A CMOS Instrumentation Chain for Charged Particles Detection in the Space Environment

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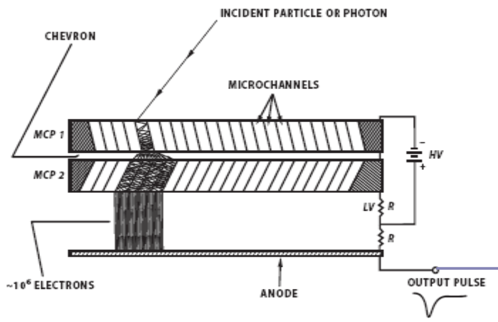
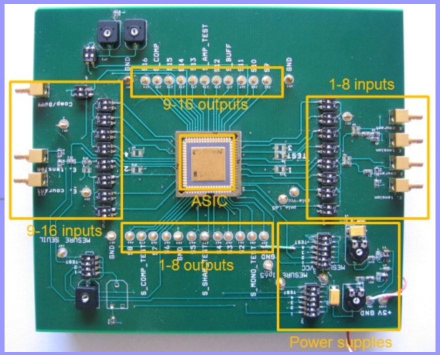
Low power CMOS instrumentation for Solar system Exploration

- Overview of the particle detection chain



MicroChannel Plate (MCP) Detector



CMOS Readout circuit

1 → event

0→ no event

Data processing

→The readout circuit provides a binary output on the presence of an event

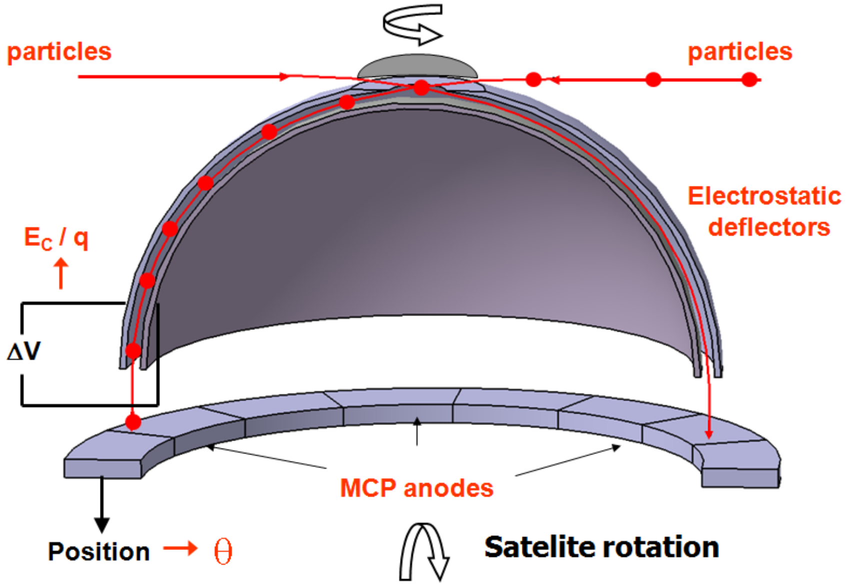
→ To measure the plasma distribution function → Count particles

Content

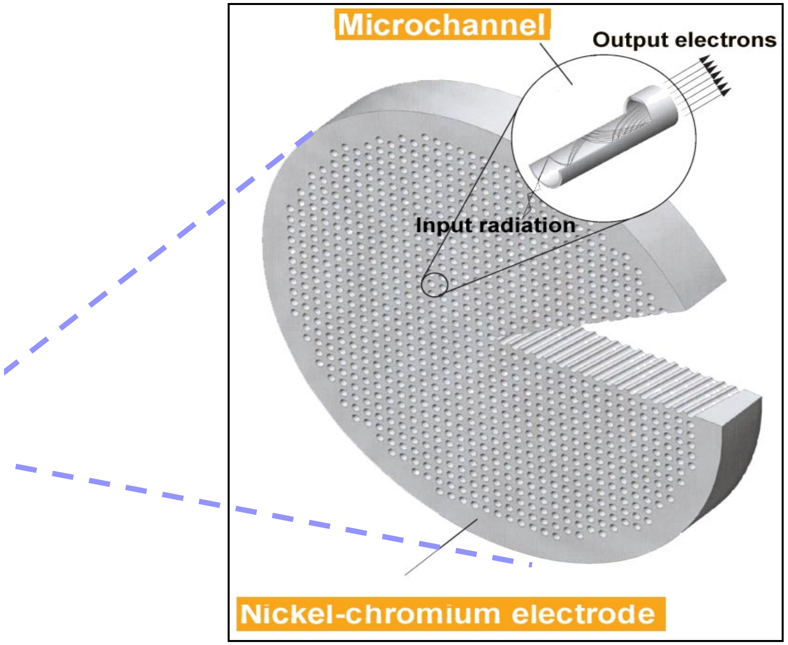
- MCP KEY PARAMETERS
- Amptek A111
- ASIC specifications and challenges
- ASIC CDIC16 description
- Experimental Results
- Conclusion

Content

Top-hat electrostatic analyzer

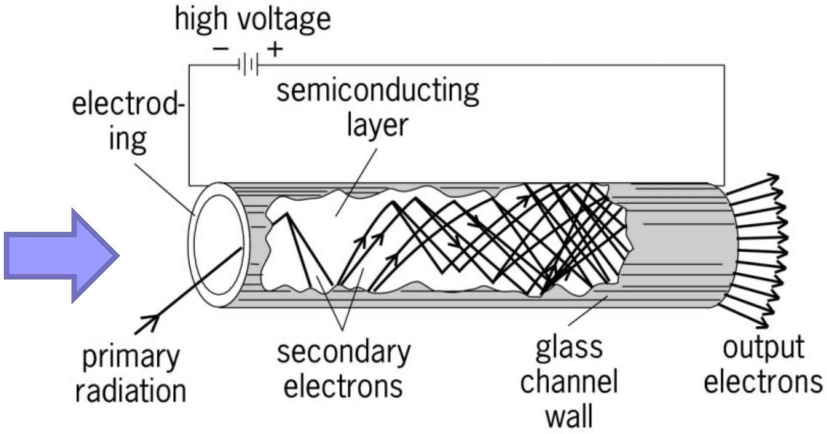


Top-hat electrostatic analyzer

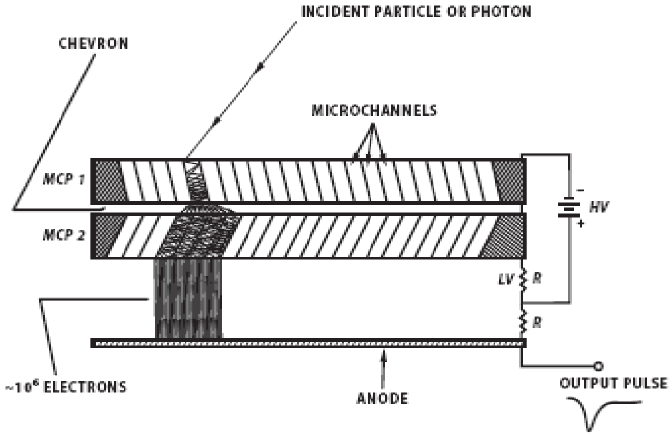


MicroChannel Amplification mechanism

$$G = \delta^n$$



To increase the gain → MCP mounted in Chevron

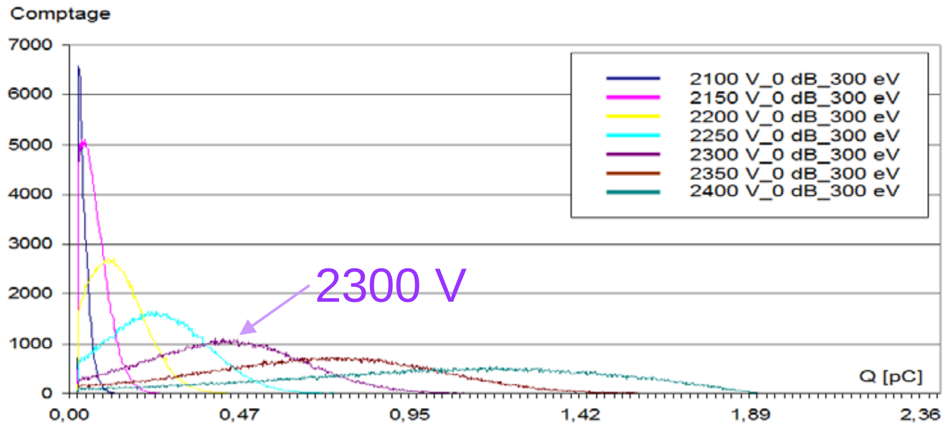


→ $10^5 < \text{Gain} < 10^7$

But Gain depends on :

- Quality of the MCP
- Polarisation voltage
- Ageeing

→ Sensor dynamic range



2300 V

MCP main characteristics

Parameter	MCPs in Chevron
Diameter (mm)	25.4
Anode number	16
High Voltage (V)	2300
Gain Spread	0 à 6.2×10^6
Equivalent input charge(pC)	0 to 1
Collecting time (ns)	0 to 1
Input parasitic capacitance (pF)	3
Max Operating Frequency (MHz)	2.5

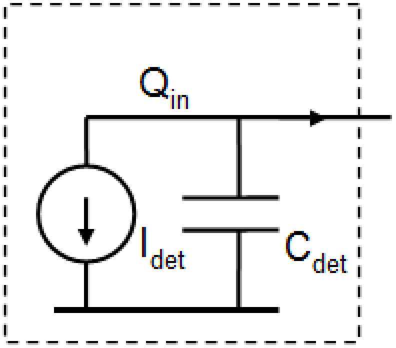
Sensor :

- Bandwidth > 2.5MHz
- Gain : V_{max} / $G^{MCP}{}_{max}$
- SNR ↔ ENC : $G^{MCP}{}_{min}/2$

MCP electrical model

Current Pulse source:

$$I_{DET} = \frac{\Delta Q_{IN}}{\Delta t}$$



MCP Model

- Maximum pulse width: 1 ns
- Maximum rise time t_r: 500 ps
- Channel recovery time: 400 ns
- Parasitic capacitance C_{det} = 3 pF

Content

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- **Amptek A111**
- ASIC specifications and chalenges
- ASIC CDIC16 analysis
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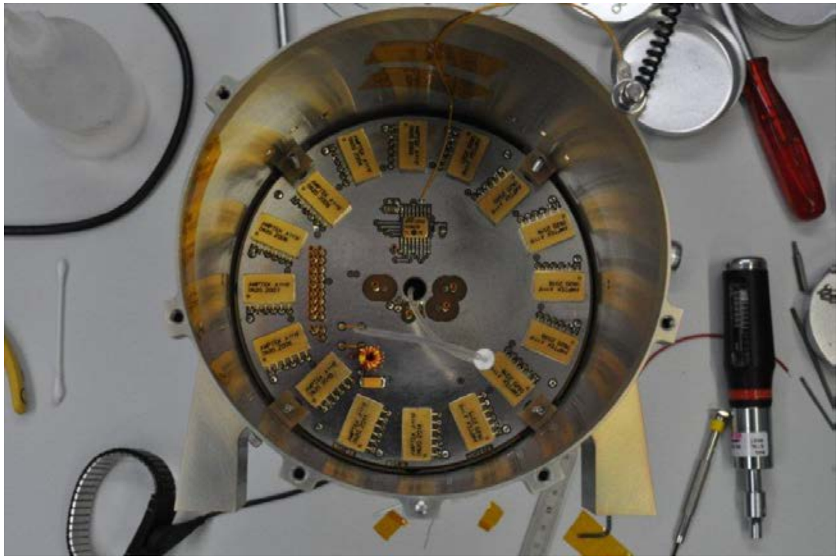
Amptek A111 characteristics

	16*AMPTEK A111
Weight	2.6 g * 16 = 41.6 g
Consumption	6 mW * 16 = 96 mW
Noise ENC	2750 + 562 e^-/pF
Detector Max capacitor	0 – 250 pF
Output voltage	4,7 V
Count rate	2.5 MHz
Temperature accepted	- 55 °C à 85 °C
Radiation tolerance	> 100 krad



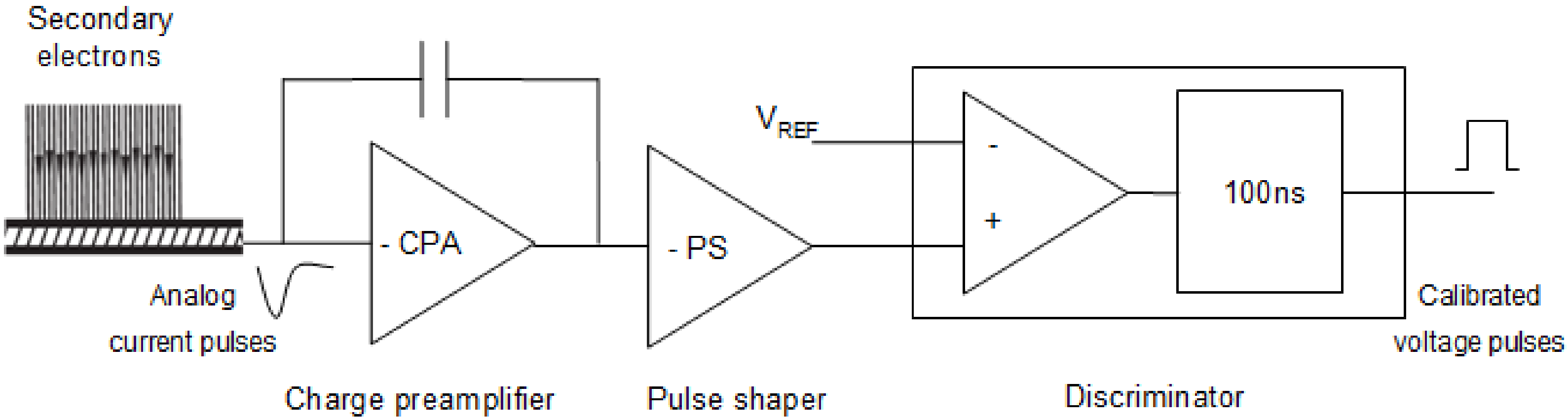
Content

Advantages and drawbacks of full custom integration (ASIC)

- +++ : low power consumption, low noise, less area, less weight, higher speed of acquisition
- --- : prone to crosstalk, flexibility, radiation tolerance,

ASIC Specifications

➔ Event detection

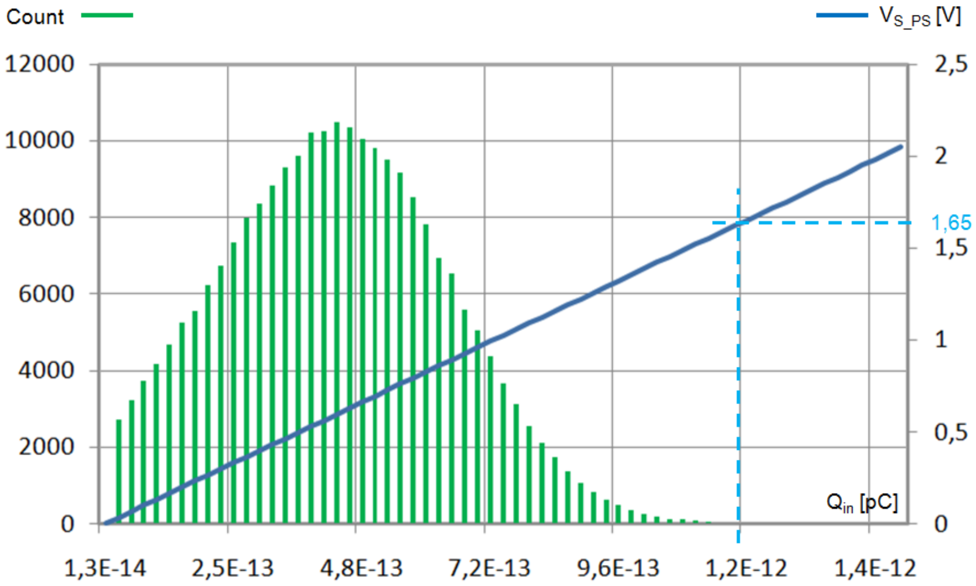


Block Diagram of the analog-digital front-end processing chain for one channel

➔ ASIC Challenges

- Noise (ENC)
- Radiation hardness
- Power Consumption
- Crosstalk
- Technology process choice

ASIC Specifications

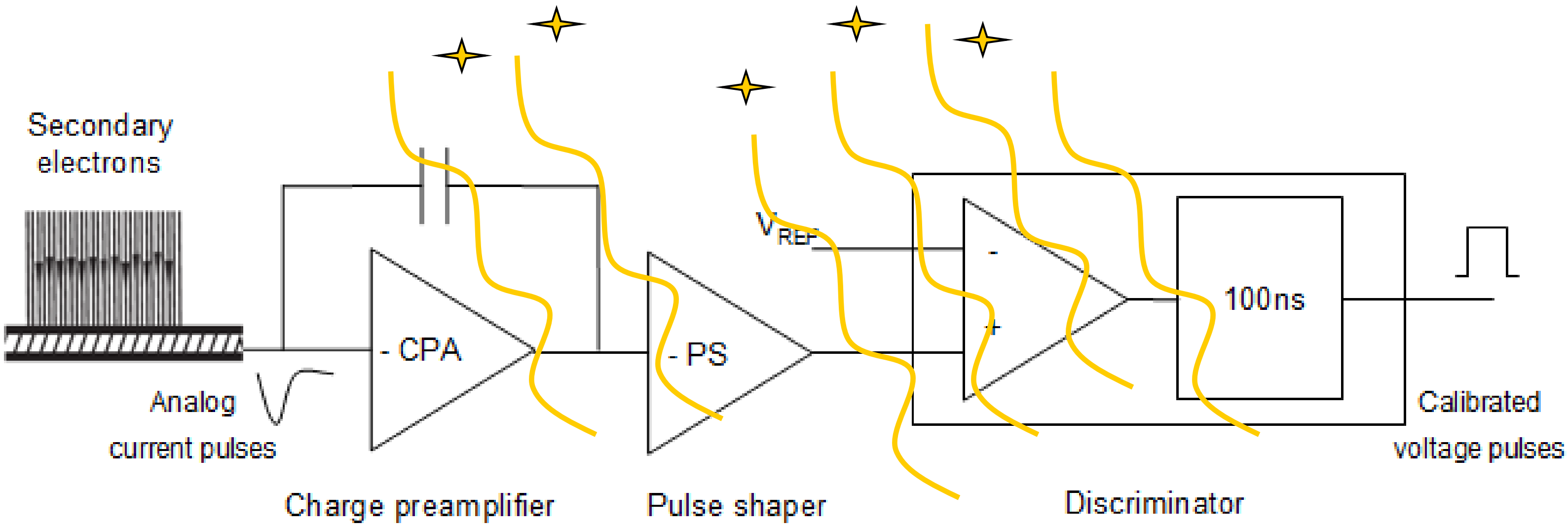


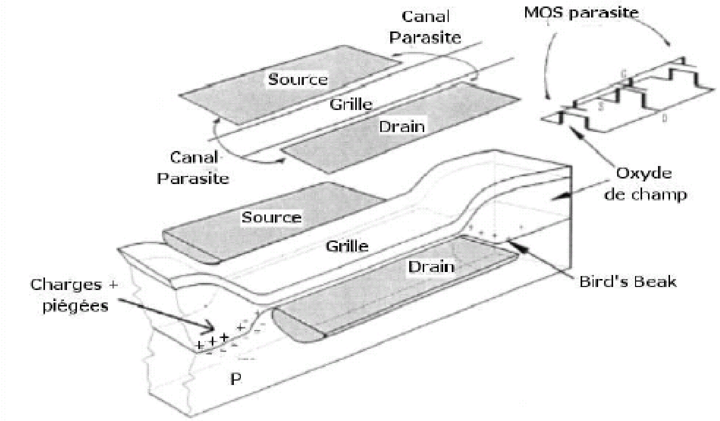
MCP gain distribution

$$Gain = \frac{\Delta V_{S\_PS}}{\Delta Q}$$

- Bandwidth: 2.5 MHz
- 16 Channels
- Gain : 1.35mV/fC
- Dynamic range : noise floor 0.58 fC (3635 e^-) to 1pC (~7.5e6 e^-)
- Power Consumption < 3 mW/channel
- Radiation hardness > 20 krad
- Tunable detection threshold voltage

Radiation Effects



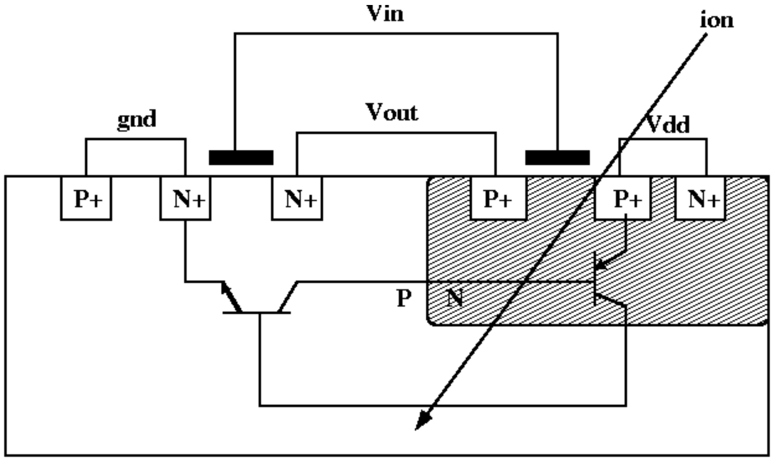


- Vth Threshold voltage shifts
- Parasitic MOS transistors

➡ Submicron technologies (tunneling effects) ≤0.35µm

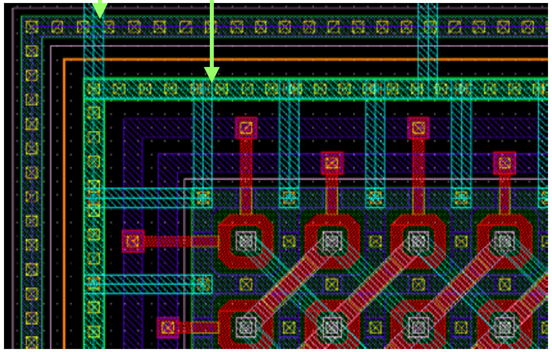
➡ Enclosed MOS transistors

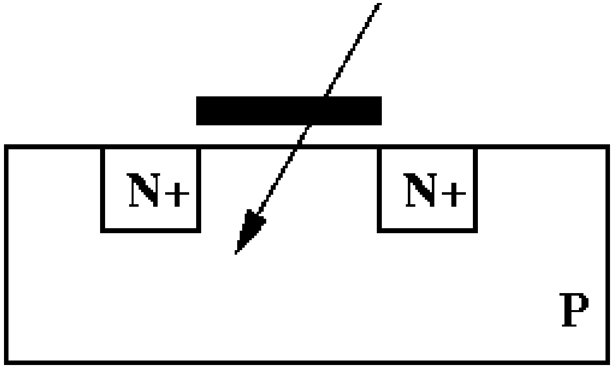
➡ PMOS switch



- Latchup

➡ Guard Rings (+ current leakage reduction)

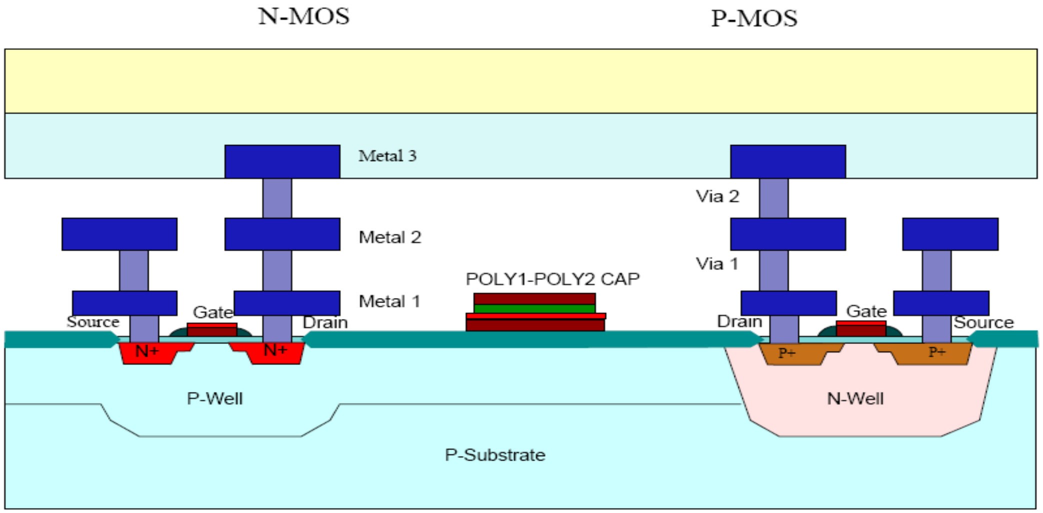




- Gate rupture

➡ No bootstrapped structure

Process AMS CMOS 0.35 µm



Austria Mikro Systeme International AG

- **Grid oxyde thickness 9nm**
- **Supply Voltage 3.3 V**
- **4 metal layers**

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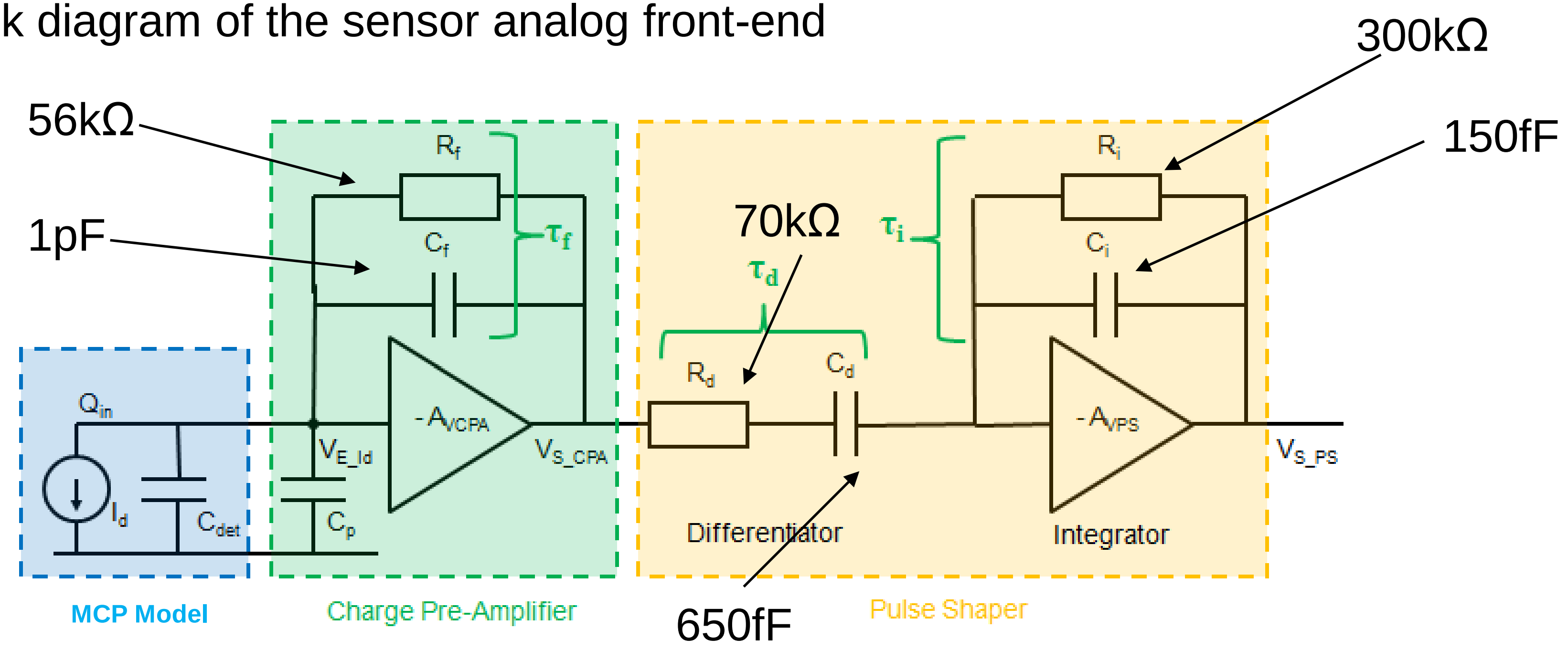
ASIC CDIC16 Analysis

Block diagram of the sensor analog front-end

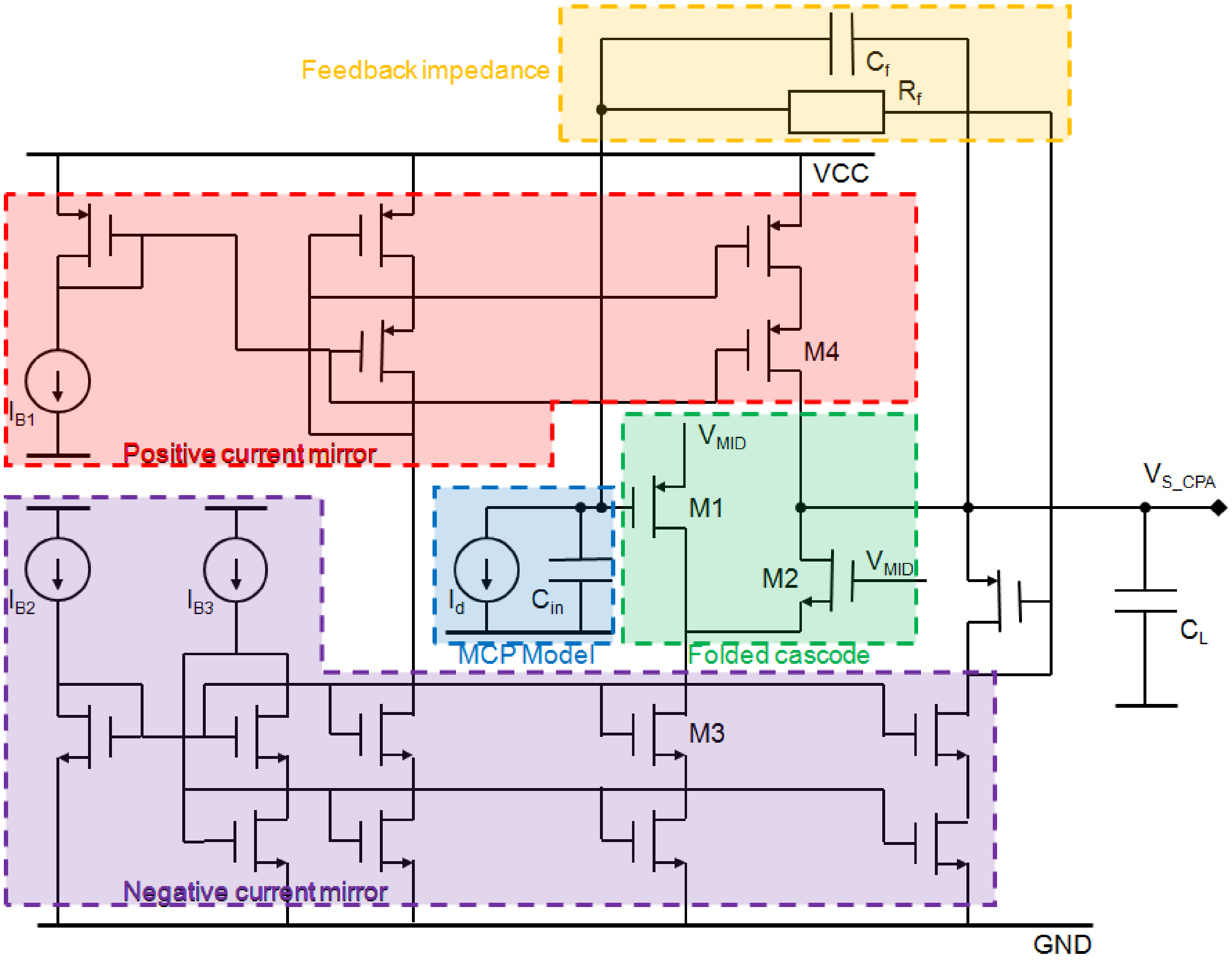


- The maximum count rate depends on the channel recovery time
- Time constant τ of the charge pre-amplifier is calculated such as to allow the wanted maximum counting rate of 2.5MHz ($t_{recovery}$ = 400ns)

$$\tau_{charge} + \tau_{discharge} \approx \frac{t_{recovery}}{6}$$

For a settling time better than 99% of the final value

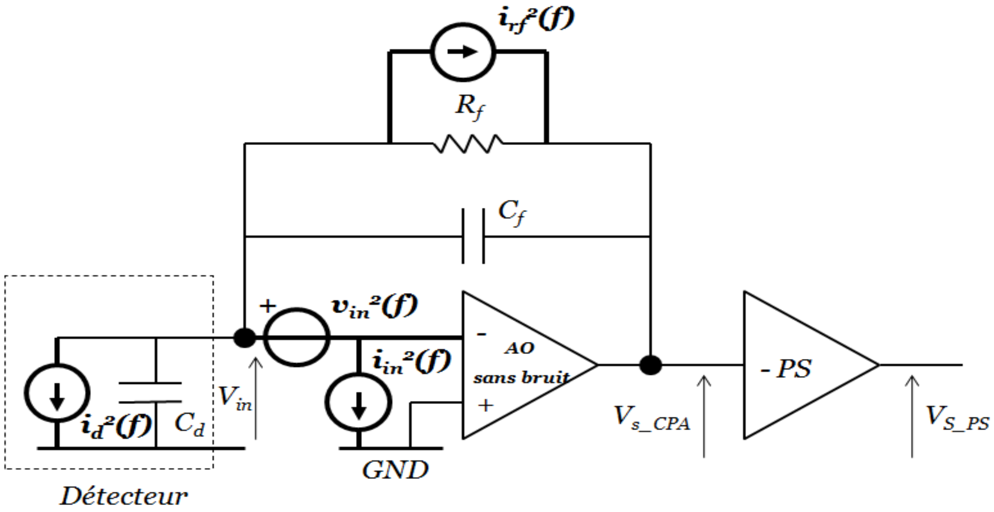
CPA amplifier schematic



$$C_{in} = C_{det} + C_p \approx 5\ \text{pF}$$

CPA Noise Analysis

Noise sources:



- Thermal Noise
- Flicker Noise
- Shot Noise

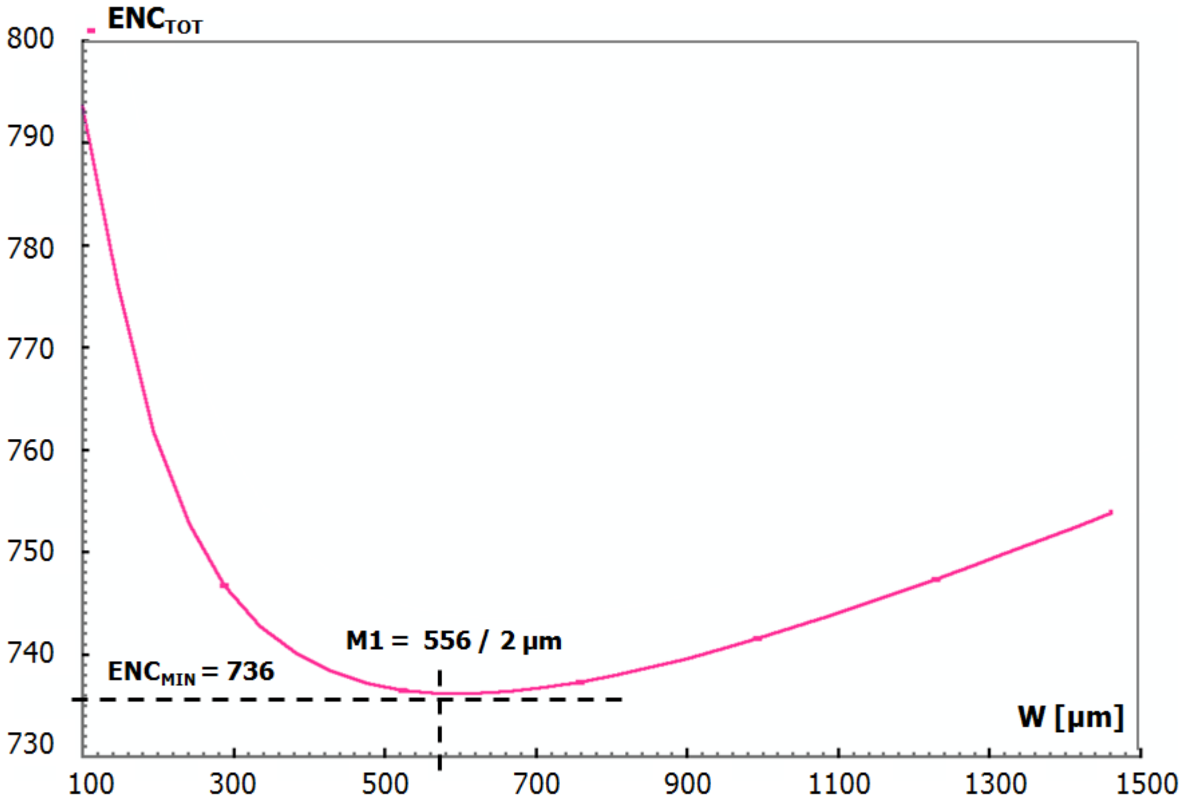
ENC : Equivalent Noise Charge

$$\boxed{ENC = \frac{V_{S\_PS_{rms}}}{V_{S\_PS}^{e^-}}}$$

Optimisation of the ENC (AMS 0.35µm)

$$ENC_{Th}^2 = \frac{1}{3} kT \frac{1}{g_m} C_t^2 \frac{e^2}{q^2 \tau_s} \qquad ENC_{1/f}^2 = \frac{K_f}{C_{OX}^2 WL} C_t^2 \frac{e^2}{2q^2} \qquad ENC_{Gre}^2 = \frac{I_{tot} \tau_s}{4} \frac{e^2}{q}$$

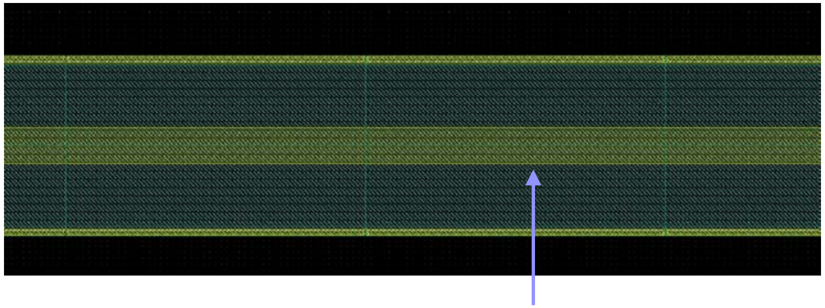
For a shaping time ts of 50ns and C_p=5pF



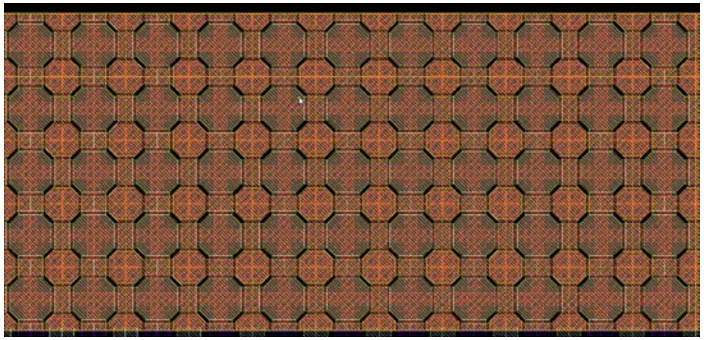
$$ENC_{TOT} = 685\ e^- + 10\ e^-/pF$$

Crosstalks

- Dynamic ground in between each input channel pin
- Coaxial cable like structure around sensitive signal path
- Power supply mesh to improve decoupling capacitor capacitance
- VDDA/VSSA /// VDDD/VSSD



Coaxial cable structure: Signal (Metal 2), Ground (Metal 1/2/3)



Power supply mesh

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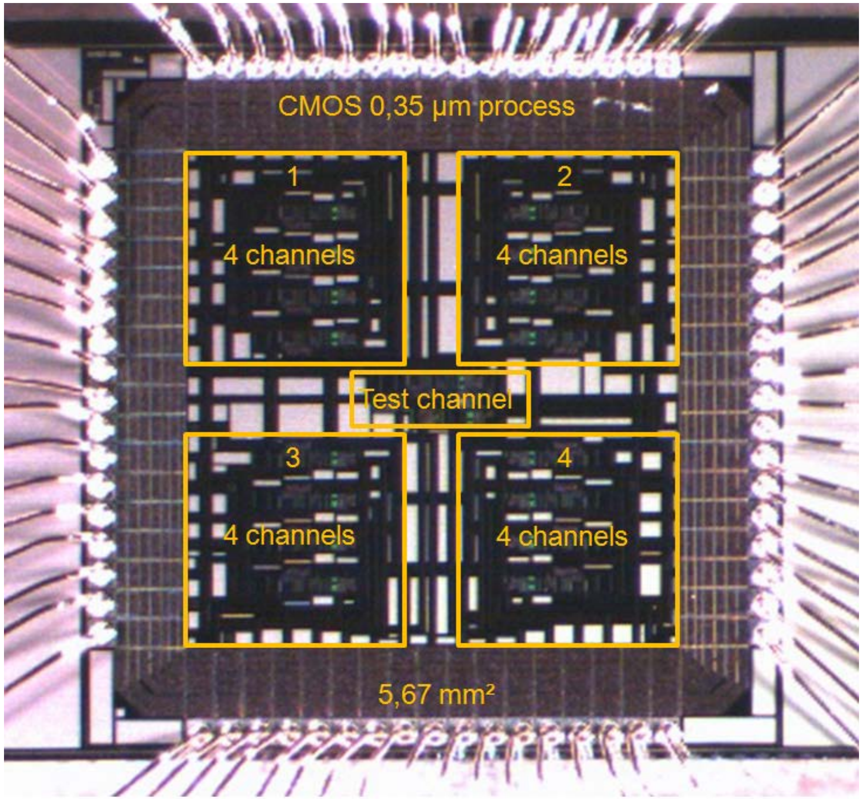
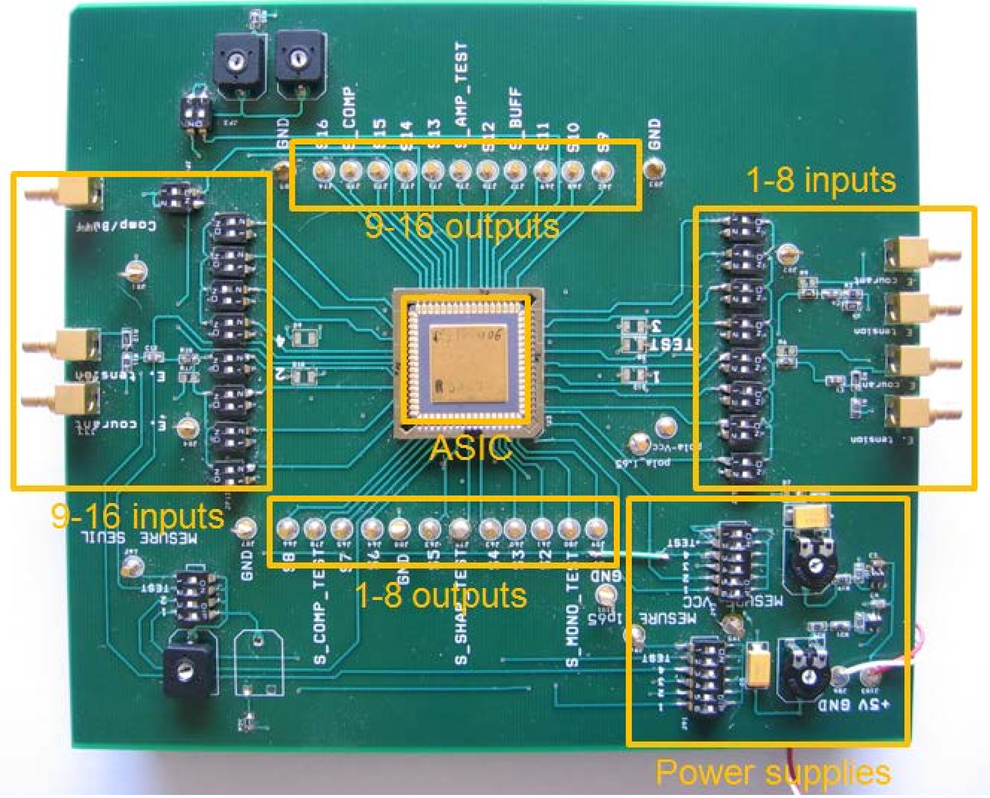
Design



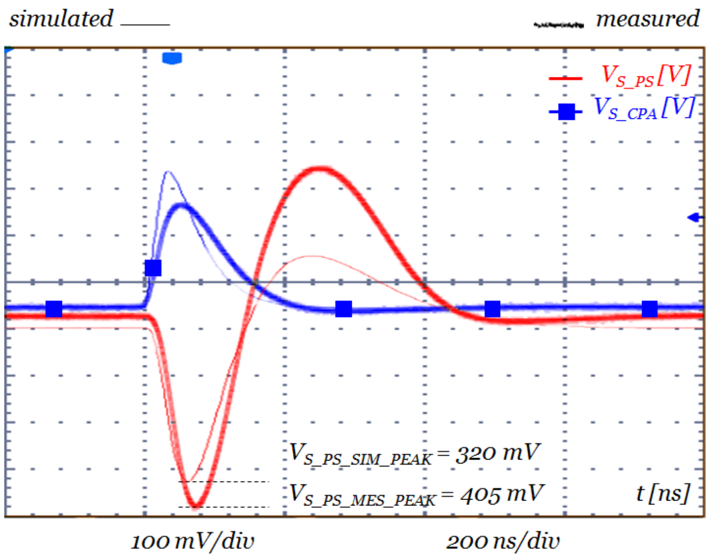
Die photograph



ASIC test board

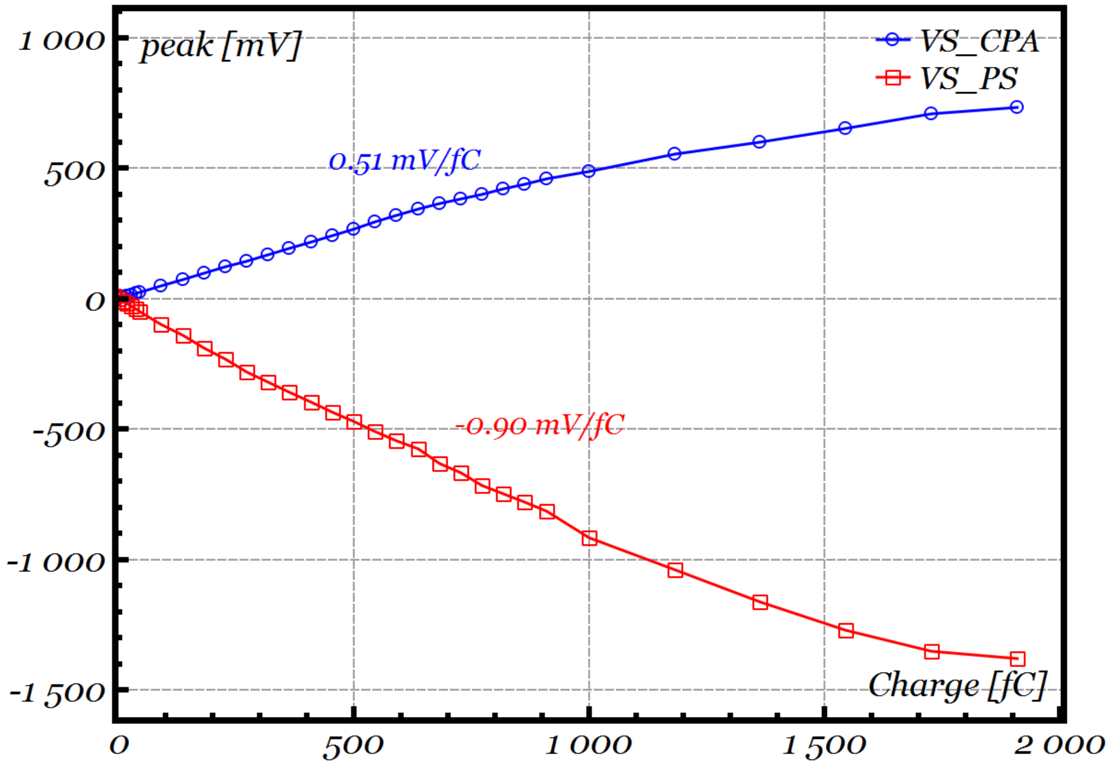
Simulations vs Measurements

C_{det} = 1 pF et
Q_{IN} = 450 fC
à 1 MHz



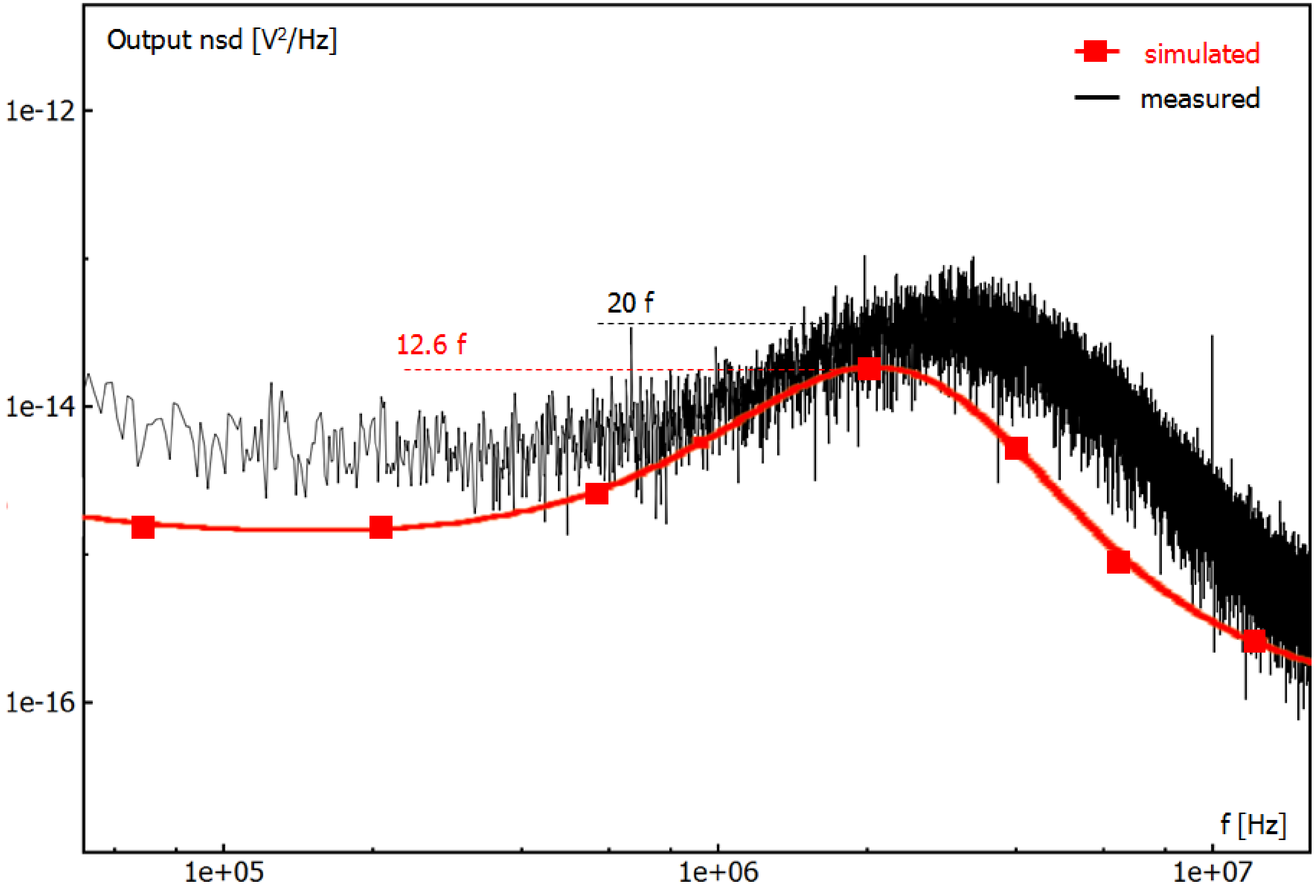
Parameter	Requirements	Simulation	Measure
Input Parasitic Capacitance	3pF	3pF	~ 3pF
Charge range	0-1pF	0-1.5pF	0-1.5pF
Peaking time	50 ns	50 ns	50 ns
Gain	1.35mV/fC	1.35mV/fC	0.92mV/fC
Counting rate	2.5 MHz	2.5 MHz	2.6 MHz
Power consumption	< 3mW	2.12mW	2.15mW
ENC noise	< 3000	754	954

System linearity



Linearity for incoming charges from 0 to 1900fC

Noise

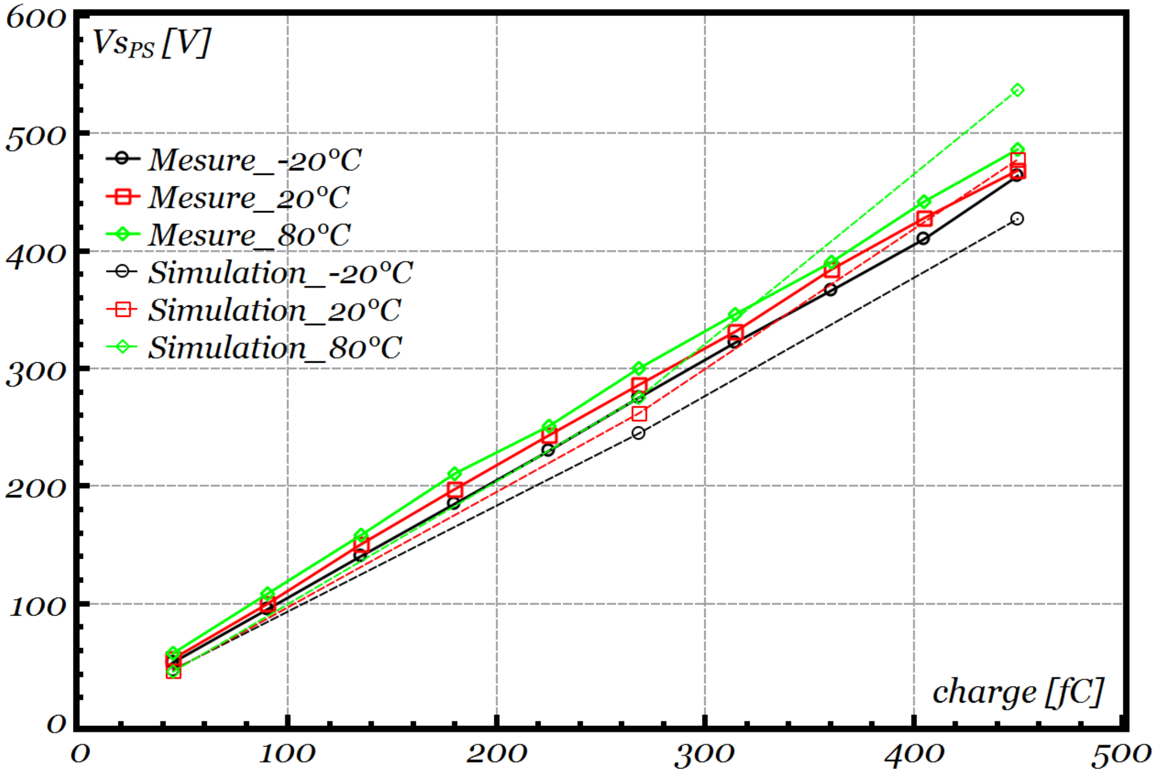


CPA + PS Noise Output Spectrum density

ENC : 20 fV²/Hz ➔ 954 e^- rms
Consumption: 2.12mW

➔ Dynamic Range = 79dB

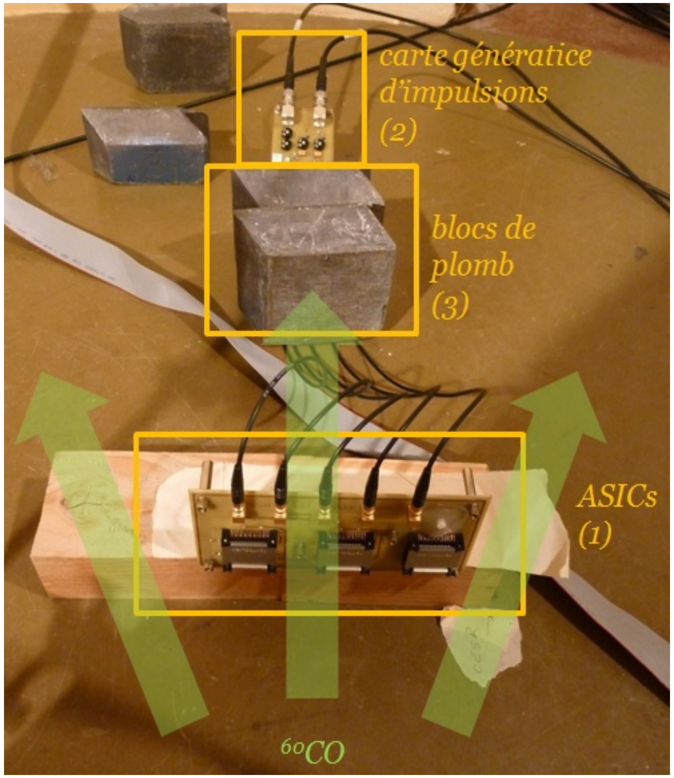
Temperature Performances



Measured (solid) and simulated (dash) CPA+PS output voltage vs input charge from 45 to 450 fC with an input parasitic capacitance of Cdet = 1pF (T from -20 to 80°C).

Radiation Tolerance

Irradiation from 0 to 360 krad (^{60}C0 at Nuclear Physics Institute of UCL (Université Catholique de Louvain))



Irradiation rate: (142 rad/h)

Radiation tolerance:

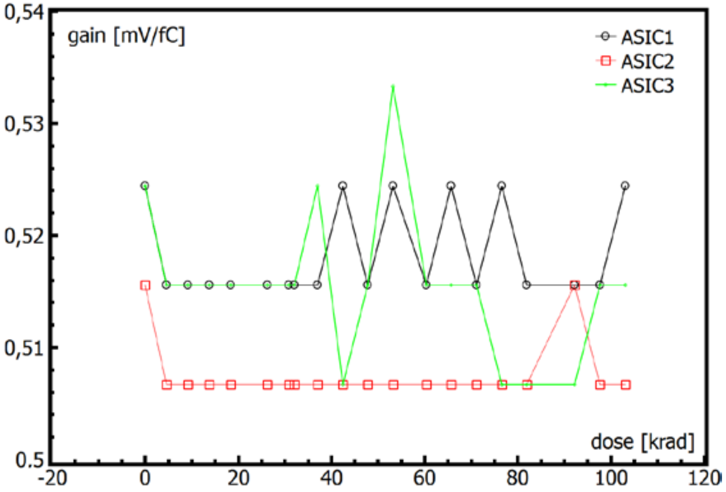
➔Gain

➔Response time

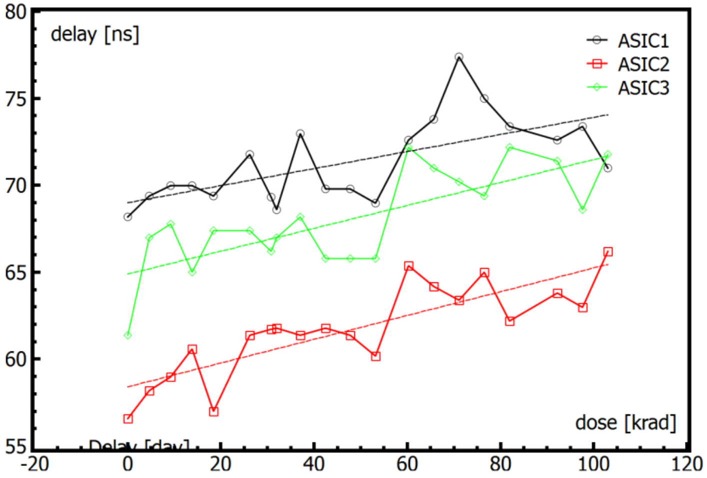
➔Pulse width

➔Consumption

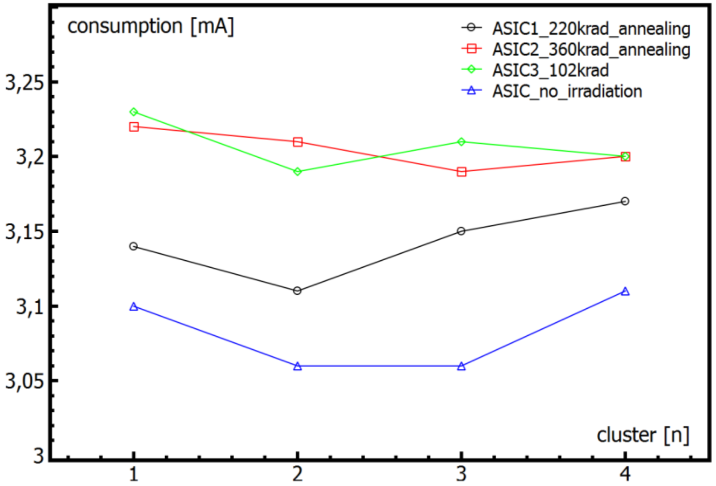
Radiation Tolerance Results



Gain of the CPA of the 3 ASICs according to the total ionizing dose. The input charge is 450fC.



Time response of the comparator of the 3 ASICs versus total ionizing dose ranging from 0 to 103krad.



Current consumption of the 4 clusters of 3 ASICs versus dose

Crosstalks

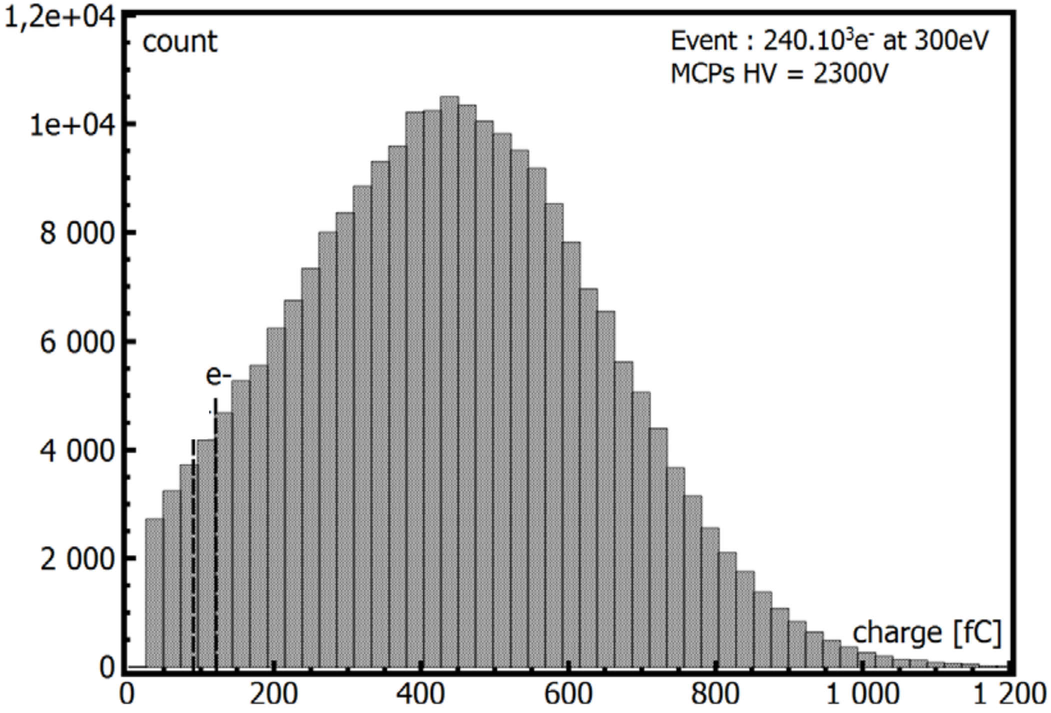


Fig. 10. MPC pulse gain distribution at 2300 V.

Minimum detected input charges:

❑ 122fC for electrons

Lost information:

❑ 6% for electrons

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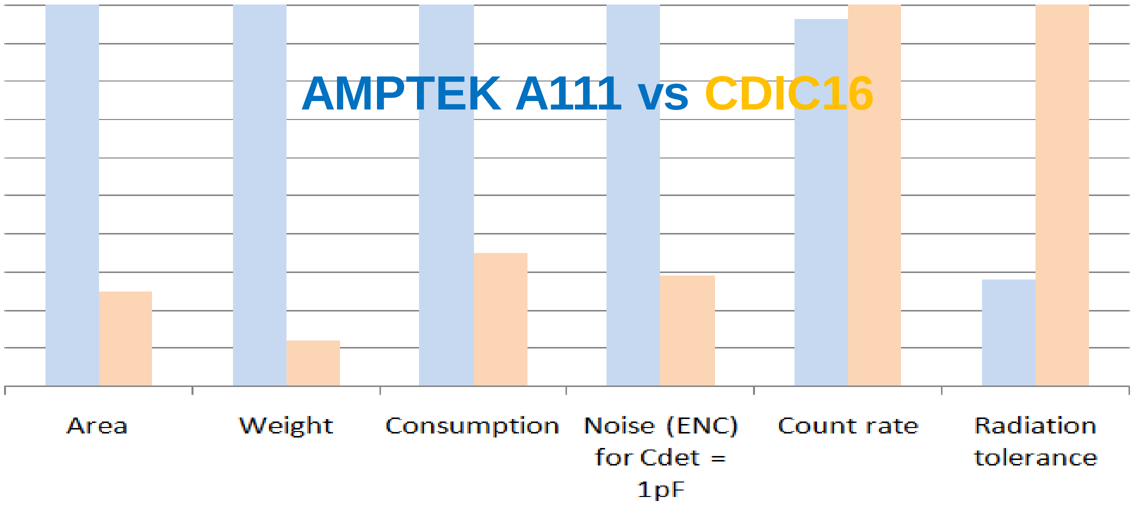
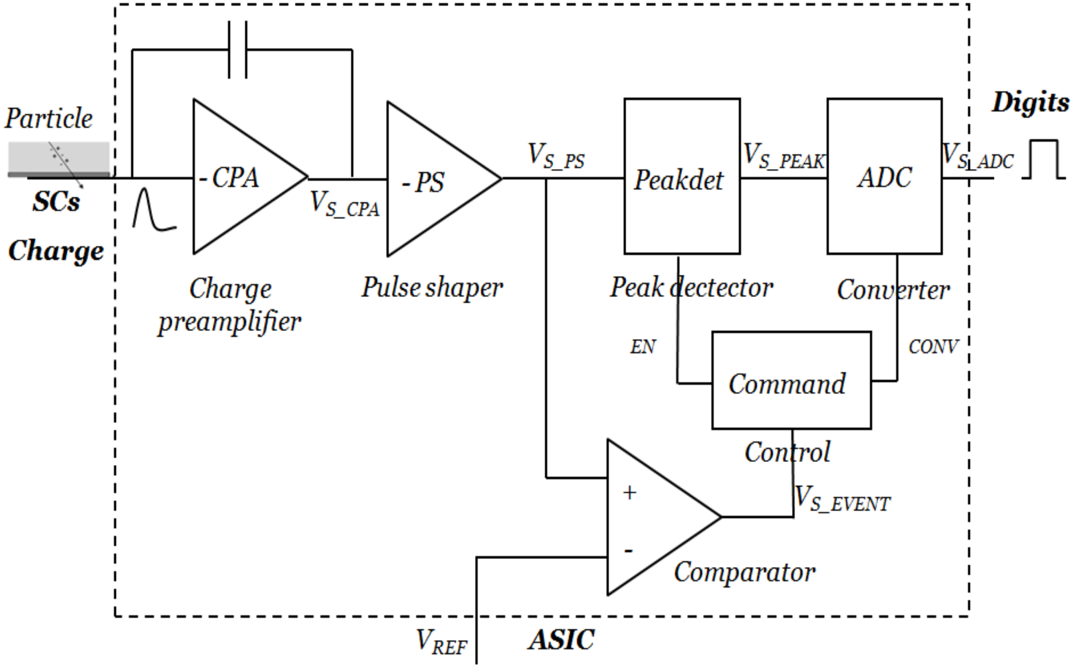
Performances

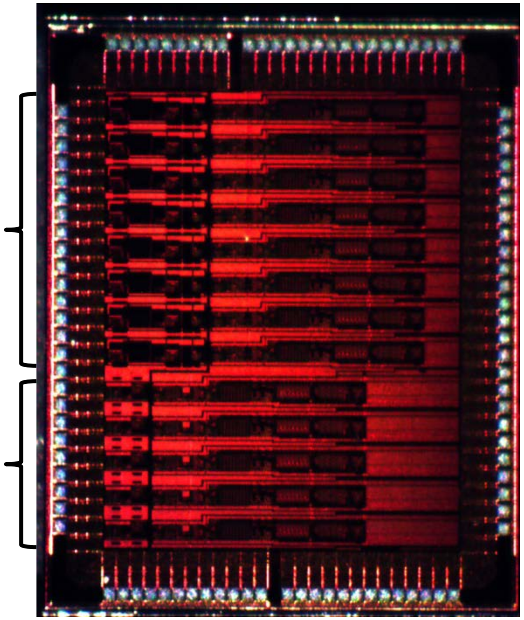
	AMPTEK A111 * 16	ASIC MCP
Area	*7317 mm^3*	1875 mm^3
Weight	2,6 g * 16 = 41,6 g	5 g
Consumption	6 mW * 16 = 96 mW	33,4 mW
Noise ENC	3312 e$^-$	954 e$^-$
Detector Max capacitor	0 – 250 pF	0 – 25 pF
Output voltage	4,7 V	3,3 V
Counting rate	2,5 MHz	2,6 MHz
Temperature accepted	- 55 °C à 85 °C	- 20 °C à 80 °C
Radiation tolerance	> 100 krad	> 360 krad



Future Work (Taranis)

- SEE tests (2013)
- 0.35µm → 0.35µm HV Isolated well (crosstalk, latchup and power supply rejection)
- Differential architecture (crosstalk)
- A CMOS Analog Front-End Chain for Si-CdZnTe Detectors (13channels + ADCs)



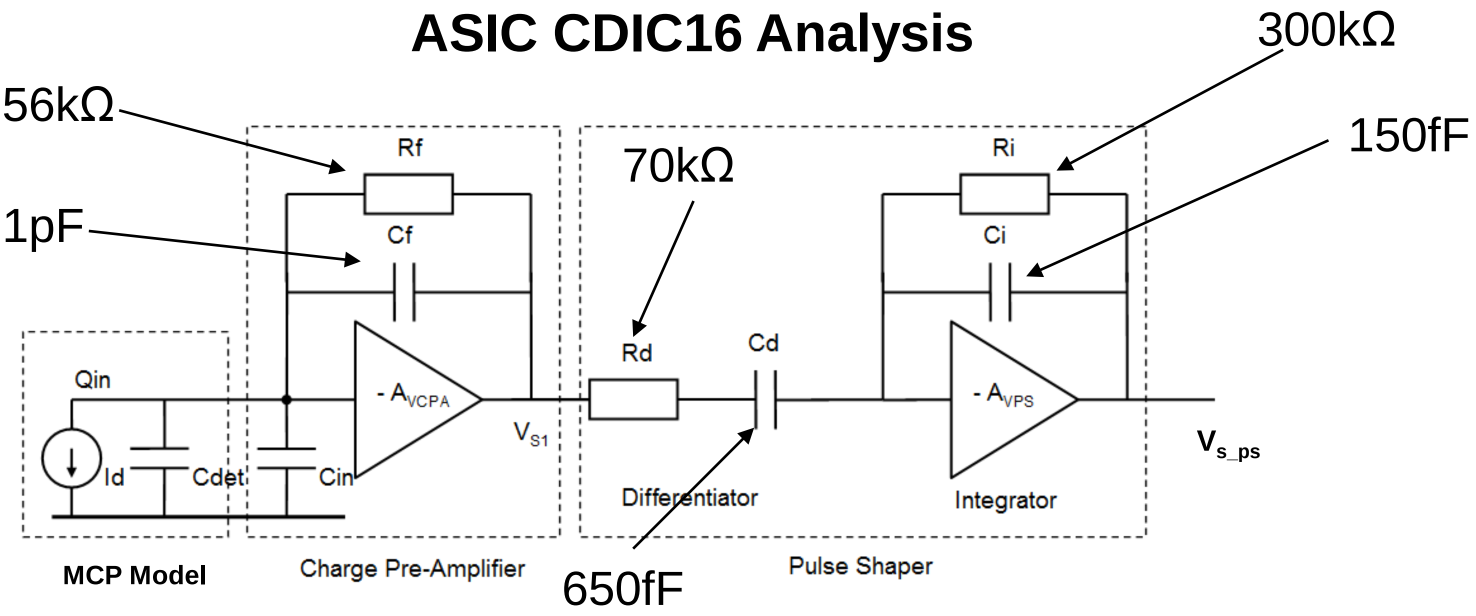


8 CdZnTe

5 Si

Questions ?

ASIC CDIC16 Analysis

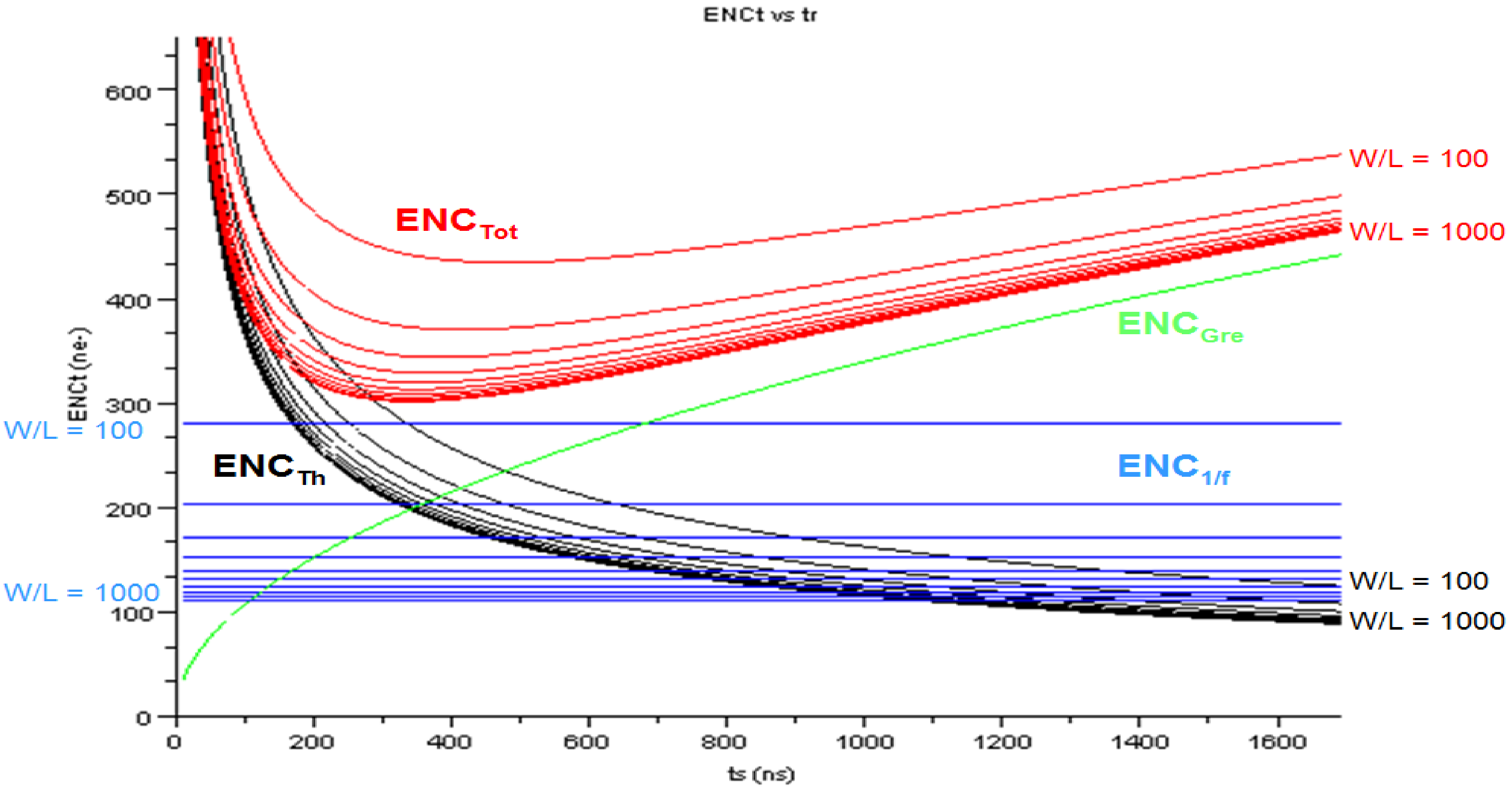


$$\frac{\Delta V_{S\_PS}}{\Delta I_d} = \left[\frac{A_1}{1+\tau_f p}\right]\left[\frac{\tau_d p}{1+\tau_d p}\right]\left[\frac{A_2}{1+\tau_i p}\right]$$

$$Gain = \frac{\Delta V_{S\_PS}}{\Delta Q}$$

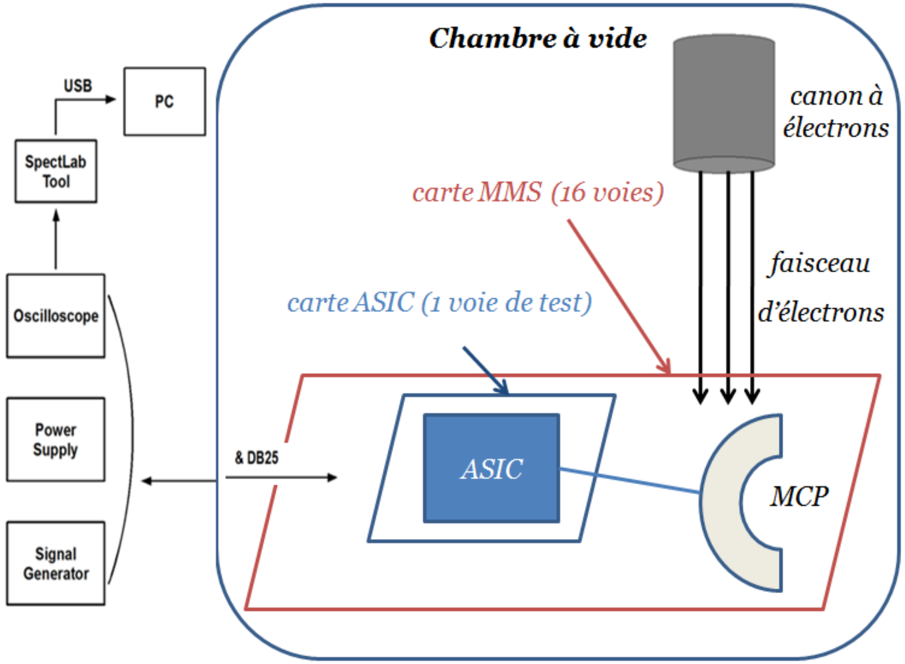
Optimization of the ENC (AMS 0.35μm)

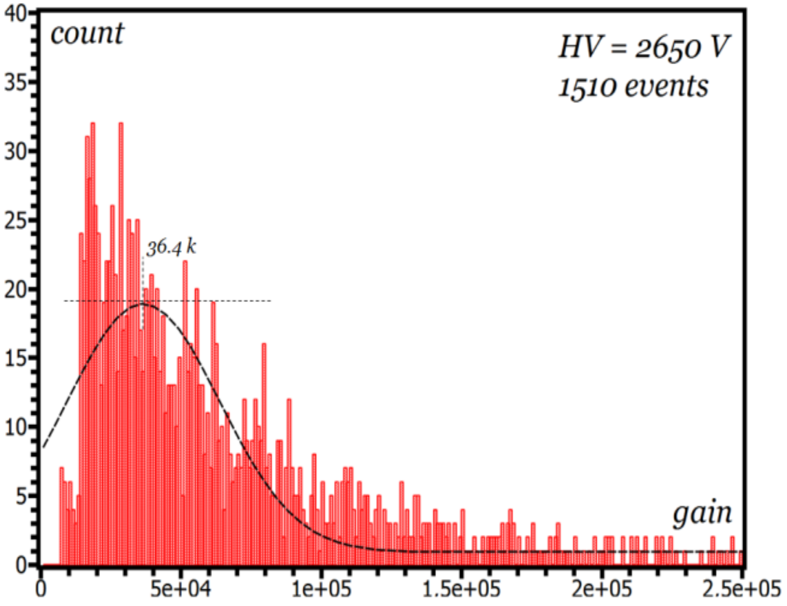
$$ENC_{Th}^2 = \frac{1}{3} kT \frac{1}{g_m} C_t^2 \frac{e^2}{q^2 \tau_s} \qquad ENC_{1/f}^2 = \frac{K_f}{C_{OX}^2 WL} C_t^2 \frac{e^2}{2q^2} \qquad ENC_{Gre}^2 = \frac{I_{tot} \tau_s}{4} \frac{e^2}{q}$$



Shaping time

Vacuum validationTest

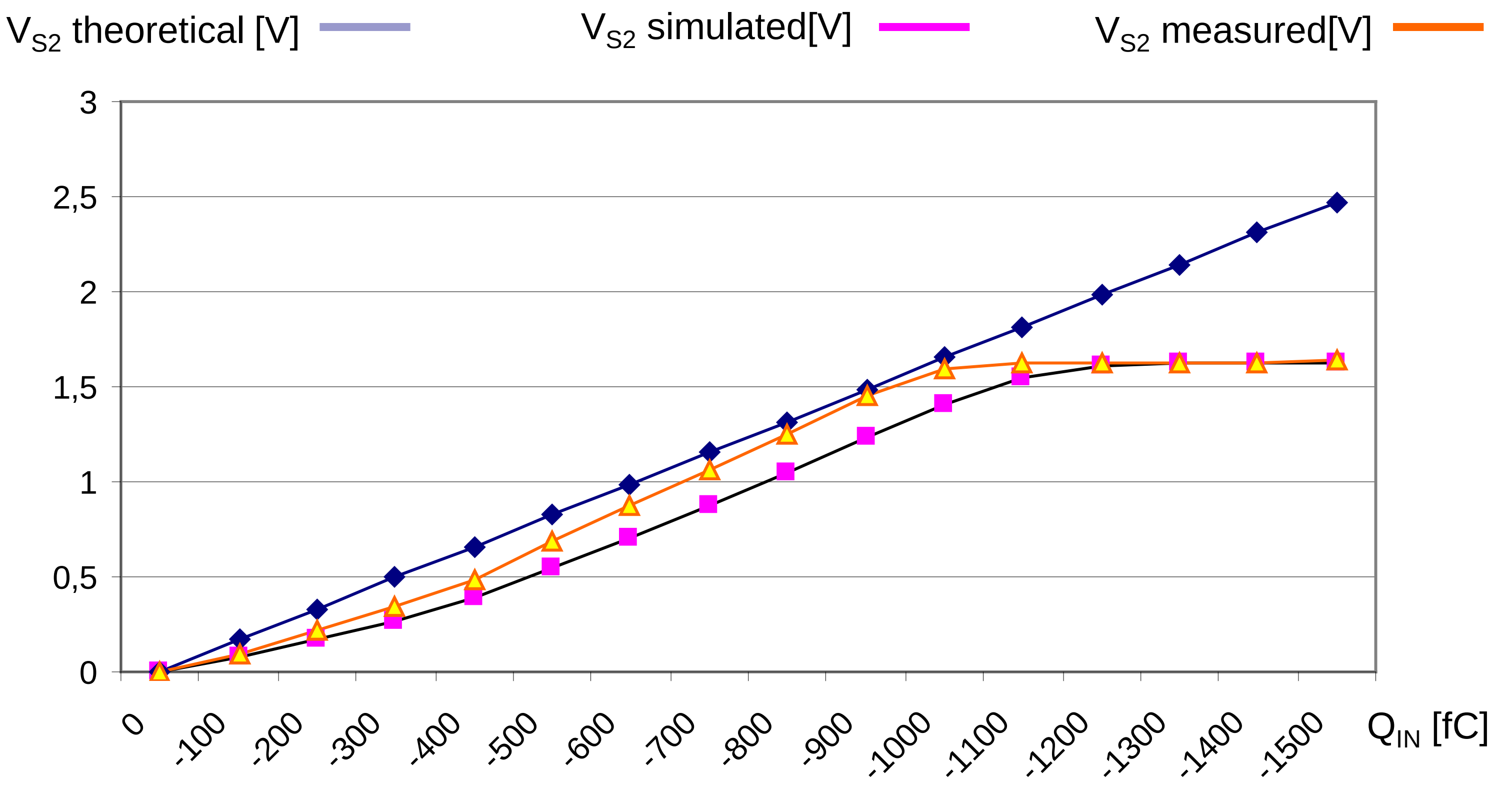




Measured MCP pulse gain distribution at 2650 V due to charges of an MCP illuminated by an electron beam.

Average gain of 36.4 k (for a 2650 V MCP bias voltage)

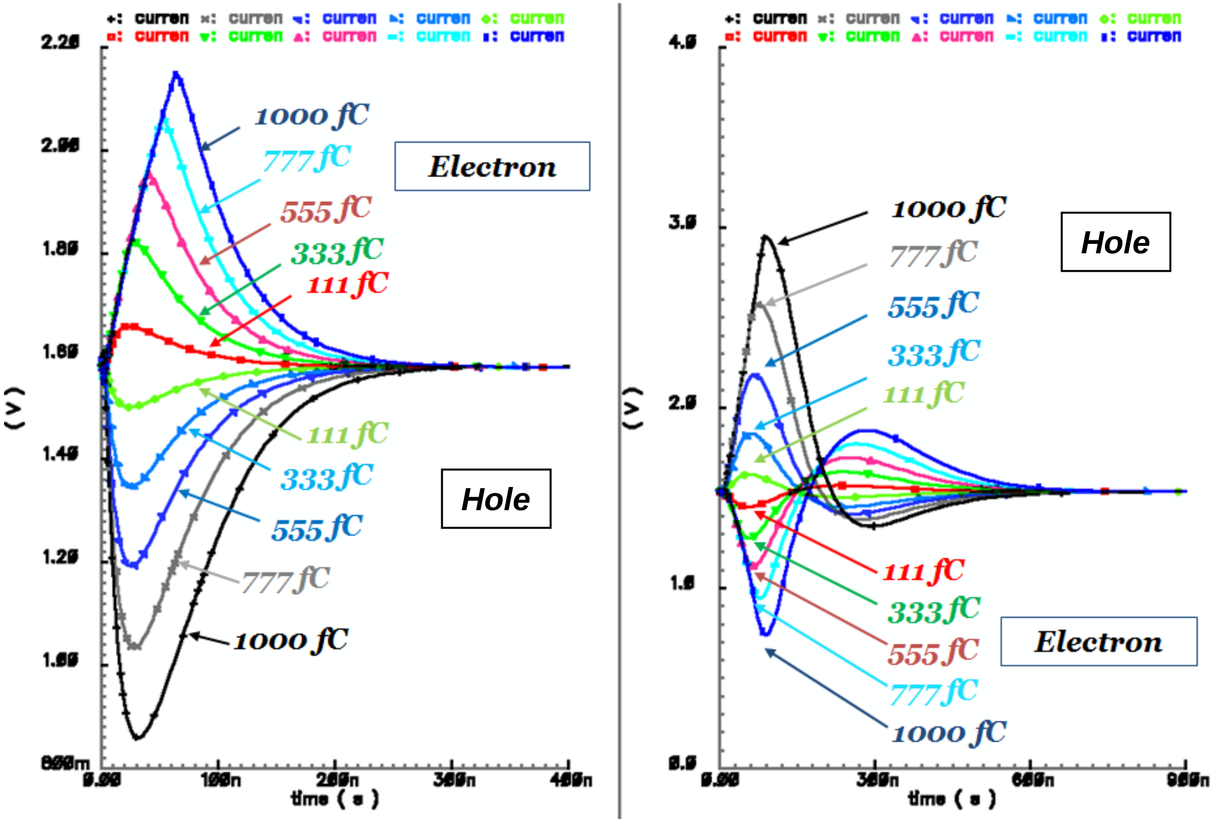
System linearity



$$Gain_{Th} = 1{,}65\ mV/fC$$

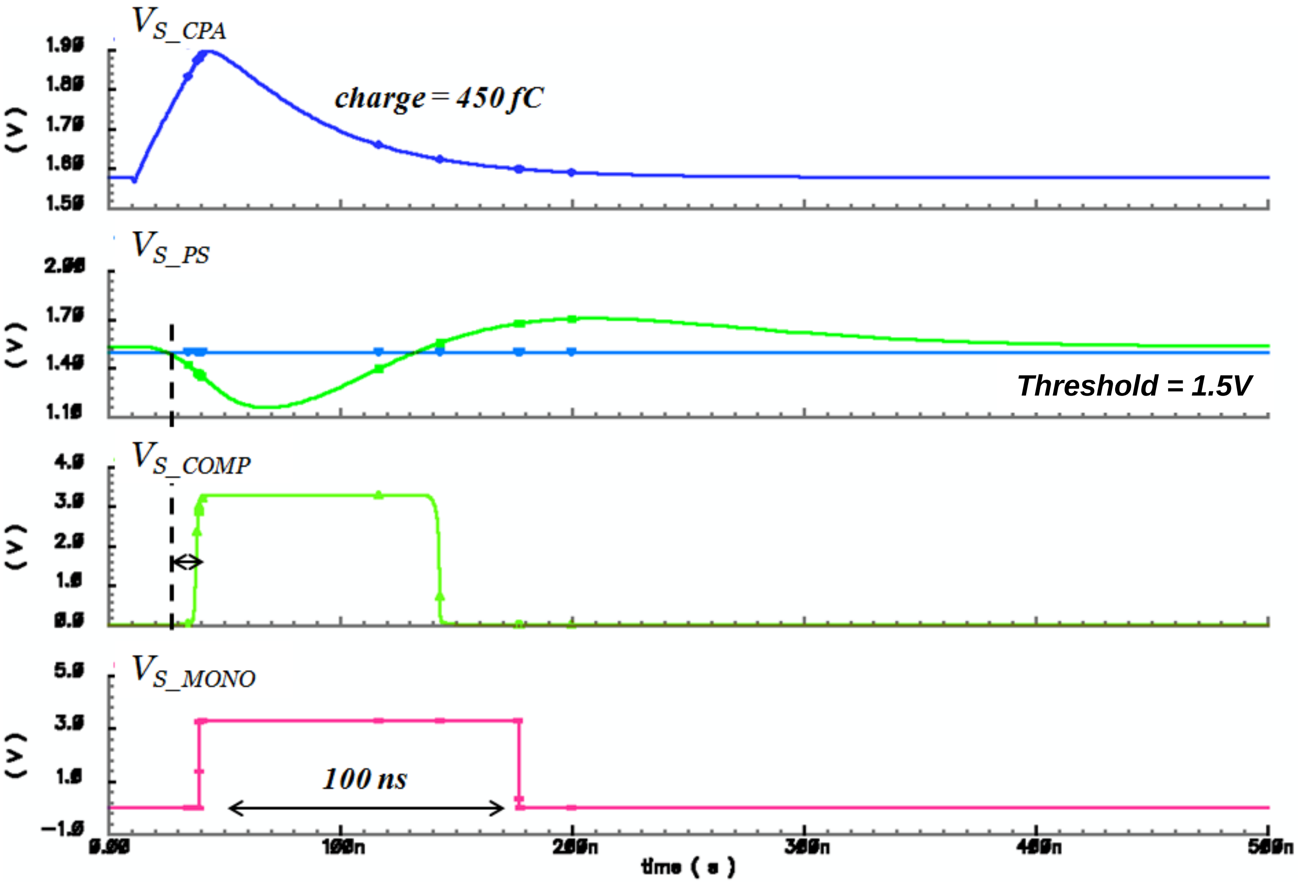
$$Gain_{Sim} = 1{,}65\ mV/fC$$

$$Gain_{Test} = 1{,}94\ mV/fC$$

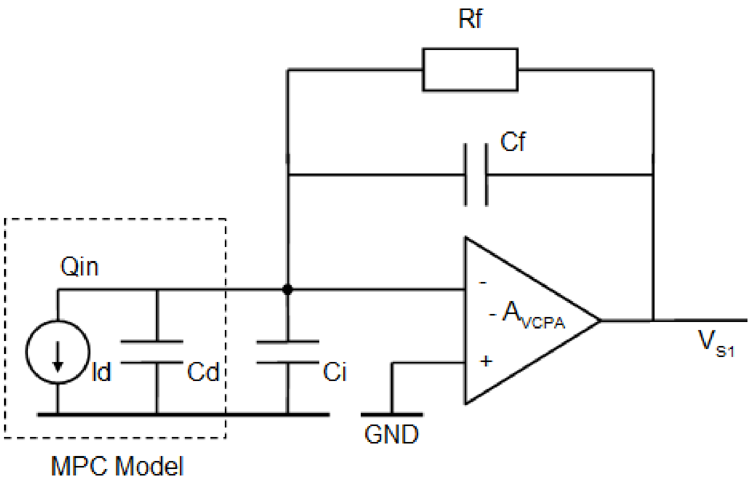


Simulated CPA (left) and PS (right) transient response

Analog-digital front end simulation

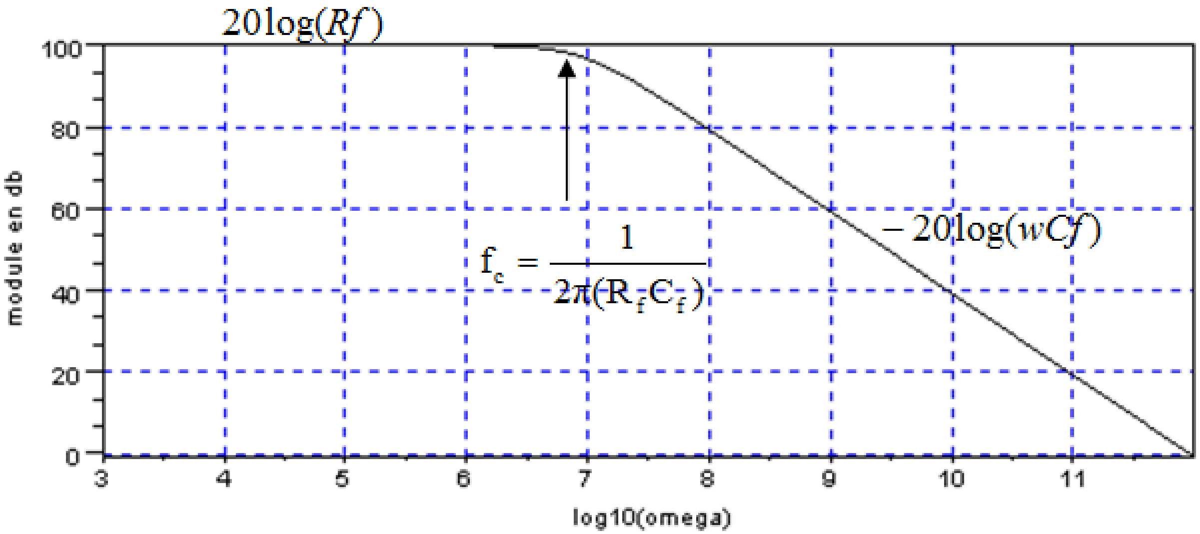


Charge Amplifier (CPA)



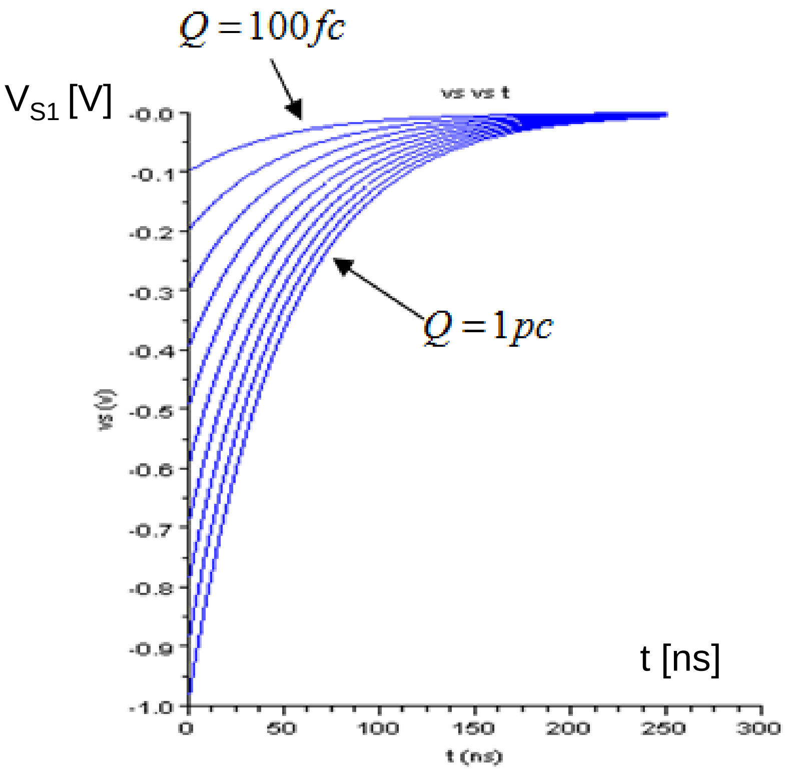
Transfer function:

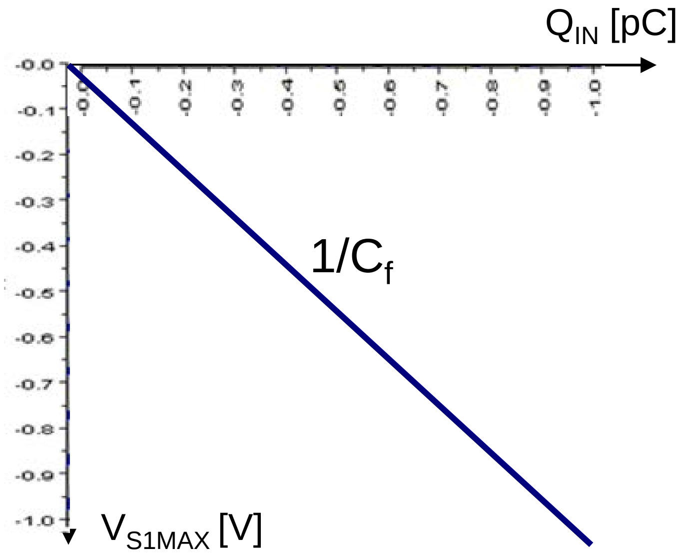
$$\frac{\Delta vo}{\Delta id} = \frac{R_f \times \left(\frac{A_{VCPA}}{A_{VCPA}+1}\right)}{1+R_f\left(C_f - \frac{(C_d+C_i)}{A_{VCPA}}\right)p} = \frac{A_1}{1+\tau_f p}$$



Charge Amplifier (CPA)

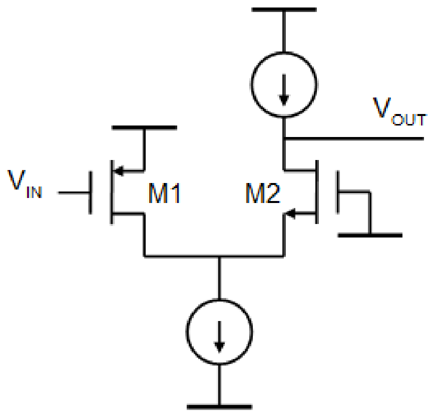
Transient response: $$V_{S1}(t) = \frac{Q}{C_f} e^{-\frac{t}{\tau_f}}$$

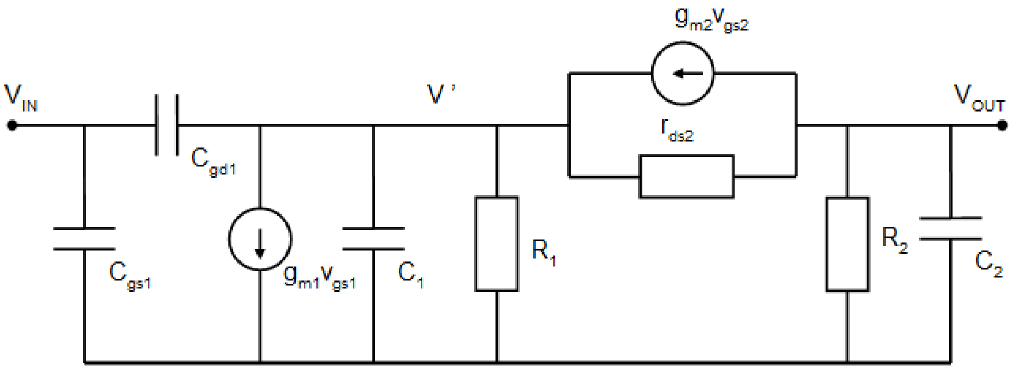




CPA analysis

Folded Cascode architecture:





$$|V_{GS}| > |V_T|$$

$$|V_{DS}| > |V_{GS} - V_T|$$

$$\frac{v_{OUT}}{v_{IN}}(p) = \frac{-g_{m1}R_2(1+g_{m2}r_{ds2})(1-(C_{gd1}/g_{m1})p)}{(1+R_2C_2p)\left[1+g_{m2}r_{ds2}+\left[(1+R_1(C_1+C_{gd1})p)(1+\frac{rds_2}{R_2}(1+R_2C_2p))\right]/R_1\right]}$$

Noise analysis

Noise Power Spectrum Density:

- **Thermal noise**

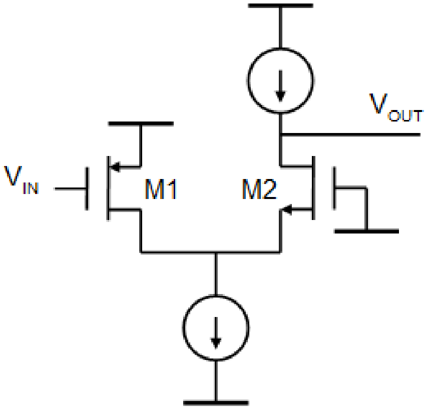
$$v_n^2(f) = 4kTR$$

- **1/f Flicker noise**

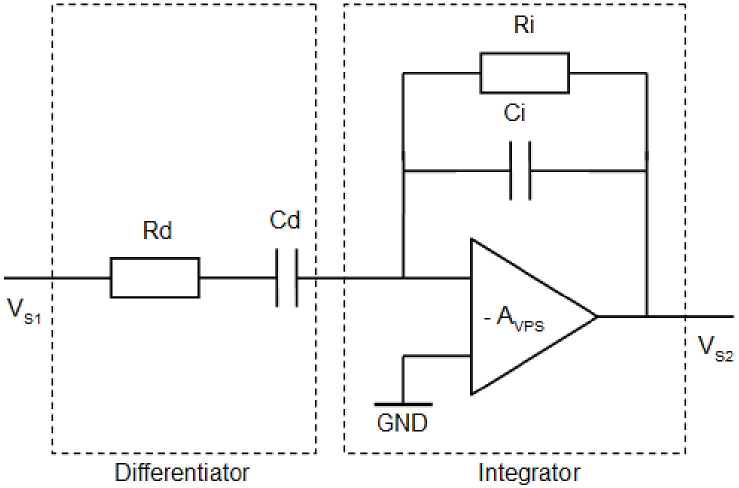
$$v_n^2(f) = \frac{k_v}{f}$$

- **Shot noise** (MCP)

$$i_n^2(f) = 2qI_D$$



Pulse Shaper

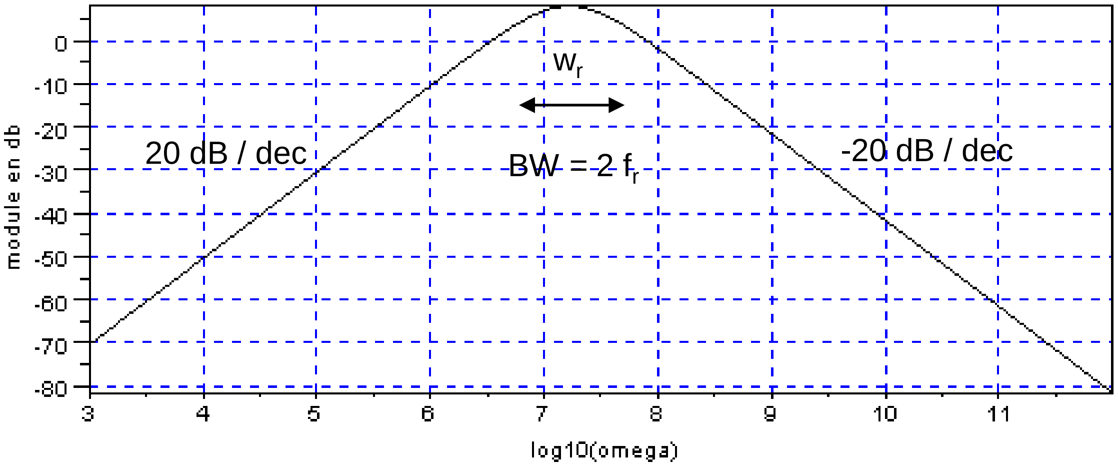


Ransfer Function:

$$\frac{\Delta V_{S2}}{\Delta V_{S1}}(p) = \frac{-R_iC_d\left(\frac{A_{VPS}}{A_{VPS}+1}\right)p}{1+(R_dC_d+R_iC_i)p+R_dR_iC_dC_ip^2}$$

τ_S : Shaping time = $\tau_d = \tau_i$

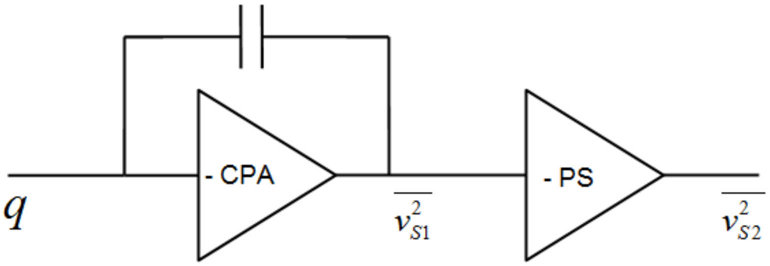
$$\mathrm{H}_2(\mathrm{p}) = \frac{\mathrm{A}_2\tau_s\mathrm{p}}{(1+\tau_s\mathrm{p})^2}$$

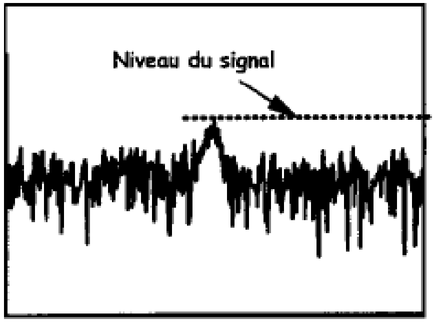


$$f_{CL} = \frac{1}{2\pi R_dC_d} = f_{CH} = \frac{1}{2\pi R_iC_i}$$

$$w_r = \frac{1}{\tau_S} \qquad Q = \frac{1}{2} \qquad z = 1$$

Bruit du pré-amplificateur et du shaper





La valeur quadratique moyenne en sortie du shaper vaut:

$$\overline{v^2_{S2}} = \int_0^\infty \left|v_{S1}(j2\pi f)\right|^2 \left|H_{PS}(j2\pi f)\right|^2 df$$

ENC : Equivalent Noise Charge

$$\boxed{ENC = \sqrt{\frac{V^2_{S2\ rms}}{\left|V_{S2}\right|^2_{PIC}}}\ \text{due à un électron}}$$

Bruit du pré-amplificateur et du shaper

ENC produite par le bruit thermique :

$$ENC_{Th}^{2} = \frac{1}{3} kT \frac{1}{g_m} C_t^2 \frac{e^2}{q^2 \tau_s}$$

ENC produite par le bruit en 1/f :

$$ENC_{1/f}^{2} = \frac{K_f}{C_{OX}^2 WL} C_t^2 \frac{e^2}{2q^2}$$

ENC produite par le bruit de grenaille :

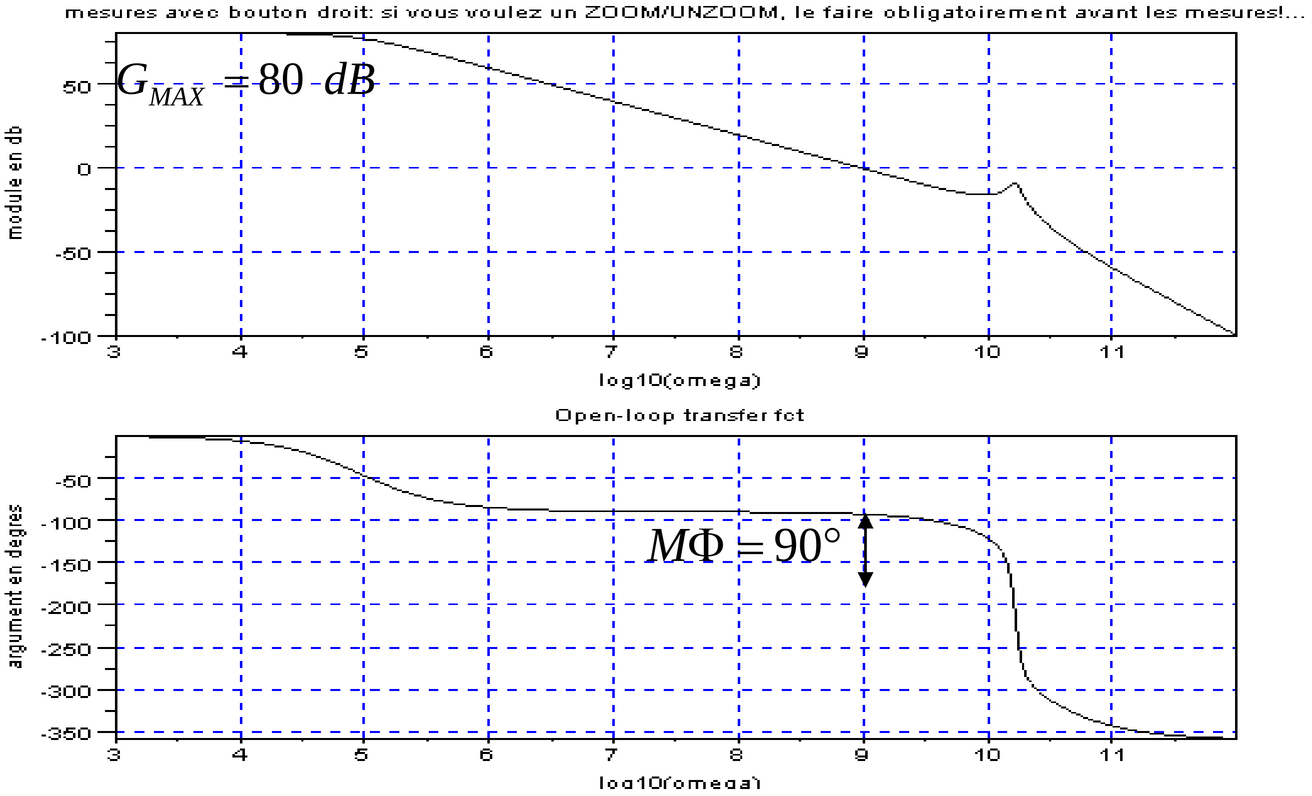
$$ENC_{Gre}^{2} = \frac{I_{tot} \tau_s}{4} \frac{e^2}{q}$$

ENC total :

$$ENC_{TOT} = \sqrt{\frac{\overline{v_{S2\ (Thermique)}^2} + \overline{v_{S2\ (1/f)}^2} + \overline{v_{S2\ (Grenaille)}^2}}{V_{S2MAX}^2}} = \sqrt{ENC_{Th}^2 + ENC_{1/f}^2 + ENC_{Gre}^2}$$

Stability Analysis

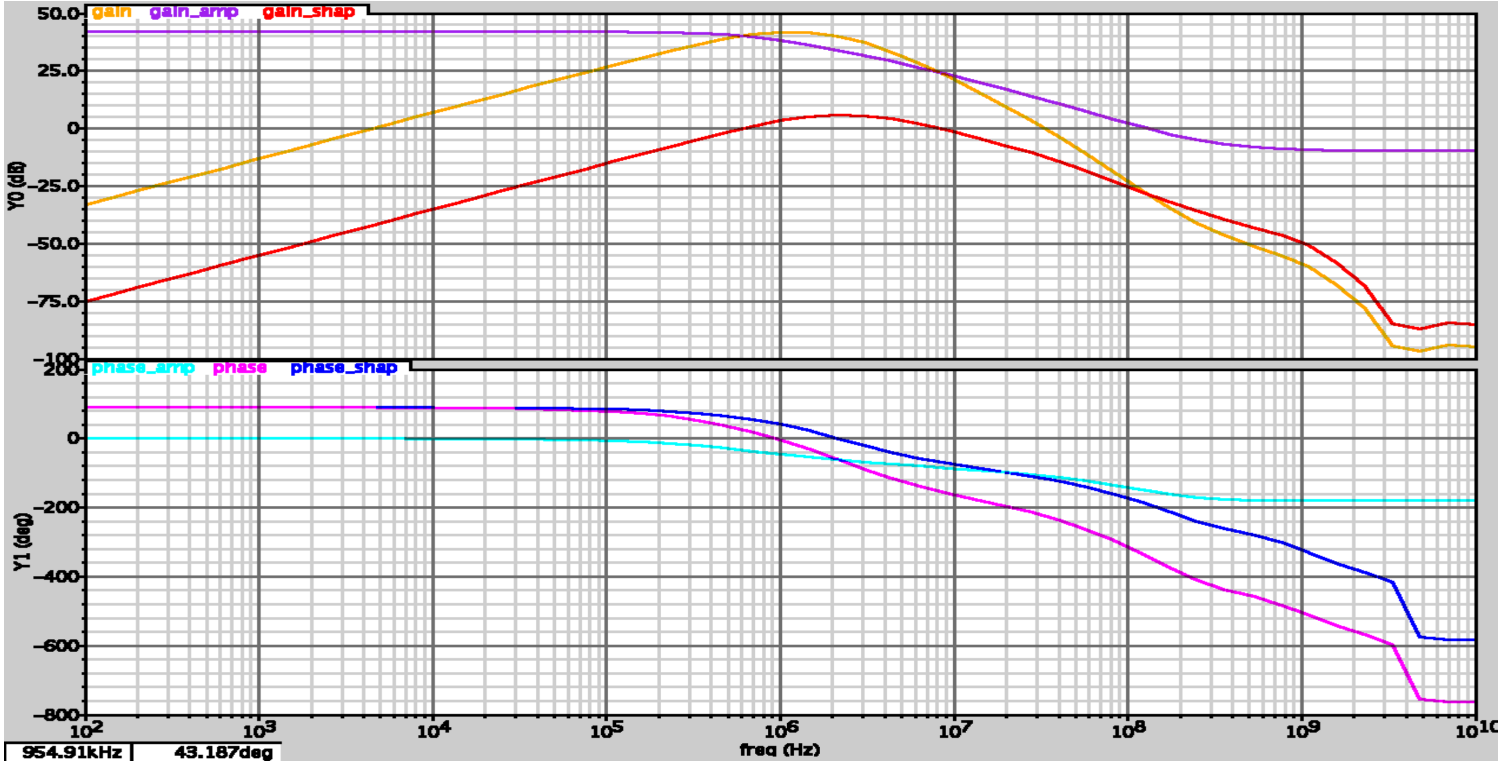
Open Loop Bode diagram:



Gain Bandwidth Product : 6,4 MHz

Performances de la partie analogique

Diagramme de Bode



Paramètres	Valeurs
Gain de plateau	41,6 dB
Fréquence de coupure basse des asymptotes	0,458 MHz
Fréquence de coupure haute des asymptotes	2,56 MHz
Fréquence de résonance	1,5 MHz

Le discriminateur

Comparateur

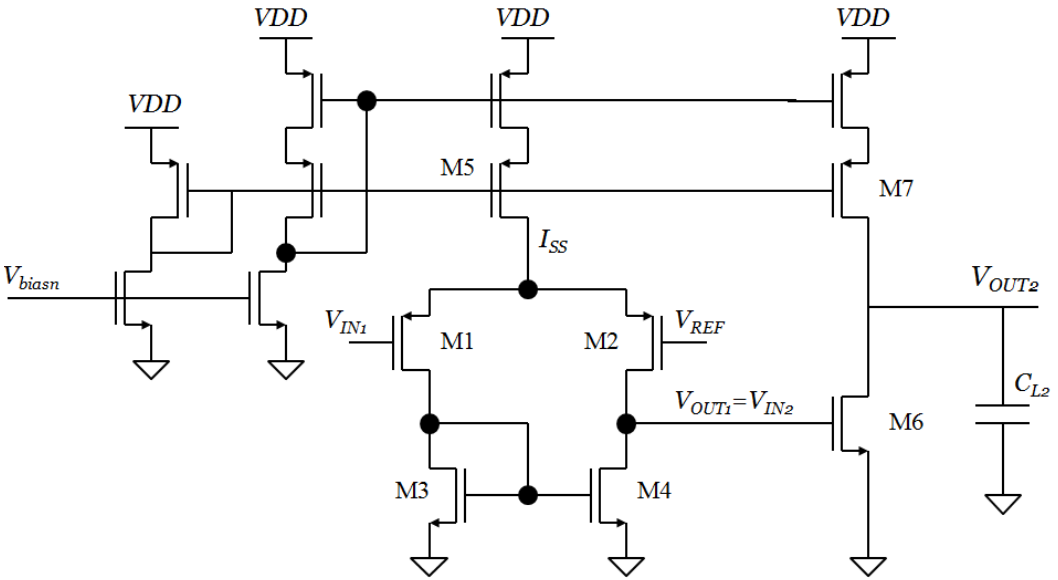


figure IV-28 : Comparateur composé d'une paire différentielle de type P et d'une source commune de type N et polarisé par un miroir de courant de type wind swing.

Monostable

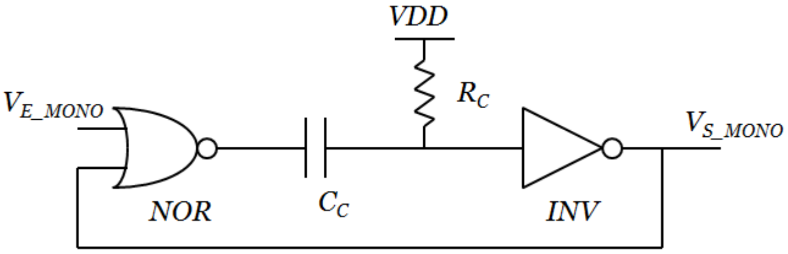
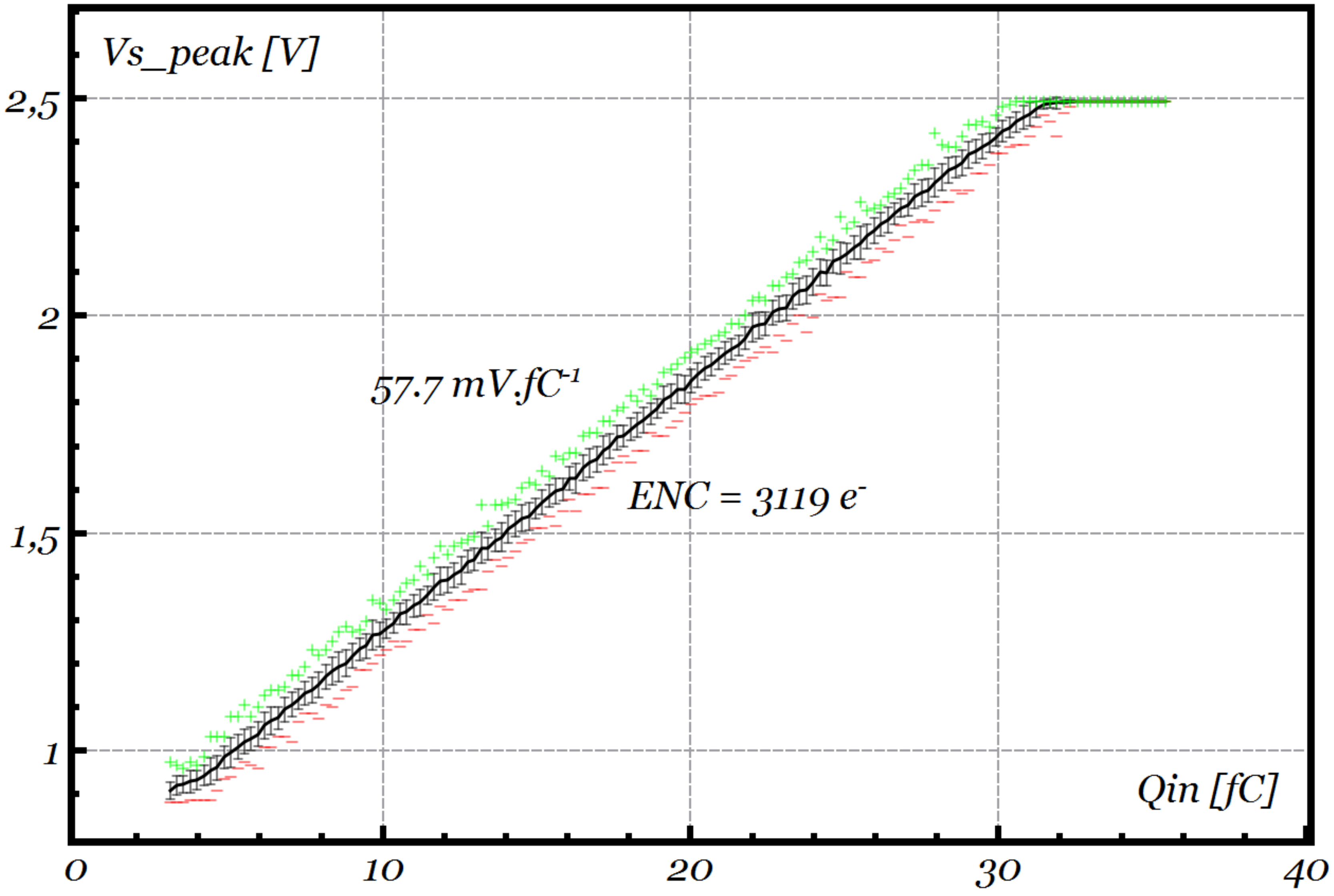
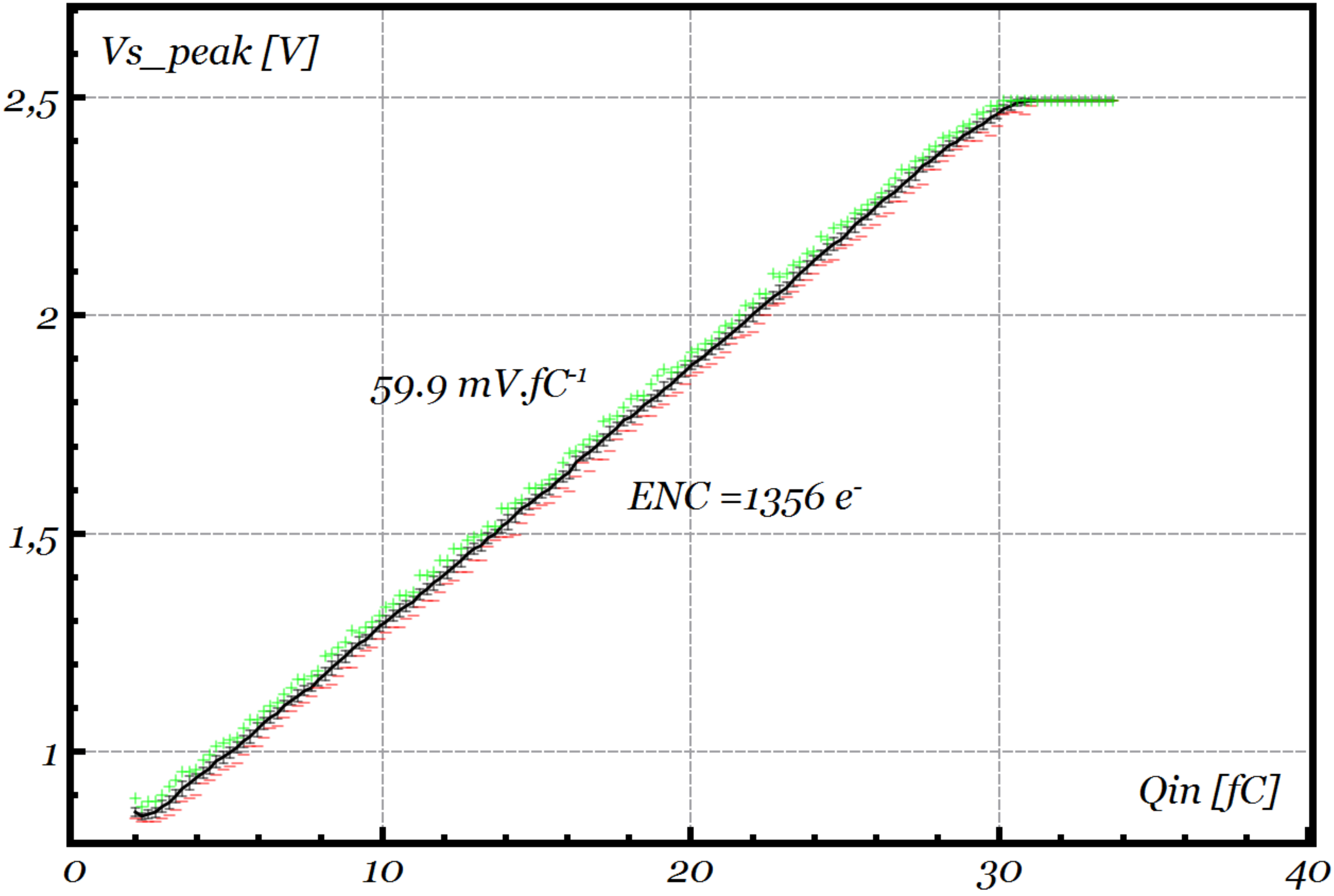


figure IV-30 : Structure du monostable qui est réalisée par une porte NOR, un inverseur et une constante de temps RC.

Si A chain gain and linearity

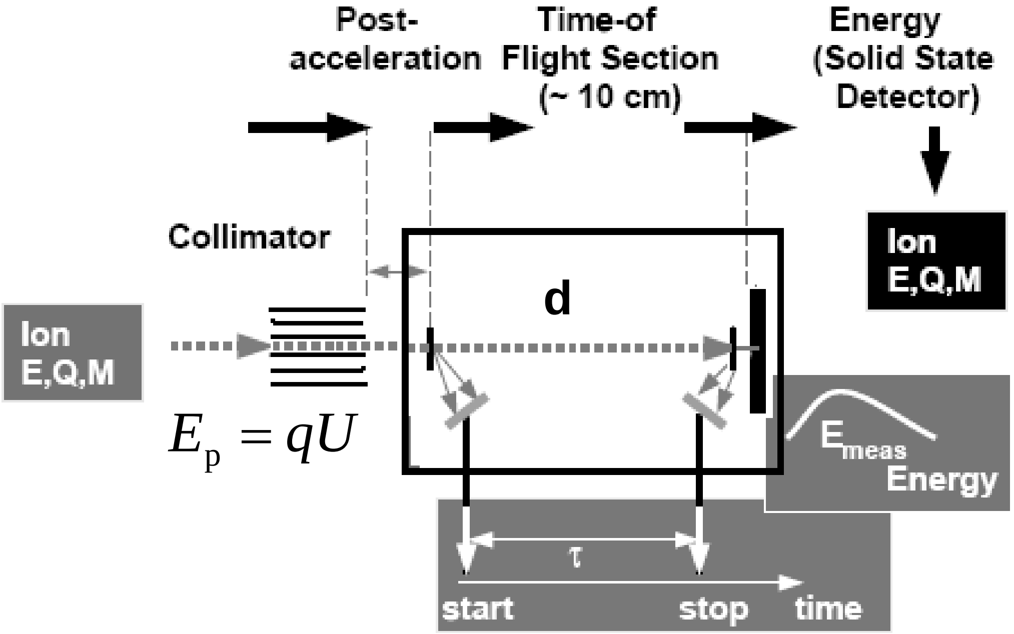


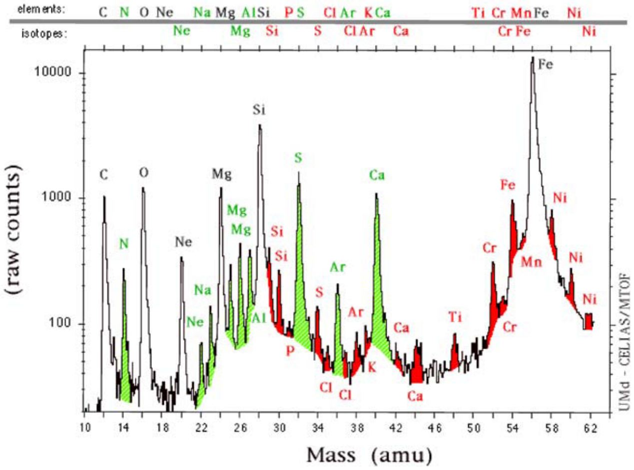
Si B chain gain and linearity



Mass Spectrometer: time-of-flight analyzer

- Isotopic Composition of Elements of an environment
- Principle :





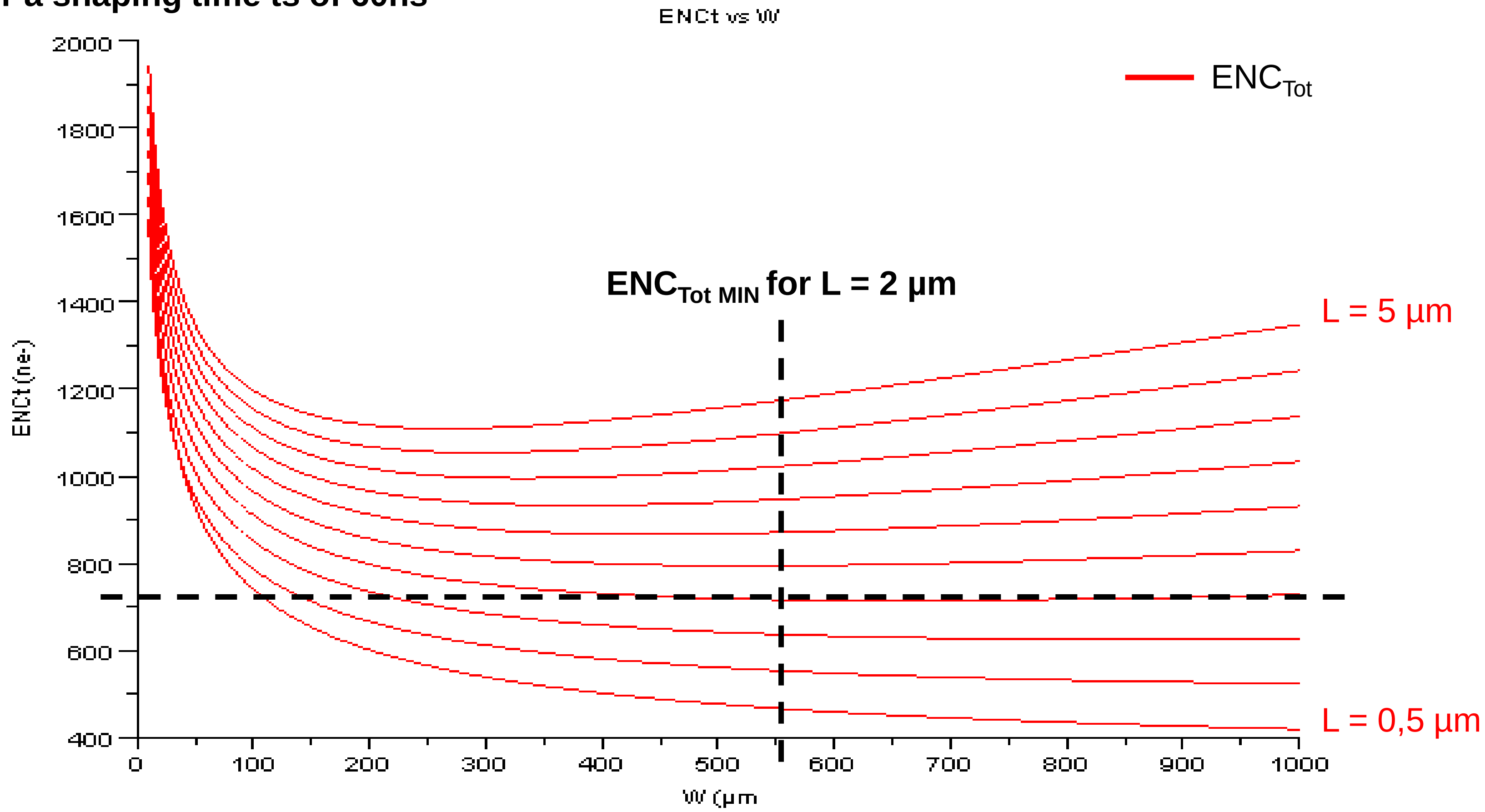
Calculation of the mass *m* :

$$\boxed{m = 2E_{meas}\frac{\tau^2}{d^2}}$$

Optimisation of the ENC (AMS 0.35µm)

$$ENC_{Th}^2 = \frac{1}{3} kT \frac{1}{g_m} C_t^2 \frac{e^2}{q^2 \tau_s} \qquad ENC_{1/f}^2 = \frac{K_f}{C_{OX}^2 WL} C_t^2 \frac{e^2}{2q^2} \qquad ENC_{Gre}^2 = \frac{I_{tot} \tau_s}{4} \frac{e^2}{q}$$

For a shaping time ts of 60ns



$ENC_{Tot\ MIN}$ for L = 2 µm

L = 5 µm

L = 0,5 µm

M1 = 556 / 2 µm

Performances

	AMPTEK A111	**[Noulis, T., Circuits, Devices & Systems, IET, 2008]**	**[Kaplon, J., Nuclear Science, IEEE , 2005]**	**CDIC16**
Process (µm)	-	AMS CMOS 0.35 µm	CMOS 0.25 µm	AMS CMOS 0.35 µm
Power supplies (V)	4.7	3.3	2.5	3.3
Intégrateur	-	2	3	1
Consumption (mW)	6	0.165 (CPA)	1.5	1.73
Noise ENC (e^-) pour C_{in} = 5pF	3312	321	< 1500	954
Detector max capacitor (pF)	0 – 250	0 – 10	0 – 25	0 – 25
Peaking Time (ns)	-	1000	22	55
Silicon area (µm^2)	-	4212	84000	77000
Count rate (MHz)	2.5	0.8	-	2.6
Radiation tolerance	> 100 krad (C060)	-	10 Mrad (X-ray)	> 360 krad (C060)