Introduction to Electronics in HEP Experiments

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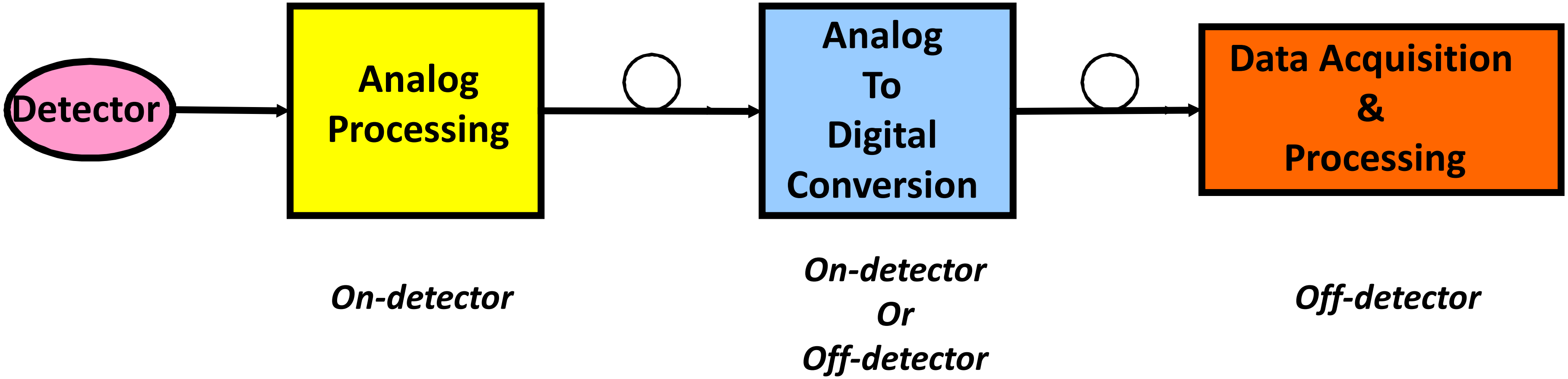
CERN

Credits and sources of information

- I have "stolen" a lot from the previous summer student lectures from Christophe de la Taille and Jorgen Christiansen and from colleagues from the PH electronics group (PH-ESE)

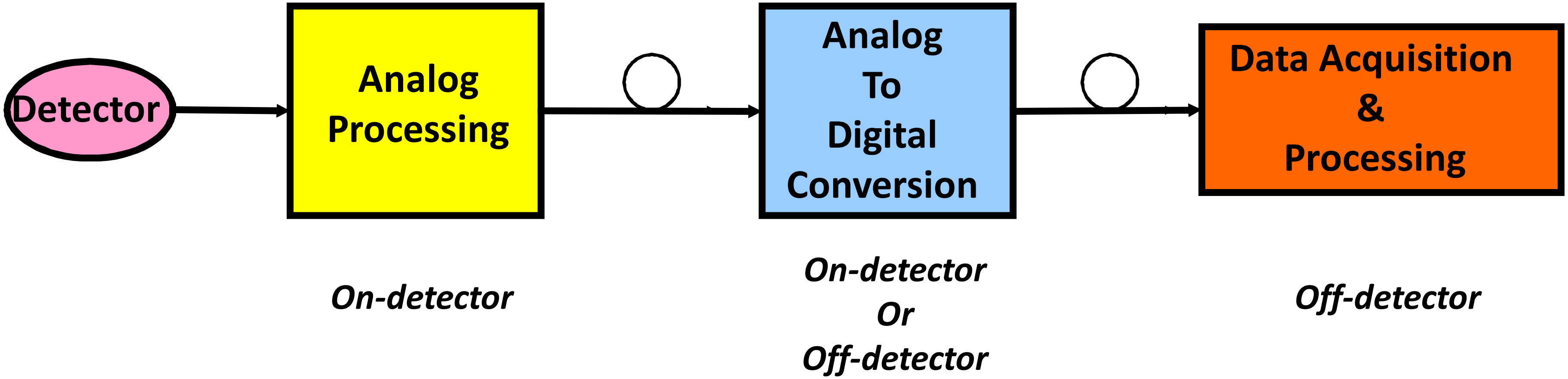
- Useful and more complete information can be found in the following sites:
  - CERN technical training ELEC 2005:
    http://indico.cern.ch/conferenceDisplay.py?confId=62928
  - LEB/LECC/TWEPP workshops from last 12 years:
    http://lhc-electronics-workshop.web.cern.ch/lhc%2Delectronics%2Dworkshop/
  - PH-ESE seminars:
    http://indico.cern.ch/categoryDisplay.py?categId=1591

Outline



- Analog processing
- Analog to digital conversion
- Technology evolution
- Off-detector digital electronics

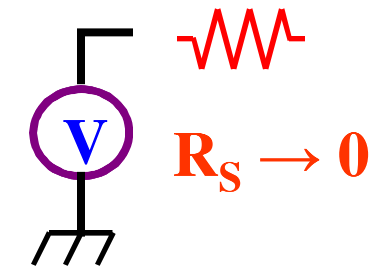
Outline



- Analog processing
- Analog to digital conversion
- Technology evolution
- Off-detector digital electronics

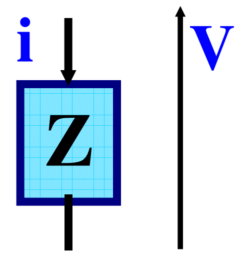
- A few basic reminders
- Modelisation of the detector
- Charge and current amplifiers
- Noise
- Example of a preamplifier design

- 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/jωC, jωL
  - Note the sign convention

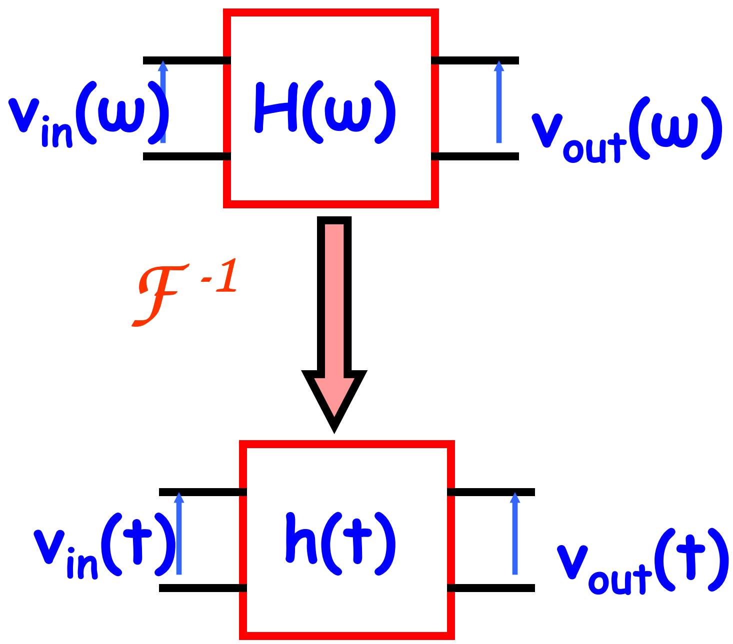


Frequency domain & time domain

- **Frequency** domain :
  - $V(\omega,t) = A \sin(\omega t + \phi)$
    - 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**

$$X(\omega) = F\{x(t)\} = \int_{-\infty}^{\infty} x(t)\, e^{-j\omega t}\, dt$$

  - A few useful Fourier transforms in appendix below



$$F(\omega)=\int_{-\infty}^{\infty}x(t)\,e^{-j\omega t}\,dt$$

Usualfunctions

$$\delta(t)\rightarrow 1$$

$$\nu(t)\rightarrow\frac{1}{j\omega}$$

$$e^{-at}\rightarrow\frac{1}{j\omega+a}$$

$$1-e^{-at}\rightarrow\frac{1}{j\omega(j\omega+a)}$$

$$t^{n-1}e^{-at}\rightarrow\frac{1}{(j\omega+a)^{n}}$$

Linearity

$$ah_1(t)+bh_2(t)\rightarrow aF_1(\omega)+bF_2(\omega)$$

Integration,derivation

$$h(t)\rightarrow F(\omega);\,h'(t)\rightarrow j\omega F(\omega)$$

$$h(t)\rightarrow F(\omega);\,\int h(t)dt\rightarrow\frac{F(\omega)}{j\omega}$$

IMPEDANCES

Capacitor

$$Q=CV$$

$$I(t)=CV'(t)$$

$$I(\omega)=Cj\omega V(\omega)$$

$$Z(\omega)=\frac{V(\omega)}{I(\omega)}=\frac{1}{j\omega C}$$

Inductor

$$V(t)=LI'(t)$$

$$V(\omega)=Lj\omega I(\omega)$$

$$Z(\omega)=\frac{V(\omega)}{I(\omega)}=j\omega L$$

Using Ohm's law

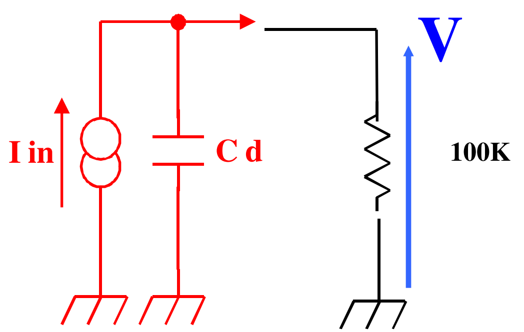
- Example of photodiode readout
  - Used in high speed optical links
  - Signal : ~ 10 µA when illuminated
  - Modelisation :
    - Ideal current source Iin
    - pure capacitance C_d
- Simple I to V converter : R
  - R = 100 kΩ gives 1V output for 10 µA

10 Gb/s optical receiver

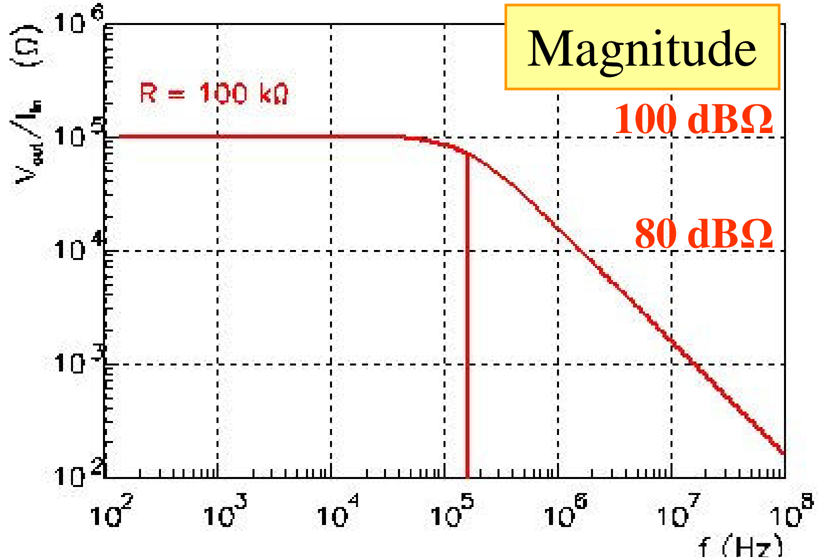
- Speed ?
  - Transfer function H(ω) = v_{out}/i_{in}
  - H has the dimension of Ω and is often called « transimpedance » *and even more often (improperly) « gain »*

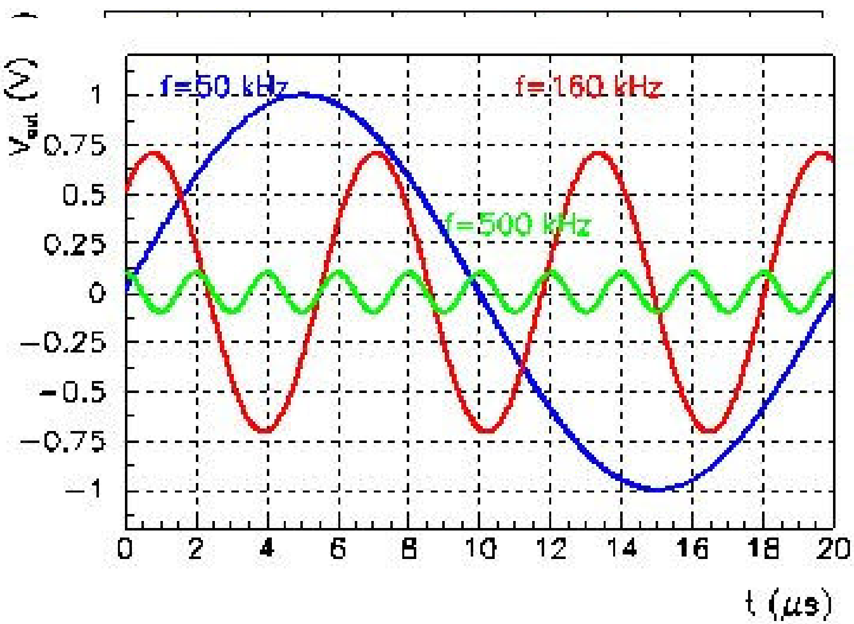
$$H(\omega)=\frac{1}{j\omega C_d+\frac{1}{R}}=\frac{1}{C_d(j\omega+\frac{1}{RC_d})}$$

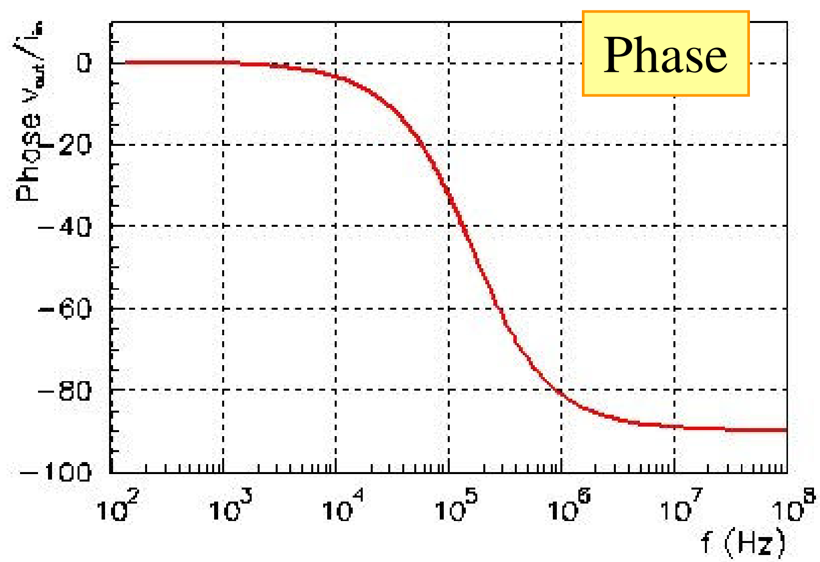
  - $1/RC_d$ is called a « pole » in the transfer function



- Bode plot
  - Magnitude (dB) $20\log|H(\omega)| = 20\log\left|\frac{1}{C_d(j\omega+\frac{1}{RC_d})}\right|$
  - -3dB bandwidth : $f_{-3dB} = 1/2\pi RC_d$
    - $R=10^5\Omega$, C_d=10pF => f_{-3dB}=160 kHz
    - At f_{-3dB} the signal is attenuated by 3dB = √2, the phase is -45°
  - Above f_{-3dB} , gain rolls-off at -20dB/decade







- Impulse response $h(t) = F^{-1}\left(\dfrac{1}{C_d\left(j\omega + \dfrac{1}{RC_d}\right)}\right)$

$$= \frac{R}{\tau}\exp\left(-\frac{t}{\tau}\right)$$

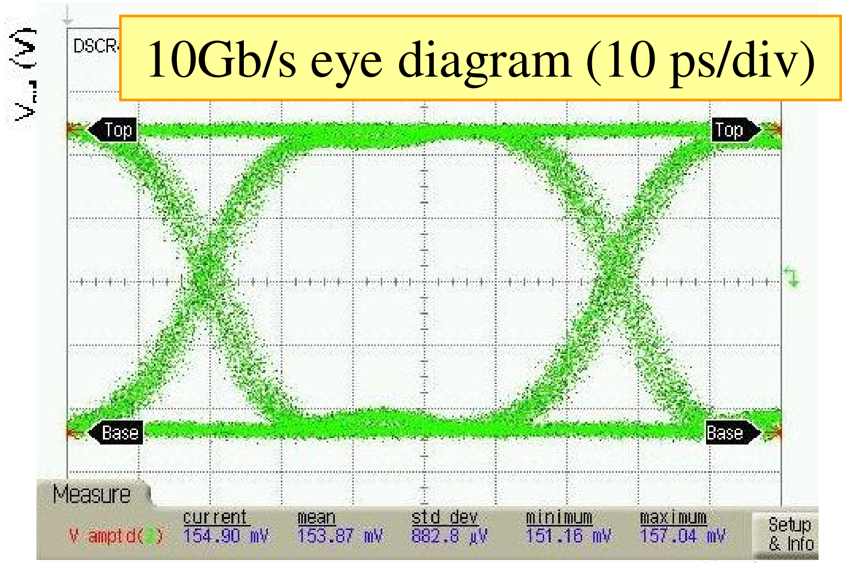
  - τ *(tau)* = RC_d = 1 µs : time constant

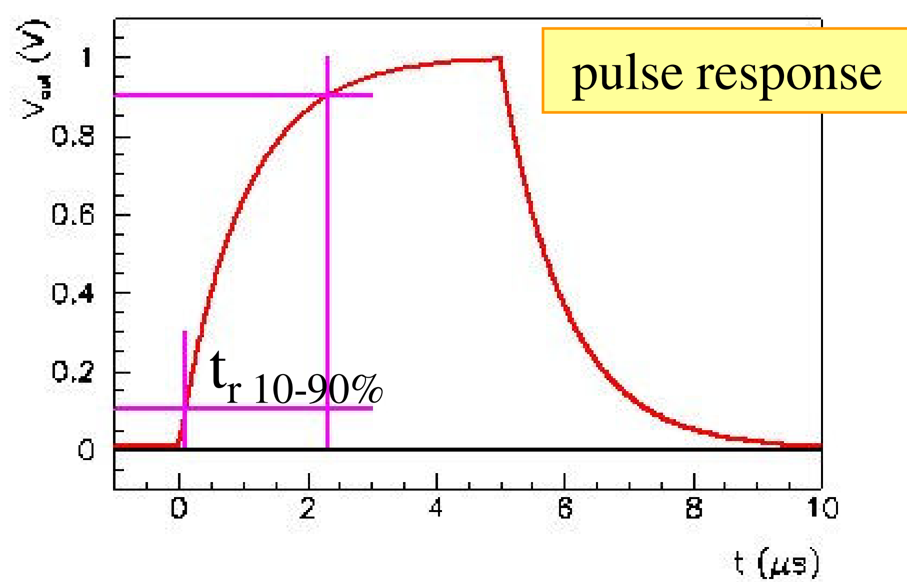
- Step response : rising exponential

$$h(t) = F^{-1}\left(\frac{1}{j\omega} \times \frac{1}{C_d\left(j\omega + \dfrac{1}{RC_d}\right)}\right)$$

$$= R\left(1 - \exp\left(-\frac{t}{\tau}\right)\right)$$

  - Rise time : $t_{10\text{-}90\%}$ = 2.2 τ
  - « eye diagram »
- Speed : ~ 10 µs = 100 kb/s !
  - 5 orders ofmagnitude away from a 10 Gb/s link !





- Y is a source linked to X
  - y = μ x
- Open loop
  - x = δ e
  - y = μ x
  - s = σ y = σ μ δ e
- Closed loop

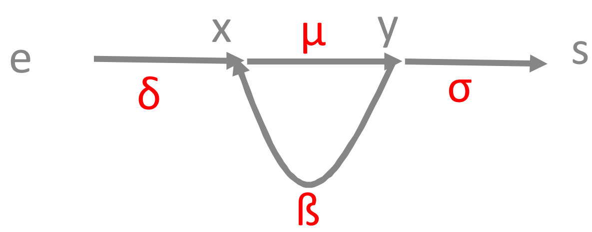
$$\mathbf{x} = \delta\mathbf{e} - \beta\mathbf{y}$$

$$\mathbf{y} = \mu\mathbf{x} = \mu\delta\mathbf{e} - \mu\beta\mathbf{y}$$

$$\mathbf{y} = \frac{\mathbf{e}\delta\mu}{\mathbf{1}+\beta\mu}$$

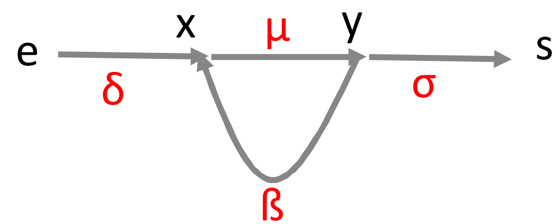
$$\mathbf{s} = \sigma\mathbf{y} = \frac{\mathbf{e}\sigma\delta\mu}{\mathbf{1}+\beta\mu}$$

$$\frac{\mathbf{s}}{\mathbf{e}} = \frac{\sigma\delta\mu}{\mathbf{1}+\beta\mu}$$



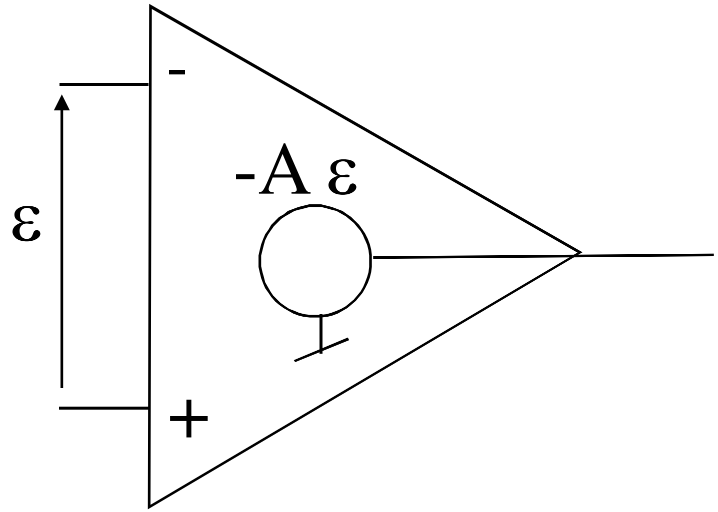
- **μ** is the open loop gain
- **βμ** is the loop gain

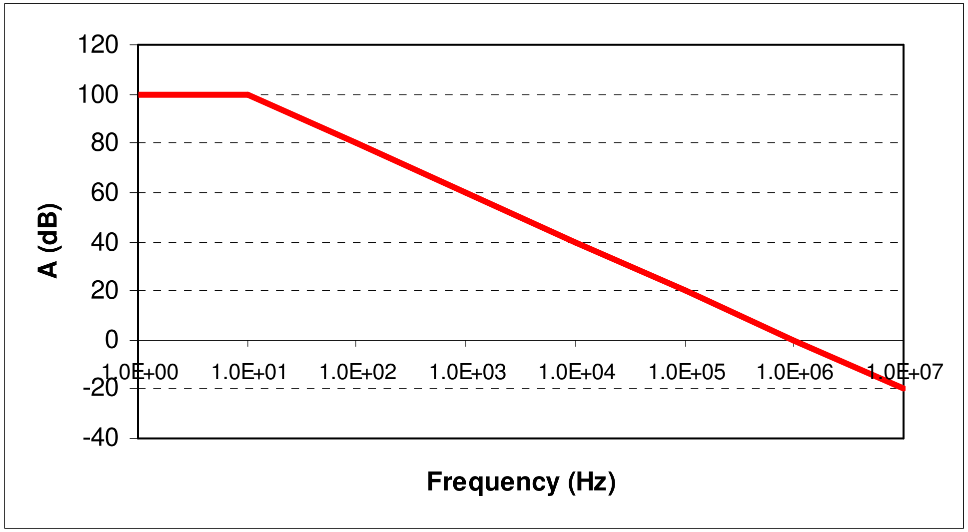
Interest of feedback



- In electronics
  - μ is an amplifier gain
  - β is the feedback loop
- If μ is large enough the gain of the system is independent of the amplifier gain

$$\frac{\mathbf{s}}{\mathbf{e}} = \frac{\sigma\delta\mu}{1+\beta\mu} \approx \frac{\sigma\delta}{\beta}$$





- Gain A very large
- Input impedance very high
  - i.e input current = 0
- A(ω) as shown

- Direct gain calculation

$$\mathbf{Vin = -\varepsilon + I\ R1}$$

$$\mathbf{Vout = -A\varepsilon\ ;\ Vout = (R1 + R2) I}$$

$$\mathbf{\frac{Vout}{Vin} = \frac{A}{1 + A\frac{R1}{R1+R2}}}$$

- Feedback equation

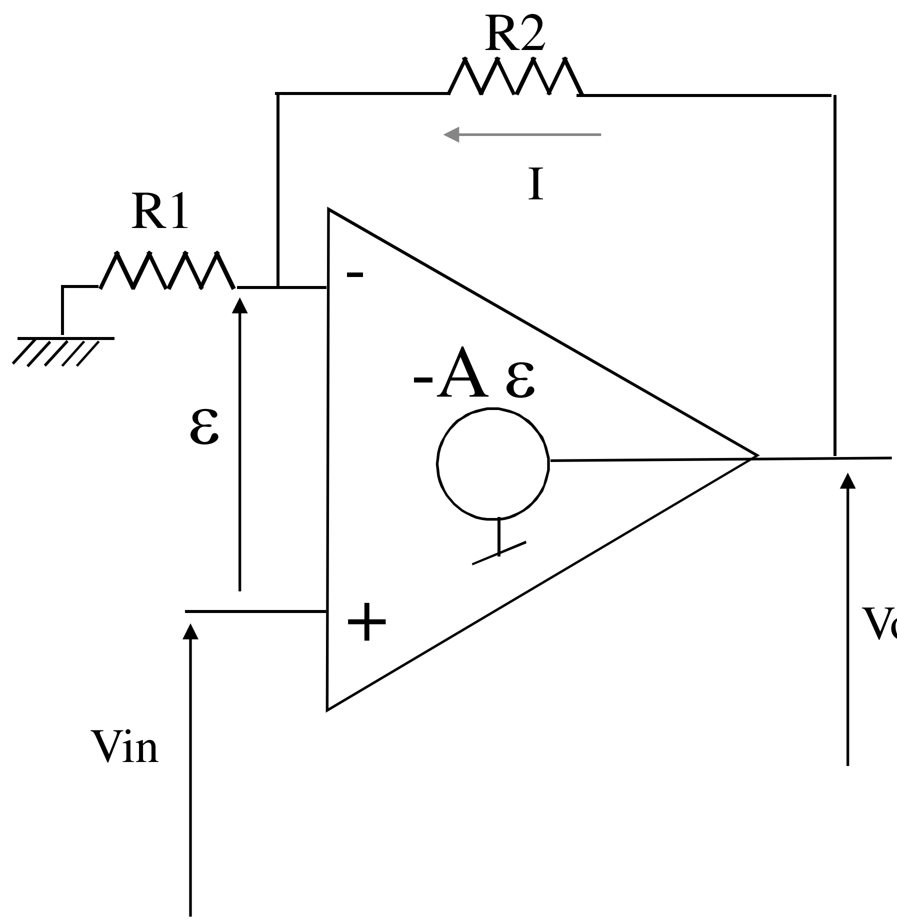
$$\mathbf{\frac{s}{e} = \frac{\sigma\delta\mu}{1+\beta\mu}}$$

$$\mathbf{\mu = A;\ \beta = \frac{R1}{R1+R2};\ \delta = \sigma = 1}$$

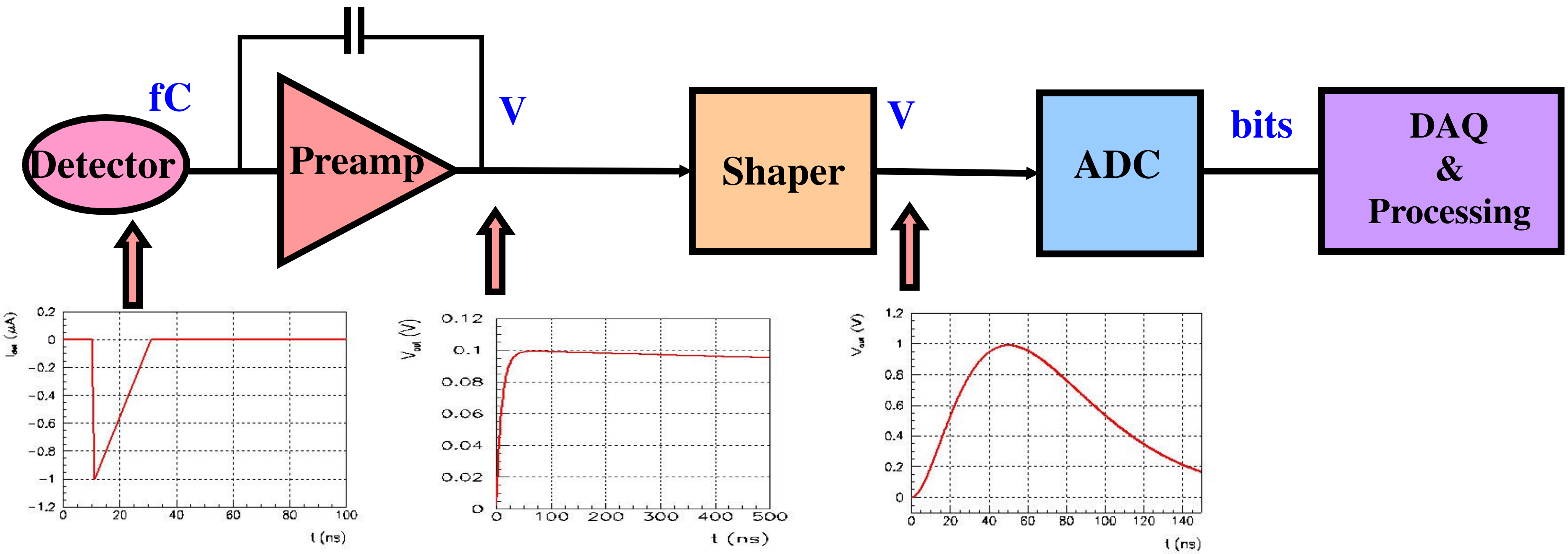
$$\mathbf{\frac{Vout}{Vin} = \frac{A}{1 + A\frac{R1}{R1+R2}}}$$

- Ideal Opamp

$$A = \infty;\ \frac{Vout}{Vin} = \frac{R1+R2}{R1}$$



- Most front-ends follow a similar architecture



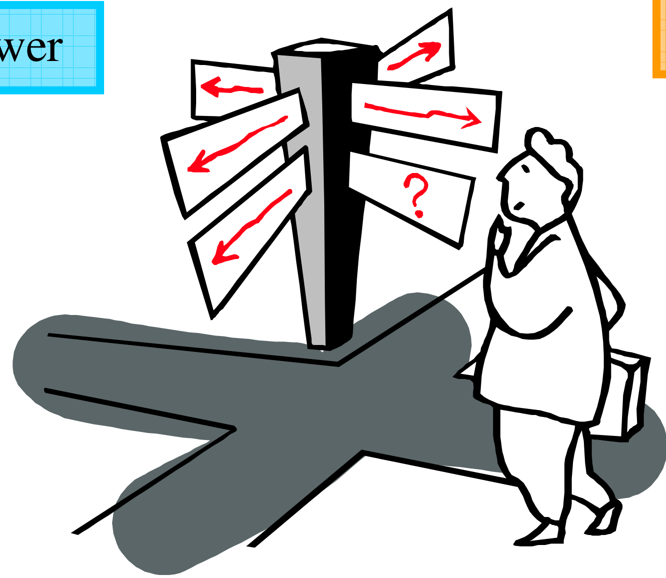
- Very small signals (fC) -> need amplification
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Several thousands to millions of channels

Readout electronics : requirements

Low noise

Low power

High speed



Large dynamic range

High reliability

Radiation hardness

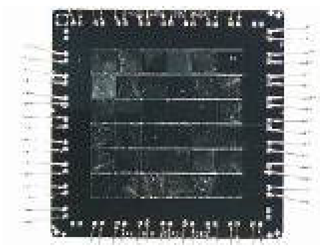
Low cost !

(and even less)

Low material

Detector(s)

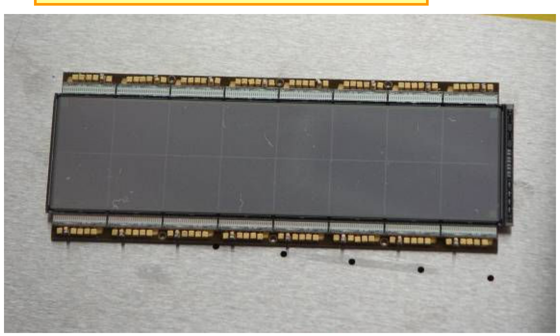
- A large variety
- A similar modelization



6x6 pixels,4x4 mm^2

PMT for Antares

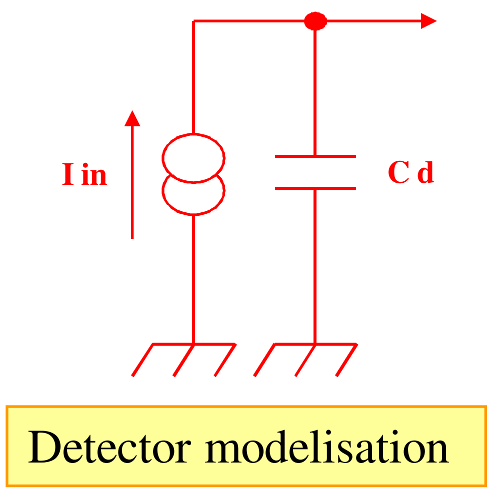
CMS Pixel module

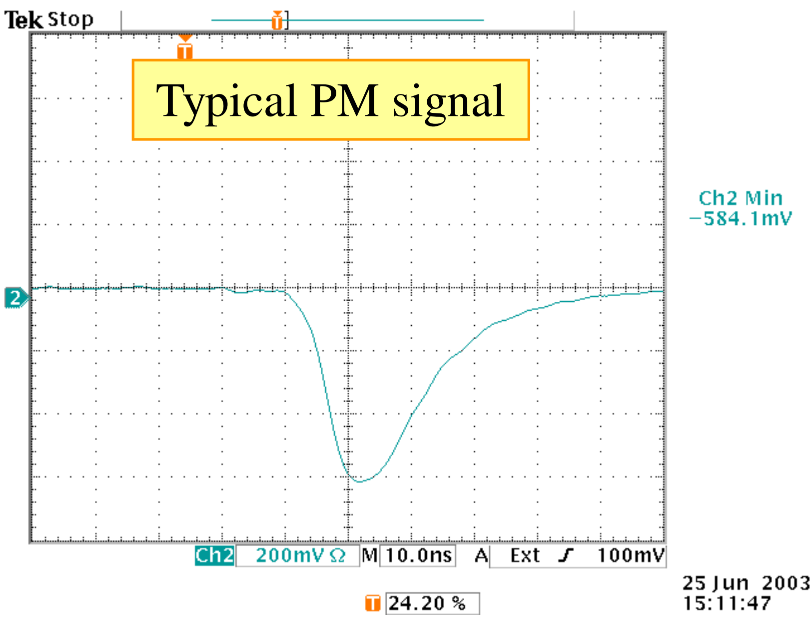


ATLAS Liquid Argon Electromagnetic calorimeter

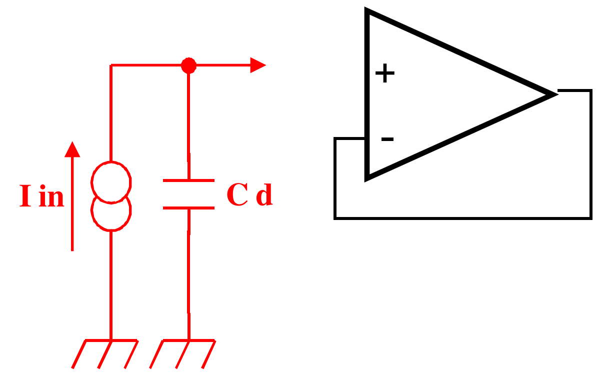
Detector modelization

- Detector = capacitance Cd
  - Silicon : 0.1-10 pF
  - PMs : 3-30pF
  - Ionization chambers 10-1000 pF
- Signal : current source
  - Silicon : ~1fC/100µm
  - PMs : 1 photoelectron -> 10^5-10^7 e^-
  - Wire chambers : a few 10^3 e^-
  - Modelized as an impulse (Dirac) : $i(t)=Q_0\delta(t)$
- Missing :
  - High Voltage bias
  - Connections, grounding
  - Neighbours
  - Calibration…

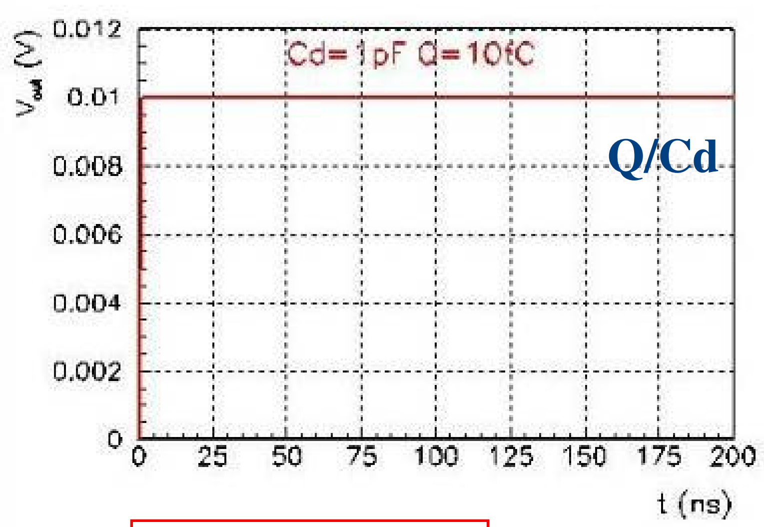




- Signal
  - Signal = current source
  - Detector = capacitance C_d
  - Quantity to measure
    - Charge => integrator needed + ADC
    - Time => discriminator + TDC



- Integrating on Cd
  - Simple : $V = Q/C_d$
  - « Gain » : $1/C_d$: 1 pF -> 1 mV/fC
  - Need a follower to buffer the voltage…
  - Input follower capacitance : Ca // Cd
  - Gain loss, possible non-linearities
  - Crosstalk
  - Need to empty Cd…

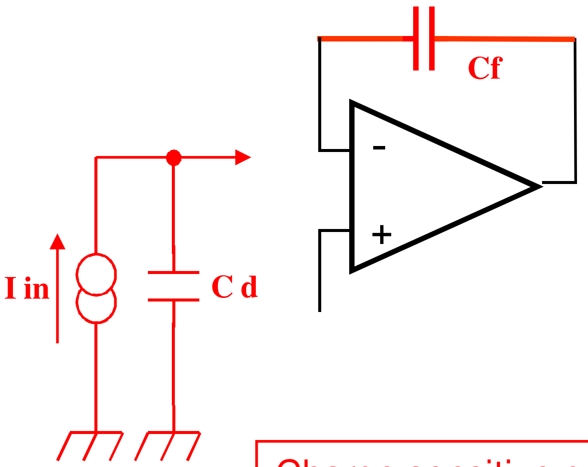


Impulse response

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 : $v_{out}(t) = -1/C_f \int i_{in}(t)dt$

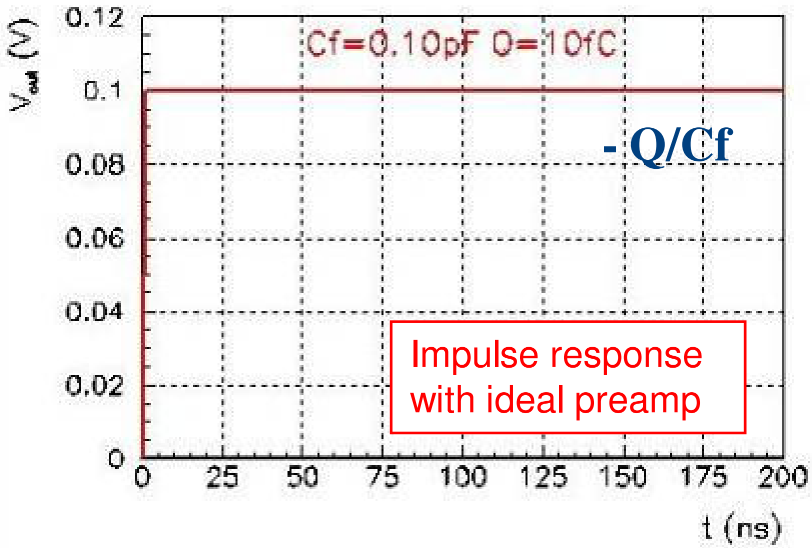
$$\boxed{v_{out}(t) = - Q/C_f}$$



Charge sensitive preamp

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

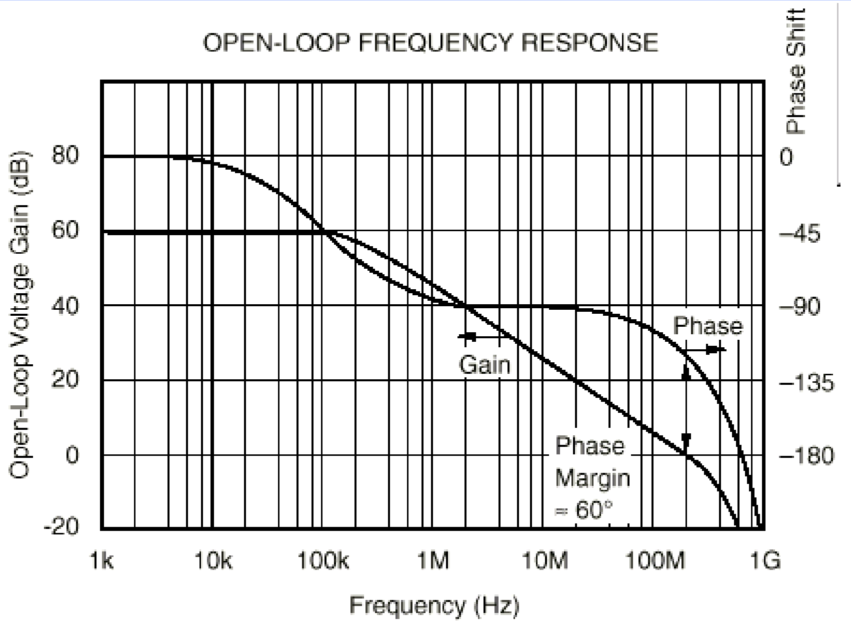
- Integration on Cf
  - Simple : $V = - Q/C_f$
  - Unsensitive to preamp capacitance C_{PA}
  - Turns a short signal into a long one
  - The front-end of 90% of particle physics detectors…
  - But always built with custom circuits…

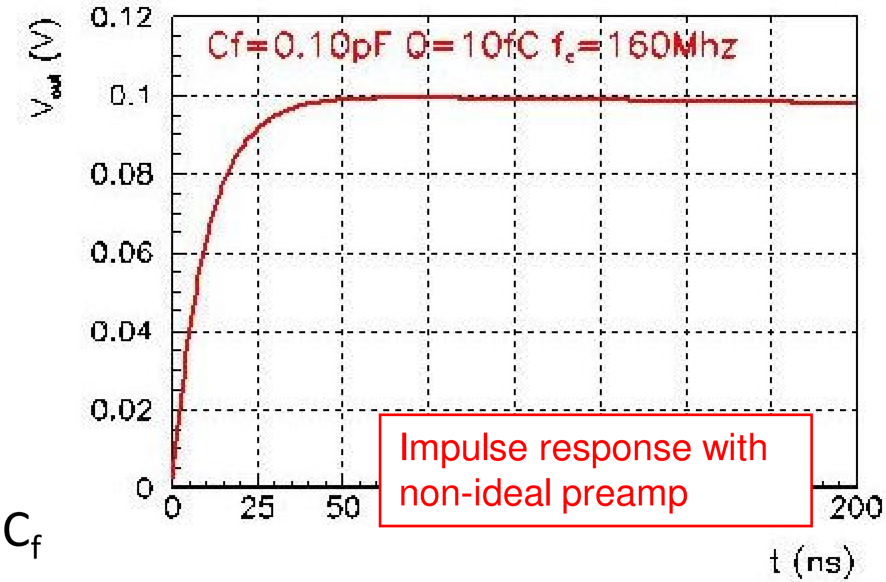


Impulse response with ideal preamp

Non-ideal charge preamplifier

- Finite opamp gain $$\frac{V_{out}(\omega)}{I_{in}(\omega)} = \frac{-Z_f}{1+\frac{C_d}{G_0 C_f}}$$
  - Small signal loss in $C_d / G_0 C_f$ << 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
    - $G_0\omega_0$: ω_c gain bandwidth product
- Preamp risetime
  - Due to gain variation with ω
  - Time constant : τ *(tau)* = $C_d / G_0\omega_0 C_f$
  - Rise-time : $t_{10\text{-}90\%} = 2.2\,\tau$
  - Rise-time optimised with $G_0\omega_0$ (ω_c) or C_f





$$Vin = \varepsilon$$

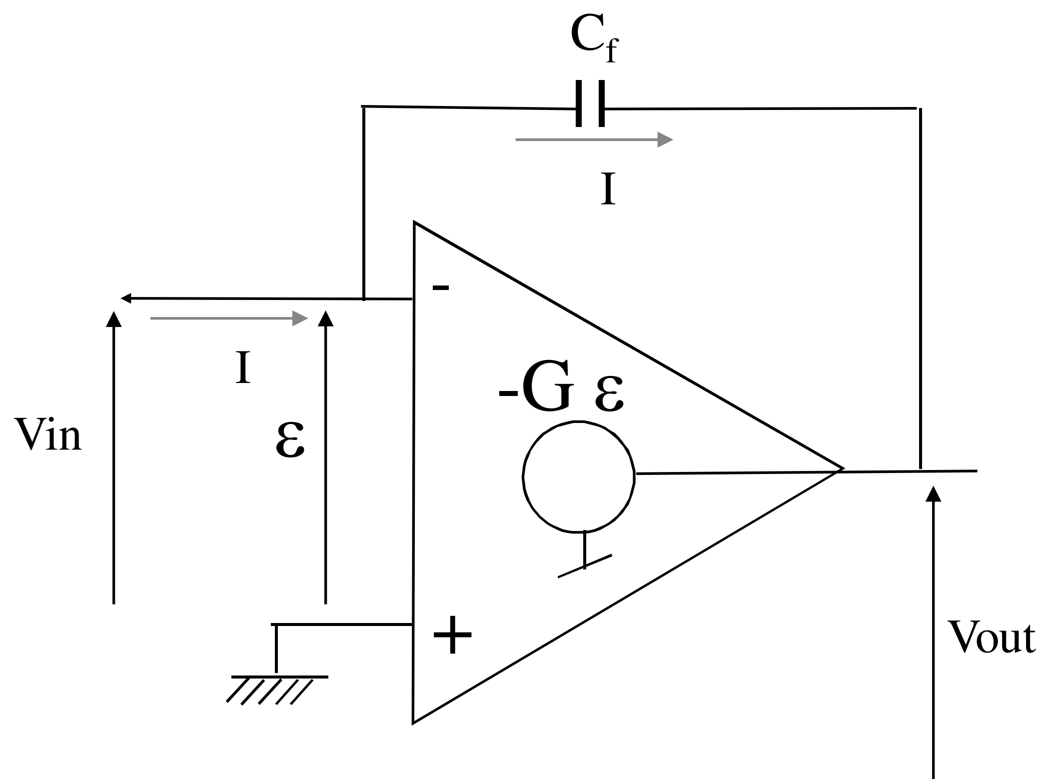
$$Vout = -G\varepsilon \ ; \ Vout = -\frac{1}{C_f j\omega} I + \varepsilon$$

$$\frac{Vin}{I} = Zin = \frac{1}{C_f j\omega(1+G)} \approx \frac{1}{C_f j\omega G}$$

$$G = \infty \to Zin = 0$$

$$G = \frac{G_0}{1+\frac{j\omega}{\omega_0}}$$

$$Zin = \frac{1+\frac{j\omega}{\omega_0}}{C_f j\omega G_0} = \frac{1}{j\omega C_f G_0} + \frac{1}{C_f G_0 \omega_0}$$



Charge preamp seen from the input

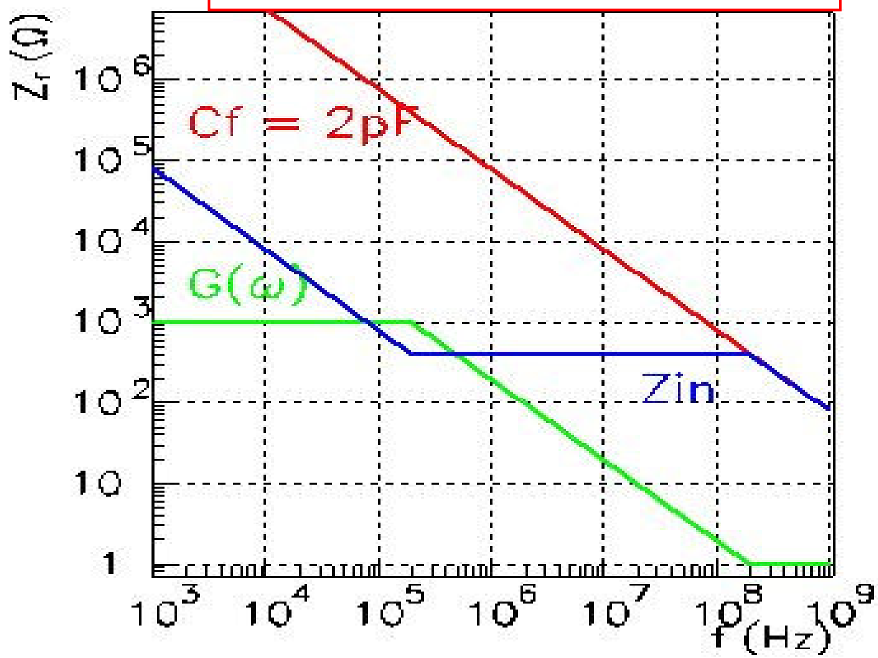
- Input impedance with ideal opamp
  - Zin = Zf / G+1
  - Zin->0 for ideal opmap
  - « Virtual ground » : Vin = 0
  - Minimizes sensitivity to detector impedance
  - Minimizes crostalk

- Input impedance with real opamp

$$Z_{in} = \frac{1}{j\omega G_0 C_f} + \frac{1}{G_0 \omega_0 C_f}$$

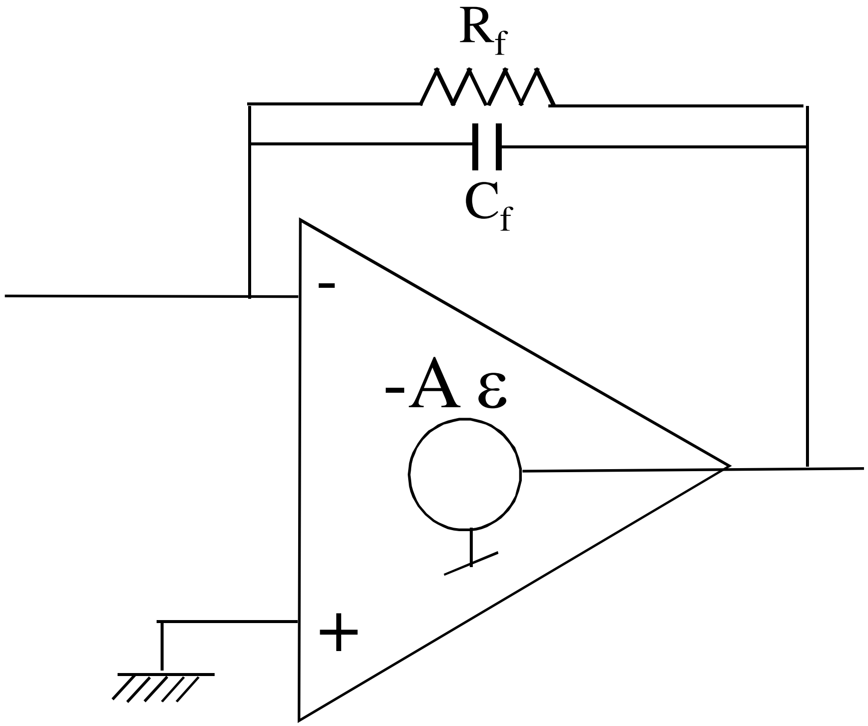
  - Resistive term : $R_{in} = \frac{1}{G_0 \omega_0 C_f} = \frac{1}{\omega_c C_f}$
    - Example : $\omega_C = 10^9$ rad/s C_f= 2 pF
      => Rin = 500Ω
  - Determines the input time constant : $t = R_{eq}C_d$
  - Good stability

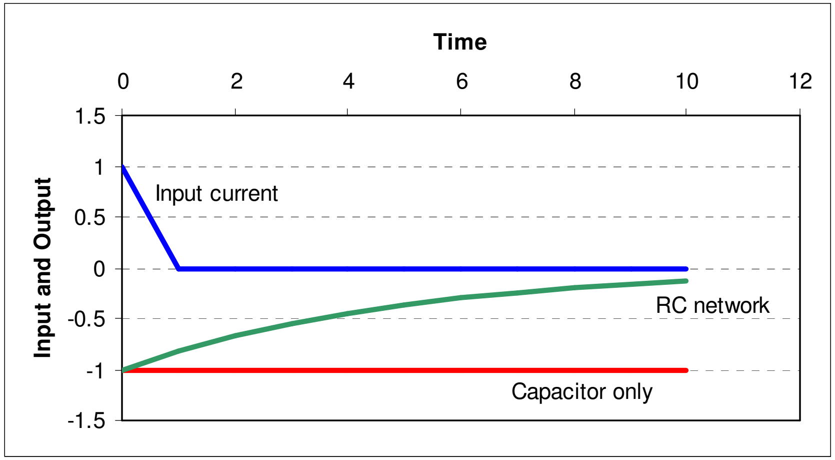
Input impedance of charge preamp

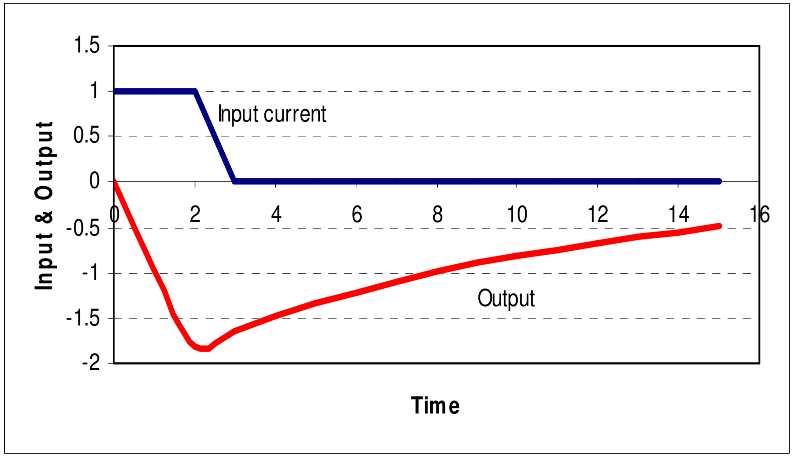


Pile up

- It is necessary to discharge the feedback capacitor
  - Successive input pulses would add up until saturation
- Several ways to do it, the simpler being to put a resistor in parallel



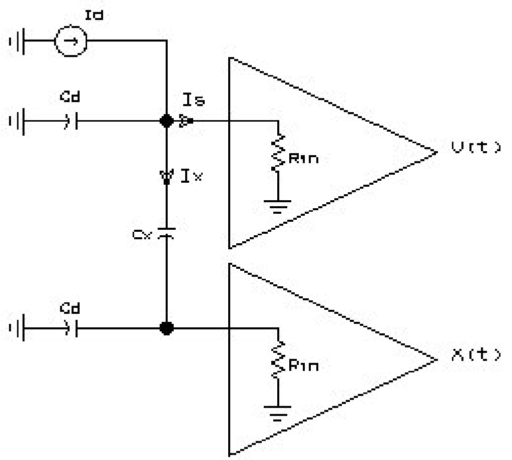


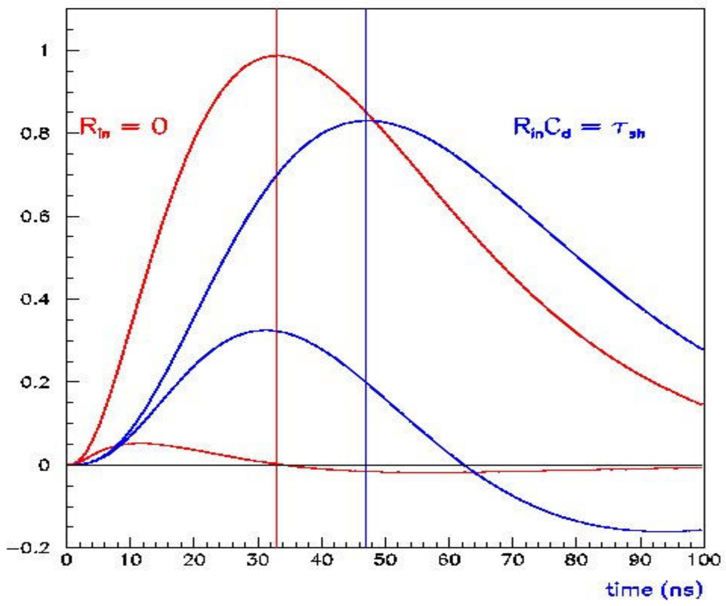


Crosstalk

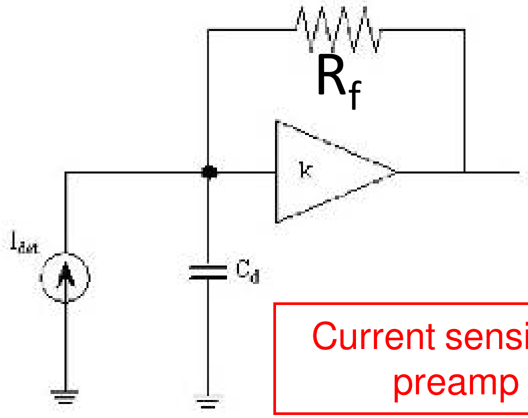
- Capacitive coupling between neighbours
  - Crosstalk signal is differentiated and with same polarity
  - Small contribution at signal peak
  - Proportionnal to Cx/Cd and preamp input impedance
  - Slowed derivative if RinCd ~ tp => non-zero at peak

- Inductive coupling
  - Inductive common ground return
  - “Ground apertures” = inductance
  - Connectors : mutual inductance

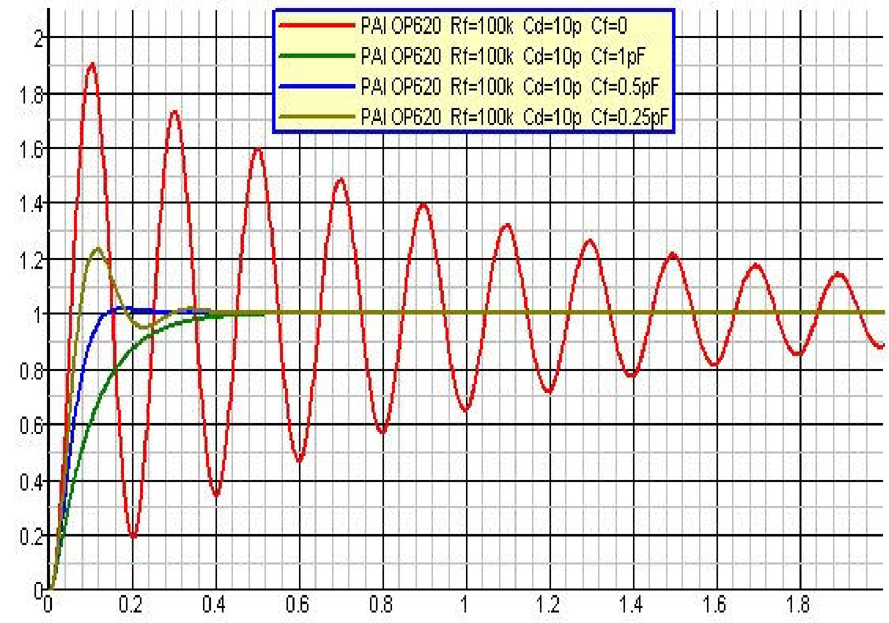




- Transimpedance configuration
  - $V_{out}(\omega)/i_{in}(\omega) = - R_f / (1+Z_f/GZ_d)$
  - Gain = R_f
  - High counting rate
  - Typically optical link receivers
- Easily oscillatory
  - Unstable with capacitive detector
  - Inductive input impedance
  - Resonance at : $$F_{res} = \frac{1}{2\pi\sqrt{L_{eq}C_d}}$$
  - Quality factor : $$Q = \frac{R}{\sqrt{\frac{L_{eq}}{C_d}}}$$
    - Q > 1/2 -> ringing
  - Damping with capacitance C_f in parallel to R_f
    - Easier with fast amplifiers



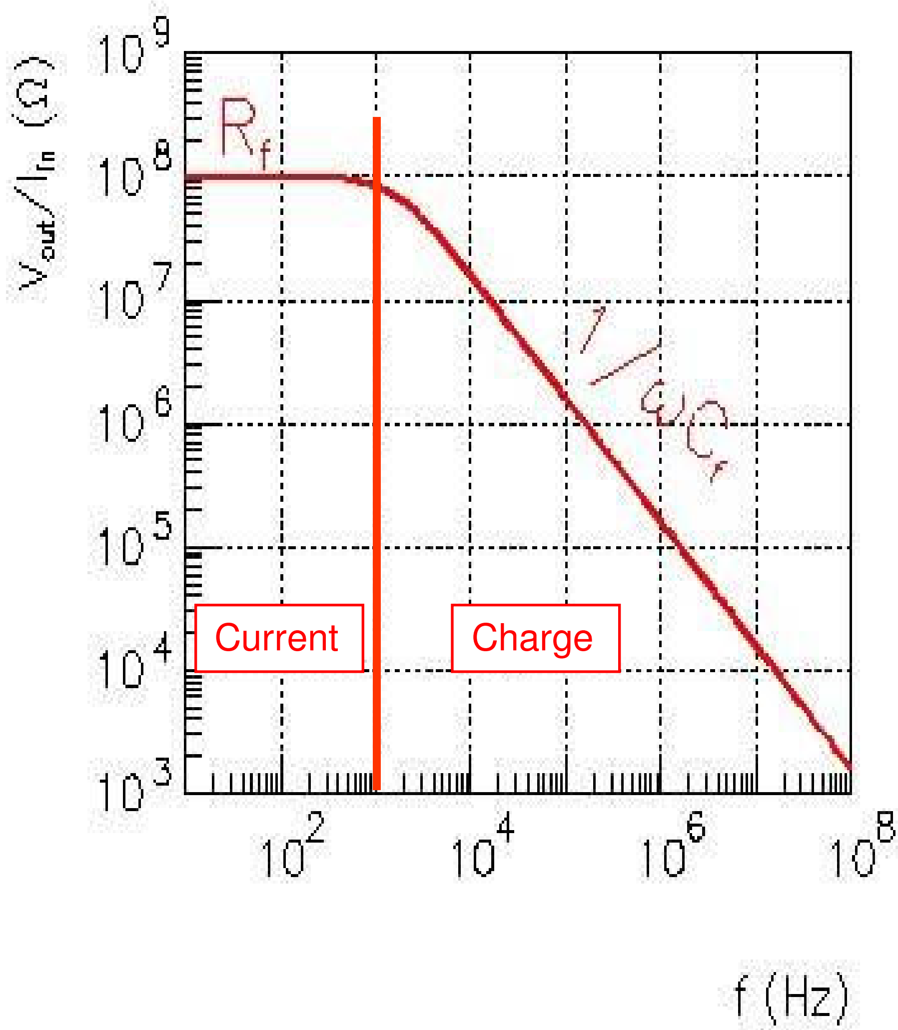
Current sensitive preamp



Step response of current sensitive preamp

Charge vs Current preamps

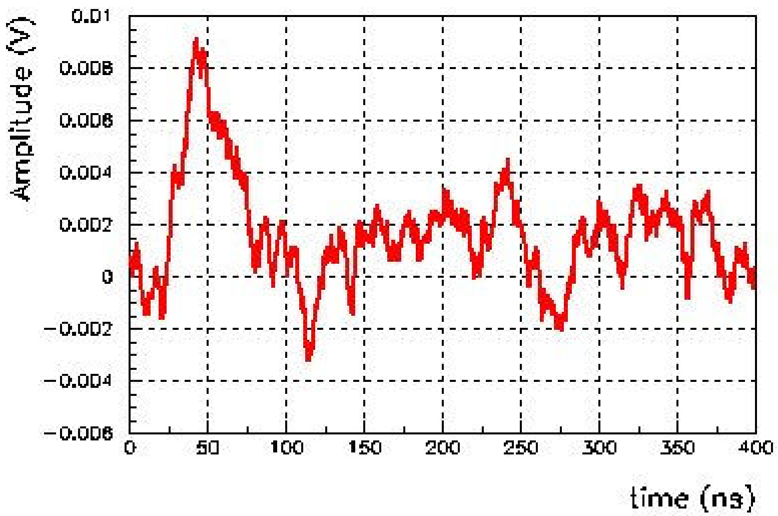
- Charge preamps
  - Best noise performance
  - Best with short signals
  - Best with small capacitance
- Current preamps
  - Best for long signals
  - Best for high counting rate
  - Significant parallel noise
- Charge preamps are not slow, they are long
- Current preamps are not faster, they are shorter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



Electronics noise

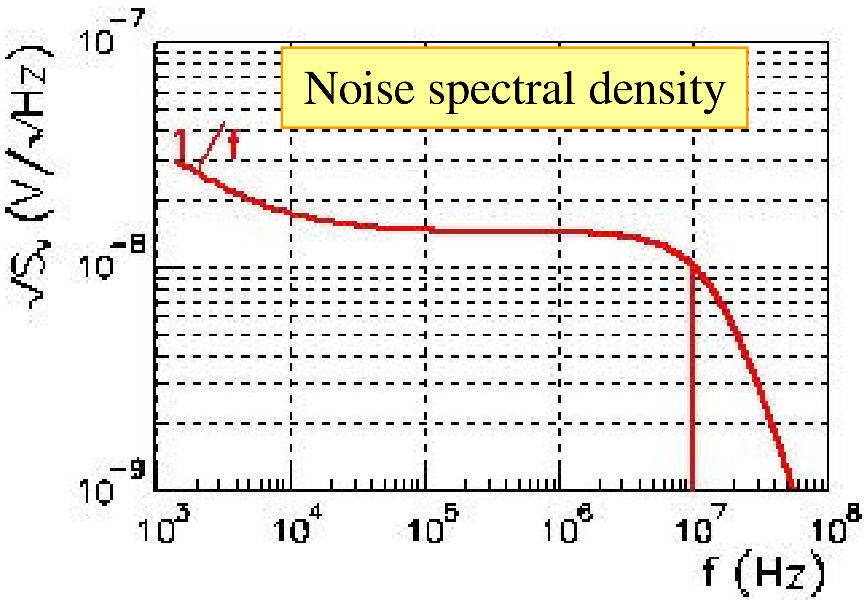
- Definition of Noise
  - Random fluctuation superimposed to interesting signal
  - Statistical treatment

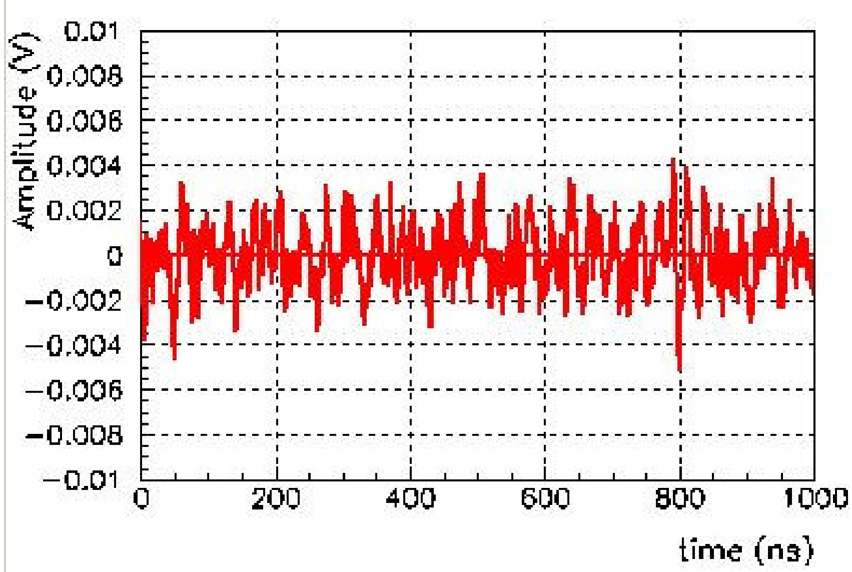
- Three types of noise
  - Fundamental noise (Thermal noise, shot noise)
  - Excess noise (1/f …)
  - Parasitics -> EMC/EMI (pickup noise, ground loops…)

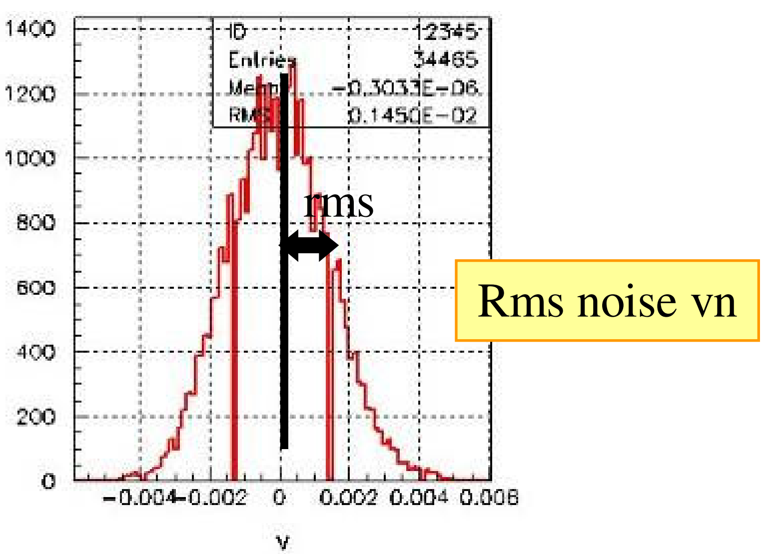


Electronics noise

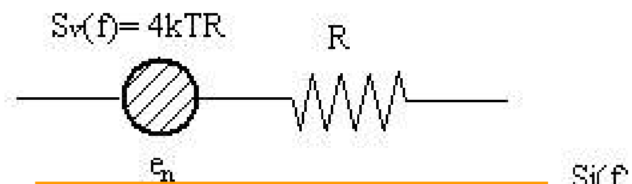
- Modelization
  - Noise generators : e_n, i_n
  - Noise spectral density of e_n & i_n : $S_v(f)$ & $S_i(f)$
    - $S_v(f) = |\mathcal{F}(e_n)|^2$ (V^2/Hz)
    - $S_i(f) = |\mathcal{F}(i_n)|^2$ (A^2/Hz)
- *Rms* noise Vn
  - $V_n^2 = \int e_n^2(t)\,dt = \int S_v(f)\,df$
- When going through a device H(2πf)
  - $S_{vout}(f) = |H(2\pi f)|^2 S_{vin}(f)$



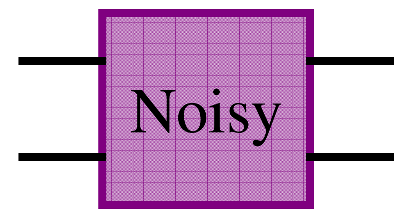


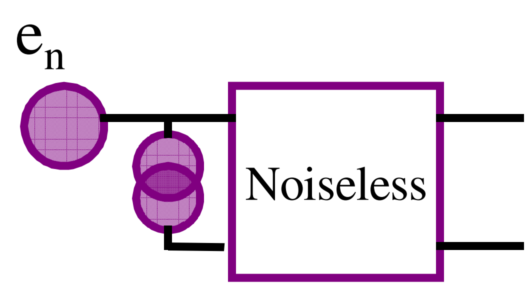


- Fundamental noise
  - Thermal noise (resistors) : $S_v(f) = 4kTR$
  - Shot noise (junctions) : $S_i(f) = 2qI$
  - 1/f noise in CMOS devices
- Noise referred to the input
  - All noise generators can be referred to the input as 2 noise generators :
  - A voltage one e_n in series : series noise
  - A current one i_n in parallel : parallel noise
  - Two generators : no more, no less… why ?
    - To take into account the source impedance
- Golden rule
  - Always calculate the signal before the noise what counts is the signal to noise ratio
  - Don't forget noise generators are V^2/Hz => calculations in module square
  - Practical exercice next slide



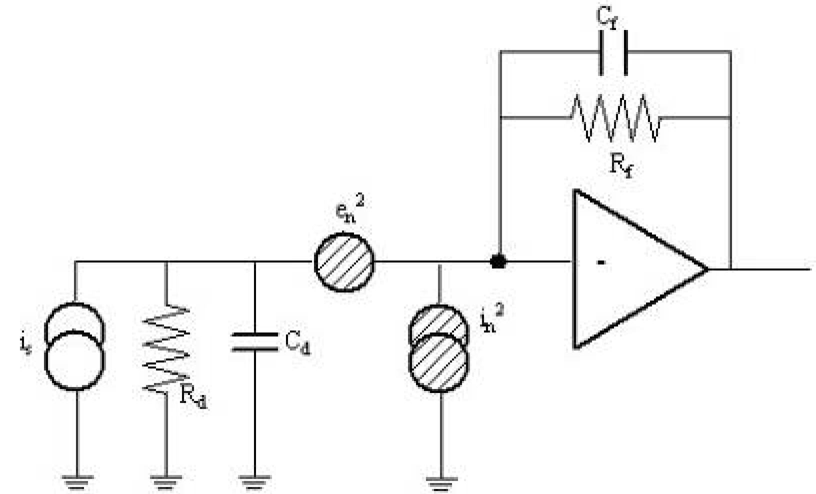
Thermal noise generator





Noise generators referred to the input

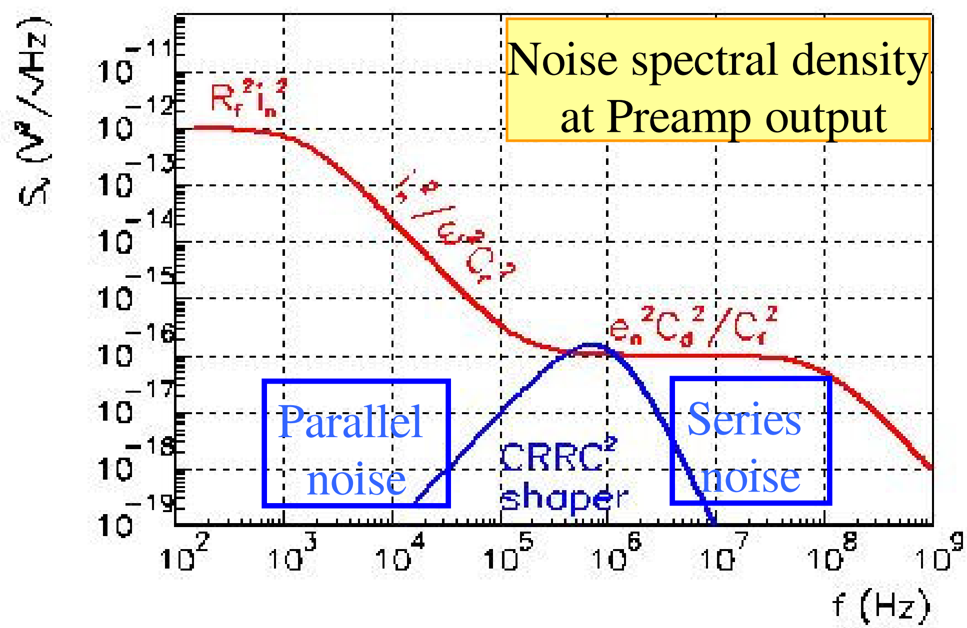
- 2 noise generators at the input
  - Parallel noise : (i_n^2) (leakage currents)
  - Series noise : (e_n^2) (preamp)



- Output noise spectral density :

$$S_v(\omega) = \frac{i_n^{\ 2} + \dfrac{e_n^{\ 2}}{|Z_d|^2}}{\omega^2 C_f^{\ 2}} = \frac{i_n^{\ 2}}{\omega^2 C_f^{\ 2}} + \frac{e_n^{\ 2} C_d^{\ 2}}{C_f^{\ 2}}$$

  - Parallel noise in $1/\omega^2$
  - Series noise is flat, with a « noise gain » of C_d/C_f

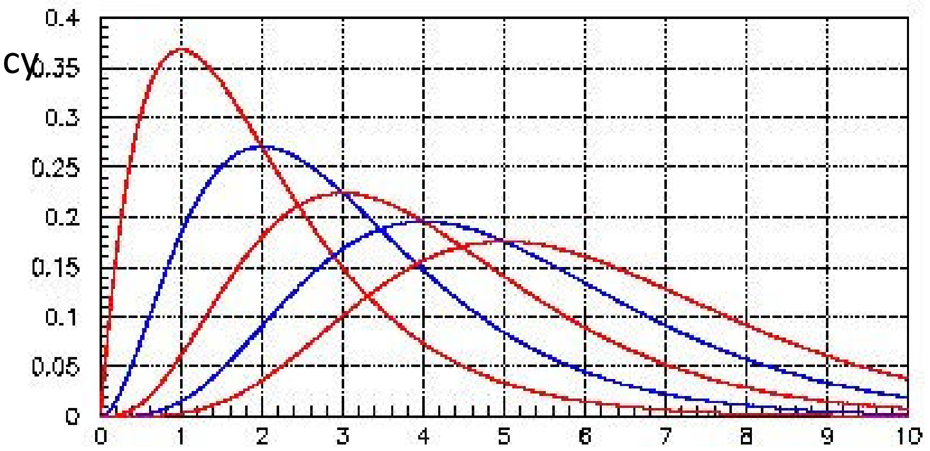


- *rms* noise V_n
  - $V_n^2 = \int S_v(\omega)\, d\omega/2\pi \rightarrow \infty$ (!)
  - Benefit of shaping…

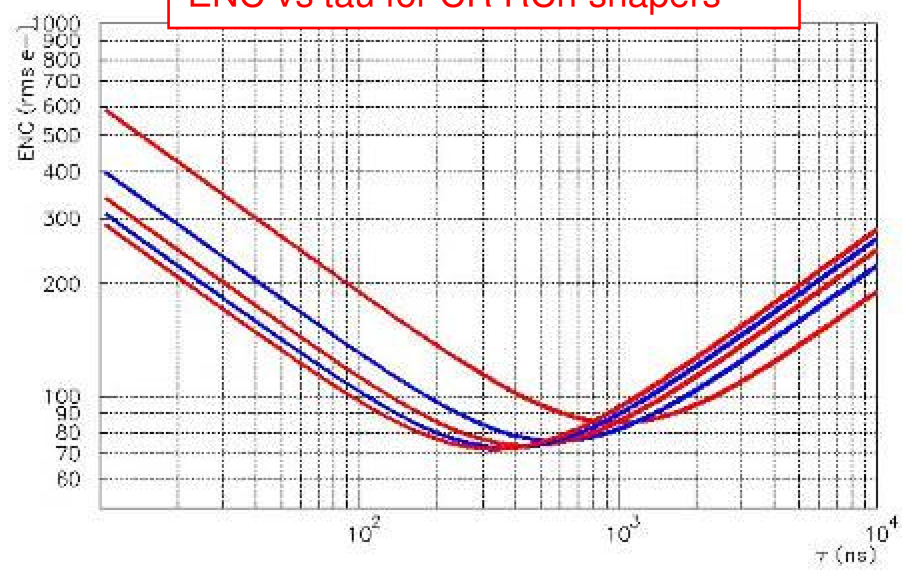
Equivalent Noise Charge (ENC) after $CRRC^n$

- 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 $\tau_{opt} = \tau_c/\sqrt{2n-1}$
- Peaking time tp (5-100%)
  - ENC(**tp**) independent of n
- Complex shapers are obsolete :
  - Power of digital filtering
  - Analog filter = CRRC ou $CRRC^2$

Step response of CR RCn shapers



ENC vs tau for CR RCn shapers



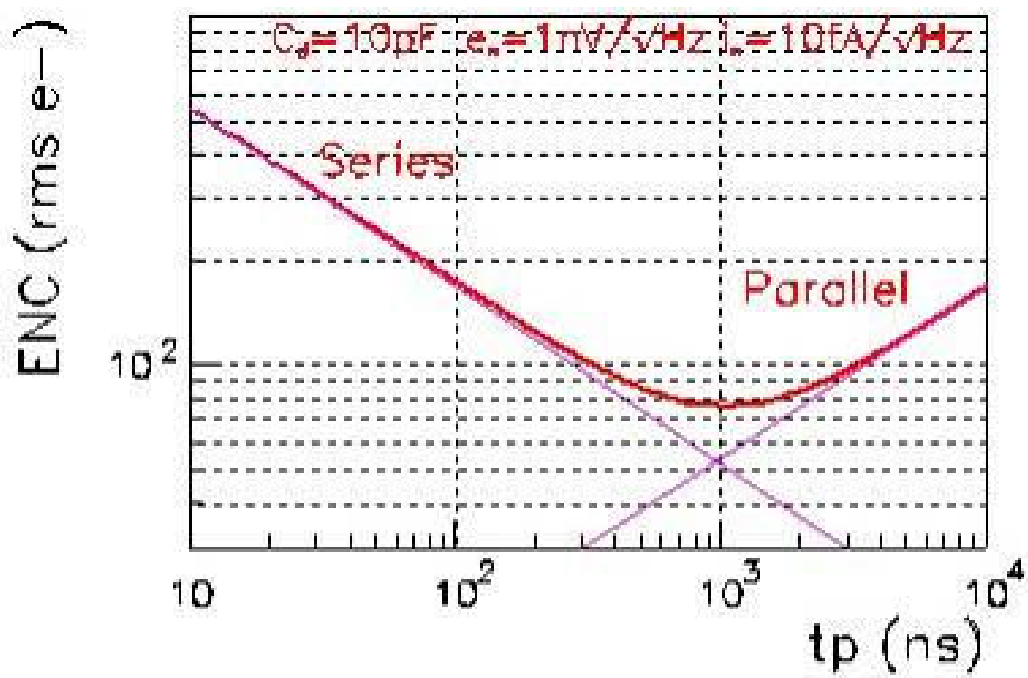
Equivalent Noise Charge (ENC) after CRRC^n

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

$$ENC = 174 \frac{e_n C_{tot}}{\sqrt{t_p}} \oplus 166 i_n \sqrt{t_p}$$

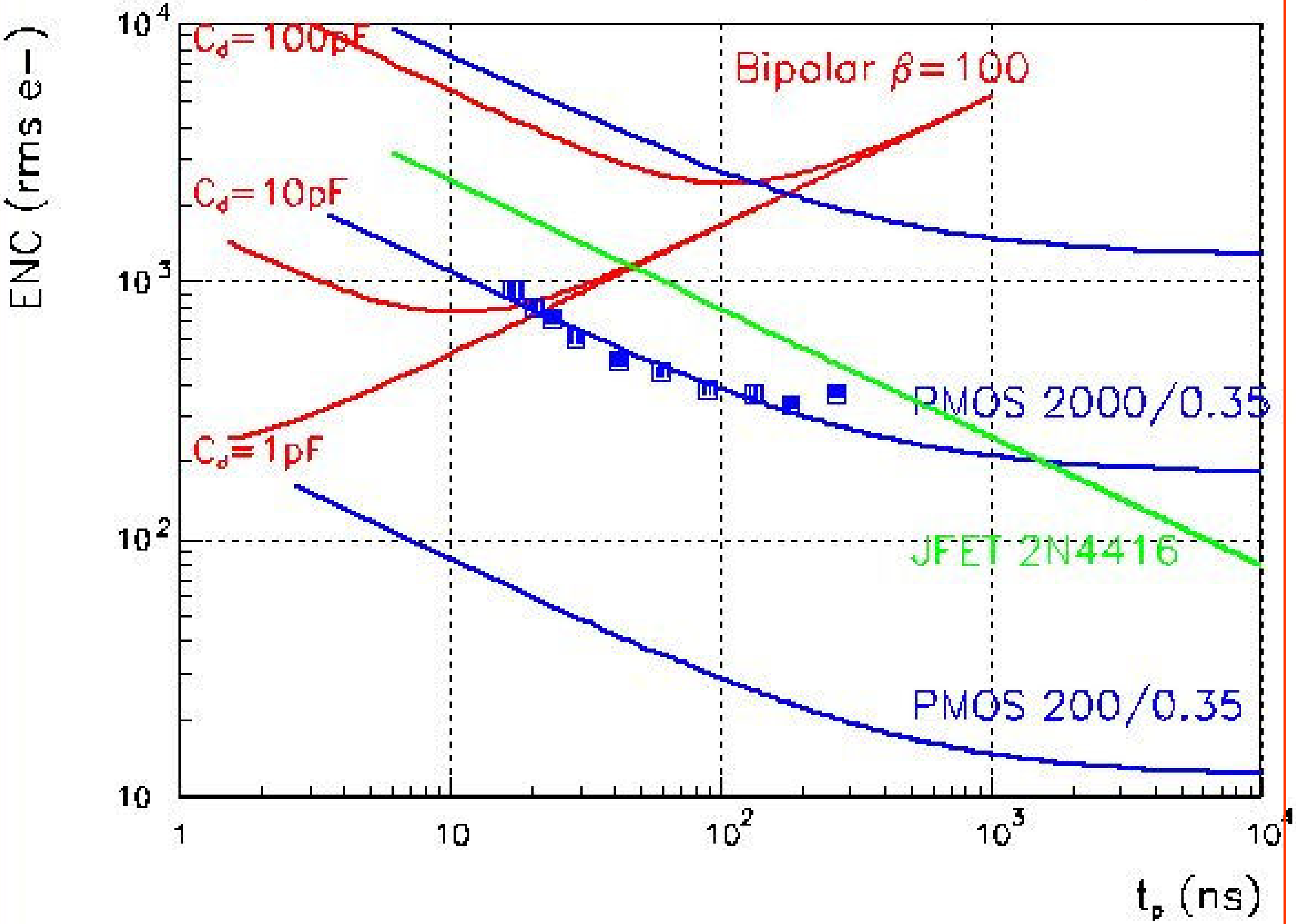
  - e_n in nV/ √Hz, i_n in pA/ √Hz are the preamp noise spectral densities
  - C_{tot} (in pF) is dominated by the detector (C_d) + input preamp capacitance (C_{PA})
  - t_p (in ns) is the shaper peaking time (5-100%)

- 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



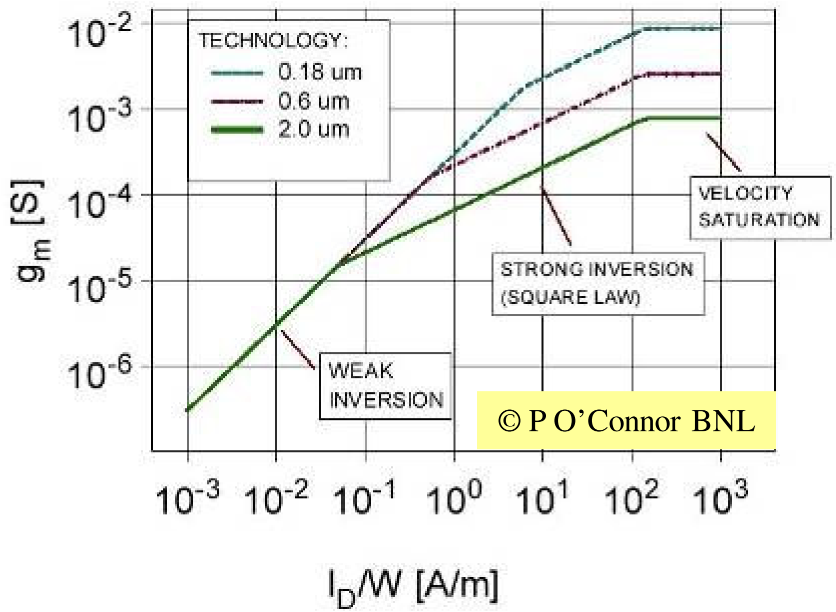
ENC for various technologies

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



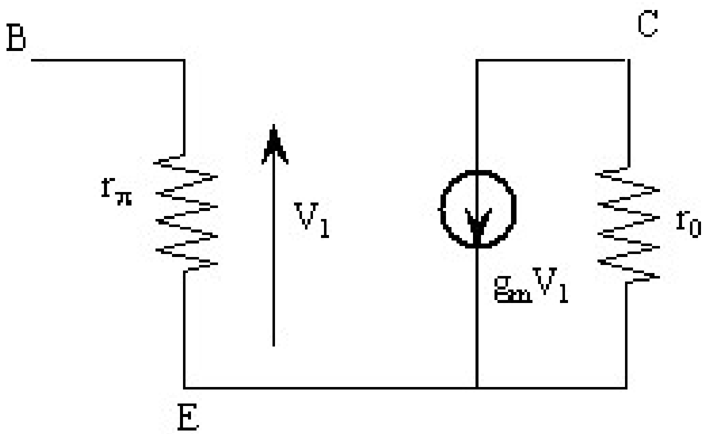
- **Parameters**
- Bipolar :
  - g_m = 20 mA/V
  - $R_{BB'}$=25 Ω
  - e_n= 1 nV/√Hz
  - I_B=5uA
  - i_n = 1 pA/√Hz
  - C_{PA}=100fF
- **PMOS 2000/0.35**
  - g_m = 10 mA/V
  - e_n = 1.4 nV/√Hz
  - C_{PA} = 5 pF
  - 1/f :

- 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

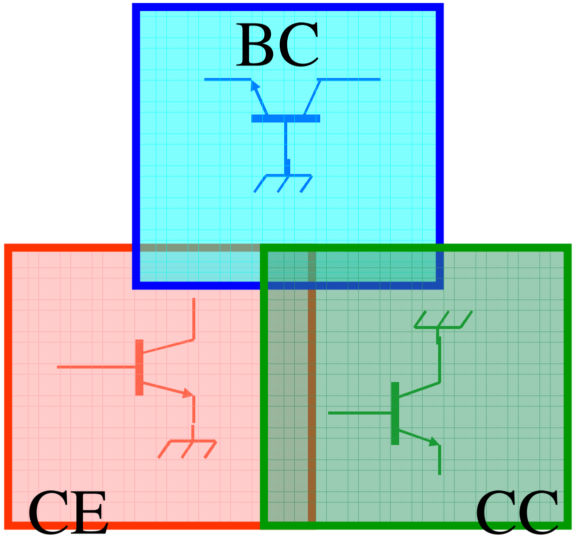


- Optimum size in weak inversion
  - g_m proportionnal to I_D (indep of W,L)
  - ENC minimal for C_{GS} minimal, provided the transistor remains in weak inversion

- Performant design is at transistor level
- Simples models
  - Hybrid π model
  - Similar for bipolar and MOS
  - Essential for desgin
- **Three basic bricks**
  - Common emitter (CE) = V to I (transconductance)
  - Common collector (CC) = V to V (voltage buffer)
  - Common base (BC) = I to I (current conveyor)
- Numerous « composites »
  - Darlington, Paraphase, Cascode, Mirrors…

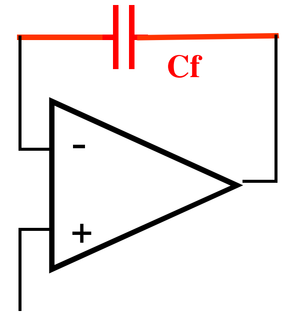


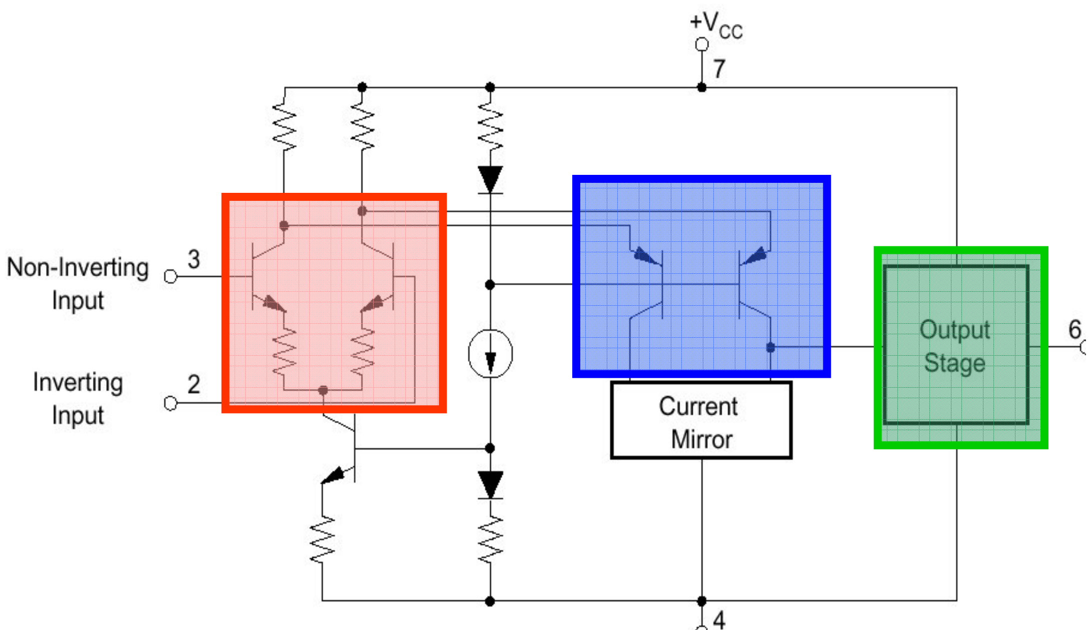
Low frequency hybrid model of bipolar



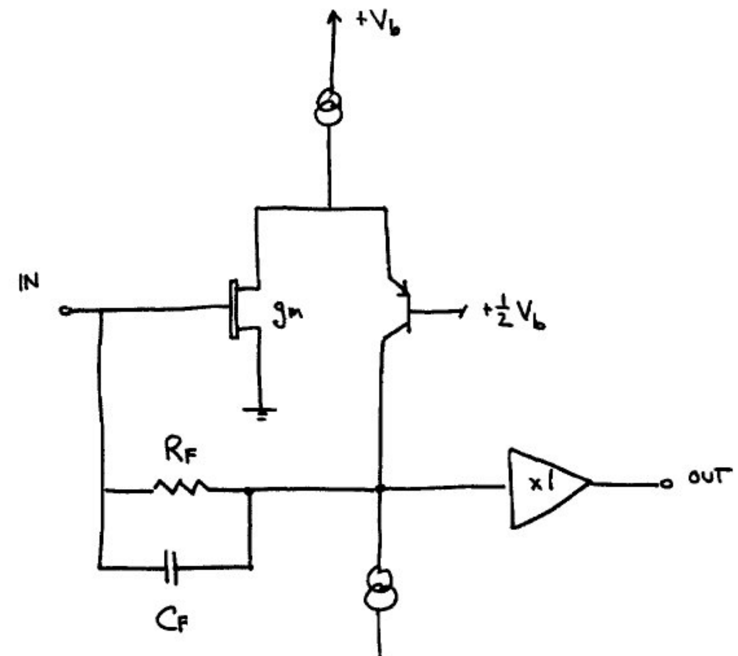
Example : designing a charge preamp (1)

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





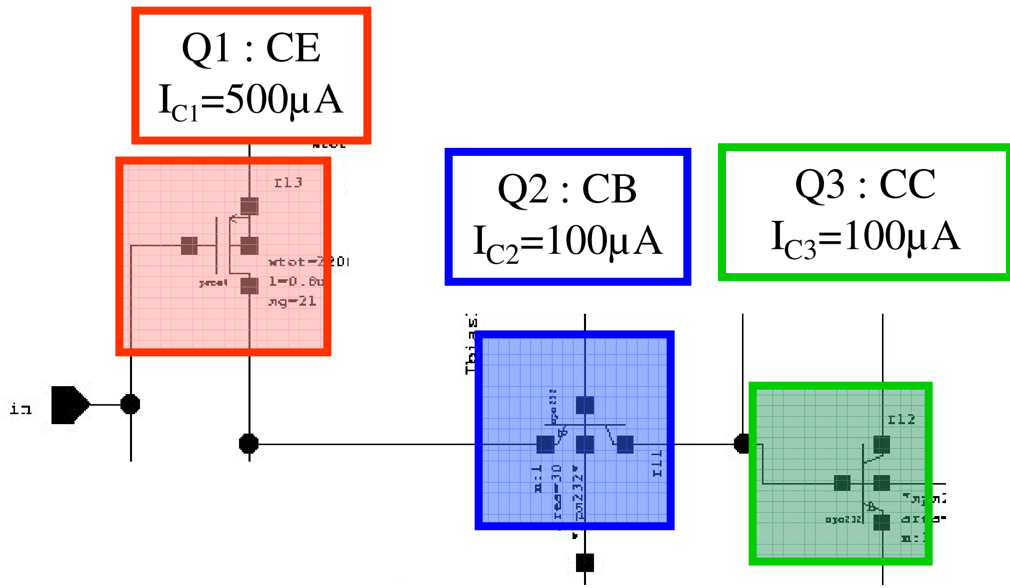
Schematic of a OP620 opamp ©BurrBrown



Charge preamp ©Radeka 68

Example : designing a charge preamp (2)

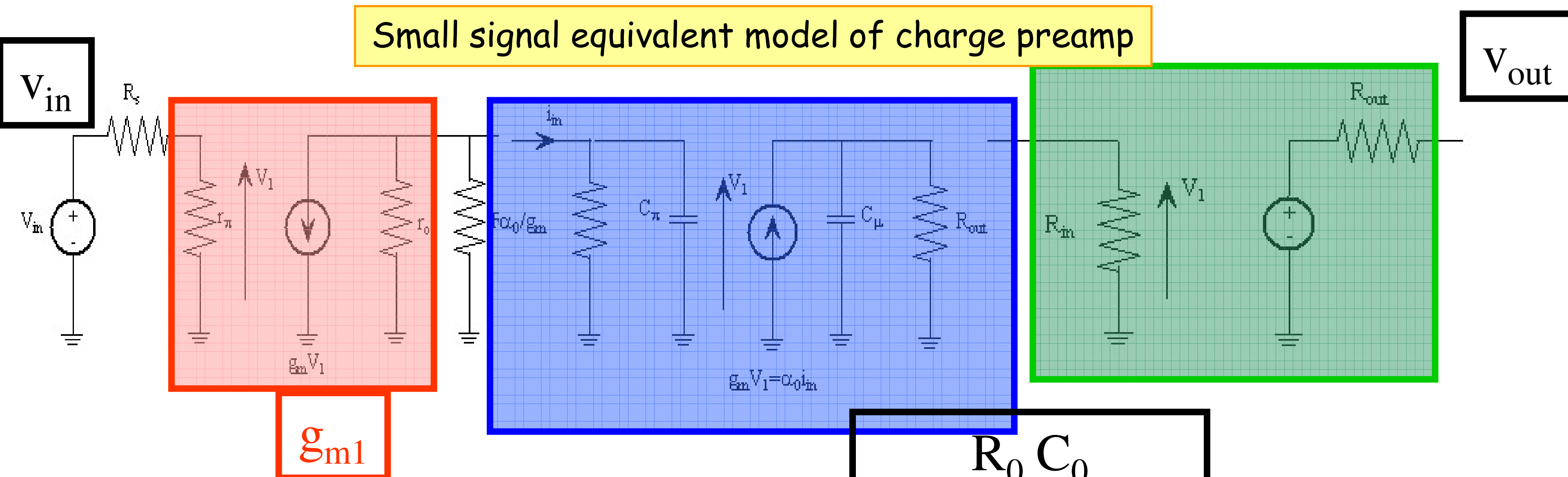
- Simplified schematic
- Optimising components
  - What transistors (PMOS, NPN ?)
  - What bias current ?
  - What transistor size ?
  - What is the noise contributions of each component, how to minimize it ?
  - What parameters determine the stability ?
  - Waht is the saturation behaviour ?
  - How 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

Example : designing a charge preamp (3)

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



$R_0\ C_0$

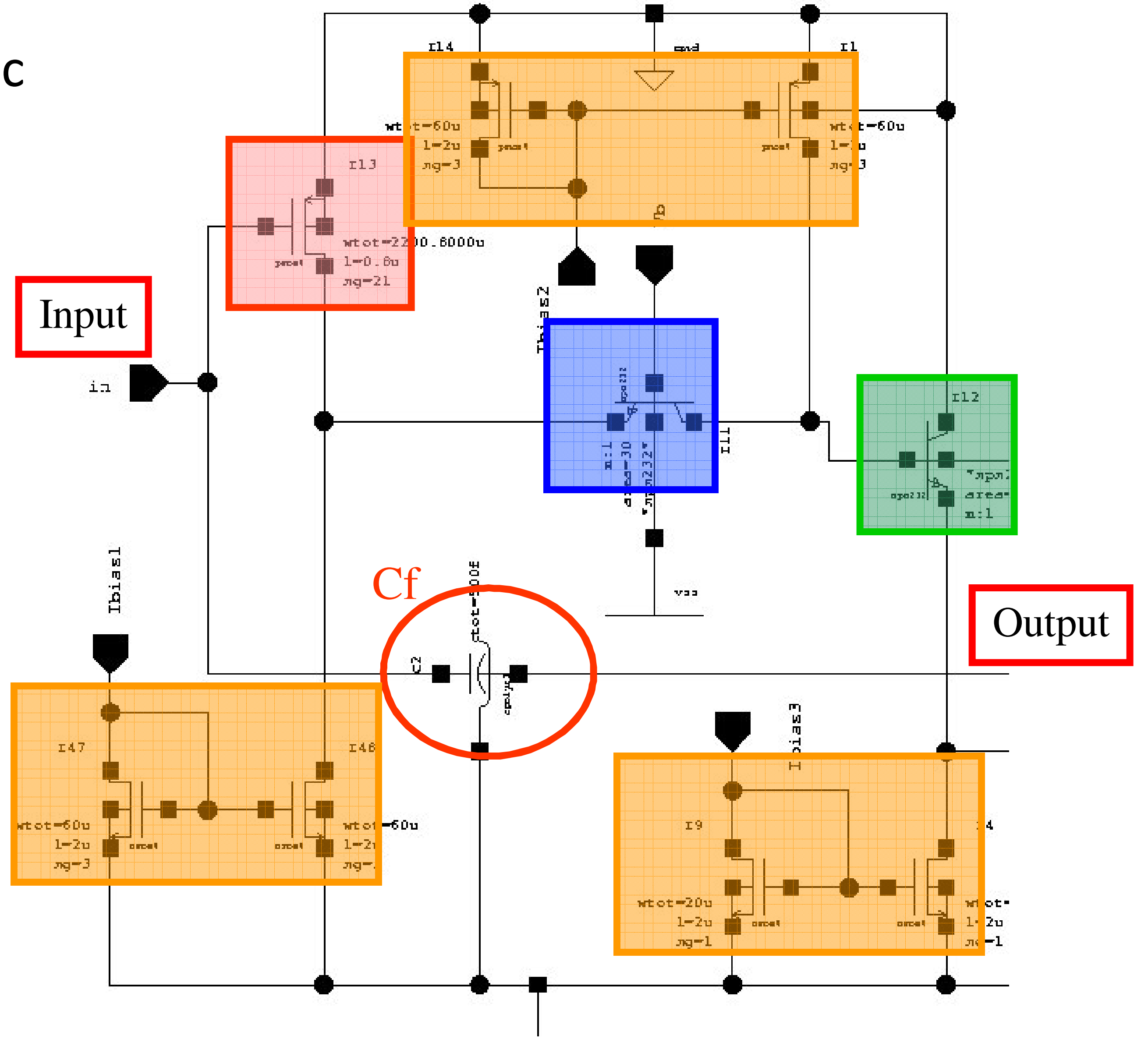
R0 = Rout2//Rin3//r04

- **Gain (open loop) :**

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

  - *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 !*

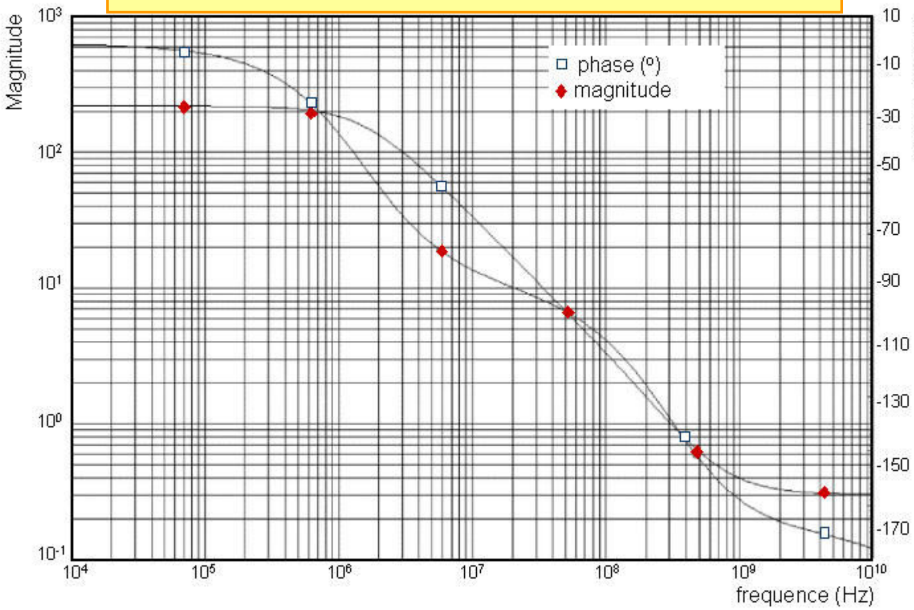
- Complete schematic
  - Adding bias elements



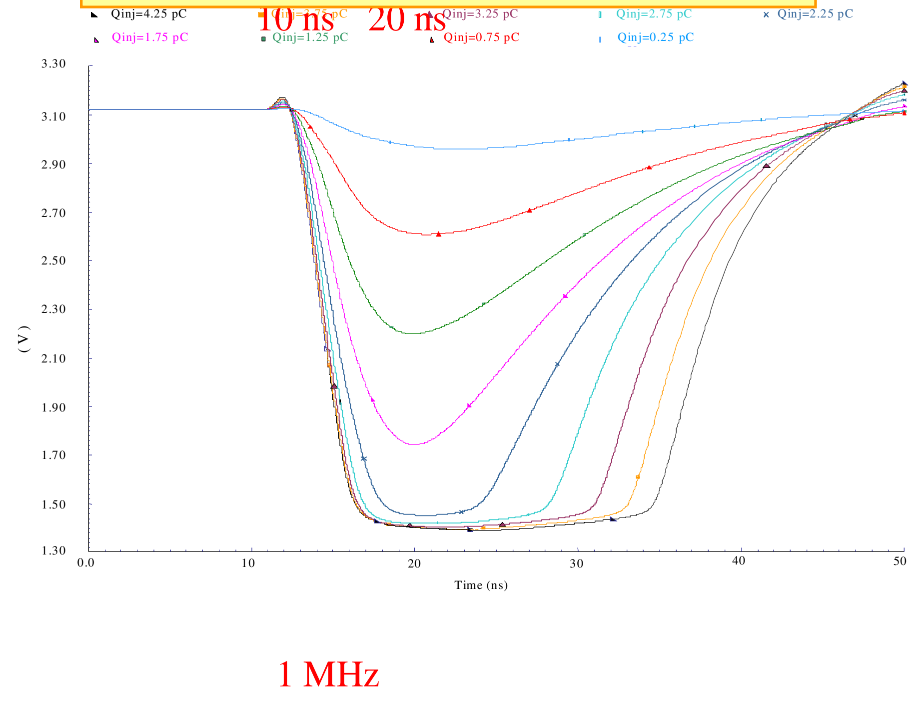
Example : designing a charge preamp (5)

- 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

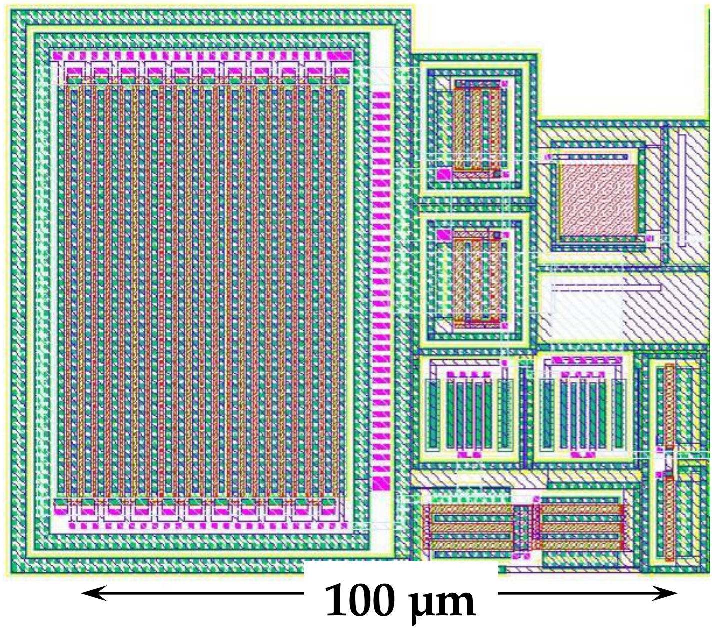


Saturation behaviour

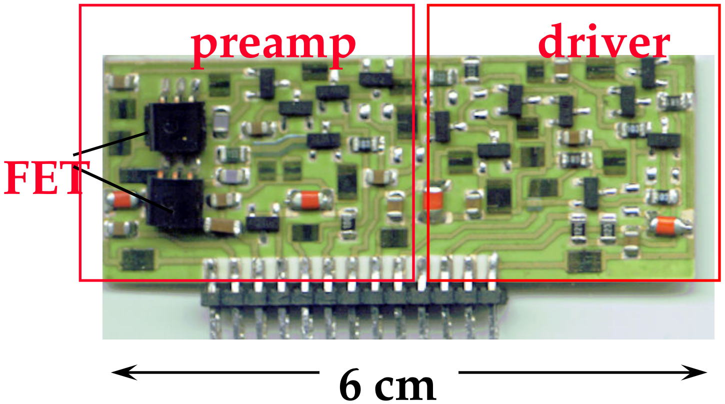


Example : designing a charge preamp (6)

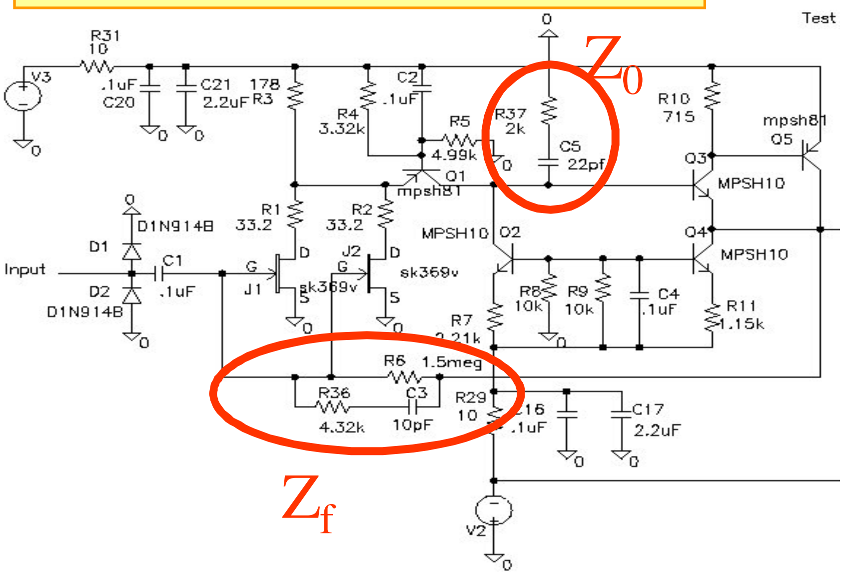
- Layout
  - Each component is drawn
  - They are interconnected by metal layers
- Checks
  - DRC : checking drawing rules
    (isolation, minimal dimensions…)
  - ERC : extracting the corresponding electrical schematic
  - LVS (layout vs schematic) : comparing extracted schematic and original design
  - Simulating extracted schematic with parasitic elements
- Generating GDS2 file
  - Fabrication masks : « reticule »

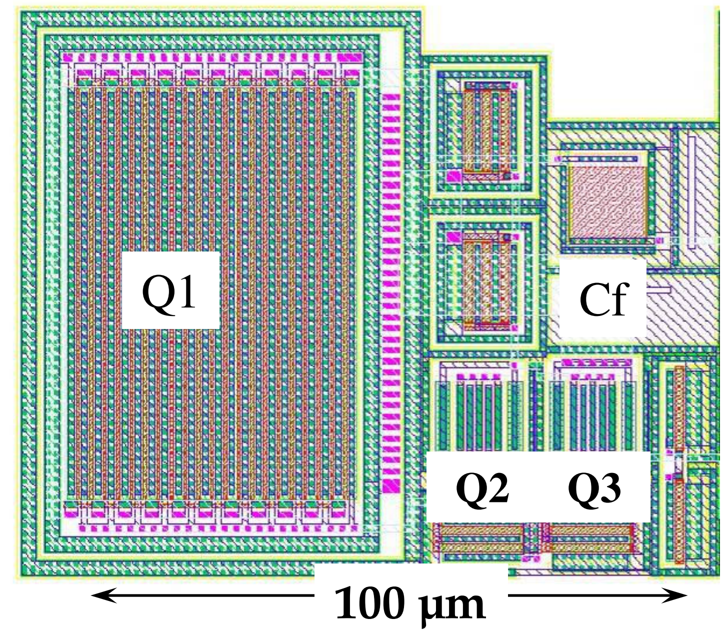


- Acces to microelectronics

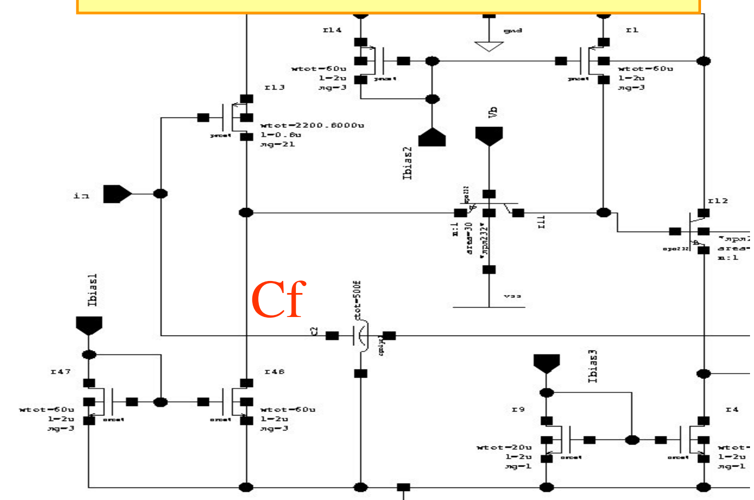


Charge preamp in SMC hybrid techno





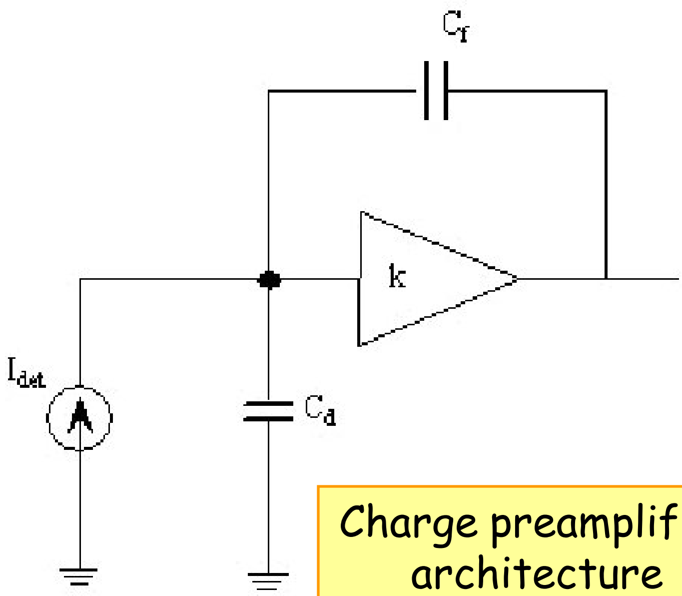
Charge preamp in 0.8µm BiCMOS



- **Charge sensitive preamplifiers**
  - Output proportionnal to the incoming charge

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

  - « Gain » : $1/C_f$; C_f = 1 pF -> 1 mV/fC
  - Transforms a short pulse into a long one
  - Low input impedance -> current sensitive
  - Virtual resistance R_{in}-> stable with capacitive detector
  - The front-end of 90% of particle physics detectors…
  - But always built with custom circuits…
- **Noise minimization**
  - Minimize source capacitance
  - Operate at optimum shaping time
  - Preamp series noise (en) better with high trans-conductance (gm) in input transistor



Charge preamplifier architecture