Ultra-Fast Silicon Detectors

- Low Gain Avalanche Detectors for timing: UFSD
- Analysis of the parameters influencing time resolution
- Testbeam results
- R&D community and funding
- UFSD for real experiments

INFN and Torino University, UC Santa Cruz

Nicolo Cartiglia, INFN, Torino

Time resolution

$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + ?$$

Usual "Jitter" term

Time walk and Shape variations

Amplifier non ideal behavior

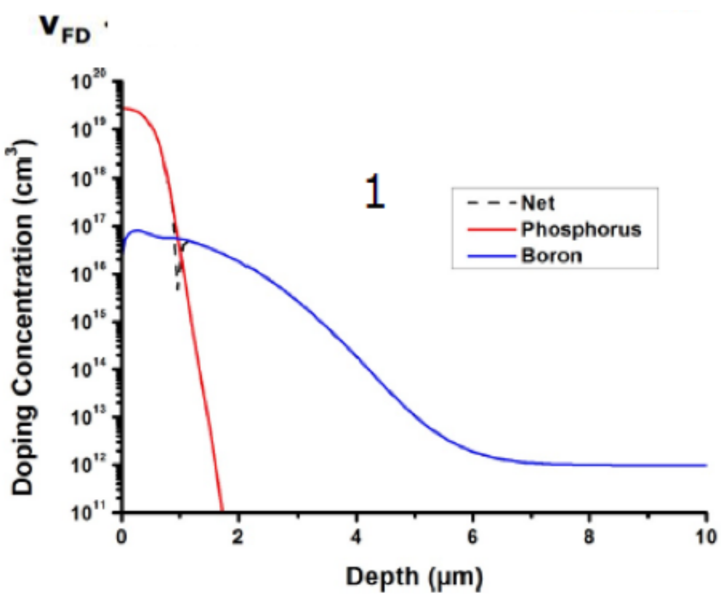
Low Gain Avalanche Detectors (LGADs)

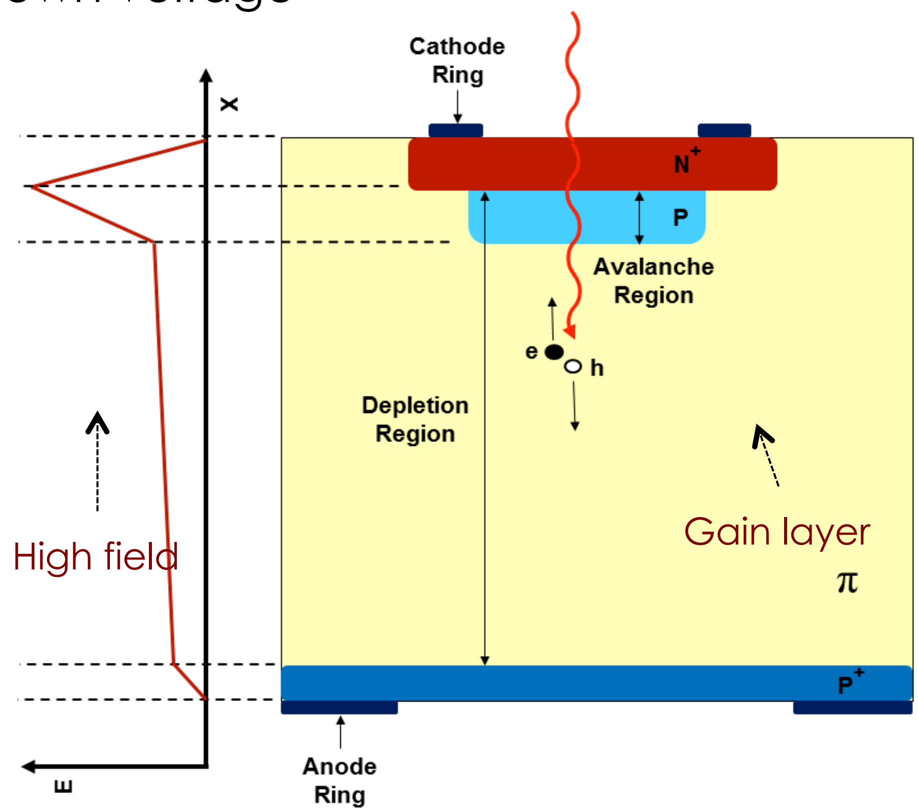
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage





LGAD are a cross breed between APD and standard sensor

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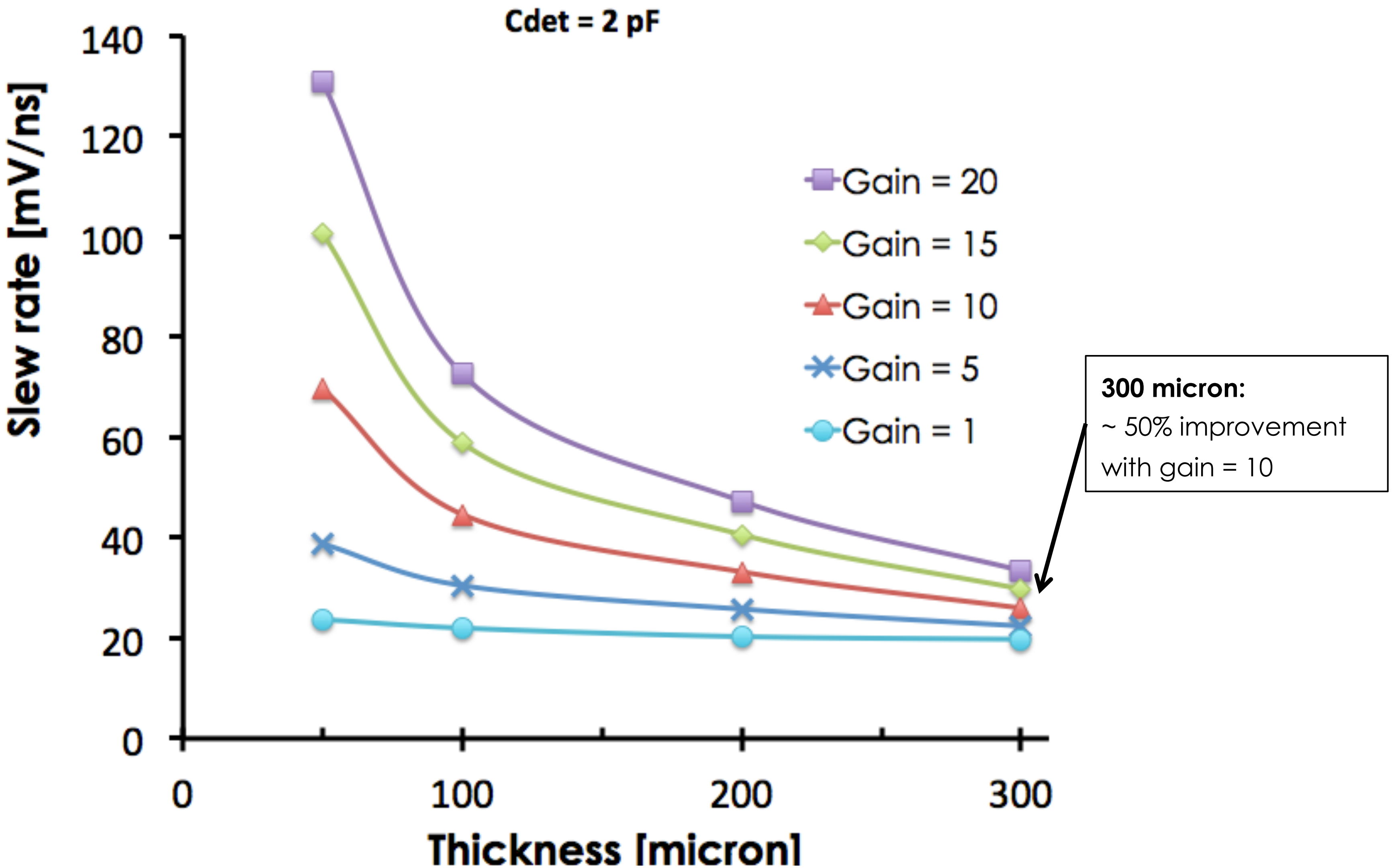
Slope and detector thickness



Significant improvements in time resolution require thin detectors

Ultra Fast Silicon Detectors

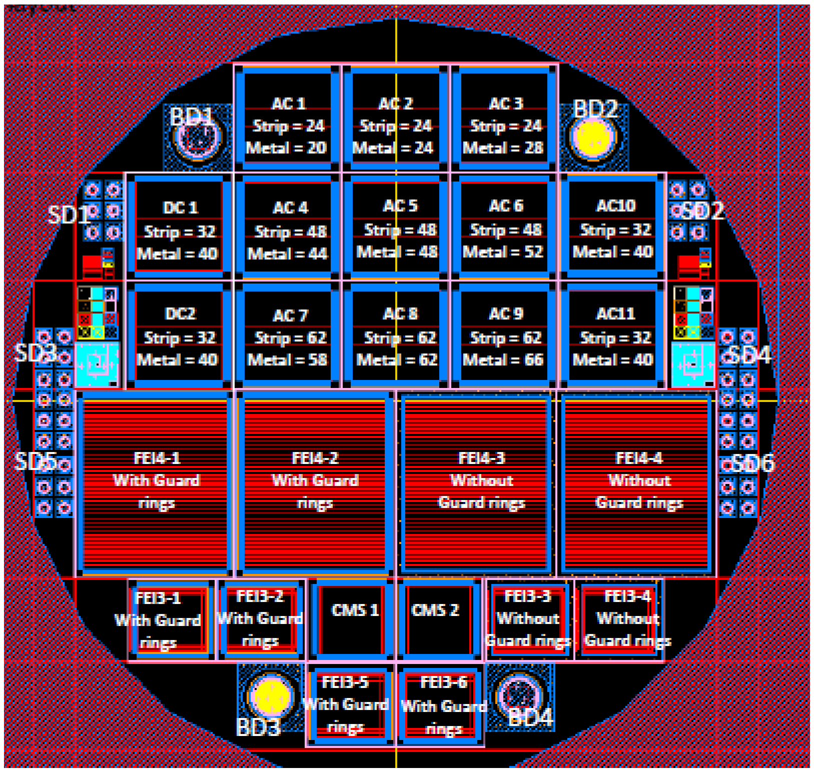
UFSD are LGAD detectors optimized to achieve the best possible time resolution

Specifically:

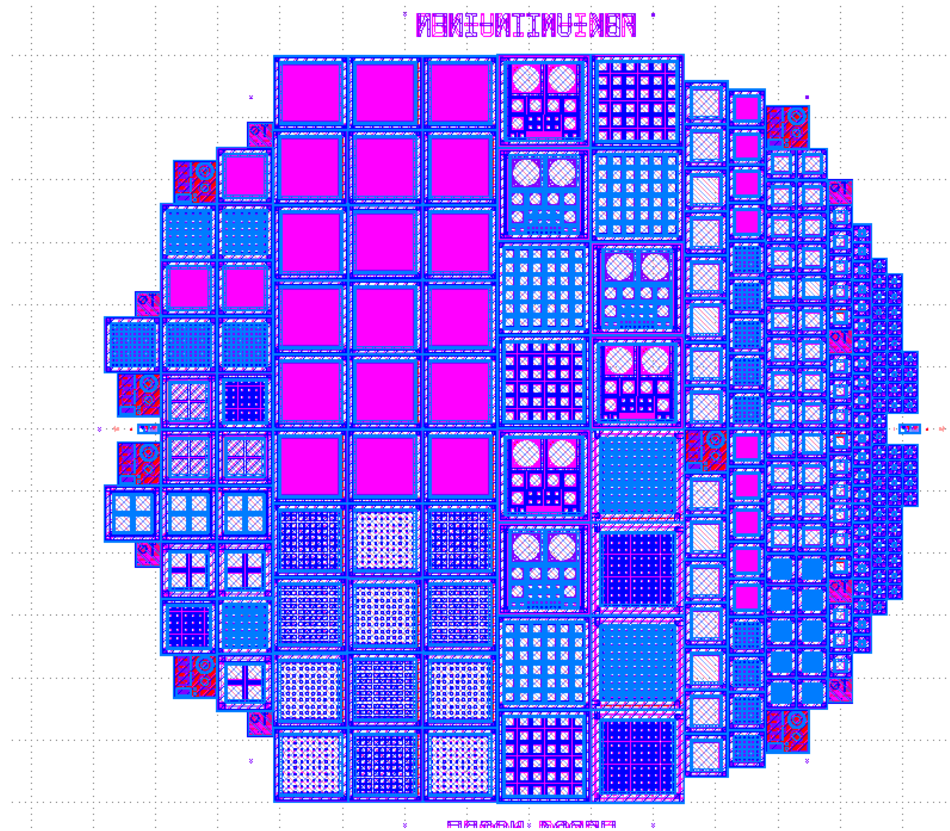
1. Thin to maximize the slew rate (dV/dt)
2. Parallel plate – like geometries (pixels..) for most uniform weighting field
3. High electric field to maximize the drift velocity
4. Highest possible resistivity to have uniform E field
5. Small size to keep the capacitance low
6. Small volumes to keep the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

FBK and CNM productions

As you can see, a lot of geometries and innovations



CNM- Barcelona



FBK - Trento

Simulation

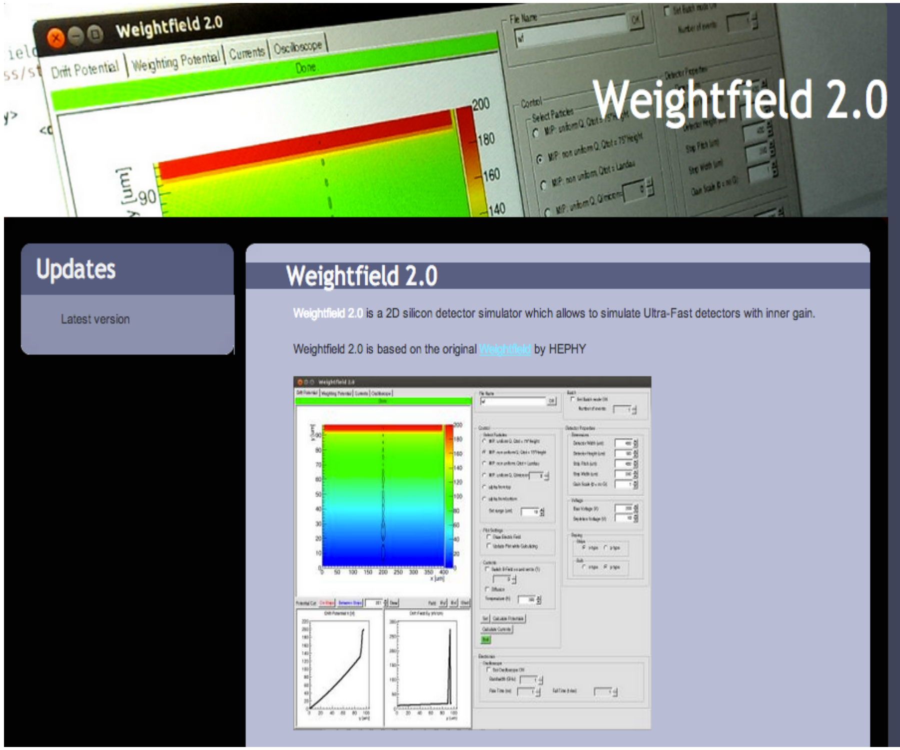
We developed a full sensor simulation to optimize the sensor design

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

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

It includes:

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



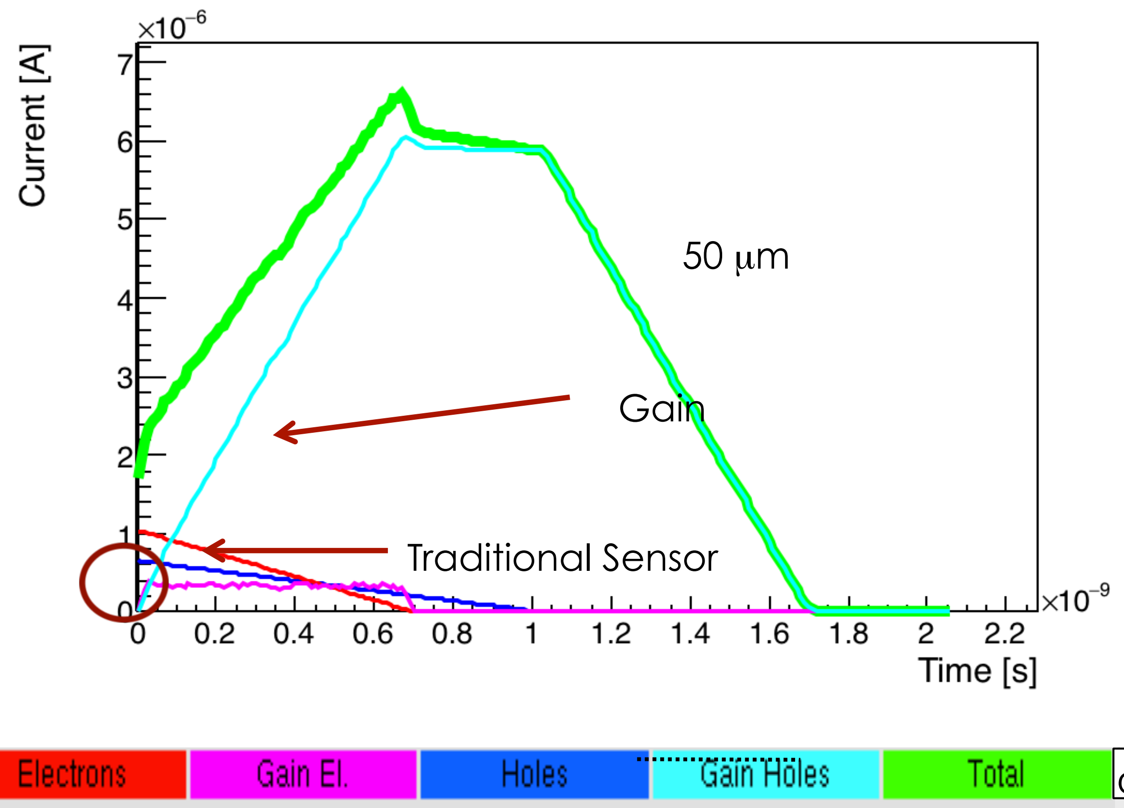
For each event, it produces a file with the current output that can be used as input in the simulation of the electronic response.

Signal characteristics

Nicolo Cartiglia, INFN, Torino

The signal from UFSDs is different from that of traditional sensors:

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



Simulated Weightfield2

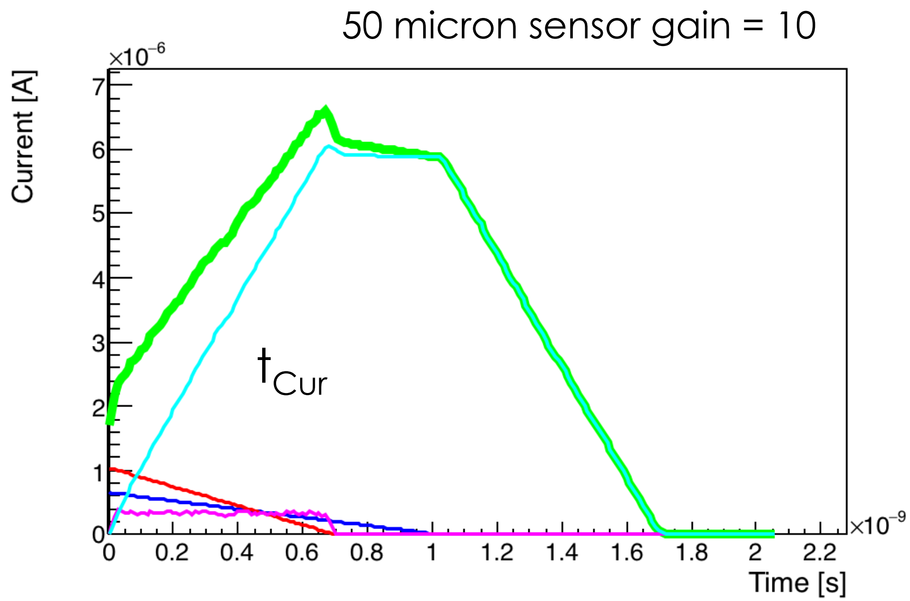
Traditional sensors

Charges generated uniquely by the incident particle

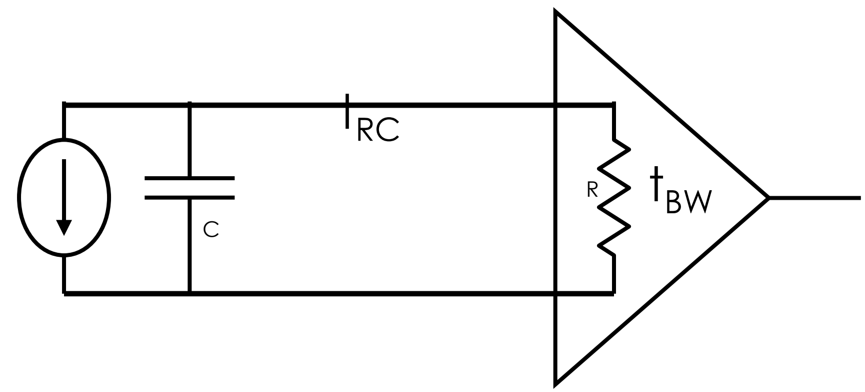
Ultra-Fast Silicon Detectors

Current due to gain holes creates a longer and higher signal

Analysis of the noise and rise-time



$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2$$



The current rise time (t_{Cur})

The RC circuit (t_{RC})

Amplifier BW f (t_{BW} ~0.35/f)

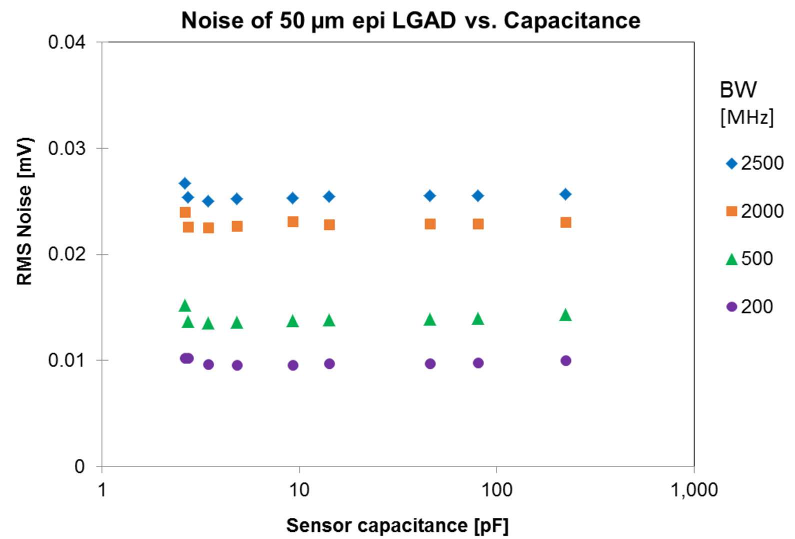
There are 3 quantities determining the output rise time after the amplifier:

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

Electronic noise in BB amplifiers

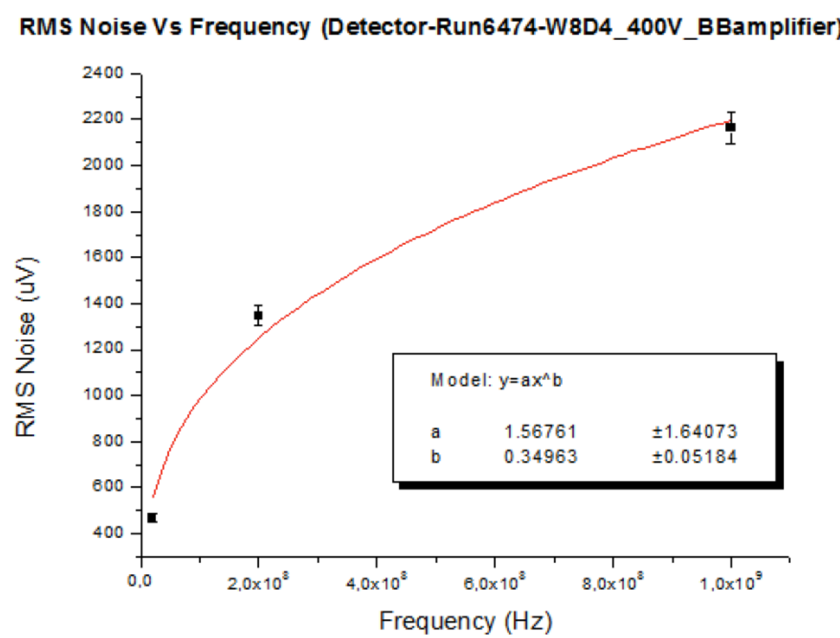
For capacitive sources, the input capacitance is not a noise source.

With Broad Band amplifier, the input capacitance has no effect on the RMS noise



The electronic noise goes like sqrt(BW)

$$N \propto \sqrt{BW} \sim \frac{0.35}{\sqrt{t_{BW}}}$$

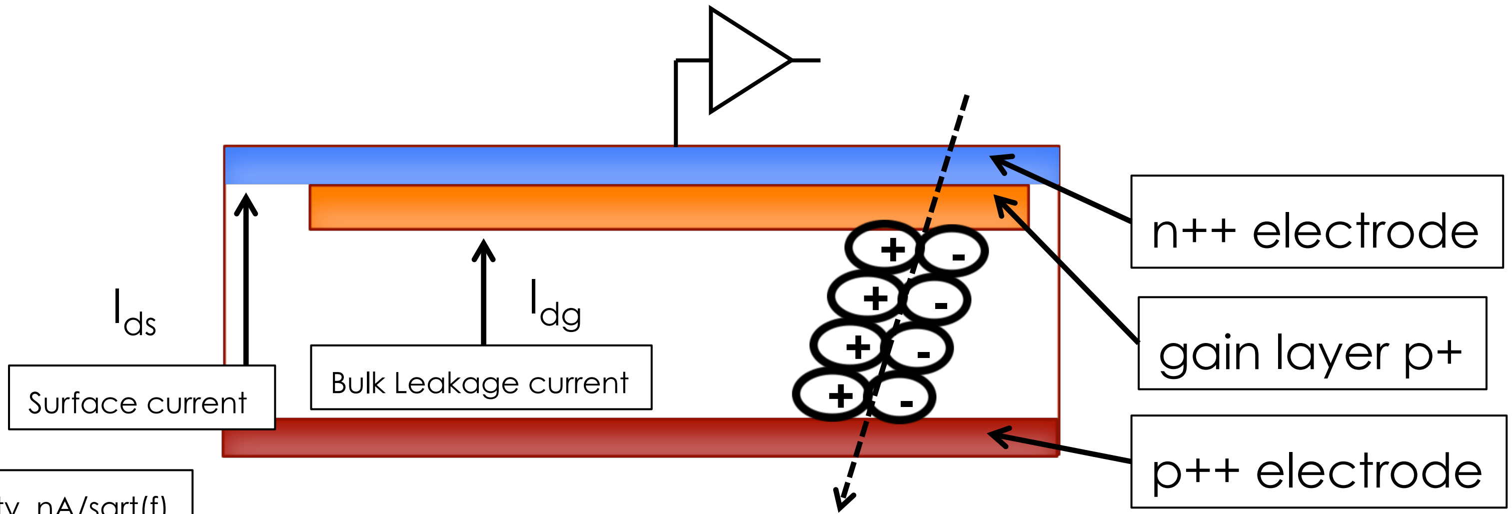


Our current best design:

Noise =15 uV

(input noise, 1 GHz BW)

Shot noise in LGAD - APD



Current density, nA/sqrt(f)

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

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

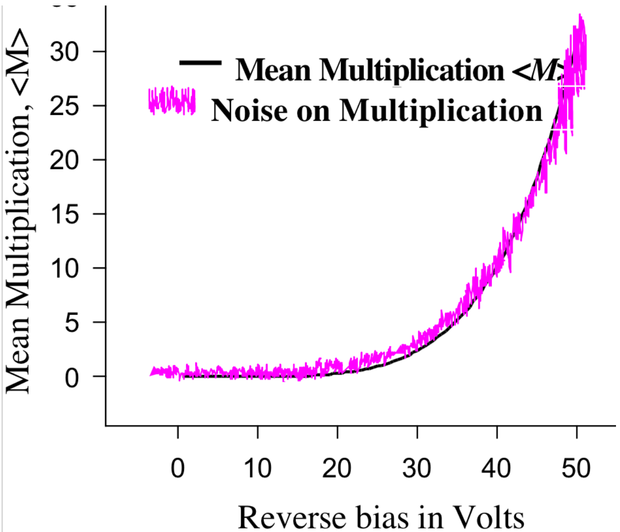
$$F = Mk + \left(2 - \frac{1}{M}\right)(1-k)$$

$$F \sim M^x$$

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

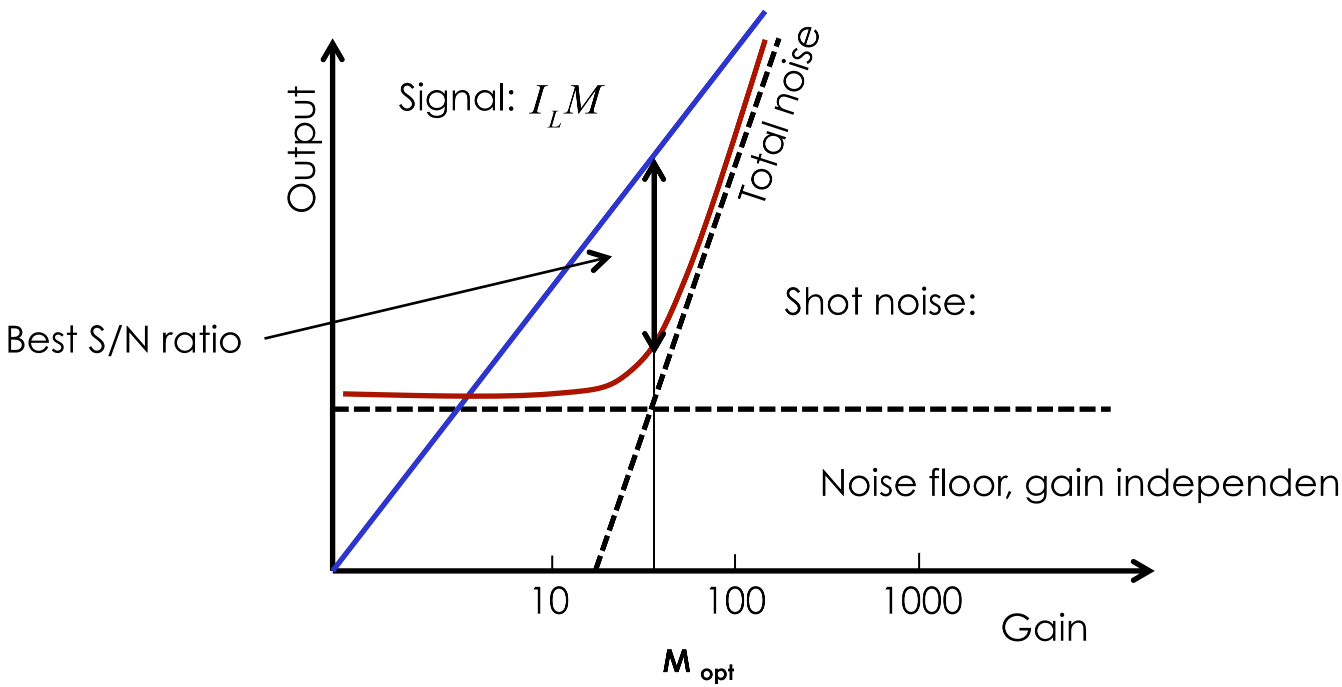
k = e/h ionization rate
x = excess noise index
M = gain

Noise in LGAD & APD – Aide Memoire



Noise increases faster than then signal ➔ the ratio S/N becomes worse at higher gain.

There is an Optimum Gain value: 10-20?



The Shot noise voltage term

Let's assume a 4 mm² pad, 50 micron thick.

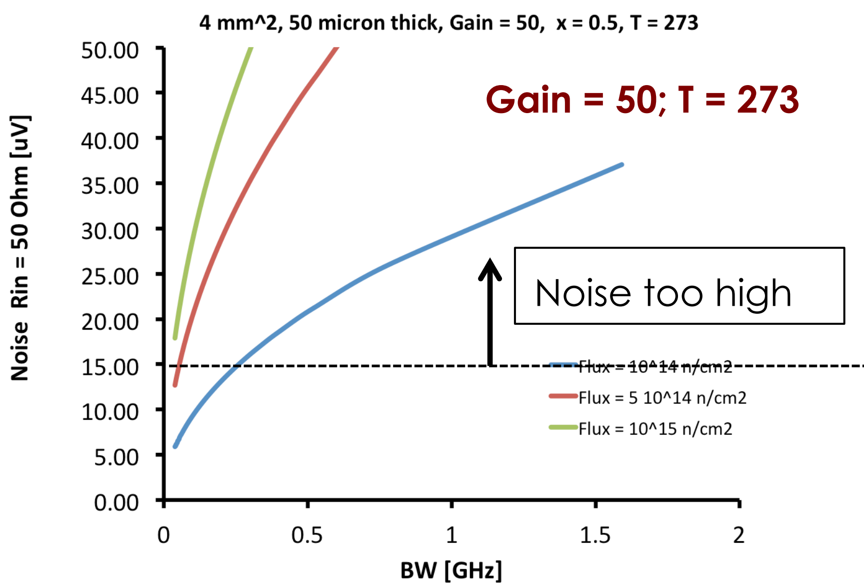
What is the effect of shot noise as a function of radiation?

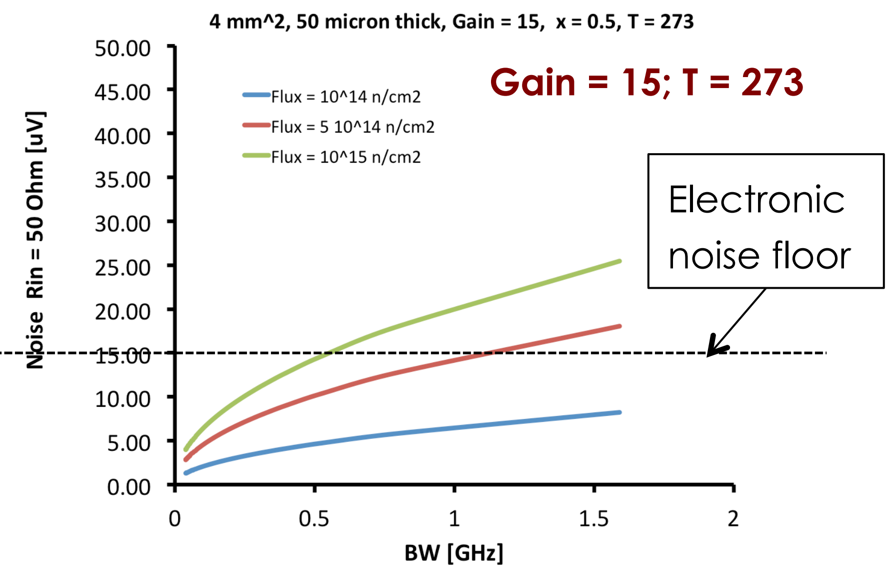
$I = \alpha * \Phi * \text{Volume} \qquad \alpha = 3\ 10^{-17}$ /cm

Steep dependence on gain

Shot noise: $$i = \sqrt{\int i^2_{Shot}\, df} = \sqrt{2eI * (Gain)^{2+x} * BW}$$

Voltage Shot noise: $$v_{Shot} = i_{Shot} * R_{input}$$





Voltage Shot noise:

- ➔ **Cool the detectors by 20-30 degrees**
- ➔ **Low gain!! Keep the gain below ~ 20**

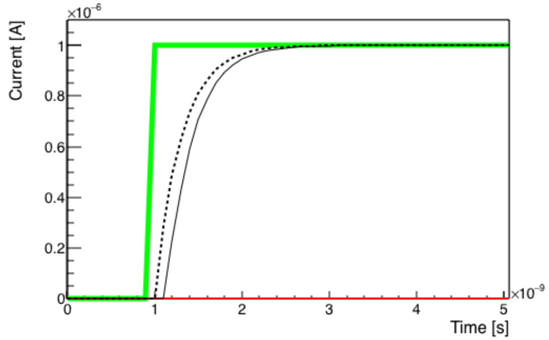
The slope term: dV/dt

The rise time of the output signal is due to the sum of the current rise time, the RC system and the amplifier BW:

$$\tau_{rise} = \sqrt{\tau_{Cur}^2 + \tau_{RC}^2 + \tau_{BW}^2}$$

For a BB amplifier, the general output is:

$$V(t) \propto \text{Gain}\,(1. - e^{-t/\tau_{rise}})$$



And the derivative is:

$$\frac{dV}{dt} \propto \text{Gain}\,\frac{1}{\tau_{rise}}\,e^{-t/\tau_{rise}}$$

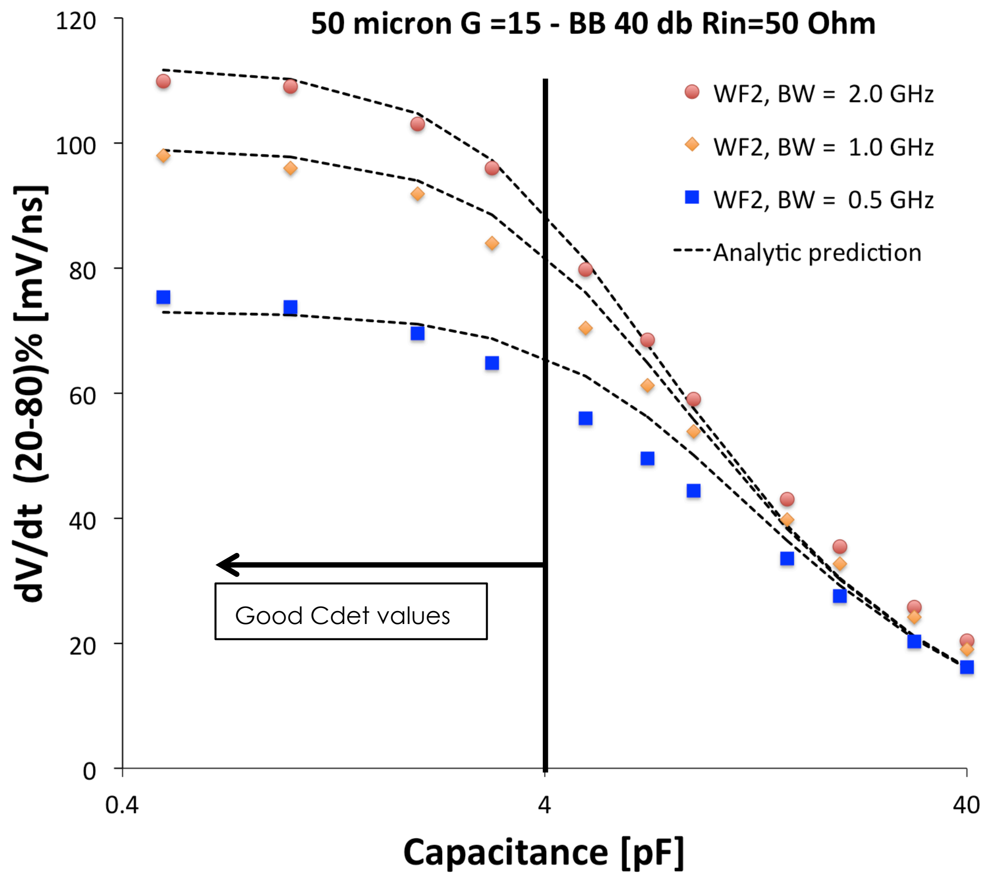
What is controlling the slope? Capacitance and BW

In the following:

1. τ_{Cur} = 150 ps, as it is for 50 micron detectors
2. τ_{RC} : R = 50 Ohm and I varied C (obviously it's identical to do the opposite)
3. τ_{BW} : BW: 0.5 GHz, 1 GHz, 2 GHz
4. Analytic expression: derivative calculated after 100 ps $\frac{dV}{dt}\Big|_{t_0=100\,ps} \propto \text{Gain}\,\frac{1}{\tau_{rise}}\,e^{-t_0/\tau_{rise}}$

➔ **The detector capacitance does not increase the noise but it decreases the signal!**

➔ **Need to keep Cdet < 4-6 pF**



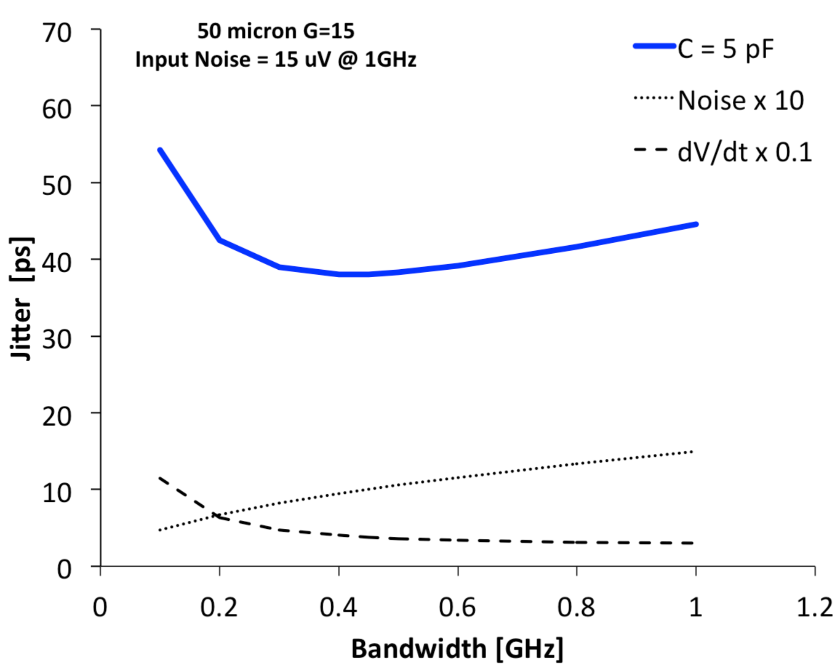
Determination of the best BW

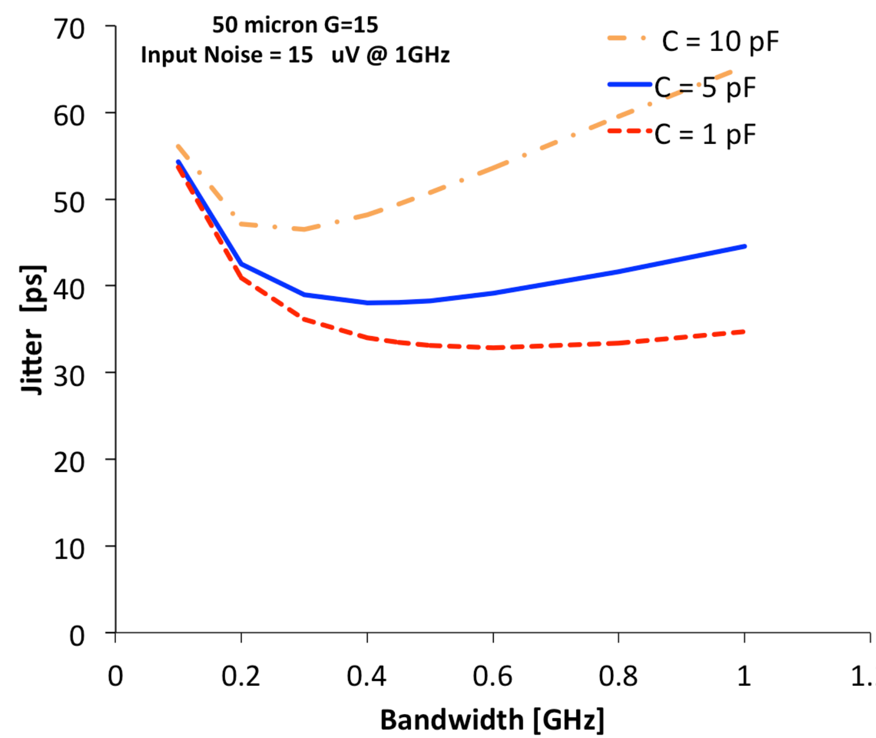
Let's calculate the jitter term as a function of BW

$$\text{Jitter} = N \frac{1}{dV/dt|_{t_0=100\,ps}} = \frac{k}{\sqrt{t_{BW}}} \frac{1}{\text{Gain}\, \frac{1}{\tau_{rise}} e^{-t_0/\tau_{rise}}} = \frac{k}{\text{Gain}} \frac{\tau_{rise}}{\sqrt{t_{BW}}} e^{t_0/\tau_{rise}}$$

Normalization: N = 15 uV @ 1GHz

$$\tau_{Rise} = \sqrt{\tau_{Cur}^2 + \tau_{RC}^2 + \tau_{BW}^2}$$



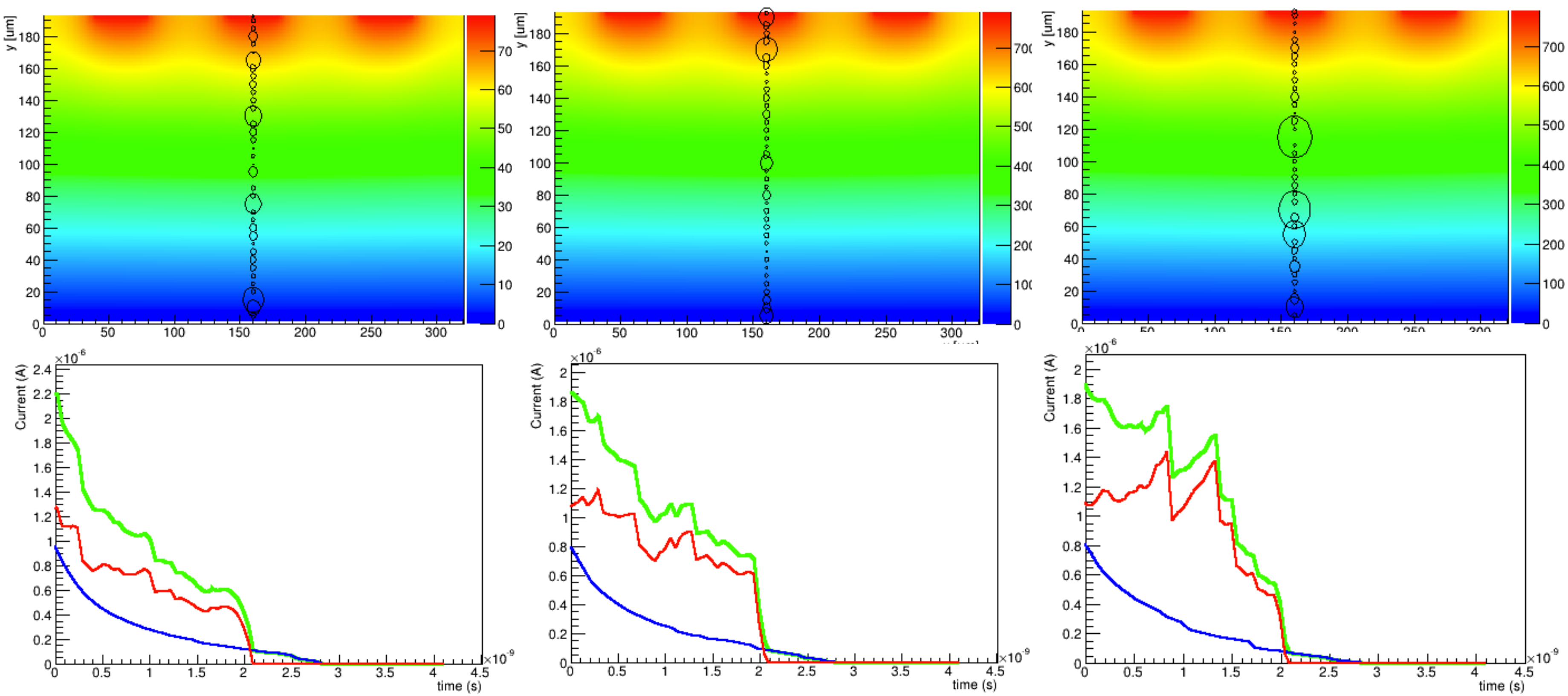


Broad minimum at BW ~ 4-500 MHz with Cdet = 5 pF: Jitter ~ 40 ps

Landau Fluctuations

Landau Fluctuations cause two major effects:

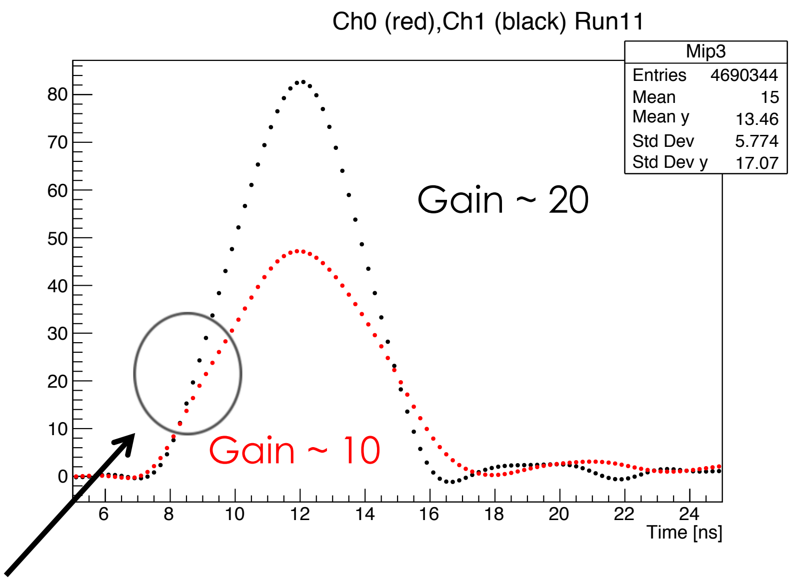
- Amplitude variations ➔ assume perfect time walk compensation
- Non uniform ➔ much harder to compensate

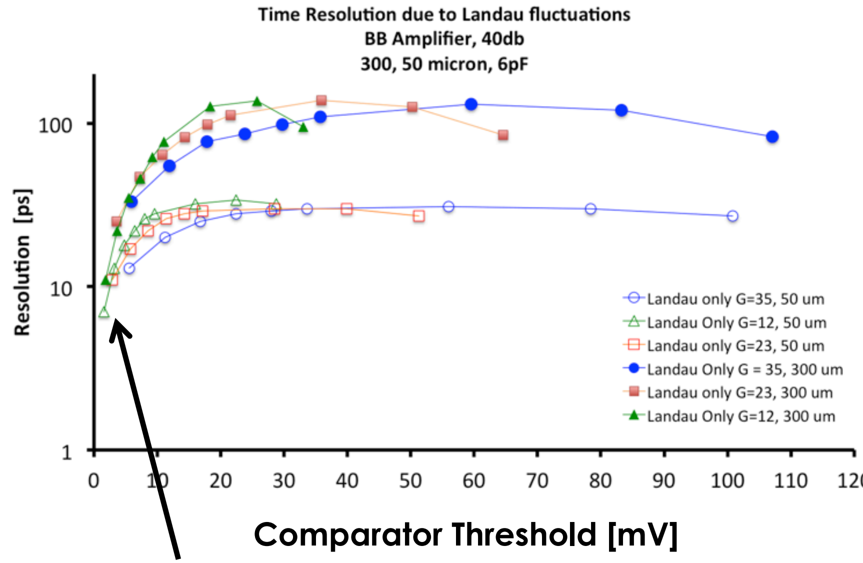


What is the best approach to smooth the fluctuations and retain very fast signals?

Nicolo Cartiglia, INFN, Torino

Determination of the best comparator threshold





To maximize dV/dt

place Vth at 20-30% of the curve

To minimize Landau Fluctuations:

place Vth as low as possible

Best compromise at Vth ~ 15% of the maximum

Thin sensors:

Much less sensitive to Landau fluctuation

Gains~ 15-20 allow for higher thresholds, well above the noise

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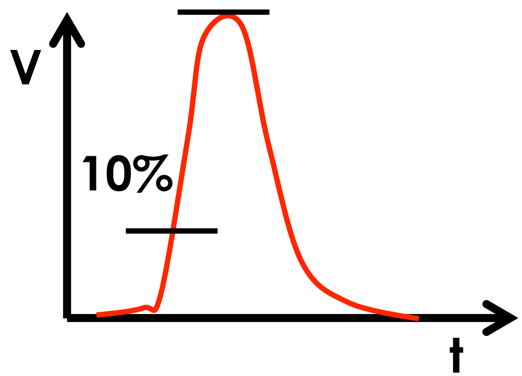
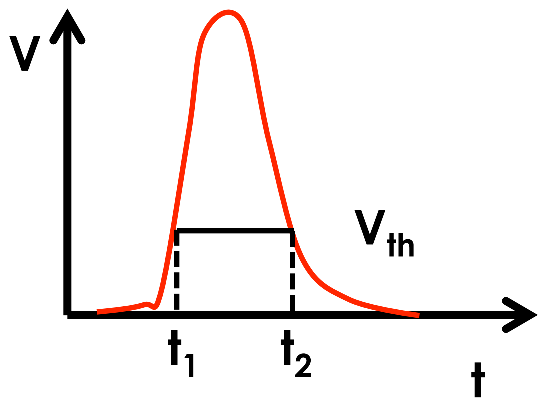
Time walk compensating circuit



Constant Fraction Discriminator

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



Time over Threshold

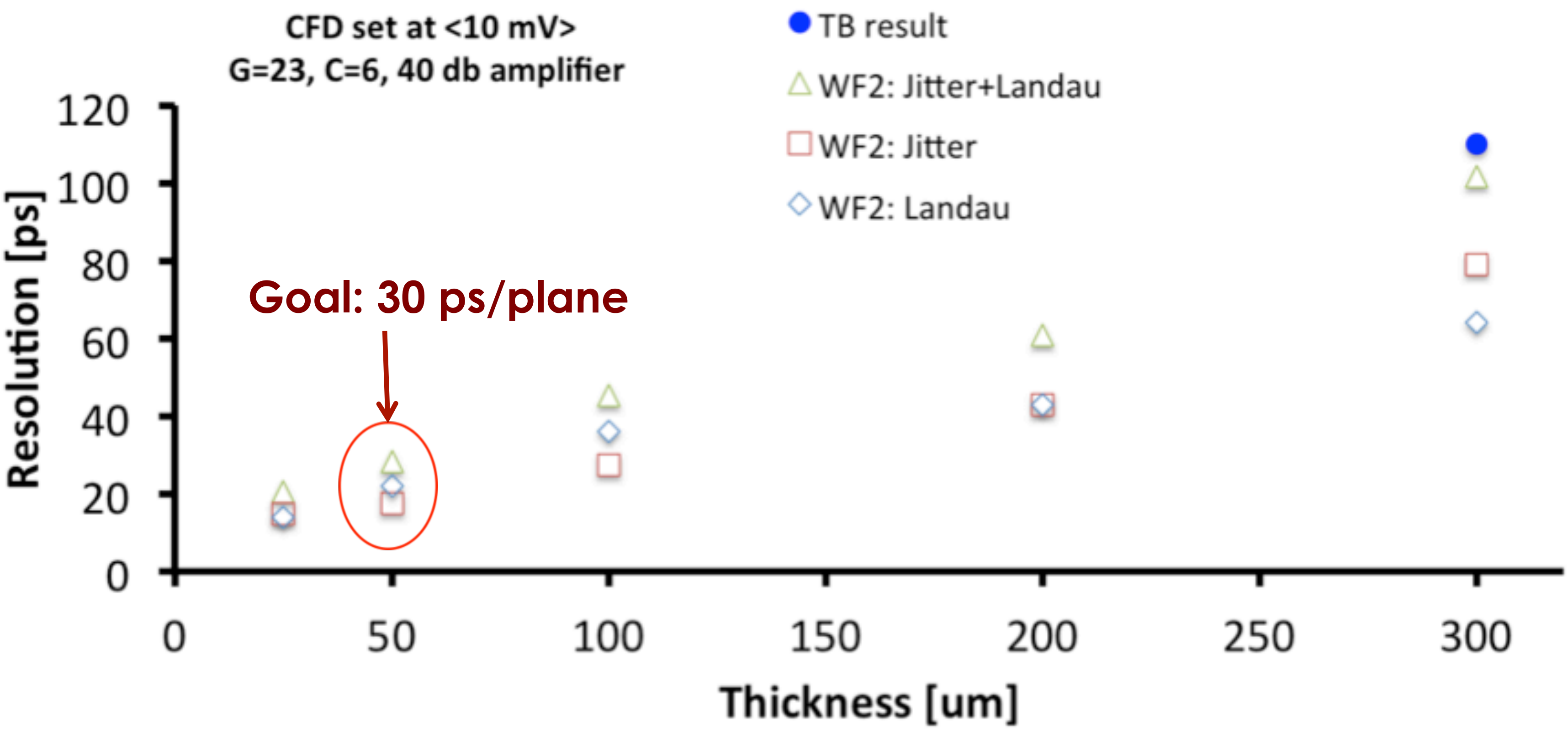
The amount of time over the threshold is used to correct for time walk

What is the most "solid" method considering the electronic implementation and the signal shape variations due to radiation damage?

I bet on CFD, as the falling edge suffers from charge trapping.

Testbeam results and extrapolation

2014 Frascati: 2 LGAD 7x7mm^2 300µm (C = 12pF, Gain =10)
2014 CERN: 2 LGAD 7x7mm^2 300 µm (C = 12pF, Gain =10)
2015 CERN: 2 LGAD 3x3mm^2 300 µm (C = 4pF, Gain =10 - 20)



WF2 = Weightfield2, simulation program.
Contribution of the Jitter and Landau parts to the total time resolution as a function of the sensor thickness.

Wrap-up on Sensors and Electronics

Noise:

- It does not depend on the detector capacitance.
- It depends on the sqrt(BW).
- Shot noise requires detector cooling

Slope dV/dt:

- It depends on the signal rise time, the circuit RC and the amplifier BW.
- It depends on the value of capacitance
- It depends linearly on the gain when the signal is controlled by the gain hole current.

Landau fluctuations:

- Their effect can be minimized by choosing a very low comparator threshold.

Jitter N/(dV/dt):

- For a 50 micron thick sensor, C = 5pF, R=50 Ohm, the appropriate BW is BW ~ 400-500 MHz ➔ may not be ideal for Landau fluctuations, need more work.
    - For G = 15, N = 15 uV @ 1 GHz Jitter ~ 40 ps
    - For G = 20, N = 10 uV @ 1 GHz Jitter ~ 20 ps

Time walk correction:

- Constant fraction and Time-Over-Threshold easily implemented in in custom ASIC. Need to study the more robust for the specific UFSD signal.

R&D Community and Funding

RD50: CERN-based silicon working group

- Very strong, 20-30 people, ~ 5 institutes, 10 talks at the last RD50 workshops (3-4/Dec-2015, https://indico.cern.ch/event/456679/)
- Radiation studies with neutron, protons in several institutions. Gallium implant.
- Full commitment of CNM (Barcelona) for silicon development
- 4 new sensors productions funded via RD50

ATLAS: High granularity timing detectors

- Large electronics community, last meeting on fast electronics November/2015, 20 people (https://indico.cern.ch/event/463100/)
- Now part of the ATLAS upgrade discussion, 10 ml $, 10 sq meter
- Rumors about a large Japanese company entering LGAD production

CMS: CT-PPS

- Proof of concept detector by 2016
- Development of full custom ASIC, 110 nm CMOS

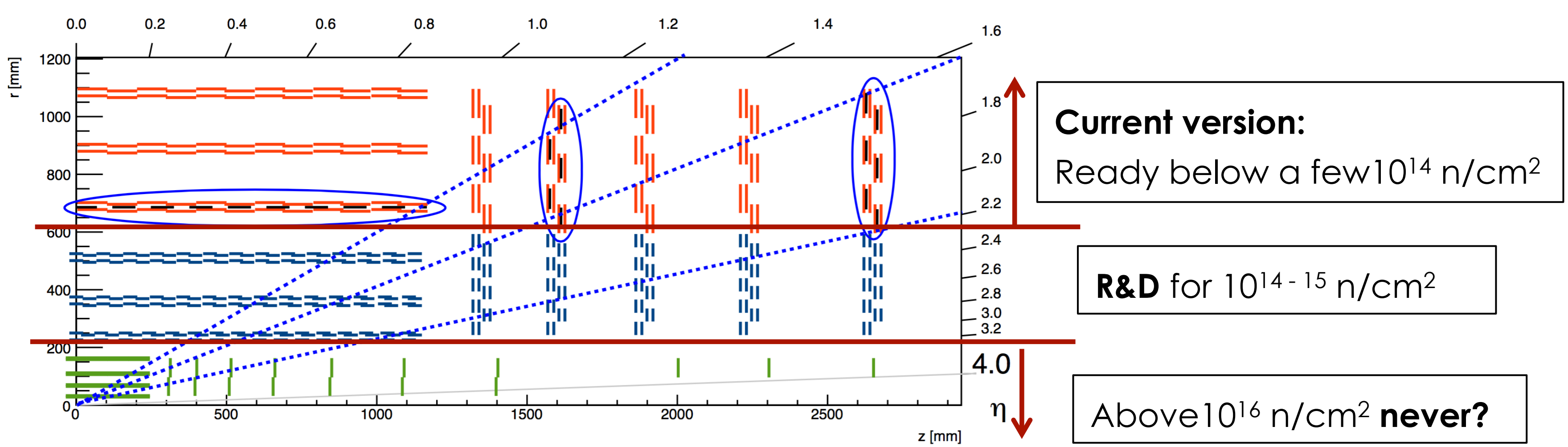
Italy: R&D

- Support from INFN within Gruppo V,
- Support of FBK for sensor production, several sensor productions in 2016

Horizon 2020: AIDA2, ERC

UFSD summary

- **Low gain** allows controlling noise, segmentation, early breakdown
- **The UFSD technology is mature**: 2 (maybe even 3,4) silicon foundries are working on various projects.
- **Large community**, well funded
- **Specifications of the electronics is almost complete** in term of capacitance, BW, dV/dt, noise, power. Proof of concept coming soon.
- **Fully custom ASIC chip design started**
- **Radiation damage starts to be important above "a few 10^{14} n_{eq}/cm^2"**.
  Several innovative ideas to push this limit above 10^{15} n_{eq}/cm^2
- **Segmentation under control**



Lindsey Gray, FNAL

Nicolo Cartiglia, INFN, Torino

Two possible applications of UFSD sensors

ATLAS High Granularity Timing Detectors

CMS CT-PPS

ATLAS High-Granularity Timing Detector HGTD

Hartmut Sadrozinski, UCSC

Suppression of pile-up (Run 2)

4 active layers per side (~10 m^2 in total) in front of FCAL
HGTD baseline dimensions:
Z =[3475, 3545] mm ; **ΔZ=70mm**
Rmin ~ -90 mm (η max≃4.3)
Rmax ~ 600 mm (η min≃2.4)
Possible to extend η =5.0 (Rmin ~ 50mm)
Required timing resolution: 50 – 100 ps

There are several technologies being considered.

Radiation Levels: (scaled to 3000 fb^{-1}):
- $(1\text{-}3)\times10^{15}$ n/cm2 ;
- $(0.3\text{-}2.4)\times10^{15}$ hadrons/cm2 (>20MeV)
- ~100 Mrad

A challenging project for the radiation resistance of UFSD.

ATLAS High-Granularity Timing Detector HGTD

Hartmut Sadrozinski, UCSC

- Offline pileup rejection can be addressed with forward tracker.

- At trigger level pileup rejection with tracking is more challenging due to latency constraint:
    - FTK++ will provide full tracking at 100 kHz (input)
    - L1 Track Trigger *might* provide high-p_T tracks at 1 MHz
    - L0 triggers rely only on Muon and Calo (40 MHz—>1 MHz).

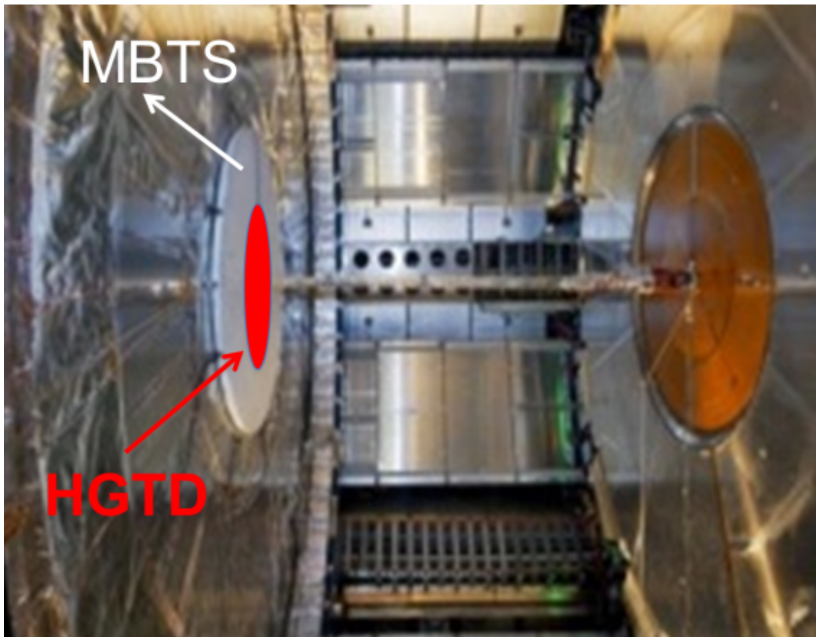
- Timing algorithms are intrinsically fast (no pattern recognition required) — > Exploring potential of timing detector for “L0 Time”.

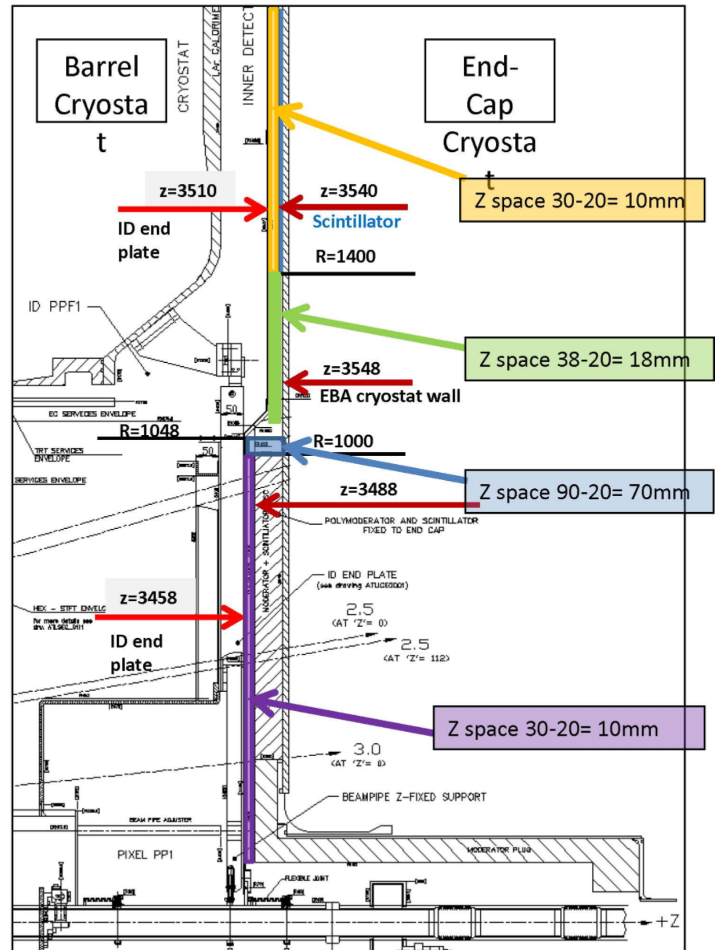
- A L0 Time pileup suppression can directly enhance the physics capabilities of the HL-LHC by reducing VBF jet trigger thresholds.

ATLAS HGTD cont.

Squeezed space between Barrel and Front-end Calorimeter
Thinness of LGAD an advantage

Hartmut Sadrozinski, UCSC



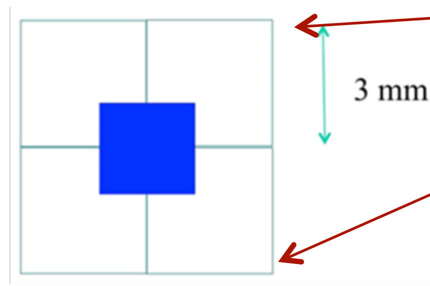


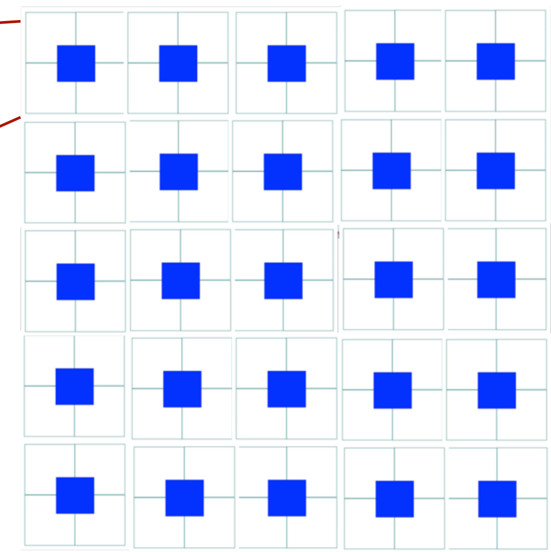
CNM LGAD Proposal for Atlas HGTD

50 um LGAD

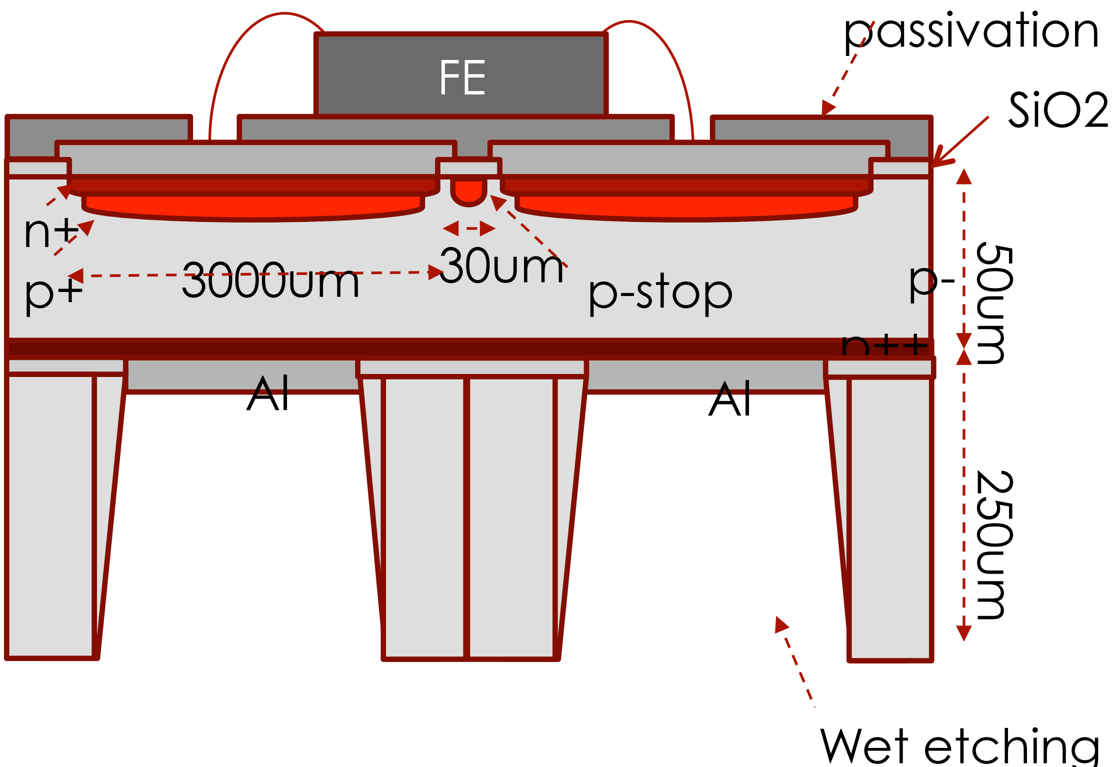
Hartmut Sadrozinski, UCSC

2x2 array with 1 ASIC



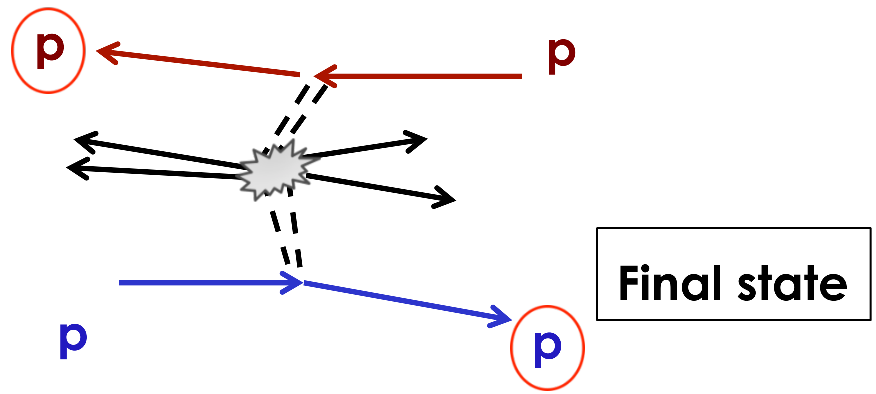


10 x 10 Module

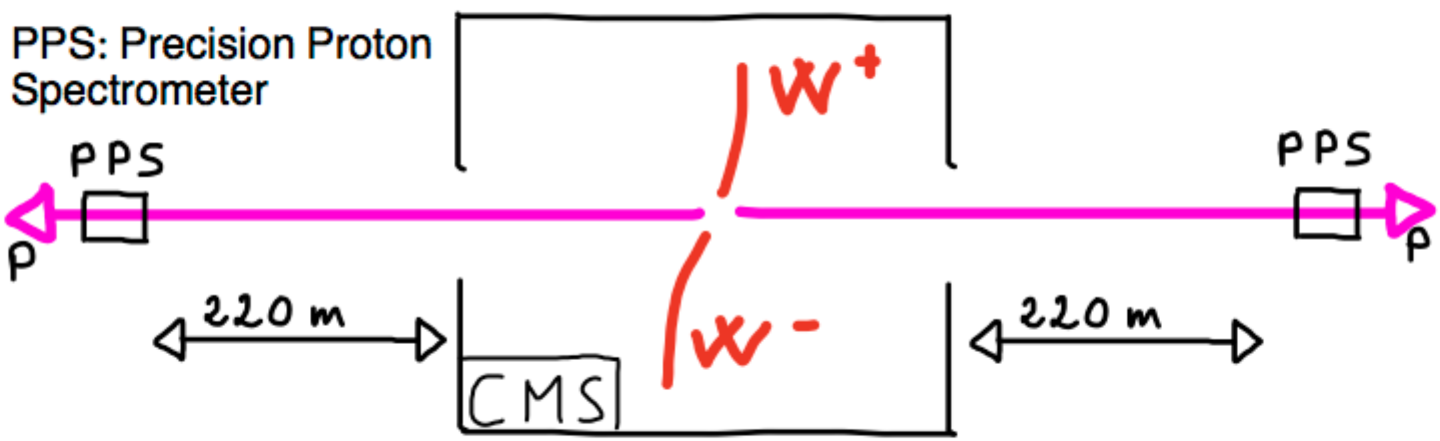


The CT-PPS for CMS

There is a class of events that have two protons in the final state



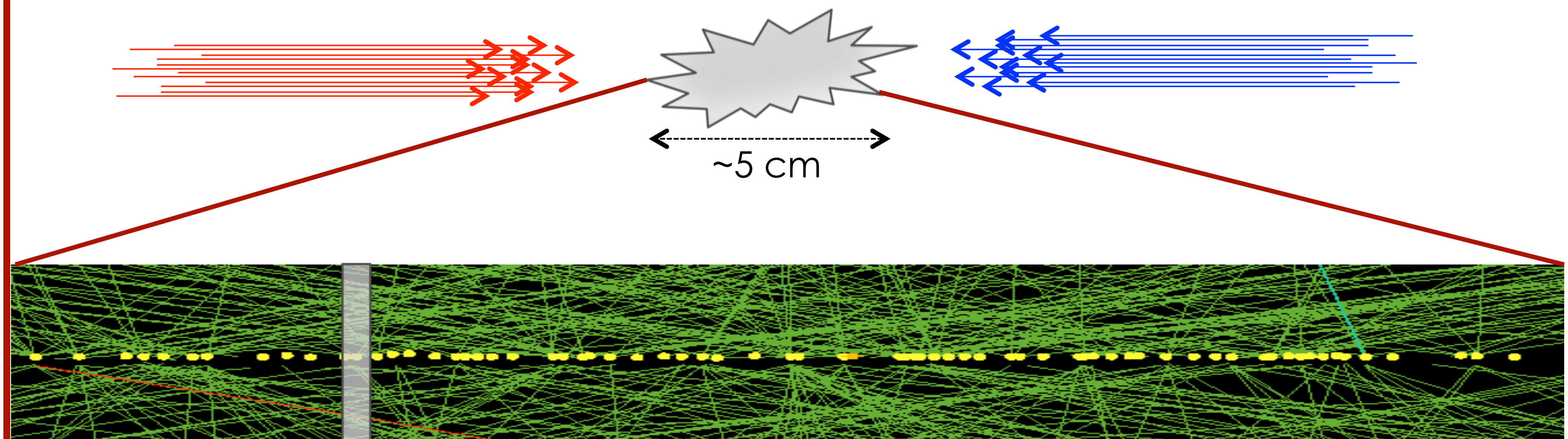
We need to know **the position** and **the time** of the two protons



As presented at the LHCC, UFSD have now the full engineering support of the collaboration for installation in 2016

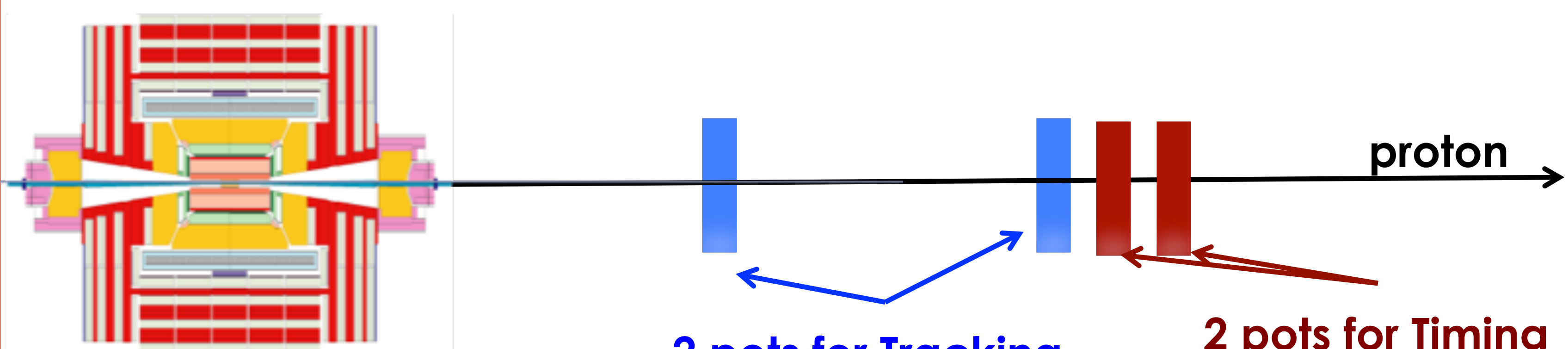
Why do we need timing?

Pileup! At each bunch crossing, there are many interactions (~ 50)

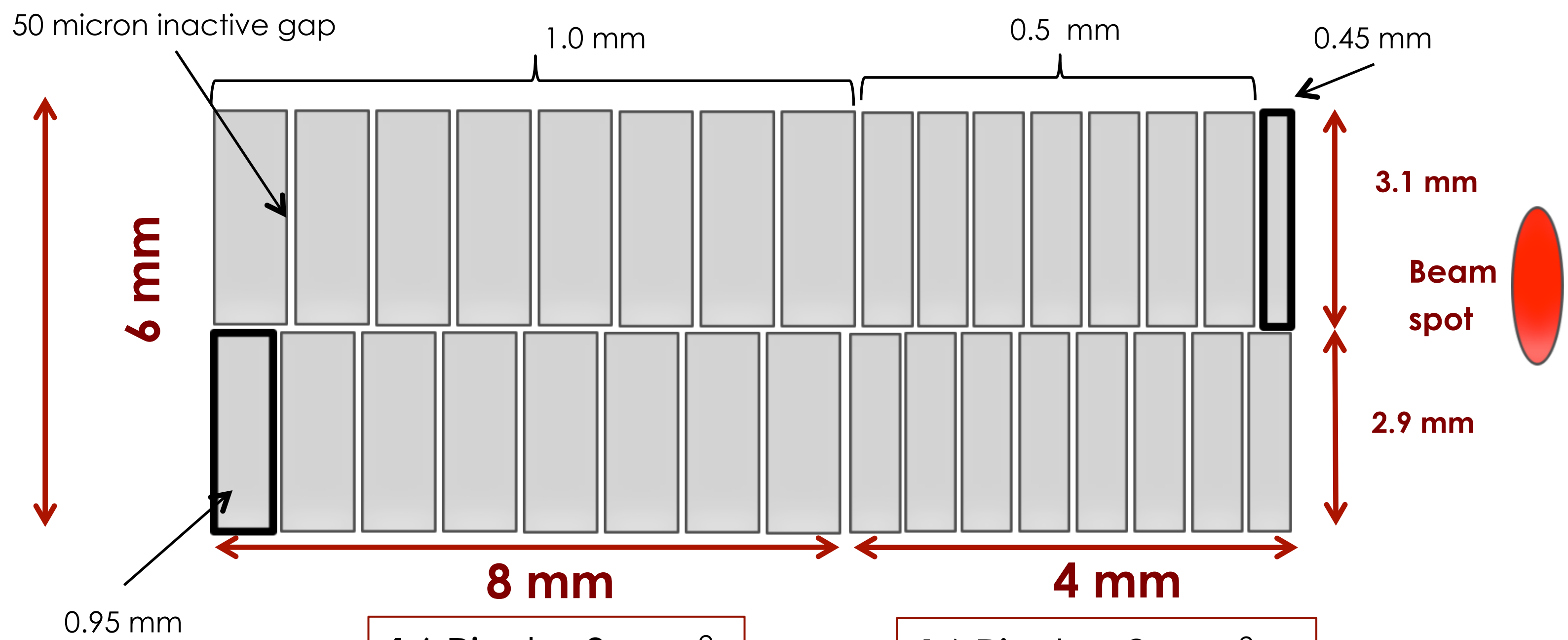


A precision of ~ 10 ps is needed to associate the proton to the correct vertex using "z-by-timing"

First demonstrator: position and timing are performed by two separate sensors



UFSD Sensors for CT-PPS

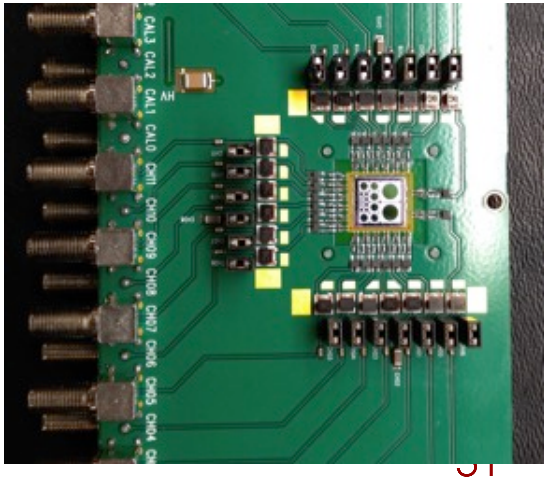


16 Pixel ~ 3 mm²
Cap. Pixel ~ 6 pF

16 Pixel ~ 2 mm²
Cap. Pixel ~ 4 pF

Asymmetric designed
Area = 12mmX6mm;
Thickness = 50 um;
# of pixels = 32
# of planes: 6 per side
Time scale: 1 year !!!

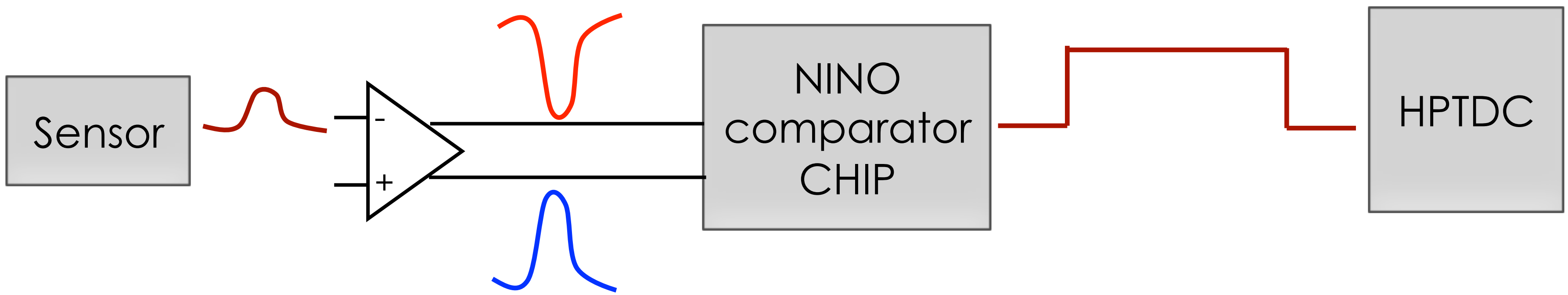
Prototype read-out board (UCSC)



Electronics: surface mounted and full custom ASIC chips are developed. Project fully funded.

CT-PPS Silicon read-out system

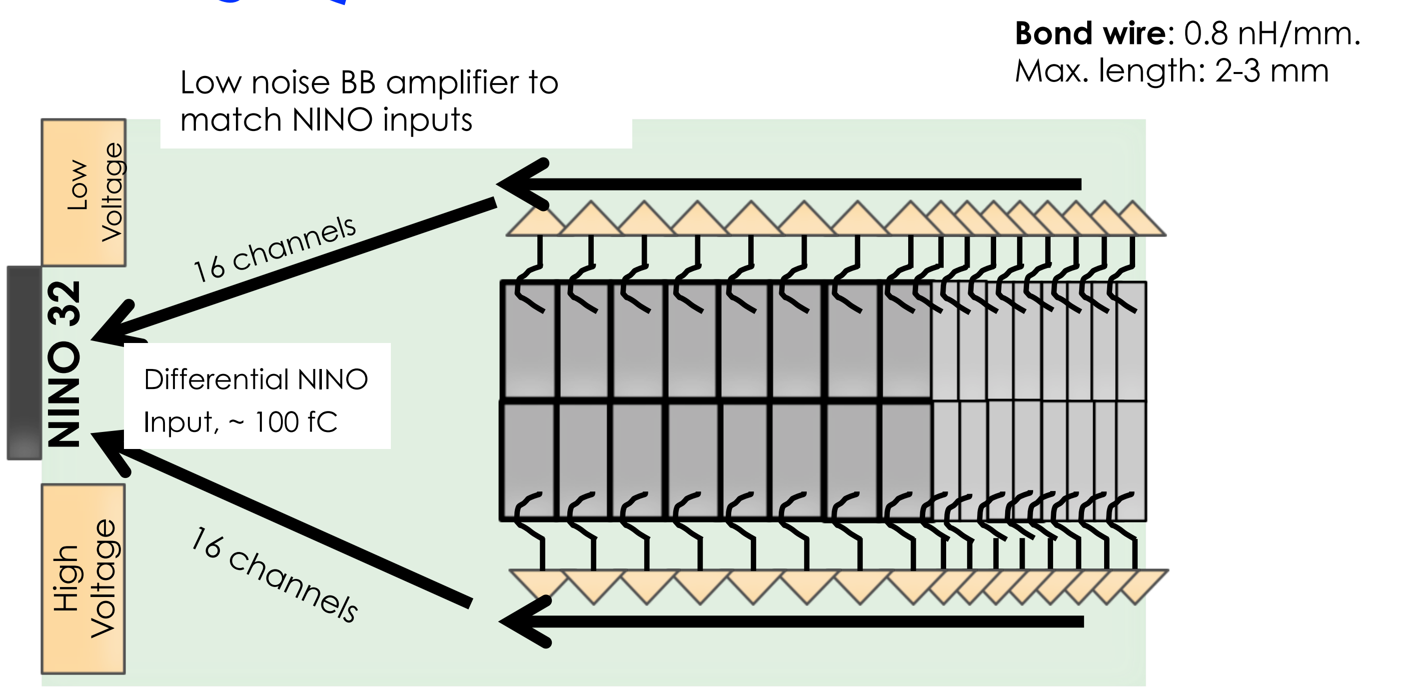
Currently the block diagram is the following:



Goal:

40 ps per plane

(including NINO and HPTDC)



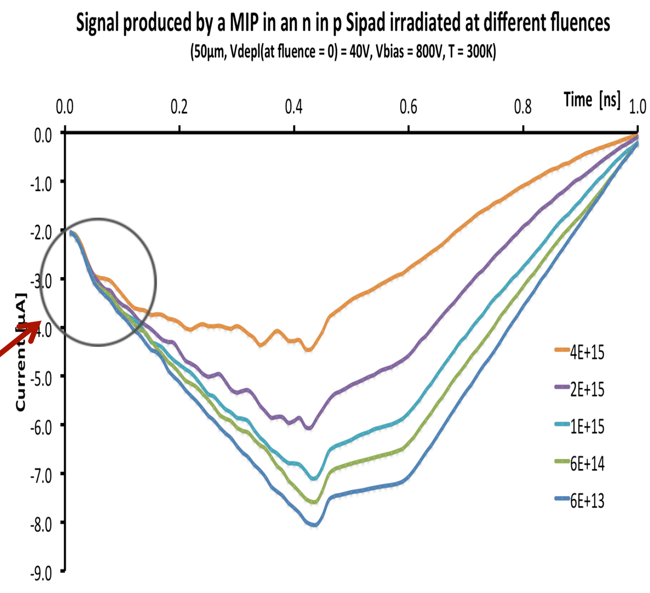
Irradiation - I

Irradiation causes 3 main effects:

1. Decrease of charge collection efficiency due to trapping
2. Changes in doping concentration
3. Increased leakage current (Shot noise, already covered)

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



Nicolo Cartiglia, INFN, Torino

Irradiation - II

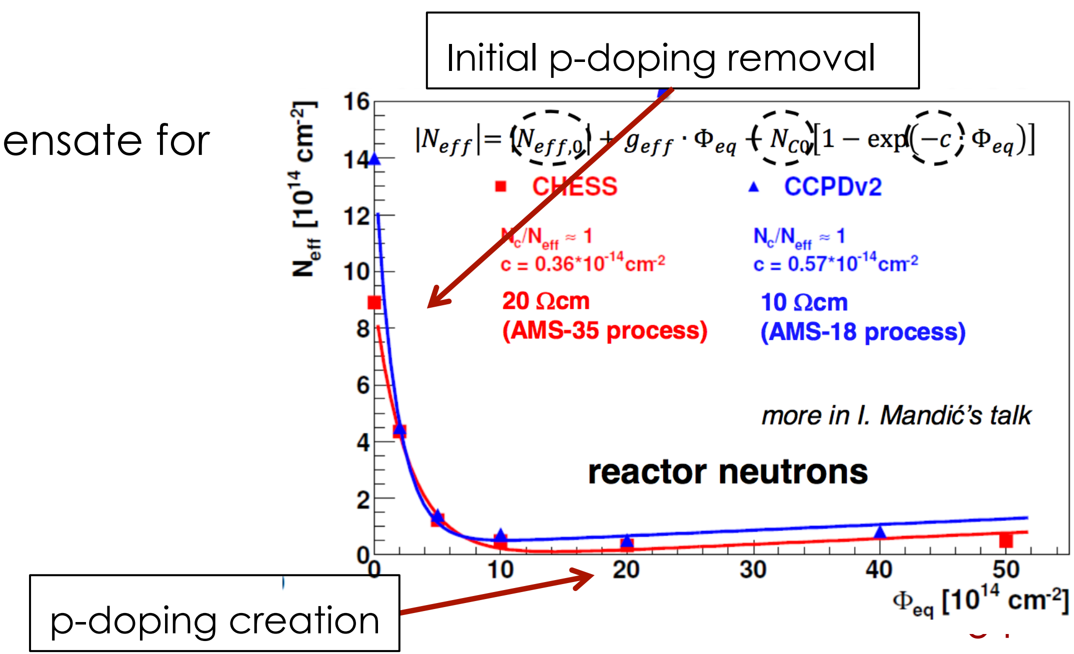
2) Changes in doping concentration

Important semantic remark: **p-doping** not only indicates p-dopant atoms such as Boron, but **everything that acts as an acceptor,** i.e. also negatively charged defects.

- Irradiation normally creates p-doping, n-silicon becomes p-silicon.
  ➔ This additional p-doping is due to defects creation.
- However: there is evidence **that irradiation causes "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.

Two paths:

- Short term: use Vbias to compensate for the loss on gain
- Long term: Gallium doping



The next few years: fully funded R&D

2016:

- **Thin sensor prototypes**. By the end of 2016 I expect a much better understanding of the gain mechanism, and how thin sensors work.
- **Irradiation program**. Damage, trapping, gain changes in thin sensors, use of Gallium instead of Boron?
- **Sensor demonstrator for ATLAS, CMS**

- **Discrete component read-out,** on the PPS geometry
- **First custom chip**, 4-8 channel, analog-comparator
- **Installation of system demonstrator in PPS**

- **Lot's of testbeam**

2017:

- **Additional sensor production**, exploring large production capability
- **R&D on full custom read-out chip**