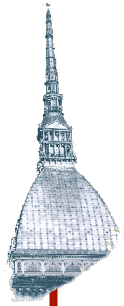


Signal formation and timing with LGAD sensors

- Signal formation
- The effect of gain
- UFSD: LGAD optimized for timing measurements
- Concurrent time and position measurements
- Noise sources
- Future directions

Nicolo Cartiglia
INFN Torino, Italy

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

Current from thin and thick detectors

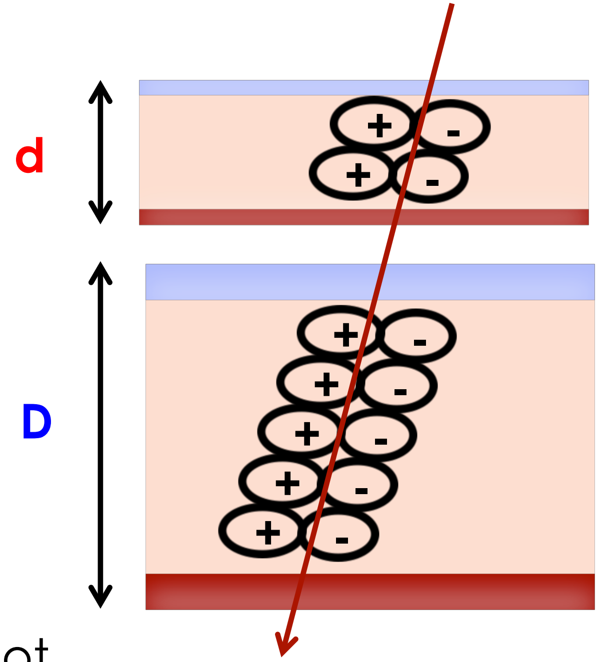
(Simplified model for pad detectors)

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:

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

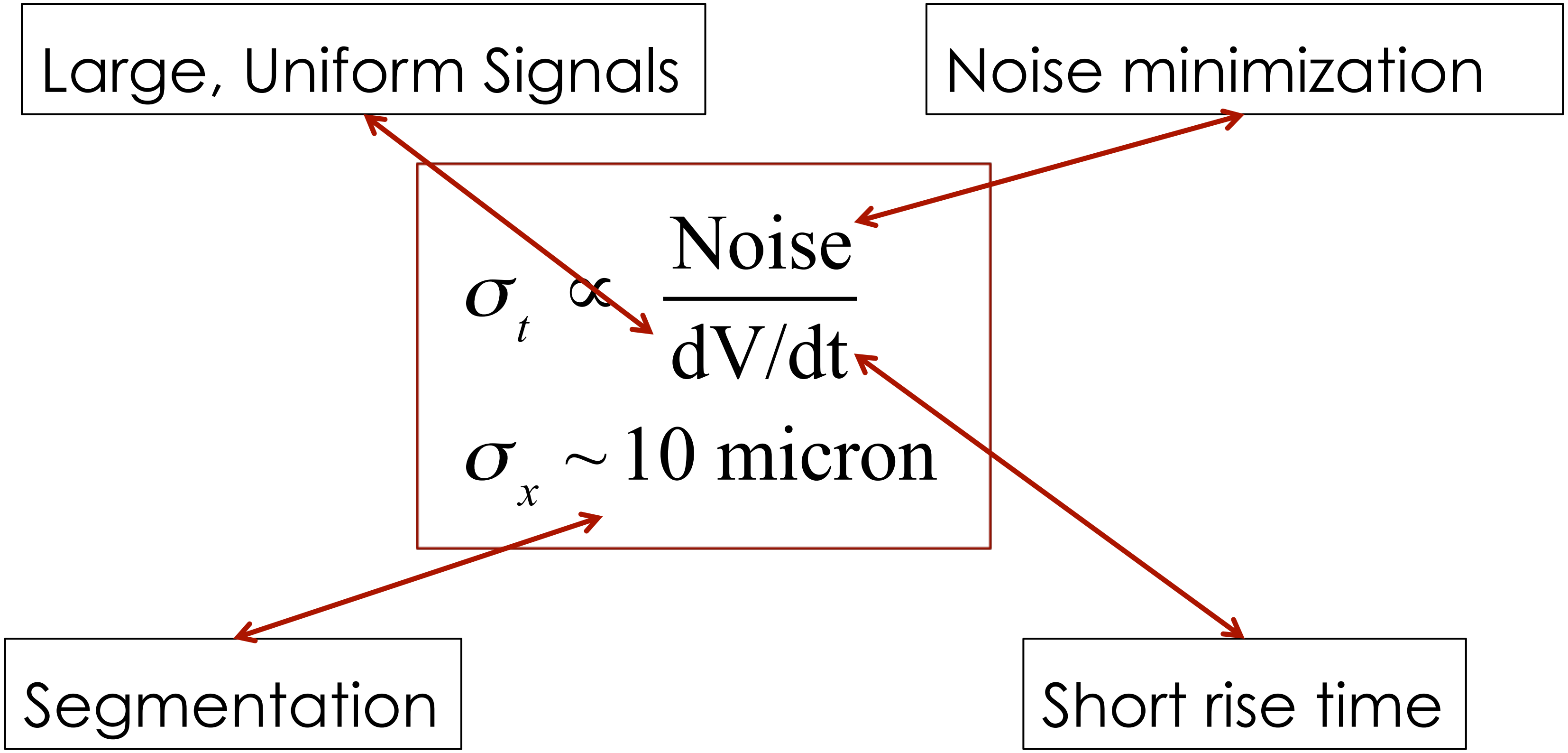
Number of e/h = 75/micron

Weighting field

velocity

➔ Initial current = constant

Time and position resolution



Large, Uniform Signals

Noise minimization

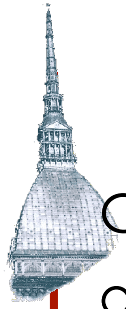
$$\sigma_t \propto \frac{\text{Noise}}{\text{dV/dt}}$$

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

Segmentation

Short rise time

How can we do better than what is shown in Marcello's, Arabella's and Harmtut's talk?



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:

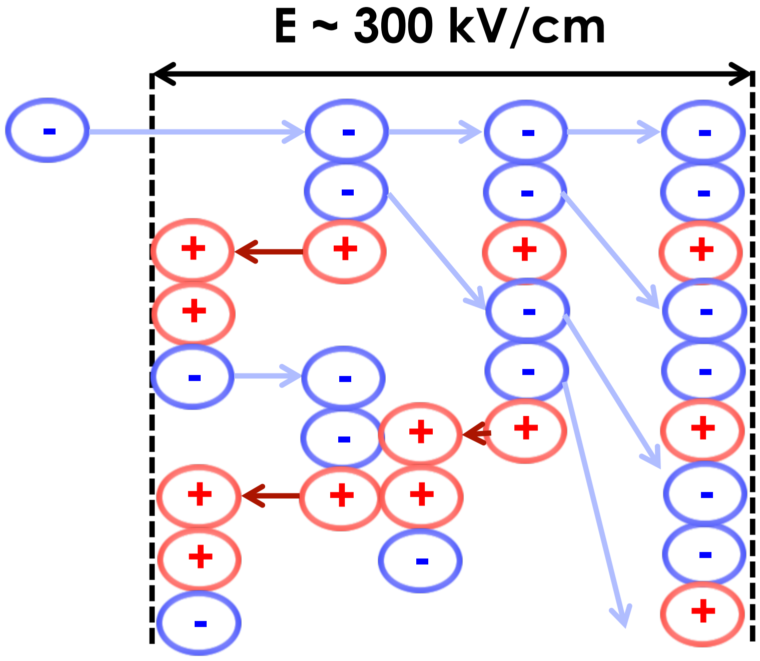
$$G = e^{\alpha\, l}$$

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

α = strong E dependance

α ~ 0.7 pair/μm for electrons,

α ~ 0.1 for holes



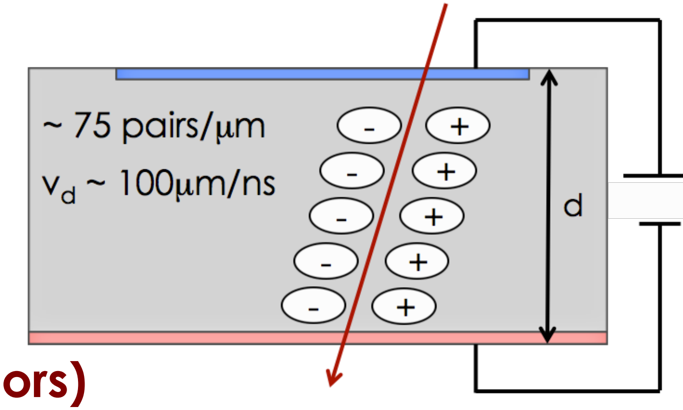
Concurrent multiplication of electrons and holes generate very high gain

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 thick silicon detector, we need **V_{bias} = 10 kV**



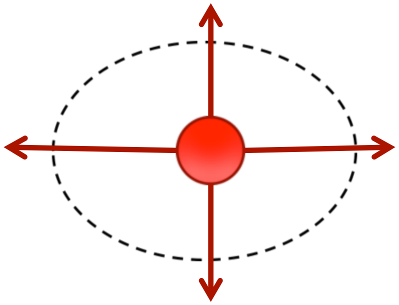
10 kV !!

Not possible

(maybe with 50 micron sensors)

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!!

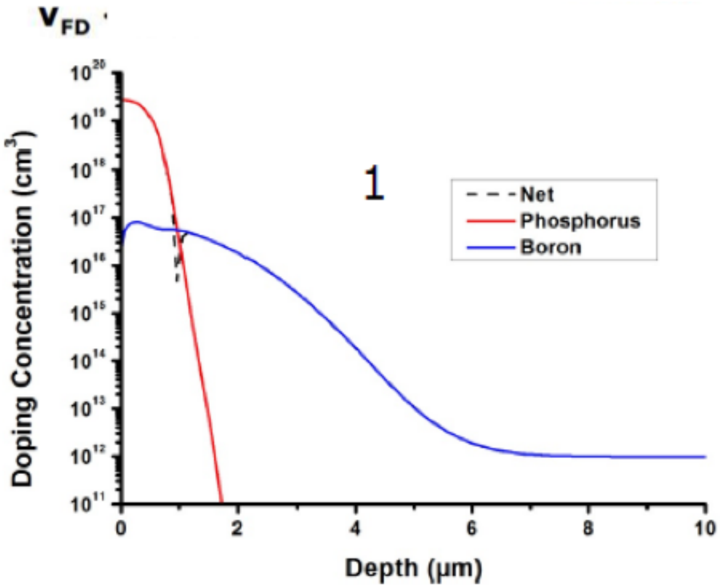
Low Gain Avalanche Detectors (LGADs)

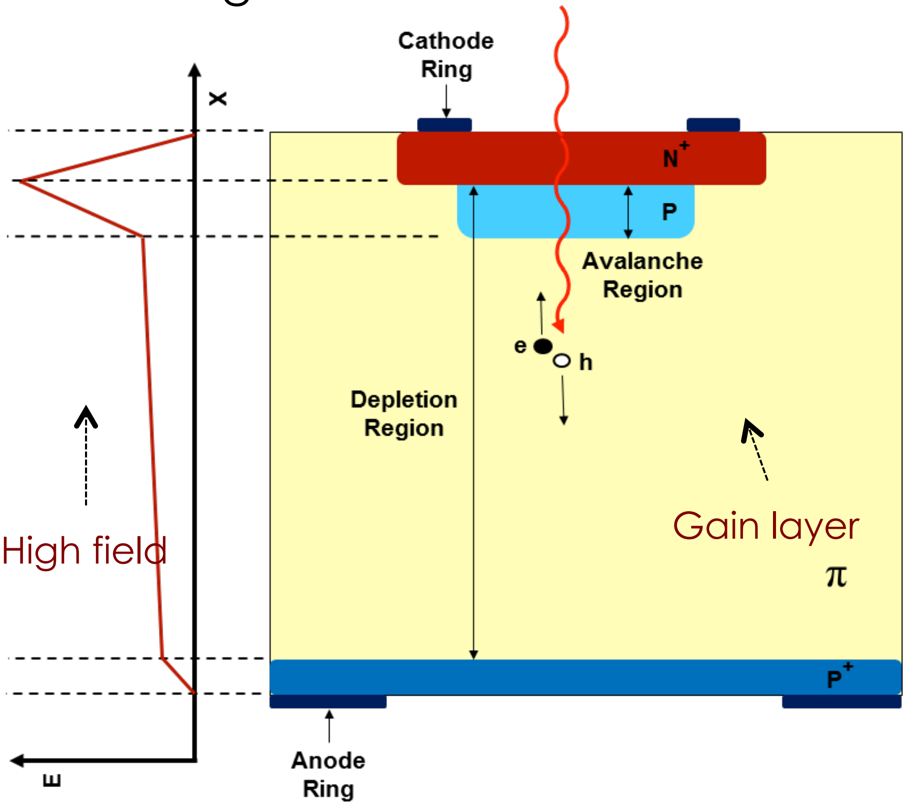
The LGAD sensors, as proposed and manufactured by CNM

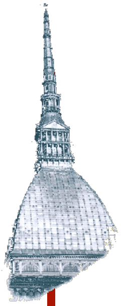
(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage

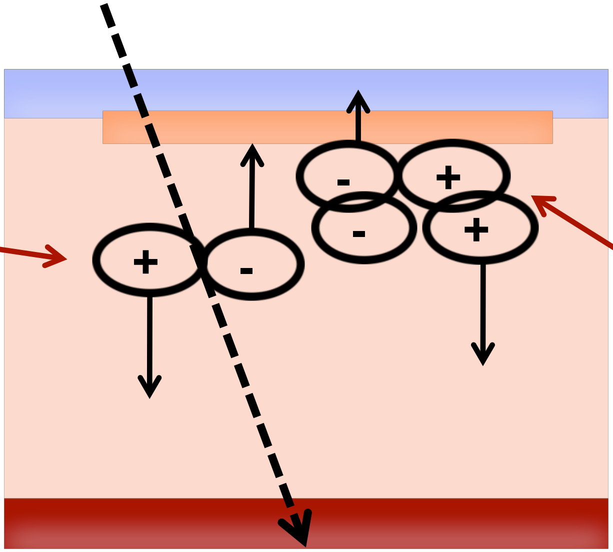






How gain shapes the signal

Initial electron, holes

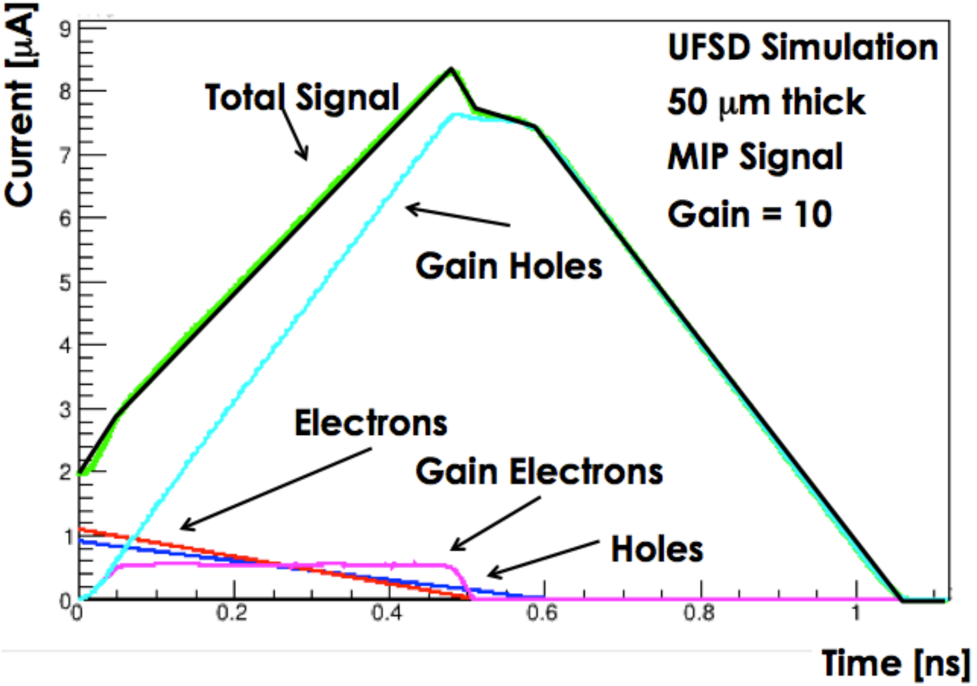


Gain electron:

absorbed immediately

Gain holes:

long drift home



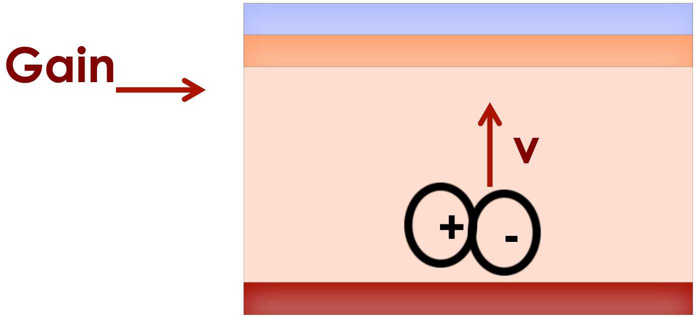
Electrons multiply and produce additional electrons and holes.

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

➔ **No holes multiplications**

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)

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

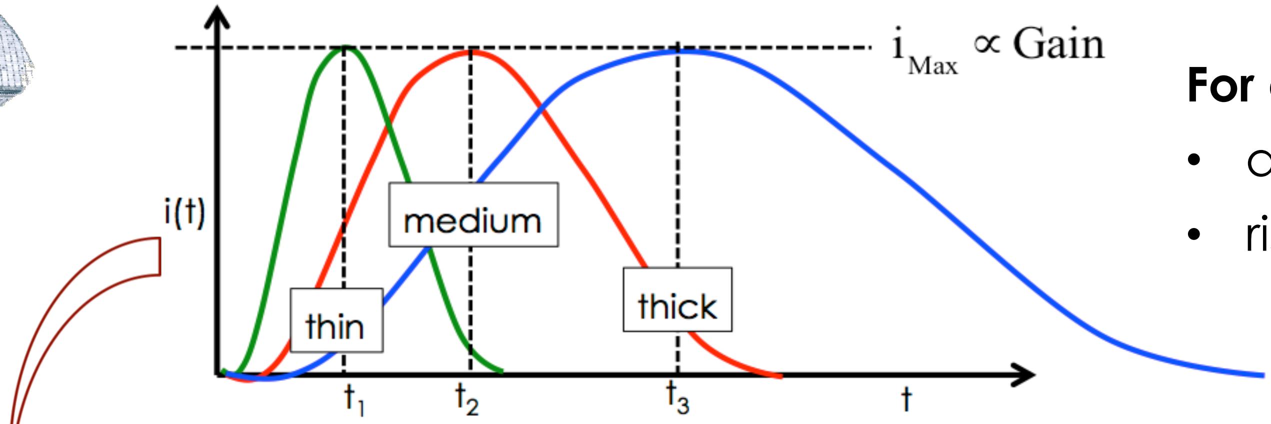
➔ **Gain current ~ 1/d**

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

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

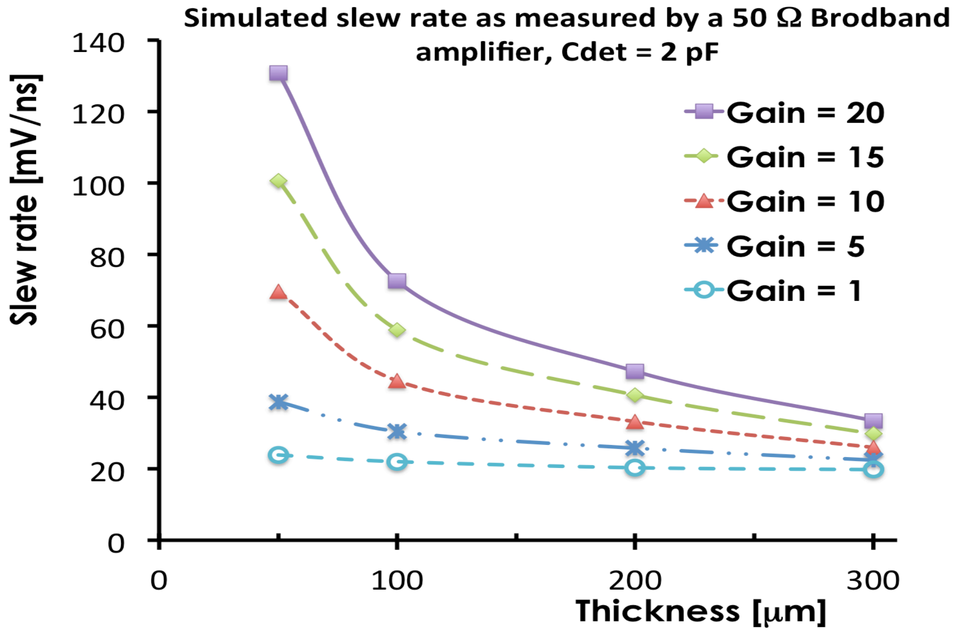
!!!

Gain and slew rate vs thickness



For a fixed gain:

- amplitude = constant
- rise time ~ 1/thickness



The slew rate:

- Increases with gain
- Increases ~ 1/thickness

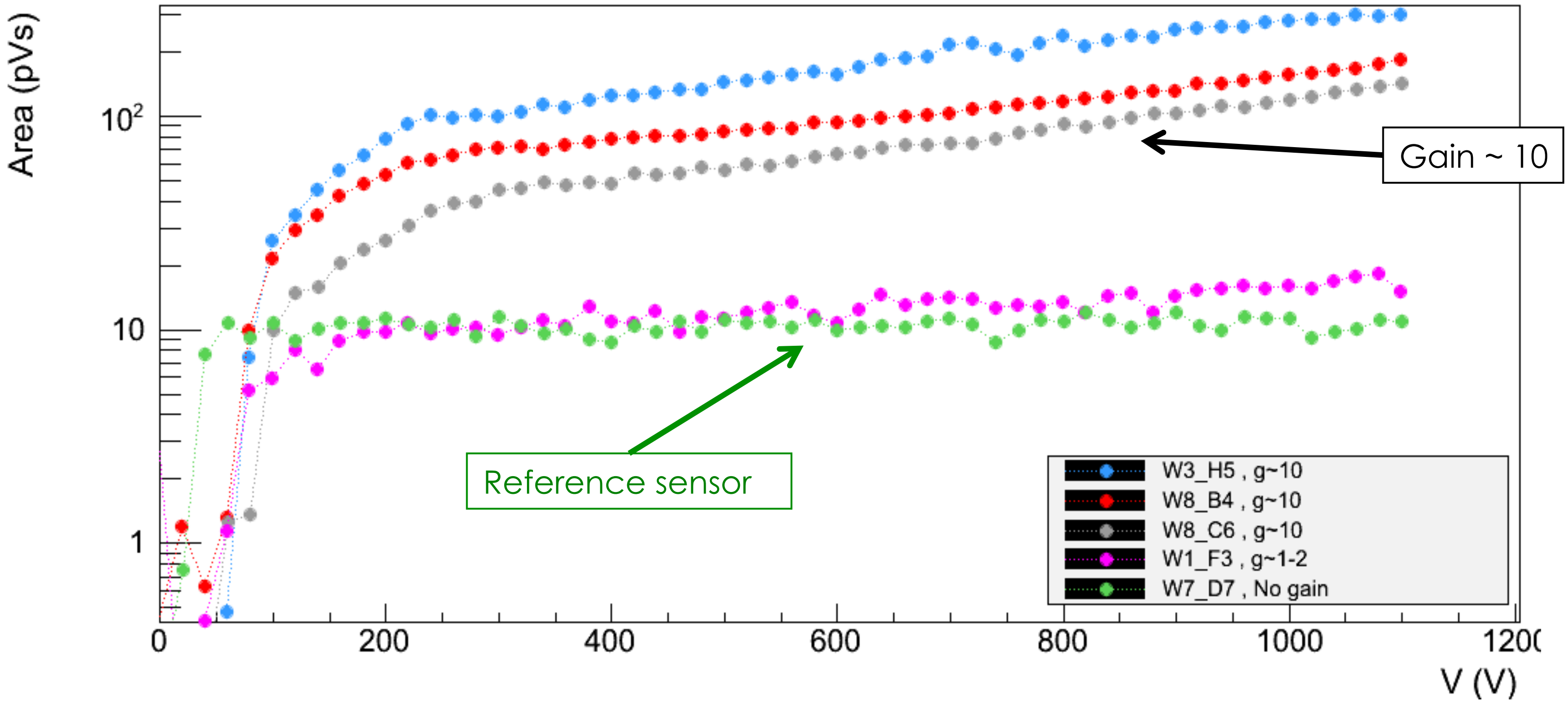
$$\frac{dV}{dt} \propto \frac{G}{d}$$

➔ **Go thin!!**

Significant improvements in time resolution require thin detectors

Signal amplitude

In LGAD the gain has a very smooth dependence on the applied external voltage



Gain ~ 10

Reference sensor

What is the correct gain?

The answer at the root of the LGAD approach is:

The correct gain is the MINIMUM gain that does the job

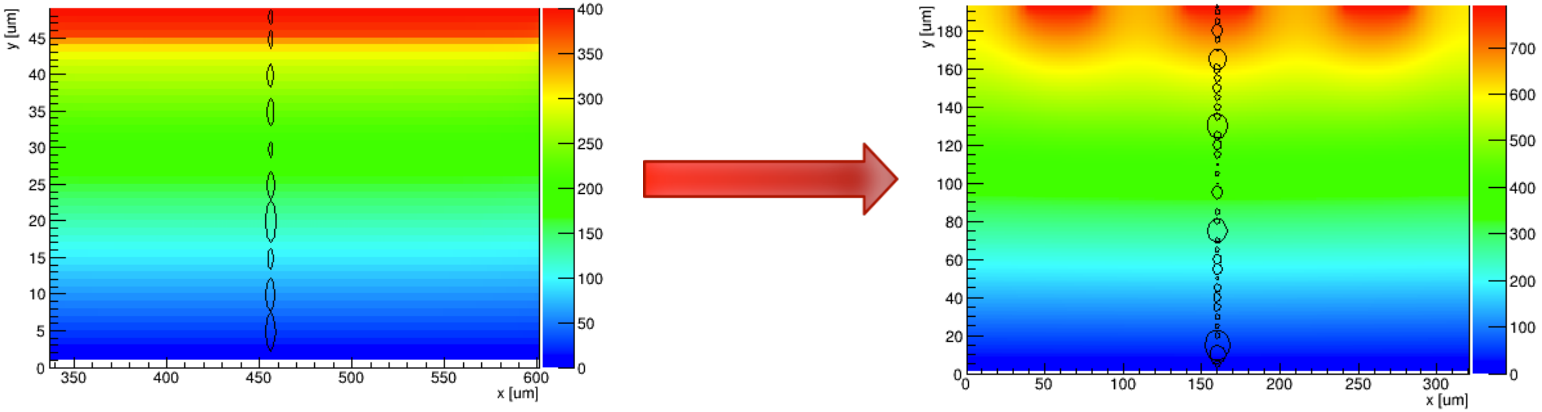
Why?

Gain has obvious drawback in terms of much higher noise, higher leakage current, higher thermal load, segmentation, early breakdown…

The value of the "correct gain" does not exists
it depends on the application.

Merging timing with position resolution

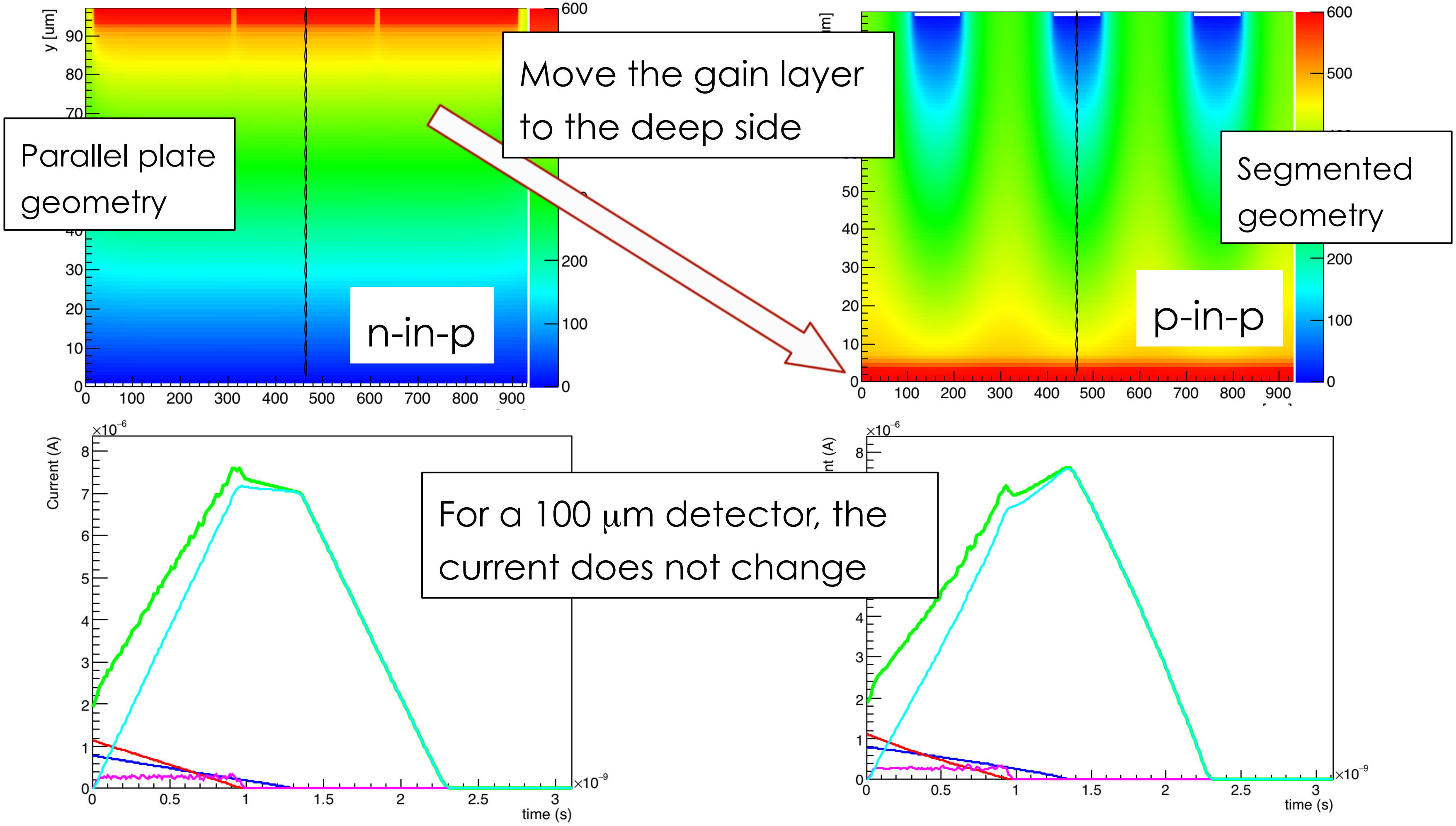
Electrode segmentation makes the E field very non uniform, and therefore ruins the timing properties of the sensor



We need to find a geometry that has very uniform E field and gain, 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

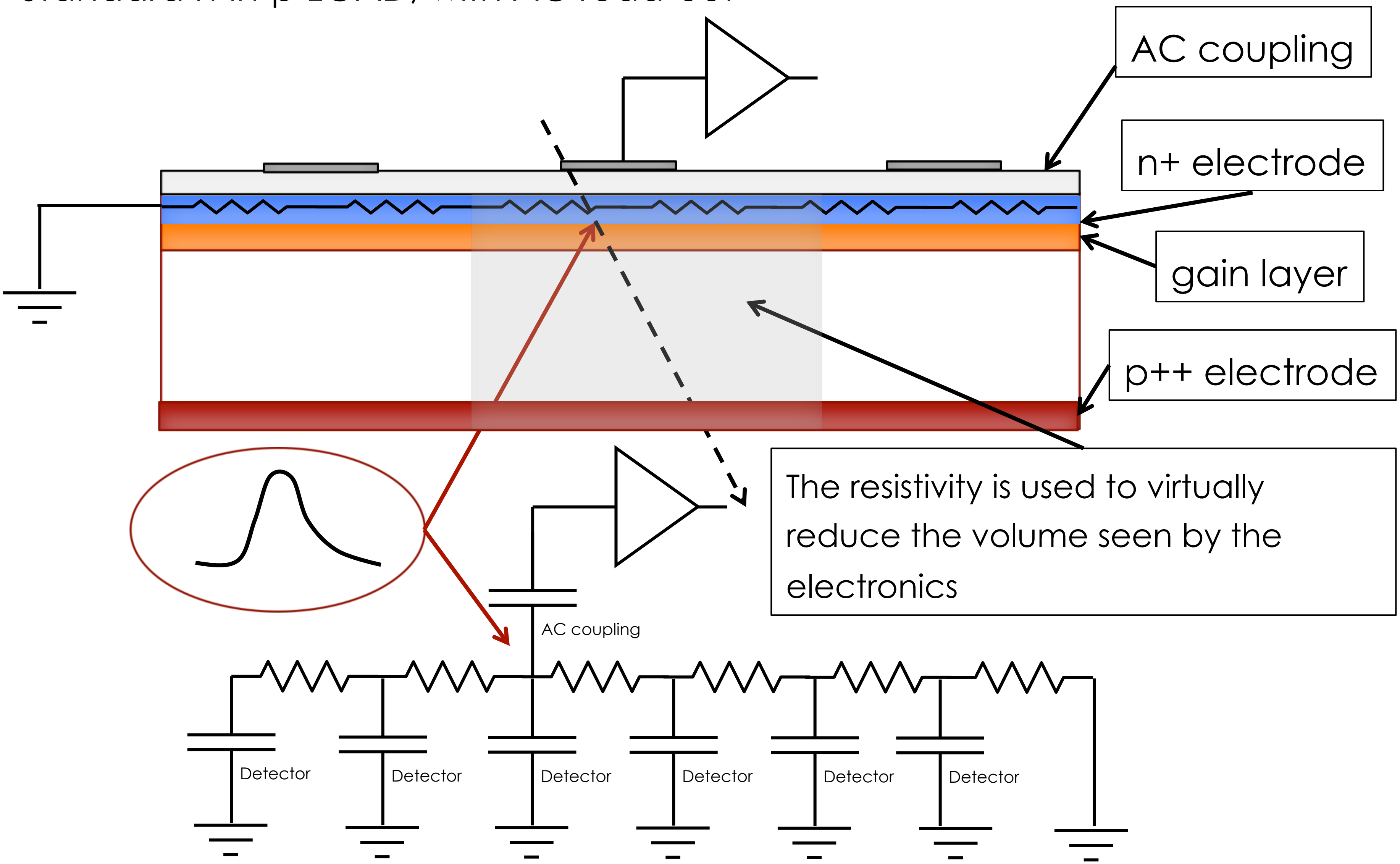
Segmented geometry

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

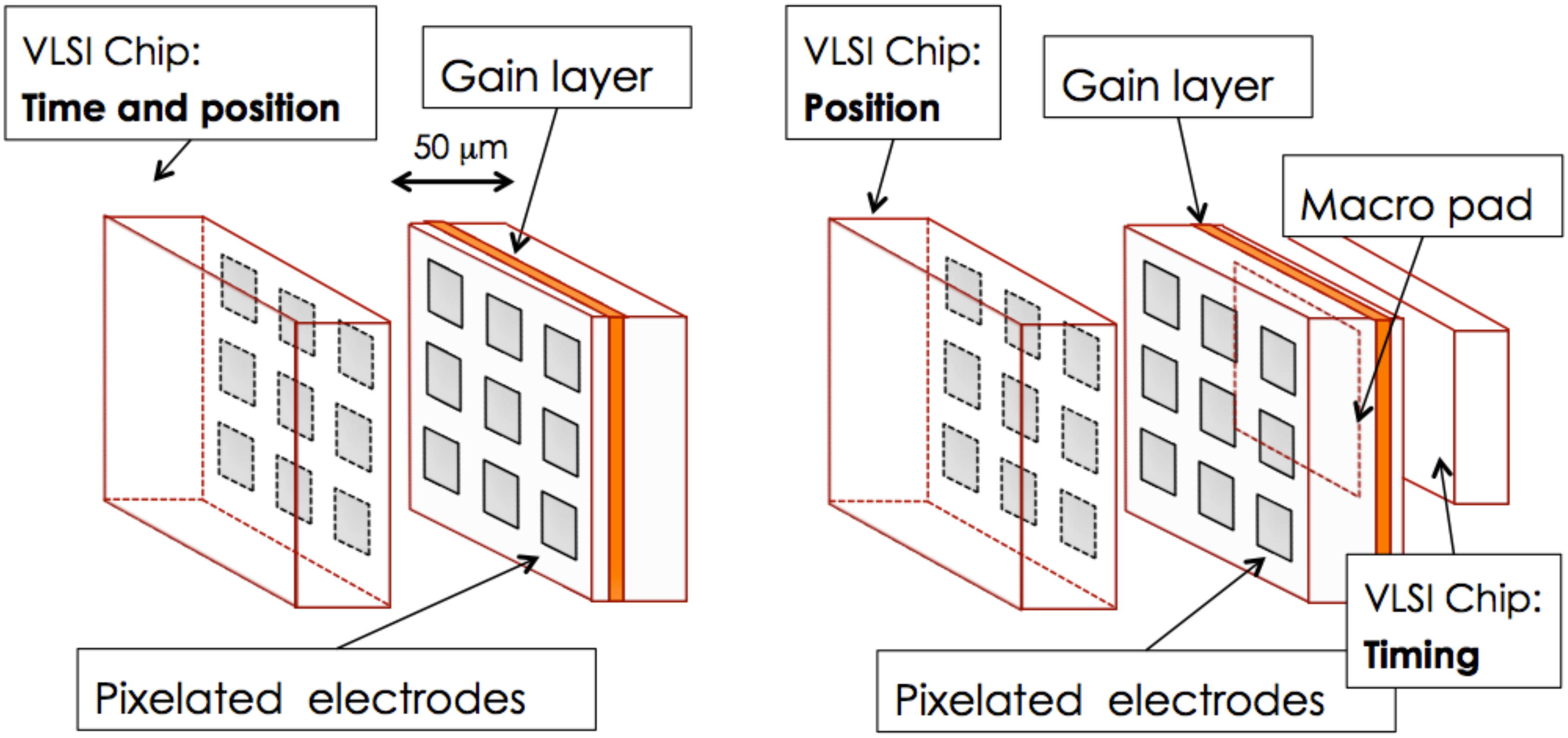
2) Segmentation: AC coupling

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



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

3) Segmentation: splitting gain and position measurements



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

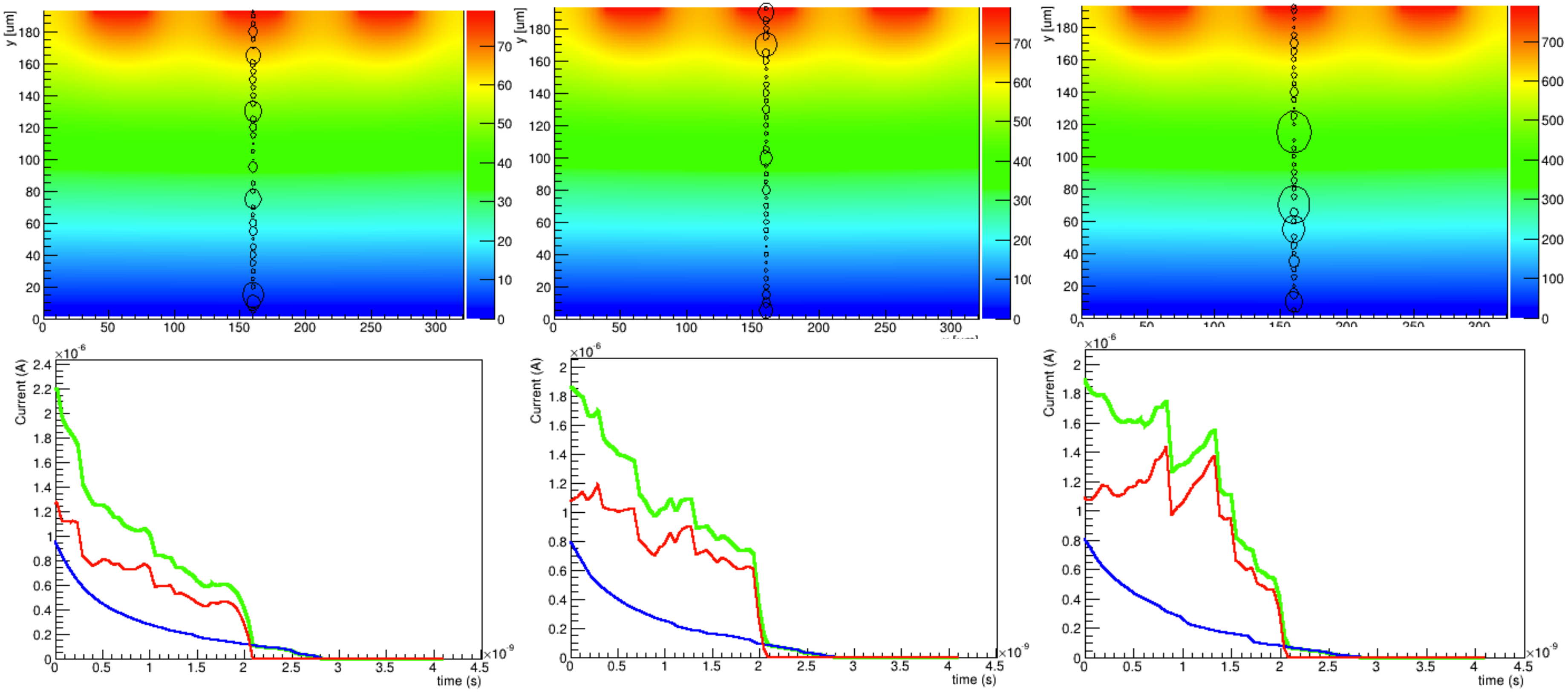
However we might split the position and the time measurements

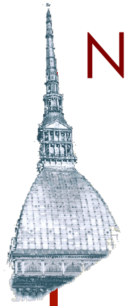
Non-Uniform Energy deposition

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.

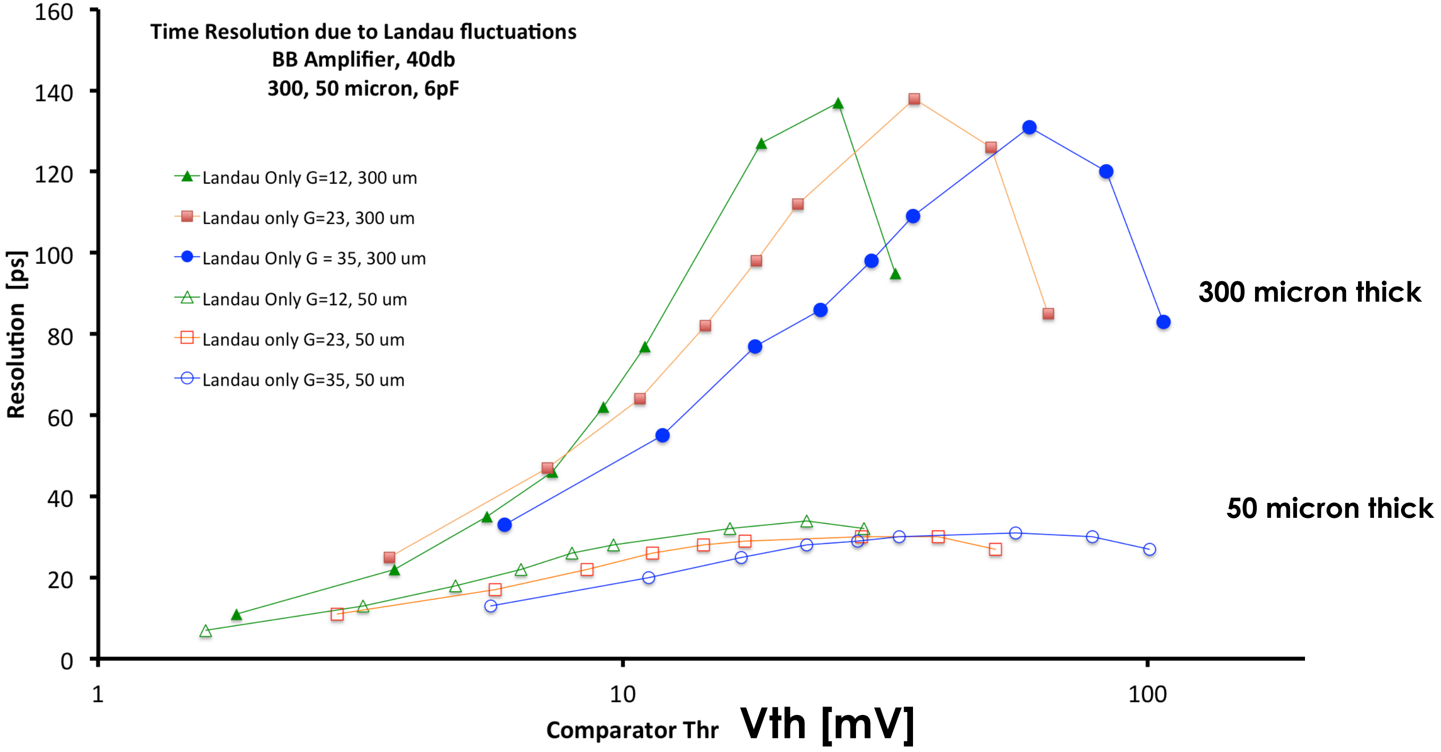
These are 3 examples of this effect:





Noise due to Landau fluctuation in energy deposition

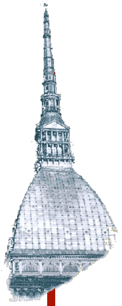
Resolution due only to shape variation, assuming perfect time walk compensation



To minimize Landau noise:

➔ Set the comparator threshold as low as you can

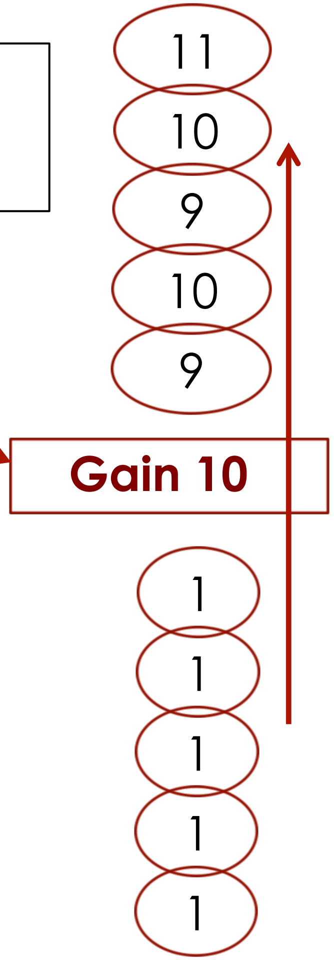
➔ Use thin sensors



Noise due to gain: excess noise factor

The gain is not constant:

➔ it generates additional fluctuations in the current



The current that goes through a gain M is noisier by an extra factor F:

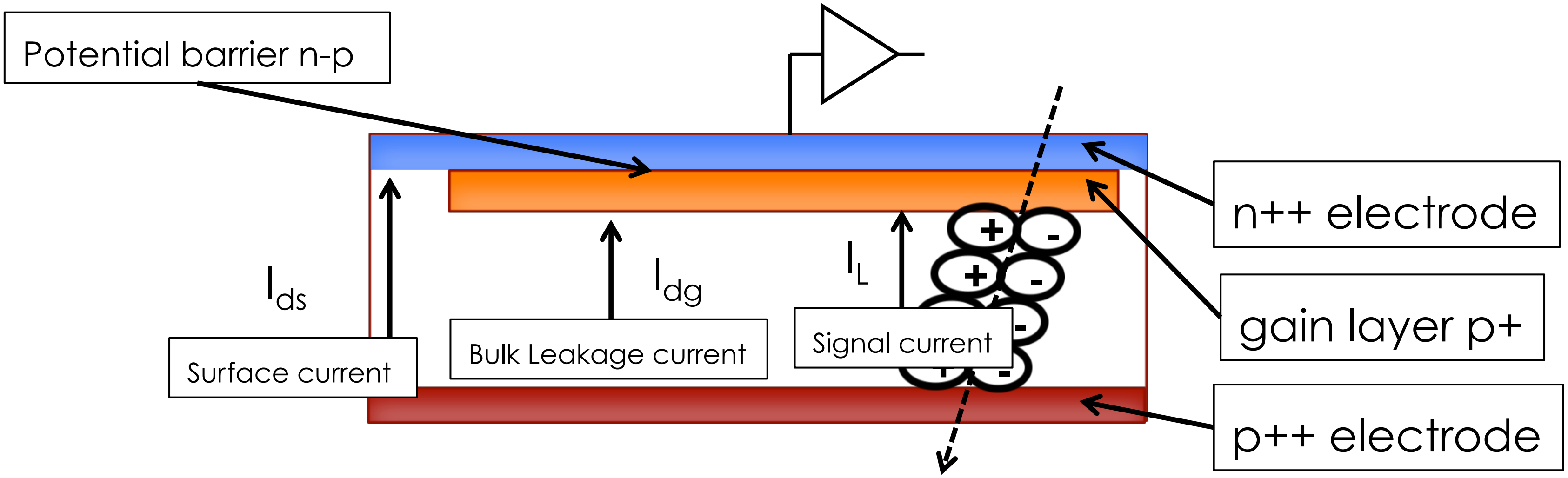
$$F = \frac{\langle M^2 \rangle}{\langle M \rangle^2} \Rightarrow \langle M^2 \rangle = \langle M \rangle^2 F$$

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

$$F \sim M^x$$

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

Noise due to a potential barrier (Shot noise)

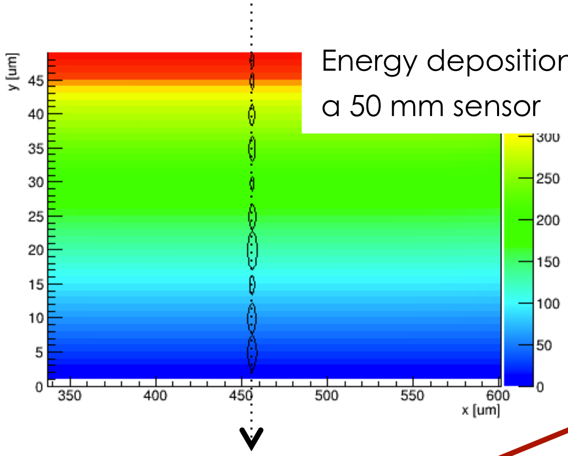


$$i^2_{Shot} = 2eI_{Det} = 2e\left[I_{Surface} + (I_{Bulk} + I_{Signal})M^2F\right]$$

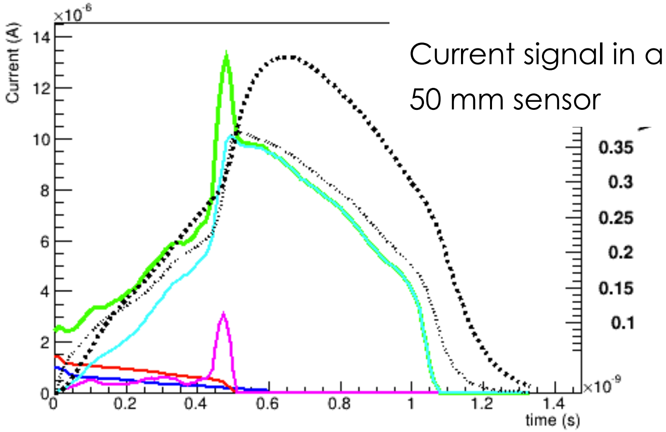
Bulk current and signal suffer from ENF

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

What is the best pre-amp choice?

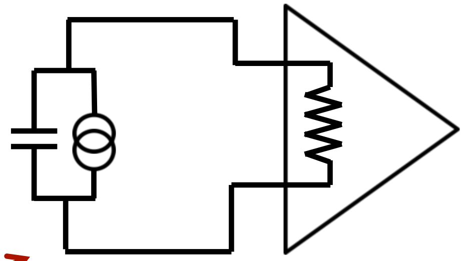


Energy deposition in a 50 mm sensor

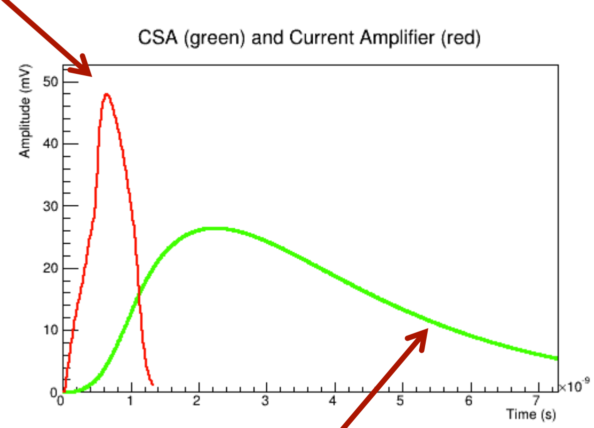


Current signal in a 50 mm sensor

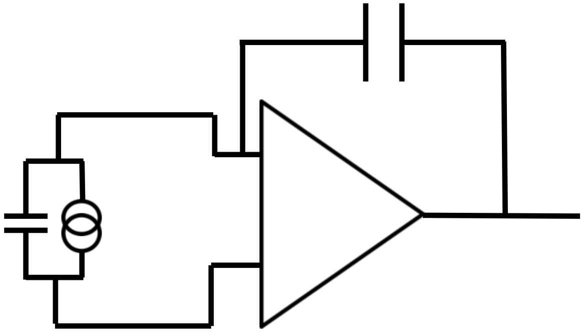
Current Amplifier



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



Integrating Amplifier



- Slower slew rate
- Lower noise
- Signal smoothing
- Less power

The players: signal, noise and slope

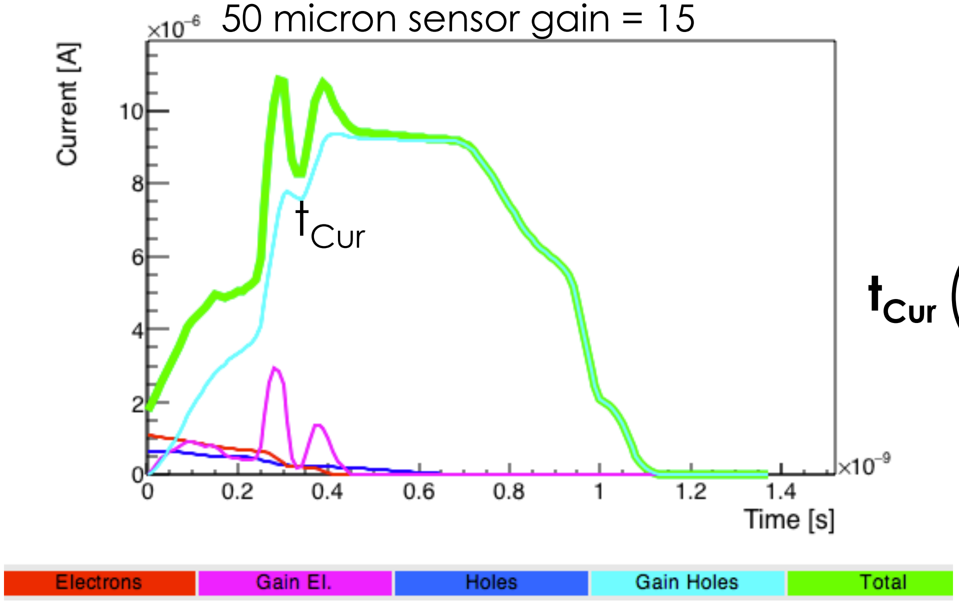
Excess Noise

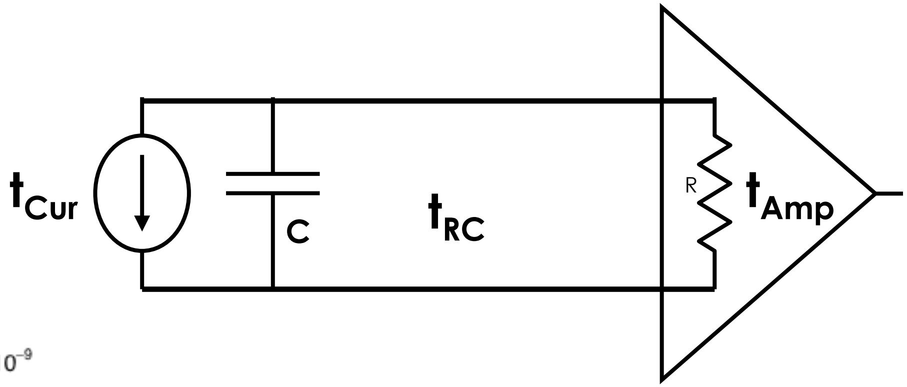
Landau Noise

Shot Noise

Electronic Noise

50 micron sensor gain = 15





The current rise time (t_{Cur})

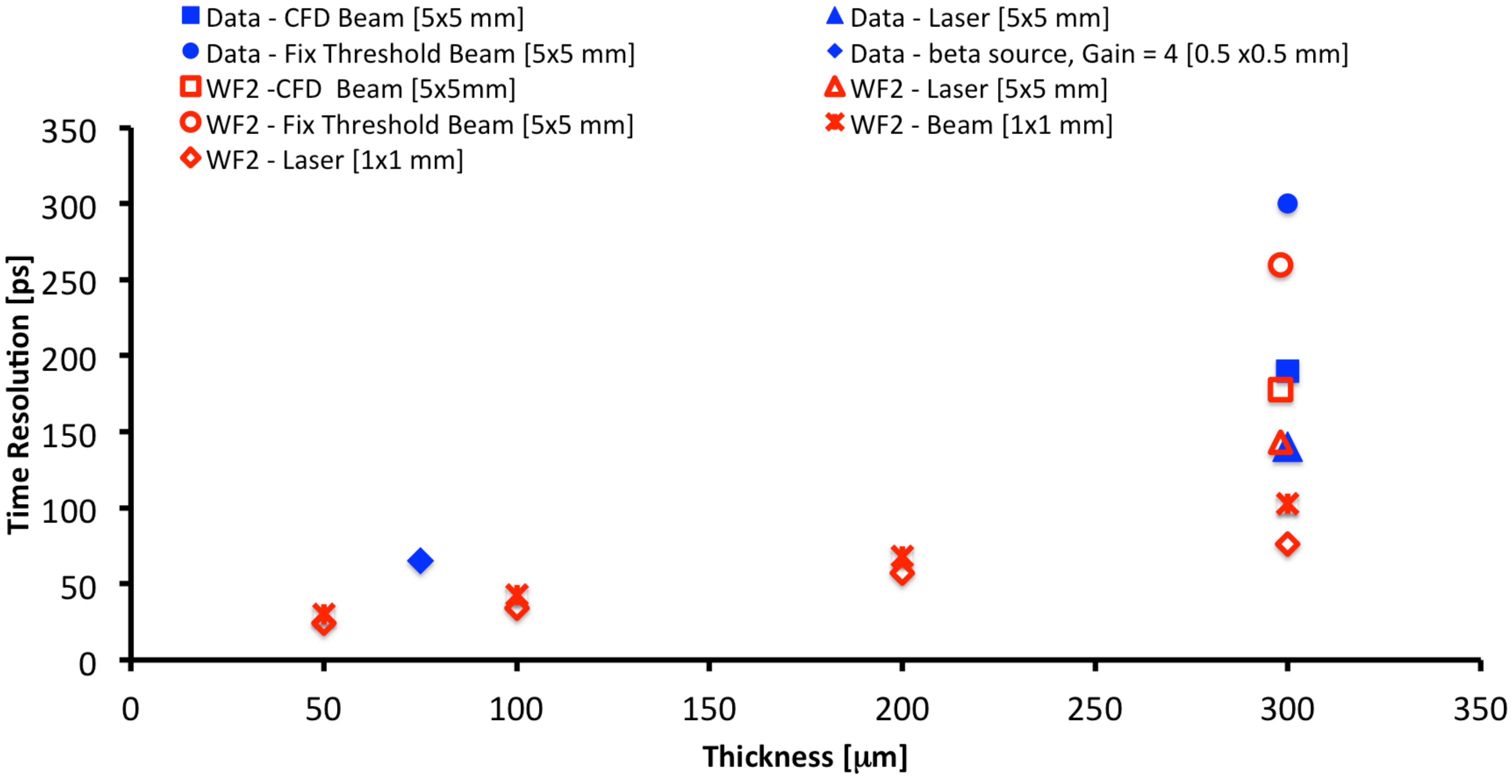
Amplifier rise time (t_{Amp})

There are 3 quantities determining the output rise time after the amplifier:

1. The signal rise time (t_{Cur})
2. The RC circuit formed by the detector capacitance and the amplifier input impedance (t_{RC})
3. The amplifier rise time (t_{Amp})

Current results and 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.



UFSD - Irradiation - I

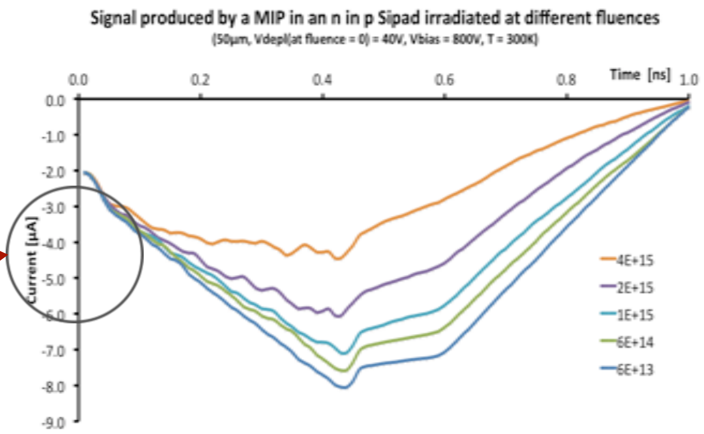
Irradiation causes 3 main effects:

1. Decrease of charge collection efficiency due to trapping
2. Changes in doping concentration
3. Increased leakage current

1) Decrease of charge collection efficiency due to trapping

We ran a full simulation of CCE effect. In 50 micron thick sensors the effect is rather small: **up to 10^{15} neq/cm^2 the effect is negligible in the fast initial edge used for timing.**

Electronics need to be calibrated for different signal shapes



UFSD - Irradiation - II

2) Changes in doping concentration

There is evidence for importan “initial acceptor removal” at fluences above a few 10^{14} n_{eq}/cm^2

➔ the “real” p-doping of the LGAD gain layer is deactivated.

R&D paths (very active RD50 topic)

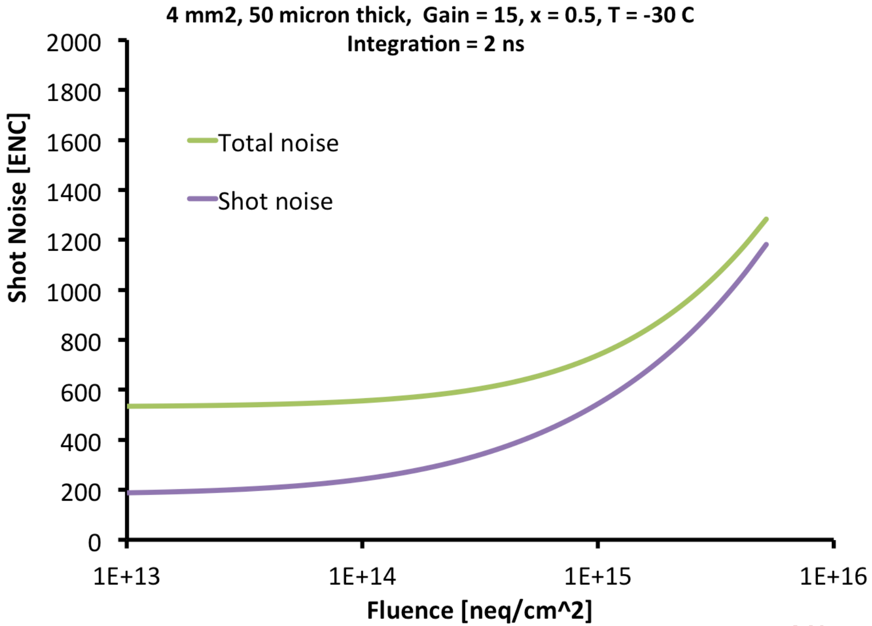
- Use Vbias to compensate for the loss on gain
- Use additional dopant (add C to the gain area)
- Use Gallium doping

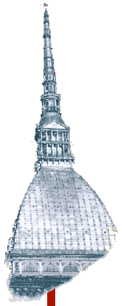
3) Increased leakage current

Assuming Gain ~ 15, T = -30C,

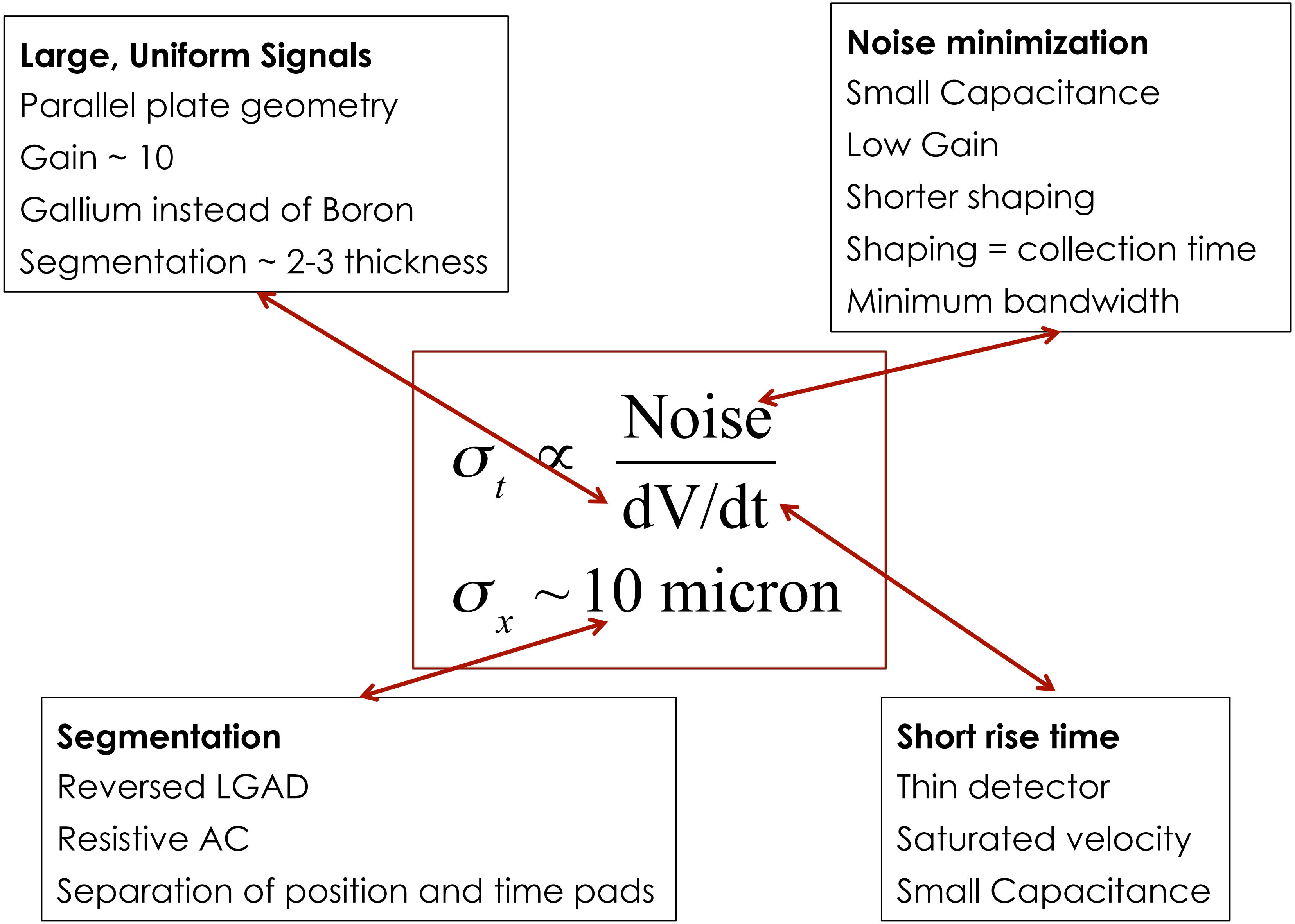
Shot noise starts to be important at fluences above ~ 10^{15} n^{eq}/cm^2

- Keep the sensor cold
- Low gain
- Small sensor





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

Ultra Fast Silicon Detectors

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

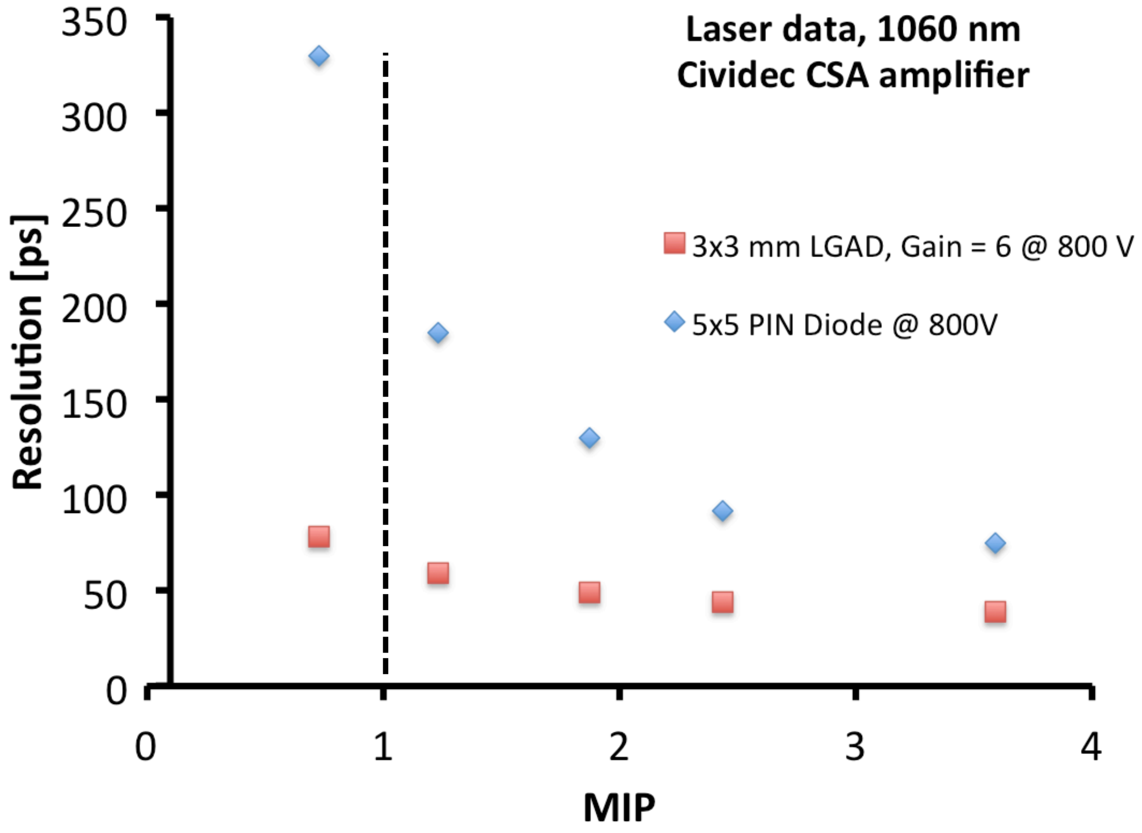
Not all geometries allow excellent timing

1. Thin to maximize the slew rate (dV/dt)
2. Parallel plate – like geometries 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)

Backup

Time resolution of UFSD and PIN diodes

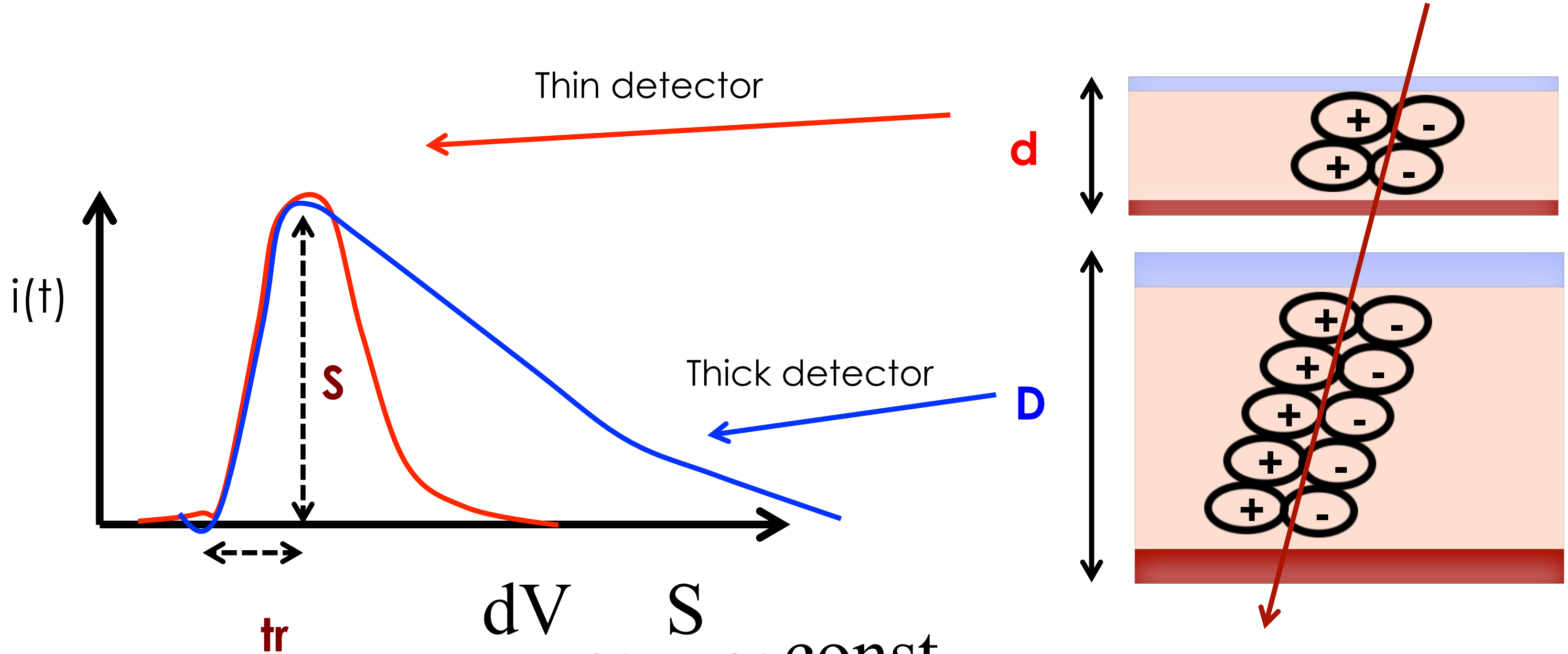
(laser pulses)



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

Thin vs Thick detectors

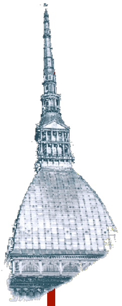
(Simplified model for pad detectors)



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

Thick detectors have longer signals, not higher signals

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



Noise Summary

$$Q_n^2 \propto 2k_1 e I_{Det} * T_s + k_2 \frac{C_{Det}^2}{T_S}$$

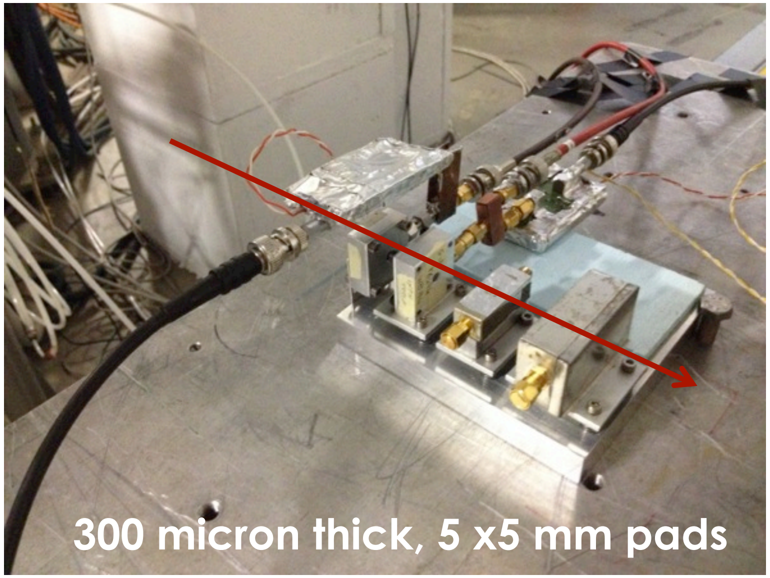
➔ **Current Noise^2** ~ detector leakage current x T_s
➔ **Voltage Noise^2** ~ C_{det}^2/T_s ~ C_{det} (since T_s ~ C_{det})

In UFSD the minimum noise is at shorter shaping time than in PIN diodes

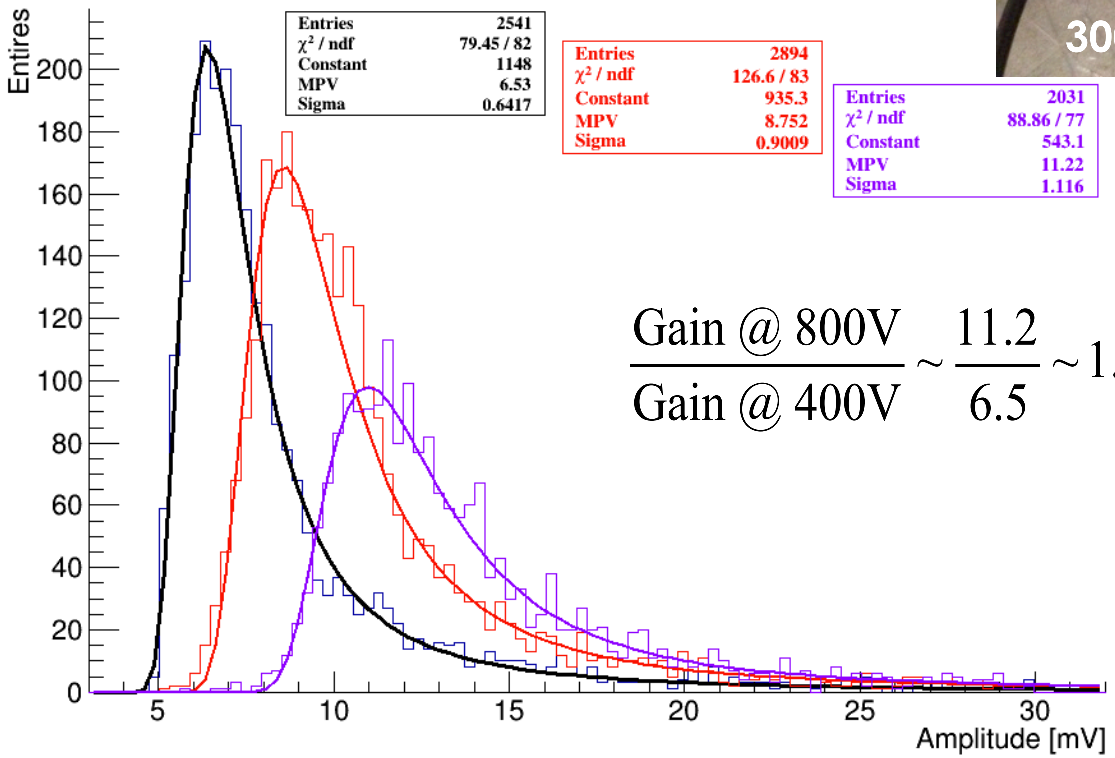
- Design gain with very small ENF
- Keep the leakage current low (small device)
- Keep the gain low (the noise increases faster than the signal)
- Keep the capacitance small (to keep the voltage noise low)

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.



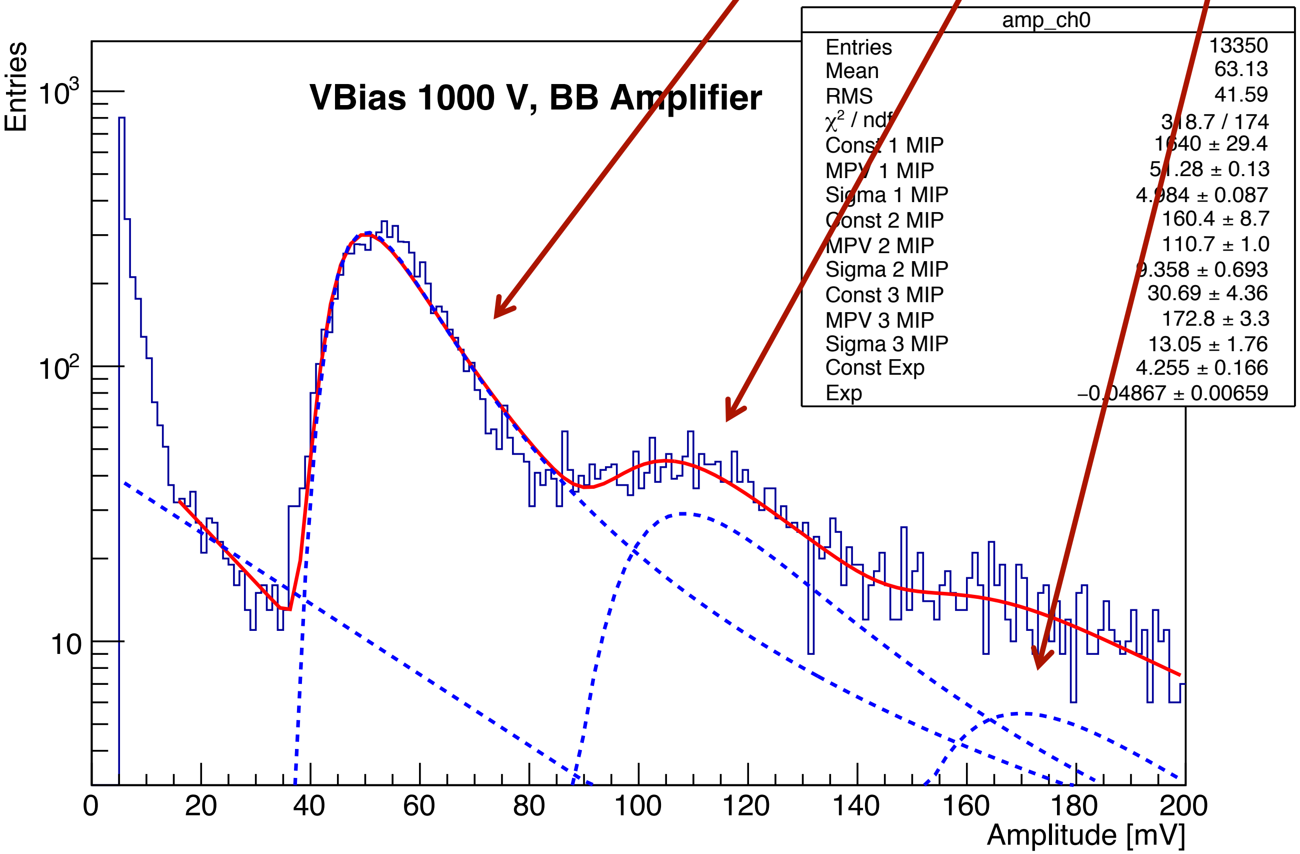
$$\frac{\text{Gain @ 800V}}{\text{Gain @ 400V}} \sim \frac{11.2}{6.5} \sim 1.7$$

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

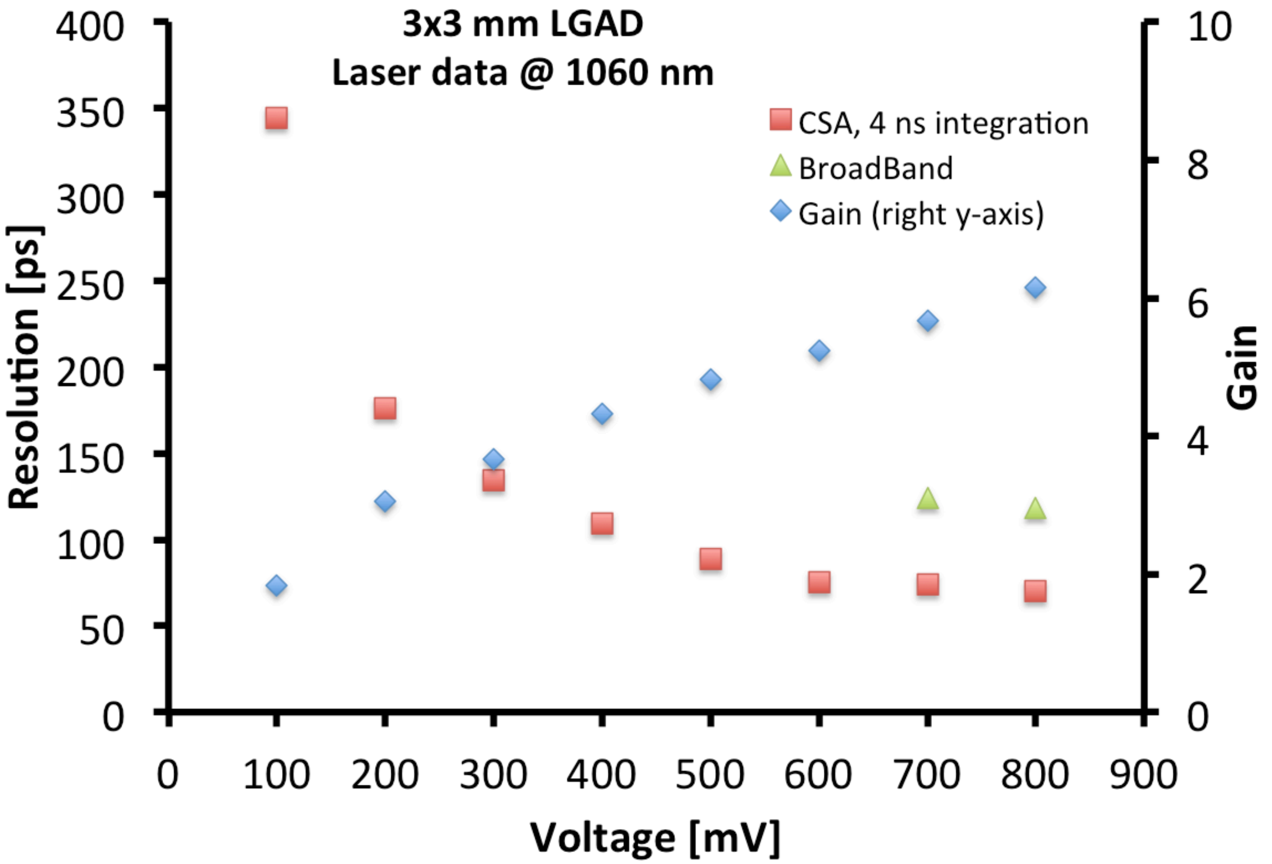
Very linear behavior of UFSD with increasing charge



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:

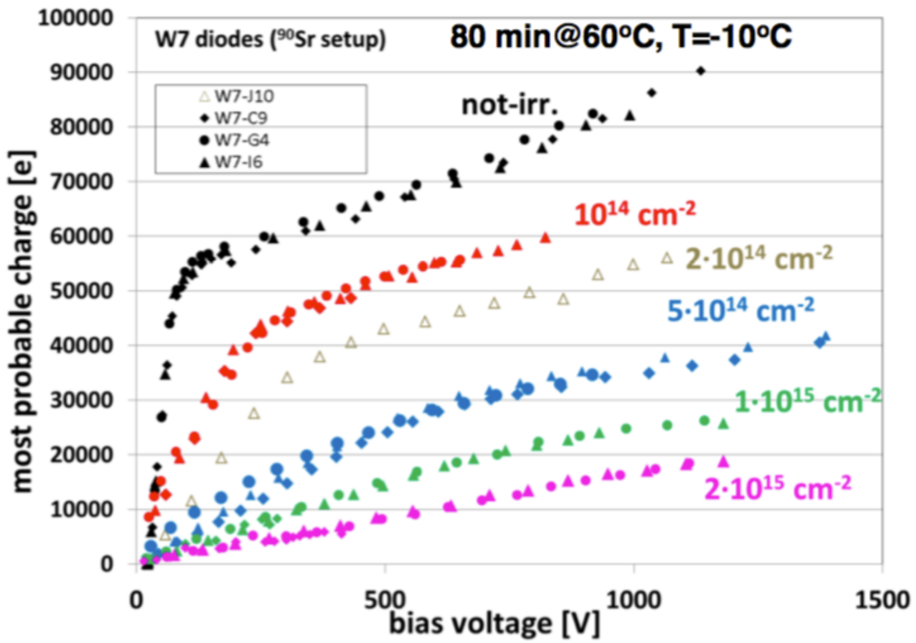
achieved ~ 70 ps resolution with laser pulses

Irradiation tests

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

Several reasons:

- Charge trapping (thick sensors!)
- Lower Efield (p-doping creation)
- Gain layer inactivation



What-to-do next:

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

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

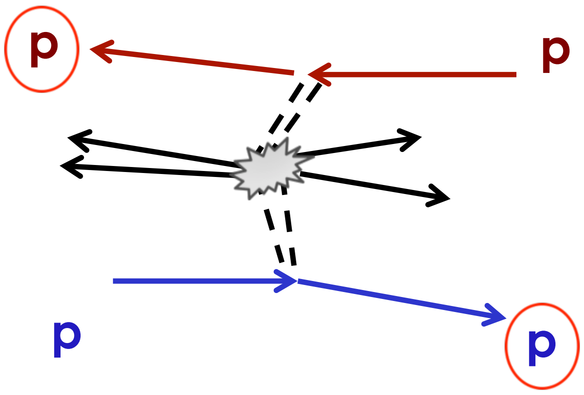
The CT-PPS detector for forward protons

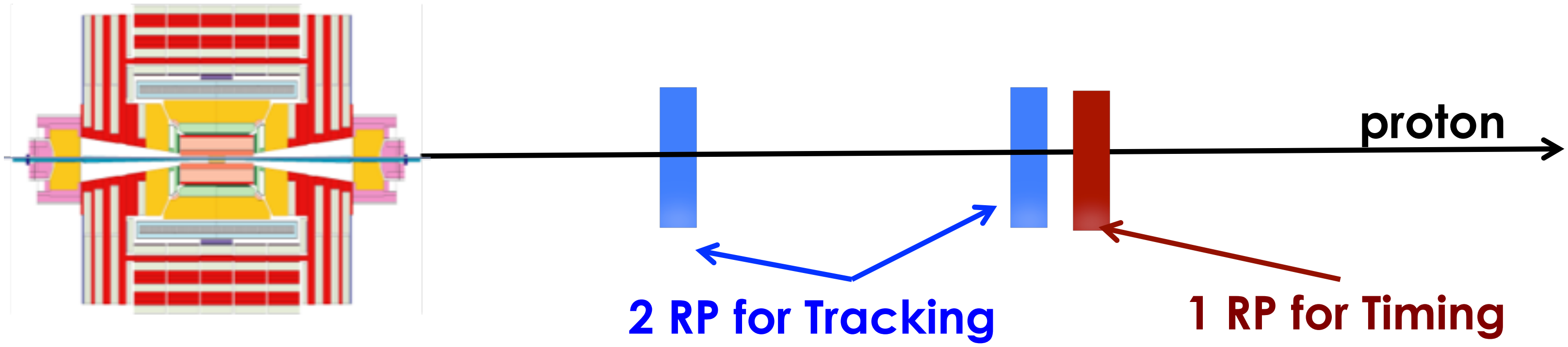
There is a class of events with 2 protons in the final states. We need to measure these protons:

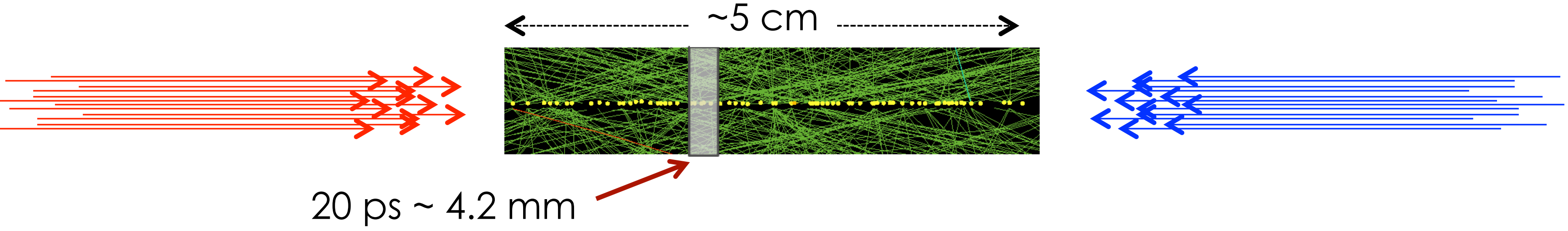
Tracking and timing in Roman pots

How do we determine the proton vertex?

Using z-by-timing

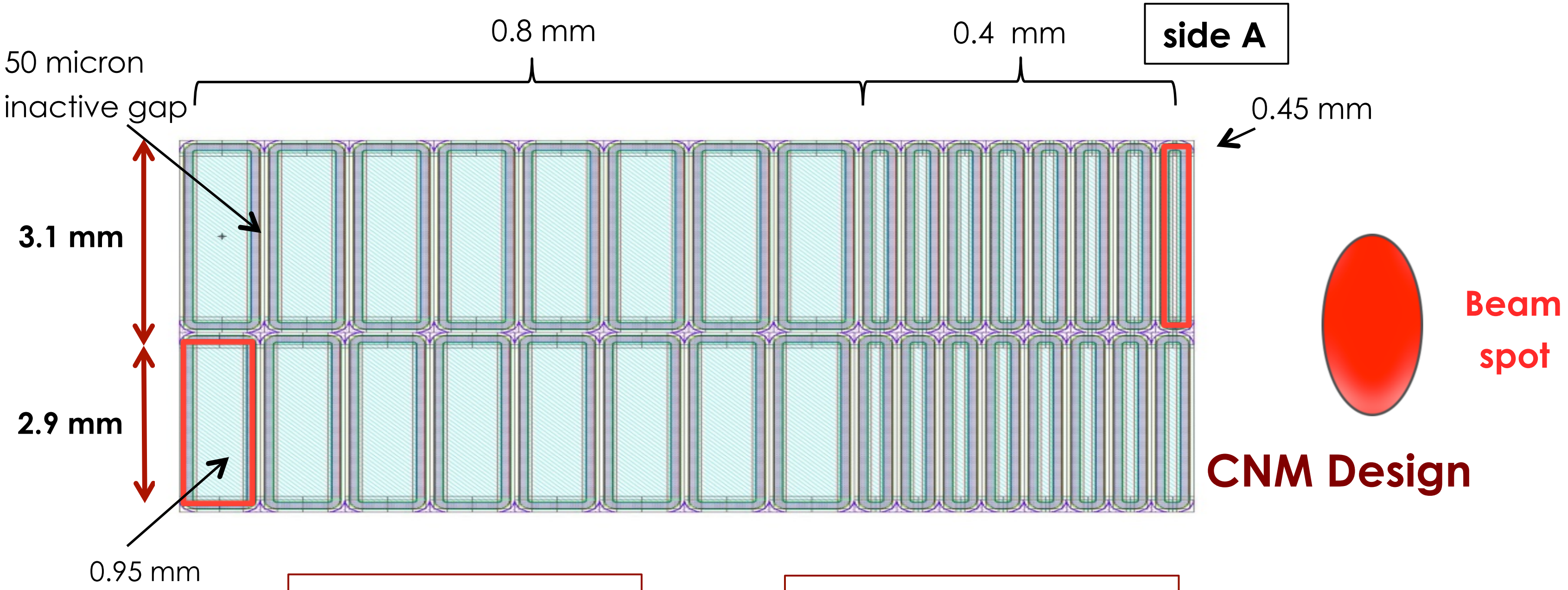






A precision of ~20 ps on the time of each proton will determine the vertex position with a precision of ~ 4.2 mm ("z-by-timing" resolution $\Delta z = c\,\Delta(t_1 - t_2)/2$)

Sensor geometry for CT-PPS



CNM Design

16 Pixel ~ 3 mm^2
Cap. Pixel ~ 6 pF

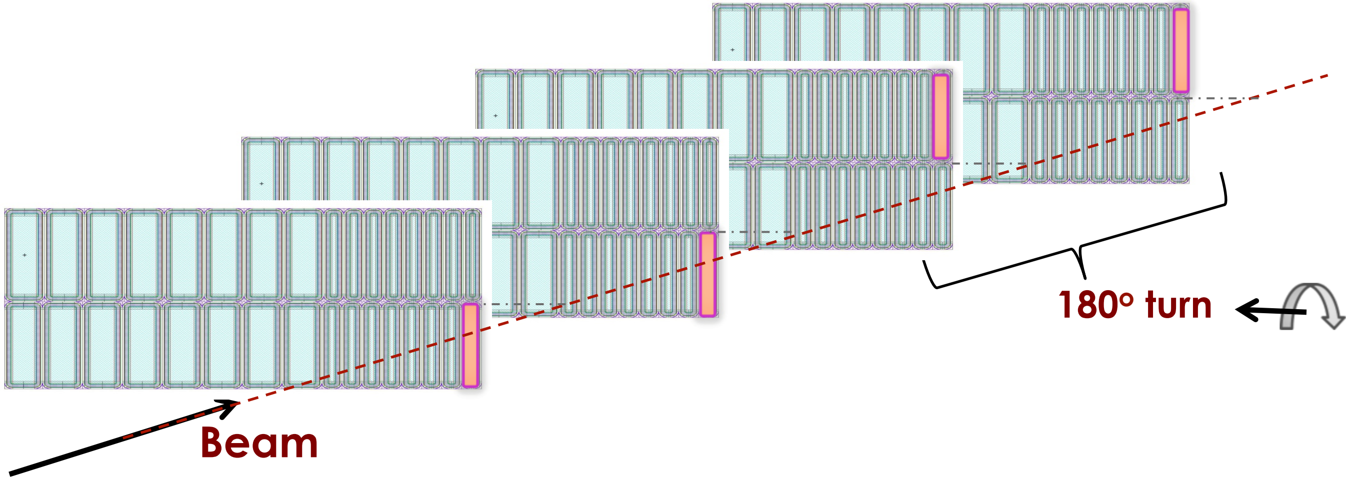
16 Pixel ~ 2 mm^2
Cap. Pixel ~ 4 pF

Asymmetric design
Area = 12mm x 6mm;
Thickness = 50 μm;
# of channels = 32 Gain ~ 15
Slim edge of ~200 μm on side A

Expected time resolution: ~30 ps

Layout of detector planes

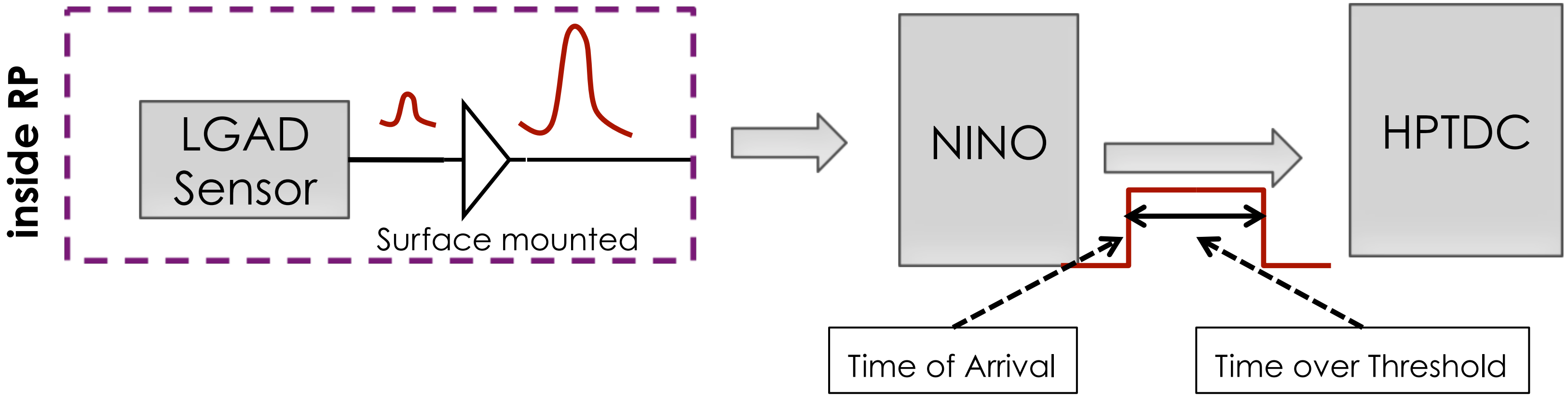
4 (6) planes per station (qualitative sketch):

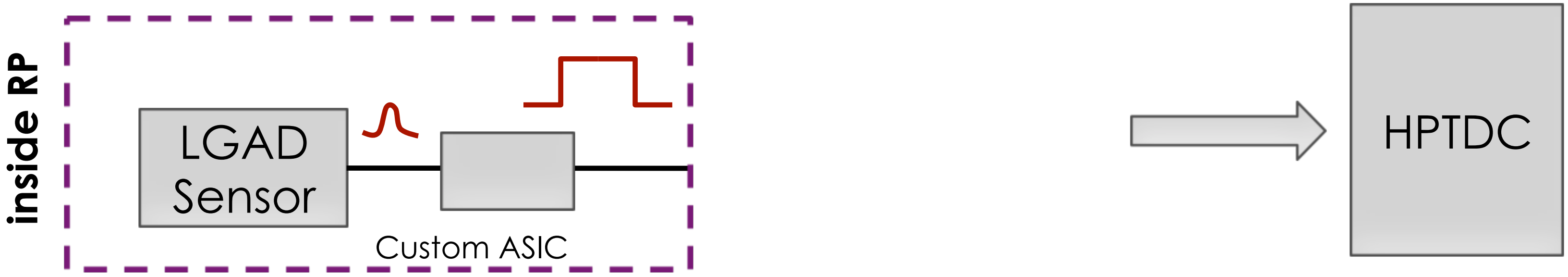


No cracks aligned:
2 (3) planes facing the beam
2 (3) turned by 180°

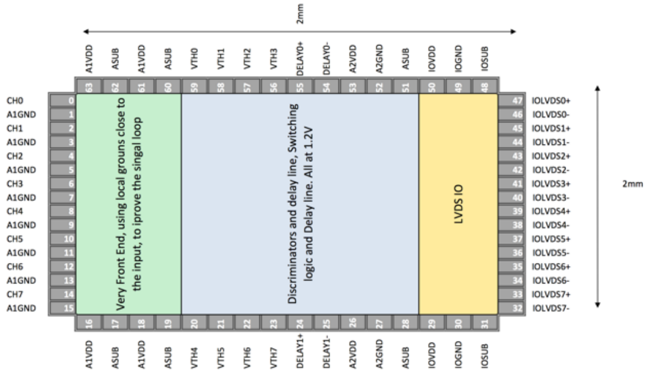
CT-PPS read-out system

Two readout systems under developments:





- Noise performance: ~ 500 ENC for 6pF detector
  (slope 50 ENC/pF)
- Design of the comparator completed
- Implementation of Time Over Threshold for time walk compensation
- Submission date: May (130 nm)
- Ready in July



Next Steps

1. Wafer Productions

   New production company, FBK in Trento

   50 micron thick sensors by **Summer 2016.**

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

   ➔ This will be the first system demonstrator: segmented silicon, with 30 ps time resolution.

5. New testbeams coming this summer

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

UFSD - Shot noise

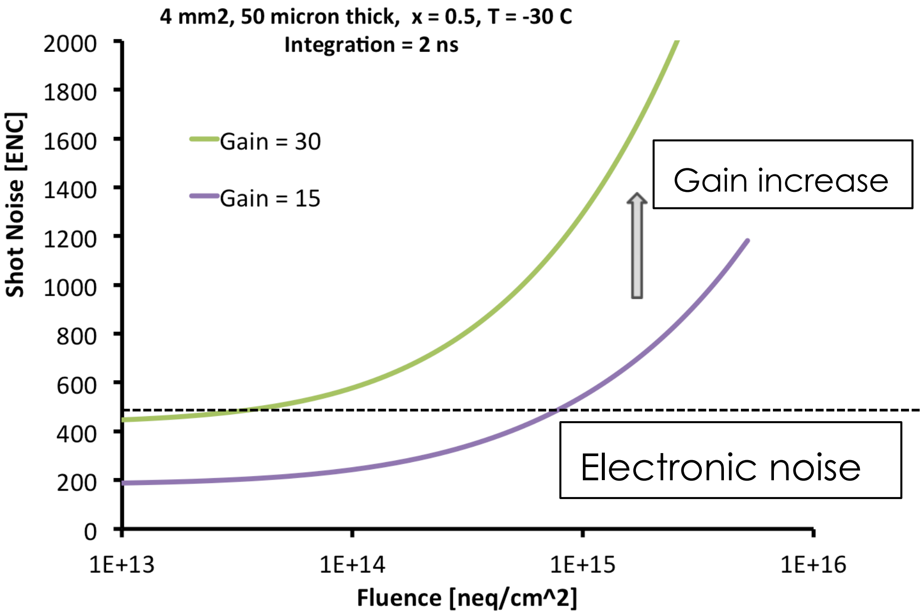
Let's assume a 4 mm^2 pad, 50 micron thick, and a electronic noise of 500 ENC

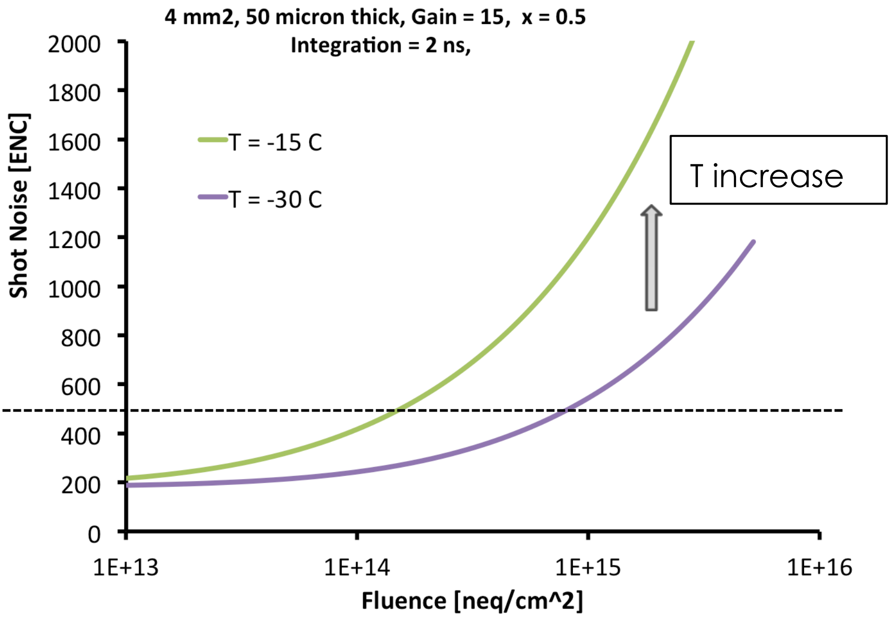
What is the effect of shot noise as a function of radiation?

$I = \alpha * \Phi *$ Volume $\quad \alpha = 3\ 10^{-17}$ /cm

Shot noise: $$ENC = \sqrt{\int i^2_{Shot}\, df} = \sqrt{\frac{I * (Gain)^{2+x}}{2e} * \tau_{Int}}$$

Steep dependence on gain





To minimize Shot noise:

- ➔ Low gain!! Keep the gain below ~ 20
- ➔ Cool the detectors
- ➔ Use small pads to have less leakage current

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:

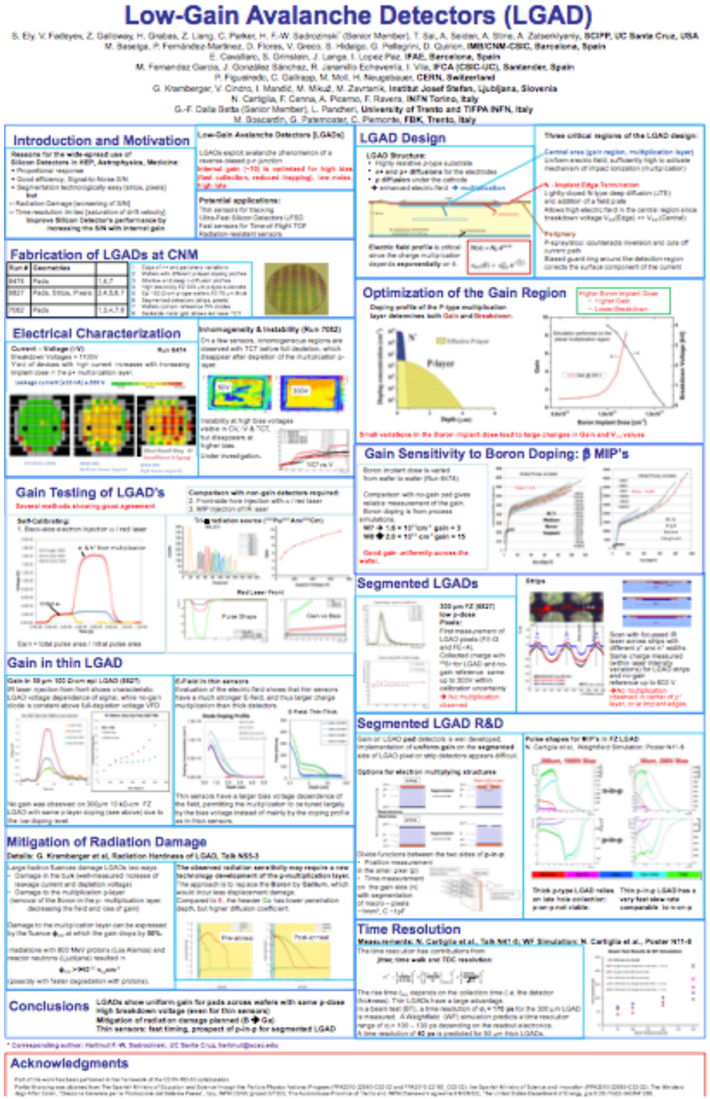
$$\sigma_t \propto \frac{\text{Noise}}{dV/dt}$$

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**
M. Baselga, P. Fernández-Martínez, D. Flores, V. Greco, S. Hidalgo, G. Pellegrini, D. Quirion, **IMB/CNM-CSIC, Barcelona, Spain**
E. Cavallaro, S. Grinstein, J. Lange, I. Lopez Paz, **IFAE, Barcelona, Spain**
M. Fernandez Garcia, J. González Sánchez, R. Jaramillo Echeverria, I. Vila, **IFCA (CSIC-UC), Santander, Spain**
P. Figueiredo, C. Gallrapp, M. Moll, H. Neugebauer, **CERN, Switzerland**
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

Optimization of the Gain Region

Electrical Characterization

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

Acknowledgements

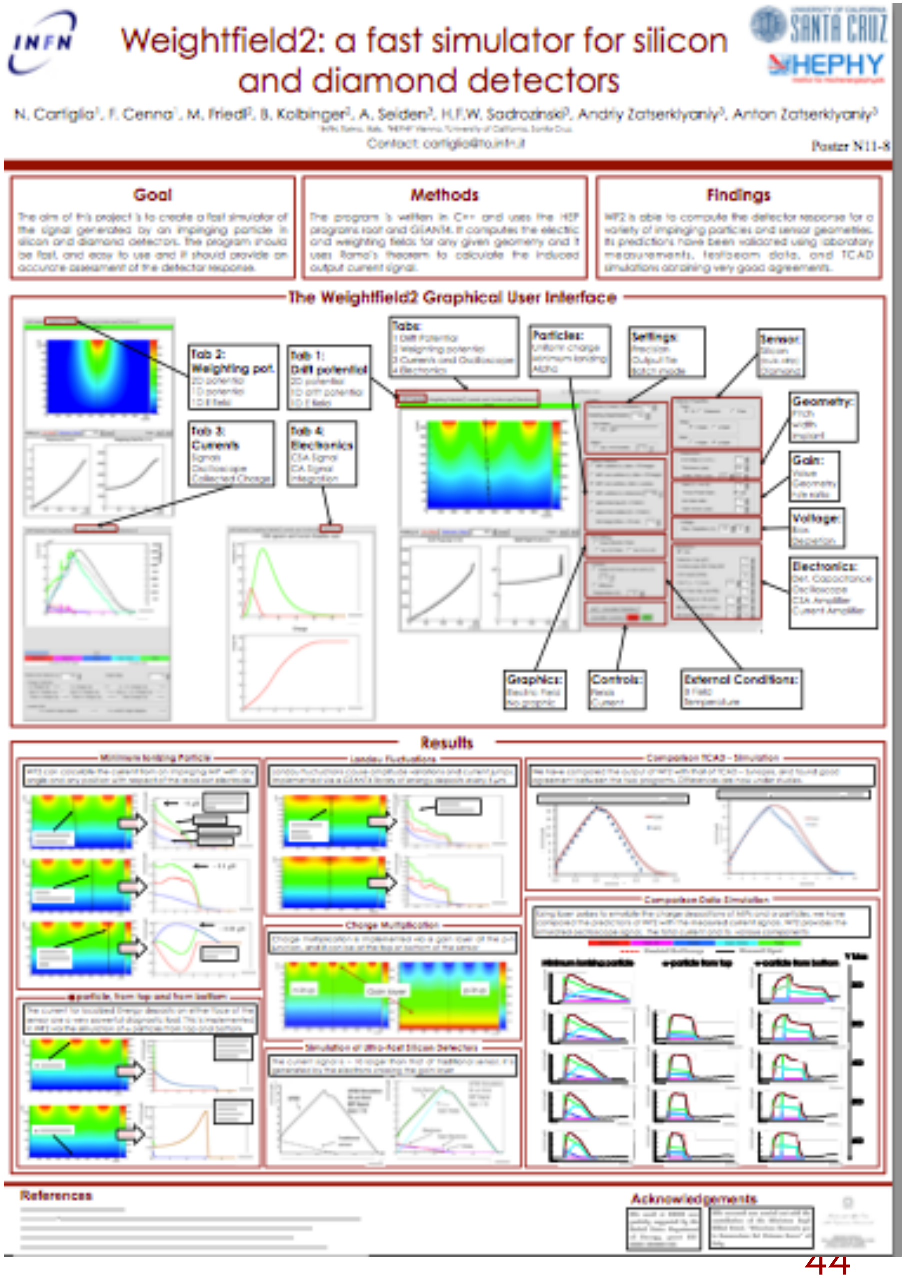
Poster Session IEEE N26-13

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

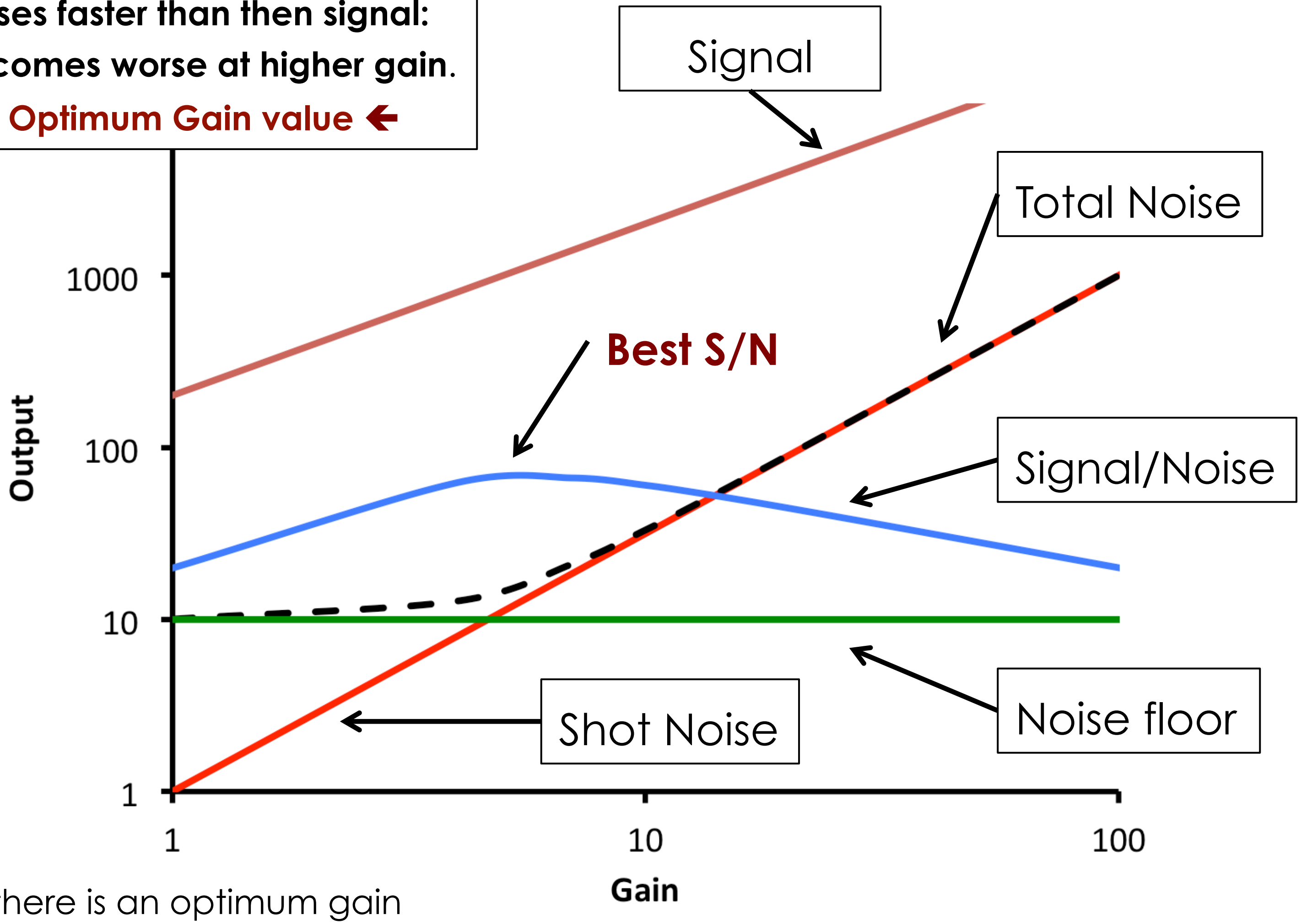
Acknowledgements

Poster Session IEEE N11-8

UFSD Optimum S/N

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

➔There is an Optimum Gain value 🡐



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

Noise for Gain = 1 and Gain = 10

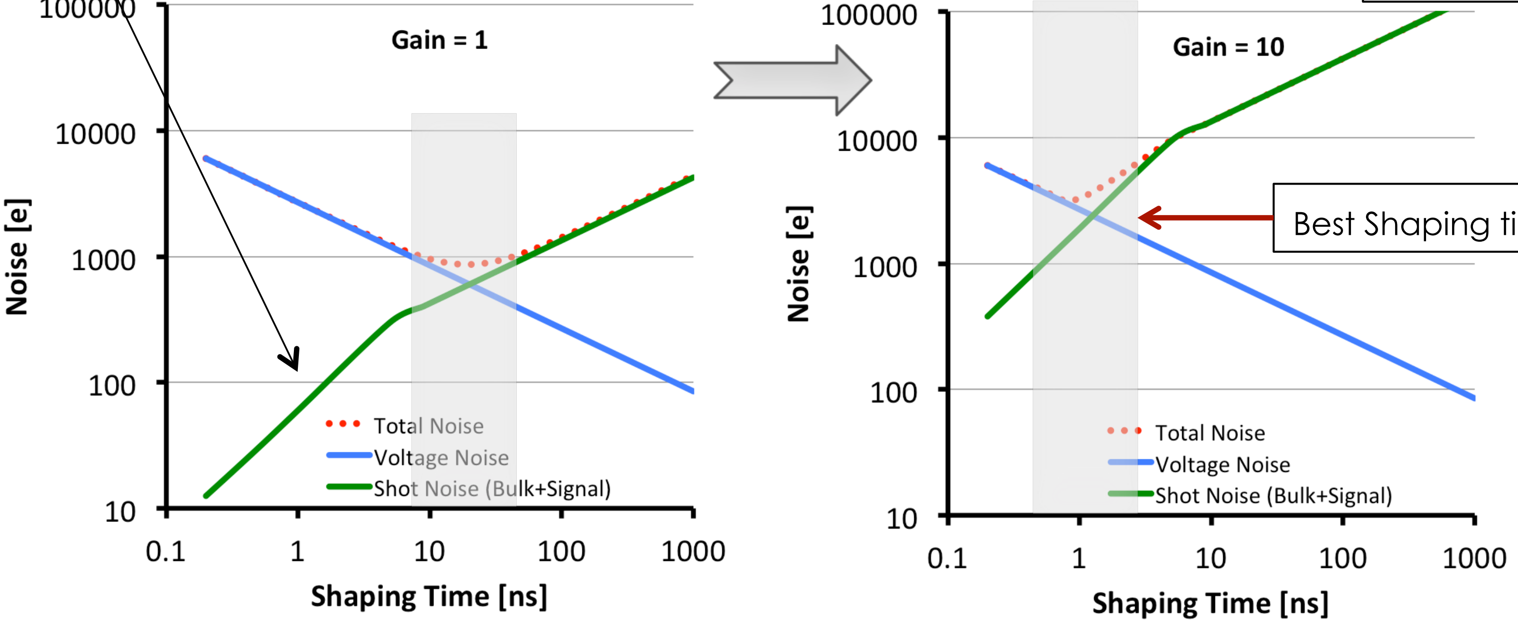
Let's use the following parameterization (Spieler, Semiconductor Detector, pag 35):

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

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.

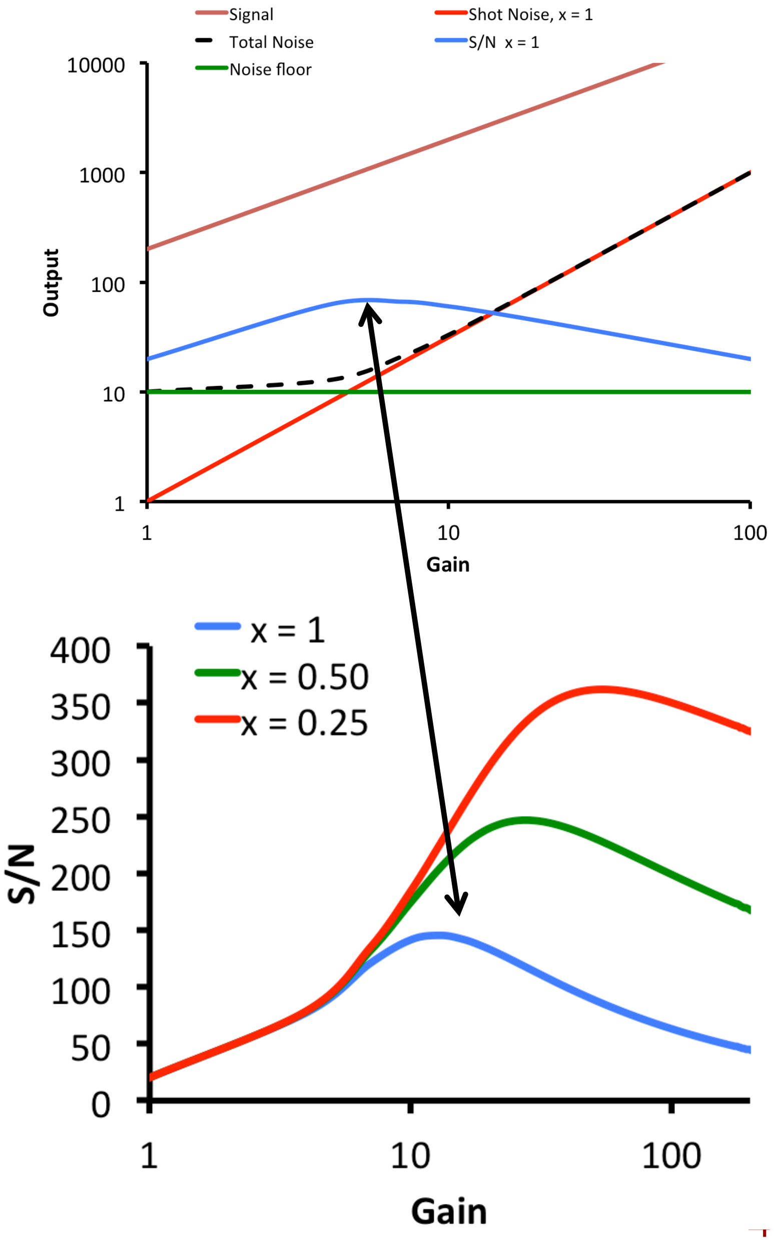
➔There is an Optimum Gain value ➔

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

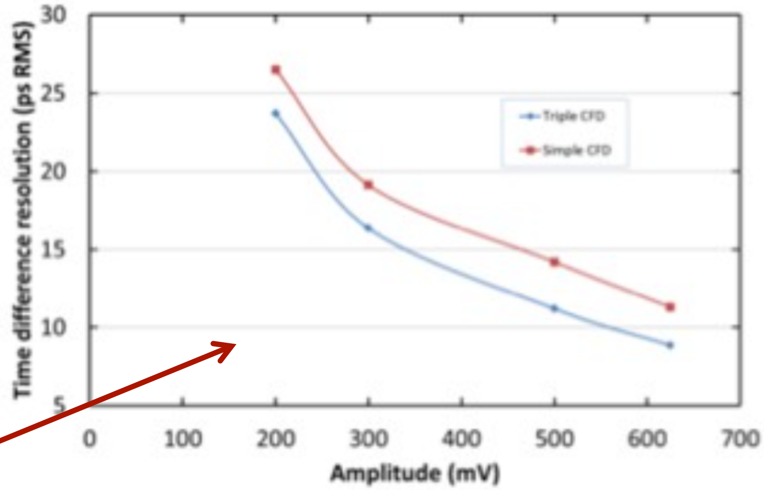
Summary

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



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

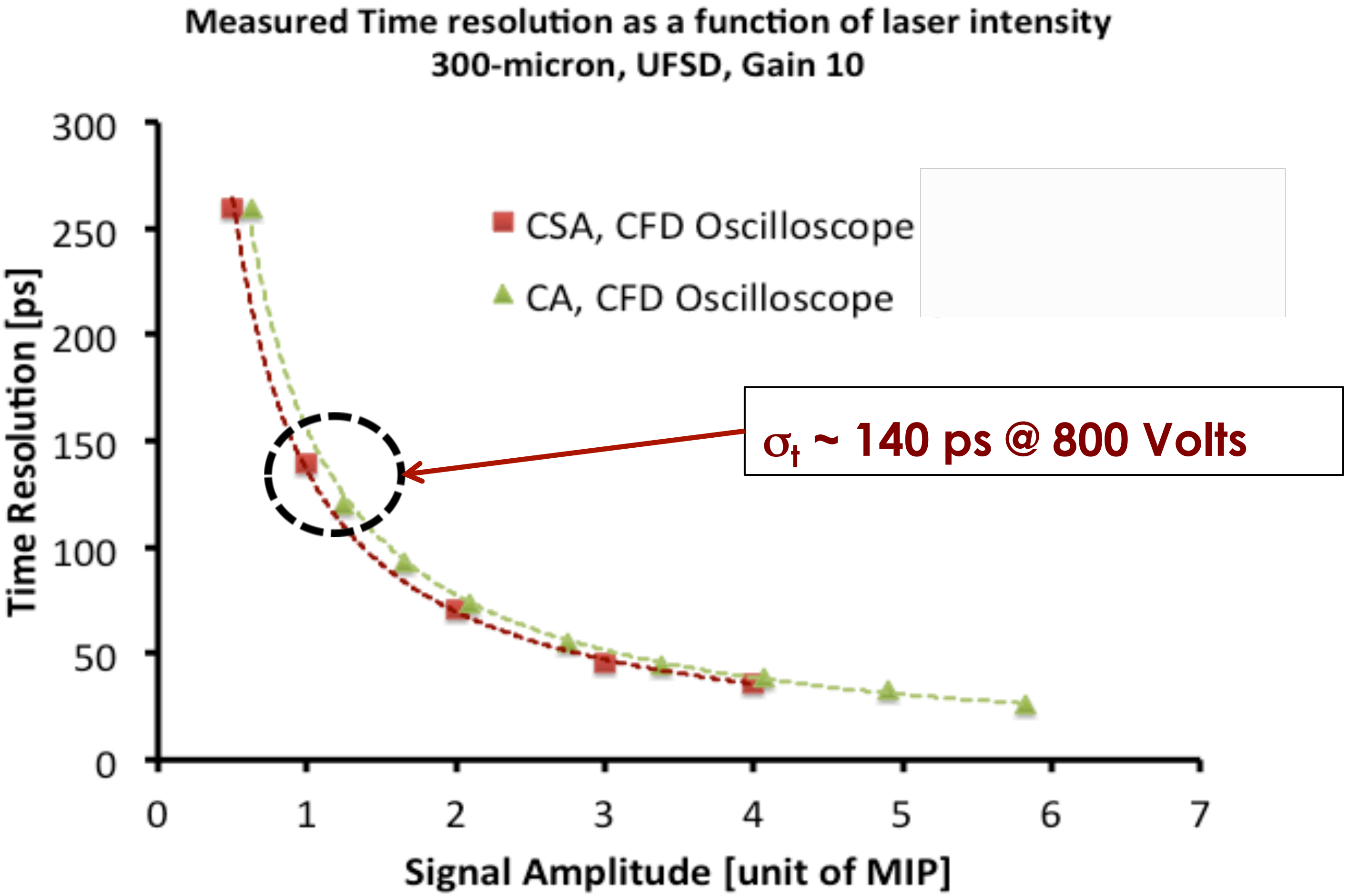
See:

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

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)



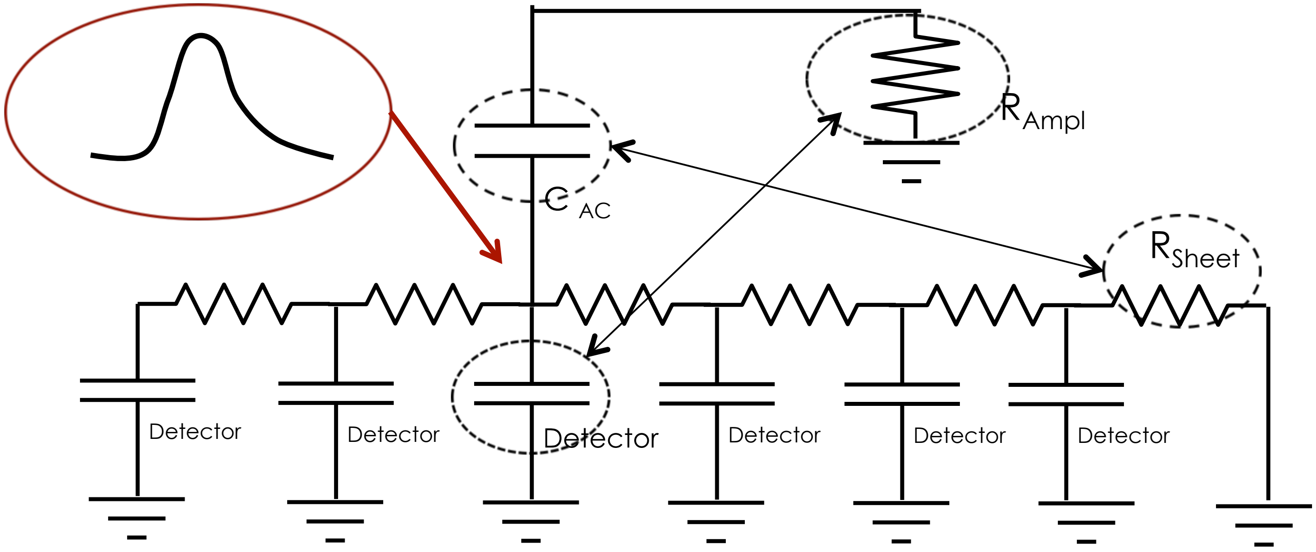
Measured Time resolution as a function of laser intensity
300-micron, UFSD, Gain 10

σ_t ~ 140 ps @ 800 Volts

Details of Resistivity and AC coupling

Additional Rise time

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

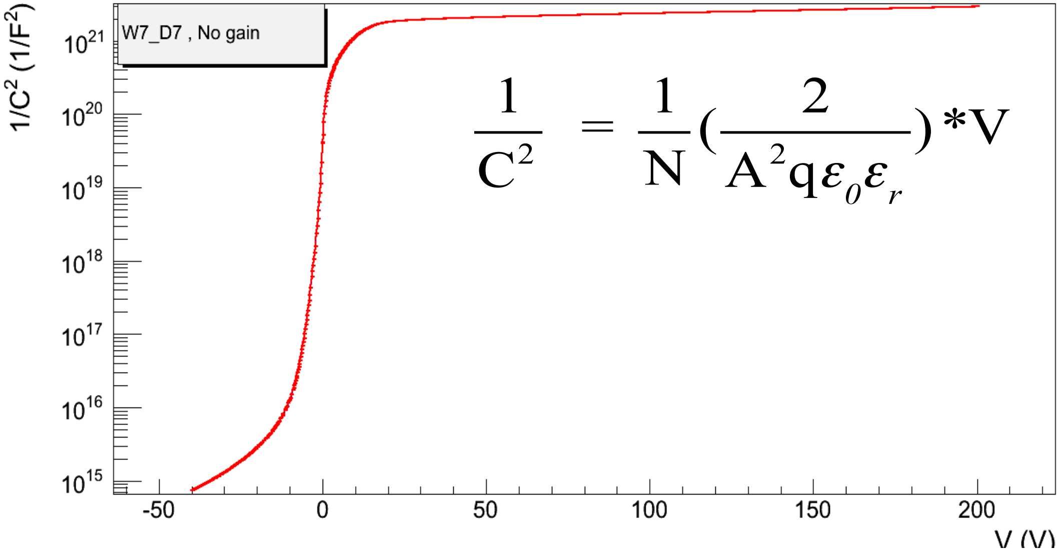


Freezing time

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

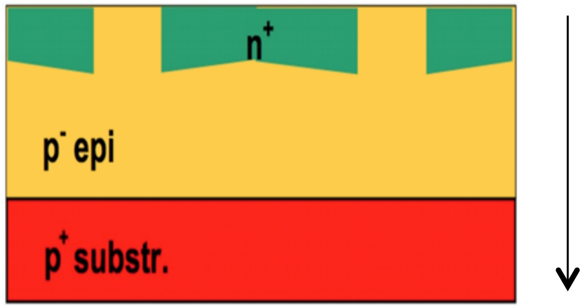
Only a small part of the detector is involved

Doping profile from CV measurement - I

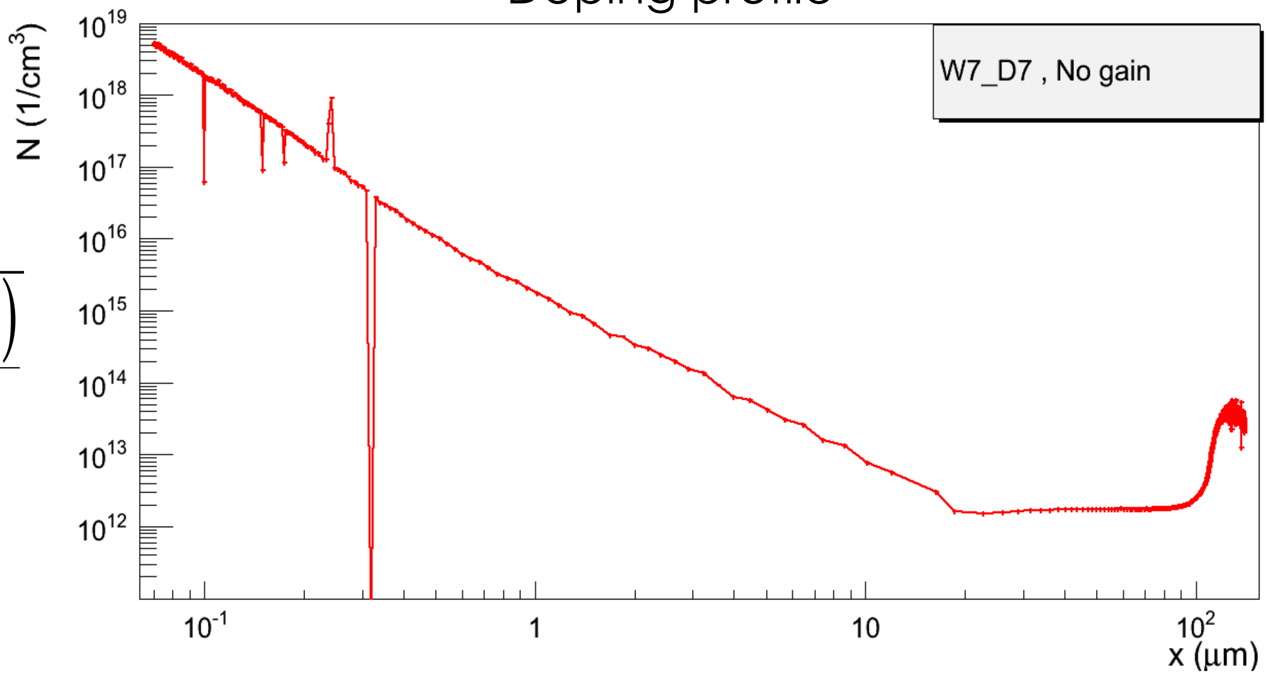


$$\frac{1}{C^2} = \frac{1}{N}\left(\frac{2}{A^2 q\varepsilon_0\varepsilon_r}\right)*V$$

No-gain sensor



Doping profile



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

Doping

TOFFEE chip: custom made for UFSD read-out

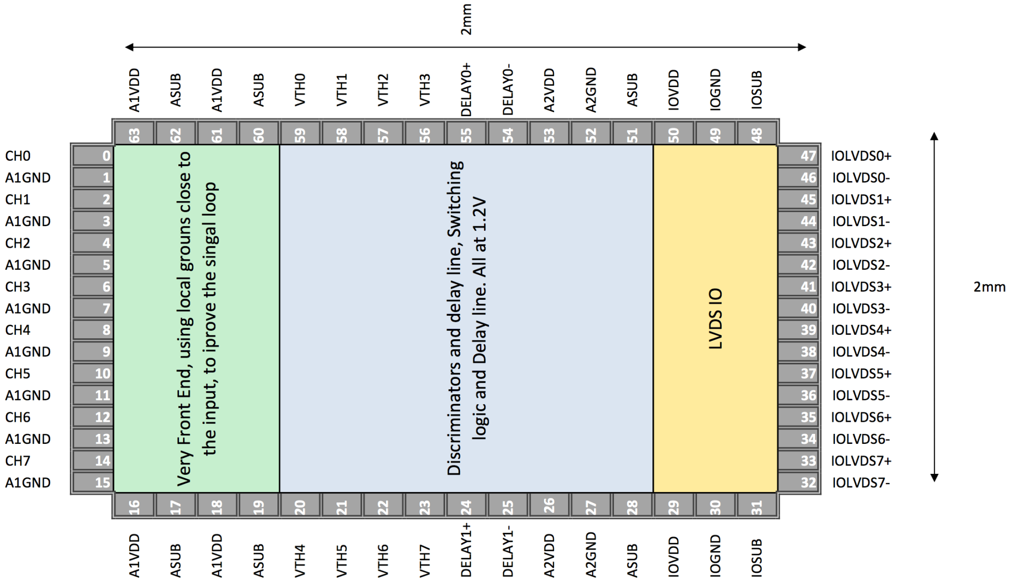
Fully custom made chip for UFSD read-out
130 nm IMEC (UTM), 1.2 V, 8 mW/ch.

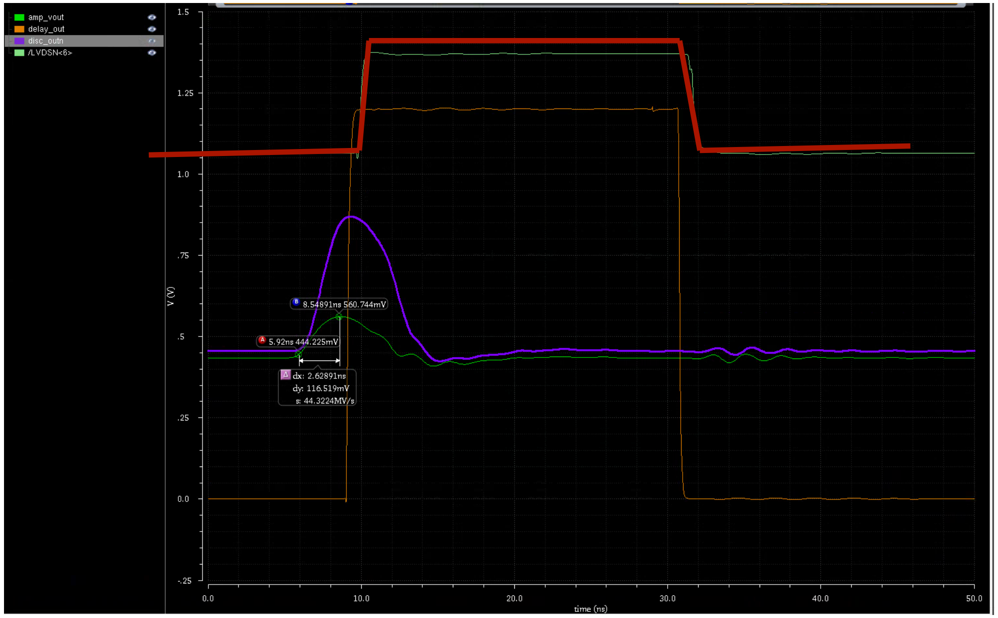
Time_over_Threshold output

LVDS output signals

Submitted last week

Available mid summer



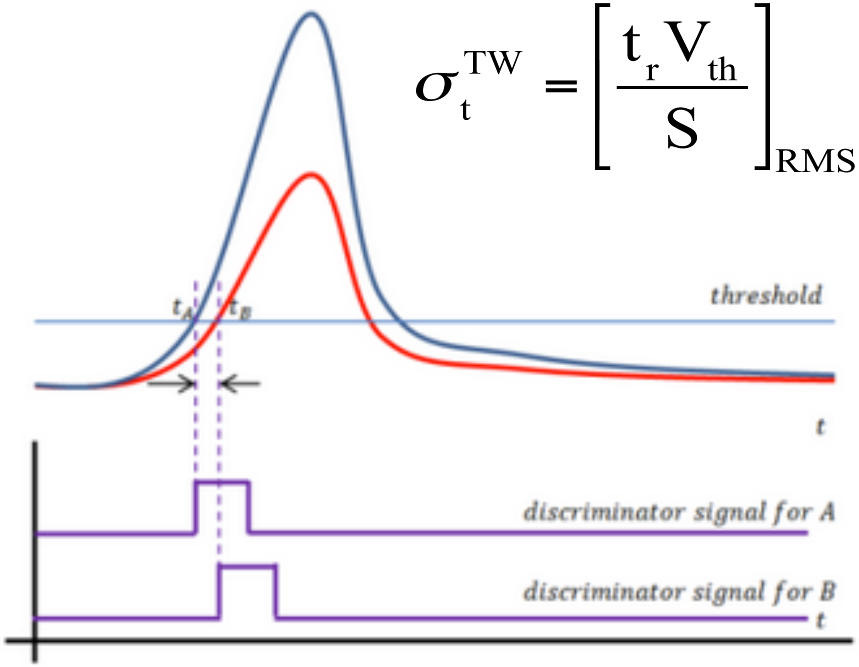


Time walk and Time jitter

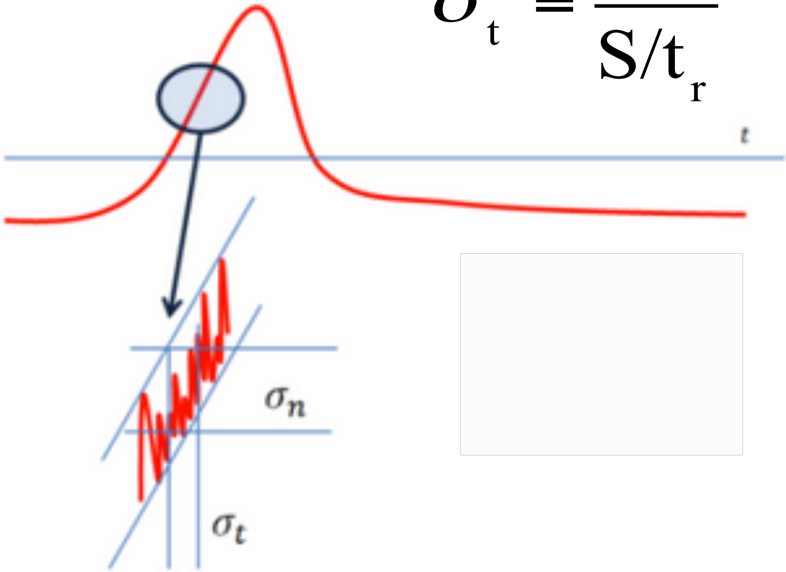
Time walk: the voltage value V_{th} is reached at different times by signals of different amplitude

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

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