front-end electronics

Roberto Cardarelli

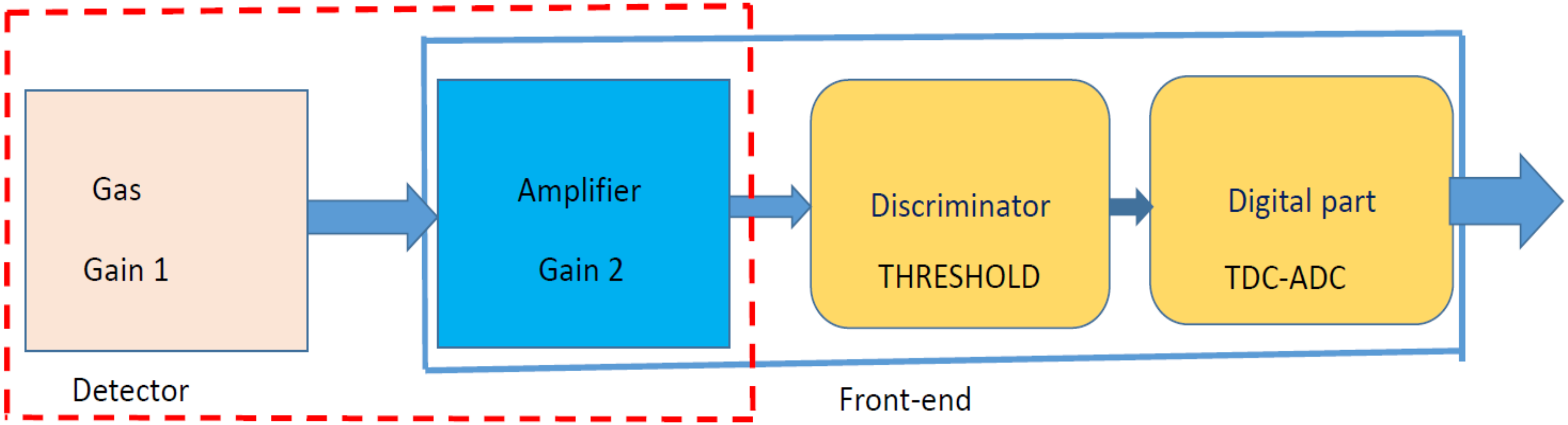
INFN Rome Tor Vergata and Ginevra University

Introduction

- New high-energy experiments in accelerator machines require particle detectors to have high counting capabilities, high time resolution and high spatial resolution. These requests have a major impact on the design of gas detectors and on the electronic front end
- Increasing the counting capacity implies moving the amplification from the gas to the electronics which must have high gains and very low noise
- Increasing the time resolution requires very rapid multiplication processes in the gas, very intense electric fields, fast electronics and the measurement of the signal Amplitude for the correction of the rising time

Diagram of Front-end

- Basic concept to move the gas gain to the amplifier gain to degrease ‹Q›



Gas and amplifier gain v.s. RPC working mode

Gain gas	RPC working mode	Gain amplifier
• High gain	Streamer	low gain
• Medium gain	saturation avalanche	medium
• Low gain	avalanche	high

Increase amplifier gain decrease the average charge in the gas and increase the RPC rate-capability

minimum threshold reachable

Once induced and self-induced noises have been eliminated, the number of spurious signals produced by the discriminator are:

- $V_{th} = n\sigma$ $F = P(n\sigma) * BW$
- **F** frequency of false pulses discriminator from noise
- **P(nσ)** probability of having a higher tension (n * sigma noise)
- **BW** passband amplifier

Problem to transfer the gain to the amplifier

- Amplifier parameter:

1) Amplification
2) Dynamic
3) Noise

The limit to transfer the gas gain to the amplifier gain is the noise of the amplifier.

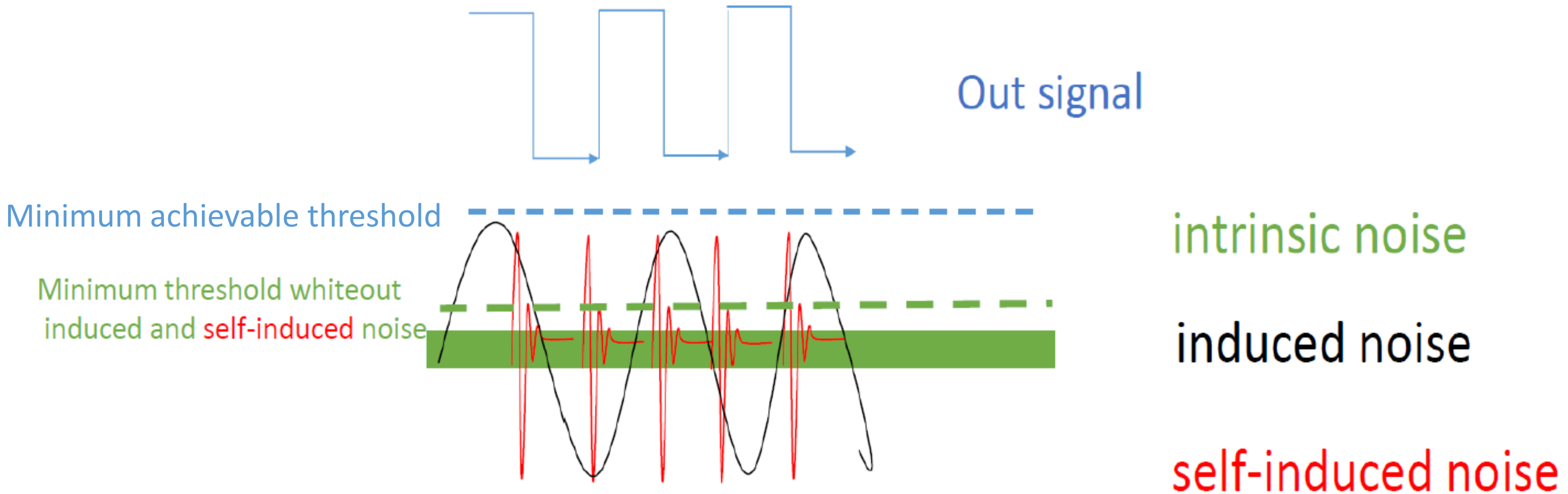
- We have tree type of noise :

1) Intrinsic noise (like thermal, 1/f, shot ……)
2) Induced noise (Very large in big dimension)
3) Self induced noise (Low Impedance)

The noise

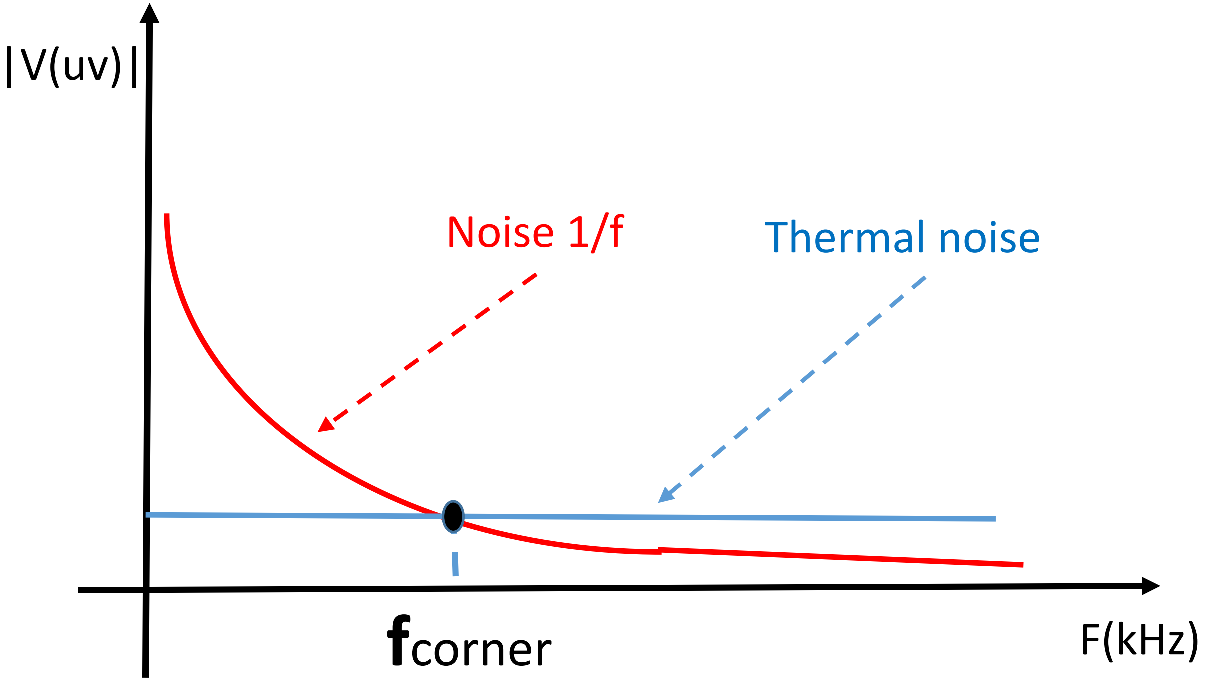
- The intrinsic noise is characteristic of the transistor and the circuit diagram
- The **induced noise** can be reduced by the Faraday cage
- The **self induced noise** can be reduced by integrating front-end electronics and the detector
- The **intrinsic noise** is the ultimate parameter limiting the low threshold operation in RPCs and gaseous detectors in general

Forms of the different types of noise



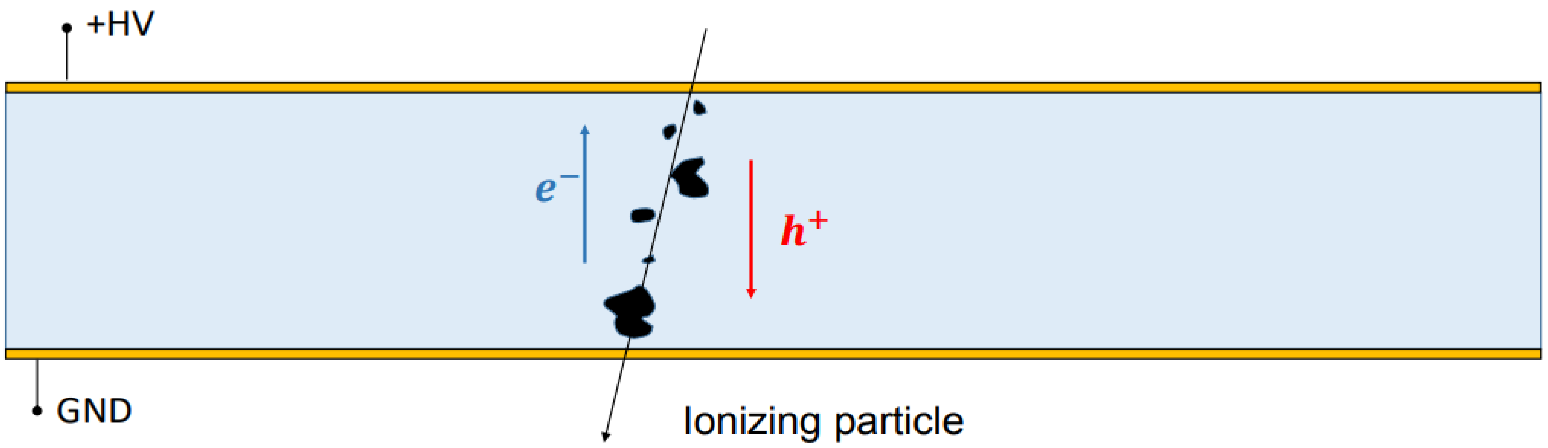
Thermal noise v.s. 1/f noise

- Corner frequency



Charge-collection noise

2. Charge-collection (or Landau) noise



is produced by the **non uniformity of the charge deposition** in the sensor:

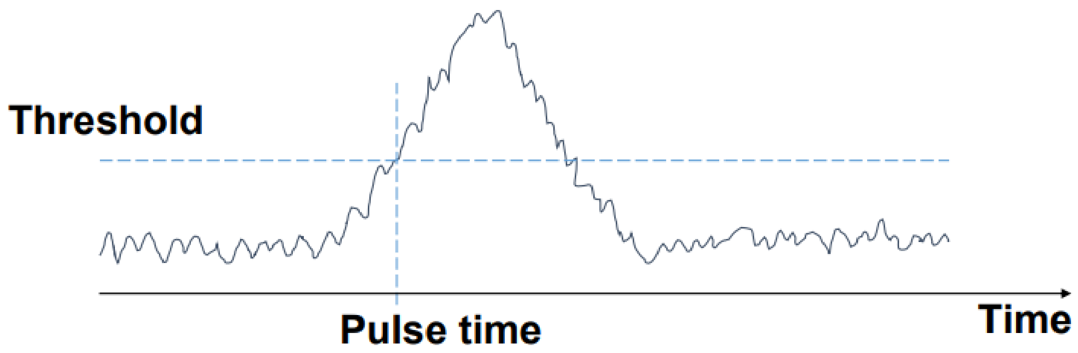
$$I_{ind} \cong v_{drift} \frac{1}{D} \boxed{\sum_i q_i}$$

When **large clusters** are absorbed at the electrodes, their contribution is removed from the induced current. The **statistical origin** of this variability of I_{ind} makes this effect irreducible in PN-junction sensors.

Electronics noise v.s. time resolution

3. Electronics noise

Once the geometry has been fixed, the time resolution depends mostly on the amplifier performance.



$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} \cong \frac{ENC}{I_{ind}}$$

Need an ultra-fast, low noise, low power-consumption electronics with fast rise time and small capacitance. Our solution:

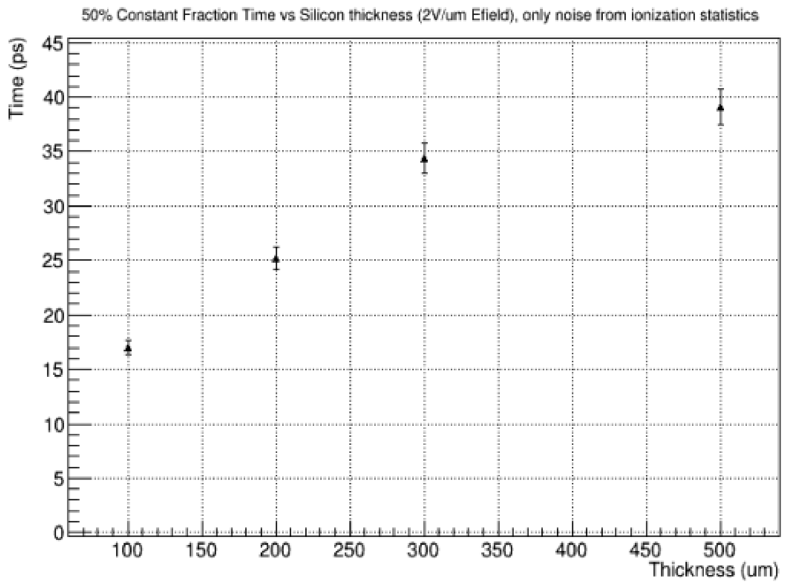
High f_t, single transistor preamplifier.

Charge collection noise

The induced current for a parallel plate readout, from Shockley-Ramo's theorem is:

$$i_{ind} = -\frac{qv}{D}$$

When the large clusters are absorbed at the electrodes, their contribution is removed from the induced current.
The statistical origin of the variability of the induced current makes this effect irreducible, so that it can be considered as an equivalent noise current.



Simulation: Time jitter introduced by the charge collection noise (or Landau noise) for a silicon detector traversed by a Minimum Ionizing Particle (MIP).

Comparison Bipolar-MOSFET- JFET Equivalent noise charge as a function of τ_M

82 E. GATTI and P. F. MANFREDI

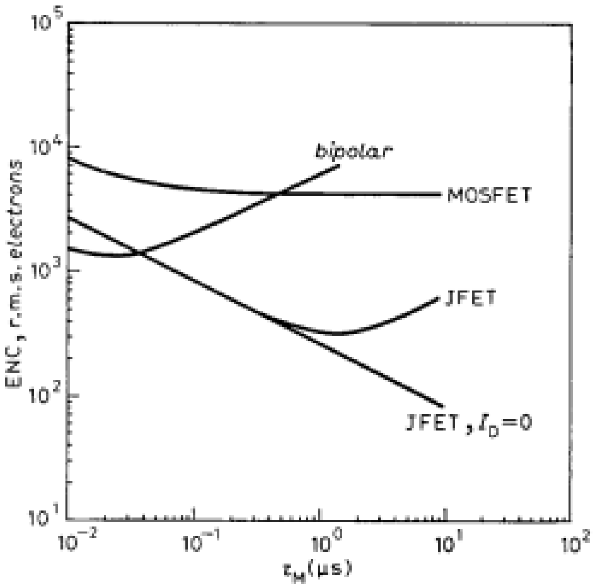
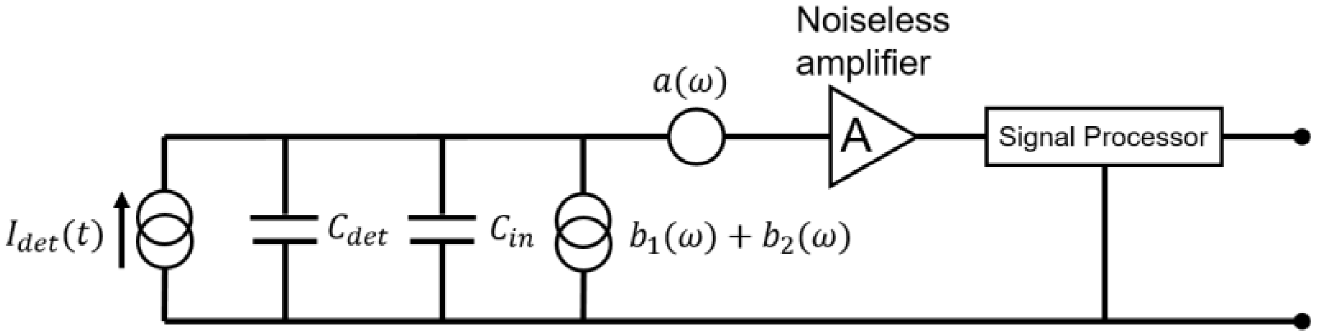


Fig. 5.7. – Equivalent noise charge as a function of τ_M for three types of active devices and a fixed value of C_D; $C_D = 30$ pF, $I_D = 10$ nA.

Equivalent Noise Charge: device comparison



$$ENC^2 = A_1 \frac{a_W}{\tau_M}(C_{det} + C_{in})^2 + A_2 \frac{ln2}{\pi} c(C_{det} + C_{in})^2 + A_3(b_1 + b_2)\tau_M$$

BJT based amplifier

$$ENC_{\text{series noise}} \propto \sqrt{k_1 \cdot \frac{C_{tot}^2}{\beta} + k_2 \cdot R_b C_{tot}^2}$$

Equivalent Noise Charge

For a NPN BJT, the amplifier current gain β can be expressed as:

$$\beta = \frac{i_C}{i_B} = \frac{\tau_p}{\tau_t}$$

τ_p = hole recombination time in Base

τ_t = electron transit time (Emitter to Collector)

Large $\beta \Longrightarrow$ Minimize the electron transit time

Equivalent Noise Charge

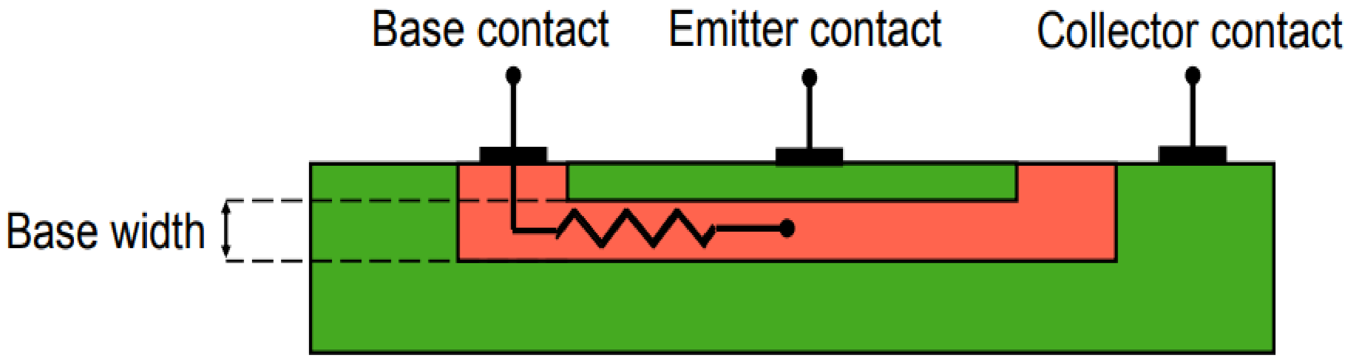
For a NPN BJT, the amplifier current gain β can be expressed as:

$$\beta = \frac{i_C}{i_B} = \frac{\tau_p}{\tau_t}$$

τ_p = hole recombination time in Base

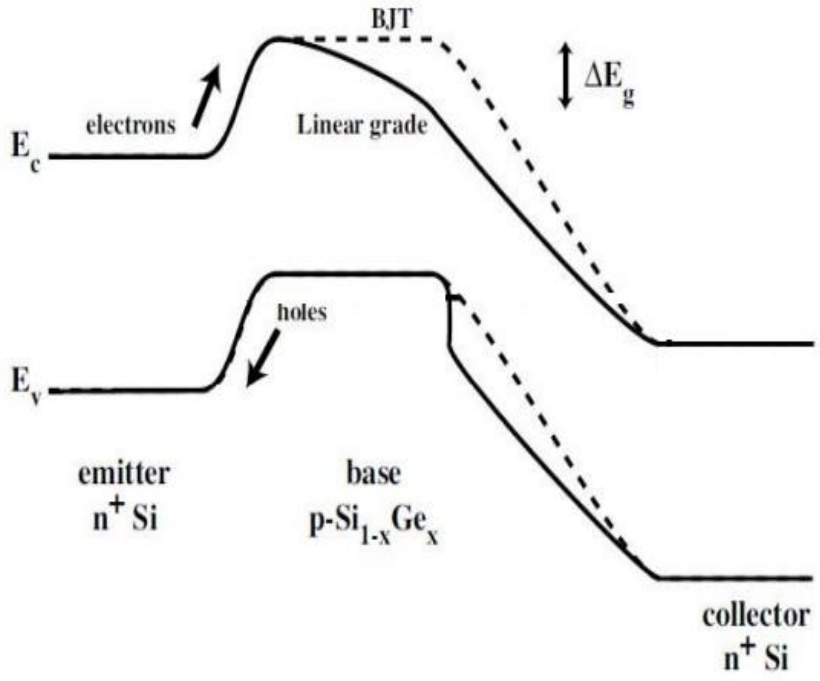
τ_t = electron transit time (Emitter to Collector)

Large $\beta \Rightarrow$ Minimize the electron transit time



SiGe HBT technology for low-noise, fast amplifiers

In SiGe Heterojunction Bipolar Transistors (HBT) the **grading** of the bandgap in the Base changes the **charge-transport mechanism** in the Base from **diffusion** to **drift**:



Grading of germanium in the base:
field-assisted charge transport in the Base, equivalent to introducing an electric field in the Base

⇒ short e⁻ transit time in Base ⇒ very high β

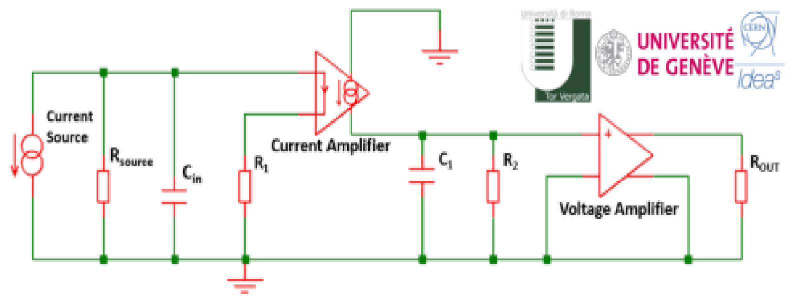
⇒ smaller size ⇒ reduction of R_b and very high f_t

Hundreds of GHz

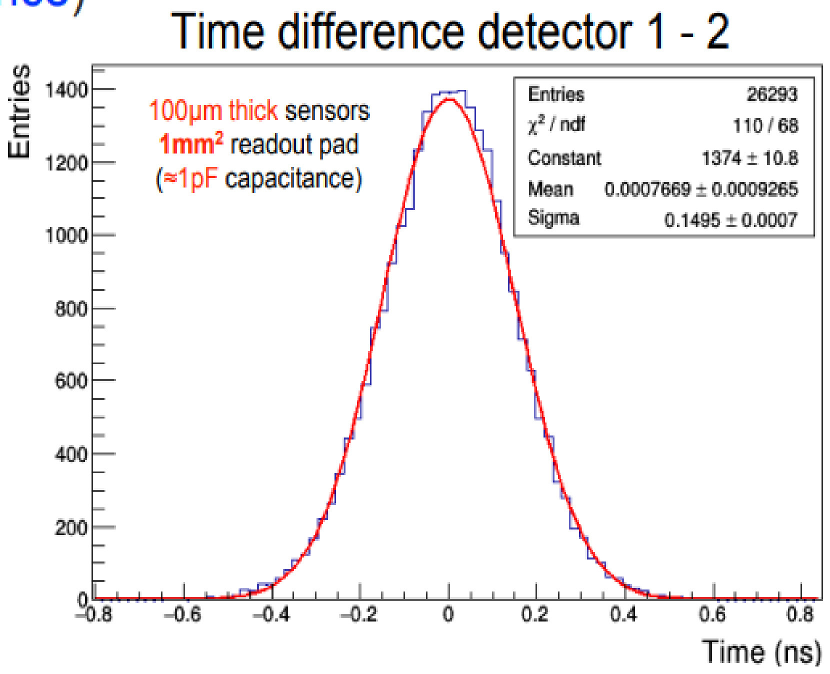
Discrete-component SiGe HBT amplifier

In 2015:

- **Proof-of-concept SiGe amplifier** and produced it with **discrete components**
- This amplifier was coupled to a 100µm thick n-on-p silicon sensor with readout pad of **1mm²** area (~1pF capacitance)



JINST 11 (2016) P03011: https://doi.org/10.1088/1748-0221/11/03/P03011



$$\sigma_T = \frac{(150 \pm 1)\text{ps}}{\sqrt{2}} = (106 \pm 1)\text{ps}$$

measured with MIPs

Remarkable result for a 1mm² silicon pad (1pF capacitance) **without internal gain**

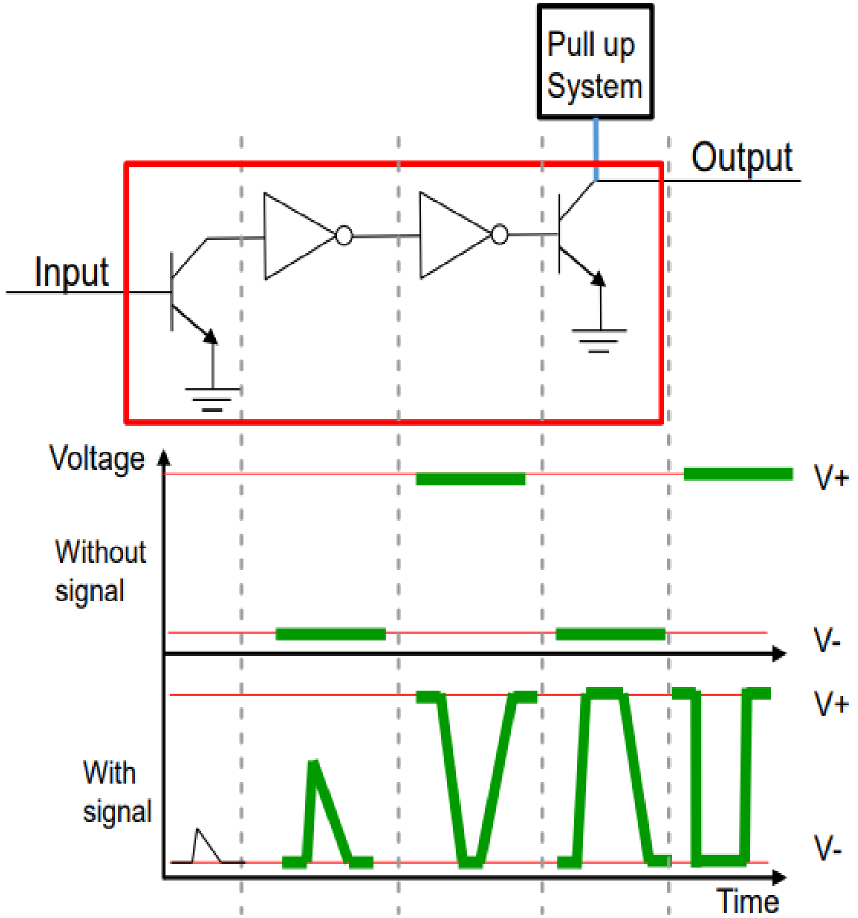
Published in JINST 11 (2016) P03011: https://doi.org/10.1088/1748-0221/11/03/P03011

Performance of SiGe (IHP BJT) amplifier

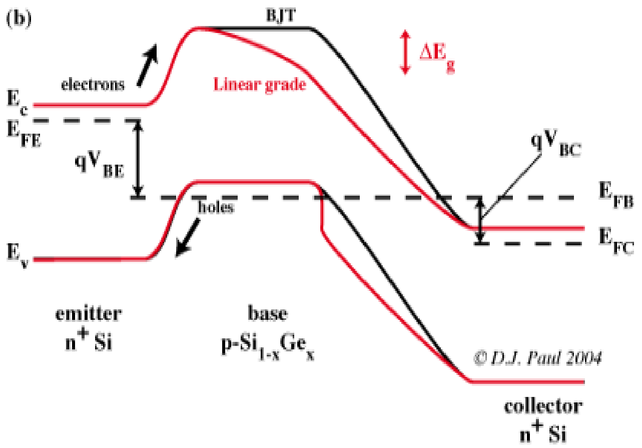
Main specifications of the simulated front-end for C_{TOT} = 500 fF

Power supply	1.8 V
Gain	90 mV/fC
ENC	300 e^- RMS
Minimum threshold	0.4 fC
Power consumption	135 μW/ch
Peaking time	1.3 ns
Simulated ToA jitter (for 1 fC signal)	82 ps

Full-Custom Silicon-Germanium HJT Discriminator



The new full-custom Discriminator circuit dedicated to the RPCs for high rate environment is developed by using **the Silicon-Germanium HJT technology.**
The main idea behind this new discriminator is the limit amplifier. If the signal surpasses the threshold, it will be amplified until saturation giving as output a square wave.



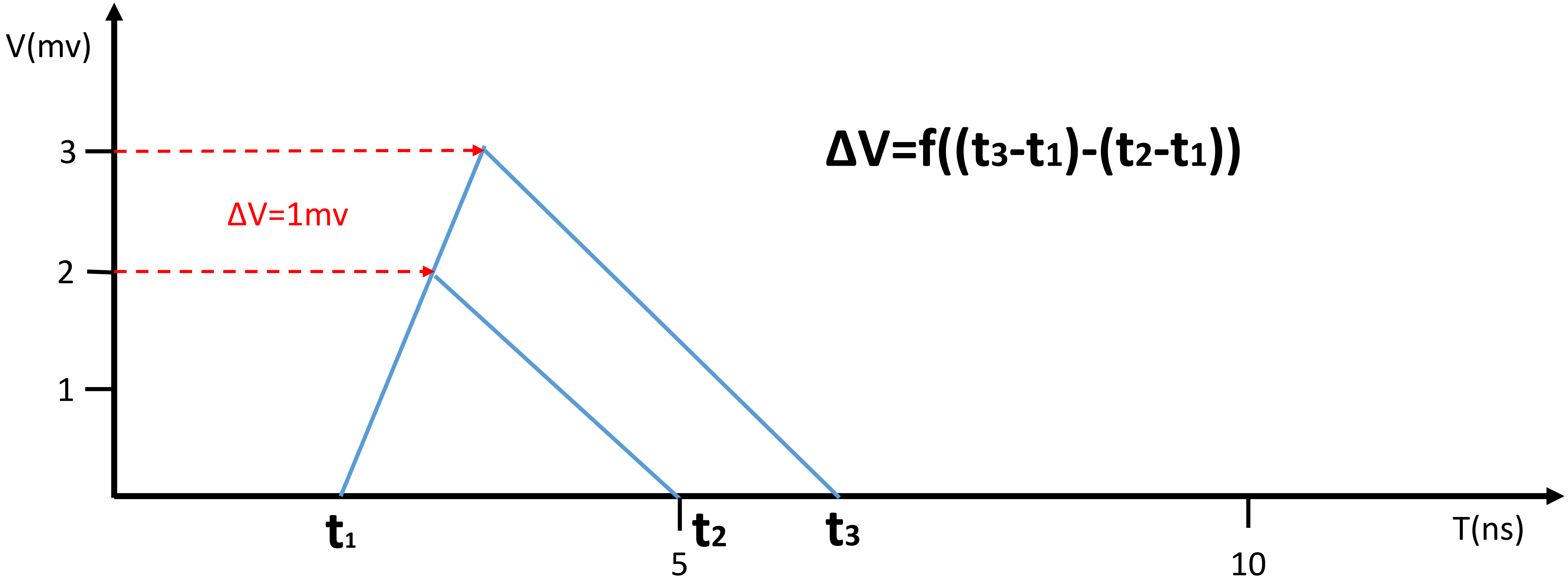
Improvement in the transition frequency and a much higher charge amplification

- **Minimum threshold achievable 0.3-0.5 mV**
- **Time-over-threshold measurement directly with the discriminator**
- **Threshold linearity up to a minimum pulse width of 3 ns**

The principle of SiGe heterojunction bipolar transistor (HJT) is to introduce a Silicon-Germanium impurity in the base of the transistor. The advantage of this device is that the band structure introduces a drift field for electrons into the base of the transistor, thus producing a ballistic effect that reduces the base transit time of the carriers injected in the collector

Time Over Threshold

- To measure the amplitude of the pulse with the TDC:



$$\Delta V = f((t_3 - t_1) - (t_2 - t_1))$$

Full-Custom ASIC Discriminator

- Optimal characteristic function with the possibility of an easy regulation of the threshold from a minimum value of few mV (see Fig. 4)
- Very small transition region of around 300 µV, practically negligible when the discriminator is used within the RPC (see Fig 4).
- Time-over-threshold measurement directly with the discriminator (see Fig 5).
- Minimum pulse width of 3 ns ; for shorter signal the discriminator goes into a charge regime with a threshold in charge (see Fig 6).

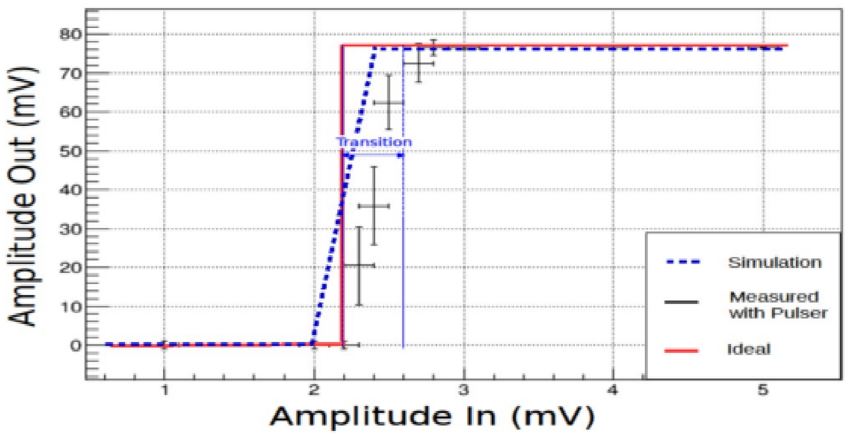


Figure 4: Characteristic function of the discriminator in Si-Ge HJT technology

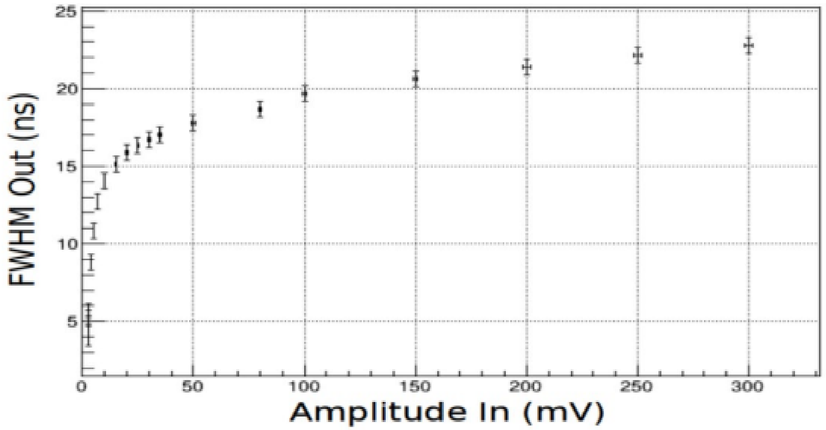


Figure 5: Dynamic of the time-over-threshold of the discriminator prototype in SiGe HJT technology.

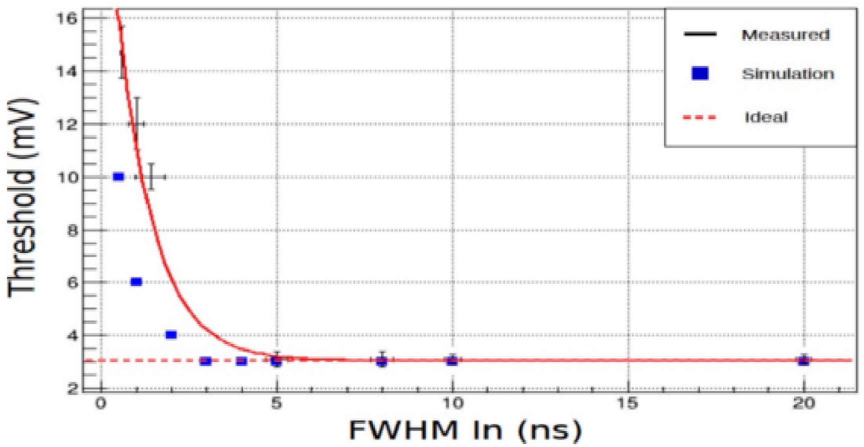


Figure 6: Minimum pulse width of the new Si-Ge prototype with the simulated and the ideal behavior of a discriminator compared

Full-Custom Amplifier

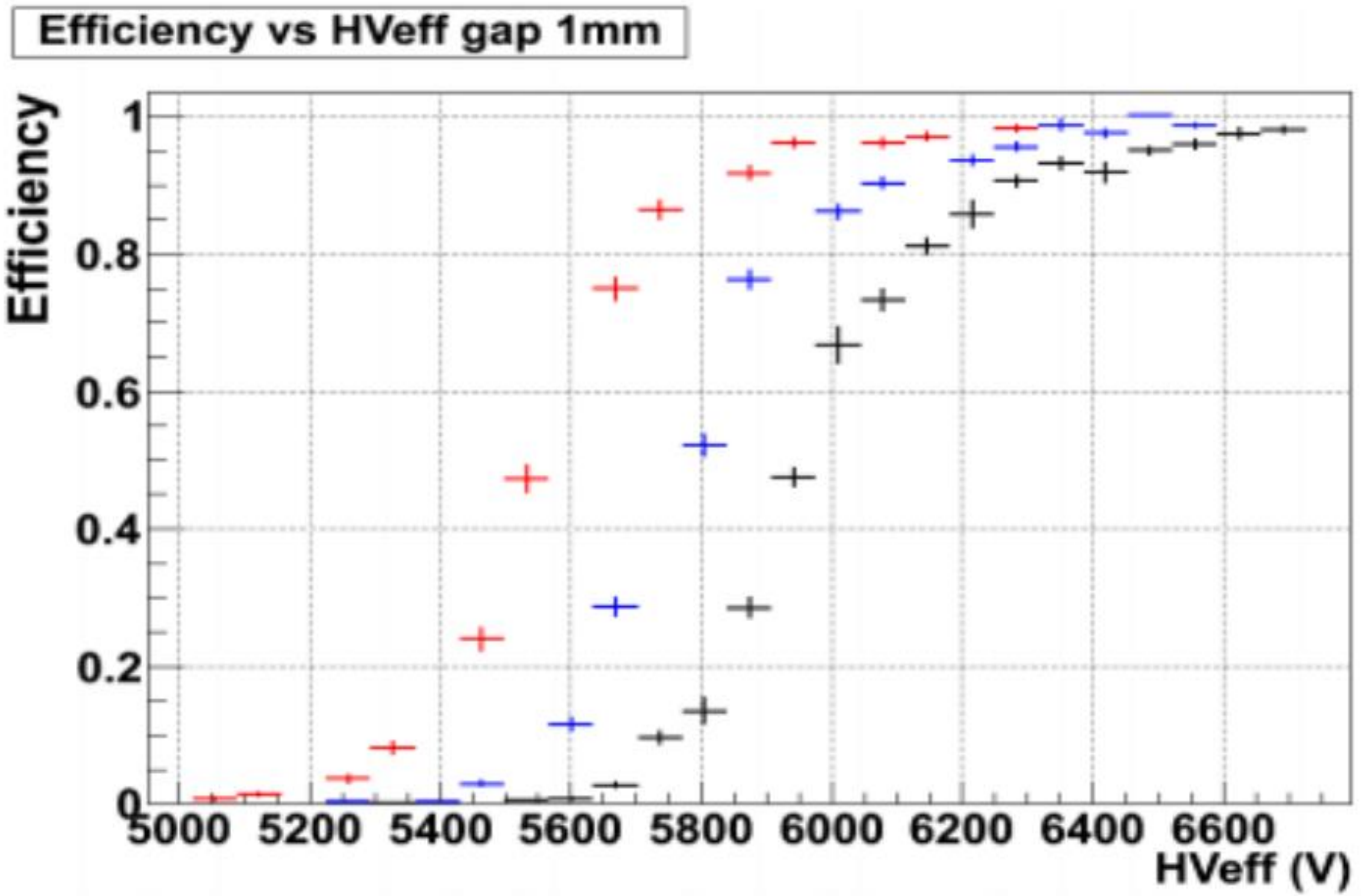


Figure 3. Efficiency curves RPC 1mm gap. In red SiGe FE; in blue Si FE; in black oscilloscope analysis with 1.5mV threshold.

Self-iduced noise effect in the discriminator

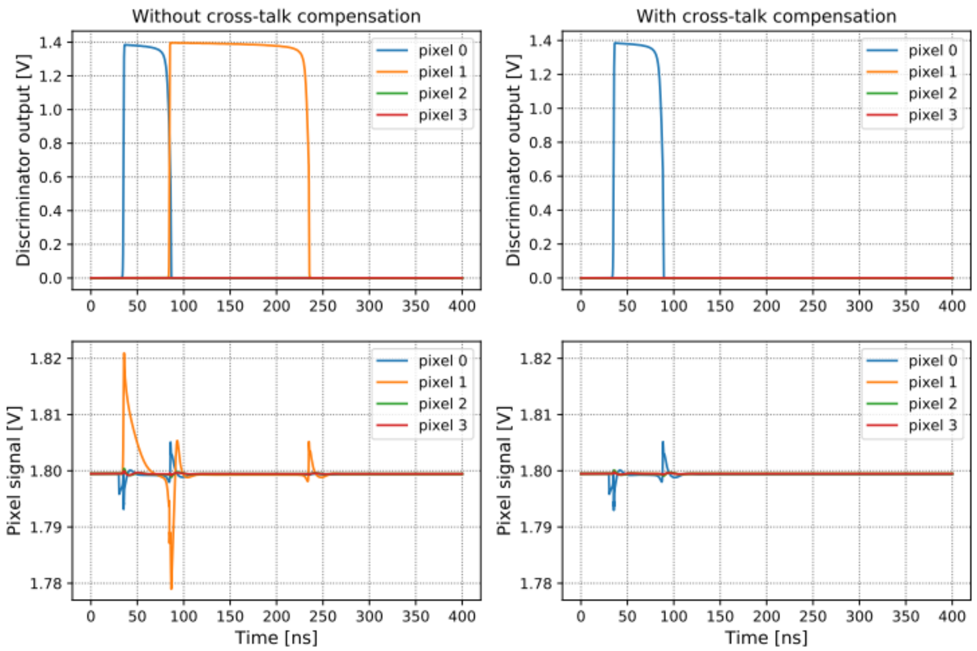


Figure 7: Discriminator output and pixels signal with (right) and without (left) cross-talk protection lines for an input charge of 0.5 fC.

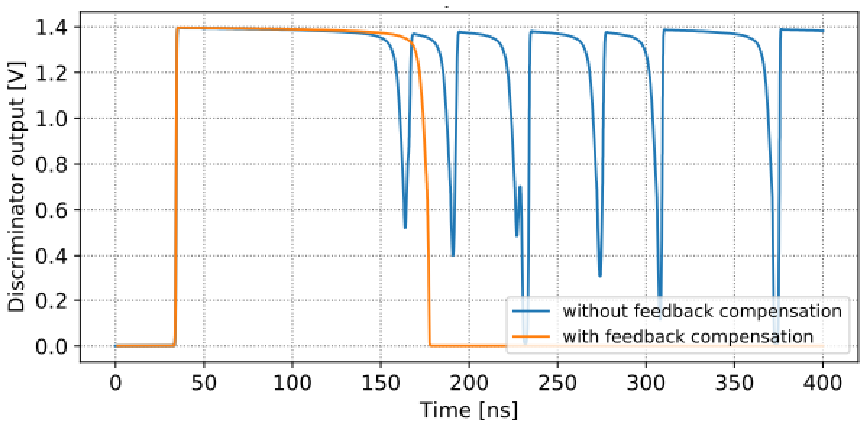
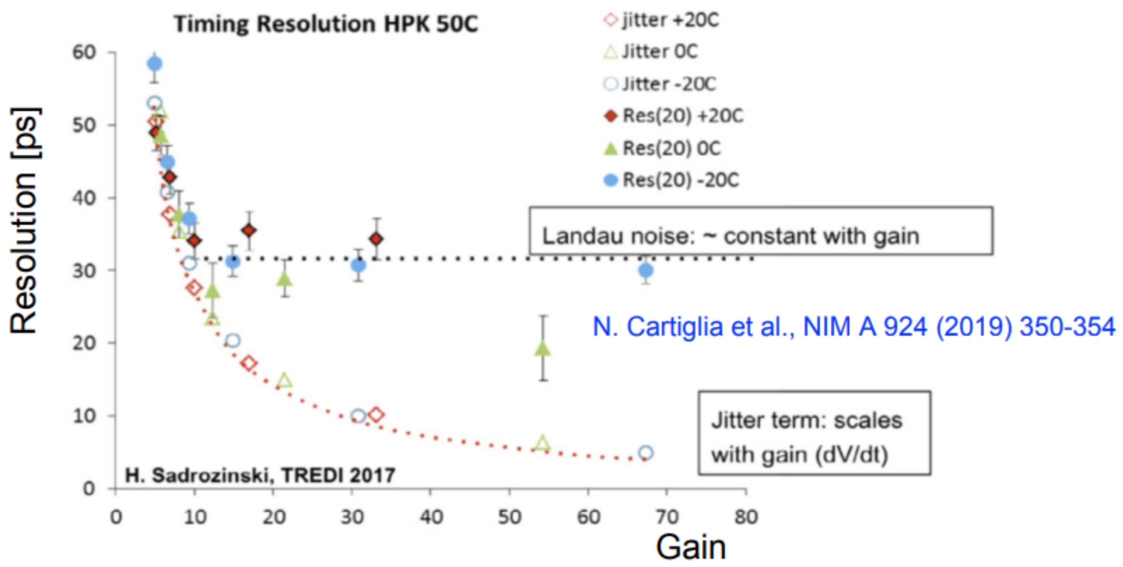


Figure 8: Discriminators output behaviour with (orange) and without (blue) self-induced noise compensation lines.

Limit in the time resolution for Landau noise proposed by **Lorenzo Paolozzi** (**Geneva University**)

2. Charge-collection (or Landau) noise



Charge collection noise represents an intrinsic limit to the time resolution for a semiconductor PN-junction detector.

~30 ps reached by present LGAD sensors.

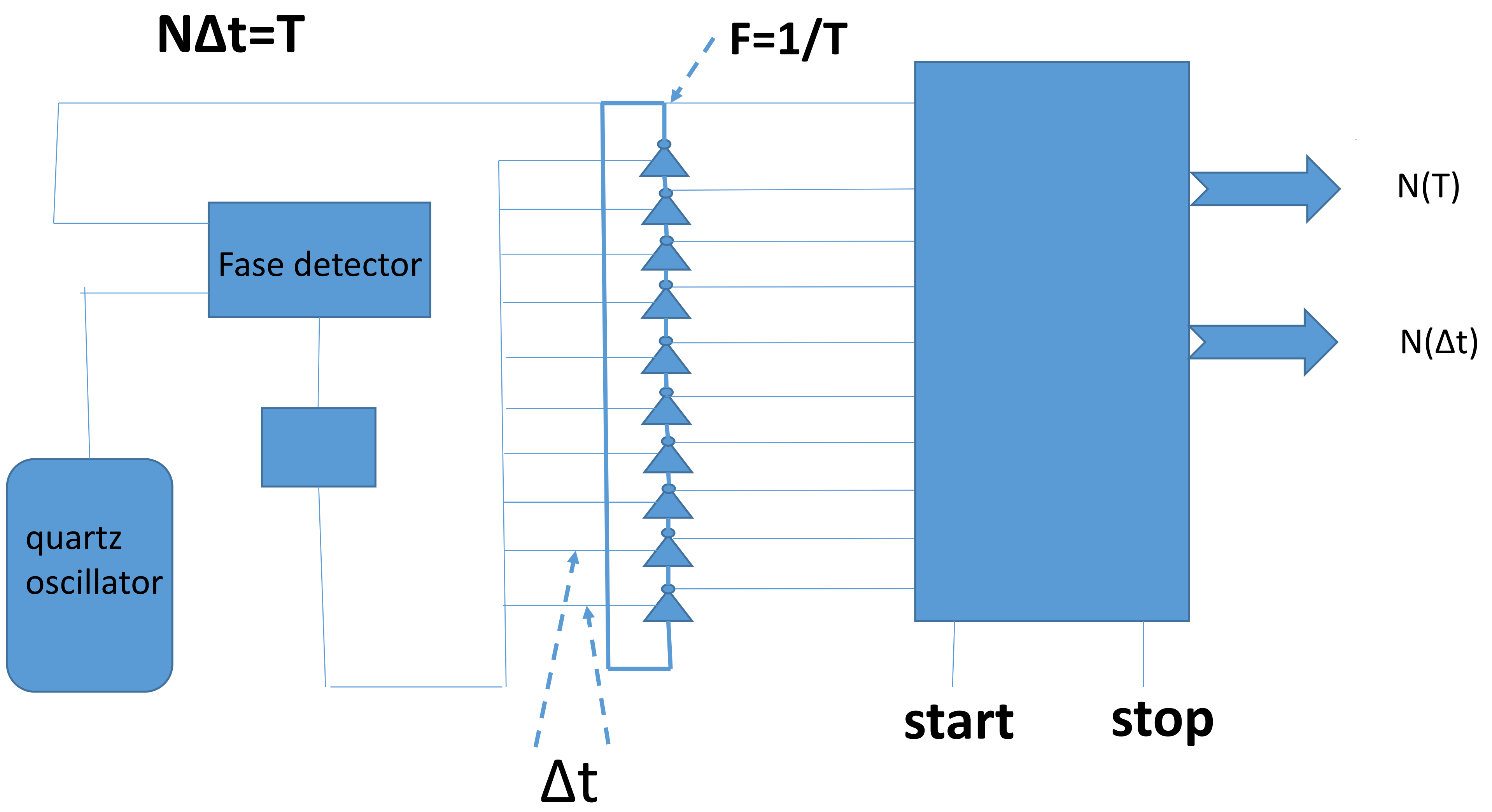
Lower contribution from sensors without internal gain

TDC basic circuit

- The TDC circuit are divided in two :

1) Digital for high dynamic
2) Analog for high precision
3) Combination for digital and Analog

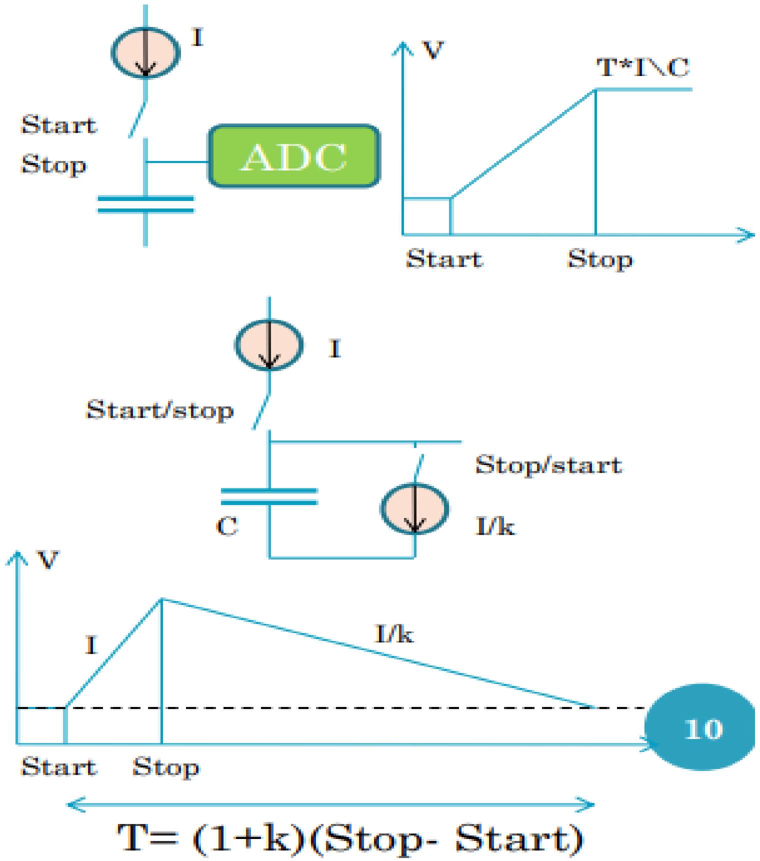
TDC Digital


NΔt=T
F=1/T
Fase detector
quartz
oscillator
Δt
start
stop
N(T)
N(Δt)

Analog TDC

Time to Amplitude

- Time to Amplitude Conversion: TAC
  - Classical type high resolution TDC implemented with discrete components
  - Delicate analog design
  - Requires ADC
  - Slow conversion time –> dead time
  - Not using same reference as coarse time
- Dual slope Wilkinson ADC/TDC
  - Time stretcher
  - Measure stretched time with counter
  - Slow: Analog de-randomizer
  - Example: NA62 GTK in-pixel design



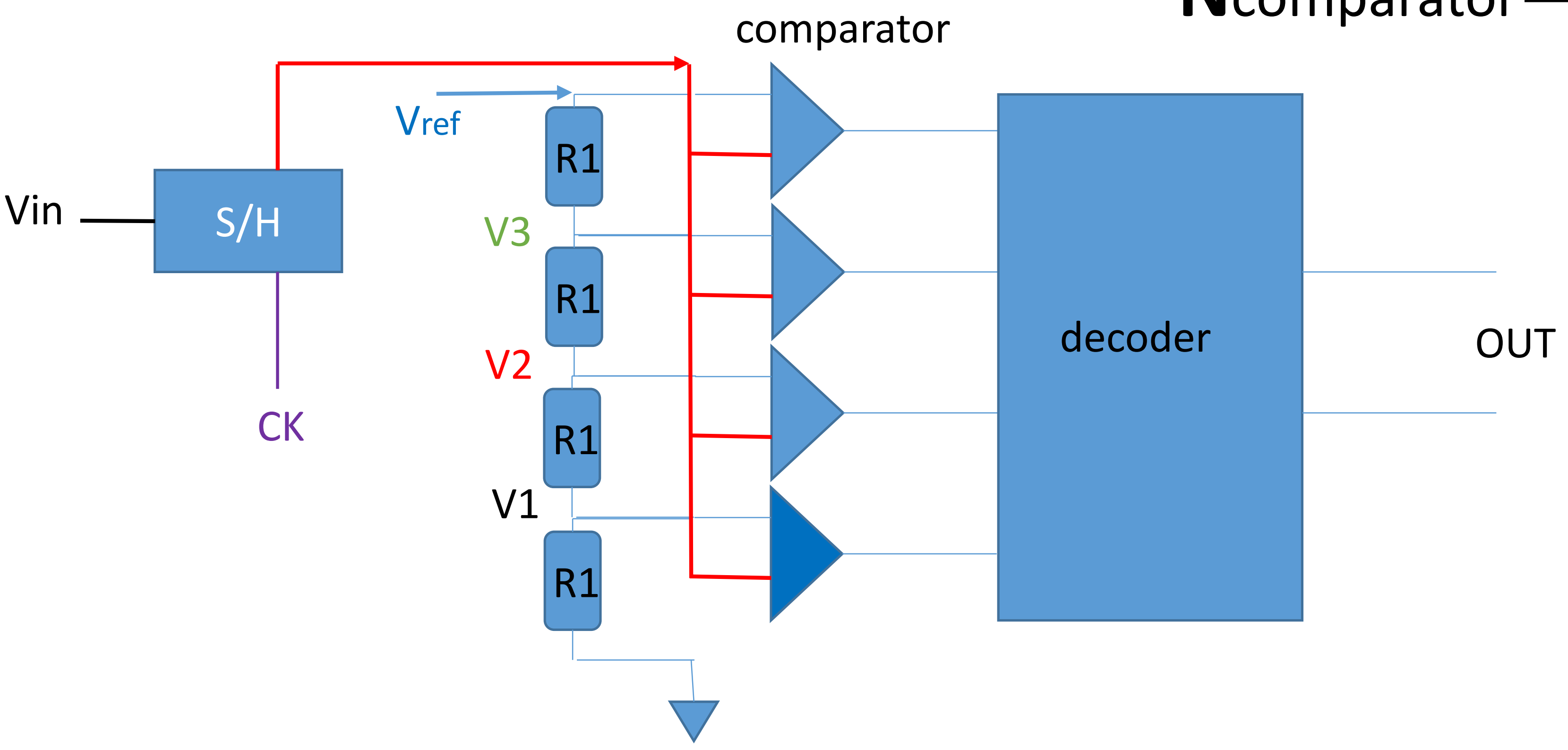
Different type of ADC

- Flash ADC: very fast and very low dead time lo dynamic
- Conversion ADC: very High dead time and dynamic

Flash ADC 4bit

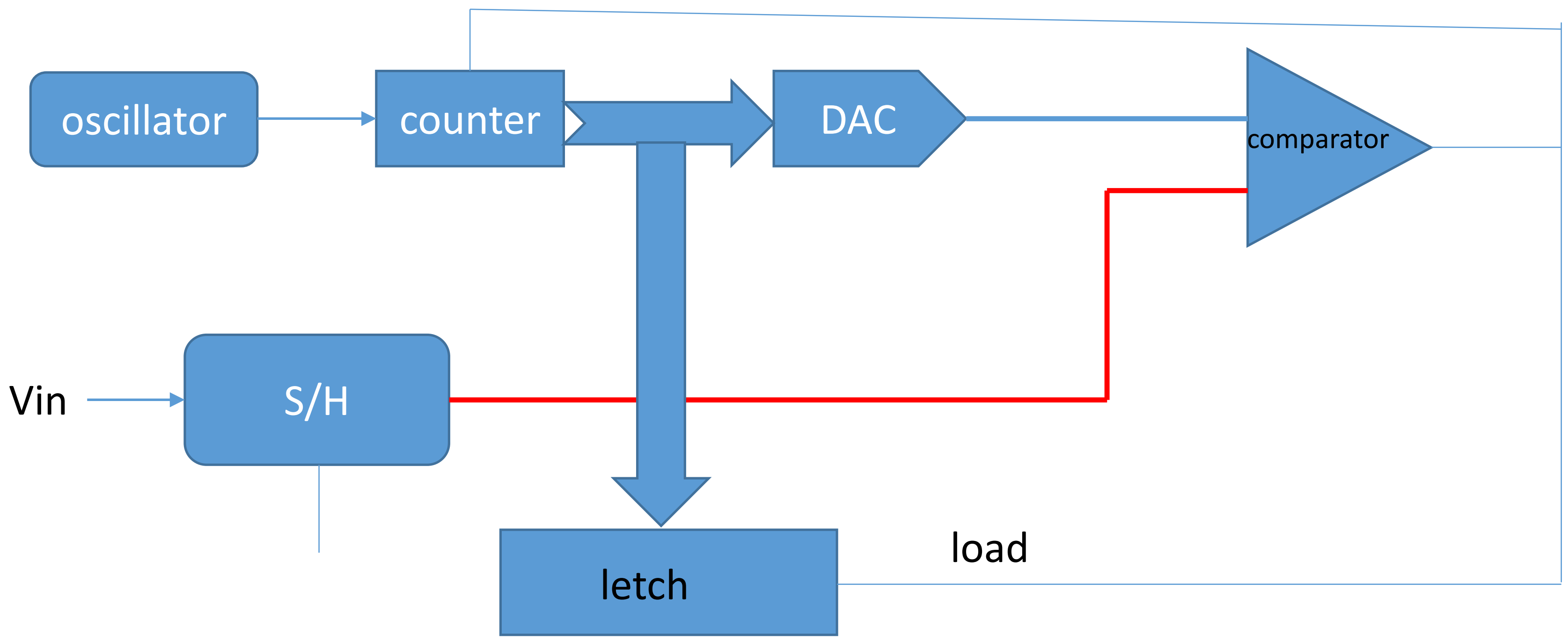
Vref > Vin > 0

$\mathbf{N}_{comparator} = \mathbf{2}^{Nbit}$



V1	V2	V3	Vref
0	1	0	1
0	0	1	1

Conversion ADC



conclusions

- Increase the gain in the amplifier of front-end is mandatory for high rate application, low noise
- The performance of the discriminator is mandatory for very low threshold
- The SiGe is very promising (BCMOS IHP technology)

designing a front end for maximum performance

requires

a very accurate knowledge of the detector