

Ultra-Fast Silicon Detector

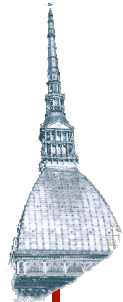
- The “4D” challenge
- A parameterization of time resolution
- The “Low Gain Avalanche Detectors” project
- Laboratory measurements
- UFSD: LGAD optimized for timing measurements
- WeightField2: a simulation program to optimize UFSD
- First measurements
- Future directions

Nicolo Cartiglia

With

INFN Gruppo V, LGAD group of RD50, FBK and Trento University, Micro-Electronics Turin group
Rome2 - INFN.

Acknowledgement



This research was carried out with the contribution of the Ministero degli Affari Esteri, “Direzione Generale per la Promozione del Sistema Paese” of Italy.



*Ministero degli Affari Esteri
e della Cooperazione Internazionale*

DIREZIONE GENERALE
PER LA PROMOZIONE DEL SISTEMA PAESE
*Unità per la cooperazione scientifica
e tecnologica bilaterale e multilaterale*

This work is currently supported by INFN Gruppo V, UFSD project (Torino, Trento Univ., Roma2, Bologna, FBK).

This work was developed in the framework of the CERN RD50 collaboration and partially financed by the Spanish Ministry of Education and Science through the Particle Physics National Program (F P A2010–22060–C 02–02 and FPA2010 – 22163 – C02 – 02).

The work at SCIPP was partially supported by the United States Department of Energy, grant DE-FG02-04ER41286.

The work is supported by HORIZON2020 Grants

The **4D** challenge

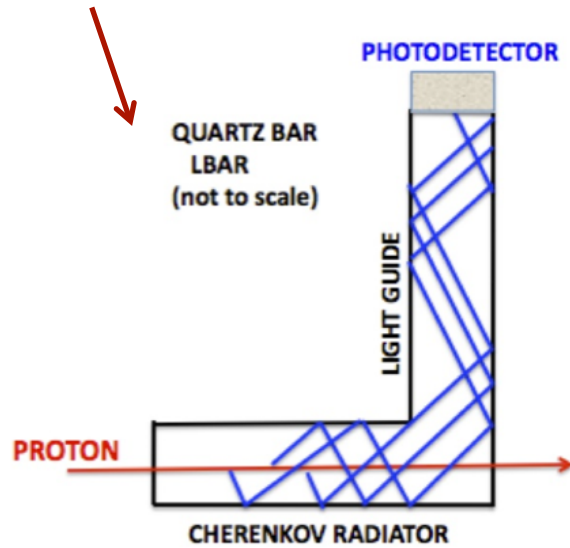
Is it possible to build a detector with concurrent excellent time and position resolution?

Can we provide in the same detector and readout chain:

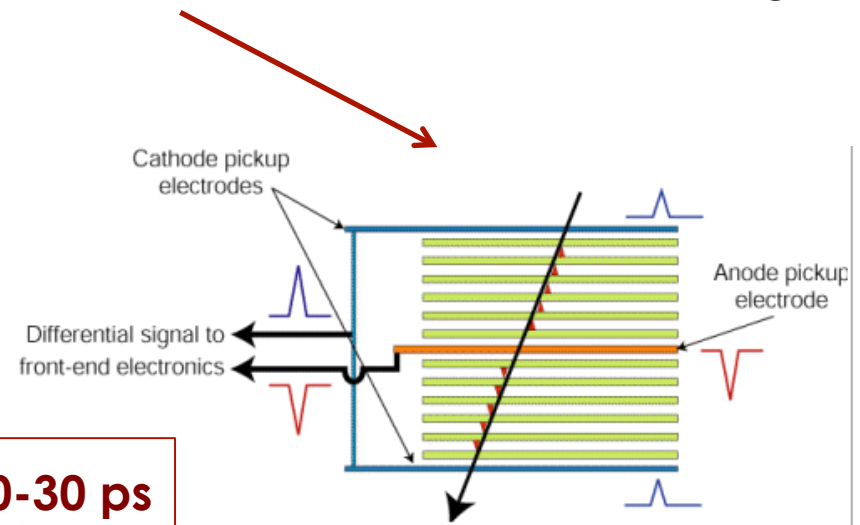
- **Ultra-fast timing resolution [~ 10 ps]**
- **Precision location information [10's of μm]**

State-of-the-art Timing Detectors

Timing detectors exploit very fast physics processes such as **Cherenkov light** emission or **electronic avalanches** to create prompt signals



CMS/ATLAS



ALICE

$$\sigma_t \sim 20-30 \text{ ps}$$
$$\sigma_x \sim 1-2 \text{ mm}$$

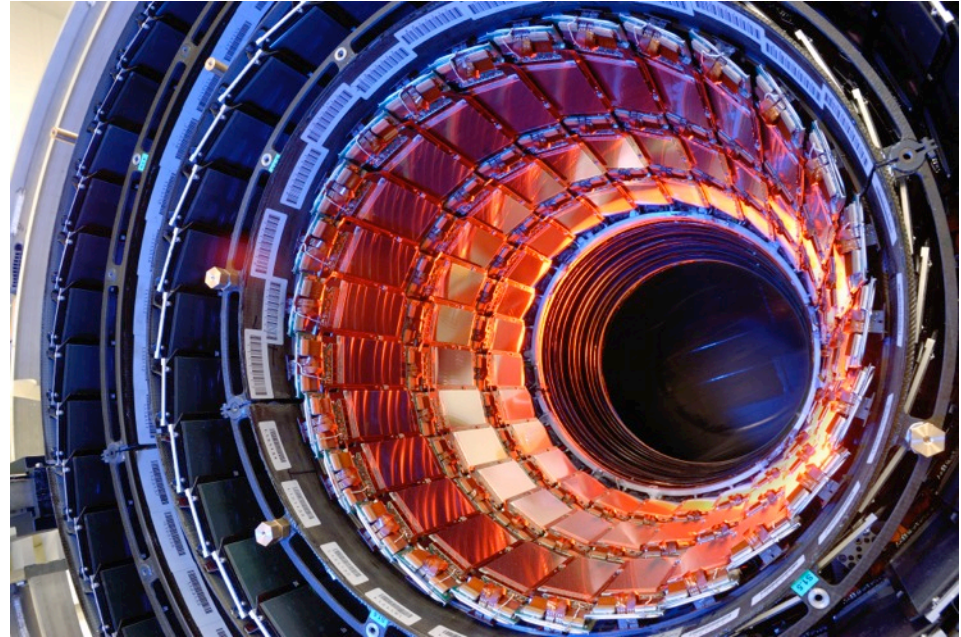
- These detectors measure time very accurately but locate particles with the **precision of $\sim 1 \text{ mm}$**
- **Good timing is obtain by using a gain mechanism**, either in the detector or in the electronics

State-of-the-art Position Detectors

Extremely good position detectors are currently in use in every major high energy physics experiment:

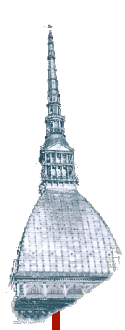
- Millions of channels
- Very reliable
- Very radiation hard

The timing capability is however limited to ~ 100-150 ps
(NA62 @CERN)



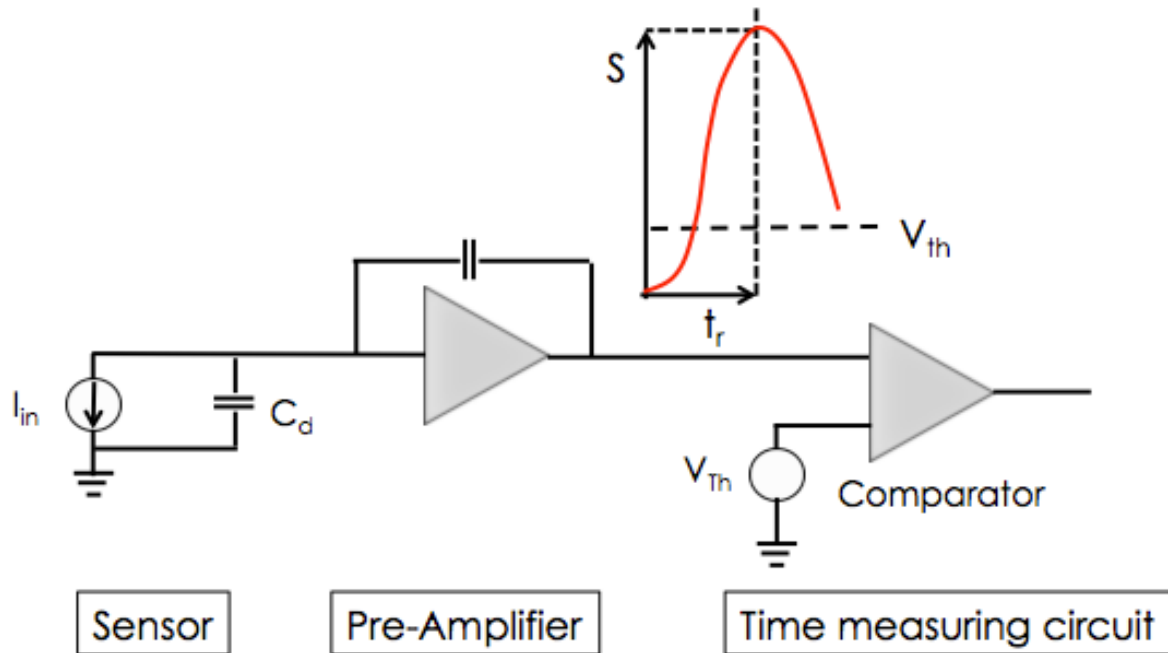
$$\sigma_t \sim 100-150 \text{ ps}$$

$$\sigma_x \sim 20-30 \text{ } \mu\text{m}$$



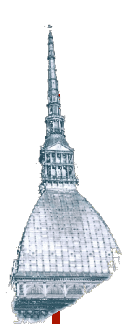
A time-tagging detector

(a simplified view)

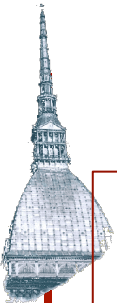


Time is set when the signal crosses the comparator threshold

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

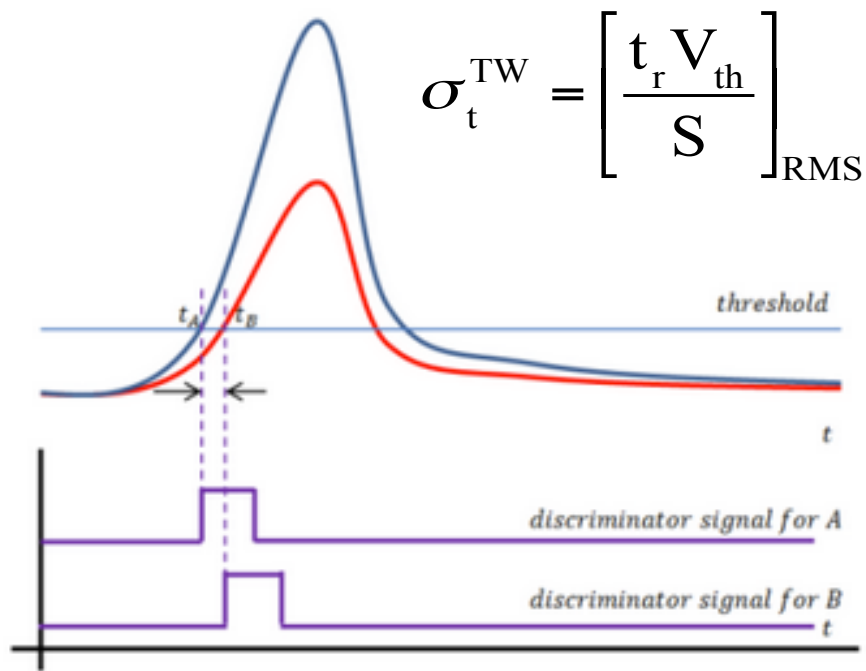


Noise source: Time walk and Time jitter

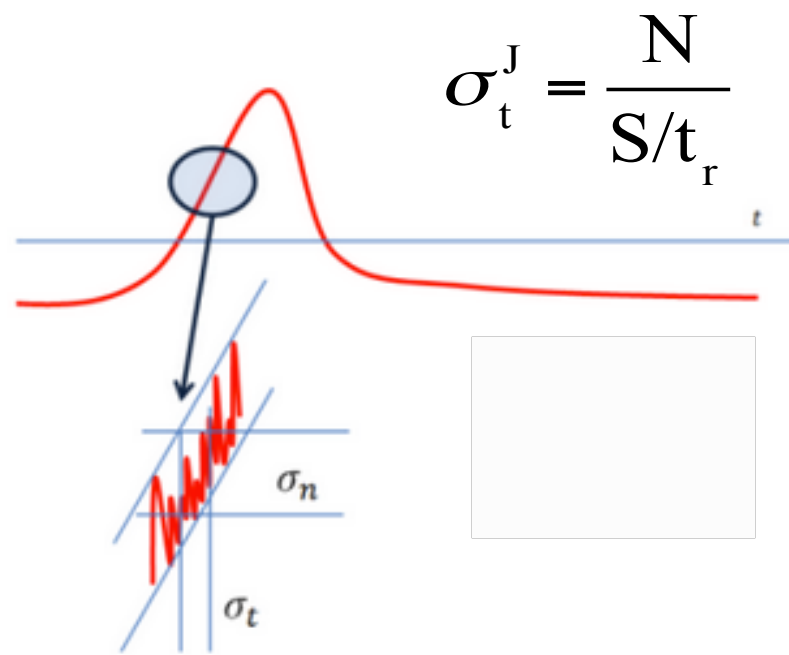


Time walk: the voltage value V_{th} is reached at different times by signals of different amplitude

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



Due to the physics of signal formation



Mostly due to electronic noise

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

Time Resolution and slew rate

Using the expressions in the previous page, we can write

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

Time Walk Jitter JTDC

where:

- $S/t_r = dV/dt =$ 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)

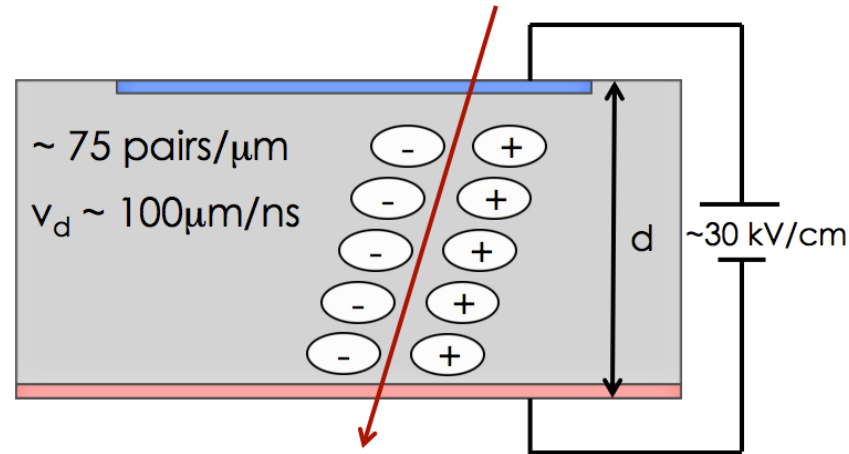
→ We need large and short signals ←

Signal formation in silicon detectors

We know we need a large signal, but **how is the signal formed?**

What is controlling the slew rate?

$$\frac{dV}{dt} \propto ?$$



A particle creates charges, then:

- The charges start moving under the influence of an external field
- The motion of the charges induces a current on the electrodes
- The signal ends when the charges reach the electrodes

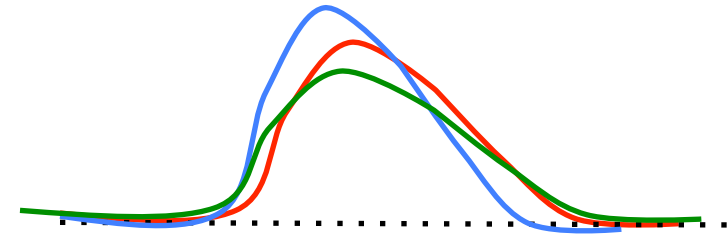
How to make a **good** signal

Signal shape is determined by Ramo's Theorem:

$$i \propto qvE_w$$

Drift velocity

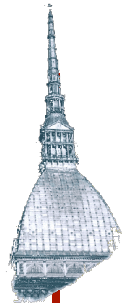
Weighting field



A key to good timing is the uniformity of signals:

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

Good signals for Timing



Velocity:

$$i \propto qvE_w$$

Weighting field:

$$i \propto qvE_w$$

Charge:

$$i \propto qvE_w$$

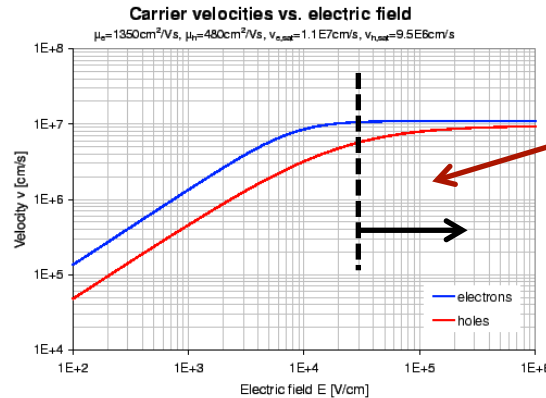
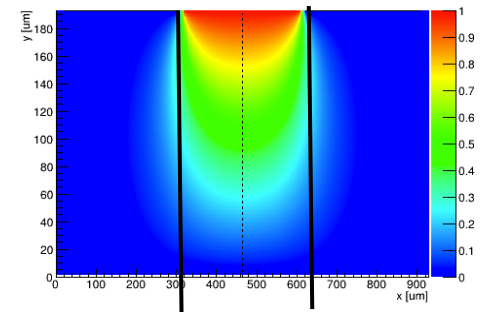
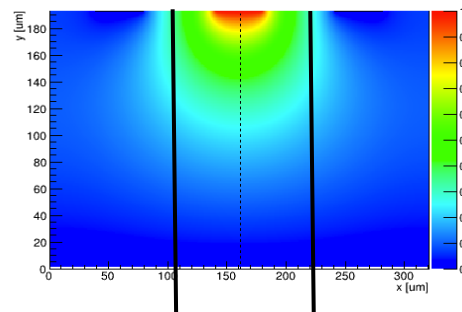


Figure: Electron and hole velocities vs. the electric field strength in silicon.

We want to operate in this regime: saturated velocity



Best: uniform weighting field in a pitch

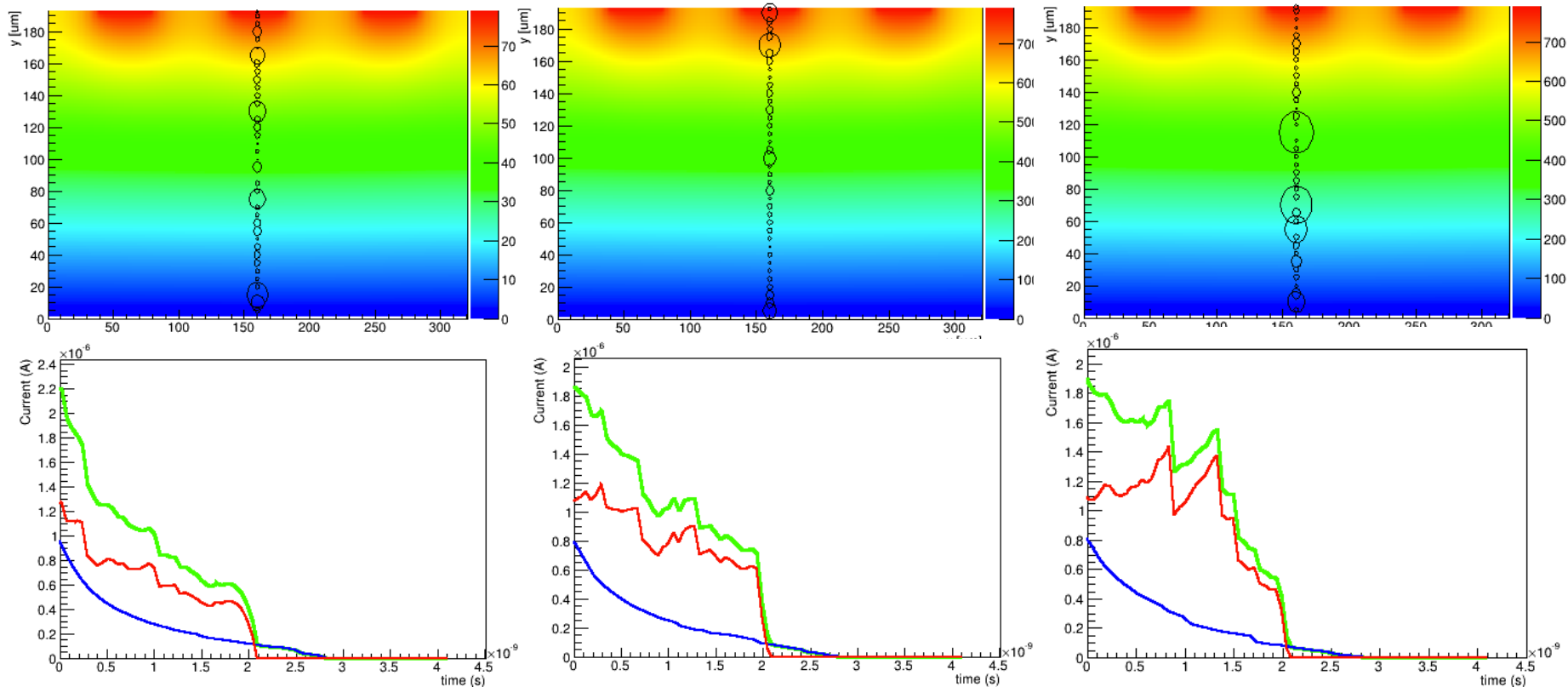
- ➔ Highest possible E field to saturate velocity
- ➔ Large pad to have uniform weighting field
- ➔ Lot's of charge

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:



What is the signal of one e/h pair?

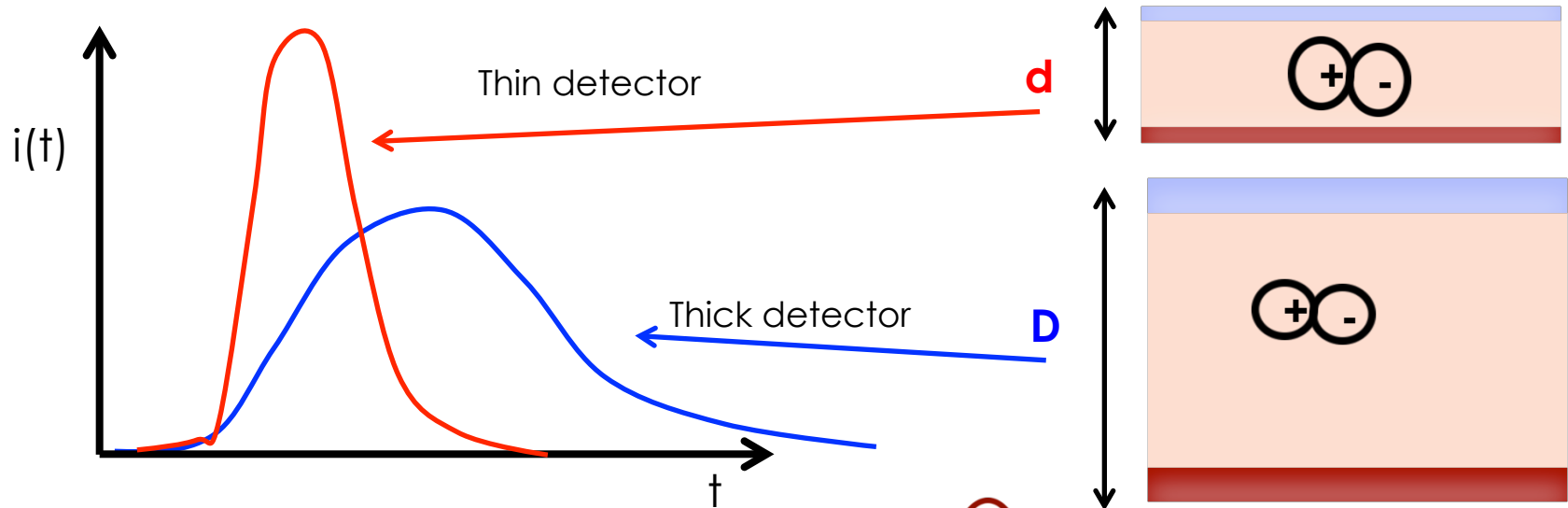
(Simplified model for pad detectors)

Let's consider **one single electron-hole pair**.

The integral of their currents is equal to the electric charge, q :

$$\int [i_{el}(t) + i_h(t)] dt = q$$

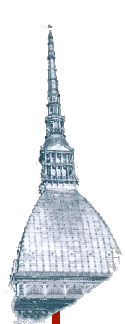
However **the shape of the signal depends on the thickness d** :
thinner detectors have higher slew rate



→ **One e/h pair generates higher current in thin detectors**

$$i \propto qv \left(\frac{1}{d} \right)$$

← Weighting field



Large signals from thick detectors?

(Simplified model for pad detectors)

Thick detectors have higher number of charges:

$$Q_{\text{tot}} \sim 75 q * d$$

However each charge contributes to the initial current as:

$$i \propto qv \frac{1}{d}$$

The initial current for a silicon detector does not depend on how thick (d) the sensor is:

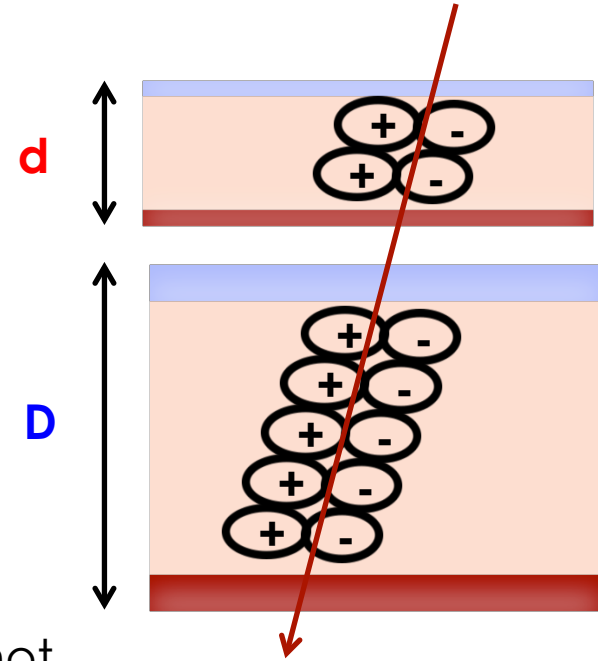
$$i = Nq \frac{k}{d} v = (75dq) \frac{k}{d} v = 75kqv \sim 1 - 2 * 10^{-6} A$$

Number of e/h = 75/micron

Weighting field

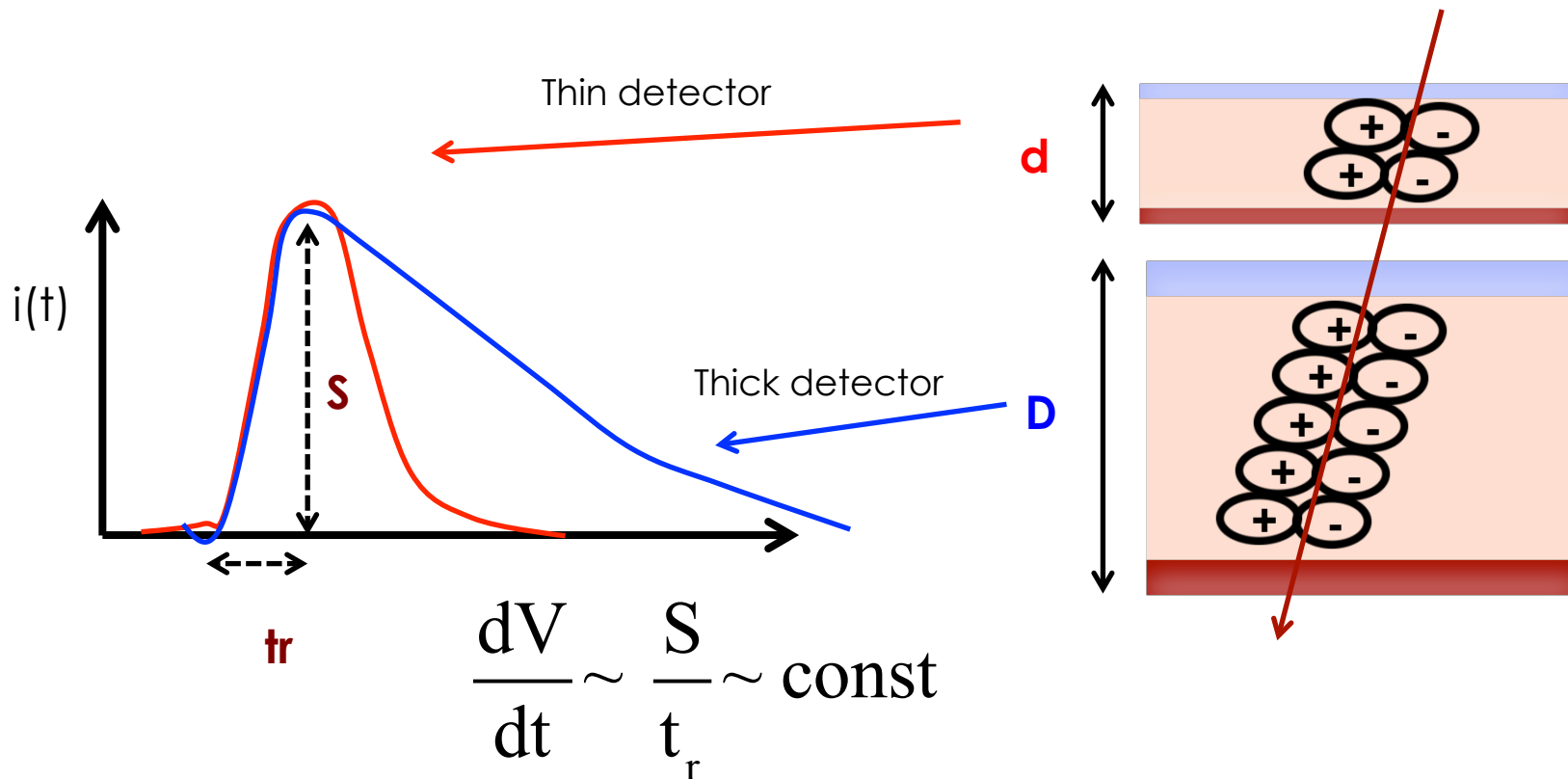
velocity

→ Initial current = constant



Thin vs Thick detectors

(Simplified model for pad detectors)



Thick detectors have longer signals, not higher signals

Best result : NA62, 150 ps on a 300 x 300 micron pixels

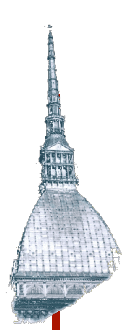
How can we do better?

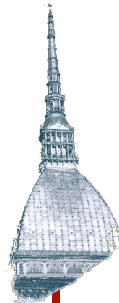
Possible approaches

We need to minimize this expression:

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

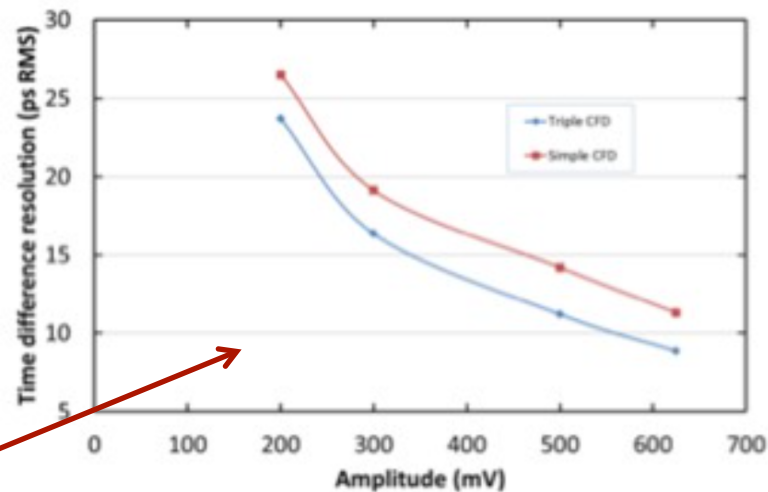
- **APD** (silicon with gain ~ 100): maximize S
 - Very large signal
- **Diamond**: minimize N , minimize t_r
 - Large energy gap, very low noise, low capacitance
 - Very good mobility, short collection time t_r
- **LGAD** (silicon with gain ~ 10): minimize N , moderate S
 - Low gain to avoid shot noise 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/cm²
- They will propose a system for the CT-PPS

See:

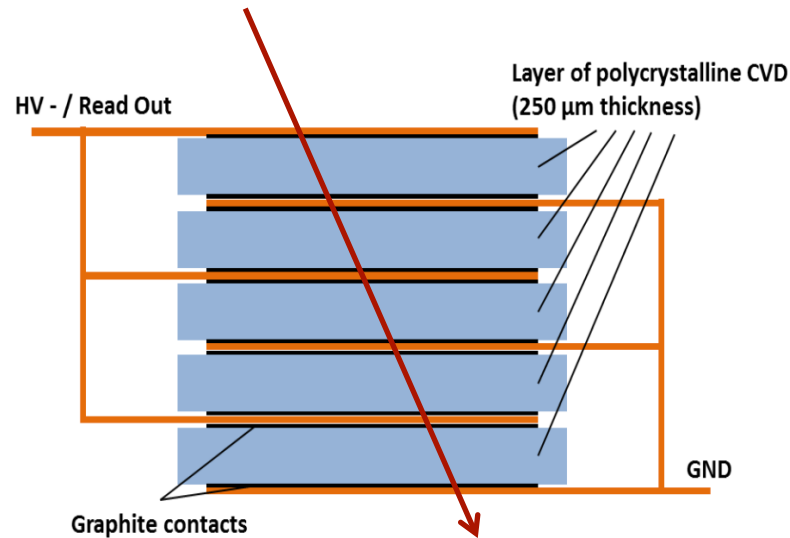
<https://indico.cern.ch/event/363665/contribution/7/material/slides/0.pdf>

The Diamond approach

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

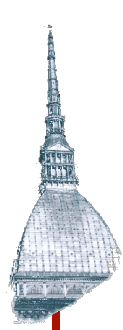


**Best resolution:
~ 100 ps**

2) Grazing

The particle crosses the diamond sensor along the longitudinal direction





The “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)

Gain in Silicon detectors

Gain in silicon detectors is commonly achieved in several types of sensors. It's based on the avalanche mechanism that starts in high electric fields: **$E \sim 300 \text{ kV/cm}$**

Charge multiplication

Gain:

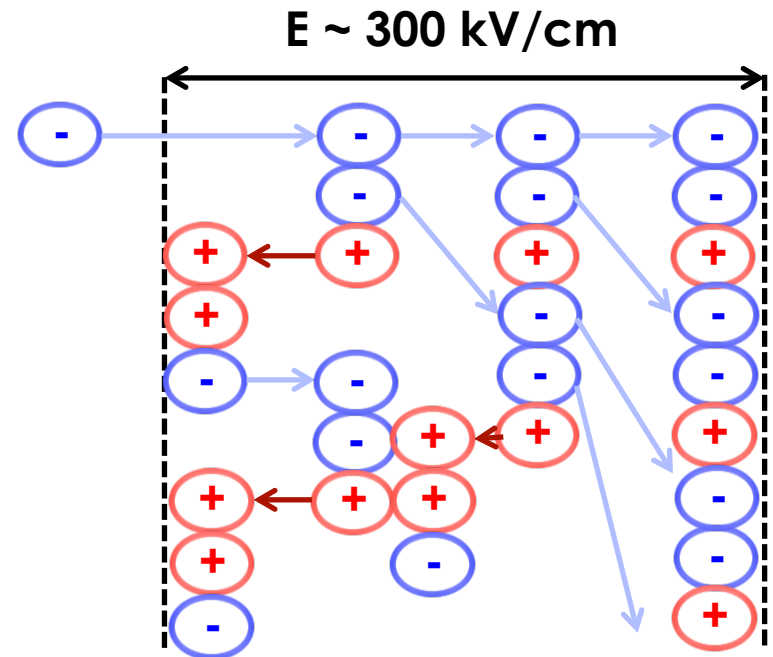
- α = strong E dependance
- $\alpha \sim 0.7 \text{ pair}/\mu\text{m}$ for electrons,
- $\alpha \sim 0.1$ for holes

$$N(l) = N_0 \cdot e^{\alpha \cdot l}$$
$$G = e^{\alpha \cdot l} \quad \alpha_{e,h}(E) = \alpha_{e,h}(\infty) \cdot \exp\left(-\frac{b_{e,h}}{|E|}\right)$$

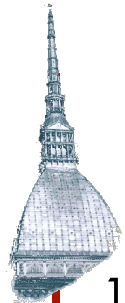
Concurrent multiplication of electrons and holes generate very high gain

Silicon devices with gain:

- **APD: gain 50-500**
- **SiPM: gain $\sim 10^4$**

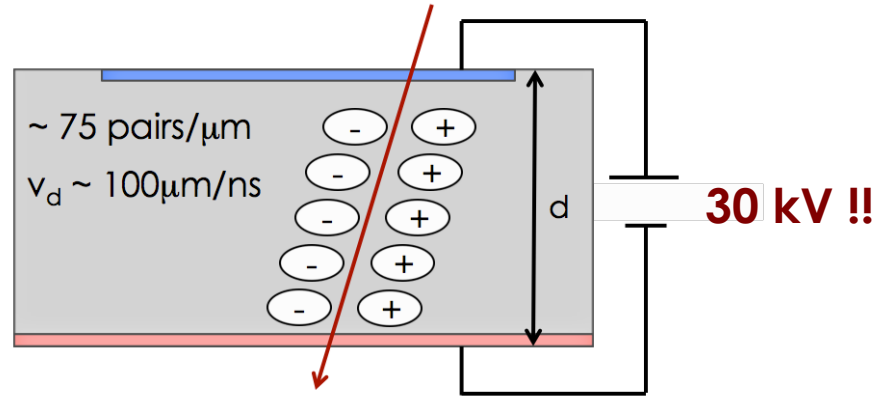


How can we achieve $E \sim 300\text{kV/cm}$?



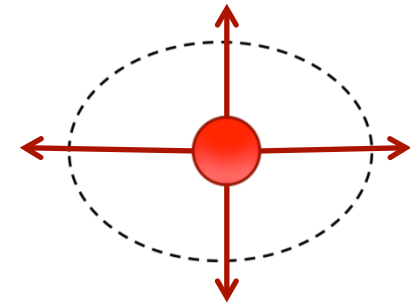
1) Use external bias: assuming a 300 micron silicon detector, we need $V_{\text{bias}} = 30\text{ kV}$

Not possible

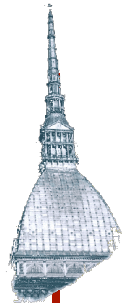


2) Use Gauss Theorem:

$$\sum q = 2\pi r * E$$



$$E = 300\text{ kV/cm} \rightarrow q \sim 10^{16} / \text{cm}^3$$



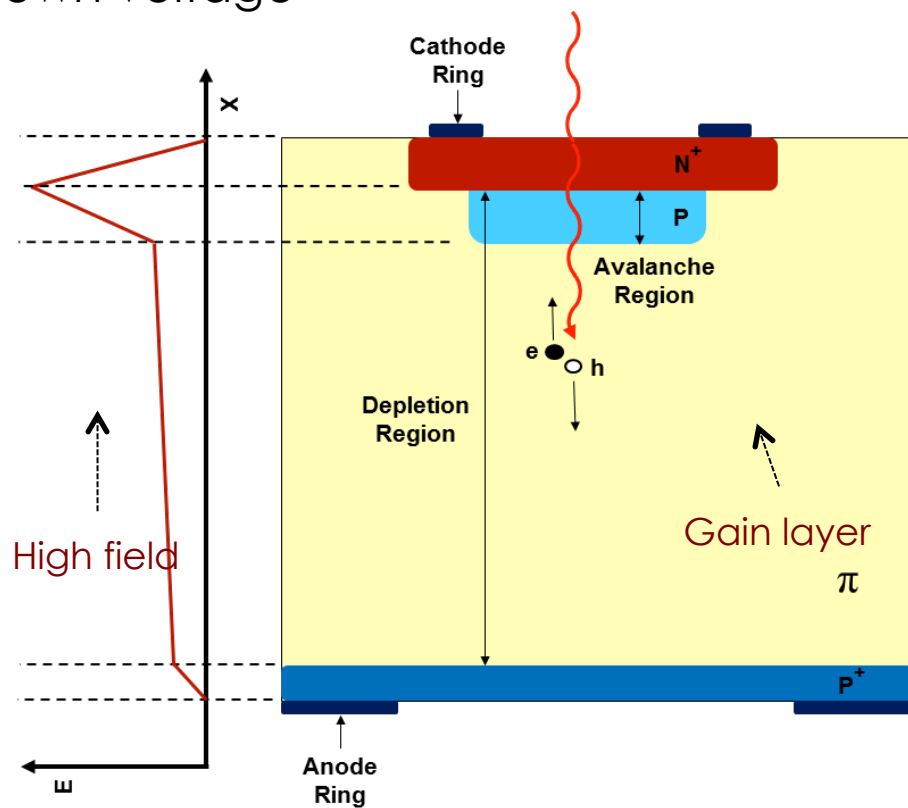
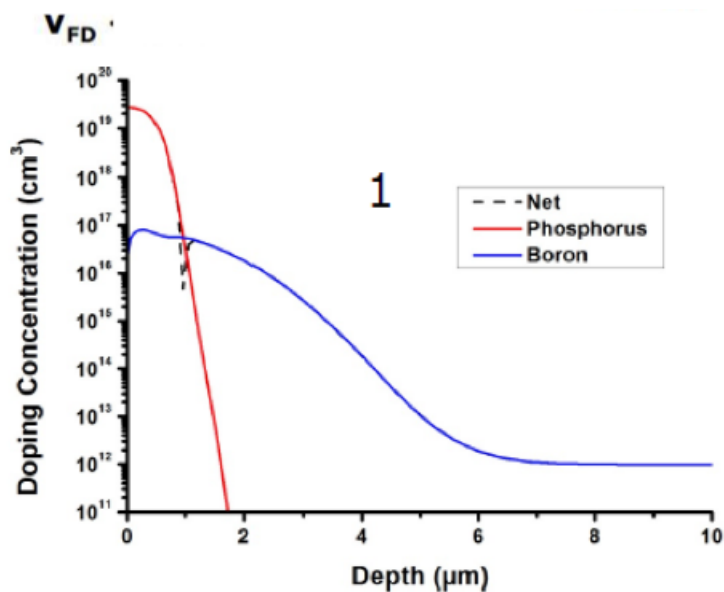
Low Gain Avalanche Detectors (LGADs)

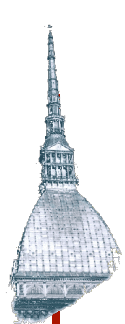
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

$E \sim 300$ kV/cm, closed to breakdown voltage

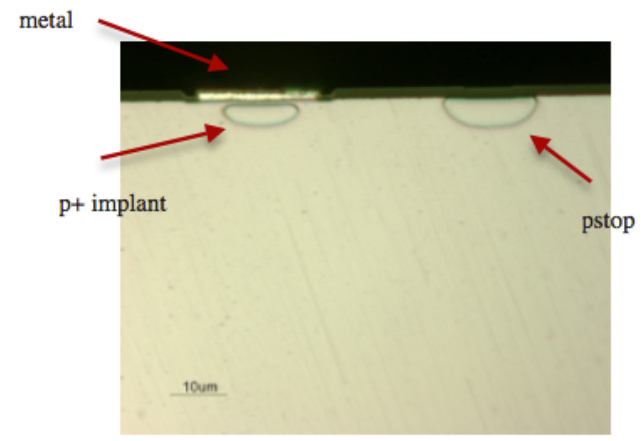
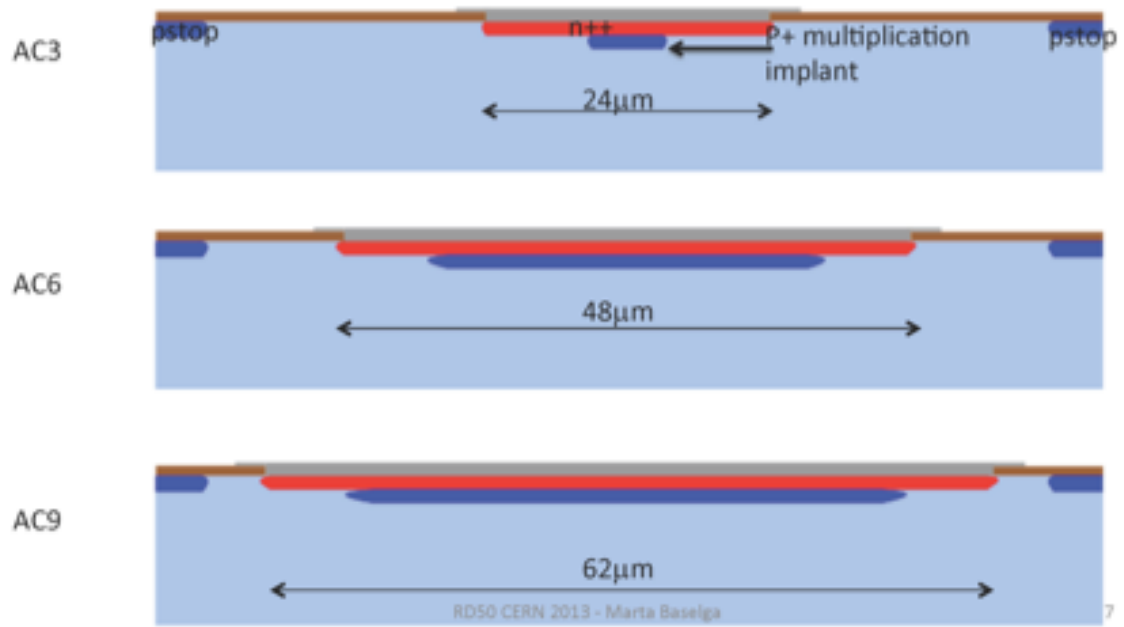


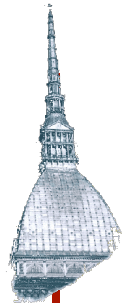


LGADs Pads, Pixels and Strips

The LGAD approach can be extended to any silicon structure, not just pads.

This is an example of LGAD strips





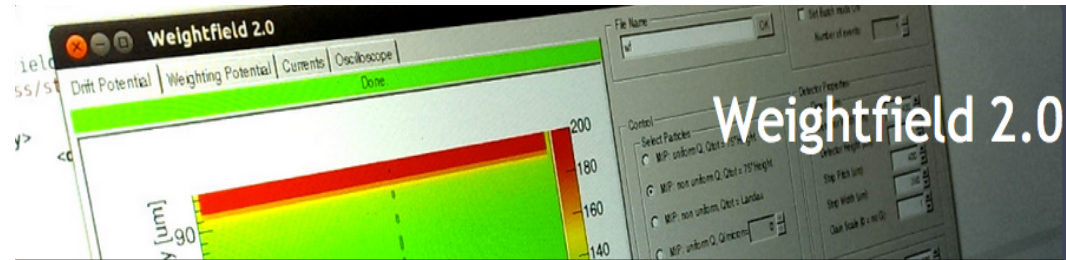
Sensor: Simulation

We developed a full sensor simulation to optimize the sensor design

WeightField2, F. Cenna, N. Cartiglia 9th Trento workshop, Genova 2014
 Available at <http://personalpages.to.infn.it/~cartigli/weightfield2>

It includes:

- Custom Geometry
- Calculation of drift field and weighting field
- Currents signal via Ramo's Theorem
- Gain
- Diffusion
- Temperature effect
- Non-uniform deposition
- Electronics



Updates

Latest version

Weightfield 2.0

Weightfield 2.0 is a 2D silicon detector simulator which allows to simulate Ultra-Fast detectors with inner gain.

Weightfield 2.0 is based on the original [Weightfield](#) by HEPHY

WeightField2: a program to simulate silicon detectors

The screenshot displays the WeightField 2.6 software interface. The main window is titled "Weightfield 2.6" and contains several panels:

- Control Panel:** Precision (1=best, 10=fastest): 10; Sampling (GigaSample): 100; File Name: ON wf; Batch: ON # of events: 1.
- Select Particles Panel:** MIP: non uniform, Qtot = Landau (selected); MIP: uniform Q, Q/micron = 75; alpha from top (E = 5 MeV); alpha from bottom (E = 5 MeV); Set range (Max = 30 um): 10.
- Detector Properties Panel:** Type: Si (selected); Strips: n-type (selected); Bulk: p-type (selected); Dimensions: # of strips (1,3,5..): 3; Detector Height (um): 285; Strip Pitch (um): 300; Strip Width (um): 290; Gain Scale (1 = no G): 1; Force Fixed Gain: ON; h/e Gain ratio: 0; Gain layer recess (um): 0.
- Voltage Panel:** Bias Voltage (V): 800; Depletion Voltage (V): 40.
- Electronics Panel:** ON (checked); Detector Cap (pF): 1; Oscilloscope BW (GHz): 2.5; Shaper T_r - T_f (ns): 3.5; Shaper Trans Imp. (mV/IQ): 4; Shaper Noise & Vth (mV): 1; PreAmp input Imp. (Ohm): 50.
- Plotting Panel:** Plotting at: On Strips (selected), Between Strips; 465; Draw; Field: |Ey|, |Ex|.
- Main Plot:** A 2D color map showing the drift potential. The x-axis is labeled "x [um]" and ranges from 0 to 900. The y-axis is labeled "y [um]" and ranges from 0 to 250. A color scale on the right indicates potential values from 0 to 800 V.
- Subplots:** Two line plots are shown below the main plot. The left plot is titled "Drift Potential V [V]" and shows a linear relationship between y [um] (0 to 300) and V [V] (0 to 800). The right plot is titled "Drift Field E (kV/cm)" and shows a nearly constant relationship between y [um] (0 to 300) and E (kV/cm) (25 to 30).

WeightField2: output currents

	4.85
Electrons	Gain El.
Holes	Gain Holes
Total	
..... Current on PreAmp input	----- Oscilloscope

Control

Precision (1=best, 10=fastest):

Sampling (GigaSample):

File Name: ON

Batch: ON # of events:

Select Particles

MIP: uniform Q, Qtot = 75*Height

MIP: non uniform Q, Qtot = 75*Height

MIP: non uniform, Qtot = Landau

MIP: uniform Q, Q/micron =

alpha from top (E = 5 MeV)

alpha from bottom (E = 5 MeV)

Set range (Max = 30 um):

Plot Settings

Draw Electric Field

No 1D Plots No 1D & 2D

Currents

Switch B-Field on and set to (T):

Diffusion

Temperature (K):

Detector Properties

Type

Si Diamond Free

Strips

n-type p-type

Bulk

n-type p-type

Dimensions

of strips (1,3,5,...):

Detector Height (um):

Strip Pitch (um):

Strip Width (um):

Gain Scale (1 = no G):

Force Fixed Gain: ON

h/e Gain ratio:

Gain layer recess (um):

Voltage

Bias Voltage (V):

Depletion Voltage (V):

Electronics

ON

Detector Cap (pF):

Oscilloscope BW (GHz):

Shaper T_r - T_f (ns):

Shaper Trans Imp. (mV/IQ):

Shaper Noise & Vth (mV):

PreAmp input Imp. (Ohm):

Particle hits Detector at: Angle (deg):

Charge Collection

e- charges (e): 14657	h+ charges (e): 9751	e- + h+ charges (e): 24408
Gain e- charges (e): 0	Gain h+ charges (e): 0	Gain e- + h+ charges (e): 0
Total e- charges (e): 14657	Total h+ charges (e): 9751	Total Charges (e): 24408

Lorentz Drift

e- Lorentz Angle (degree):	0.00	h+ Lorentz Angle (degree):	0.00
----------------------------	------	----------------------------	------

WeightField2: response of the read-out electronics

The figure displays four plots related to the detector response:

- CSA:** A green plot showing Amplitude (mV) vs Time (s) with a peak of approximately 15.5 mV at 5 ns.
- Shaper Rising edge derivative:** A blue plot showing σV_{out} (mV/ns) vs Time (s) with a peak of approximately 6.5 mV/ns at 1.5 ns.
- Charge:** A red plot showing Charge (fC) vs Time (s) with a saturation value of approximately 3.8 fC.
- Cividec broadband (50 Ohm and 40db):** A red plot showing Amplitude (mV) vs Time (s) with a peak of approximately 9 mV at 0.5 ns.

Weightfield 2.6

Control

Precision (1=best, 10=fastest):

Sampling (GigaSample):

File Name
 ON

Batch
 ON # of events:

Select Particles

MIP: uniform Q, Qtot = 75*Height

MIP: non uniform Q, Qtot = 75*Height

MIP: non uniform, Qtot = Landau

MIP: uniform Q, Q/micron =

alpha from top (E = 5 MeV)

alpha from bottom (E = 5 MeV)

Set range (Max = 30 um):

Plot Settings

Draw Electric Field

No 1D Plots No 1D & 2D

Currents

Switch B-Field on and set to (T):

Diffusion

Temperature (K):

Detector Properties

Type
 Si Diamond Free

Strips
 n-type p-type

Bulk
 n-type p-type

Dimensions

of strips (1,3,5..):

Detector Height (um):

Strip Pitch (um):

Strip Width (um):

Gain Scale (1 = no G):

Force Fixed Gain: ON

h/e Gain ratio:

Gain layer recess (um):

Voltage

Bias Voltage (V):

Depletion Voltage (V):

Electronics

ON

Detector Cap (pF):

Oscilloscope BW (GHz):

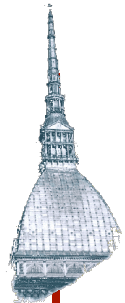
Shaper T_r - T_f (ns):

Shaper Trans Imp. (mV/fC):

Shaper Noise & V_{th} (mV):

PreAmp input Imp. (Ohm):

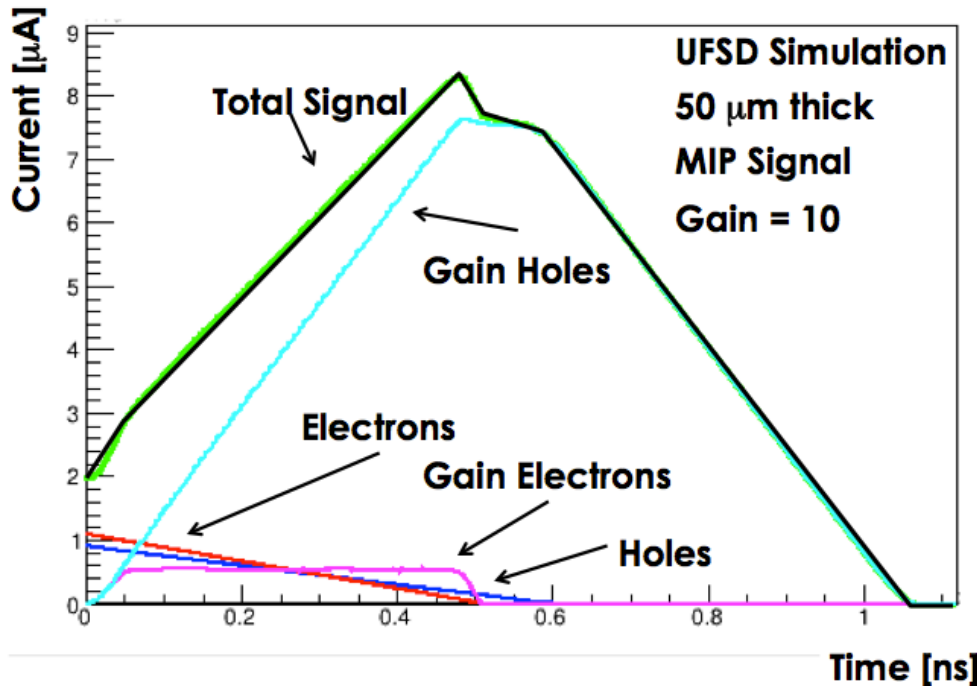
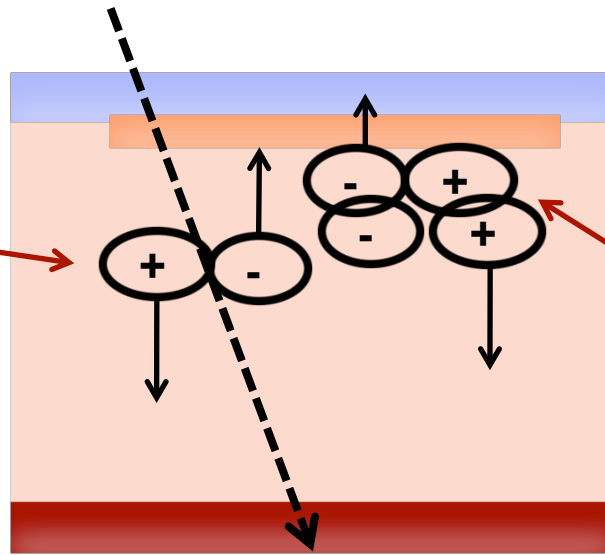
How gain shapes the signal



Gain electron:
absorbed immediately

Gain holes:
long drift home

Initial electron, holes



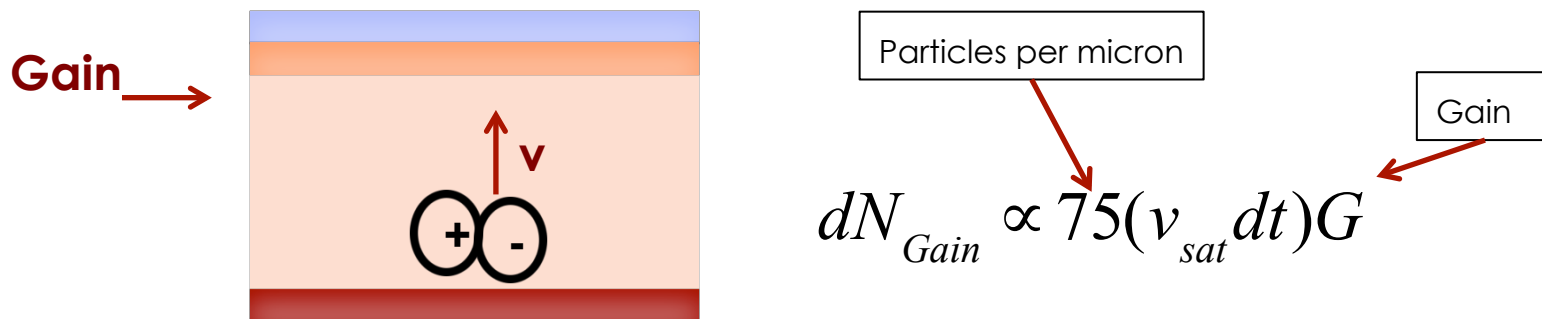
Electrons multiply and produce additional electrons and holes.

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

➔ **No holes multiplications**

Interplay of gain and detector thickness

The rate of particles produced by the gain does not depend on d (assuming saturated velocity v_{sat})



\rightarrow Constant rate of production

However the initial value of the **gain current depends on d** (via the weighing field)

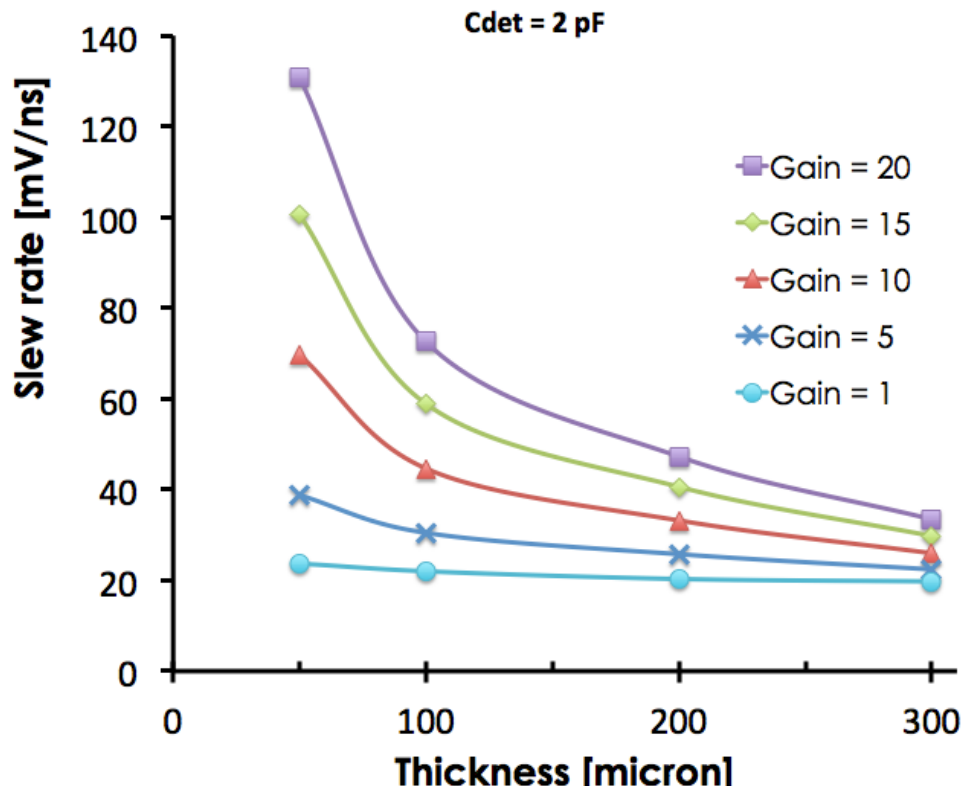
$$di_{gain} \propto dN_{Gain} qv_{sat} \left(\frac{k}{d}\right) \rightarrow \text{Gain current} \sim 1/d$$

A given value of gain has much more effect on thin detectors

Gain current vs Initial current

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

!!!
→ 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

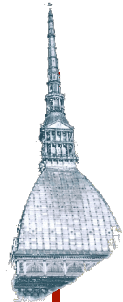
Ultra Fast Silicon Detectors

UFSD are LGAD detectors optimized to achieve the best possible time resolution

Specifically:

1. Thin to maximize the slew rate (dV/dt)
2. Parallel plate – like geometries (pixels..) for most uniform weighting field
3. High electric field to maximize the drift velocity
4. Highest possible resistivity to have uniform E field
5. Small size to keep the capacitance low
6. Small volumes to keep the leakage current low (shot noise)

First Measurements and future plans



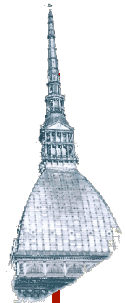
LGAD laboratory measurements

- Doping concentration
- Gain
- Time resolution measured with laser signals

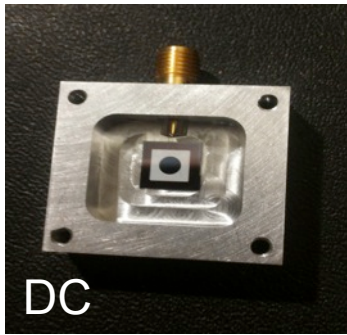
LGAD Testbeam measurements

- Landau shape at different gains
- Time resolution measured with MIPs

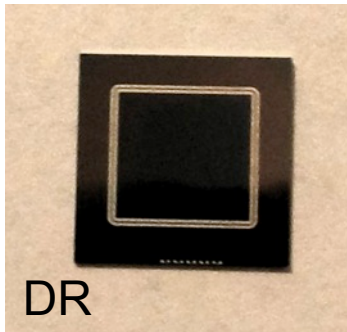
LGAD Sensors in Torino



Thickness:
300 μm



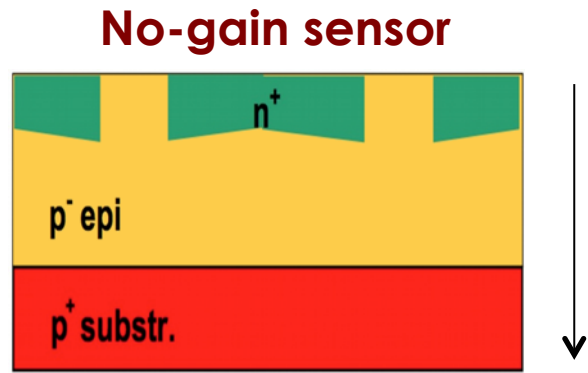
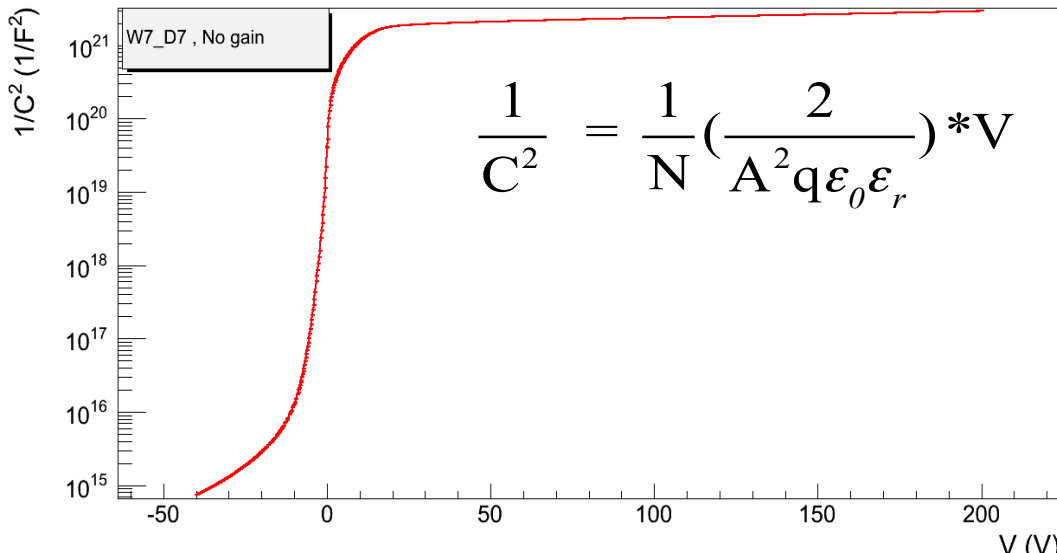
DC



DR

Run	Sensor	P-Layer Implant (E=100 KeV)	Gain	V_{break}	Metal Layer
6474	W8_B4	?	~ 10	> 500 V	DR
6474	W8_C6	?	~ 10	> 500 V	DC
6474	W9_B6	No implant	No Gain	> 500 V	DR
7062	W1_F3	$1.6 \times 10^{13} \text{ cm}^{-2}$	~ 1-2	> 500 V	DR
7062	W3_H5	$2.0 \times 10^{13} \text{ cm}^{-2}$	~ 10	> 500 V	DR
7062	W7_D7	No implant	No Gain	> 500 V	DR

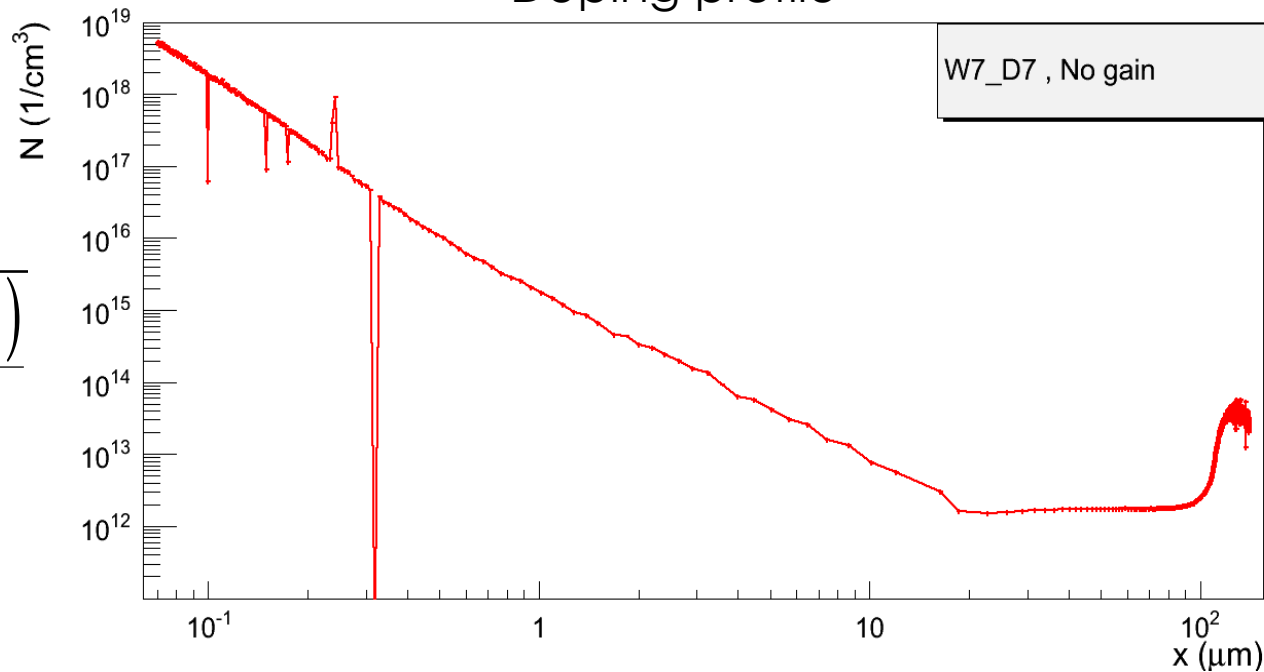
Doping profile from CV measurement - I



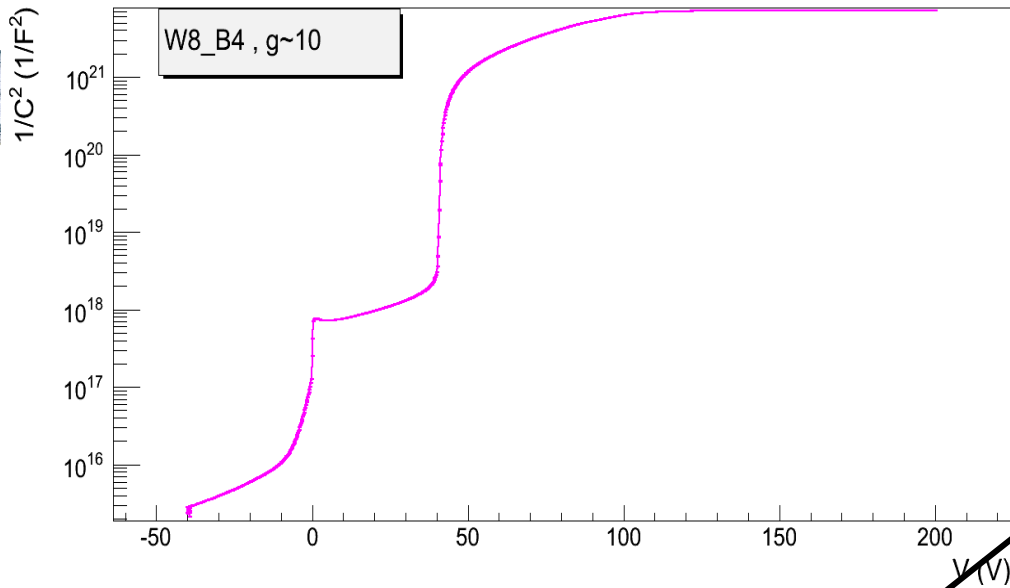
Doping profile

$$N = \frac{2}{q \epsilon_0 \epsilon_r A^2} \frac{d(1/C^2)}{dV}$$

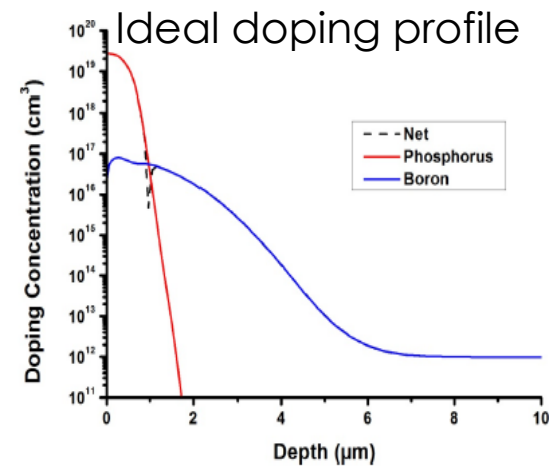
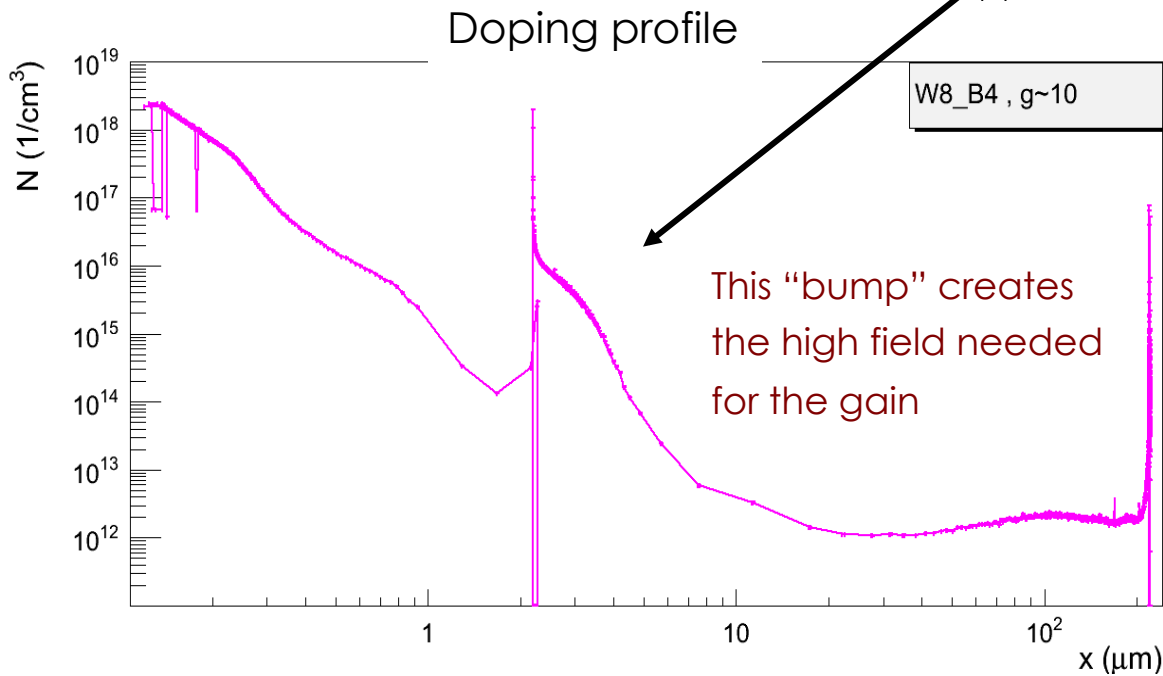
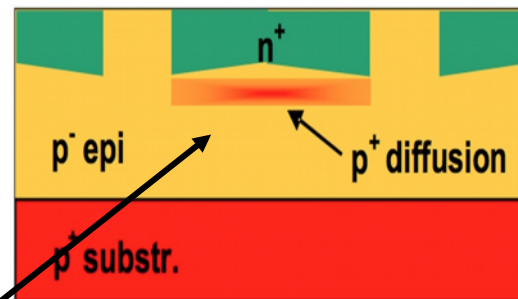
Doping



Doping profile from CV measurement - II

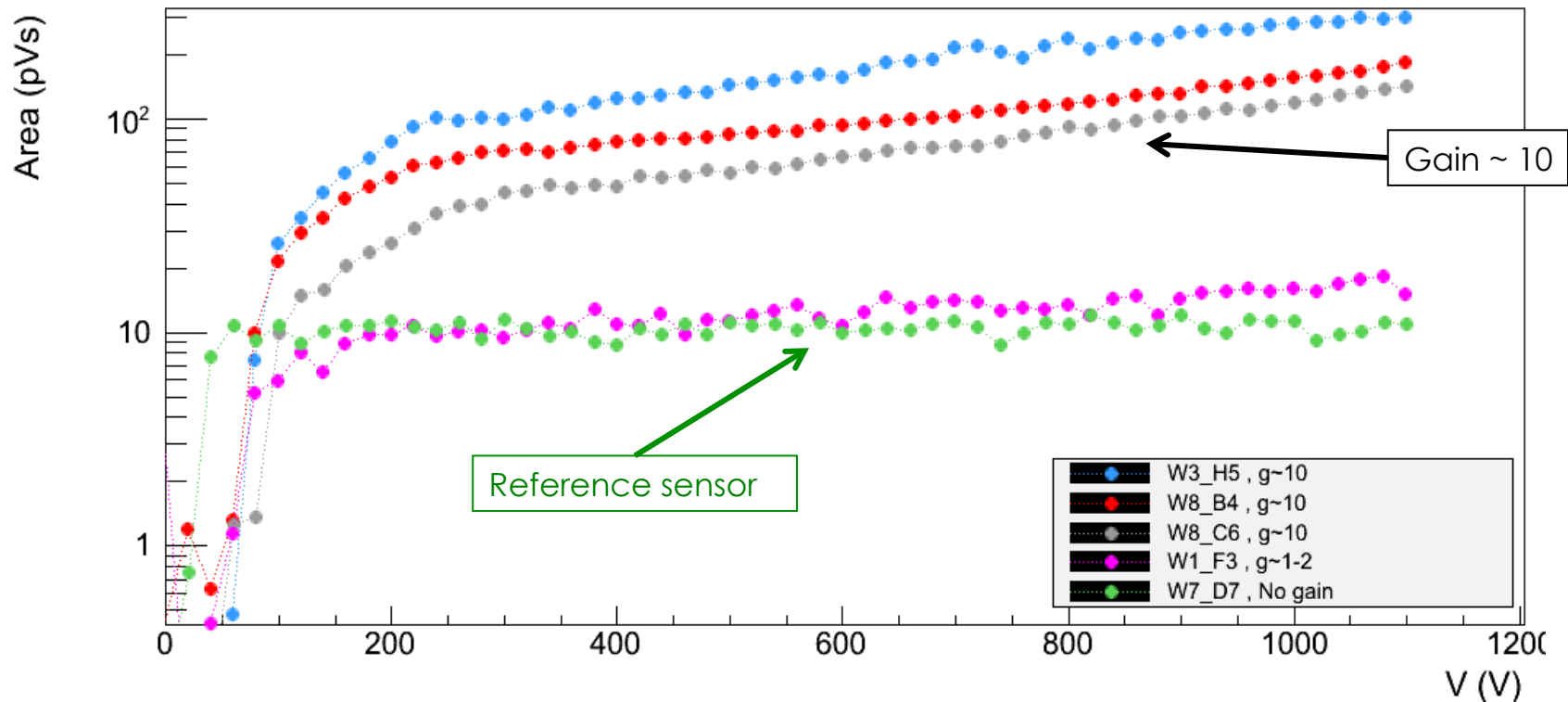


Gain sensor



Signal amplitude

Using laser signals we are able to measure the different responses of LGAD and traditional sensors

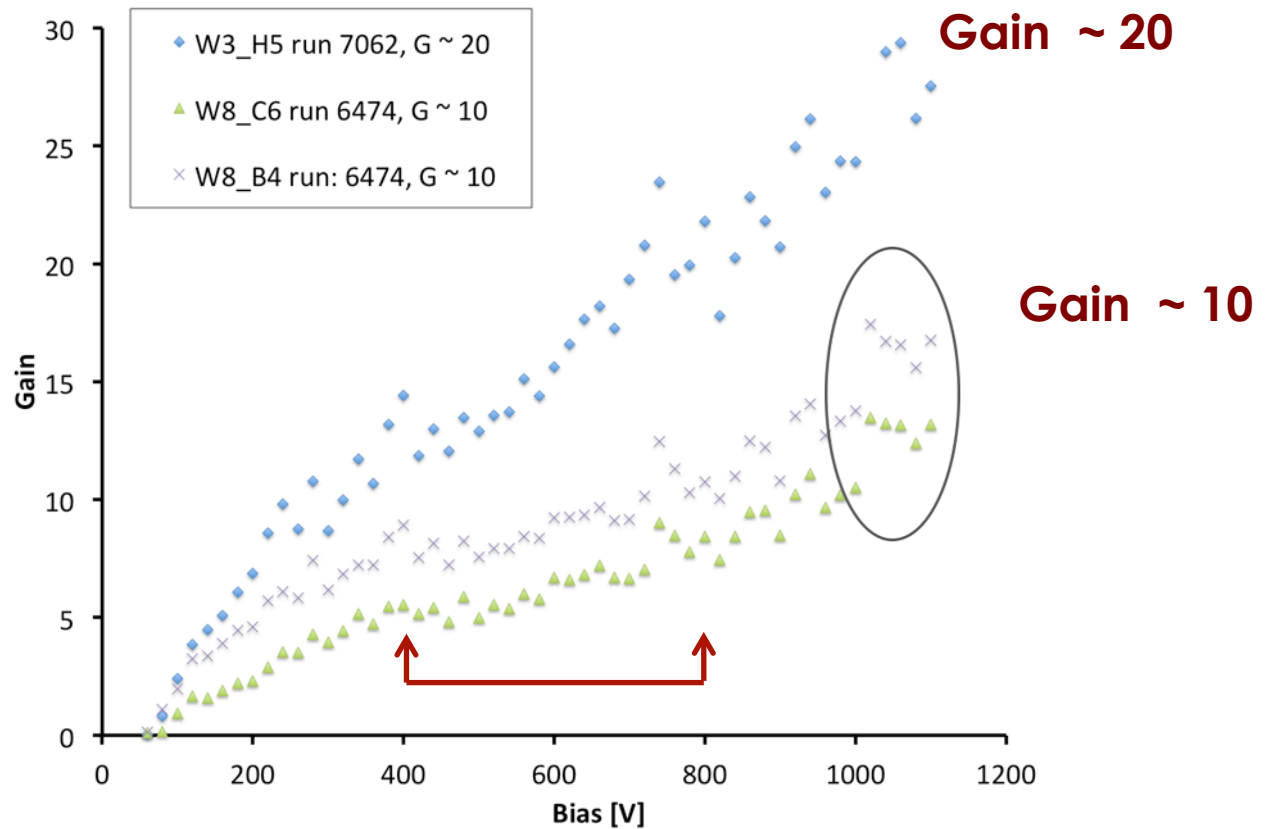


Gain

The gain is estimated as the ratio of the output signals of LGAD detectors to that of traditional one

The gain increases linearly with V_{bias} (not exponentially!)

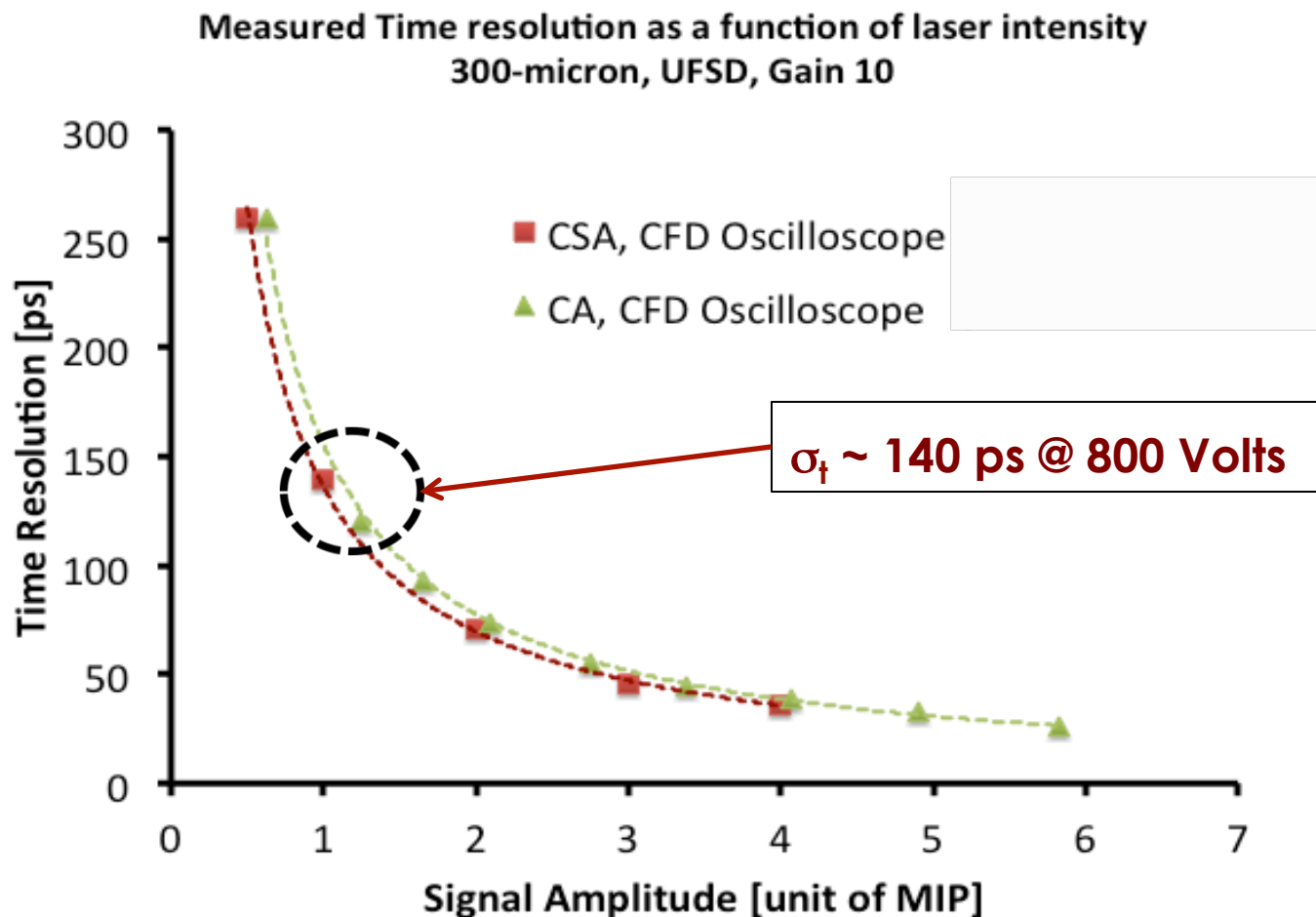
$$\frac{\text{Gain @ 800V}}{\text{Gain @ 400V}} \sim 2$$



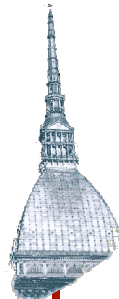
Laser Measurements on CNM LGAD

We use a 1064 nm picosecond laser to emulate the signal of a MIP particle (without Landau Fluctuations)

The signal output is read out by either a Charge sensitive amplifier or a Current Amplifier (Cividec)

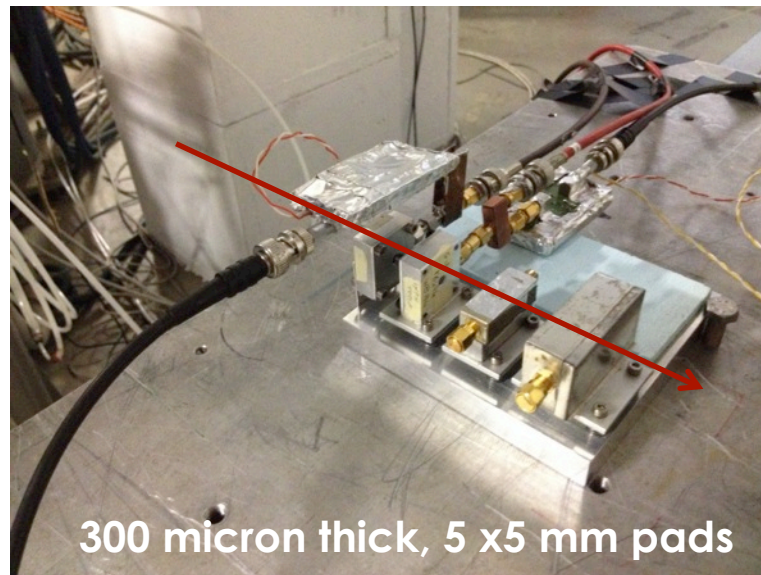


Testbeam Measurements on CNM LGAD

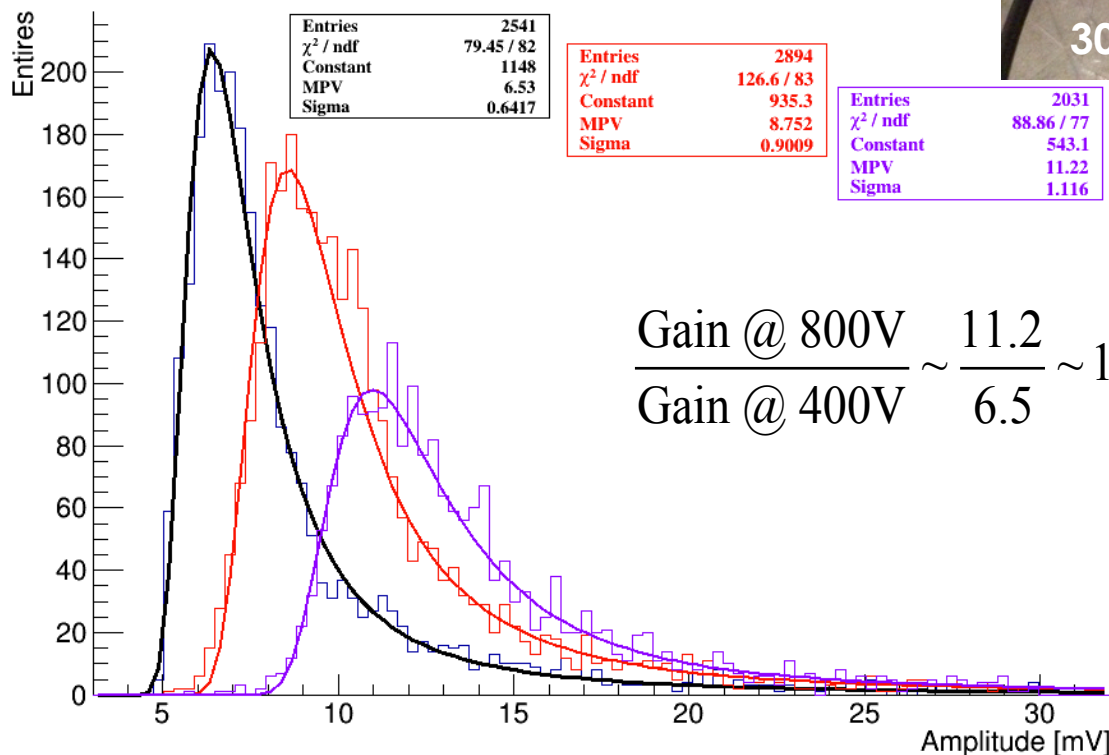


In collaboration with Roma2, we went to Frascati for a testbeam using 500 MeV electrons

As measured in the lab, the gain ~ doubles going from 400 -> 800 Volt.



300 micron thick, 5 x5 mm pads

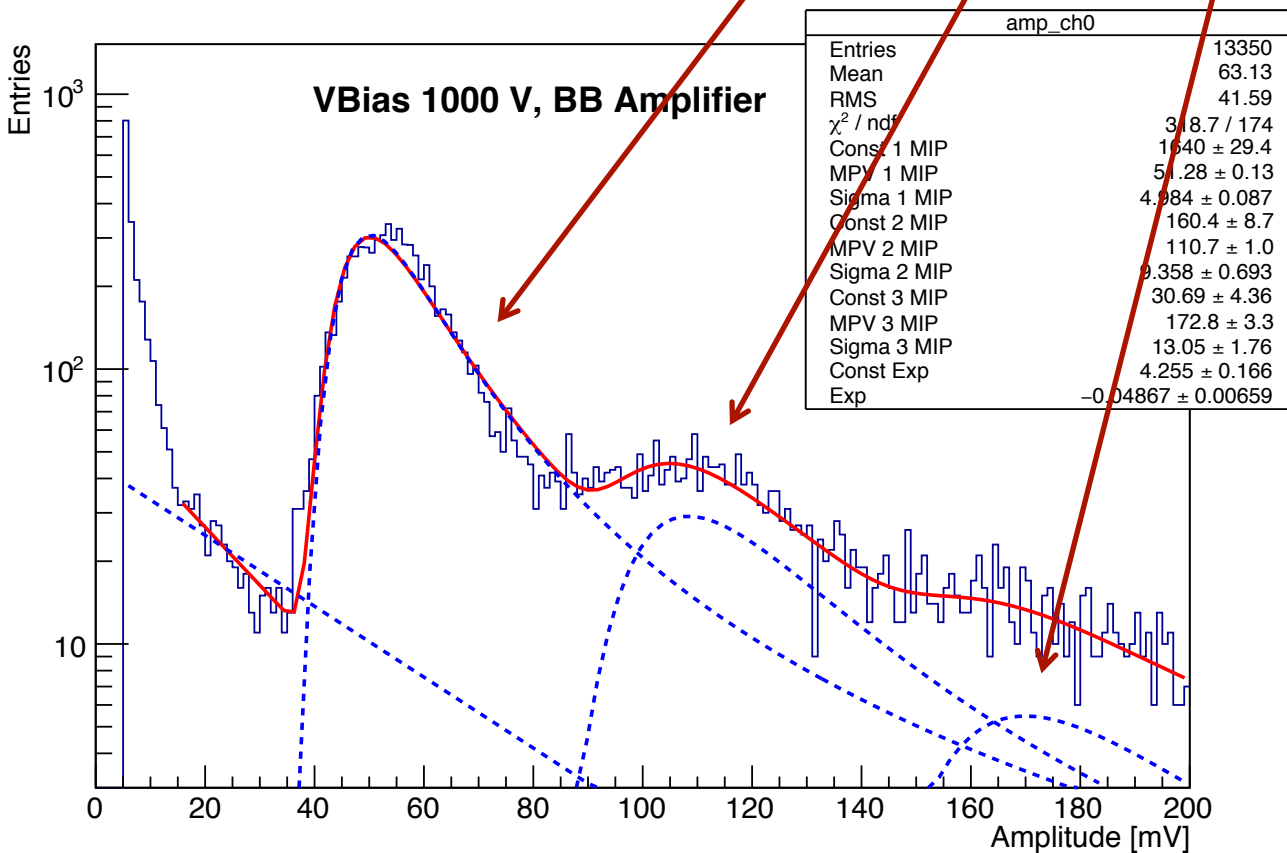


The gain mechanism preserves the Landau amplitude distribution of the output signals

100 GeV pion Testbeam with CNM LGAD

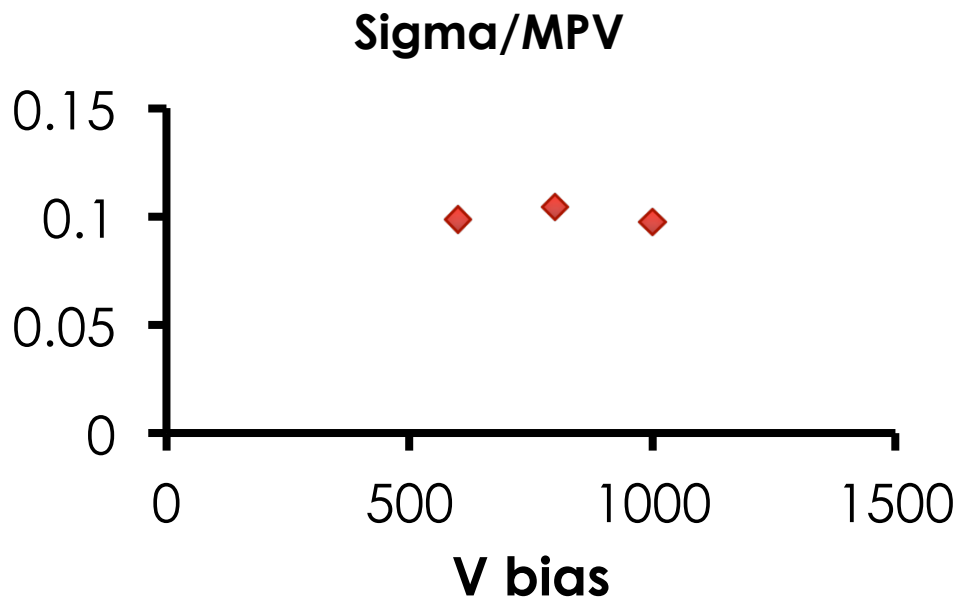
Testbeam data understood as the sum of 1 MIP, 2 MIP or 3 MIP

Very linear behavior of UFSD with increasing charge

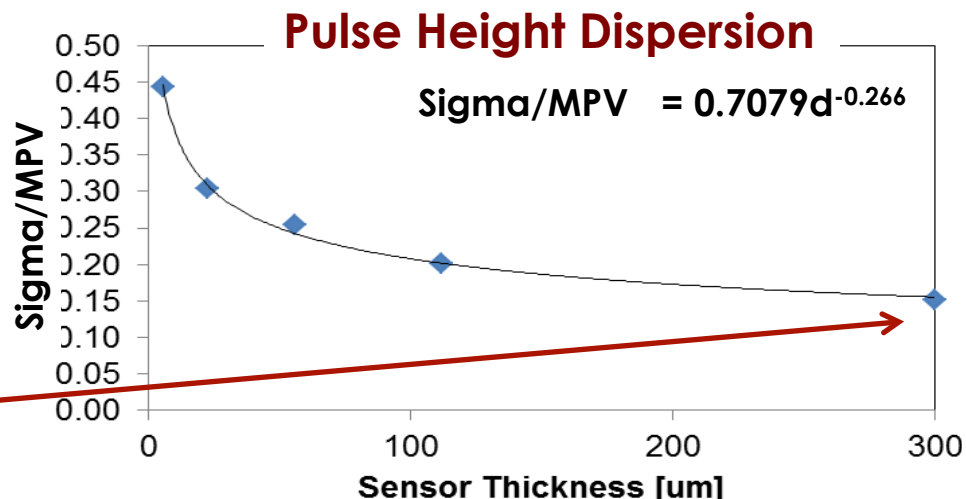


Properties of the Landau distributions

The ratio σ/MPV is constant as a function of multiplication indicating that the excess noise factor is not playing a role yet



According to our fits, the Landau have a smaller width than what is proposed by the parameterization of Meroli et al.

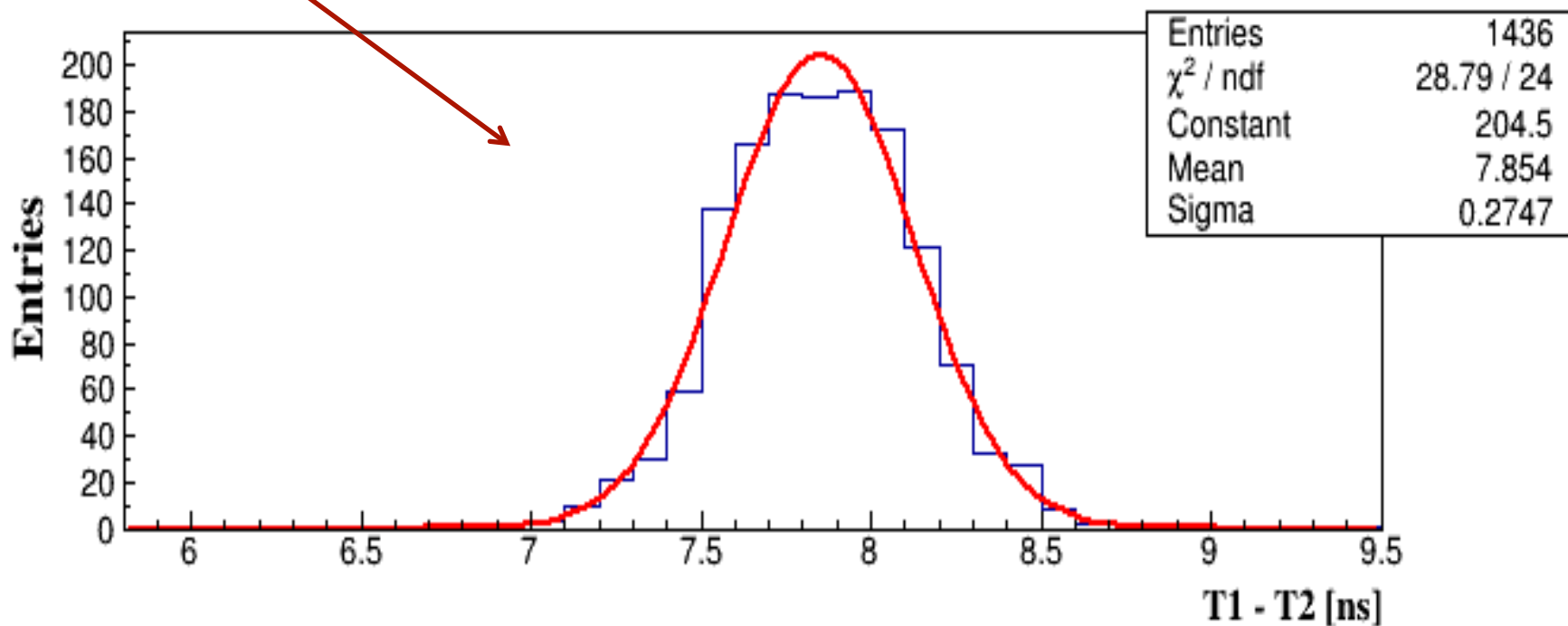


Testbeam Measurements on CNM LGAD

Time difference between two LGAD detectors crossed by a MIP

Tested different types of electronics (Rome2 SiGe, Cividec),
Not yet optimized for these detectors

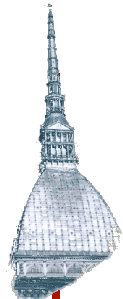
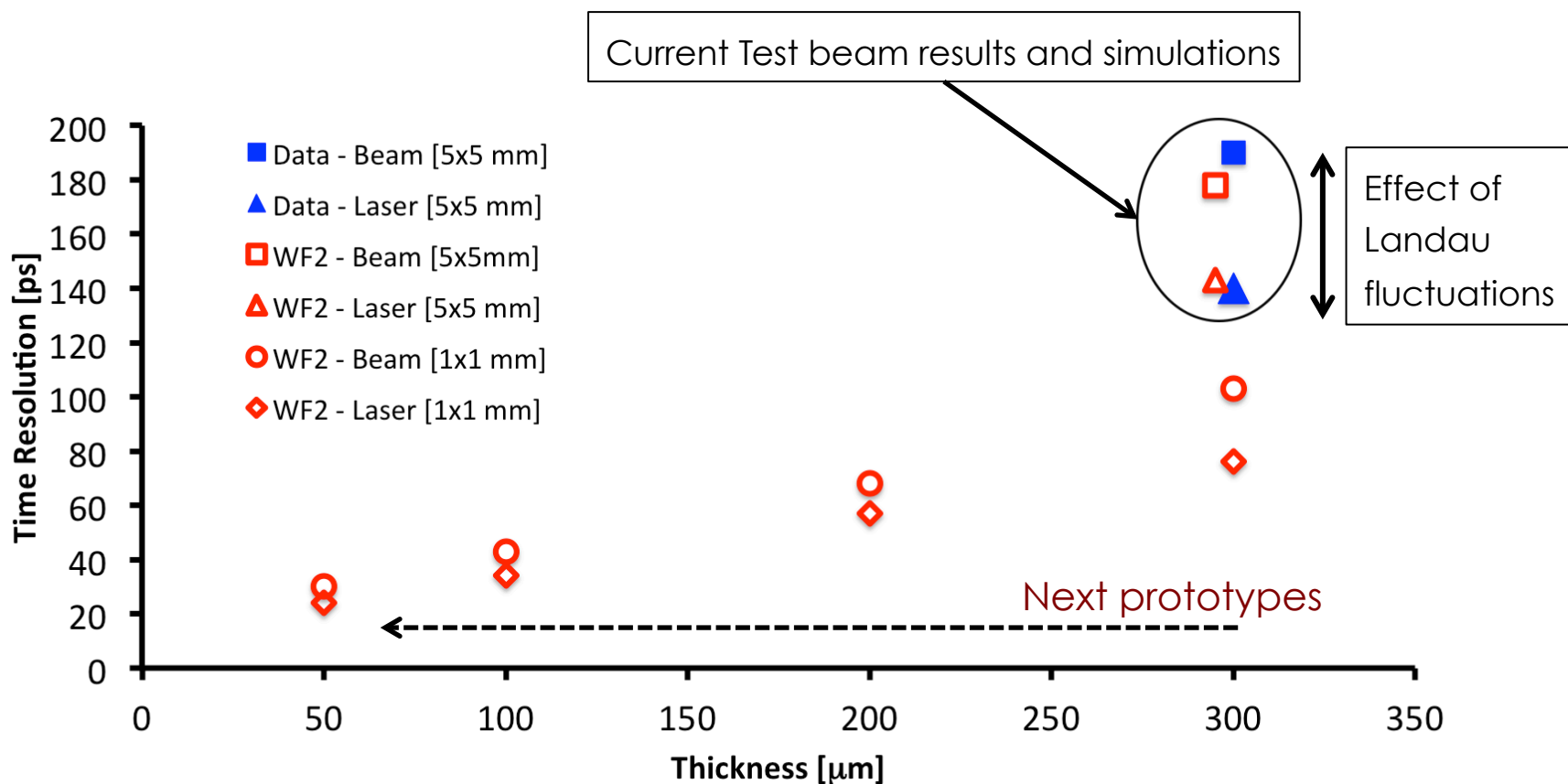
$\sigma_t \sim 190 \text{ ps @ 800 Volts}$



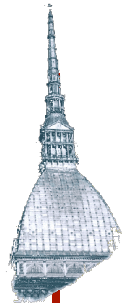
Present results and future productions

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

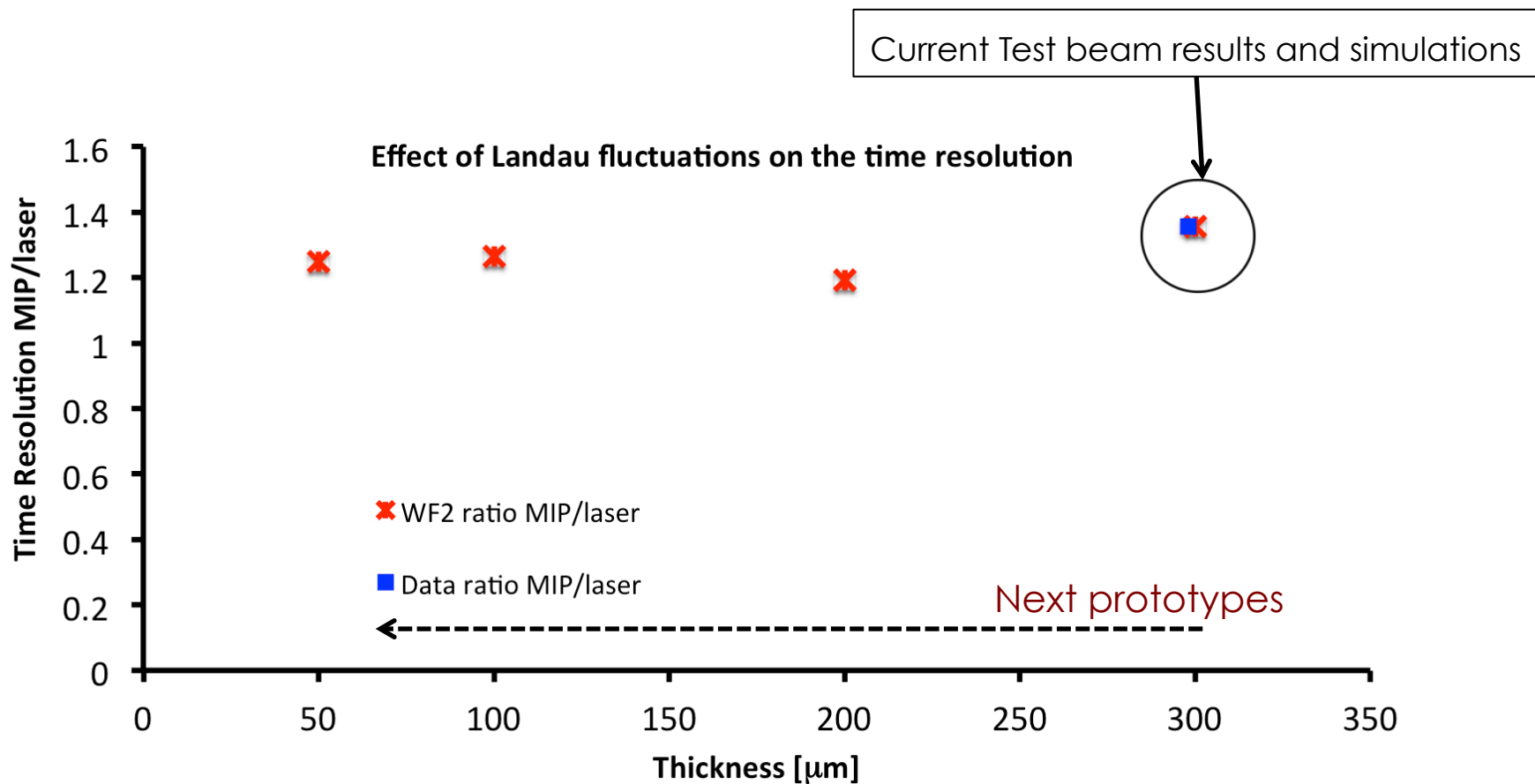
Assuming the same electronics, and 1 mm² LGAD pad with gain 10, we can predict the timing capabilities of the next sets of sensors.



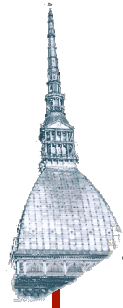
Effect of Landau Fluctuations on the time resolution



The effect of Landau fluctuations in a MIP signal are degrading the time resolution by roughly 30 % with respect of a laser signal



Irradiation tests



The gain decreases with irradiations:
at 10^{14} n/cm² is 20% lower

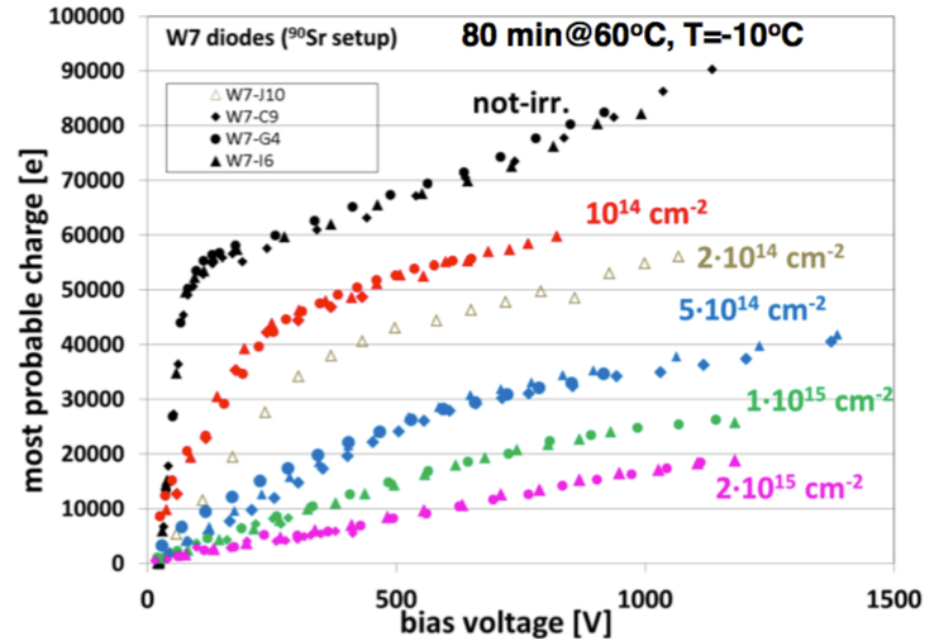
→ **Due to boron disappearance**

What-to-do next:

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

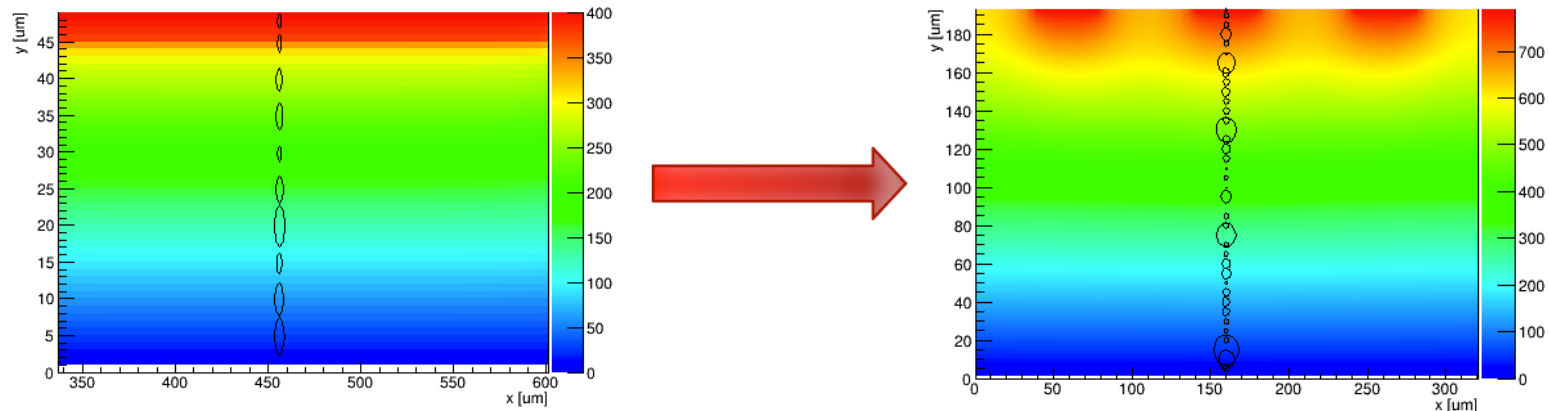
2) Use Gallium instead of Boron for gain layer (in production now)

3) Design the UFSD to have a gain higher than we need, ~ 30 at 500 V.
- We use UFSD at gain 10-15, at 200 Volt
- When radiation damage lowers the gain, we increase V_{bias} to compensate



Merging timing with position resolution

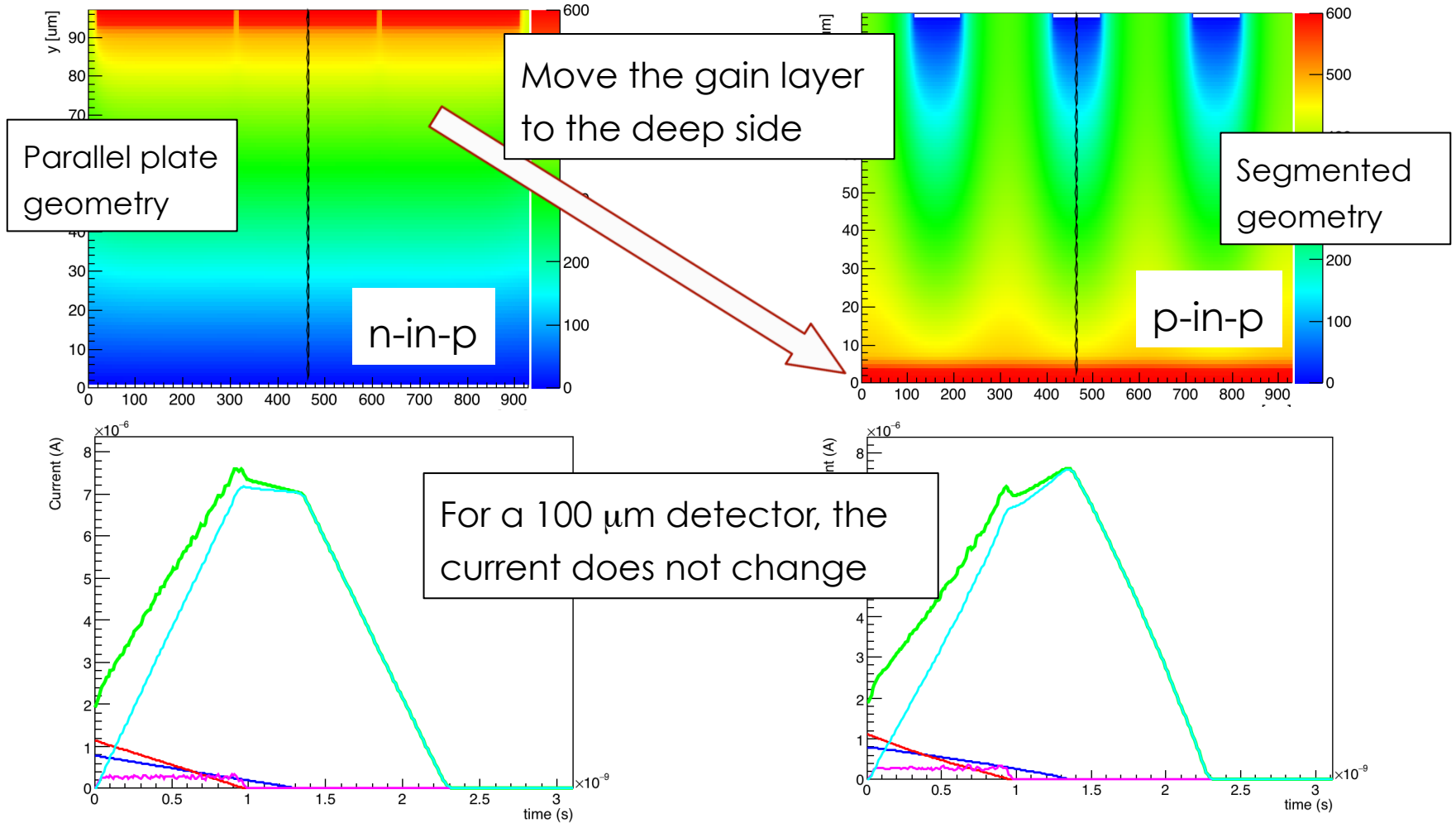
Electrode segmentation makes the E field very non uniform, and therefore ruins the timing properties of the sensor



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

1) Segmentation: buried junction

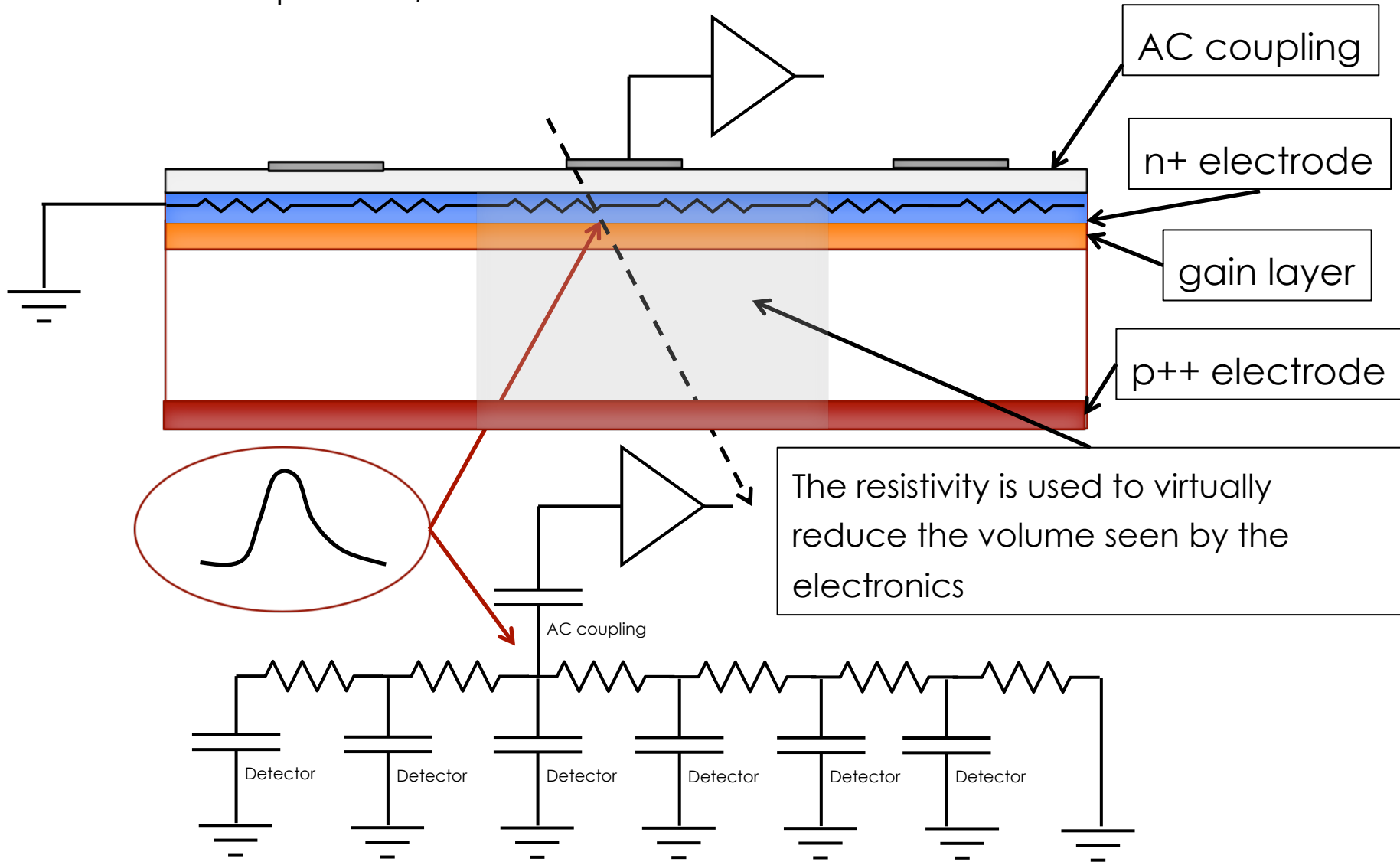
Separate the multiplication side from the segmentation side



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

2) Segmentation: AC coupling

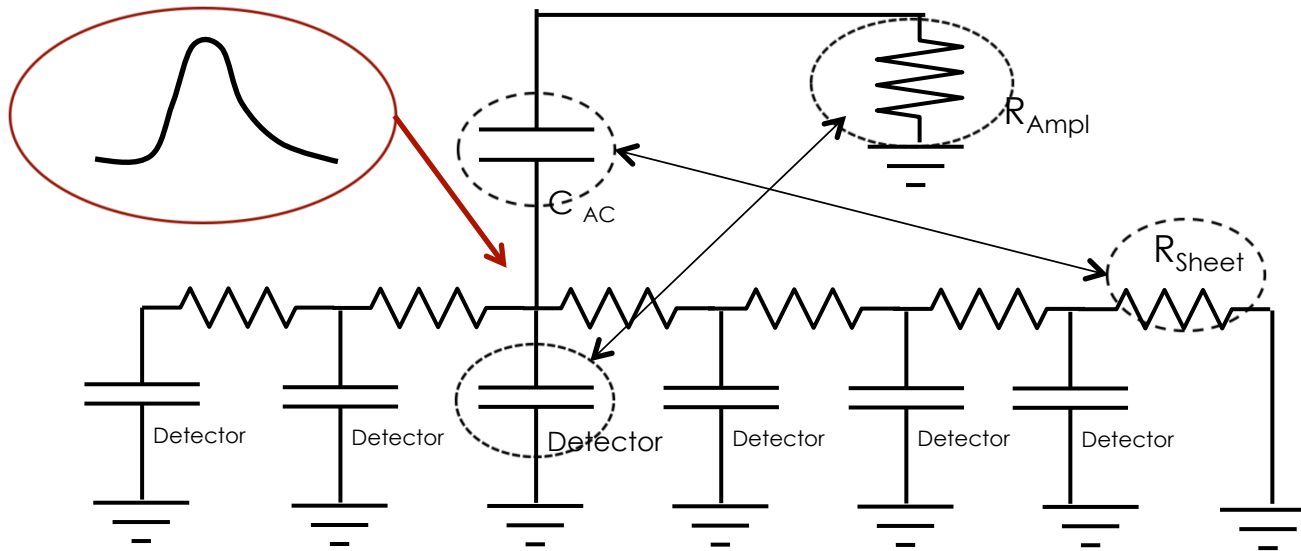
Standard n-in-p LGAD, with AC read-out



Details of Resistivity and AC coupling

Additional Rise time

$$R_{\text{Ampl}} * C_{\text{detector}} \sim 100 \Omega * 1 \text{pF} \sim \mathbf{100 \text{ ps}}$$

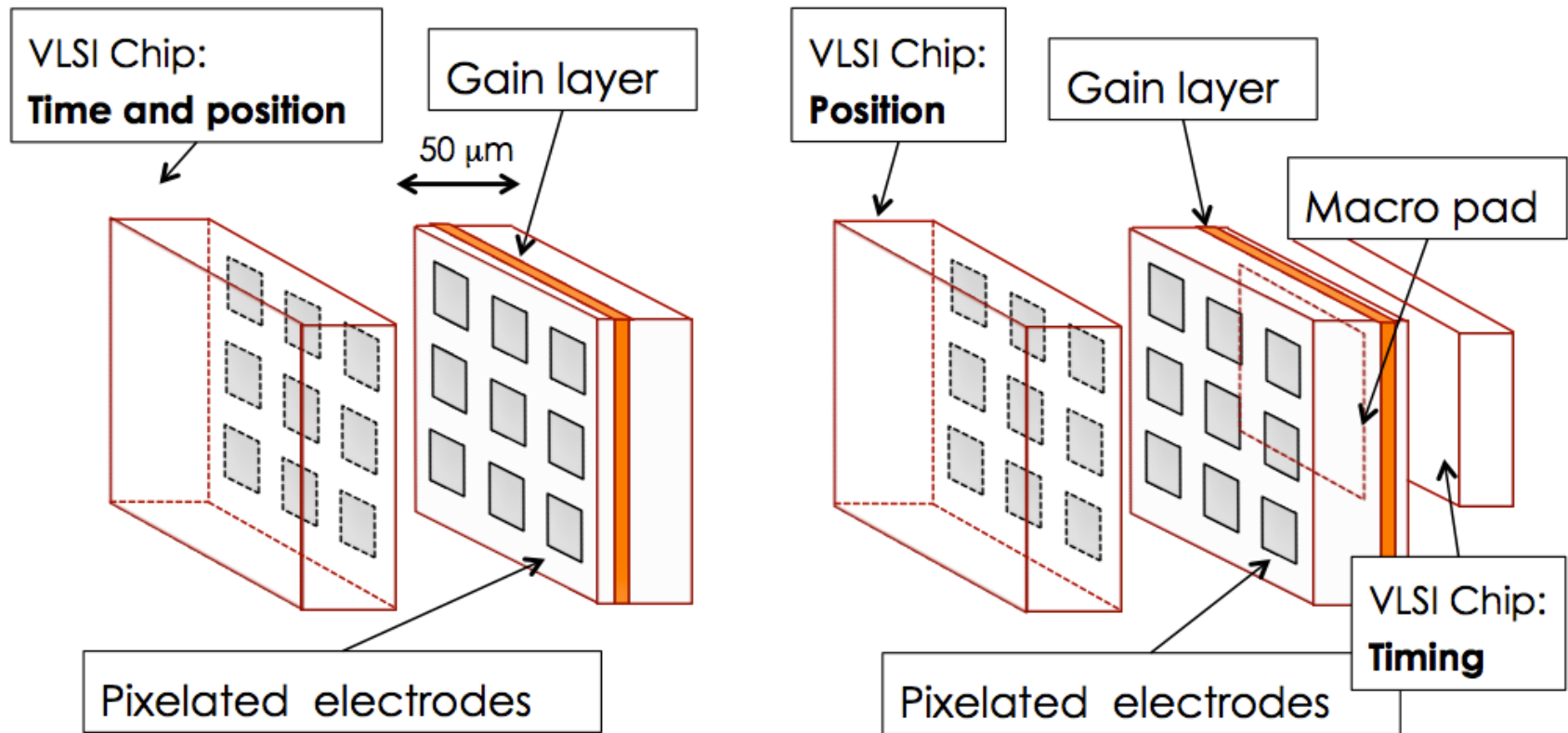


Freezing time

$$R_{\text{Sheet}} * C_{\text{AC}} \sim 1 \text{k}\Omega * 100 \text{pF} \sim 100 \text{ ns}$$

Only a small part of the detector is involved

3) Segmentation: splitting gain and position measurements

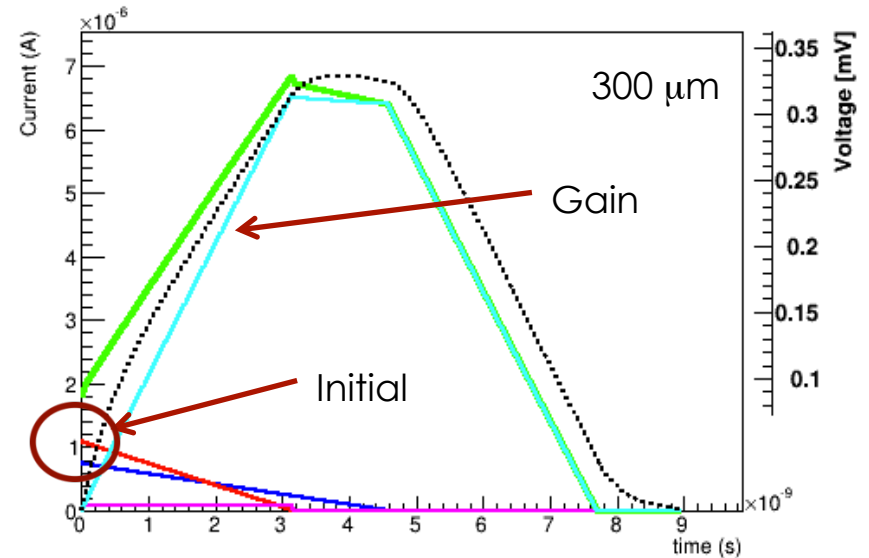
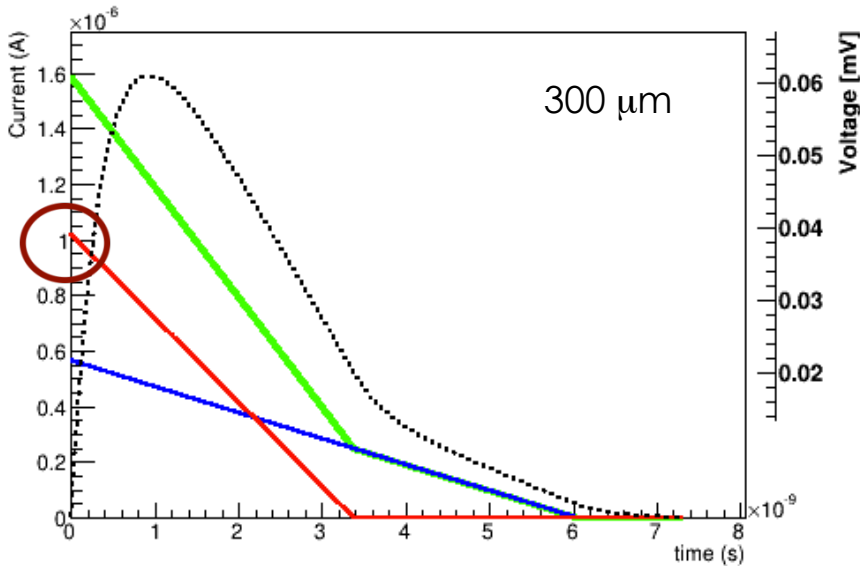
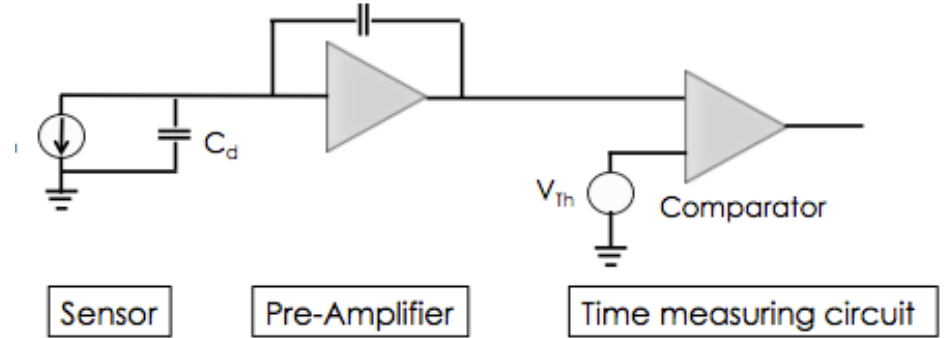


The ultimate time resolution will be obtained with a custom ASIC. However we might split the position and the time measurements

Electronics

To fully exploit UFSDs, dedicated electronics needs to be designed.

The signal from UFSDs is different from that of traditional sensors



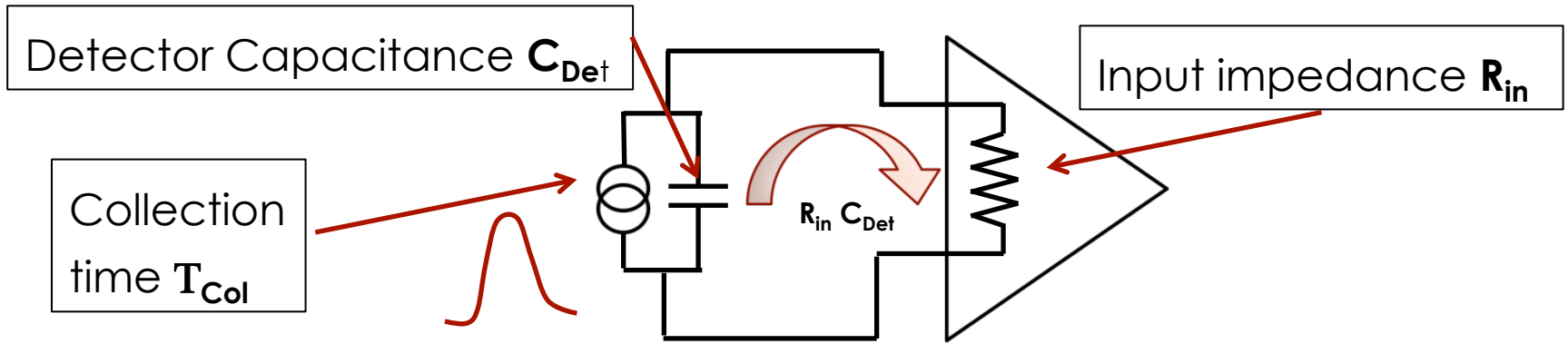
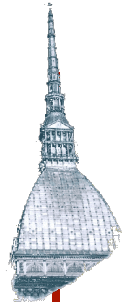
Pads with no gain

Charges generated uniquely by the incident particle

Pads with gain

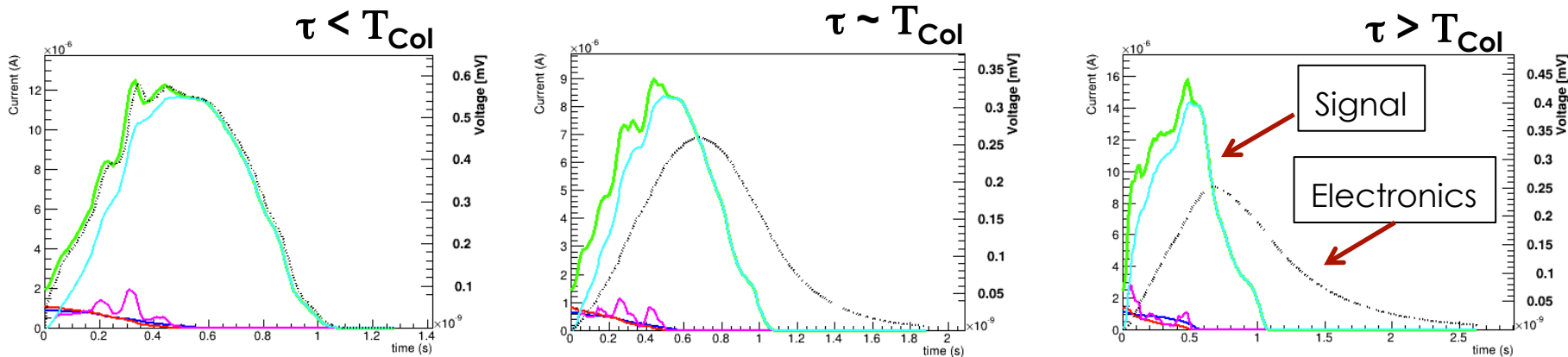
Current due to gain holes creates a longer and higher signal

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



There are two time constants at play:

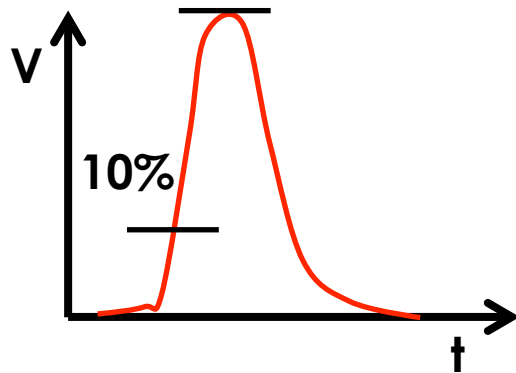
- T_{Col} : the signal collection time (or equivalently the rise time)
- $\tau = R_{in} C_{Det}$: the time needed for the charge to move to the electronics



τ/T_{Col} increases \rightarrow dV/dt decreases
 \rightarrow Smoother current

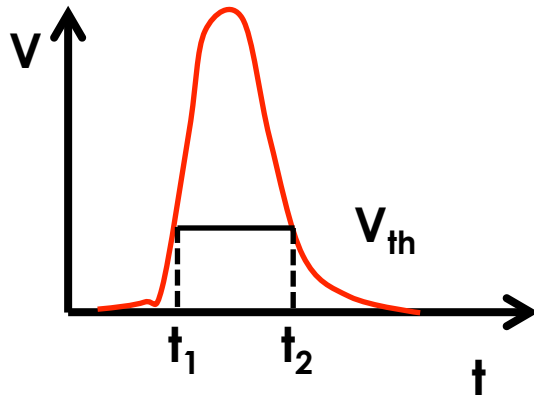
Need to find the optimum balance

What is the best “time measuring” circuit?



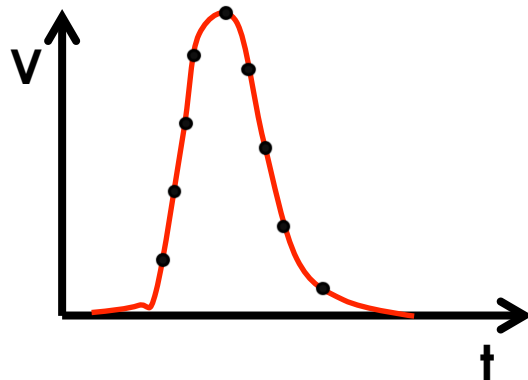
Constant Fraction Discriminator

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

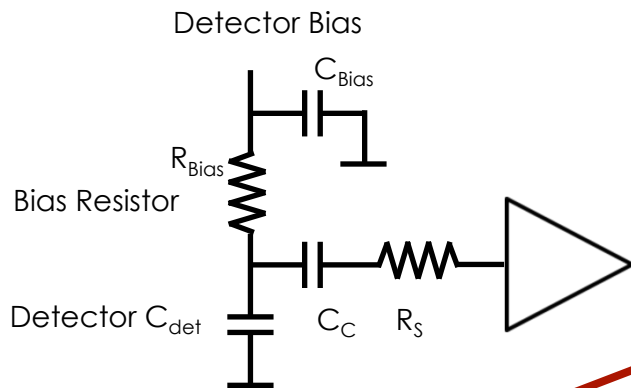


Multiple sampling

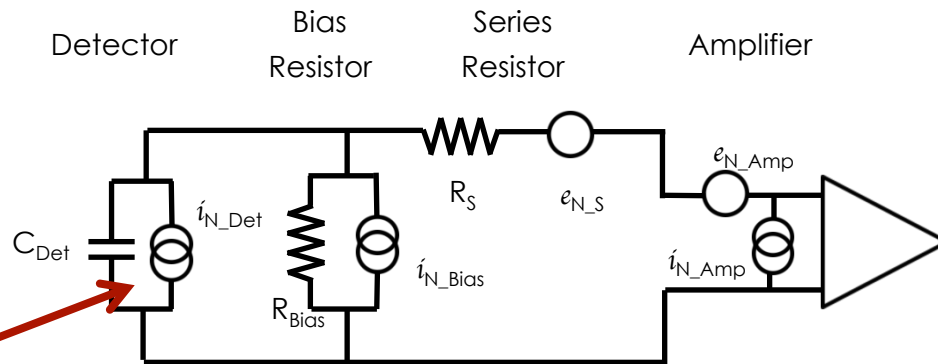
Most accurate method, needs a lot of computing power.

Noise - I

Real life



Noise Model



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

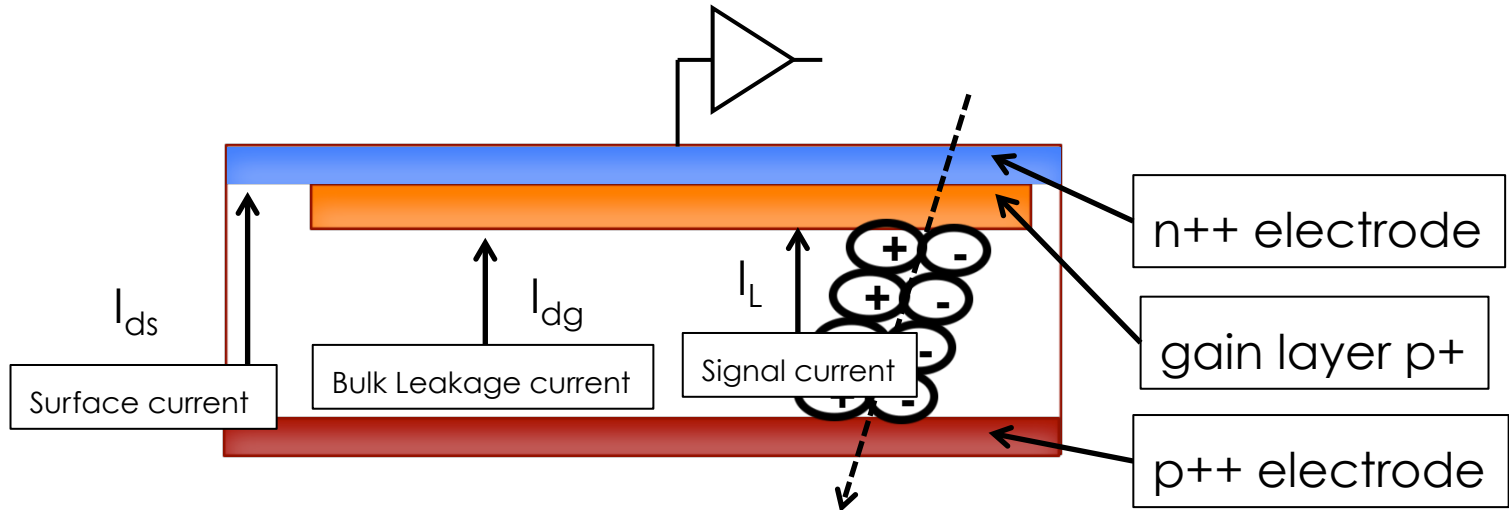
$$Q_n^2 = (2eI_{Det} + \frac{4kT}{R_{Bias}} + i_{N_Amp}^2) F T_s + (4kTR_s + e_{N_Amp}^2) F_v \frac{C_{Det}^2}{T_s} + F_{vf} A_f C_{Det}^2$$

$$2eI_{Det} * \text{Gain}$$

low gain!

This term dominates for short shaping time

Details of shot noise in LGAD - APD



$$i_{Shot}^2 = 2eI_{Det} = 2e \left[I_{Surface} + (I_{Bulk} + I_{Signal}) M^2 F \right]$$

$$F = Mk + \left(2 - \frac{1}{M} \right) (1 - k)$$

$$F \sim M^x$$

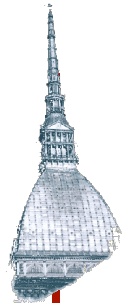
$k = e/h$ ionization rate

$x =$ excess noise index

$M =$ gain

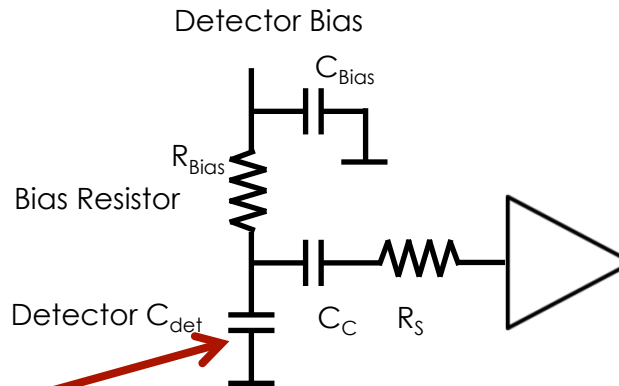
Correction factor to the standard Shot noise, due to the noise of the multiplication mechanism

$$F = \frac{\langle M^2 \rangle}{\langle M \rangle^2} \Rightarrow \langle M^2 \rangle = \langle M \rangle^2 F$$



Noise - II

Real life



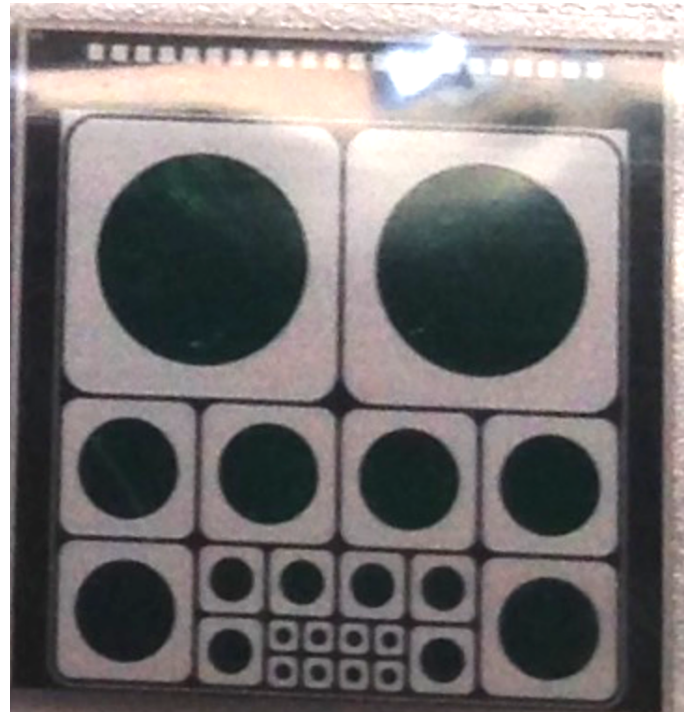
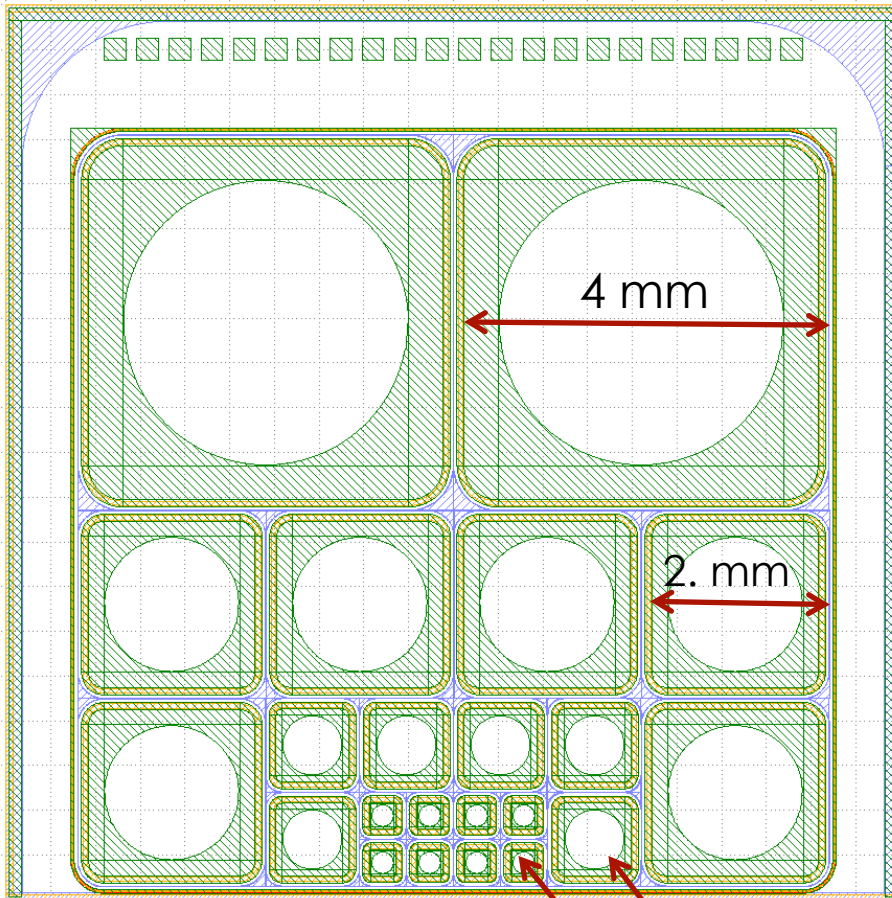
$$ENF = kG + \left(2 - \frac{1}{G}\right)(1 - k)$$

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.

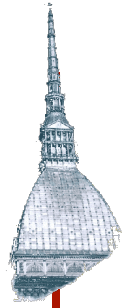
Next CNM productions



Timescale:

- **Spring 2015:** 200 micron
- **Summer 2015:** 100 micron
- **Summer 2015:** 50 micron

These new productions will allow a detailed exploration of the UFSD timing capabilities, including border effects between pads, and distance from the sensor edge.



Next Steps

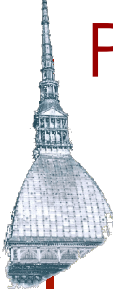
1. Wafer Production
200 micron thick sensors by **Spring-2015**
100 and 50 micron thick sensors by **Summer 2015**.
2. Production of UFSD doped with Gallium instead of Boron.
3. Study of reversed-UFSD started for the production of pixelated UFSD sensors (FBK, Trento).
4. UFSD are included in the CMS TDR CT-PPS as a solution for forward proton tagging
5. Use of UFSD in beam monitoring for hadron beam. INFN patent and work on-going
6. Interest in UFSD for 4D tracking at high luminosity
7. Testbeam analyses just started. Results coming soon...

UFSD – Summary

We are just starting to understand the timing capability of UFSD

- Low-gain avalanche diodes (LGAD) offer silicon sensors with an enhanced signal amplitude: UFSD are LGAD detectors optimized for timing resolution.
- Several options under studies to obtain concurrently excellent space and time resolutions.
- We developed a program, **Weightfield2** to simulate the behaviors of LGAD and optimized them for fast timing (available at <http://personalpages.to.infn.it/~cartigli/Weightfield2.0/>)

Timescale: 1 year to asses UFSD timing capabilities



Presented at IEEE, oral and posters, presentations

Nicola Cartiglia, INFN, Torino - UFSD; DESY, 20 March 2015

Low-Gain Avalanche Detectors (LGAD)

S. Ely, V. Fedeyev, Z. Gallaway, H. Gales, C. Liang, C. Parker, H.-W. Sadrzinski¹ (Senior Member), T. Shi, A. Siddons, A. Stone, A. Zaitsevskiy, INFN, UC Santa Cruz, USA
M. Bessio, P. Fernandez-Martinez, D. Fiora, V. Greco, S. Högler, G. Pellegrini, D. Quaroni, INFN/CN-CSC, Barcelona, Spain
E. Cavallaro, S. Dimitrov, J. Lango, I. Lopez-Pico, INFN, Barcelona, Spain
M. Fernandez-Gonzalez, J. Gonzalez-Sanchez, N. Gonzalez-Echeverria, I. Vitor, INFN/CSC/UC, Santander, Spain
P. Figini, G. Gallazzi, M. Müll, H. Neugebauer, CERN, Switzerland
G. Kramberger, V. Chiro, I. Mandic, M. Mikuz, M. Zavarzan, Institut Jozef Stefan, Ljubljana, Slovenia
N. Cartiglia, F. Cenna, A. Fiorino, F. Favaro, INFN, Torino, Italy
G.-F. Dalla Betta (Senior Member), L. Panzeri, University of Trento and TIFPA INFN, Italy
M. Baccarini, G. Pavesio, C. Piemonte, INFN, Trento, Italy

Introduction and Motivation

Requires for the wide-spread use of Silicon Detectors in HEP, Astrophysics, Medicine

- Highly sensitive
- Small footprint, Signal-to-Noise Ratio
- Superior technology edge (300nm process)
- Radiation Damage (minimizing of DR)
- Time resolution (the fabrication of a thin-well)
- Improve Silicon Detector performance by increasing the SR with internal gain

LGAD Design

Three critical regions of the LGAD design:

- Central area gain region: multiplication layer
- Custom electric field: sufficiently high to achieve breakdown of charge ionization (MUT)
- High electric field in the central region since breakdown voltage $V_{BD}(E_{eff}) = V_{BD}(Central)$

LGAD Structure

- Highly insulating p-type substrate
- Low gain p-diffusion for the electrodes
- p-diffusion under the surface
- enhanced electric field \rightarrow multiplication

Fabrication of LGADs at CNM

Run #	Geometry	Gate length	Gate width	Gate voltage
0011	100µm	10µm	10µm	10V
0012	100µm	10µm	10µm	10V
0013	100µm	10µm	10µm	10V
0014	100µm	10µm	10µm	10V

Optimization of the Gain Region

Doping profile of the P-type multiplication layer determines both Gain and Breakdown.

Higher Boron Implant dose \rightarrow higher Gain \rightarrow higher Breakdown

Electrical Characterization

Current - Voltage (IV) Characterization

Small variations in the Boron implant dose lead to large changes in Gain and V_{BD} values

Gain Sensitivity to Boron Doping: β MP's

Boron implant dose is varied from wider to wider (Plot 0476)

Small variations in the Boron implant dose lead to large changes in Gain and V_{BD} values

Gain Testing of LGAD's

Comparison with non-gain detectors required

Gain $\sim 10^2$ to 10^3 (at 100V)

Segmented LGADs

330µm PZ (8027) 100µm PZ

Gain $\sim 10^2$ to 10^3 (at 100V)

Gain in thin LGAD

Gain $\sim 10^2$ to 10^3 (at 100V)

Segmented LGAD R&D

Thin p-type LGAD wires

Gain $\sim 10^2$ to 10^3 (at 100V)

Mitigation of Radiation Damage

Large fraction of the total radiation dose is absorbed by the bulk

Time Resolution

Time resolution ~ 40 ps (at 100V)

Conclusions

LGADs show uniform gain for pads across wafers with same p-dose

Mitigation of radiation damage planned

Acknowledgments

Work supported by INFN, INFN/CN-CSC, INFN/TIFPA



Weightfield2: a fast simulator for silicon and diamond detectors

N. Cartiglia¹, F. Cenna¹, M. Friedl², B. Koblinger³, A. Seiden², H.-W. Sadrzinski⁴, Andriy Zaitsevskiy⁵, Anton Zaitsevskiy⁶
¹INFN, Torino, Italy; ²INFN, Trento, Italy; ³DESY, Hamburg, Germany; ⁴INFN, UC Santa Cruz, USA; ⁵INFN, CN-CSC, Barcelona, Spain; ⁶INFN, CN-CSC, Barcelona, Spain



Goal

The aim of this project is to create a fast simulator of the signals generated by an impinging particle in silicon and diamond detectors. The program should be fast and easy to use and it should provide an accurate assessment of the detector response.

Methods

The program is written in C++ and uses the HEP programs ROOT and GEANT4. It computes the electric and weighting fields for any given geometry and it uses Romo's algorithm to calculate the induced output current signal.

Findings

WF2 is able to compute the detector response for a variety of impinging particles and sensor geometries. Its predictions have been validated using laboratory measurements, test-beam data, and TCAD simulations obtaining very good agreements.

The Weightfield2 Graphical User Interface

- Tab 1: Diff potential
- Tab 2: Weighting pot.
- Tab 3: Currents
- Tab 4: Electronics
- Particles: Particle type, position, energy, direction
- Settings: Simulation parameters
- Geometry: High, with, without
- Gain: Gain, Gain, Gain
- Voltage: Voltage, Voltage, Voltage
- Electronics: Electronics, Electronics, Electronics
- External Conditions: External Conditions, External Conditions

Results

Minimize the geometry of impinging particles

Low-dose fluctuations

Comparison TCAD - Simulation

Change Multiplication

Simulation of the induced current

Simulation of the induced current

References

[1] ... [2] ... [3] ...

Acknowledgments

Work supported by INFN, INFN/CN-CSC, INFN/TIFPA

Additional references

Several talks at the 22nd, 23rd and 24th RD50 Workshops:

23rd RD50: <https://indico.cern.ch/event/265941/other-view?view=standard>

22nd RD50: http://panda.unm.edu/RD50_Workshop/

10th Trento Workshop, Trento, Feb 2015.

9th Trento Workshop, Genova, Feb 2014.

F. Cenna “**Simulation of Ultra-Fast Silicon Detectors**”

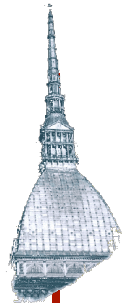
N. Cartiglia “**Timing capabilities of Ultra-Fast Silicon Detector**”

Papers:

[1] N. Cartiglia, Ultra-Fast Silicon Detector, 13th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD13), 2014 JINST 9 C02001, <http://arxiv.org/abs/1312.1080>

[2] H.F.-W. Sadrozinski, N. Cartiglia et al., Sensors for ultra-fast silicon detectors, Proceedings "Hiroshima" Symposium HSTD9, DOI: 10.1016/j.nima.2014.05.006 (2014).

Backup



The “Low-Gain Avalanche Detector” project

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

- 730 e/h pair per micron instead of 73 e/h
- Finely segmented
- Radiation hard
- No dead time
- Very low noise (low shot noise)
- No cross talk

Low-Gain Avalanche Detectors (LGAD)

S. Ely, V. Fadeyev, Z. Dattaway, H. Grates, Z. Liang, C. Parker, K. F.-W. Sadrizadeh (Senior Member), T. Sai, A. Seiden, A. Stone, A. Zolotarevskiy, SCIPP, UC Santa Cruz, USA
 M. Sasegla, P. Fernández-Martínez, D. Flores, V. Greco, S. Hedges, G. Pellegrini, D. Quirón, IMBICNM-CBIC, Barcelona, Spain
 C. Cavallari, S. González, J. Longo, I. López-Pascual, Barcelona, Spain
 M. Fernández García, J. González Sánchez, N. Jovanović Echeverría, I. Vila, IFCA (CSIC-UC), Santander, Spain
 P. Figini, G. Dall'aga, M. Stoll, H. Noguchi, CERN, Switzerland
 G. Kramberger, V. Conzo, I. Mandić, M. Mair, M. Završnik, Institut Jožef Stefan, Ljubljana, Slovenia
 N. Cartiglia, F. Cirrera, A. Picomo, F. Ravera, INFN Torino, Italy
 G.-F. Dalla Bernardina (Senior Member), L. Fanfani, University of Trento and INFN-INFN, Italy
 M. Bassacchi, G. Zanone, C. Zucchetti, FBK, Trento, Italy

The posters provide detailed technical information about LGADs, including their structure, fabrication processes, electrical characteristics, and performance metrics. Key findings include the ability to achieve high gain (up to 100x) and high signal rates (up to 100 MHz) while maintaining low noise and high radiation tolerance.

Poster Session IEEE N26-13


How can we progress? Need simulation



We developed a full simulation program to optimize the sensor design, WeightField2, (<http://cern.ch/weightfield2>)

It includes:

- Custom Geometry
- Calculation of drift field and weighting field
- Currents signal via Ramo's Theorem
- Gain
- Diffusion
- Temperature effect
- Non-uniform deposition
- Electronics



Weightfield2: a fast simulator for silicon and diamond detectors

N. Cartiglia¹, F. Cenna¹, M. Friedl², B. Kolbinger³, A. Seiden³, H.F.W. Sadrozinski⁴, Andriy Zatserklyany⁵, Anton Zatserklyany⁵

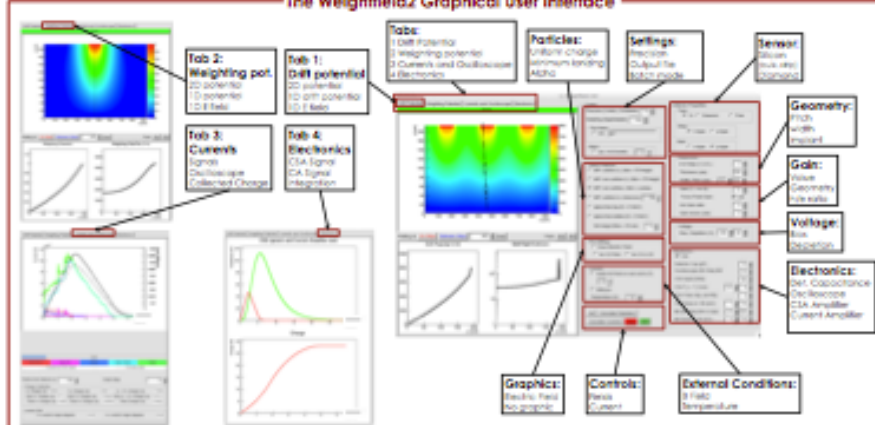
¹INFN, Santa Cruz, ²INFN, Torino, ³University of California, Santa Cruz, ⁴INFN, Torino, ⁵INFN, Santa Cruz

Contact: cartiglia@to.infn.it

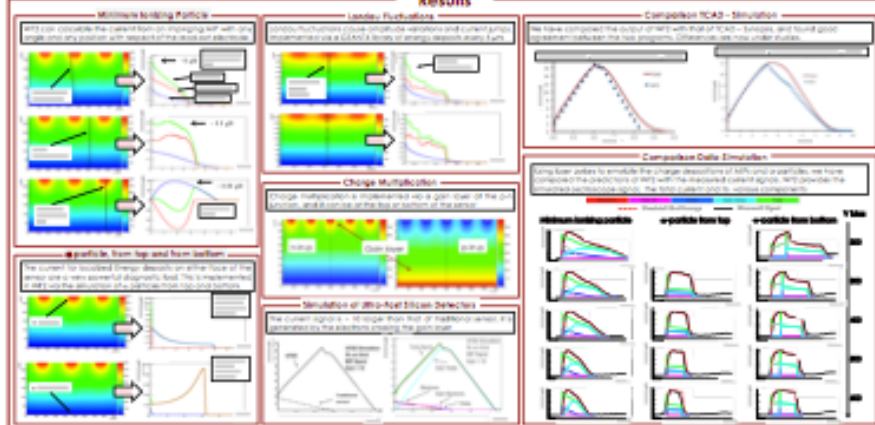
Poster N11-8

<p>Goal</p> <p>The aim of this project is to create a fast simulator of the signal generated by an impinging particle in silicon and diamond detectors. The program should be fast, and easy to use and it should provide an accurate assessment of the detector response.</p>	<p>Methods</p> <p>The program is written in C++ and uses the HEP programs ROOT and GEANT4. It computes the electric and weighting fields for any given geometry and it uses Ramo's theorem to calculate the induced output current signal.</p>	<p>Findings</p> <p>WF2 is able to compute the detector response for a variety of impinging particles and sensor geometries. Its predictions have been validated using laboratory measurements, testbeam data, and TCAD simulations obtaining very good agreements.</p>
---	---	---

The Weightfield2 Graphical User Interface



Results



References

[1] ...

[2] ...

[3] ...

Acknowledgements

[1] ...

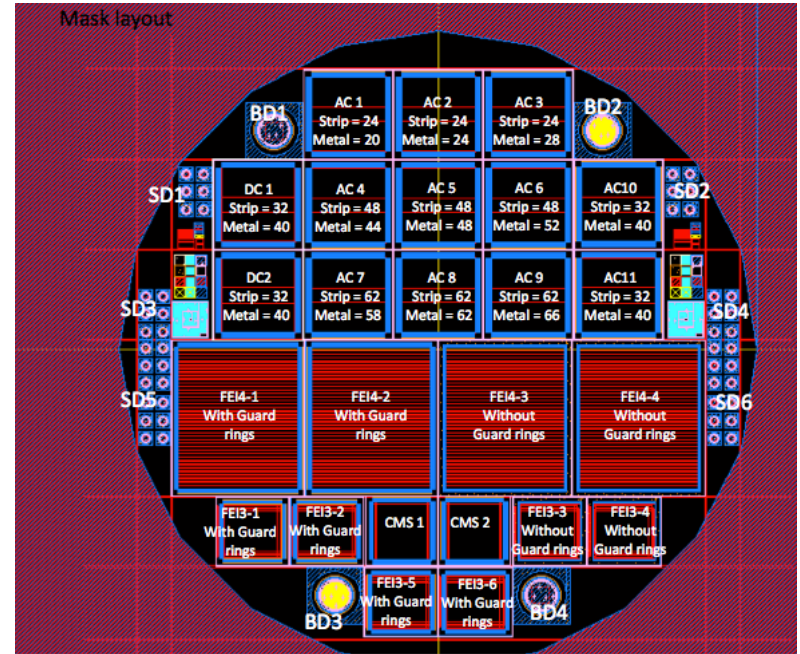
[2] ...

[3] ...

CNM LGADs mask

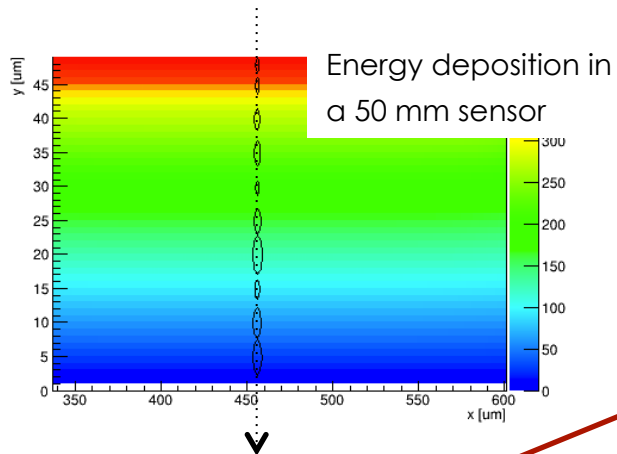
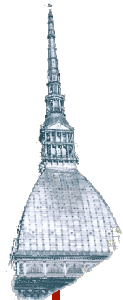
CNM, within the RD50 project, manufactured several runs of LGAD, trying a large variety of geometries and designs

This implant controls the value of the gain

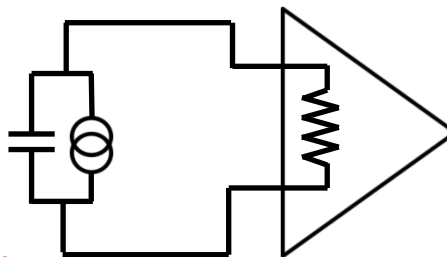


Wafer Number	P-layer Implant (E = 100 keV)	Substrate features	Expected Gain
1-2	$1.6 \times 10^{13} \text{ cm}^{-2}$	HRP 300 (FZ; $\rho > 10 \text{ K}\Omega \cdot \text{cm}$; $<100>$; T = $300 \pm 10 \mu\text{m}$)	2 – 3
3-4	$2.0 \times 10^{13} \text{ cm}^{-2}$	HRP 300 (FZ; $\rho > 10 \text{ K}\Omega \cdot \text{cm}$; $<100>$; T = $300 \pm 10 \mu\text{m}$)	8 – 10
5-6	$2.2 \times 10^{13} \text{ cm}^{-2}$	HRP 300 (FZ; $\rho > 10 \text{ K}\Omega \cdot \text{cm}$; $<100>$; T = $300 \pm 10 \mu\text{m}$)	15
7	(---) PiN Wafer	HRP 300 (FZ; $\rho > 10 \text{ K}\Omega \cdot \text{cm}$; $<100>$; T = $300 \pm 10 \mu\text{m}$)	No Gain

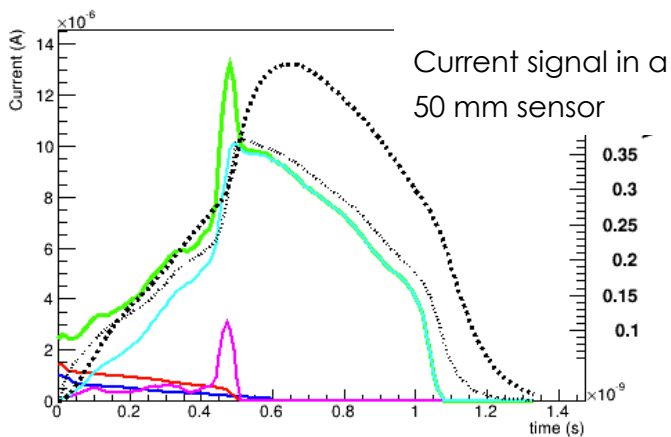
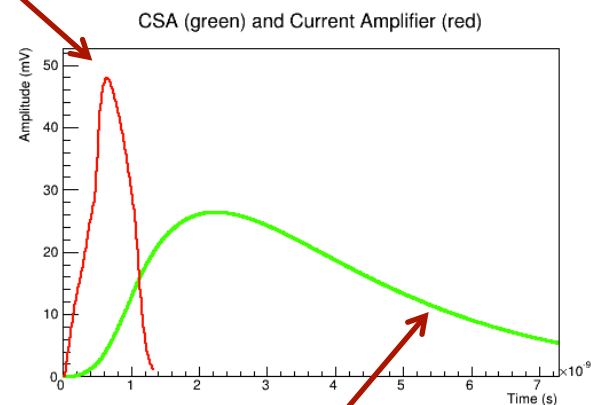
Electronics: What is the best pre-amp choice?



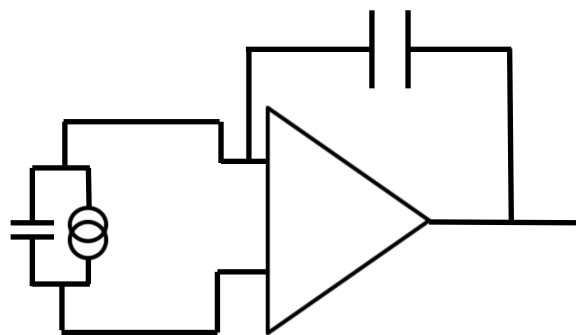
Current Amplifier



- Fast slew rate
- Higher noise
- Sensitive to Landau bumps

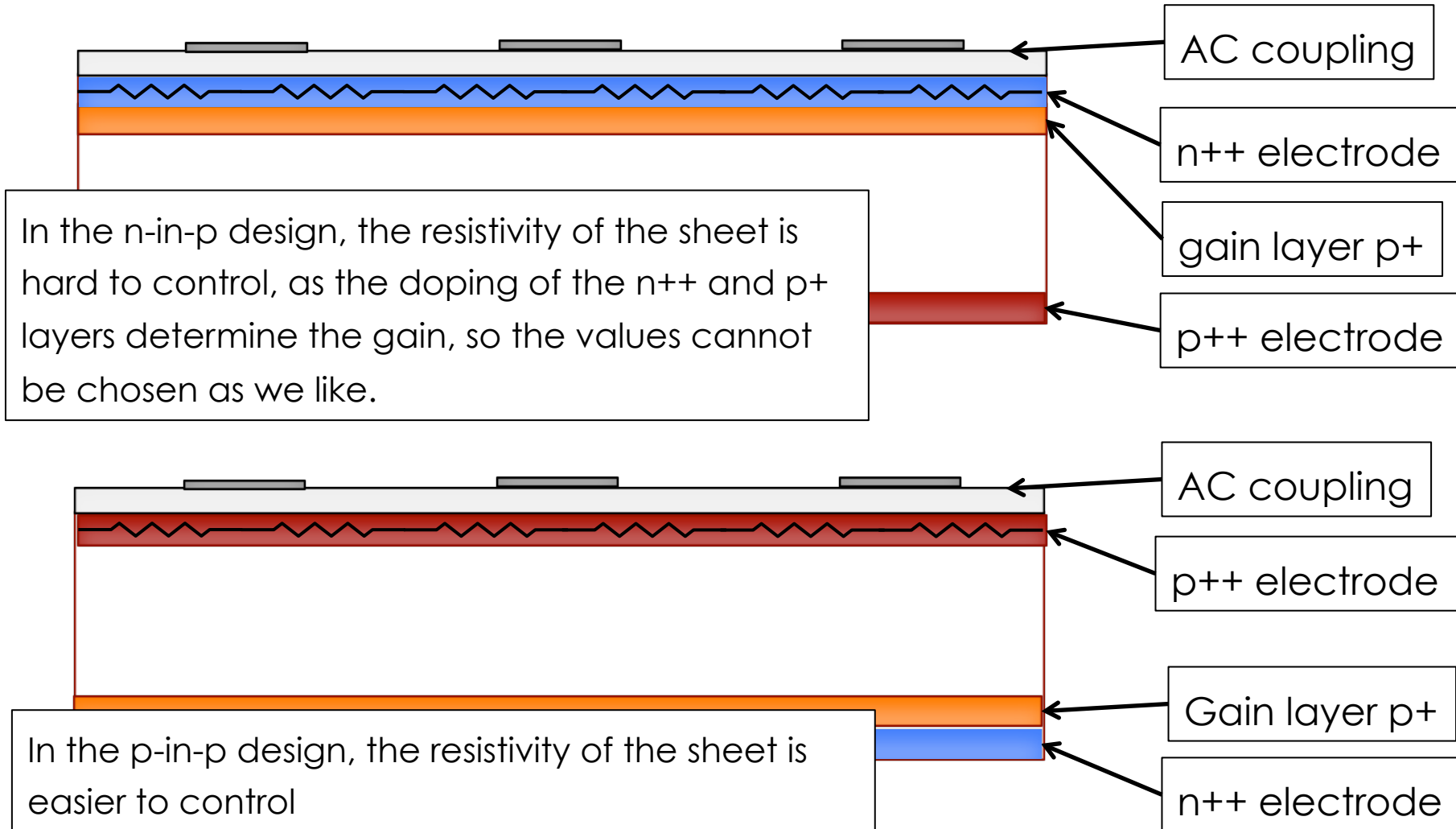


Integrating Amplifier



- Slower slew rate
- Quieter
- Integration helps the signal smoothing

Details of AC coupling - II



Drift Velocity

$$i \propto qvE_w$$

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

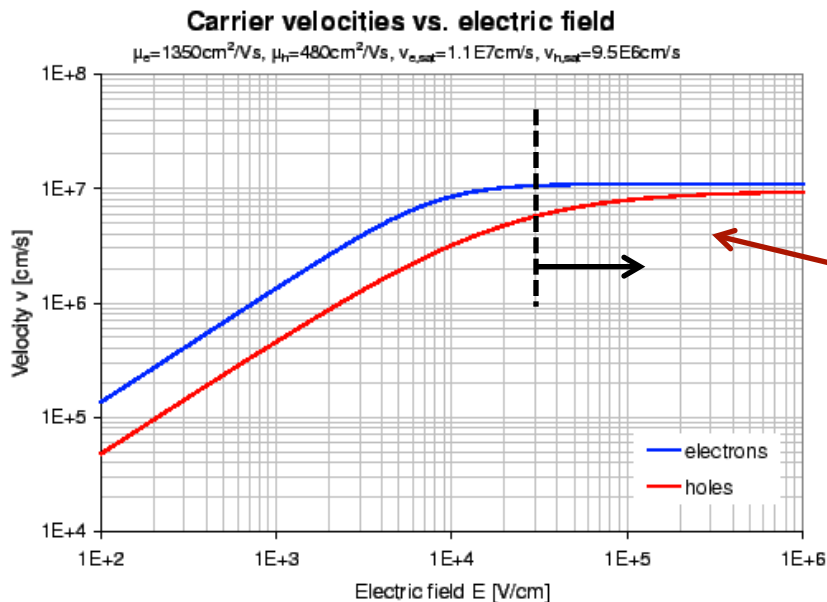
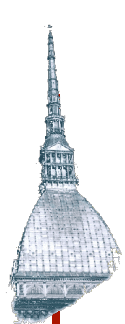


Figure: Electron and hole velocities vs. the electric field strength in silicon.

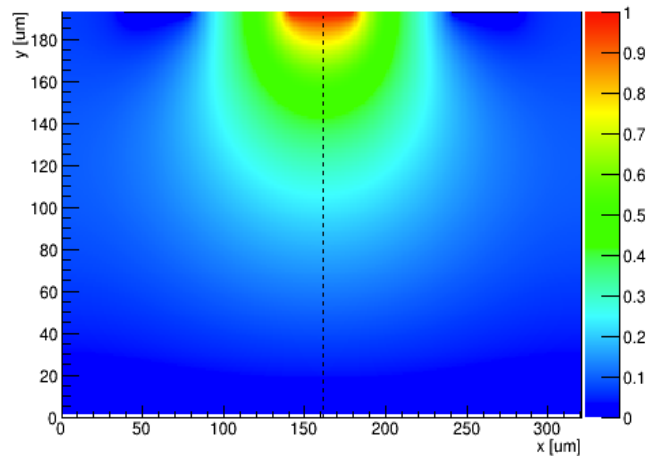
We want to operate in this regime



Weighting Field: coupling the charge to the electrode

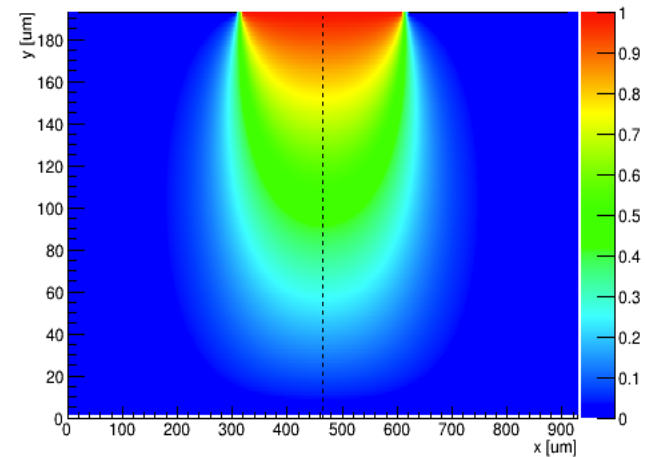
$$i \propto qvE_w$$

Strip: 100 μm pitch, 40 μm width



Bad: almost no coupling away from the electrode

Pixel: 300 μm pitch, 290 μm width



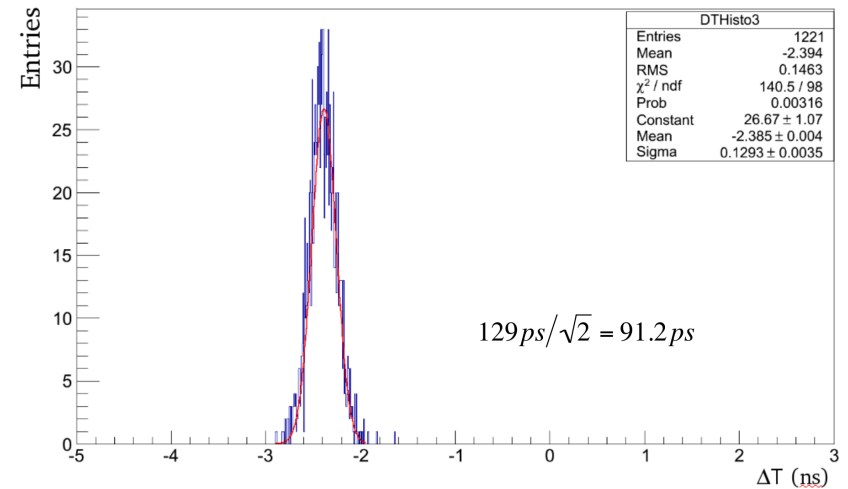
Good: strong coupling almost all the way to the backplane

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

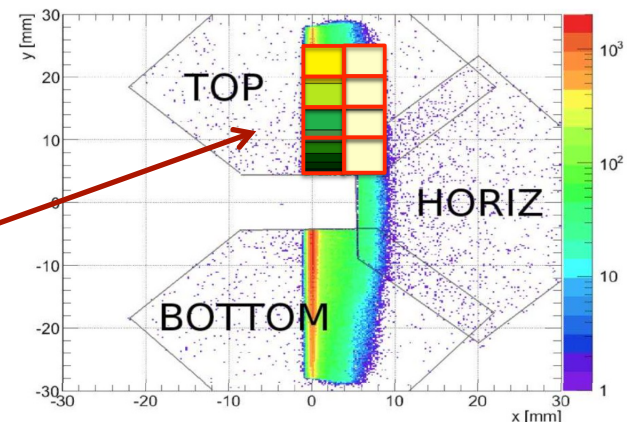
The Diamond approach - II

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 $\sim 4.5 \times 4.5 \text{ mm}^2$ detectors



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



Noise for Gain = 1 and Gain = 10

Let's use the following parameterization (Spieler, Semiconductor Detector, pag 35):

$$Q_n^2 = 12 \left[\frac{e^2}{\text{nA} \cdot \text{ns}} \right] (I_{\text{Bulk}} + I_{\text{Signal}}) M^{2+x} \tau + 3.6 \cdot 10^4 \left[\frac{e^2 \text{ ns}}{\text{pF}^2 \text{ nV}^2 / \text{Hz}} \right] e^2_{N_Amp} \frac{C_{\text{Det}}^2}{\tau}$$

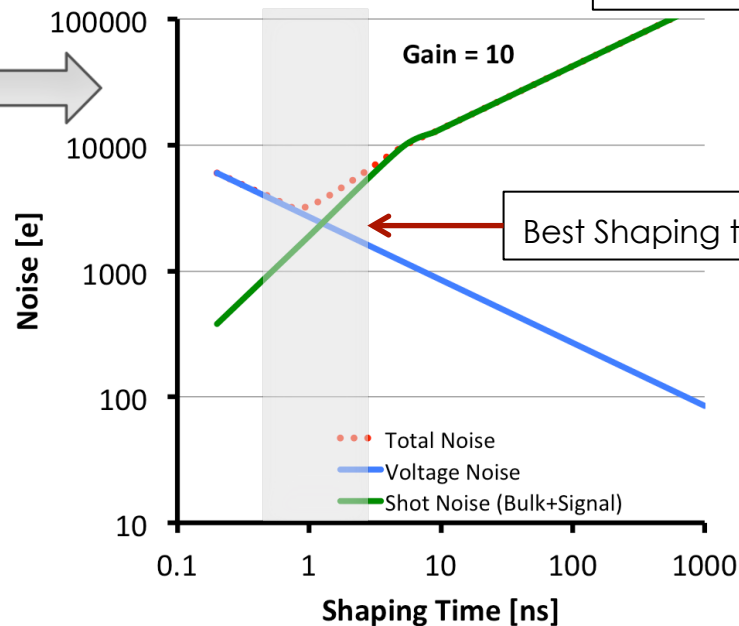
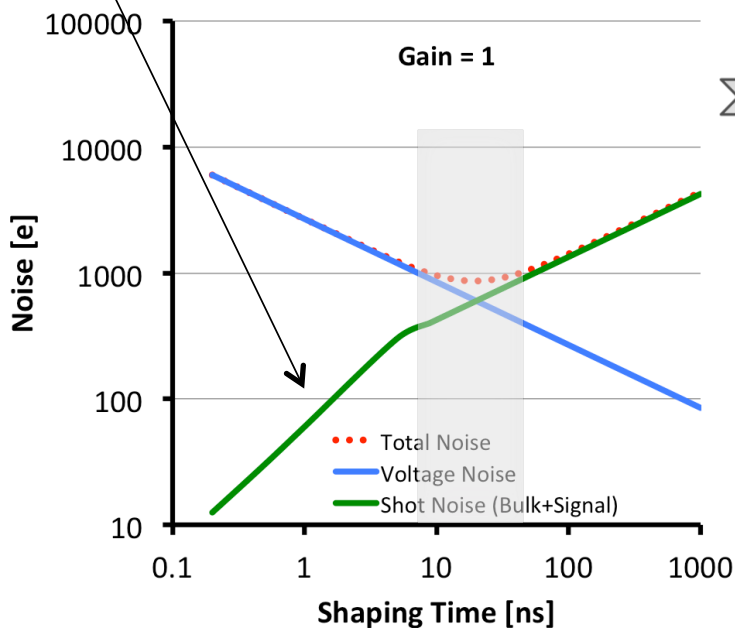
Current noise very important at small shaping time

Shot Noise

Voltage Noise

$I_{\text{bulk}} = 1 \text{ nA}$
 $I_{\text{signal}} = 300 \text{ nA} \cdot 5 \text{ ns}$
 $x = 1$
 $C_{\text{det}} = 1 \text{ pF}$

Effect of the gain



The minimum noise value is pushed higher and to a much shorter shaping time:

1000e- at 20 ns with Gain = 1 → 3000e- @ 1 ns with Gain = 10

→ LGADs need very short shaping time ←

LGAD Optimum S/N: numbers

The noise increases faster than the signal:
the ratio S/N becomes worse at higher gain.

→ There is an Optimum Gain value ←

Let's consider the following situation:

- Signal = 20k e⁻
- Shaping time 1 ns
- Voltage Noise = 1k e⁻
- Shot Noise (G = 1) = 10 e⁻
- Excess Noise Factor M^x x = 0.25, 0.5, 1

Summary

- 1) For a given ENF, there is an optimum gain
- 2) The optimum gain is a function of the excess noise exponent x: higher x values cause lower optimum gains
- 3) Higher optimum gains require shorter shaping time

