ANALOGUE CIRCUITS

TECHNIQUES

Part II

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Outline

From “active” components available in modern IC technologies, to the examples of amplifiers design used for High Energy Physics applications

- 1- Introduction to analogue circuit
- 2- Active elements in Integrated Circuit
- 3- The bipolar transistor

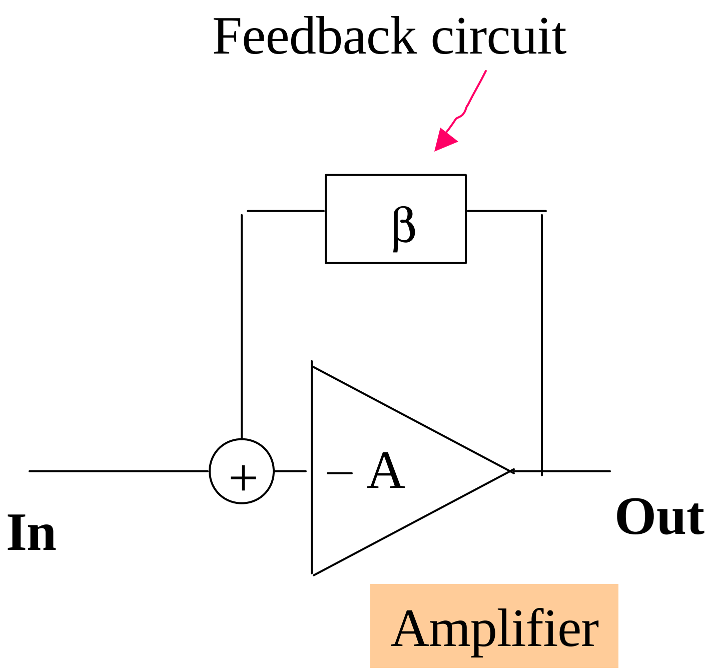
Outline

- 4- Basic of amplifier
- 5- Differential amplifier
- 6- OTA
- 7- Two-stage differential amplifier
- 8- Other amplifiers circuits
- 9- Cascode circuits

- 10- Charge Sensitive Preamplifier
- 11- Transimpedance Preamplifier
- 12- Preamplifiers conclusions

10 – Charge Sensitive Preamplifier

Reminder :



A = Forward Path gain

β = Feedback gain

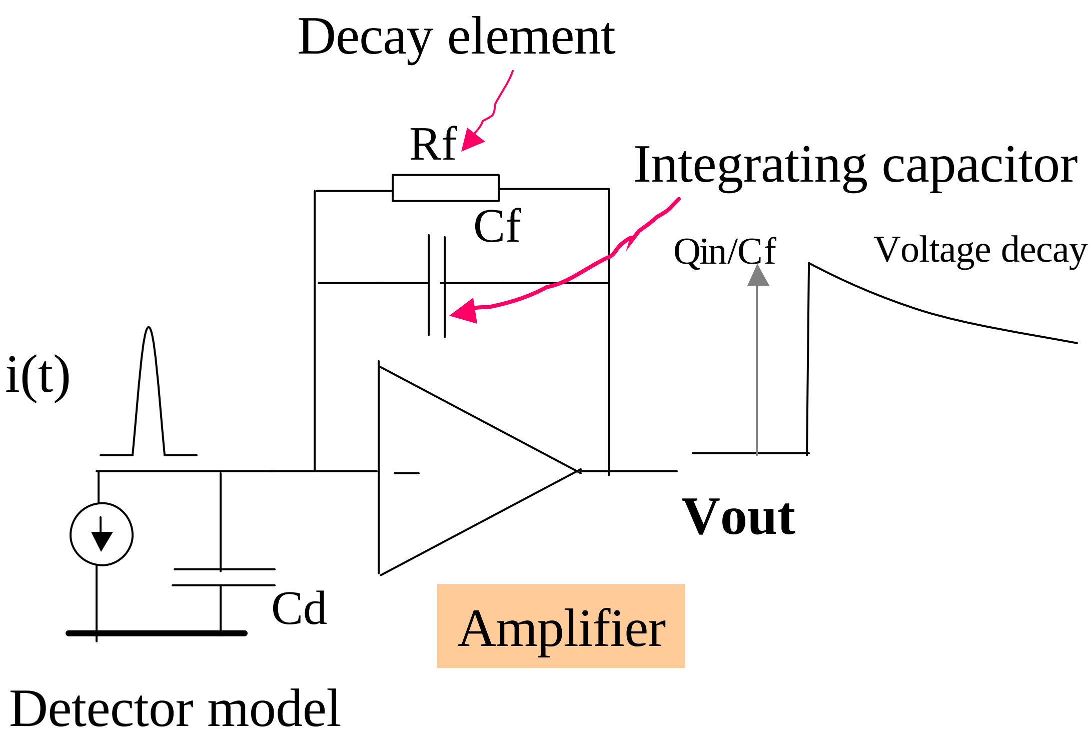
A β = Open Loop Gain

$$\text{Out/In} = \frac{A}{1 + A\beta} = \text{Closed Loop Gain}$$

Stability is assumed if the Open Loop Gain (A β, complex number) is far away from -1

10 – Charge Sensitive Preamplifier

Reminder :



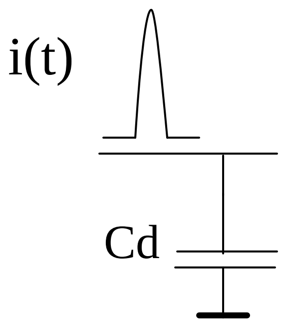
$$Q_{in} = \int_0^t i(t)dt$$

The charge is integrated on the feedback capacitance (Cf)

$$Vout = Q_{in} / C_f$$

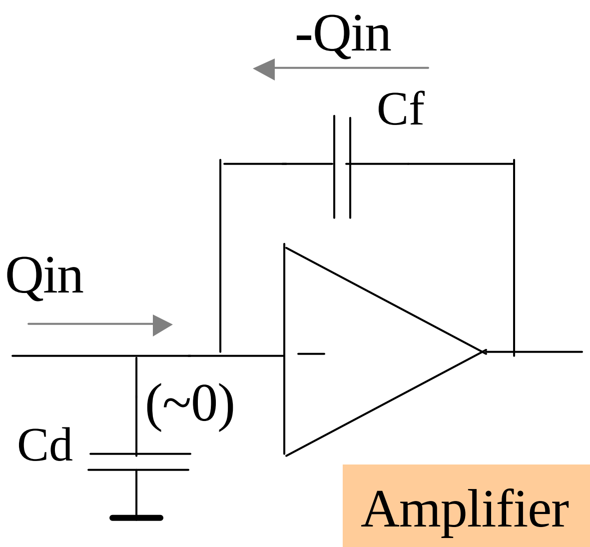
The output voltage Vout decays with Rf.Cf time constant (pile-up problem)

10 – Charge Sensitive Preamplifier



Charge from detector builds up a voltage on the detector node capacitance

$$V_{det} = \frac{Q_{in}}{C_d}$$



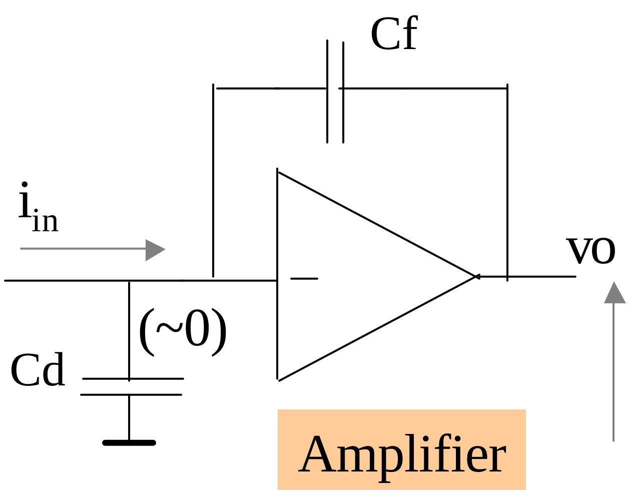
The preamplifier reacts in such a way that its input node voltage stays unchanged : the output voltage Vout is moving to the point where :

Vout.Cf = -Qin

The input node charge (also voltage) variation is zero

10 – Charge Sensitive Preamplifier

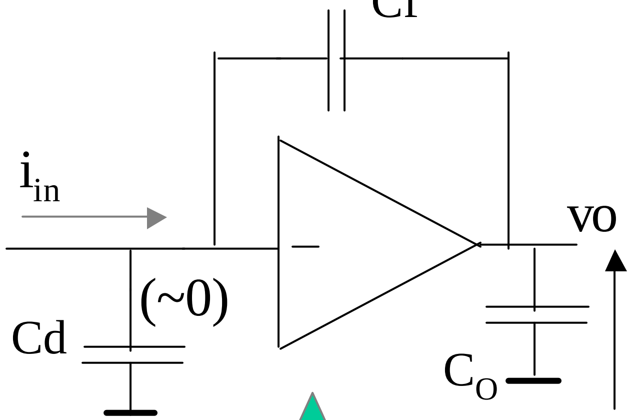
Frequency domain



In case of an ideal amplifier (infinite gain, no BW limit) :

$$vo = \frac{i_{in}}{s.C_f}$$

10 – Charge Sensitive Preamplifier

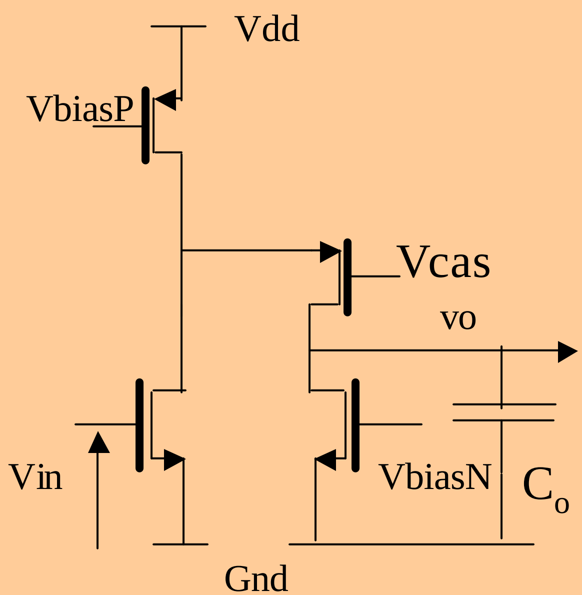


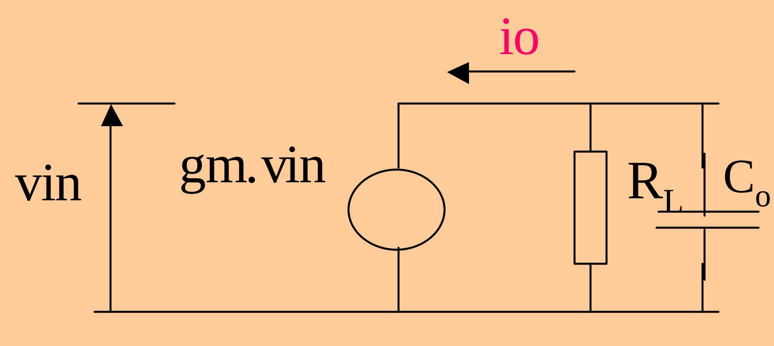
Frequency domain

Consider now a non-ideal amplifier, loaded with capacitance C_o :

$$\frac{vo}{vin} = \frac{gm.R_L}{1+sC_o.R_L}$$

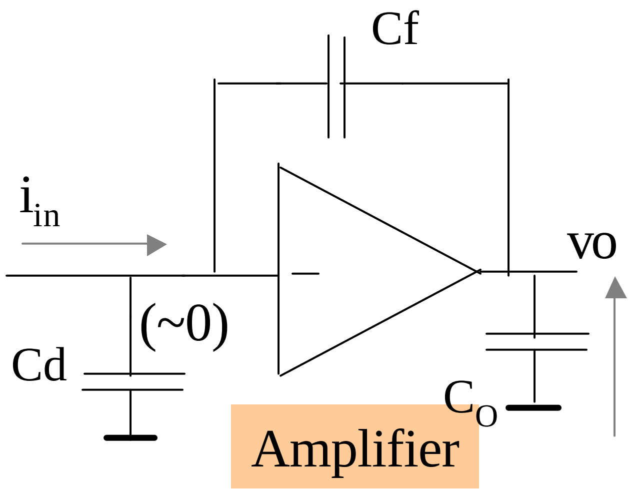
Amplifier





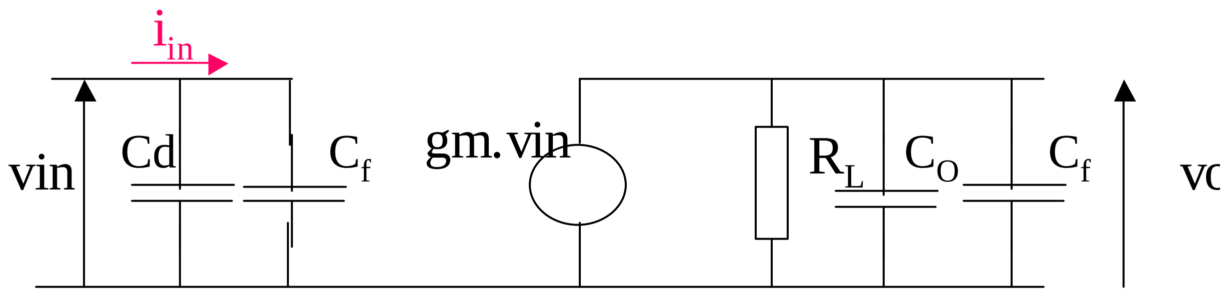
Small signal model

10 – Charge Sensitive Preamplifier



Frequency domain

If we consider Cf acting not as a feedback element, but just as a capacitive load on input and output (forward path gain A) :

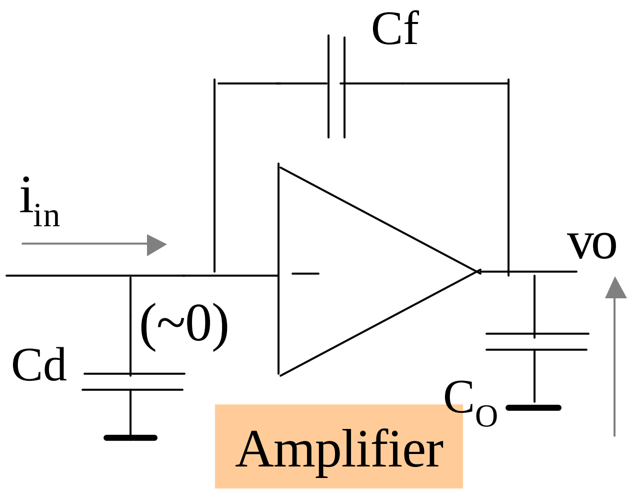


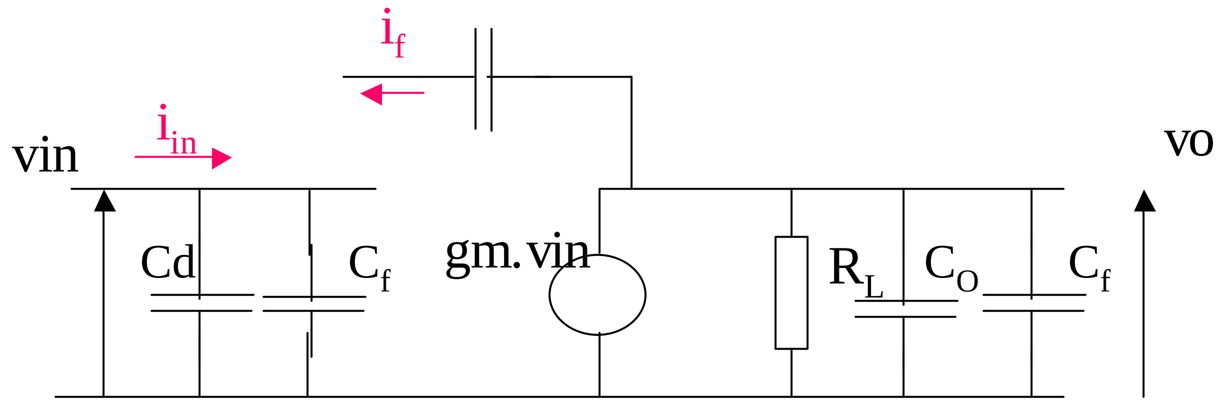
Small signal model

$$\frac{vin}{i_{in}} = \frac{1}{s(Cd + Cf)} \qquad \frac{vo}{vin} = \frac{gm.R_L}{1 + s(Co + Cf).R_L}$$

10 – Charge Sensitive Preamplifier

Frequency domain





Forward Gain
(A)

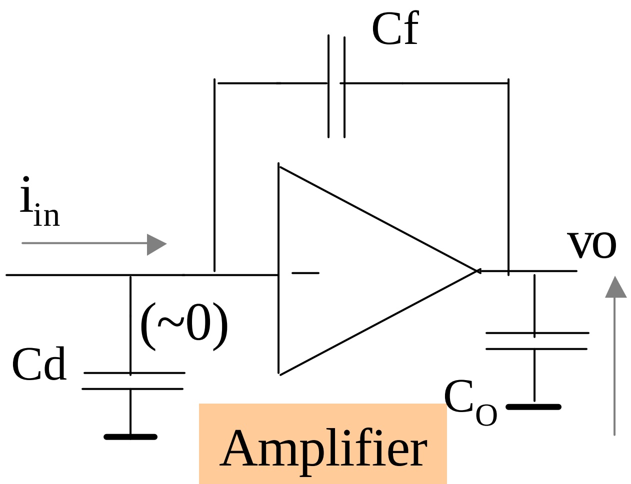
$$\frac{vo}{i_{in}} = \frac{gm.R_L}{1+s(Co+Cf).R_L} \cdot \frac{1}{s(Cd+Cf)}$$

Feedback Gain
(β)

$$\frac{i_f}{vo} = s.Cf$$

10 – Charge Sensitive Preamplifier

Frequency domain



Open loop Gain formula

$$\frac{i_f}{i_{in}} = A.ß$$

In our case, the product Aβ is :

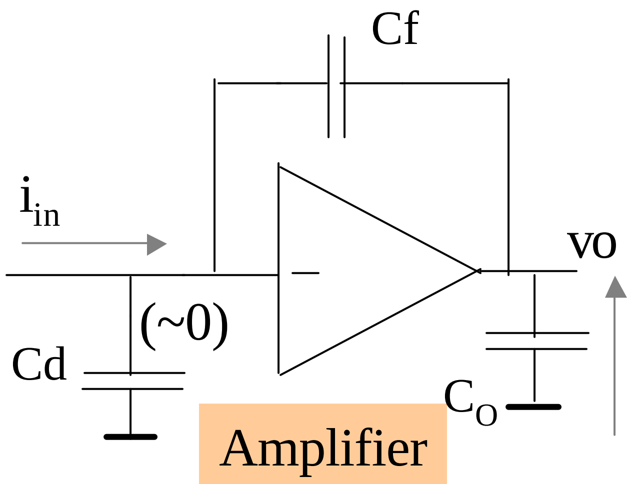
$$Aß = \frac{gm.R_L}{1+s(Co+Cf).R_L} \cdot \frac{Cf}{(Cd+Cf)}$$

Aβ is a one pole system, such that 1+Aβ cannot be zero.

The charge preamplifier is difficult to make unstable

10 – Charge Sensitive Preamplifier

Frequency domain



Closed loop Gain Calculation

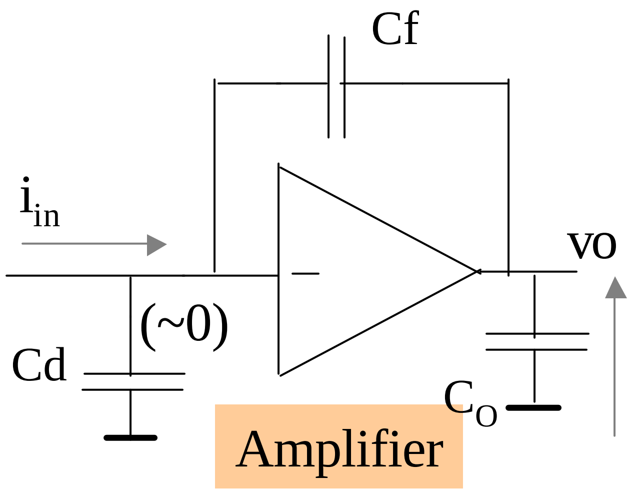
$$\frac{vo}{i_{in}} = \frac{A}{1+Aß}$$

$$\frac{vo}{i_{in}} = \frac{1}{sCf} \cdot \frac{1}{1+s\frac{(Cd+Cf)(Co+Cf)}{gm.Cf}}$$

Ideal Integrator response

Pole added by amplifier limited BW

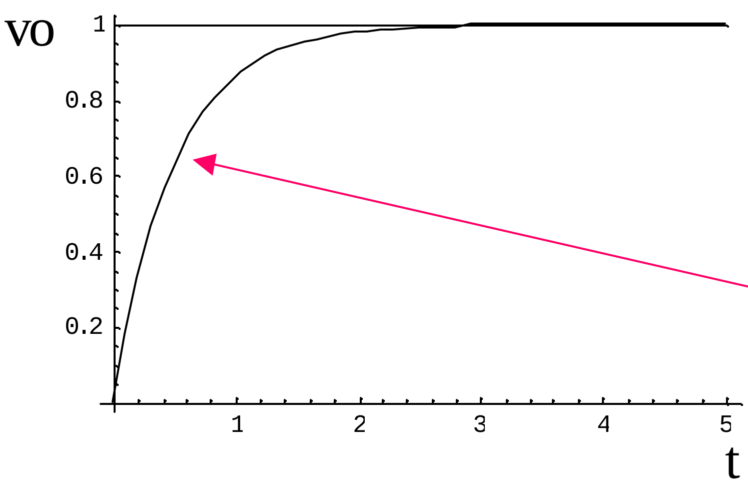
10 – Charge Sensitive Preamplifier



Frequency domain

It can be shown that the input impedance of the charge preamplifier is given by :

$$Rin = \frac{(Co + Cf)}{gm.Cf}$$

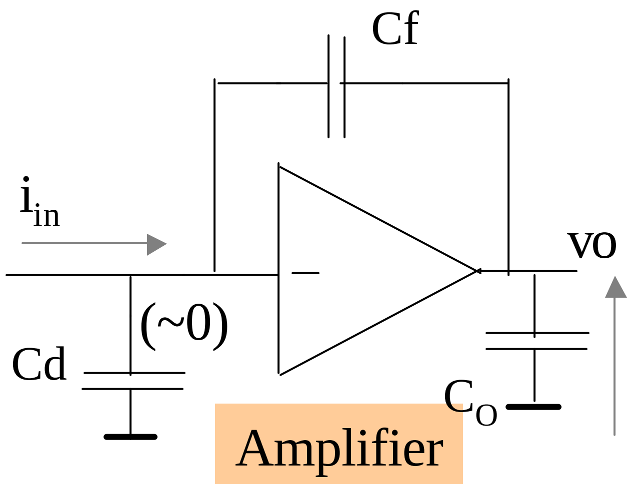


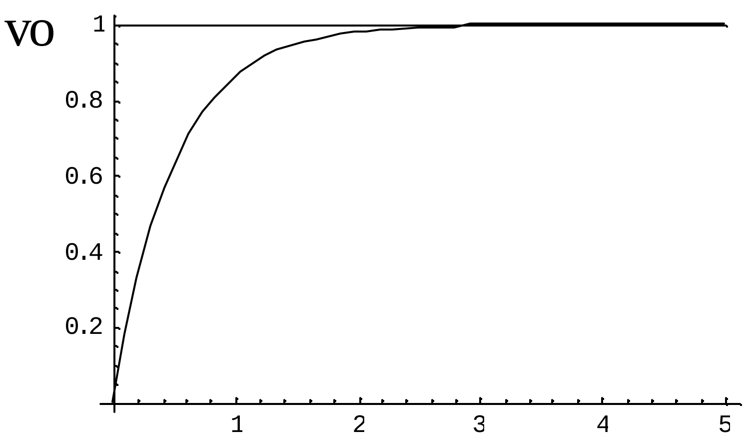
$$\frac{vo}{i_{in}} = \frac{1}{sCf} . \frac{1}{1 + sRin.(Cd + Cf)}$$

Input node RC time constant

10 – Charge Sensitive Preamplifier

Frequency domain





Numerical values

Cf=0.1pF, Ro = 500K, Co=1pF, Cin=20pF

gm=0.003S

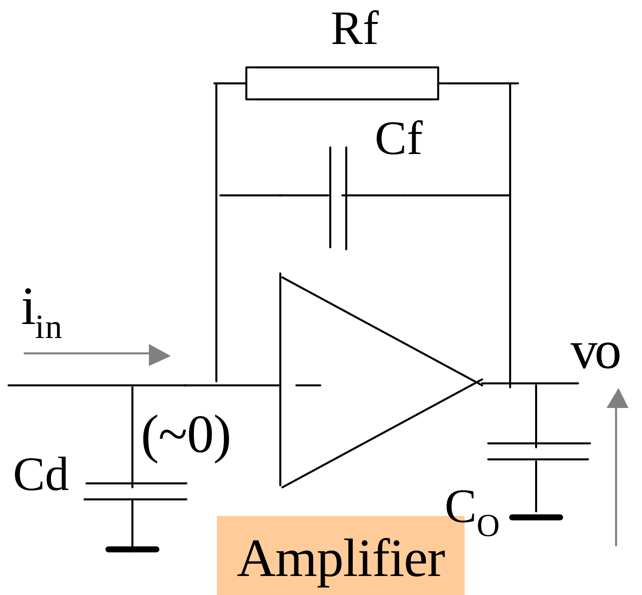
$$Rin = \frac{(Co + Cf)}{gm.Cf} \quad \text{gives} \quad Rin = 3.7 Kohms$$

$$\frac{vo}{i_{in}} = \frac{1}{sCf} . \frac{1}{1 + \underbrace{sRin.(Cd + Cf)}}$$

Input node RC time constant=75ns

10 – Charge Sensitive Preamplifier

With Resistive feedback element

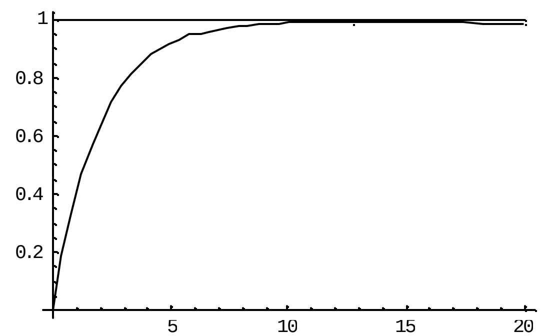


$$\frac{vo}{i_{in}} = \frac{1}{sCf}\cdot\frac{Rf}{1+s.Rf.Cf}\cdot\frac{1}{1+sRin.(Cd+Cf)}$$

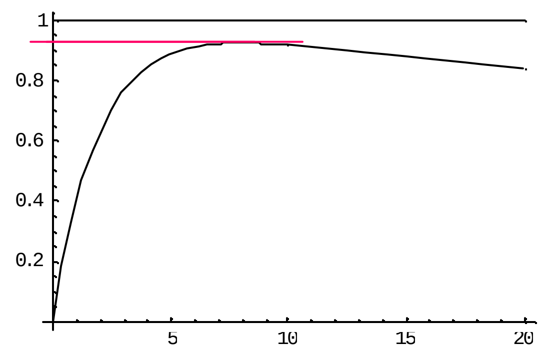
Feedback RC

Input node RC

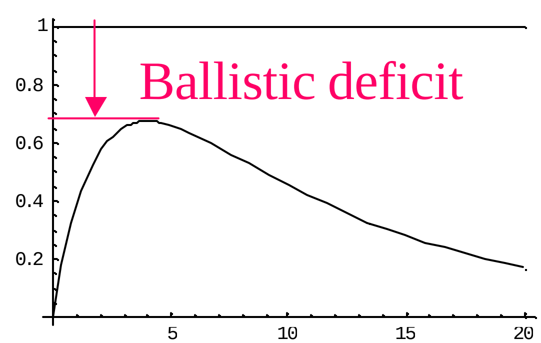
RfCf=500RinCin



RfCf=50RinCin

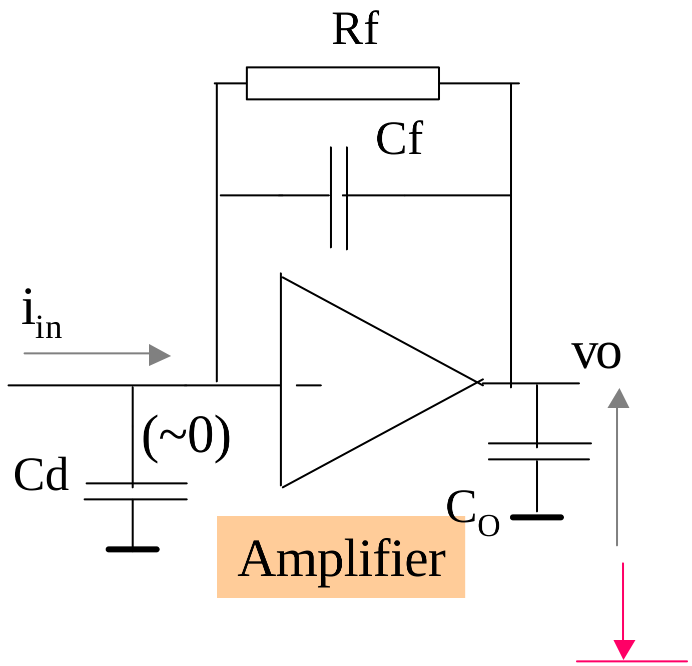


RfCf=5RinCin



10 – Charge Sensitive Preamplifier

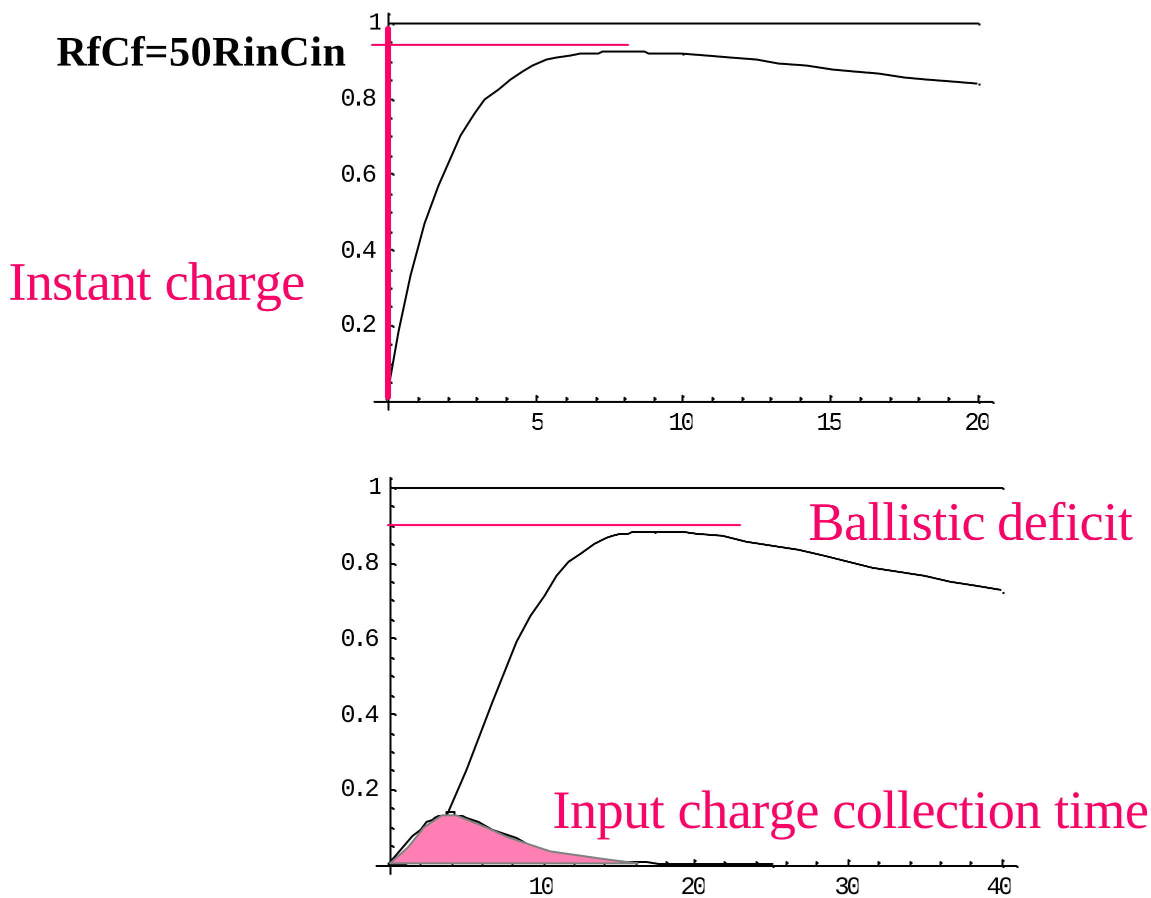
Charge collection time



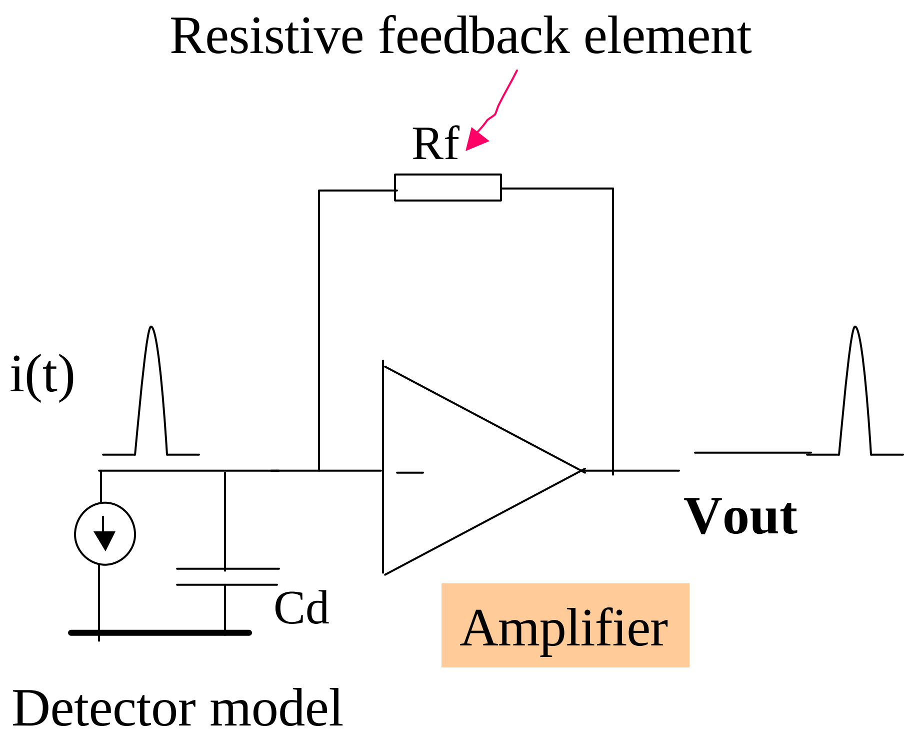
$$\frac{vo}{i_{in}} = \frac{1}{sCf} \cdot \frac{Rf}{1+s.Rf.Cf} \cdot \frac{1}{1+sRin.(Cd+Cf)}$$

Feedback RC

Input node RC



11 – Transimpedance Preamplifier



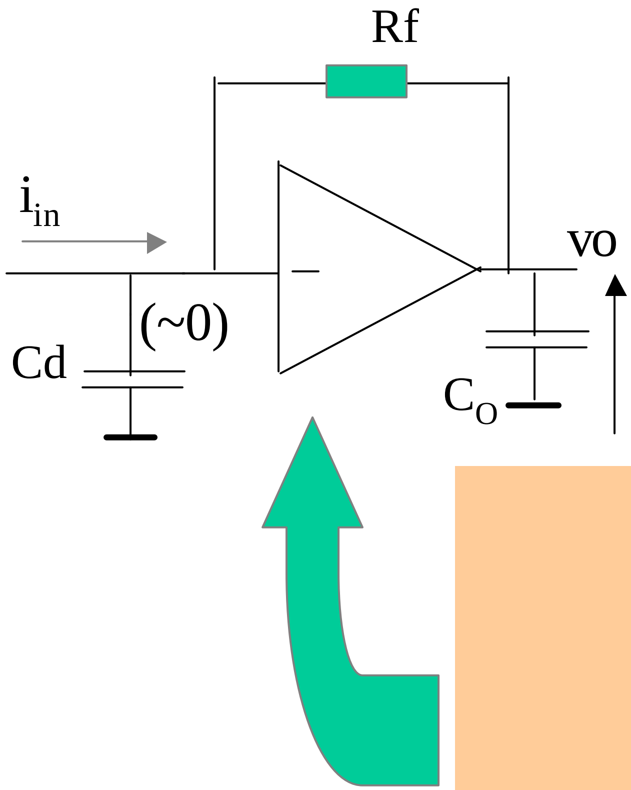
$$\left(Q_{in} = \int_0^t i(t)dt\right)$$

$$Vout(t) = R_f . i_{in}(t)$$

The instantaneous output voltage is the image of the current flow at the detector output (ideal case !)

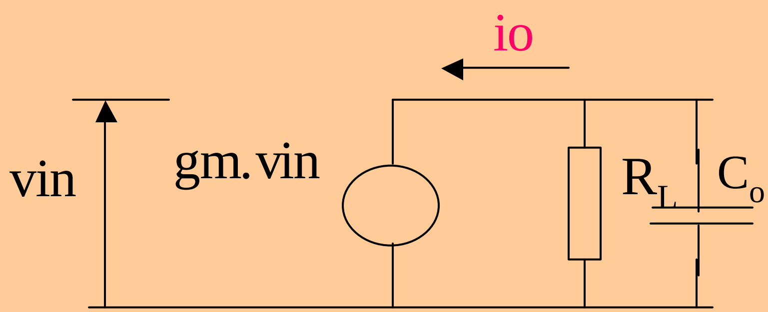
11 – Transimpedance Preamplifier

Frequency domain



Amplifier

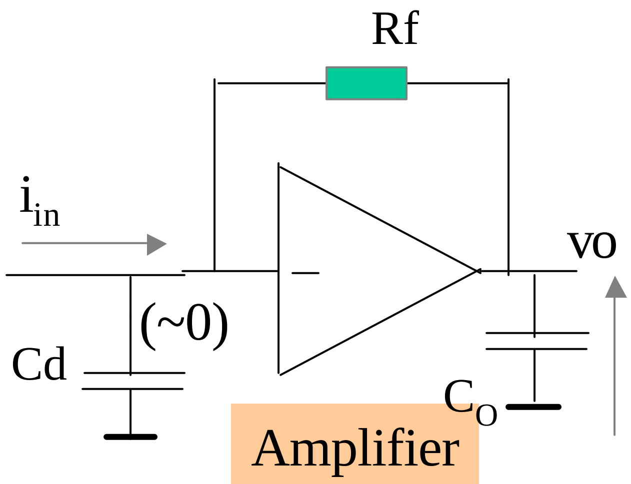
Consider now a non-ideal amplifier, loaded with capacitance C_o :



Small signal model

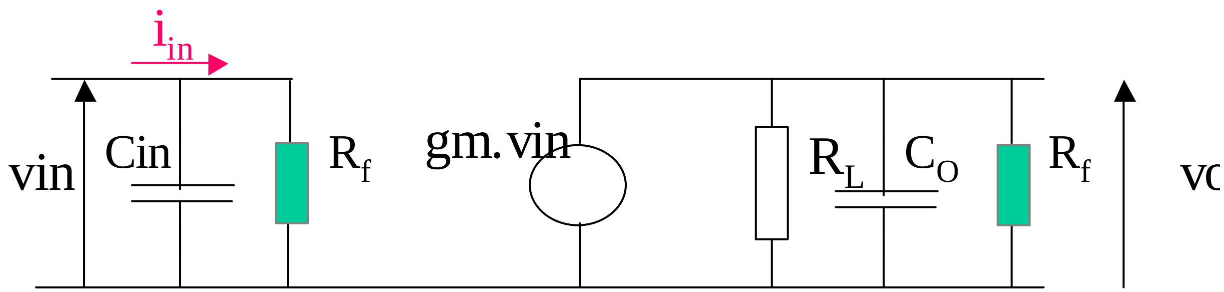
$$\frac{vo}{vin} = \frac{gm.R_L}{1 + sC_o.R_L}$$

11 – Transimpedance Preamplifier



Frequency domain

If we consider Rf acting not as a feedback element, but just as a resistive load on input and output (forward path gain A) :



Small signal model

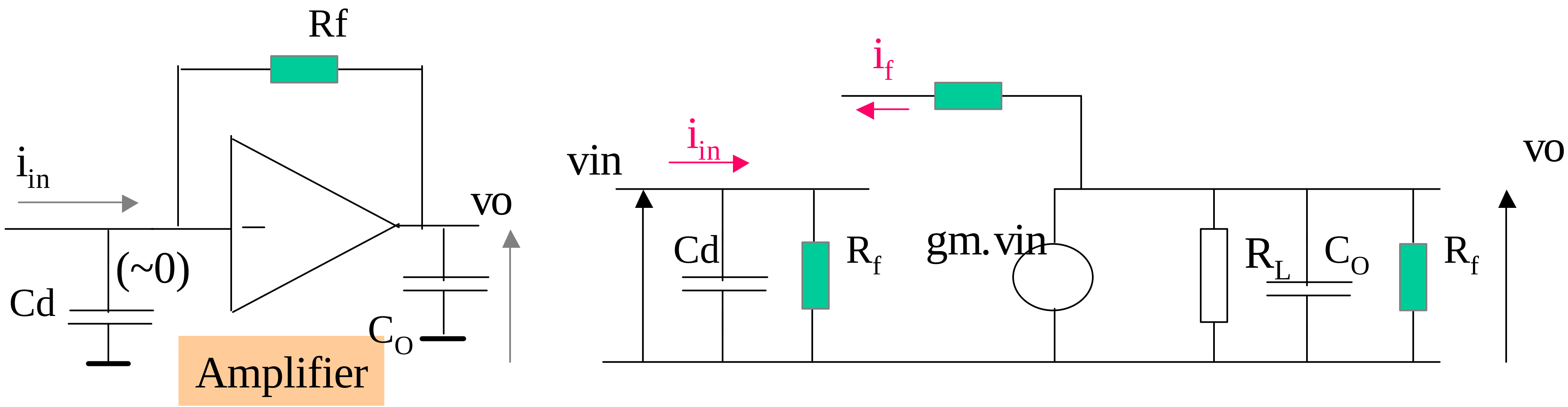
$$\frac{vin}{i_{in}} = \frac{Rf}{1 + s.Rf.Cin}$$

$$\frac{vo}{vin} = \frac{gm.Ro}{1 + s.Ro.Co}$$

With $Ro = R_f // R_L$

11 – Transimpedance Preamplifier

Frequency domain



Forward Gain (A)

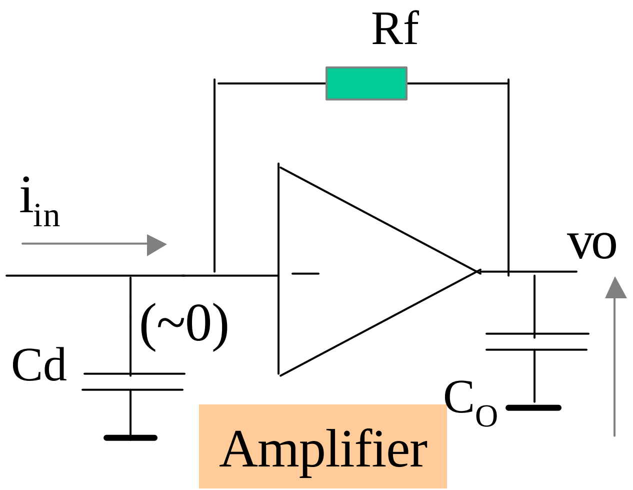
$$\frac{vo}{i_{in}} = \frac{gm.Ro}{1+s.Co.Ro} \cdot \frac{Rf}{1+s.Rf.Cin} \quad (Ro=R_f//R_L)$$

Feedback Gain (β)

$$\frac{i_f}{vo} = \frac{1}{Rf}$$

11 – Transimpedance Preamplifier

Frequency domain



Open loop Gain formula

$$\frac{i_f}{i_{in}} = A.ß$$

The open loop gain (product Aβ) is :

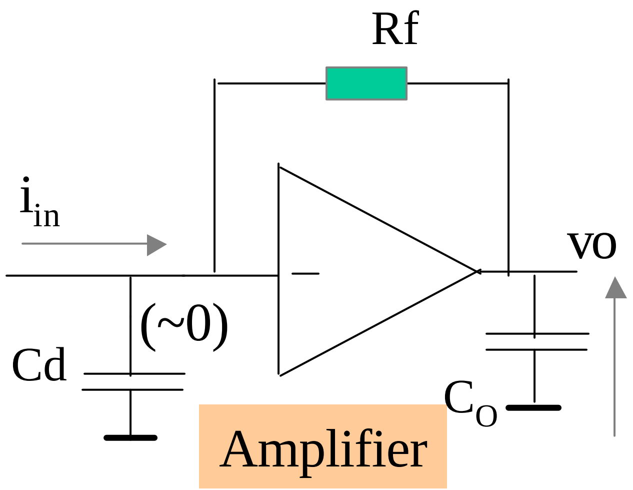
$$Aß = \frac{gm.Ro}{(1+s.Co.Ro)(1+s.Cin.Rf)} \qquad (Ro=R_f//R_L)$$

Aβ has two poles, 1+Aβ can be zero, and the closed loop circuit being unstable

The transimpedance preamplifier is difficult to make …. stable

11 – Transimpedance Preamplifier

Frequency domain



Closed loop Gain Calculation

$$\frac{vo}{i_{in}} = \frac{A}{1 + Aß}$$

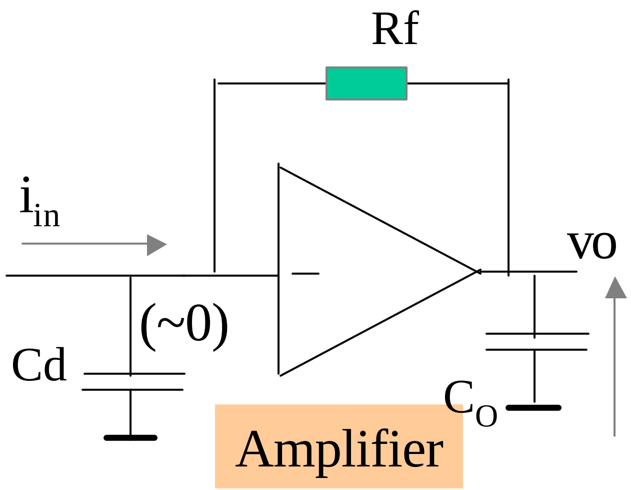
$$\frac{vo}{i_{in}} = Rf.\frac{1}{1 + \frac{(1 + s.Ro.Co)(1 + s.Cin.Rf)}{A_0}}$$

Ideal transimpedance response

Two poles circuit response

$(Ro = R_f // R_L)$ and $A_0 = gm.Ro$

11 – Transimpedance Preamplifier



Under the strong assumption that poles Cin/Rf.Ao and Ro.Co are widely separated :

$$\frac{vo}{i_{in}} \approx Rf.\frac{1}{(1+s.\frac{Cin.Rf}{A_0})(1+s.Ro.Co)}$$

It can be shown that the input impedance of the transimpedance preamplifier is given by :

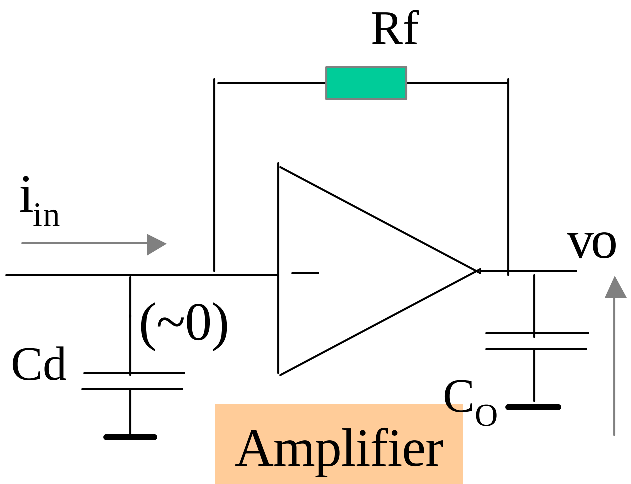
$$Rin = \frac{Rf}{A_0}$$

$$\frac{vo}{i_{in}} \approx Rf.\frac{1}{(1+sRin.Cin)(1+sRo.Co)}$$

Two real pole circuit

11 – Transimpedance Preamplifier

Widely spaced poles

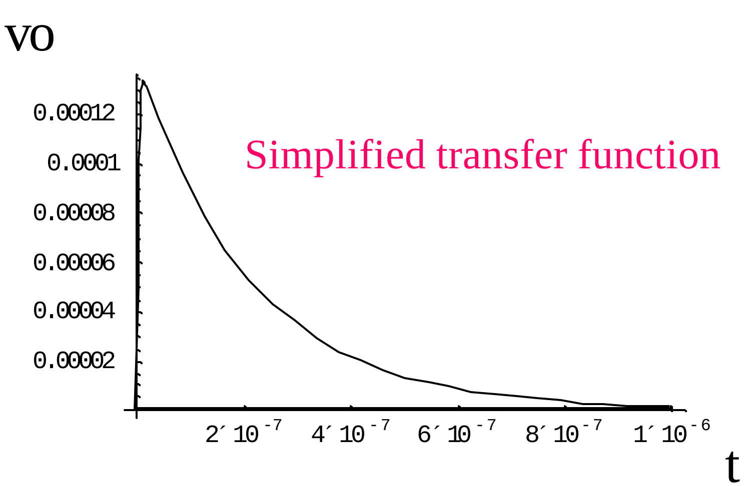


Numerical values :

Rf=30K, Ro = 500K, Co=0.1pF, Cin=200pF

gm=0.001S

$$Rin = \frac{Rf}{A_0} \quad \text{gives} \quad Rin = 1Kohms$$



1fC response

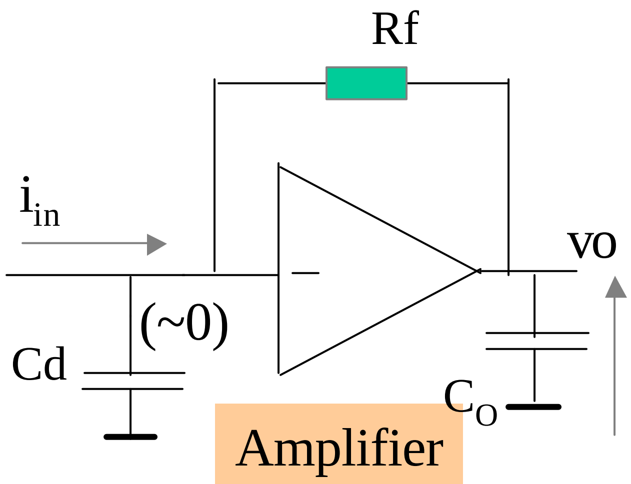
$$\frac{vo}{i_{in}} \approx Rf . \frac{1}{(1 + sRin.Cin)(1 + sRo.Co)}$$

Input node RC time constant
Rin.Cin= 200ns

Internal pole
Ro.Co= 3ns

11 – Transimpedance Preamplifier

Widely spaced poles



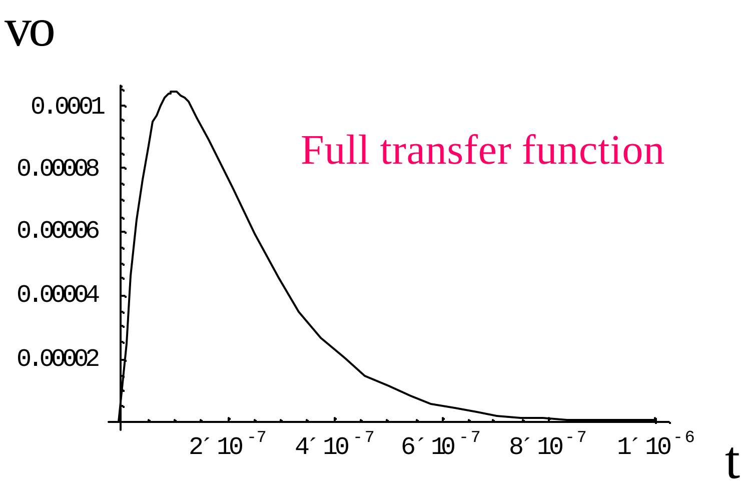
Numerical values :

Rf=30K, Ro = 500K, Co=0.1pF, Cin=200pF

gm=0.001S

Computing the true transfer function with the same numerical values :

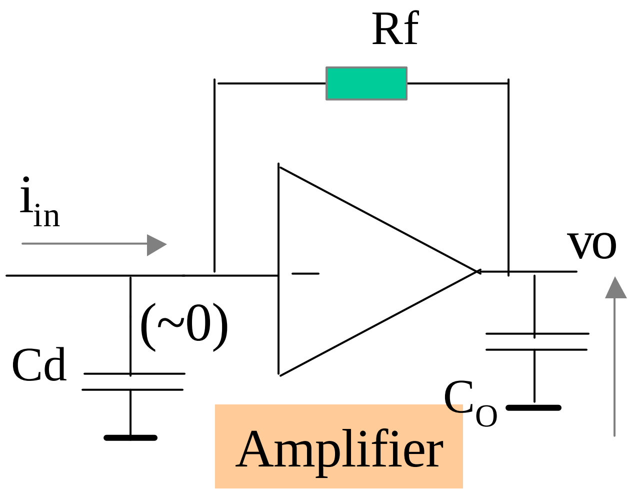
$$\frac{vo}{i_{in}} = Rf.\frac{1}{1+\frac{(1+s.Ro.Co)(1+s.Cin.Rf)}{A_0}}$$



1fC response

11 – Transimpedance Preamplifier

Example with some realistic numbers, fast preamplifier



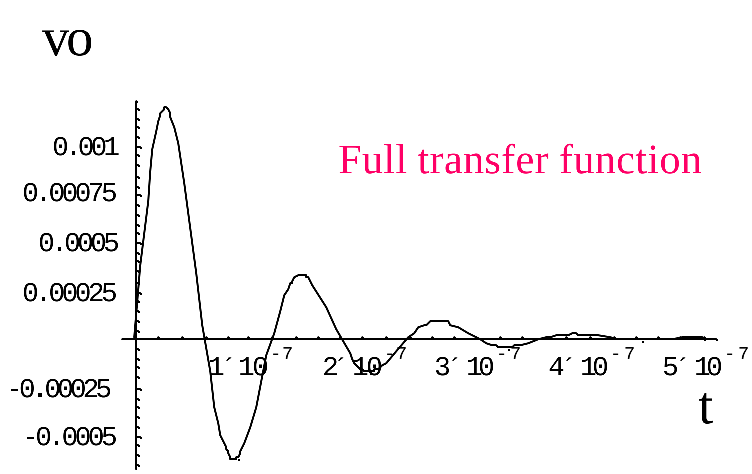
Consider numerical values fitting with silicon strip detector :

Rf=30K, Ro = 500K, Co=0.1pF, Cin=20pF

gm=0.003S

Computing the true transfer funtion :

$$\frac{vo}{i_{in}} = Rf.\frac{1}{1+\frac{(1+s.Ro.Co)(1+s.Cin.Rf)}{A_0}}$$



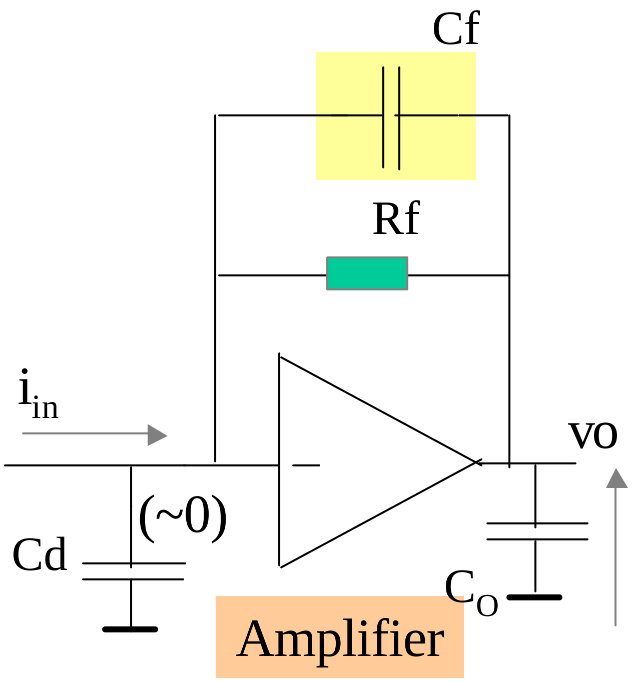
1fC response

The circuit is close to instability !

(equivalent input impedance 300 ohms, RinCin=7ns, RoCo=3ns

11 – Transimpedance Preamplifier

Example with some realistic numbers, fast preamplifier



Transimpedance stability is obtained by the addition of the feedback capacitance Cf

The open loop gain (product Aβ) is changed as:

$$A\beta = \frac{Ao.(1+s.Cf.Rf)}{(1+s.Co.Ro)(1+s.Cin.Rf)}$$

($Ro=R_f//R_L$) and $A_0=gm.Ro$

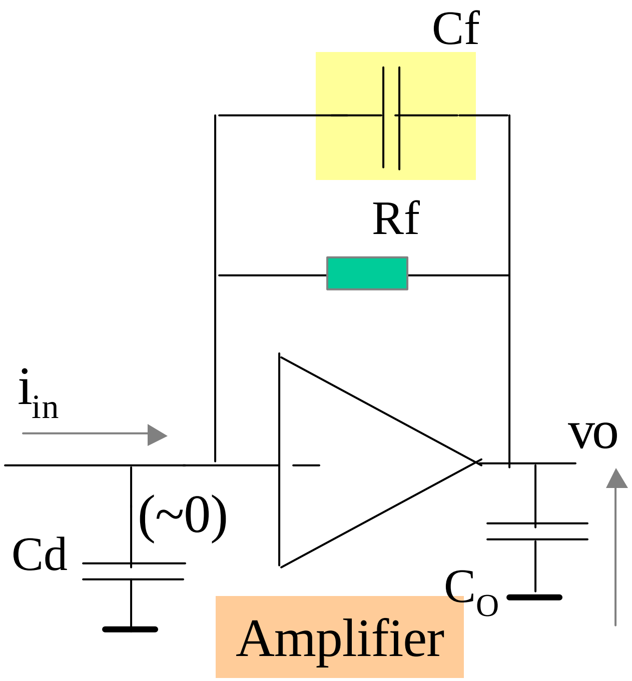
If Cf.Rf is made equal to Co.Ro time constant :

$$A\beta = \frac{Ao}{(1+s.Cin.Rf)}$$

The circuit becomes stable

11 – Transimpedance Preamplifier

Example with some realistic numbers, fast preamplifier



Transimpedance stability is obtained by the addition of the feedback capacitance Cf

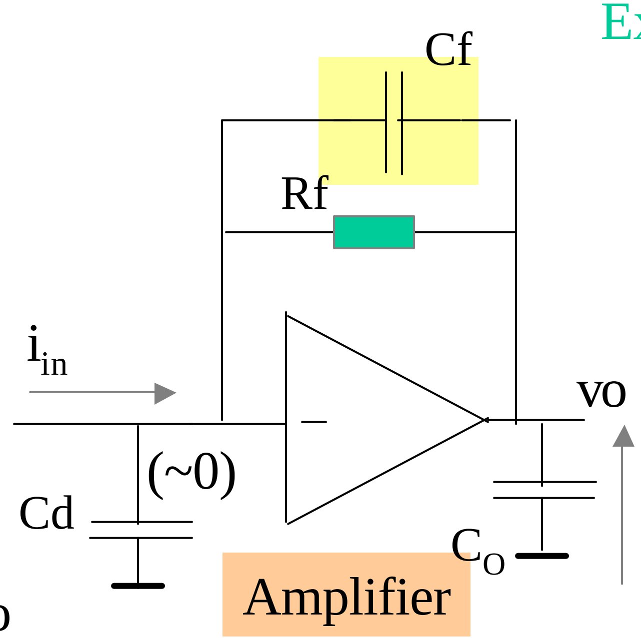
Closed loop Gain Calculation

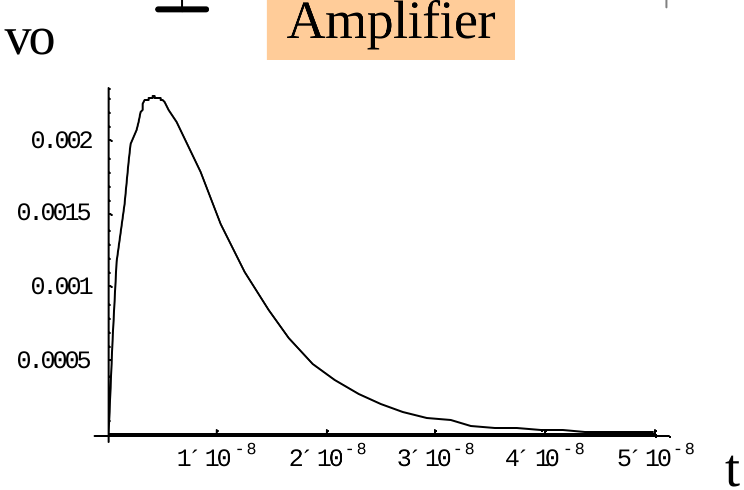
If Cf.Rf is made equal to Co.Ro time constant :

$$\frac{vo}{i_{in}} = Rf.\frac{1}{(1+s.Ro.Co)(1+s.\frac{Cin.Rf}{A_o})}$$

11 – Transimpedance Preamplifier

Example with some realistic numbers, fast preamplifier





1fC response

Numerical values :

Rf=30K, Ro = 500K, Co=0.1pF, Cin=20pF

gm=0.003S, Cf=0.1pF

$$\text{Rin} = \frac{\text{Rf}}{A_0} \quad \text{gives} \quad \text{Rin} = 350\,ohms$$

$$\frac{\text{vo}}{i_{in}} \approx \text{Rf}.\frac{1}{(1+s.\frac{\text{Rf}}{A_o}.\text{Cin})(1+s\text{Ro}.Co)}$$

Input node RC time constant

Rin.Cin= 7 ns

Internal pole

Ro.Co= 3 ns

12 – Preamplifiers conclusions

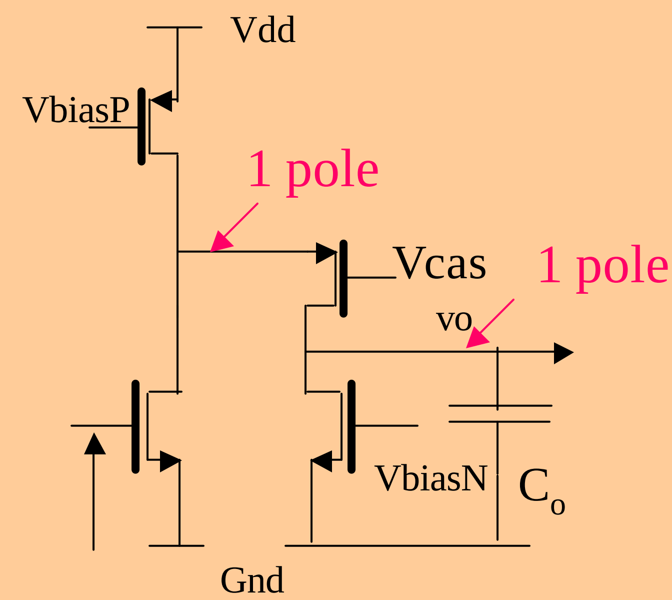
	Charge Preamp	Transimpedance
Time constant	>50ns	>5ns
Input Impedance	Kohms range	100ohms range
Stability	Easy	Difficult
Gain	Q/Cf Ballistic deficit	Time response dependance

12 – Preamplifiers conclusions

Simplifications were done for all the preceding formulations:

We assumed main amplifiers with one pole only. In all cases, it is not true and amplifiers should be modeled with at least two internal poles

The true closed loop gain formulations are in general complex. “Spice” simulations are mandatory to finalize the stability issue and predict precisely the transfer function



12 – Preamplifiers conclusions

During the preamplifier design discussions, we did not considered :

• The noise issue (sets constraints on gm, RC time constants)

• The signal gain and dynamic range

• Power supply noise rejection

• Common mode issue

Vin

• ….

A preamplifier design is a compromise between many aspects (specifications), the choice of a particular design will depend on :

. The signal range and collection time

. The S/N ratio (noise prediction)

. The available power

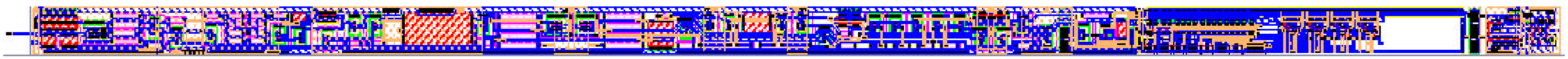
Other parameters to consider :

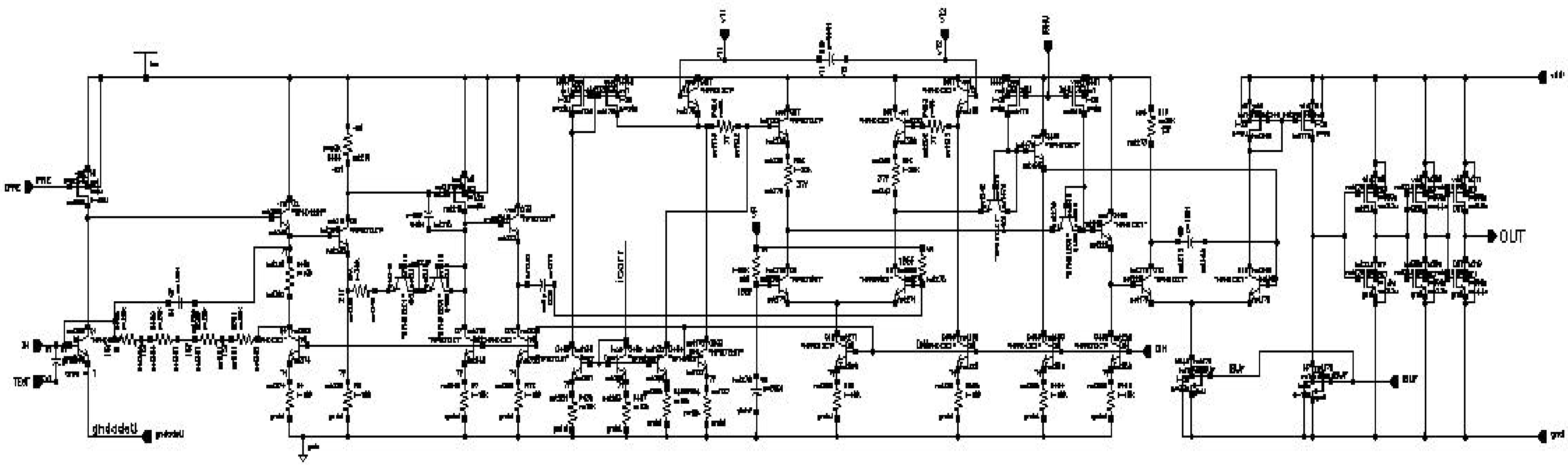
. Dynamic range & pile-up

. Large signal recovery

. PSRR, Common mode etc …

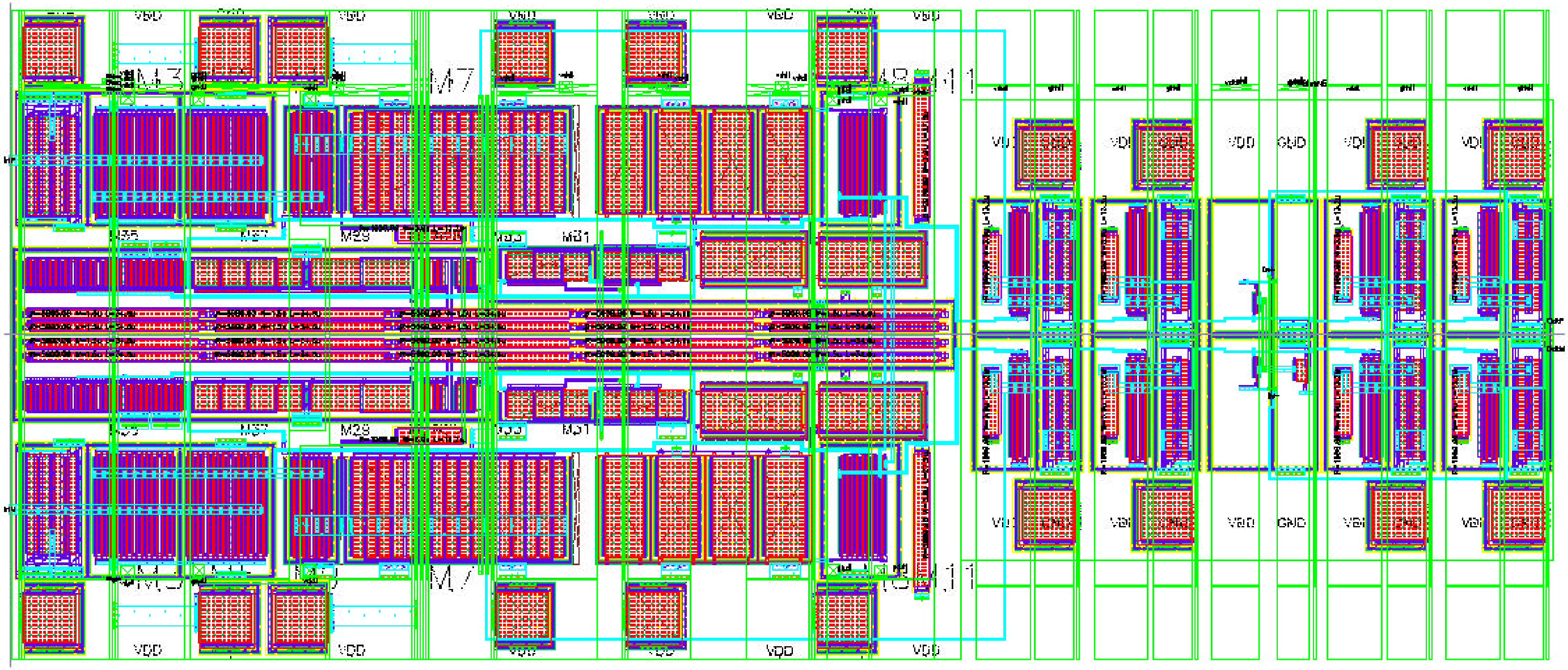
12 – Preamplifiers conclusions





Low noise analog amplifier chain for Silicon Tracker BiCMOS 0.8um, 20ns rise time

12 – Preamplifiers conclusions



“Modern” fast amplifier design   CMOS 0.25um, 1.5ns rise time, fully differential