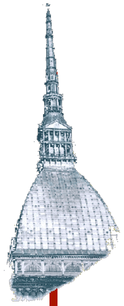
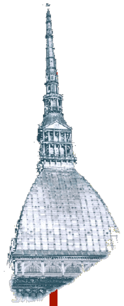


4-Dimensional High Precision Tracking

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

Nicolo Cartiglia
INFN Torino, Italy

with
INFN Gruppo V, RD50, FBK (Trento), Univ. of Trento, CNM (Barcelona), UCSC



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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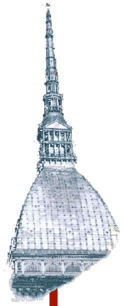


The **4D** challenge

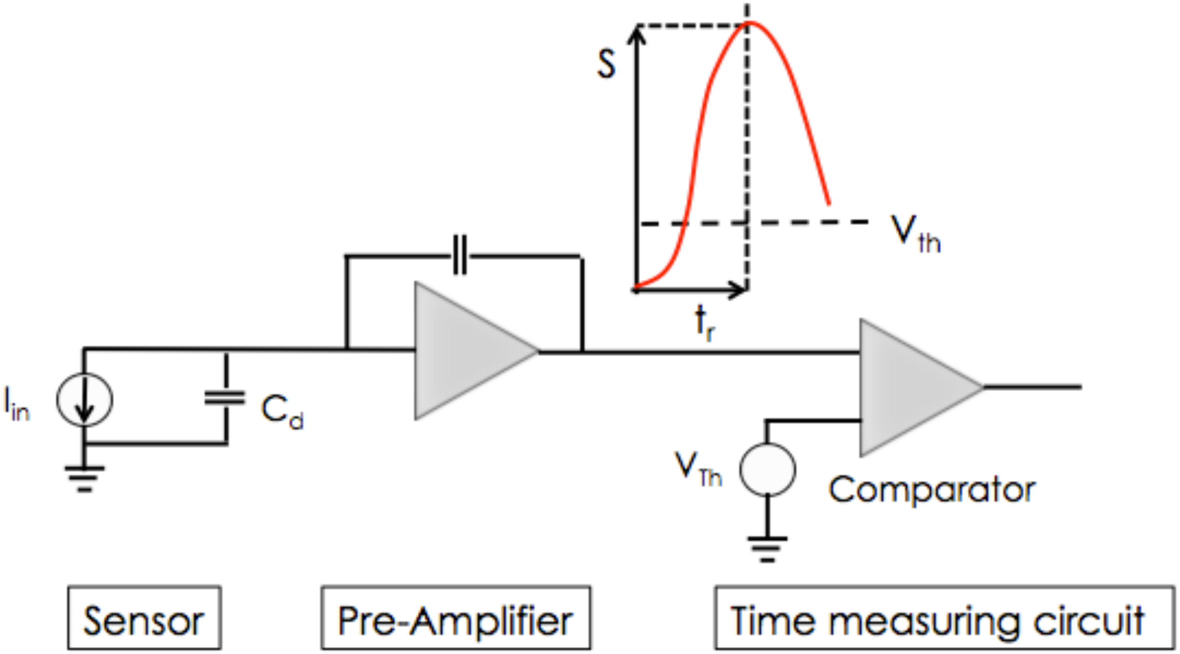
Is it possible to build a detector with concurrent excellent time and position resolution?

Can we provide in the same detector and readout chain:

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

A time-tagging detector

(a simplified view)



Time is set when the signal crosses the comparator threshold

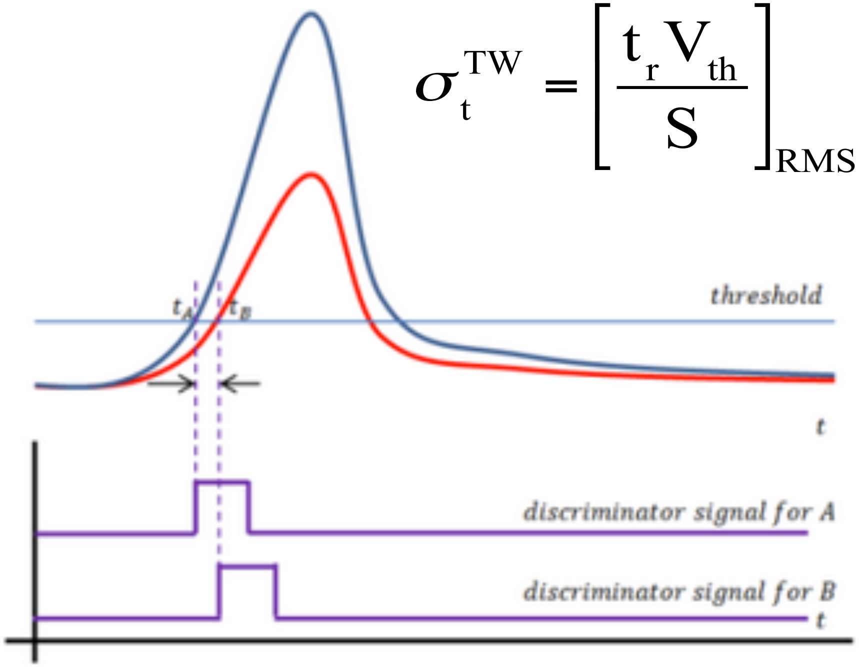
The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning.

Noise source: Time walk and Time jitter

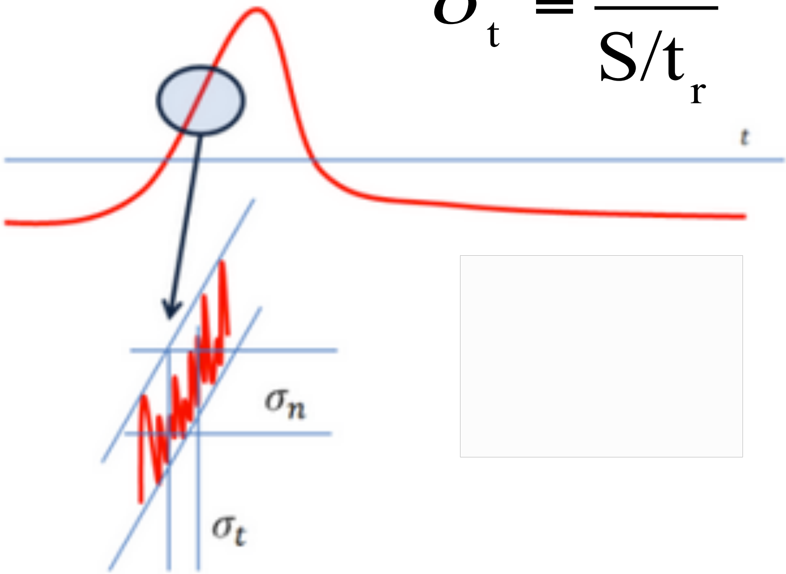
Time walk: the voltage value V_{th} is reached at different times by signals of different amplitude

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

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

Time Resolution, noise 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

In summary:

$$\sigma_t \propto \frac{\text{Noise}}{dV/dt}$$

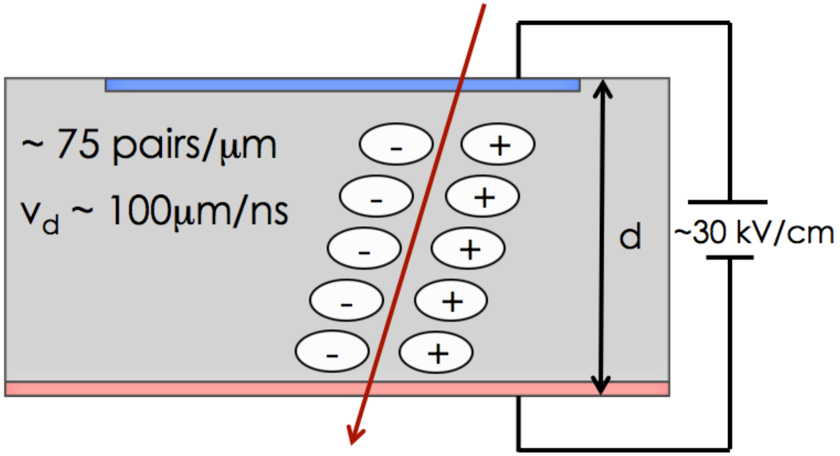
Signal formation in silicon detectors

Signal shape is determined by Ramo's Theorem:

$$i \propto q v E_w$$

Drift velocity

Weighting field



What is controlling the slew rate?

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

Signal shape

Velocity:

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

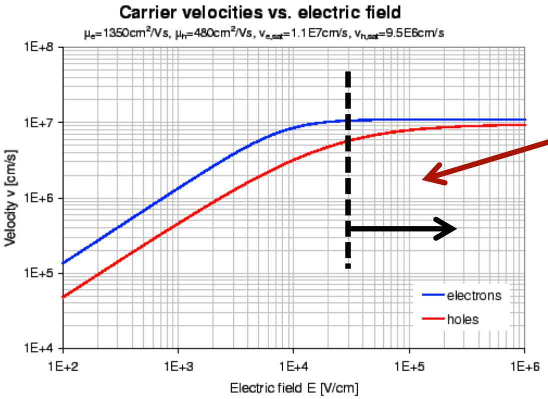
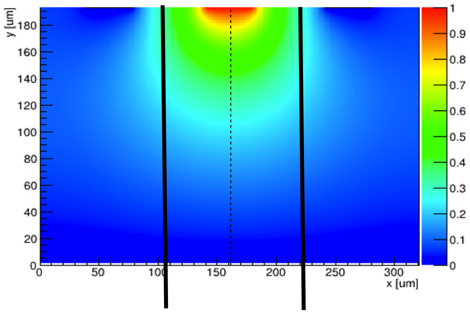


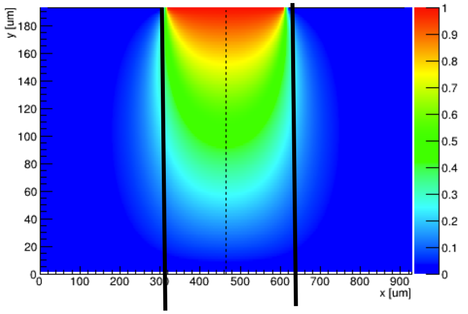
Figure: Electron and hole velocities vs. the electric field strength in silicon.

We want to operate in this regime: saturated velocity

Weighting field:

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





Best: uniform weighting field in a pitch

Charge:

$$i \propto \boxed{q}vE_w$$

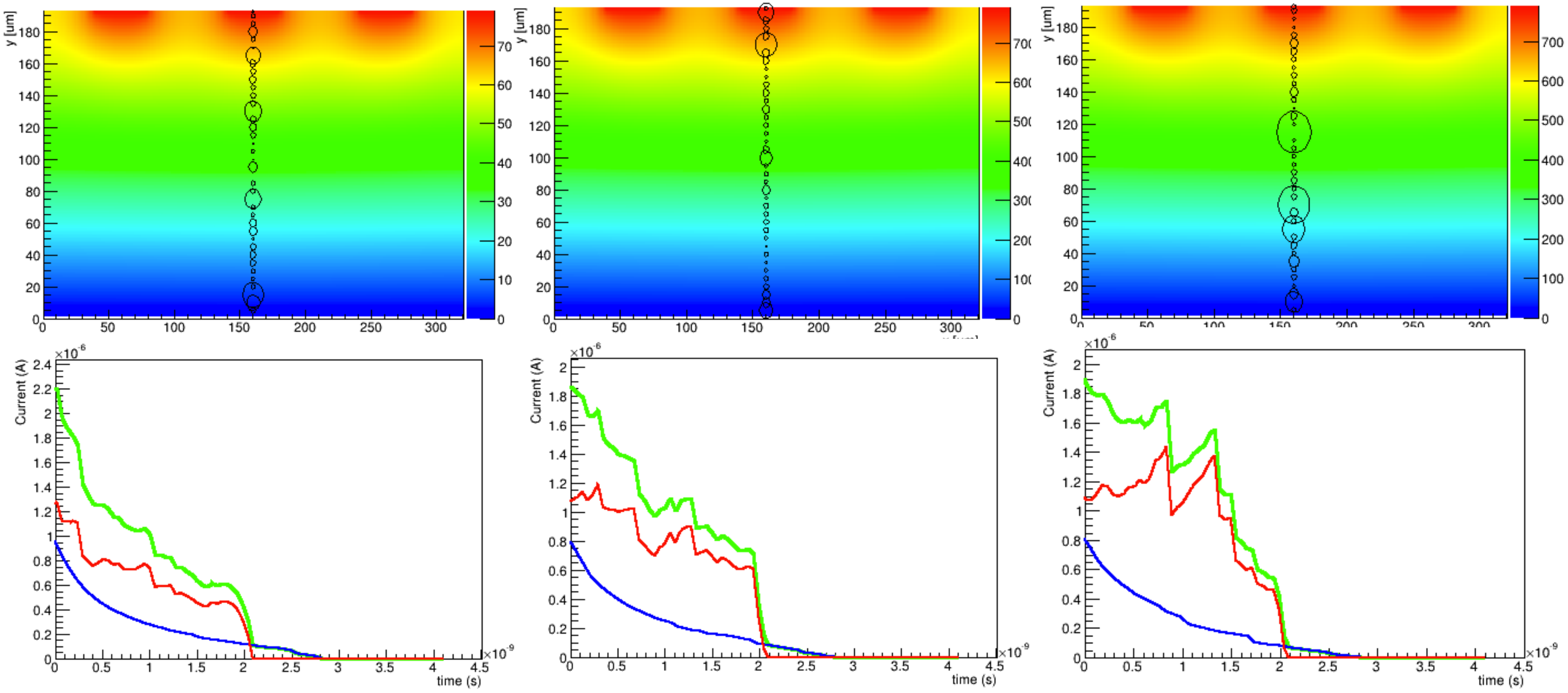
- ➔ Highest possible E field to saturate velocity
- ➔ Large pad to have uniform weighting field
- ➔ Lot's of charge

Non-Uniform Energy deposition

Landau Fluctuations cause two major effects:

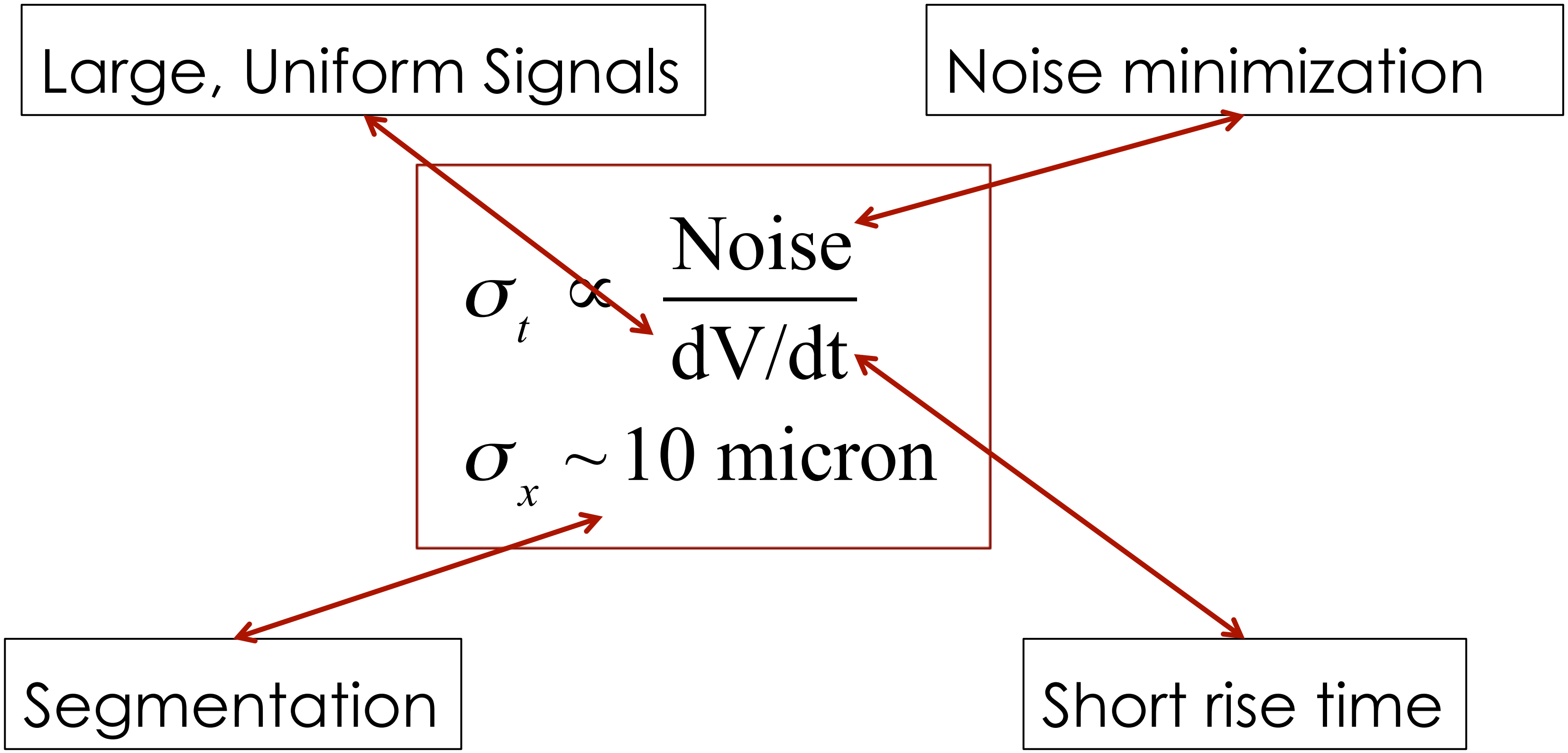
- Amplitude variations, that can be corrected with time walk compensation
- For a given amplitude, the charge deposition is non uniform.

These are 3 examples of this effect:



4-Dimensional High Precision Tracking

The R&D program



Large, Uniform Signals

Noise minimization

$$\sigma_t \propto \frac{\text{Noise}}{\text{dV/dt}}$$

$$\sigma_x \sim 10 \text{ micron}$$

Segmentation

Short rise time

What is the signal of one e/h pair?

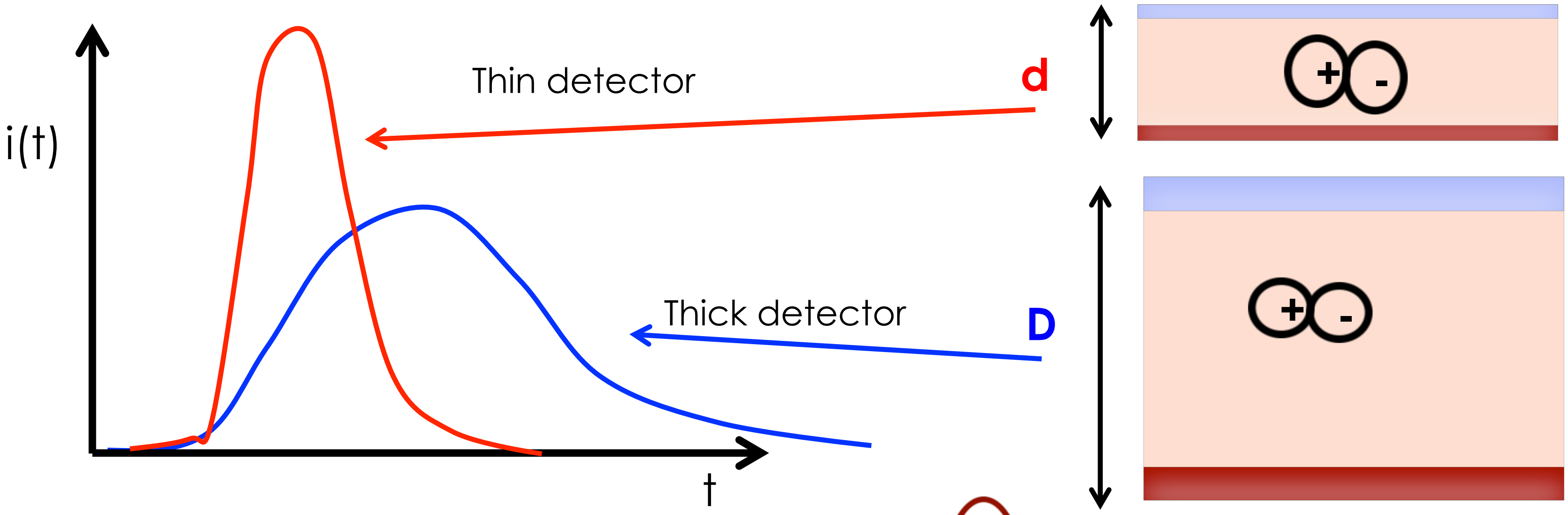
(Simplified model for pad detectors)

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



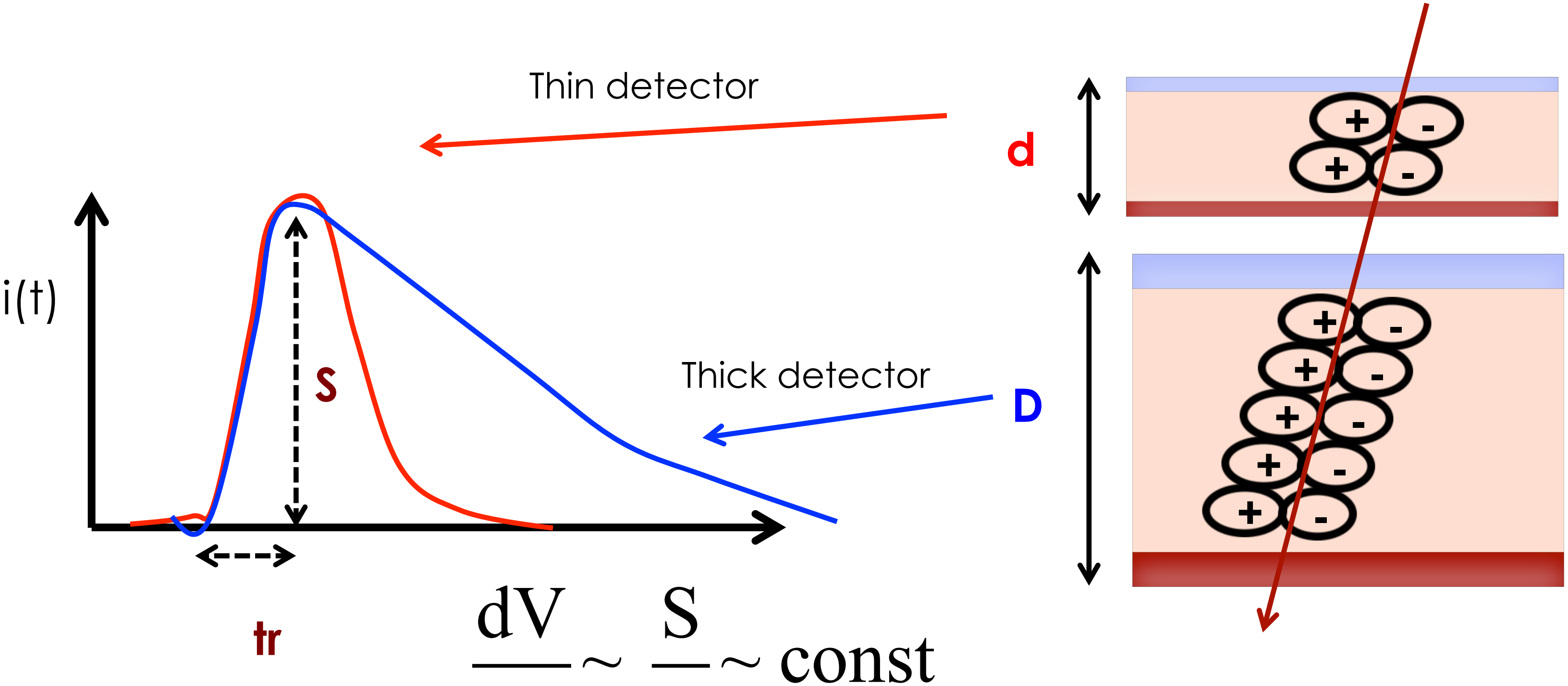
→ **One e/h pair generates higher current in thin detectors**

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

Weighting field

Thin vs Thick detectors

(Simplified model for pad detectors)

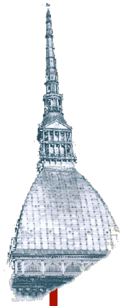


$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim \text{const}$$

Thick detectors have longer signals, not higher signals

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

How can we do better?



Possible approaches

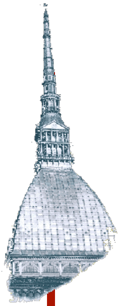
We need to minimize this expression:

$$\sigma_t = \left(\frac{\mathrm{N}}{\mathrm{S}/\mathrm{t}_\mathrm{r}}\right)$$

- **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 “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 ~ 300 kV/cm**

Charge multiplication

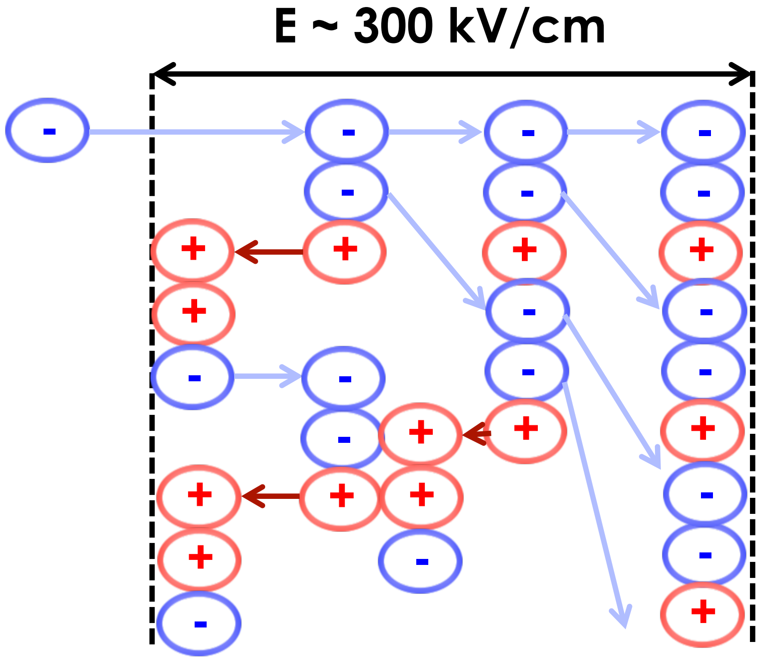
$$N(l) = N_0 \cdot e^{\alpha \cdot l}$$

Gain:

$$G = e^{\alpha\, l}$$

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

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

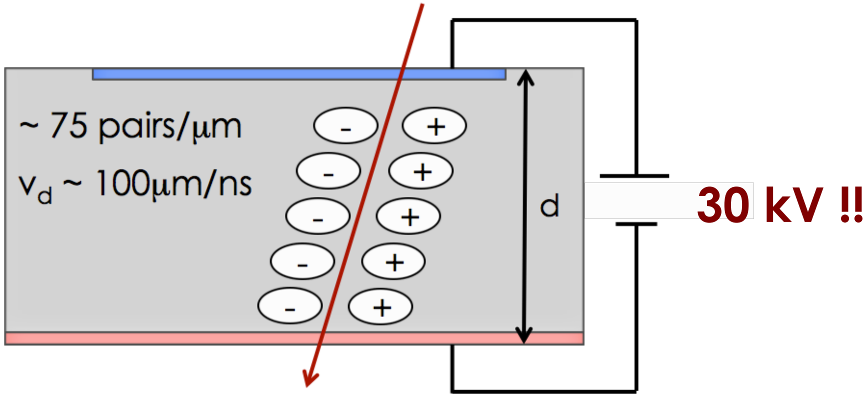
Silicon devices with gain:

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

How can we achieve E ~ 300kV/cm?

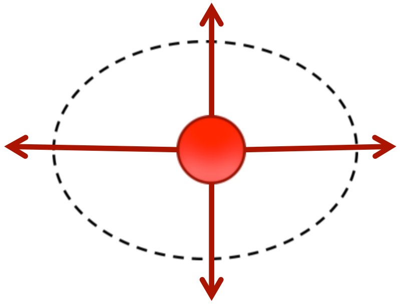
1) Use external bias: assuming a 300 micron silicon detector, we need **V_{bias} = 30 kV**

Not possible



2) Use Gauss Theorem:

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



E = 300 kV/cm ➔ q ~ 10^{16} /cm^3

Need to have 10^{16}/cm^3 charges !!

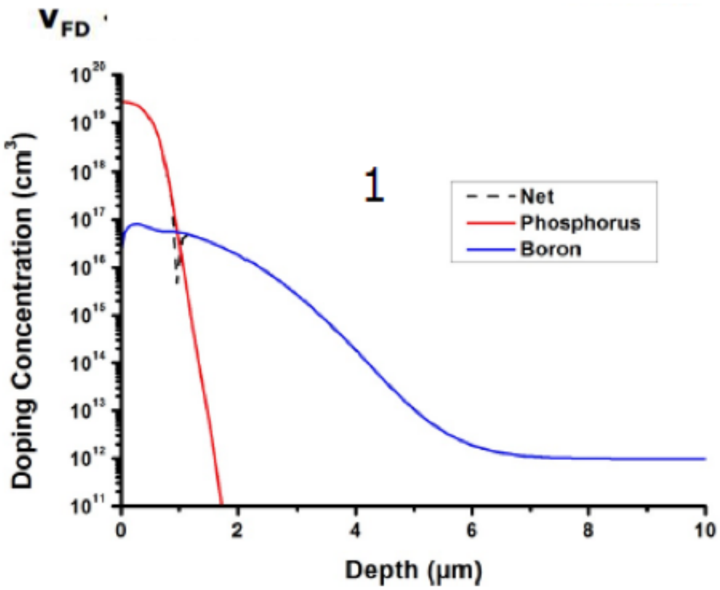
Low Gain Avalanche Detectors (LGADs)

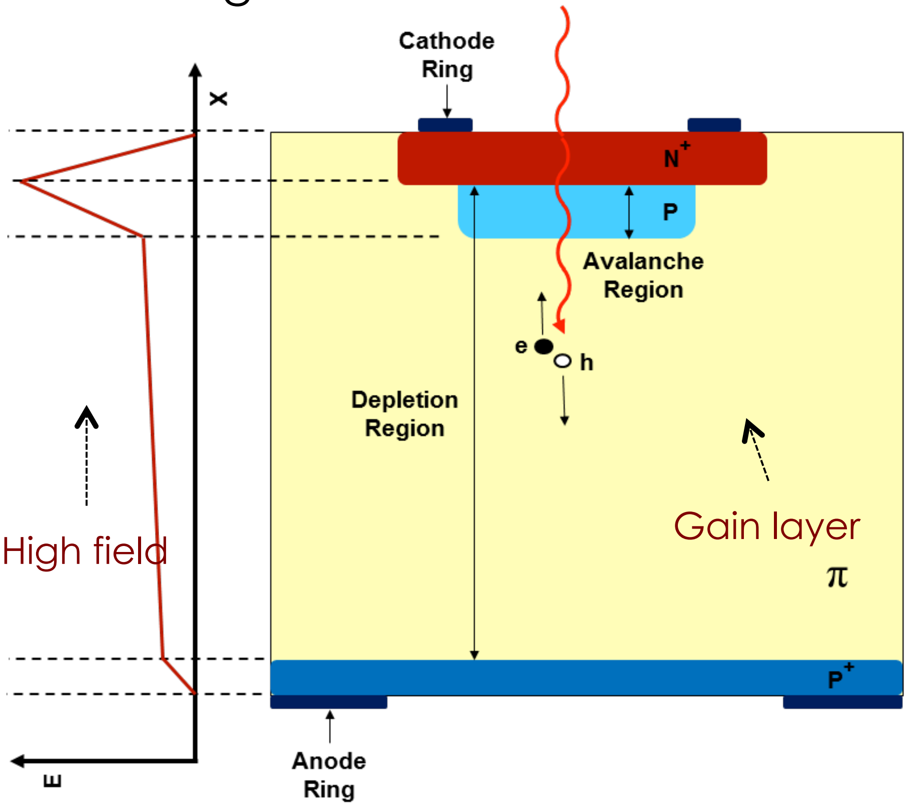
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage





Sensor: Simulation

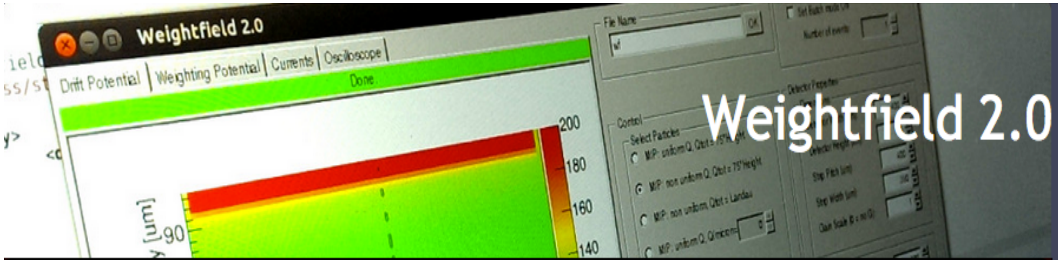
We developed a full sensor simulation to optimize the sensor design

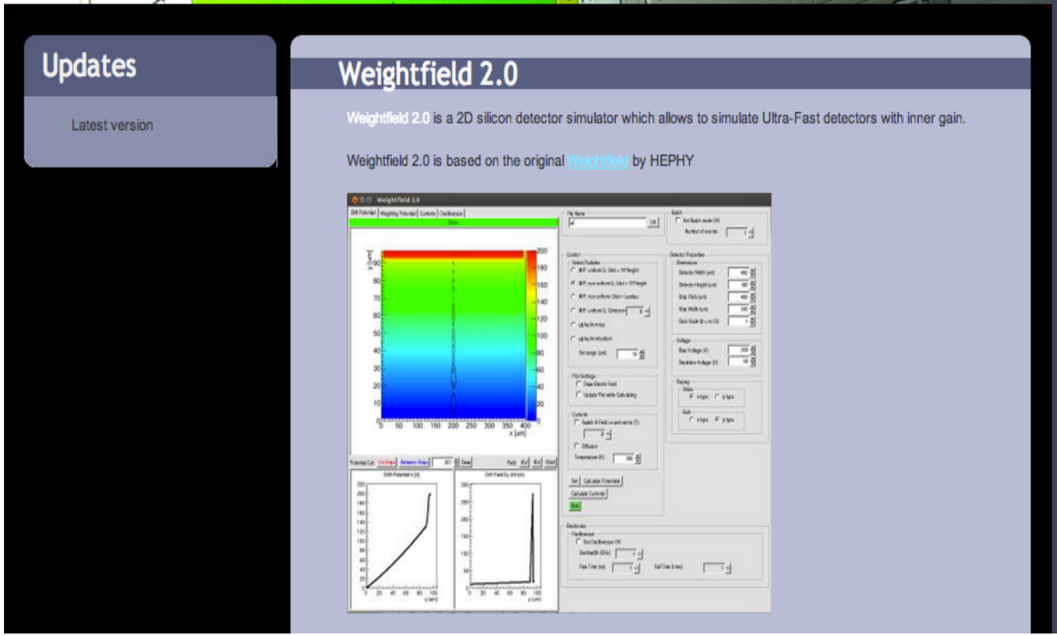
WeightField2, F. Cenna, N. Cartiglia 9th Trento workshop, Genova 2014

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



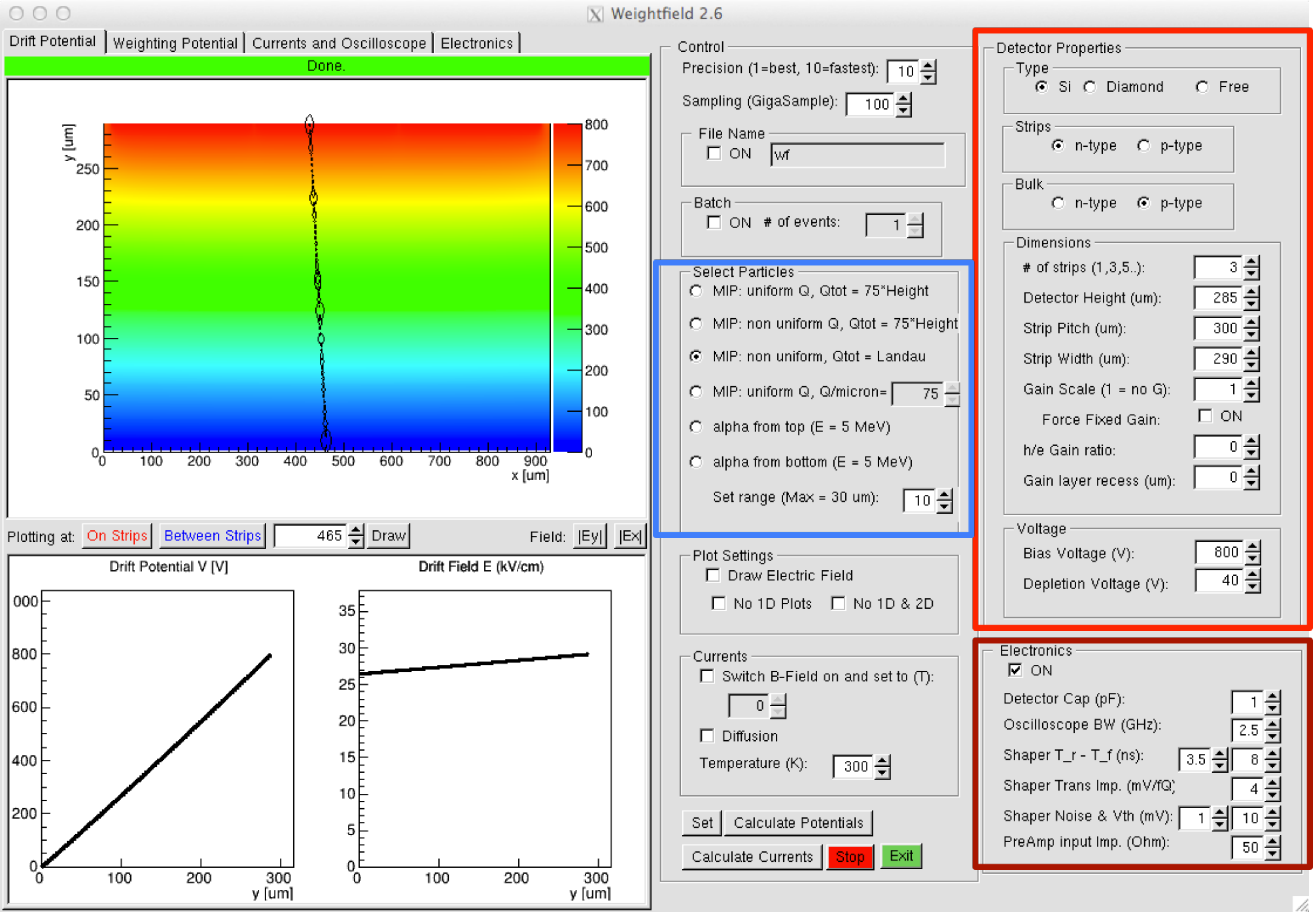


Weightfield 2.0

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



Plotting at: 465

Control

Precision (1=best, 10=fastest): 10

Sampling (GigaSample): 100

File Name

☐ ON wf

Batch

☐ ON # of events: 1

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= 75
- ○ alpha from top (E = 5 MeV)
- ○ alpha from bottom (E = 5 MeV)

Set range (Max = 30 um): 10

Plot Settings

☐ Draw Electric Field

☐ No 1D Plots ☐ No 1D & 2D

Currents

☐ Switch B-Field on and set to (T): 0

☐ Diffusion

Temperature (K): 300

Detector Properties

Type

● Si ○ Diamond ○ Free

Strips

● n-type ○ p-type

Bulk

○ n-type ● p-type

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

Bias Voltage (V): 800

Depletion Voltage (V): 40

Electronics

☑ ON

Detector Cap (pF): 1

Oscilloscope BW (GHz): 2.5

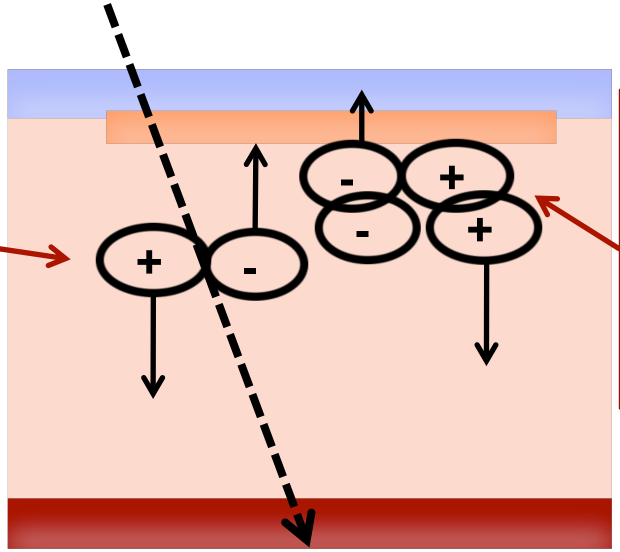
Shaper T_r - T_f (ns): 3.5 8

Shaper Trans Imp. (mV/fQ) 4

Shaper Noise & Vth (mV): 1 10

PreAmp input Imp. (Ohm): 50

How gain shapes the signal



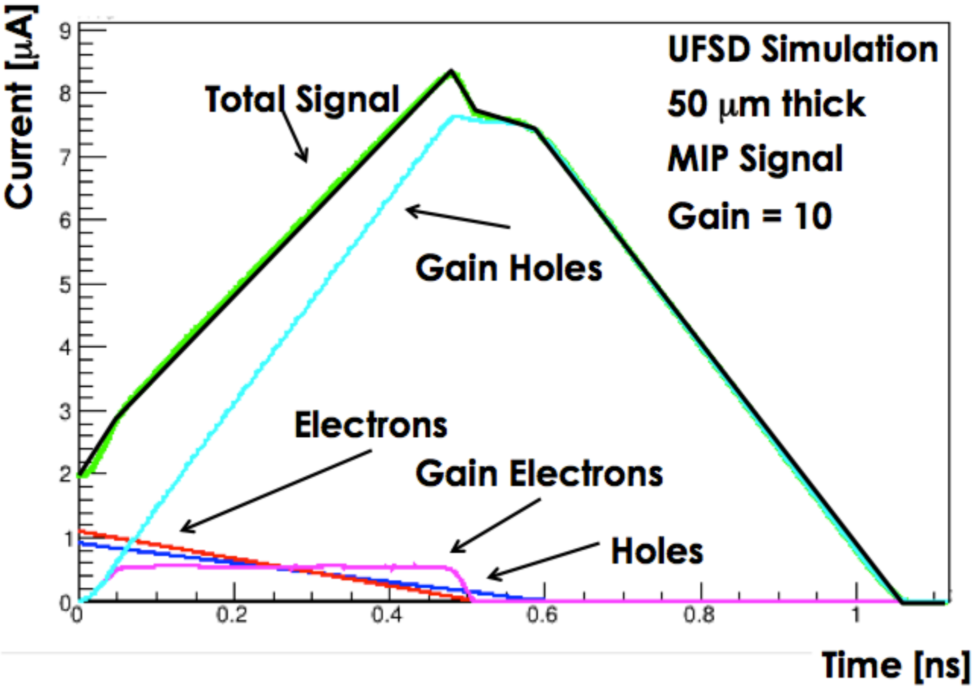
Initial electron, holes

Gain electron:

absorbed immediately

Gain holes:

long drift home

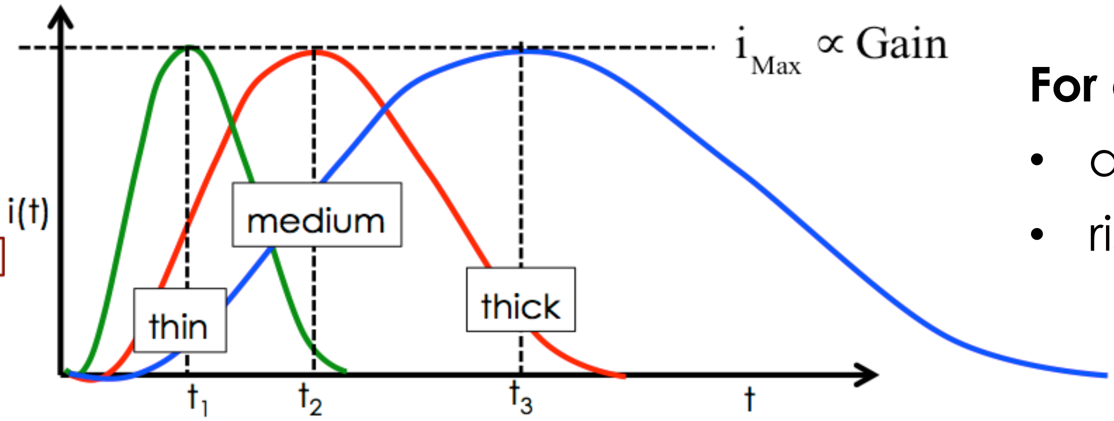


Electrons multiply and produce additional electrons and holes.

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

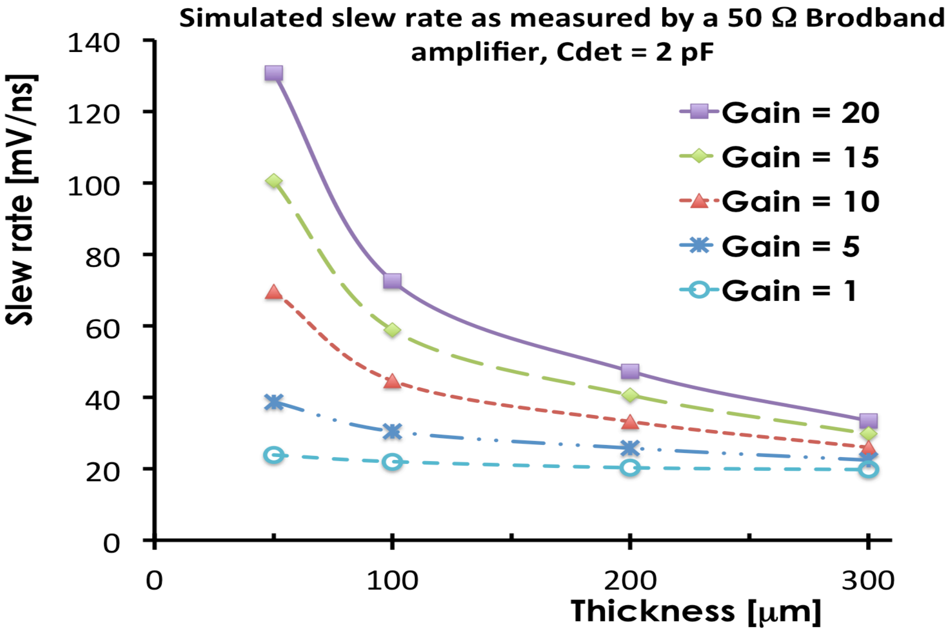
➔ **No holes multiplications**

Gain and slew rate vs thickness



For a fixed gain:

- amplitude = constant
- rise time ~ 1/thickness

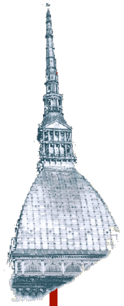

Simulated slew rate as measured by a 50 Ω Brodband amplifier, Cdet = 2 pF

The slew rate:

- Increases with gain
- Increases ~ 1/thickness

➔ Go thin!!

Significant improvements in time resolution require thin detectors



Ultra Fast Silicon Detectors

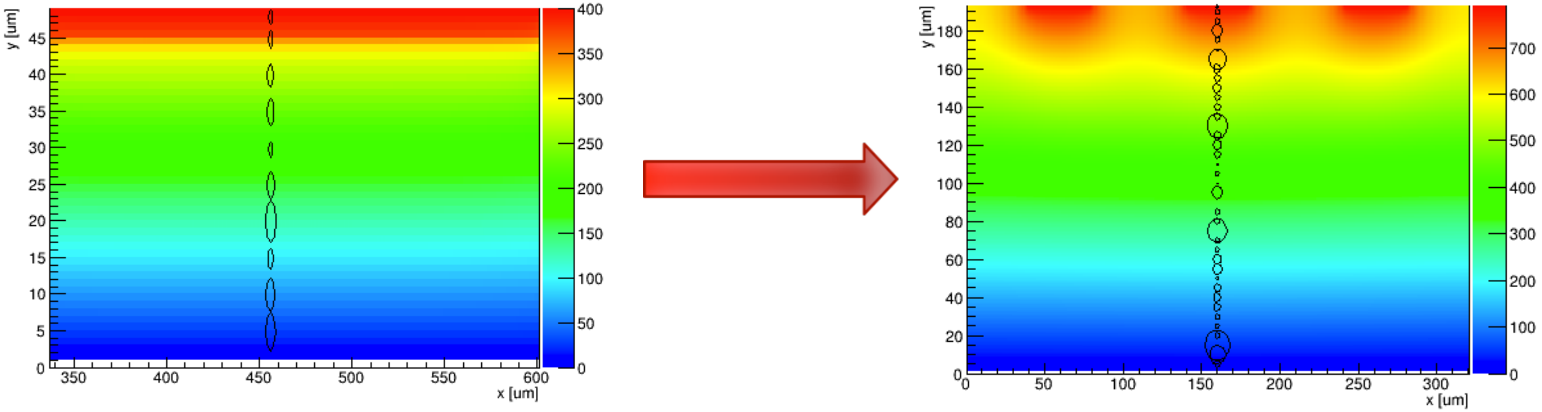
UFSD are LGAD detectors optimized to achieve the best possible time resolution

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)

Merging timing with position resolution

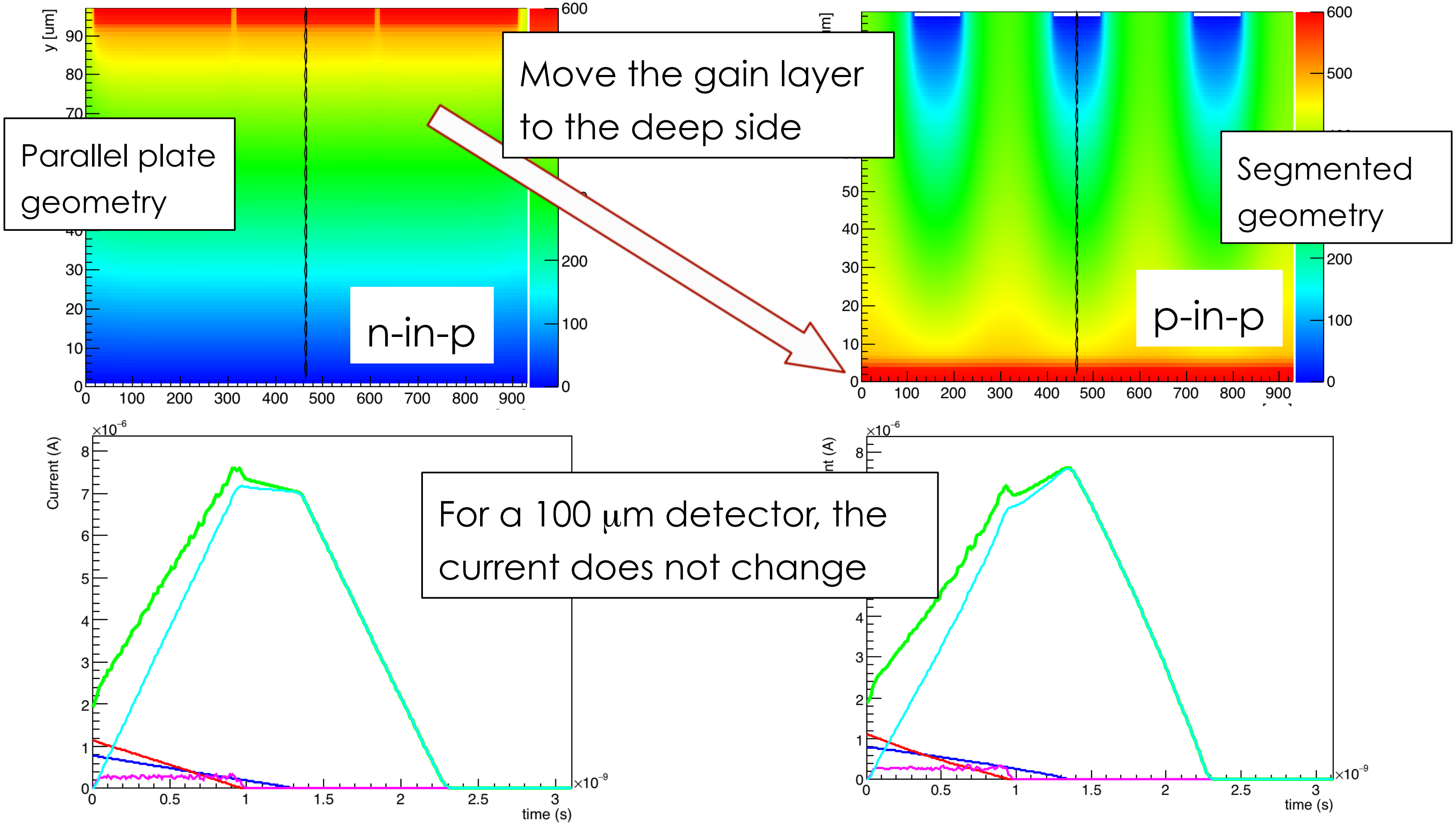
Electrode segmentation makes the E field very non uniform, and therefore ruins the timing properties of the sensor



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

1) Segmentation: buried junction

Separate the multiplication side from the segmentation side



Parallel plate geometry

Move the gain layer to the deep side

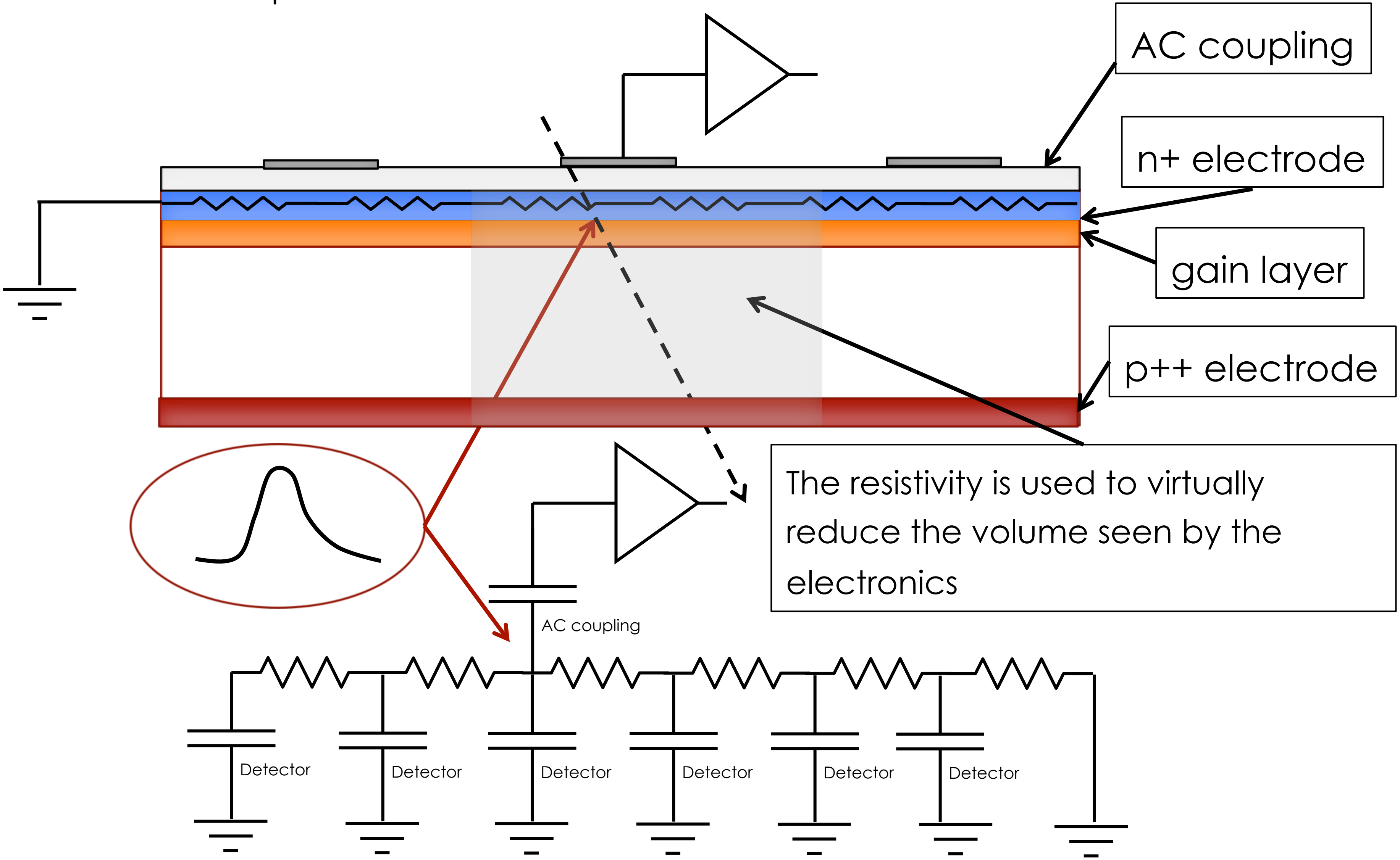
Segmented geometry

For a 100 μm detector, the current does not change

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

2) Segmentation: AC coupling

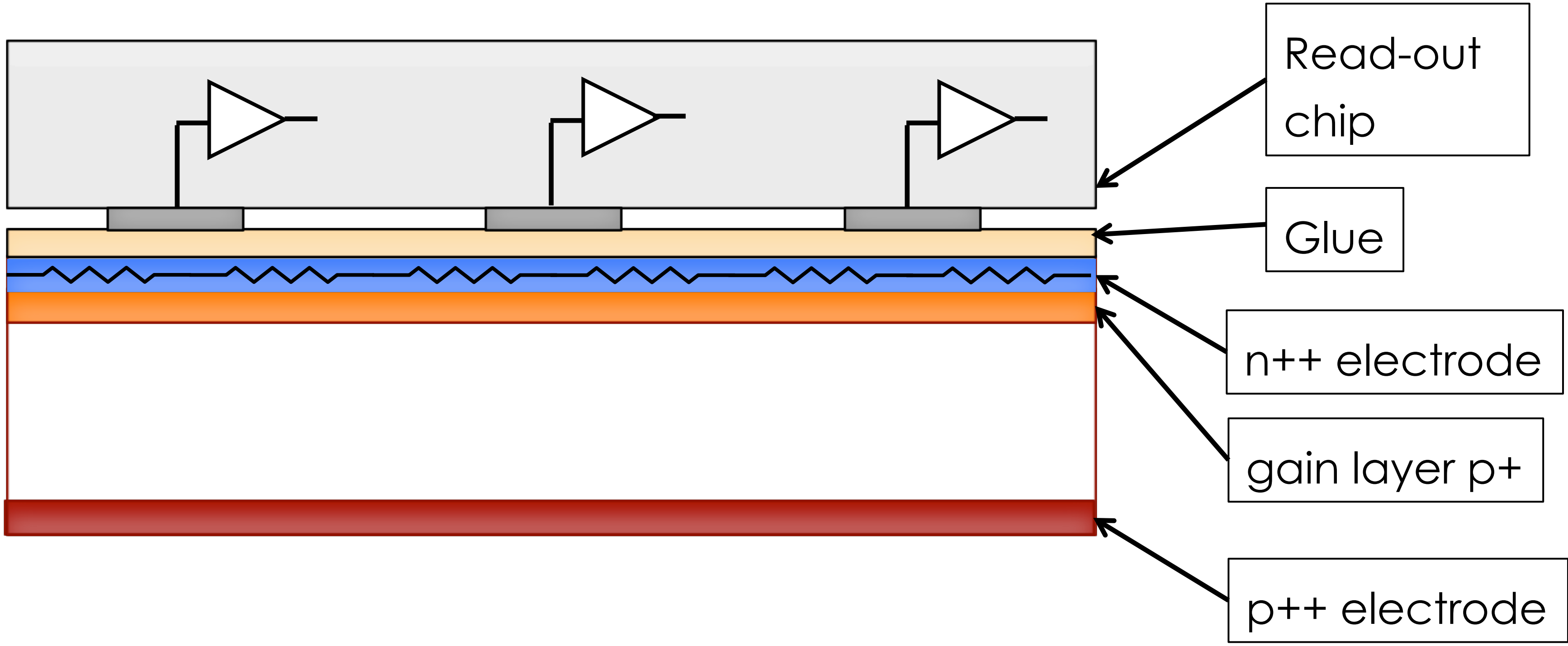
Standard n-in-p LGAD, with AC read-out



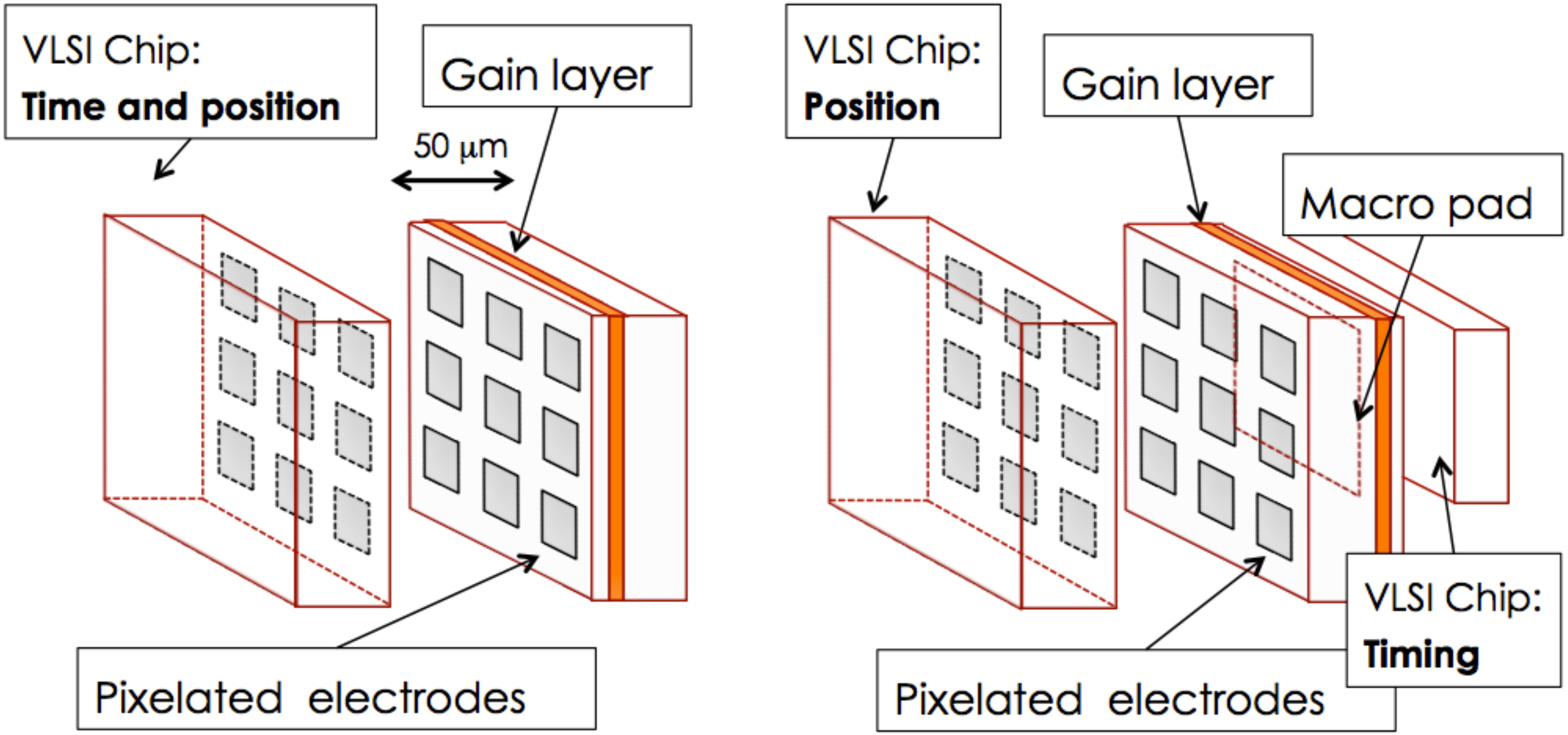
The resistivity is used to virtually reduce the volume seen by the electronics

2-bis) Details of AC coupling

Can we envision to use glue instead of bump bonding?



3) Segmentation: splitting gain and position measurements



VLSI Chip:
Time and position

Gain layer

50 µm

Pixelated electrodes

VLSI Chip:
Position

Gain layer

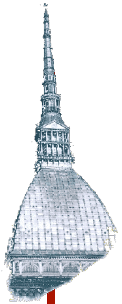
Macro pad

VLSI Chip:
Timing

Pixelated electrodes

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

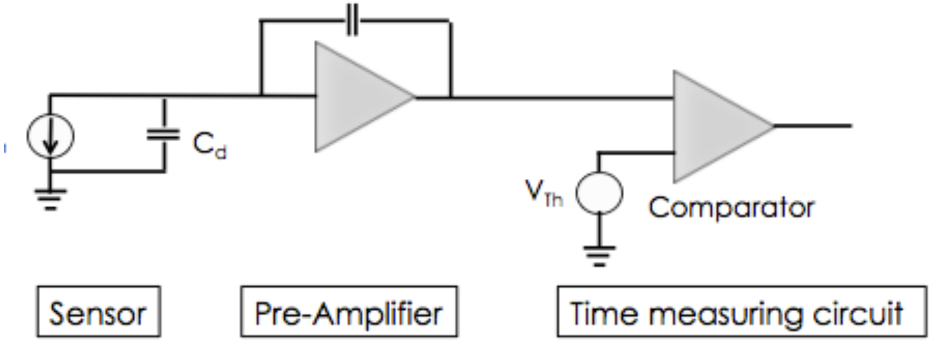
However we might split the position and the time measurements

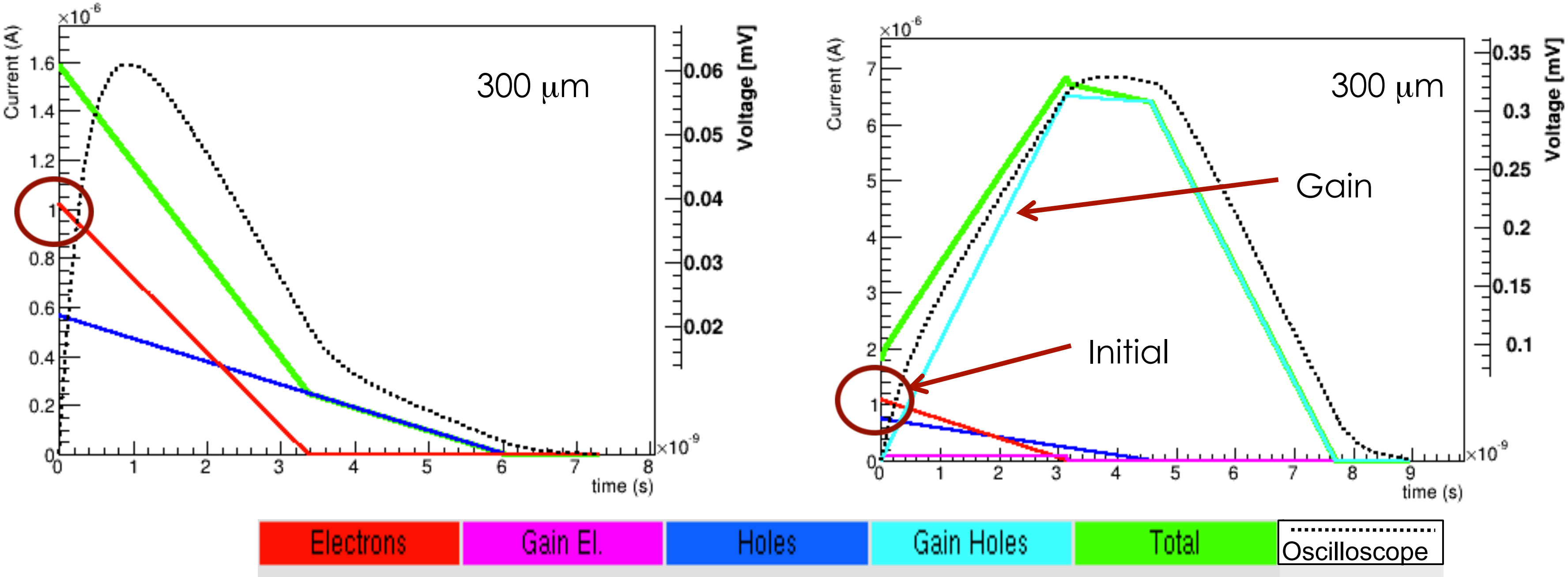


Electronics

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

The signal from UFSDs is different from that of traditional sensors





Simulated Weightfield2

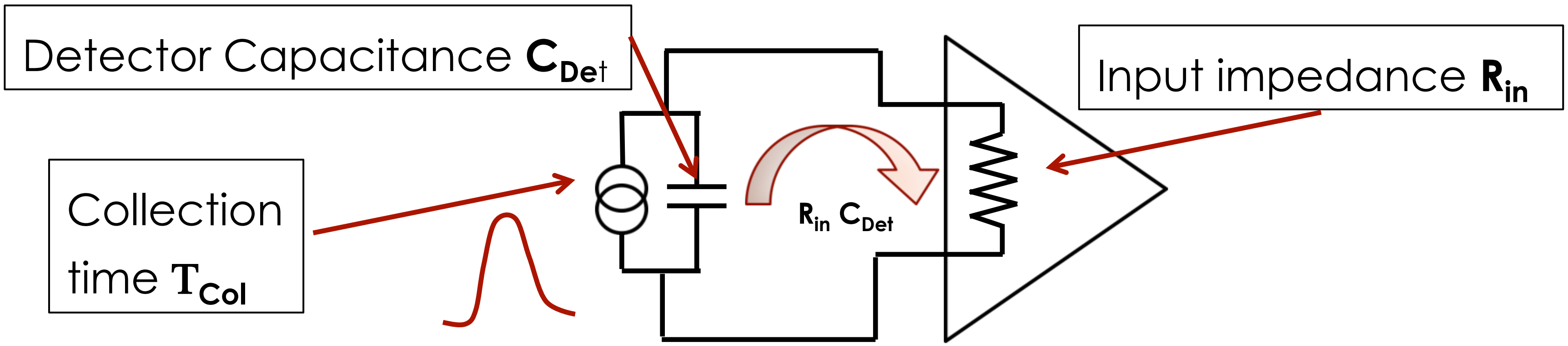
Pads with no gain

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 $\mathbf{C_{Det}}$

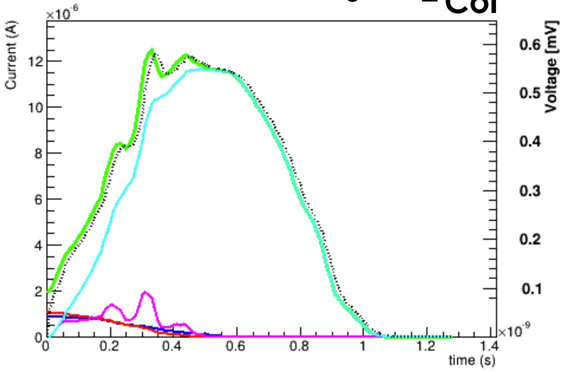
Collection time $\mathbf{T_{Col}}$

Input impedance $\mathbf{R_{in}}$

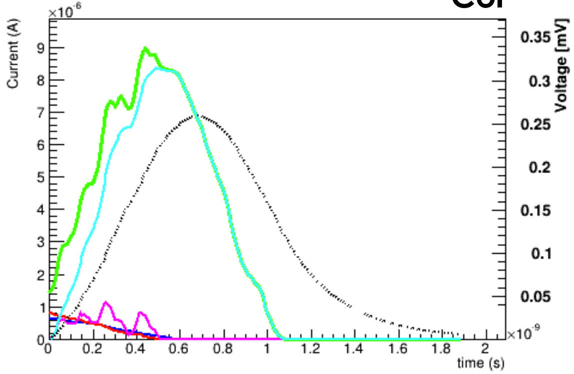
There are two time constants at play:

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

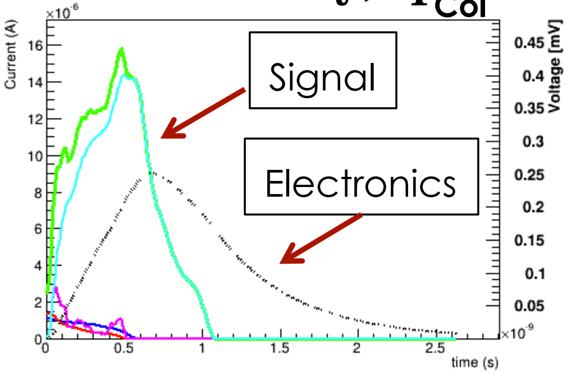
$\tau < T_{Col}$



$\tau \sim T_{Col}$



$\tau > T_{Col}$



Signal

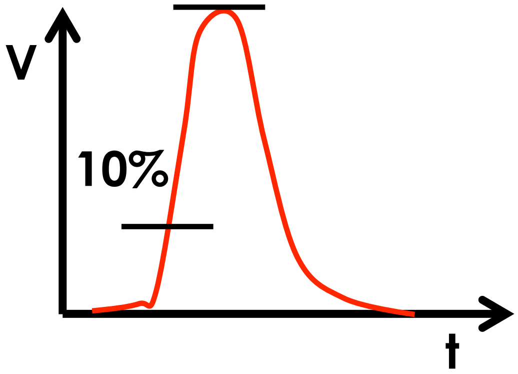
Electronics

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

➔ Smoother current

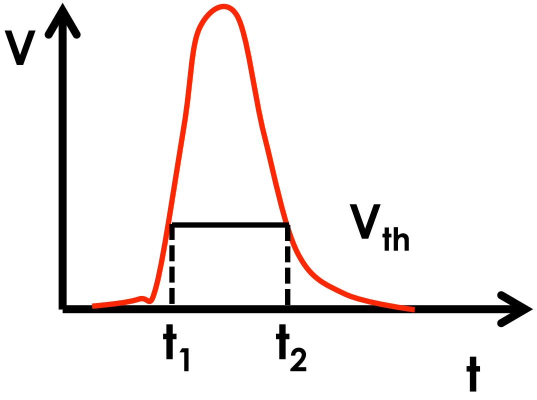
Need to find the optimum balance

What is the best “time measuring” circuit?



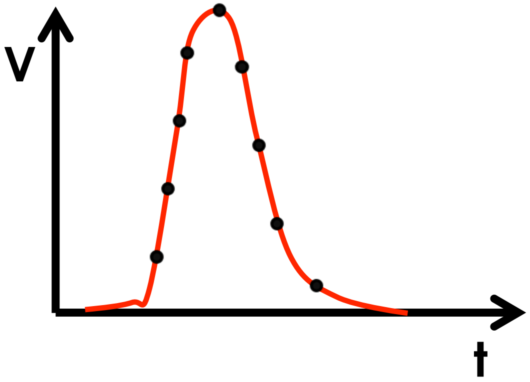
Constant Fraction Discriminator

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



Time over Threshold

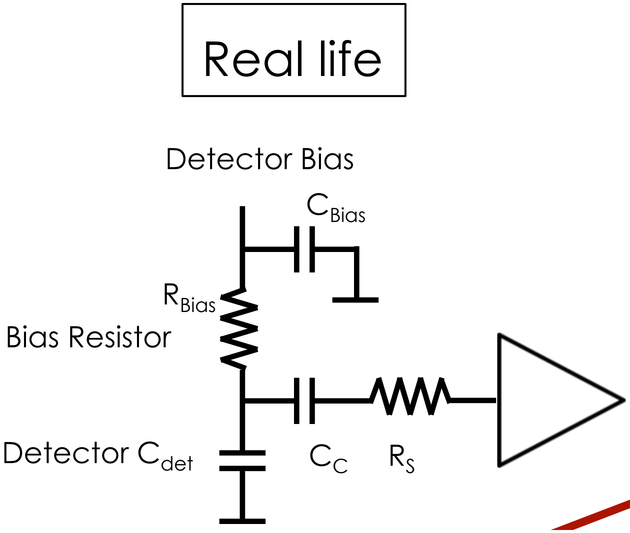
The amount of time over the threshold is used to correct for time walk

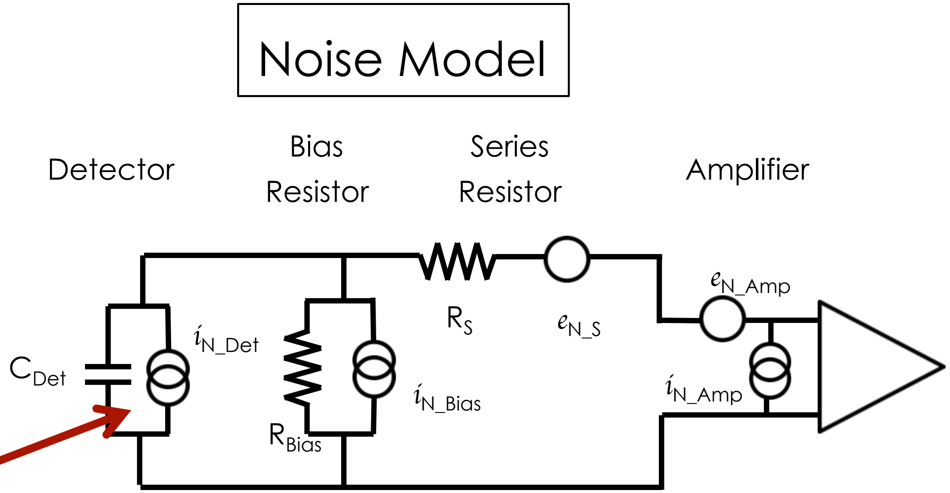


Multiple sampling

Most accurate method, needs a lot of computing power.

Noise





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

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

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

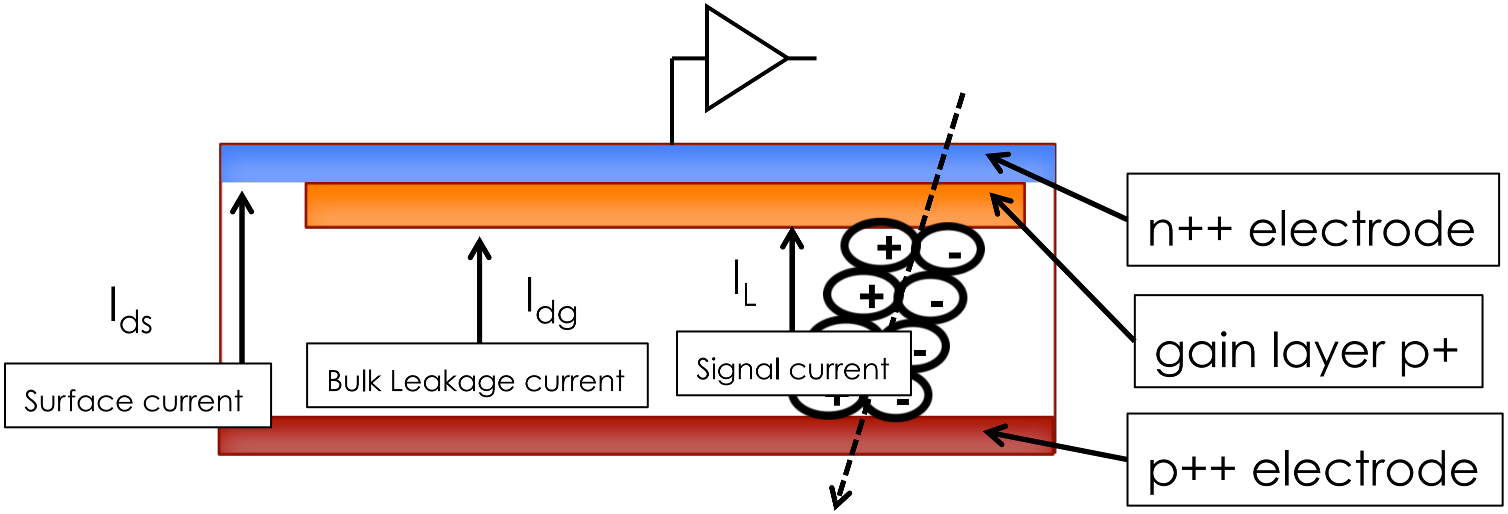
low gain!

This term dominates for short shaping time

➔ **Current Noise²** ~ detector leakage current x T_s

➔ **Voltage Noise²** ~ C_{det}^2/T_s ~ C_{det} for T_s ~ C_{det}

Details of shot noise in LGAD - APD



I_{ds}

Surface current

I_{dg}

Bulk Leakage current

I_L

Signal current

n++ electrode

gain layer p+

p++ electrode

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

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

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

$$F \sim M^x$$

k = e/h ionization rate
x = excess noise index
M = gain

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

Noise for Gain = 1 and Gain = 10

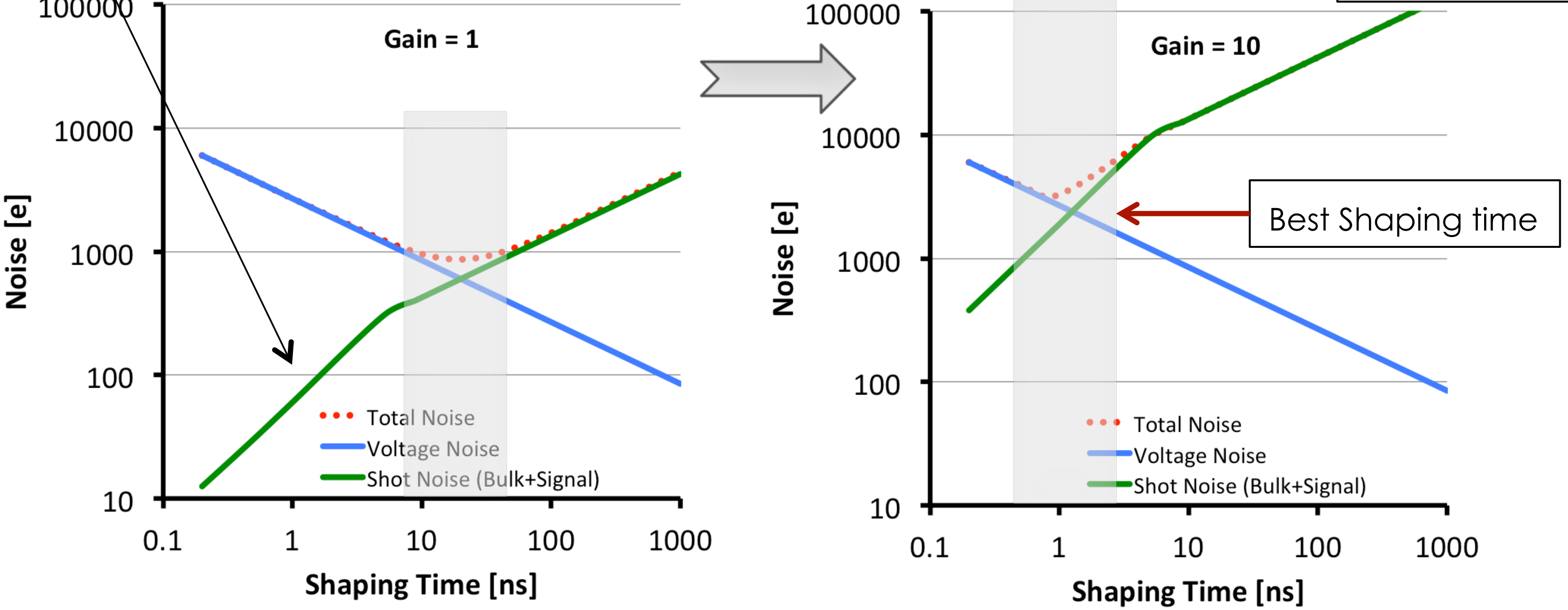
Let's use the following parameterization (Spieler, Semiconductor Detector, pag 35):

$$Q_n^2 = \underbrace{12\,[\frac{e^2}{nA*ns}](I_{Bulk}+I_{Signal})M^{2+x}\tau}_{\text{Shot Noise}} + \underbrace{3.6*10^4[\frac{e^2 ns}{pF^2 nV^2/Hz}]e^2_{N\_Amp}\frac{C^2_{Det}}{\tau}}_{\text{Voltage Noise}}$$

Current noise very important at small shaping time

I_{bulk} = 1nA
I_{signal} = 300 nA * 5 ns
x = 1
C_{det} = 1 pF

Effect of the gain



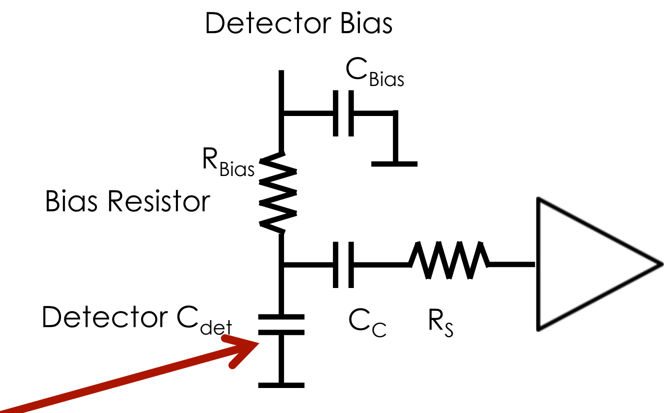
The minimum noise value is pushed higher and to a much shorter shaping time:

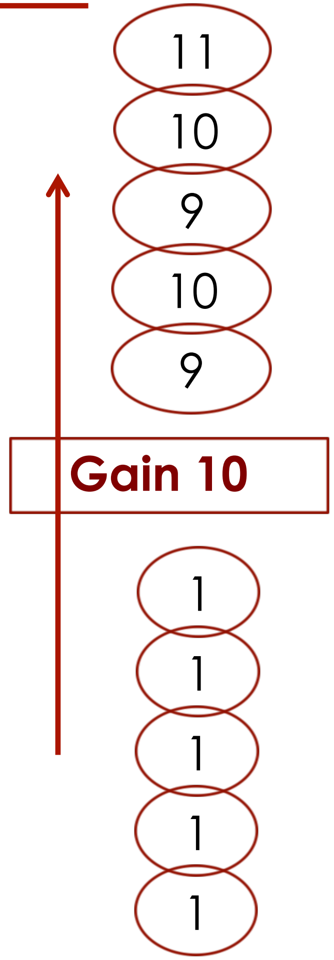
1000e- at 20 ns with Gain = 1 ➔ 3000e- @ 1 ns with Gain = 10

➔UFSDs need very short shaping time ⇐

Noise due to gain: excess noise factor

Real life





NOISE DUE TO GAIN:

Excess noise factor:

low gain, very small k

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

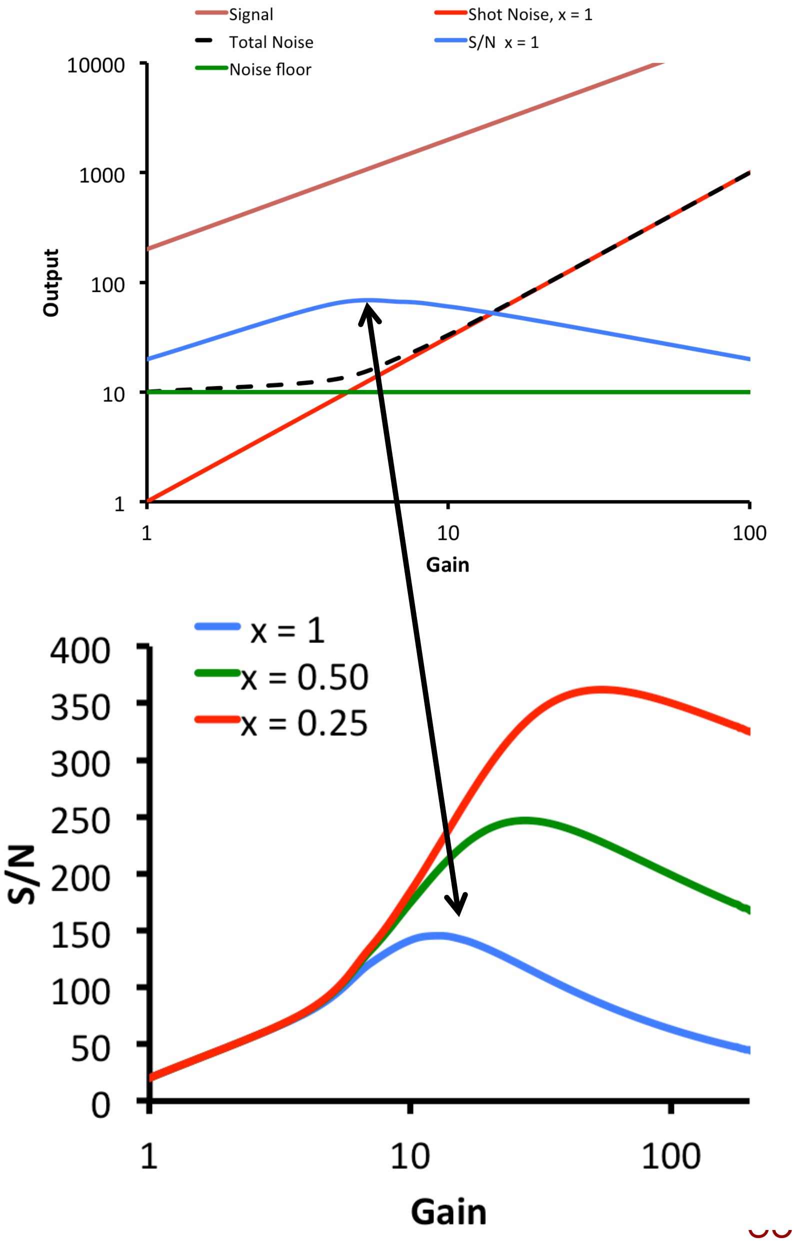
k = ratio h/e gain

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

UFSD Optimum S/N: numbers

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

➔There is an Optimum Gain value ➔

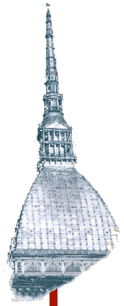


Let's consider the following situation:

- Signal = 20k e-
- Shaping time 1 ns
- Voltage Noise = 1k e-
- Shot Noise (G = 1) = 10 e- I
- 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



Measurements and future plans

UFSD laboratory measurements

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

UFSD Testbeam measurements

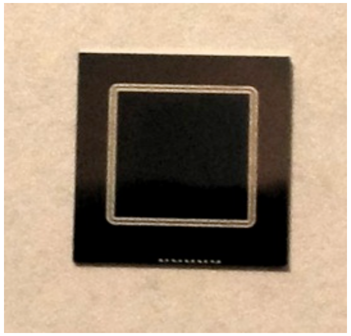
- Landau shape at different gains
- Time resolution measured with MIPs and lasers

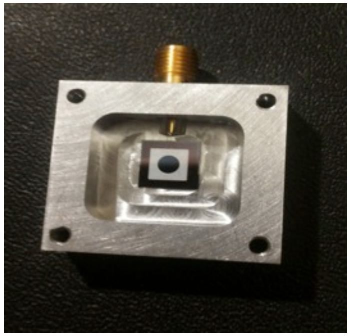
LGAD Sensors productions

CNM first production:

300 micron thick,

➔ several single pad geometries and gains



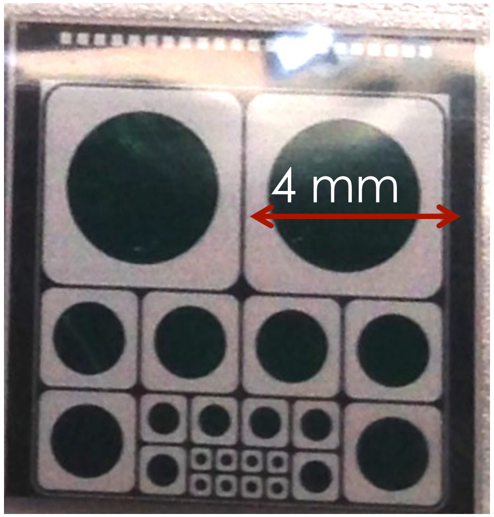


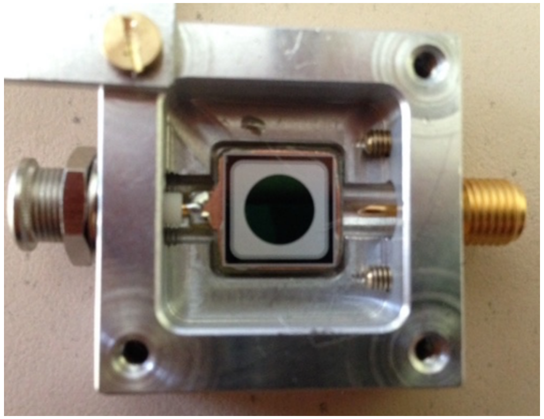
CNM second production:

300 micron thick,

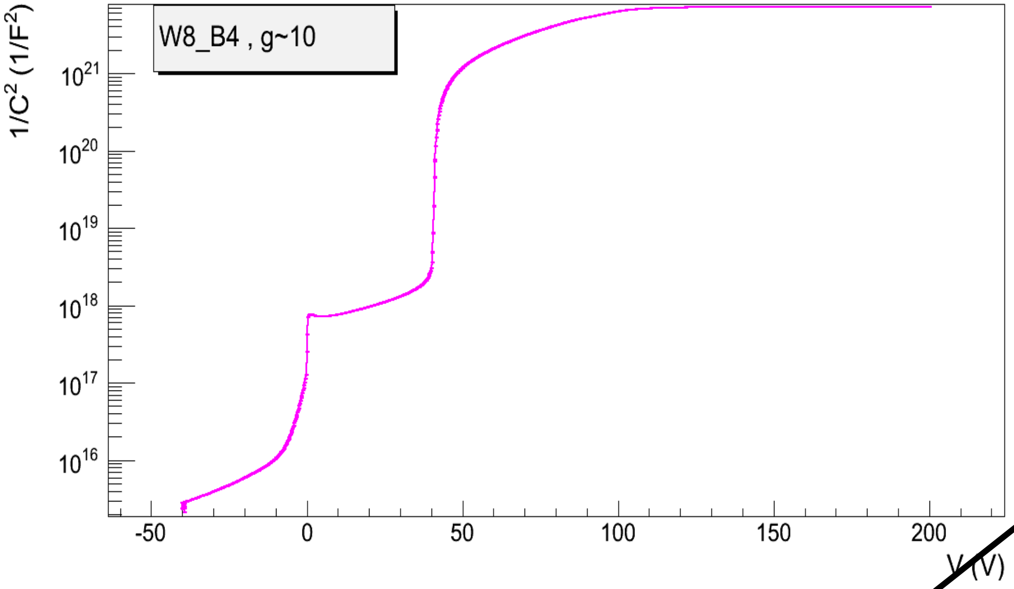
➔ several single pad geometries and gains

➔ Multipad sensors

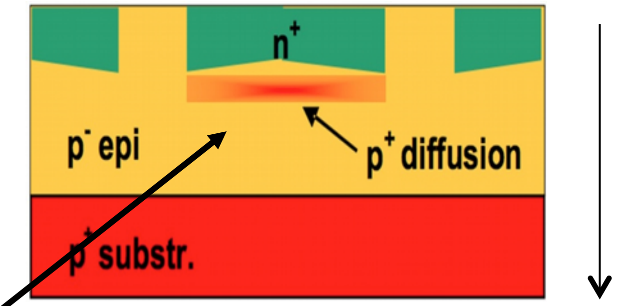




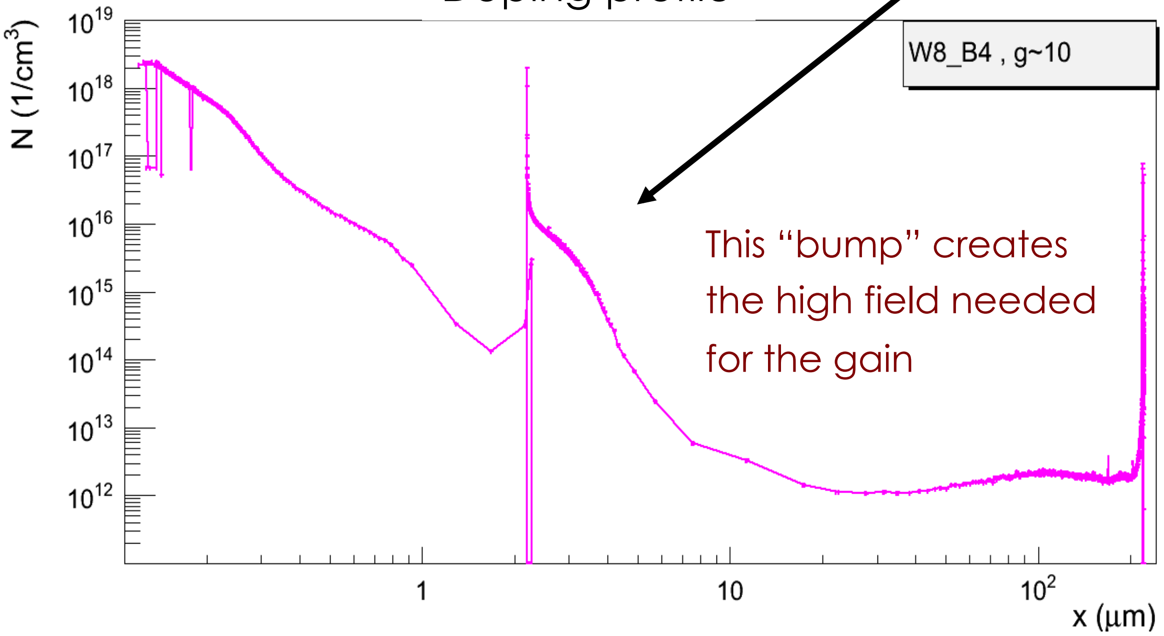
Doping profile from CV measurement - II



Gain sensor

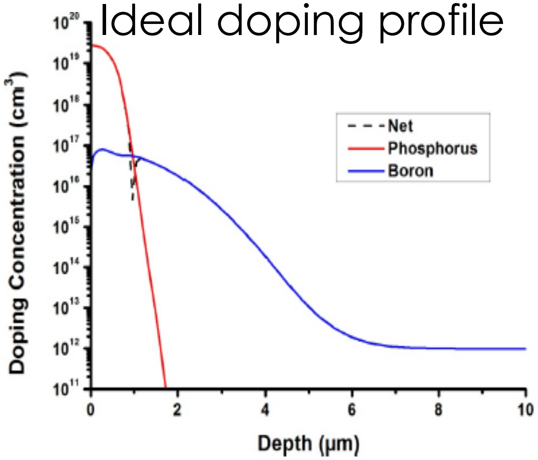


Doping profile



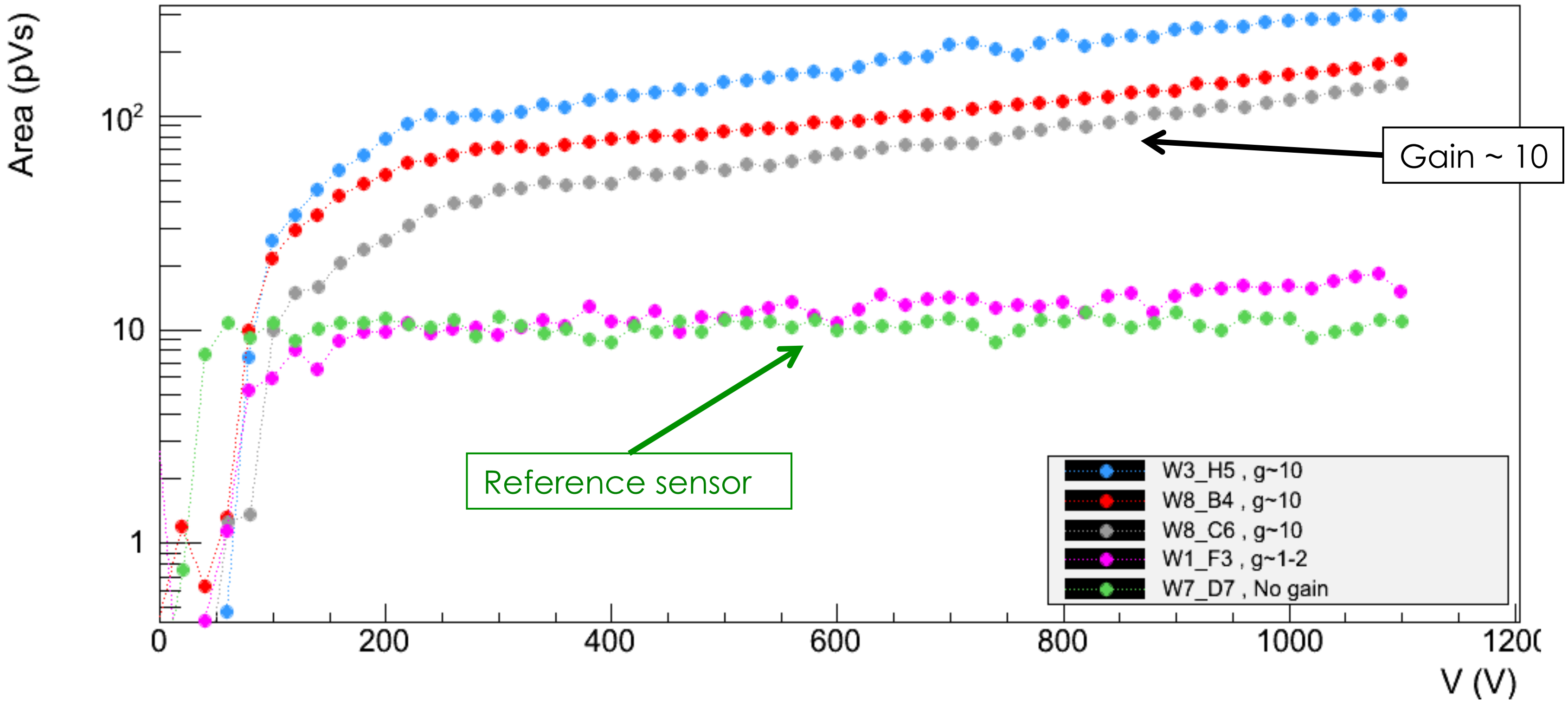
This “bump” creates the high field needed for the gain

Ideal doping profile



Signal amplitude

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

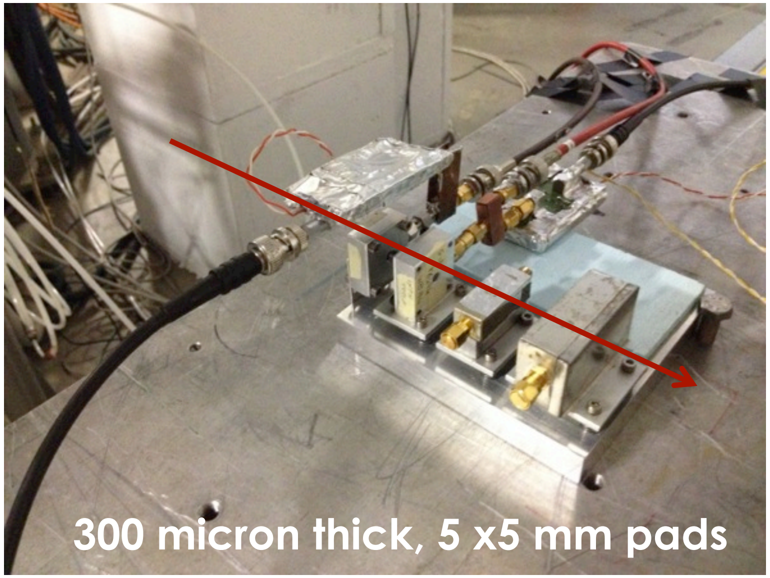


Gain ~ 10

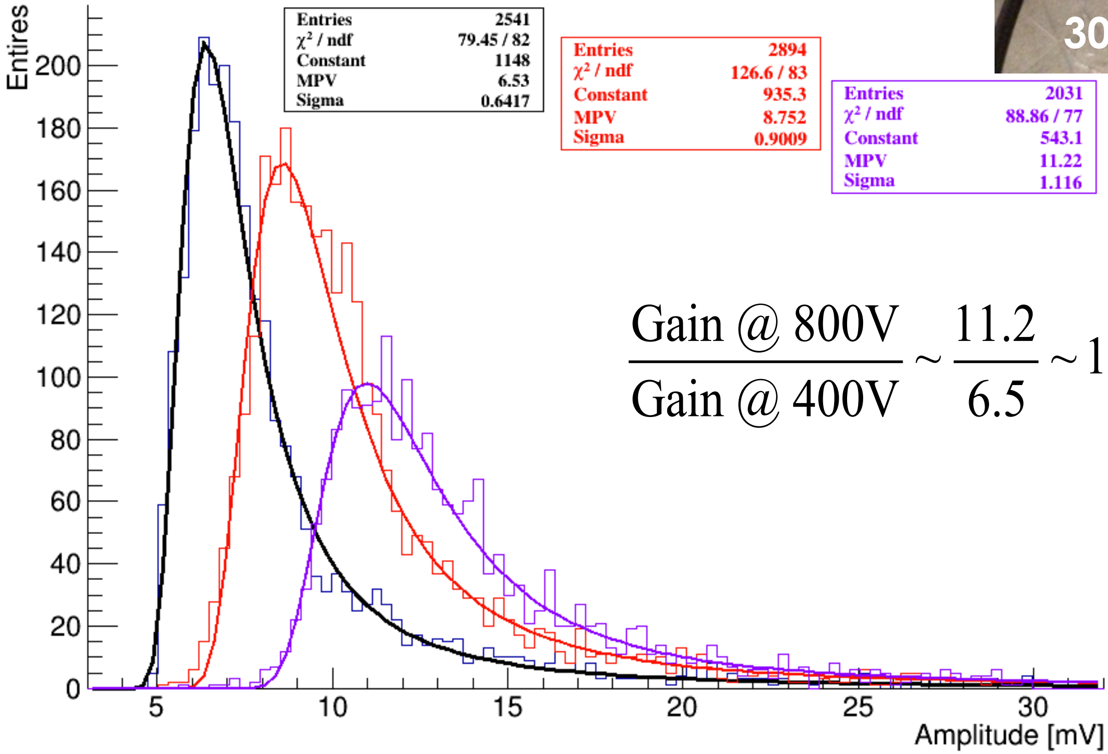
Reference sensor

Testbeam Measurements on CNM LGAD

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


300 micron thick, 5 x5 mm pads

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



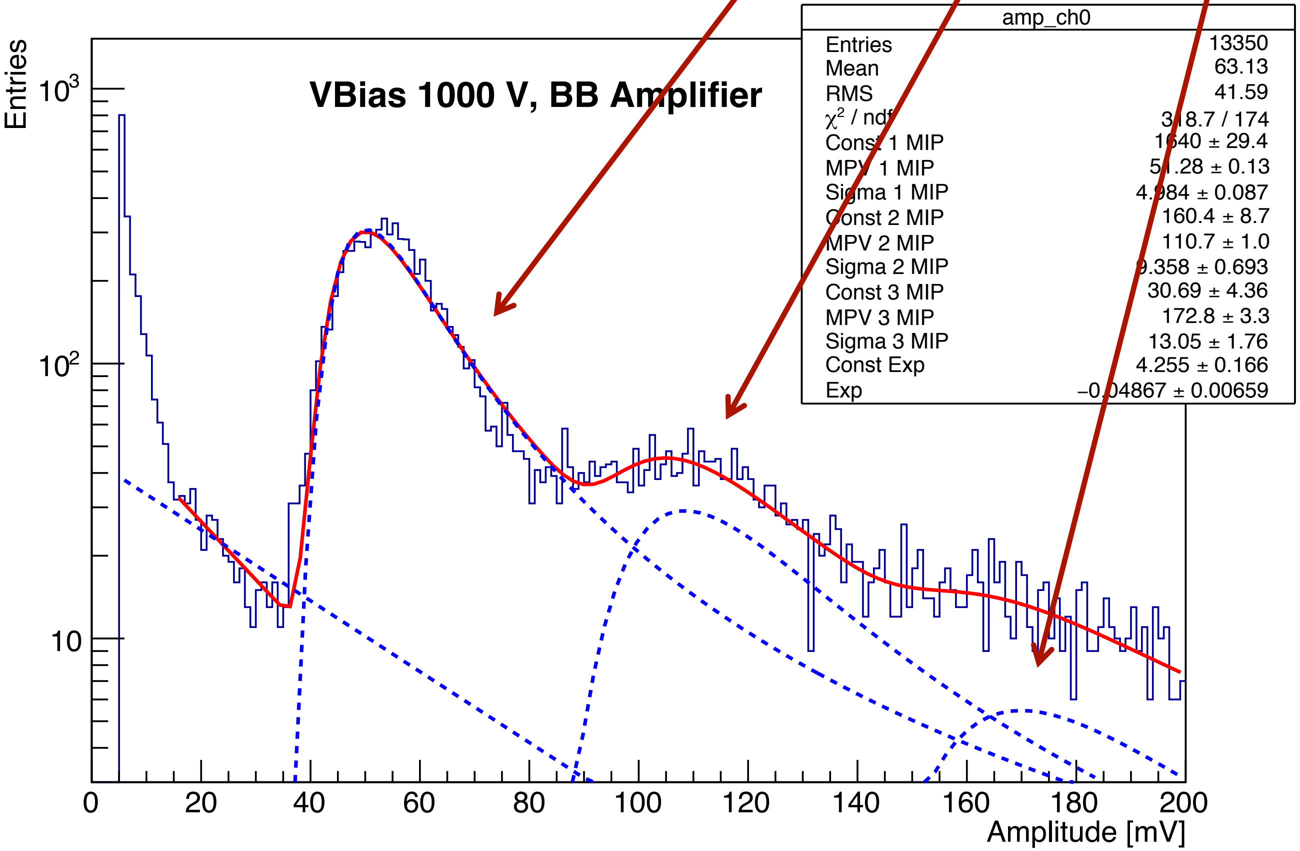
$$\frac{\text{Gain @ 800V}}{\text{Gain @ 400V}} \sim \frac{11.2}{6.5} \sim 1.7$$

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

100 GeV pion Testbeam with CNM LGAD

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

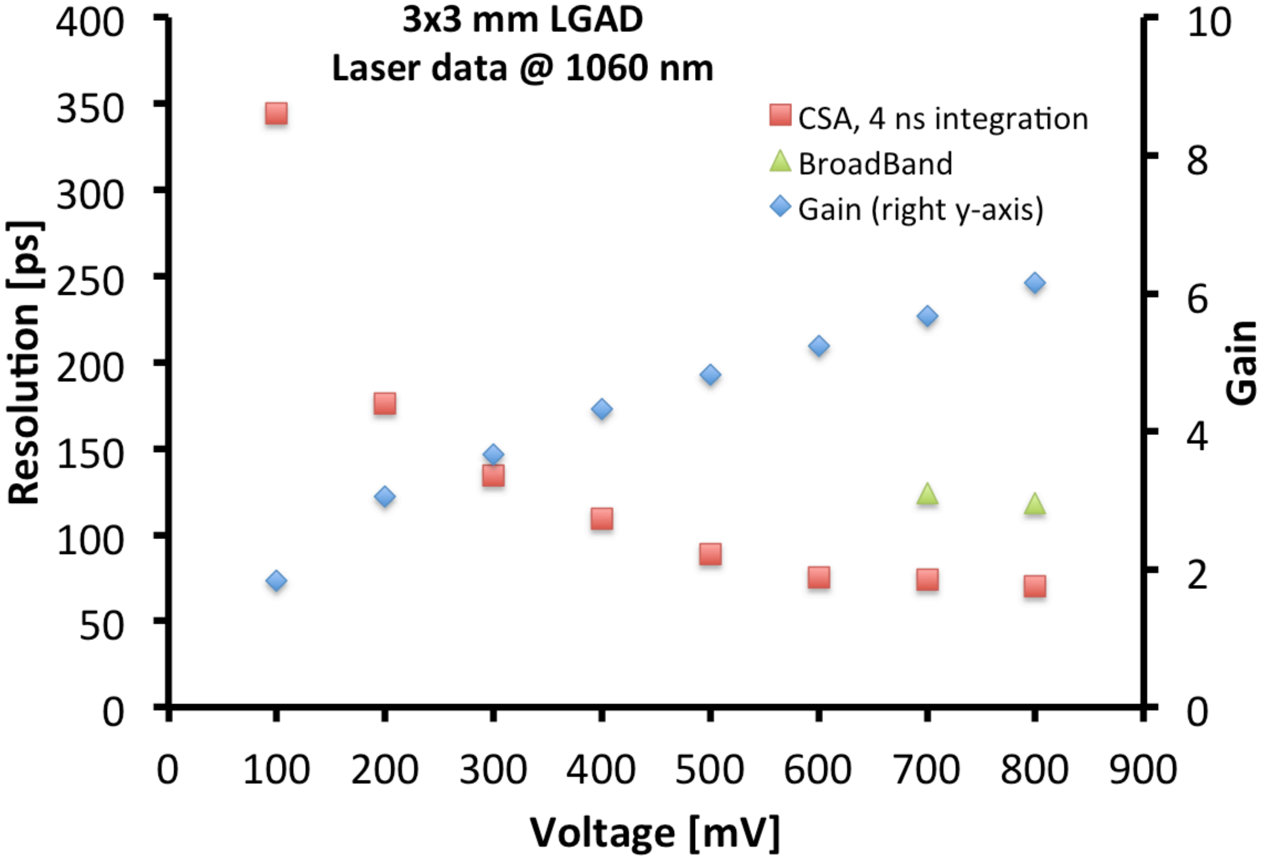
Very linear behavior of UFSD with increasing charge



amp_ch0	
Entries	13350
Mean	63.13
RMS	41.59
χ^2 / ndf	318.7 / 174
Const 1 MIP	1640 ± 29.4
MPV 1 MIP	51.28 ± 0.13
Sigma 1 MIP	4.984 ± 0.087
Const 2 MIP	160.4 ± 8.7
MPV 2 MIP	110.7 ± 1.0
Sigma 2 MIP	9.358 ± 0.693
Const 3 MIP	30.69 ± 4.36
MPV 3 MIP	172.8 ± 3.3
Sigma 3 MIP	13.05 ± 1.76
Const Exp	4.255 ± 0.166
Exp	−0.04867 ± 0.00659

Time resolution vs gain

(laser pulses)

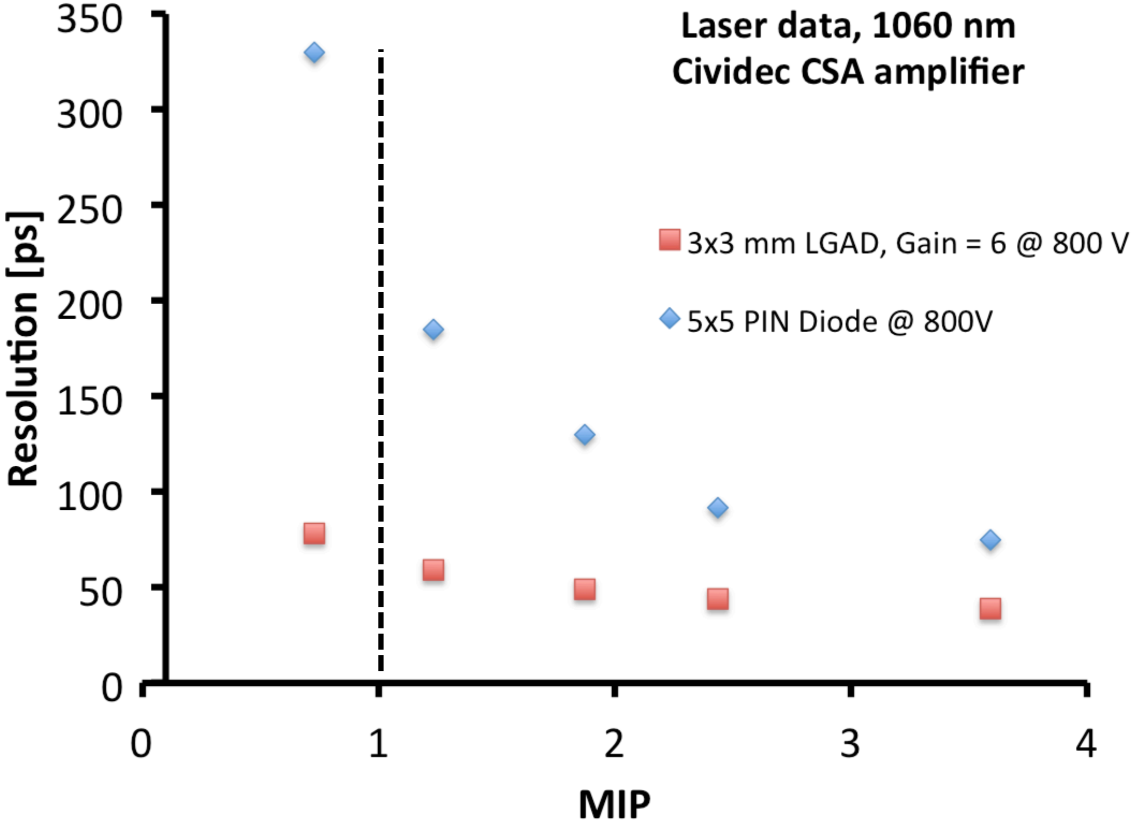


Second round of prototypes:

achieved ~ 70 ps resolution with laser pulses

Time resolution of UFSD and PIN diodes

(laser pulses)

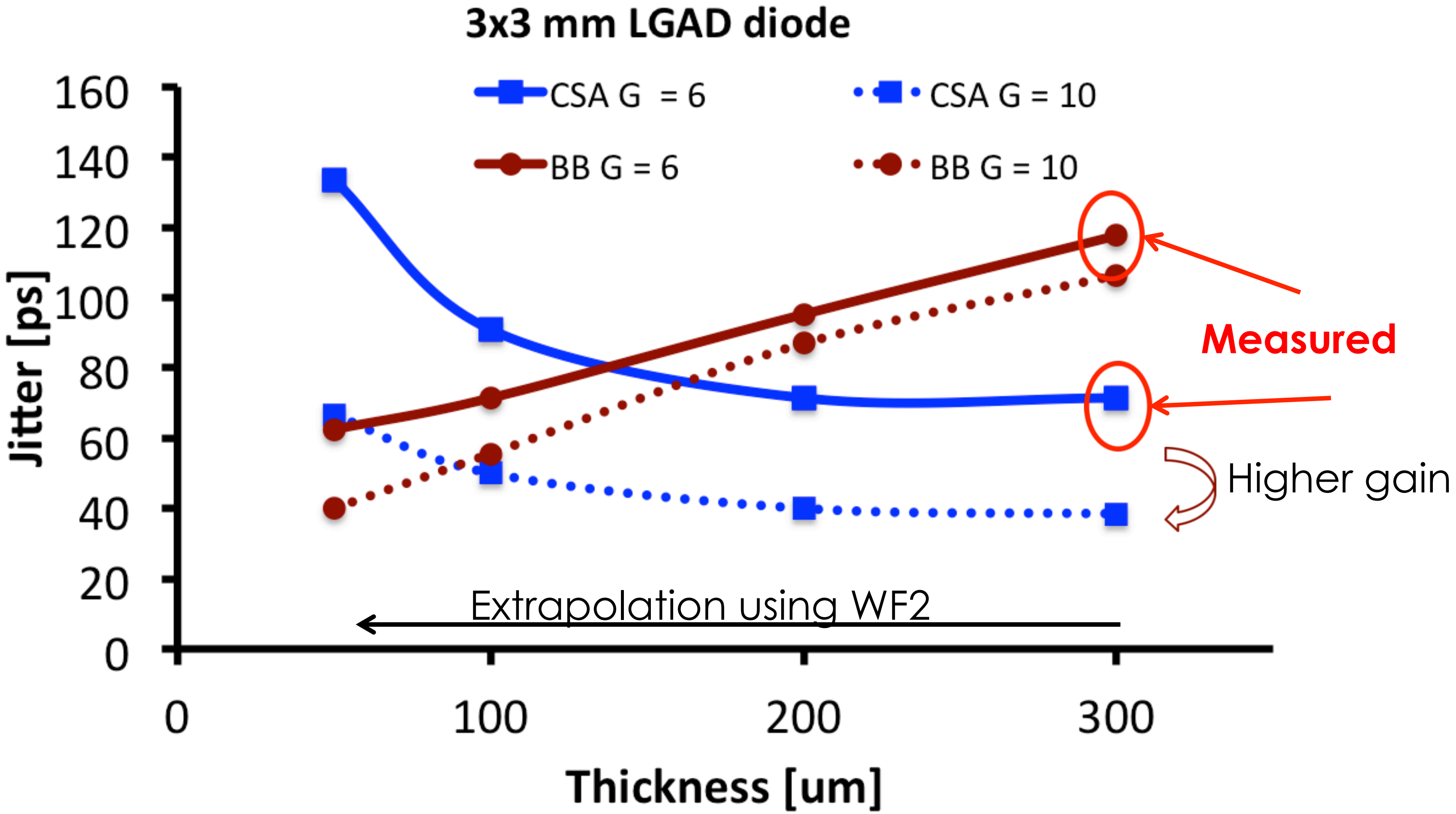


A UFSD with gain ~ 6 shows a factor of 3 better time resolution than PIN diodes: 70 ps vs 200 ps

Choice of preamplifiers

CSA = Charge Sensitive Amplifier, 4 ns shaping (Cividec – CSA)

BB = 2 GHz Broadband Amplifier (Cividec – BB)

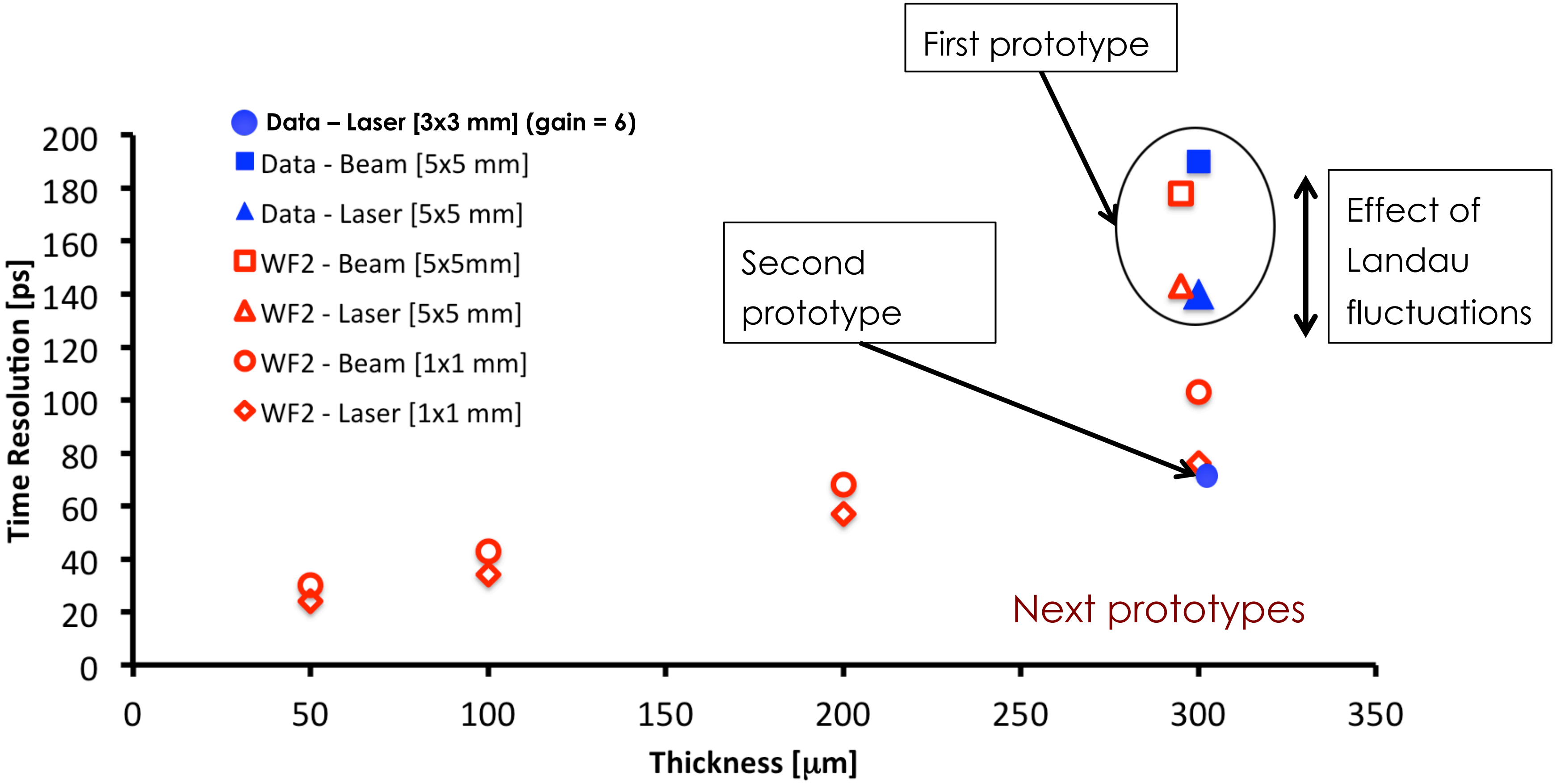


Best results for shaping ~ collection time

Thin detectors require almost no integration

Extrapolation to thinner sensors

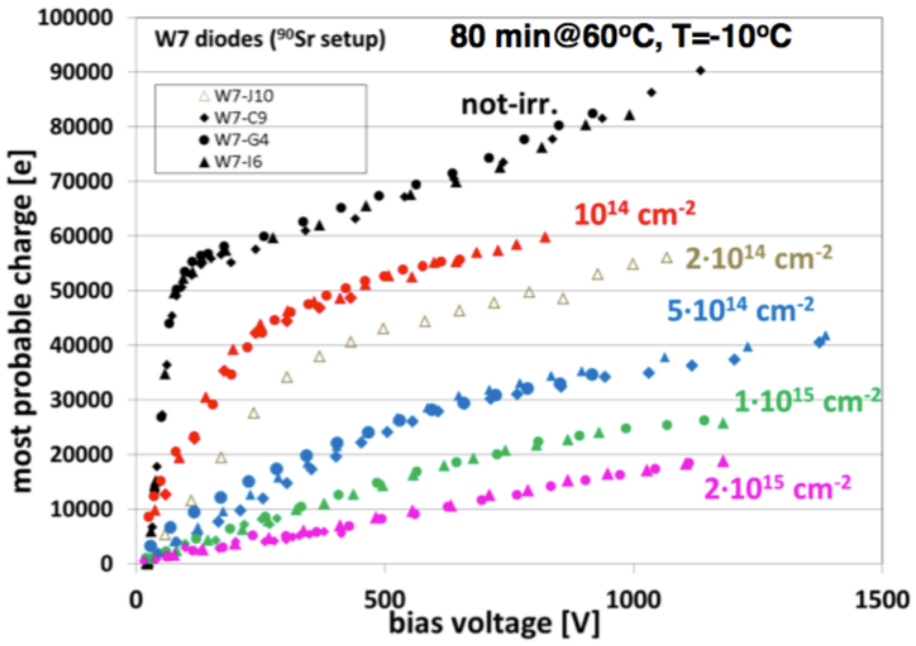
Assuming the same electronics, and 1 mm^2 LGAD pad with gain 10, we can predict the timing capabilities of the next sets of sensors.



Irradiation tests

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

➔ Due to boron disappearance

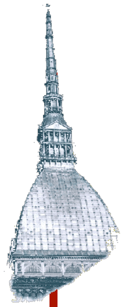


What-to-do next:

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

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

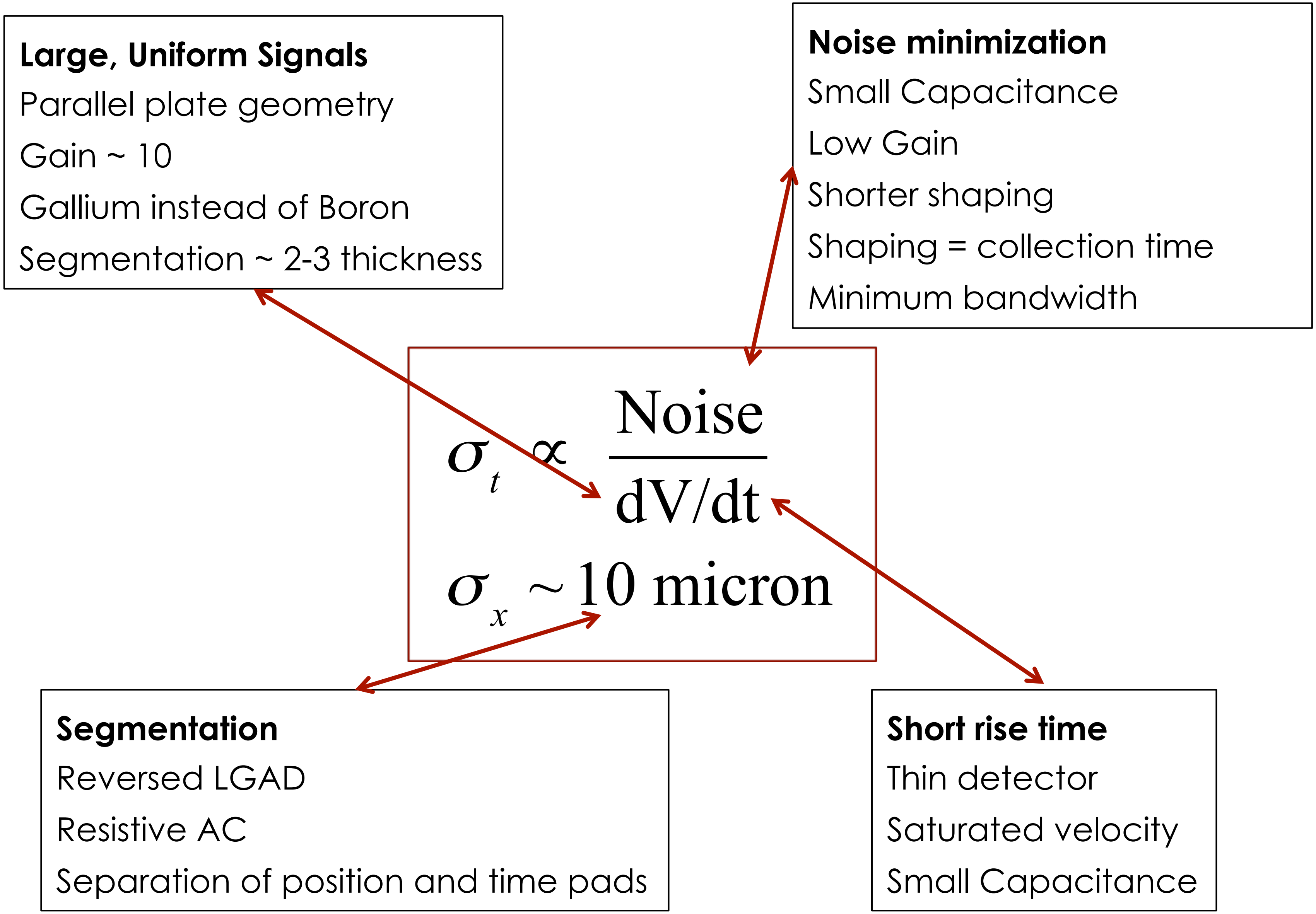
3) Design the UFSD to have a gain higher than we need, ~ 30 at 500 V.
   - We use UFSD at gain 10-15, at 200 Volt
   - When radiation damage lowers the gain, we increase Vbias to compensate



Next Steps

1. Wafer Productions
   2-300 micron thick sensors by **Summer-2015**
   100 and 50 micron thick sensors by **Fall 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 calorimeter timing applications
7. New testbeams coming this summer

Summary



Large, Uniform Signals
Parallel plate geometry
Gain ~ 10
Gallium instead of Boron
Segmentation ~ 2-3 thickness

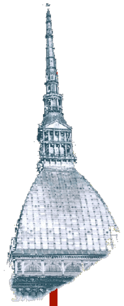
Noise minimization
Small Capacitance
Low Gain
Shorter shaping
Shaping = collection time
Minimum bandwidth

$$\sigma_t \propto \frac{\text{Noise}}{\text{dV/dt}}$$

$$\sigma_x \sim 10 \text{ micron}$$

Segmentation
Reversed LGAD
Resistive AC
Separation of position and time pads

Short rise time
Thin detector
Saturated velocity
Small Capacitance



Additional references

Full documentation at: www.cern.ch/nicolo

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

9th, 10th Trento Workshop, Trento, Feb 2015.

Papers:

Nicolo Cartiglia et al, Design Optimization of Ultra-Fast Silicon Detector NIMA (2015), http://dx.doi.org/10.1016/j. nima.2015.04.025i

F. Cenna et al, Weightfield2: A fast simulator for silicon and diamond solid state detector, NIMA (2015) http://dx.doi.org/10.1016/j.nima.2015.04.015 (pdf)

Gian-Franco Dalla Betta et al, Design and TCAD simulation of double-sided pixelated low gain avalanche detectors, NIMA doi:10.1016/j.nima.2015.03.039 (pdf)

N. Cartiglia, et al., Performance of Ultra-Fast Silicon Detectors, JINST 9 (2014) C02001. arXiv:1312.1080, doi:10.1088/1748-0221/9/02/C02001

H.-W. Sadrozinski et al., Sensors for ultra-fast silicon detectors, NIM. A765 (2014) 7-11. doi: 10.1016/j.nima.2014.05.006

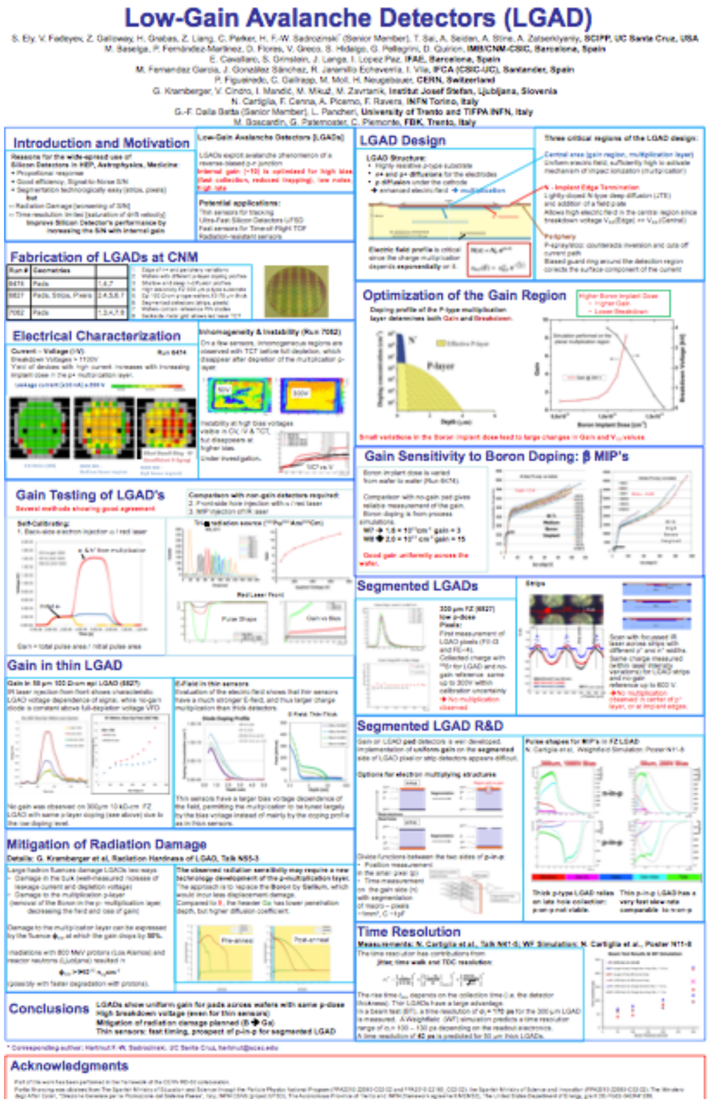
H.-W. Sadrozinski, et al., Ultra-fast silicon detectors, NIM A730 (2013) 226-231. doi: 10.1016/j.nima.2013.06.033 9

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. Galloway, H. Grabas, Z. Liang, C. Parker, H. F.-W. Sadrozinski* (Senior Member), T. Sai, A. Seiden, A. Stine, A. Zatserklyaniy, **SCIPP, UC Santa Cruz, USA**
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G. Kramberger, V. Cindro, I. Mandić, M. Mikuž, M. Zavrtanik, **Institut Josef Stefan, Ljubljana, Slovenia**
N. Cartiglia, F. Cenna, A. Picerno, F. Ravera, **INFN Torino, Italy**
G.-F. Dalla Betta (Senior Member), L. Pancheri, **University of Trento and TIFPA INFN, Italy**
M. Boscardin, G. Paternoster, C. Piemonte, **FBK, Trento, Italy**

Introduction and Motivation

LGAD Design

Fabrication of LGADs at CNM

Electrical Characterization

Optimization of the Gain Region

Gain Sensitivity to Boron Doping: β MIP's

Gain Testing of LGAD's

Segmented LGADs

Gain in thin LGAD

Segmented LGAD R&D

Mitigation of Radiation Damage

Time Resolution

Conclusions

Acknowledgments

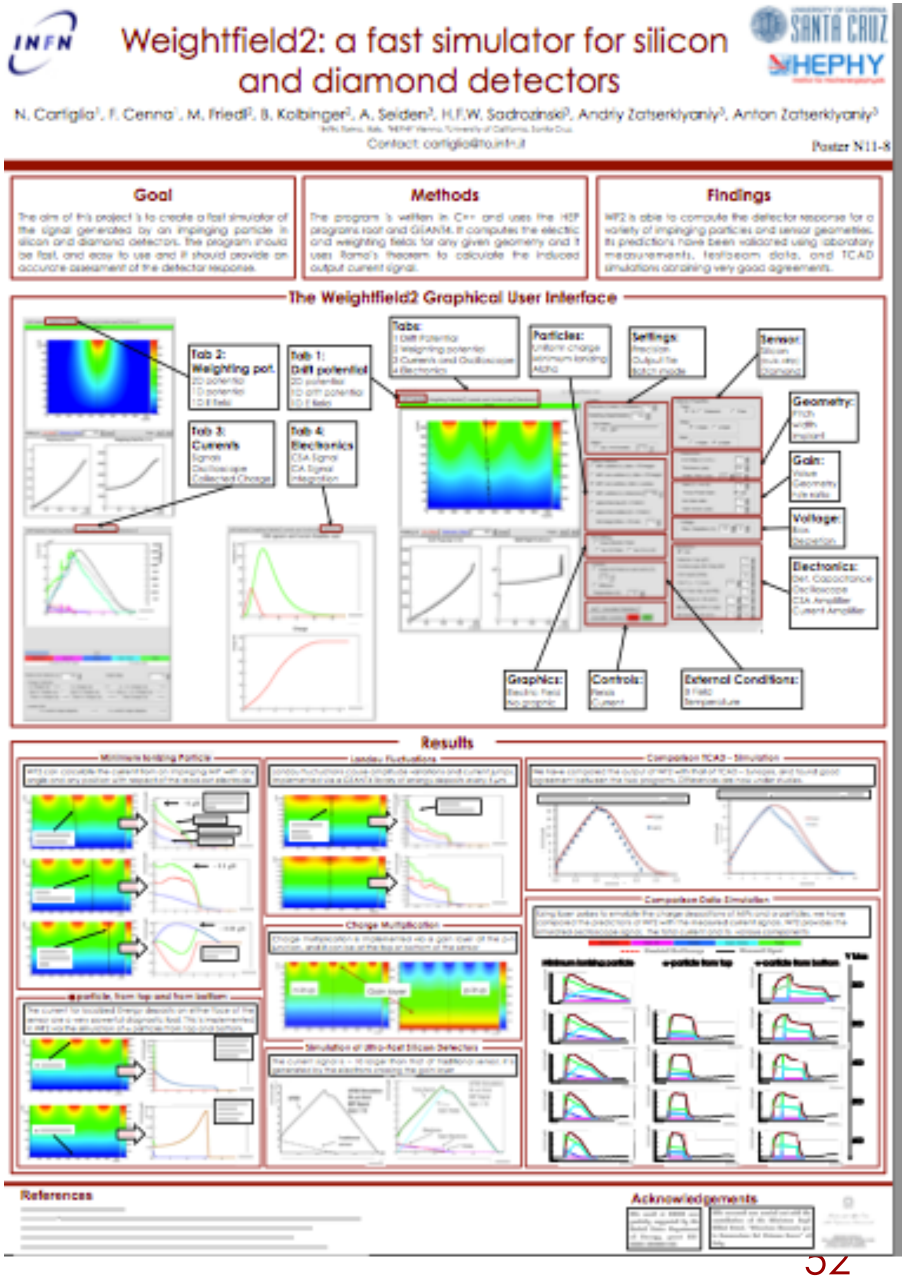
Poster Session IEEE N26-13

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. Cartiglia[1], F. Cenna[1], M. Friedl[2], B. Kolbinger[2], A. Seiden[3], H.F.W. Sadrozinski[3], Andriy Zatserklyaniy[3], Anton Zatserklyaniy[3]

Contact: cartiglia@to.infn.it

Poster N11-8

Goal

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.

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 Ramo's theorem 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, testbeam data, and TCAD simulations obtaining very good agreements.

The Weightfield2 Graphical User Interface

Results

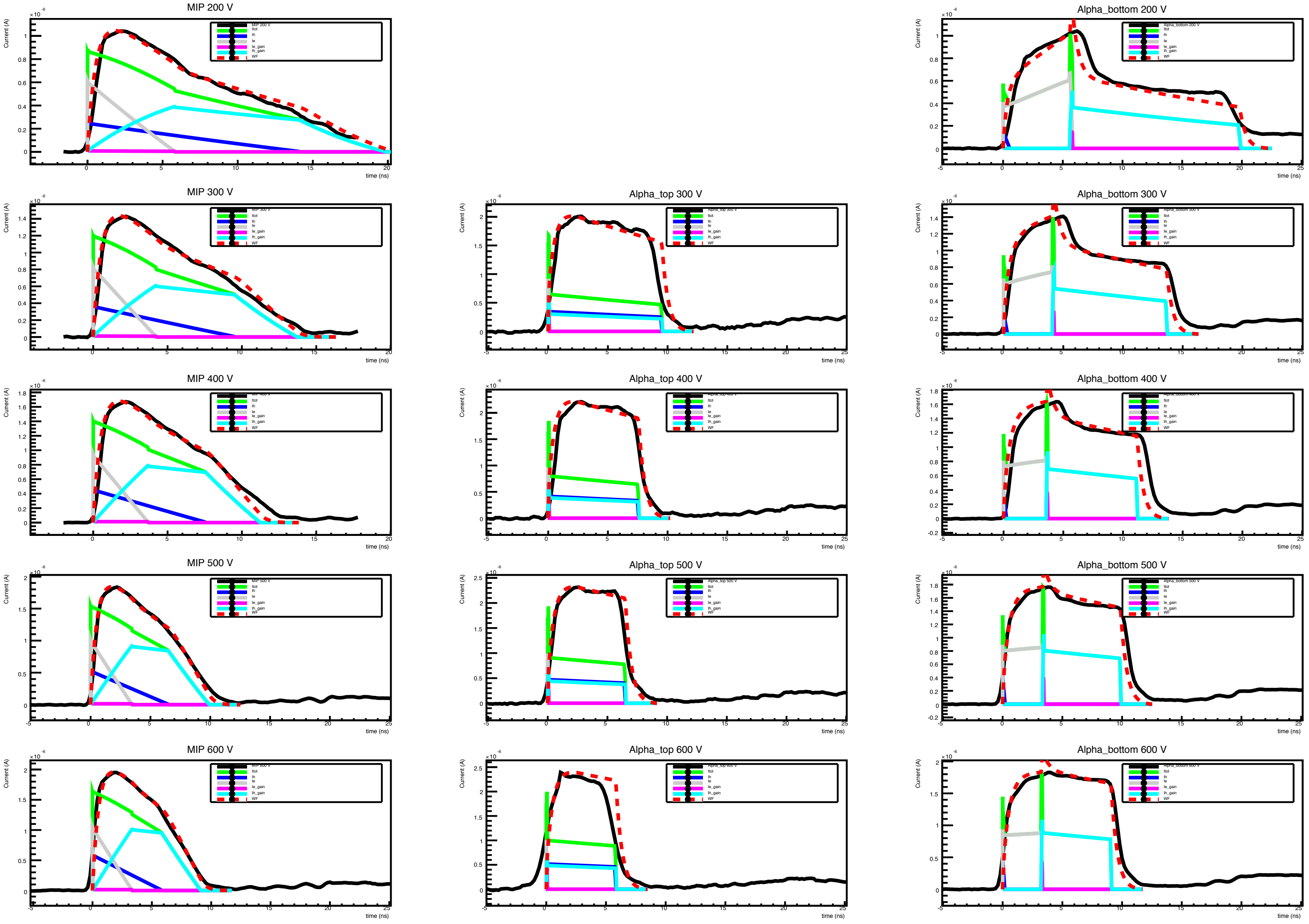
References

Acknowledgements

Poster Session IEEE N11-8

Comparison Data Simulation

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



200

300

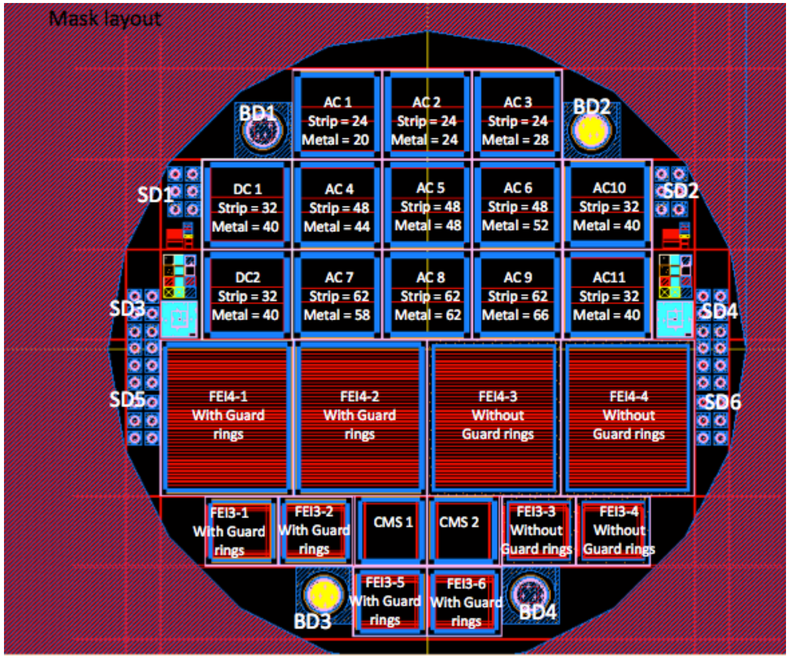
400

500

600

CNM LGADs mask

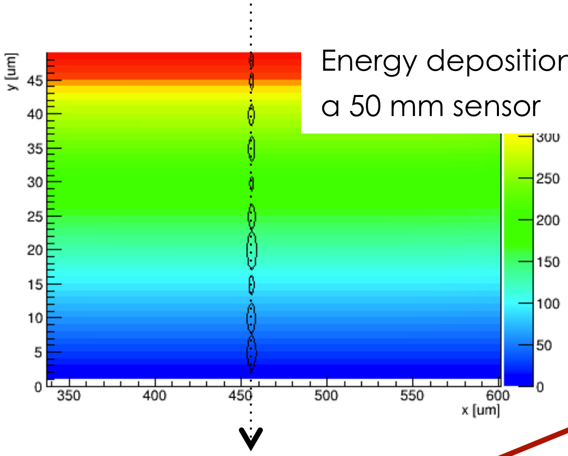
CNM, within the RD50 project, manufactured several runs of LGAD, trying a large variety of geometries and designs



This implant controls the value of the gain

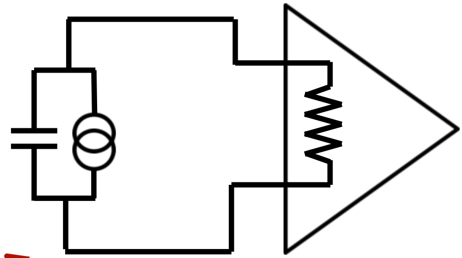
Wafer Number	P-layer Implant (E = 100 keV)	Substrate features	Expected Gain
1-2	1.6 × 10^{13} cm^{-2}	HRP 300 (FZ; ρ >10 KΩ ·cm; <100>; T = 300±10 μm)	2 – 3
3-4	2.0 × 10^{13} cm^{-2}	HRP 300 (FZ; ρ >10 KΩ ·cm; <100>; T = 300±10 μm)	8 – 10
5-6	2.2 × 10^{13} cm^{-2}	HRP 300 (FZ; ρ >10 KΩ ·cm; <100>; T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

Electronics: What is the best pre-amp choice?

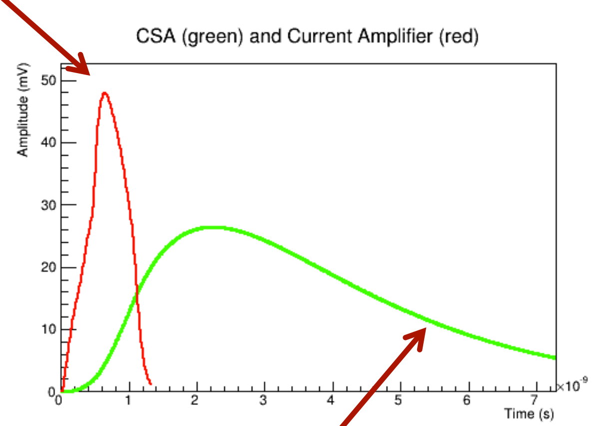


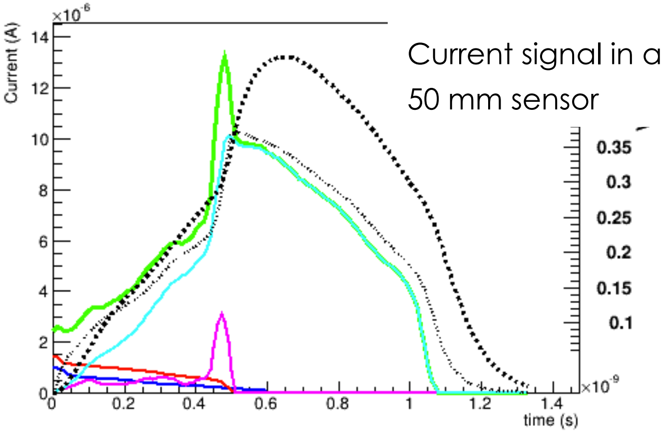
Energy deposition in a 50 mm sensor

Current Amplifier



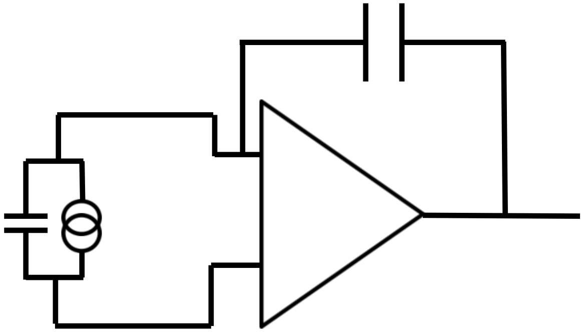
- Fast slew rate
- Higher noise
- Sensitive to Landau bumps





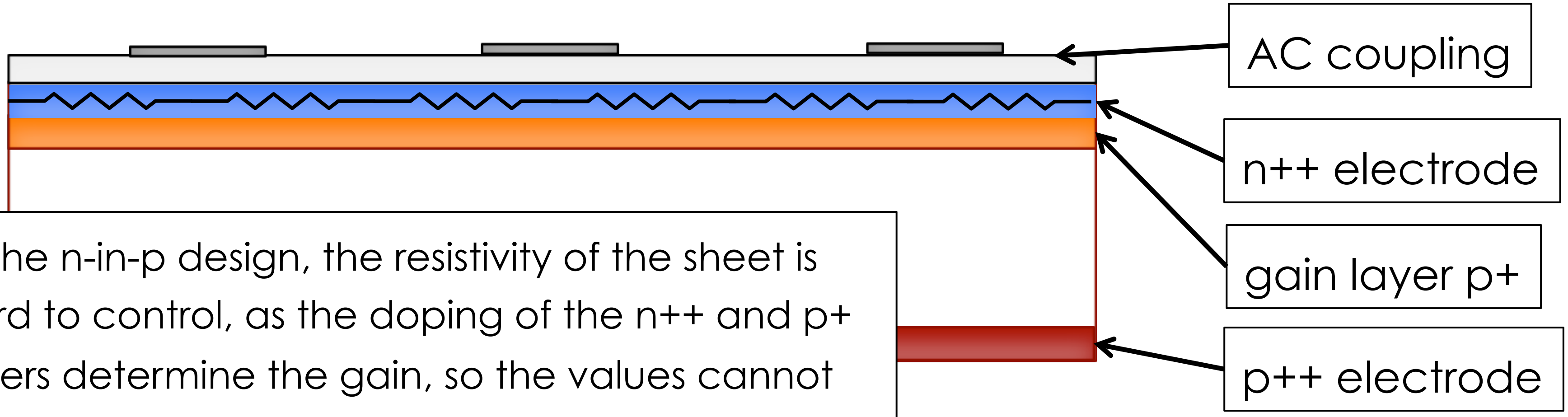
Current signal in a 50 mm sensor

Integrating Amplifier



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

Details of AC coupling - II



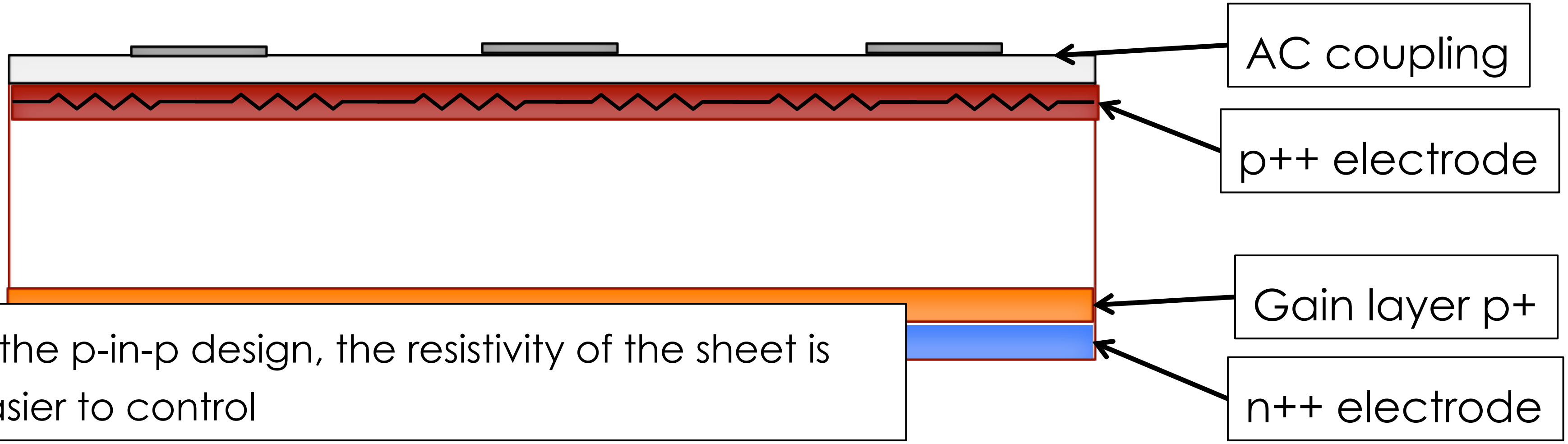
AC coupling

n++ electrode

gain layer p+

p++ electrode

In the n-in-p design, the resistivity of the sheet is hard to control, as the doping of the n++ and p+ layers determine the gain, so the values cannot be chosen as we like.



AC coupling

p++ electrode

Gain layer p+

n++ electrode

In the p-in-p design, the resistivity of the sheet is easier to control

Drift Velocity

$$i \propto q v E_w$$

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

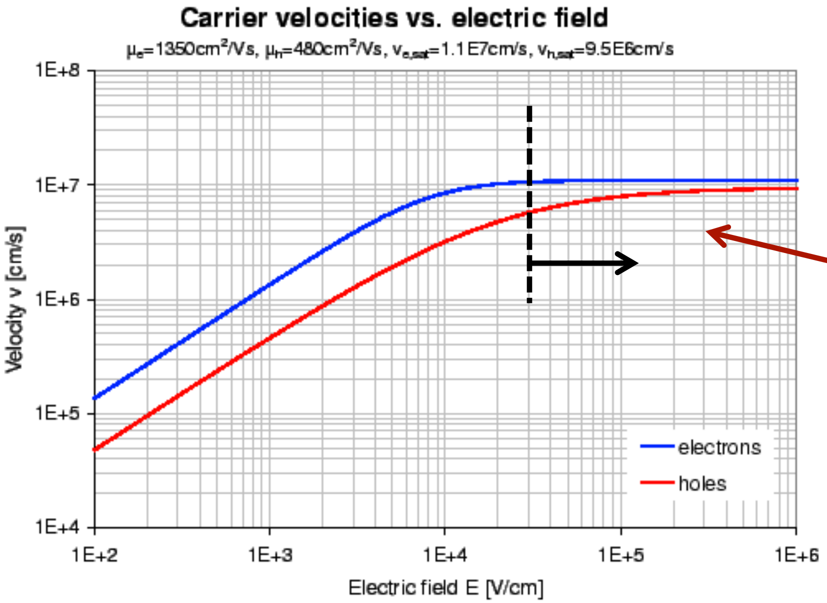


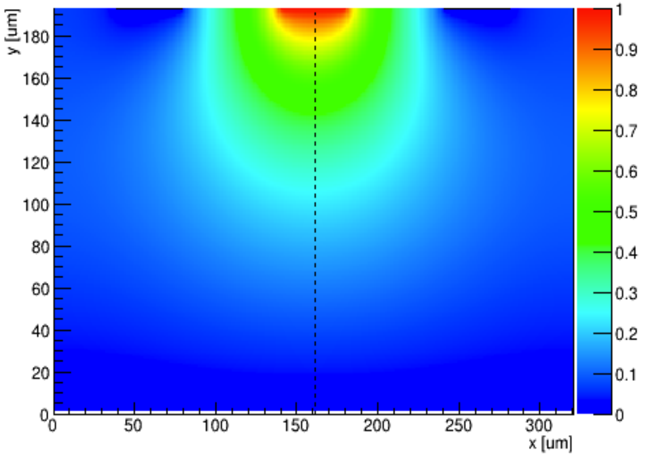
Figure: Electron and hole velocities vs. the electric field strength in silicon.

We want to operate in this regime

Weighting Field: coupling the charge to the electrode

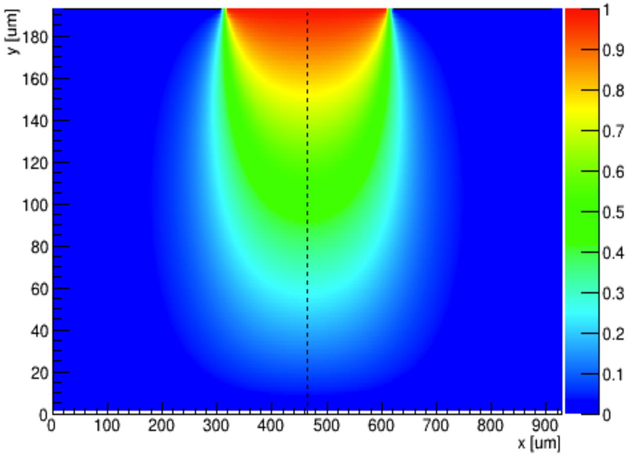
$$i \propto qv\boxed{E_w}$$

Strip: 100 μm pitch, 40 μm width



Bad: almost no coupling away from the electrode

Pixel: 300 μm pitch, 290 μm width



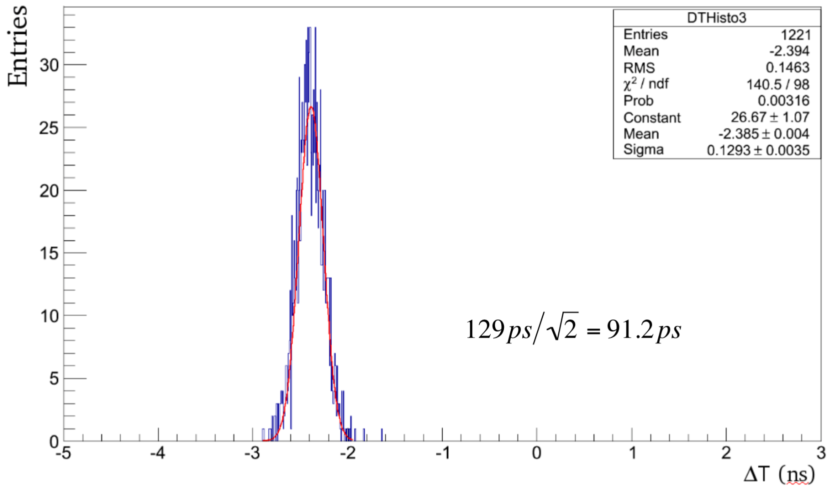
Good: strong coupling almost all the way to the backplane

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

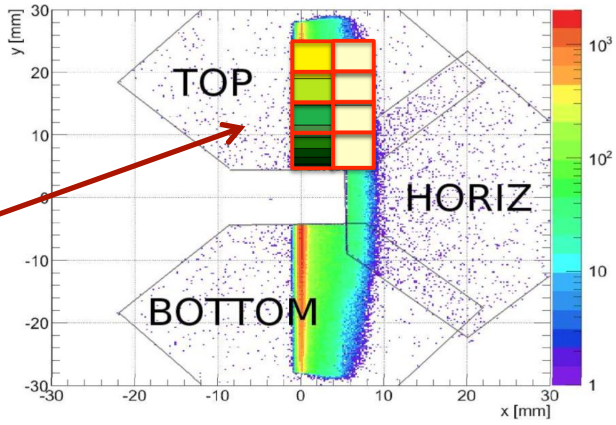
The Diamond approach - II

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

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



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



Noise for Gain = 1 and Gain = 10

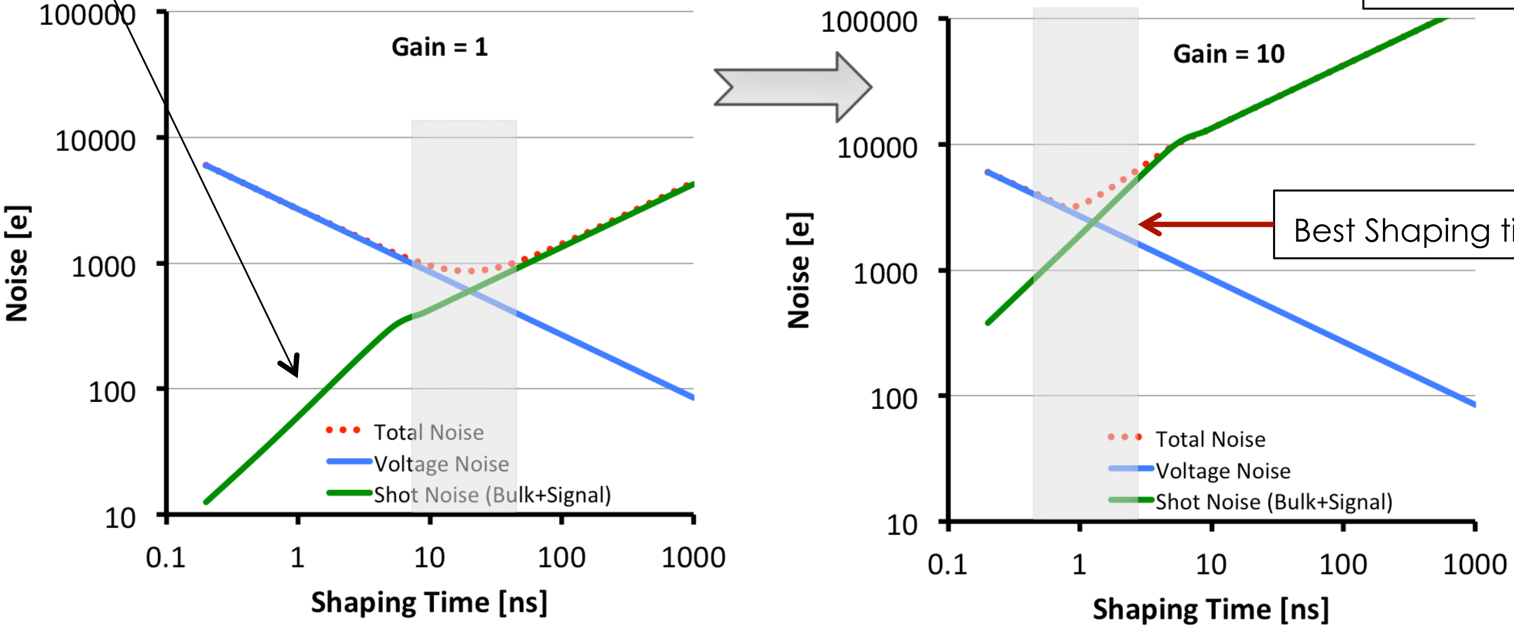
Let's use the following parameterization (Spieler, Semiconductor Detector, pag 35):

$$Q_n^2 = \underbrace{12\left[\frac{e^2}{nA*ns}\right](I_{Bulk}+I_{Signal})M^{2+x}\tau}_{\text{Shot Noise}} + \underbrace{3.6*10^4\left[\frac{e^2 ns}{pF^2 nV^2/Hz}\right]e^2_{N\_Amp}\frac{C^2_{Det}}{\tau}}_{\text{Voltage Noise}}$$

Current noise very important at small shaping time

I_{bulk} = 1nA
I_{signal} = 300 nA * 5 ns
x = 1
C_{det} = 1 pF

Effect of the gain

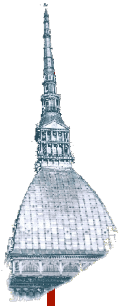


Best Shaping time

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

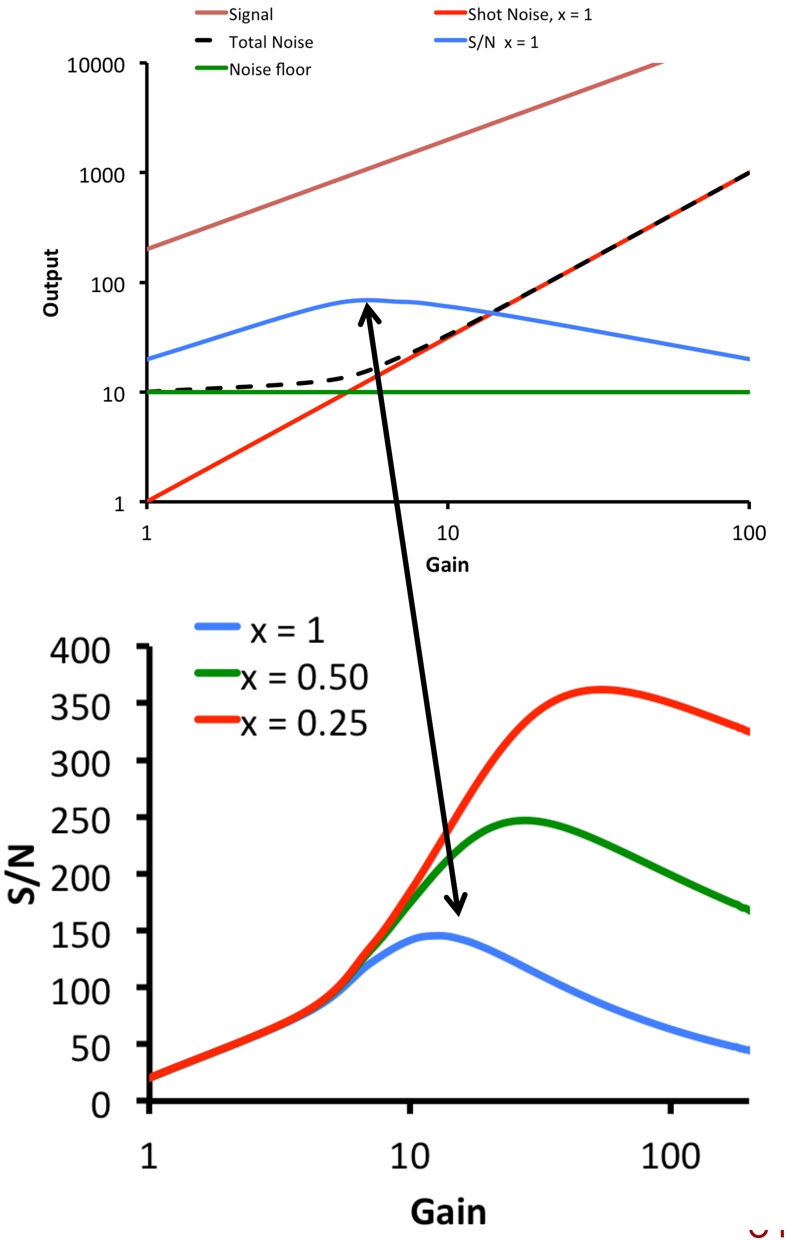
➔LGADs need very short shaping time 🡸



LGAD Optimum S/N: numbers

The noise increases faster than then 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- I
- 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

Large signals from thick detectors?

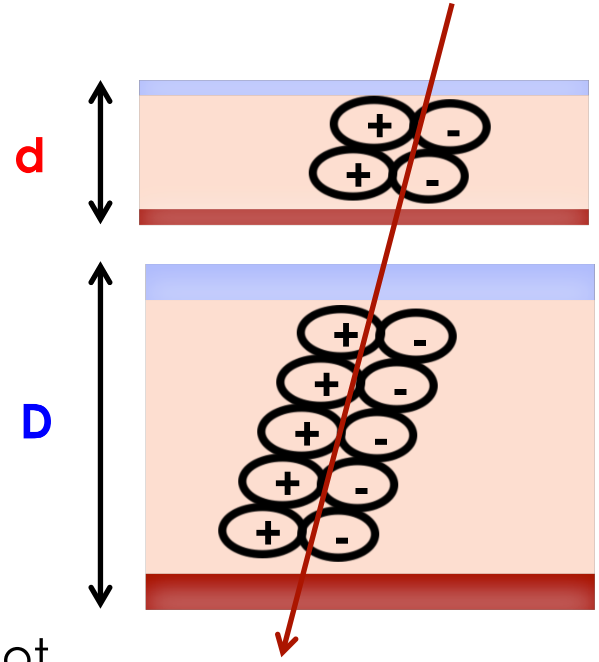
(Simplified model for pad detectors)

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

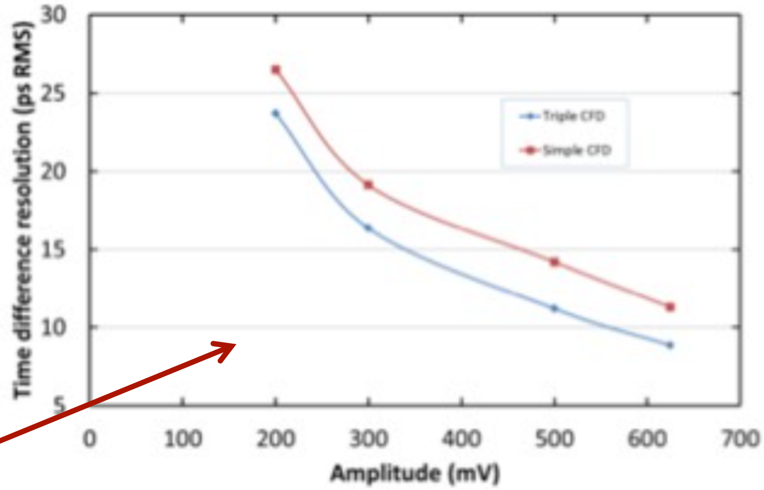
Weighting field

velocity

➔ Initial current = constant

The APD approach

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



So far they reported:

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

See:

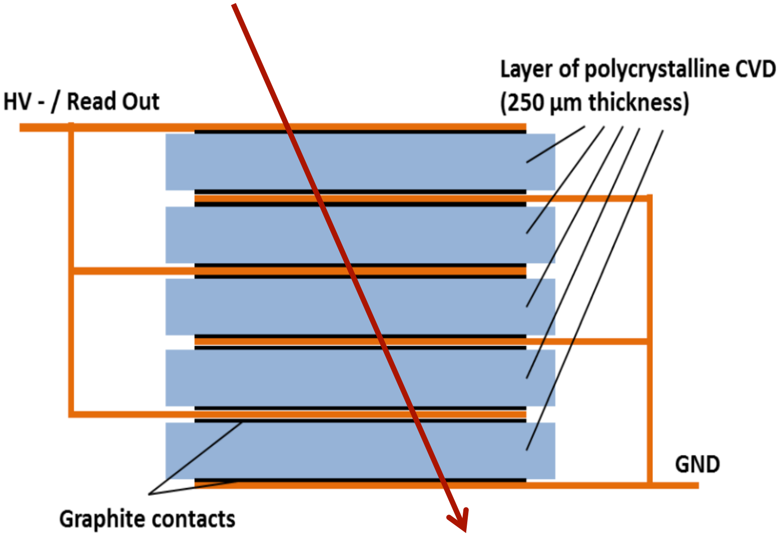
https://indico.cern.ch/event/363665/contribution/7/material/slides/0.pdf

The Diamond approach

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



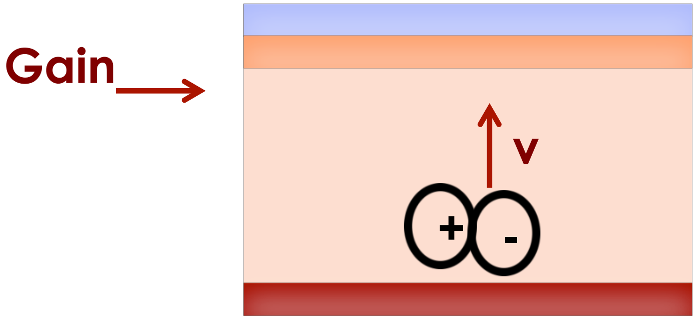
Best resolution: ~ 100 ps

2) Grazing

The particle crosses the diamond sensor along the longitudinal direction

Interplay of gain and detector thickness

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



Particles per micron

Gain

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

➔ **Constant rate of production**

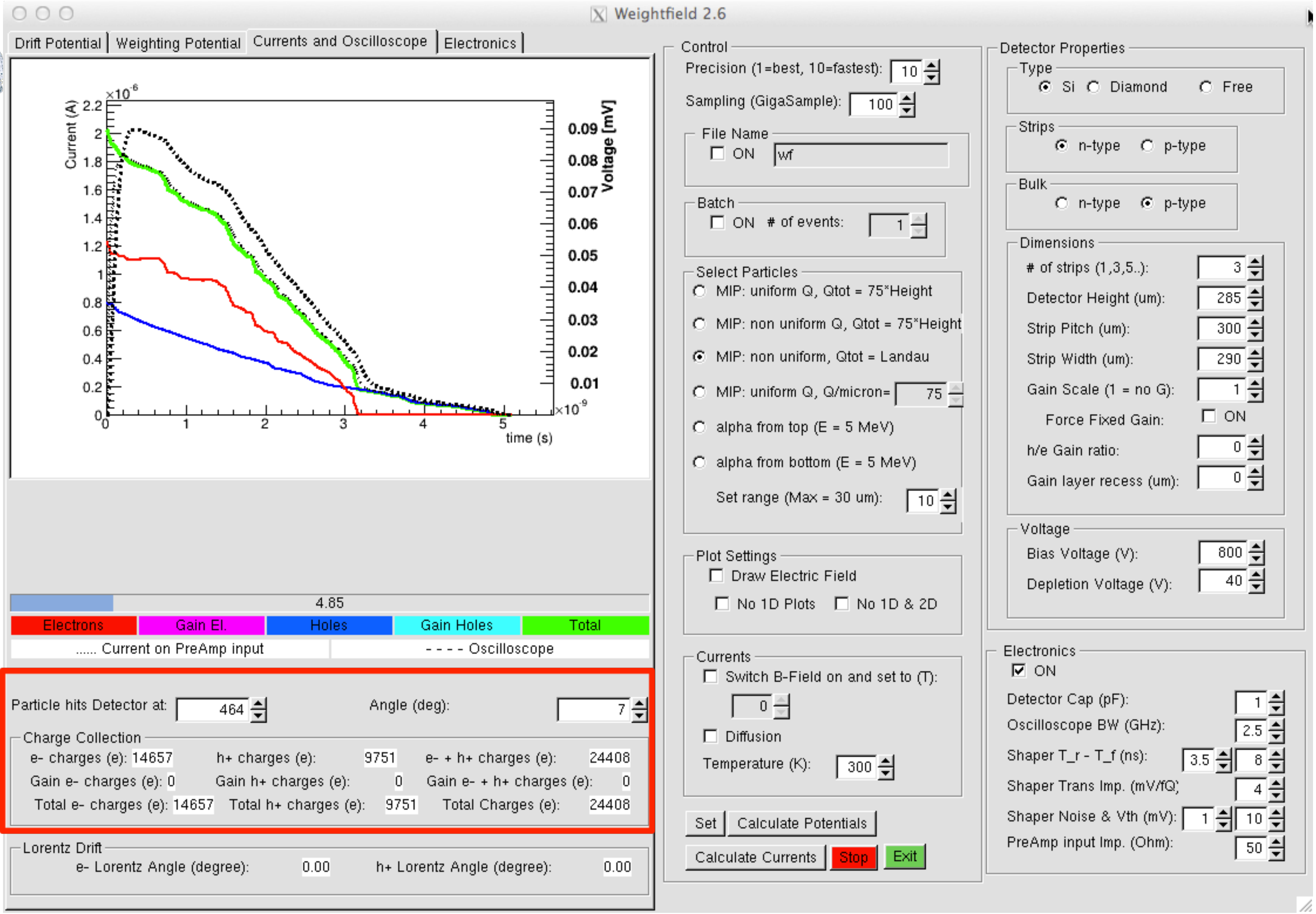
However the initial value of the **gain current depends on d**
(via the weighing field)

$$di_{gain} \propto dN_{Gain}qv_{sat}(\frac{k}{d})$$

➔ **Gain current ~ 1/d**

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

WeightField2: output currents



Particle hits Detector at: 464
Angle (deg): 7

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

Control

Precision (1=best, 10=fastest): 10
Sampling (GigaSample): 100

File Name
☐ ON wf

Batch
☐ ON # of events: 1

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= 75
○ alpha from top (E = 5 MeV)
○ alpha from bottom (E = 5 MeV)
Set range (Max = 30 um): 10

Plot Settings
☐ Draw Electric Field
☐ No 1D Plots ☐ No 1D & 2D

Currents
☐ Switch B-Field on and set to (T): 0
☐ Diffusion
Temperature (K): 300

Detector Properties

Type
● Si ○ Diamond ○ Free

Strips
● n-type ○ p-type

Bulk
○ n-type ● p-type

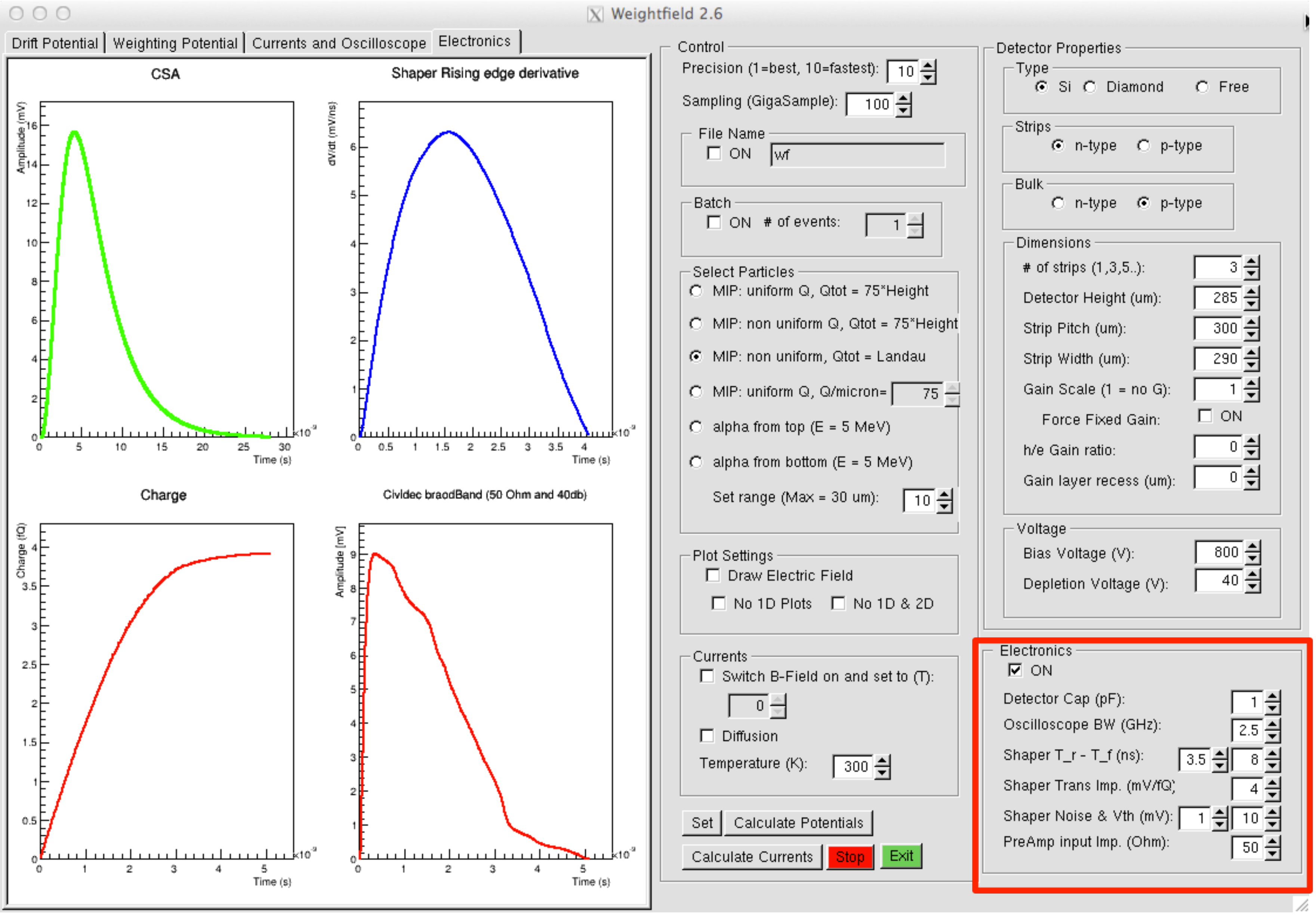
Dimensions
# of strips (1,3,5..): 3
Detector Height (um): 285
Strip Pitch (um): 300
Strip Width (um): 290
Gain Scale (1 = no G): 1
Force Fixed Gain: ☐ ON
h/e Gain ratio: 0
Gain layer recess (um): 0

Voltage
Bias Voltage (V): 800
Depletion Voltage (V): 40

Electronics

☑ ON
Detector Cap (pF): 1
Oscilloscope BW (GHz): 2.5
Shaper T_r - T_f (ns): 3.5 8
Shaper Trans Imp. (mV/fQ) 4
Shaper Noise & Vth (mV): 1 10
PreAmp input Imp. (Ohm): 50

WeightField2: response of the read-out electronics



Control
Precision (1=best, 10=fastest): 10
Sampling (GigaSample): 100

File Name
☐ ON wf

Batch
☐ ON # of events: 1

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= 75
○ alpha from top (E = 5 MeV)
○ alpha from bottom (E = 5 MeV)
Set range (Max = 30 um): 10

Plot Settings
☐ Draw Electric Field
☐ No 1D Plots ☐ No 1D & 2D

Currents
☐ Switch B-Field on and set to (T): 0
☐ Diffusion
Temperature (K): 300

Detector Properties
Type
● Si ○ Diamond ○ Free

Strips
● n-type ○ p-type

Bulk
○ n-type ● p-type

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

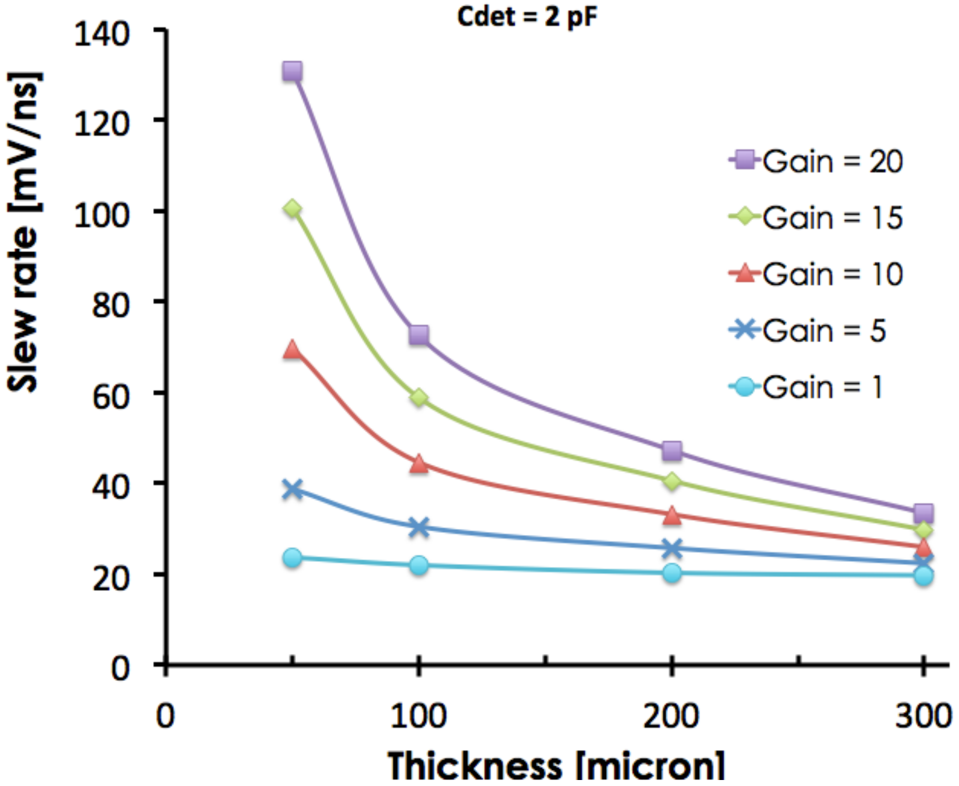
Voltage
Bias Voltage (V): 800
Depletion Voltage (V): 40

Electronics
☑ ON
Detector Cap (pF): 1
Oscilloscope BW (GHz): 2.5
Shaper T_r - T_f (ns): 3.5 8
Shaper Trans Imp. (mV/fQ) 4
Shaper Noise & Vth (mV): 1 10
PreAmp input Imp. (Ohm): 50

Gain current vs Initial current

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

!!!



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

Full simulation

(assuming 2 pF detector capacitance)

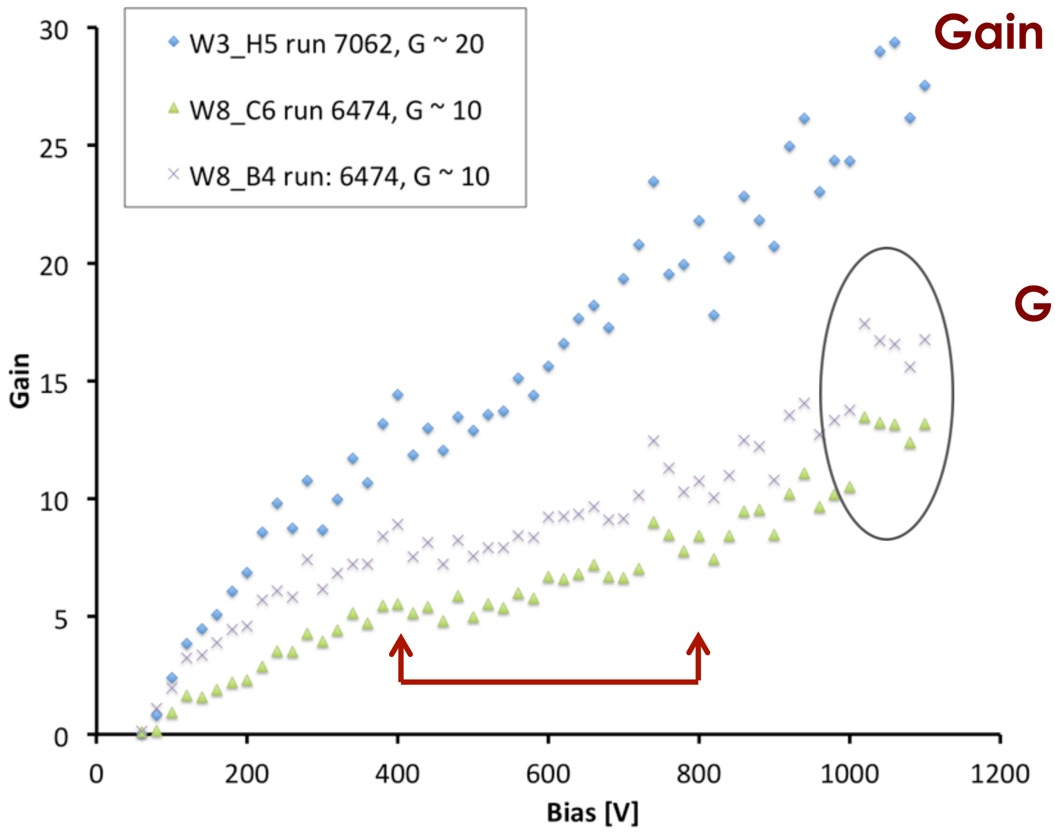
Significant improvements in time resolution require thin detectors

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!)

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



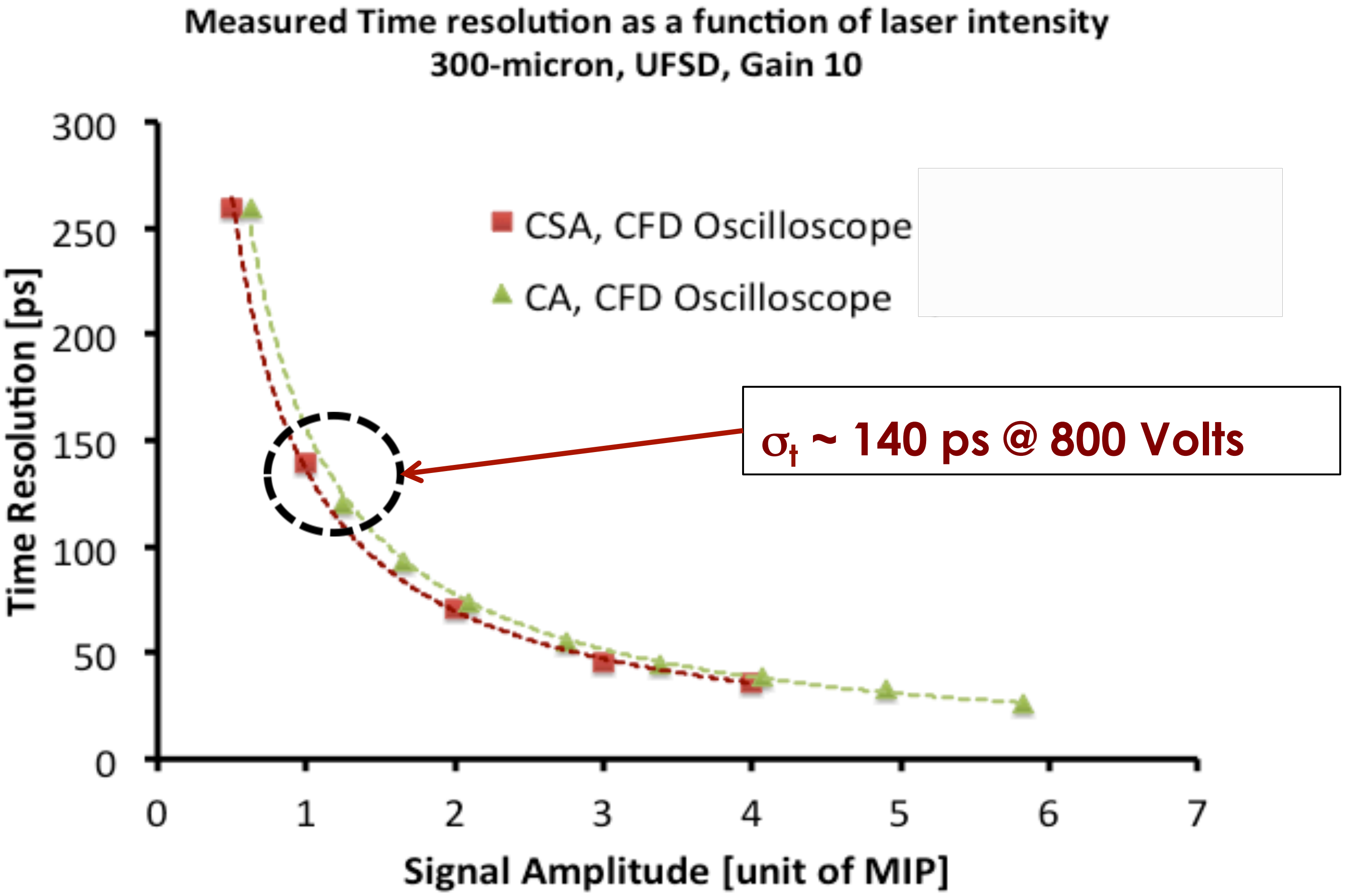
Gain ~ 20

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)



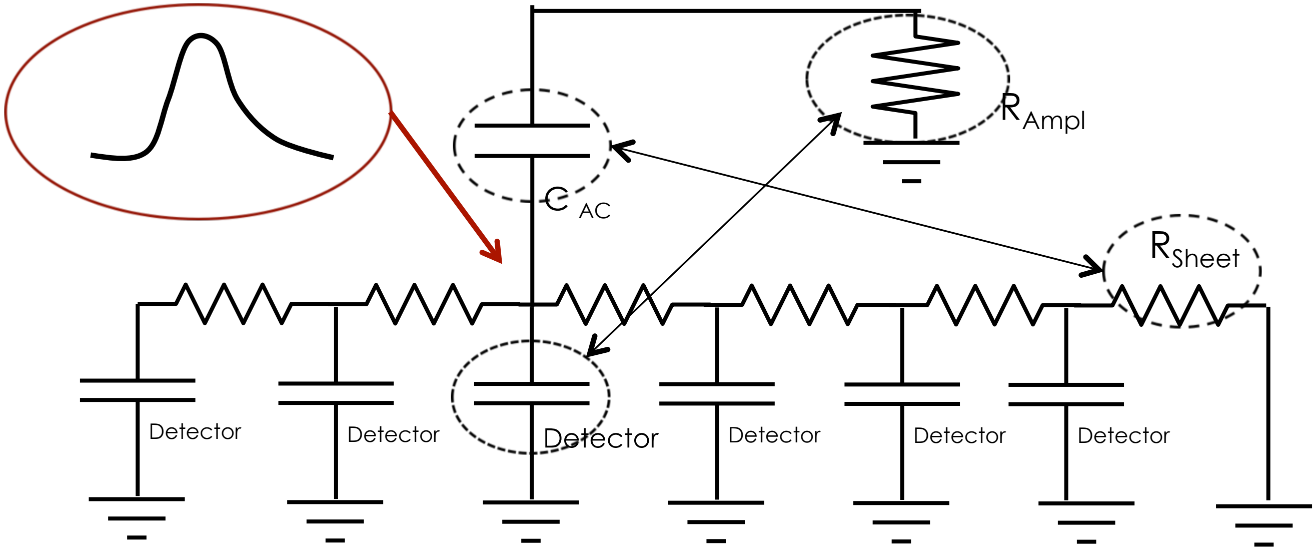
Measured Time resolution as a function of laser intensity
300-micron, UFSD, Gain 10

σ_t ~ 140 ps @ 800 Volts

Details of Resistivity and AC coupling

Additional Rise time

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

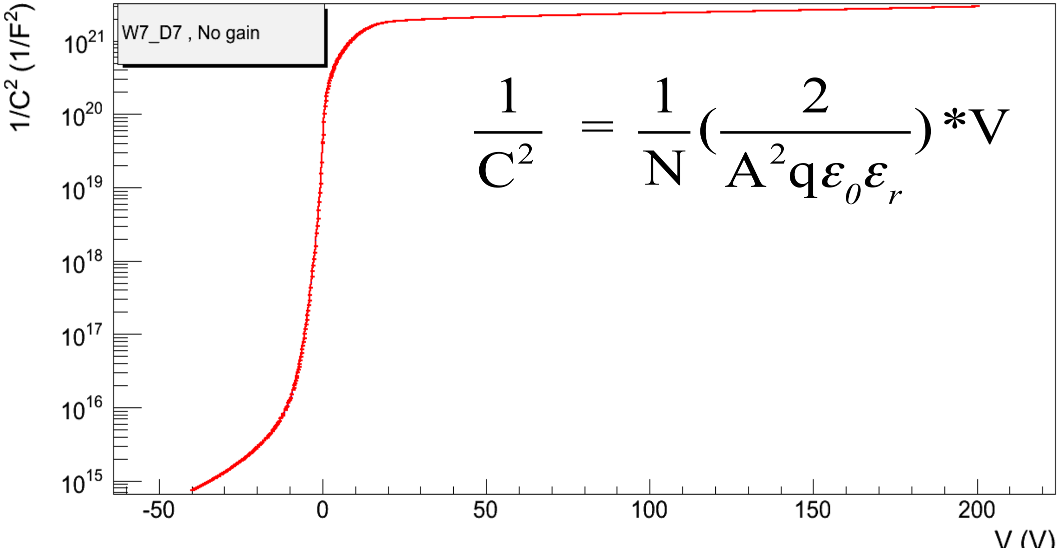


Freezing time

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

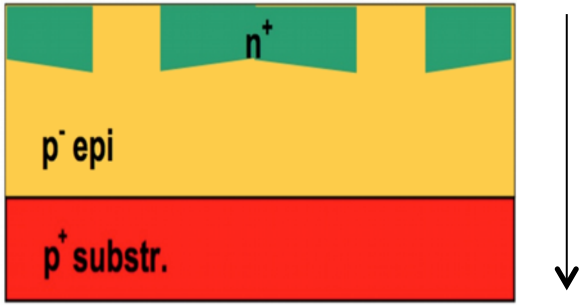
Only a small part of the detector is involved

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