Timing Performance of Silicon and Diamond Tracking Systems

- The “4D” challenge
- Aide memoire on time resolution
- Properties of a sensor for good timing measurements
- Approaches: APD, Diamond, and LGAD
- Merging timing and position measurements
- Electronics
- Future directions

The **4D** challenge

Is it possible to build a detector with concurrent excellent time and position resolution?

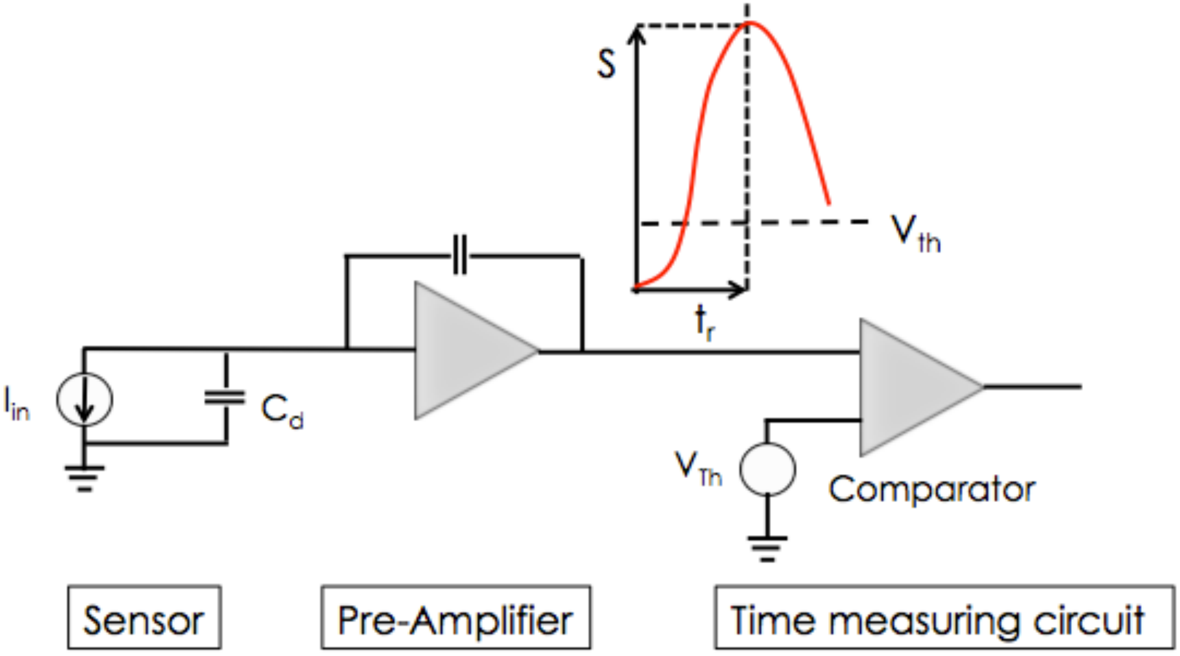
Can we provide in the same detector and readout chain:

- **Ultra-fast timing resolution [~ 10 ps]**
- **Precision location information [10's of μm]**

The challenge
is not
to achieve excellent time resolution,
but
it is to merge timing and tracking.

A time-tagging detector

(a simplified view)



Time is set when the signal crosses the comparator threshold

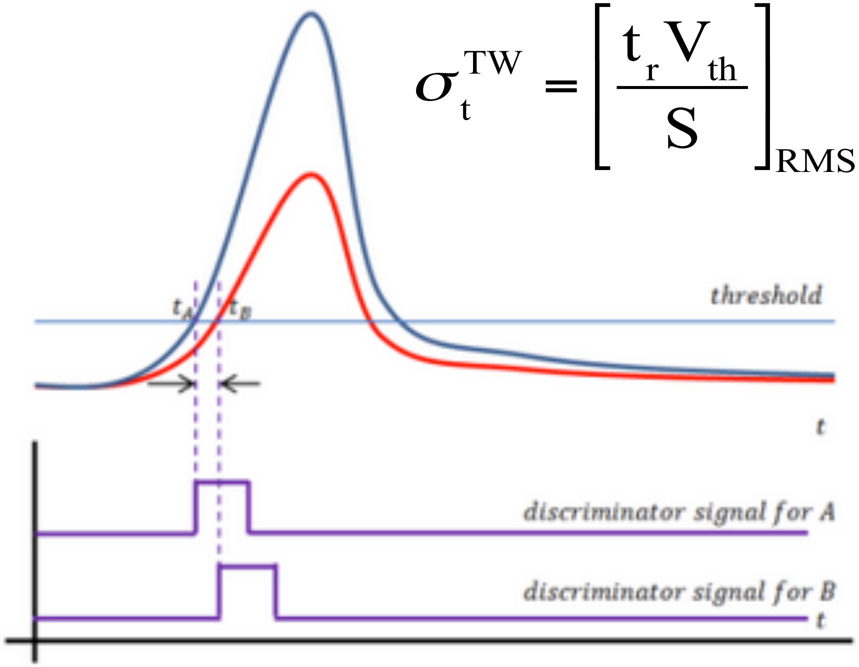
The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning.

Noise source: Time walk and Time jitter

Time walk: the voltage value V_{th} is reached at different times by signals of different amplitude

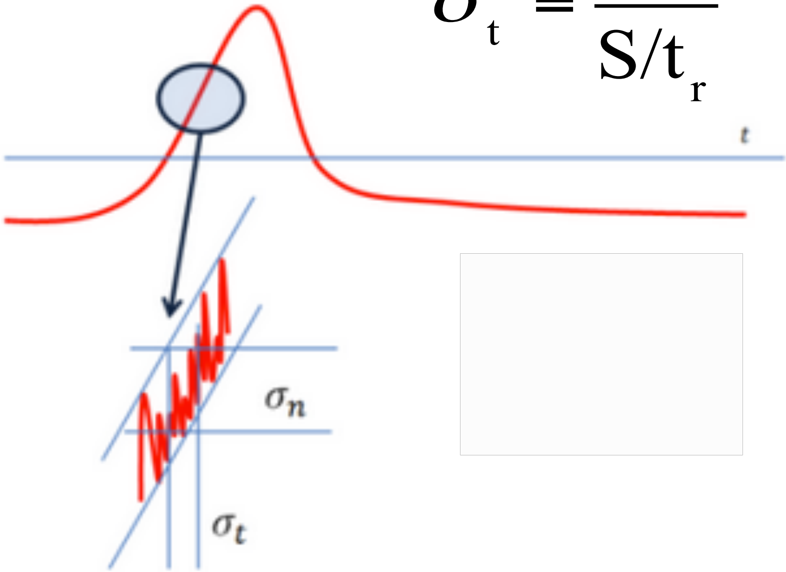
Jitter: the noise is summed to the signal, causing amplitude variations

$$\sigma_t^{TW} = \left[\frac{t_r V_{th}}{S}\right]_{RMS}$$



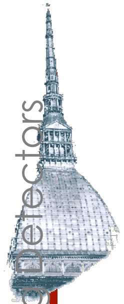
Due to the physics of signal formation

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



Mostly due to electronic noise

$$\sigma_{Total}^2 = \sigma_{Jitter}^2 + \sigma_{\text{Time Walk}}^2 + \sigma_{TDC}^2$$



Time Resolution and slew rate

Using the expressions in the previous page, we can write

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

where:

- t_r = signal rise time
- S/t_r = dV/dt = slew rate
- N = system noise
- V_{th} = 10 N

Assuming constant noise, to minimize time resolution
we need to maximize the S/t_r term
(i.e. the slew rate dV/dt of the signal)

➔ We need large and short signals ➔

Additional complications

We need to minimize this expression:

$$\sigma_t^2 = \left(\left[\frac{V_{th}}{S/t_r}\right]_{RMS}\right)^2 + \left(\frac{N}{S/t_r}\right)^2$$

But we also need:

- Very fine segmentation to provide position resolution
- Thin, low material budget to fit in a tracker
- Light
- A-magnetic
- Radiation resistant
- Cheap
- Reliably available

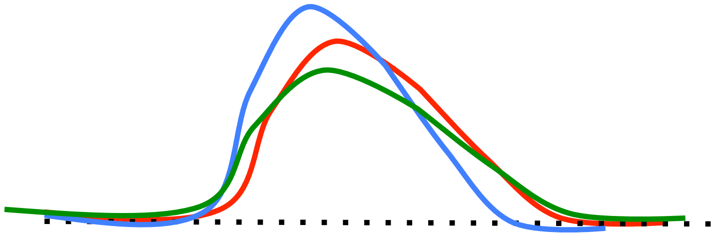
Key to good timing: uniform signals

Signal shape is determined by Ramo's Theorem:

$$i \propto qvE_w$$

Drift velocity

Weighting field



A key to good timing is the uniformity of signals:

Drift velocity and **Weighting field** need to be **as uniform as possible**

Drift Velocity

$$i \propto q \boxed{v} E_w$$

- ➔ Highest possible E field to saturate velocity
- ➔ Highest possible resistivity for velocity uniformity

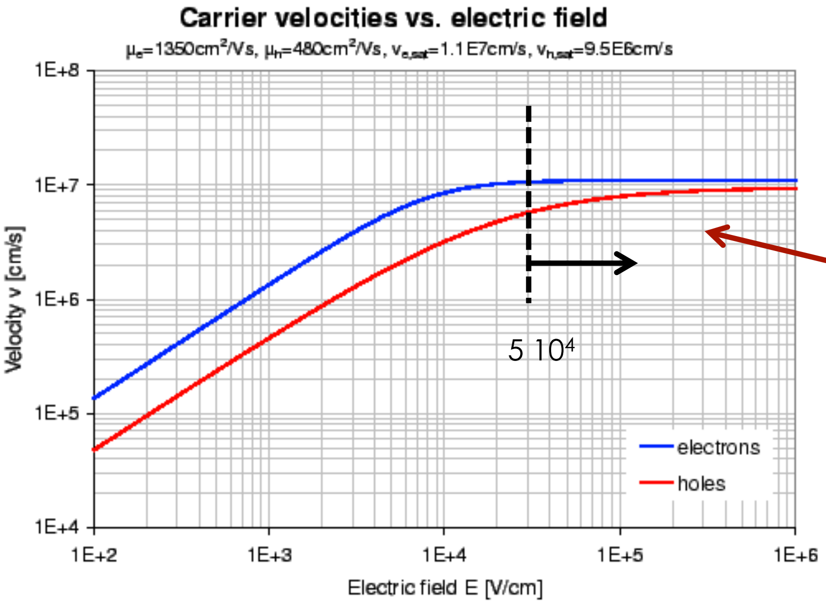


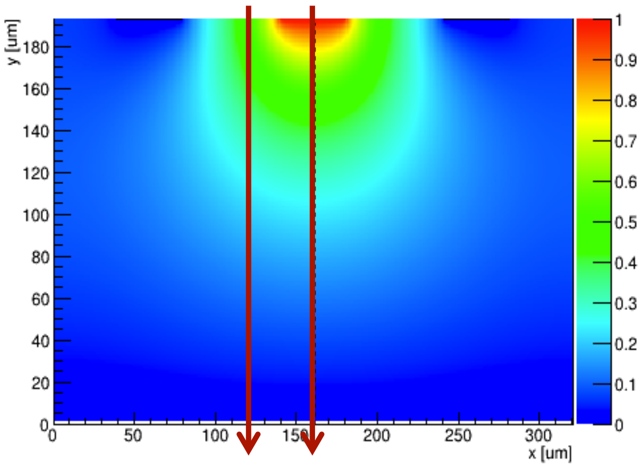
Figure: Electron and hole velocities vs. the electric field strength in silicon.

We want to operate in this regime

Weighting Field: coupling the charge to the electrode

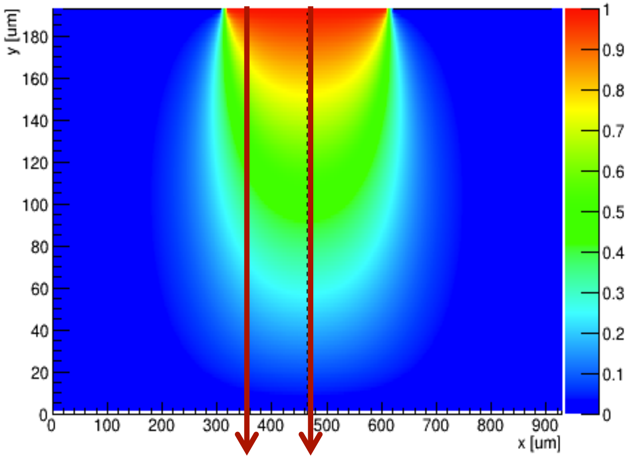
$$i \propto qv\boxed{E_w}$$

Strip: 100 μm pitch, 40 μm width



Bad: almost no coupling away from the electrode

Pixel: 300 μm pitch, 290 μm width



Good: strong coupling almost all the way to the backplane

The weighting field needs to be as uniform as possible, so that the coupling is always the same, regardless of the position of the charge

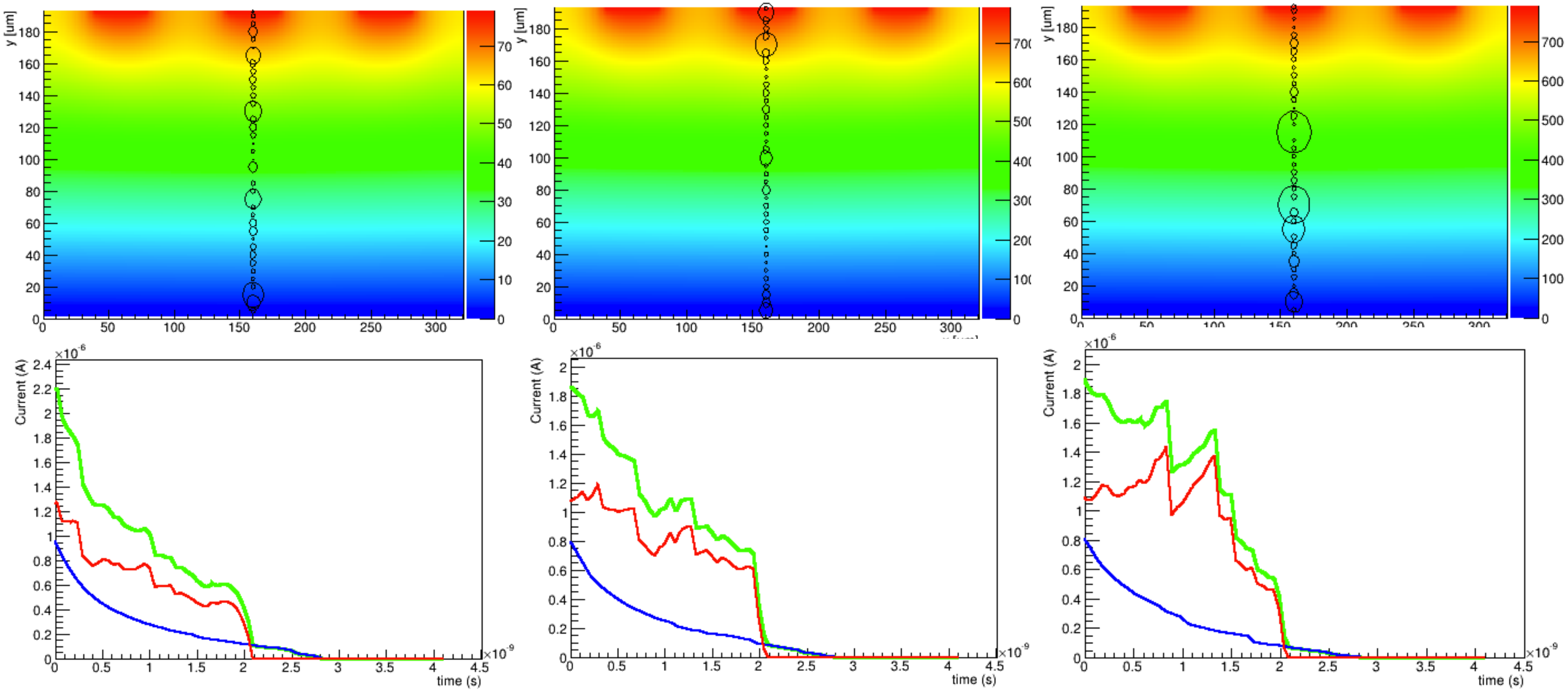
Electrode width ~ pixel pitch > sensor thickness

Non-Uniform Energy deposition

Landau Fluctuations cause two major effects:

- Amplitude variations, that can be corrected with time walk compensation
- For a given amplitude, the charge deposition is non uniform.

These are 3 examples of this effect:



Basic requests for good timing performance

A sensor should be designed to have:

1. **Large signal**
2. **Short rise time**
3. Parallel plate – like geometries for **uniform weighting field**
4. High electric field to **maximize the drift velocity**
5. Very **uniform E field**
6. Small size to keep the **capacitance low**
7. Small volumes to keep the **leakage current low**

Possible approaches

We need to minimize this expression:

$$\sigma_t^2 = \left(\left[\frac{V_{th}}{S/t_r}\right]_{RMS}\right)^2 + \left(\frac{N}{S/t_r}\right)^2$$

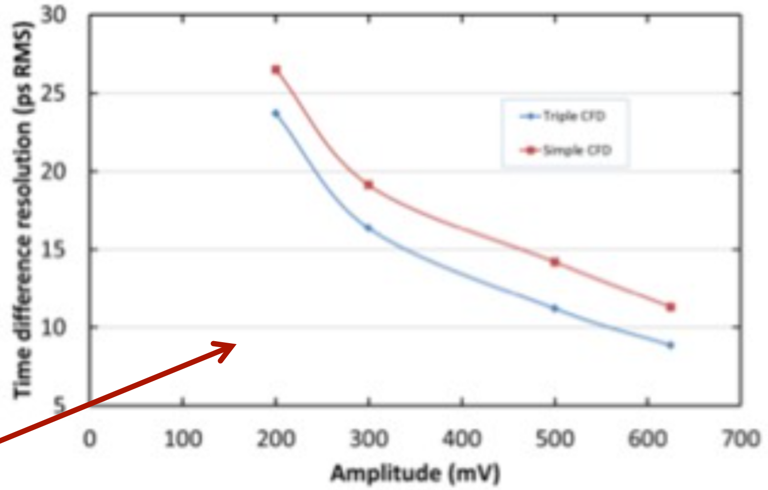
- **APD** (silicon with gain ~ 100): maximize S
    - Very large signal

- **Diamond:** minimize N, minimize t_r
    - Large energy gap, very low noise, low capacitance
    - Very good mobility, short collection time t_r

- **LGAD** (silicon with gain ~ 10): minimize N, moderate S
    - Low gain to avoid shot noise and excess noise factor

The APD approach

The key to this approach is the large signal: if your signal is large enough, everything becomes easy.



So far they reported:

- Excellent time resolution
- Good radiation resistance up to < 10^{14} neq/cm^2
- They will propose a system for the CT-PPS

See:

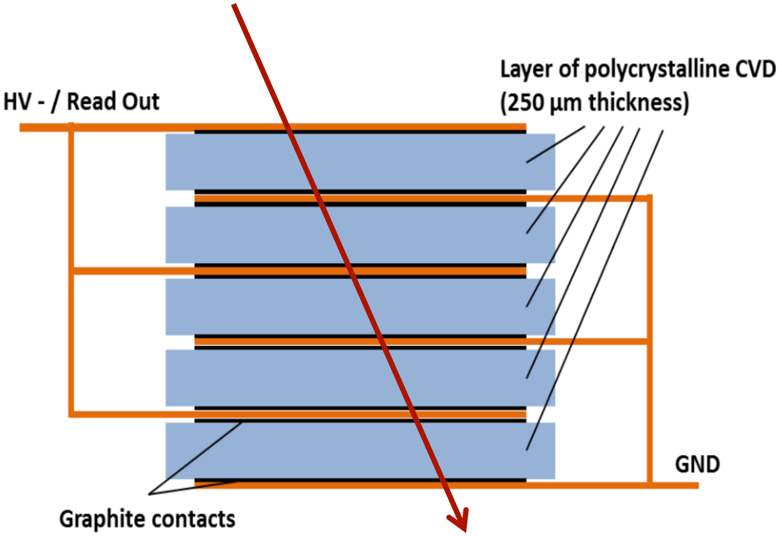
https://indico.cern.ch/event/363665/contribution/7/material/slides/0.pdf

The Diamond approach - I

Diamond detectors have small signal: two ways of fighting this problem

1) Multilayer stack

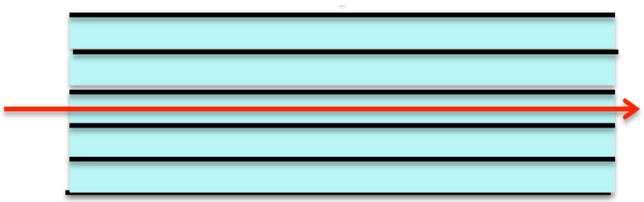
The signal is increased by the sum of many layers while it keeps very short rise time



Best resolution: ~ 100 ps

2) Grazing

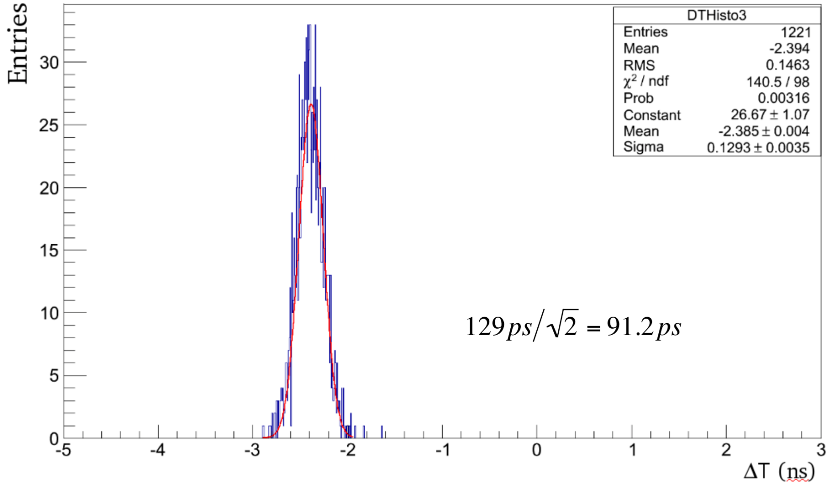
The particle crosses the diamond sensor along the longitudinal direction



The Diamond approach - II

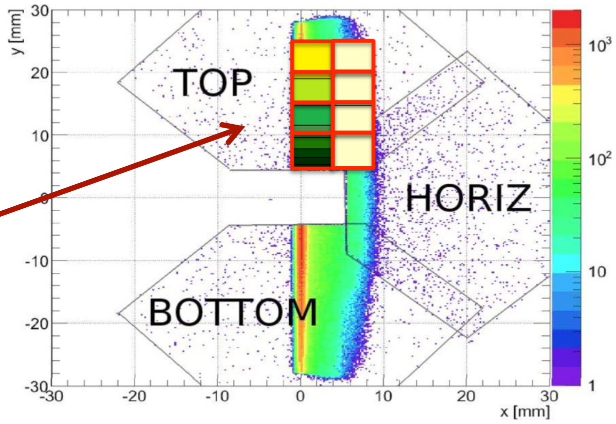
TOTEM collaboration: couple diamond detector with a tailored front-end and a full digitizing readout (SAMPIC, Switching Capacitor Sampler)

Excellent results at a very recent testbeam with ~ 4.5 x 4.5 mm^2 detectors



$$129ps/\sqrt{2} = 91.2ps$$

The result allows TOTEM to introduce timing measurement is their Roman Pot set-up:
Vertical top pots used for timing



The "Low-Gain Avalanche Detector" approach

Is it possible to manufacture a silicon detector that looks like a normal pixel or strip sensor, but with a much larger signal (RD50)?

- 750 e/h pair per micron instead of 75 e/h?
- Finely Segmented
- Radiation hard
- No dead time
- Very low noise (low shot noise)
- No cross talk
- Insensitive to single, low-energy photon

Many applications:

- Low material budget (signal in 30 micron == signal 300 micron)
- Excellent immunity to charge trapping (larger signal, shorter drift path)
- Very good S/N: 5-10 times better than current detectors
- Good timing capability (large signal, short drift time)

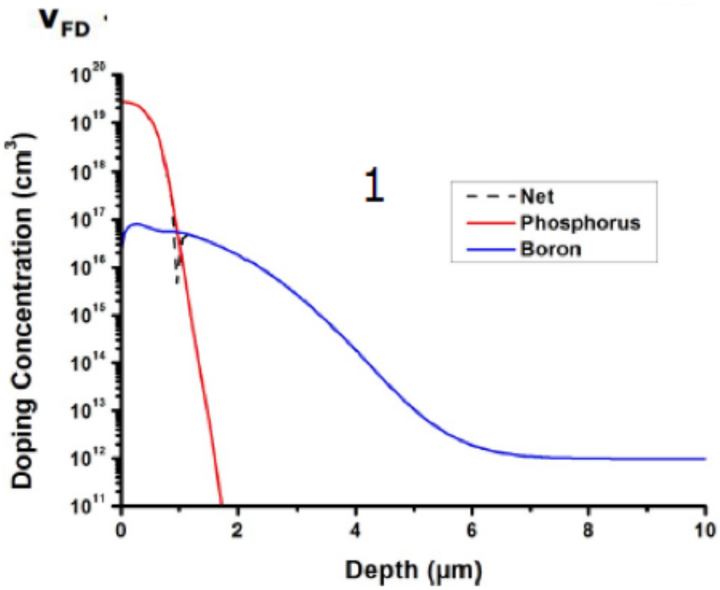
Low Gain Avalanche Detectors (LGADs)

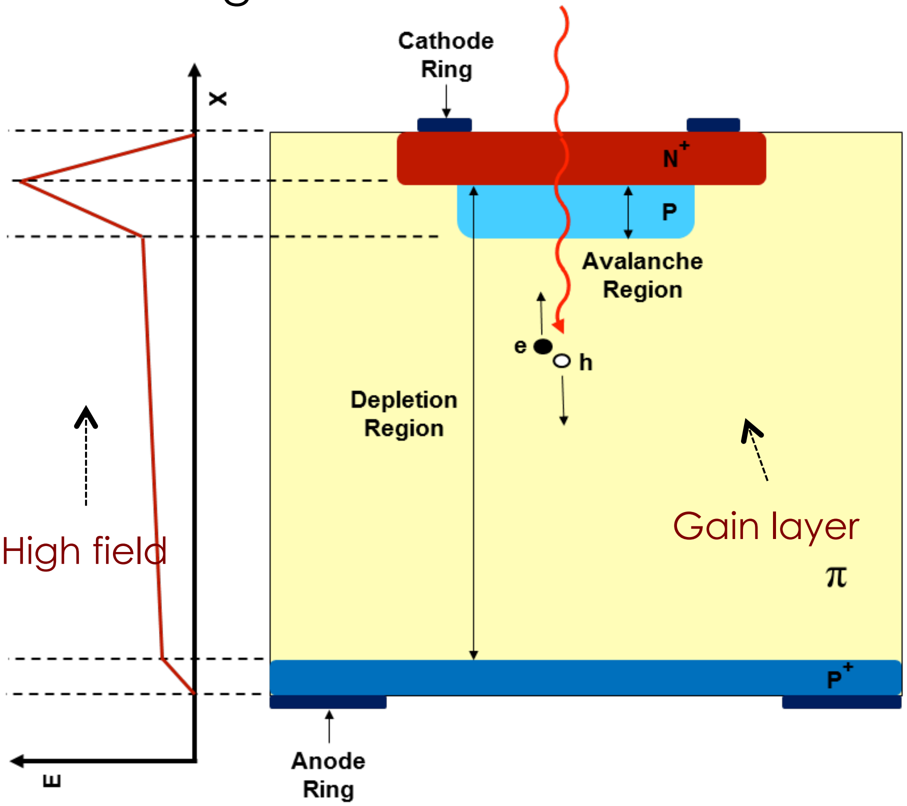
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage



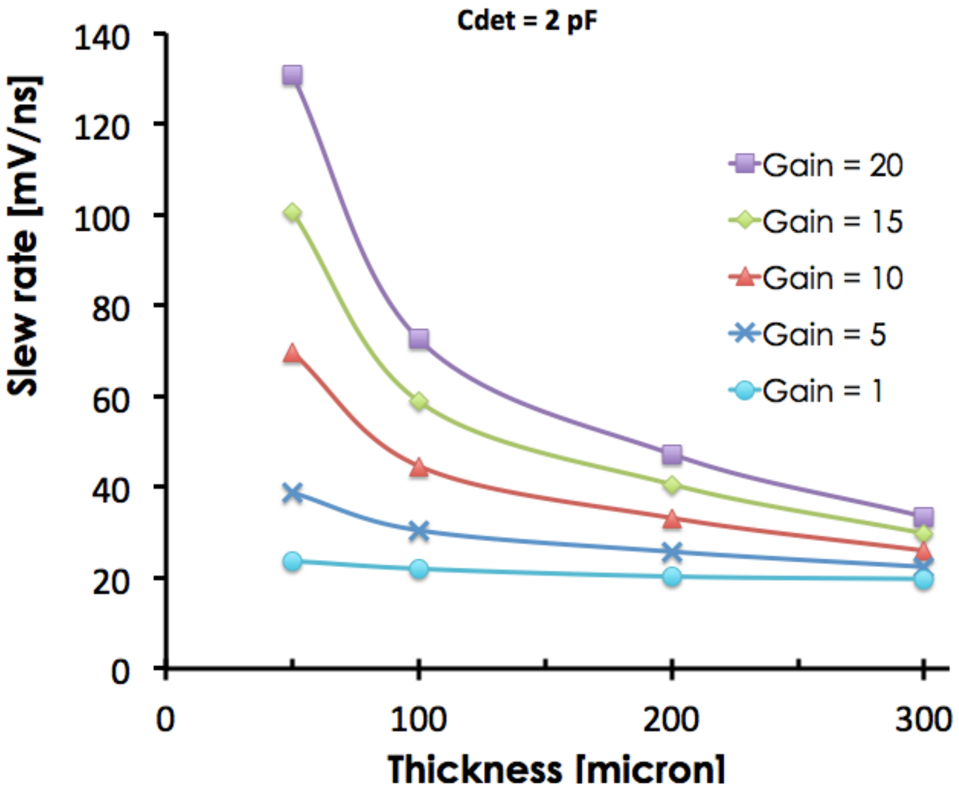


LGAD: Gain current vs Initial current

$$\frac{di_{gain}}{i} \propto \frac{dN_{Gain} q v_{sat} \frac{k}{d}}{k q v_{sat}} = \frac{75(v_{sat} dt) G q v_{sat} \frac{k}{d}}{k q v_{sat}} \propto \boxed{\frac{G}{d}} dt$$

!!!

➔ Go thin!!



(Real life is a bit more complicated, but the conclusions are the same)

Full simulation

(assuming 2 pF detector capacitance)

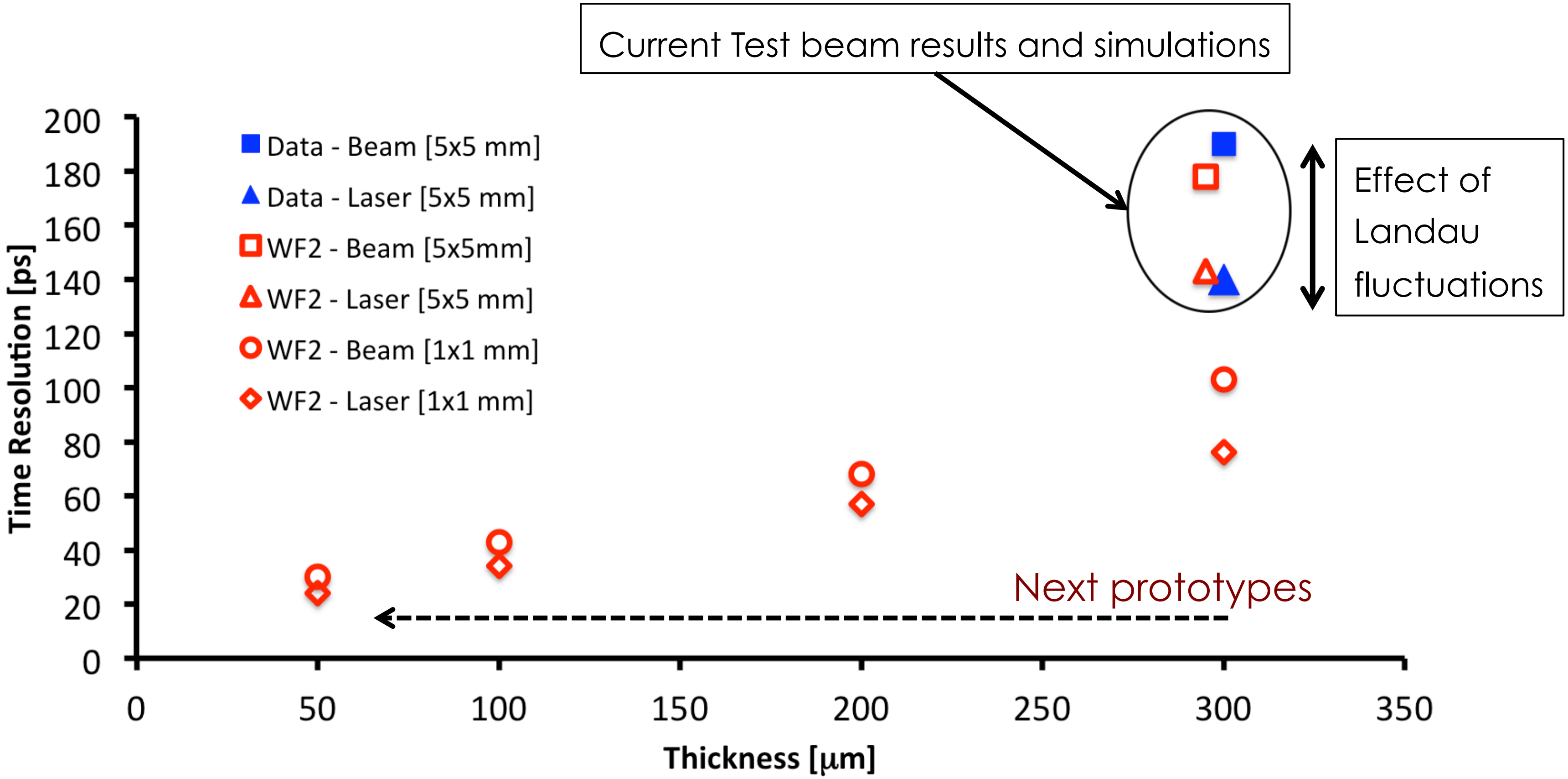
300 micron:
~ 2-3 improvement
with gain = 20

Significant improvements in time resolution require thin detectors

LGAD: Present results and future productions

With WF2, we can reproduce very well the laser and testbeam results.

Assuming the same electronics, and 1 mm^2 LGAD pad with gain 10, we can predict the timing capabilities of the next sets of sensors.


Current Test beam results and simulations

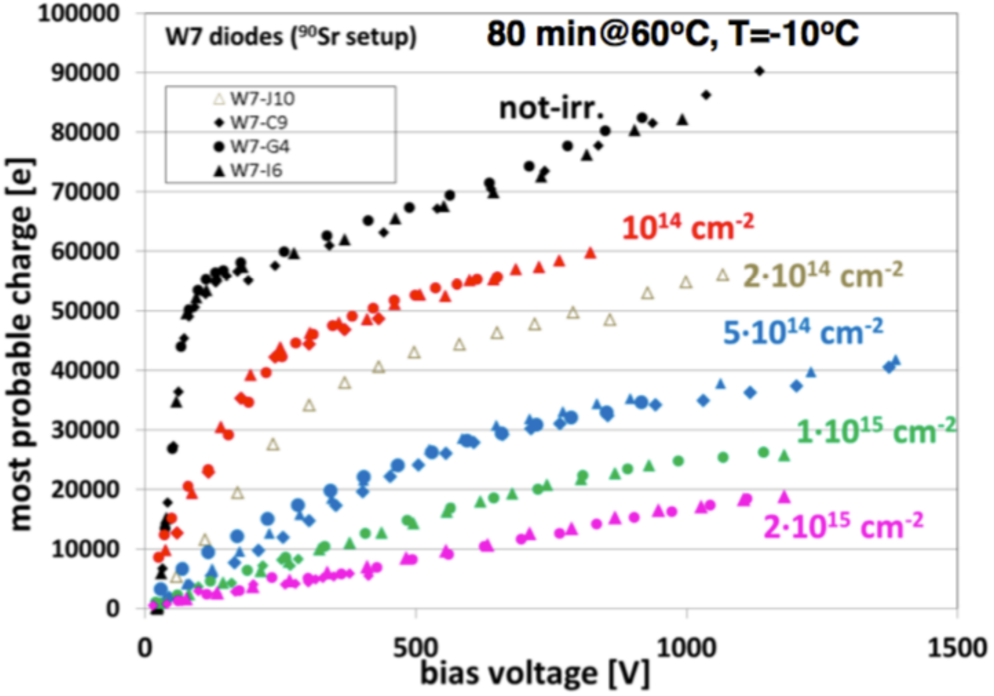
Effect of Landau fluctuations

Next prototypes

LGAD: Irradiation tests

The gain decreases with irradiations:
at 10^{14} n/cm^2 is 20% lower

➔ Most likely due to boron disappearance



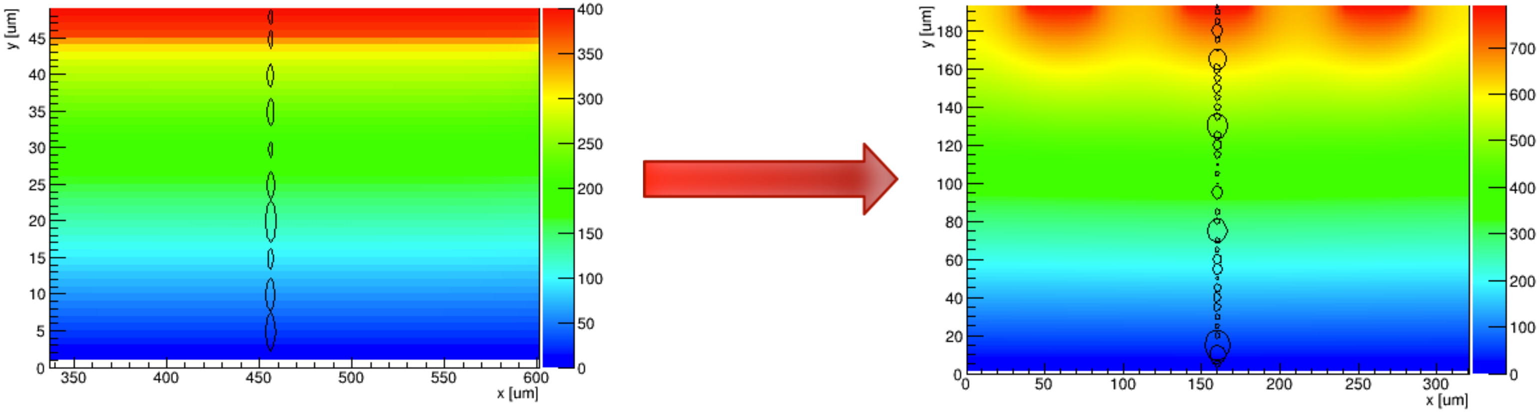
What-to-do next:

Planned new irradiation runs (neutrons, protons), new sensor geometries

Use Gallium instead of Boron for gain layer (in production now)

Merging timing with position resolution

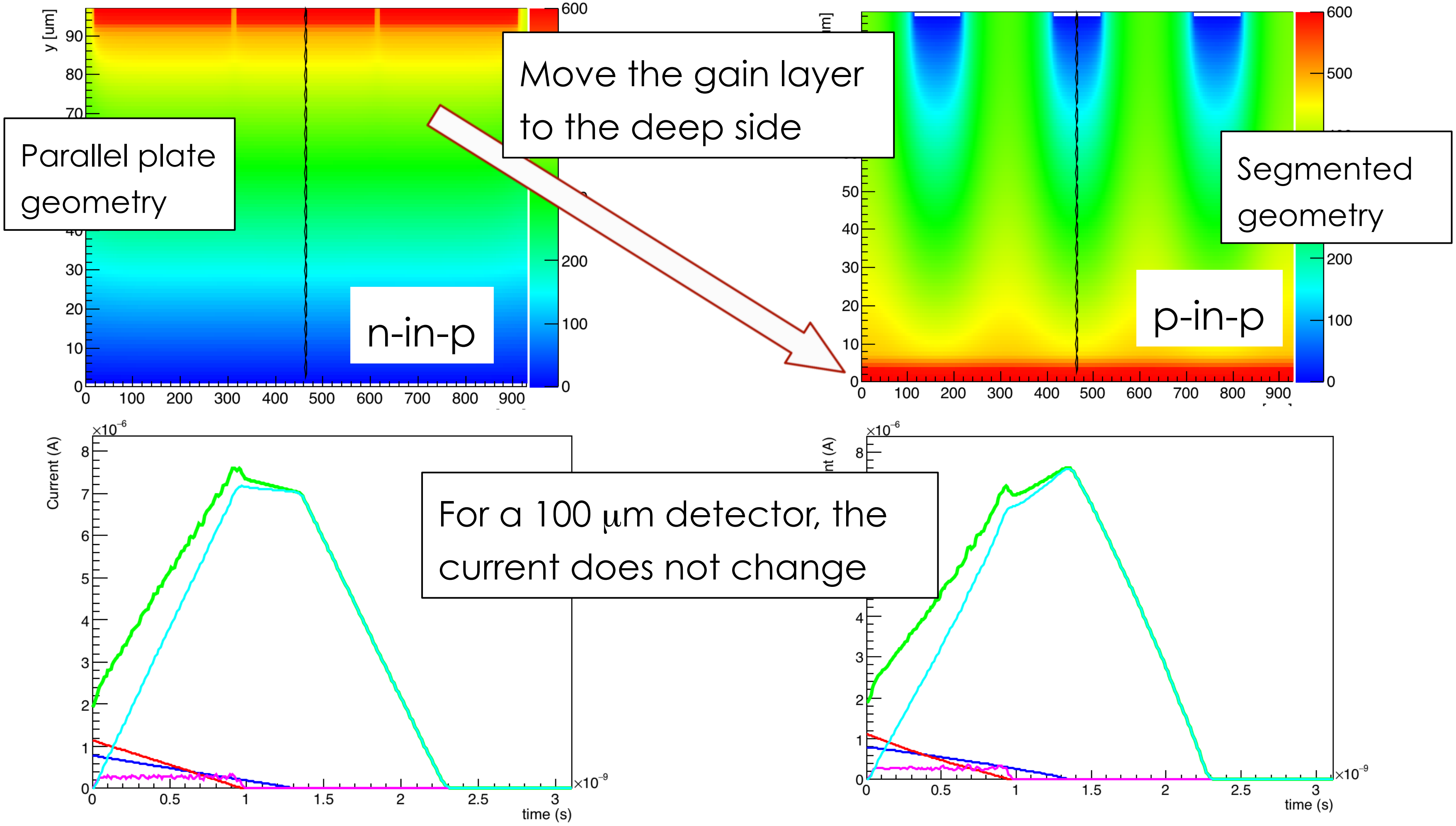
Electrode segmentation makes the E field very non uniform, and therefore ruins the timing properties of the sensor



We need to find a geometry that has very uniform E field, while allowing electrode segmentation.

1) Segmentation: buried junction

Separate the multiplication side from the segmentation side



Parallel plate geometry

n-in-p

Move the gain layer to the deep side

Segmented geometry

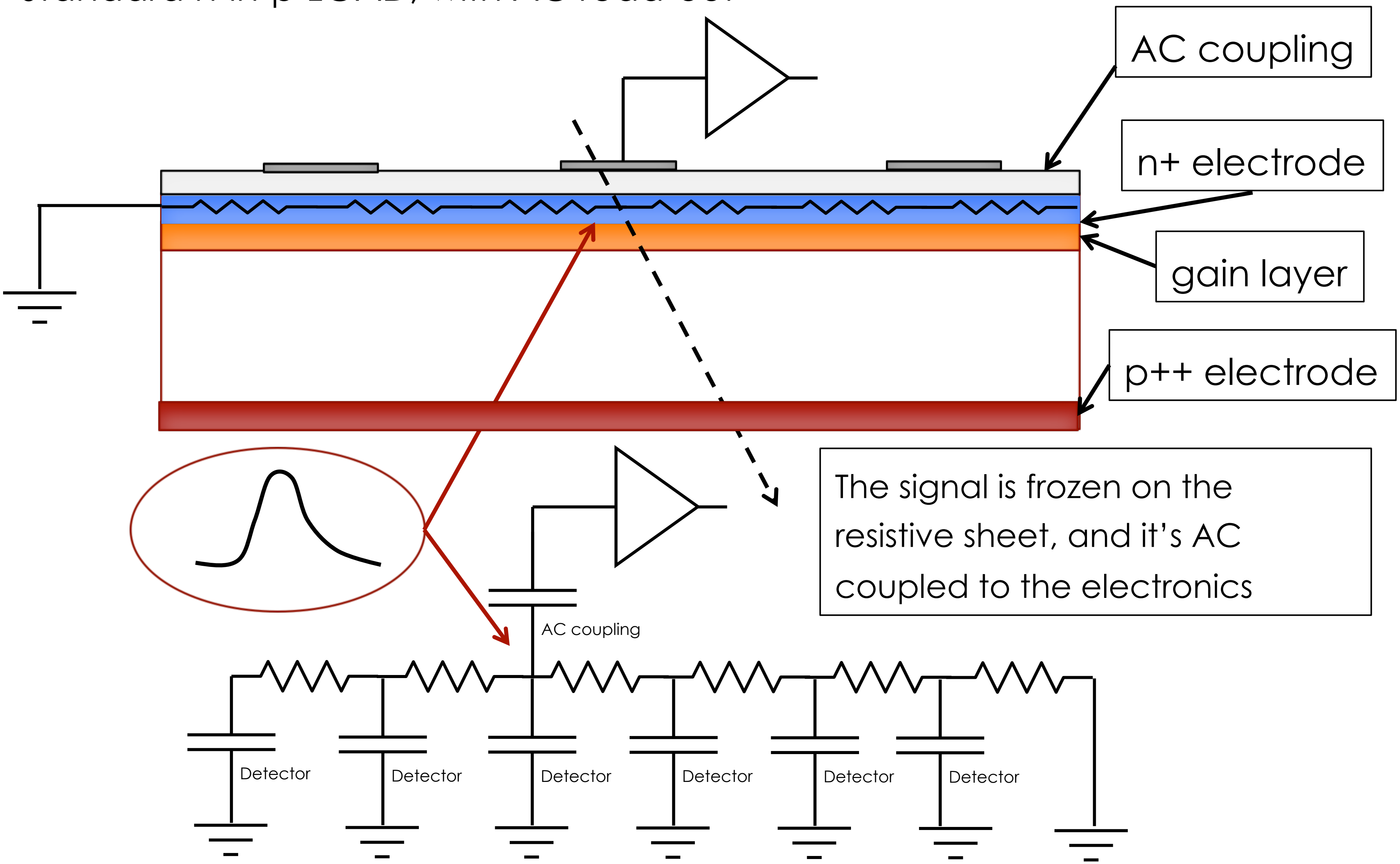
p-in-p

For a 100 μm detector, the current does not change

Moving the junction on the deep side allows having a very uniform multiplication, regardless of the electrode segmentation

2) Segmentation: AC coupling

Standard n-in-p LGAD, with AC read-out



AC coupling

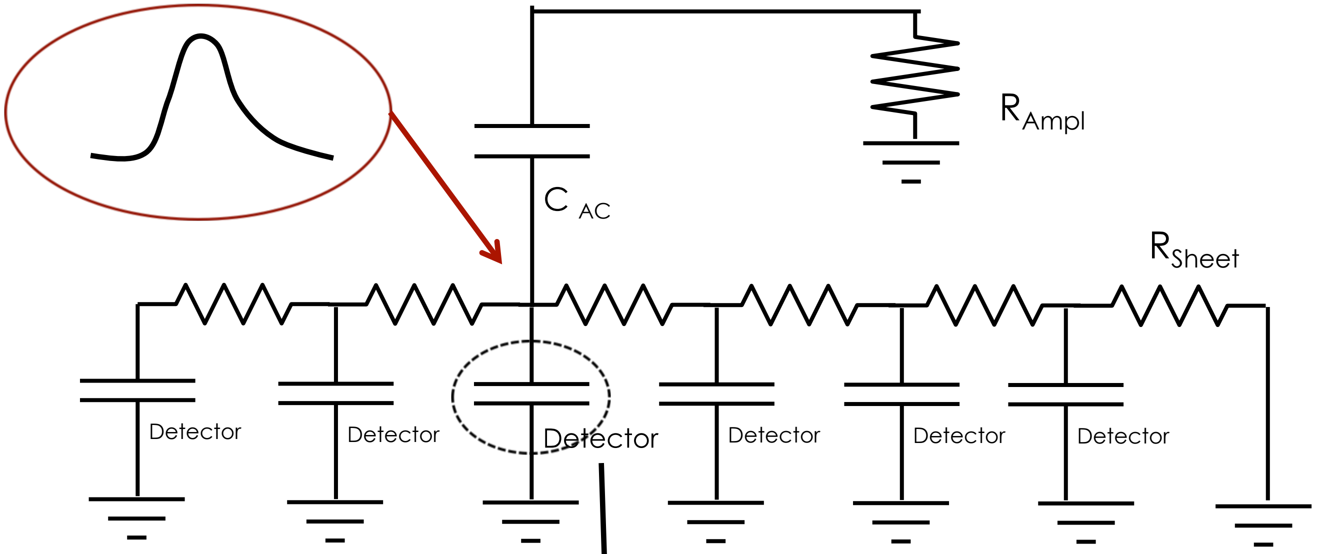
n+ electrode

gain layer

p++ electrode

The signal is frozen on the resistive sheet, and it's AC coupled to the electronics

Details of AC coupling

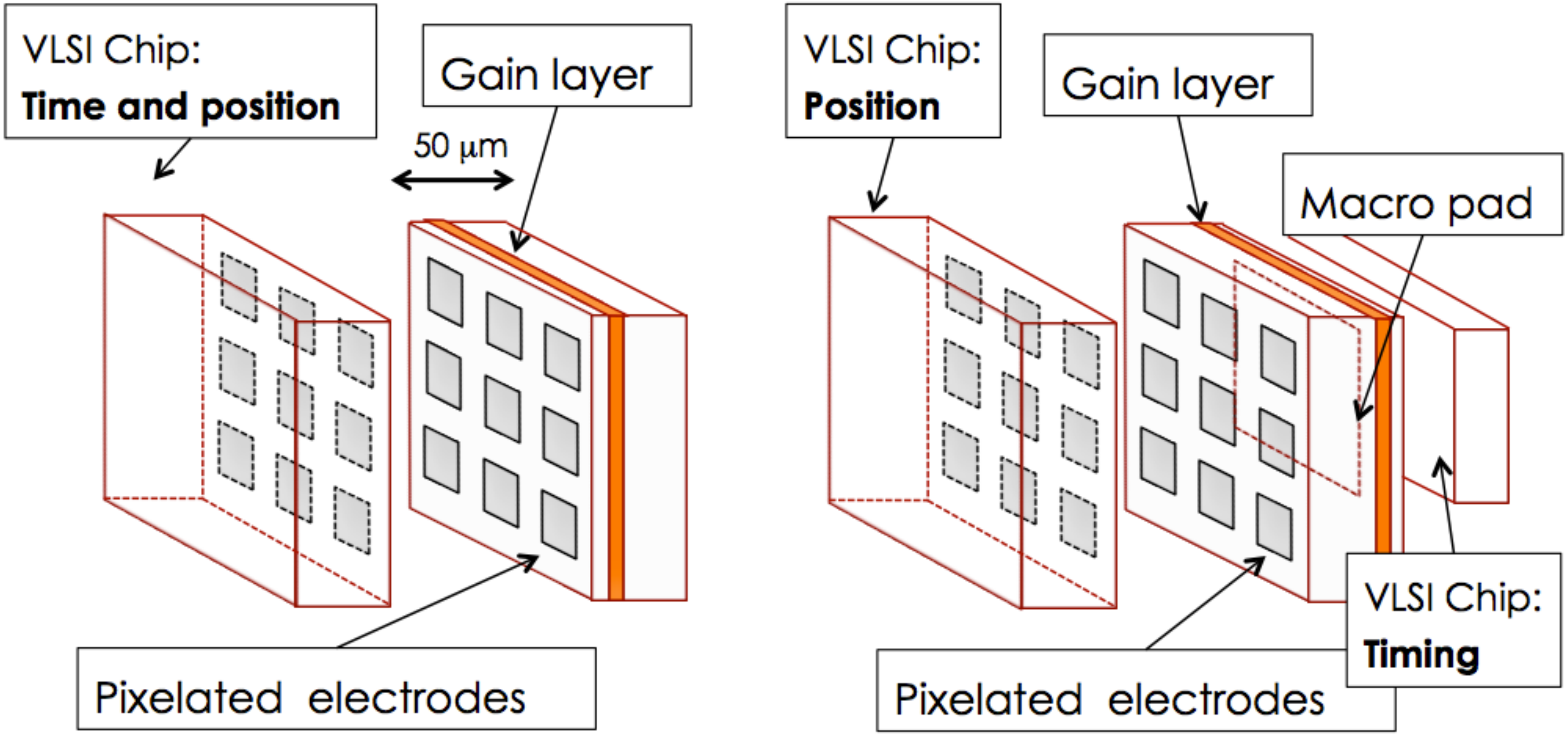


Only a small part of the detector is involved

Additional Rise time ~ $R_{Ampl} * C_{detector}$ ~ 100 Ω ∗ 1pF ~ 100 ps

Freezing time ~ $R_{Sheet} * C_{AC}$ ~ 1kΩ ∗ 100pF ~ 100 ns

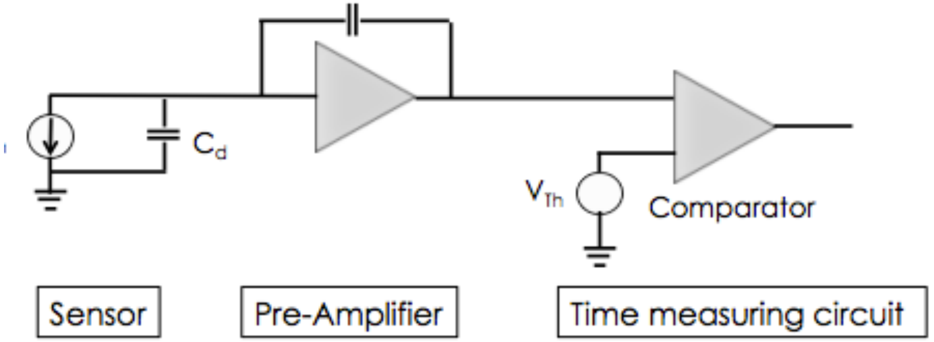
3) Segmentation: splitting gain and position measurements



The ultimate time resolution will be obtained with a custom ASIC.

However we might split the position and the time measurements

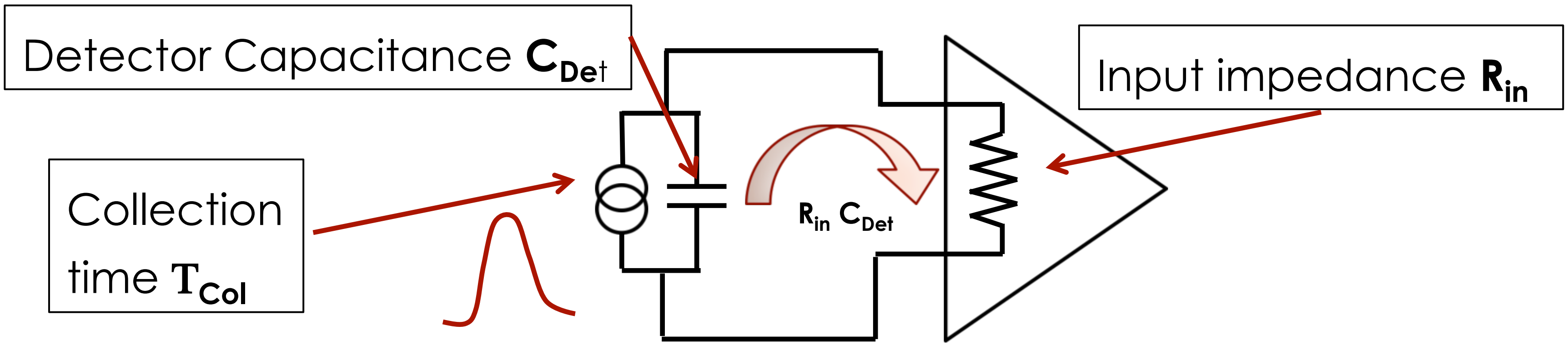
Electronics



The electronics to concurrently measure time and position is vastly more complicated than that of time or position separately.

Full integration has been achieved by NA62, on a relative small area: 300 micron pixel, 150 ps resolution.

Interplay of T_{Col} and $\tau = R_{in} C_{Det}$



Detector Capacitance C_{Det}

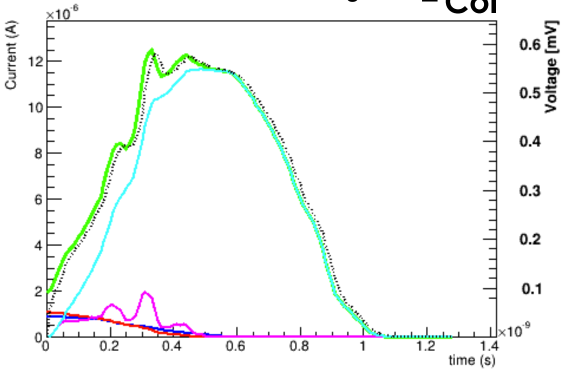
Collection time T_{Col}

Input impedance R_{in}

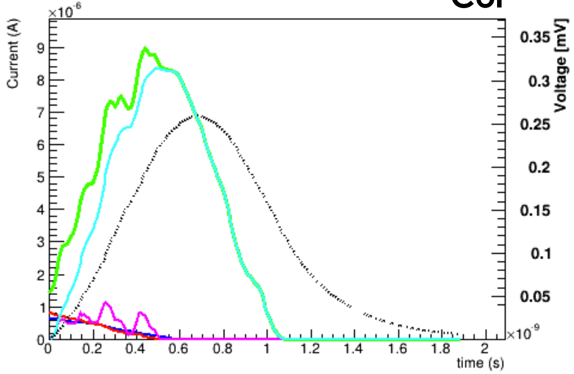
There are two time constants at play:

- T_{Col} : the signal collection time (or equivalently the rise time)
- $\tau = R_{in} C_{Det}$: the time needed for the charge to move to the electronics

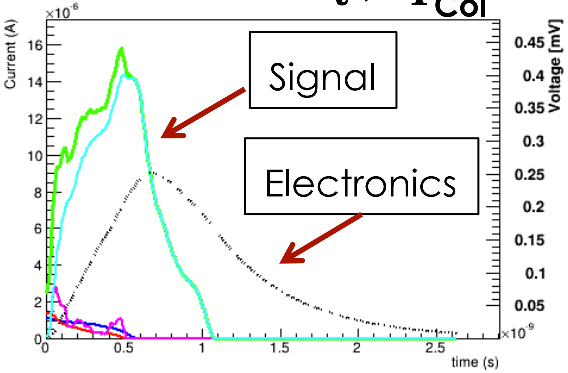
$\tau < T_{Col}$



$\tau \sim T_{Col}$



$\tau > T_{Col}$

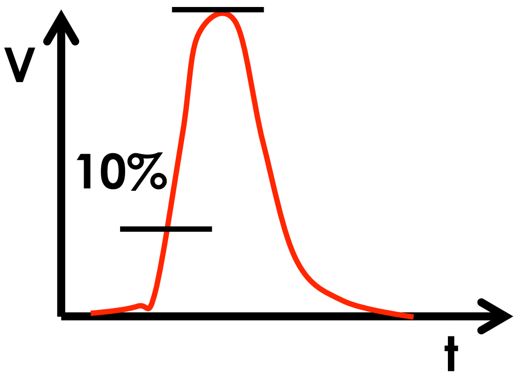


τ / T_{Col} increases ➔ dV/dt decreases

➔ Smoother current

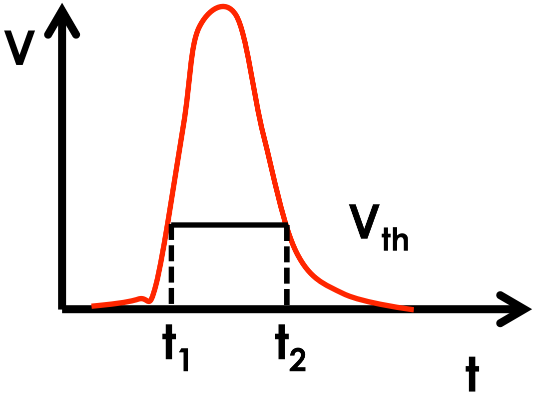
Need to find the optimum balance

Electronics for a time tagging detector



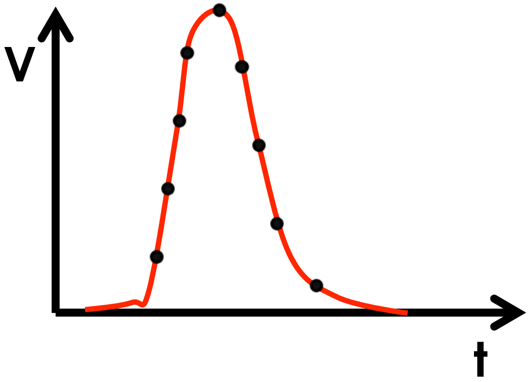
Constant Fraction Discriminator

The time is set when a fixed fraction of the amplitude is reached



Time over Threshold

The amount of time over the threshold is used to correct for time walk

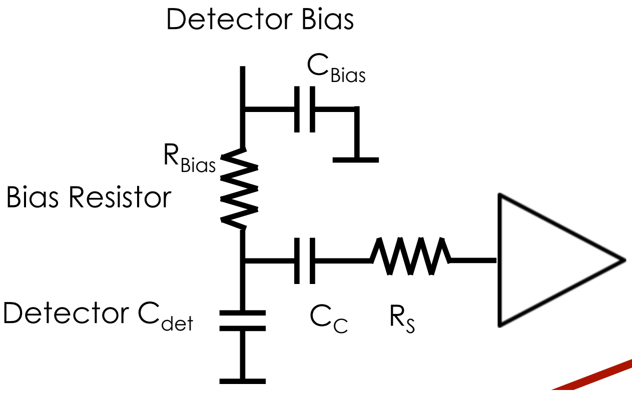


Multiple sampling

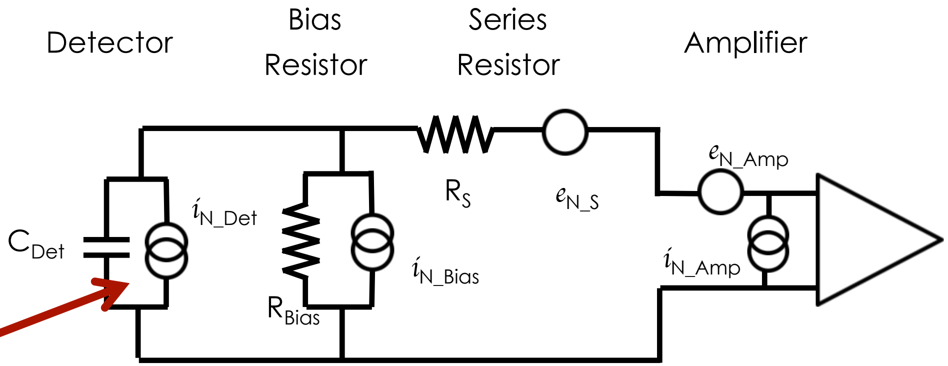
Most accurate method, needs a lot of computing power

Noise - I

Real life



Noise Model



This term, the detector current shot noise, depends on the gain

$$Q_n^2 = (2eI_{Det} + \frac{4kT}{R_{Bias}} + i^2_{N\_Amp})F_i T_s + \underbrace{(4kTR_s + e^2_{N\_Amp})F_v \frac{C^2_{Det}}{T_S}} + F_{vf} A_f C^2_{Det}$$

$$\downarrow$$

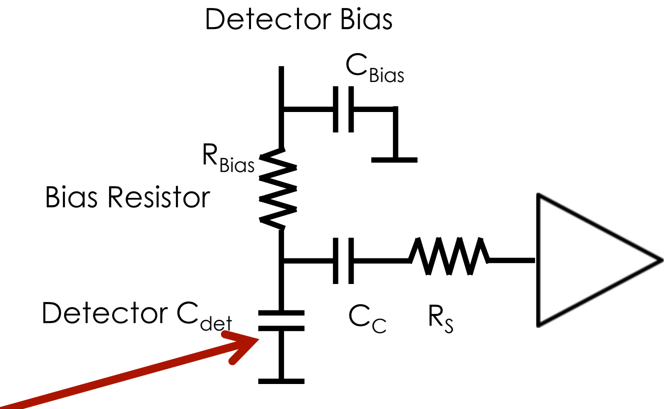
$$\boxed{2eI_{Det} * \mathrm{Gain}}$$

low gain!

This term dominates for short shaping time

Noise - II

Real life



$$ENF = kG + (2 - \frac{1}{G})(1 - k)$$

k = ratio h/e gain

NOISE DUE TO GAIN:

Excess noise factor:

low gain, very small k

Low leakage current and low gain (~ 10) together with short shaping time are necessary to keep the noise down.

Conclusions and outlook

- Excellent time resolution in a "single channel" configuration is easily achievable

- The real challenge is to merge timing and position resolution:
  - maintain the sensor characteristics needed for good timing while achieving read-out segmentation
  - keep the read-out power under control
  - radiation hard

- Maybe the solution lies in a much stronger integration of sensor and read-out, HVCMOS or similar.