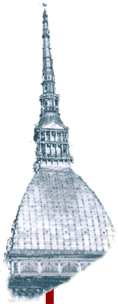


Tracciatori in 4D

Day 1:

- Why timing?
- A Time tagging system
- Gain in Silicon detectors
- Signal formation, go thin!

Day 2:

- Radiation damage
- Read-out
- From a pixel to a tracker

Bonus: design your own detector ➔ prepare for tomorrow

4D tracking with ultra-fast silicon detectors
http://iopscience.iop.org/article/10.1088/1361-6633/aa94d3/pdf
https://arxiv.org/abs/1704.08666

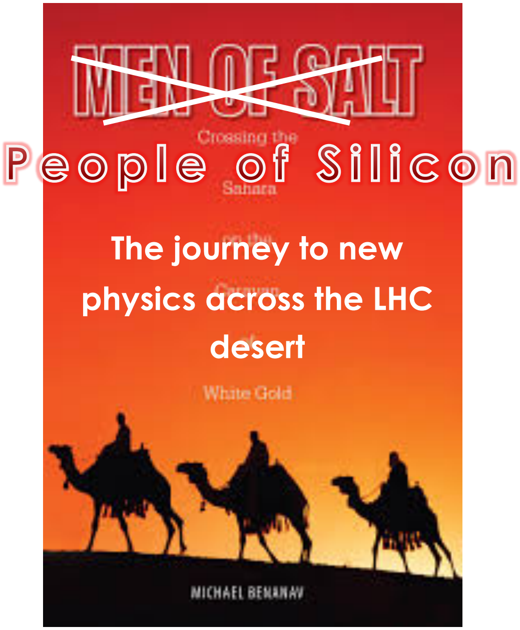
Preamble: Timing layers, 4D- and 5D-tracking

Besides a few indirect signals of new physics, particle physics today faces a discovery desert.

We need to cross an **energy- cross section** desert to reach the El-dorado of new physics.

Very little help in the direction of this path is coming from nature, the burden is on the accelerator and experimental physicists to provide the means for this crossing.

Timing is one of the enabling technologies to cross the desert



The effect of timing information

The inclusion of track-timing in the event information has the capability of changing radically how we design experiments.

Timing can be available at different levels of the event reconstruction, in increasing order of complexity:

1) Timing in the event reconstruction ➔ **Timing layers**
    - this is the easiest implementation, a layer ONLY for timing
2) Timing at each point along the track ➔ **4D tracking**
    - tracking-timing
3) Timing at each point along the track at high rate ➔ **5D tracking**
    - Very high rate represents an additional step in complication, very different read-out chip and data output organization

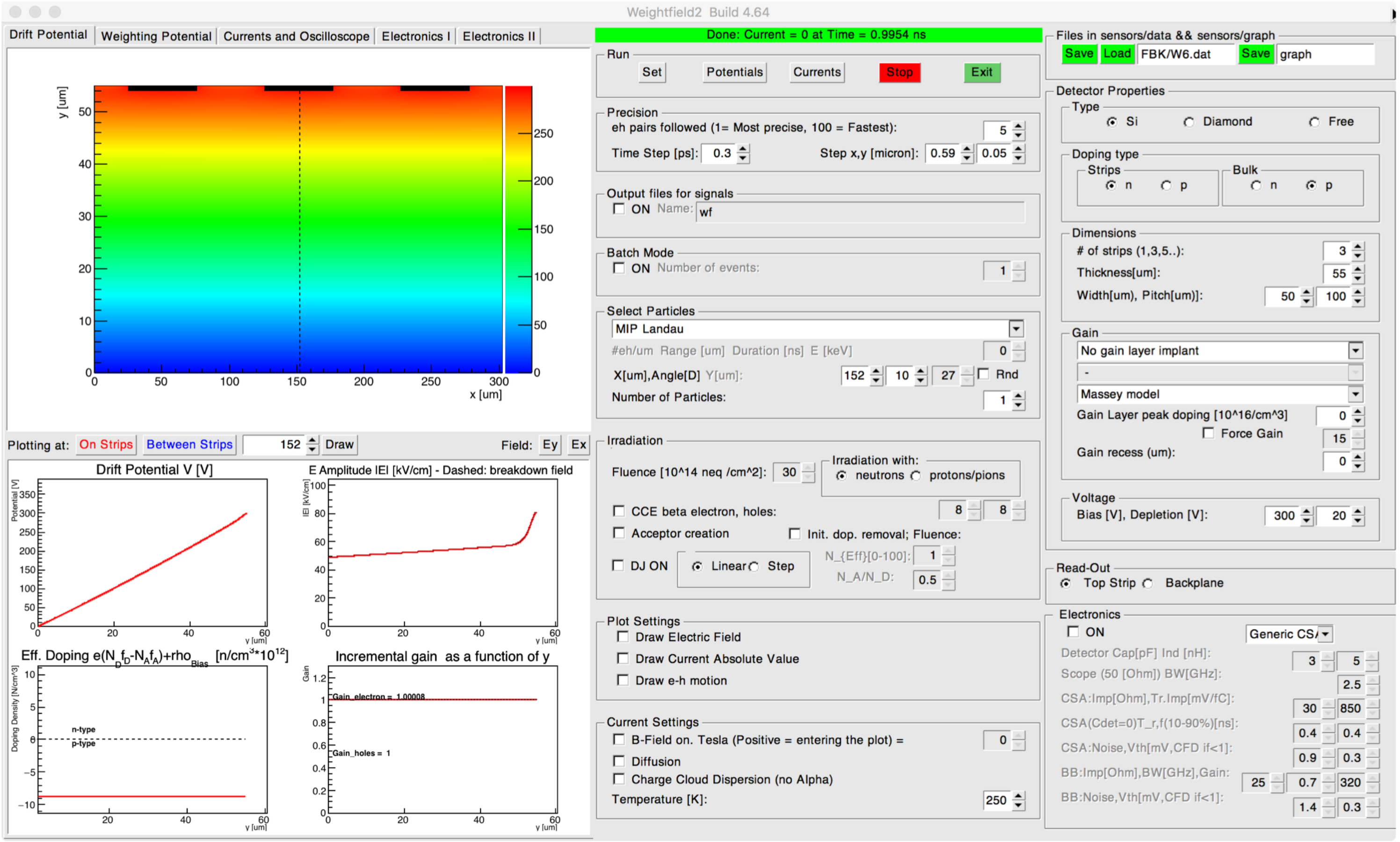
Preamble: simulator Weightfield2

Available at:

http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html

It requires Root build from source, it is for Linux and Mac.

It will not replace TCAD, but it helps in understanding the sensors response



Weightfield2 Build 4.64

Done: Current = 0 at Time = 0.9954 ns

Plotting at: 152

Run

Precision

eh pairs followed (1= Most precise, 100 = Fastest): 5

Time Step [ps]: 0.3

Step x,y [micron]: 0.59 0.05

Output files for signals

☐ ON Name: wf

Batch Mode

☐ ON Number of events: 1

Select Particles

MIP Landau

#eh/um Range [um] Duration [ns] E [keV] 0

X[um],Angle[D] Y[um]: 152 10 27 ☐ Rnd

Number of Particles: 1

Irradiation

Fluence [10^14 neq /cm^2]: 30

Irradiation with: ● neutrons ○ protons/pions

☐ CCE beta electron, holes: 8 8

☐ Acceptor creation

☐ Init. dop. removal; Fluence:

☐ DJ ON ● Linear ○ Step

N_{Eff}[0-100]: 1

N_A/N_D: 0.5

Plot Settings

☐ Draw Electric Field

☐ Draw Current Absolute Value

☐ Draw e-h motion

Current Settings

☐ B-Field on. Tesla (Positive = entering the plot) = 0

☐ Diffusion

☐ Charge Cloud Dispersion (no Alpha)

Temperature [K]: 250

Files in sensors/data && sensors/graph

FBK/W6.dat

graph

Detector Properties

Type: ● Si ○ Diamond ○ Free

Doping type

Strips: ● n ○ p

Bulk: ○ n ● p

Dimensions

\# of strips (1,3,5..): 3

Thickness[um]: 55

Width[um), Pitch[um)]: 50 100

Gain

No gain layer implant

\-

Massey model

Gain Layer peak doping [10^16/cm^3] 0

☐ Force Gain 15

Gain recess (um): 0

Voltage

Bias [V], Depletion [V]: 300 20

Read-Out

● Top Strip ○ Backplane

Electronics

☐ ON Generic CS/

Detector Cap[pF] Ind [nH]: 3 5

Scope (50 [Ohm]) BW[GHz]: 2.5

CSA:Imp[Ohm],Tr.Imp[mV/fC]: 30 850

CSA(Cdet=0)T_r,f(10-90%)[ns]: 0.4 0.4

CSA:Noise,Vth[mV,CFD if<1]: 0.9 0.3

BB:Imp[Ohm],BW[GHz],Gain: 25 0.7 320

BB:Noise,Vth[mV,CFD if<1]: 1.4 0.3

Weightfield2

Highlights:

- It is completely open source
- it's fast
- It generates the signal from several sources (MIP, alpha, lasers..)
- Runs in batch mode writing output files
- It loads/save configurations
- It has basics electronics simulation

It crashes occasionally

How to use it:

Obtain the last version from

http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html

1) From the download page, get the latest version
2) Unzip it and then type:
3) Make or 3-bis) make -f Makefile_MacOS10.10_root6
4) ./weightfield

Consideriamo la situazione ad LHC, esperimento CMS

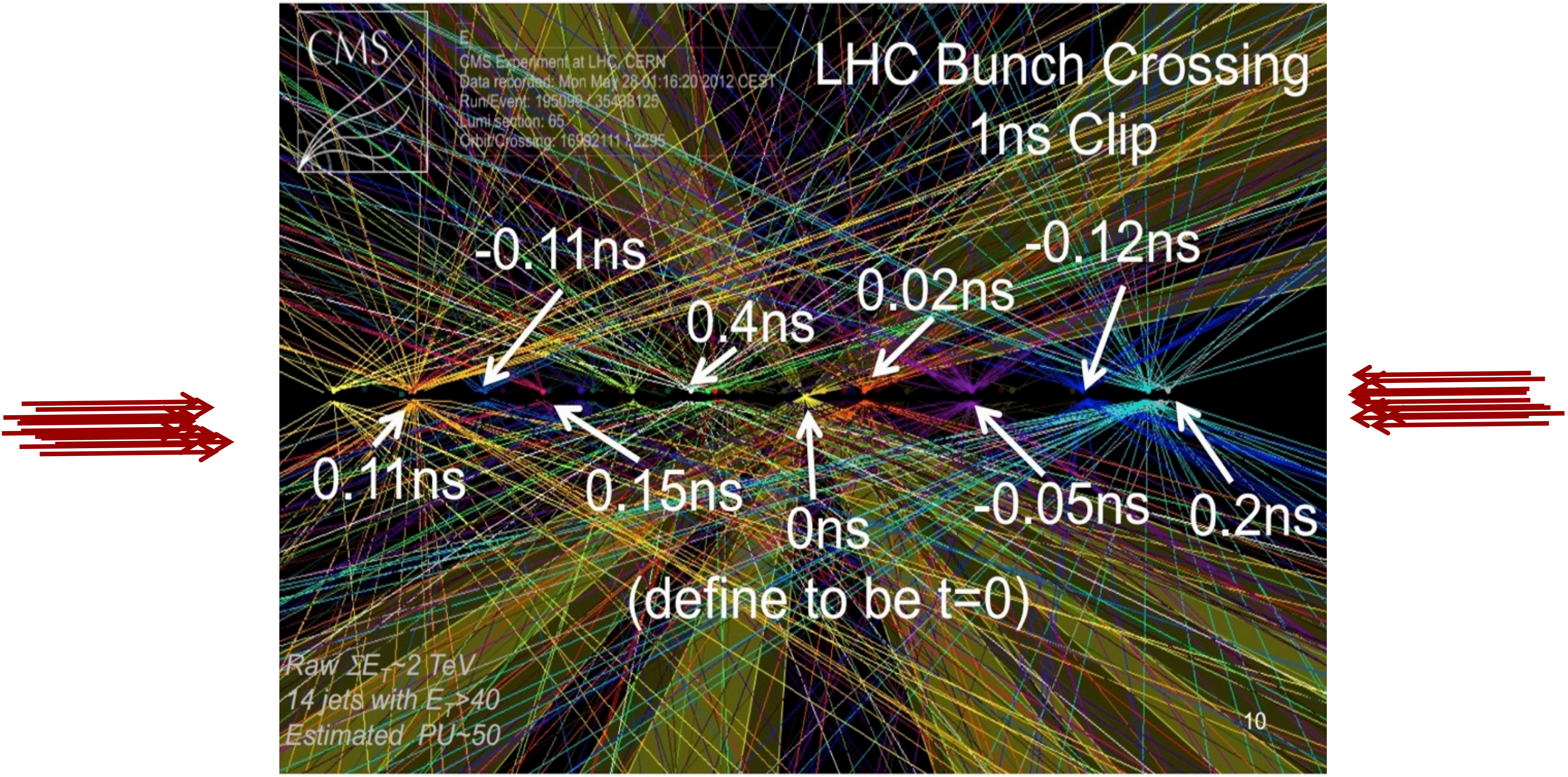
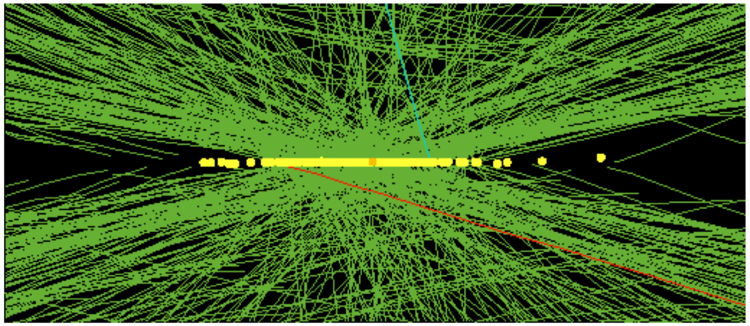


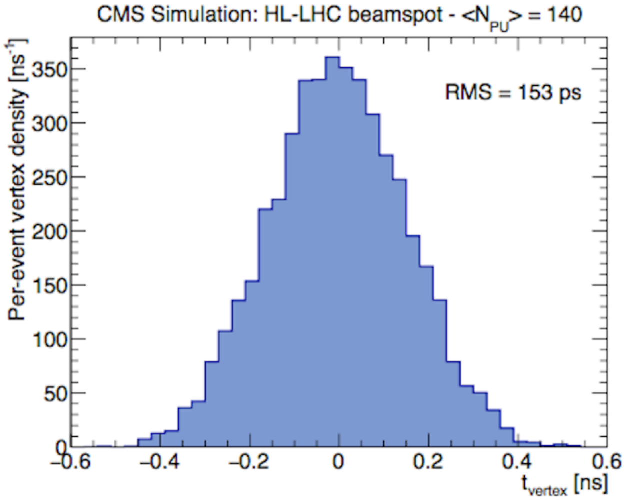
Figure 1 Interaction time of many proton-proton vertexes happening in the same bunch crossing in the case of ~ 50 overlapping events. The vertexes are spaced 10's of pico seconds apart.

Is timing really necessary?



The research into 4D tracking is strongly motivated by the HL-LHC experimental conditions:

150-200 events/bunch crossing



According to CMS simulations:

- **Time RMS between vertexes: 153 ps**
- **Average distance between two vertexes: 500 um**
- **Fraction of overlapping vertexes: 10-20%**
  - Of those events, a large fraction will have significant degradation of the quality of reconstruction

At HL-LHC: Timing is equivalent to additional luminosity

One extra dimension: tracking in 4Dimension

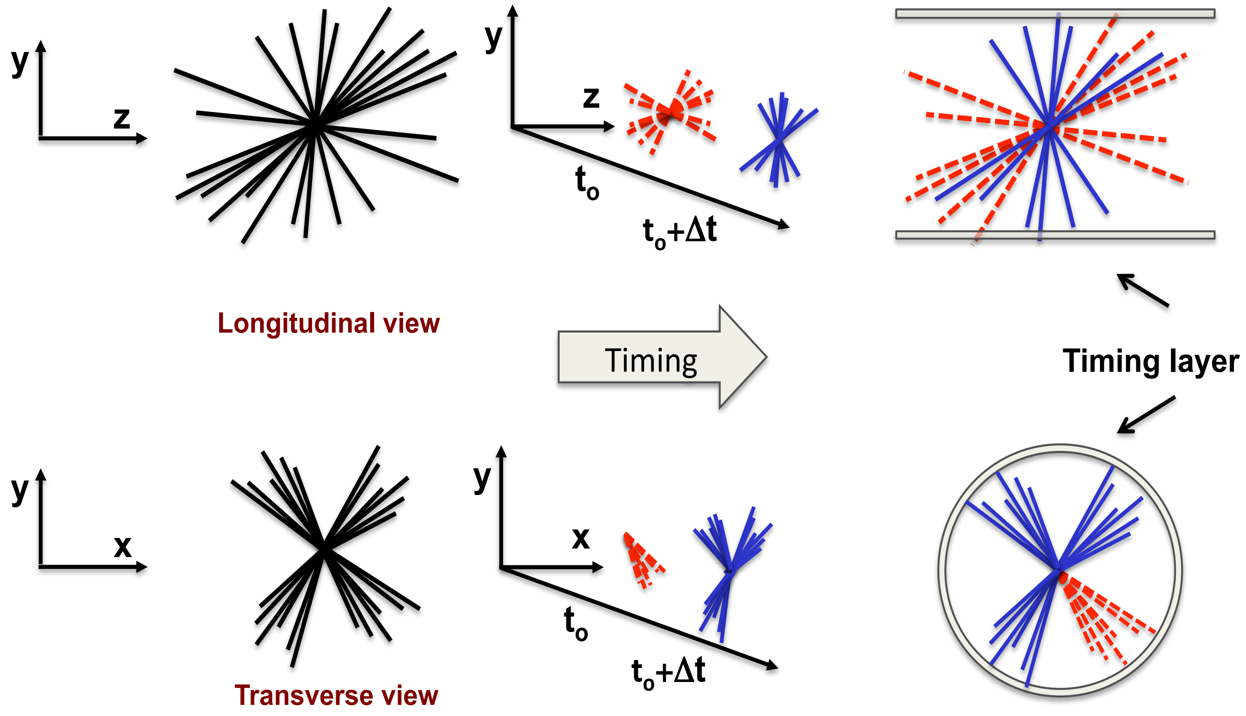
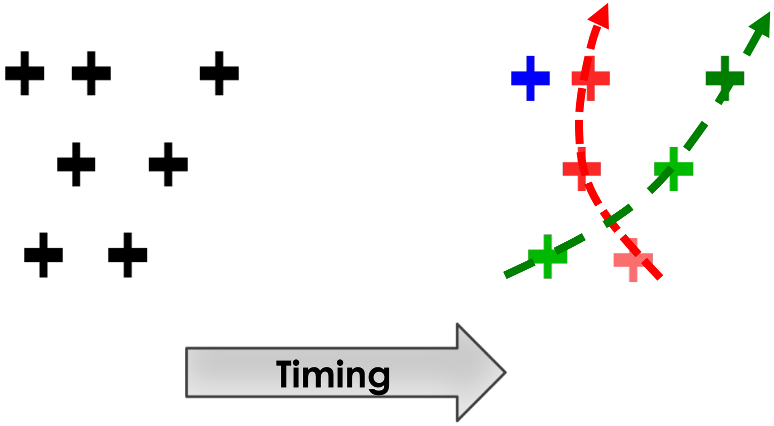


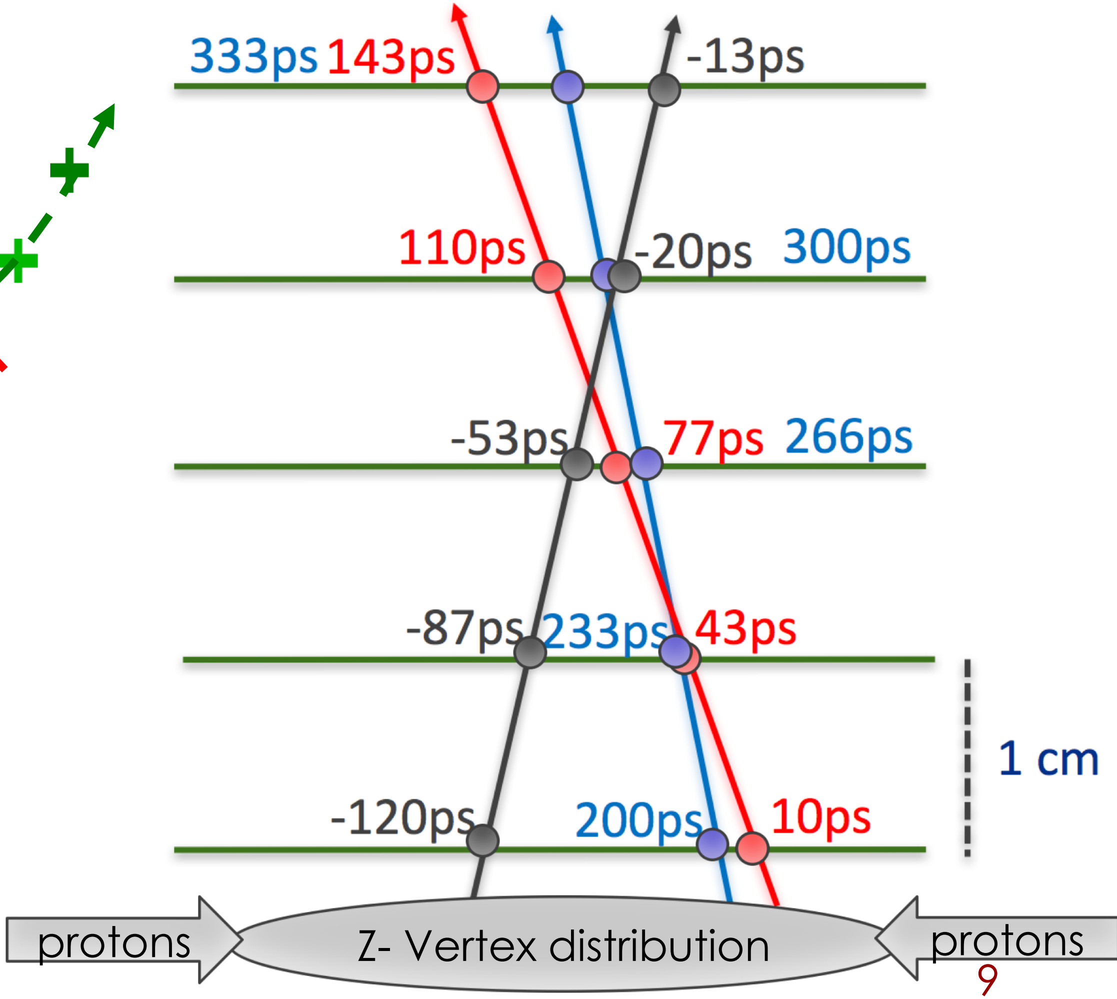
Figure 4 Schematic representation of the power of timing information in distinguishing overlapping events using a timing layer.

Timing at each point along the track

➔Massive simplification of patter recognition, new tracking algorithms will be faster even in very dense environments

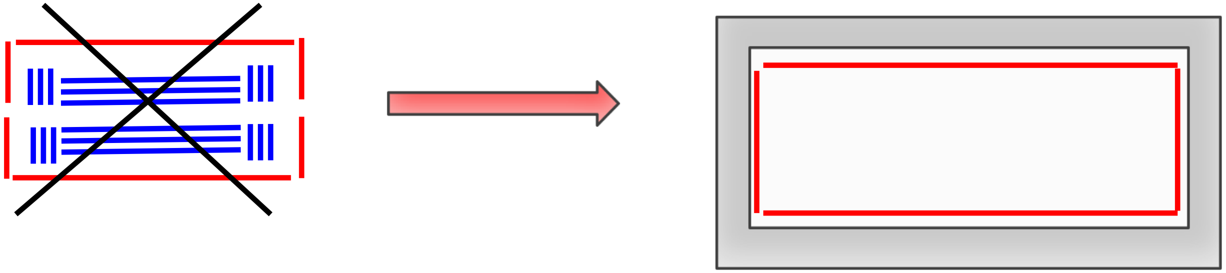
➔ Use only "time compatible points"



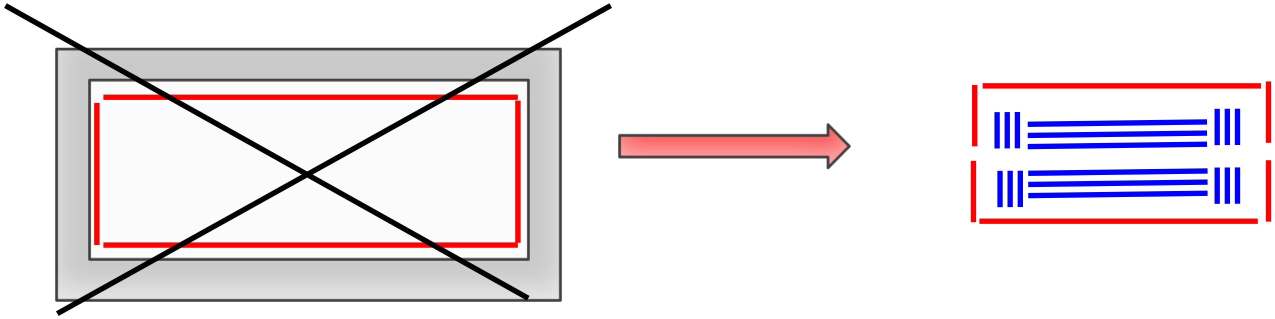


Where do we place a single timing layer?

The tracking community thinks it is a wonderful idea, clearly to be implemented **outside the tracker volume**, in front of the calorimeter



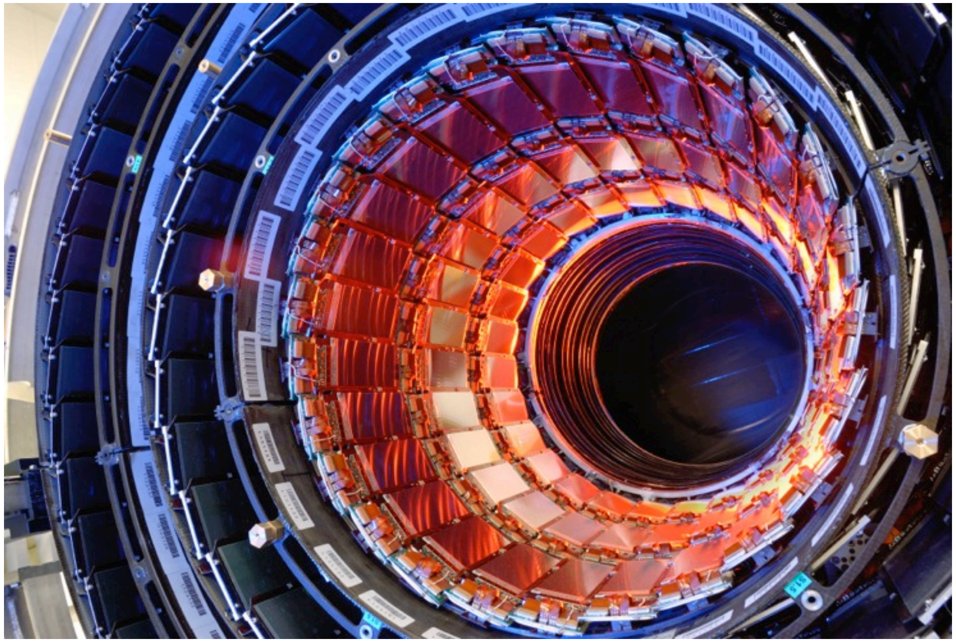
The calorimeter community thinks it is a wonderful idea, clearly to be implemented **far from the calorimeter,** in the tracker volume



We are now in contact with **the muon community….**

State-of-the-art Position Detectors

Extremely good position detectors are currently in use in every major high energy physics experiment:



- Millions of channels
- Very reliable
- Very radiation hard

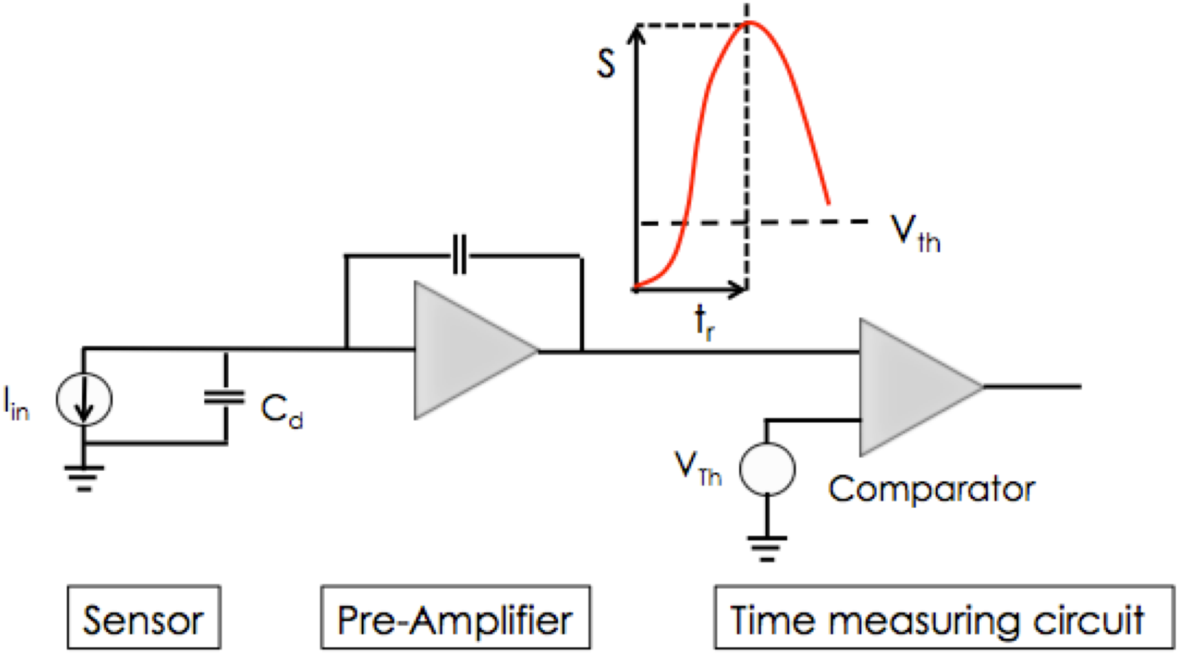
The timing capability is however limited to ~ 100-150 ps (NA62 @CERN)

σ_t ~ 100-150 ps

σ_x ~ 20-30 μm

Silicon 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.

Strong interplay between sensor and electronics

Time resolution

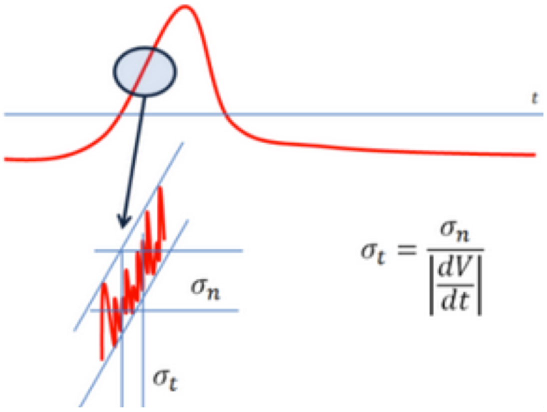
$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \text{TDC}$$

Usual "Jitter" term

Here enters everything that is "Noise" and the steepness of the signal

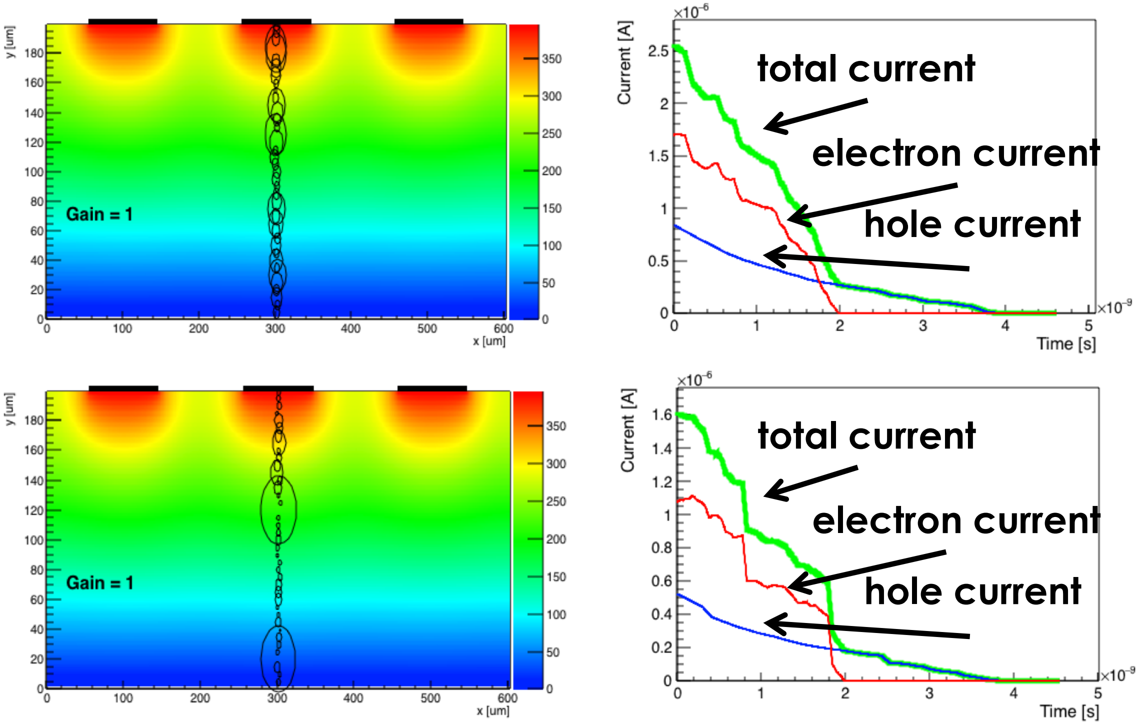
Time walk: Amplitude variation, corrected in electronics

Shape variations: non homogeneous energy



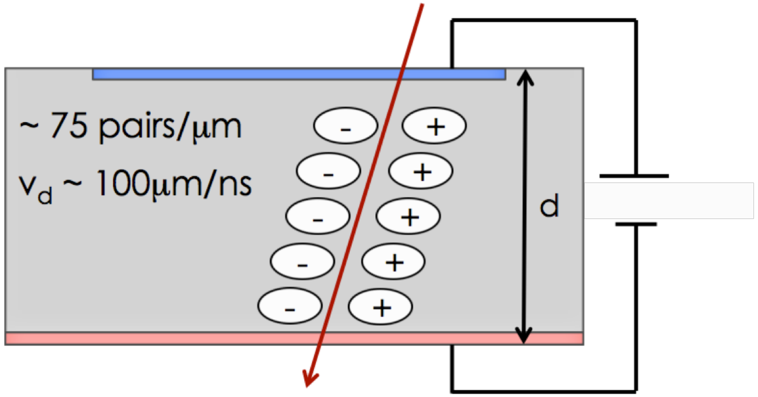
$$\sigma_t = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|}$$

Need large dV/dt



Gain needs E ~ 300kV/cm. How can we do it?

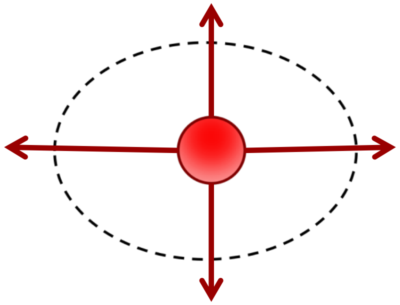
1) Use external bias: assuming a 50 micron silicon detector, we need **V_{bias} = ~ 600 - 700 V**



Difficult to achieve

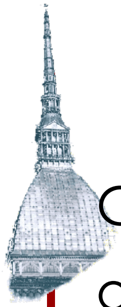
2) Use Gauss Theorem:

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



E = 300 kV/cm ➔ q ~ 10^{16} /cm^3

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



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: V ~ 300 kV/cm

Charge multiplication

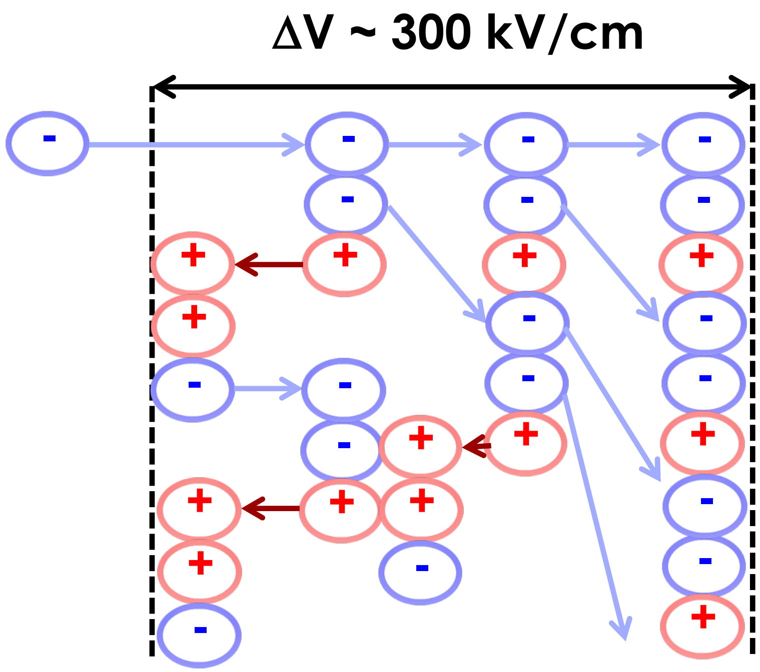
$$N(l) = N_0 \cdot e^{�\cdot l}$$

Gain:

$$\mathrm{G} = \mathrm{e}^{\alpha\ 1}$$

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

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**

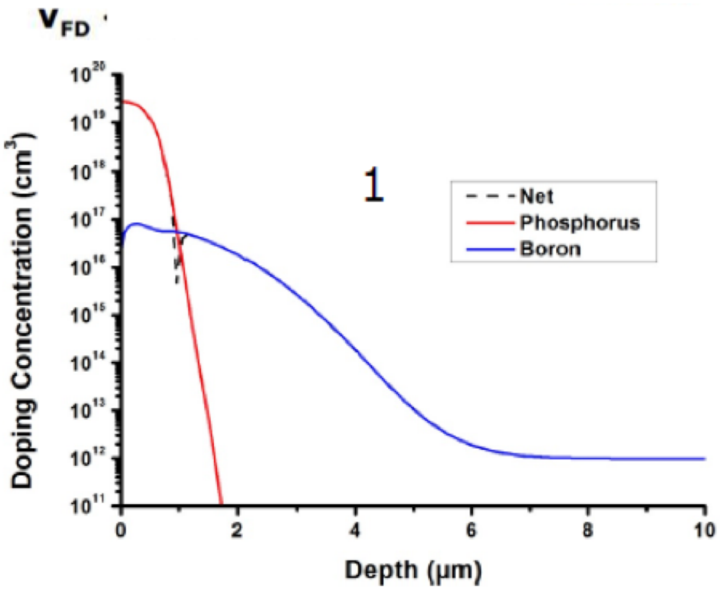
Low Gain Avalanche Detectors (LGADs)

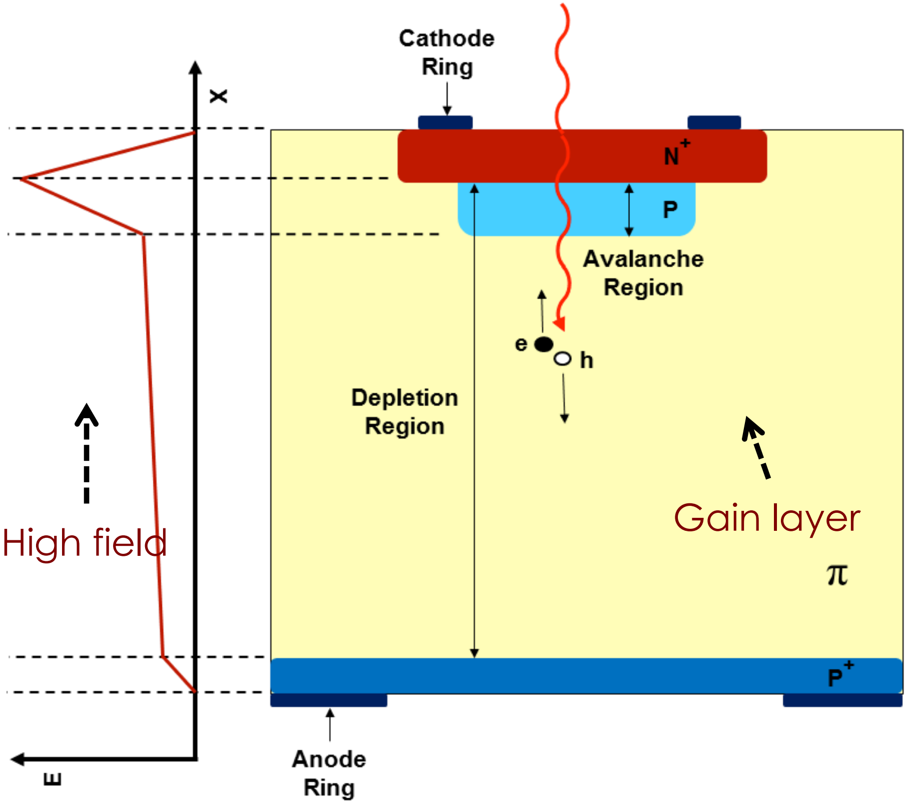
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

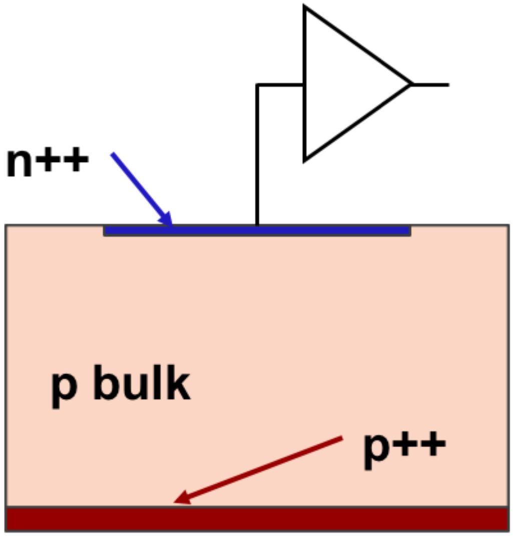
High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage

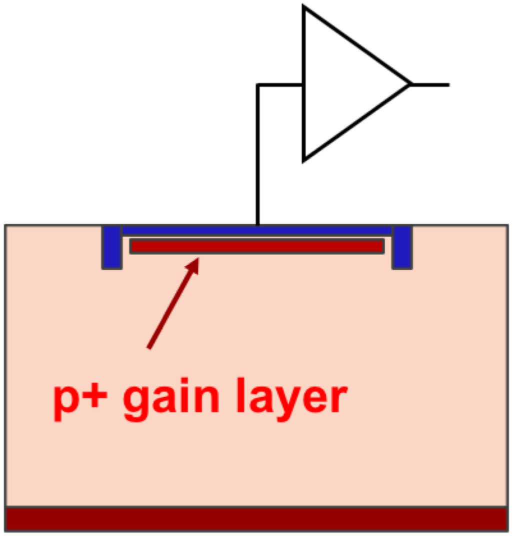




Difference PiN - LGAD



Traditional silicon diode



Low Gain Avalanche Diode

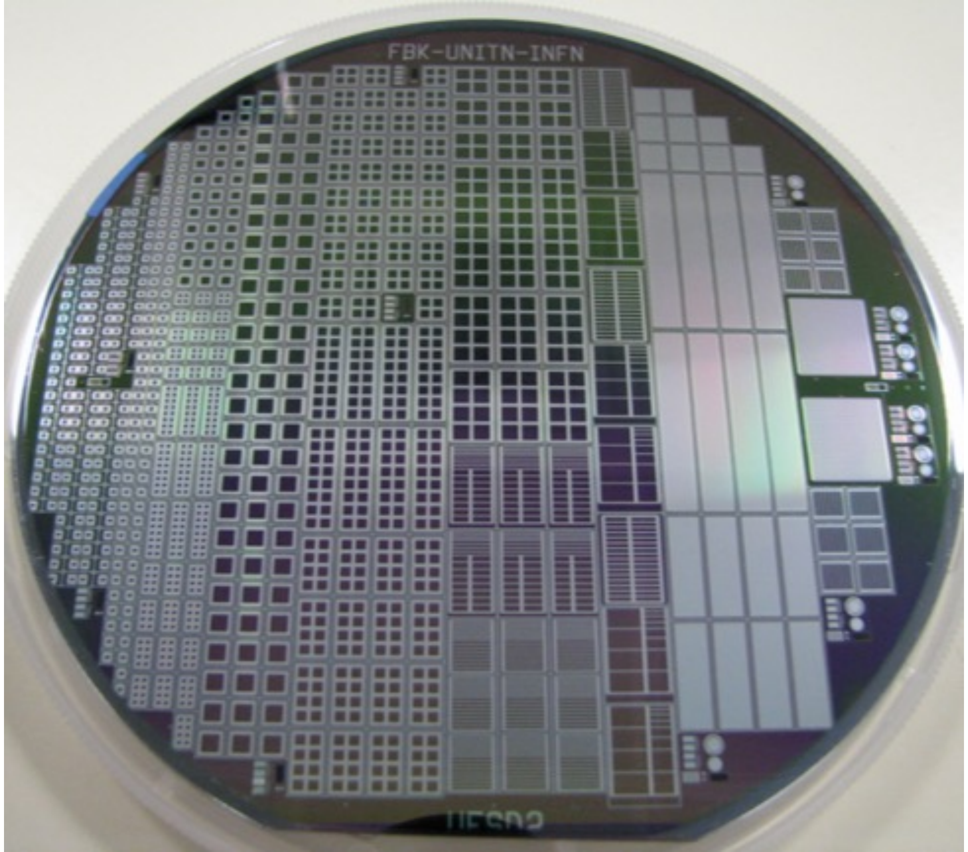
Come di fanno dei sensori?

Collaborazione molto intensa (~ una riunione a settimana per 3 anni…)

FBK – Trento Uni – INFN

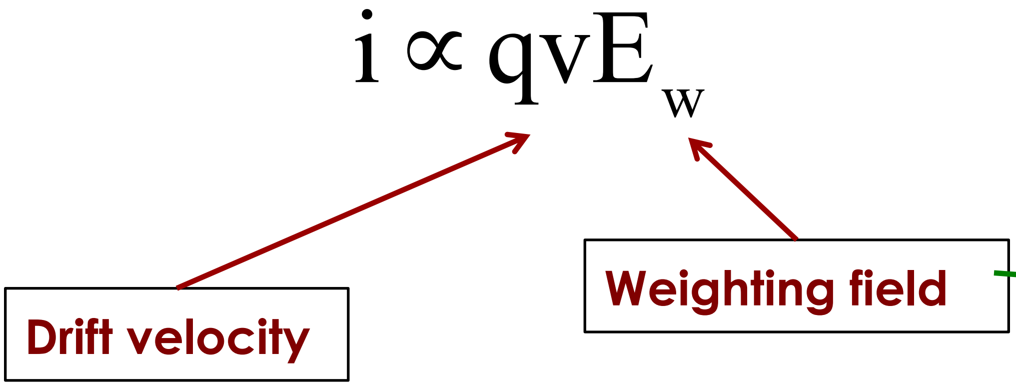
UFSD1: 300-micron. First LGAD production at FBK. Gain layer study, edges

UFSD2: 50-micron. Very successful, good gain and overall behavior, excellent time resolution. Gain layer doping: Boron, Gallium, Boron + Carbon, Gallium+Carbon



Not all geometries are possible

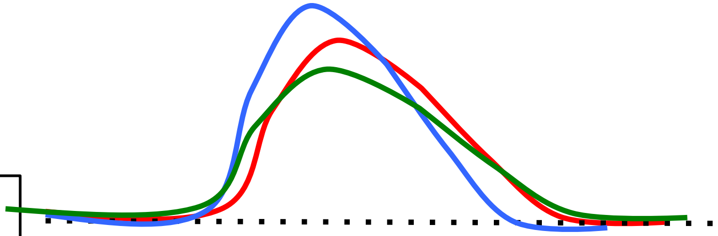
Signal shape is determined by Ramo's Theorem:



$$i \propto qvE_w$$

Drift velocity

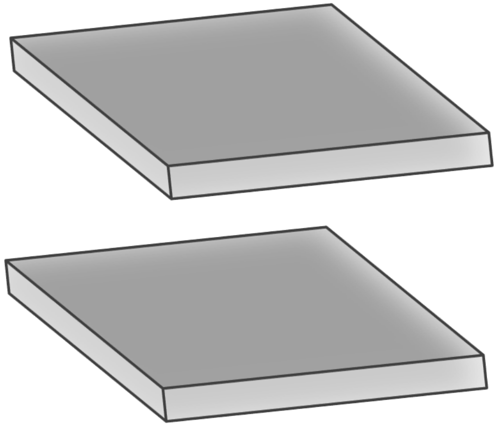
Weighting field



The key to good timing is the uniformity of signals:

Drift velocity and Weighting field need to be as uniform as possible

Basic rule: **parallel plate geometry**



Drift Velocity

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

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

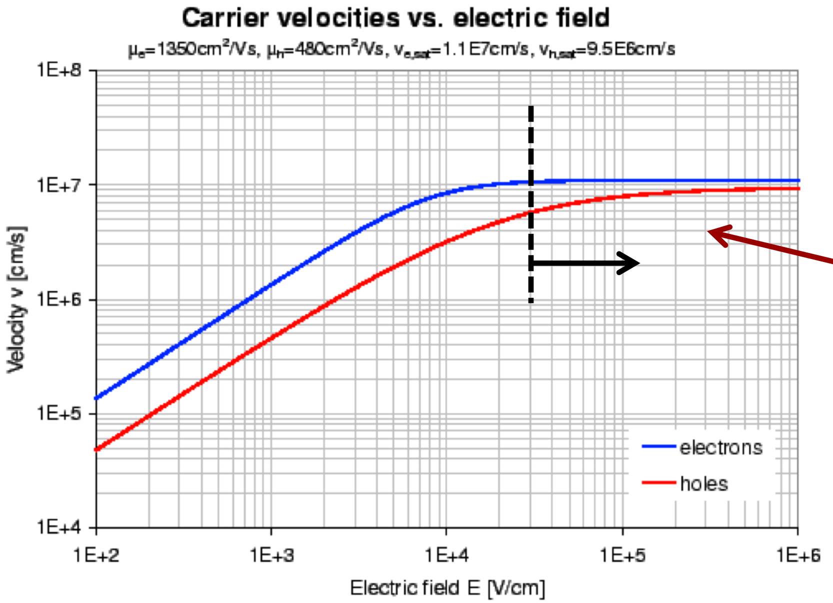


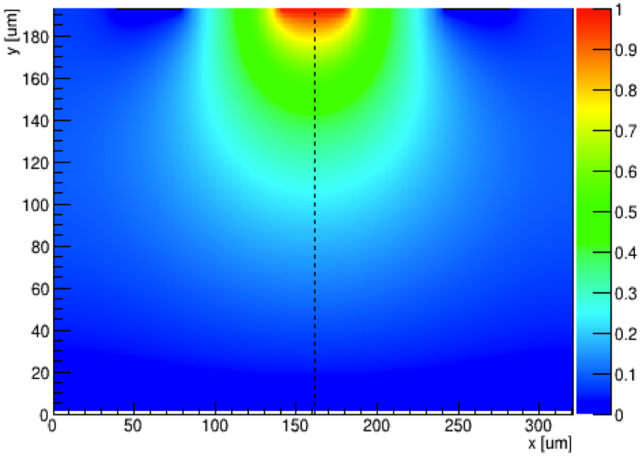
Figure: Electron and hole velocities vs. the electric field strength in silicon.

We want to operate in this regime

Weighting Field: coupling the charge to the electrode

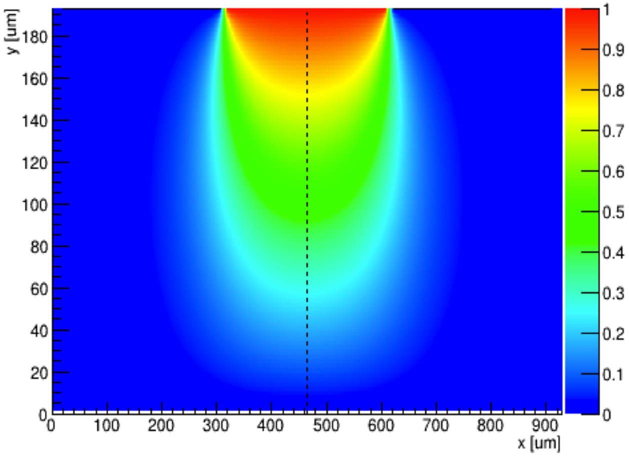
$$i \propto qv\enclose{circle}{E_w}$$

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

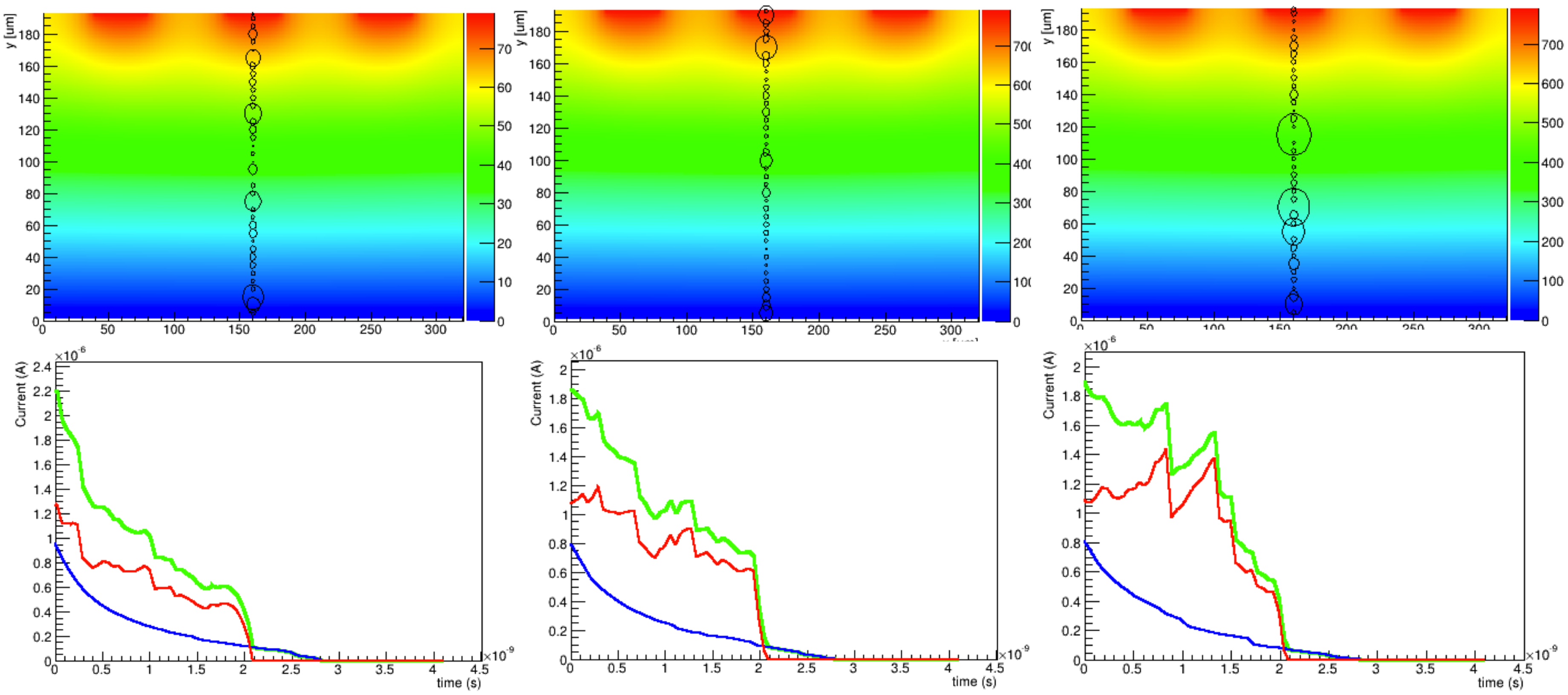
The weighting field needs to be as uniform as possible, so that the coupling is always the same, regardless of the position of the charge

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:

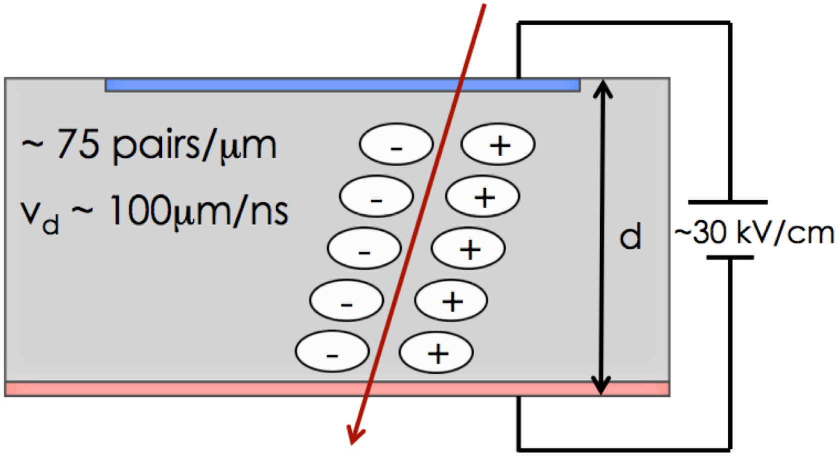


Signal formation in silicon detectors

We know we need a large signal, but **how is the signal formed?**

What is controlling the slew rate?

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



A particle creates charges, then:

- The charges start moving under the influence of an external field
- The motion of the charges induces a current on the electrodes
- The signal ends when the charges reach the electrodes

What is the signal of one e/h pair?

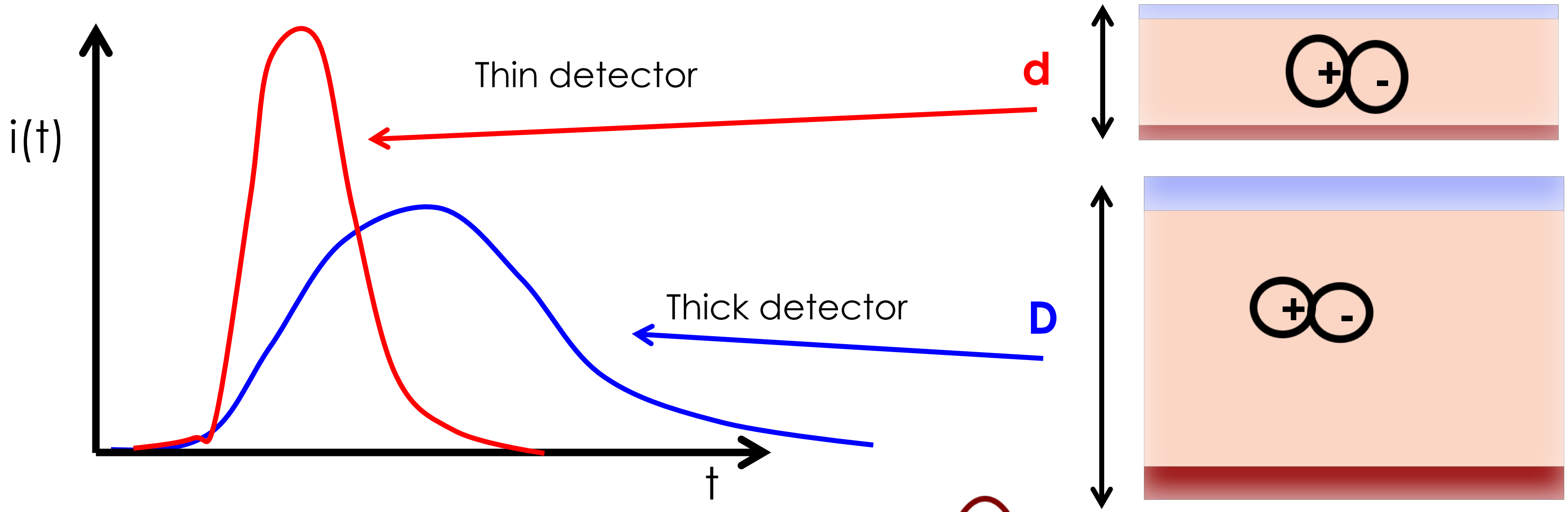
(Simplified model for pad detectors)

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

Large signals from thick detectors?

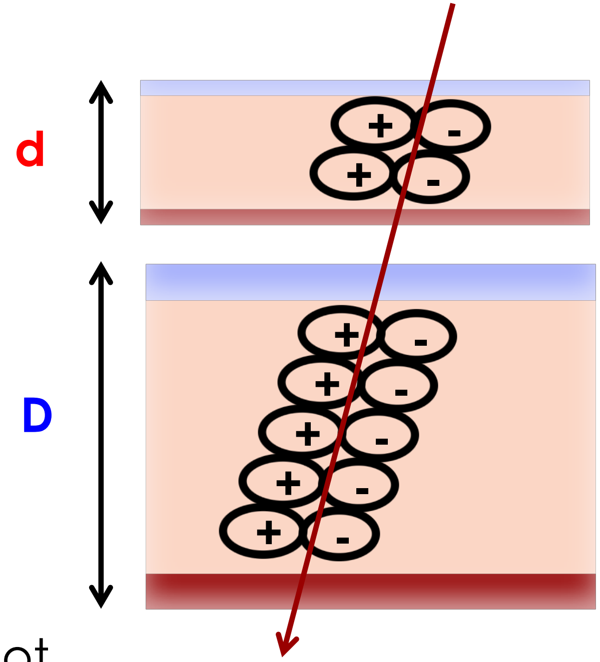
(Simplified model for pad detectors)

Thick detectors have higher number of charges:

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

However each charge contributes to the initial current as:

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



The initial current for a silicon detector does not depend on how thick (d) the sensor is:

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

Number of e/h = 75/micron

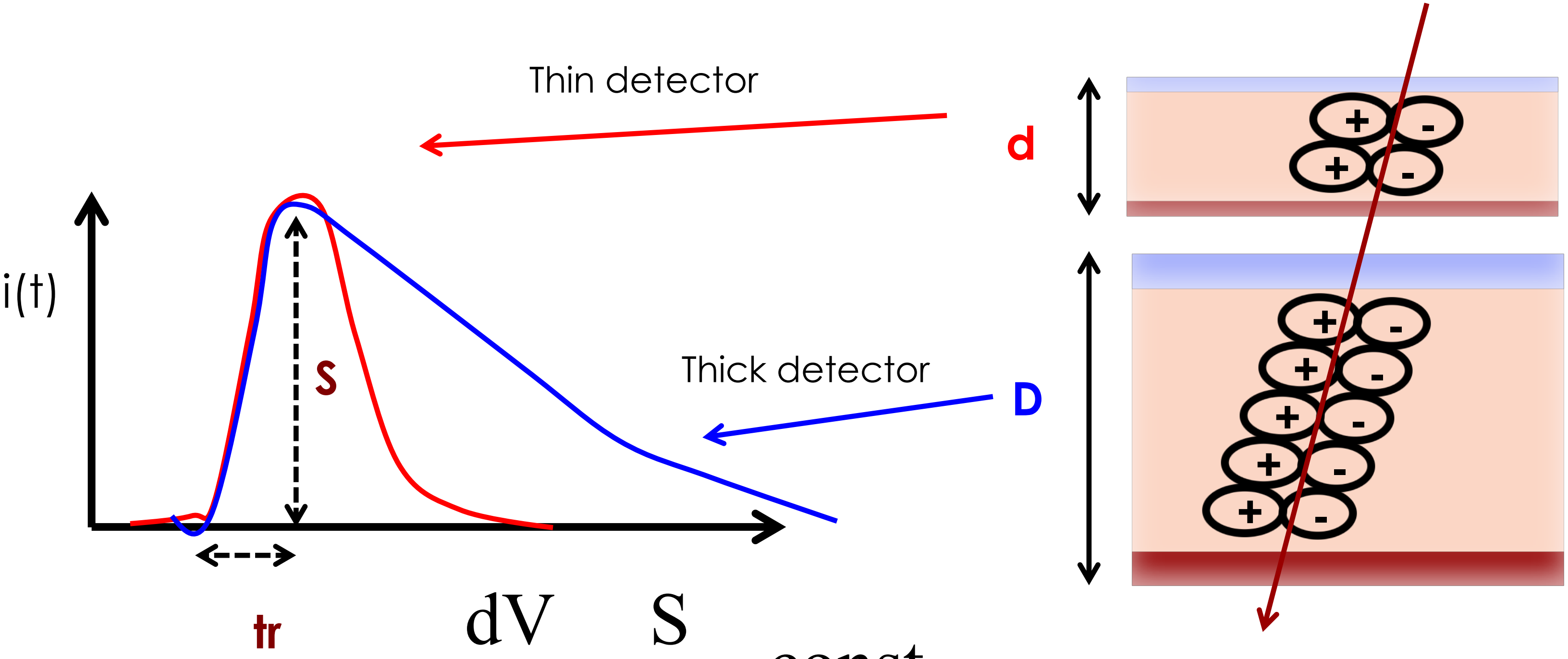
Weighting field

velocity

➔ Initial current = constant

Thin vs Thick detectors

(Simplified model for pad detectors)

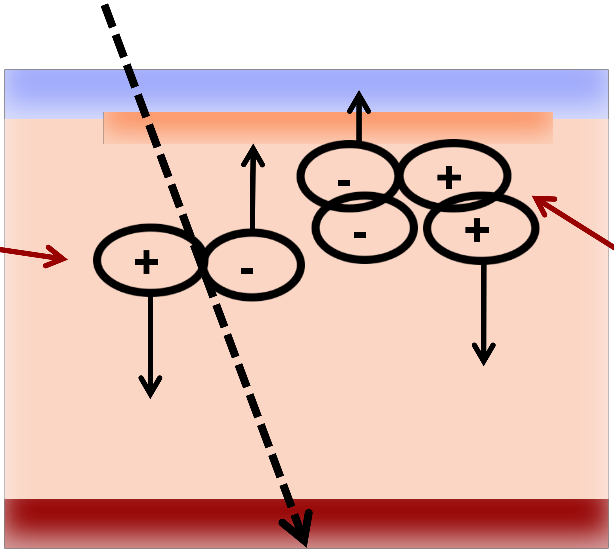


$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim \text{const}$$

Thick detectors have longer signals, not higher signals

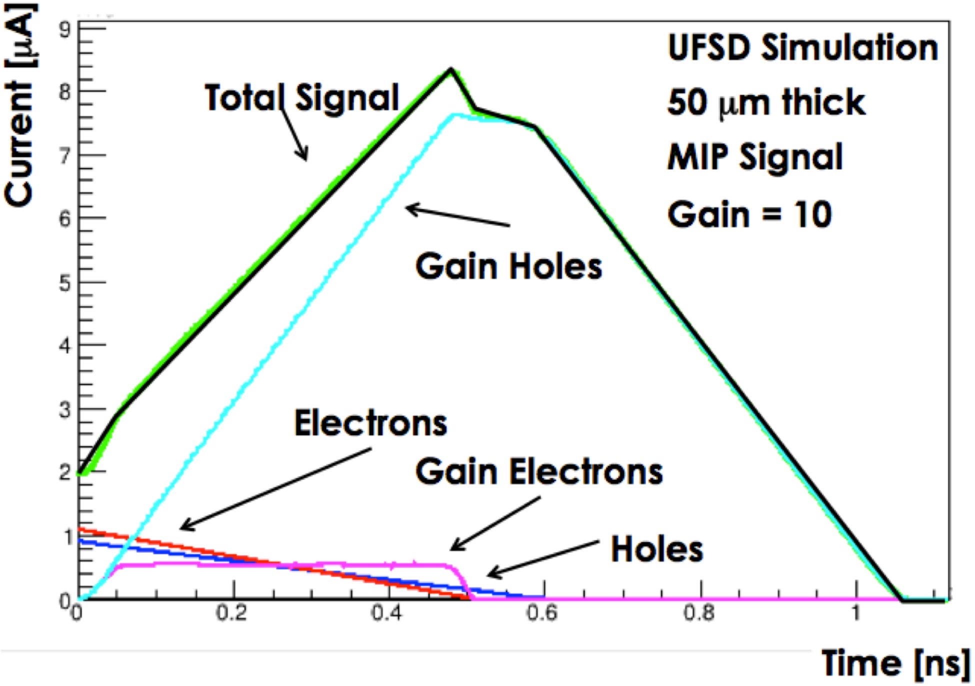
We need to add gain

How gain shapes the signal



Initial electron, holes

Gain electron:
absorbed immediately
Gain holes:
long drift home



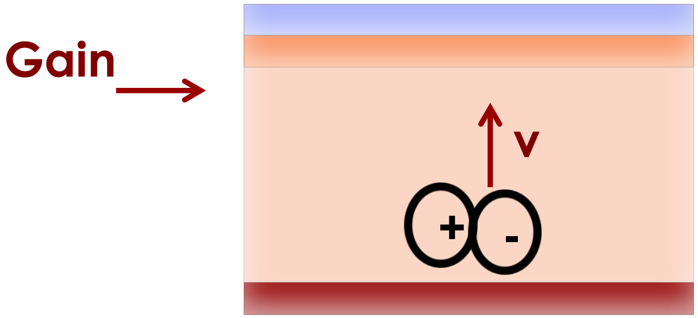
Electrons multiply and produce additional electrons and holes.

- **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)

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

➔ **Gain current ~ 1/d**

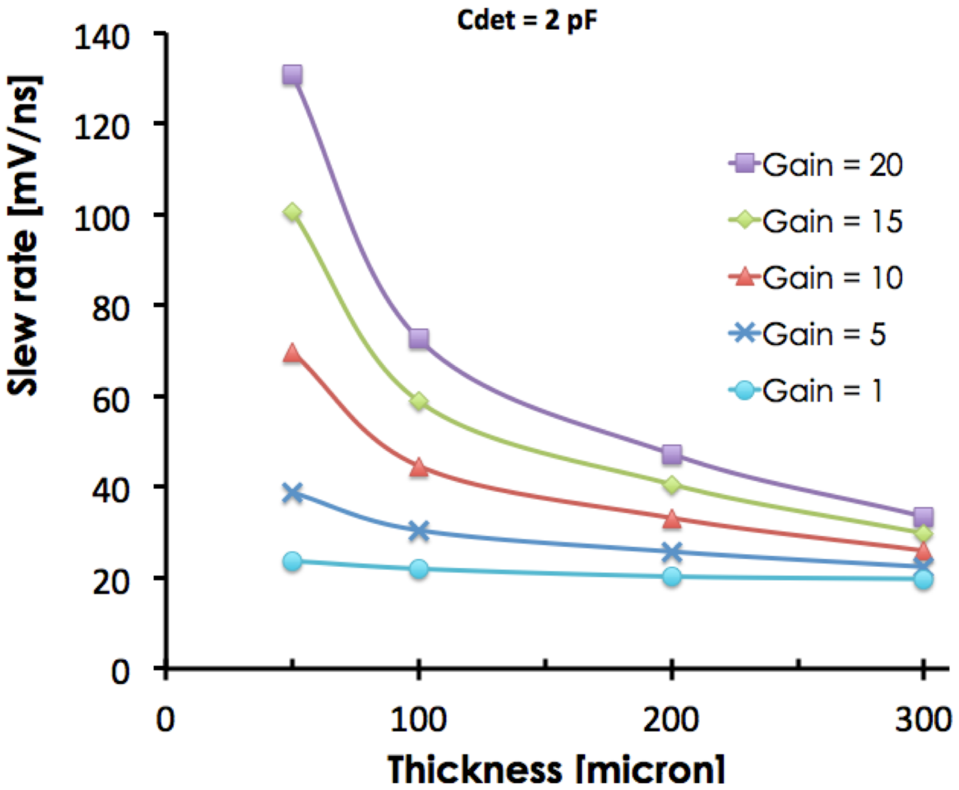
A given value of gain has much more effect on thin detectors

Gain current vs Initial current

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

!!!

➔ **Go thin!!**



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

Full simulation

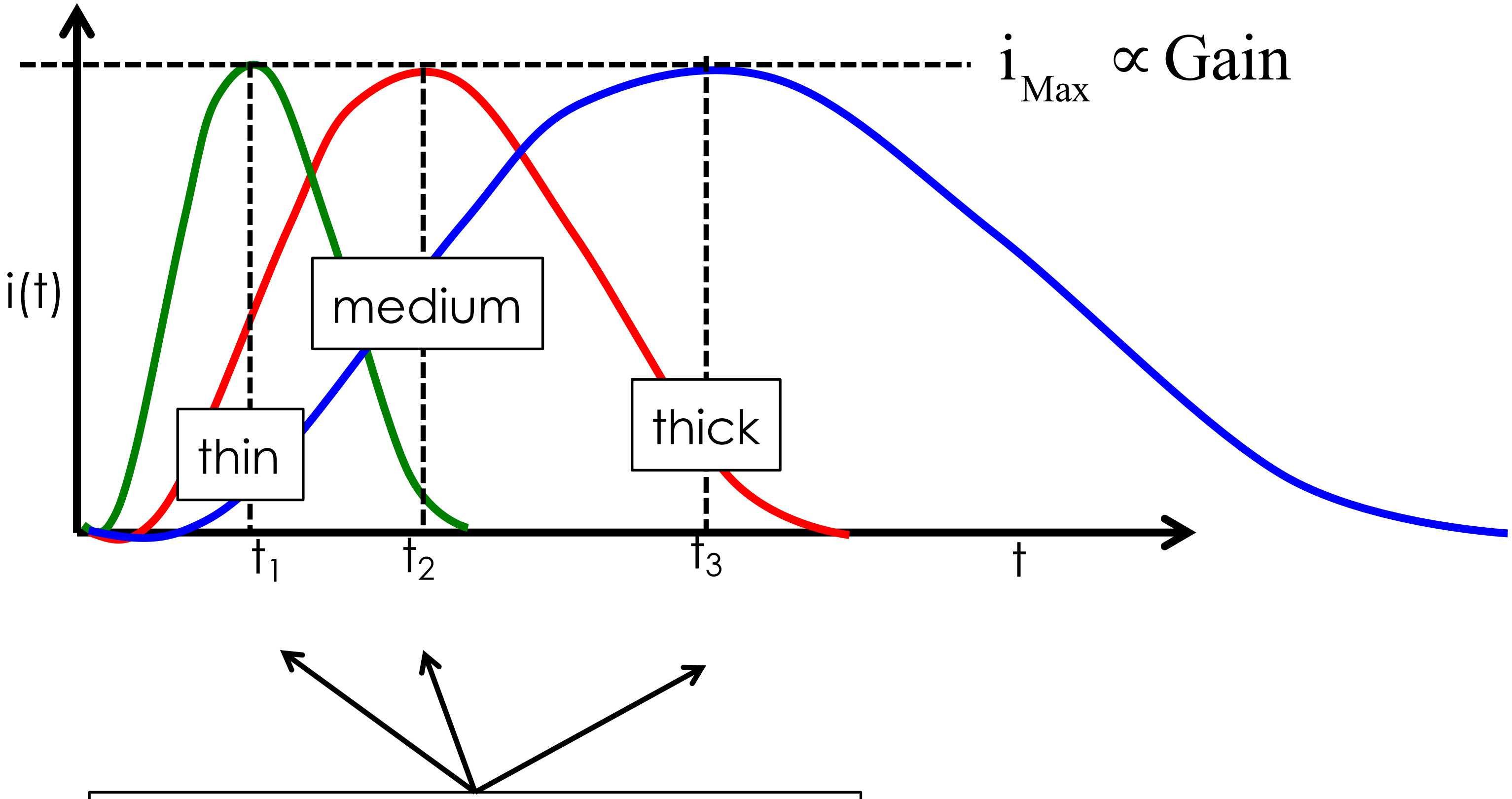
(assuming 2 pF detector capacitance)

300 micron:
~ 2-3 improvement
with gain = 20

Significant improvements in time resolution require thin detectors

Gain and Maximum current

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



The rise time depends only on the sensor thickness ~ 1/d

Ultra Fast Silicon Detectors

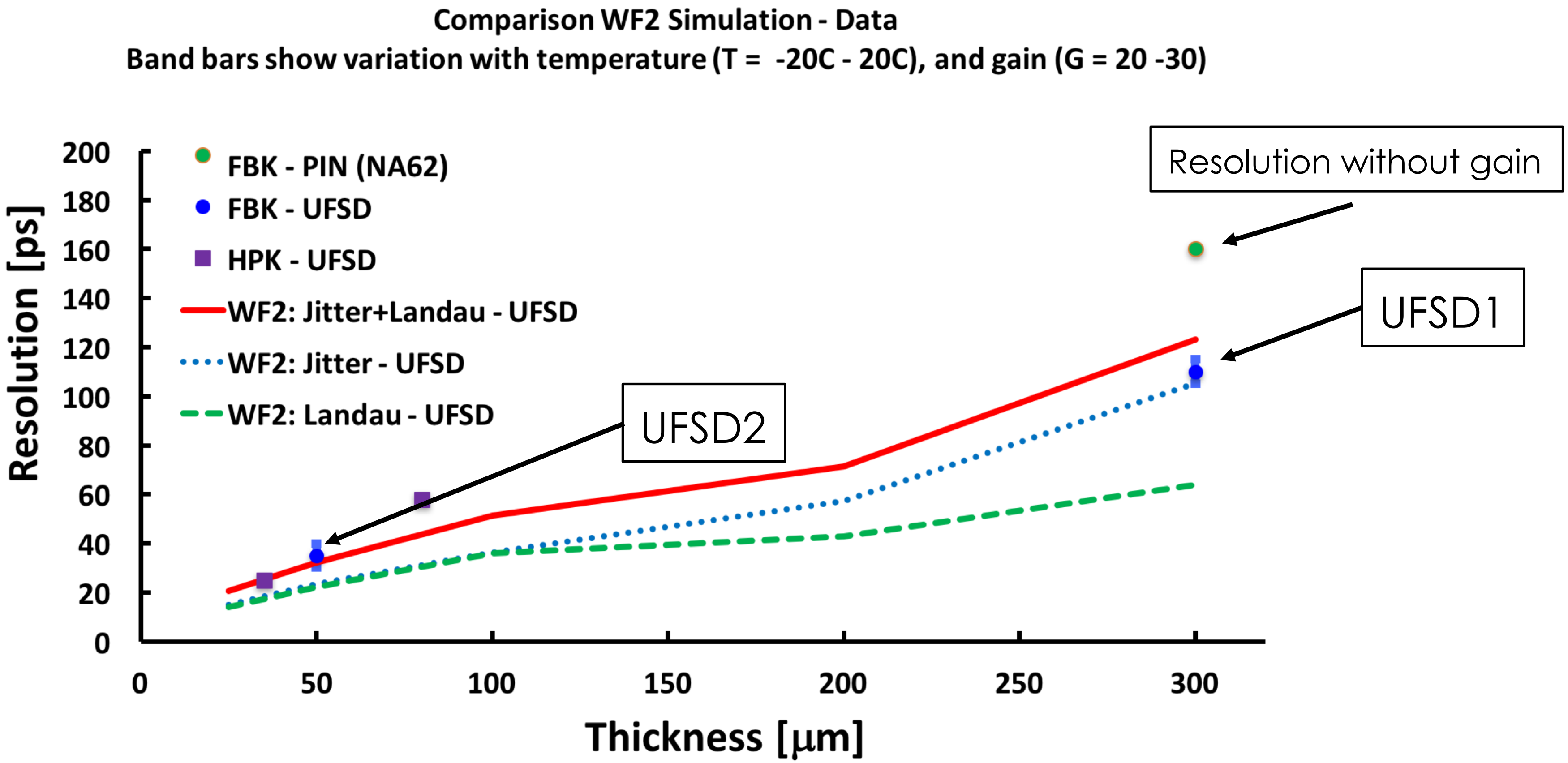
UFSD are LGAD detectors optimized to achieve the best possible time resolution

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)

UFSD time resolution summary

UFSD achieved 30 ps time resolution



Resolution without gain

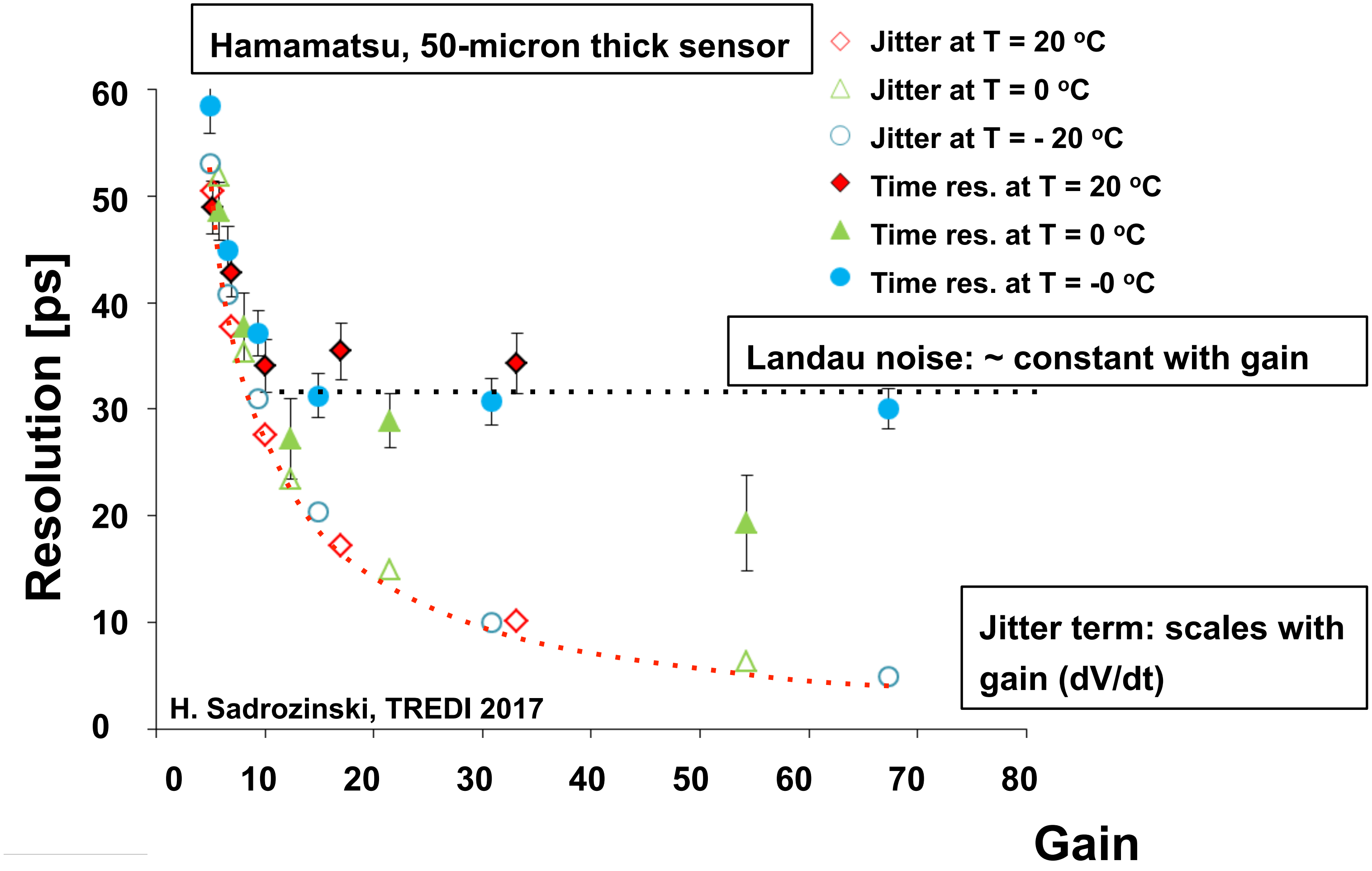
UFSD1

UFSD2

UFSD: HPK time resolution

UFSD from Hamamatsu: 30 ps time resolution,

Value of gain ~ 20



Irradiation effects

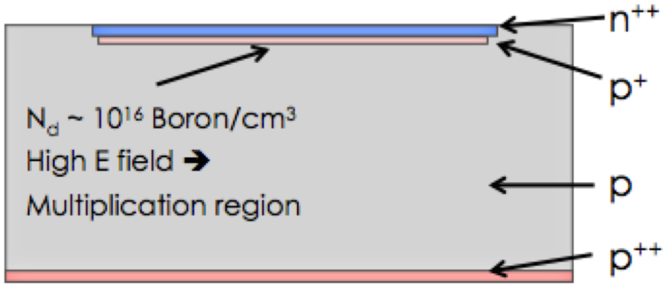
Irradiation causes 3 main effects:

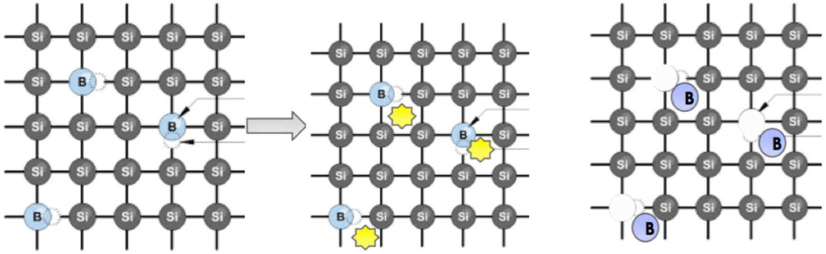
- Decrease of charge collection efficiency due to trapping
  - ➔ Very small in thin sensor
- Increased leakage current, shot noise ➔ back up slides
- Gain layer disappearance ➔ following slides

Gain layer de-activation

Unfortunate fact: irradiation de-activate p-doping removing Boron from the reticle

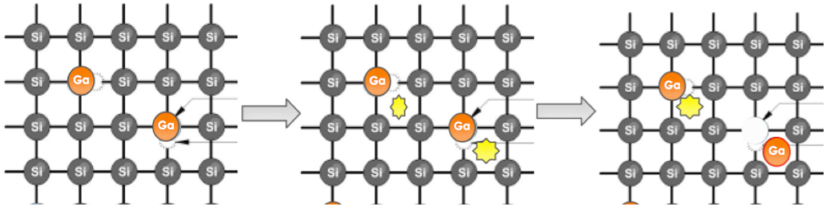
$$N(\emptyset) = N(0) * e^{-c\emptyset}$$



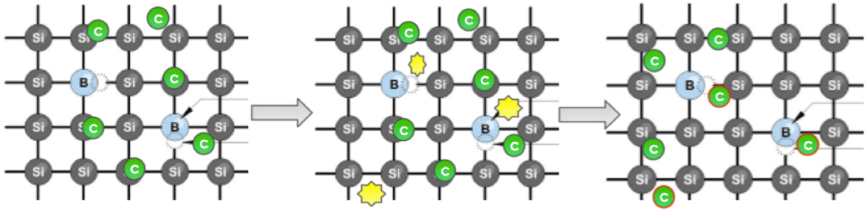


Boron
Radiation creates interstitial defects that inactivate the Boron: Si_i + B_s → Si_s + B_i

Two possible solutions: 1) use Gallium, 2) Add Carbon

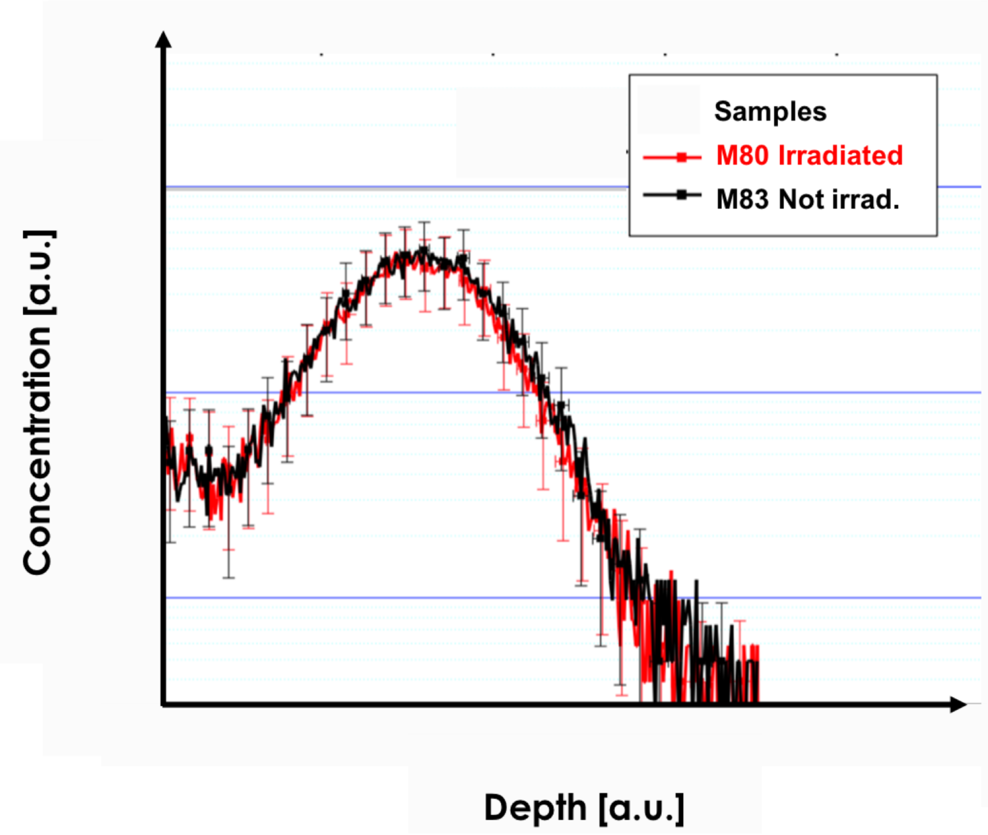


Gallium
From literature, Gallium has a lower possibility to become interstitial



Carbon
Interstitial defects filled with Carbon instead of with Boron and Gallium

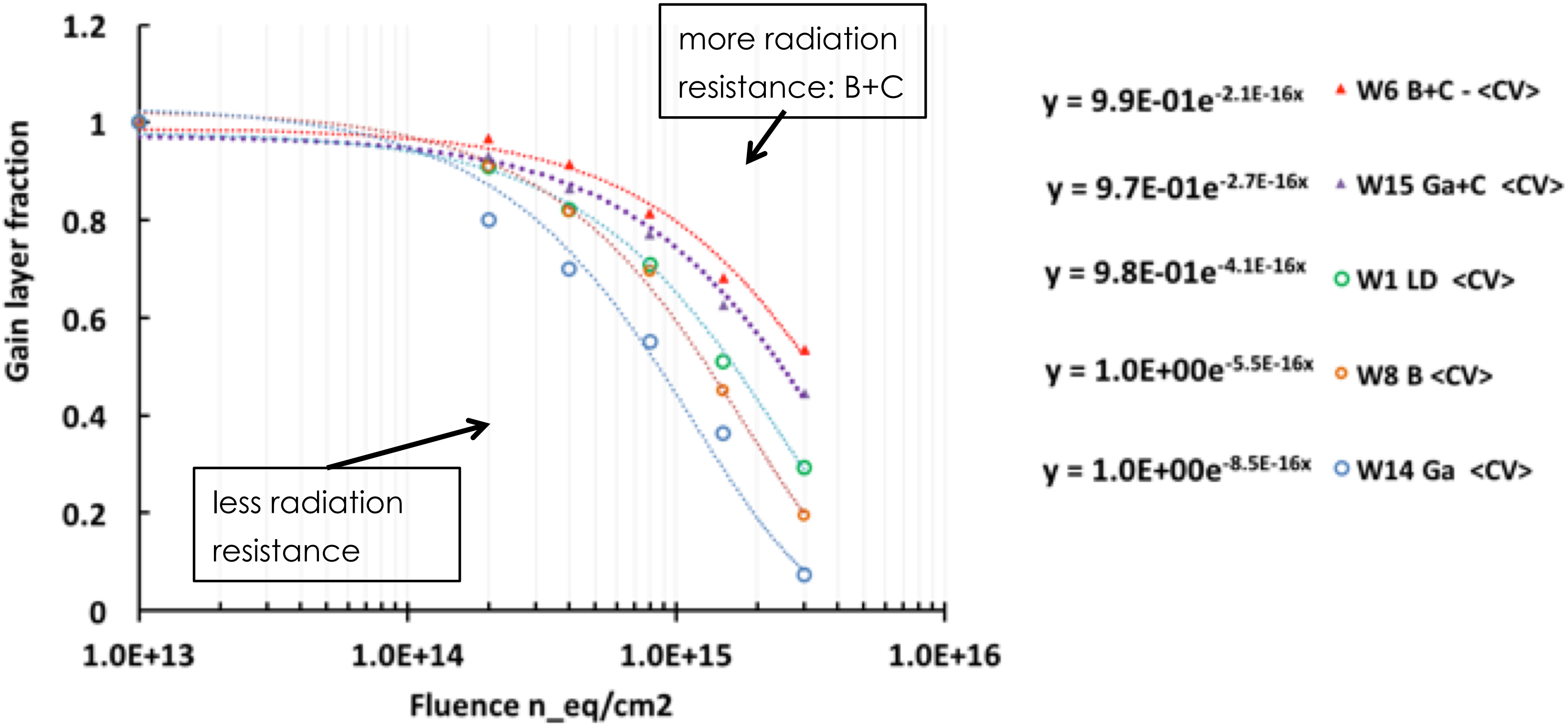
Is the Boron still there?



Yes, **the Boron is still there**, but it is not active any more…

Instead of being "substitutional" (i.e. in the place of a Silicon atom) **is "interstitial"** (i.e. In the middle of the lattice, not electrically active)

UFSD2: studio della resistenza alle radiazioni



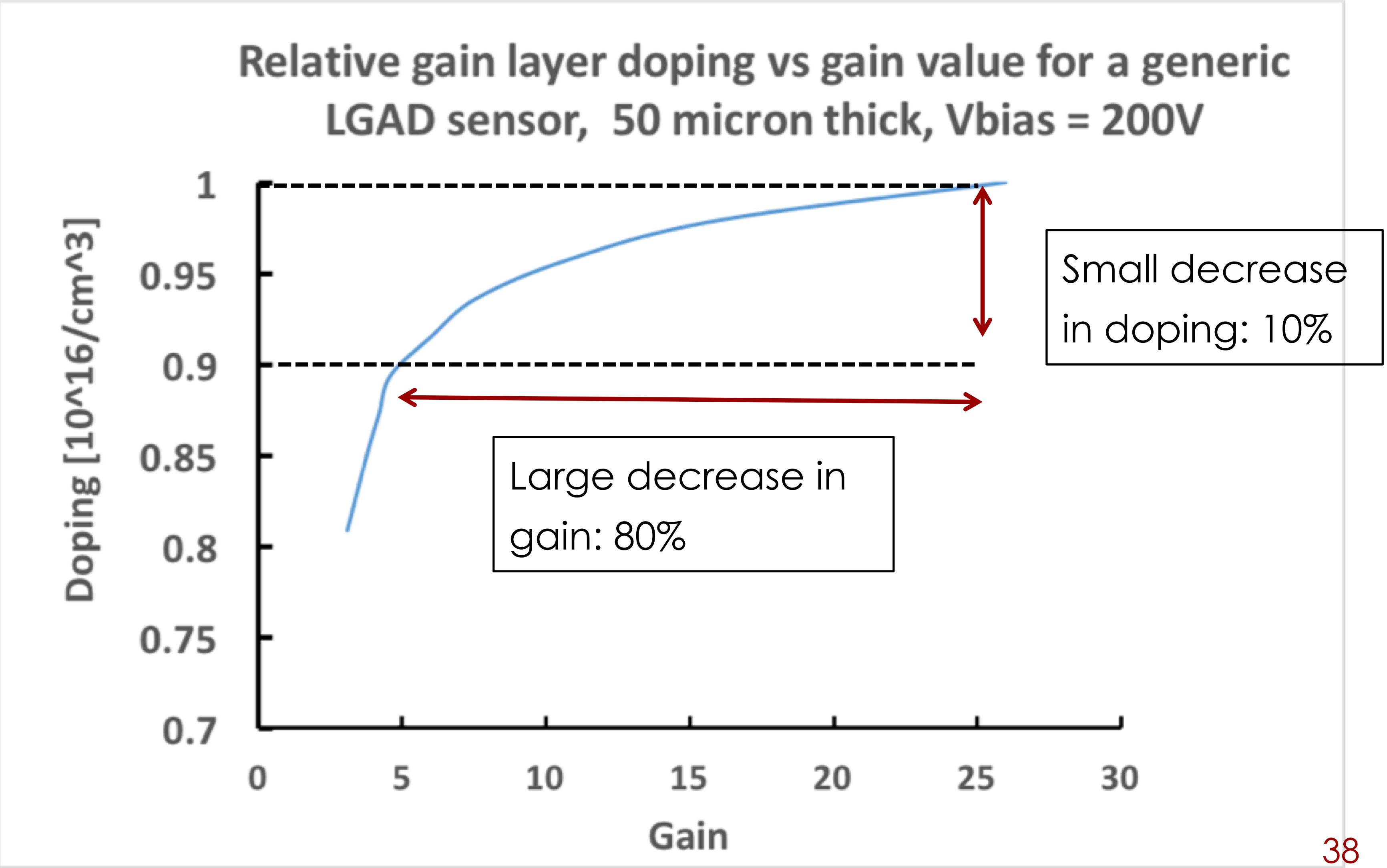
more radiation resistance: B+C

less radiation resistance

1) Gallium is actually is less rad-hard than Boron
2) Carbon addition works really well, increasing by a factor of 2 the radiation hardness

Gain vs gain layer doping

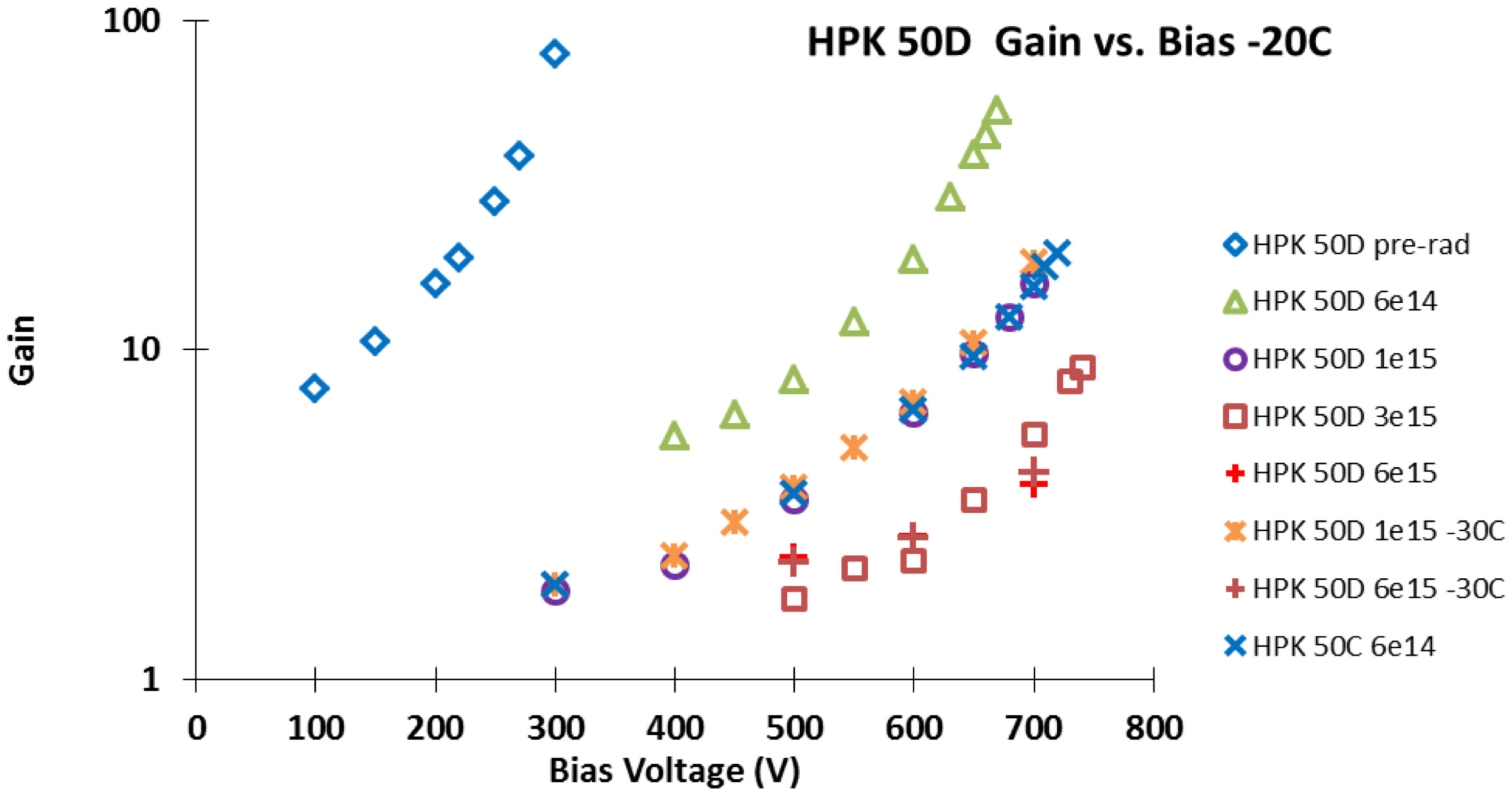
Unfortunately, the gain is very sensitive to the doping level



Small decrease in doping: 10%

Large decrease in gain: 80%

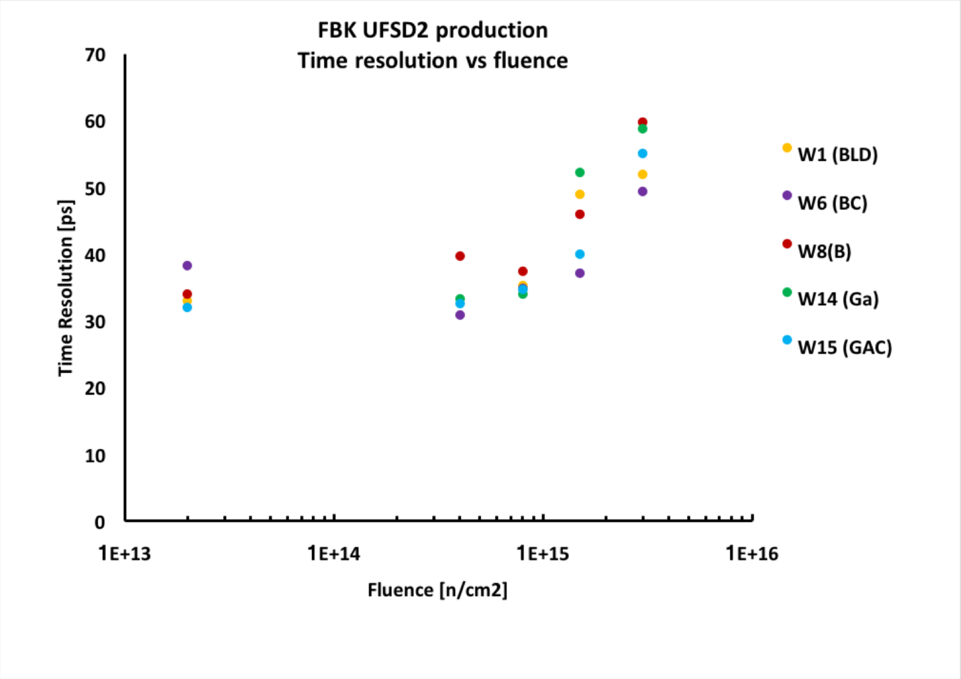
Gain in irradiated sensors

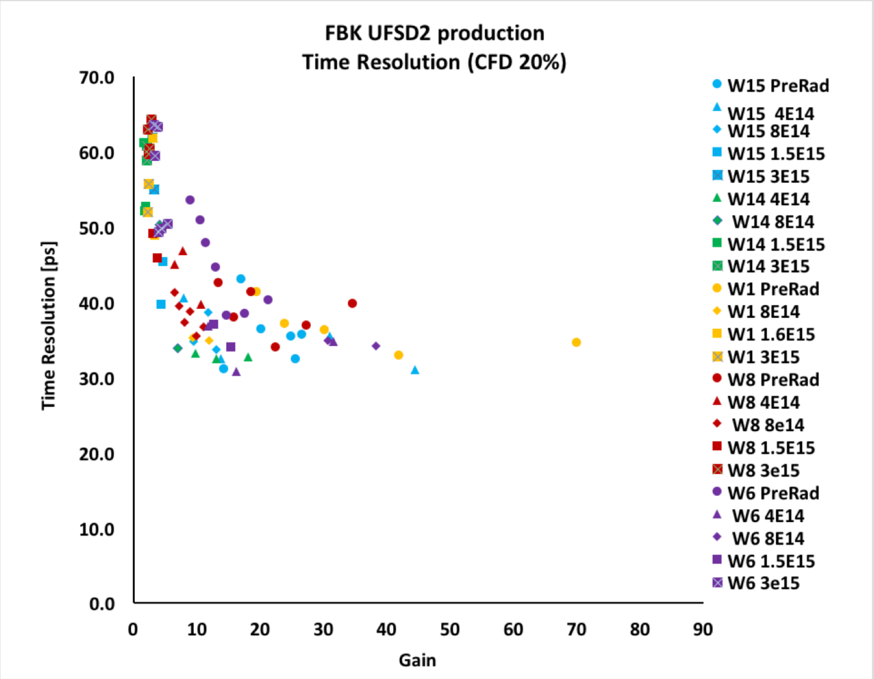


the gain layer disappearance is compensated by external bias

UFSD: Time resolution after irradiation

FBK production of UFSD sensors: time resolution for different fluence





Very complex irradiation campaign, lot’s of samples and fluences

Achieved:

- **Unchanged time resolution of ~ 35 ps, up to ~ 2E15 n/cm2**
- **Time resolution of 50 ps up to 3E15 n/cm2**

Why noise in LGAD does not degrade time resolution?

Time resolution in LGAD is determined by jitter and charge non uniformity:

$$\sigma_t^2 = \left(\frac{N}{dV/dt}\right)^2 + \sigma_{Non\ Uniform\ Ionization}^2$$

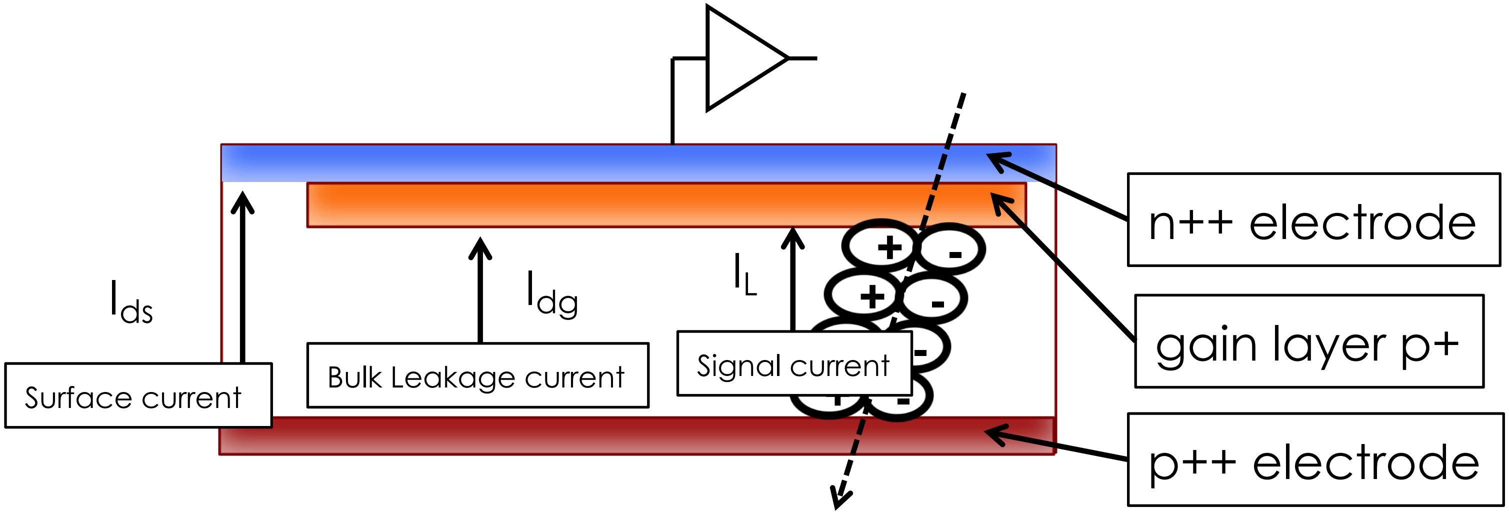
The jitter term contains electronic noise and Current noise:

$$\textbf{Jitter} = \frac{\sqrt{N_{el}^2 + N_{Current\ Noise}^2}}{dV/dt}$$

Current noise: noise due to the combination of

- High leakage current ➔ Shot Noise
- Randomness of multiplication mechanism ➔ Excess noise factor

Current noise in LGAD



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

Excess noise factor:
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

The role of the excess noise factor

Excess noise factor: noise of the multiplication process

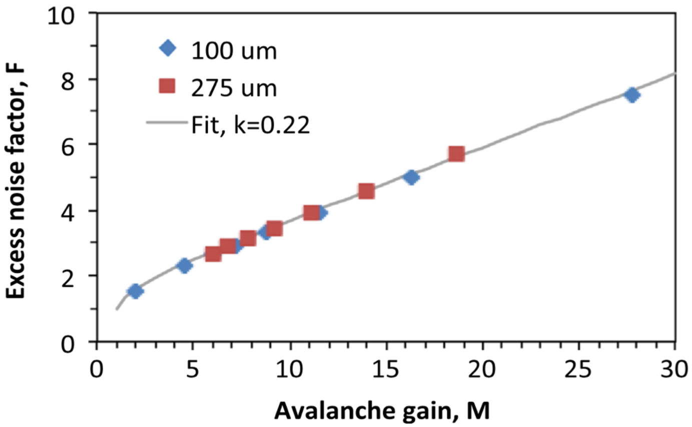
$$F = Mk + \left(2 - \frac{1}{M}\right)(1-k)$$

$$F \sim M^{x}$$

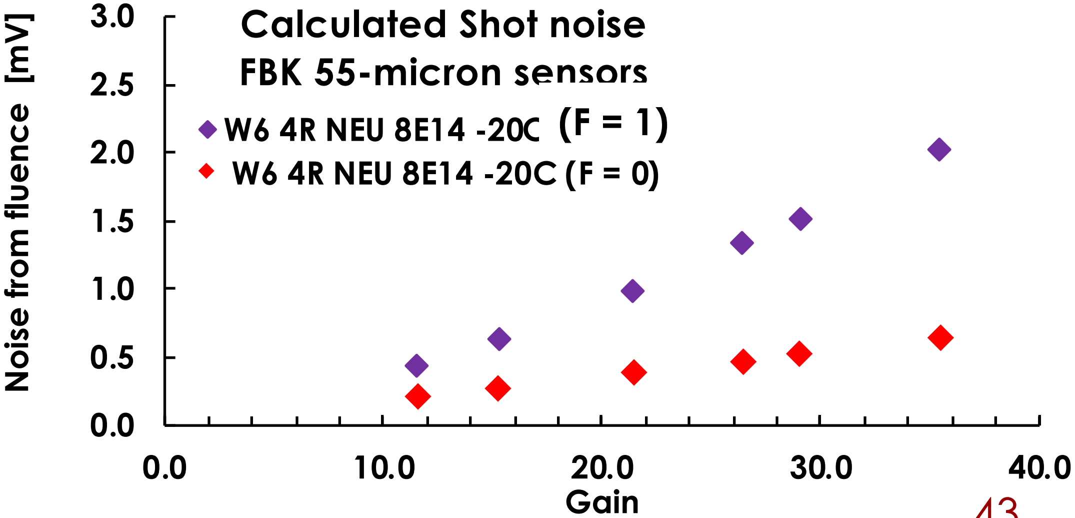
k = e/h ionization rate

x = excess noise index

M = gain

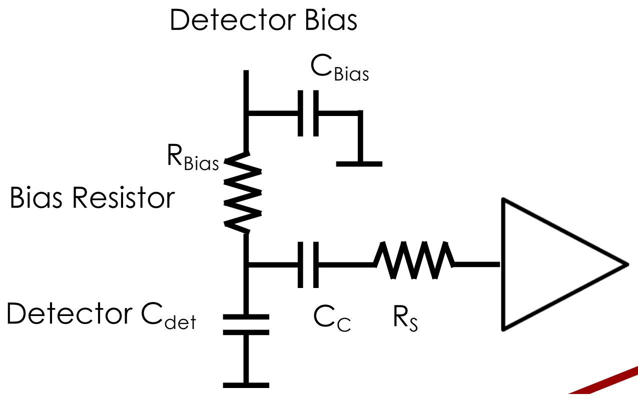


Current noise is actually dominated by the excess noise factor: at gain = 20 the excess noise factor more than doubles the shot noise without it

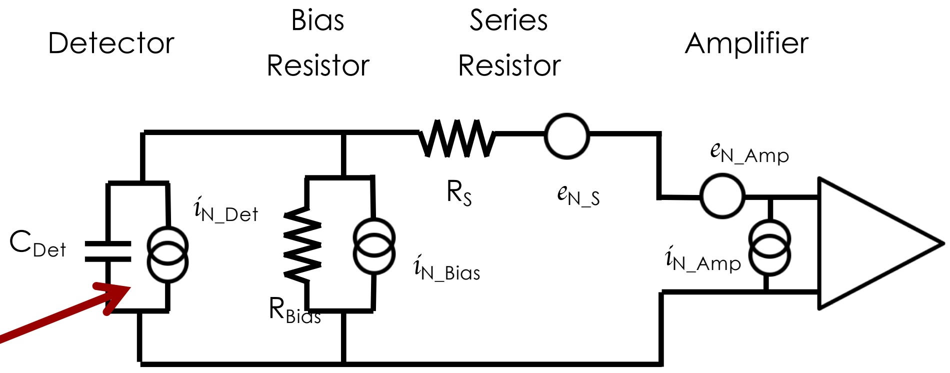


Formal noise description

Real life



Noise Model



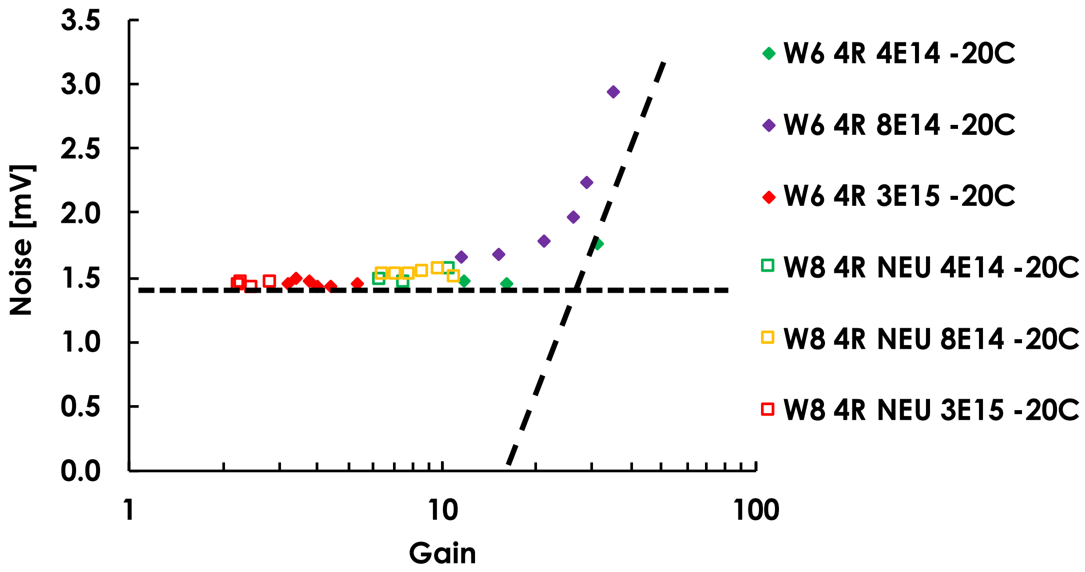
Only a part of this term, the detector current shot noise, depends on the gain

$$Q_n^2 = (2eI_{Det}) A_i \tau + \left(\frac{4kT}{R_{Bias}} + i_{N\_Amp}^2\right) A_i \tau + \underbrace{(4k\tau R_s + e_{N\_Amp}^2) A_v \frac{C_{Det}^2}{\tau}}_{\frac{Q_{n0}^2}{\tau}} + A_{vf} A_f C_{Det}^2$$

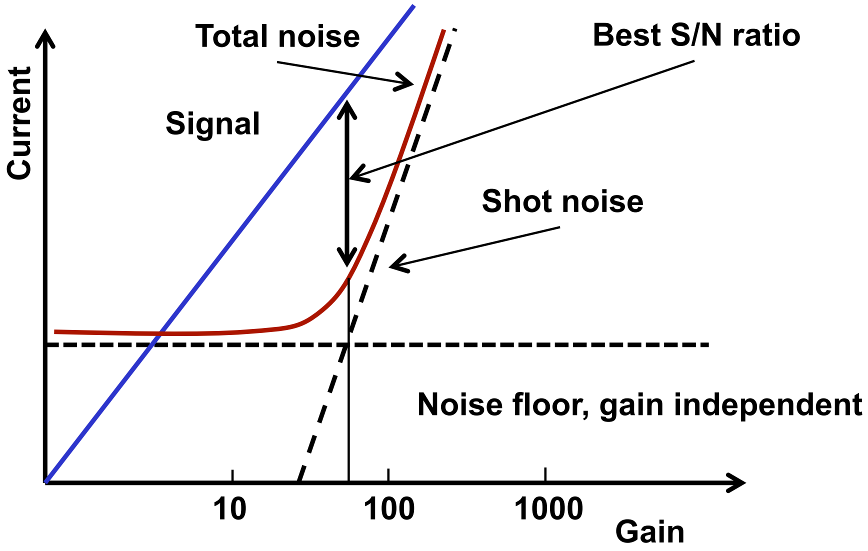
Keeping only the most important terms and setting $A_i = 1$

Let's explore the shot noise…

Noise increase as a function of fluence and gain

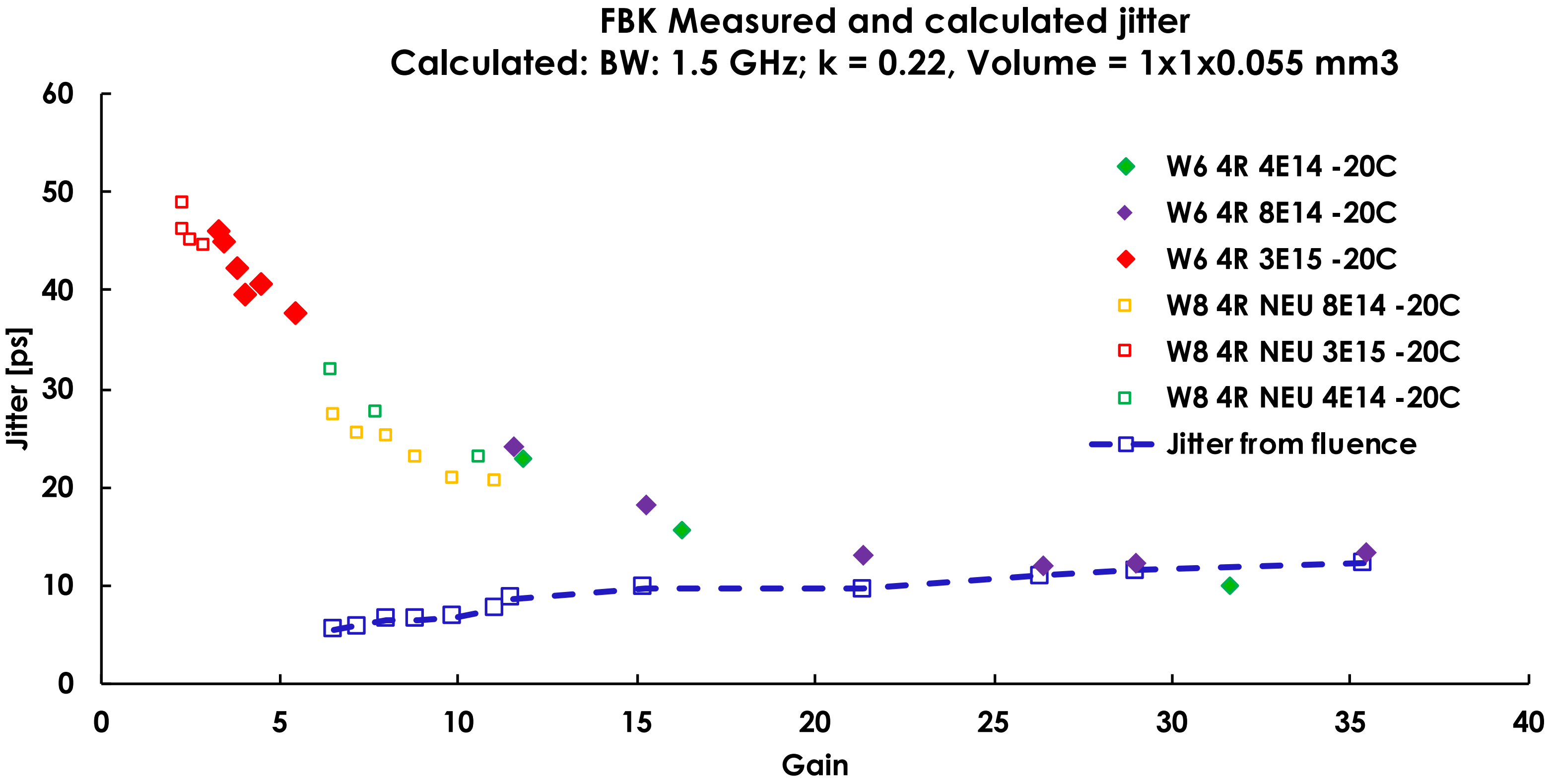


Data and model look similar.



Goal: the noise from Silicon current should stay below that of the electronics

Current noise and Jitter

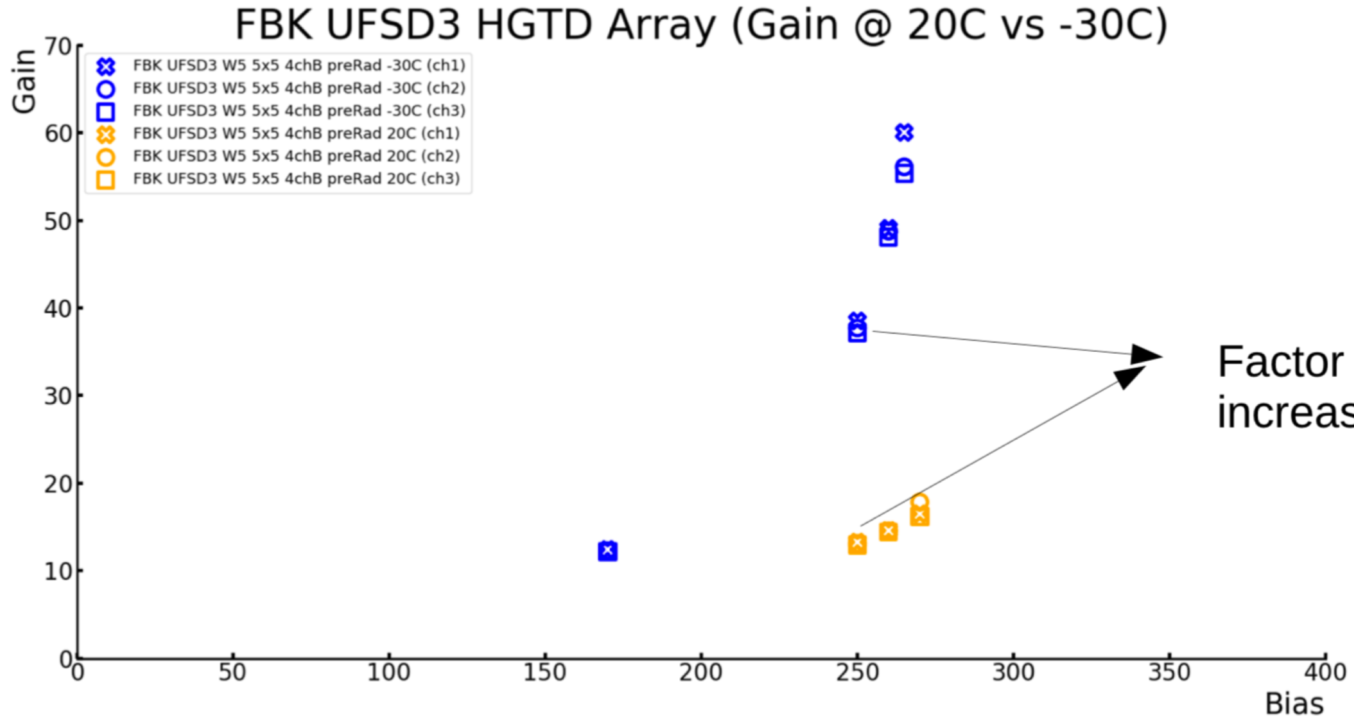


The Jitter, instead of decreasing, is becoming constant due to the contribution of the current noise.

Effect of Temperature: excellent

Trackers normally are kept at low temperature, ~ -30 C

- More gain due to longer mean path between collisions
- Less noise, the leakage current is lower (a factor of 2 every 7 C

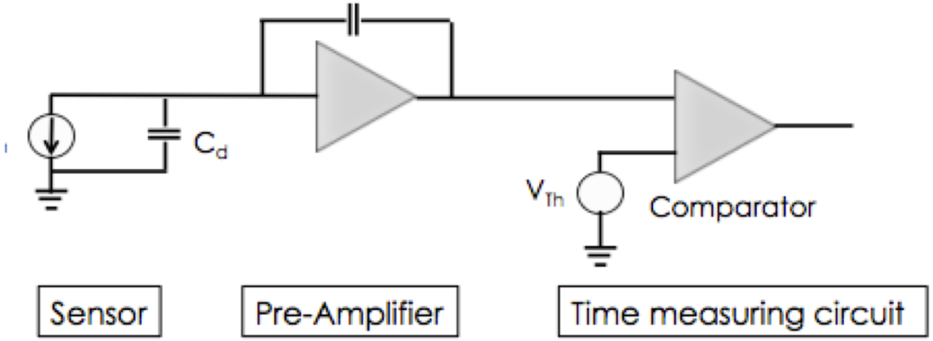


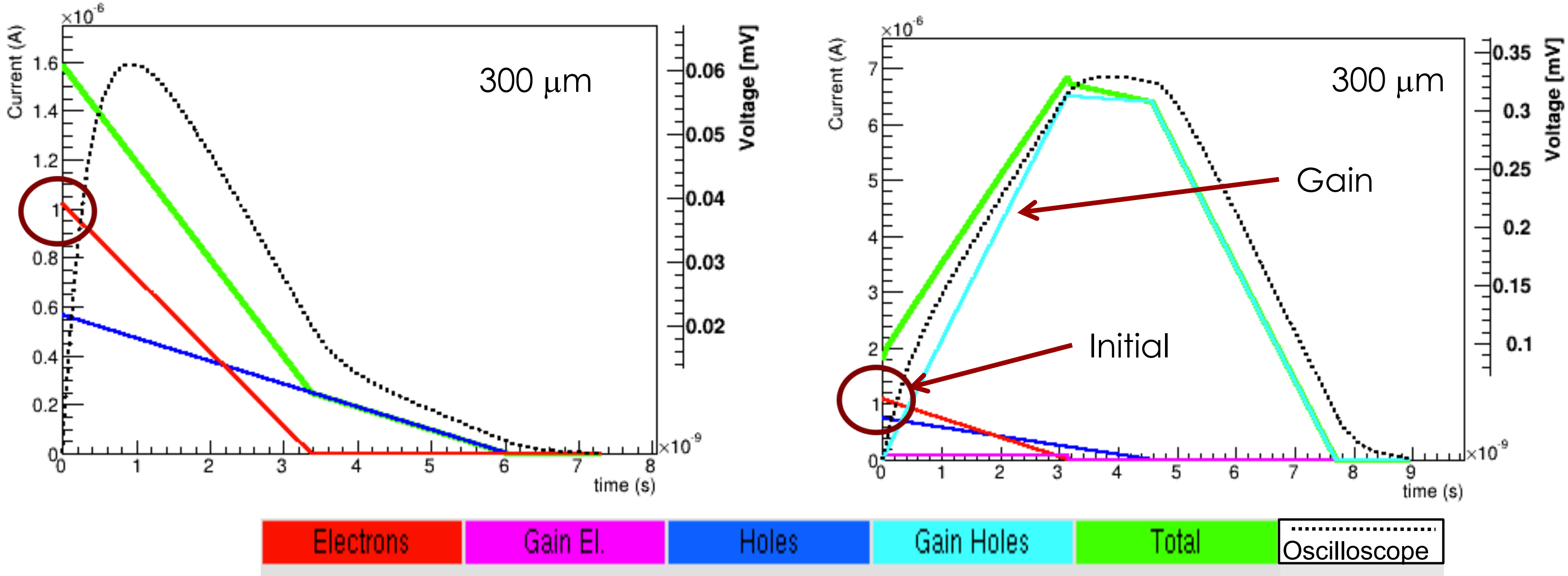
Factor of ~ 3 to 4 increase in gain

Electronics

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

The signal from UFSDs is different from that of traditional sensors





Simulated Weightfield2

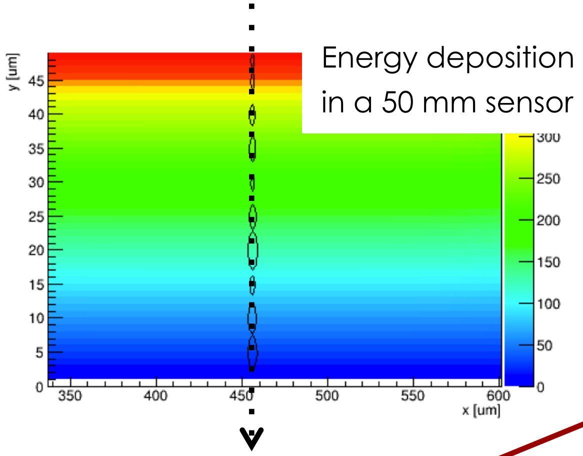
Pads with no gain

Charges generated uniquely by the incident particle

Pads with gain

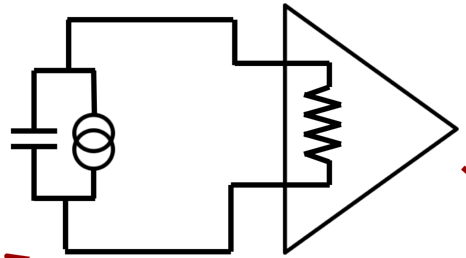
Current due to gain holes creates a longer and higher signal

Electronics: What is the best pre-amp choice?

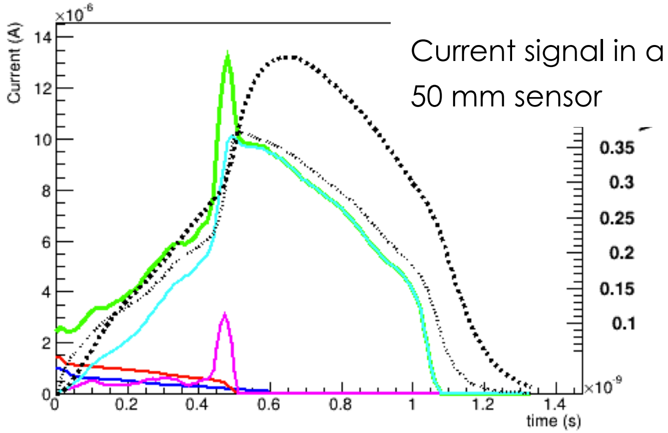


Energy deposition in a 50 mm sensor

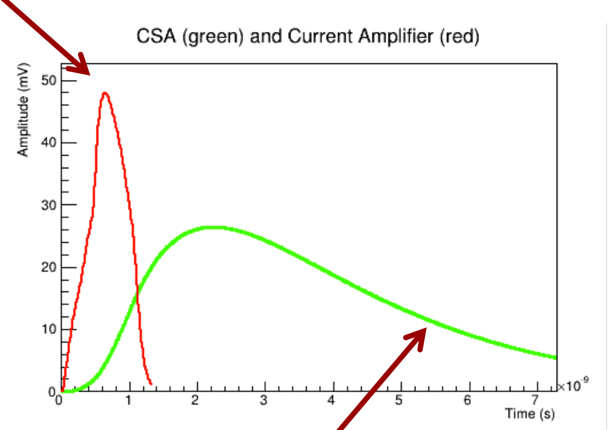
Current Amplifier



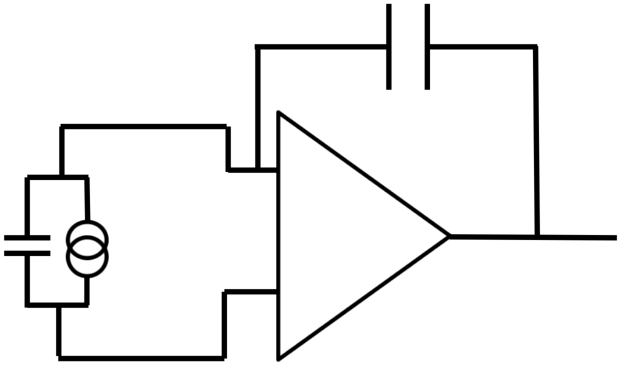
- Fast slew rate
- Higher noise
- Sensitive to Landau bumps



Current signal in a 50 mm sensor



Charge Sensitive Amplifier



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

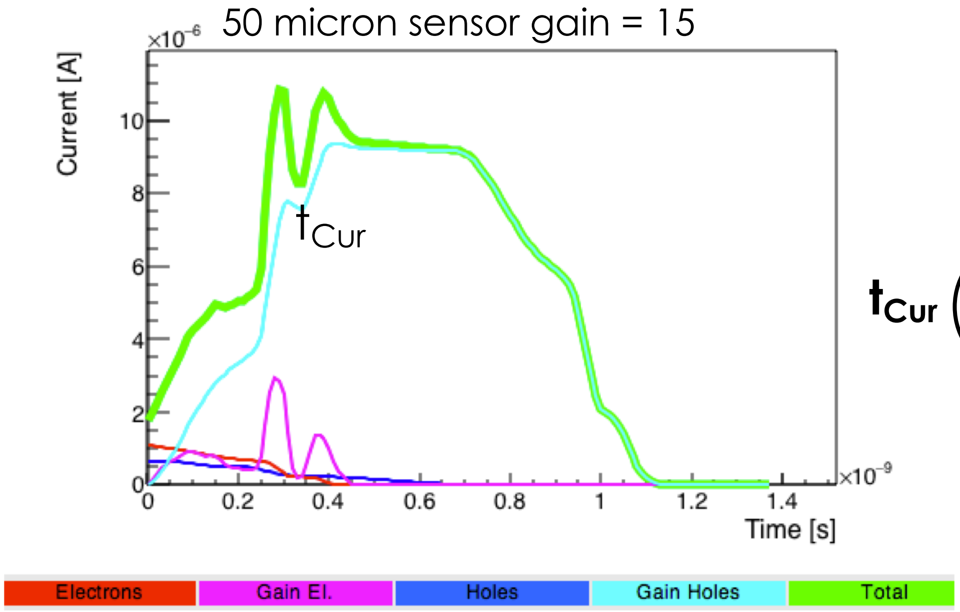
The players: signal, noise and slope

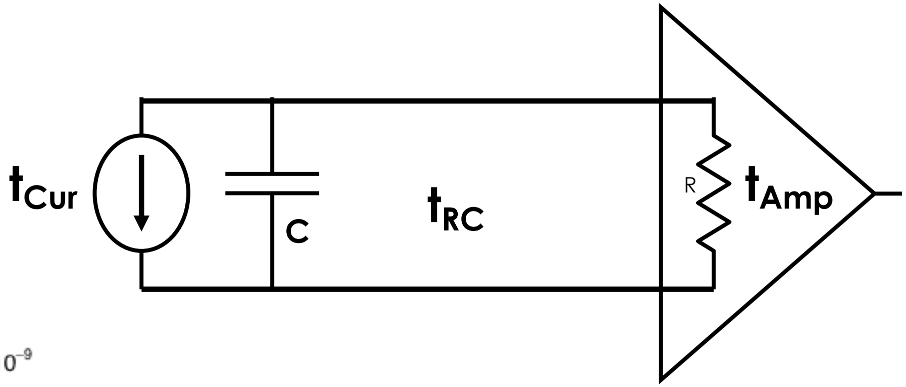
Signal dV/dt

Landau Noise

Shot Noise

Electronic Noise





The current rise time (t_{Cur})

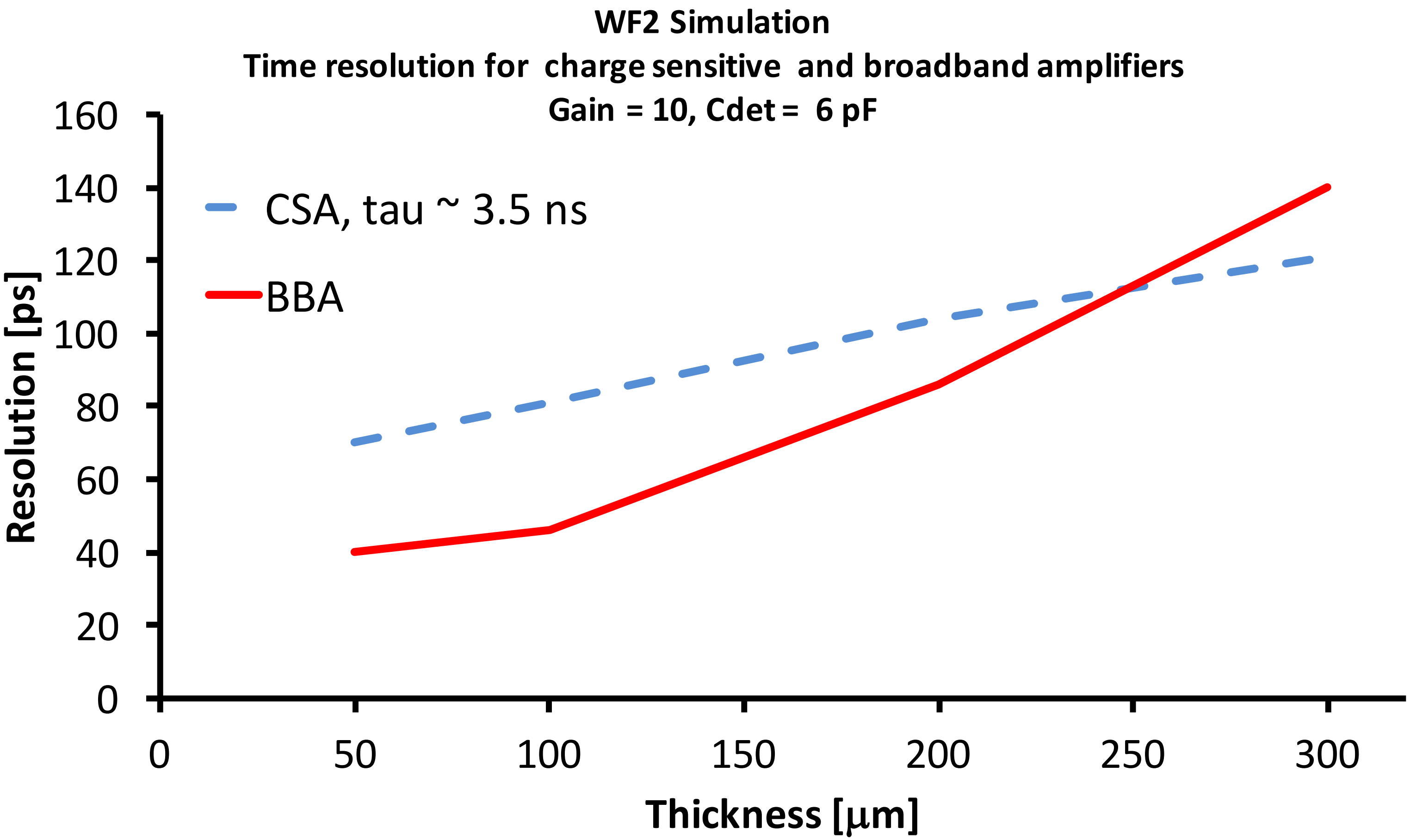
The RC circuit (t_{RC})

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})

Integrator or current amplifier?



- integrators work best with signals that are of the same length of their integration time
- Current amplifiers work best with very fast signals

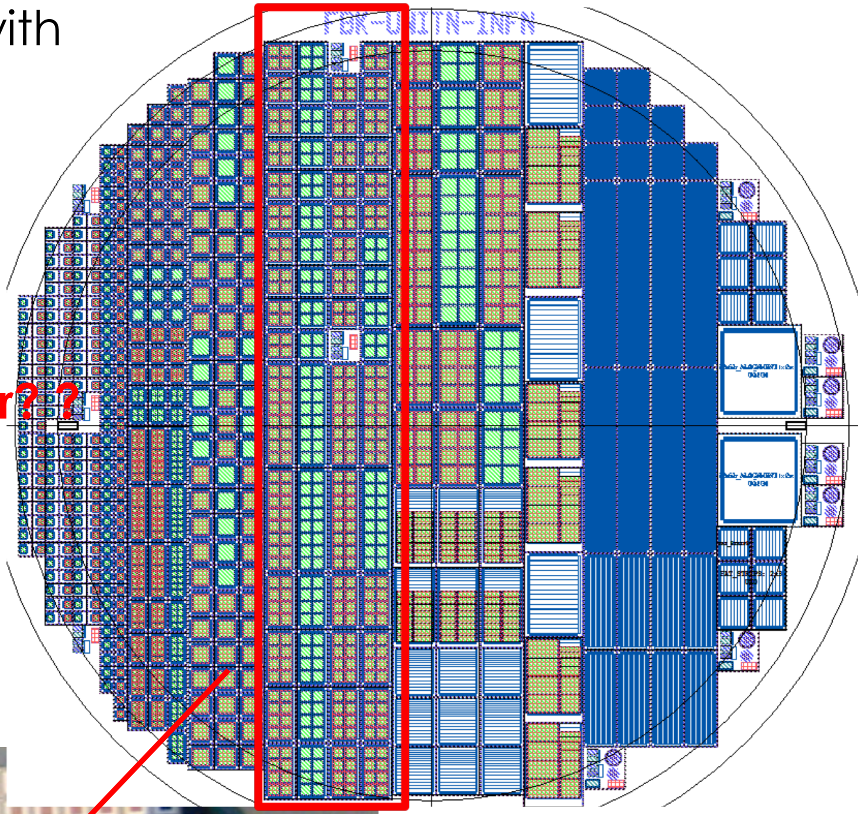
From one pad to a Timing Layer

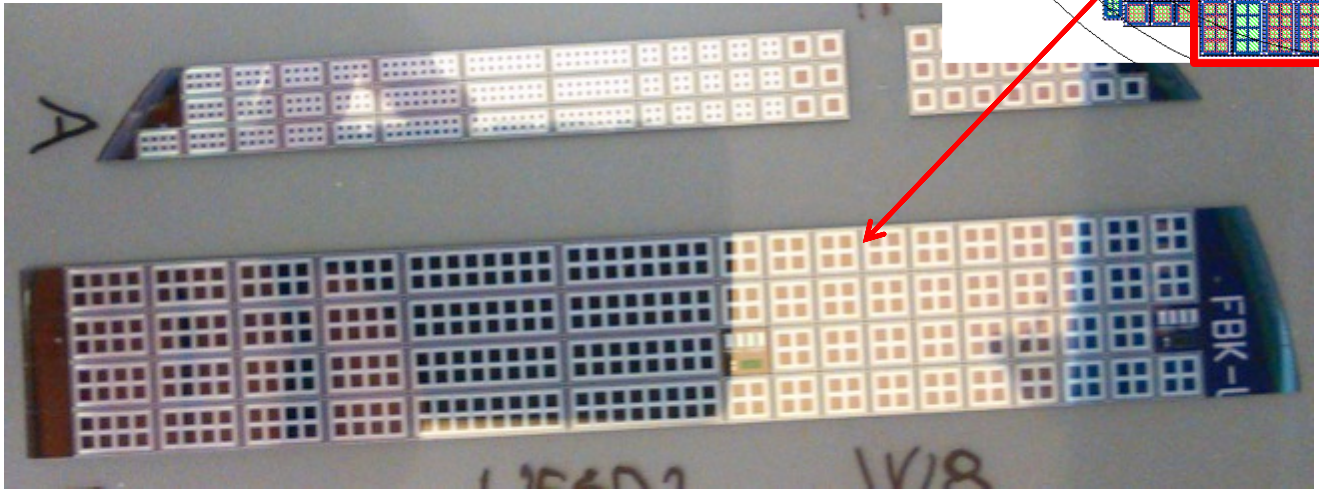
We have produced thousands of UFSDs, with many shapes, thicknesses, gains etc..

We know very well how a single pads and small array work, however….

Are we able to produce a full large tracker? ?

- **Uniformity**
- **Fill factor**



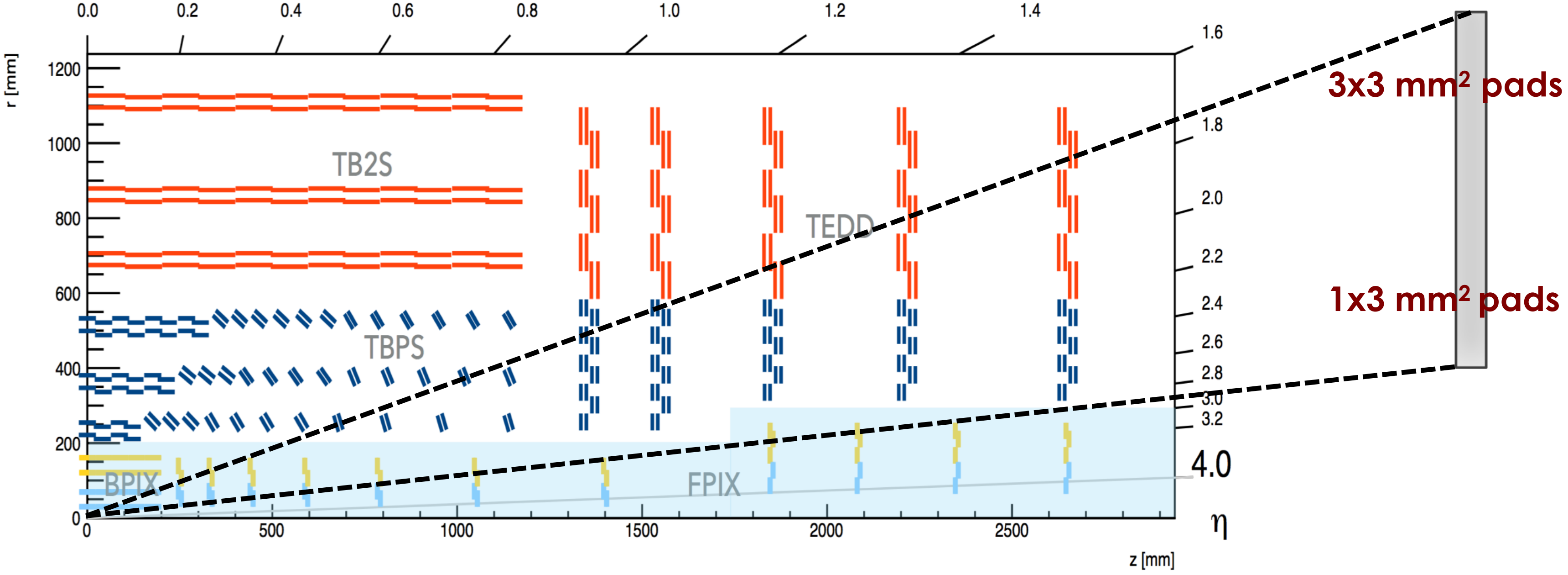


And now we need to build the detector..

CMS and ATLAS have now in their upgrade proposal the combined construction of ~ 20 m2 of UFSD sensors.

Main challenges:

- Sensor: moving from one pad to large area
- Electronics: need to design an appropriate chip



And: backend electronics, mechanics, cooling, HV & LV distribution, High precision clock, data transmission

ATLAS-CMS path to construction

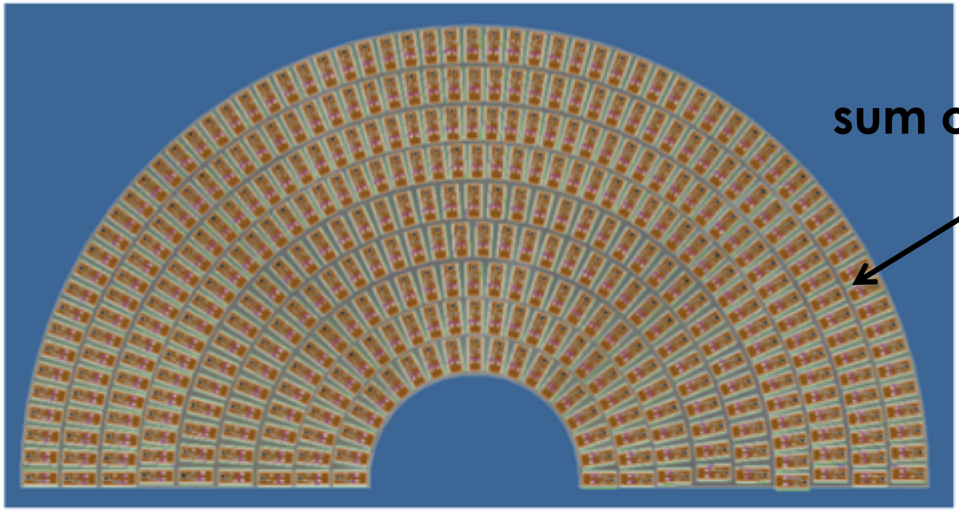
Key topics to be addressed:

1. **Radiation hardness**: time resolution and operating conditions
    - Spoiler: the situation looks reasonable
2. **Highest possible fill factor:** dead area between pads
3. **Multi pad sensors:** pad isolation, breakdown voltage
4. **Large area:** yield, cost
5. **~ 30 ps time resolution at the end of HL_LHC lifetime**
    - 35-micron thick option
        - Looks reasonable, it is a “read-out chip” problem

ETL: Endcap Timing Layer

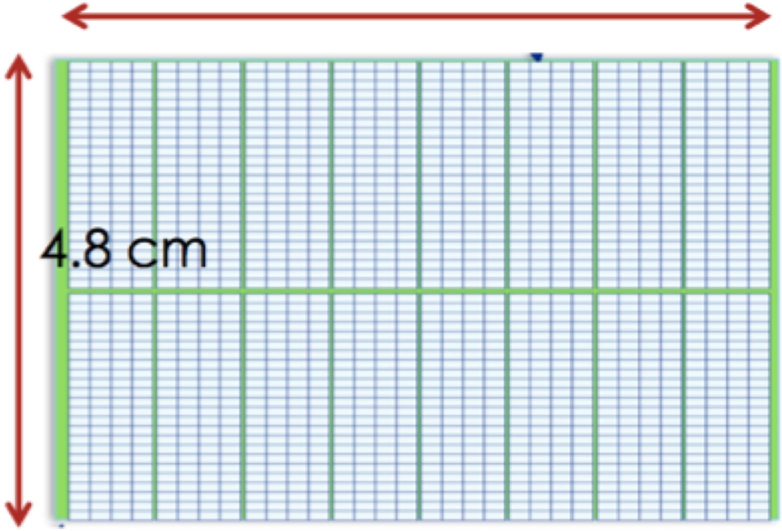
The chosen sensors for ETL are UFSD

one layer
per side,
each made of
two disks



sum of two half disk

~ 1800 sensors:
- 4.8 x 9.6 cm^2 --- Large Sensors
- Thickness of active area: 40-50 microns
- Pad size: 1 x 3 mm^2 (1536 pads)



CMS requests for ETL sensors

The sensor should be large:

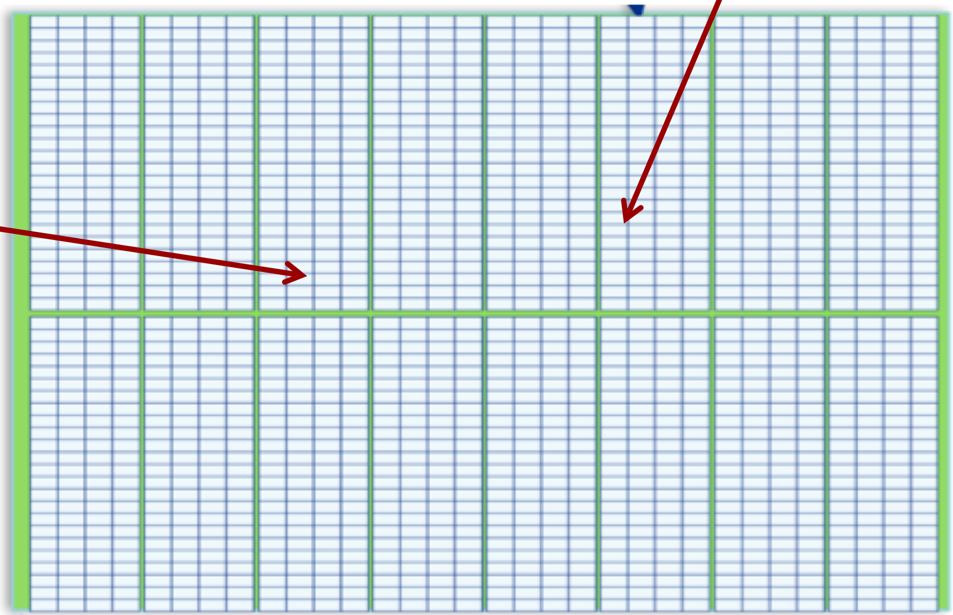
1) One sensor, 5 x 10 cm^2. This is difficult, implies an almost "defect free" process

2) CMS will consider smaller sensors

Segmented with high fill factor:

The distance between pads should be very small.

1) > 95 % fill factor



The gain should be uniform:

1) No more than ~ 20% gain variation

2) Gain ~ 20 at < 20 V away from breakdown

Radiation hard:

1) Unchanged resolution (~ 30 ps) up to 5e14 n_{eq}/cm^2.

2) Less than a factor of 2 degradation up to 10e14 n_{eq}/cm^2

Hold high voltage after irradiation:

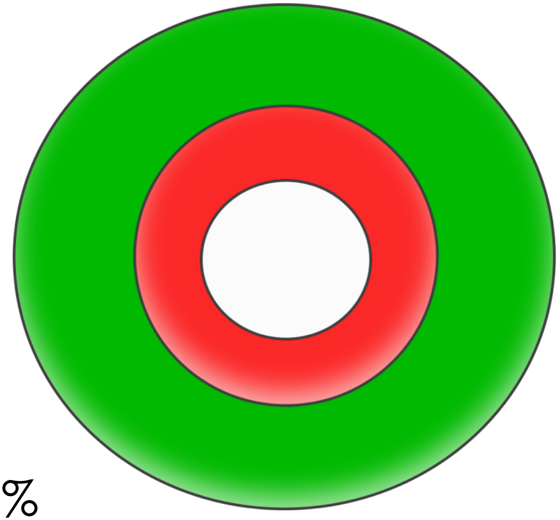
1) Need to have good HV capability after irradiation (~ 600 – 700 V),

SENSORS: state of the art

UFSD: 35 ps resolution for fluences up to **5 - 6e14 neq/cm^2**

State-of-the-art sensors guarantee 80% of the ETL coverage

Low radiation : radius 55 – 110 cm ~2.8 m2 , ~80%
High radiation: radius 25 – 55 cm ~0.7 m2, ~20%

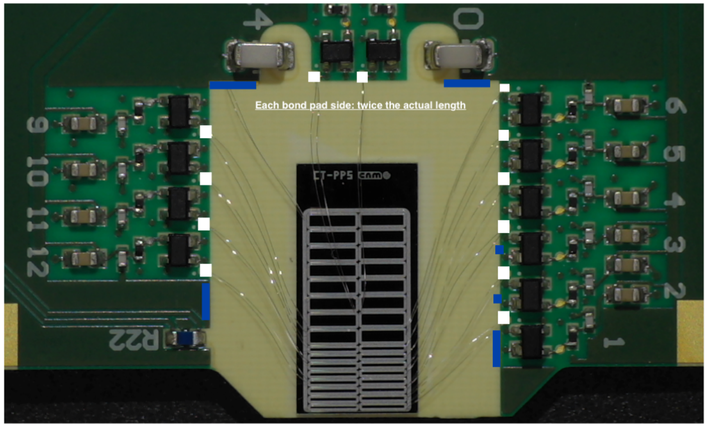


There are several options to cover the additional 20%

- R&D will demonstrate new solutions → next 18 months
- Allow degradation of resolution (~ 60 ps after 3000 fb-1)
- Have two layers

ASIC for Timing application

It is difficult to develop a **read-out board** that reads a few pads with good timing precision



It is much more difficult to develop **a chip** to read ~ 100 channels

Very difficult mixed environments, precise analog with digital part

And:

- keep the power consumption low:

  ALTIROC chip for the ATLAS timing layer: 2.5 mW/mm2

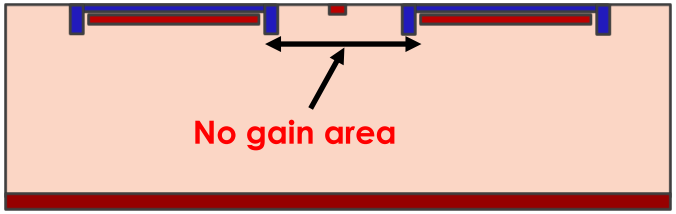
  Only 0.5 mA for the front end (< 1 mW), almost impossible

  If used in CMS (sensors ~8 m2 per side) ➔ 20 kW !! Very large

- The noise scales as $C_{Detector}/Q_{signal}$, need to keep the pads small

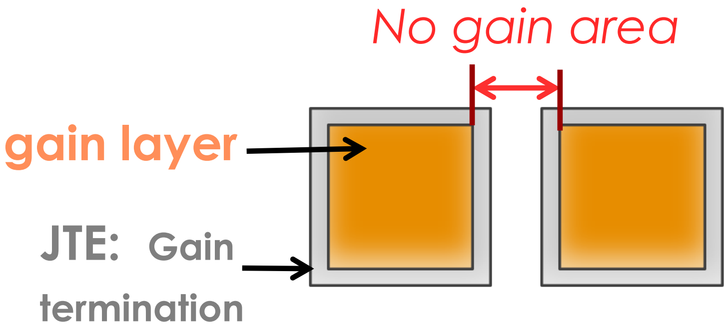
Fill factor

The fill factor is mainly determined by the inactive gap between sensors.



Current measured gap size:

- ~ 70 micron for CNM
- ~ 100 micron for HPK
- ~ 70 micron for FBK



This gap affects directly the detector acceptance as we have only one layer: a 70 micron gap corresponds to a 91% fill factor

Goal: 30 micron gap = 96% fill factor

Currently under study, looks possible…

Fill factor: optimization of current design

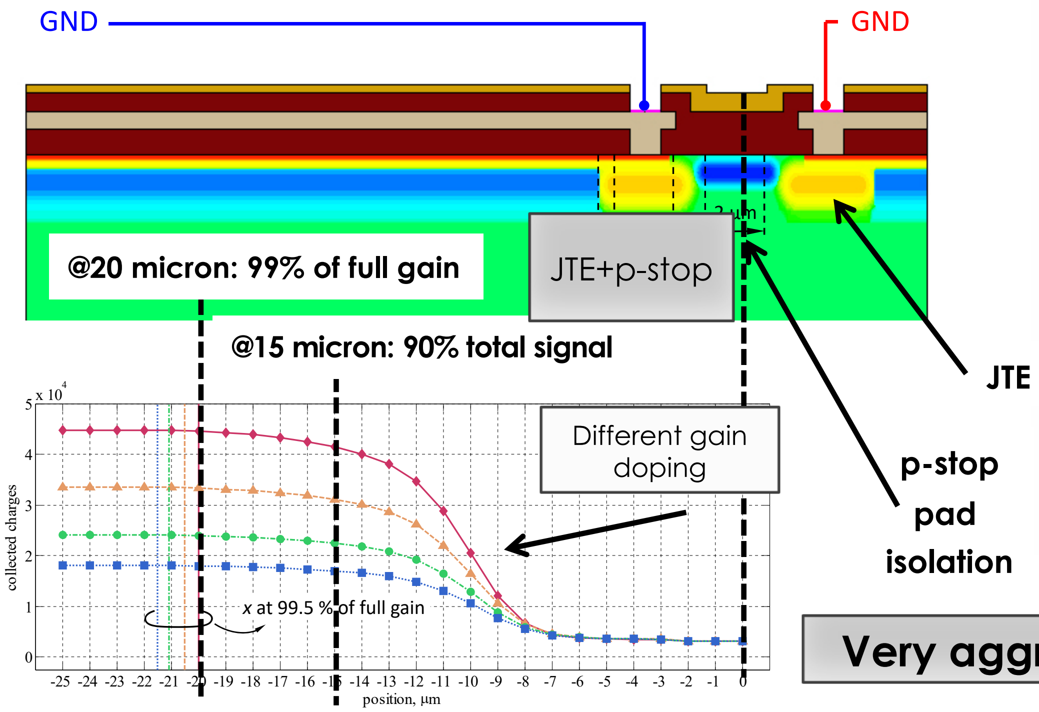
The gap is due to **two components**:

1) Adjacent gain layers need to be isolated (**JTE & p-stop**)

2) Bending of the E field lines in the region around the JTE area

Both under optimization Different junction termination/p-stop design

- **CMS Goal: 30 micron gap = 96% fill factor**



@20 micron: 99% of full gain

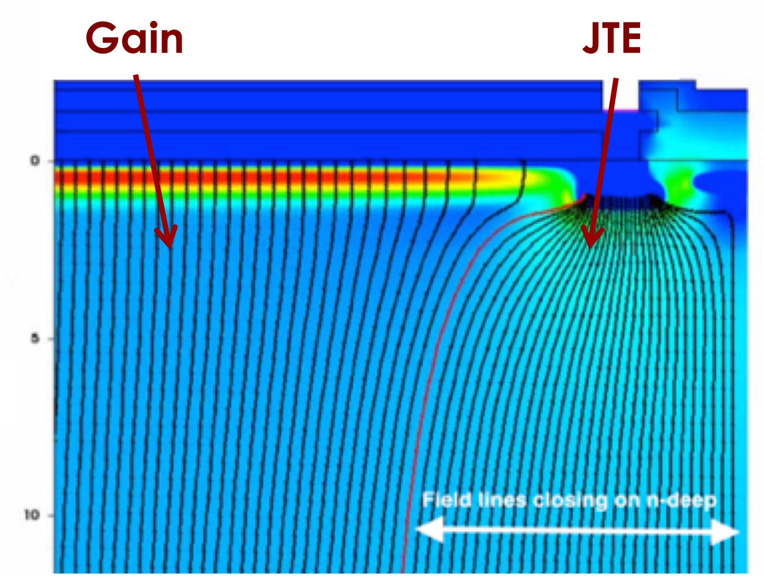
JTE+p-stop

@15 micron: 90% total signal

Different gain doping

JTE

p-stop pad isolation

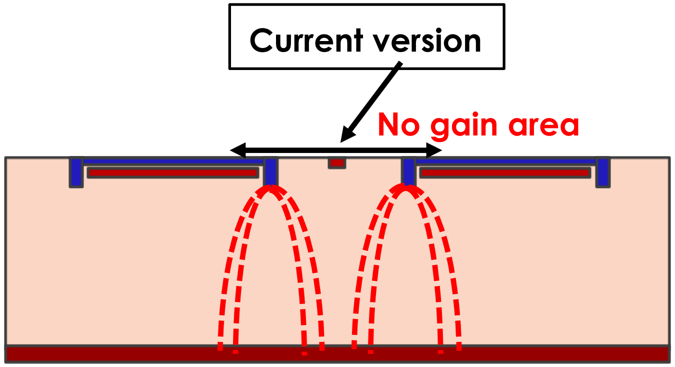


Very aggressive design: <10 micron per side

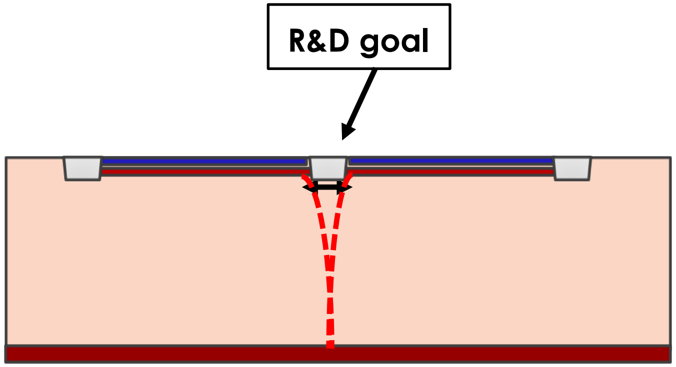
Fill factor solution 1: trenches

Trenches (the same technique used in SiPM):

- No pstop,
- No JTE ➔ no extra electrode bending the field lines



JTE + p-stop design

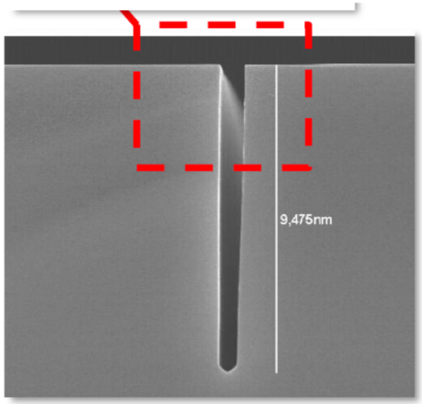


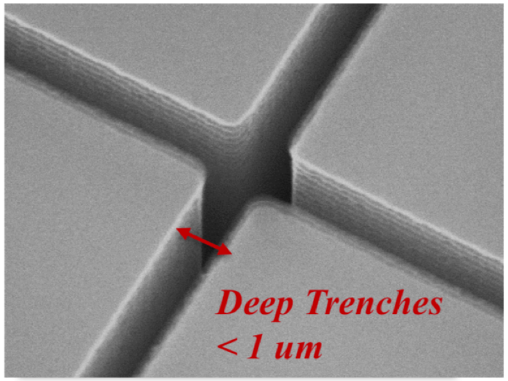
Trench design

Trench isolation technology

- Typical trench width < 1 um
- Max Aspect ratio: 1:20
- Trench filling with: SiO_2, Si_3N_4, PolySi

CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS





Carbon tuning: is more Carbon better?

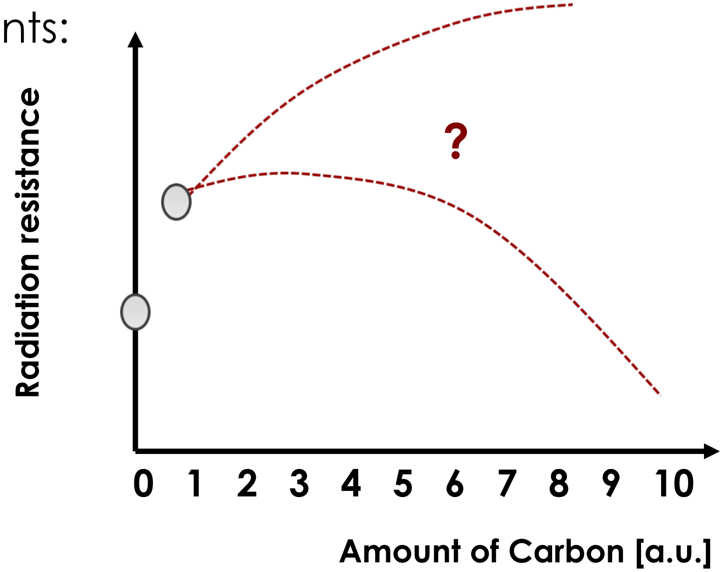
We have 2 experimental measurements:

- No carbon
- 1 unit of C ➔ 2 x better

We don't know what is the best carbon density:
In the UFSD3 FBK production we will explore 3 additional carbon levels to map the phase space

➔ **Delivered: August 2018**

➔ **Preliminary answers by end of 2018**

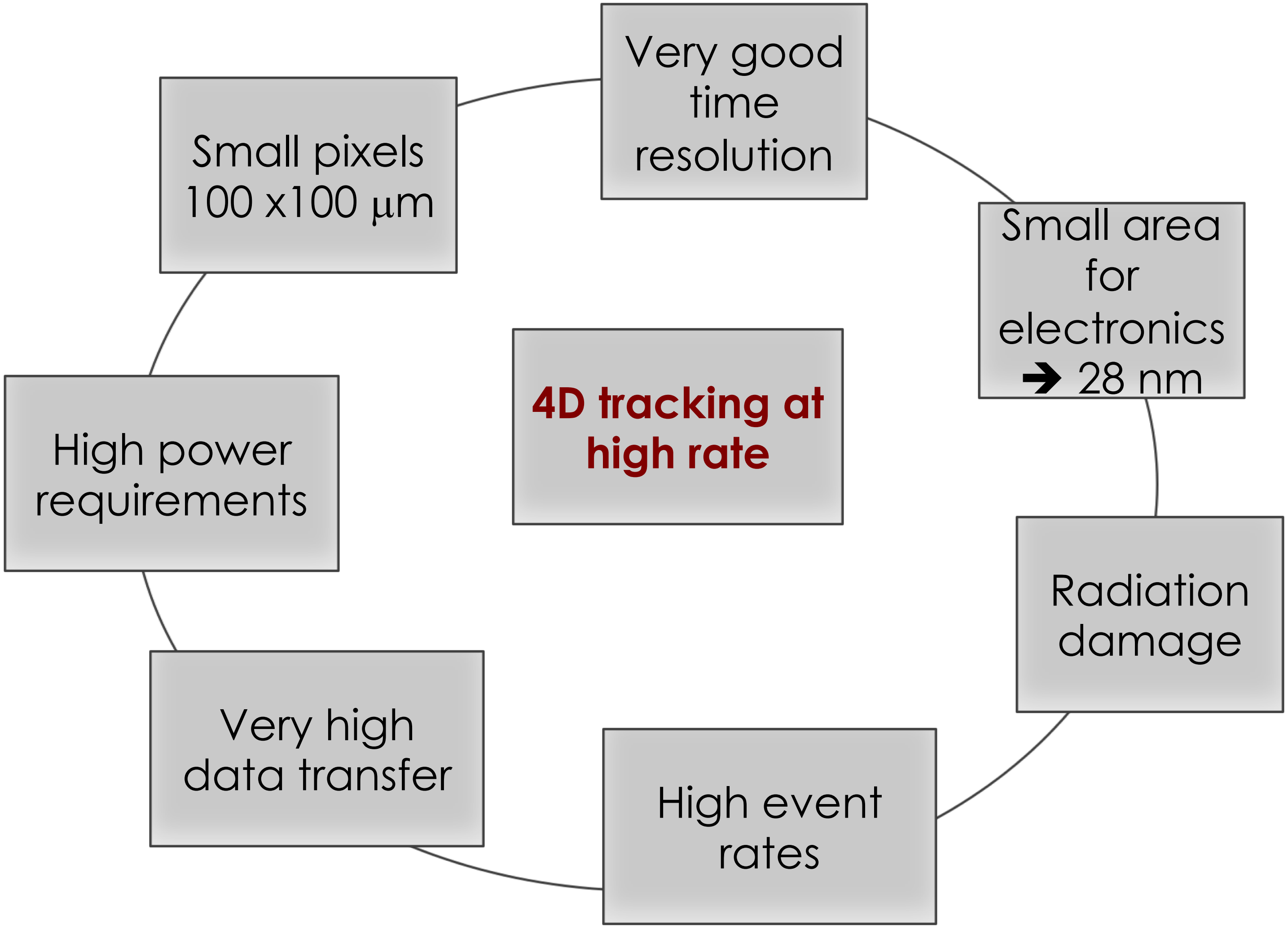


Wafer #	UFSD2	Dose Pgain	Carbon
1	W1	1.00	
2	W1-Epi	0.98	
3		0.98	A
4	Epi	0.98	A
5		1.00	A
6		0.98	B
7		1.00	B
8		1.00	B
9		1.00	C
10		1.02	C
11		1.02	D

From a Timing Layer to a 5D tracker

Imagine tracking with ~ 1000-2000 tracks @ 40 MHz crossing

This situation is the pinnacle of complications..



4D tracking at high rate

Very good time resolution

Small area for electronics → 28 nm

Radiation damage

High event rates

Very high data transfer

High power requirements

Small pixels 100 x100 μm

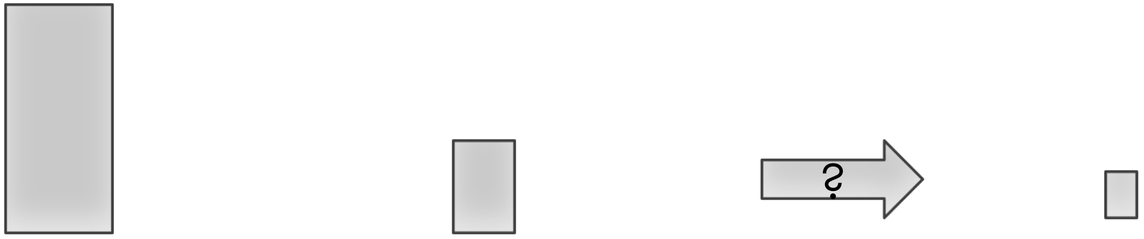
5D tracking: sensors and electronics

Let’s consider a normal size pixel: 100 x 100 micron

Can we fit the electronics?

- ➔ the preamplifier does not scale with the technological node,
- ➔ memory and TDC do.

Example: TDC evolution



130 nm:
70 x 150 micron

65 nm:
40 x 60 micron

28 nm:
~20 x 30 micron

5D tracking requires either 65nm or 28nm electronics

5D tracking: read-out and algorithms

Power is nothing without control

Let’s suppose we have the sensors and the read-out chip:

- ➔ our job might be over
- ➔ lot’s of other people need to work hard…

Taking advantage of 5D tracking requires a very complex backend:

Very fast data transfer

Real-time tracking requires the development of specific 4D tracking algorithms.

- ➔ Sometimes called “retina”, being pursued by several groups.

Alternatives Silicon Sensors for timing

- 3D sensors for timing
- Resistive Silicon Detectors
- Monolithic timing sensors

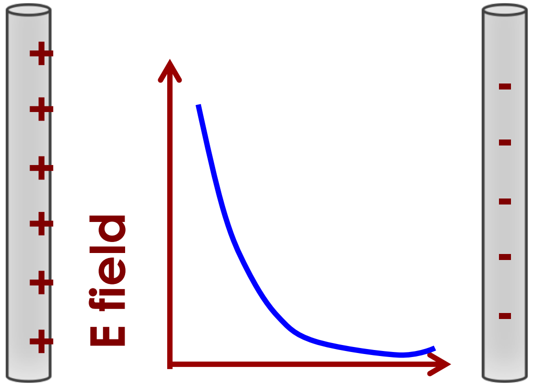
3D sensors for timing applications

3D sensors enjoy good performance even at fluences $\phi \sim 10^{16}$ n/cm^2

Can they be used in 4D-tracking?

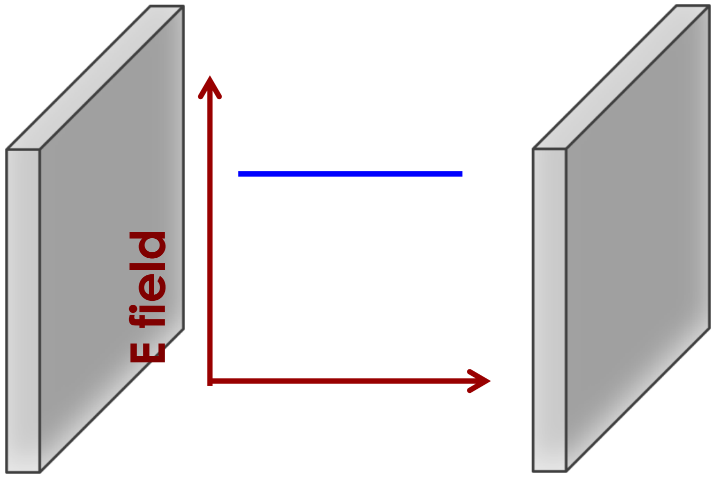
Can diamond 3D work?

In their "column" geometry, they cannot, the Efield is not uniform enough



However, using trenches gives a parallel plate geometry, and a weighting field ~ 1/d

➔ Insensitive to non-uniform charge deposition **GOOD!**



Challenges:

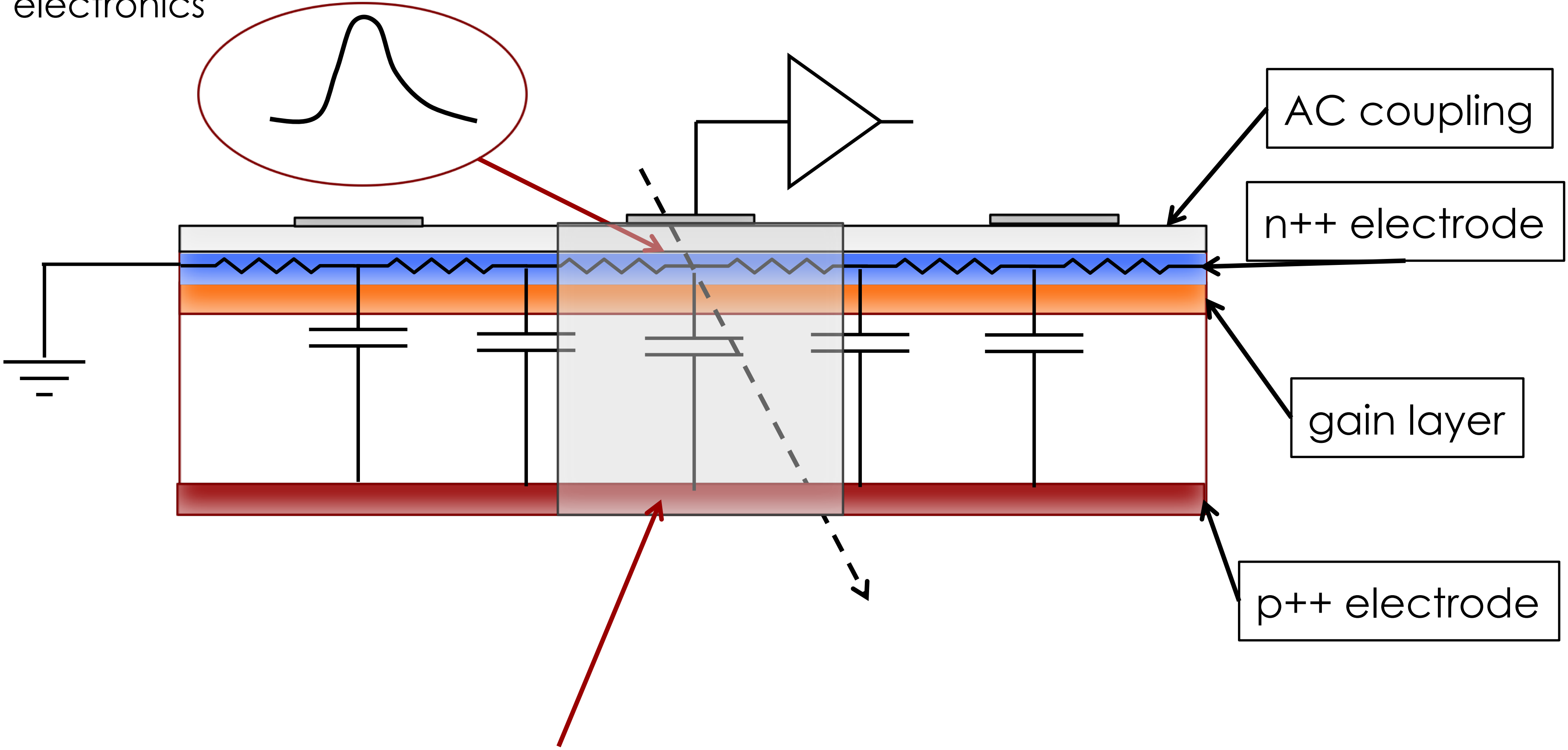
- Position dependent current shape
- Strong signal reduction with irradiation

Fill factor solution 2: Resistive electrode

The signal is frozen on the resistive sheet, and it's AC coupled to the electronics

➔ 100% fill factor

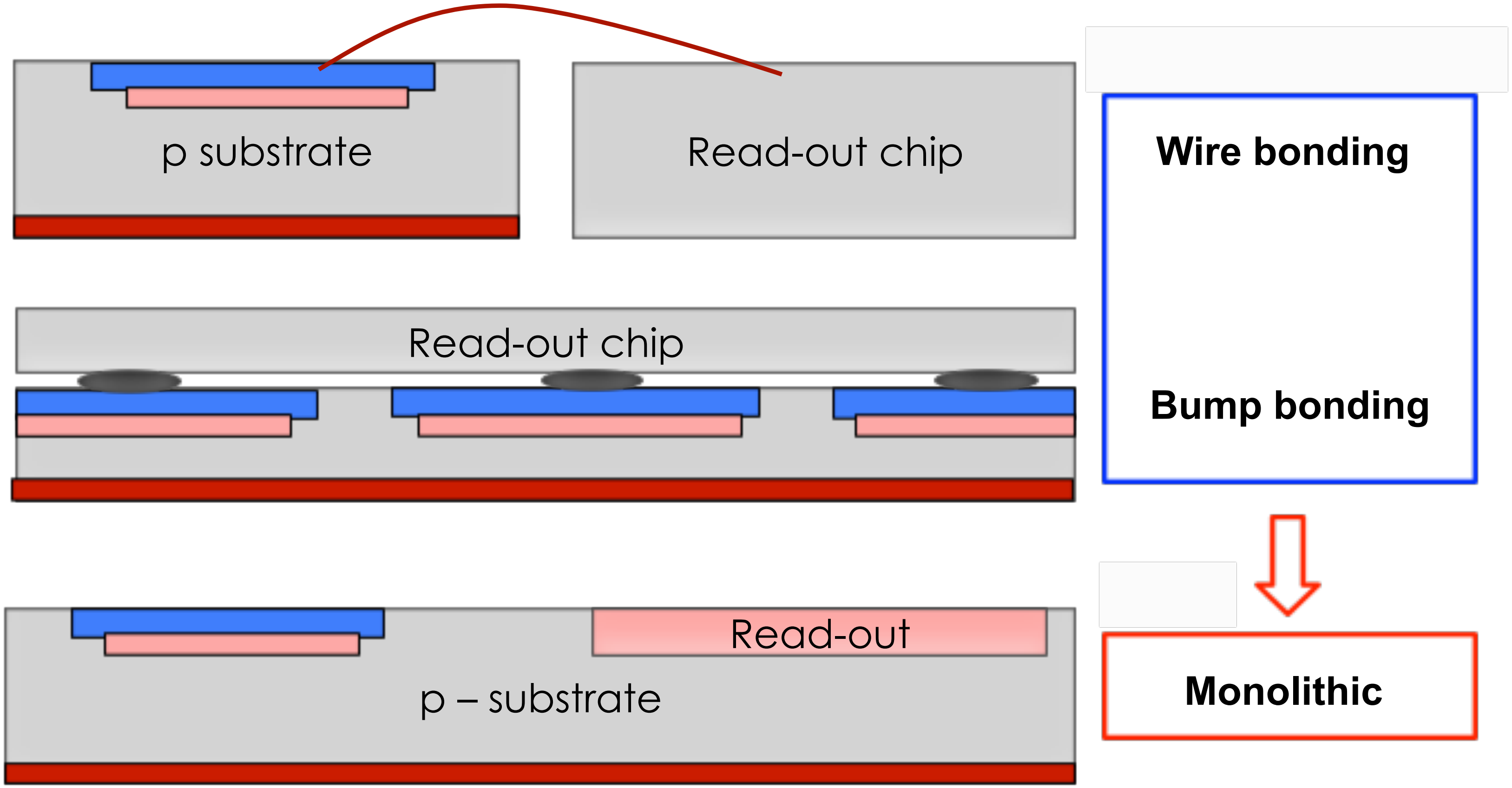
➔Segmentation is achieved via AC coupling



The AC read-out sees only a small part of the sensor:

small capacitance and small leakage current.

R&D: Can we use Monolithic technology?



Wire bonding

Bump bonding

Monolithic

Summary and outlook

Timing layers, 4D- and 5D- tracking are being developed for the next generation of experiments

It is a challenging and beautiful developments, that requires a collective effort to succeed.

There is no “one technology fits all”: depending on segmentation, precision, radiation levels and other factors the best solution changes.

It would be great if in our journey we stumble upon a highway, to take us out of the desert

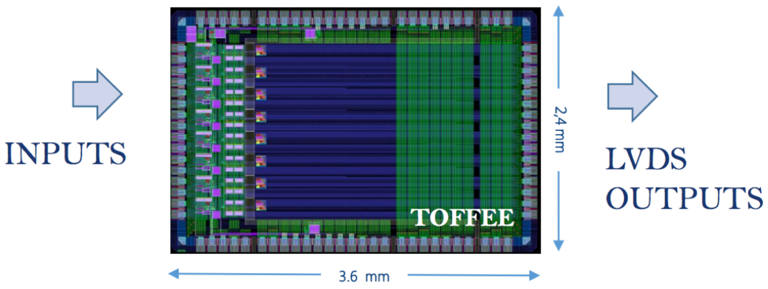
Full bibliography:
http://personalpages.to.infn.it/~cartigli/NC_site/UFSD_References.html

Two examples of UFSD and read-out chips

Single pad + TOFFEE

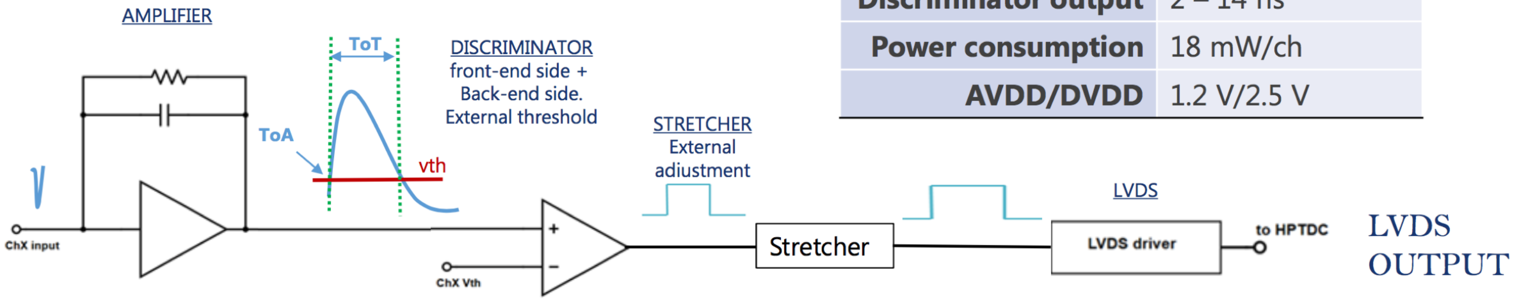
Multipad + TDCPix

TOFFEE: a chip for timing applications



Technology	CMOS 110 nm
Channels	8
Sensor capacitance	2-10 pF
Input dynamic range	3 fC – 60 fC
Analog gain	7 mV/fC
GBW	14 GHz
RMS noise (C=6pF)	800 μV
Discriminator output	2 – 14 ns
Power consumption	18 mW/ch
AVDD/DVDD	1.2 V/2.5 V

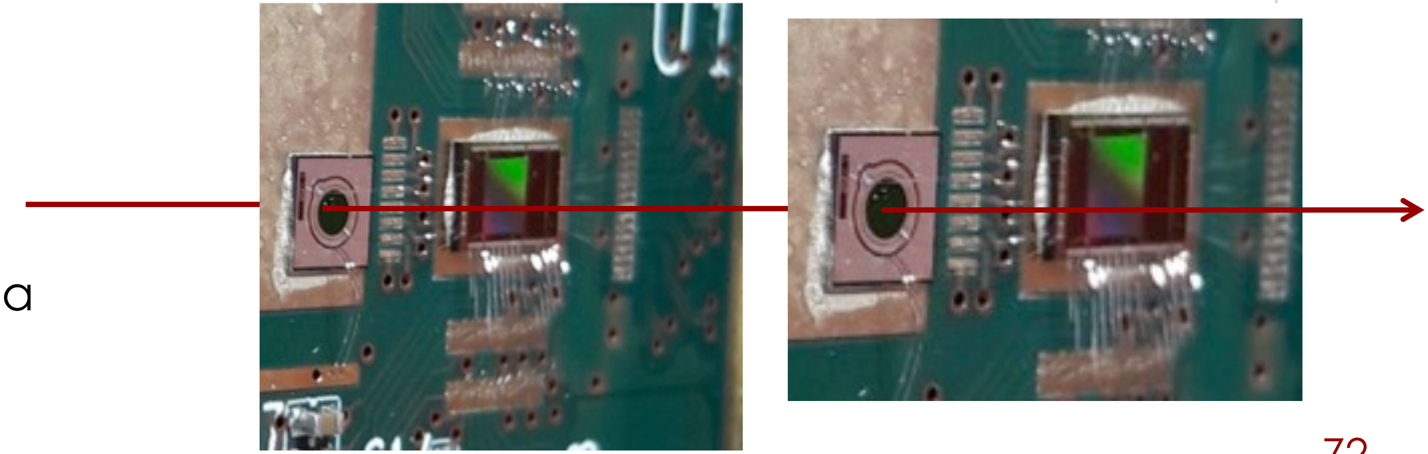
The channel architecture



The LVDS output is meant for time digitization with HPTDC (rising and falling edges). **A Strecher is required**.

Beam test at

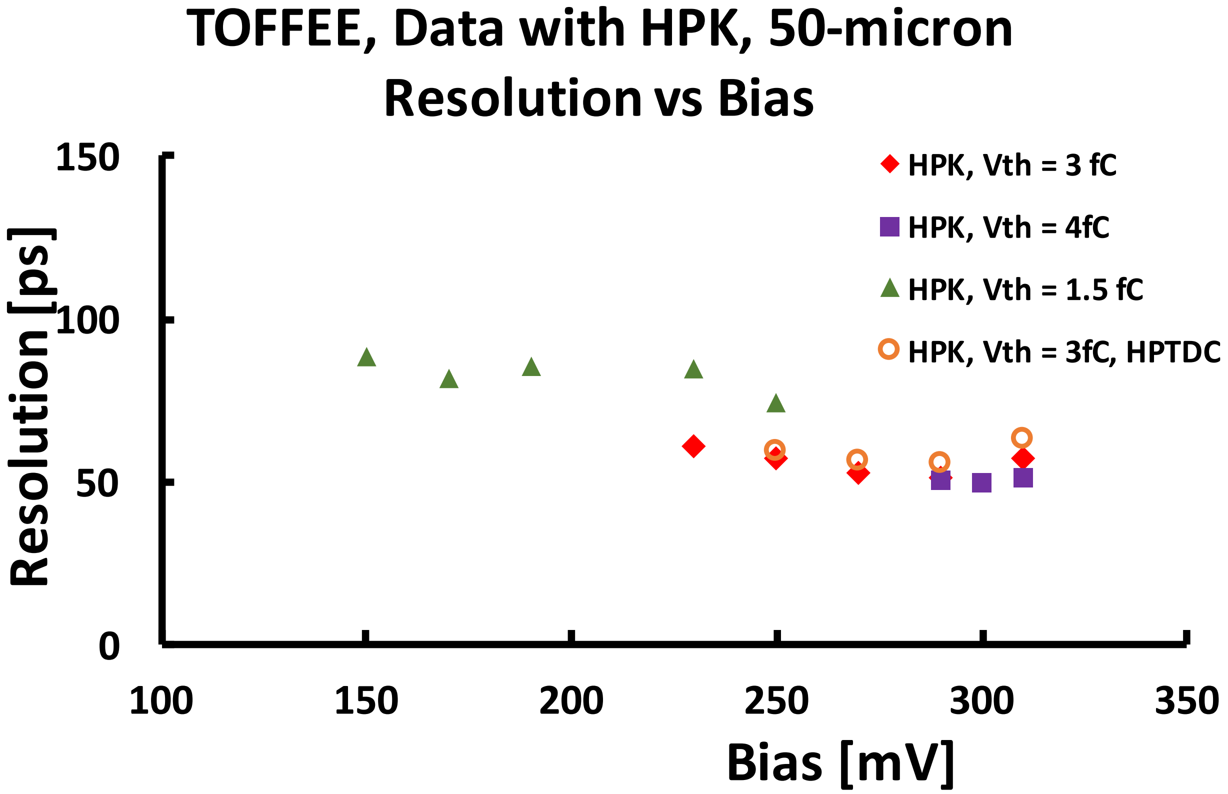
CERN north area



TOFFEE: beam test results

TOFFEE is the first version of a multipurpose 8-channel chip with Time-over-Threshold time-walk correction.

It achieves a resolution of 55 ps, including the digital part.



Multi-pad sensors: TDCpix & FBK-UFSD

Bump-bonded NA62 TDCpix ROC to FBK-UFSD sensor

NA62 ROC: 40x45 pads, each 300x300 μm^2 (1800 pads)

- More than 99% of pads working
- Same voltage behavior as single pad: breakdown above 280 V
- **First example of 4D tracking!**