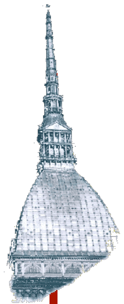
Ultra-Fast Silicon Detector

- 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

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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

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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]**

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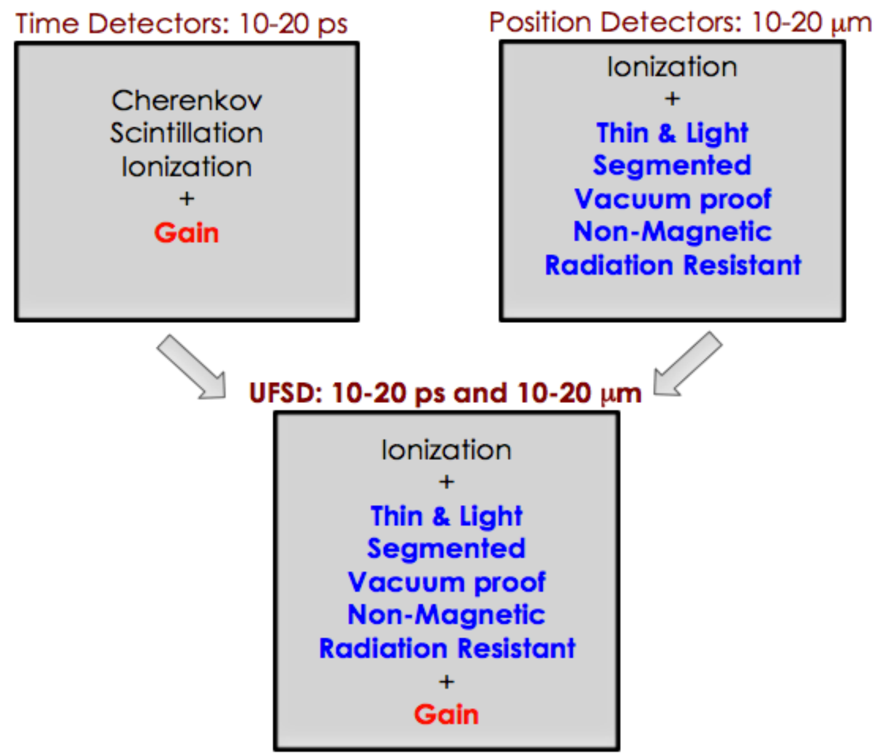
Our path: Ultra-fast Silicon Detectors

Is it possible to build **a silicon detector** with concurrent excellent timing and position resolutions?

Why silicon?

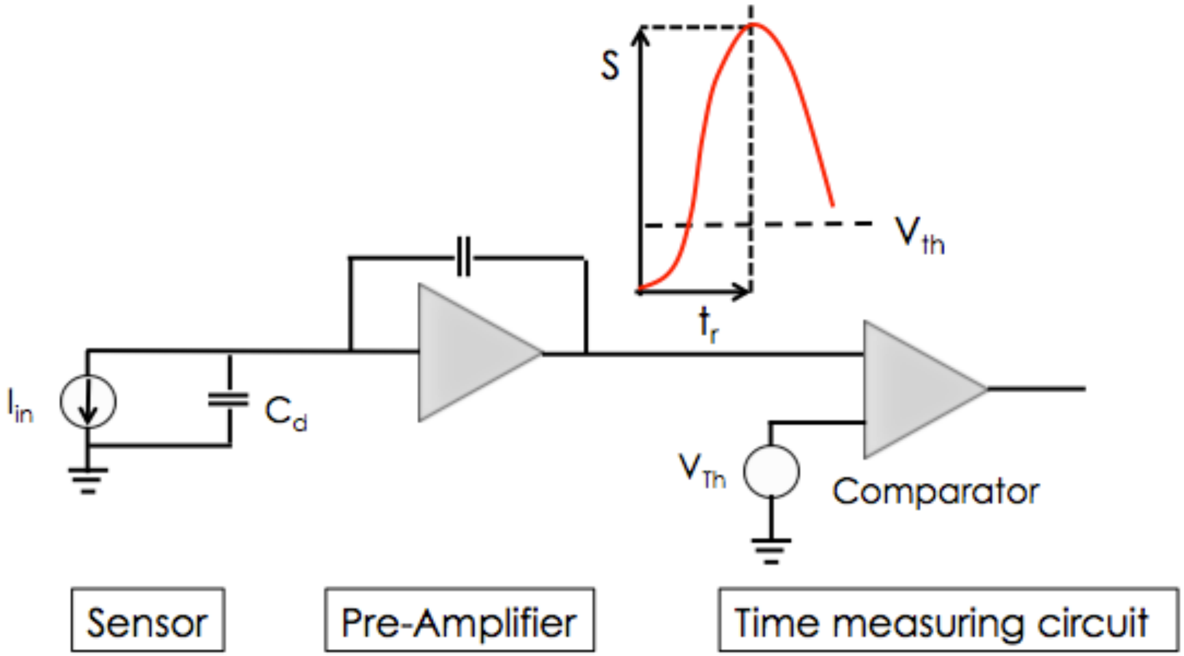
- It already has excellent position resolution
- Very well supported in the community
- Finely segmented
- Thin
- Light
- A-magnetic
- Small
- Radiation resistant



But can it be precise enough?

A time-tagging detector

(a simplified view)



Time is set when the signal crosses the comparator threshold

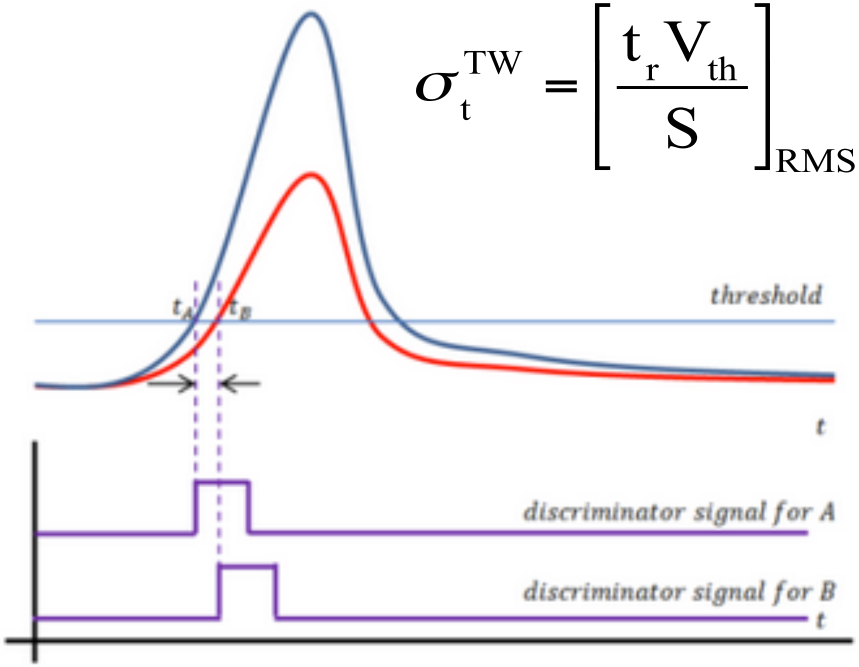
The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning.

Noise source: Time walk and Time jitter

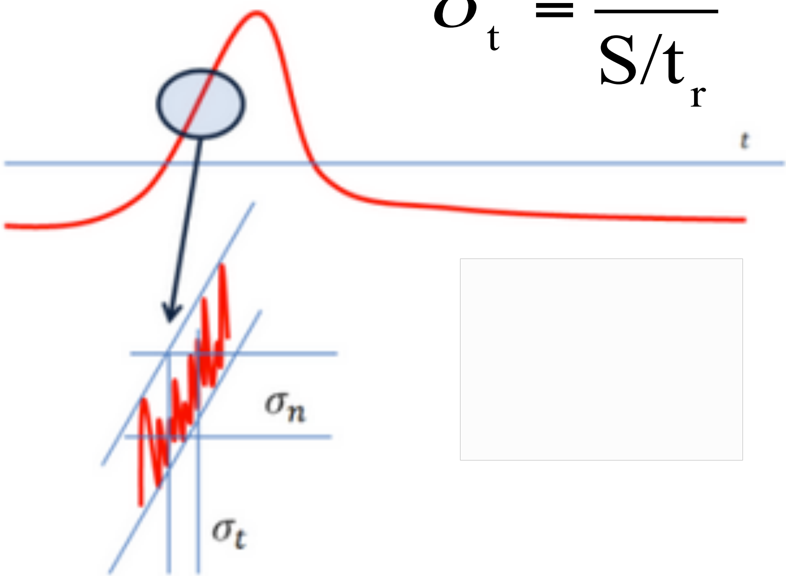
Time walk: the voltage value V_{th} is reached at different times by signals of different amplitude

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

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



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



Due to the physics of signal formation

Mostly due to electronic noise

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

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Time Resolution and slew rate

Using the expressions in the previous page, we can write

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

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)

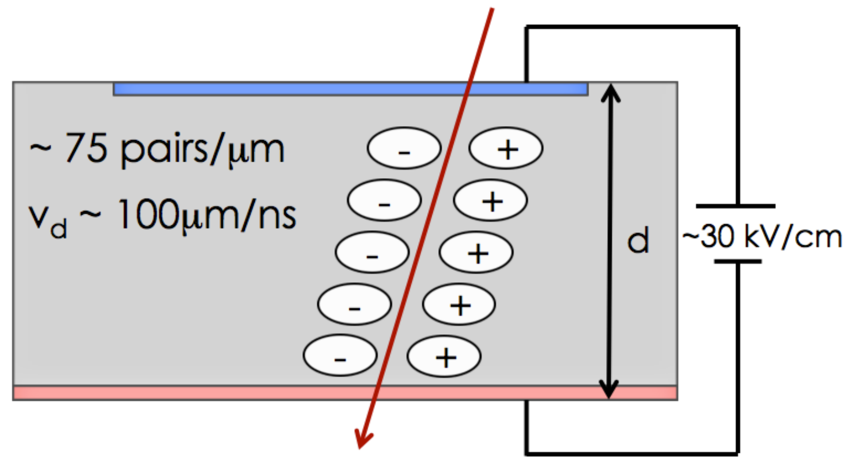
➔ We need large and short signals ⟵

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

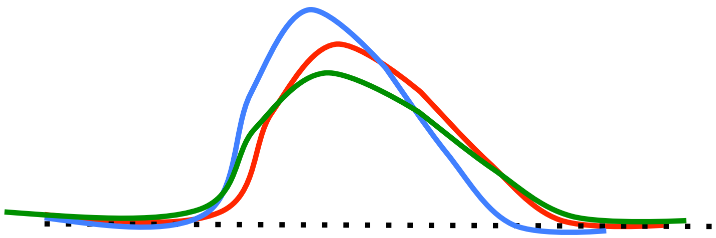
How to make a **good** signal

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**

Drift Velocity

$$i \propto q v E_w$$

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

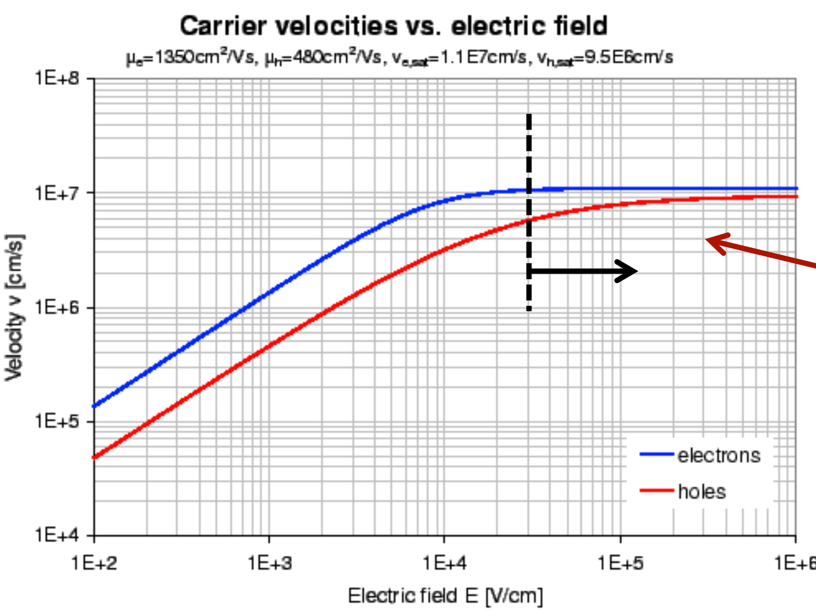


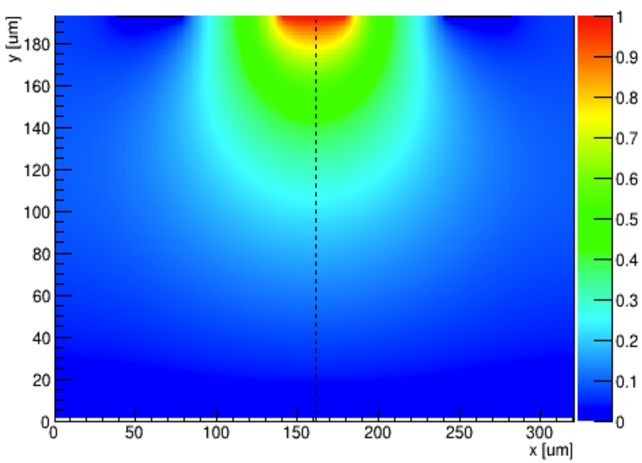
Figure: Electron and hole velocities vs. the electric field strength in silicon.

We want to operate in this regime

Weighting Field: coupling the charge to the electrode

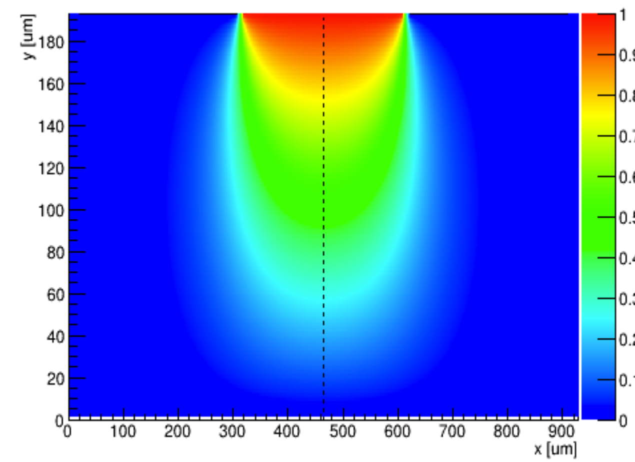
$$i \propto qvE_w$$

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

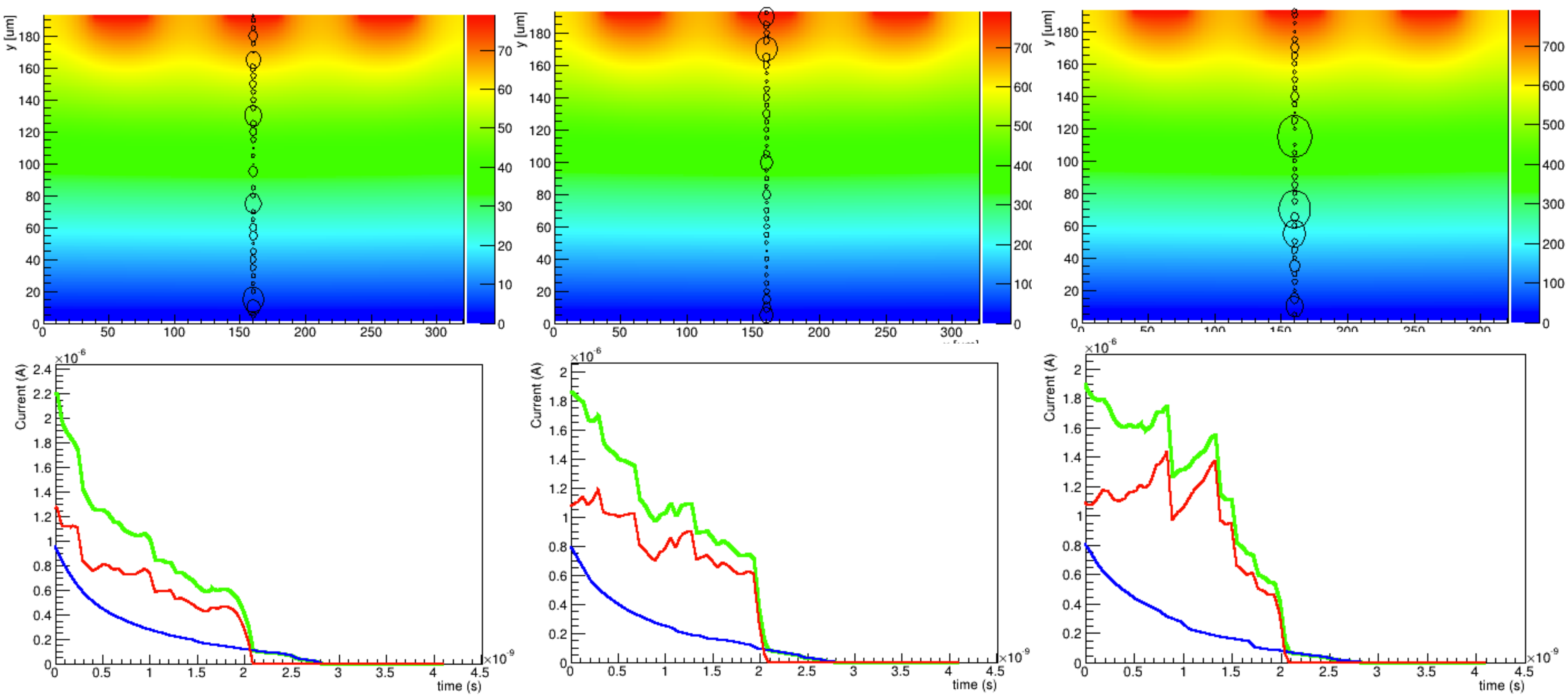
The weighting field needs to be as uniform as possible, so that the coupling is always the same, regardless of the position of the charge

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?

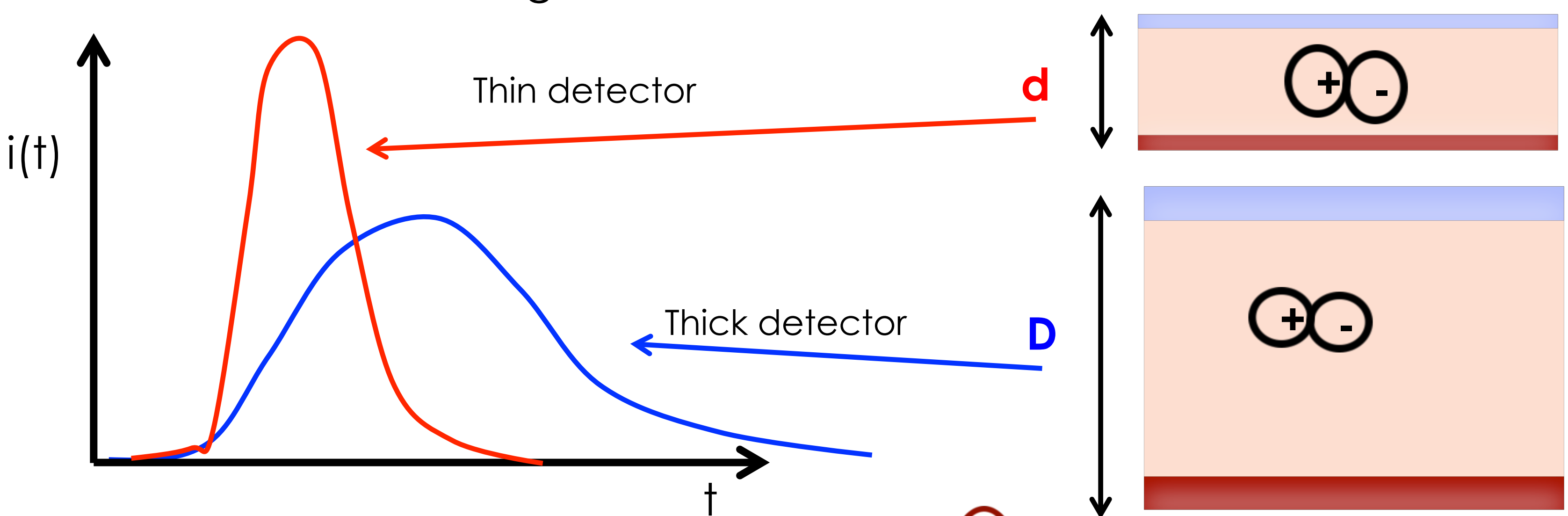
(Simplified model for pad detectors)

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**

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

Weighting field

Large signals from thick detectors?

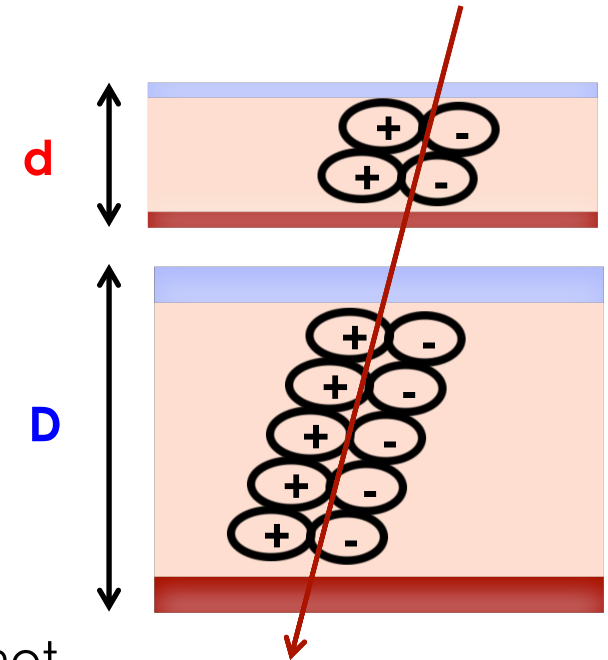
(Simplified model for pad detectors)

Thick detectors have higher number of charges:

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

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:

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

Number of e/h = 75/micron

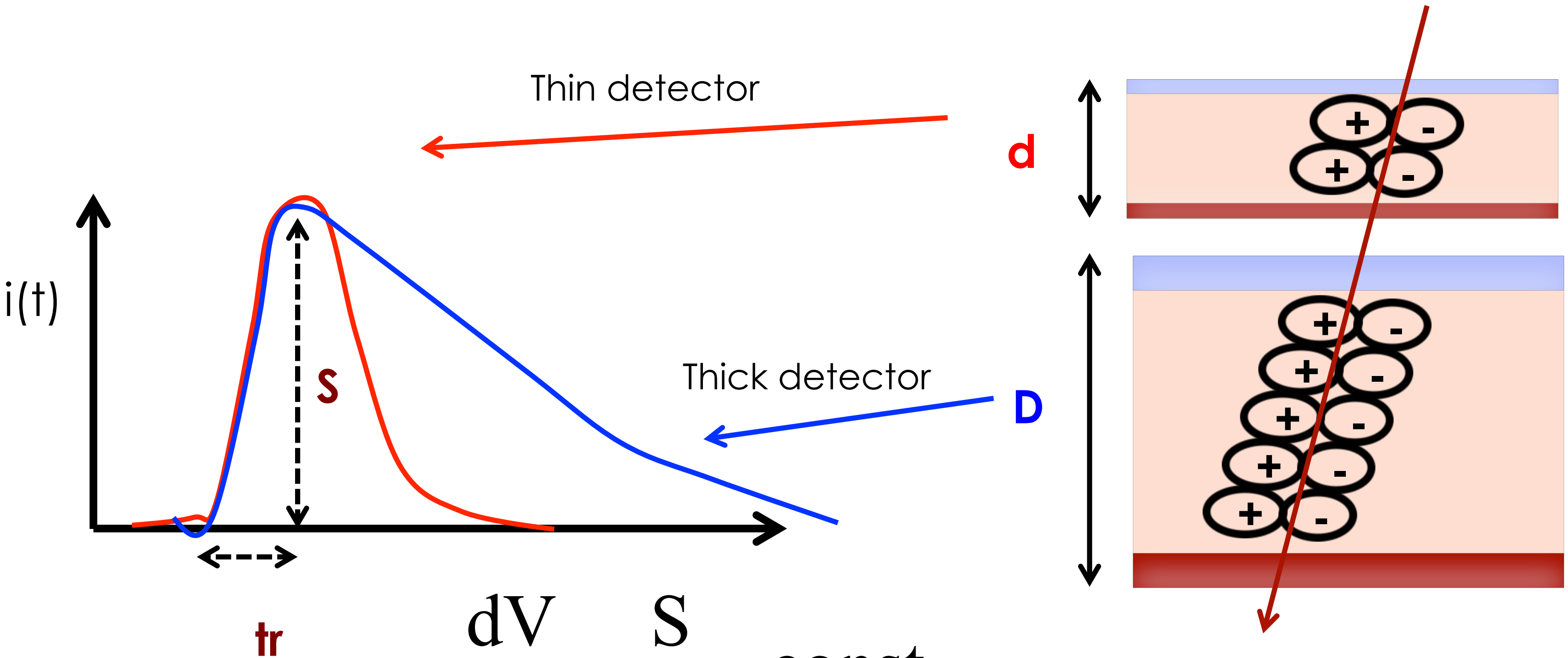
Weighting field

velocity

➔ **Initial current = constant**

Thin vs Thick detectors

(Simplified model for pad detectors)



$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim \text{const}$$

Thick detectors have longer signals, not higher signals

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

To do better, we need to add gain

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)?

- 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 (30 micron == 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 ~ 300 kV/cm**

Charge multiplication

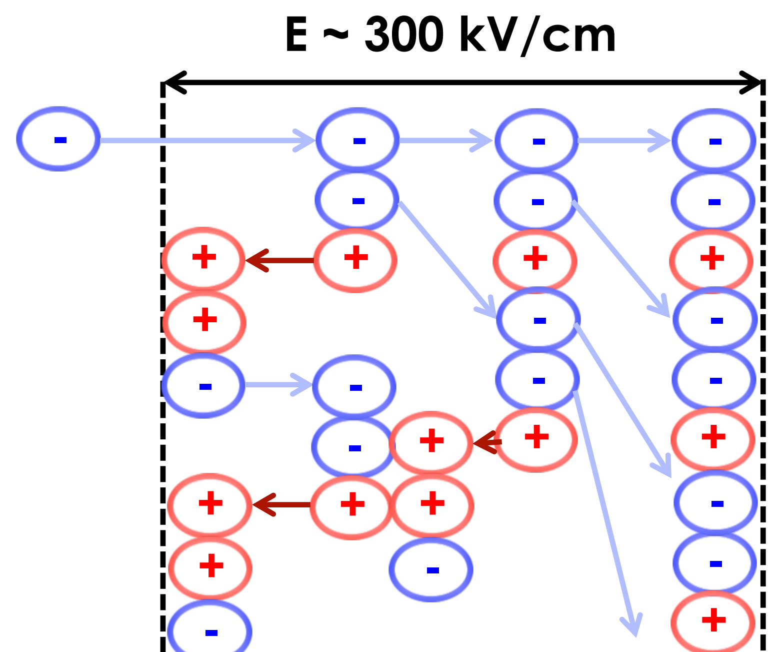
$$N(l) = N_0 \cdot e^{\alpha \cdot l}$$

Gain:

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

α = strong E dependance
α ~ 0.7 pair/μm for electrons,
α ~ 0.1 for holes

Concurrent multiplication of electrons and holes generate very high gain



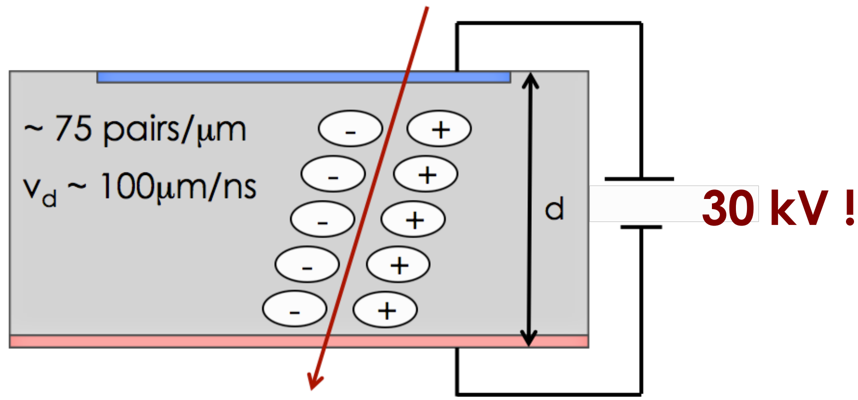
Silicon devices with gain:

- **APD: gain 50-500**
- **SiPM: gain ~ 10^4**

How can we achieve E ~ 300kV/cm?

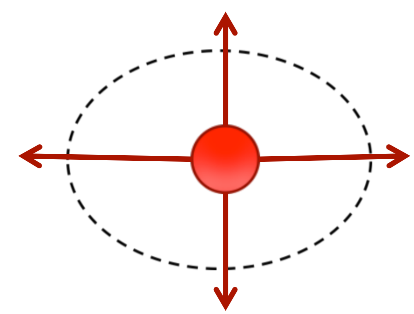
1) Use external bias: assuming a 300 micron silicon detector, we need $\mathbf{V_{bias}}$ **= 30 kV**

Not possible



2) Use Gauss Theorem:

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



E = 300 kV/cm ➔ q ~ 10^{16} /cm^3

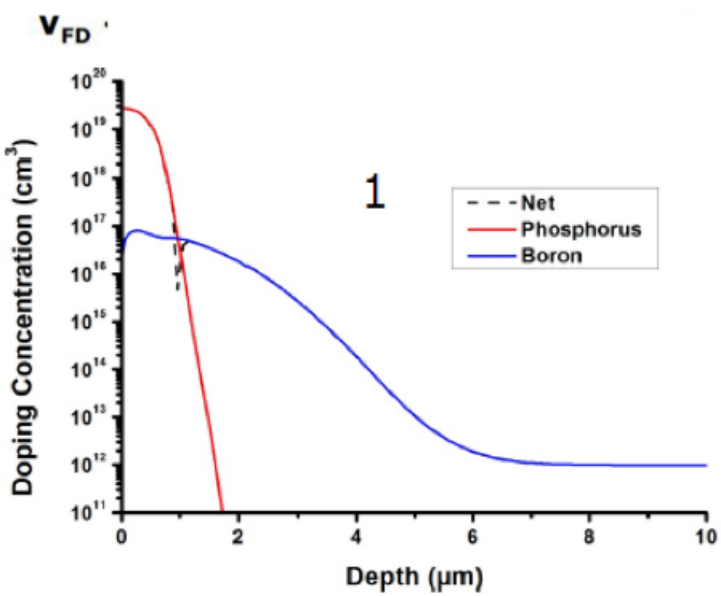
Low Gain Avalanche Detectors (LGADs)

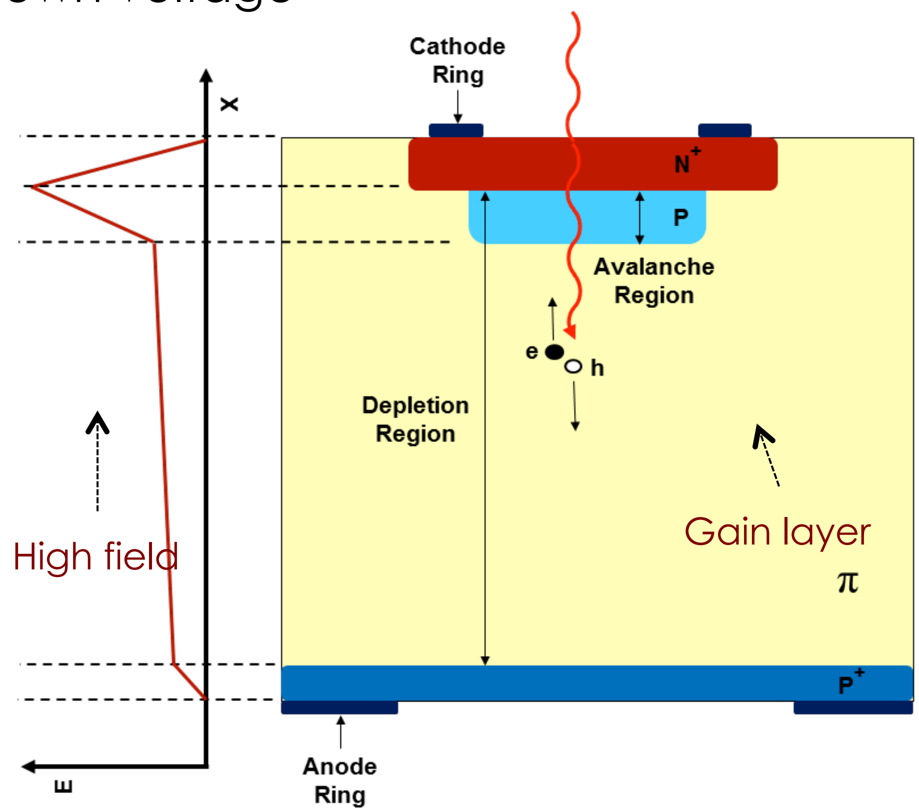
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage





Why low gain? Can we use APD or SiPM instead?

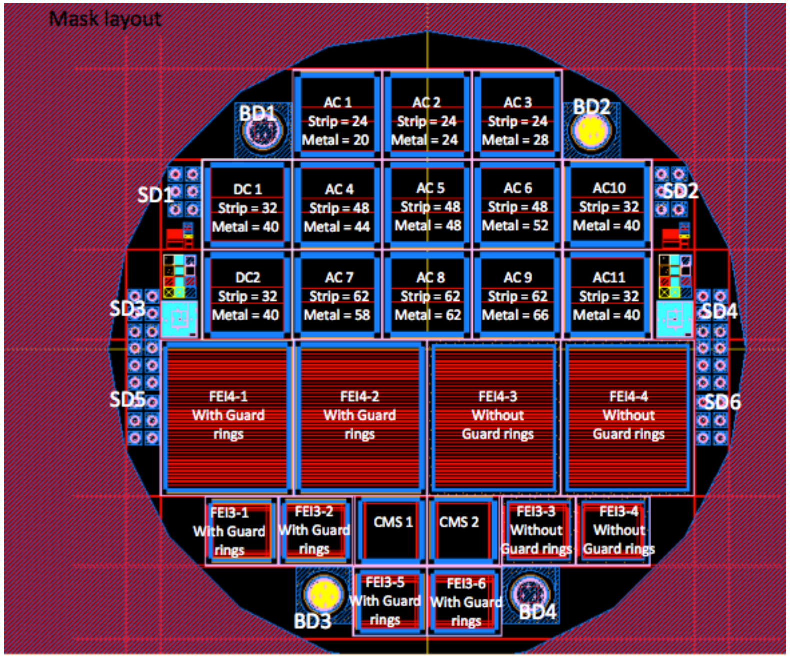
My personal conclusion: I think it's possible to obtain very good timing: APDs, SiPMs have very high gain, so they are excellent in "single shot" timing.

However, we are seeking to obtain something more powerful: a very low noise, finely pixelated device, able to provide excellent timing in any geometry, and also able to work in the presence of many low energy photons without giving fake hits.

These requirements make the use of high gain devices challenging

CNM LGADs mask

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



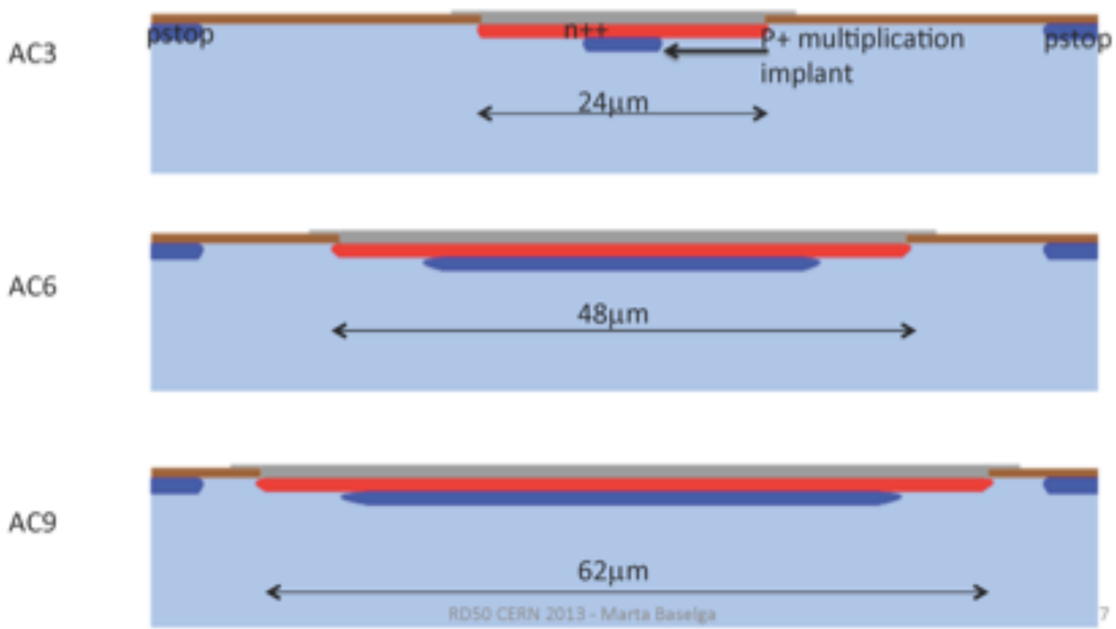
This implant controls the value of the gain

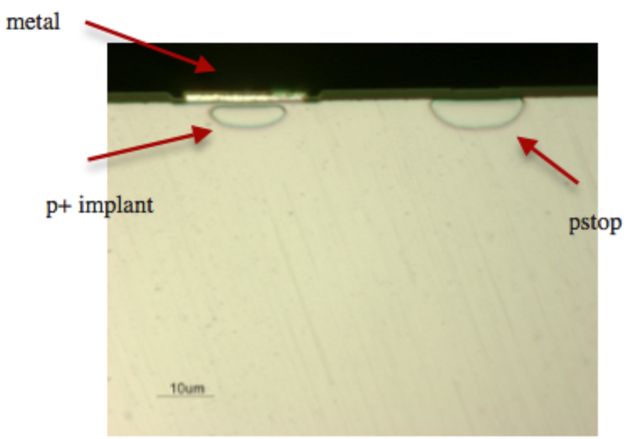
Wafer Number	P-layer Implant (E = 100 keV)	Substrate features	Expected Gain
1-2	1.6×10^{13} cm^{-2}	HRP 300 (FZ; ρ >10 KΩ·cm; <100>; T = 300±10 μm)	2 – 3
3-4	2.0×10^{13} cm^{-2}	HRP 300 (FZ; ρ >10 KΩ·cm; <100>; T = 300±10 μm)	8 – 10
5-6	2.2×10^{13} cm^{-2}	HRP 300 (FZ; ρ >10 KΩ·cm; <100>; T = 300±10 μm)	15
7	(---) PiN Wafer	HRP 300 (FZ; ρ >10 KΩ·cm; <100>; T = 300±10 μm)	No Gain

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

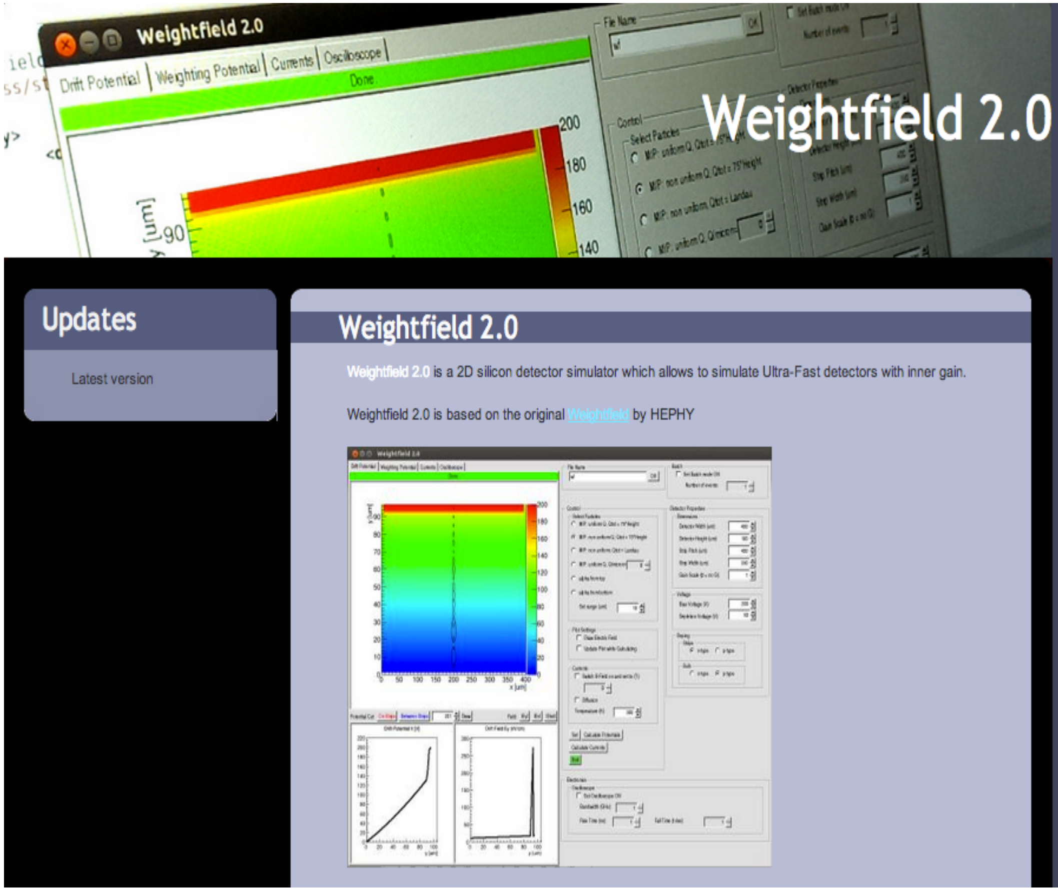
We developed a full sensor simulation to optimize the sensor design

WeightField2, F. Cenna, N. Cartiglia 9th Trento workshop, Genova 2014

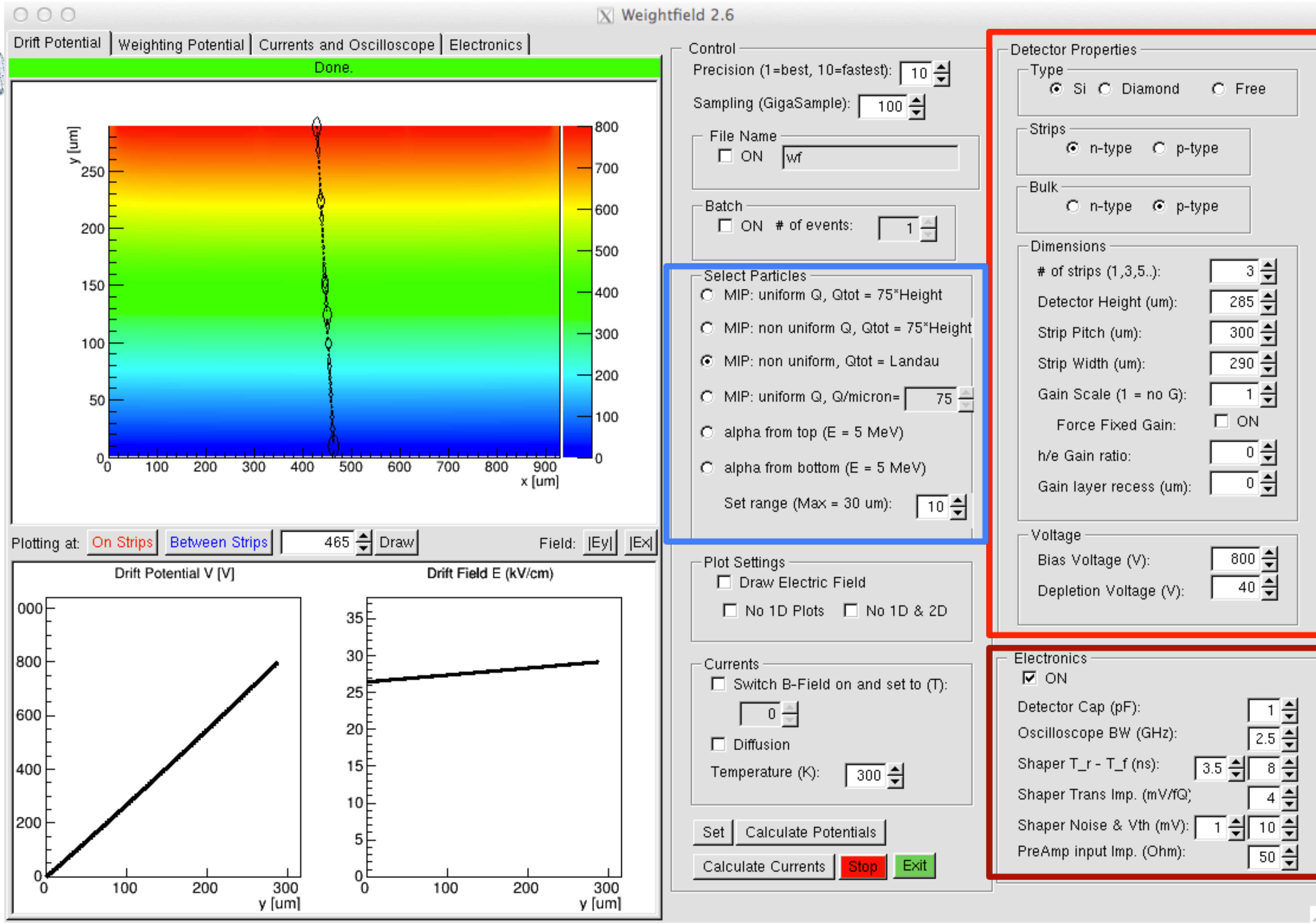
Available at http://personalpages.to.infn.it/~cartigli/weightfield2

It includes:

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



WeightField2: a program to simulate silicon detectors



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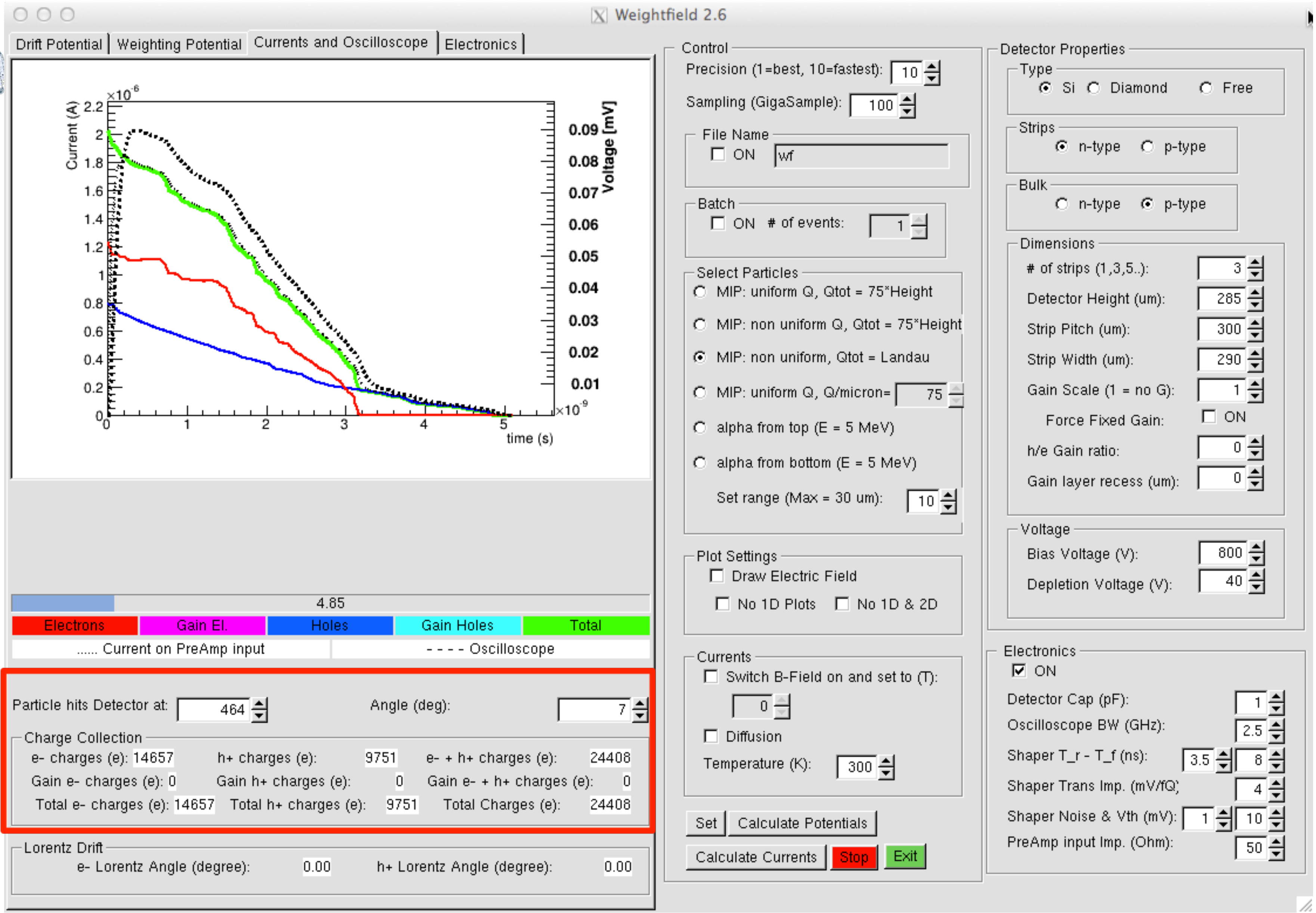
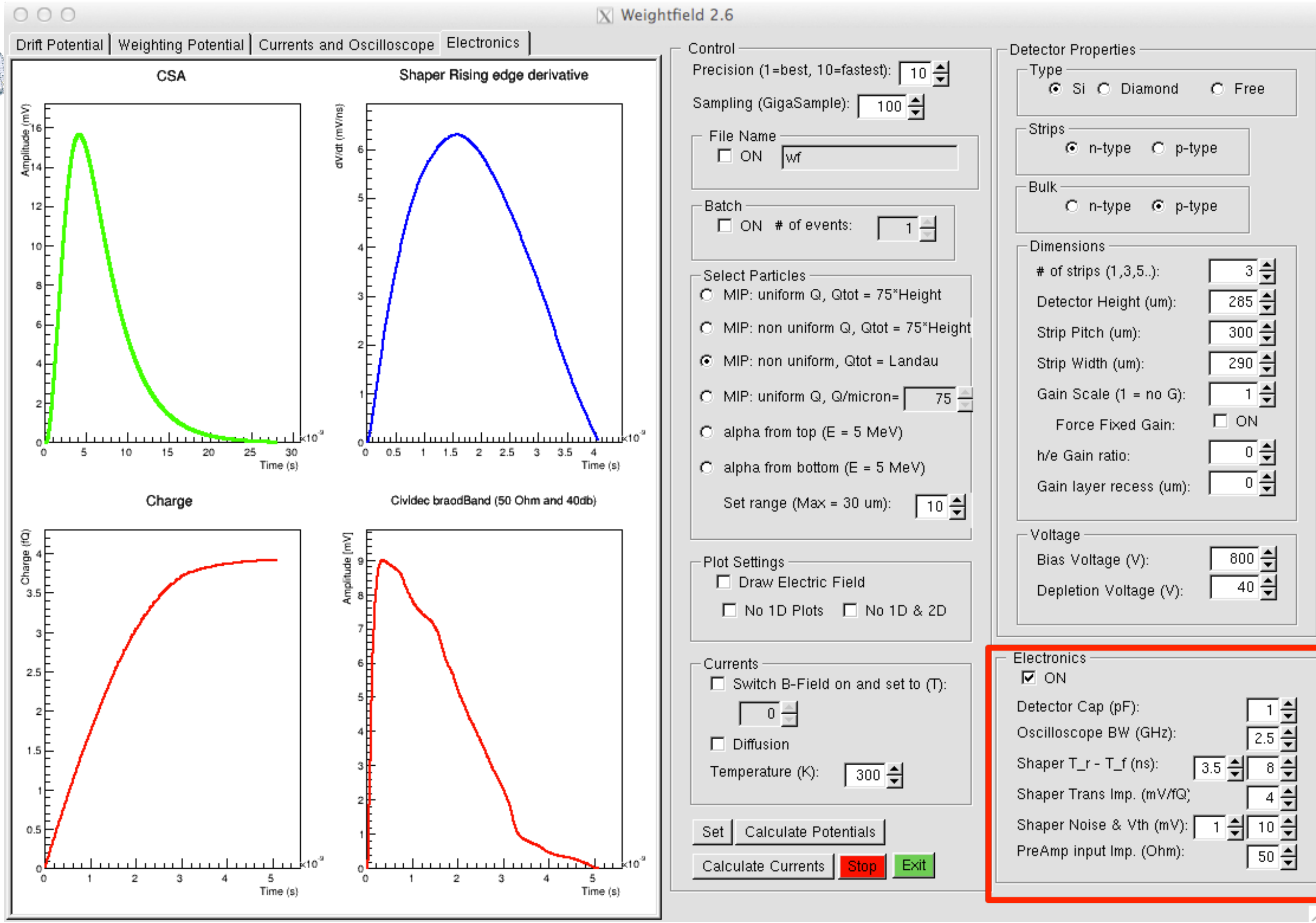
WeightField2: output currents



WeightField2: response of the read-out electronics



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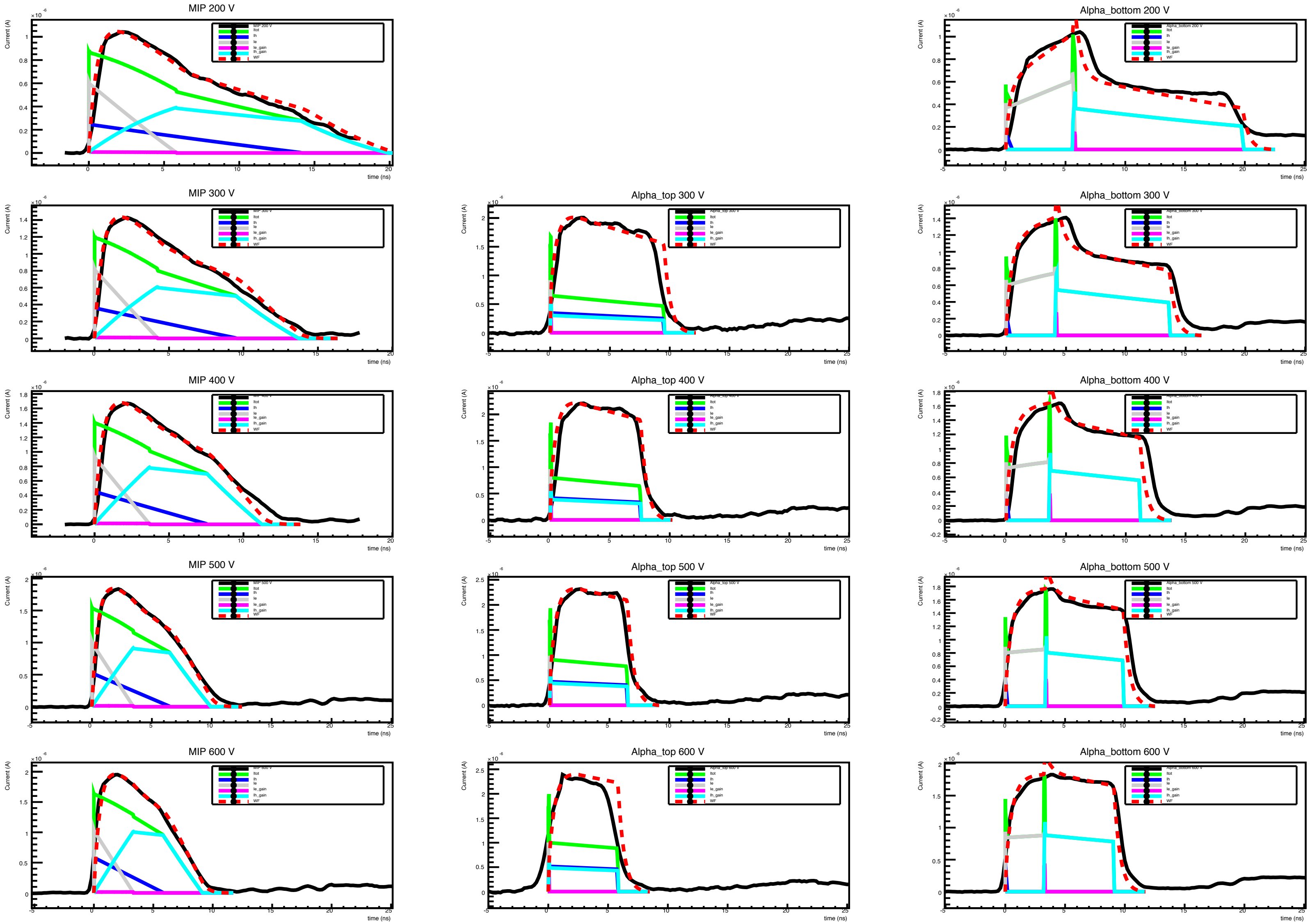
Comparison Data Simulation

MIP | **Alpha from Top** | **Alpha from bottom** | **V bias**



200

300

400

500

600

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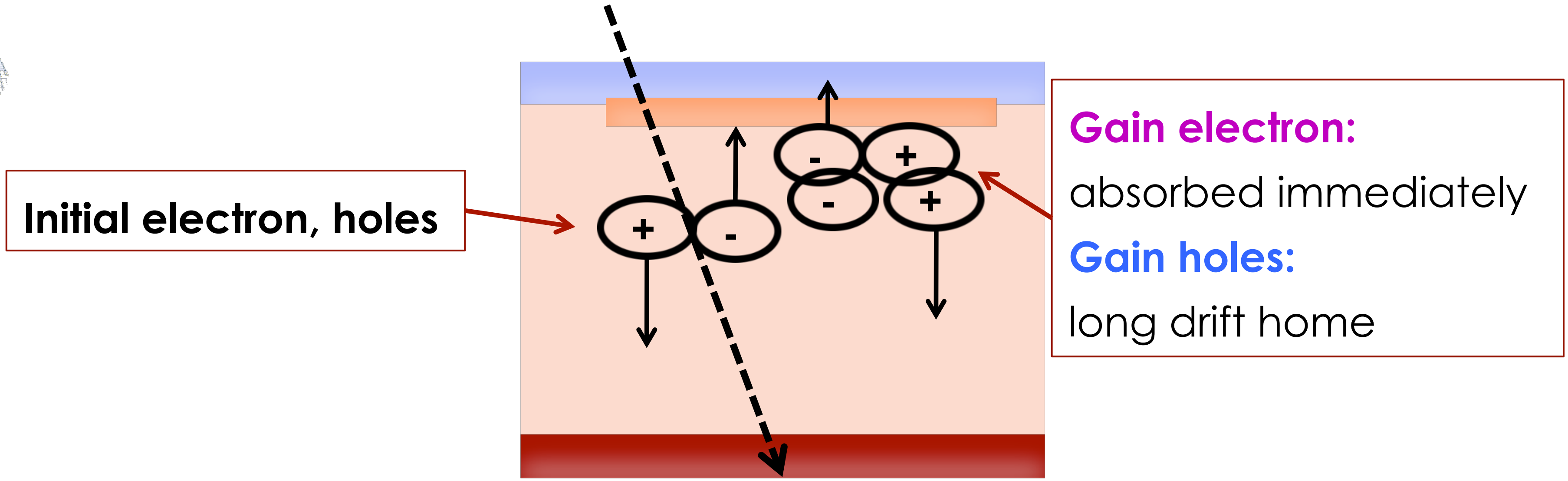
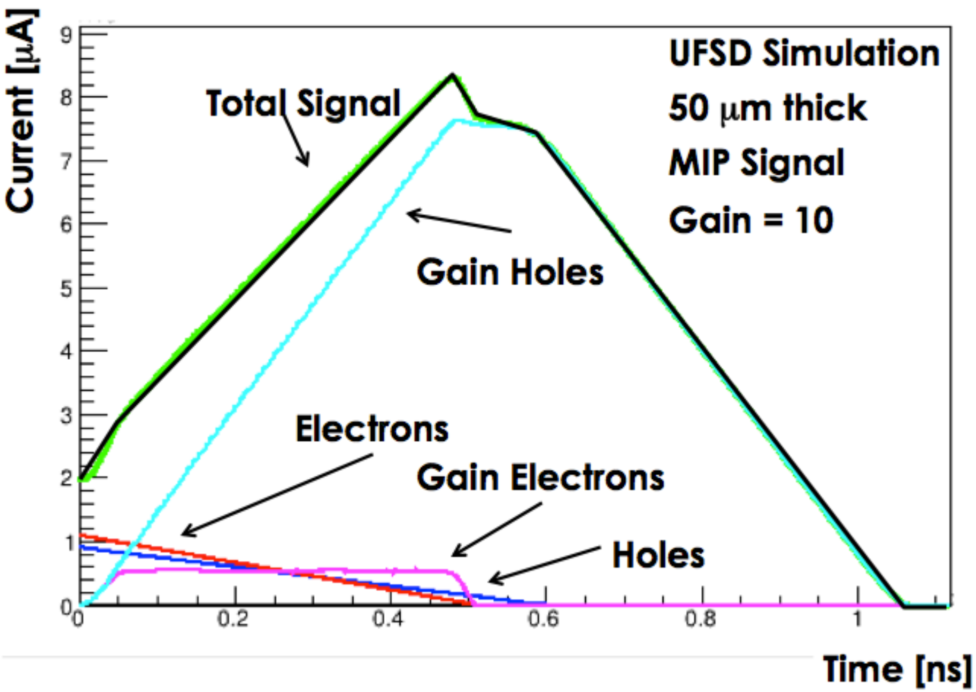
How gain shapes the signal





Electrons multiply and produce additional electrons and holes.

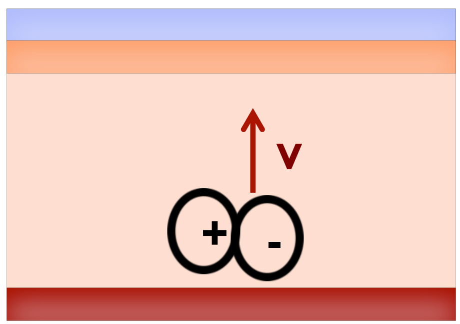
- **Gain electrons have almost no effect**
- **Gain holes dominate the signal**

➔ **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})

Gain



Particles per micron

Gain

$$dN_{Gain} \propto 75(v_{sat}dt)G$$

➔ **Constant rate of production**

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

$$di_{gain} \propto dN_{Gain} q v_{sat} \left(\frac{k}{d}\right)$$

➔ **Gain current ~ 1/d**

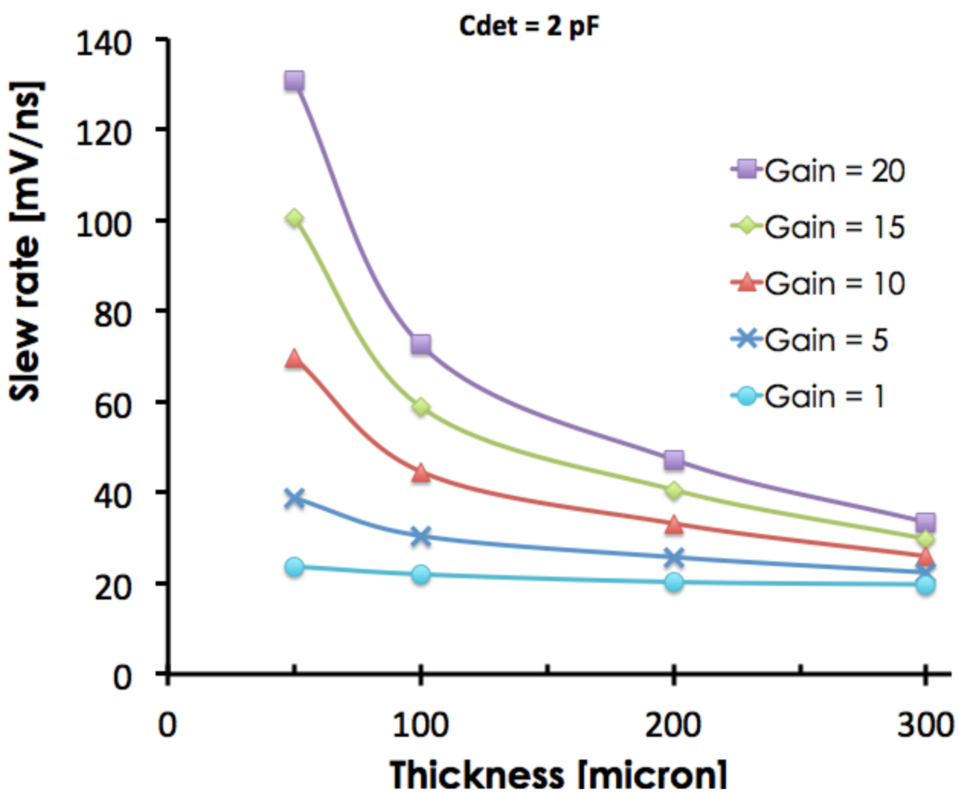
A given value of gain has much more effect on thin detectors

Gain current vs Initial current

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

!!!

➔ 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

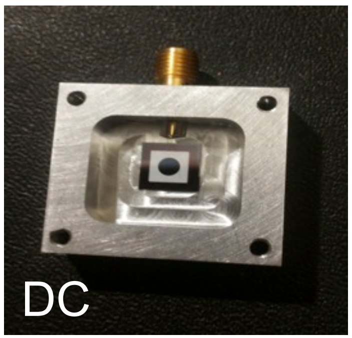
- Doping concentration
- Gain
- Time resolution measured with laser signals

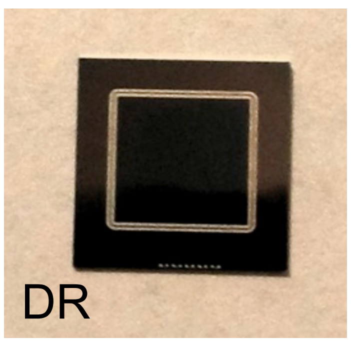
LGAD Testbeam measurements

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

LGAD Sensors in Torino

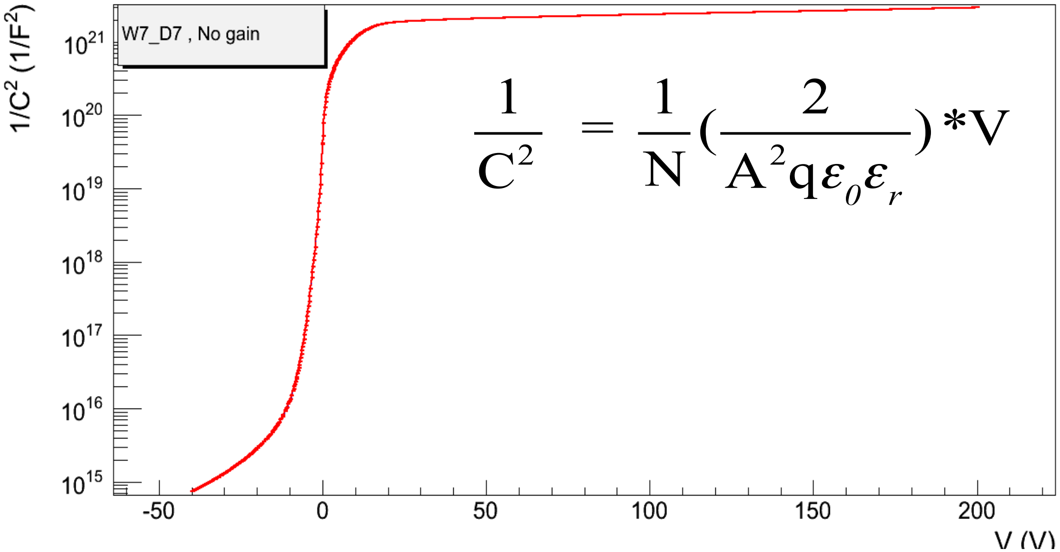
Thickness:
300 μm





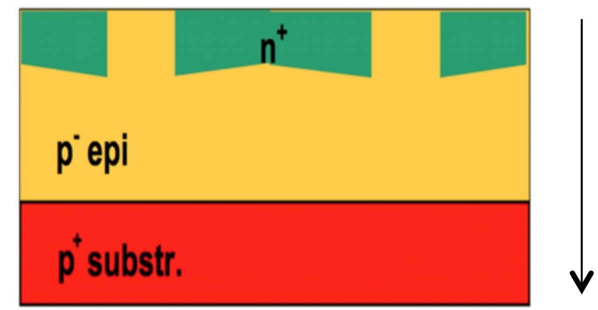
Run	Sensor	P-Layer Implant (E=100 KeV)	Gain	V_{break}	Metal Layer
6474	W8_B4	?	~ 10	> 500 V	DR
6474	W8_C6	?	~ 10	> 500 V	DC
6474	W9_B6	No implant	No Gain	> 500 V	DR
7062	W1_F3	1.6×10^{13} cm^{-2}	~ 1-2	> 500 V	DR
7062	W3_H5	2.0×10^{13} cm^{-2}	~ 10	> 500 V	DR
7062	W7_D7	No implant	No Gain	> 500 V	DR

Doping profile from CV measurement - I



$$\frac{1}{C^2} = \frac{1}{N}\left(\frac{2}{A^2 q \varepsilon_0 \varepsilon_r}\right) * V$$

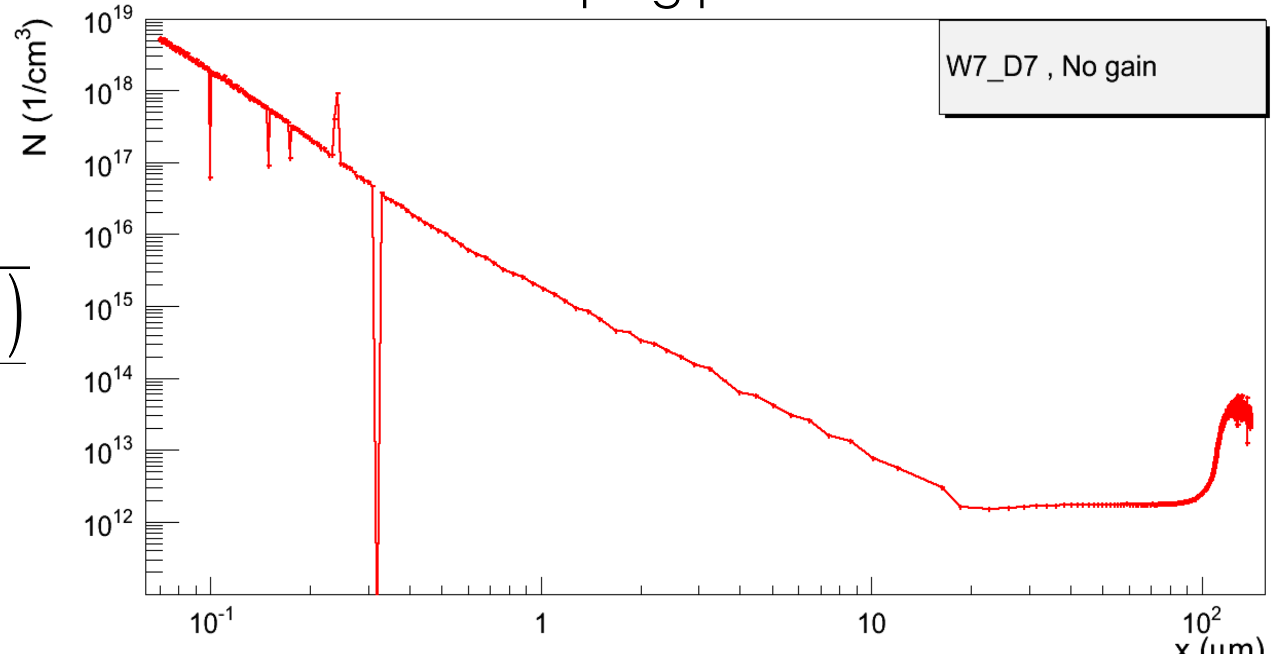
No-gain sensor



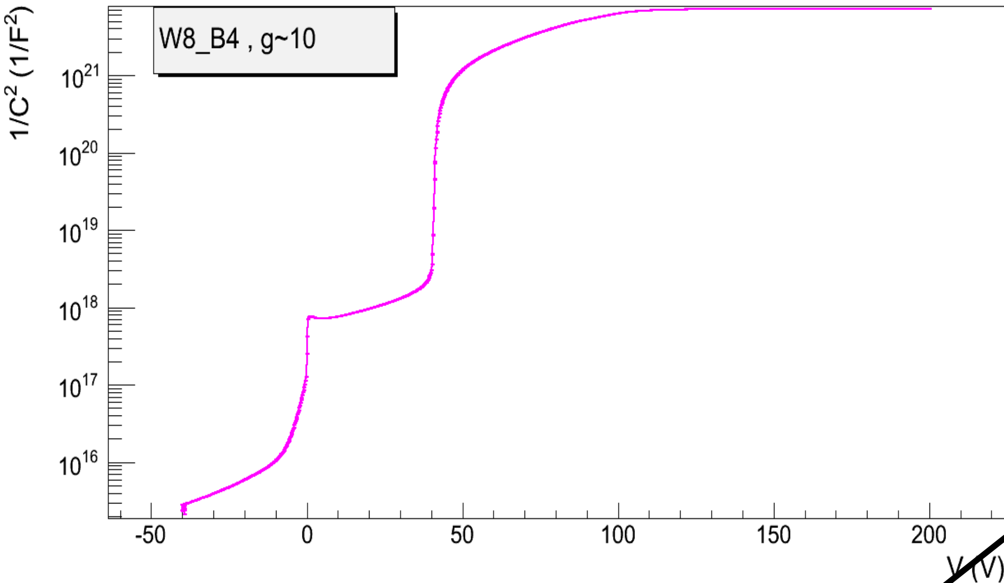
$$N = \frac{2}{q\varepsilon_0\varepsilon_r A^2 \frac{d\left(1/C^2\right)}{dV}}$$

Doping

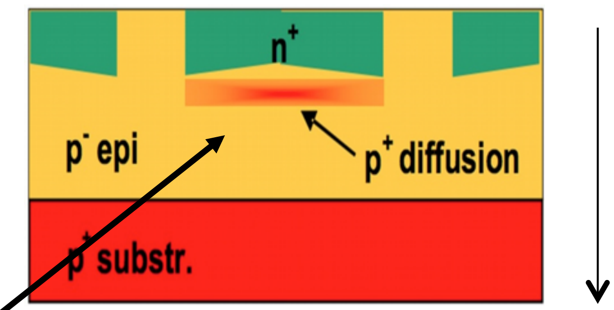
Doping profile



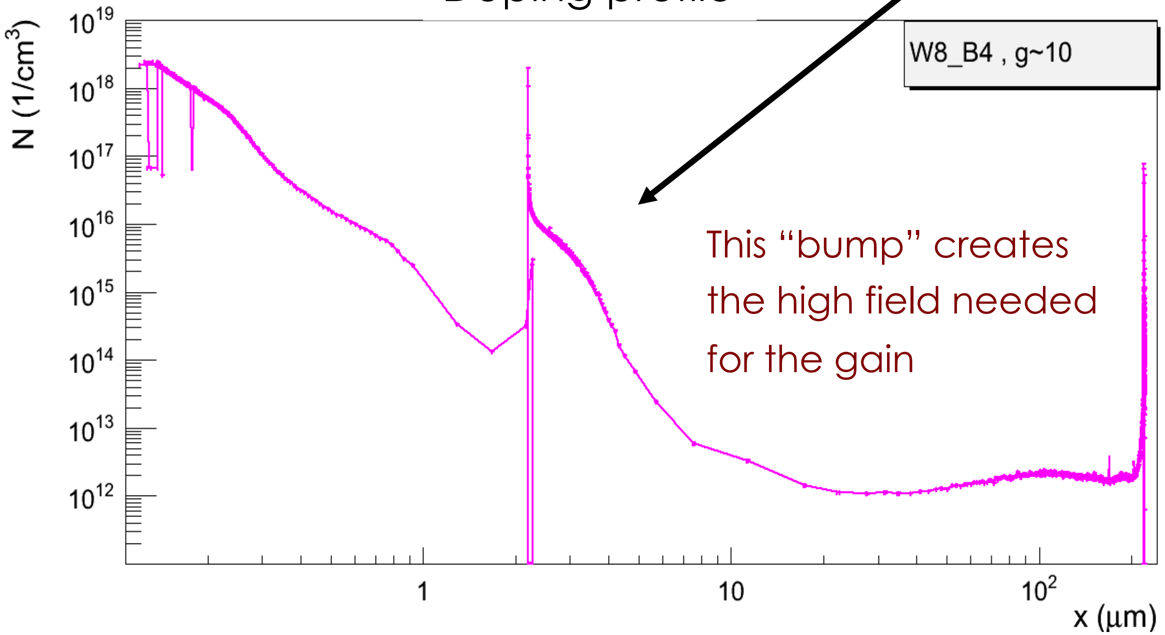
Doping profile from CV measurement - II



Gain sensor

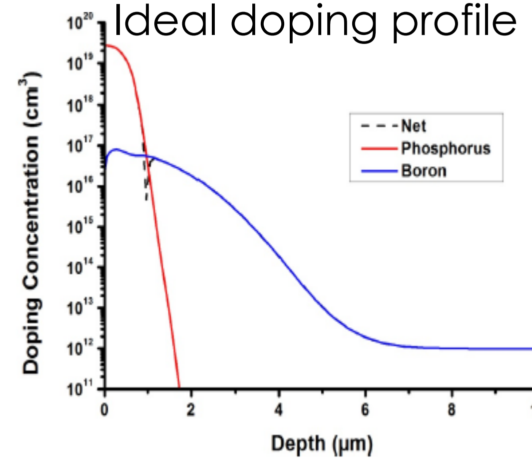


Doping profile



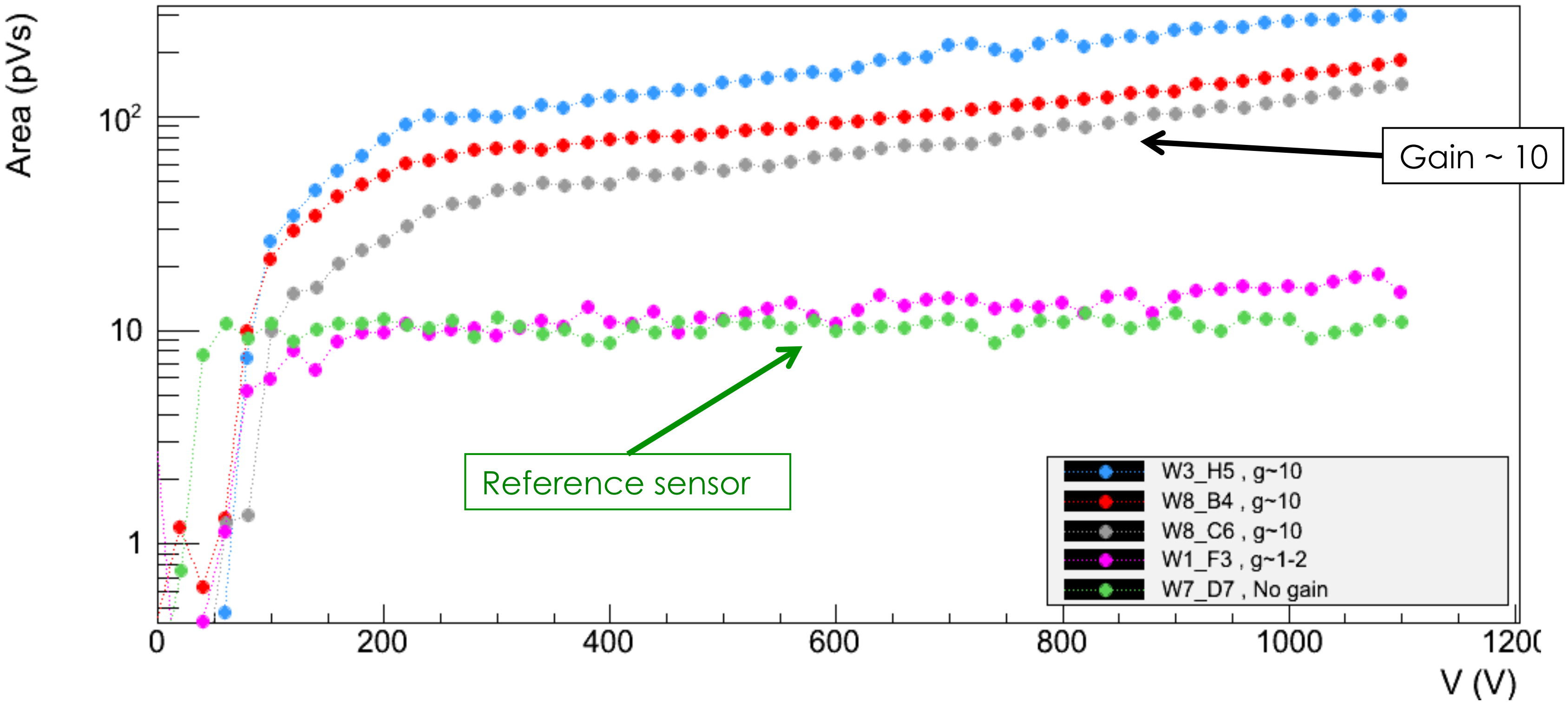
This "bump" creates the high field needed for the gain

Ideal doping profile



Signal amplitude

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

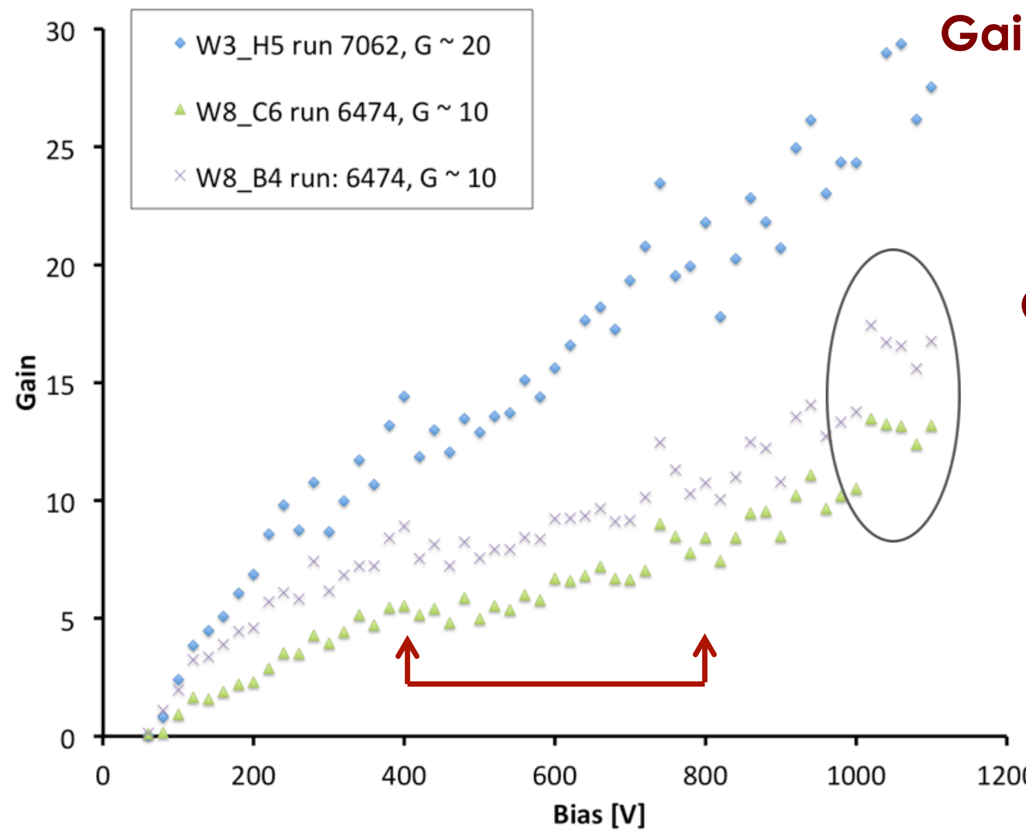


Gain

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

The gain increases linearly with Vbias (not exponentially!)

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



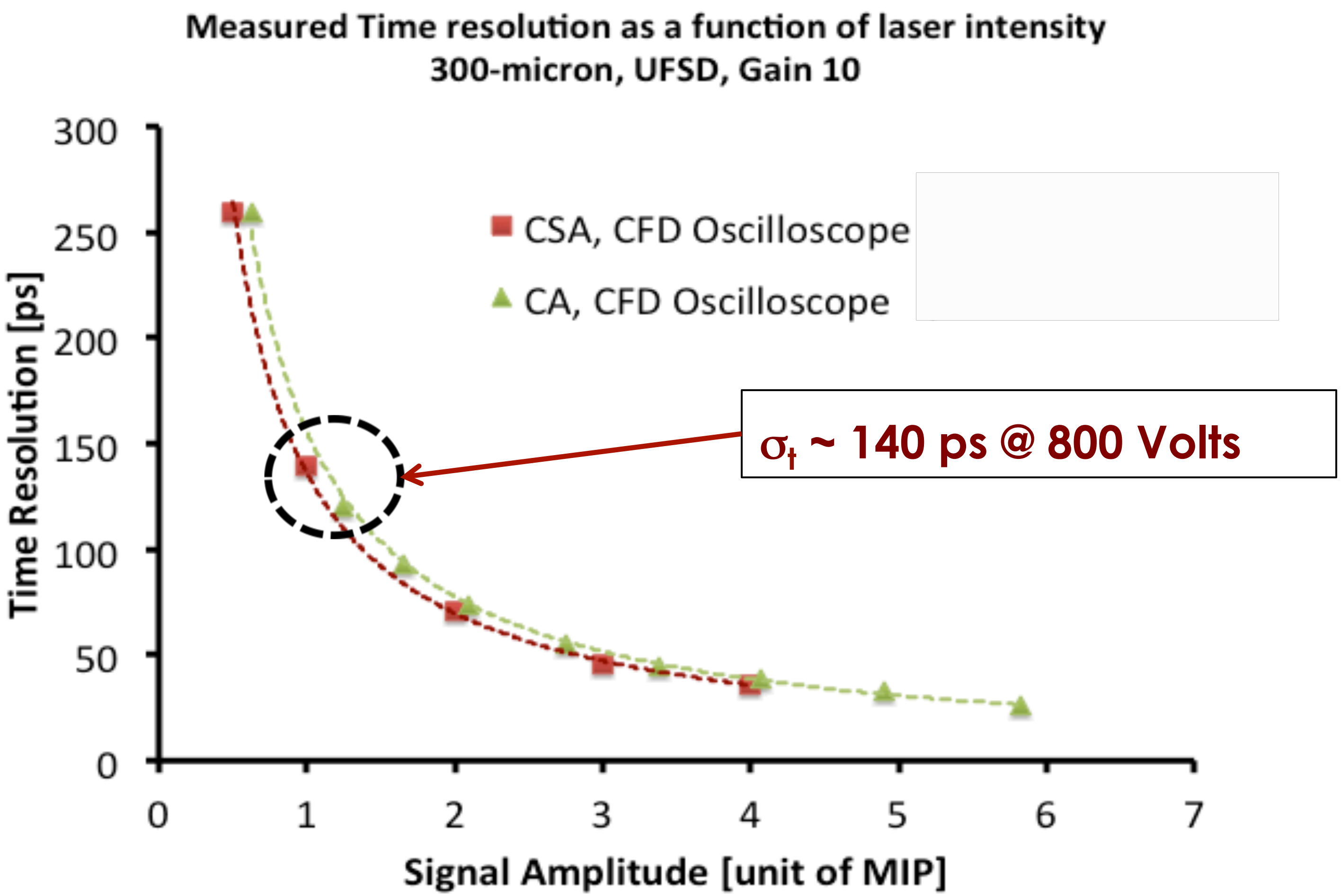
Gain ~ 20

Gain ~ 10

Laser Measurements on CNM LGAD

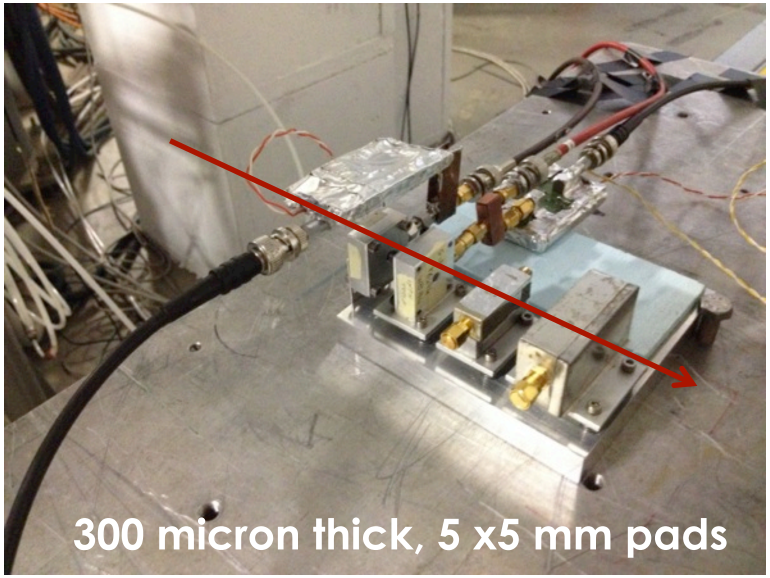
We use a 1064 nm picosecond laser to emulate the signal of a MIP particle (without Landau Fluctuations)

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

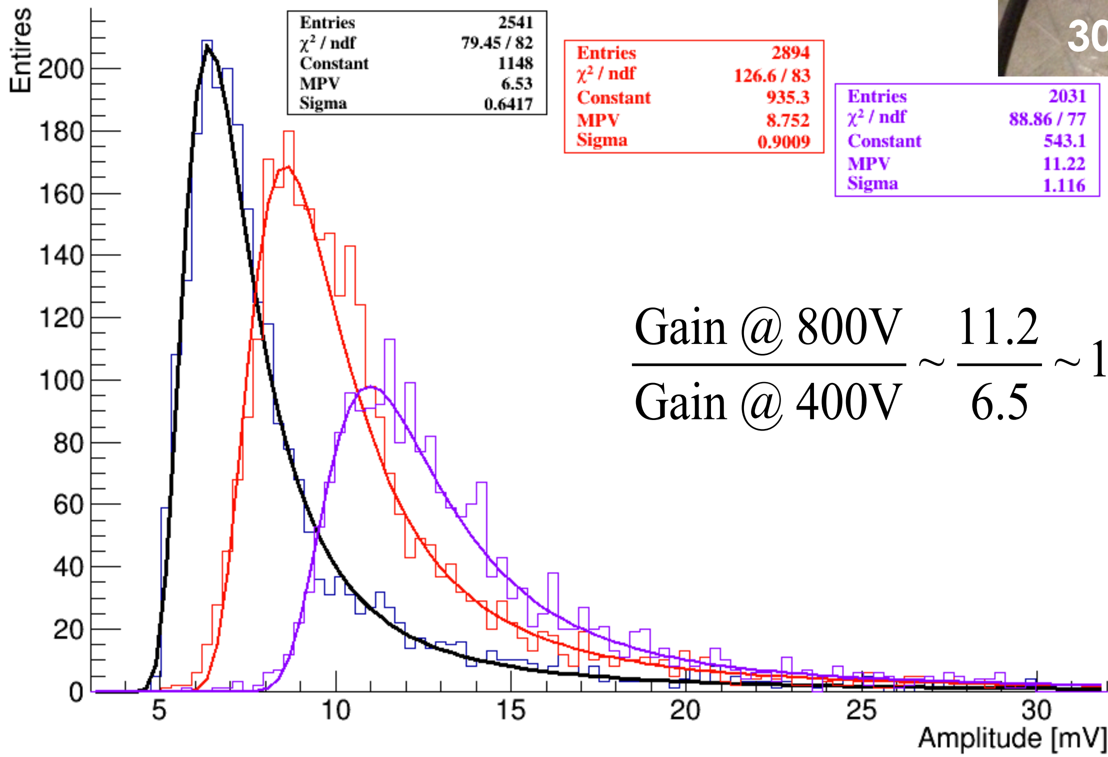


Testbeam Measurements on CNM LGAD

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.



$$\frac{\text{Gain @ 800V}}{\text{Gain @ 400V}} \sim \frac{11.2}{6.5} \sim 1.7$$

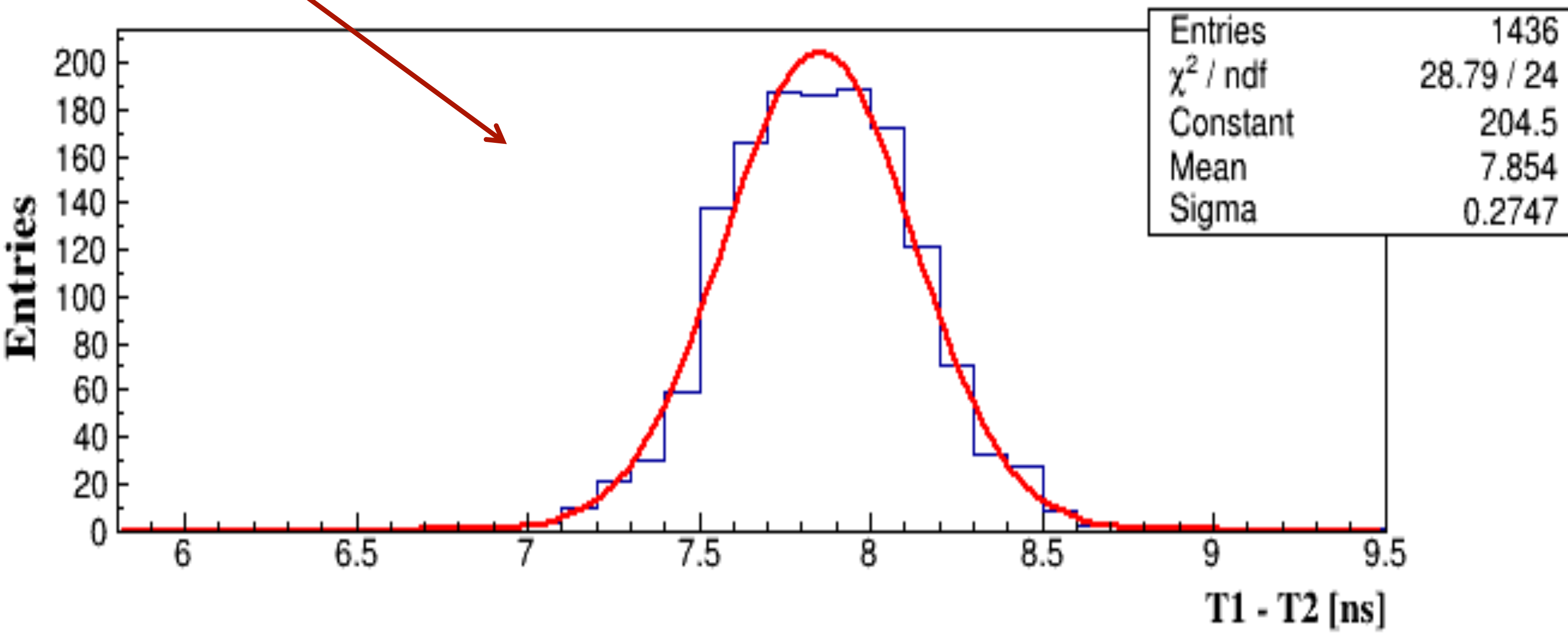
The gain mechanism preserves the Landau amplitude distribution of the output signals

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

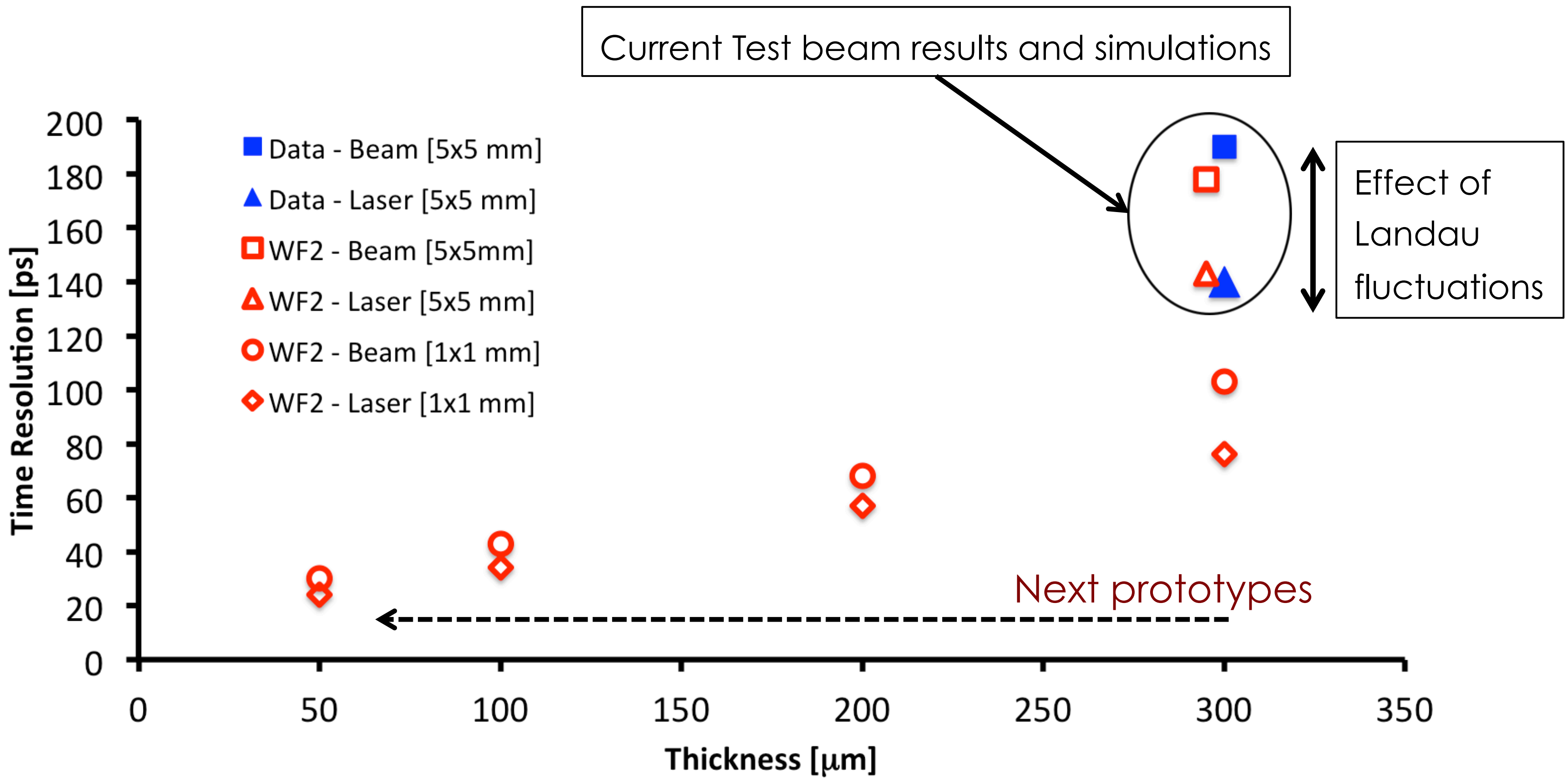
σ_t ~ 190 ps @ 800 Volts



Present results and future productions

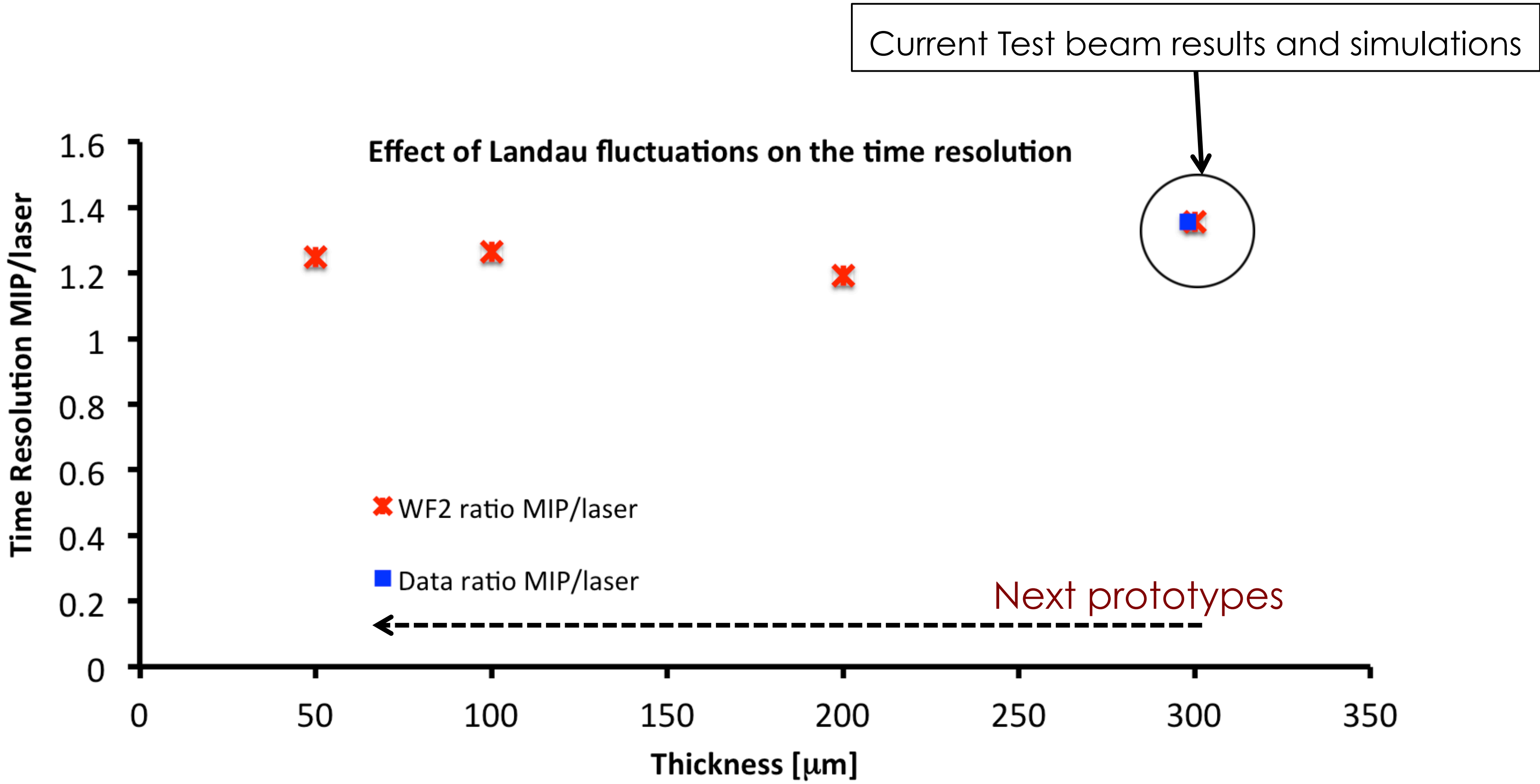
With WF2, we can reproduce very well the laser and testbeam results.

Assuming the same electronics, and 1 mm^2 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

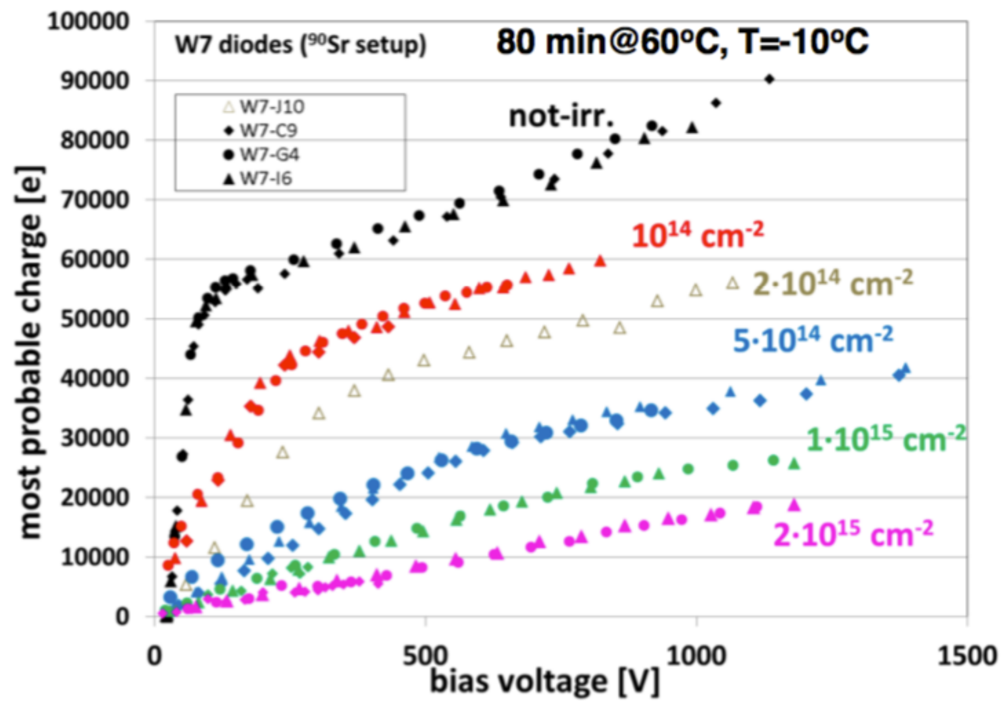
The effect of Landau fluctuations in a MIP signal are degrading the time resolution by roughly 30 % with respect of a laser signal



Irradiation tests

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

➔ **Due to boron disappearance**



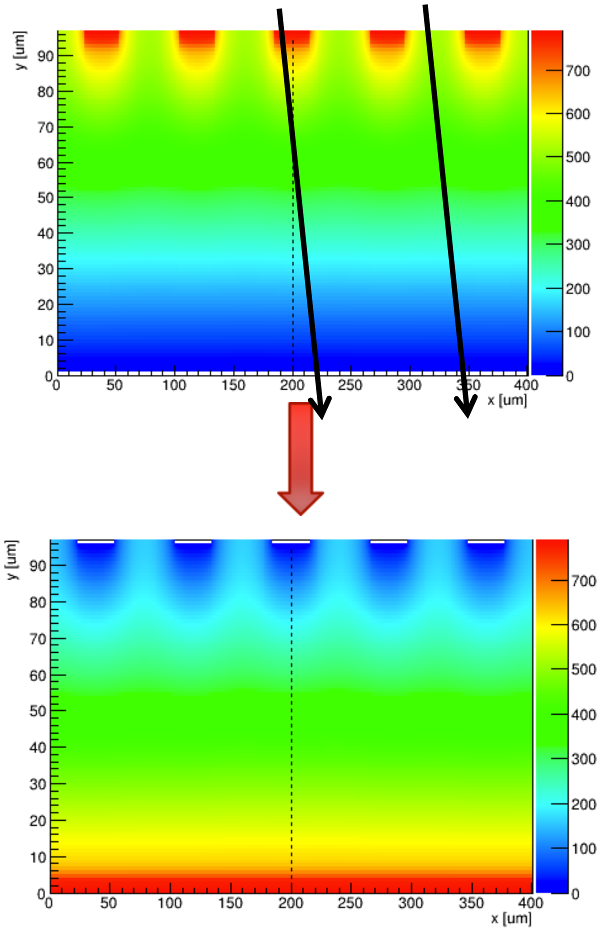
What-to-do next:

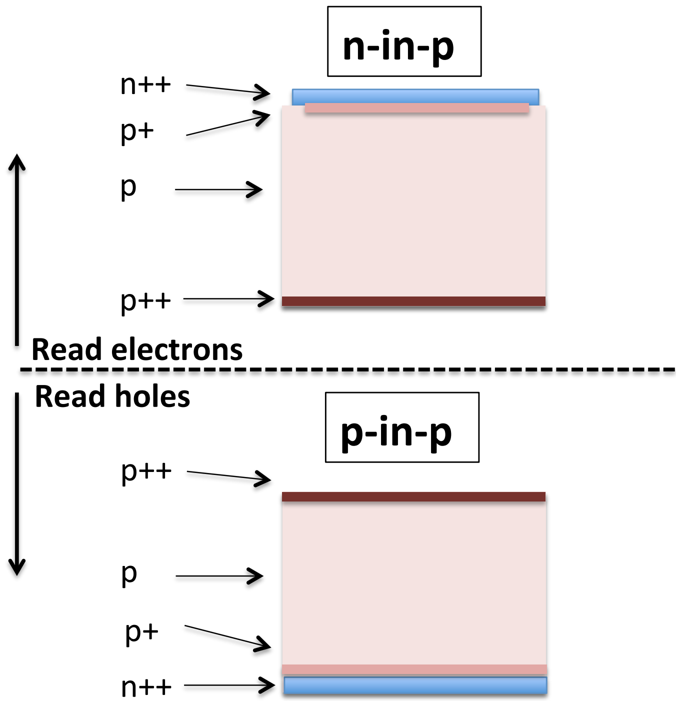
Planned new irradiation runs (neutrons, protons), new sensor geometries

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

Gain in finely segmented sensors

Segmentation makes the effect of gain more difficult to predict, and most likely very dependent on the hit position





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

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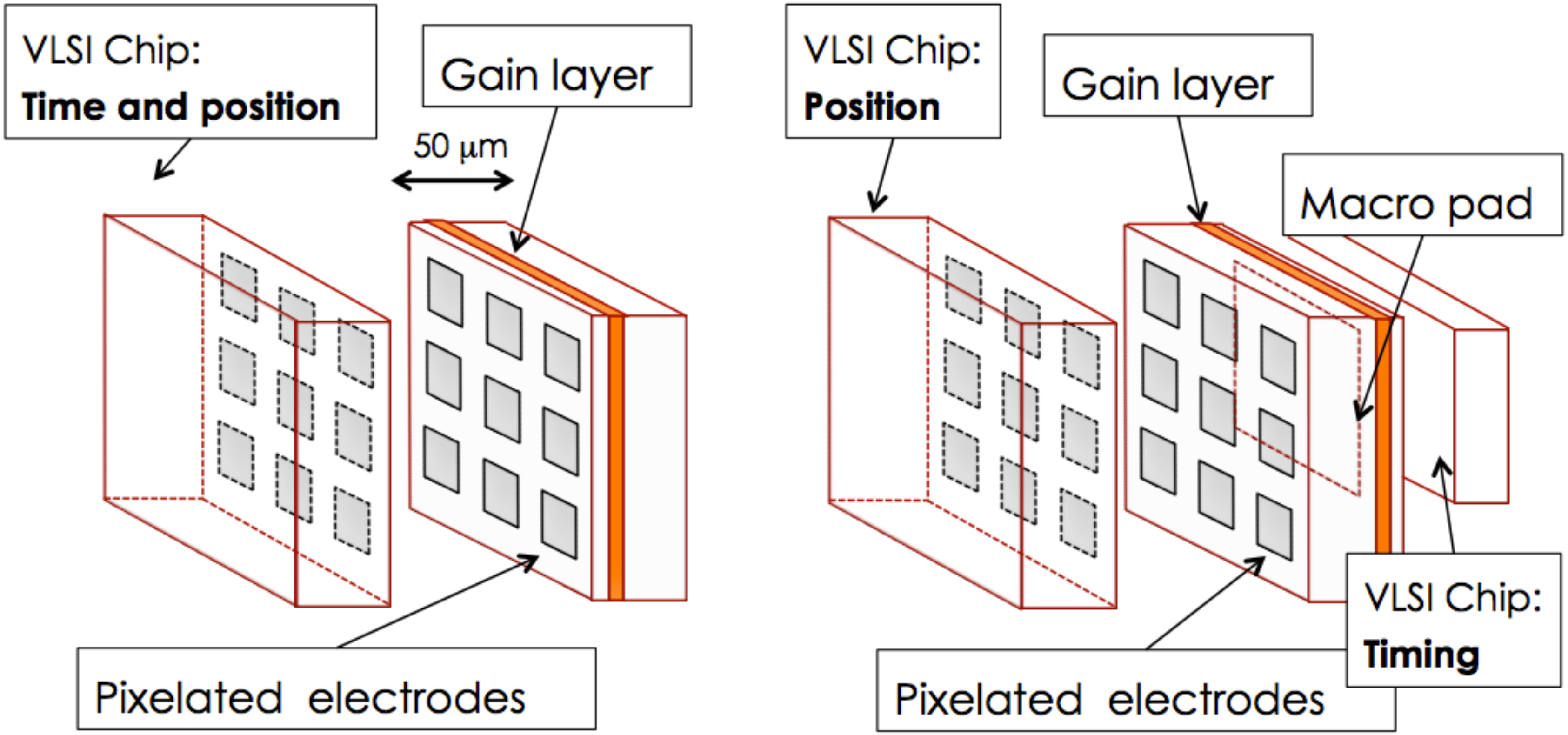
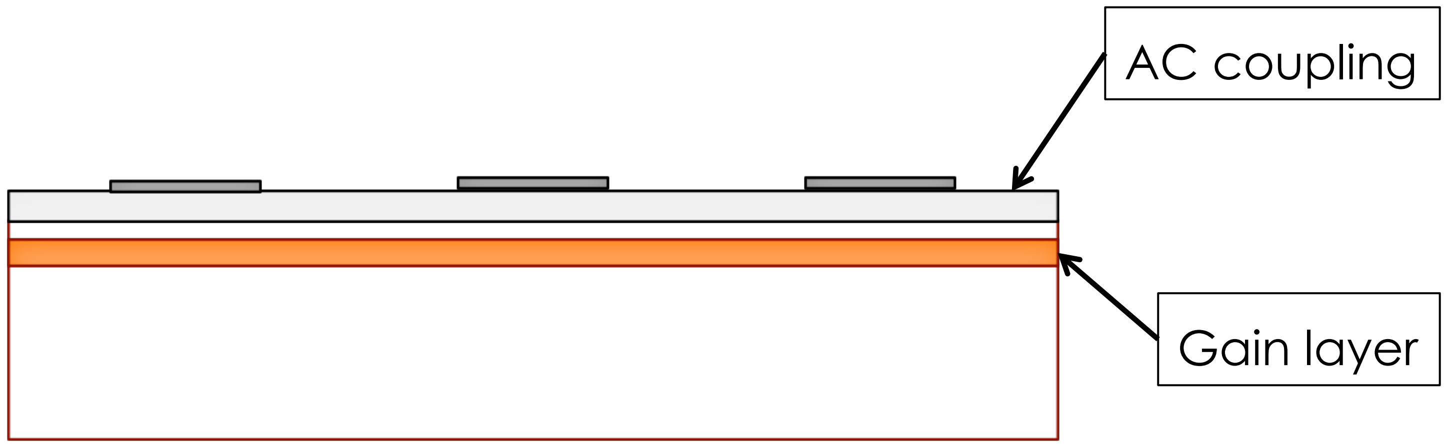
Splitting gain and position measurements



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

Using AC coupling to achieve segmentation

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



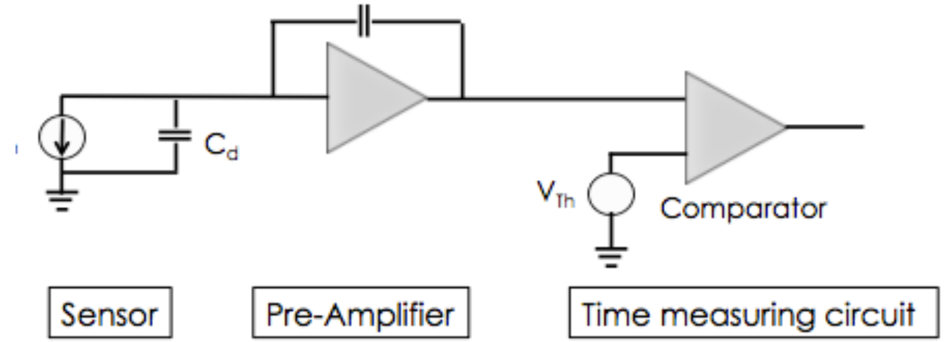
Very uniform field due to large pads,

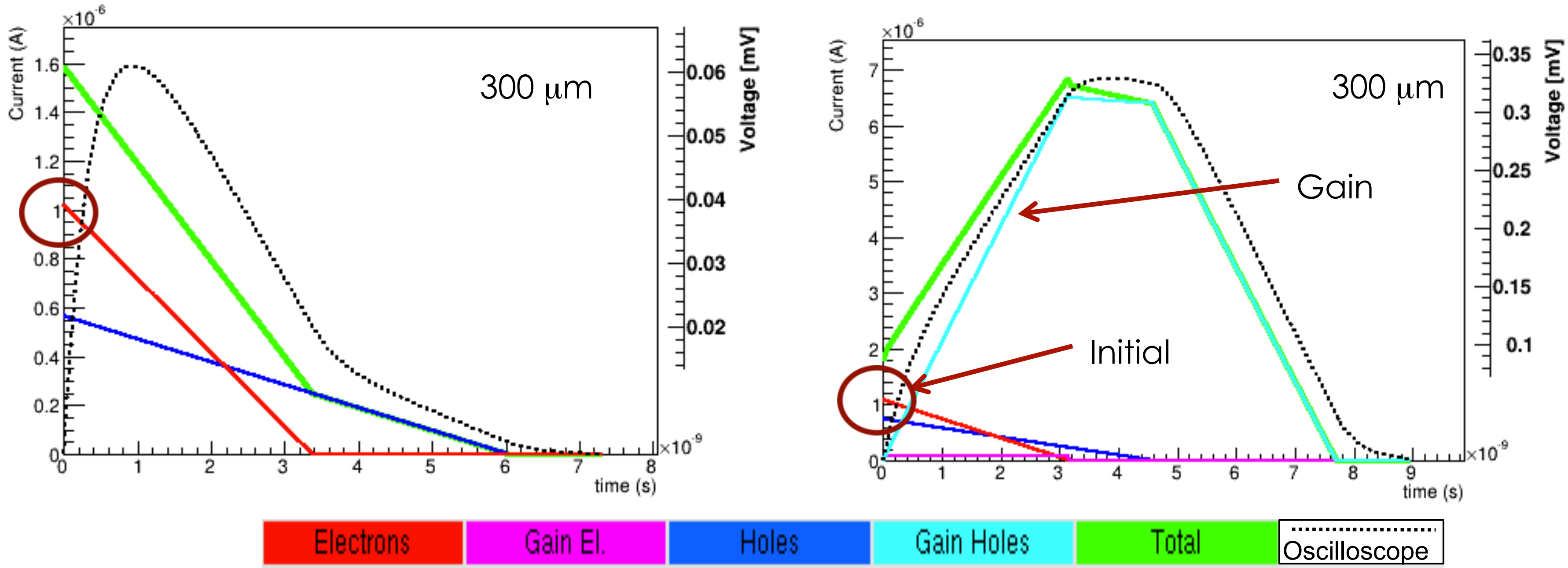
Segmentation due to AC coupling pick-up

Electronics

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

The signal from UFSDs is different from that of traditional sensors





Simulated Weightfield2

Pads with no gain

Charges generated uniquely by the incident particle

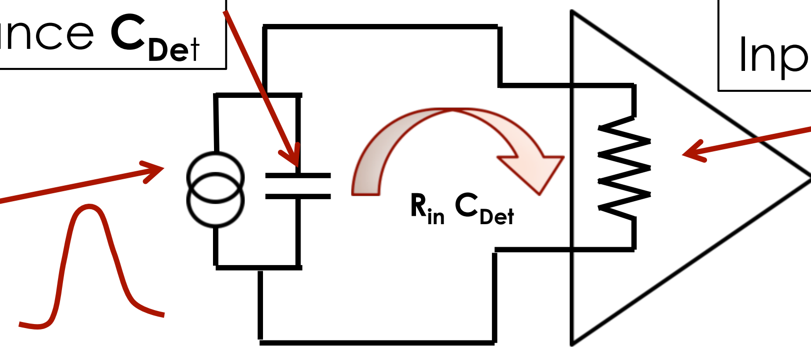
Pads with gain

Current due to gain holes creates a longer and higher signal

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

Detector Capacitance C_{Det}

Collection time T_{Col}

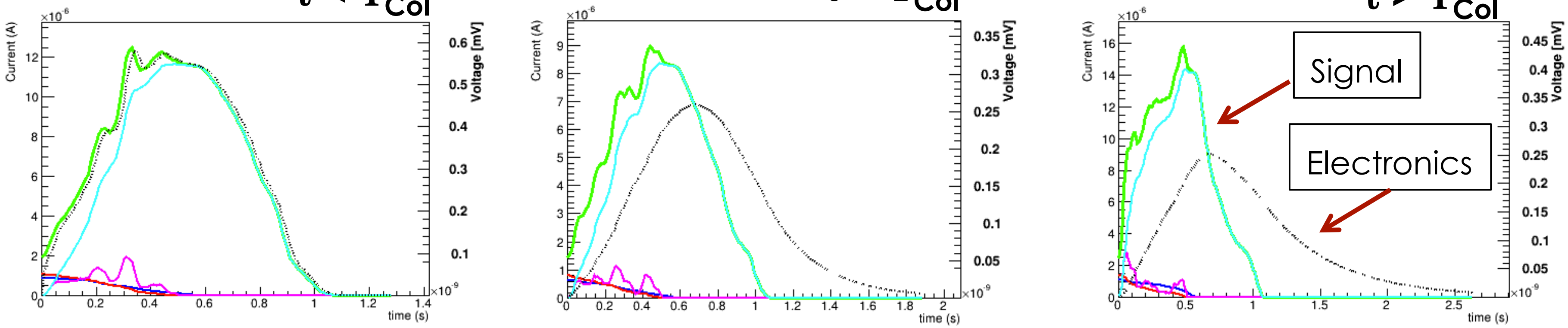


Input impedance R_{in}

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

$\tau < T_{Col}$ $\tau \sim T_{Col}$ $\tau > T_{Col}$

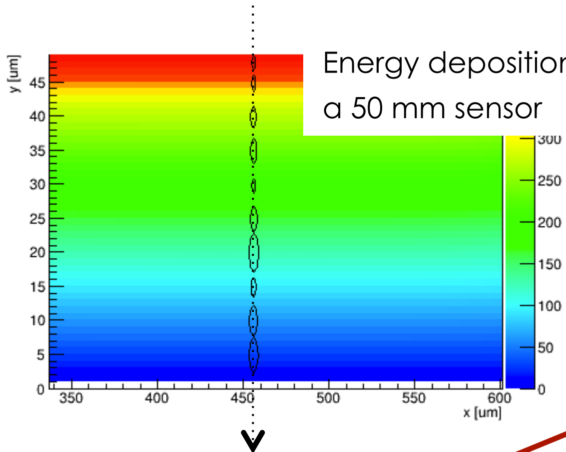


τ / T_{Col} increases ➔ dV/dt decreases

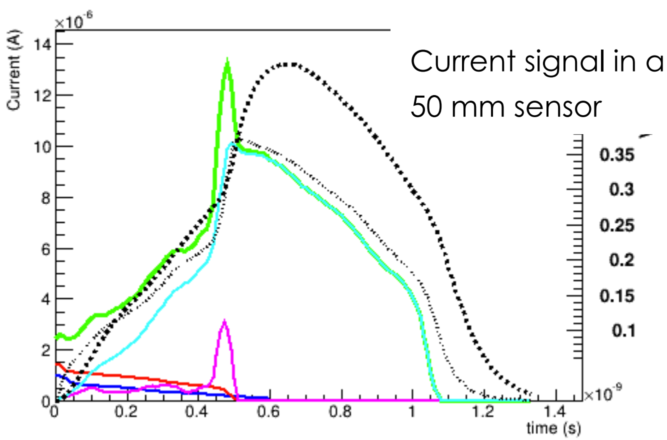
➔ Smoother current

Need to find the optimum balance

Electronics: What is the best pre-amp choice?

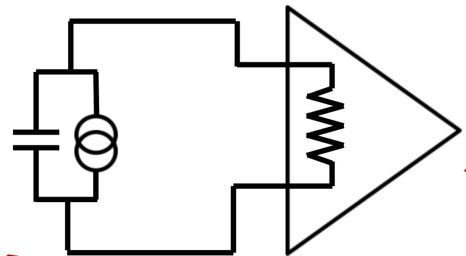


Energy deposition in a 50 mm sensor

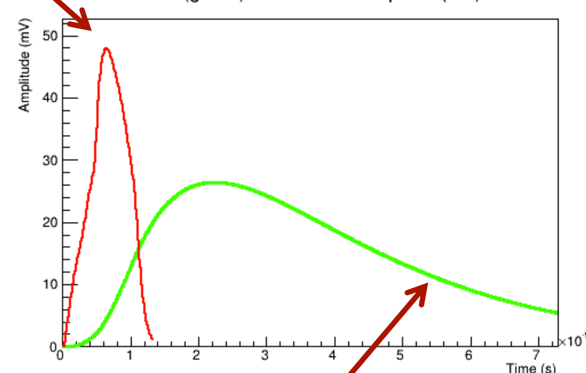


Current signal in a 50 mm sensor

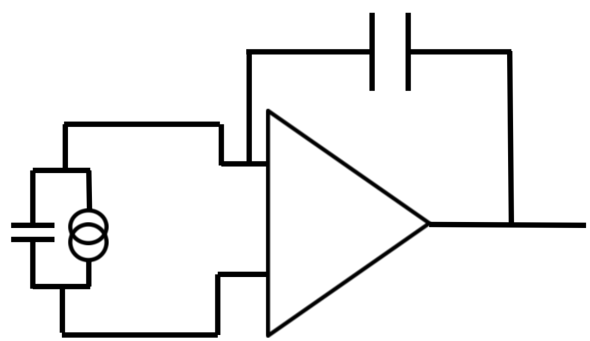
Current Amplifier



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

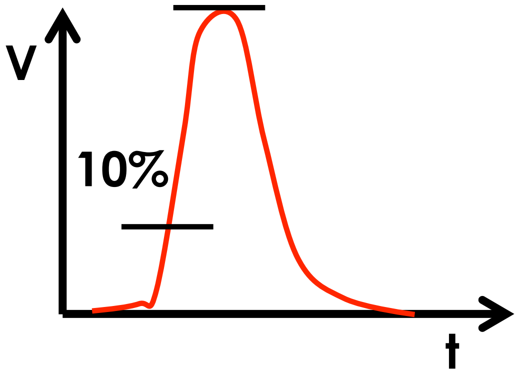


Integrating Amplifier



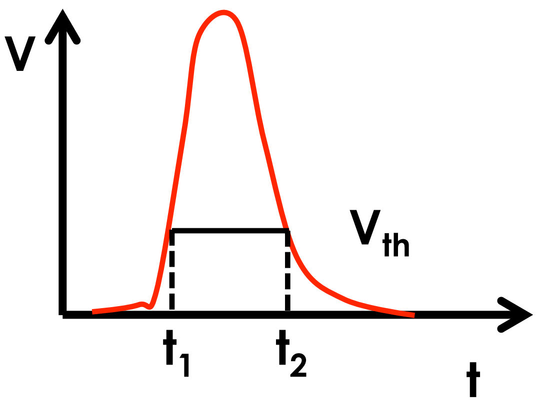
- Slower slew rate
- Quieter
- Integration helps the signal smoothing

What is the best "time measuring" circuit?



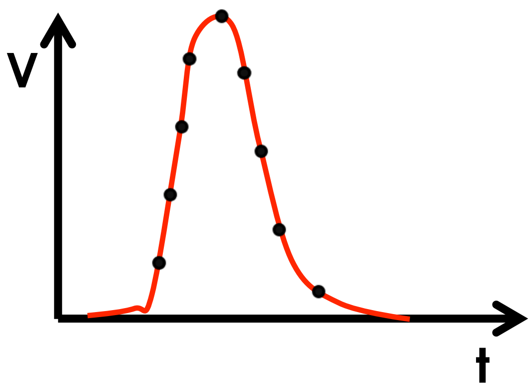
Constant Fraction Discriminator

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



Time over Threshold

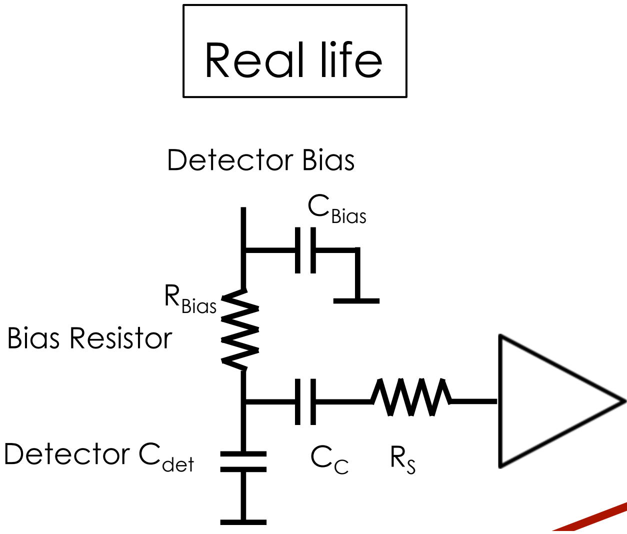
The amount of time over the threshold is used to correct for time walk

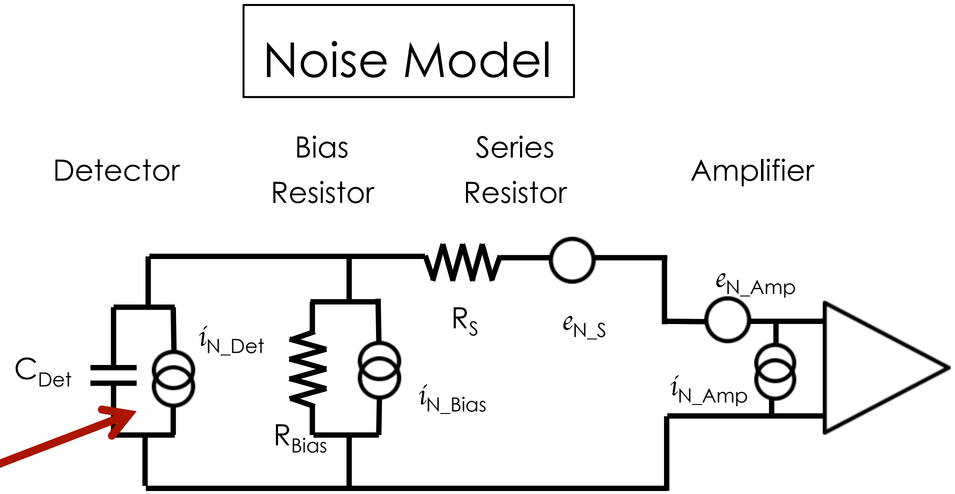


Multiple sampling

Most accurate method, needs a lot of computing power

Noise - I





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

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

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

low gain!

This term dominates for short shaping time

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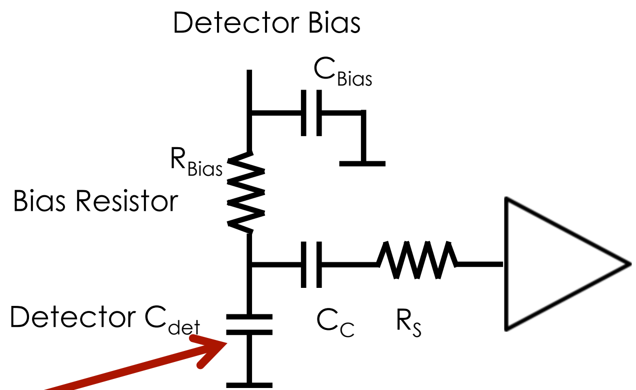
Noise - II

Real life



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

k = ratio h/e gain

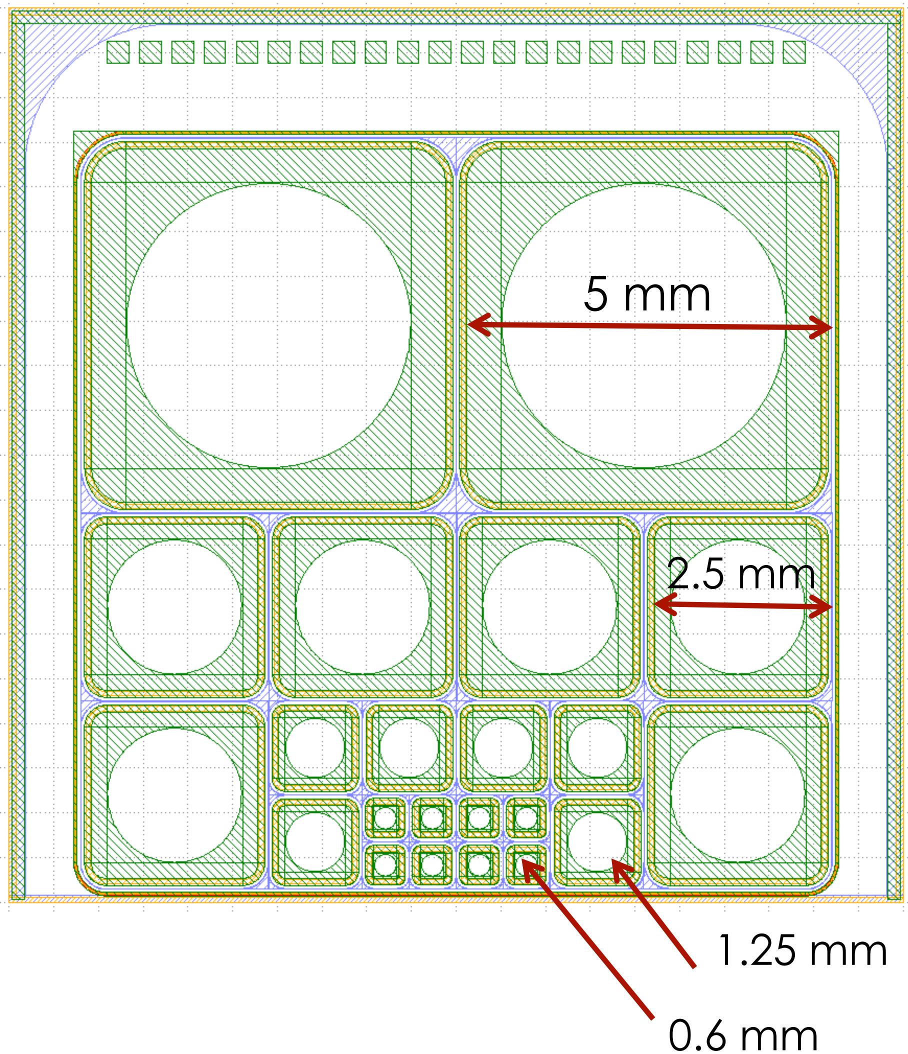
NOISE DUE TO GAIN:

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.

Next CNM productions



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

Timescale:

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

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

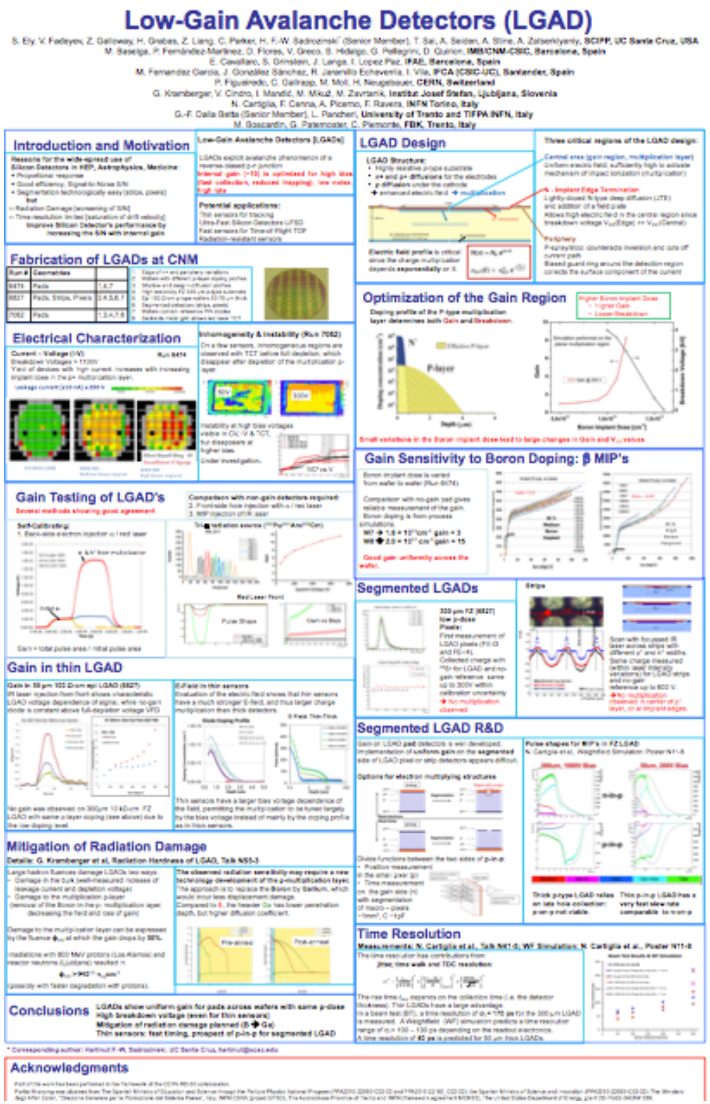
We are just starting to understand the timing capability of UFSD

- 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



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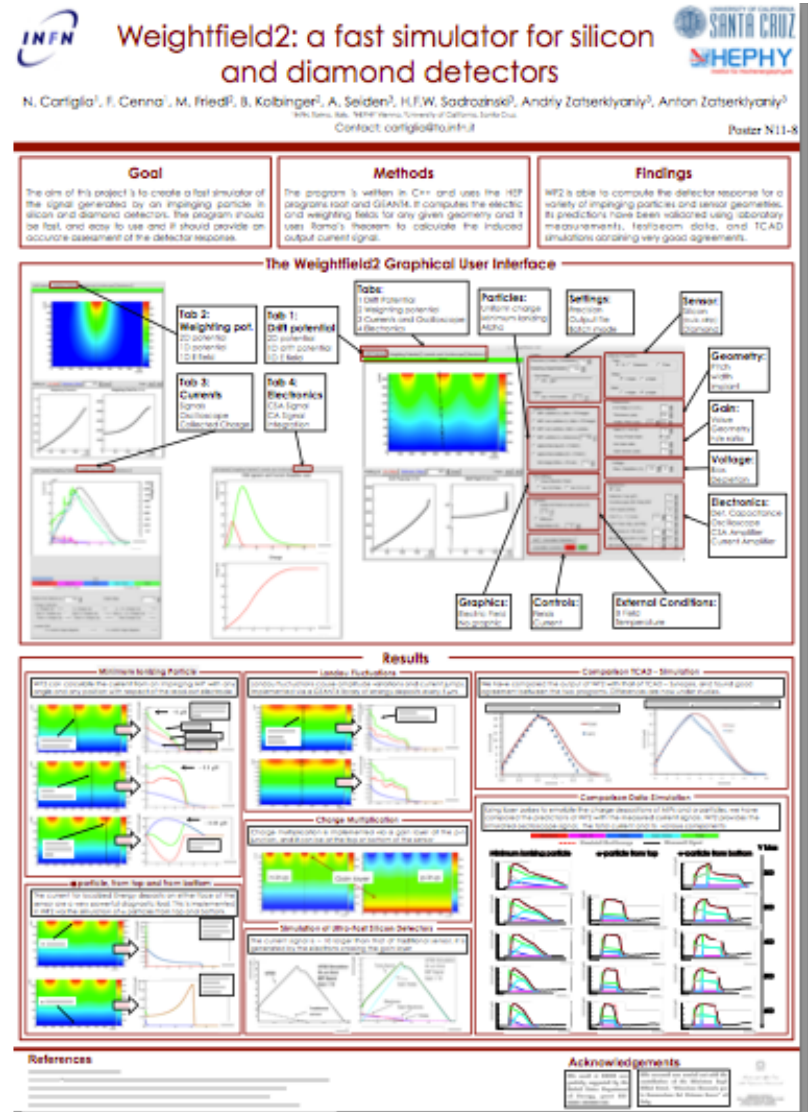


Poster Session IEEE N11-8

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/

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).

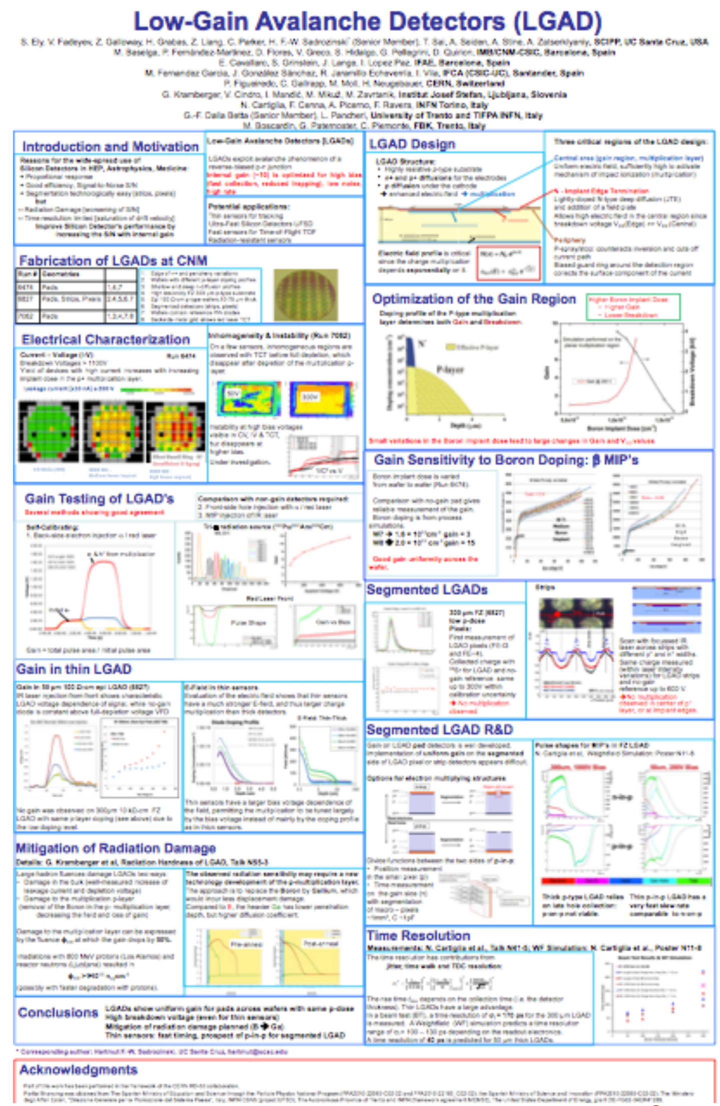
Backup

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



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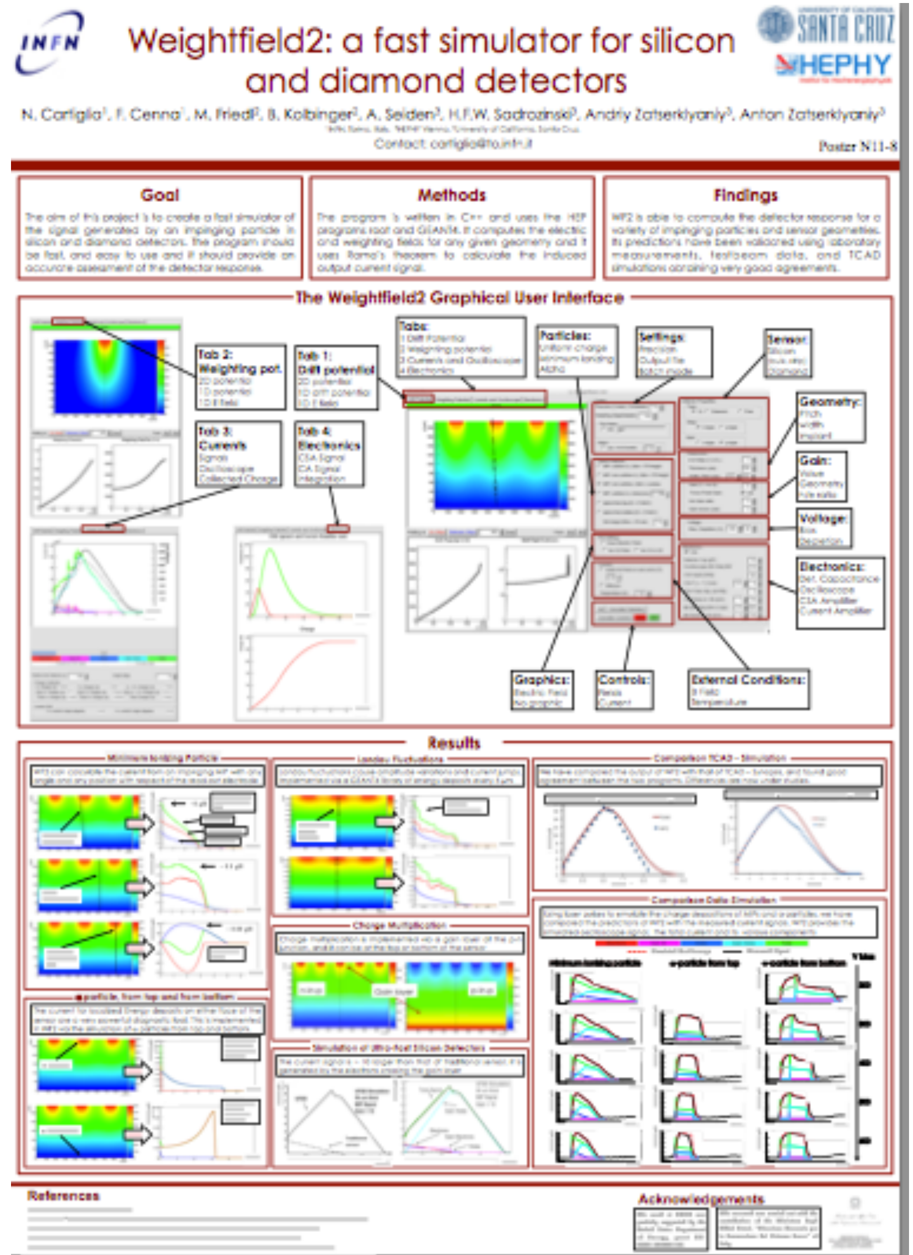
How can we progress? Need simulation

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



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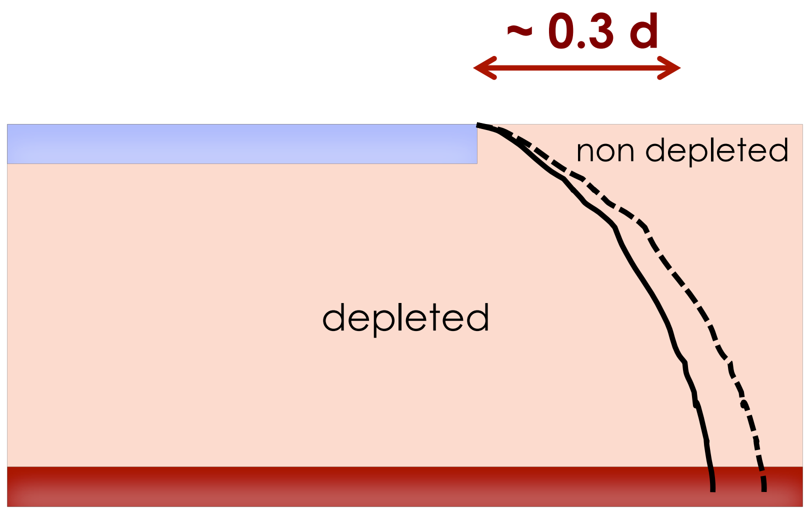
Sensor thickness and slim edge

Rule: when the depletion volume reaches the edge, you have electrical breakdown.
It's customary to assume that the field extends on the side by ~ 1/3 of the thickness.



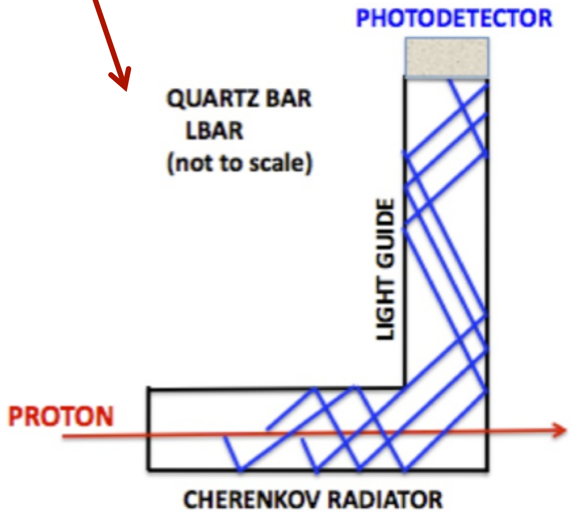
edge = k* thickness

- k = 1 very safe
- k = 0.5 quite safe
- K = 0.3 limit

By construction, thin detectors (~ 100 micron) might have therefore slim edge

State-of-the-art Timing Detectors

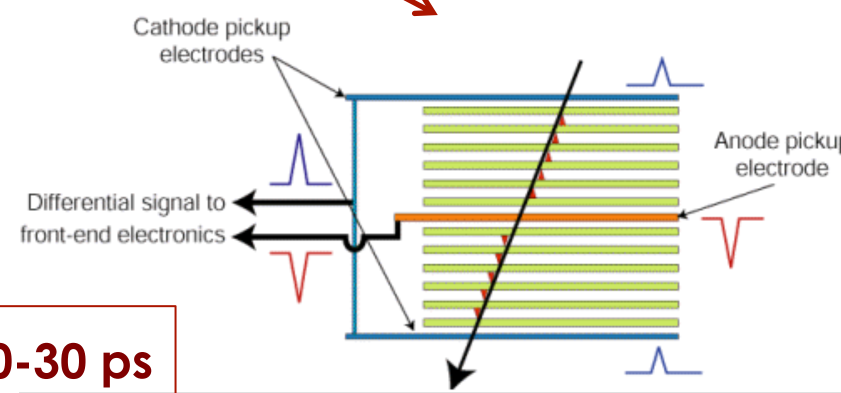
Timing detectors exploit very fast physics processes such as **Cherenkov light** emission or **electronic avalanches** to create prompt signals



CMS/ATLAS

σ_t ~ **20-30 ps**

σ_x ~ **1-2 mm**



ALICE

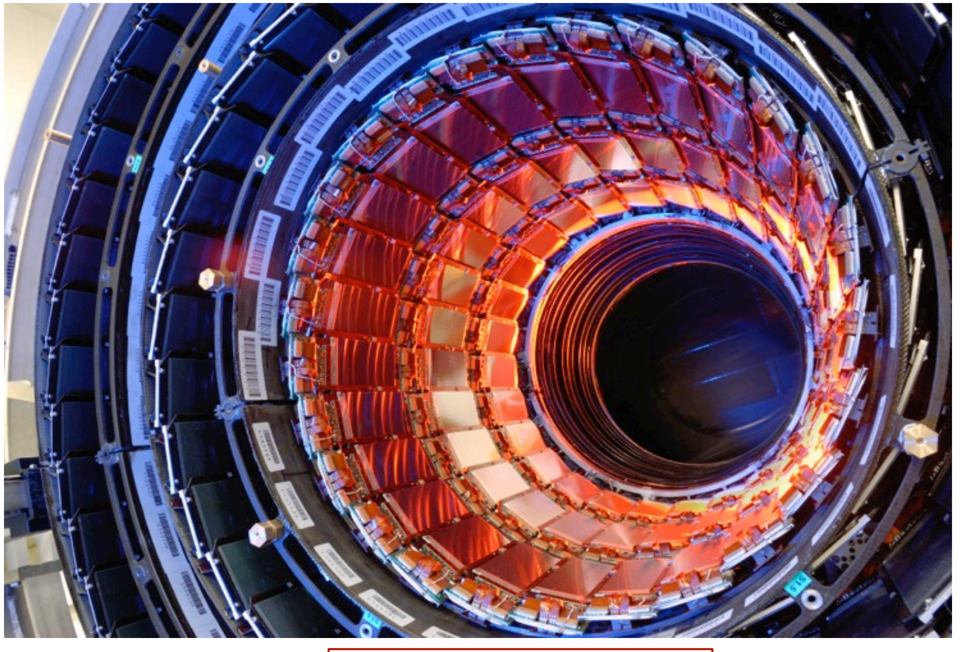
- These detectors measure time very accurately but locate particles with the precision of ~ 1 mm
- Good timing is obtain by using a gain mechanism, either in the detector or in the electronics

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)



σ_t ~ 100-150 ps
σ_x ~ 20-30 μm