cnrs IN2P3 Les deux infinis

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Omega

ÉCOLE POLYTECHNIQUE UNIVERSITÉ PARIS-SACLAY

FE for time measurements

N. Seguin-Moreau on behalf of OMEGA

Organization for Micro-Electronics desiGn and Applications

INTRODUCTION

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

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

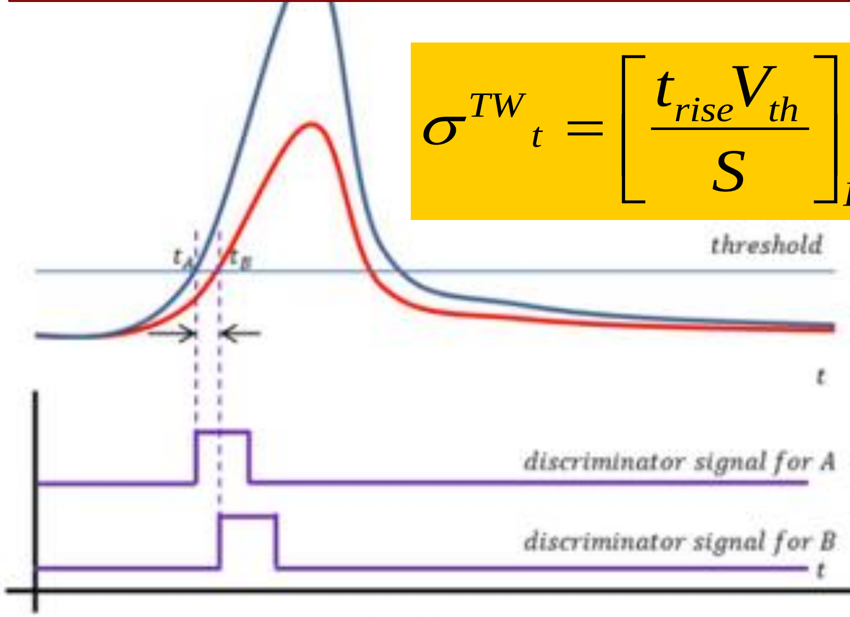
- **CMS High Granularity CALorimeter**: (Si pin diodes)
  - Dynamic range EM showers: few fC up to ~10 pC (2500-5000 mips)
  - Calorimetry => Precision /linearity < 1%
  - Fast timing ability (50ps) for > 10 mips desirable
  - Peaking time 15-20 ns (minimize noise, minimise Out of Time pileup)
  - Power on detector < ~10 mW/channel all included   (except power loss in cables/converters and power dissipated by sensors after irradiation).

- **ATLAS High Granularity Timing Detector** (LGAD or Si Pin diodes)
  - Time performance < 50 ps : To reject Time Pile up events => better particle identification
  - Dynamic range: up to few Mips or 200Mips (depending on Preshower)

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

Time walk and Time jitter

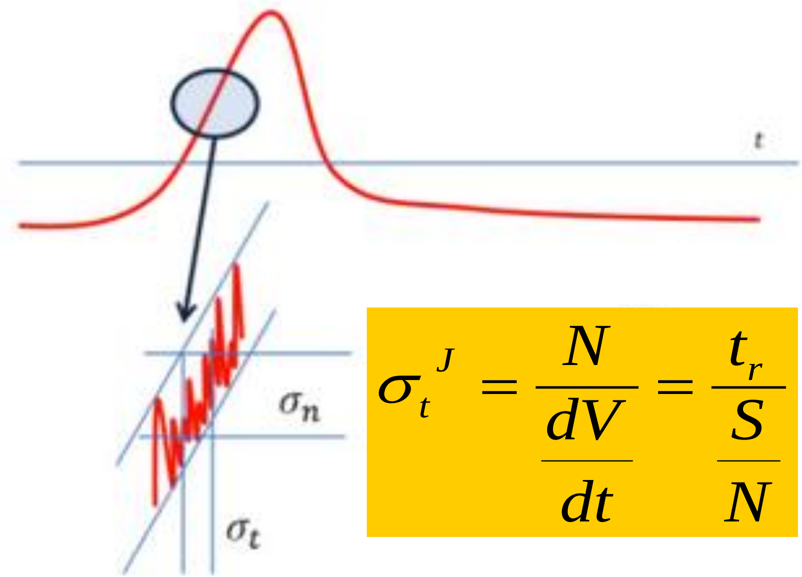
Time walk: the voltage value Vo is reached at different time for signal of different amplitudes



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

Time walk effect

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



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

Jitter effect

Due to the physics of signal formation

Mostly due to electronic noise

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

+(Landau Shape)^2

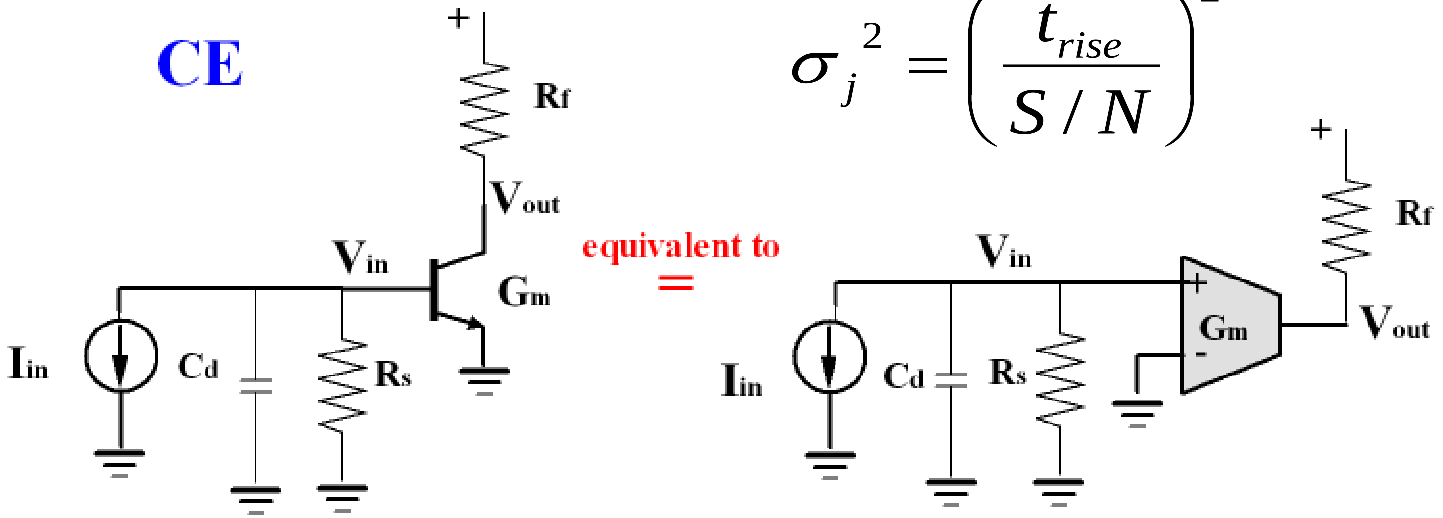
Jitter

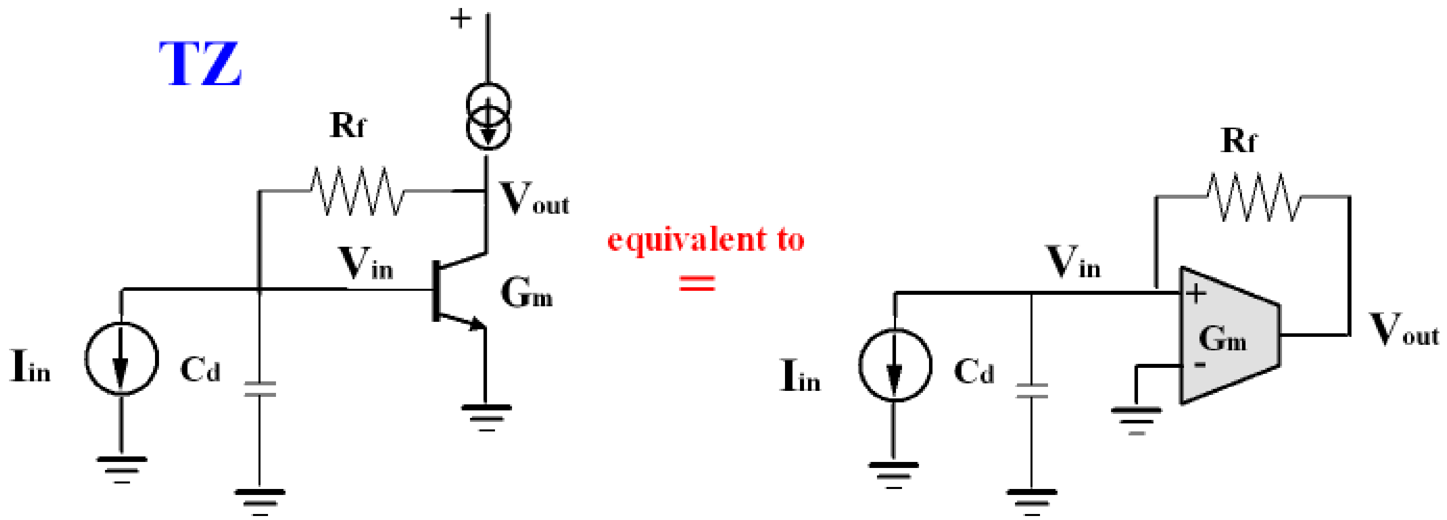
Time Walk

TDC

HF CONFIGURATIONS: CE and TZ

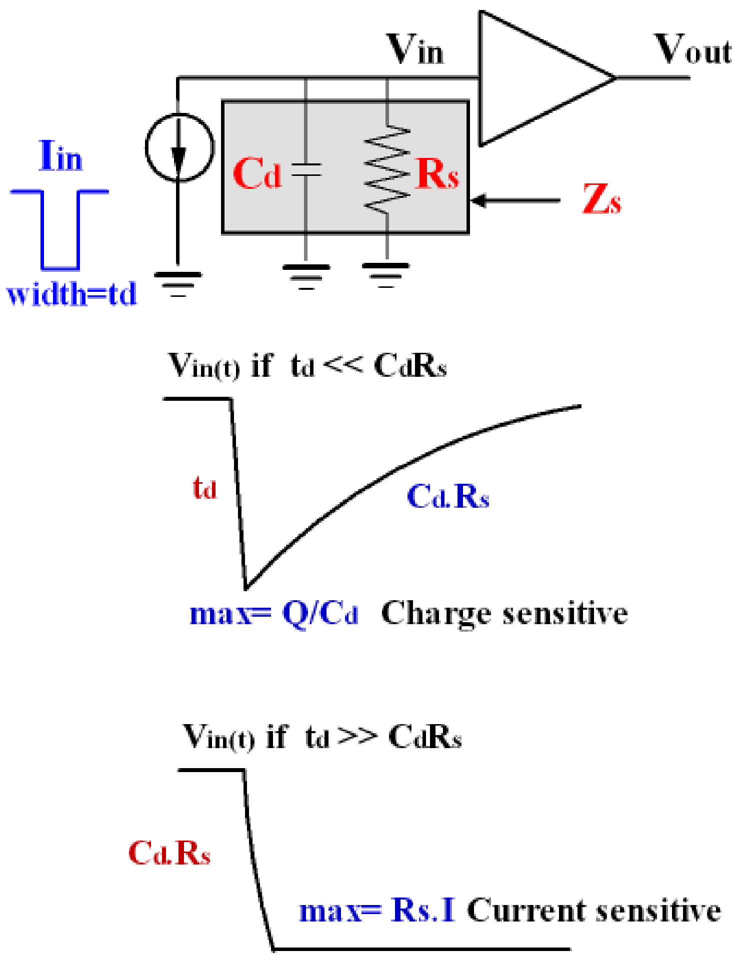
$$\sigma_j^{\ 2} = \left(\frac{t_{rise}}{S/N} \right)^2$$

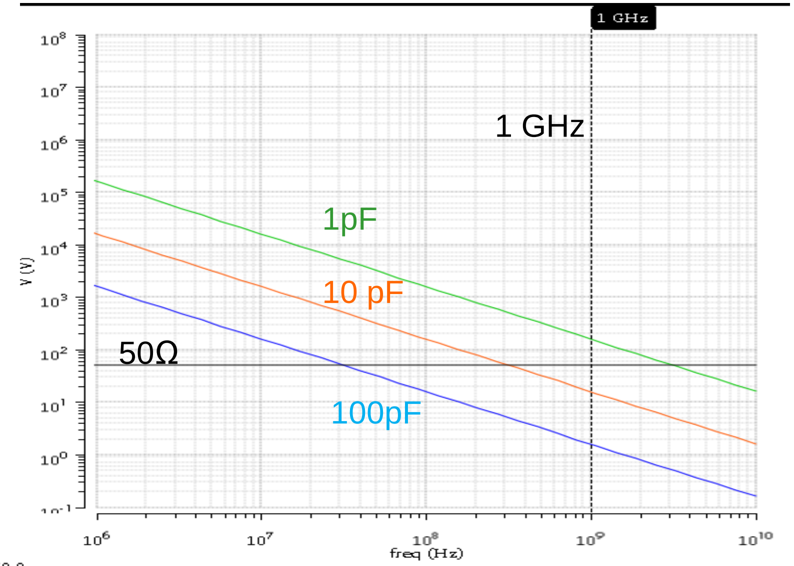


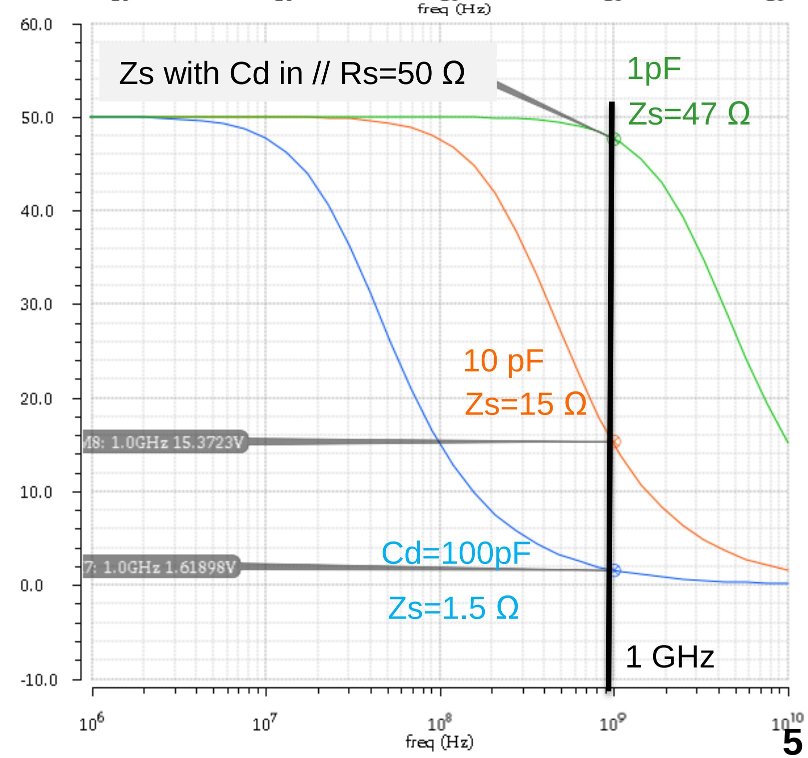


Vin @1 GHz

- 1 GHz, Cd=few tenths of pF, width of the input signal <1ns
- Cd>10 pF, Zs@1GHz dominated by Cd
- Rise time: tr= td when td<<CdRs and tr=CdRs when td>>CdRs

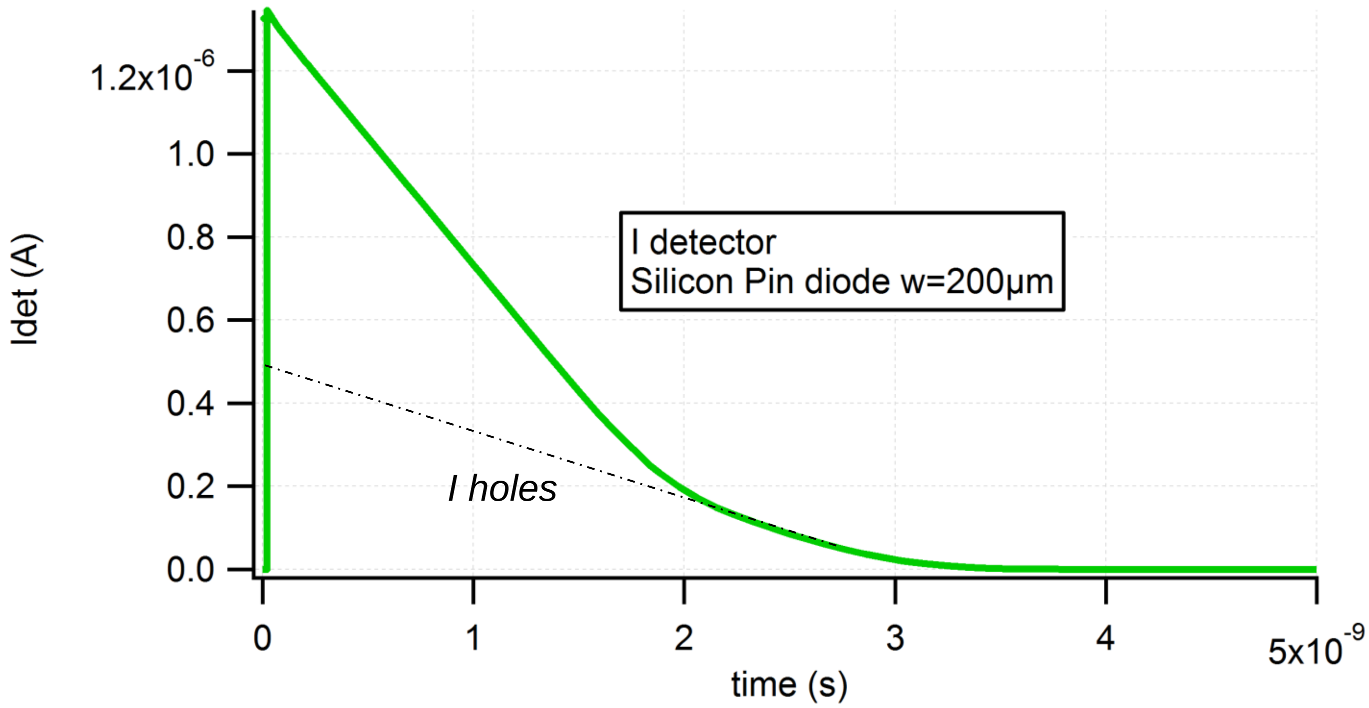




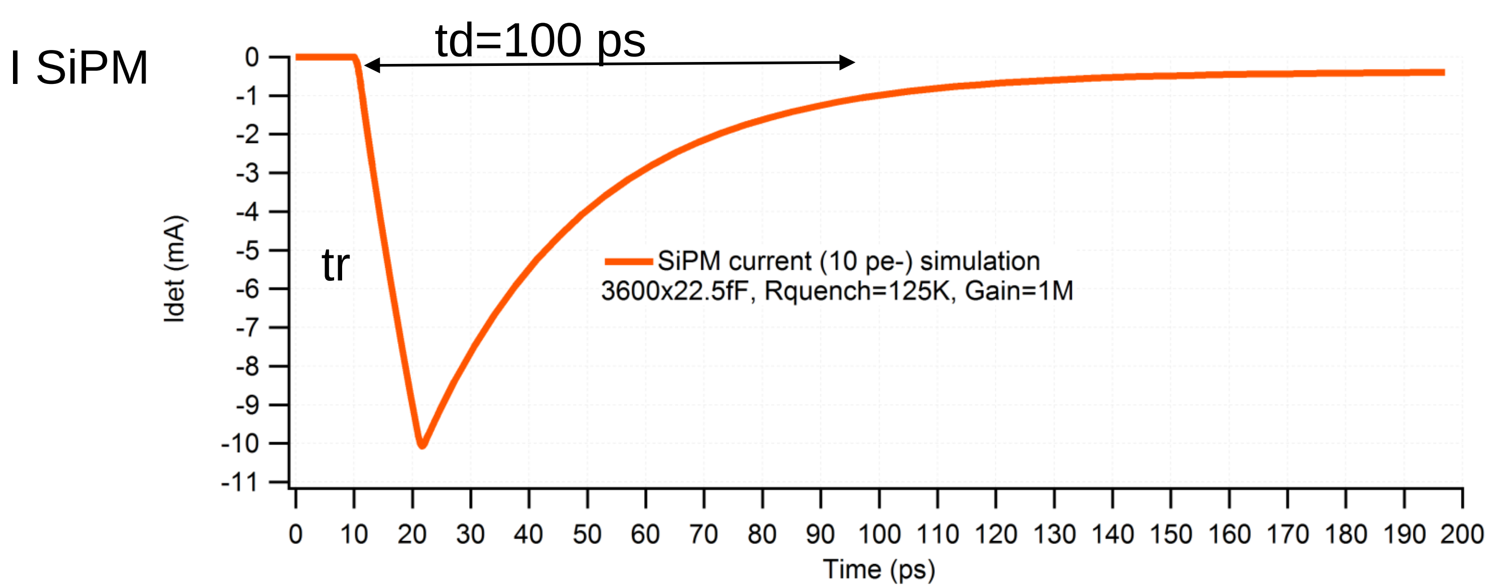


Detector signal: Si Pin diode

- Simulation of a Si Pin diode detector: w =200µm
- tr is very short but the drift time is quite « long »: td= 3 ns



- Simulation of a SiPM detector (10pe-)
  - 3600x22.5fF (80 pF), Gain=1M, Rquench=125K, Cquench=5fF, CL=10pF
- tr is very short (10 ps), td very short (100ps),
- Cd=80pF, Rin=50Ω => td<< RinCd =>Preamp rise time must be minimized (Fast preamp in Petiroc: tr_amplifier 10-90% =300ps)



CE and TZ : Vout (= S) at High Frequency and Cd>10pF

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

Cd>10 pF, Zs@1GHz dominated by Cd

- **CE** using an OTA with gain G_m
  - $V_{OUT} = -G_m (Z_F // Z_L) V_{IN}$

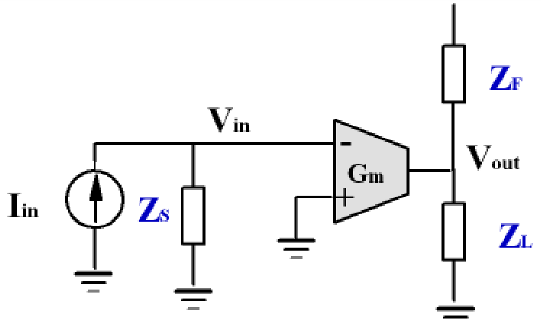
With Z_L neglected and Z_s=C_d and Z_F=R_F

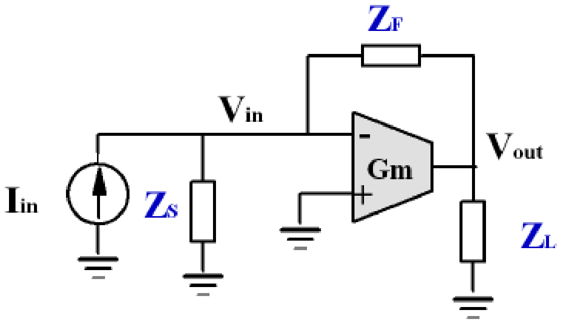
  - $V_{IN} = Z_S I_{IN} = \frac{1}{j\omega C_d} I_{IN}$
  - $V_{OUT} = -G_m Z_F V_{IN} = -\frac{G_m ZF}{j\omega C_d} I_{IN}$
  - $\mathbf{V_{OUT} = -G_m R_F \frac{Q_{IN}}{C_d}}$
  - $Z_{IN} = Zs \Rightarrow C_d$
  - $Z_{OUT} = Z_F = R_F$

- **TZ** using an OTA with gain G_m
  - $I_{OUT} = V_{OUT} / Z_L + (V_{OUT} - V_{IN}) / Z_F$
  - $I_{IN} = V_{IN} / Z_S - (V_{OUT} - V_{IN}) / Z_F$
  - $I_{OUT} = -G_m V_{IN}$

With Z_L neglected and Z_s= C_d and Z_F=R_F

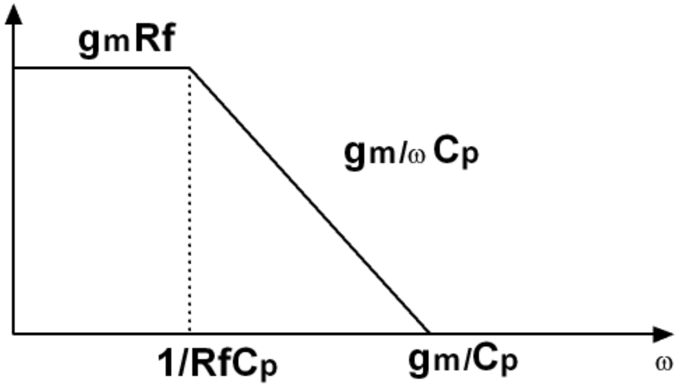
  - $I_{IN} = \frac{V_{in}}{Z_s} - I_{OUT}$
  - $V_{IN} = \frac{I_{IN}}{(\frac{1}{Z_S} + G_m)} = \frac{\frac{1}{G_m}}{1 + j\omega\frac{C_d}{G_m}} I_{IN}$
  - $V_{OUT} = (1 - G_m Z_F) V_{IN}$
  - $\mathbf{V_{OUT}} = \frac{\frac{1}{G_m} - R_F}{1 + j\omega\frac{C_d}{G_m}} I_{IN} \approx -G_m R_F \frac{I_{IN}}{j\omega C_d} = \mathbf{-G_m R_F \frac{Q_{IN}}{C_d}}$
  - $Z_{IN} = \frac{\frac{1}{G_m}}{1 + j\omega\frac{C_d}{G_m}}$ => $1/G_m$ in // with C_d
  - $Z_{OUT} = \frac{R_F}{1 + G_m R_F} \sim \frac{1}{G_m}$

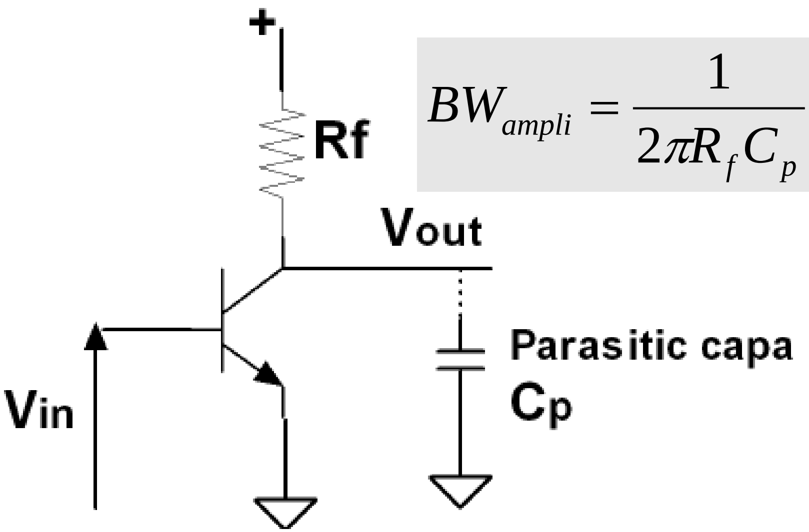




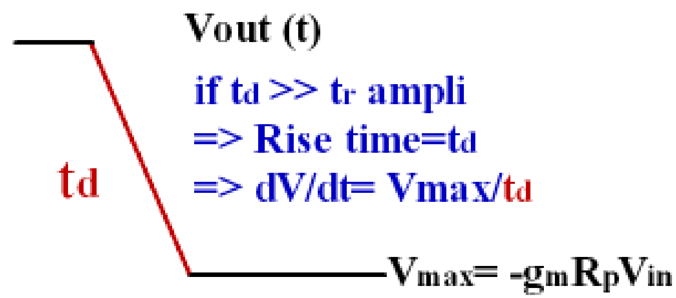
$$V_{out}(s) = -g_m (R_f // C_p) V_{in}(s)$$

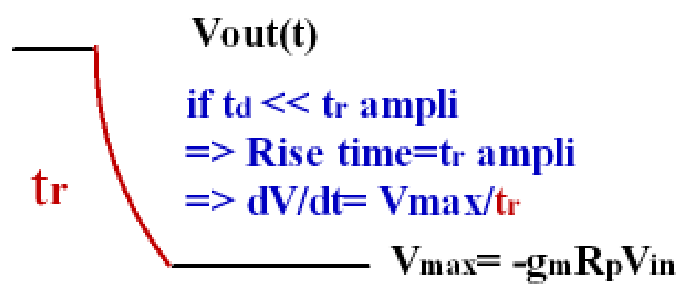
$$\frac{V_{out}(\omega)}{V_{in}(\omega)} = -g_m \frac{R_f}{j\omega C_p \left(R_f + \frac{1}{j\omega C_p} \right)} = \frac{-g_m R_f}{j\omega C_p R_f + 1}$$





$$BW_{ampli} = \frac{1}{2\pi R_f C_p} = \frac{0.35}{t_{r\_ampli}}$$



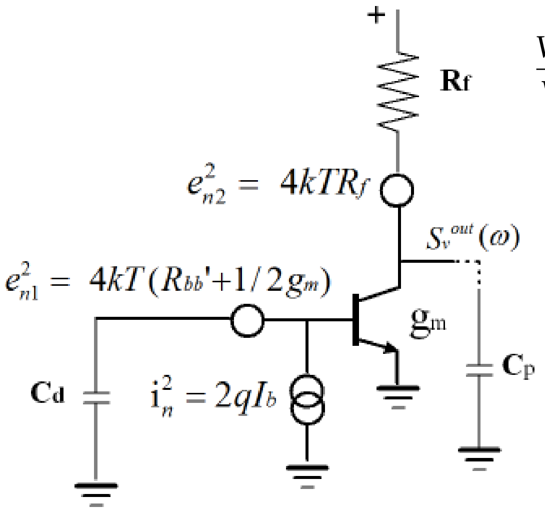


$$\sigma_t^{\ J} = \frac{N}{\frac{dV}{dt}} = \frac{t_r}{\frac{S}{N}}$$

$$\frac{dV}{dt} \approx \frac{V_{max}}{\sqrt{t_{r\_ampli}^2 + t_d^2}}$$

NOISE TZ and CE (N)

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



$$\frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{-g_m R_f}{j\omega R_f C_p + 1}$$

$$S_v^{out}{}_{Bipolar}(\omega) = (g_m R_f)^2 \left(4kTR_{bb'} + \frac{4kT}{2g_m} \right) + 4kTR_f$$

$$S_v^{out}{}_{MOS}(\omega) = (g_m R_f)^2 \left(4kTR_{GG'} + \frac{4kT\Gamma}{g_m} \right) + 4kTR_f + k\frac{I_D}{f}$$

- Similar noise for CE and TZ
- Parallel noise ($2qI_b$ or $2qI_G$) negligible at HF
- rms noise v_n depends on the √BW
- Noise is independent of Cd
- But the signal is not independent of Cd
- S/N depends of Cd and BW

$$v_n^2 = \int S_v(\omega) |H(\omega)|^2 \frac{d\omega}{2\pi}$$

$$v_n^2 = \int S_v(\omega) \frac{(g_m R_f)^2}{(1+\omega^2 R_f^2 C_p^2)} \frac{d\omega}{2\pi}$$

$$N = v_n \approx R_f \sqrt{2kTg_m BW}$$

$$V_{OUT} = -g_m R_f \frac{Q_{IN}}{C_d}$$

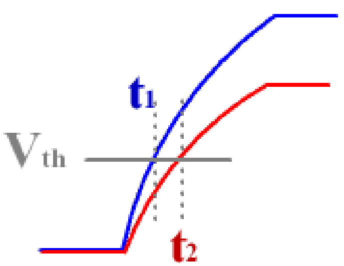
$$\frac{S}{N} \approx \frac{\alpha\sqrt{g_m}}{C_d\sqrt{BW}} \approx \alpha \frac{\sqrt{g_m}\sqrt{t_{r\_ampli}}}{C_d}$$

$$\sigma_t^{\ J} = \frac{N}{\frac{dV}{dt}} = \frac{N}{\frac{S}{\sqrt{t_{r\_a}^2 + t_d^2}}} = \frac{\sqrt{t_{r\_a}^2 + t_d^2}}{\frac{S}{N}} = \alpha \frac{\sqrt{t_{r\_a}^2 + t_d^2}}{\sqrt{g_m}\,\frac{\sqrt{t_{r\_a}}}{C_d}} = \alpha \frac{C_d}{\sqrt{g_m}} \frac{\sqrt{t_{r\_a}^2 + t_d^2}}{\sqrt{t_{r\_a}}}$$

Optimum value: $t_{r\_a} = t_d$

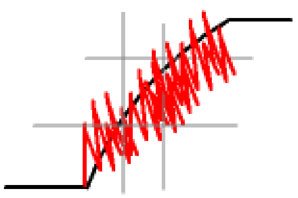
$$\sigma_t^{\ J} \approx \alpha C_d \sqrt{\frac{t_d}{g_m}}$$

Time Walk

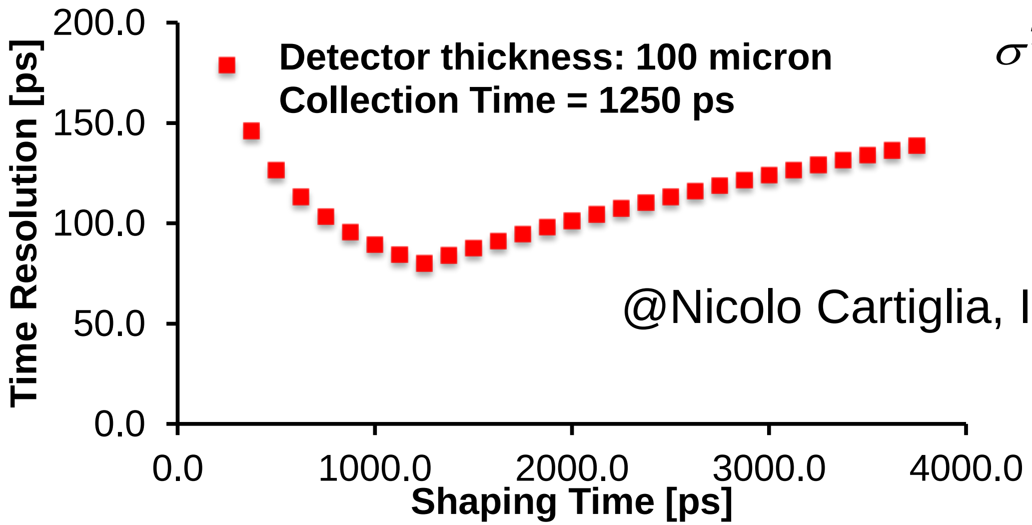


$$\sigma^{TW}_{\ t} = \left[\frac{\sqrt{t_{r\_a}^2 + t_d^2}\,V_{th}}{S} \right]_{RMS}$$

Jitter



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



@Nicolo Cartiglia, INFN Torino

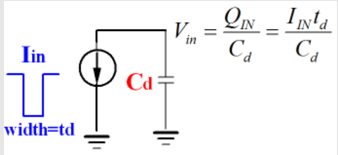
CE in TSMC 130 nm: jitter vs tr (BW) and td

Ωmega

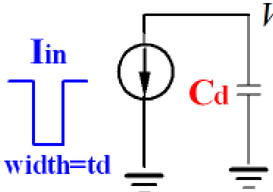
- With I source trans (0 for 2 pF or 1.8mA for 20pF)
- Follower (connected to a discriminator)
- Normalization to 1 fC, square pulse.

$$\sigma_t^{J} = \frac{N}{\frac{dV}{dt}} = \frac{t_r}{\frac{S}{N}} = \frac{\sqrt{t_{r\_ampli}^2 + t_d^2}}{\frac{S}{N}}$$

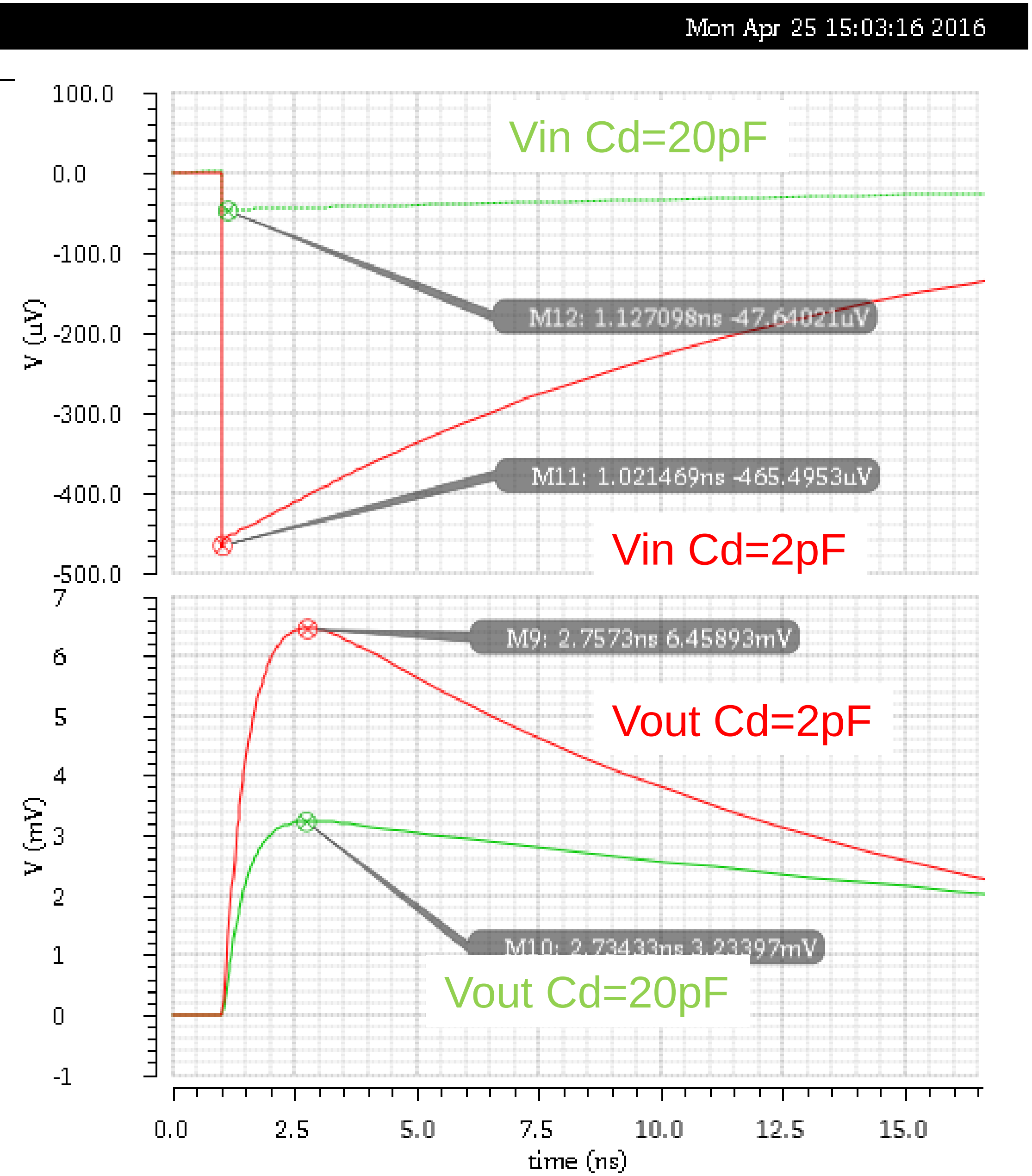
POWER: 0.5mW/ mm²

CE	Cd=2pF (Id=220 µA)	Cd=20pF (Id=2.1 mA)
td=10ps Qin=Iin.td= 100µA.10ps=**1fC** 	out = 6.9 mV out_fol=6.1 mV tr_fol=284 ps BWa=1.2 GHz rms=0.485 mV S/N=12.6 σj=284ps/12.6=23 ps	out=3.37 mV out_fol=3.1 mV tr_fol=290 ps BWa=1.2 GHz rms=1.2 mV S/N=2.6 σj=290ps/2.6=110 ps
td=1ns and tr_ampli=td CL=100fF Qin= 1µA.1ns=**1fC**	out=6.4 mV out_fol=5.9 mV tr_fol=1.1ns BWa=410 MHz rms=0.39 mV S/N=15 σj=1.1ns/15=73 ps	out=3.2 mV out_fol=3.05 mV tr_fol=1.1 ns BWa=440 MHz rms=0.8mV S/N=3.8 σj=1.1ns/3.8=288 ps

Iin pulse td=1ns 1uA : WFMs with 2 and 20pF



$$V_{in} = \frac{Q_{IN}}{C_d} = \frac{I_{IN} t_d}{C_d}$$



20pF → 2pF:
Signal=Qin/Cd x 10
I/10 => √gm divided by √10
=> S/N x √10

$$\frac{S}{N} \approx \frac{\alpha\sqrt{g_m}}{C_d\sqrt{BW}} \approx \alpha\,\frac{\sqrt{g_m}\sqrt{t_{r\_ampli}}}{C_d}$$

Our experience in fast timing measurement: PETIROC

Ωmega

- Time of Flight read-out chip (**SiGe 0.35µm**) with embedded TAC (25 ps bin) and 10-bit ADC for Q and T digitization

- Front-end
  - **Common Emitter**, DC coupled to detector
  - **Fast discriminator**

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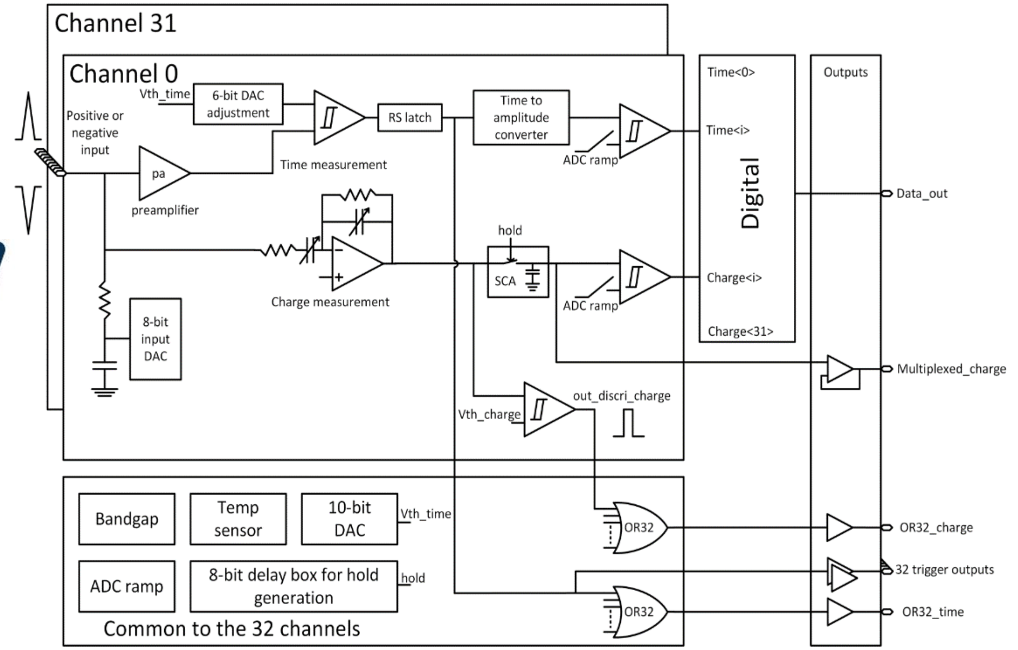
- Variable shaping time shaper for charge measurement. Dynamic range: 160 fC up to 400 pC

- 32 channels (negative input)
  - 32 trigger outputs
  - NOR32_chaage
  - NOR32 time
  - Charge measurement over 10 bits
  - Time measurement over 10 bits
  - One multiplexed charge output

- Common trigger threshold adjustment and 6bit-dac/channel for individual adjustment

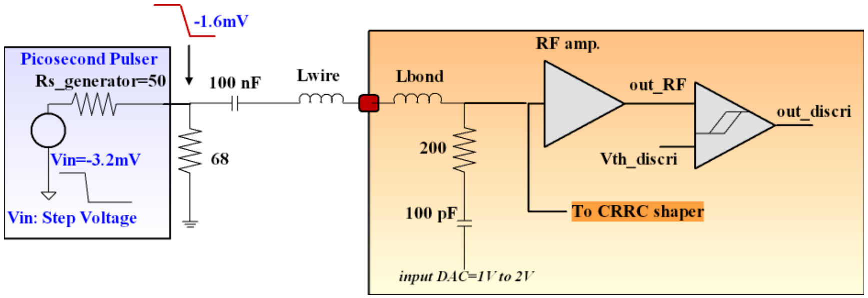
- 32 8bit-input dac for SiPM HV adjustment

- Power consumption 6 mW/ch



Parameter	Value
Detector Read-Out	SiPm
Number of Channels	32
Signal Polarity	negative
Sensitivity	voltage
Timing Resolution	< 75 ps
Dynamic Range	160 fC up to 400pC
Packaging & Dimension	TQFP 208 (28x28x1.4 mm), die : 4.7mmx4.3mm
Power Consumption	6 mW/channel
Inputs	32
Outputs	32 trigger outputs NOR32_chrage NOR32 time Charge measurement over 10 bits Time measurement over 10 bits One multiplexed charge output One multiplexed trigger output
Internal Programmable Features	Common trigger threshold adjustment and 6bit-dac/channel for individual adjustment Shaping time of the charge shaper 32 8bit-input dac for SiPM HV adjustment

PETIROC2A: BW of PA+DISCRI MEASUREMENT

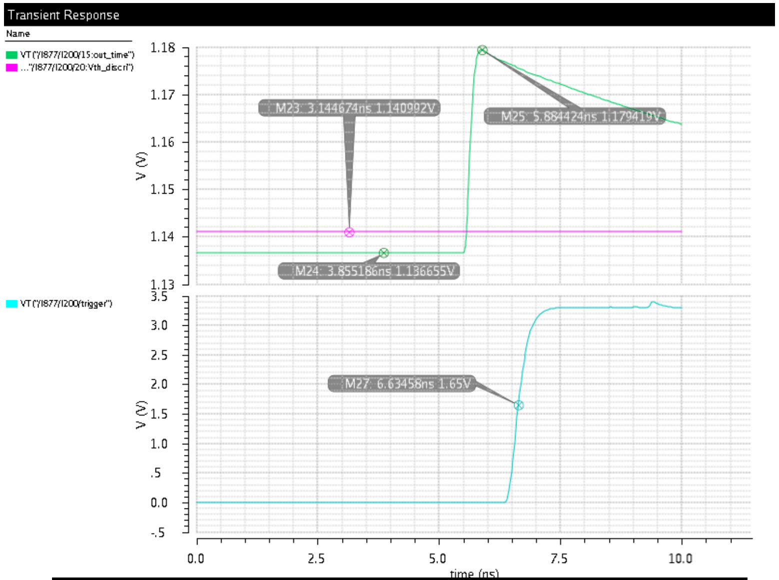


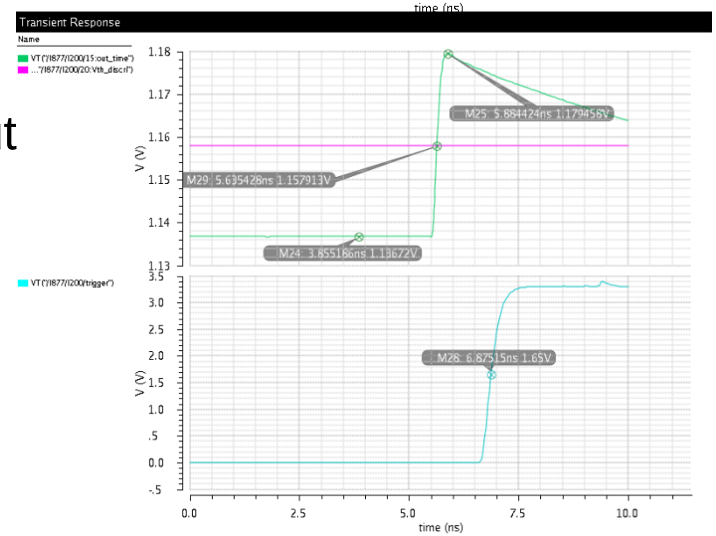
- Injection of a step

⇒ out_RF = E0(1-e-t/τ)

⇒ BW = 0.1/ $\Delta t_{10\%-50\%}$

  - Simul of PA alone : BW= 6 GHz
  - Indirect measurement at discri output
  - Threshold set at 10 and 50% of the pa output





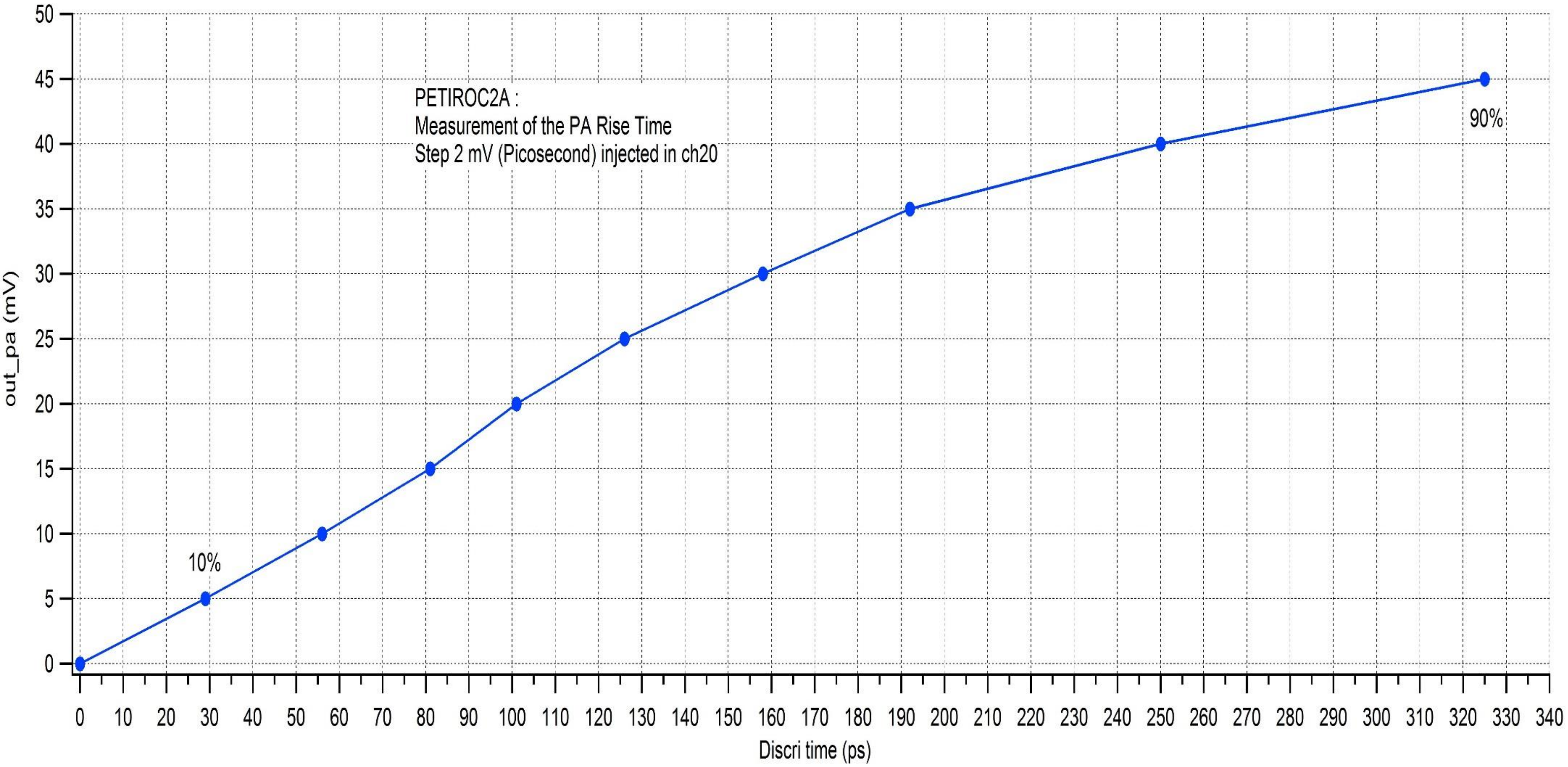
- Measurement:

  BW of PA+discri> 1GHz

  => tr (amplifier) < 300ps

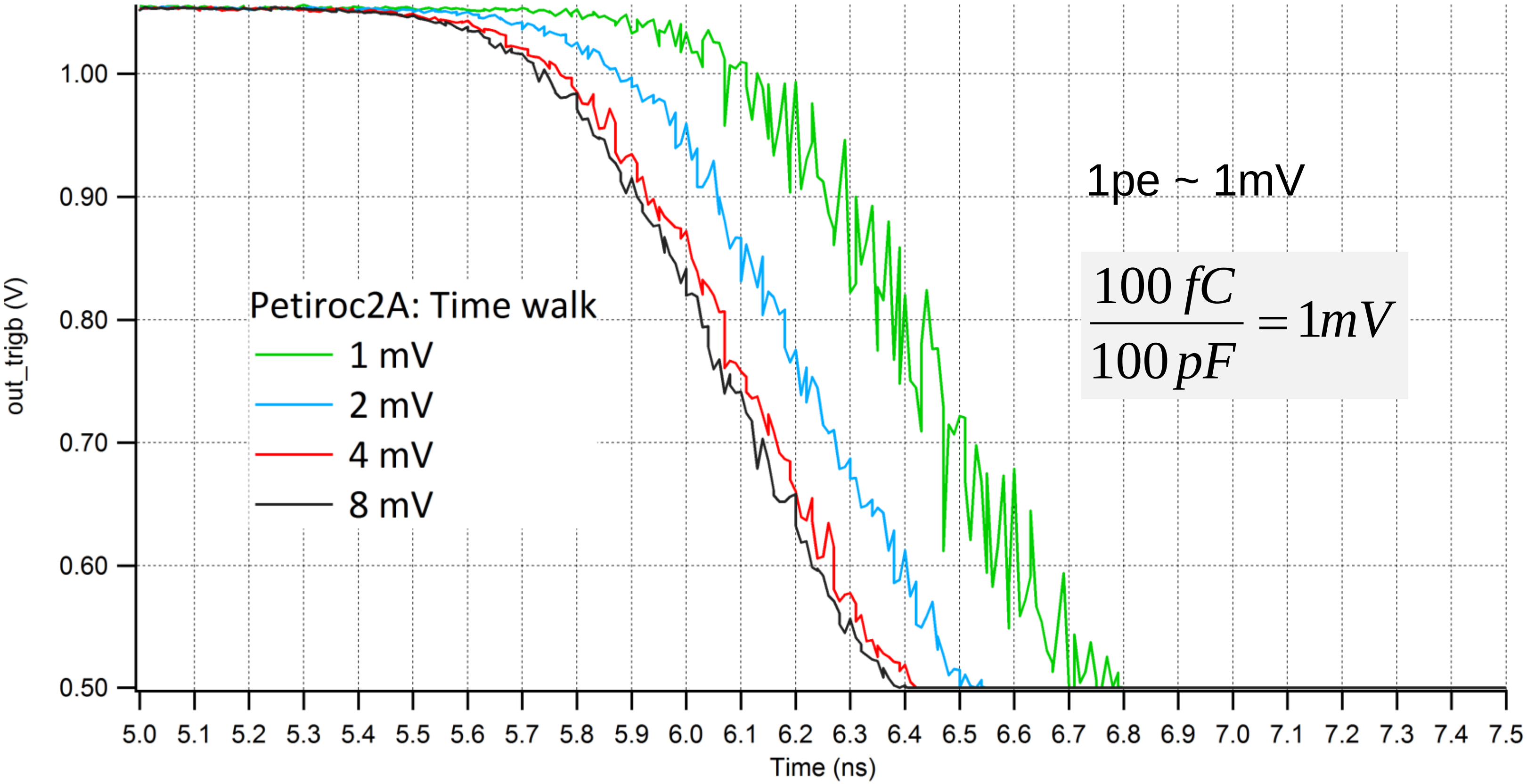
PETIROC2A: PA+DISCRI Rise Time measurement

- $t_{r\ 10\%-90\%} = 300$ ps



PETIROC2A: TIME WALK

- Time walk < 350ps

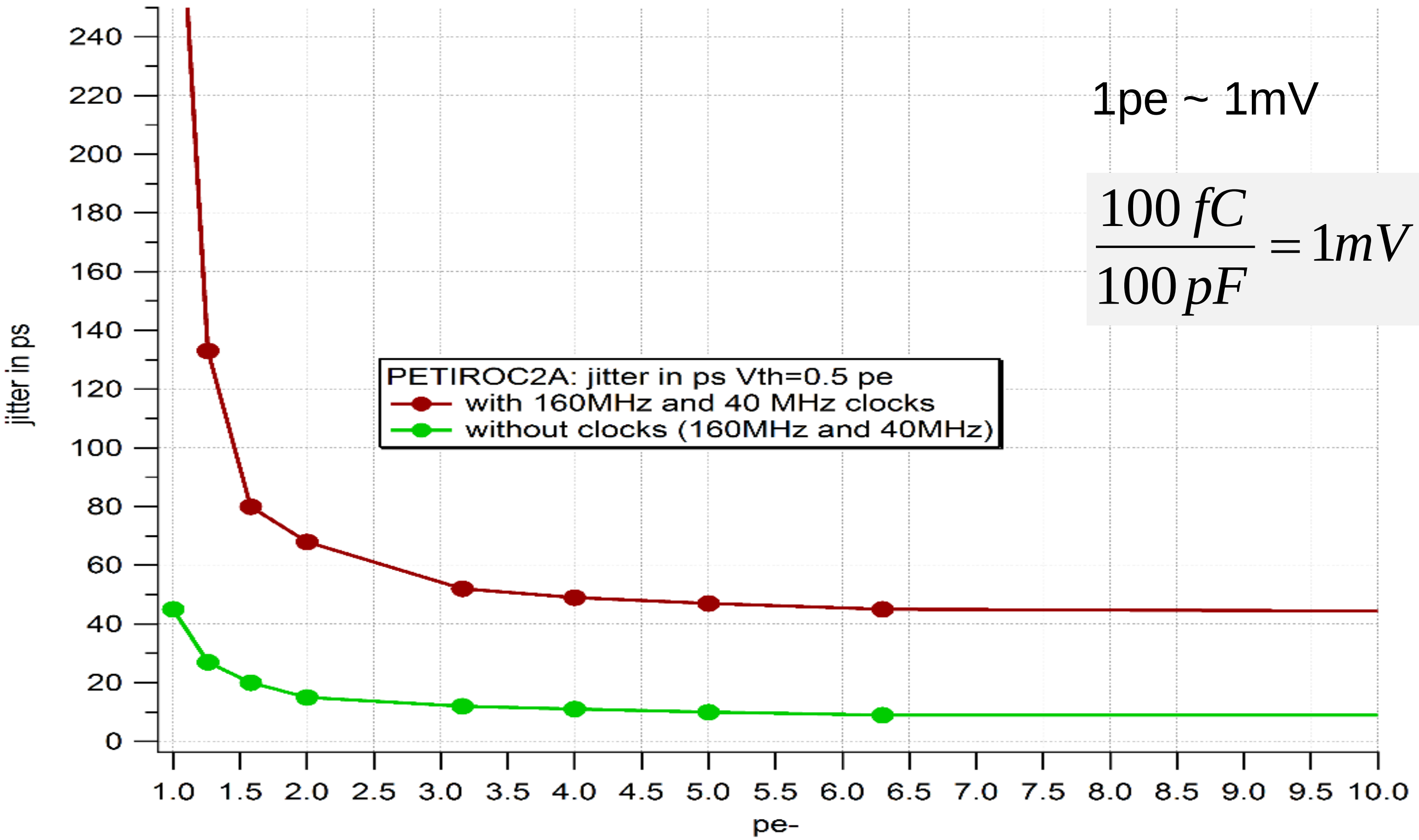


1pe ~ 1mV

$$\frac{100\,fC}{100\,pF} = 1mV$$

PETIROC2A: JITTER MEASUREMENT

- Jitter vs threshold & injection, Jitter improves with signal
- Clock couplings: through substrate, better results expected with technologies that offer triple well trans (TSMC 130nm)
- jitter<40 ps for injected charge >1pe (= 1mV at the input)



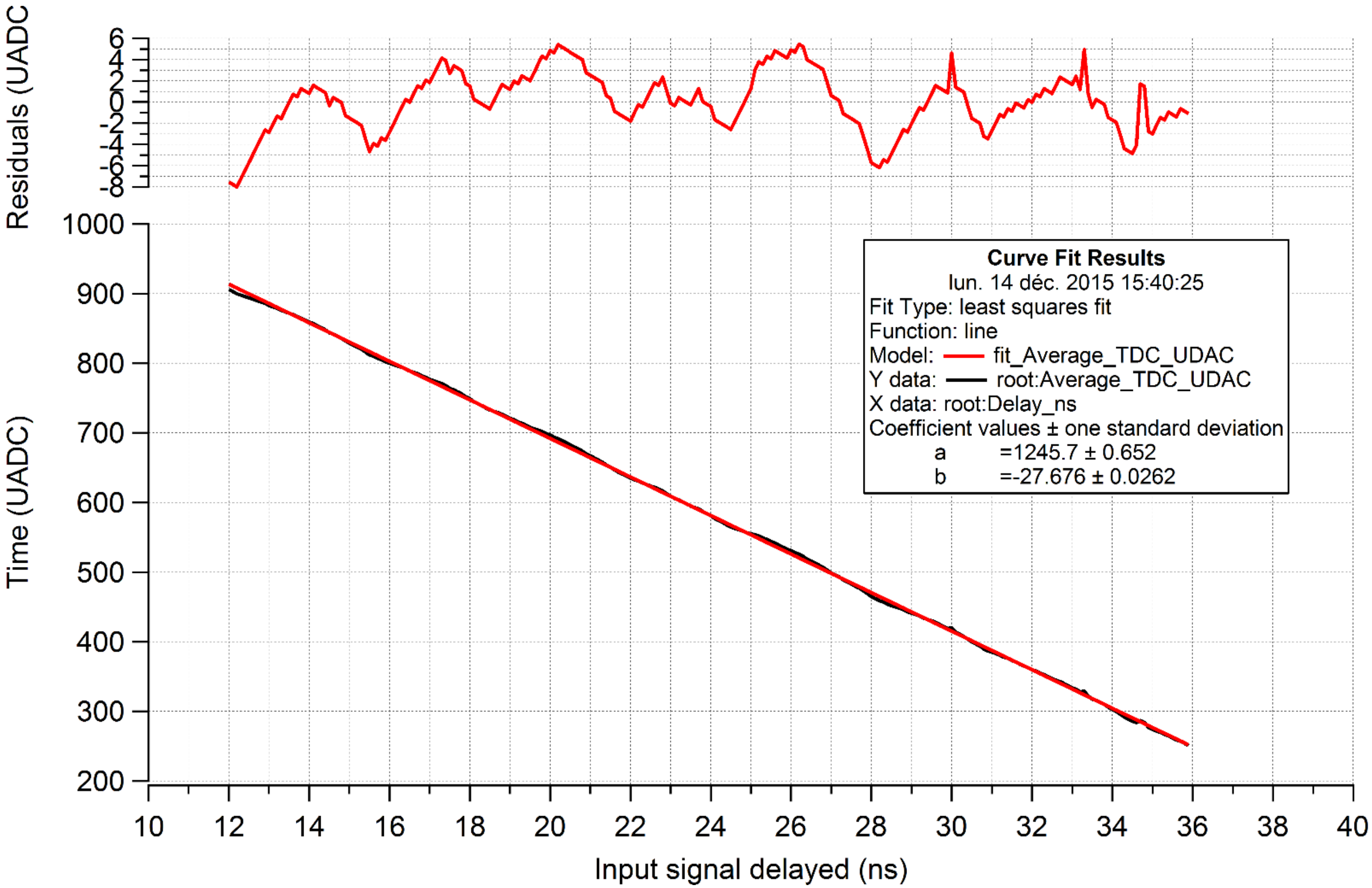
1pe ~ 1mV

$$\frac{100\,fC}{100\,pF} = 1mV$$

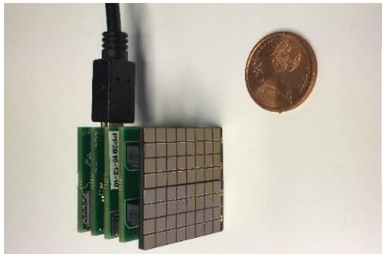
PETIROC2A: TAC MEASUREMENT

- 160 MHz clock seen on the TDC (residuals).
- rms of the histogram of the residuals: 2.6 ADC Unit

⇒ Time resolution: 2.6x27ps (step)= 70 ps rms



- Time resolution: $$\sigma_t^{\,2} = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{t_{rise}V_{th}}{S}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$$
  - jitter deeply dependent on the detector and time duration
    - Cd: must be as small as possible to have a large input signal: Vin=Qin/Cd
    - ⇒ Try to optimize thickness and area of the sensor taking into account the radiation hardness and the minimization of the drift time (the larger the drift time, the larger the jitter)
    - Preamp bandwidth should match signal duration
    - Preamp transconductance gm determines noise, scaling as sqrt(Id)
  - +TW correction to be done: Time Over Threshold (TOT), Constant Fraction Discri (CFD)
  - TDC bin



Petiroc2 and SiPM matrix

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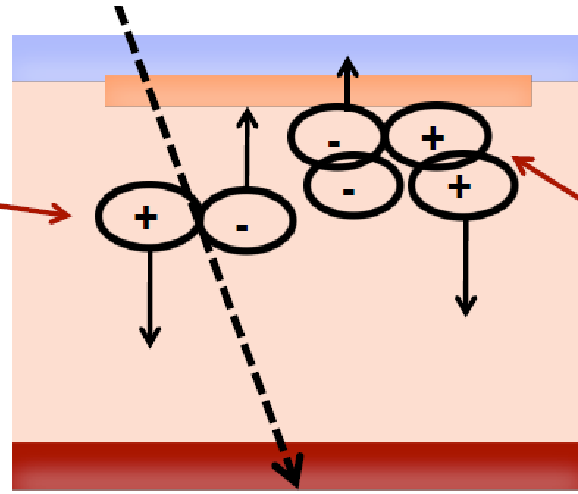
- Time measurement: TAC or DLL
  - Petiroc2: TAC time resolution <100ps
  - Petiroc2 can be used either in full digital mode using the internal ADC and TDC or in analogue mode using the 32 trigger outputs and the multiplexed charge output. The analogue mode enables the use of external TDC
- Submission of blocks in TSMC130nm in May 2016: preamps, discris, TOT for CMS and ATLAS

BACKUP

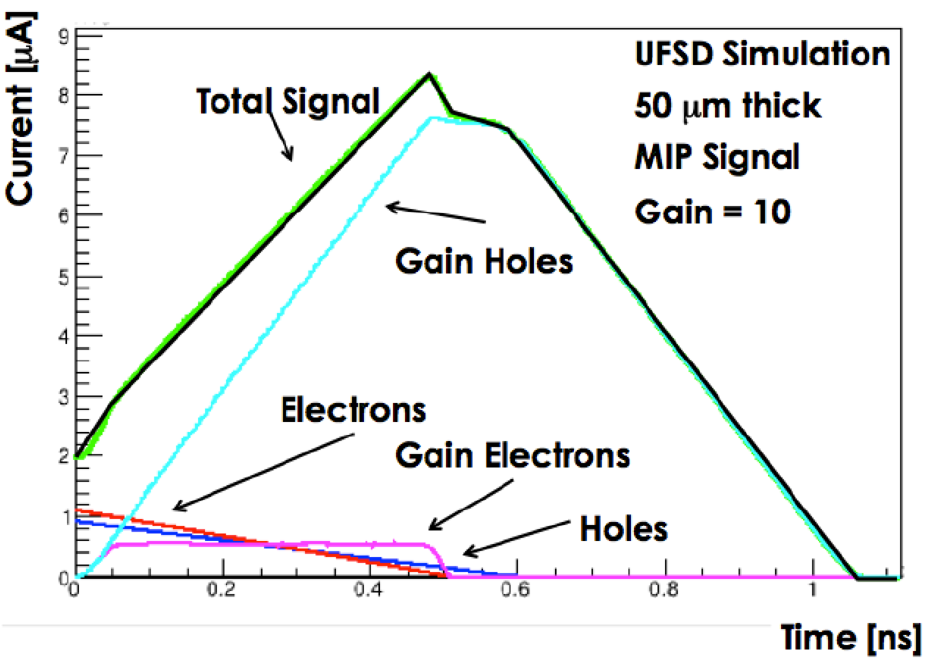
https://indico.cern.ch/event/485239/overview

LGAD SIGNAL



Gain electron: absorbed immediately

Gain holes: long drift home



Electrons multiply and produce additional electrons and holes.

- **Gain electrons have almost no effect**
- **Gain holes dominate the signal**

➔ **No holes multiplications**

CE in TSMC 130 nm: jitter vs tr (BW) and td

Omega

- Simulations for Cd=2pF and 20pF

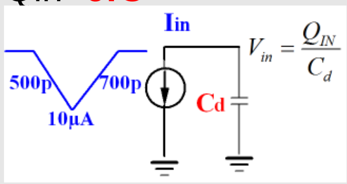
$$\sigma_t^J = \frac{\sigma_N}{\frac{dV}{dt}} = \frac{t_r}{\frac{S}{N}} = \frac{\sqrt{t_{r\_ampli}^2 + t_d^2}}{\frac{S}{N}}$$

- **Normalization made with LGAD pulse shape and 1 MIP = 6fC**

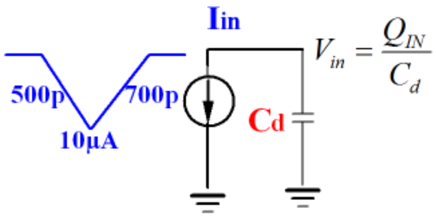
- 20pF → 2pF: Signal=Qin/Cd x 10 and I/10 => √gm divided by √10 => S/N x √10

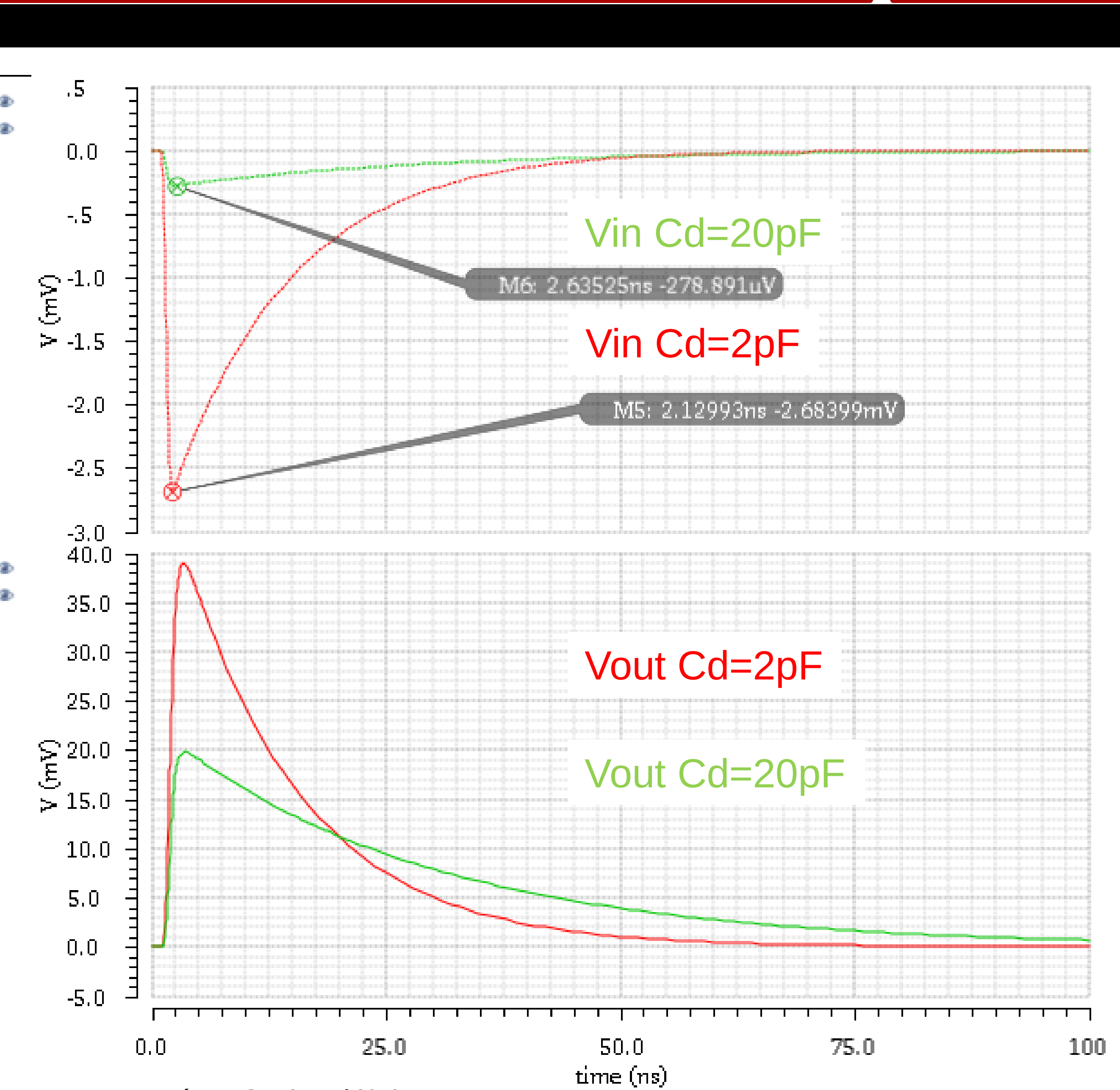
$$\frac{S}{N} \approx \frac{\alpha\sqrt{g_m}}{C_d\sqrt{BW}} \approx \alpha\,\frac{\sqrt{g_m}\sqrt{t_{r\_ampli}}}{C_d}$$

POWER: 0.5mW/ mm2

CE	Cd=2pF (Id=220 µA)	Cd=20pF (Id=2.1 mA)
tr=500ps tf=700ps Qin=**6fC** 	out_fol = 36.6 mV tr_fol=700 ps BWa=1.1 GHz rms=0.485 mV S/N=75 σj=700ps/75=10 ps	out_fol=19 mV tr_fol=708ps BWa=1.2 GHz rms=1.18 mV S/N=16 σj=708ps/16=44 ps
tr_ampli=td CL=100fF Qin=**6fC**	out_fol=35.7 mV tr=1.1 ns BWa=410 MHz rms=0.39 mV S/N=92 σj=1.1ns/92=12 ps	out_fol=18.7 mV tr_fol=1.05 ns BWa=440 MHz rms=0.8 mV S/N=23.4 σj=1.05ns/23.4=45 ps

Iin LGAD: WFMs with 2 and 20pF





20pF → 2pF:
Signal=Qin/Cd x 10
I/10 => √gm divided by √10