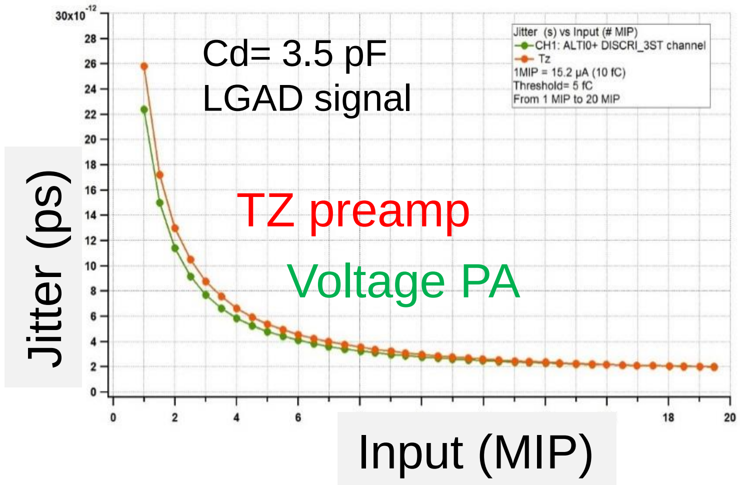
$$\sigma_t^J = \frac{e_n C_d}{Q_{in}} \sqrt{t_d}$$

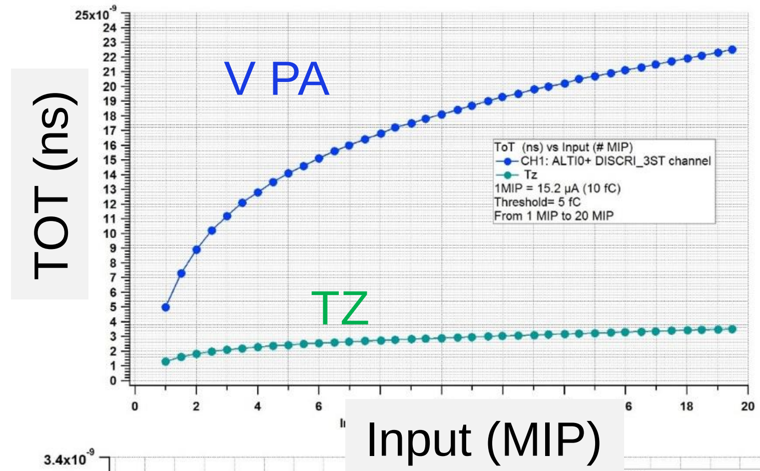


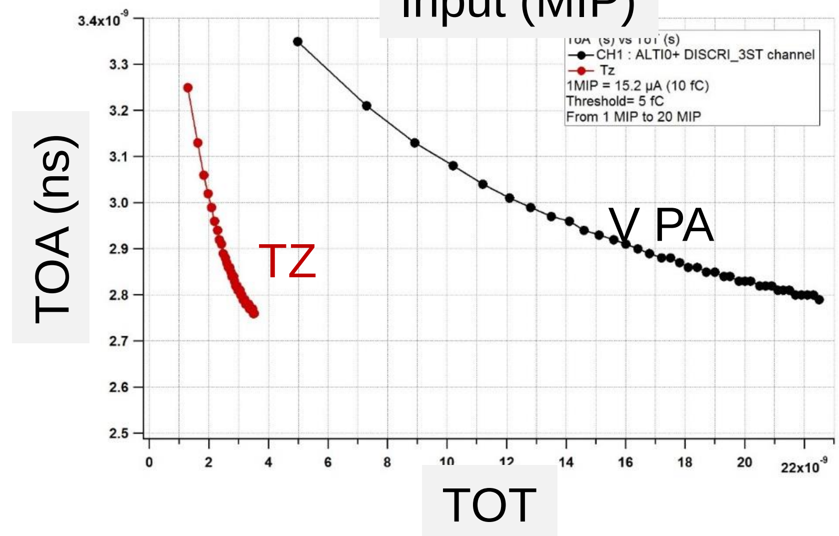




VPA, TZ PA and discriminator simulations







Jitter similar for TZ and VPA architectures but

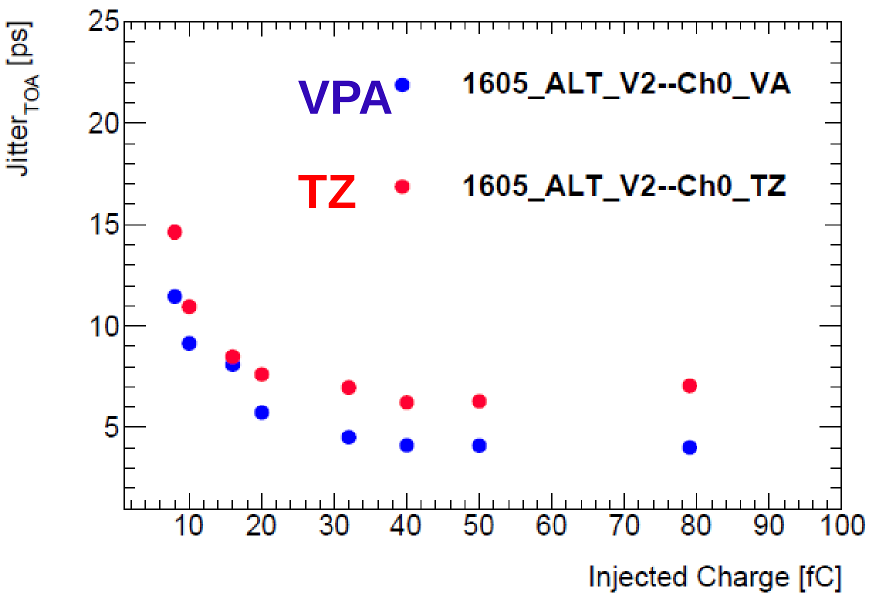
TOA vs TOT sensitivity very different between these 2 architectures

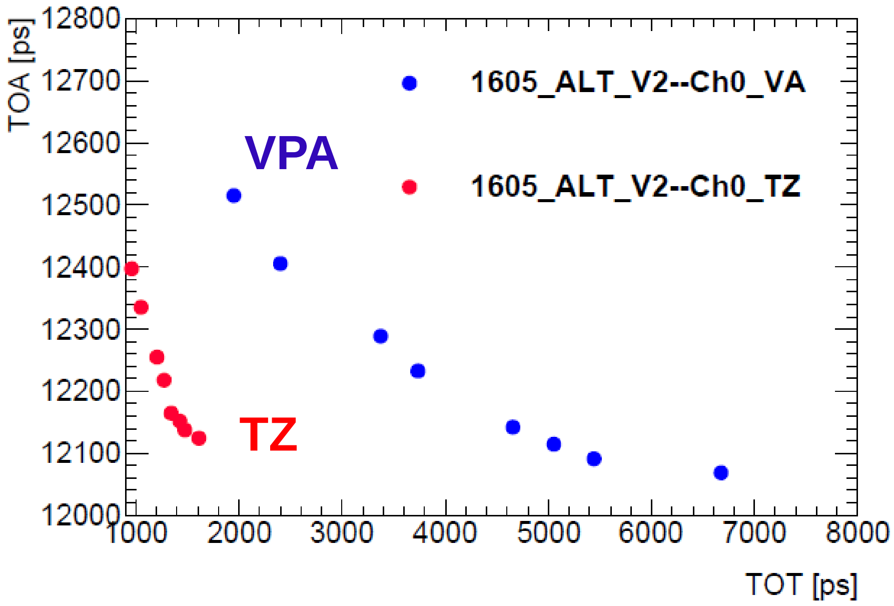
⇒ TDC for TOT meas. different for VPA and TZ_PA

⇒ Better resolution needed for TZ

ALTIROC0_V2 measurements

- ALTIROC0_V2 (Submission December 2017) : same as ALTIROC0_V1 but faster VPA and the four 20pF- channels replaced by 4 TZ preamps





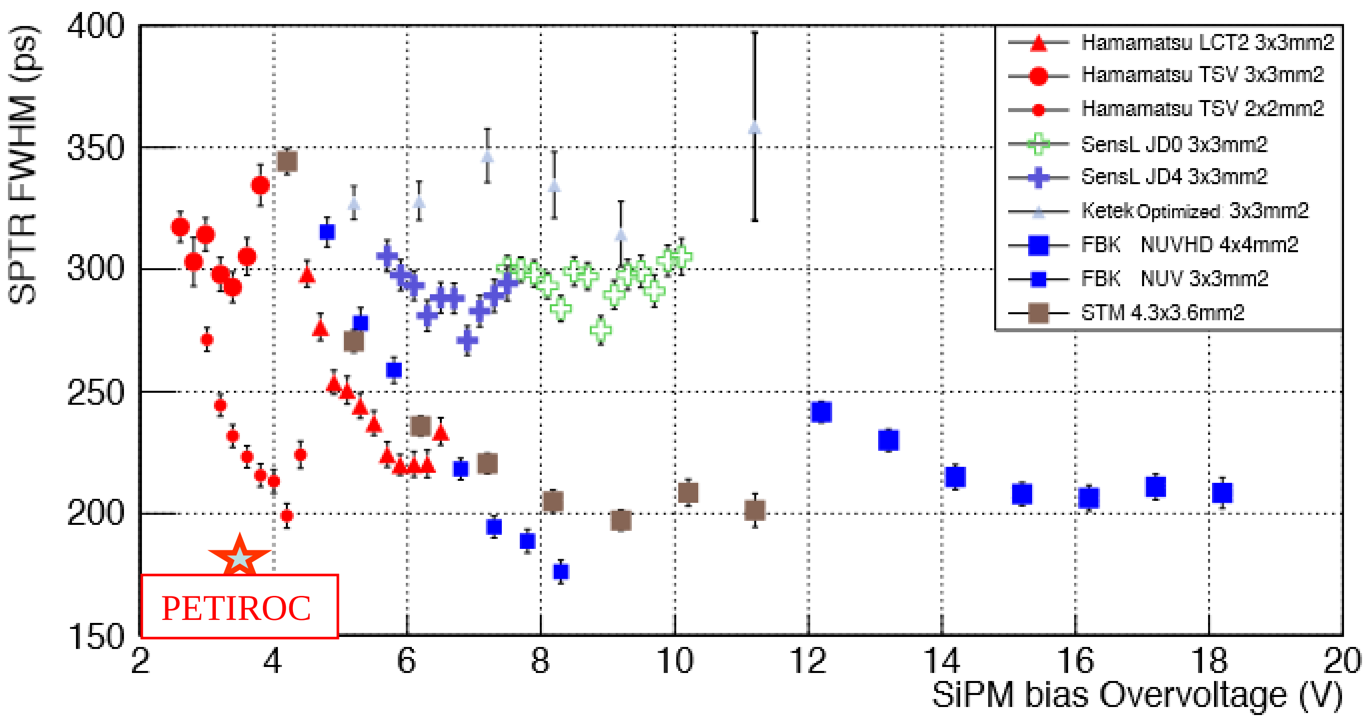
With SiPMs : SPTR [JINST 11 P10016]

- SPTR
  - FWHM ~200 ps
  - Rms ~ 80 ps

Single photon time resolution of state of the art SiPMs

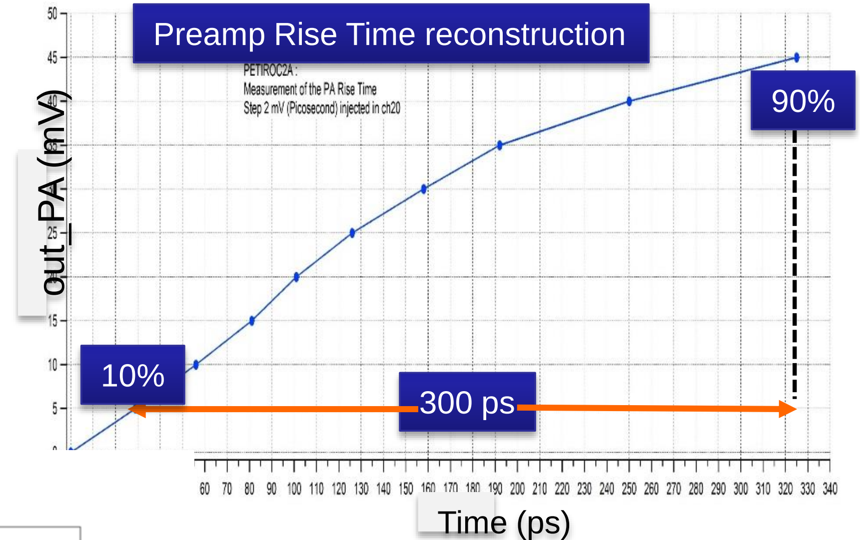
M.V. Nemallapudi,[1] S. Gundacker, P. Lecoq and E. Auffray

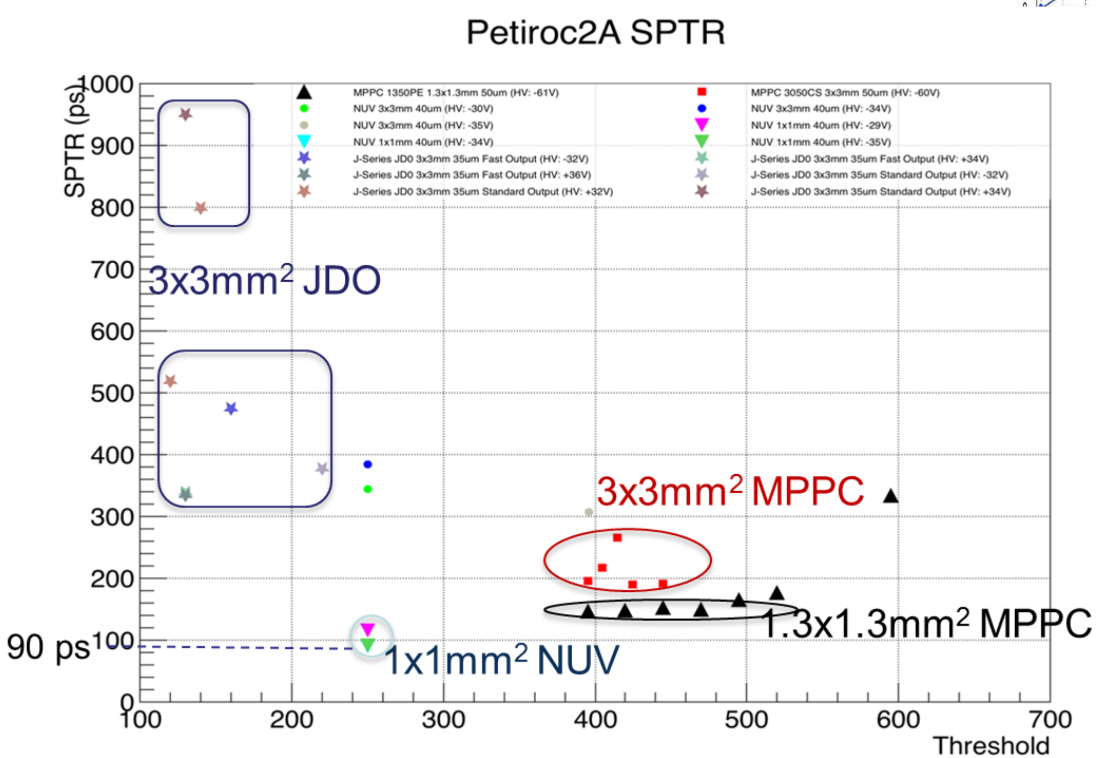
CERN,
23 Rue de Meyrin, Geneva, 1211-CH

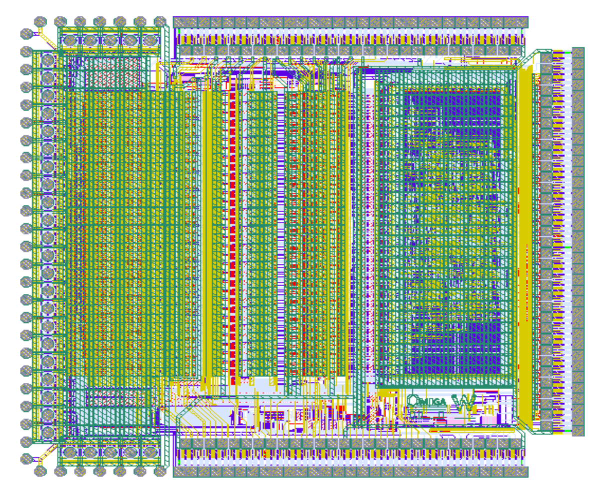


Going to lower SPTR

- Expect ~ 20 ps/pe
- NINO risetime ~1 ns
- Test with PETIROC2 (tr = 300 ps)
  - 1 GHz preamp and discri
  - SPTR = 40 ps rms (90 ps FWHM)
- Possible effect of stray inductance







© J. Fleury TIPP17

weeroc

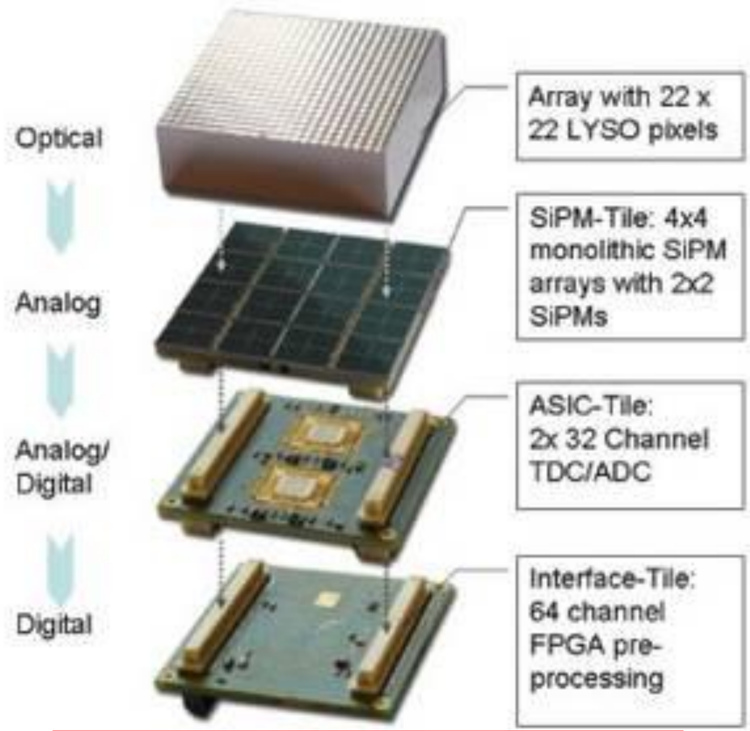
- Imaging calorimeters ramping up !
  - Require highly integrated R/O electronics : System On Chip
  - Low power, low noise, high speed, large dynamic range
  - Timing capability down to a few tens of ps
  - Lots of system issues

- Timing performance dominated by sensor characteristics
  - Capacitance, duration, MIP charge
  - Theory predicts :
  - Electronics affects only $g_m \sim Id/2U_T$

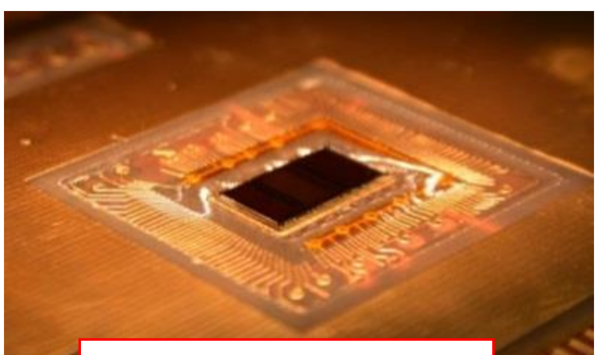
$$\sigma_t^{\,J} = \frac{e_n C_d}{Q_{in}} \sqrt{t_d}$$

- Work getting organized towards 10 ps (1 ps ?) timing

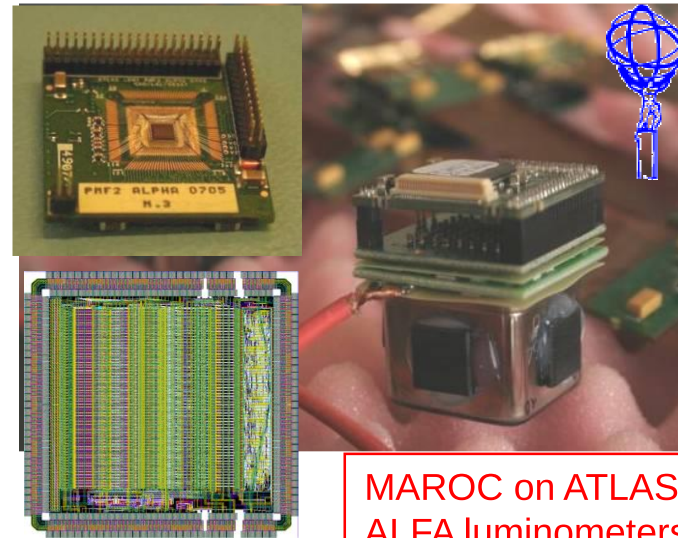
Electronics moves onto detectors



PET hyperimage project [P. Fisher]



SKIROC on ILC ECAL



MAROC on ATLAS ALFA luminometers

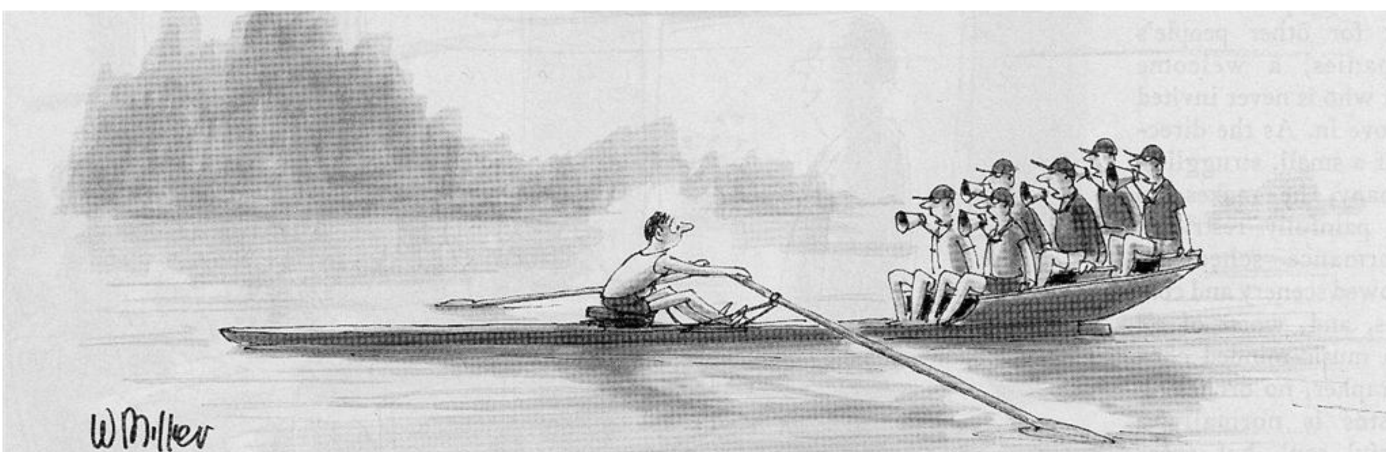
1m² RPC detector for ILC DHCAL [I. Laktineh]

Conclusion

- Importance of electronics in detector performance
- Electronics getting more and more integrated on/in detectors (and vice versa !)
- Importance of team building

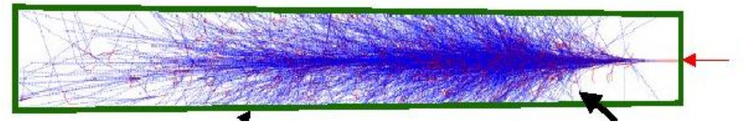
Microelectronics design teams

- Importance of team building

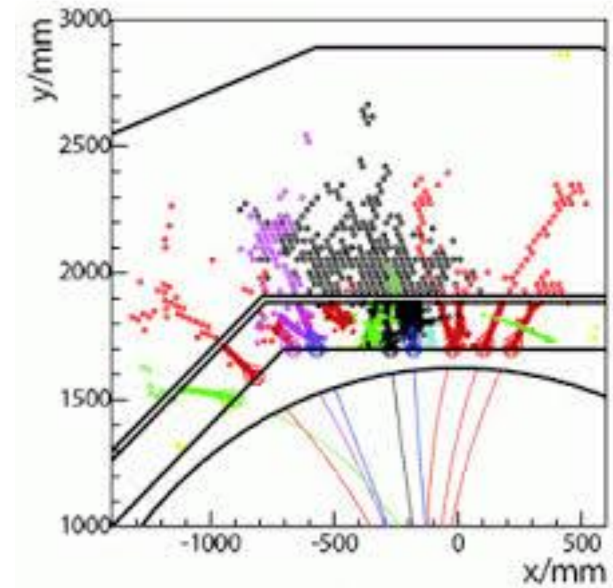


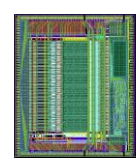
backup

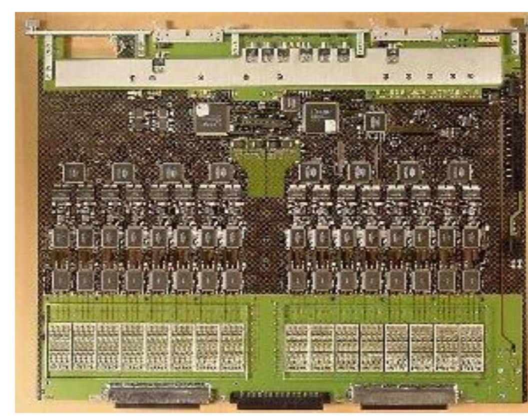
Evolution of calorimetry



- 3D calorimetry : eta, phi, Energy
- 4D calorimetry : x,y,z,E
- 5D calorimetry : x,y,z,E,t
  - High granularity=> Millions of channels = > Low power !
    - Power pulsing ~1% for ILC
    - Low power + C02 cooling for HL-LHC
  - Energy measurement : Large dynamic range
    - MIP sensitivity => low noise (~0.1 fC)
    - Up to thousands of MIPs (~10 pC)
  - Timing information
    - Nice addition for ILC for PID : few ns is enough
    - Crucial for HL-LHC : pileup mitigation, need few tens of ps
  - Embedded electronics vs data out
    - Daisy chain and low power busses for ILC
    - High speed e/optical links for HL-LHC
  - Radiation levels
    - Negligible at an ILC
    - Daunting at HL-LHC : >100 Mrad $1^{E}16N$



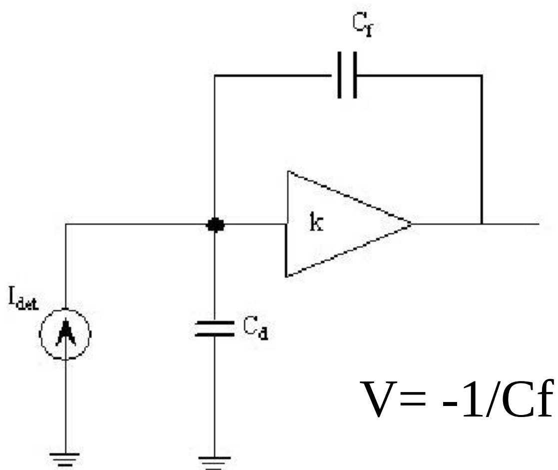




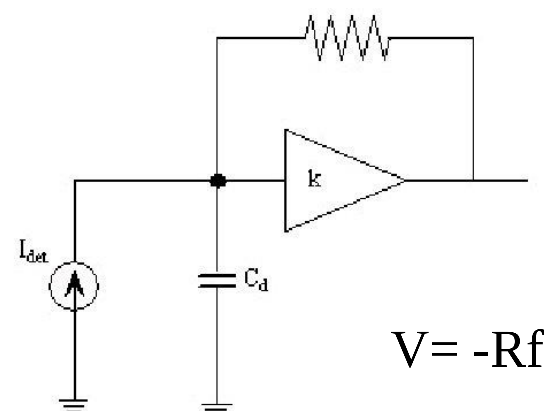
Charge and Current preamps

- Charge preamp
- Capacitive feedback Cf
- Vout/Iin = - 1/jωCf
- Perfect integrator : vout=-Q/Cf∫
- Difficult to accomodate large SiPM signals (200 pC)
- Lowest noise configuration
- Need Rf to empty Cf

- Current preamp
- Resistive feedback Rf
- Vout/Iin = - Rf
- Keeps signal shape
- Need Cf for stability

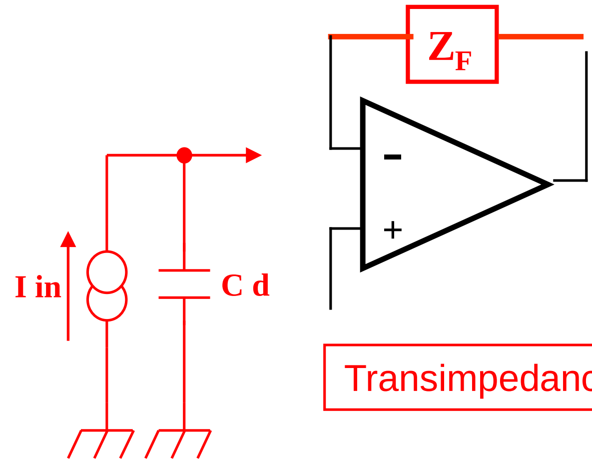


$$V = -1/Cf \int i(t)dt$$

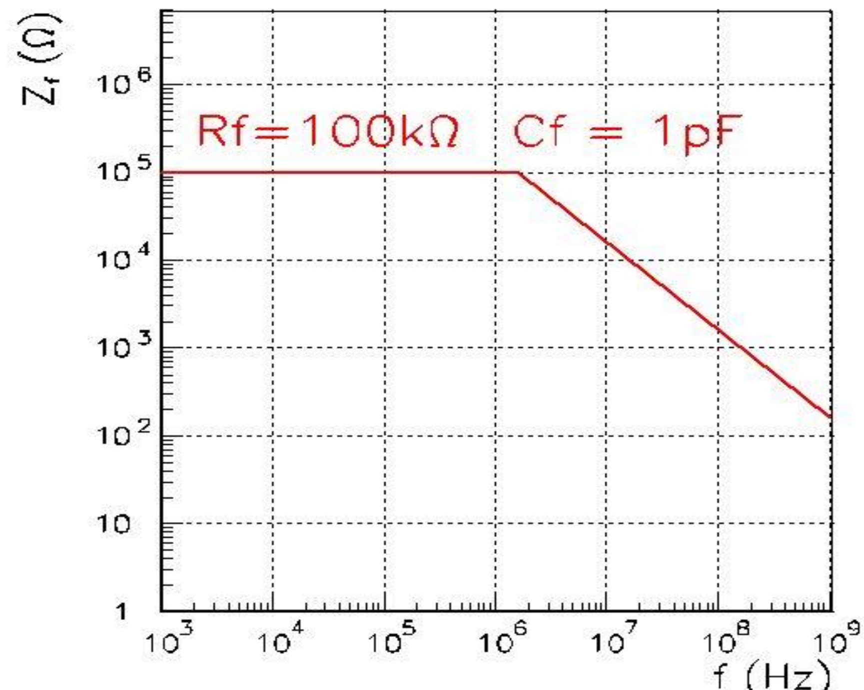


$$V = -Rf\ \ i(t)$$

- Transfer function
  - Using a VFOA with gain G
    - $V_{out} - v_{in} = - Z_f \, i_f$
    - $V_{in} = Z_d \, (i_{in} – i_f) = - v_{out}/G$
  - $V_{out}(\omega)/i_{in}(\omega) = - Z_f / (1 + Z_f /GZ_d)$
- $Zf = Rf / (1 + j\omega RfCf)$
  - At $f << 1/2\pi RfCf$:
    $V_{out}(\omega)/i_{in}(\omega) = - R_f$
    current preamp
  - At $f << 1/2\pi RfCf$:
    $V_{out}(\omega)/i_{in}(\omega) = - 1/j\omega C_f$
    charge preamp
- Ballistic deficit with charge preamp
  - Effect of finite gain : G_0
  - Output voltage «only» Q C_d/G_0C_f



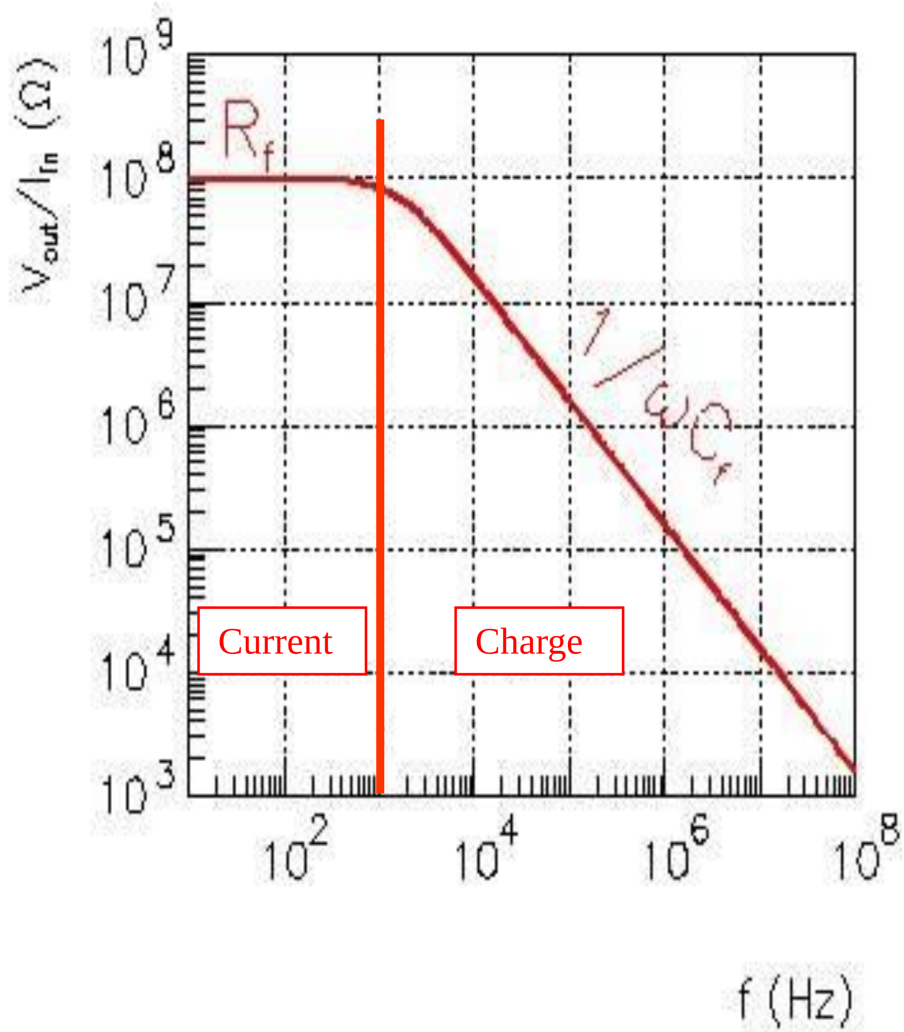
Transimpedance amplifier



Transfer function

Charge vs Current preamps

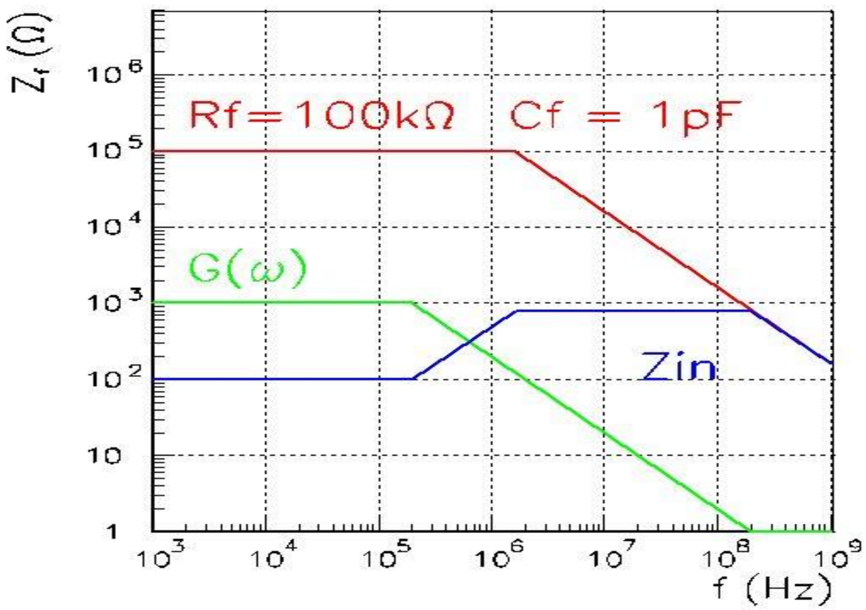
- Charge preamps
  - Best noise performance
  - Best with short signals
  - Best with small capacitance
- Current preamps
  - Best for long signals
  - Best for high counting rate
  - Significant parallel noise
- Charge preamps are not slow, they are long
- Current preamps are not faster, the are shorter (but easily unstable)



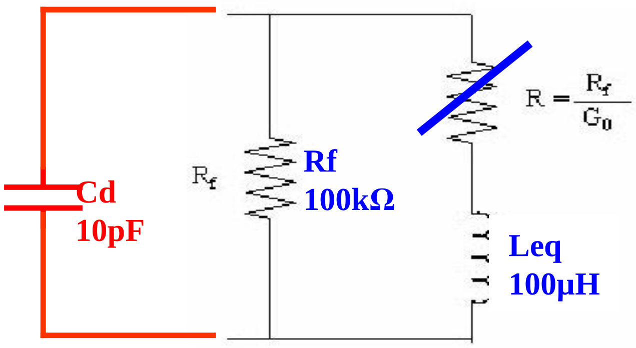
Input impedance

- Input impedance
  - Zin = Zf / G+1
  - Zin->0 virtual ground
  - Minimizes sensitivity to detector impedance
  - Minimizes crosstalk

- Equivalent model
  - $G(\omega) = G_0/(1 + j\ \omega/\omega_0)$
- Terms due to Cf
  - $Zin = 1/j\omega\ G_0C_f + 1/\ G_0\omega_0\ C_f$
  - Virtual resistance : $Req = 1/\ G_0\omega_0\ C_f$
- Terms due to Rf
  - $Zin = R_f/\ G_0 + j\ \omega\ R_f/\ G_0\omega_0$
  - Virtual inductance : $Leq = R_f/\ G_0\omega_0$
- Possible oscillatory behaviour with capacitive source



Input impedance or TZA



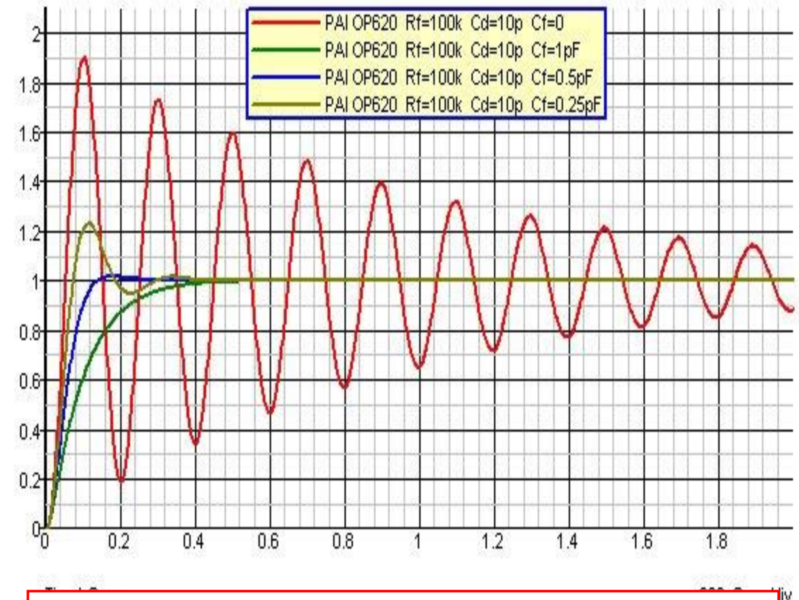
Equivalent circuit at the input

Current preamplifiers :

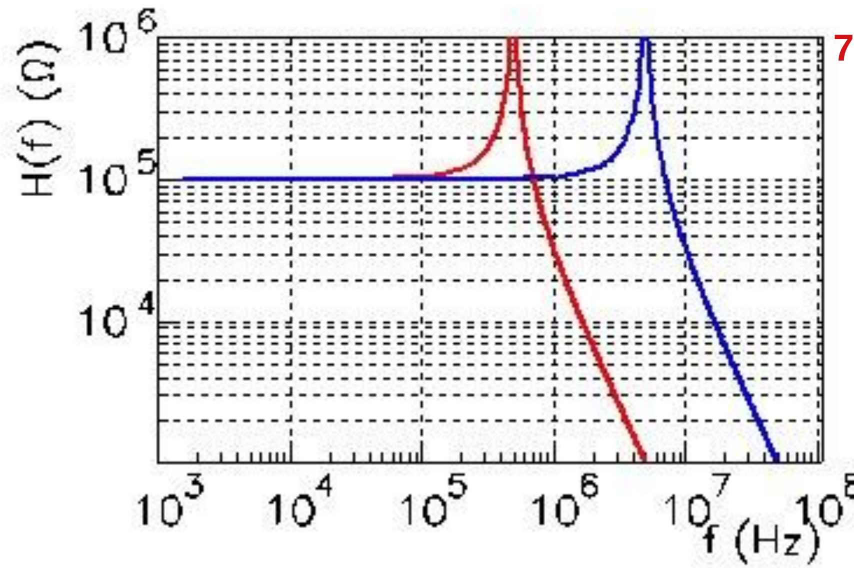
- Easily oscillatory
  - Unstable with capacitive detector
  - Inductive input impedance : L_{e} $= R_f / \omega_C$
  - Resonance at : $f_{res} = 1/2\pi \sqrt{L_{eq} C_d}$
  - Quality factor : $Q = R / \sqrt{L_{eq}/C_d}$
    - $Q > 1/2$ -> ringing
  - Damping with capacitance C_f
    - $C_f = 2 \sqrt{(C_d / R_f\, G_0 \omega_0)}$
    - Easier with fast amplifiers

- In frequency domain
  - $H(j\omega) = -Rf / (1 + j\omega\, RfC_d/))$
  - $G(\omega) = G_0 / (1 + j\omega/\omega_0)$

$H = - Rf / (1 + j\omega\, R_f C_d / G_0 - \omega^2 R_f C_d / G_0 \omega_0)$

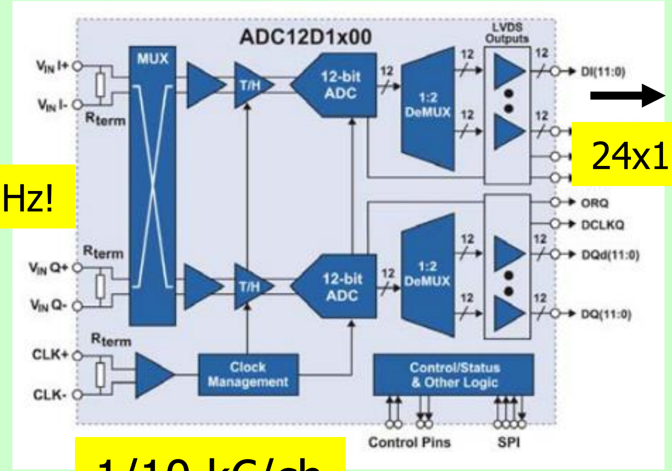


Step response of current sensitive preamp



FADCs

- 8 bits – 3 GS/s – 1.9 W → 24 Gbits/s
- 10 bits – 3 GS/s – 3.6 W → 30 Gbits/s
- 12 bits – 3.6 GS/s – 3.9 W → 43.2 Gbits/s
- 14 bits – 0.4 GS/s – 2.5 W → 5.6 Gbits/s



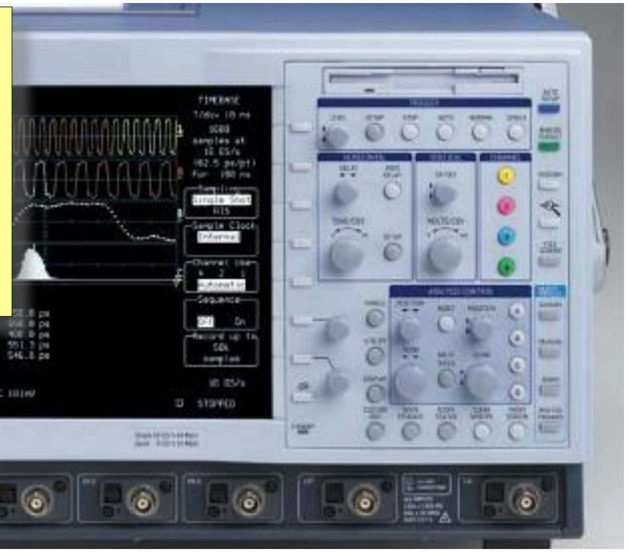
1.8 GHz!

24x1.8 Gbits/s

1/10 k€/ch

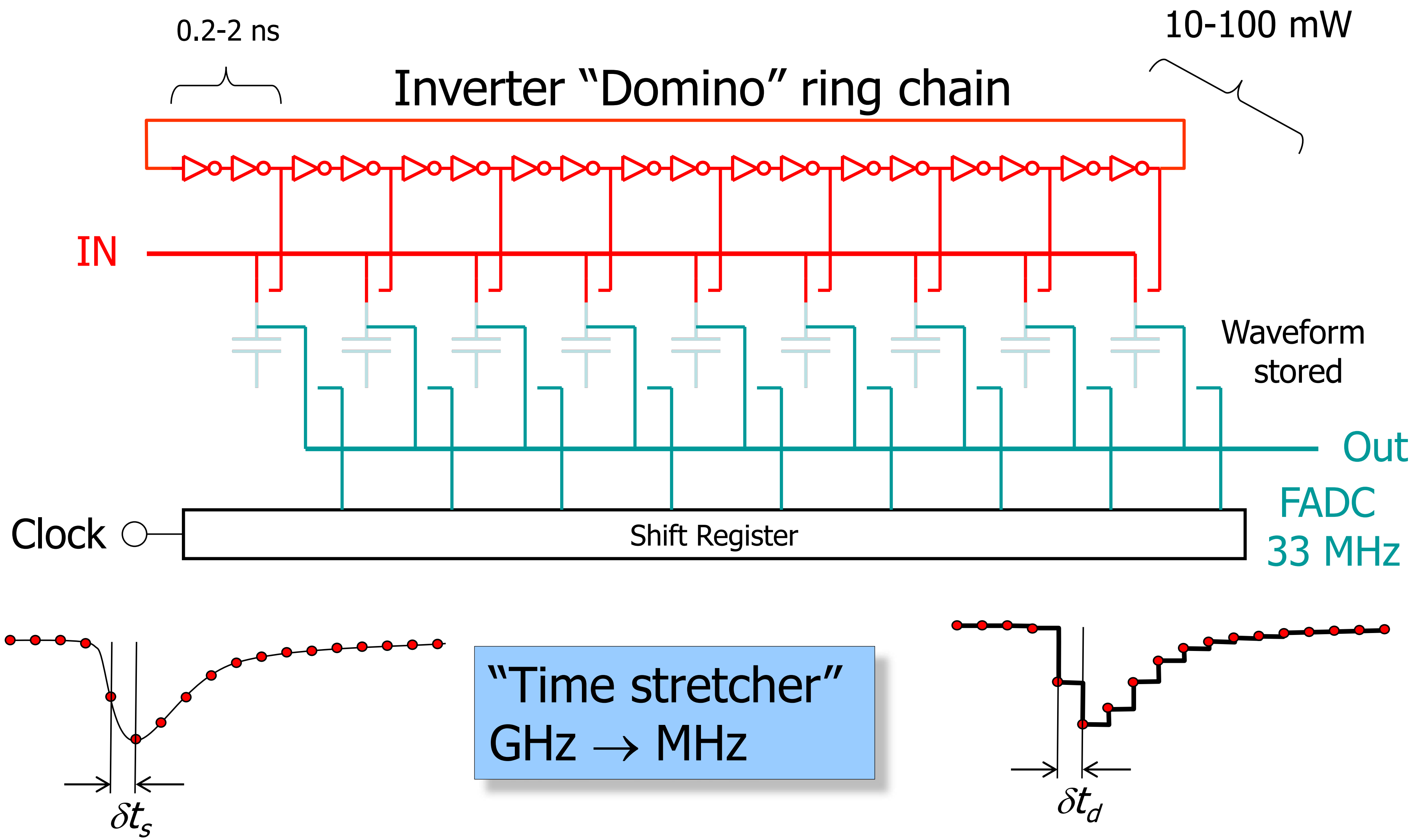
PX1500-4:
2 Channel
3 GS/s
8 bits

4 channels
5 GSPS
1 GHz BW
8 bit (6-7)
15k€

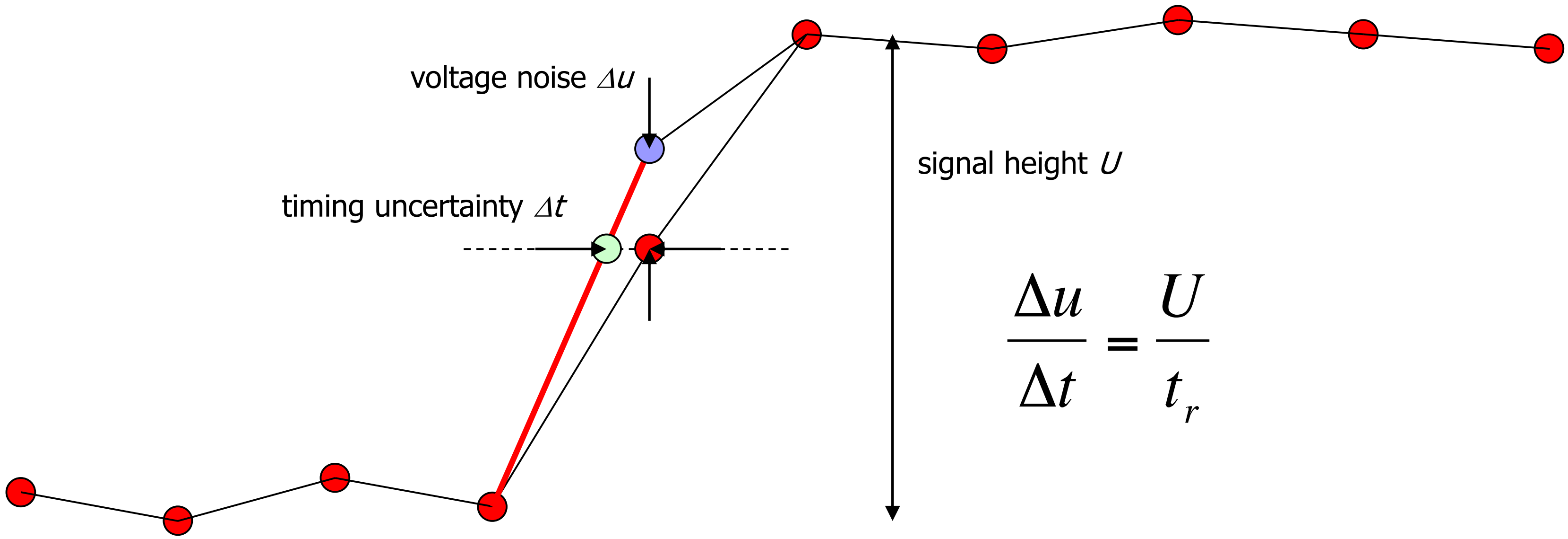


4 channels
5 GSPS
1 GHz BW
11.5 bits
900€
USB Power

Switched Capacitor Array (Analog Memory)



How is timing resolution affected?



$$\frac{\Delta u}{\Delta t} = \frac{U}{t_r}$$

$$\Delta t = \frac{\Delta u}{U} \cdot \frac{1}{\sqrt{3 f_s \cdot f_{3dB}}}$$

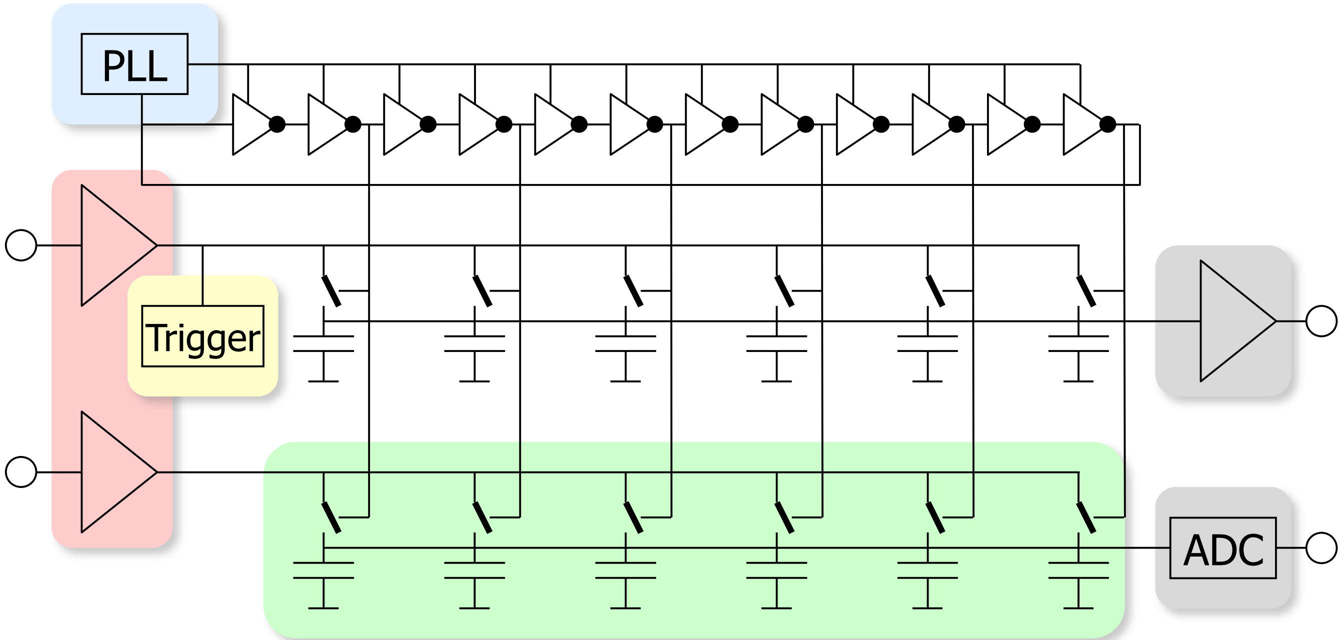
Assumes zero aperture jitter

	U	Δu	f_s	f_{3db}	Δt
today:	100 mV	1 mV	2 GSPS	300 MHz	~10 ps
optimized SNR:	1 V	1 mV	2 GSPS	300 MHz	1 ps
next generation:	1V	1 mV	10 GSPS	3 GHz	0.1 ps

Design Options

Ωmega

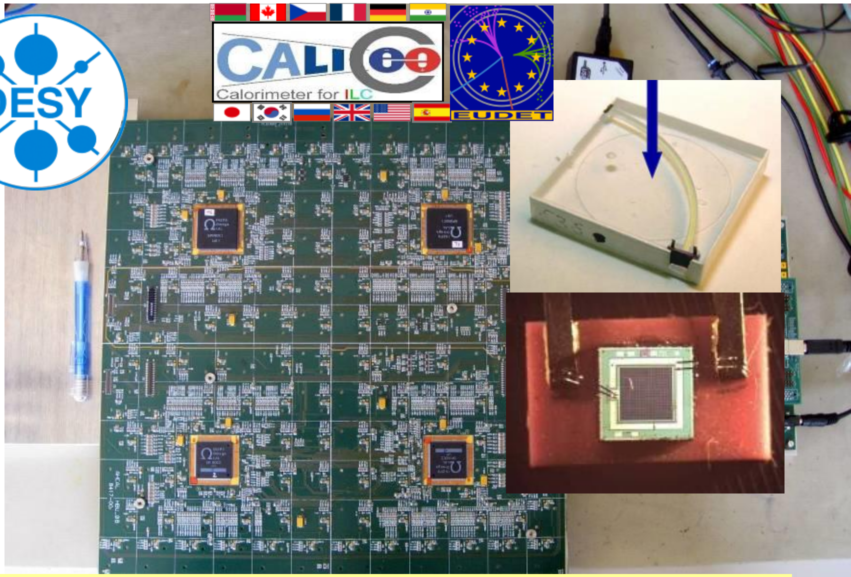
- CMOS process (typically 0.35 … 0.13 μm) → sampling speed
- Number of channels, sampling depth, differential input
- PLL for frequency stabilization
- Input buffer or passive input
- Analog output or (Wilkinson) ADC
- Internal trigger
- Exact design of sampling cell



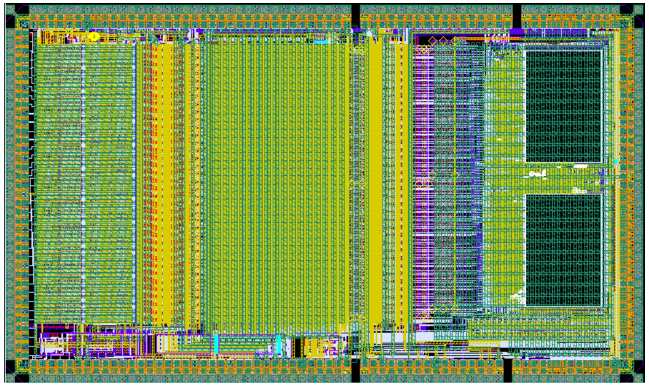
SPIROC : SiPM readout for AHCAL/ScECAL

Ωmega

- Scintillating tiles and SiPM
  - Pioneered by DESY (EUDET/AIDA)
  - Chip embedded in detector : low power !
- SPIROC : Silicon Photomultiplier Integrated Readout Chip
  - Variant of SKIROC
  - 36 channels autotrigger 15bit readout
  - Energy measurement : 15 bits in 2 gains
  - Autotrigger down to ½ p.e. (80 fC for G=1E6)
  - Time measurement to ~1 ns
  - Power dissipation : 25 µW/ch (power pulsed)



$(0.36m)^2$ Tiles + SiPM + SPIROC (144ch)



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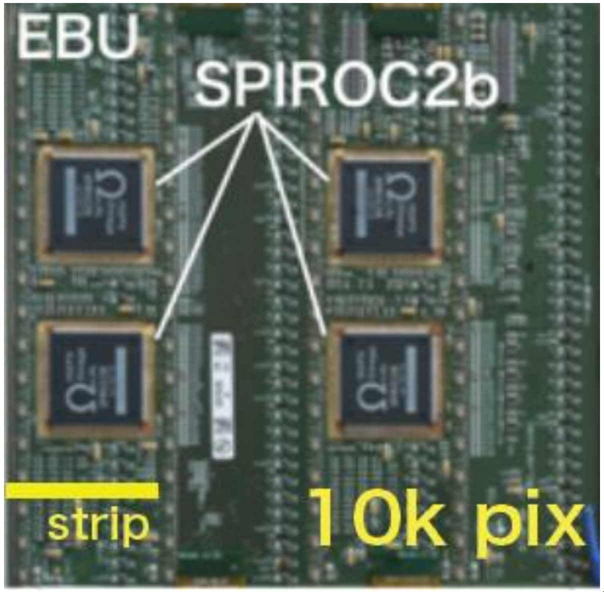
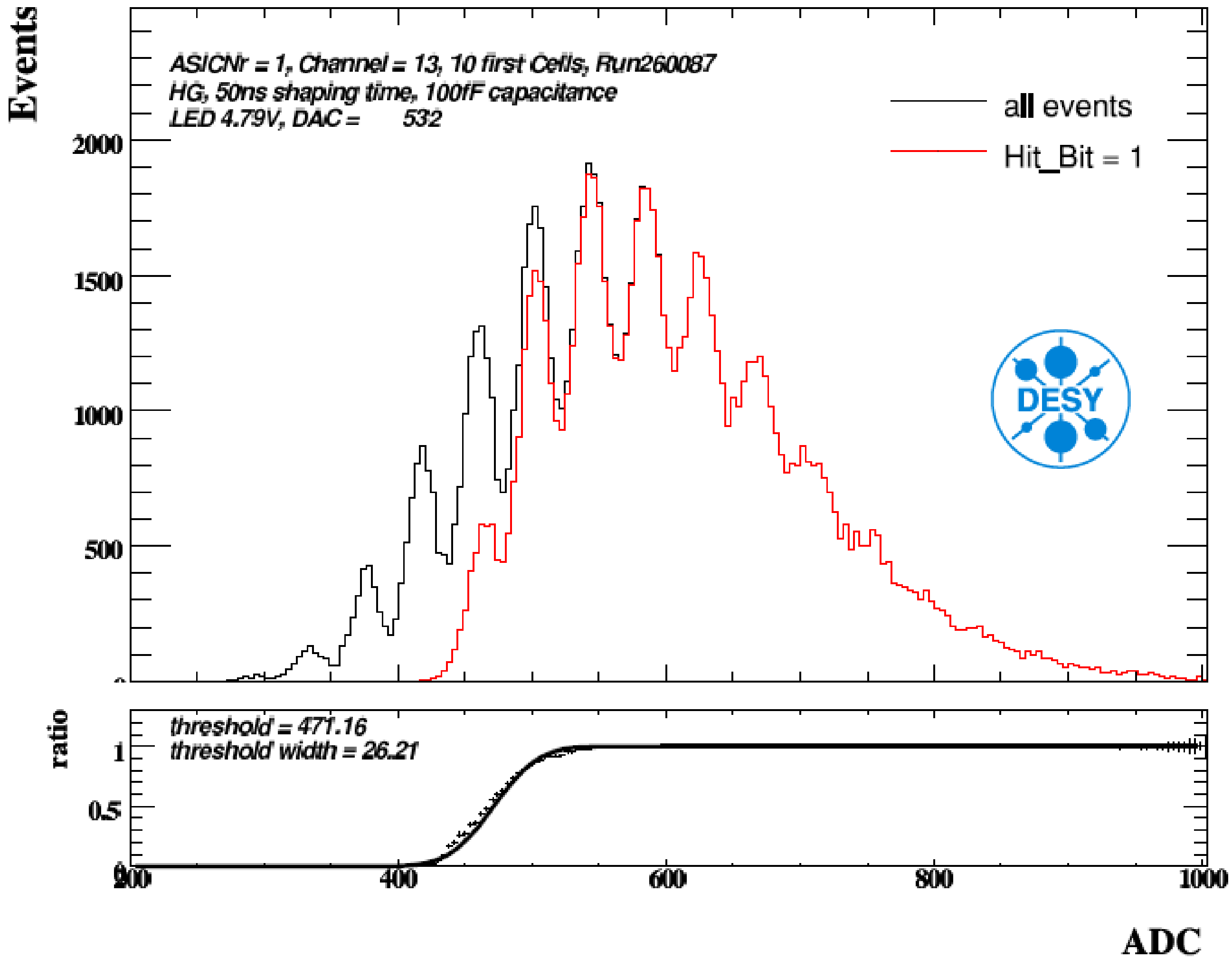


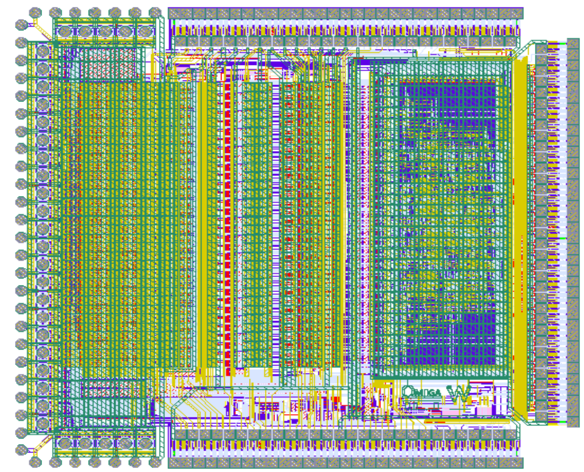
SiPM SPECTRUM with Autotrigger



PETIROC2 DESCRIPTION

- Time of Flight read-out chip with embedded TDC (25 ps bin) and ADC
- Dynamic range: 160 fC up to 400 pC
- 32 channels (negative input)
  - 32 trigger outputs
  - NOR32_chrage
  - NOR32 time
  - Charge measurement over 10 bits
  - Time measurement over 10 bits
  - One multiplexed charge output
- Common trigger threshold adjustment and 6bit-dac/channel for individual adjustment
- Variable shaping time of the charge shaper
- 32 8bit-input dac for SiPM HV adjustment
- Power consumption 6 mW/ch
- Front-end
  - Broad Band SiGe fast amplifier
  - Fast SiGe discriminator
  - 1 GHz overall bandwidth, gain = 25

AMS 0,35µm SiGe



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