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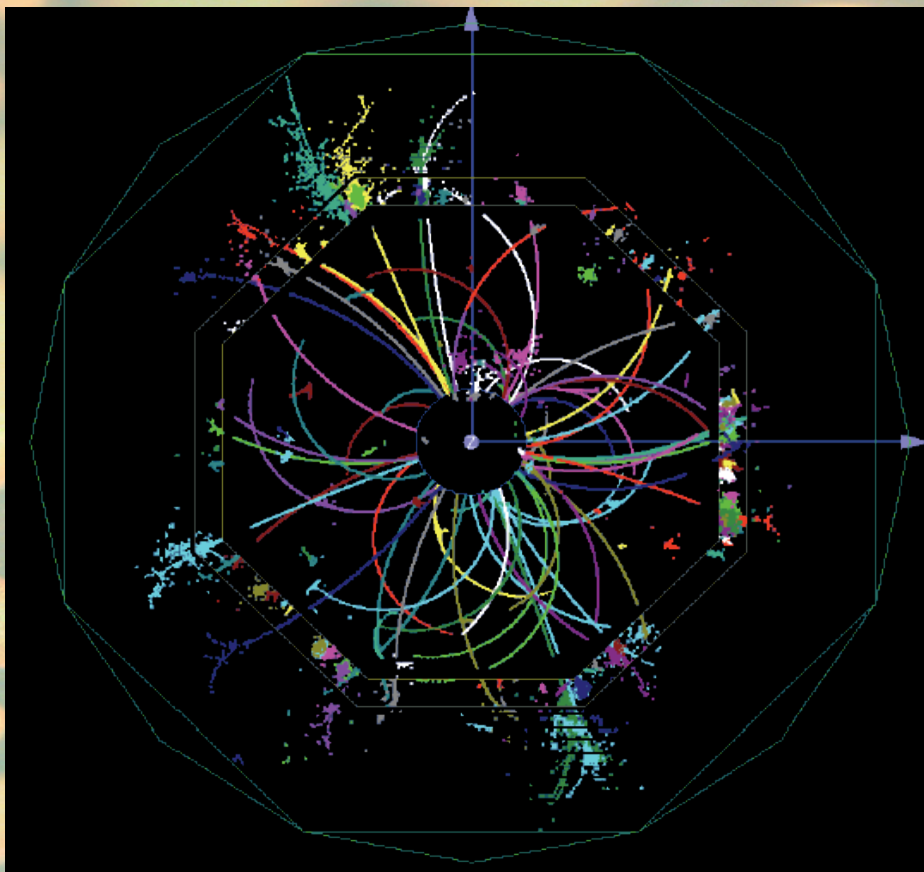
Omega



Electronics in particle physics

EDIT school CERN 2011

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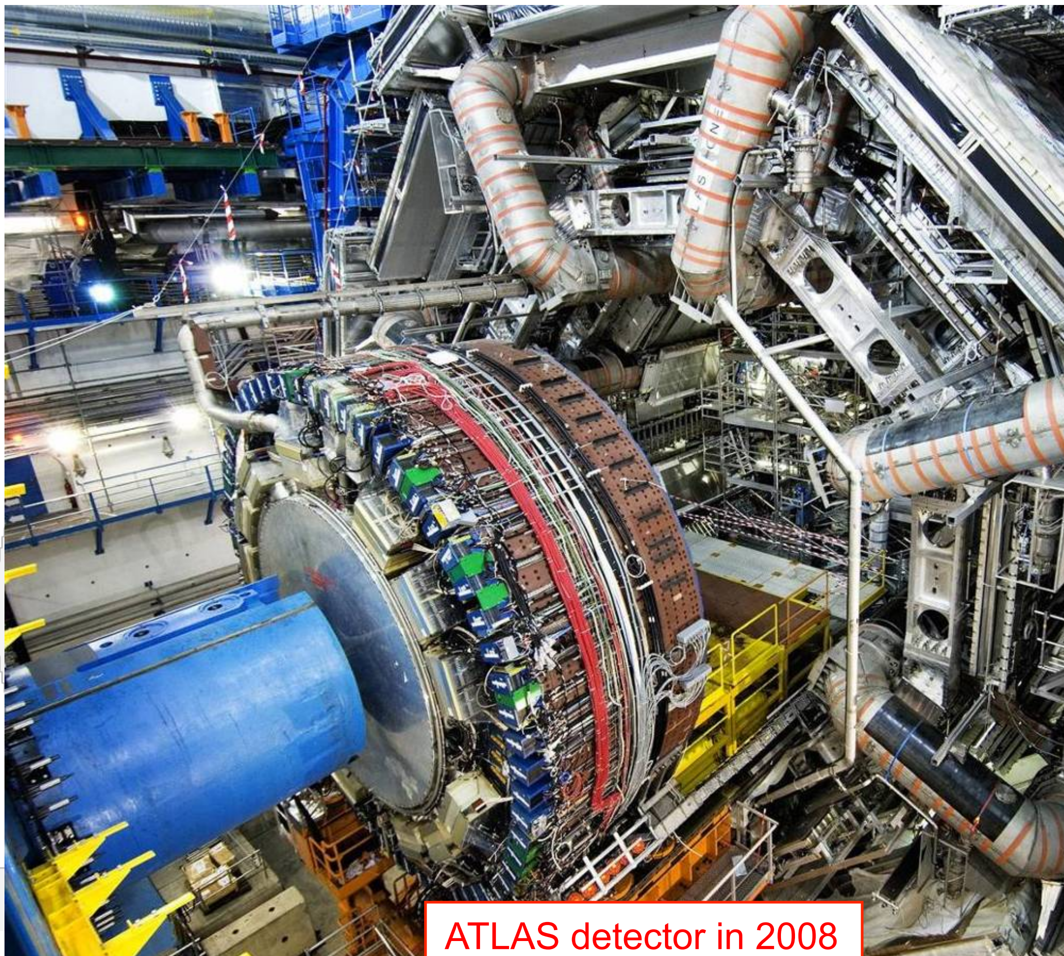
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

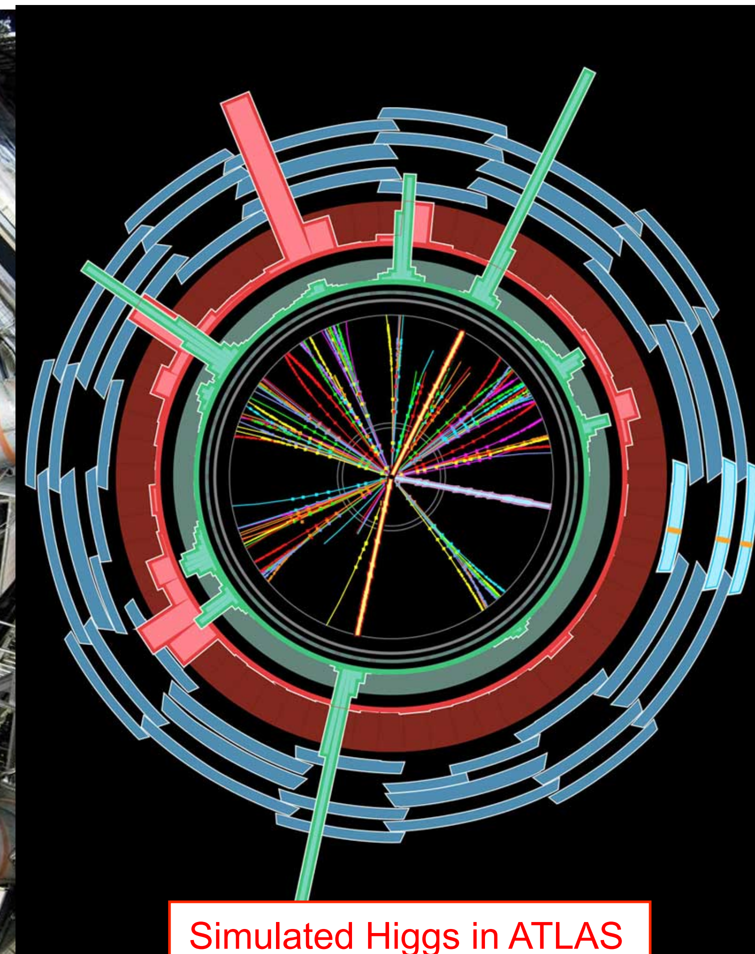
Orsay MicroElectronic Group Associated

Electronics in experiments

- A lot of electronics in the experiments…
  - The performance of electronics often impacts on the detectors
  - Analog electronics (V,A,A…) / Digital electronics (bits)



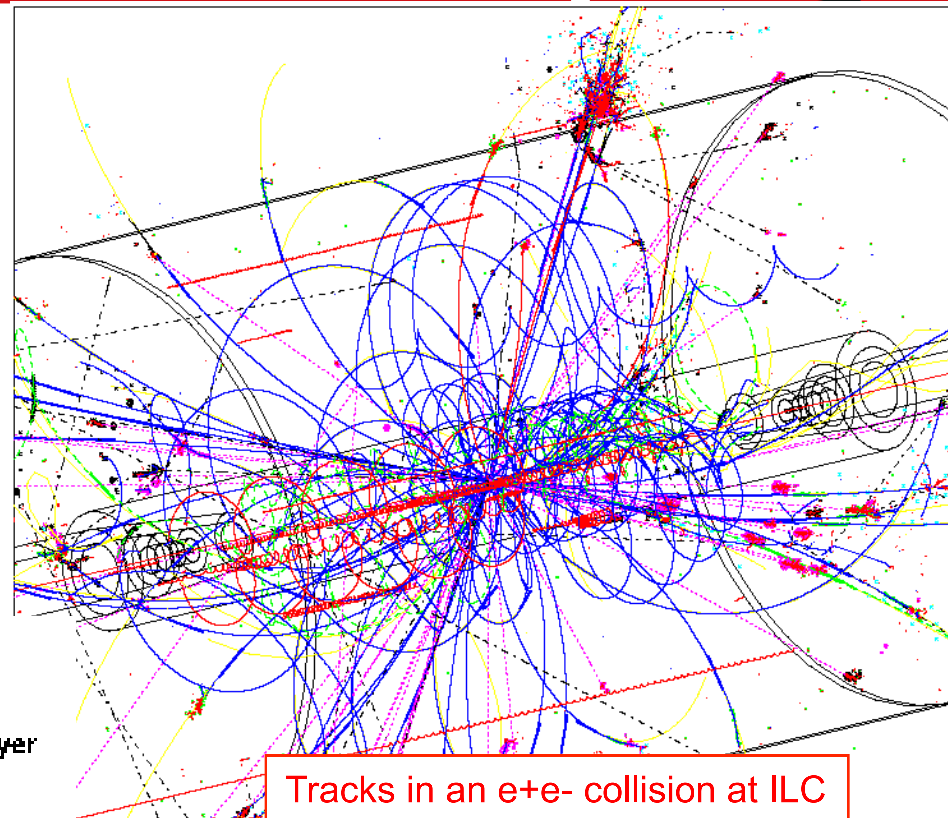
ATLAS detector in 2008



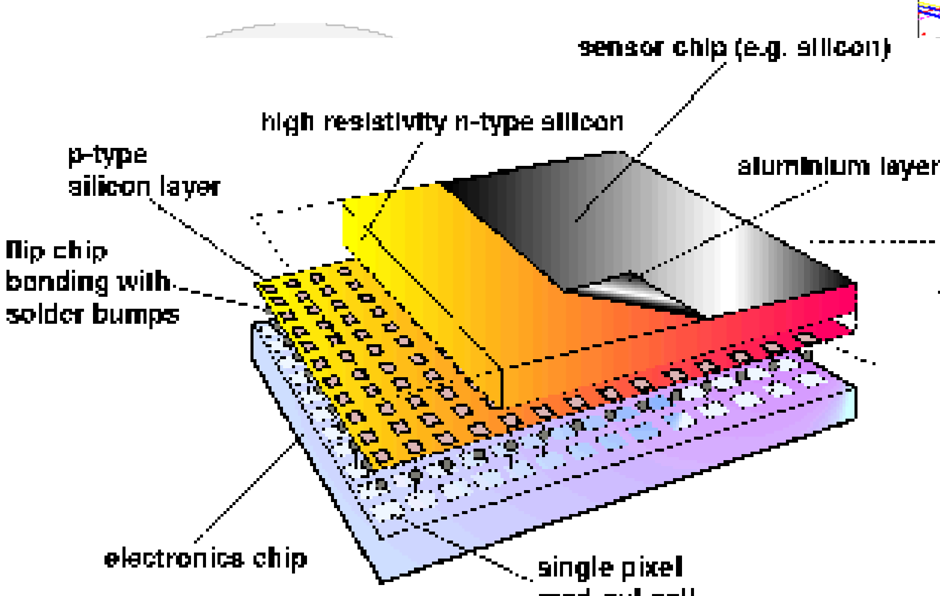
Simulated Higgs in ATLAS

Electronics enabling new detectors : trackers

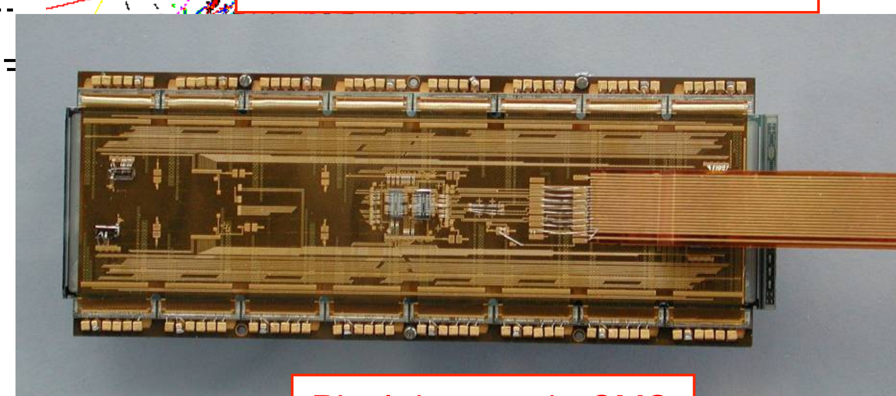
- Measurement of (charged) particle tracks
  - millions of pixels (~100 µm)
  - binary readout at 40 MHz
  - High radiation levels
  - Made possible by ASICs



Tracks in an e+e- collision at ILC



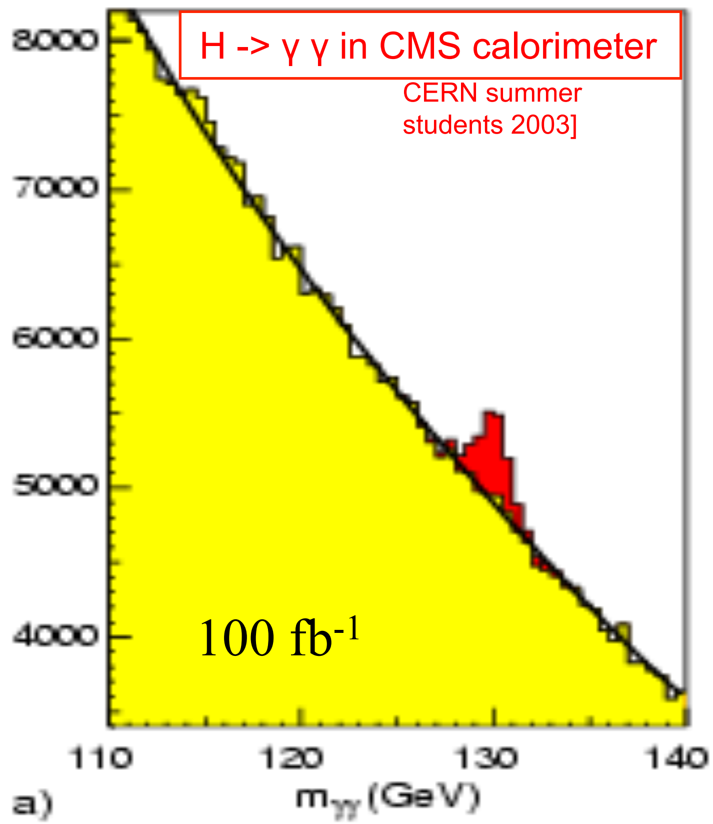
Pixel detector and readout electronics

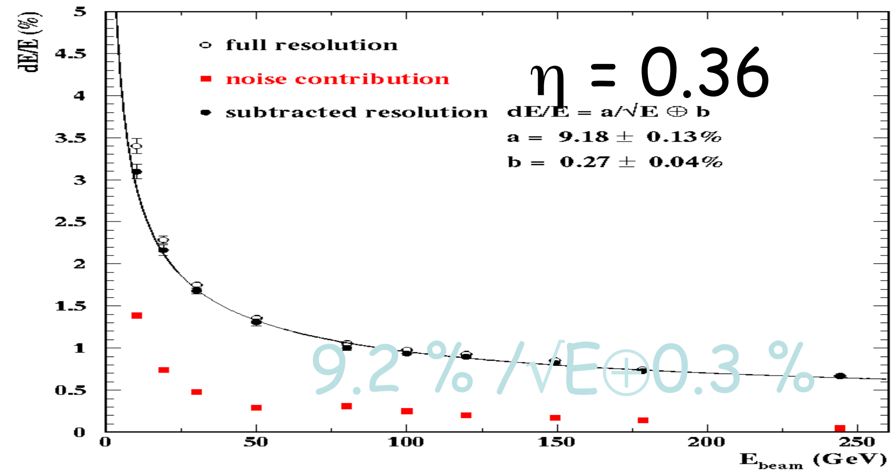


Pixel detector in CMS

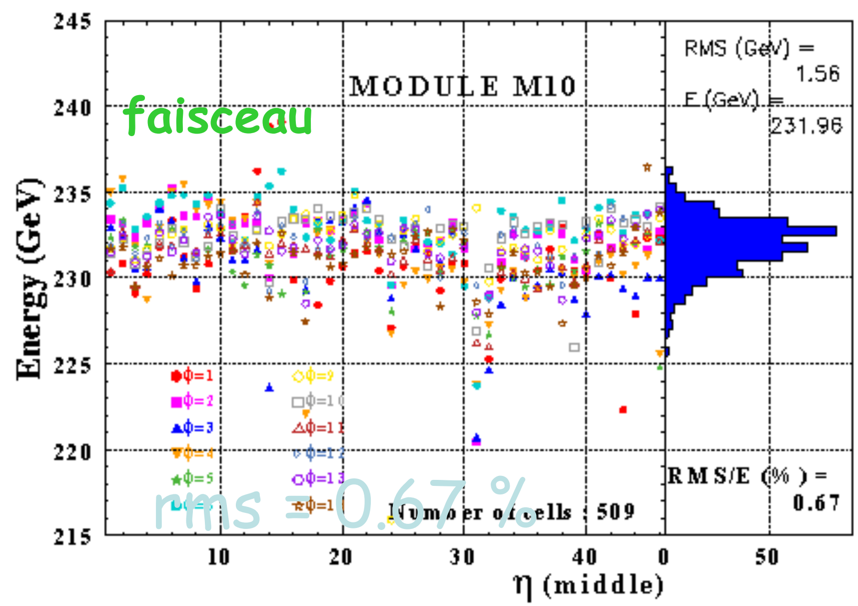
Importance of electronics : calorimeters

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

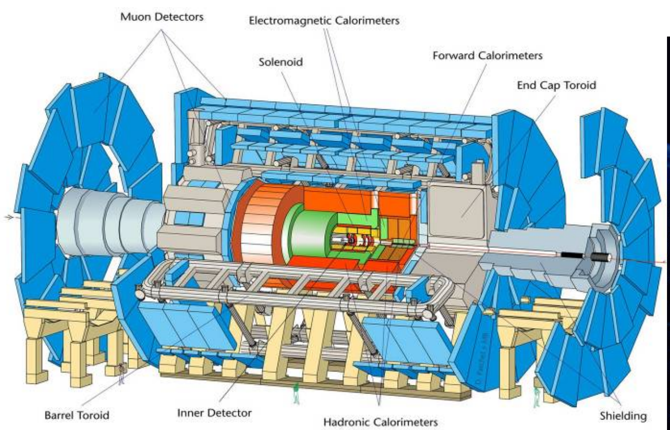




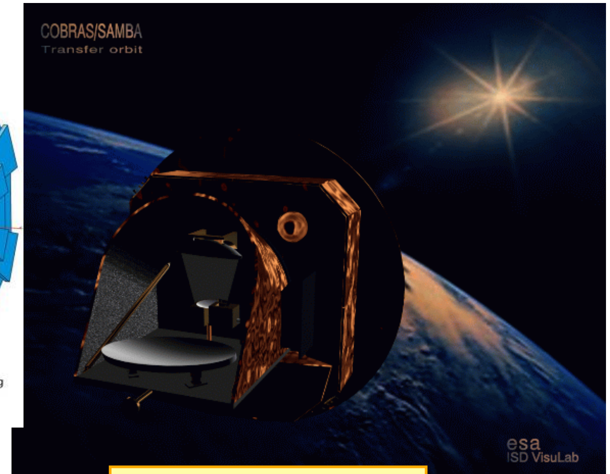
Energy resolution and uniformity in ATLAS



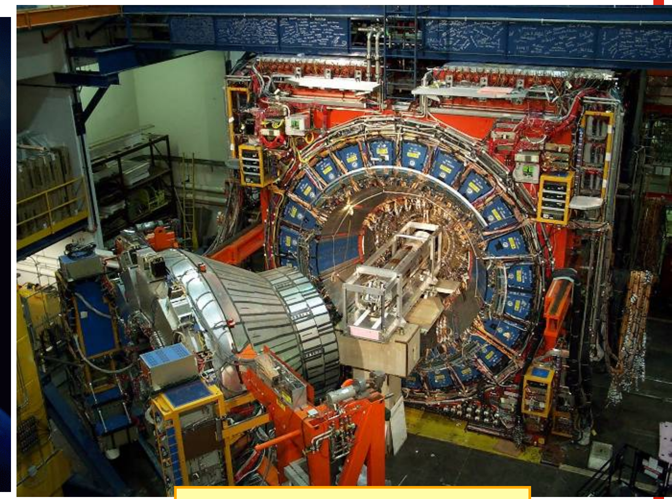
A large variety of detectors…



ATLAS : Higgs boson

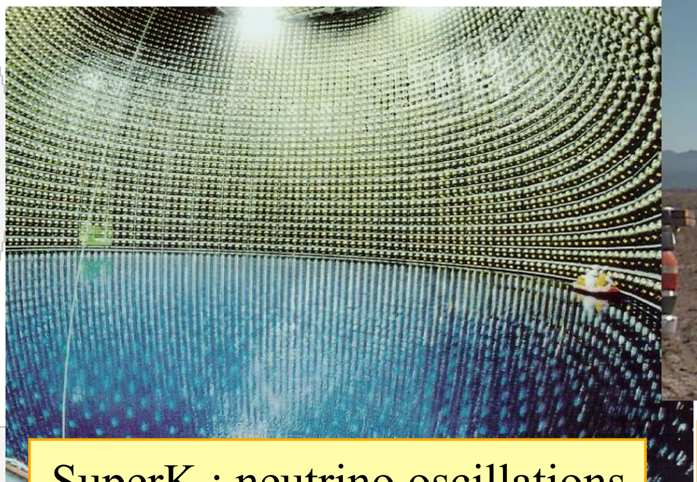


Planck : CMB



CDF : top quark

Edelweiss : dark matter

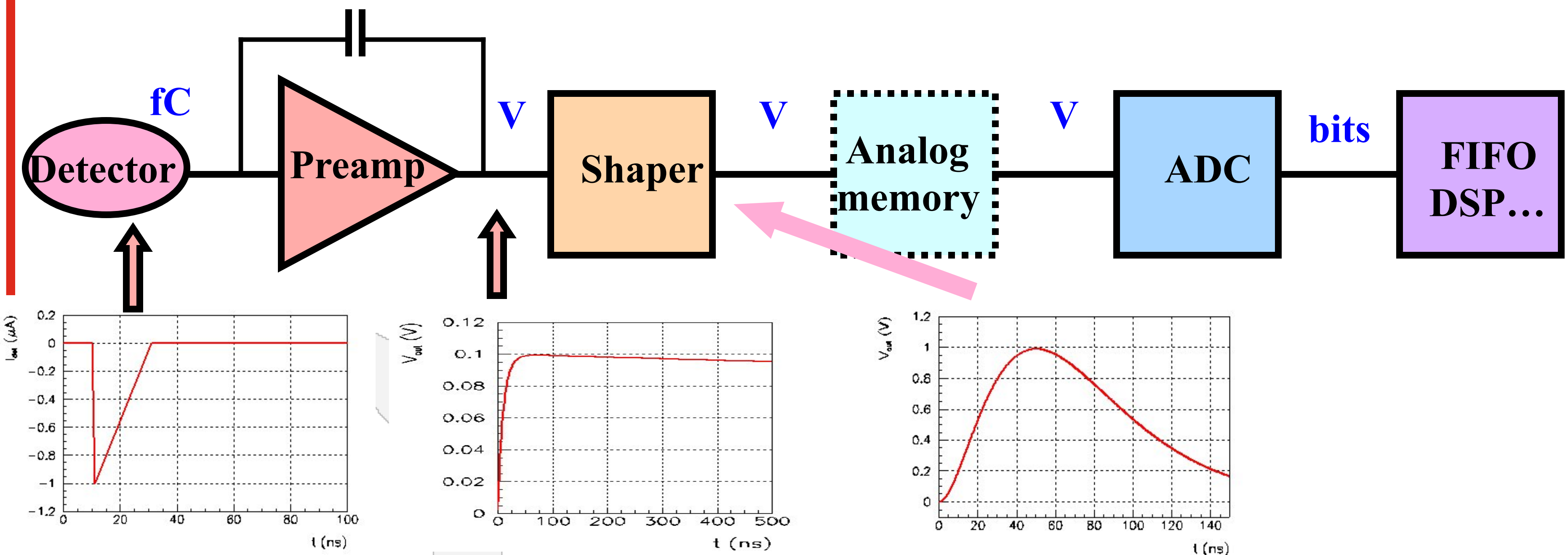


SuperK : neutrino oscillations

AUGER : cosmic rays 10^{20}eV

Overview of readout electronics

- Most front-ends follow a similar architecture



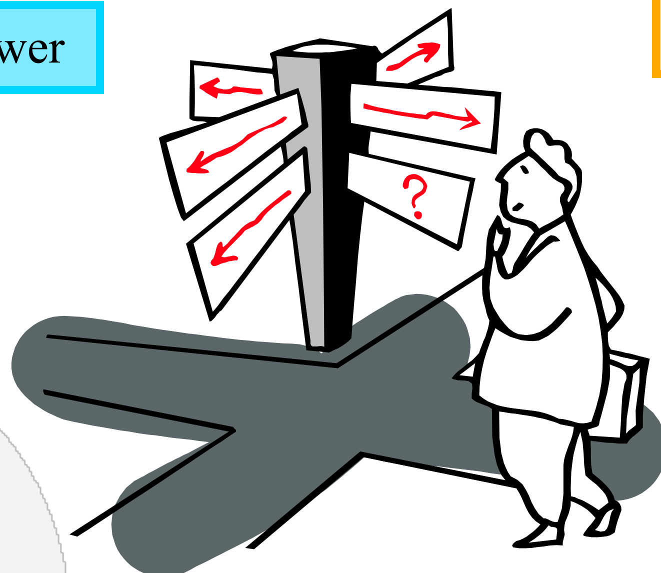
- Very small signals (fC) -> need amplification
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Several thousands to millions of channels

Readout electronics : requirements

Low noise

Low power

High speed



High reliability

Large dynamic range

Radiation hardness

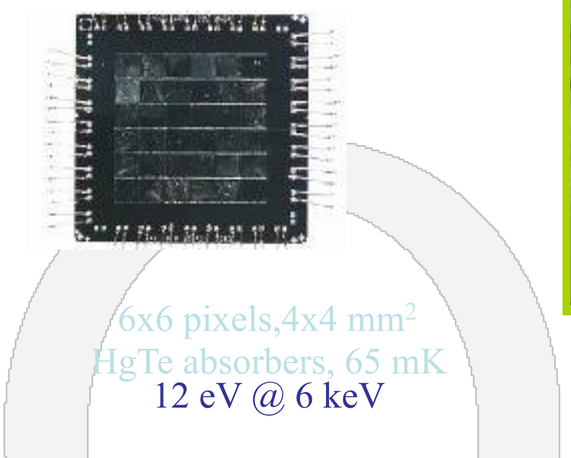
Low cost !

(and even less)

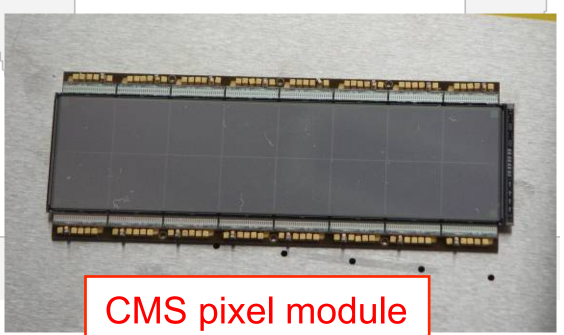
Low material

Detector(s)

- A large variety
- A similar modelization



PMT in ANTARES

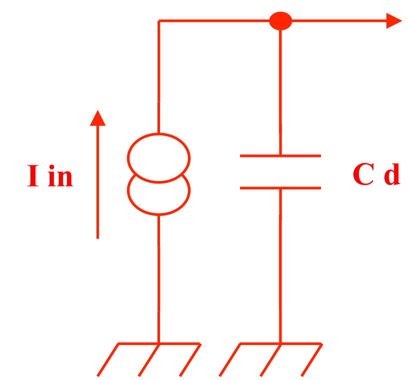


CMS pixel module

ATLAS LAr calorimeter

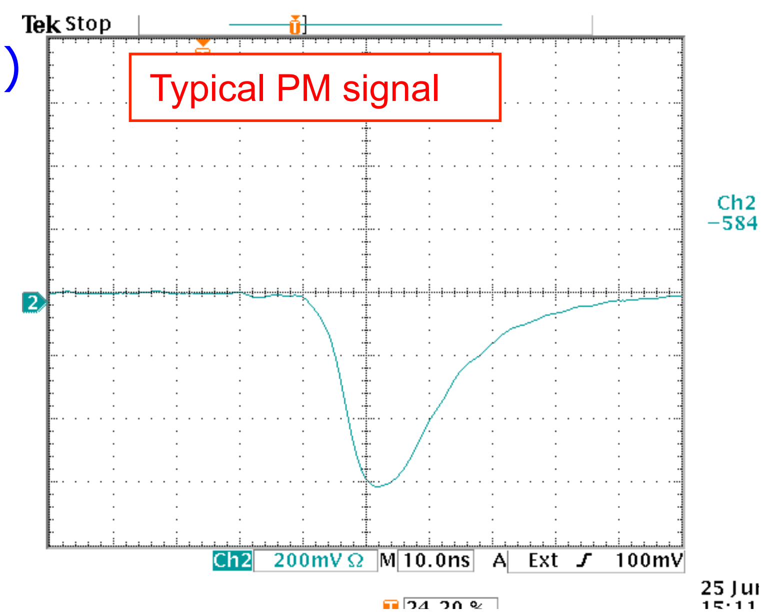
Detector modelization

- Detector = capacitance Cd
  - Pixels : 0.1-10 pF
  - PMs : 3-30pF
  - Ionization chambers 10-1000 pF
  - Sometimes effect of transmission line



Detector modeilization

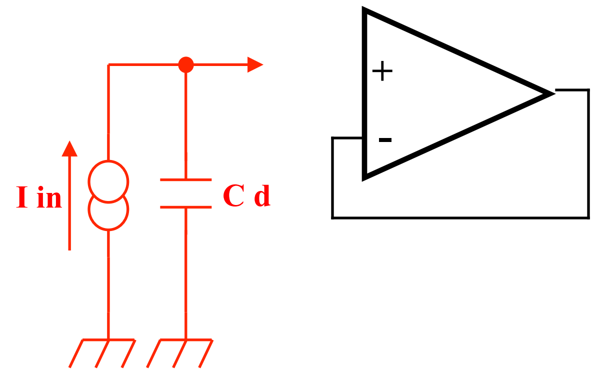
- Signal : current source
  - Pixels : ~100e-/µm
  - PMs : 1 photoelectron -> 10^5-10^7 e-
  - Modelized as an impulse (Dirac) : i(t) (t)



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

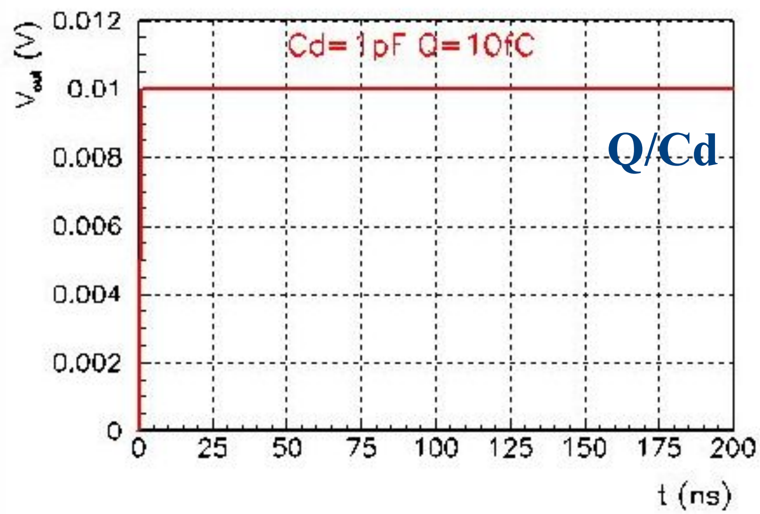
Reading the signal

- 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

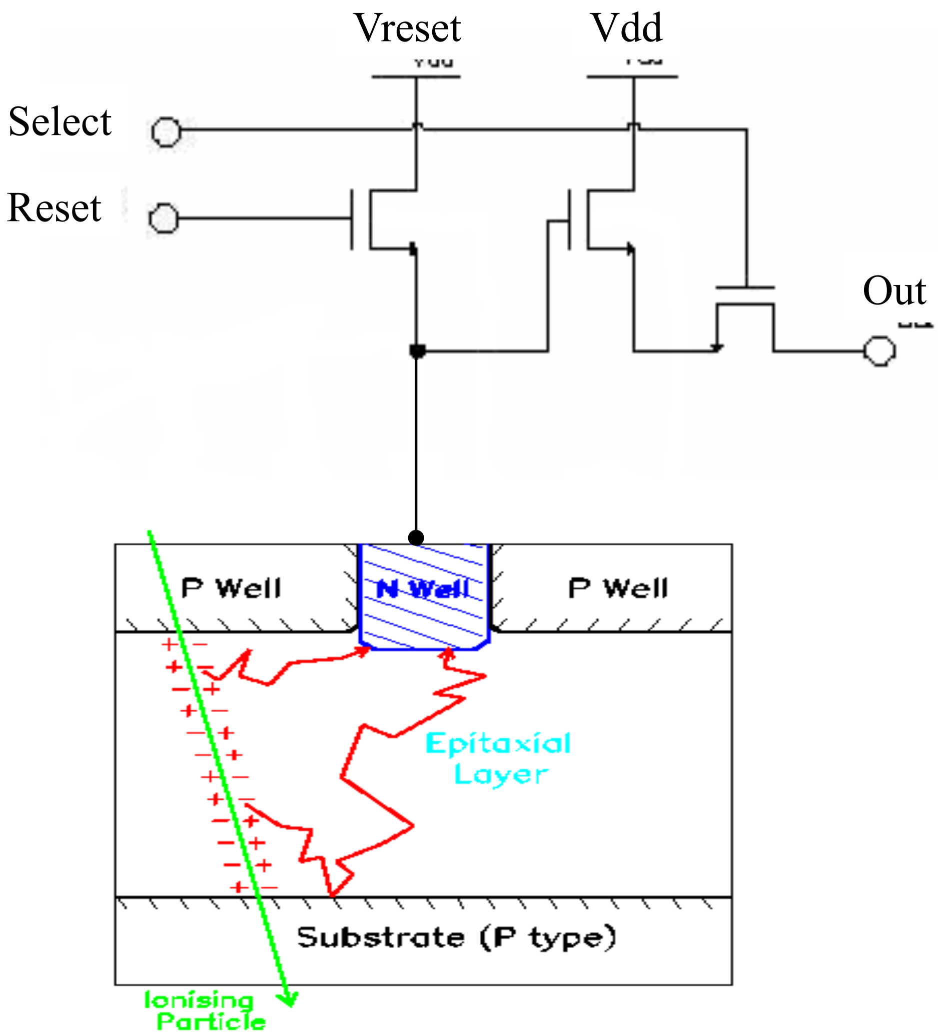


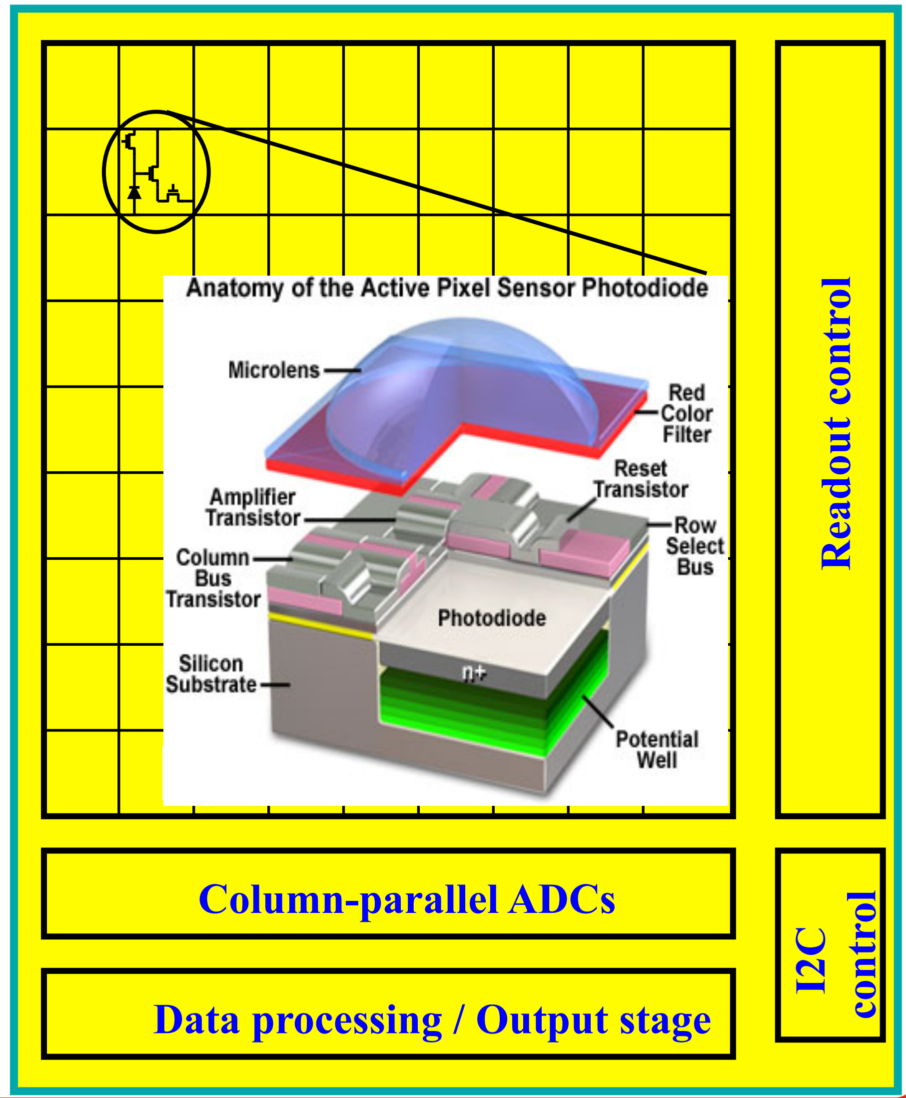
Impulse response

Monolithic active pixels

© R Turchetta RAL

- Collect charge by diffusion
- Read ~100 e- on Cd~10fF = few mV





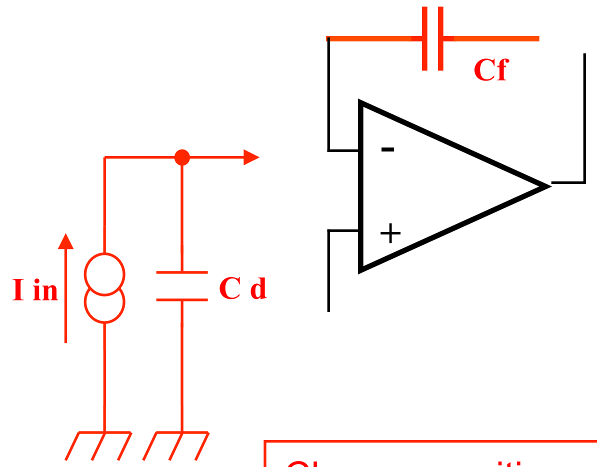
MAPS readout

Ideal charge preamplifier

- ideal opamp in transimpedance
  - Shunt-shunt feedback
  - transimpedance : v_{out}/i_{in}
  - Vin-=0 =>$V_{out}(\omega)/i_{in}(\omega) = - Z_f = - 1/j\omega C_f$
  - Integrator : $v_{out}(t) = -1/C_f \int i_{in}(t)dt$

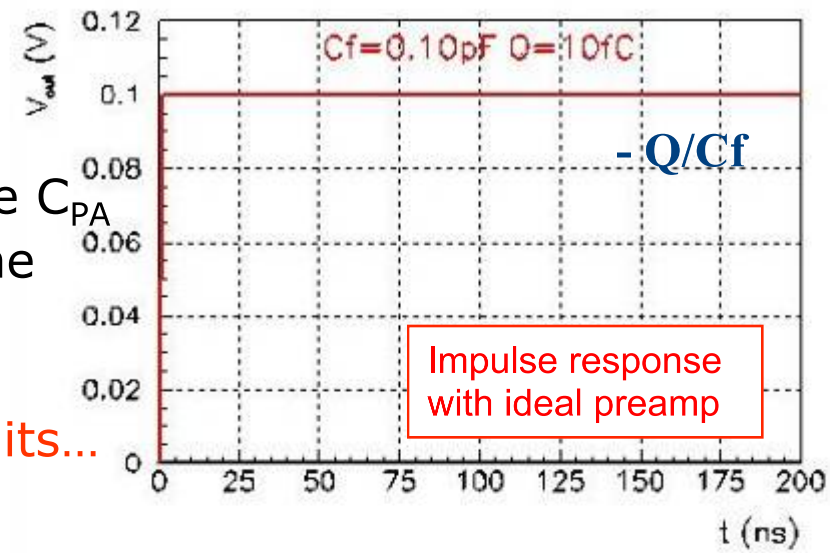
$$v_{out}(t) = - Q/C_f$$

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



Charge sensitive preamp

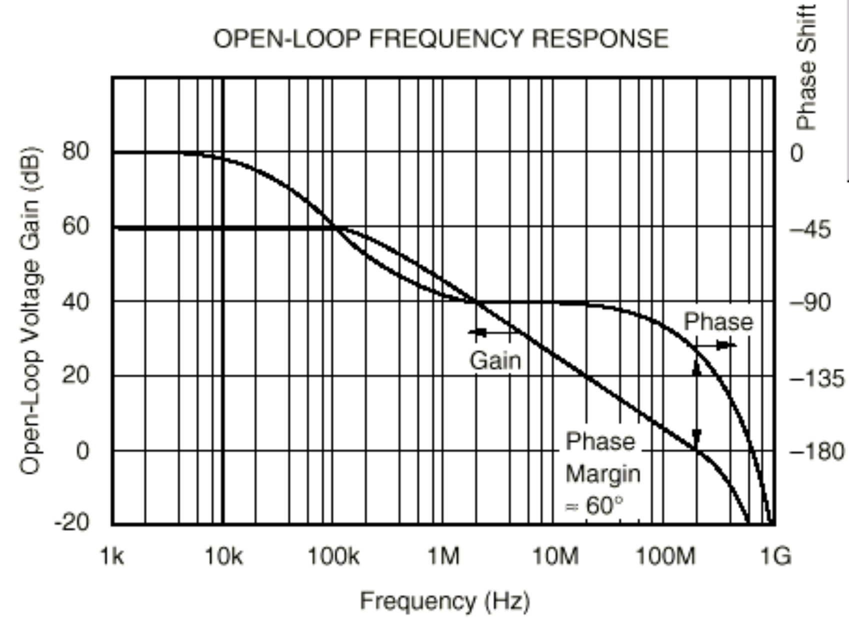
- Integration on Cf
  - Simple : $V = - Q/C_f$
  - Unsensitive to preamp capacitance C_{PA}
  - Turns a short signal into a long one
  - The front-end of 90% of particle physics detectors…
  - But always built with custom circuits…

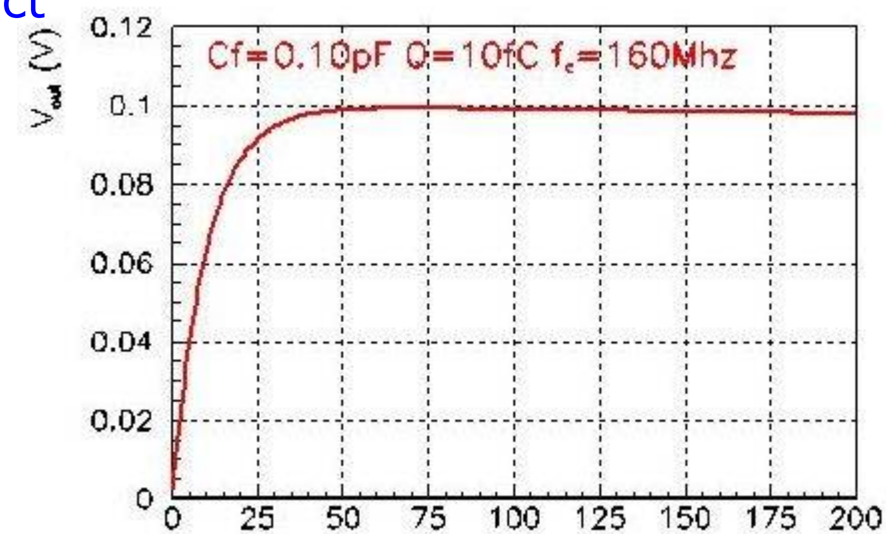


Impulse response with ideal preamp

Non-ideal charge preamplifier

- 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
- Preamp risetime
  - Due to gain variation with ω
  - Time constant : τ *(tau)*
  - $\tau = C_d/G_0\omega_0C_f$
  - Rise-time : $t_{10\text{-}90\%} = 2.2\ \tau$
  - Rise-time optimised with w_C or C_f

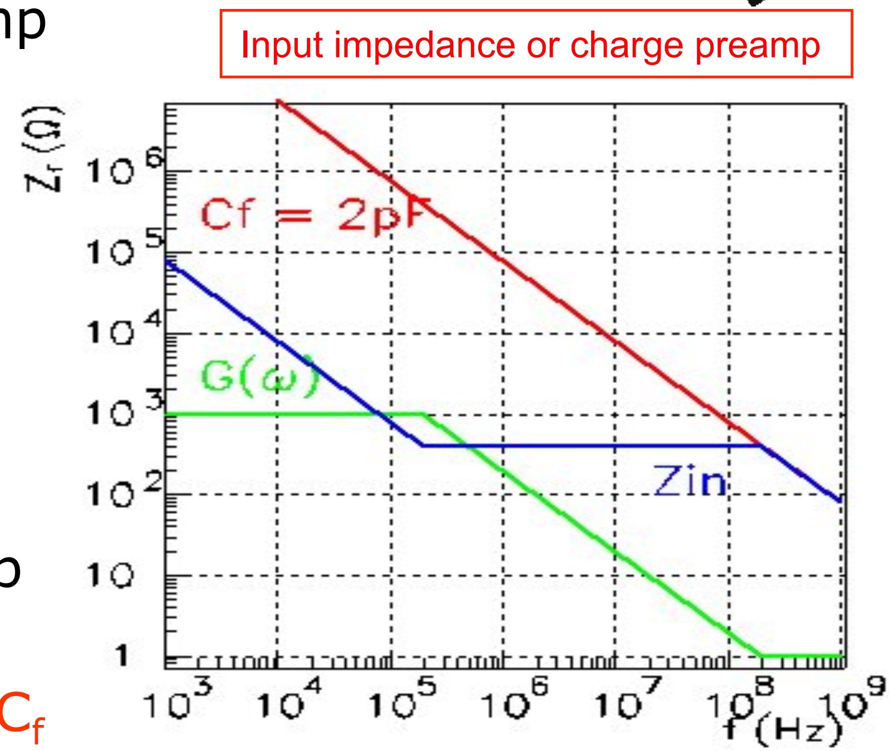




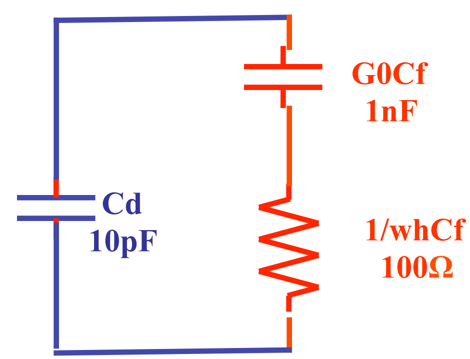
Impulse response with non-ideal preamp

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

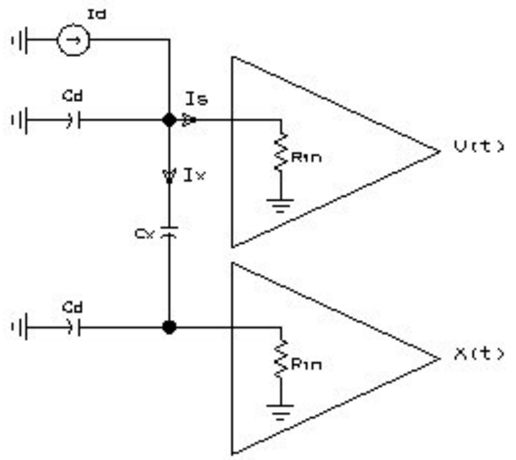


- Input impedance with real opamp
  - Zin = $1/j\omega\, G_0 C_f + 1/\, G_0 \omega_0\, C_f$
  - Resistive term : Rin = $1/\, G_0 \omega_0\, C_f$
    - Exemple : $w_C = 10^{10}$ rad/s C_f= 1 pF => Rin = 100 Ω
  - Determines the input time constant : $t = R_{eq} C_d$
  - Good stability= (…!)
  - Equivalent circuit :

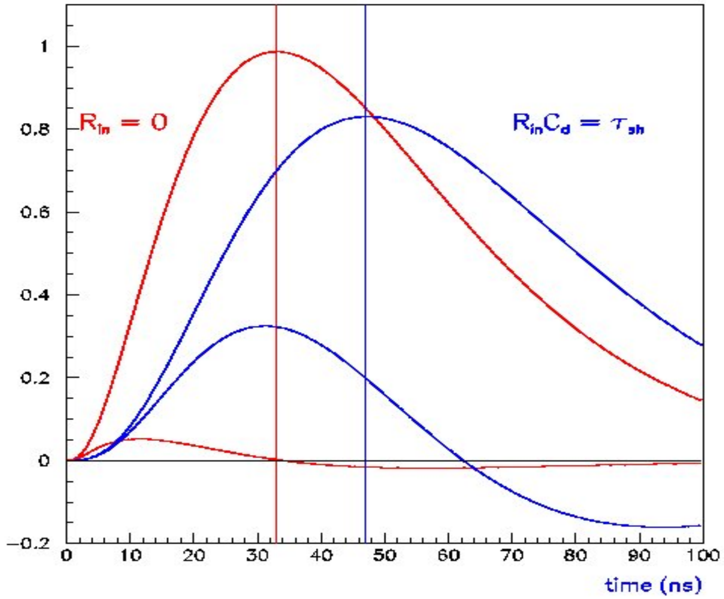


Crosstalk

- 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



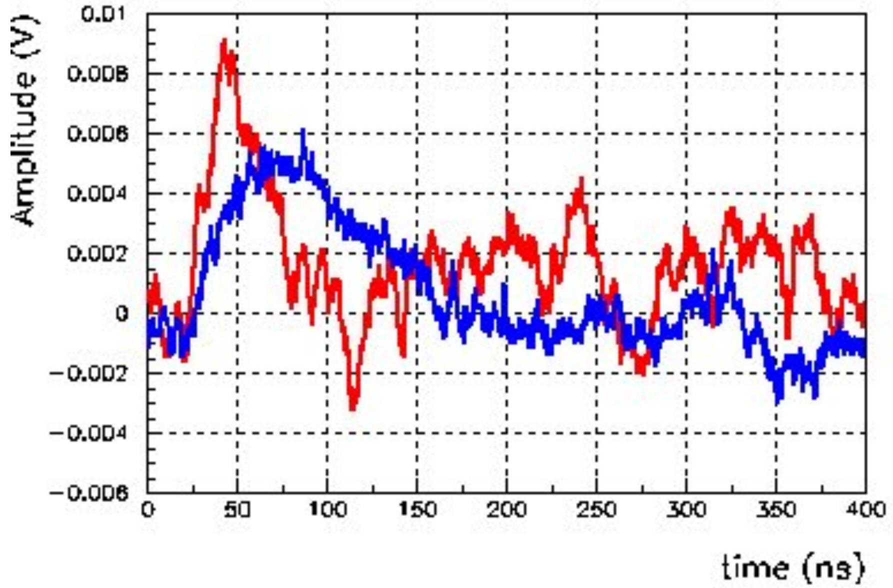
Crosstalk electrical modelization



- Inductive coupling
  - Inductive common ground return
  - Connectors : mutual inductance

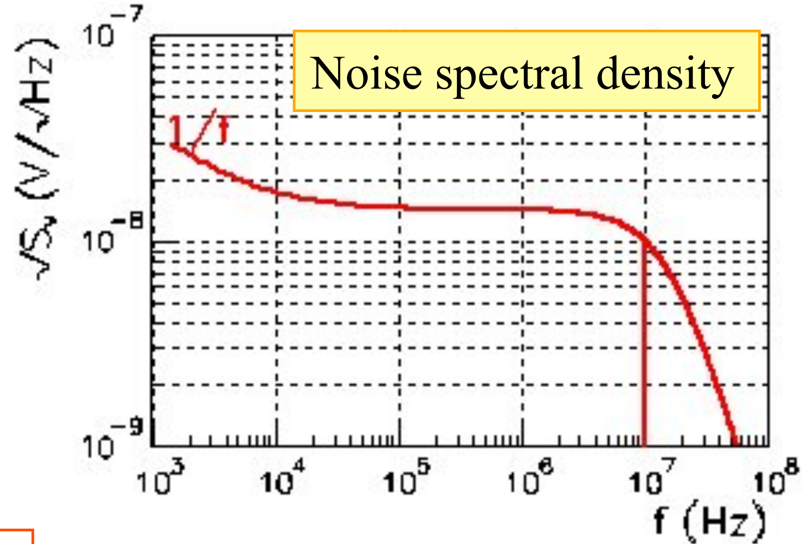
Electronics noise

- 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…)

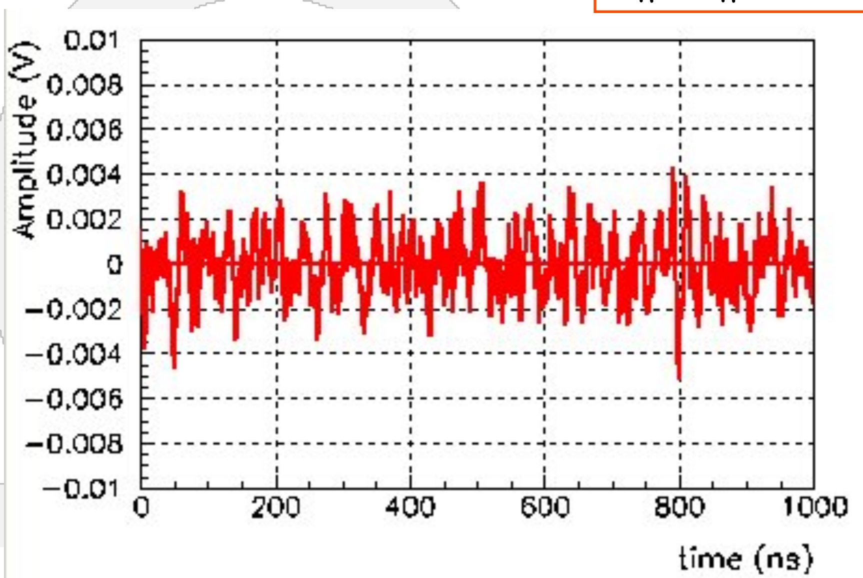


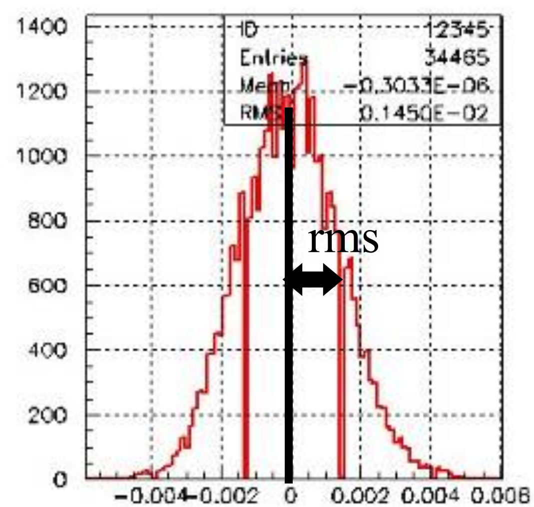
Electronics noise

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



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

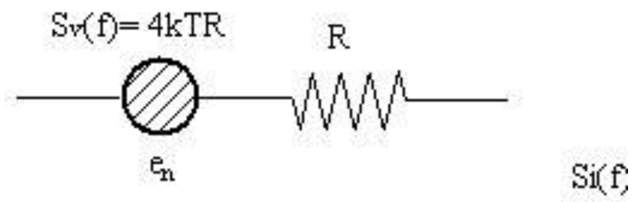




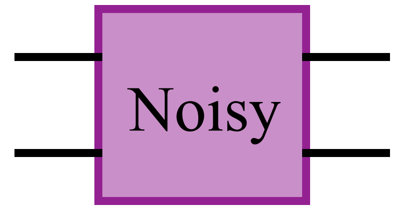
Rms noise vn

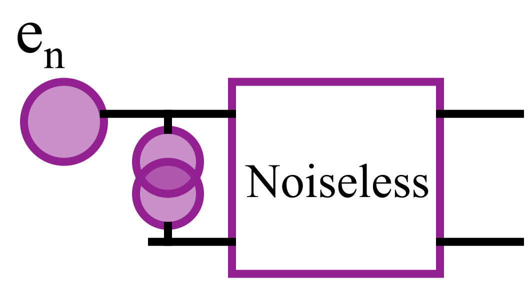
Calculating electronics noise

- 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…





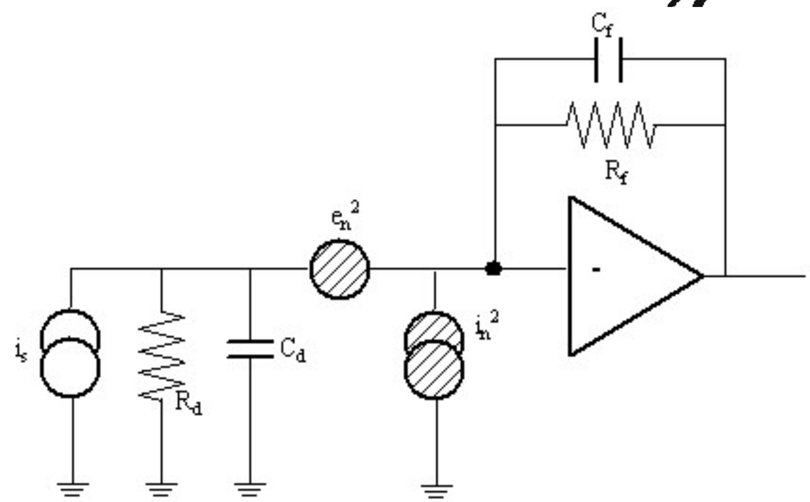
- **To take into account the Source impedance**

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

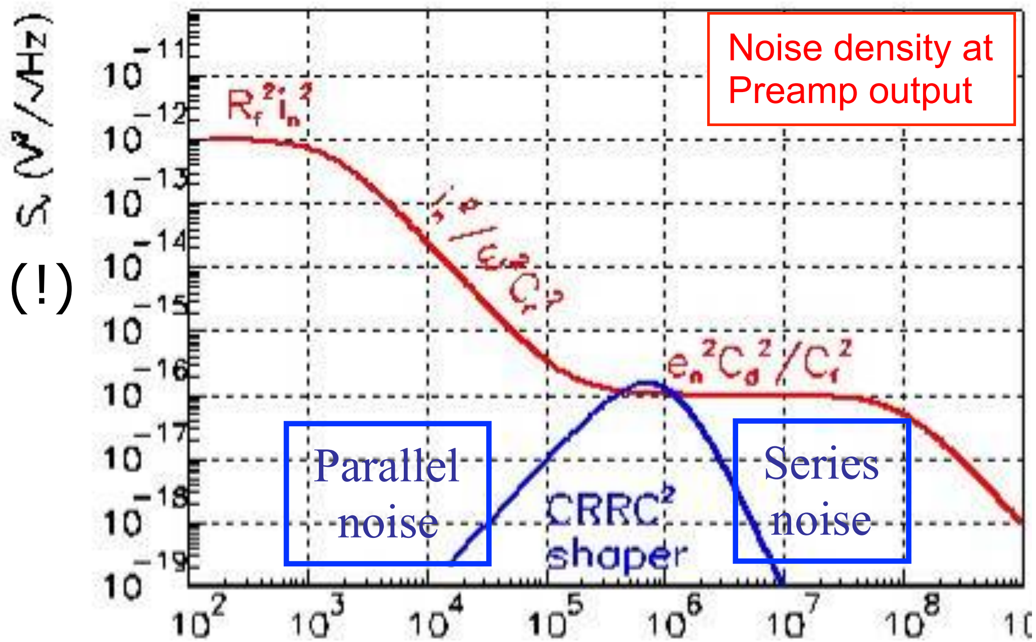
Noise generators referred to the input

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 :
  - $Sv(\omega) = (i_n^2 + e_n^2/|Z_d|^2) / \omega^2 C_f^2$
    $= i_n^2 /\omega^2 C_f^2 + e_n^2 C_d^2/C_f^2$
  - Parallel noise in $1/\omega^2$
  - Series noise is flat, with a « noise gain » of C_d/C_f
- *rms* noise V_n
  - $V_n^2 = \int Sv(\omega)\, d\omega/2\pi \to \infty$ (!)
  - Benefit of shaping…

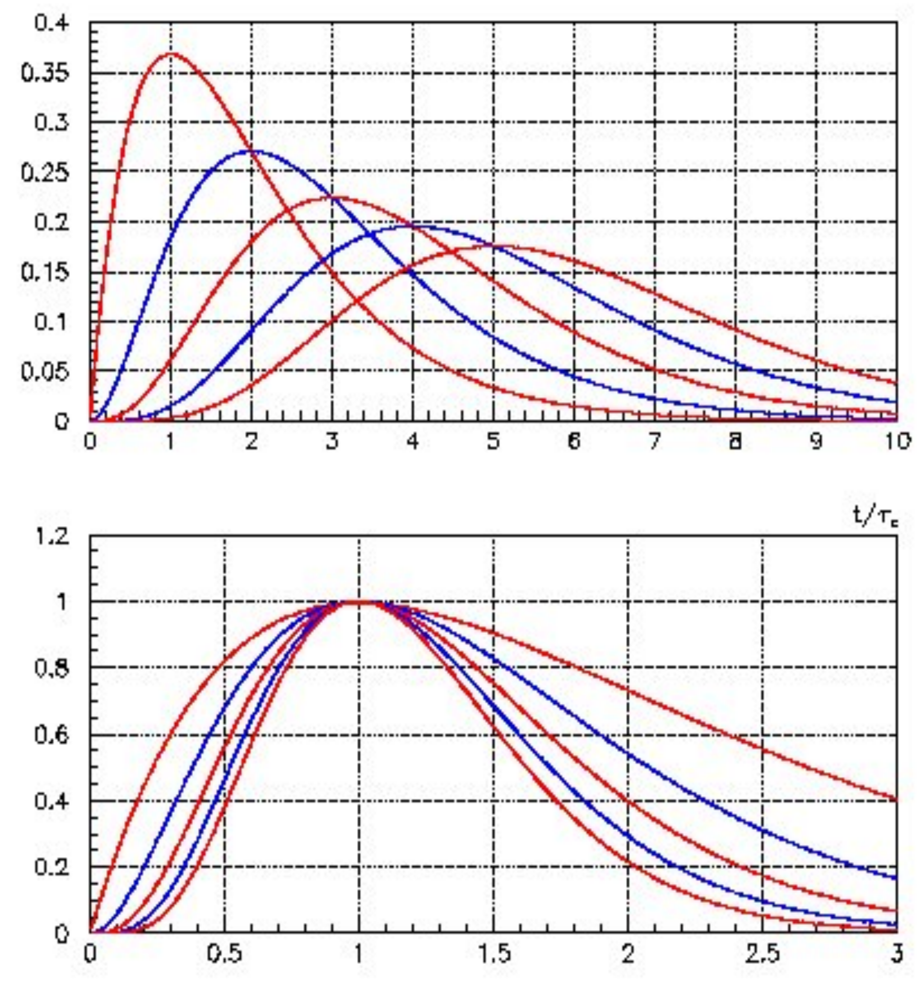


Noise generators in charge preamp



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 $\tau_{opt} = \tau_c / \sqrt{2n-1}$

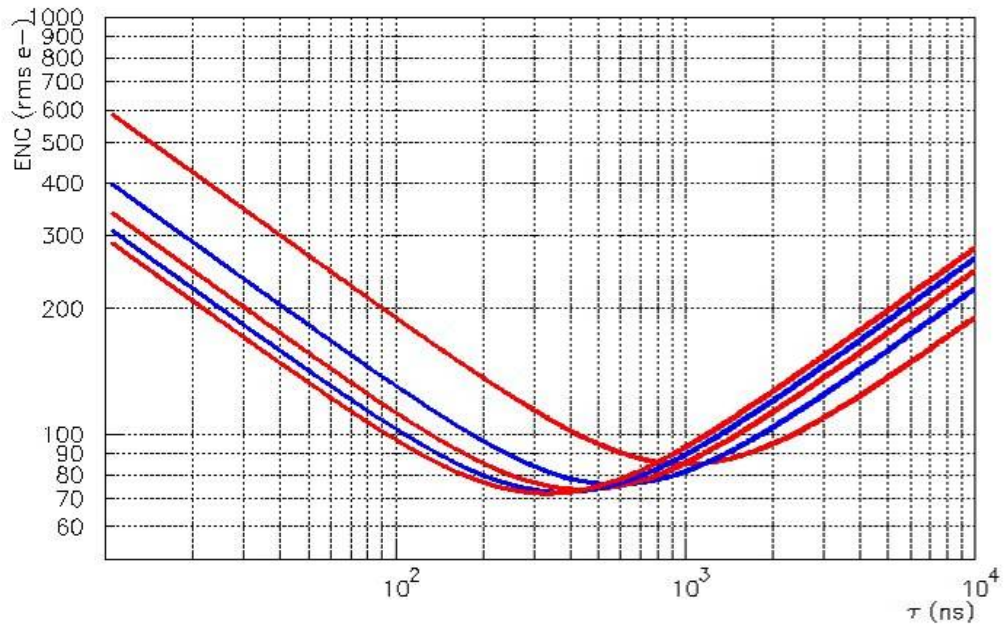


Step response of CR RCn shapers

Equivalent Noise Charge (ENC) after CRRC^n

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

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



ENC vs tau for CR RCn shapers

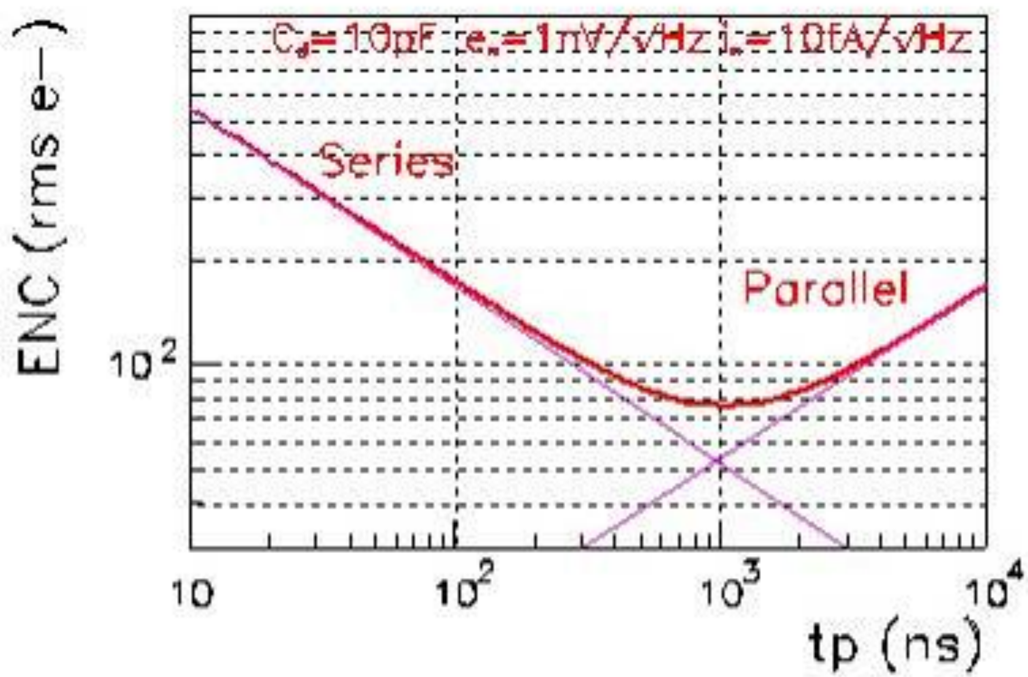
Equivalent Noise Charge (ENC) after CRRC^n

- A useful formula : **ENC (e- rms) after a CRRC² shaper :**

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

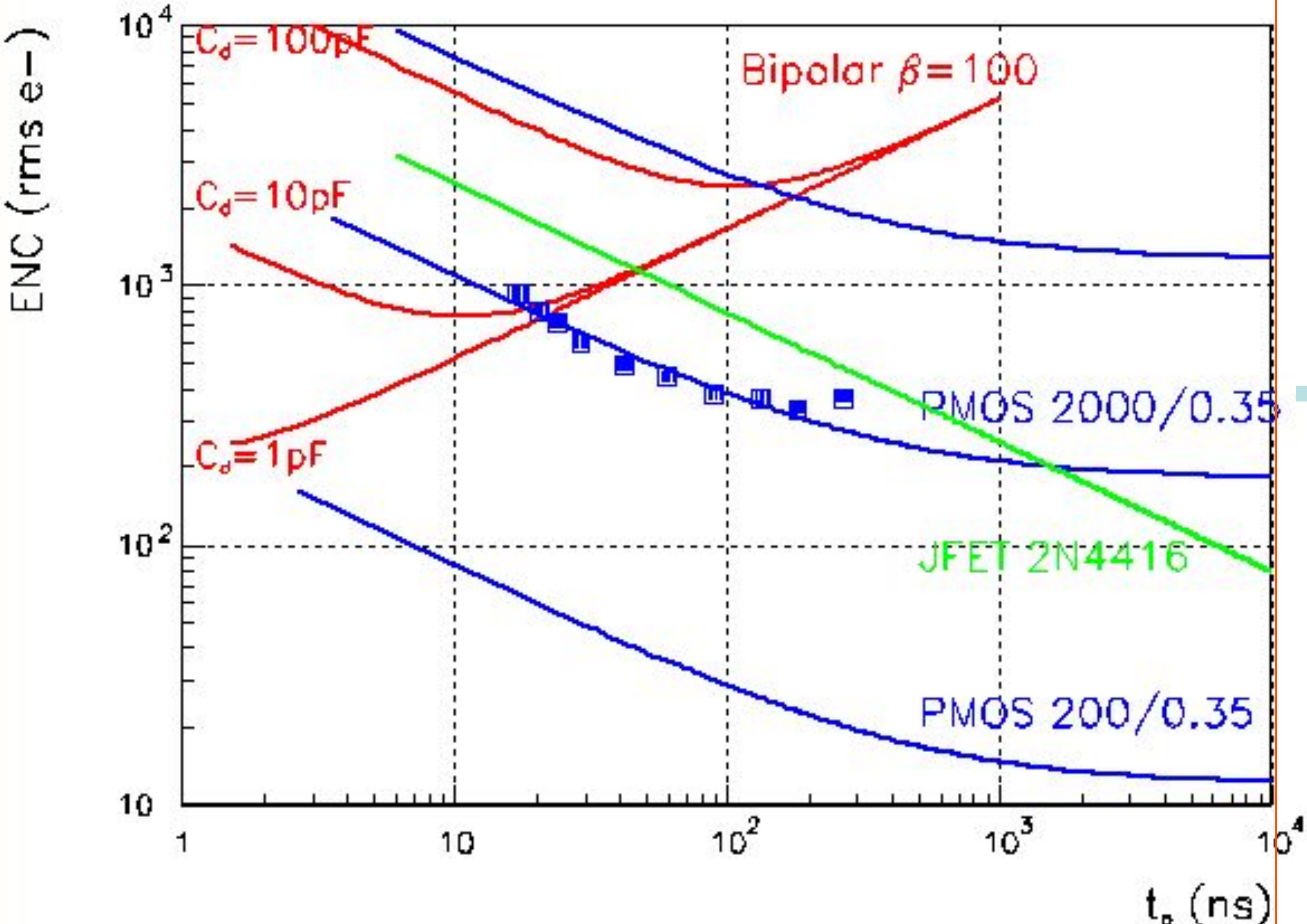
  - e_n in nV/ √Hz, i_n in pA/ √Hz are the preamp noise spectral densities
  - C_{tot} (in pF) is dominated by the detector (C_d) + input preamp capacitance (C_{PA})
  - t_p (in ns) is the shaper peaking time (5-100%)

- **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



ENC for various technologies

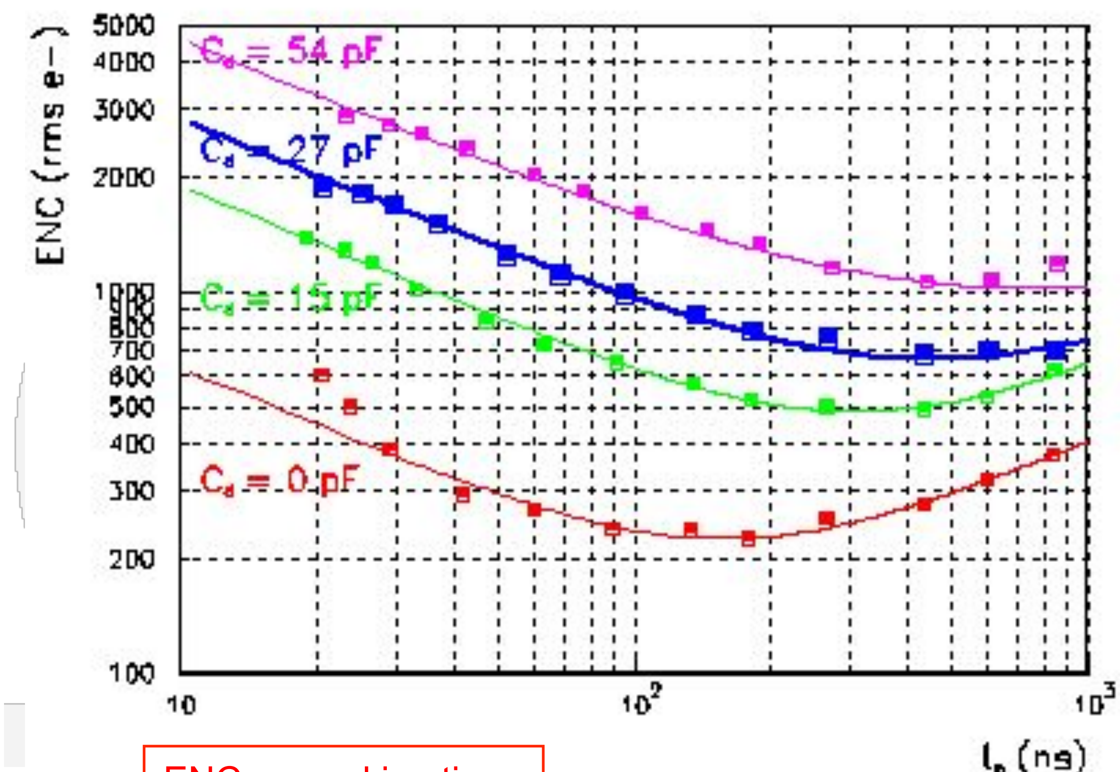
- ENC for Cd=1, 10 and 100 pF at I_D = 500 uA
  - MOS transistors best between 20 ns – 2 µs



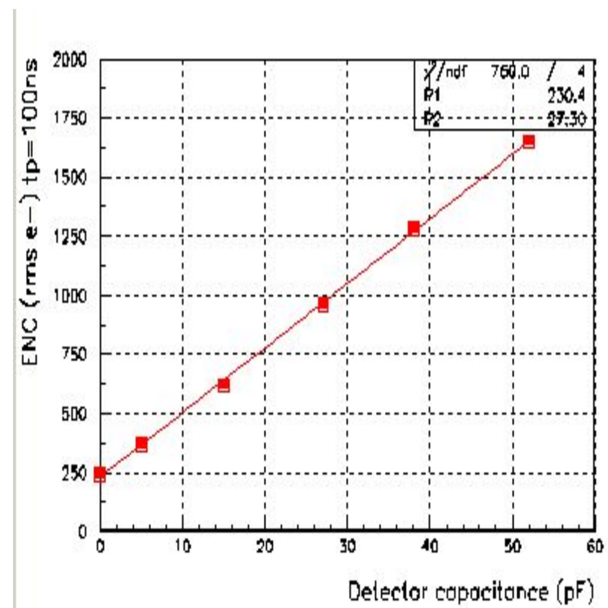
- **Parameters**
- Bipolar :
  - g_m = 20 mA/V
  - $R_{BB'}$=25 Ω
  - e_n= 1 nV/√Hz
  - I_B=5uA
  - i_n = 1 pA/√Hz
  - C_{PA}=100fF
- **PMOS 2000/0.35**
  - g_m = 10 mA/V
  - e_n = 1.4 nV/√Hz
  - C_{PA} = 5 pF
  - 1/f :

Example of ENC measurement

- SKIROC ASIC (ILC readout) : 0.35µm SiGe
  - Series : en = 1.4 nV/√Hz, C_{PA} = 7 pF
  - 1/f noise : 12 e-/pF
  - Parallel : in = 40 fA/√Hz



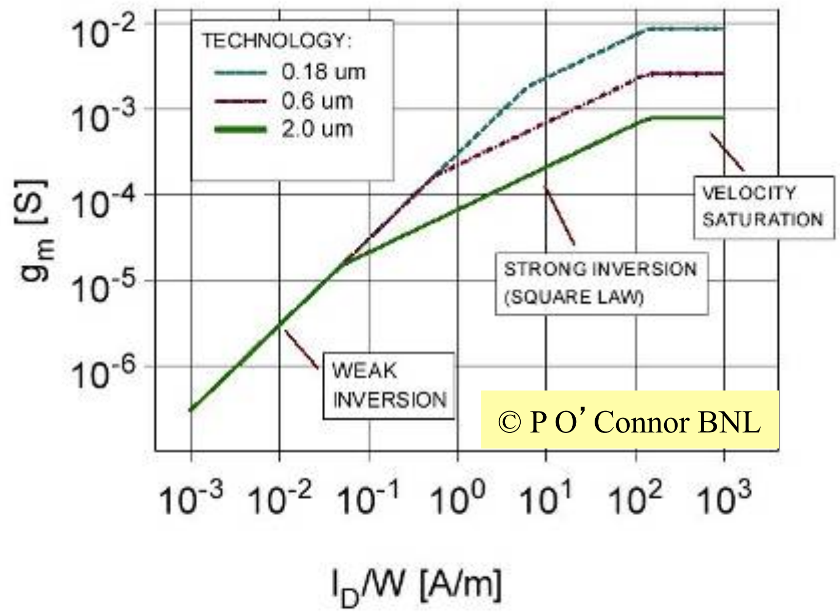
ENC vs peaking time



ENC vs Capacitance tp=100ns

MOS input transistor sizing

- Capacitive matching : strong inversion
  - g_m proportionnal to W/L $\sqrt{I_D}$
  - C_{GS} proportionnal to W*L
  - ENC propotionnal to $(Cdet+C_{GS})/\sqrt{gm}$
  - Optimum W/L : C_{GS} = 1/3 Cdet
  - Large transistors are easily in moderate or weak inversion at small current



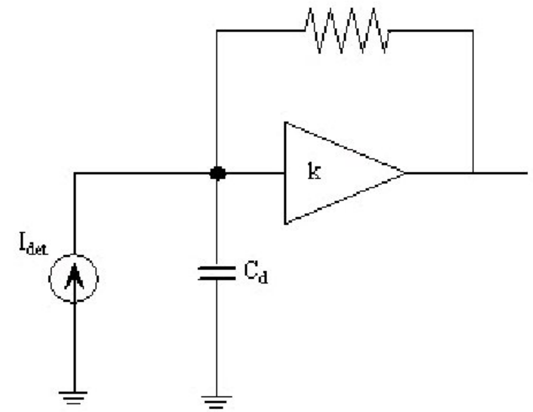
- Optimum size in weak inversion
  - g_m proportionnal to I_D (indep of W,L)
  - ENC minimal for C_{GS} minimal, provided the transistor remains in weak inversion

Current preamplifiers :

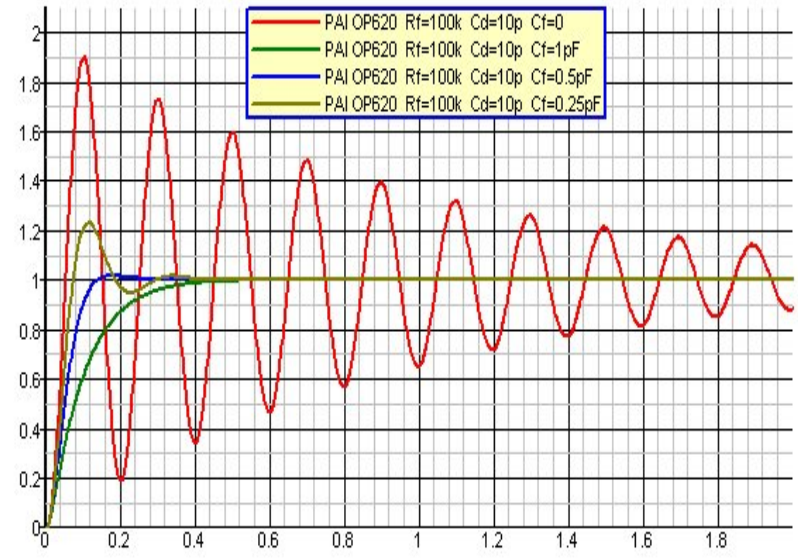
- Transimpedance configuration
  - $V_{out}(\omega)/i_{in}(\omega) = - R_f / (1+Z_f/GZ_d)$
  - Gain = R_f
  - High counting rate
  - Typically optical link receivers

- 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



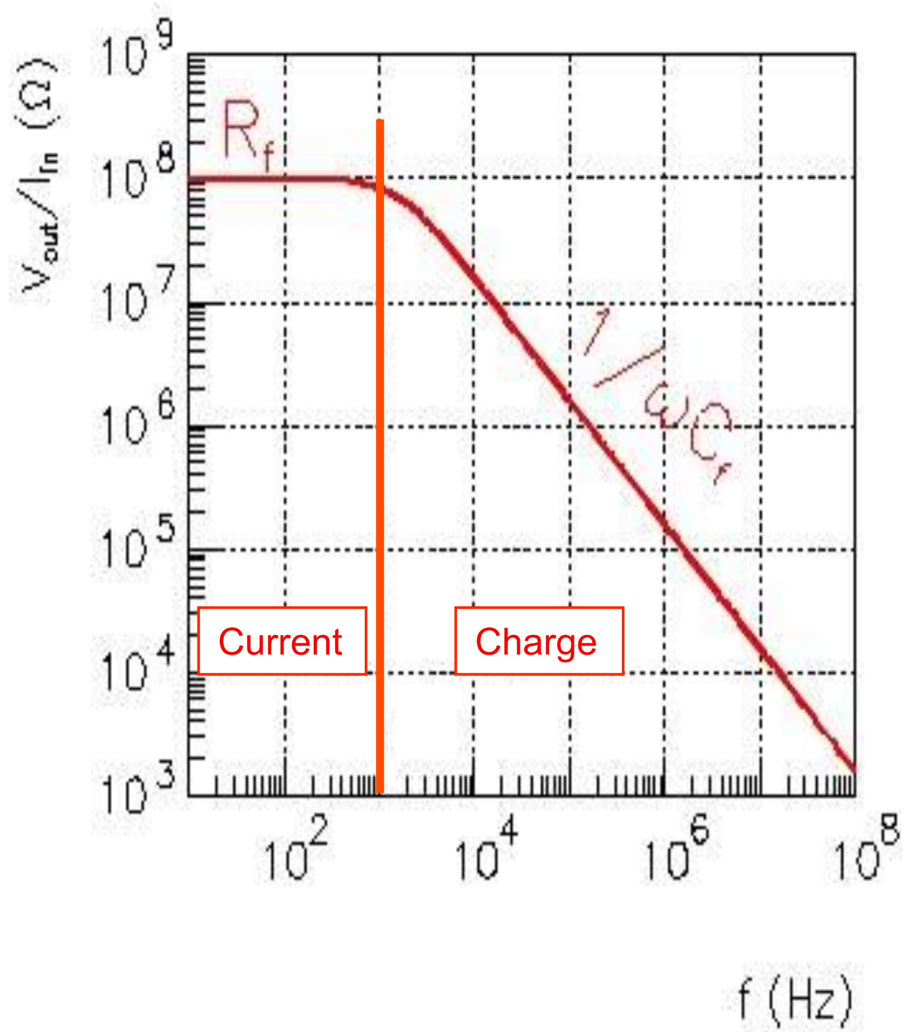
Current sensitive preamp



Step response of current sensitive preamp

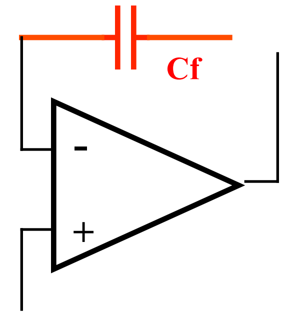
Charge vs Current preamps

- 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)

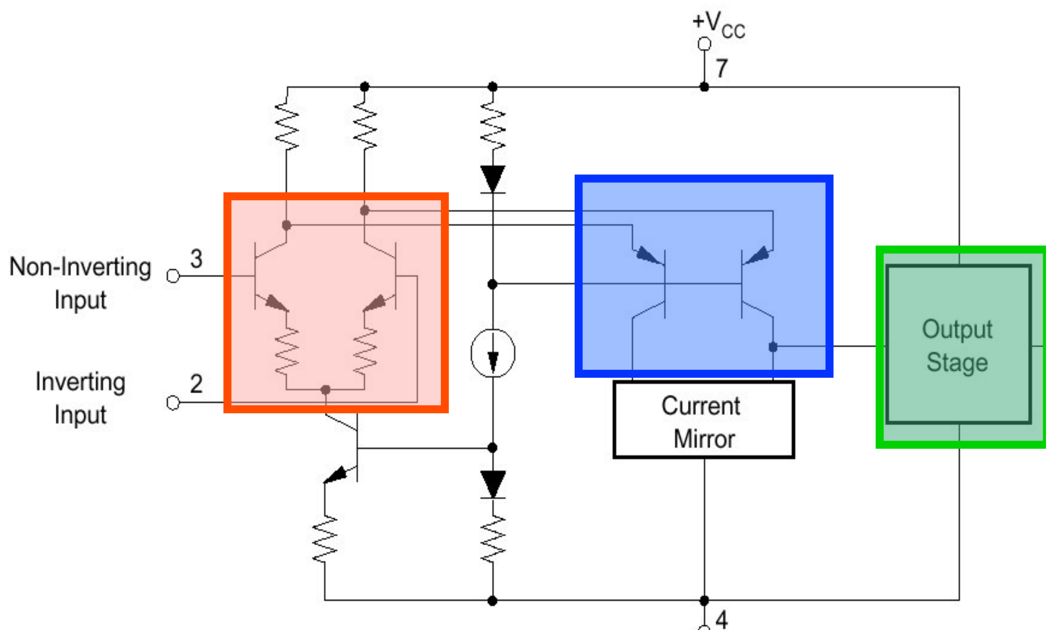


Charge preamp design

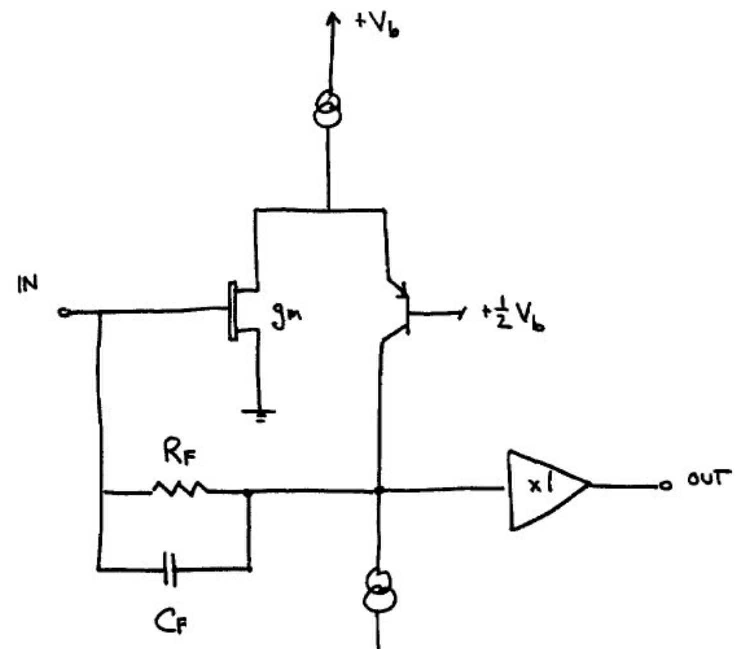
- From the schematic of principle
  - Using of a fast opamp (OP620)
  - Removing unnecessary components…
  - Similar to the traditionnal schematic «Radeka 68 »
  - Optimising transistors and currents



Charge preamp



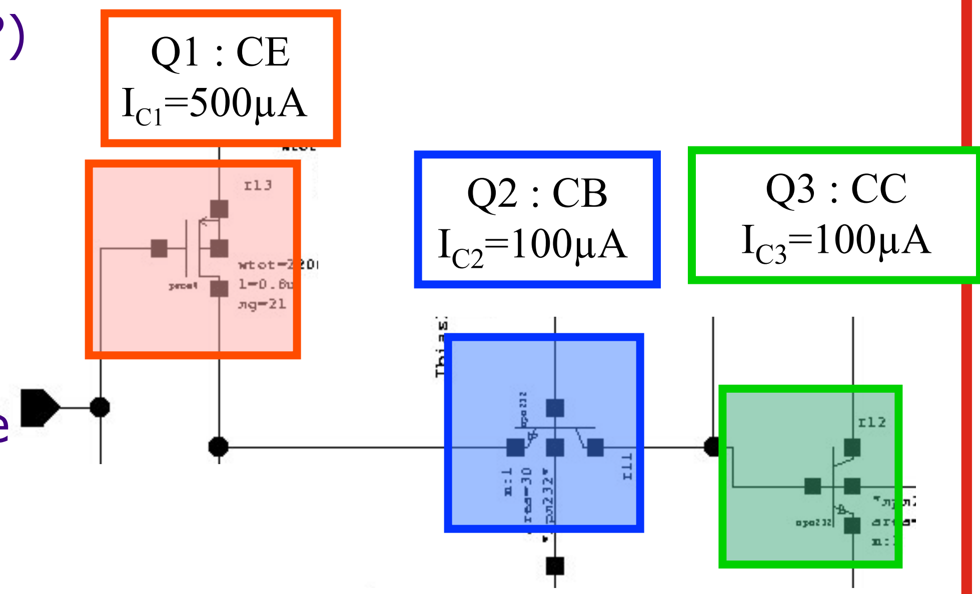
Schematic of an OP620 opamp ©BurrBrown



Original charge preamp ©Radeka 1968

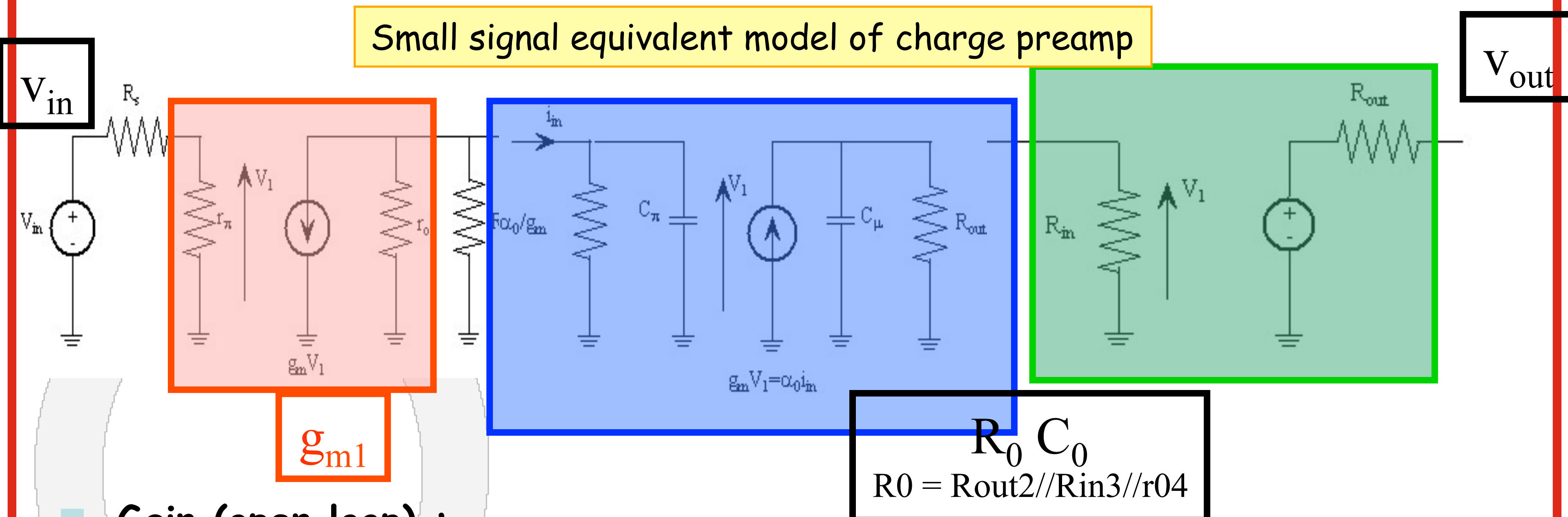
Example : designing a charge preamp (2)

- Simplified schematic
- Optimising components
  - What transistors (PMOS, NPN ?)
  - What bias current ?
  - What transistor size ?
  - What is the noise contributions 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 the sensitivity to power supplies, temperature…



Simplified schematic of charge preamp

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



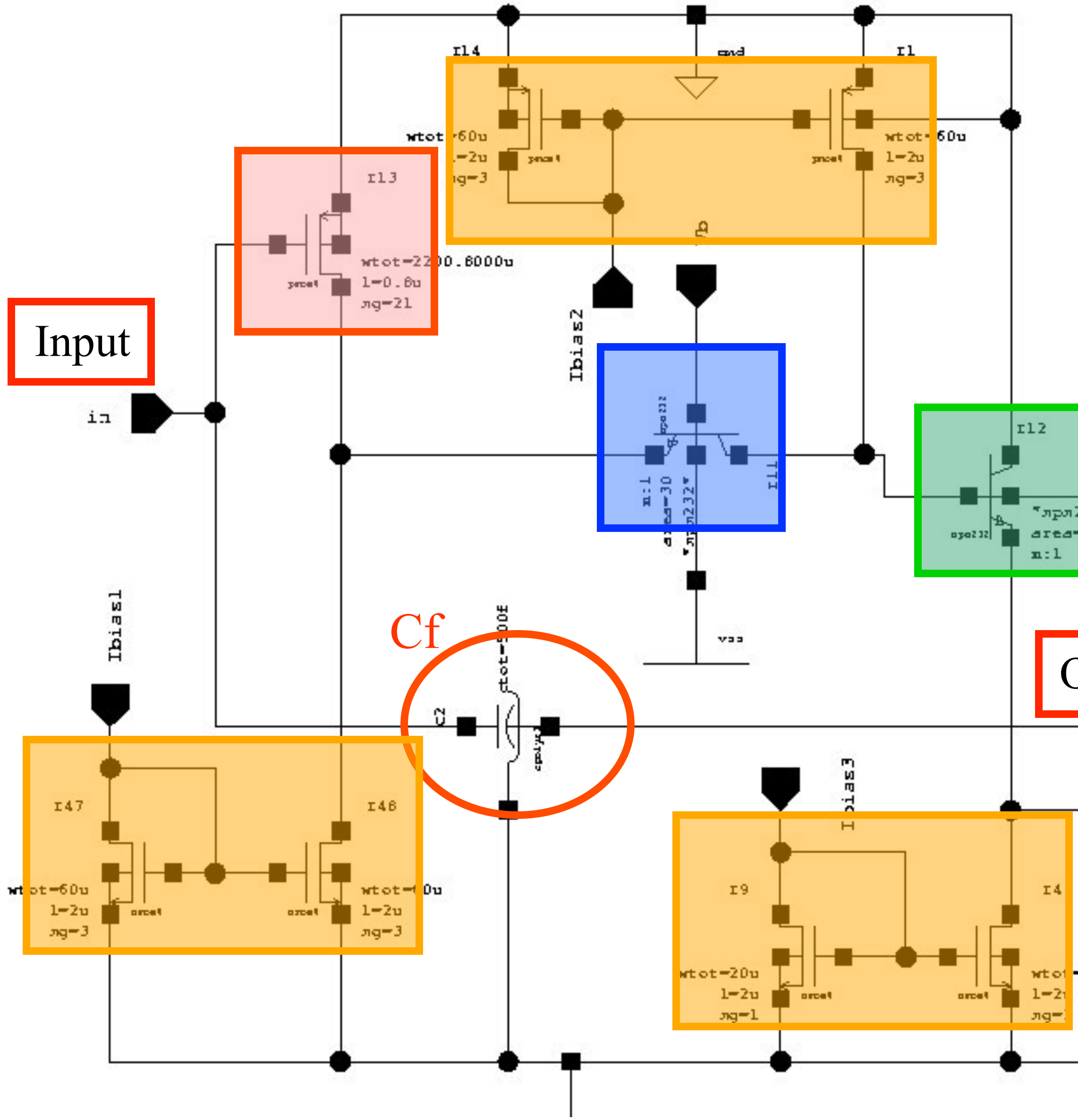
- Gain (open loop) :

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

- *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 !

Example : designing a charge preamp (4)

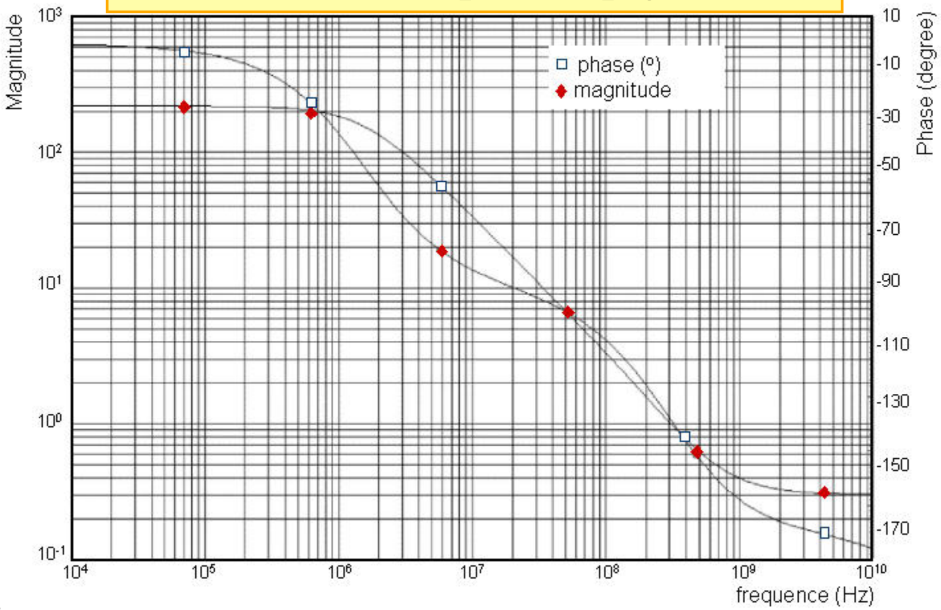
- Complete schematic
  - Adding bias elements



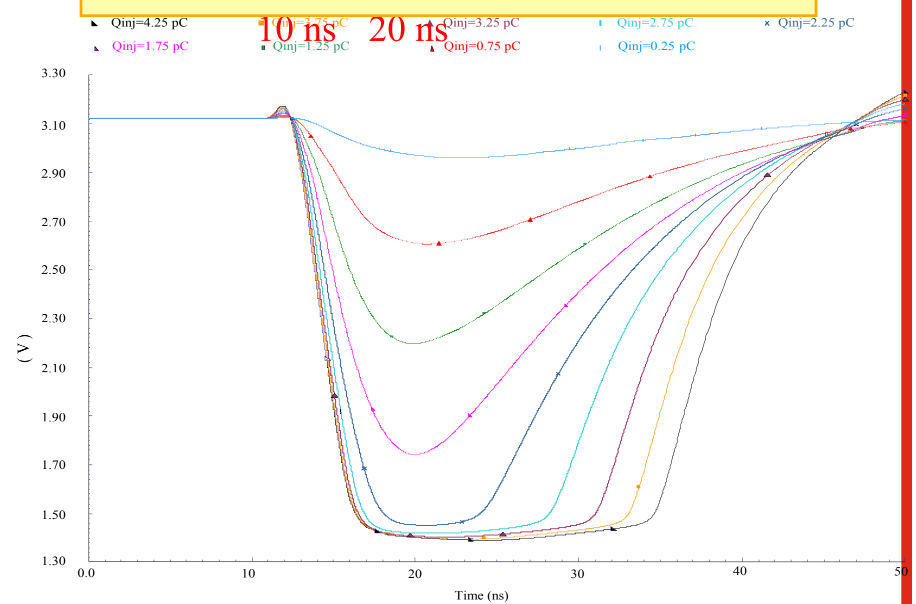
Example : designing a charge preamp (5)

- 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



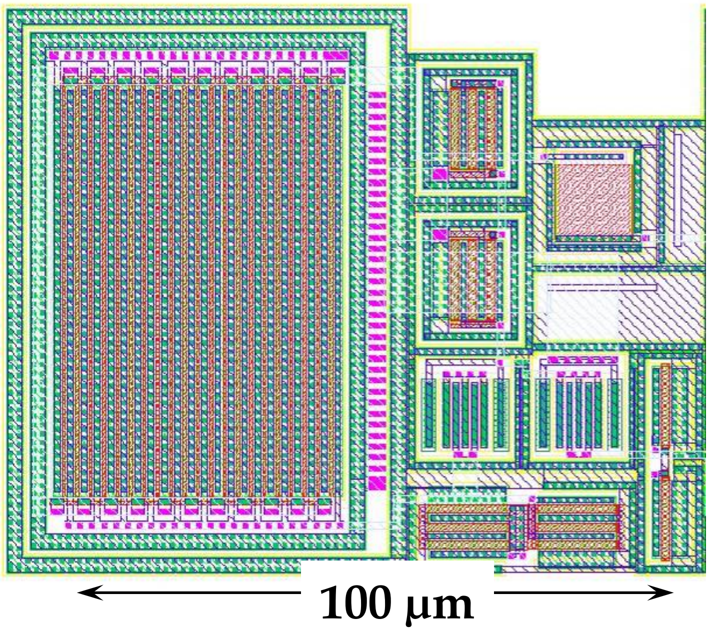
Saturation behaviour



1 MHz

Example : designing a charge preamp (6)

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

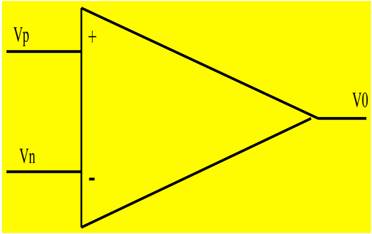


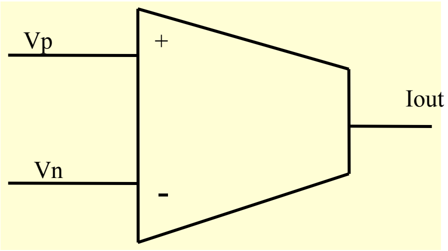
Electromagnetic compatibility (EMC-EMI)

- 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

extension slides

- Voltage feedback operationnal amplifier (VFOA)
- Voltage amplifiers, RF amplifiers (VA,LNA)
- Current feedback operationnal amplifiers (CFOA)
- Current conveyors (CCI, CCII +/-)
- Current (pre)amplifiers (ISA,PAI)
- Charge (pre)amplifiers (CPA,CSA,PAC)
- Transconductance amplifiers (OTA)
- Transimpedance amplifiers (TZA,OTZ)

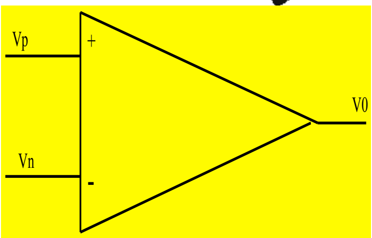




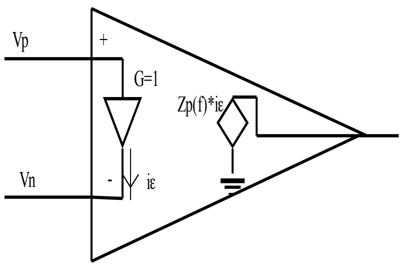
- Mixing up open loop (OL) and closed loop (CL) configurations !

Only 4 open-loop configurations

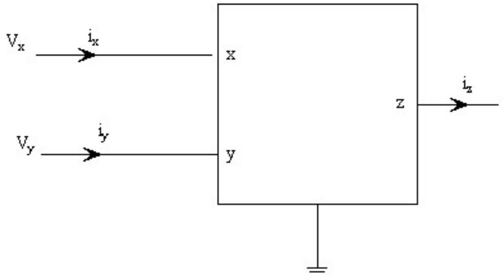
- Voltage operationnal amplifiers (OA, VFOA)
  - Vout = G(ω) Vin diff
  - Zin+ = Zin- = ∞ Zout = 0



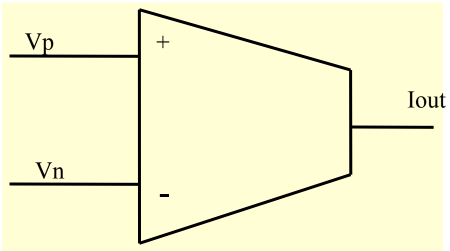
- Transimpedance operationnal amplifier (CFOA !)
  - Vout = Z(ω) iin
  - Zin- = 0 Zout = 0



- Current conveyor (CCI,CCII)
  - Iout = G(ω) Iin
  - Zin = 0 Zout = ∞

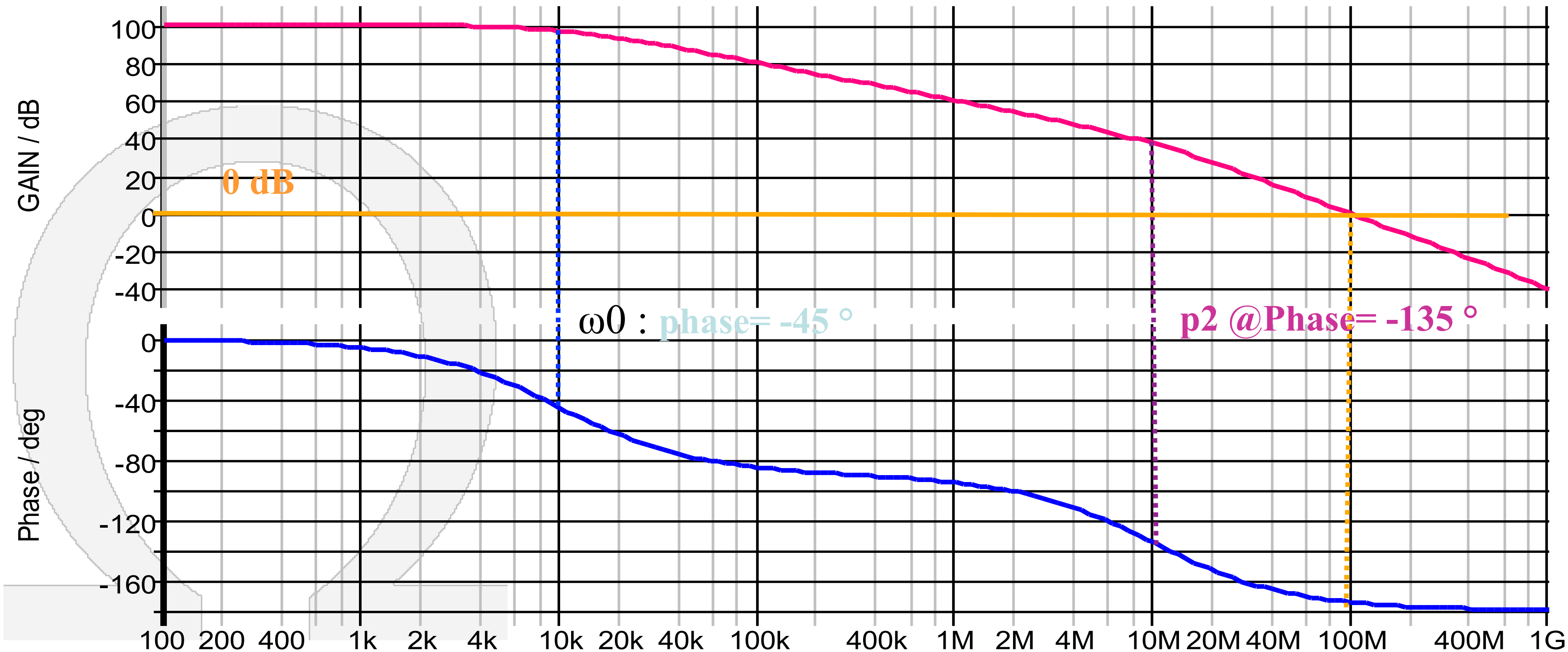


- Transconductance amplifier (OTA)
  - Iout = Gm(ω) Vin diff
  - Zin+ = Zin- = ∞ Zout = ∞



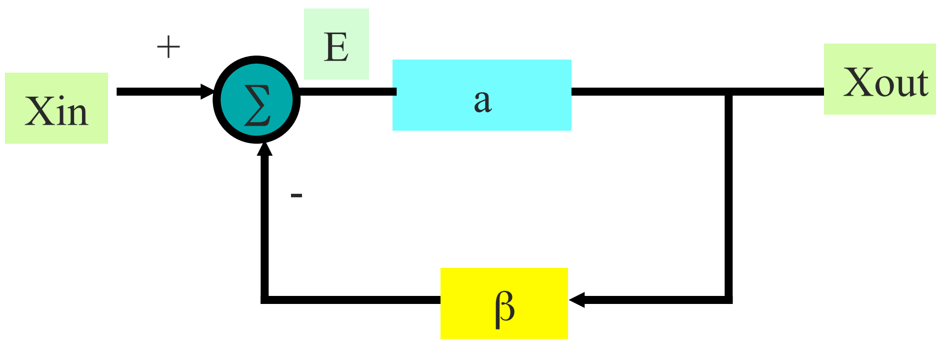
Open loop gain variation with frequency

- Define exactly what is « gain » vout/vin, vout/iin…
- « Gain » varies with frequency : $\mathbf{G(j\omega) = G_0/(1 + j\,\omega/\omega_0)}$
  - $\mathbf{G_0}$ low frequency gain
  - $\boldsymbol{\omega_0}$ dominant pole
  - $\boldsymbol{\omega_C = G_0\,\omega_0}$ Gain-Bandwidth product (sometimes referred to as unity gain frequency)

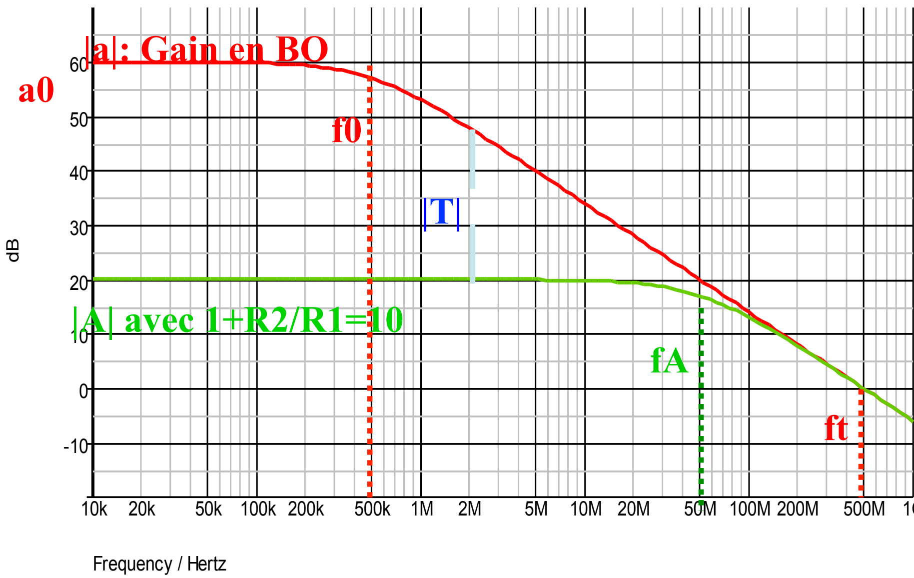


Feedback : an essential tool

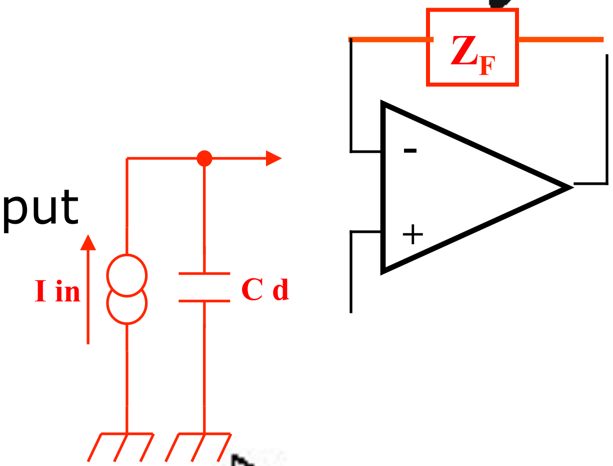
- Improves gain performance
  - Less sensitivity to open loop gain (a)
  - Better linearity
- Essential in low power design
- Potentially unstable
- Feedback constant : β = E/Xout
- Open loop gain : a = Xout/E
- Closed loop gain : Xout/Xin -> 1/β



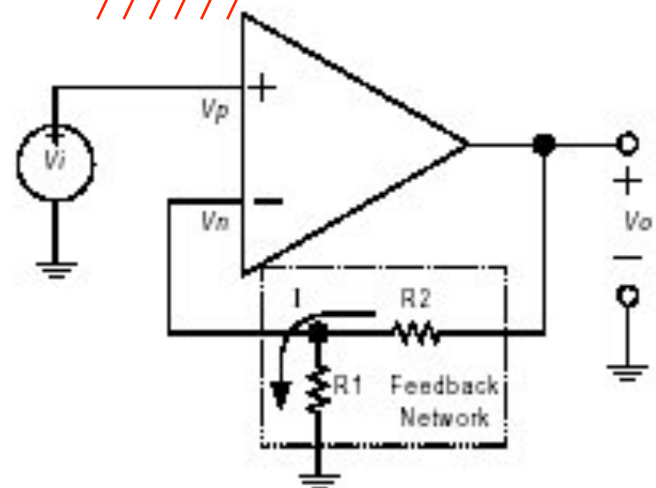
$$\frac{Xout}{Xin} = \frac{a}{1 + a\beta} = \frac{1/\beta}{1 + 1/a\beta}$$



Only 4 feedback configurations



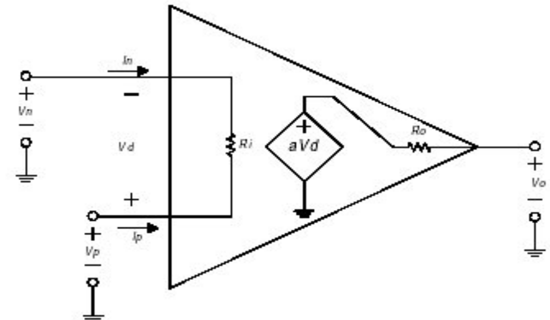
- Shunt-shunt = transimpedance
  - Small Zin (= Zin(OL)/T) -> current input
  - small Zout (= Zout(OL)/T) -> voltage output
  - De-sensitizes transimpedance = 1/β = Zf
- Series-shunt
  - Large Zin (= Zin(OL)*T) -> voltage input
  - Small Zout (= Zout(OL)/T) -> voltage
  - Optimizes voltage gain (= 1/β)

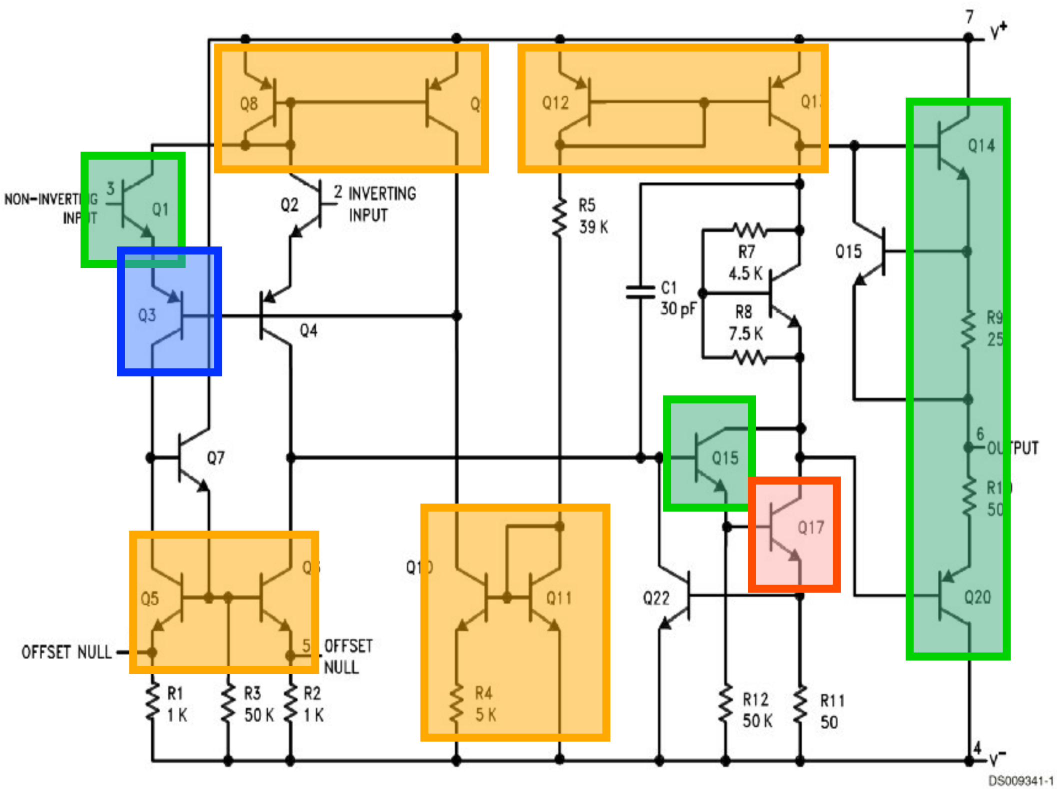


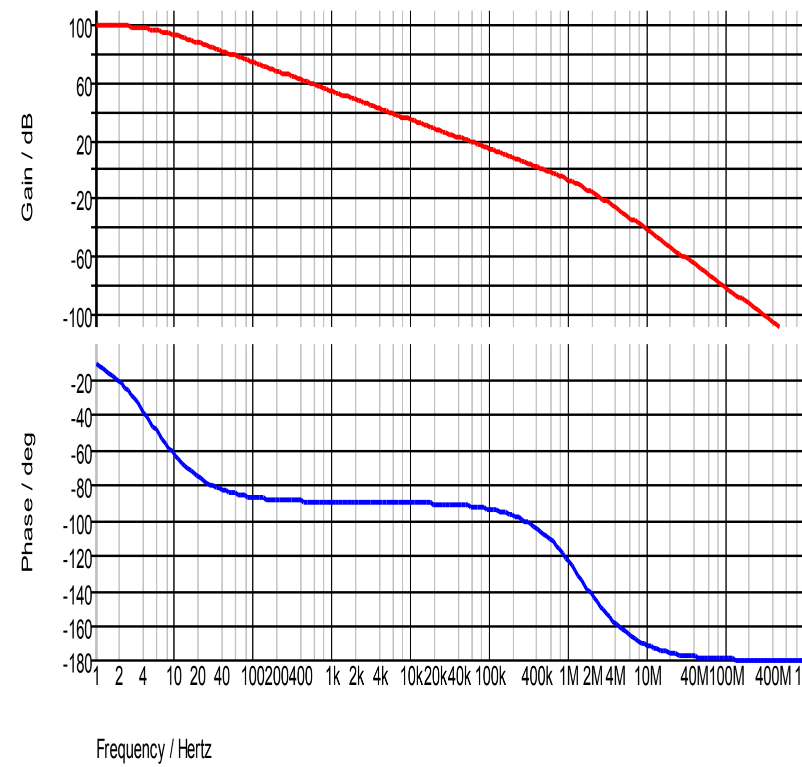
- Shunt series
  - Small Zin (= Zin(OL)/T) -> current inp
  - Large Zout (= Zout(OL)*T) -> current
  - Current conveyor
- Series-series
  - Large Zin (= Zin(OL)*T) -> voltage input
  - Large Zout (= Zout(OL)*T) -> current output
  - Transconductance
  - Ex : common emitter with emitter degenration

Voltage Feedback Operationnal Amplifiers (1)

- Back to the 70's : LM741
  - 3 stages : Paraphase=CE, Darlington=CE,
  - G0 = 200 000, f0 = 5Hz, GBW = 1 MHz, F



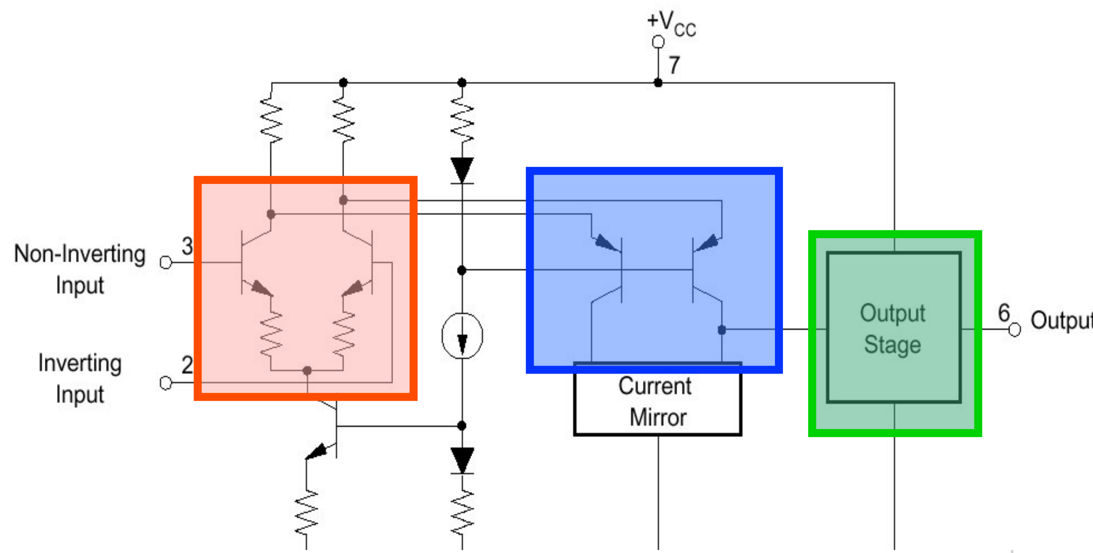


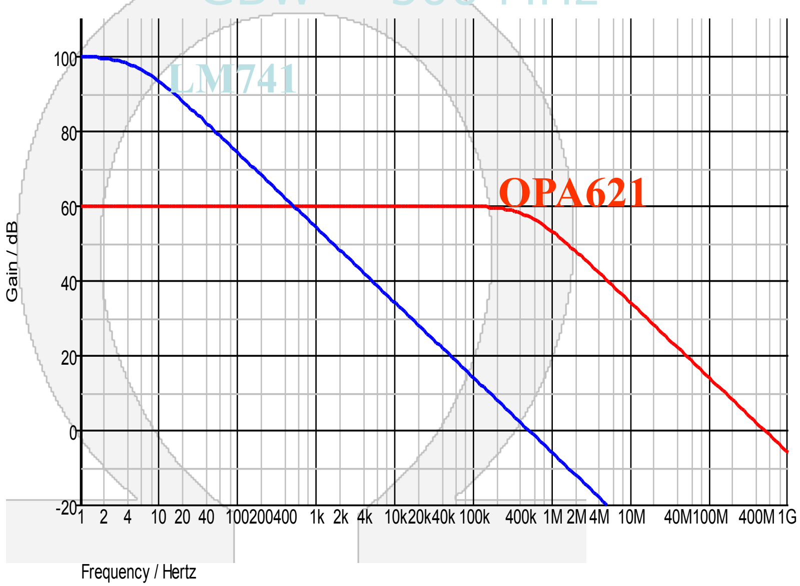


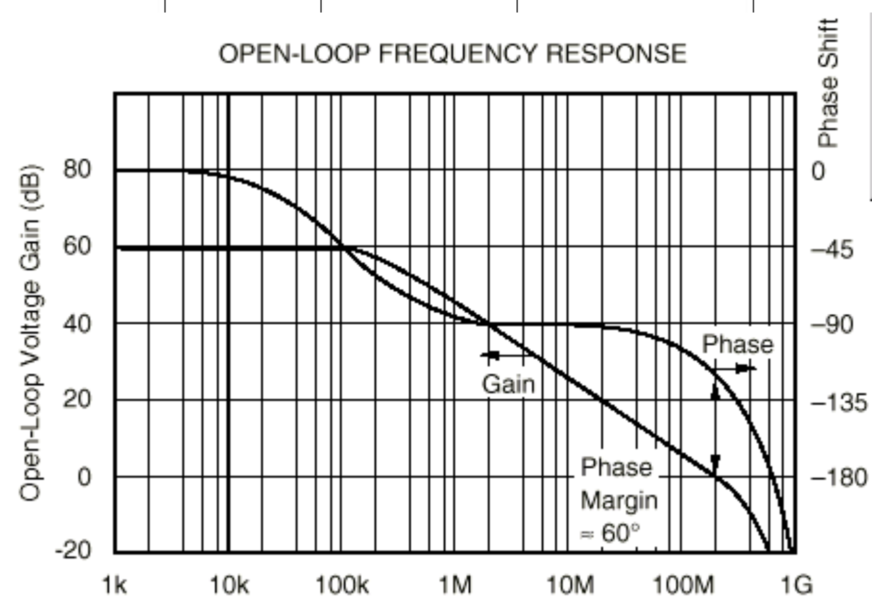
Schematic diagramm of a LM741 (1970) ©National Semiconductors

Voltage Feedback Operationnal Amplifiers (2)

- Breakthrough in the 90's : OP620-621
  - 2 stages : Cascode=CE, Push-pull = CC
  - Pd = 250 mW
  - G0 = 1 000
  - f0 = 500kHz
  - GBW = 500 MHz







Open loop frequency response of OP620

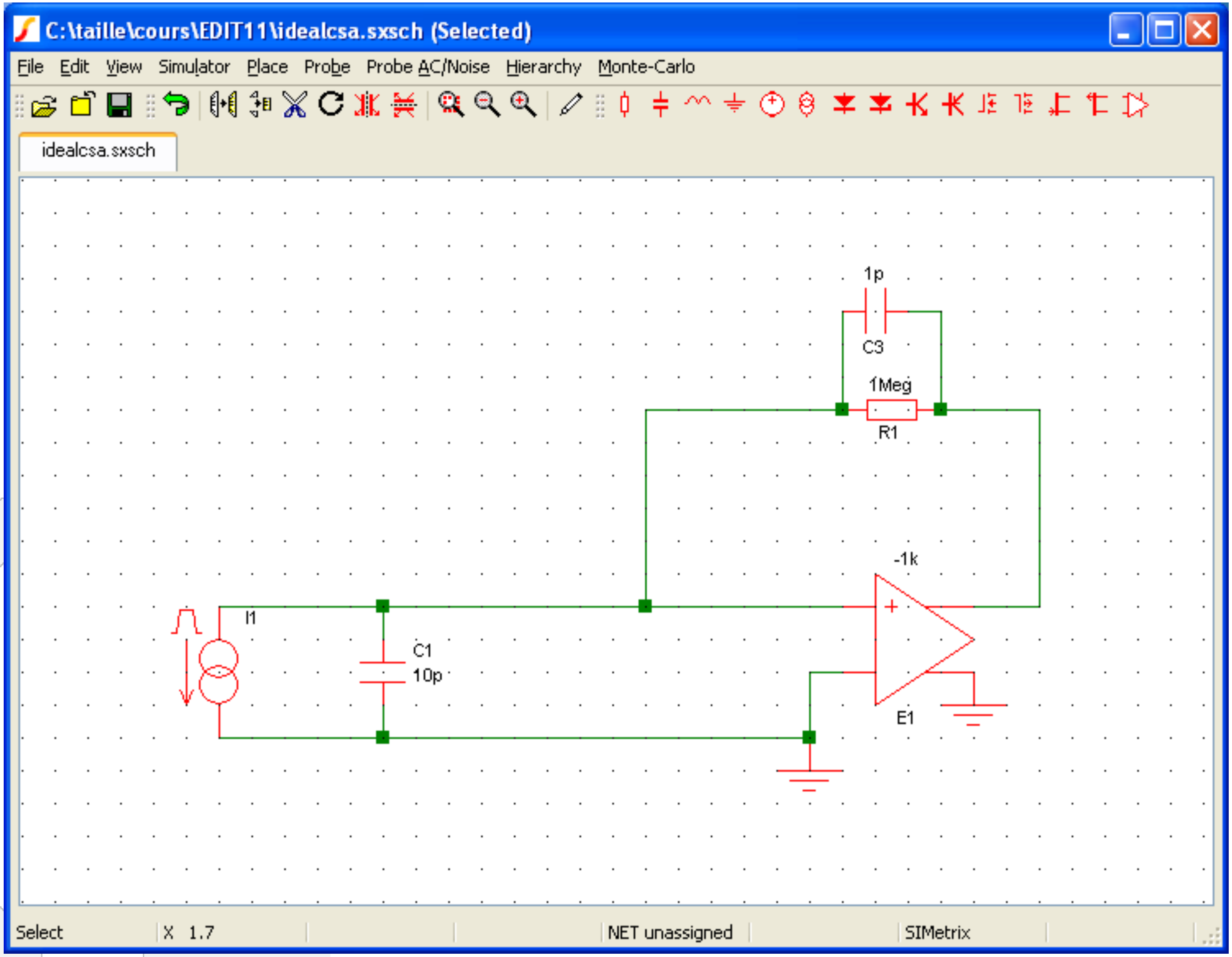
40 Gb/s transimpedance amplifier

- « Simple architecture »
  - CE + CC configuration
  - SiGe bipolar transi[redacted]
  - CC outside feedbac[redacted]
  - « pole splitting »

[redacted]

Exercice slides

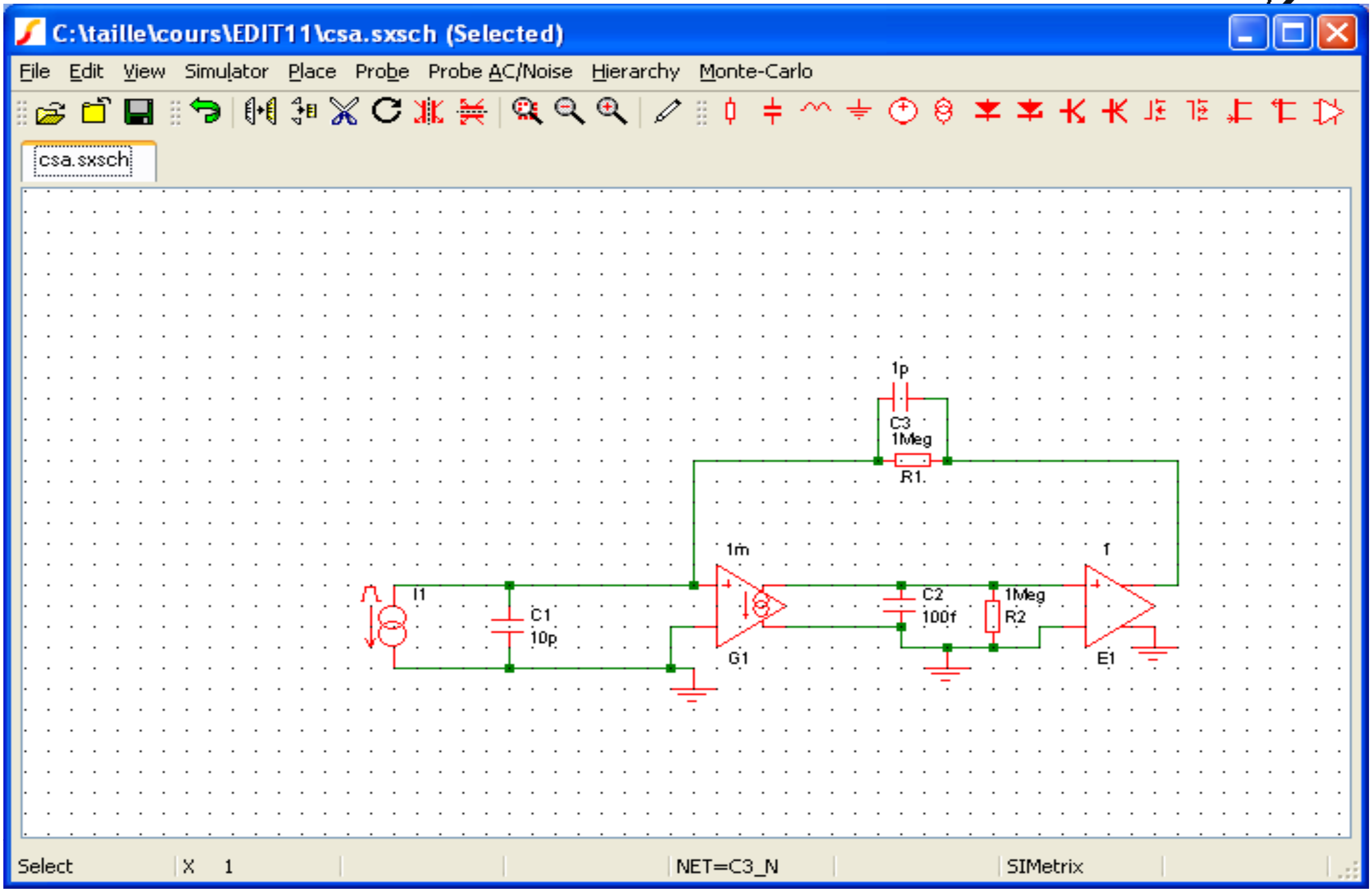
Ideal charge preamp



Ideal 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

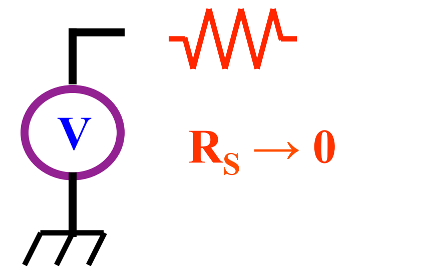
Non ideal charge preamp



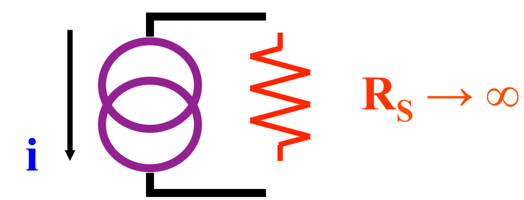
backup slides

The foundations of electronics

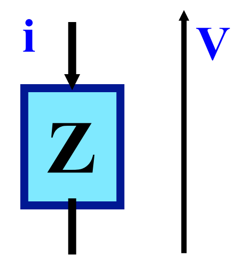
- Voltage generators or source
  - Ideal source : constant voltage, independent of current (or load)
  - In reality : non-zero source impedance R_S



- **Current generators**
  - Ideal source : constant current, independent of voltage (or load)
  - In reality : finite output source impedance R_S

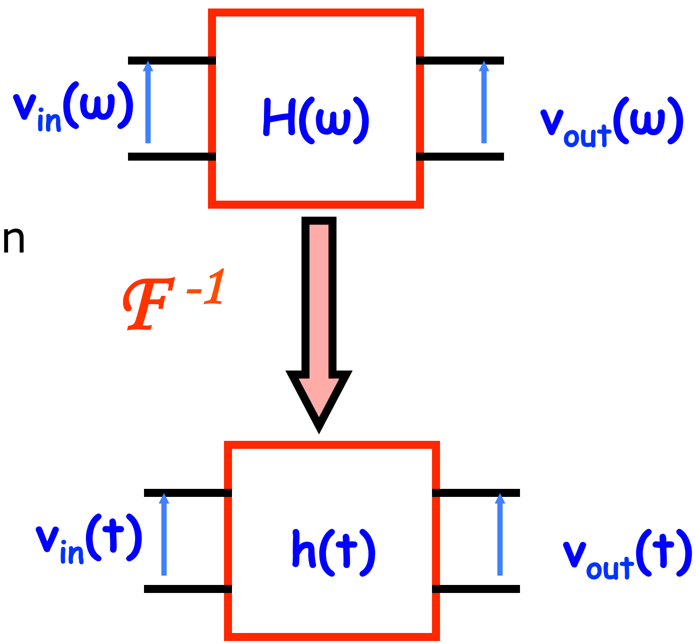


- **Ohms' law**
  - $Z = R, 1/j\omega C, j\omega L$
  - Note the sign convention



Frequency domain & time domain

- Frequency domain :
  - $V(\omega,t) = A \sin(\omega t + \varphi)$
    - Described by amplitude and phase (A, φ)
  - **Transfer function : $H(\omega)$** [or $H(s)$]
  - = The ratio of output signal to input signal in the frequency domain assuming linear electronics
  - $V_{out}(\omega) = H(\omega)\, V_{in}(\omega)$



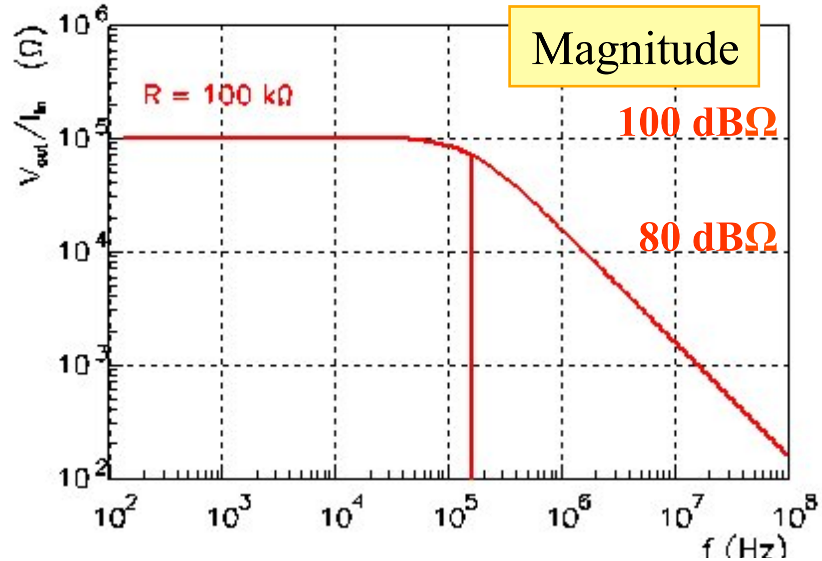
- Time domain
  - Impulse response : h(t)
  - = the output signal for an impulse (delta) input in the time domain
  - The output signal for any input signal $v_{in}(t)$ is obtained by convolution : «*» :
  - $V_{out}(t) = v_{in}(t) * h(t) = \int v_{in}(u) * h(t-u)\, du$

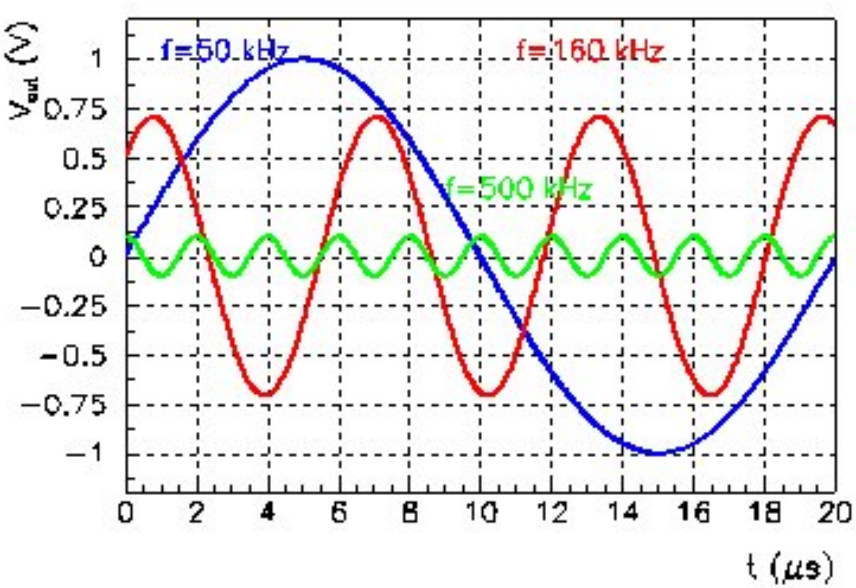
- Correspondance through Fourier transforms
  - $X(\omega) = \mathcal{F}\{x(t)\} = \int x(t) \exp(j\omega t)dt$
  - a few useful Fourier transforms in appendix

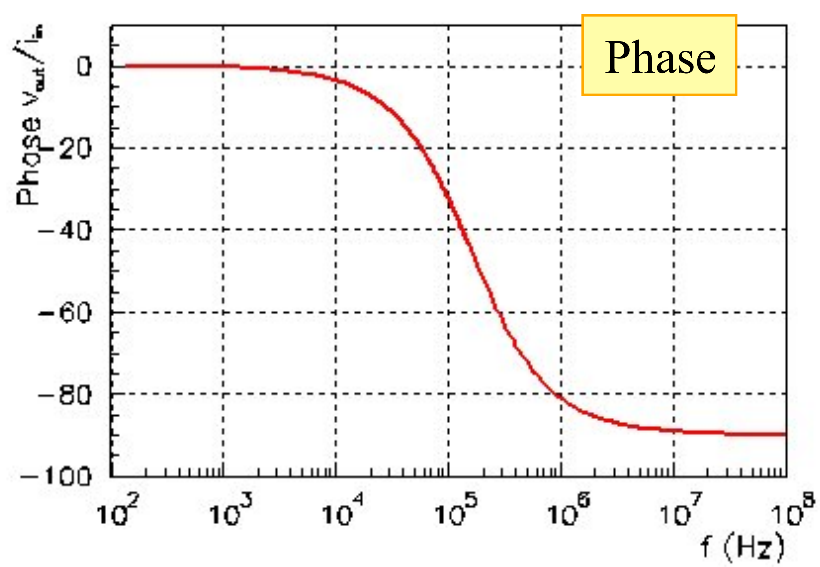
- $H(\omega) = 1$ -> $h(t) = \delta(t)$ (impulse)
- $H(\omega) = 1/j\omega$ -> $h(t) = S(t)$ (step)
- $H(\omega) = 1/j\omega\,(1+j\omega T)$ -> $h(t) = 1 - \exp(-t/T)$
- $H(\omega) = 1/(1+j\omega T)$ -> $h(t) = \exp(-t/T)$
- $H(\omega) = 1/(1+j\omega T)^n$ -> $h(t) = 1/n!\,(t/T)^{n-1} \exp(-t/T)$

- Bode plot
  - Magnitude (dB) = 20 log |H(jw)|
  - -3dB bandwidth : $f_{-3dB} = 1/2\pi RC$
    - $R=10^5\Omega$, C=10pF => f_{-3dB}=160 kHz
    - At f_{-3dB} the signal is attenuated by 3dB = √2, the phase is -45°

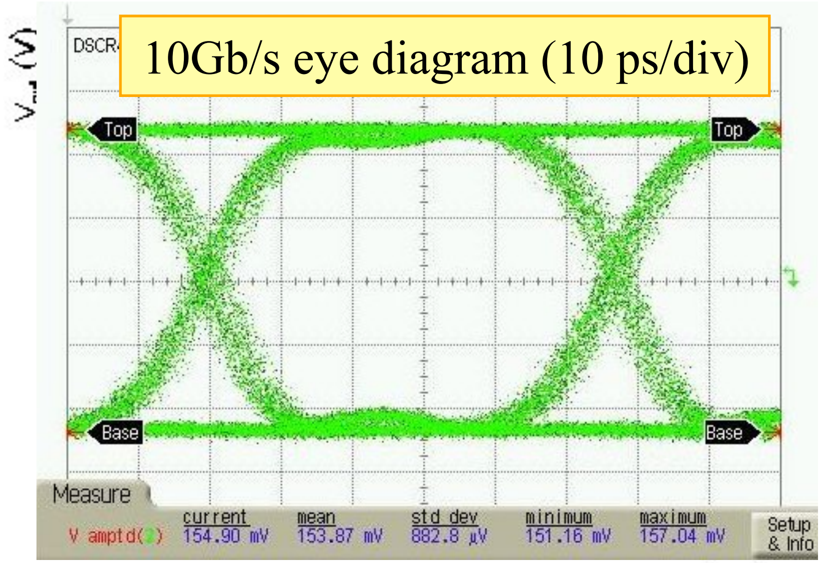
dB/







- **Impulse response**
  - $h(t) = \mathcal{F}^{-1}\{ R/(1+j\omega RC) \}$
    $= R/\tau \; \exp(-t/\tau)$
  - τ *(tau)* = RC = 1 μs : time constant



- Step response : rising exponential
  - $H(t) = \mathcal{F}^{-1}\{ 1/j\omega \; R/(1+j\omega RC) \}$
    $= R\,[\,1 - \exp(-t/\tau)\,]$
  - Rise time : $t_{10\text{-}90\%} = 2.2\,\tau$
  - « eye diagramm »