Reading out thin LGAD in real experiments

Thin detectors for timing measurement represent a new frontier on both sensors and electronics.

- Analysis of the parameters influencing time resolution
- Testbeam results
- UFSD for real experiments

INFN and Torino University, UC Santa Cruz

Time resolution

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

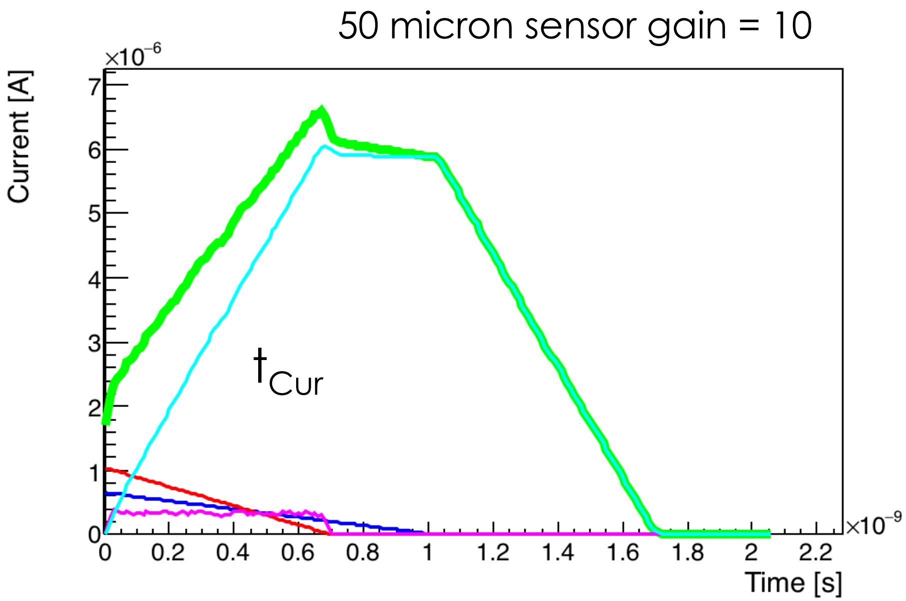
Usual "Jitter" term

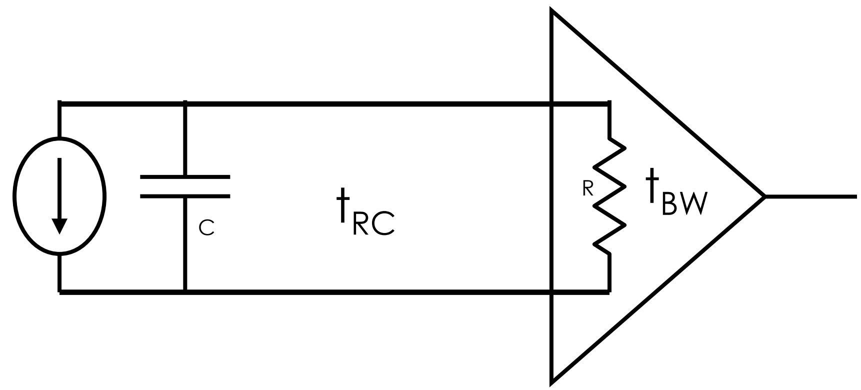
Shape variations

(assuming perfect Time Walk corrections)

Amplifier non ideal behavior

The players…





The current rise time (t_{Cur}) | The RC circuit (t_{RC}) | Amplifier BW f (t_{BW} ~0.35/f)

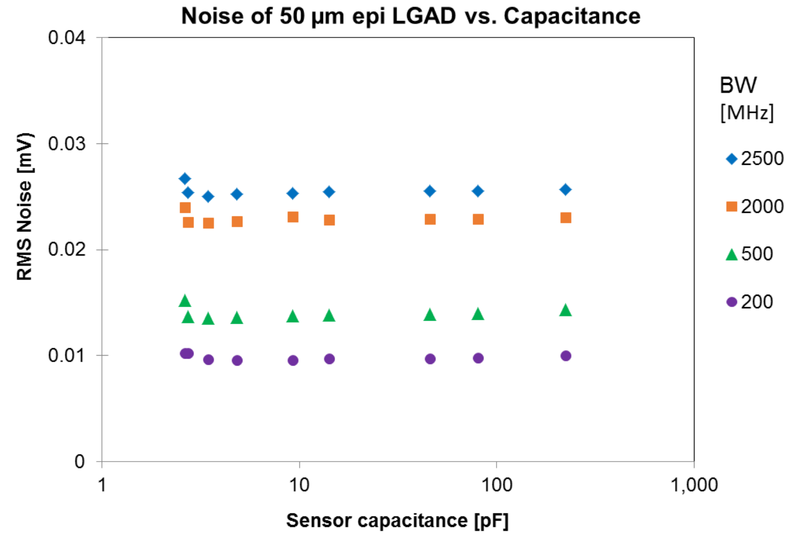
There are 3 quantities determining the output rise time after the amplifier:

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

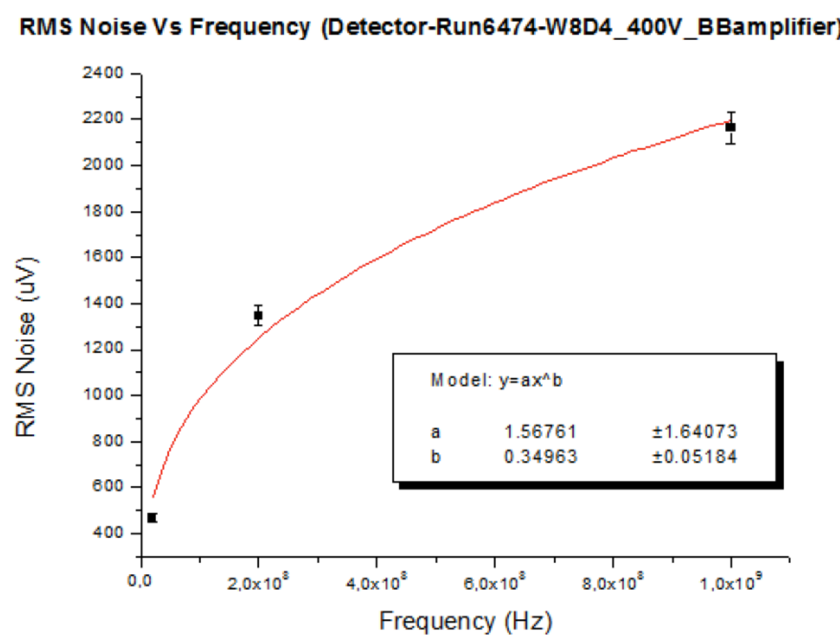
For capacitive sources, the input capacitance is not a noise source.

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)

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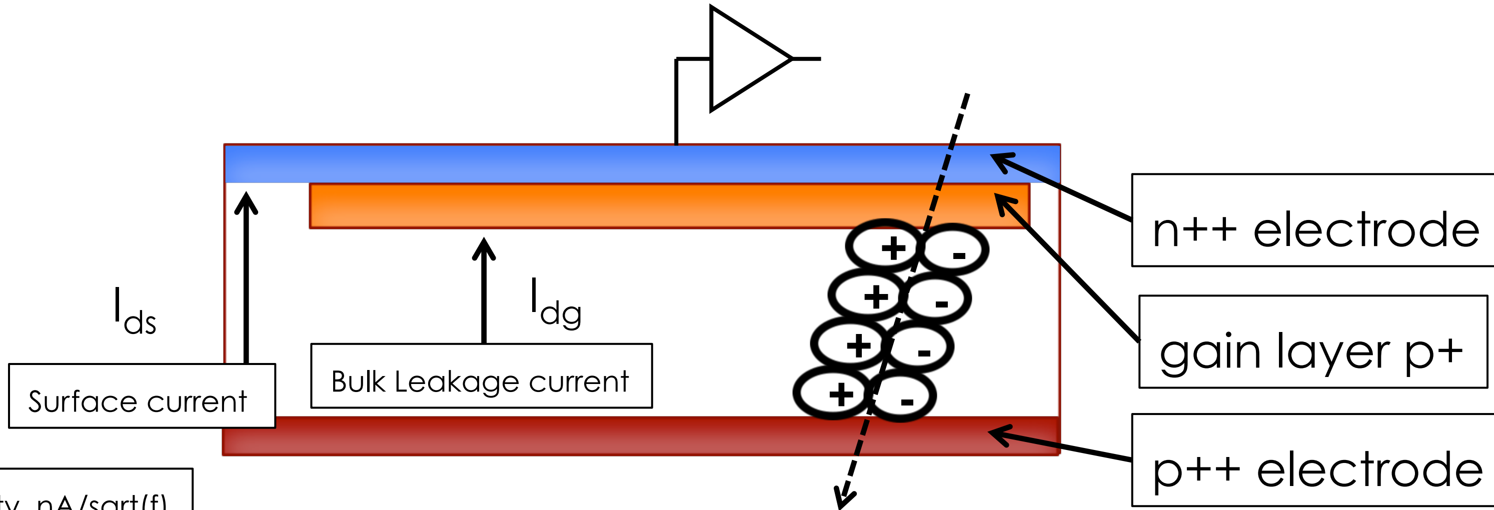
Shot noise in LGAD - APD



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

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

$$F \sim M^x$$

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

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

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The Shot noise voltage term

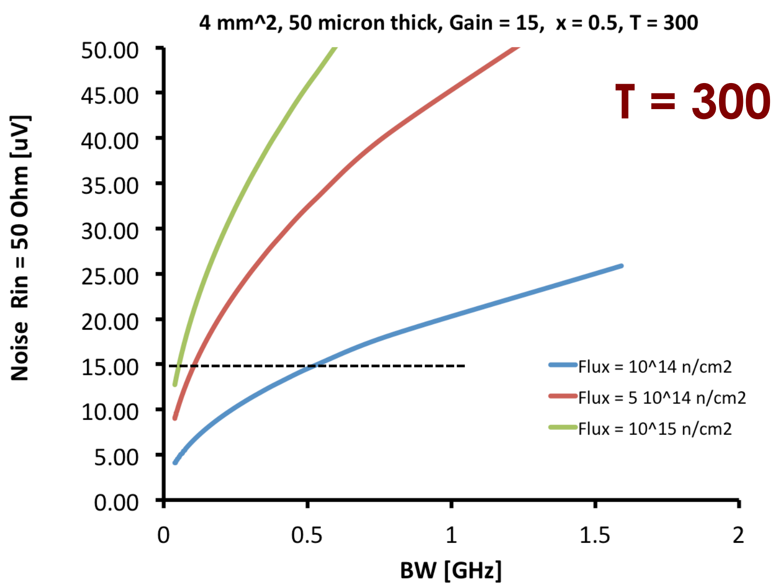
Let's assume a 4 mm[2] pad, 50 micron thick.

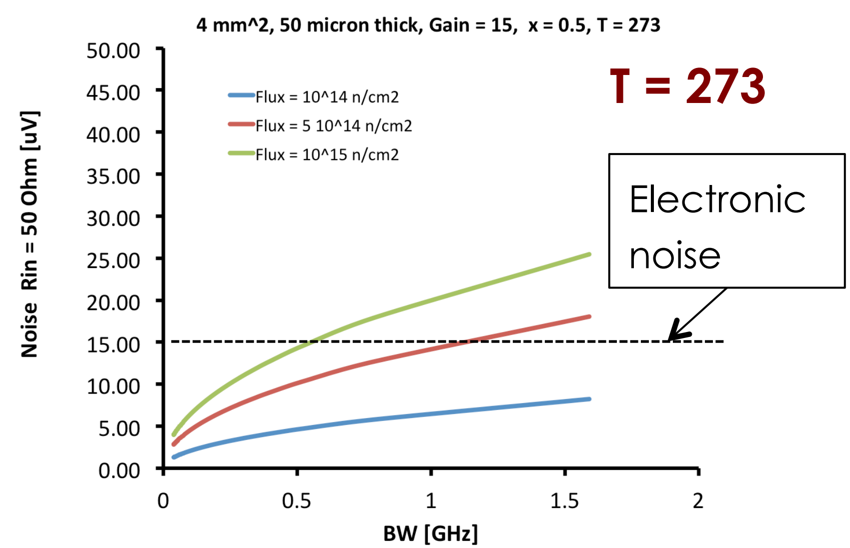
What is the effect of shot noise as a function of radiation?

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

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 can be controlled by cooling the detectors by 20-30 degrees**

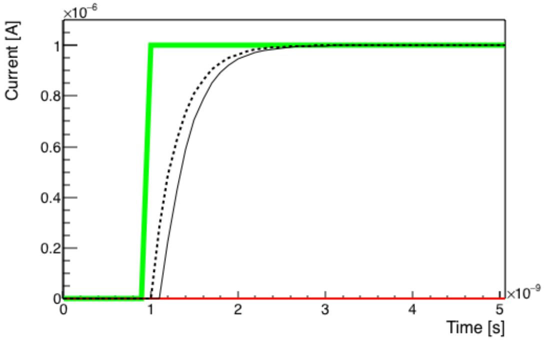
The slope term: dV/dt

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:

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

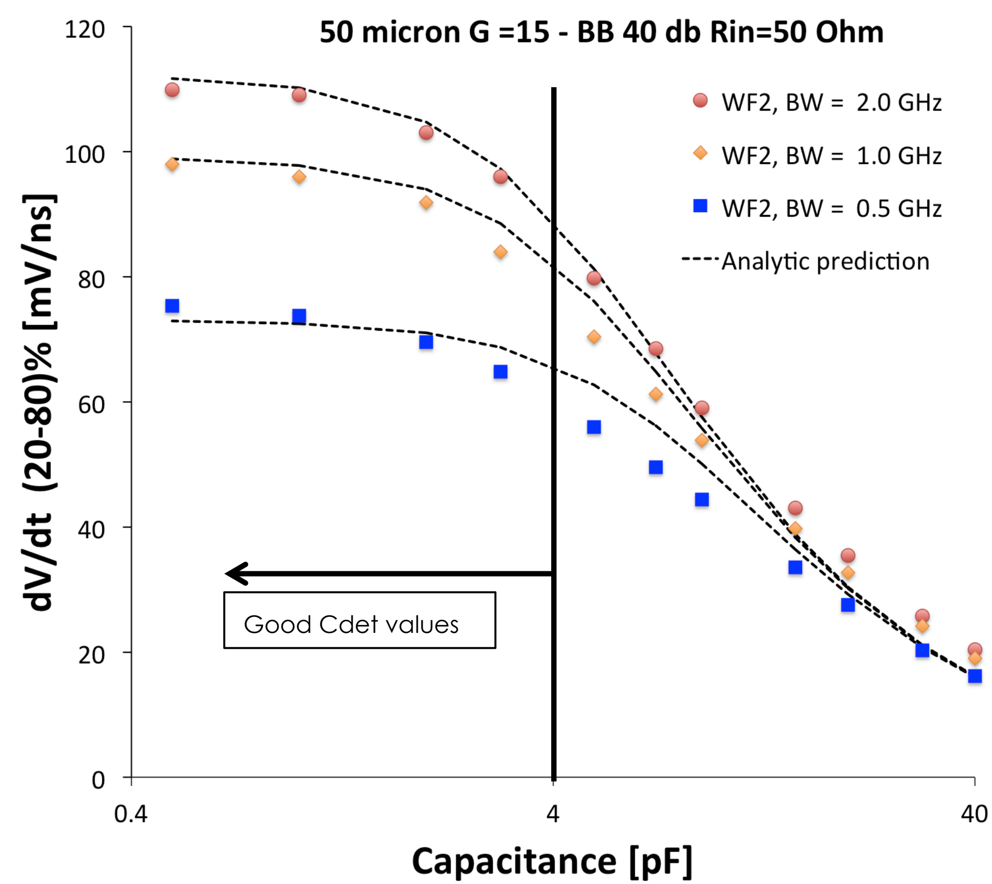
What is controlling the slope? Capacitance and BW

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**



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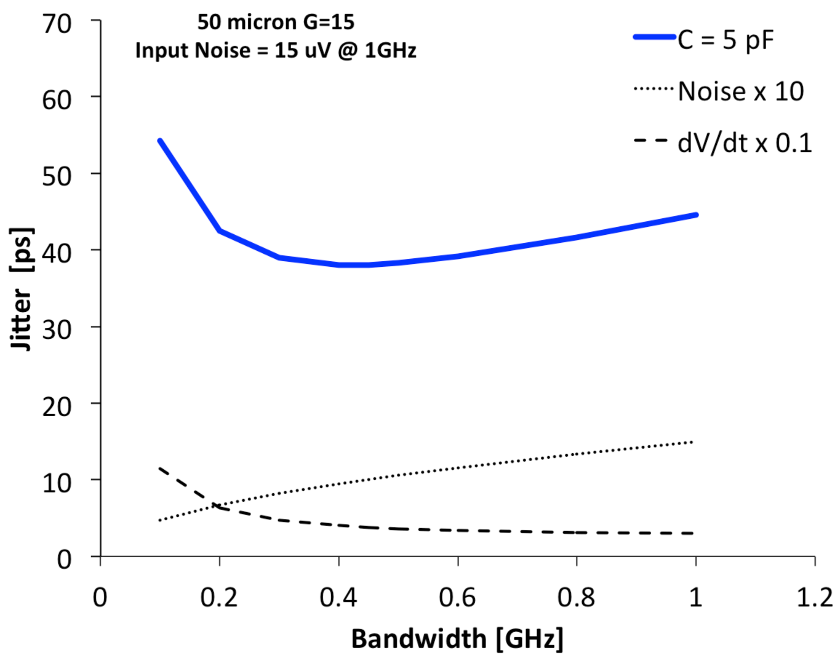
Jitter minimization

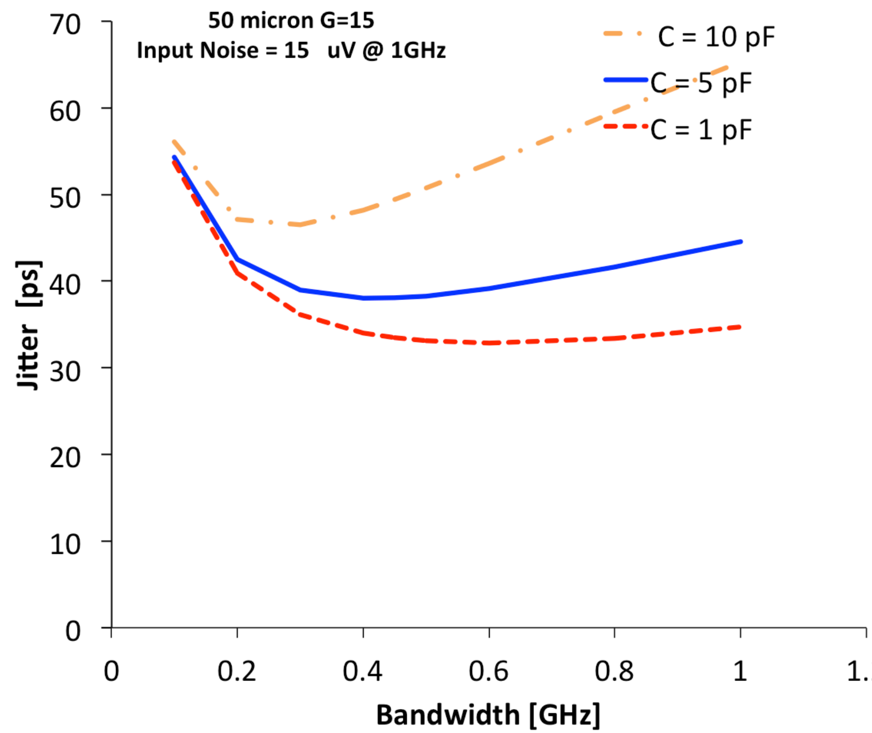
Let's calculate the jitter term as a function of BW

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

Normalization: N = 15 uV @ 1GHz

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



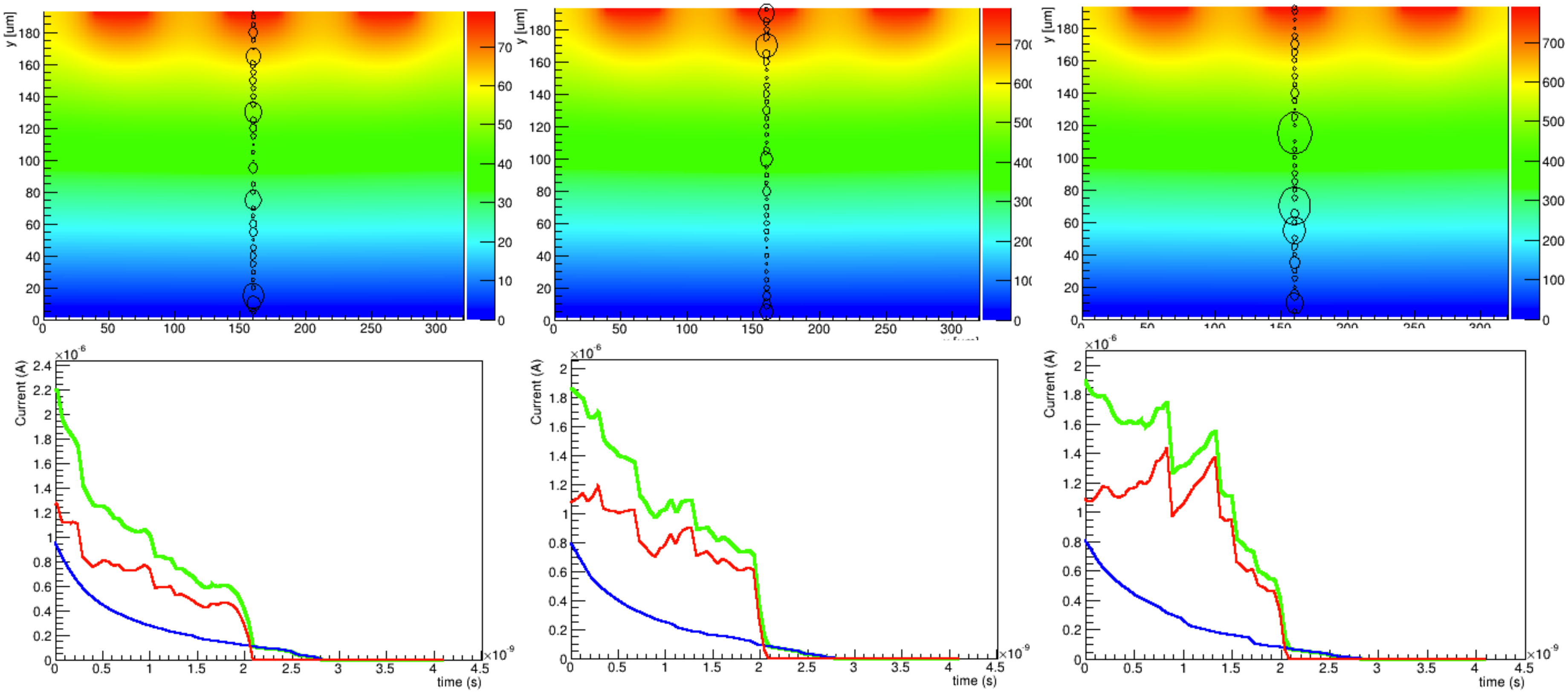


Broad minimum at BW ~ 4-500 MHz with Cdet = 5 pF: Jitter ~ 40 ps

Landau Fluctuations

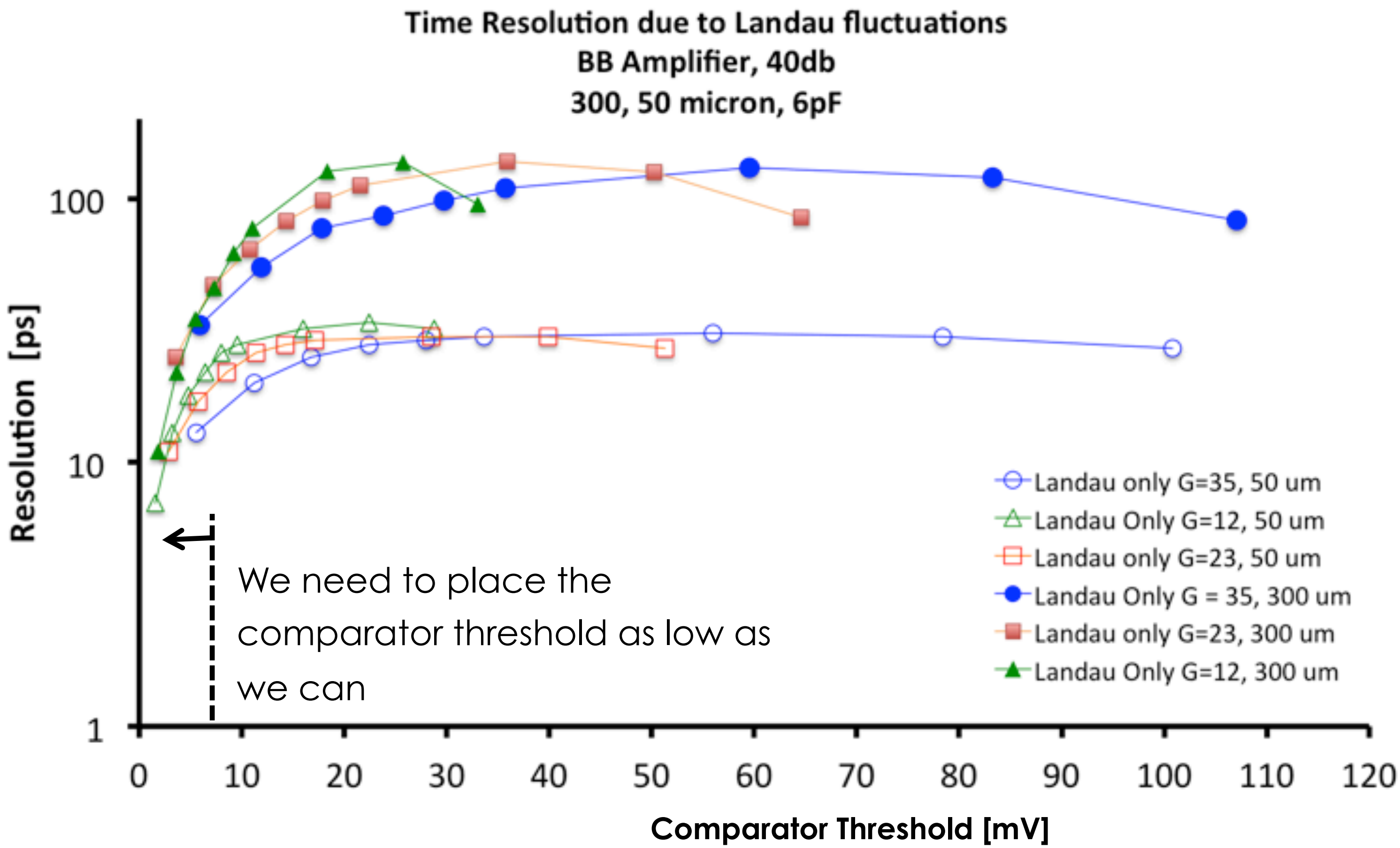
Landau Fluctuations cause two major effects:

- 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?

50 -300 micron Sensors: Landau effect



Thin sensors:

Much less sensitive to Landau fluctuation

Higher gains allow for higher thresholds, well above the noise

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.

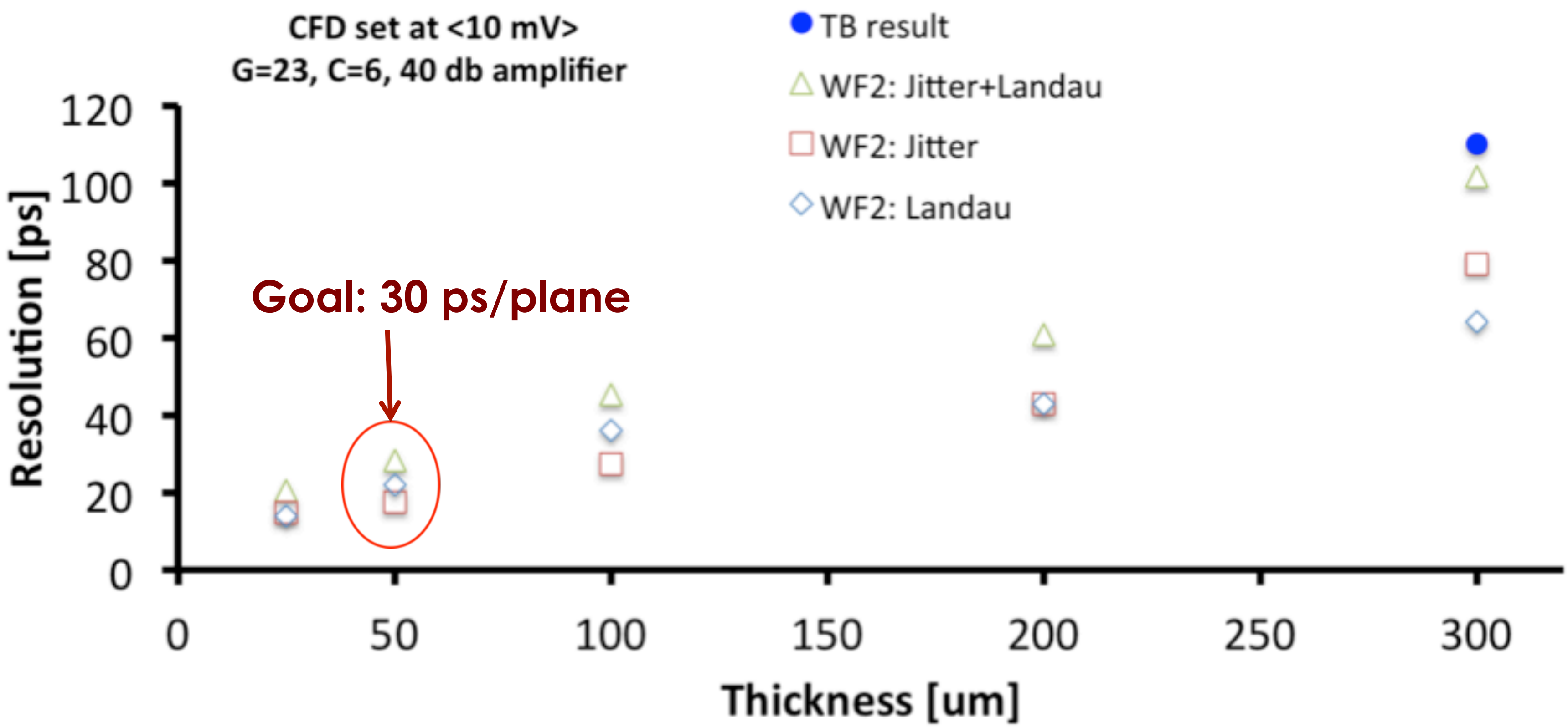
Landau fluctuations:

- 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

Testbeam results and extrapolation



WF2 = Weightfield2, simulation program.

Contribution of the Jitter and Landau parts to the total time resolution as a function of the sensor thickness.

Two possible applications of UFSD sensors

ATLAS High Granularity Timing Detectors

CMS CT-PPS

ATLAS High-Granularity Timing Detector HGTD

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

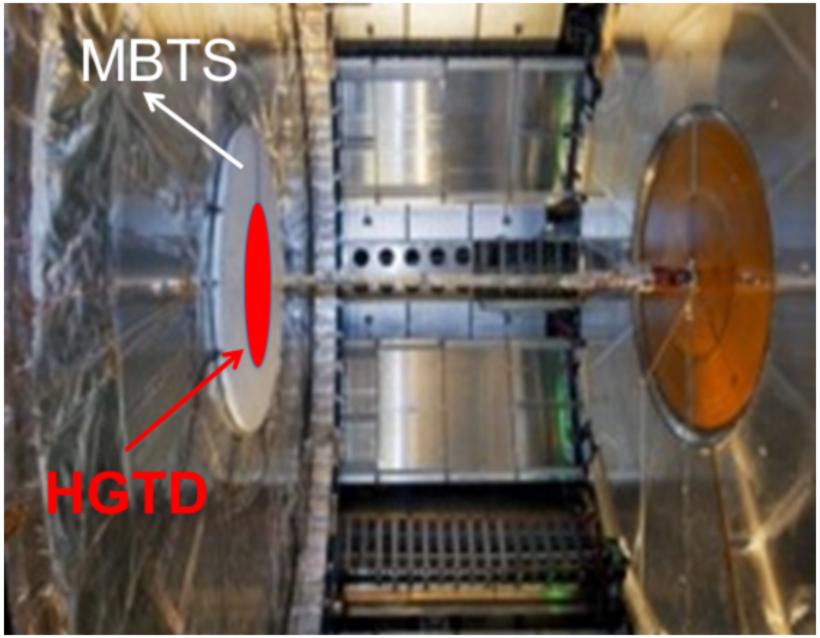
There are several technologies being considered.

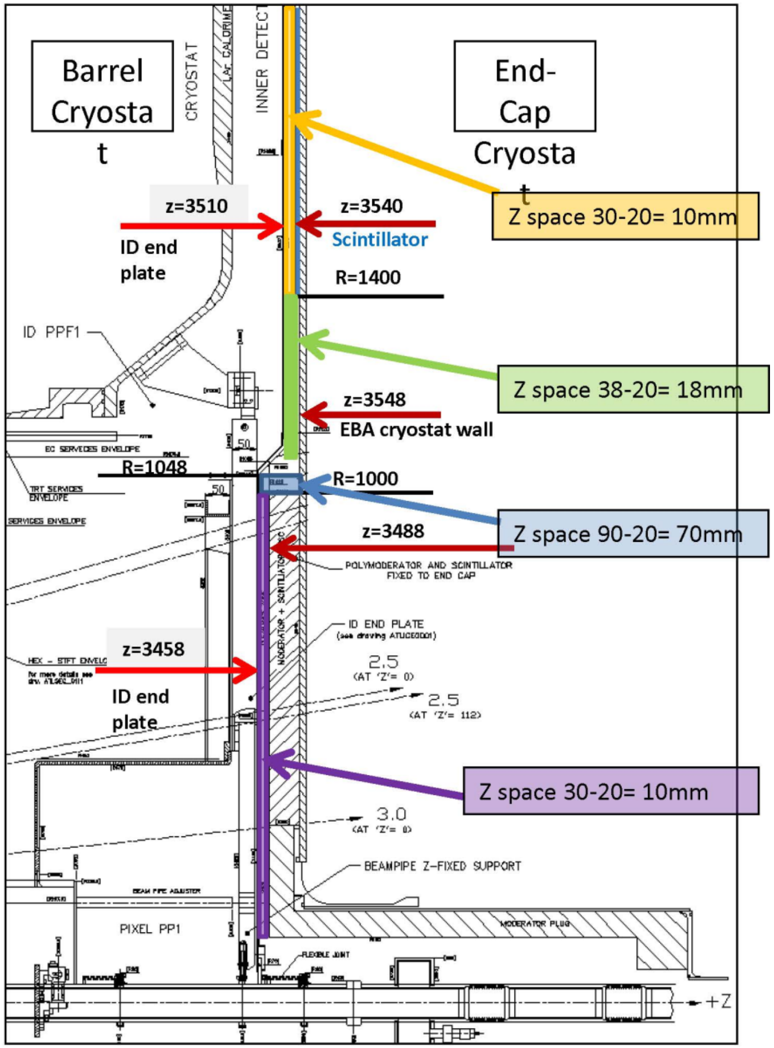
Radiation Levels: (scaled to 3000 fb^{-1}):
- $(1\text{-}3)\times10^{15}$ n/cm2 ;
- $(0.3\text{-}2.4)\times10^{15}$ hadrons/cm2 (>20MeV)
- ~100 Mrad

A challenging project for the radiation resistance of UFSD.

ATLAS HGTD cont.

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





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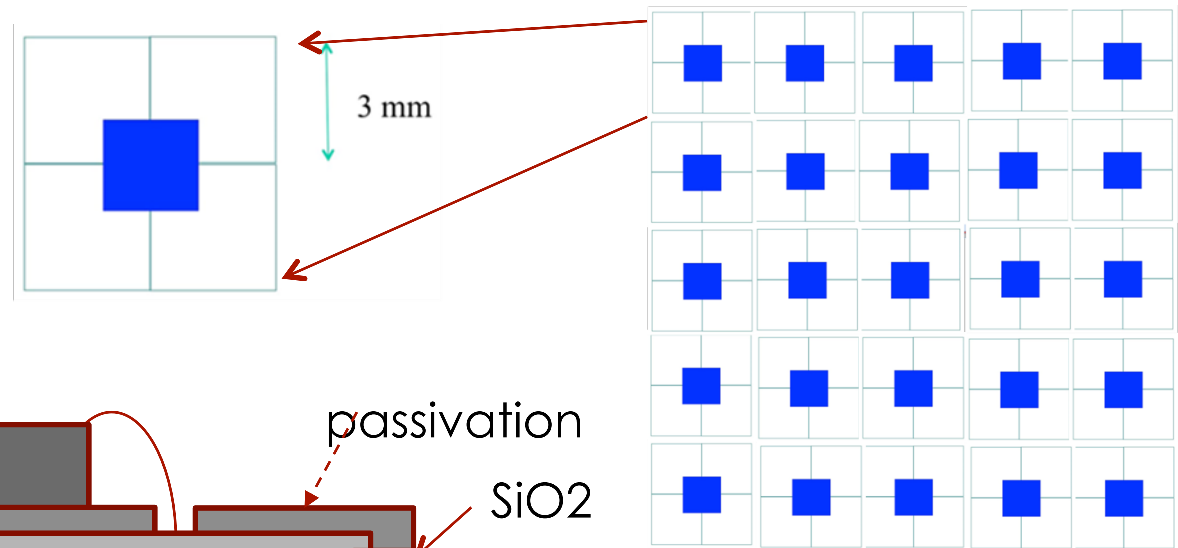
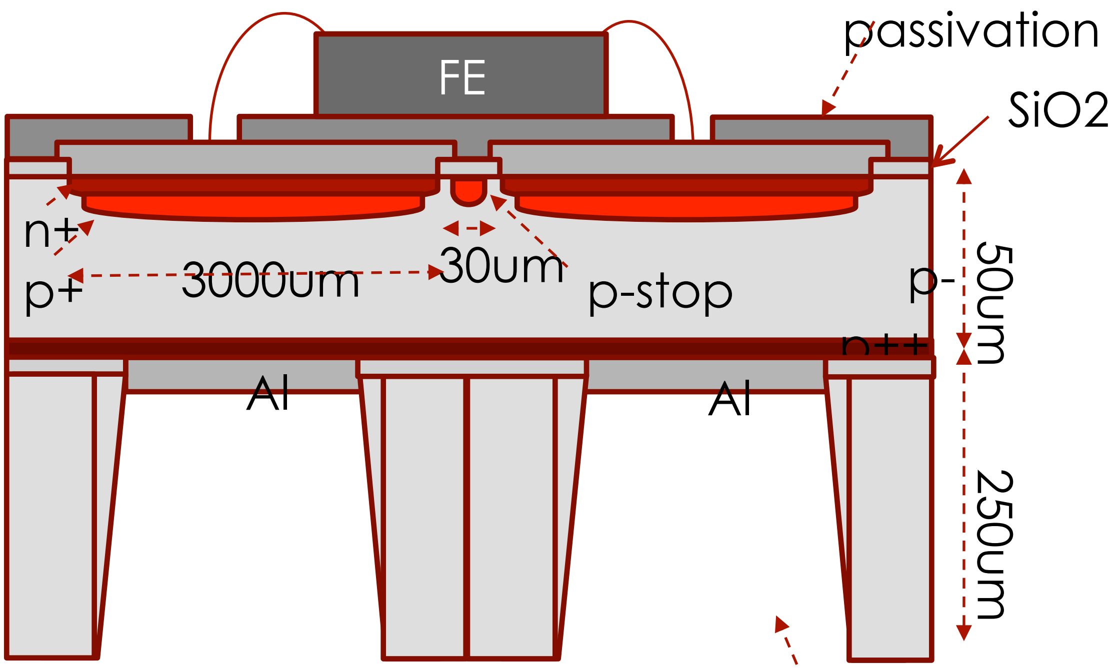
CNM LGAD Proposal for Atlas HGTD

50 um LGAD

10 x 10 Module

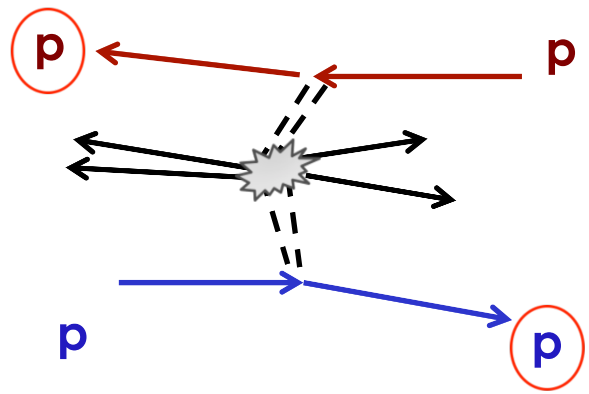
2x2 array with 1 ASIC





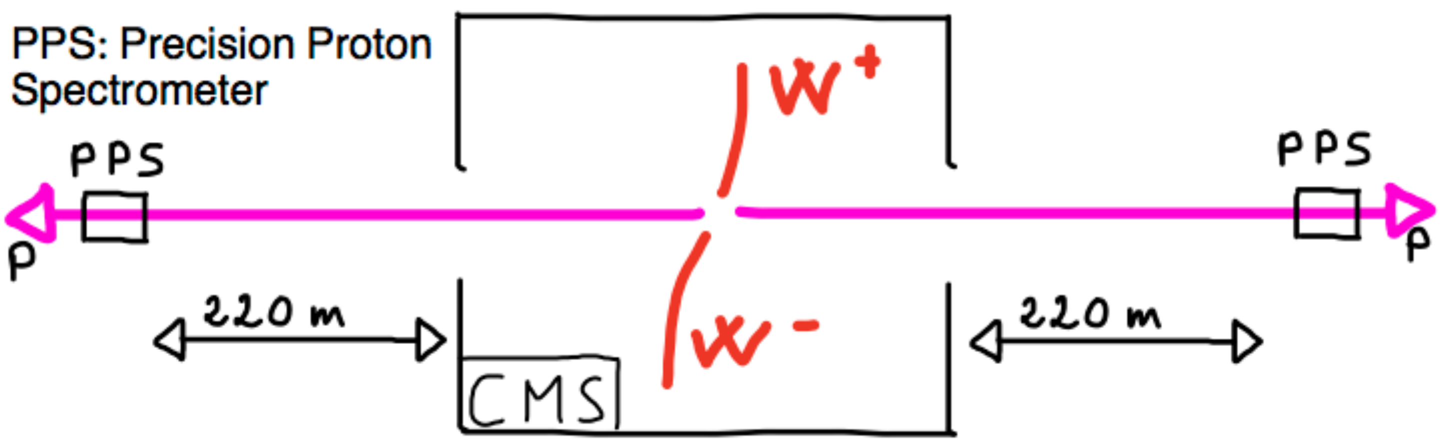
The CT-PPS for CMS

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



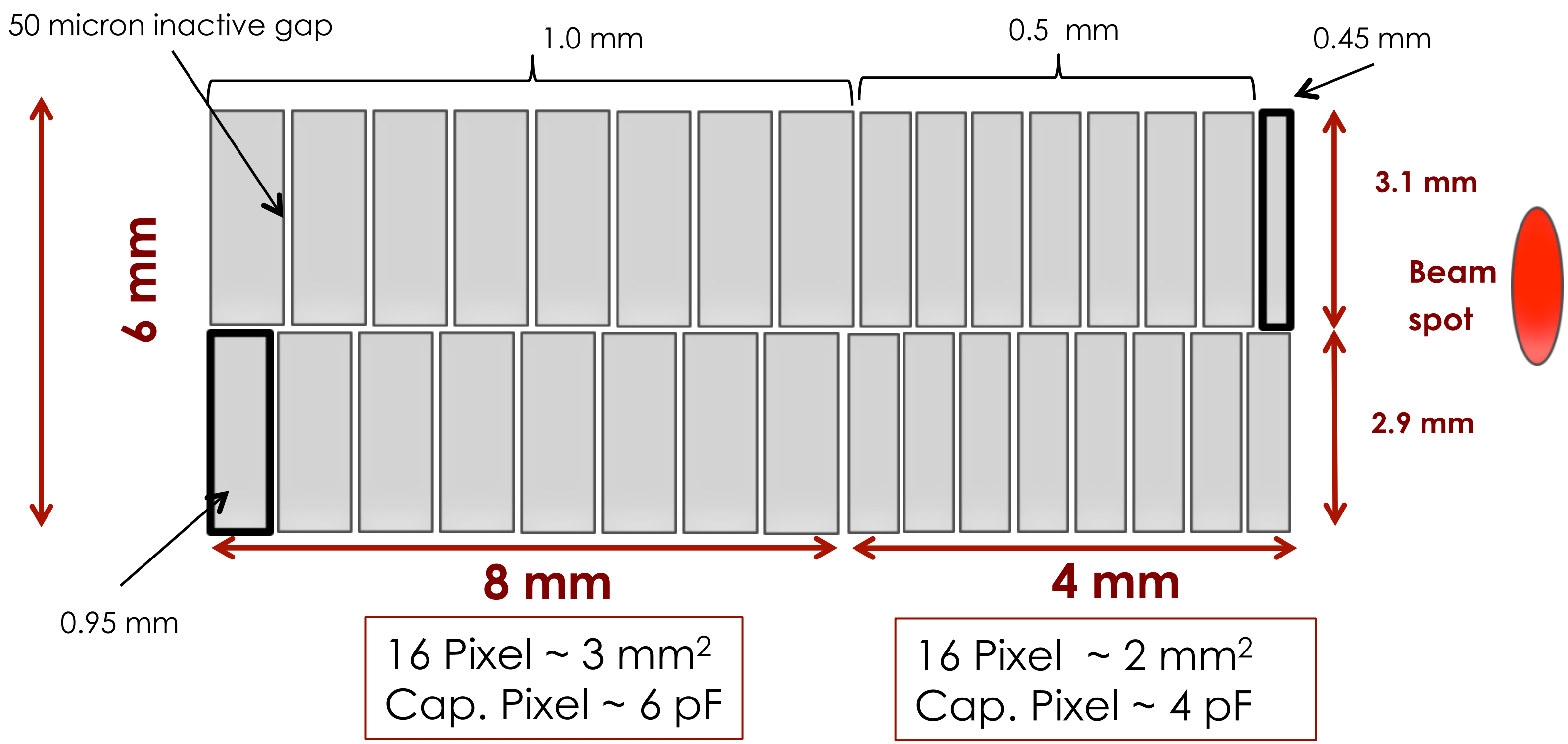
We need to know **the position** and **the time** of the two protons

PPS: Precision Proton Spectrometer



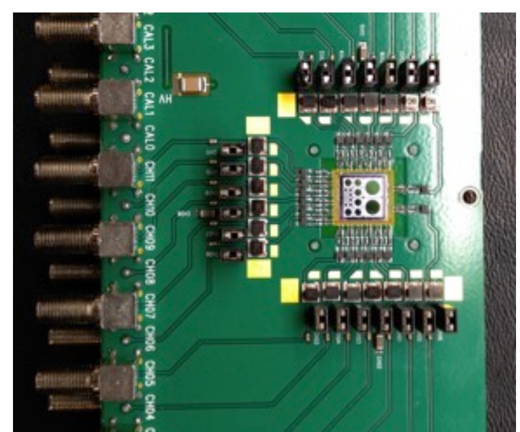
As presented at the LHCC, UFSD have now the full engineering support of the collaboration for installation in 2016

UFSD Sensors for CT-PPS



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.

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Outlook on UFSD

The exploitation of UFSD requires thin sensors and fast non-integrating amplifiers.

Our extrapolation of testbeam results to thin detectors indicates a ~ 30-40 ps time resolution for 50-micron thick sensors.

We are developing full custom ASIC electronics.

UFSD are now entering a new phase, they are considered for installation in CMS and ATLAS.

➔ We need to prove their timing capabilities as soon as possible

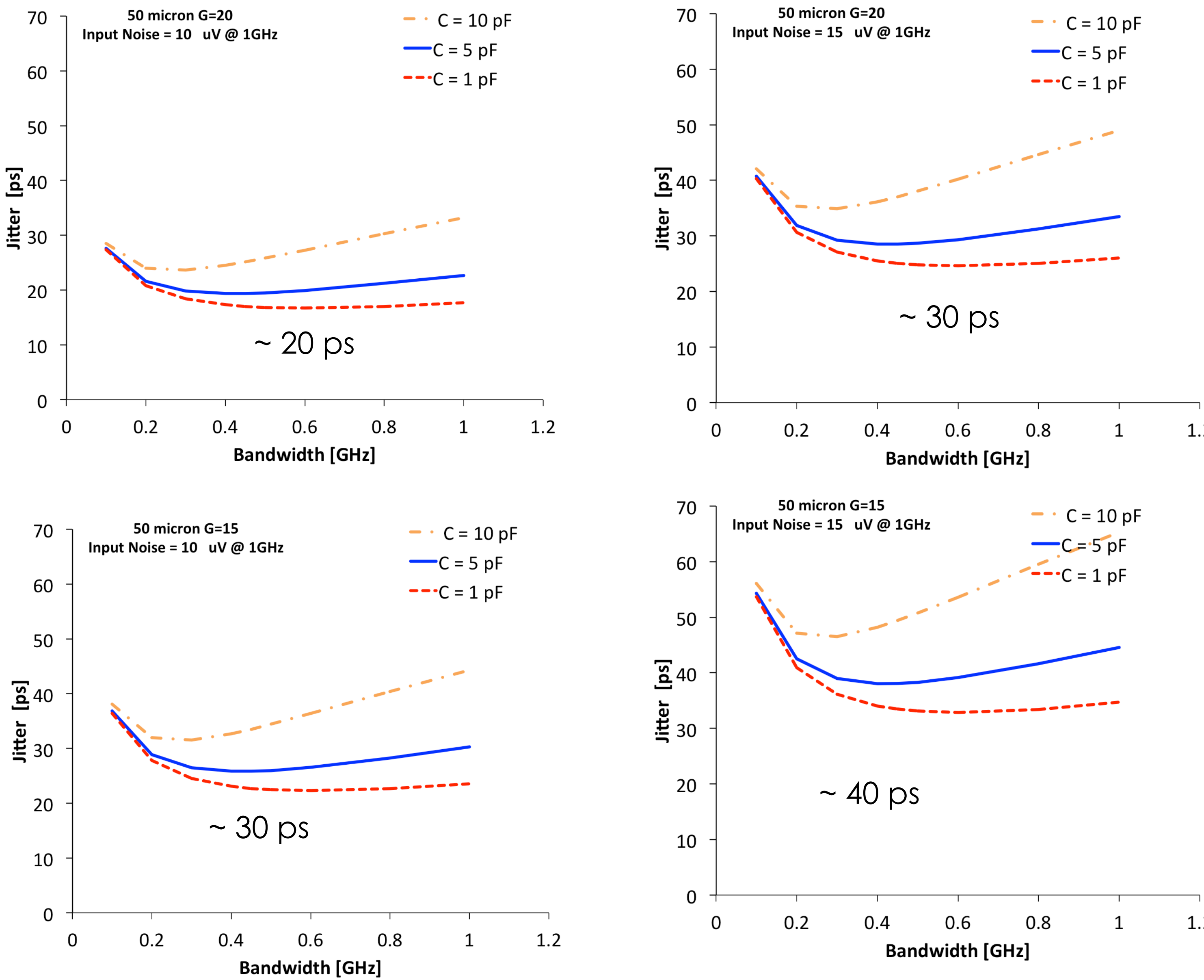
➔ We need to extend their radiation hardness range.

Backup

Noise = 10, 15 uV; Gain =15, 20

Gain = 20

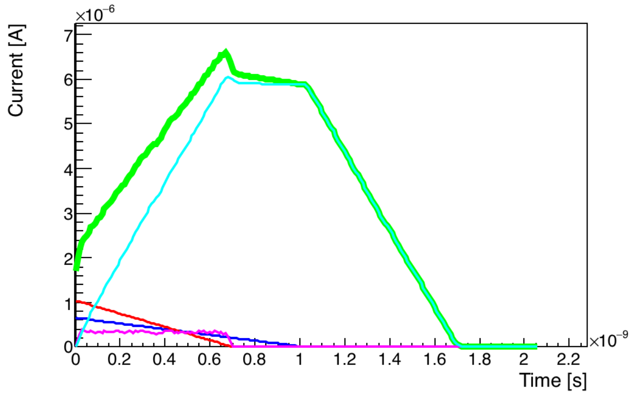
Gain = 15

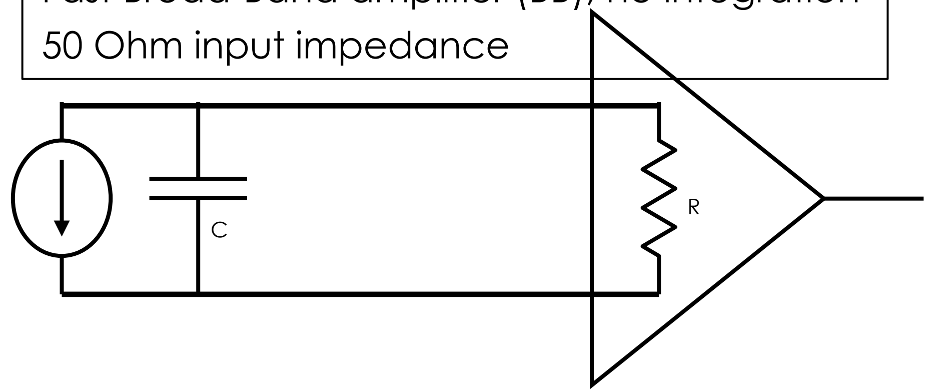


Noise = 10 uV @ 1 GHz

Noise = 15 uV @ 1 GHz

Current and voltage mode read-out





To maintain the very fast rise time, we need to operate as close as possible to the current mode (no integration) where the RC is smaller than the current rise time, **$t_{Cur} > t_{RC}$**, so the current flows into the amplifier without being integrated.

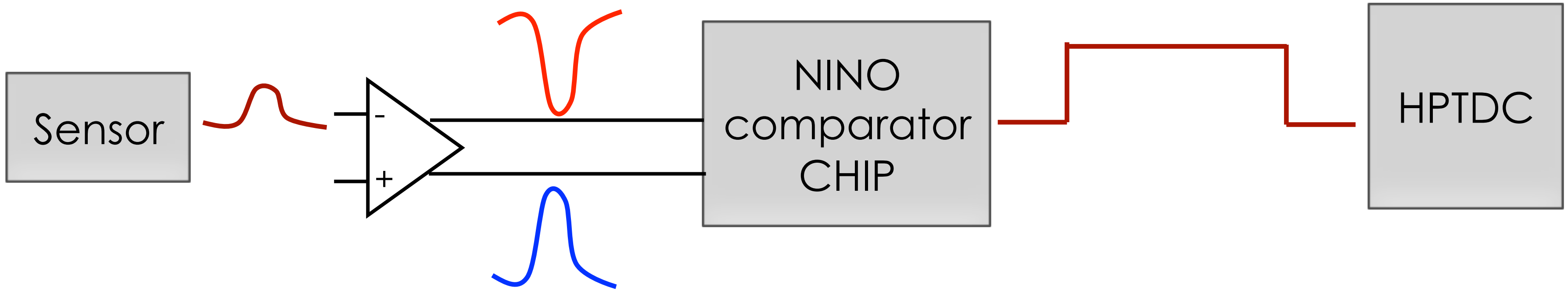
As t_{Cur} ~ 400 ps, we are actually operating in between current and voltage mode **$t_{Cur} \sim t_{RC}$**

In pure current mode, C has no effect on the pulse amplitude

In voltage mode, if C increases the amplitude decreases (the RC slows the signal)

CT-PPS Silicon read-out system

Currently the block diagram is the following:

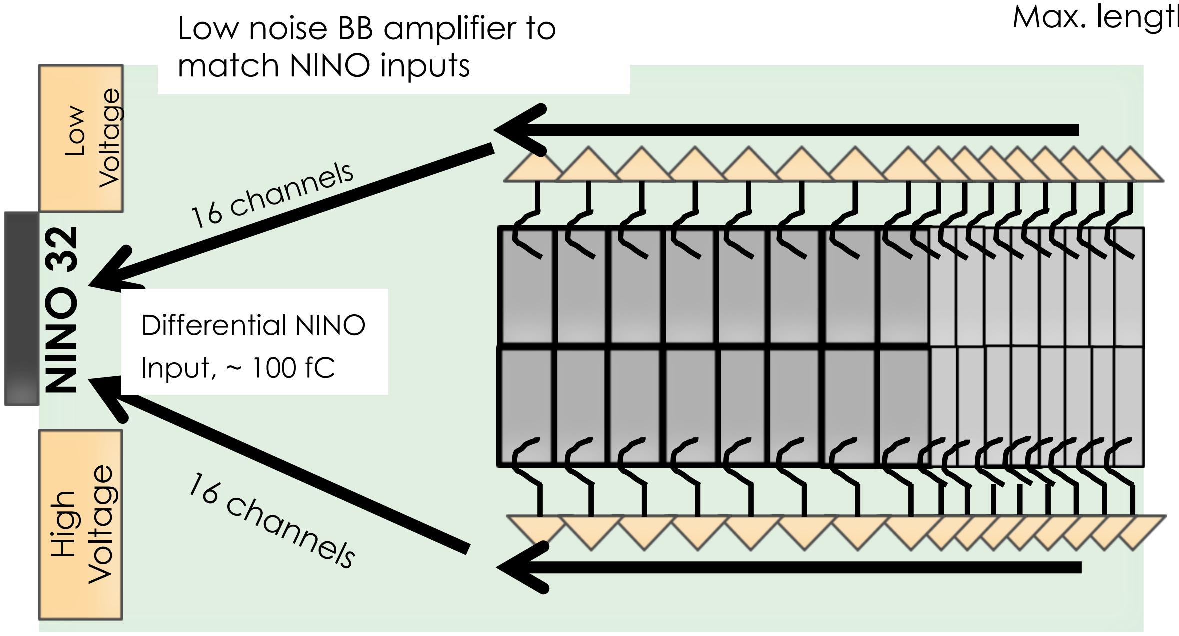


Goal:

40 ps per plane

(including NINO and HPTDC)

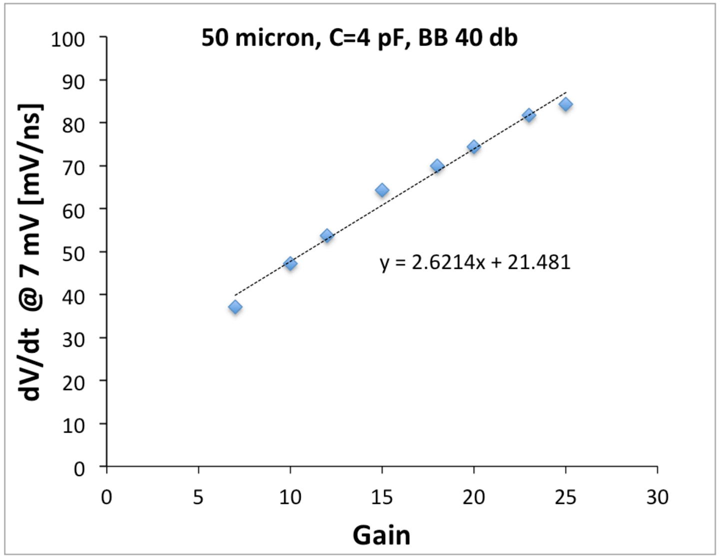
Bond wire: 0.8 nH/mm.
Max. length: 2-3 mm



The slope term

Is the slope proportional to the Gain (for a fixed t_rise) ?

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



According to WF2, this is true when the slope is completely determined by the gain holes.

For 50 micron sensors, this is actually true in the range of interest (Gain 5-25)