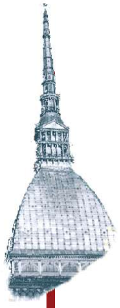
Tracking particles in space and time

Besides a few indirect signals of new physics, particle physics today faces an extraordinary drought.

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

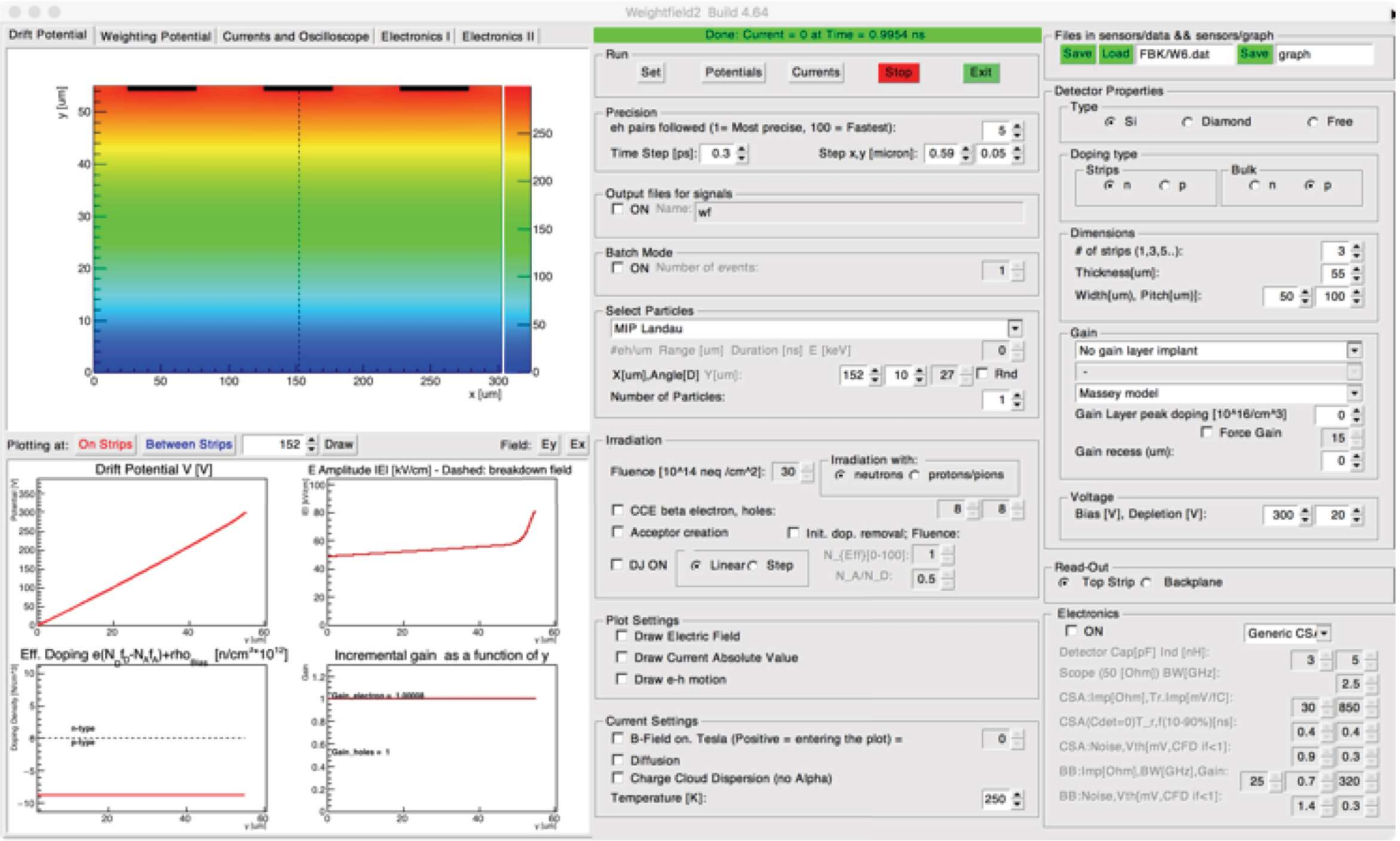
Preamble: simulator Weightfield2

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



Done: Current = 0 at Time = 0.9954 ns

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 CSA
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

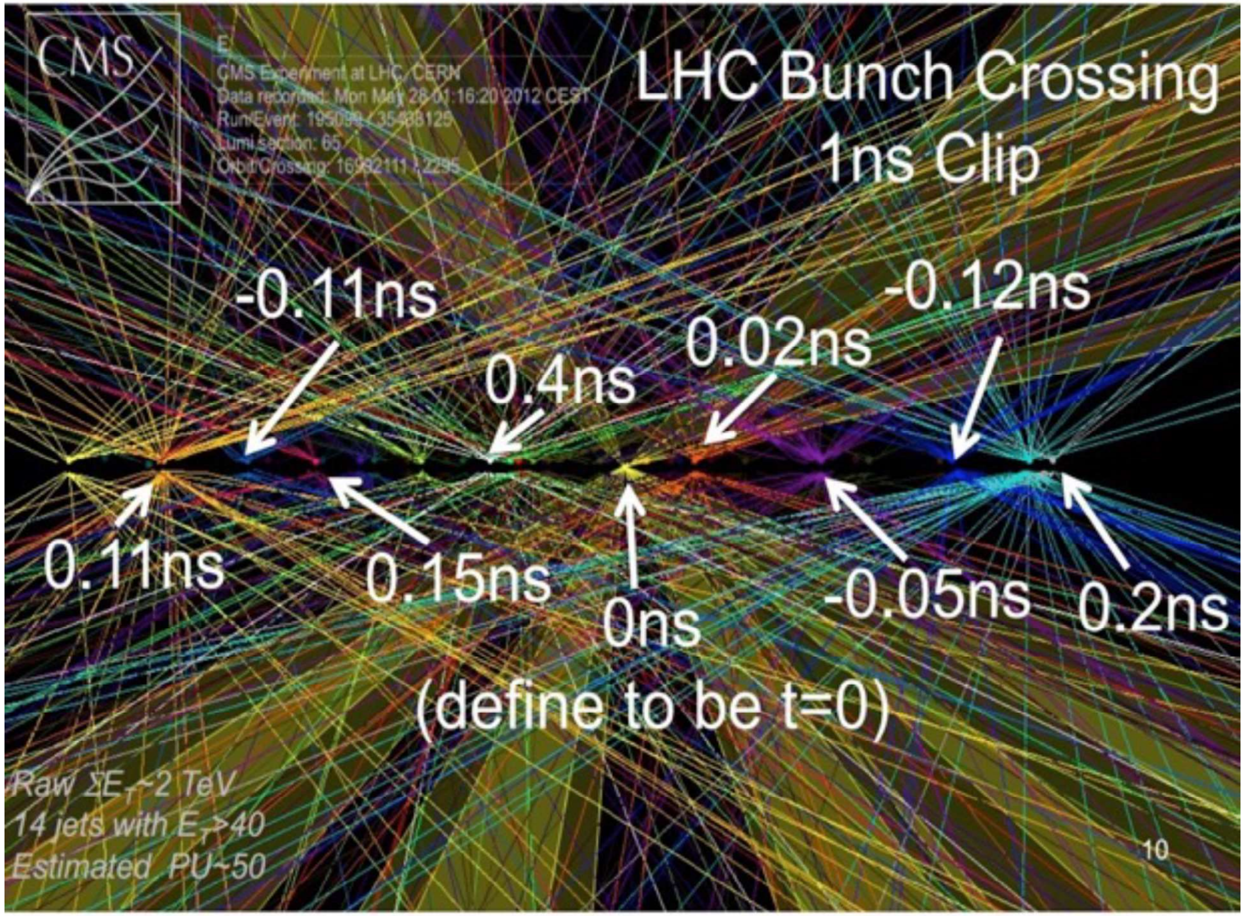
How to use it:

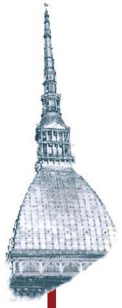
Obtain the last version from

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

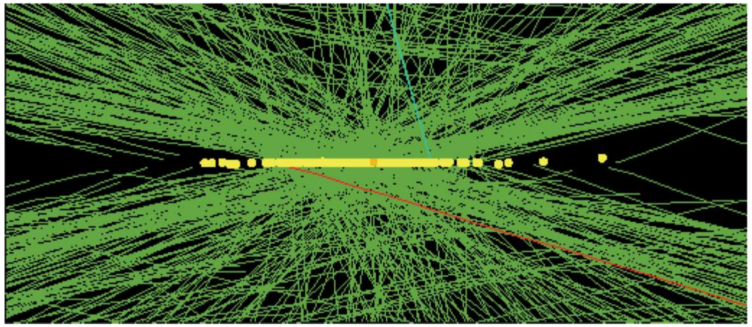
1) From the download page, get the latest version
2) Unzip it and then type:
3) Make or 3-bis) make -f Makefile_MacOS10.13_root6
4) ./weightfield

Current situation at LHC: no real need for timing



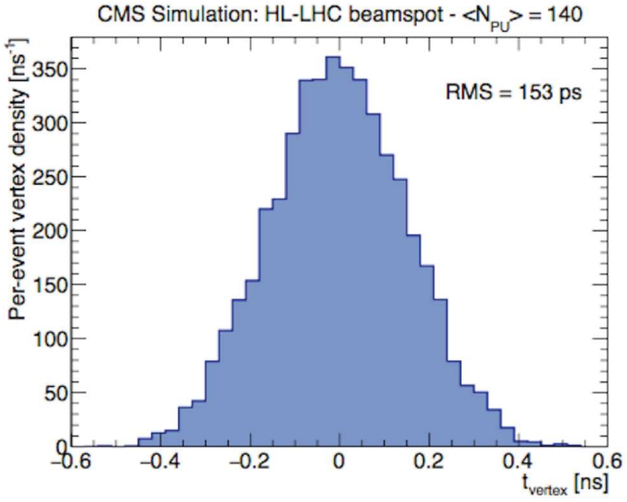


Is timing really necessary at HL-LHC?



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

150-200 events/bunch crossing

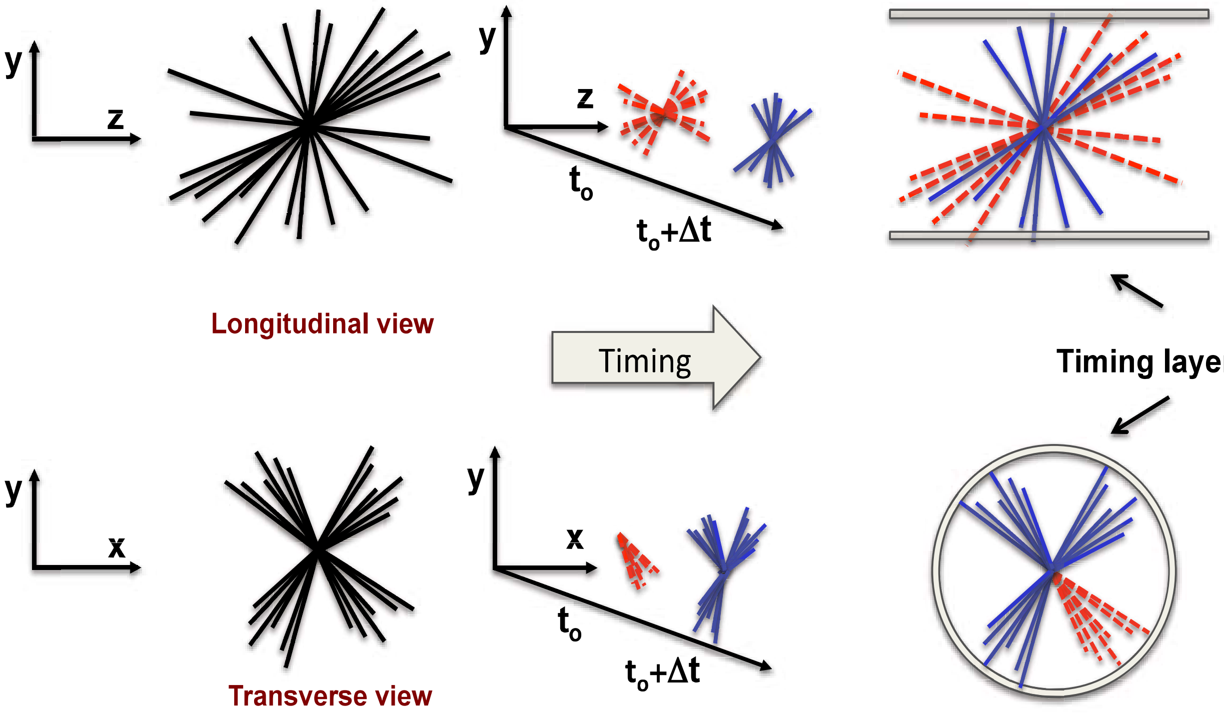


According to CMS simulations:

- **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

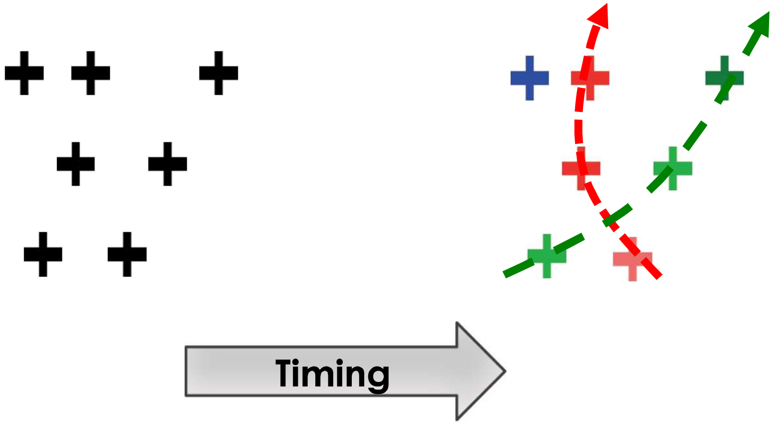


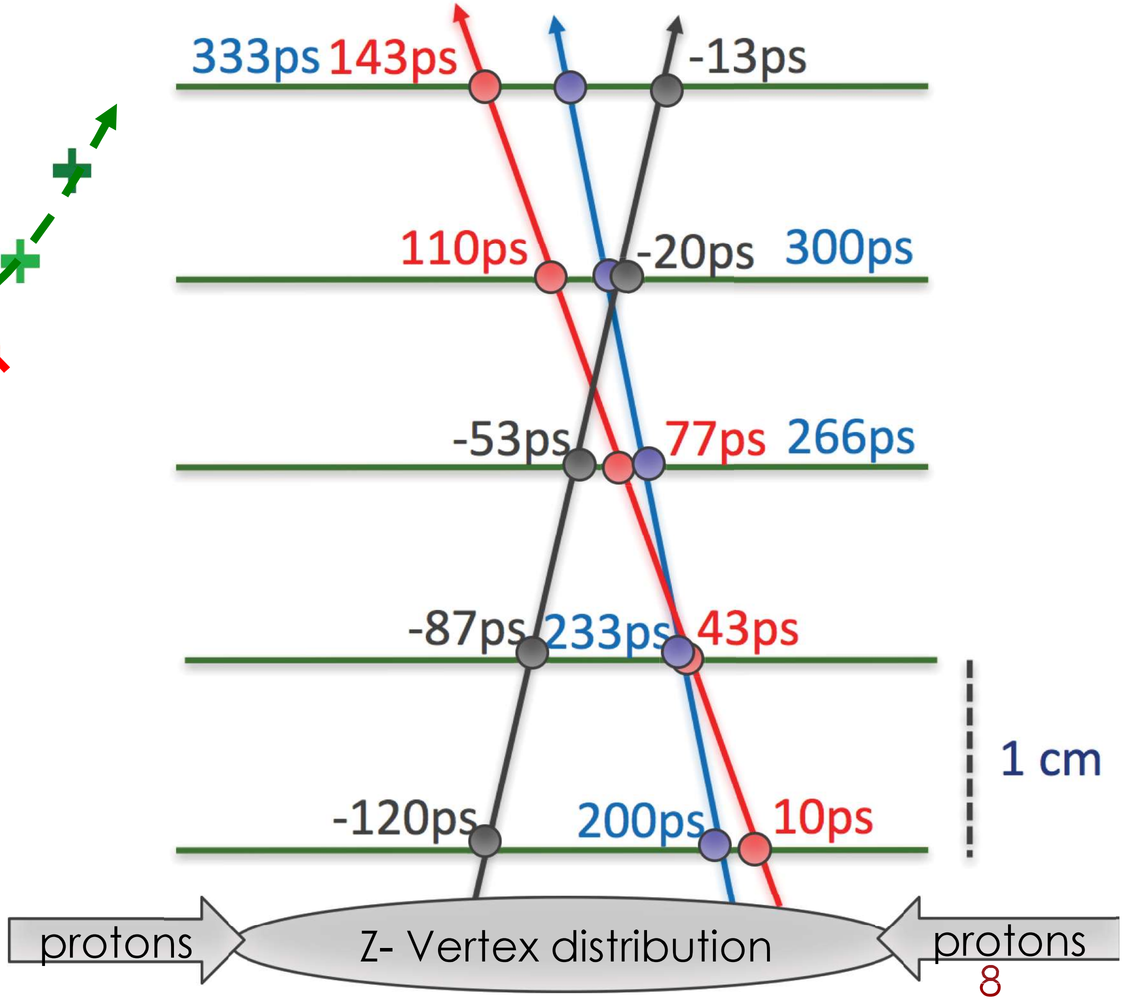
Timing complements tracking in the correct reconstruction of the events

Timing at each point along the track

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

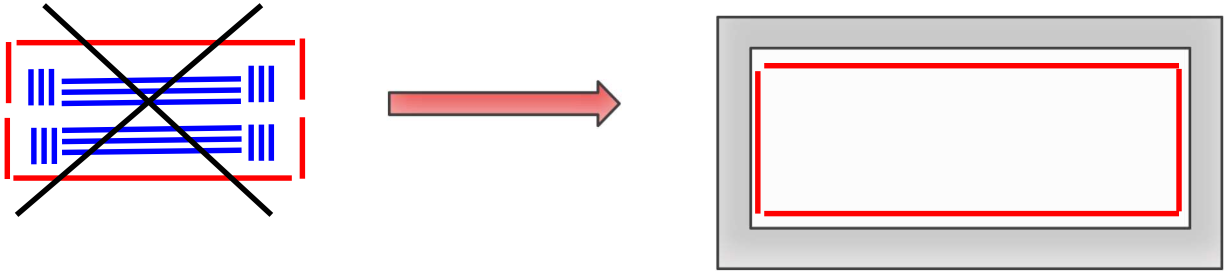
➔ Use only “time compatible points”



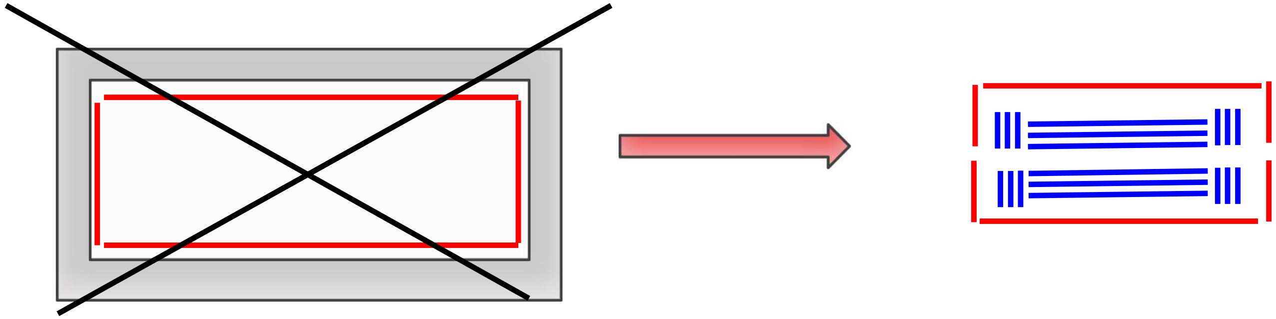


Where do we place a single timing layer?

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



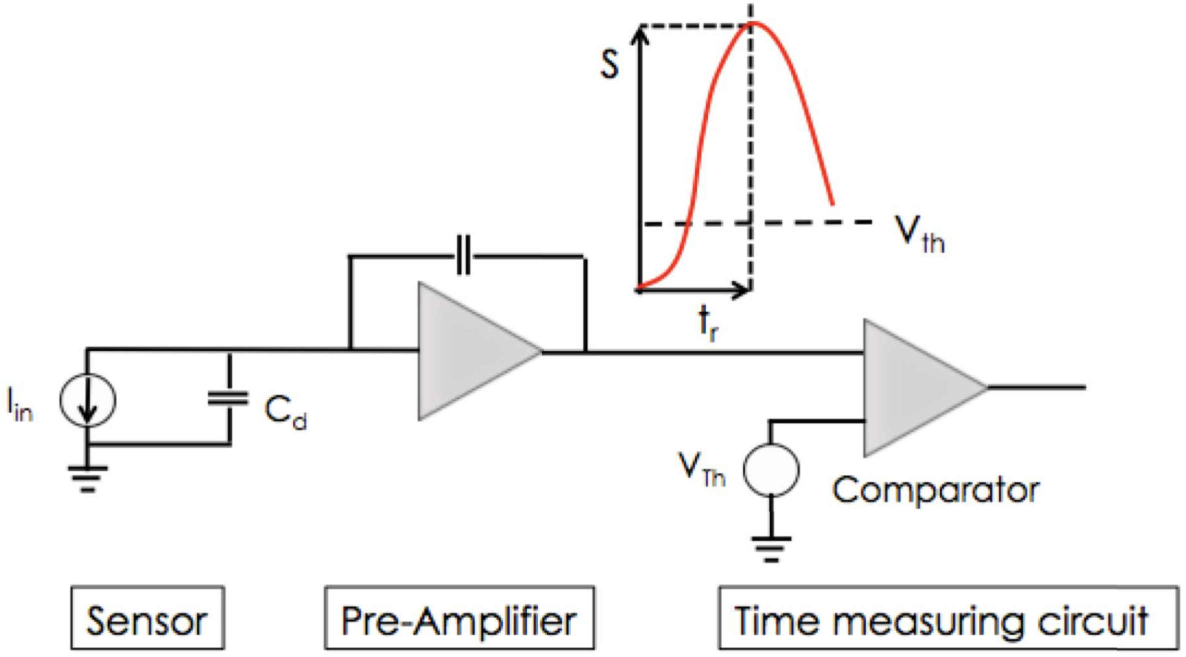
The calorimeter community thinks it is a wonderful idea, clearly to be implemented **far from the calorimeter,** in the tracker volume



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

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

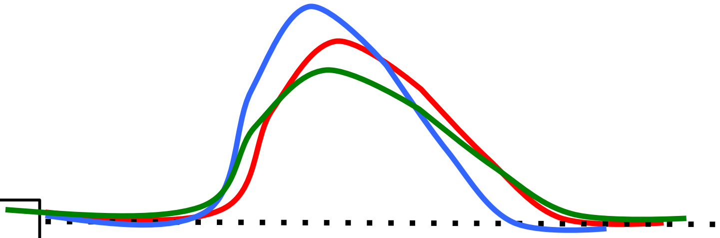
Good time resolution needs very uniform signals

Signal shape is determined by Ramo's Theorem:

$$i \propto qvE_w$$

Drift velocity

Weighting field



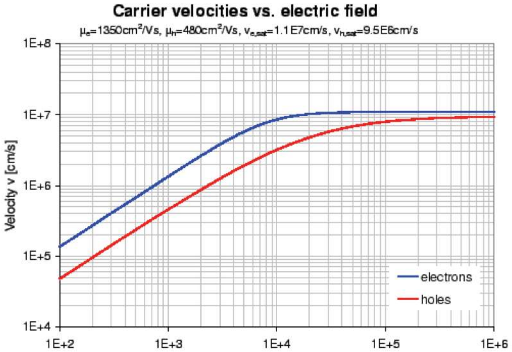
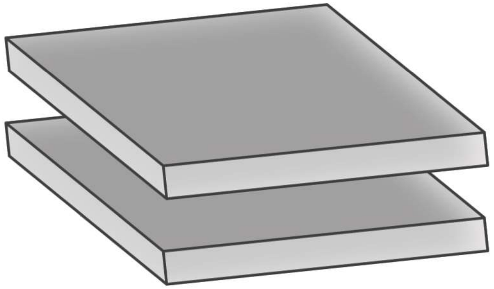


Figure: Electron and hole velocities vs. the electric field strength in silicon.



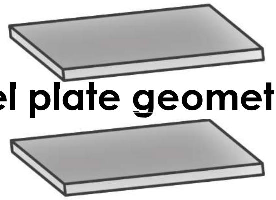
The key to good timing is the uniformity of signals:

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

Basic rule: parallel plate geometry

Time resolution

$$\sigma_t^2 = \left(\frac{Noise}{dV/dt}\right)^2 + (\Delta ionization)^2 + (\Delta shape)^2 + (TDC)^2$$

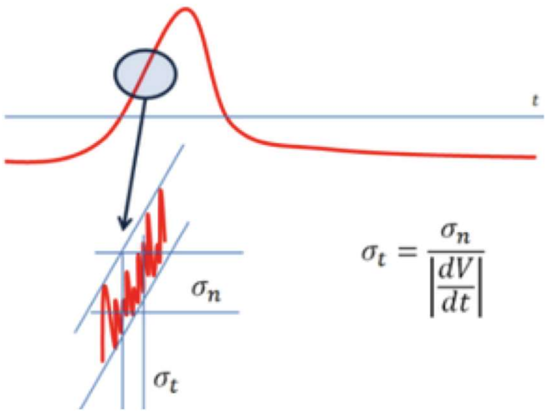


parallel plate geometry

Subleading, ignored here

Usual **“Jitter”** term

Here enters everything that is “Noise” and the steepness of the signal



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

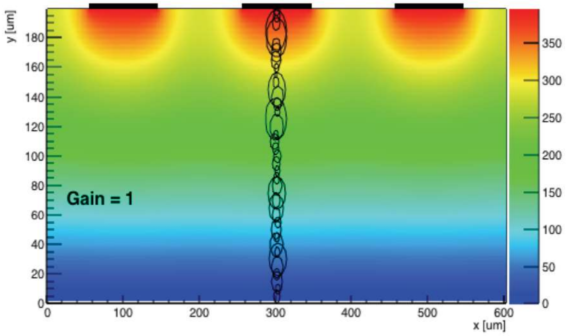
Need large dV/dt

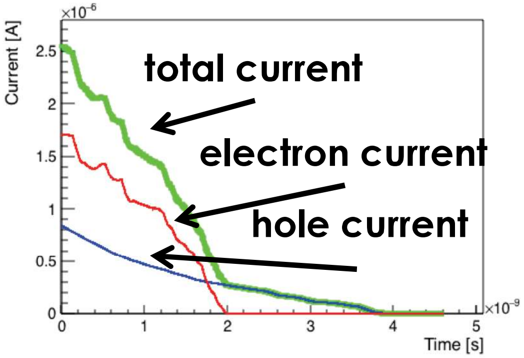
Time walk:

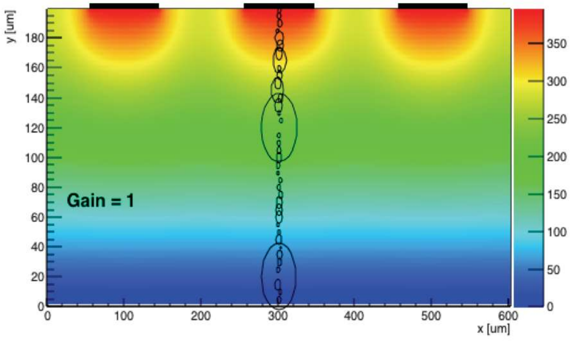
Amplitude variation, corrected in electronics

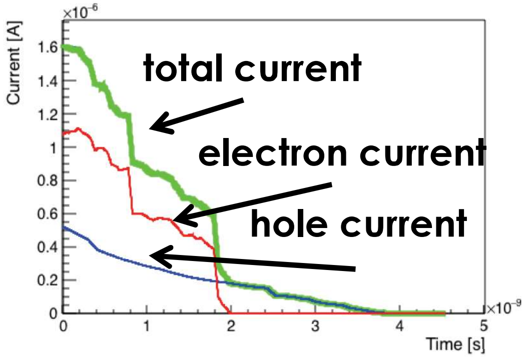
Shape variations:

non homogeneous energy deposition







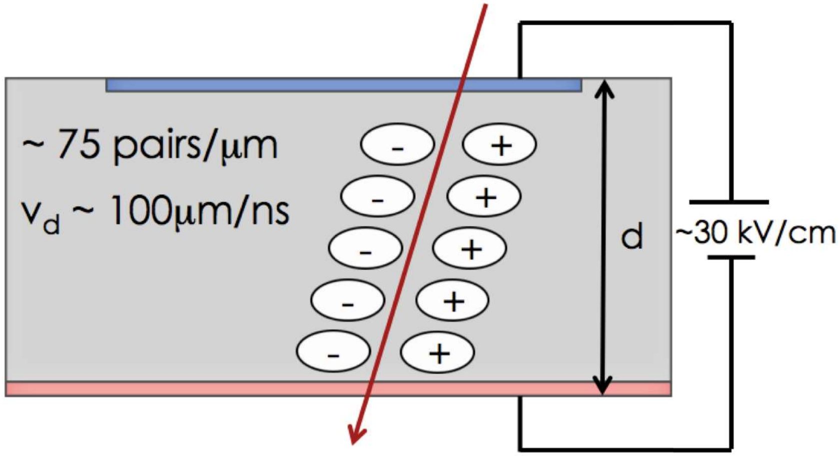


Signal formation in silicon detectors

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?

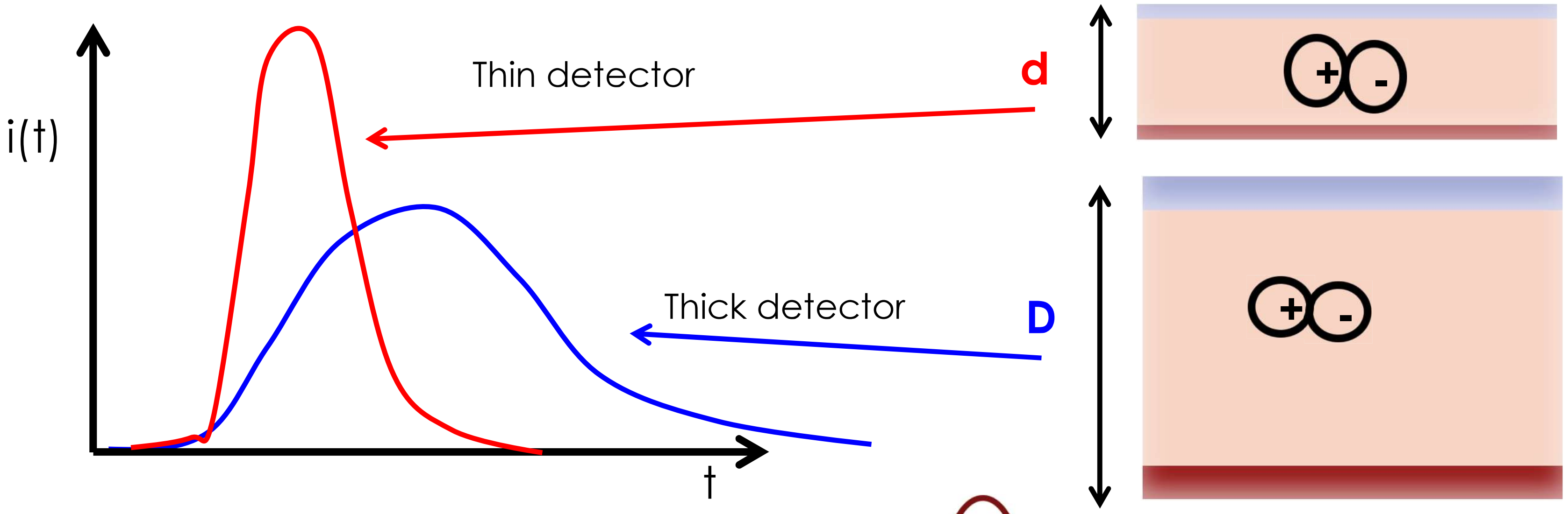
(Simplified model for pad detectors)

Let's consider **one single electron-hole pair.**

The integral of the current is equal to the electric charge, q:

$$\int [i_{el}(t)+i_h(t)]dt = q$$

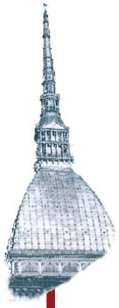
However **the shape of the signal depends on the thickness** d: thinner detectors have higher slew rate



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

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

Weighting field



Large signals from thick detectors?

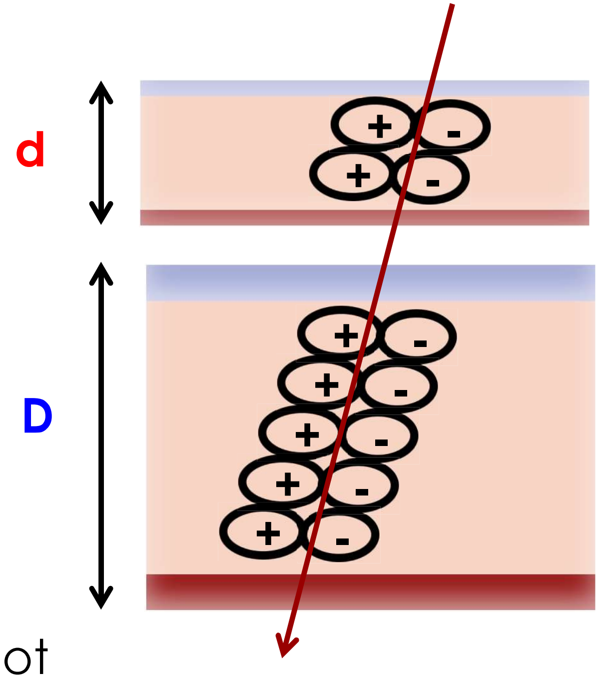
(Simplified model for pad detectors)

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

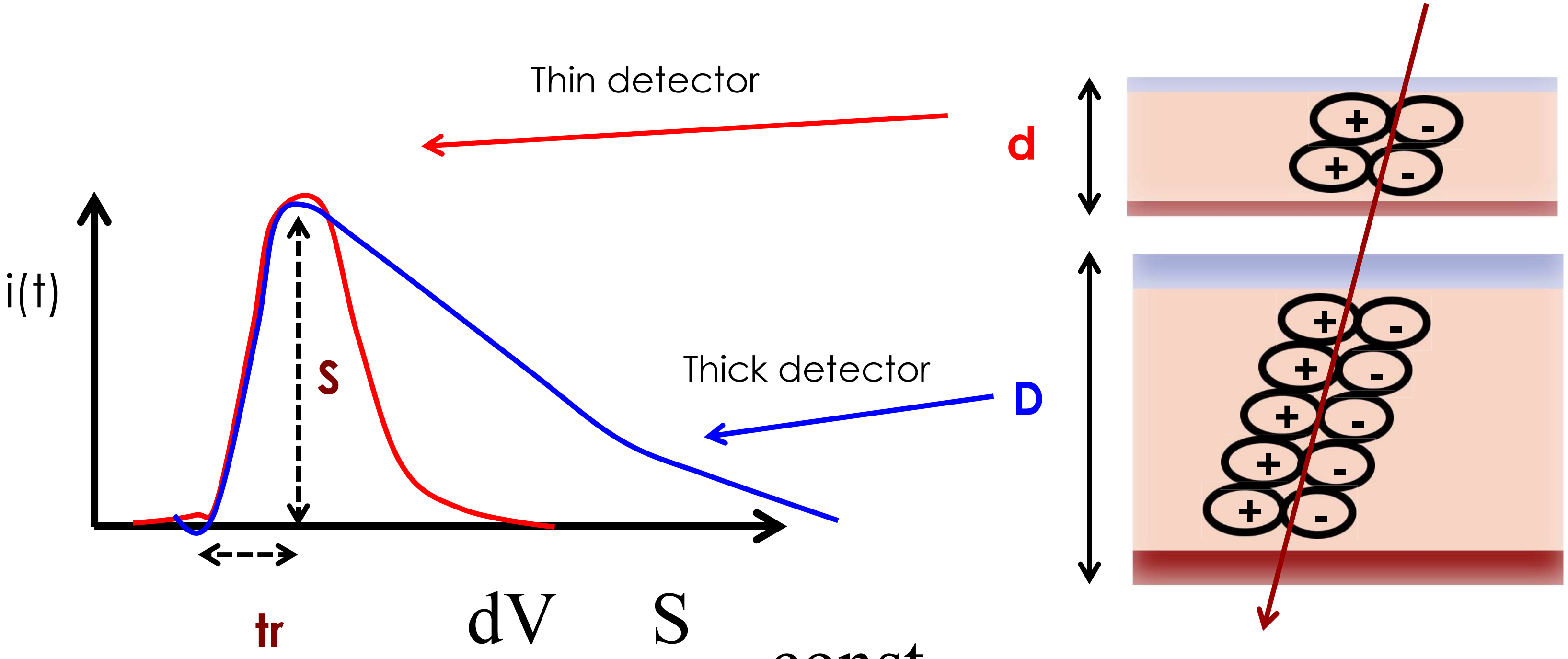
Weighting field

velocity

➔ **Initial current = constant**

Summary "thin vs thick" detectors

(Simplified model for pad detectors)



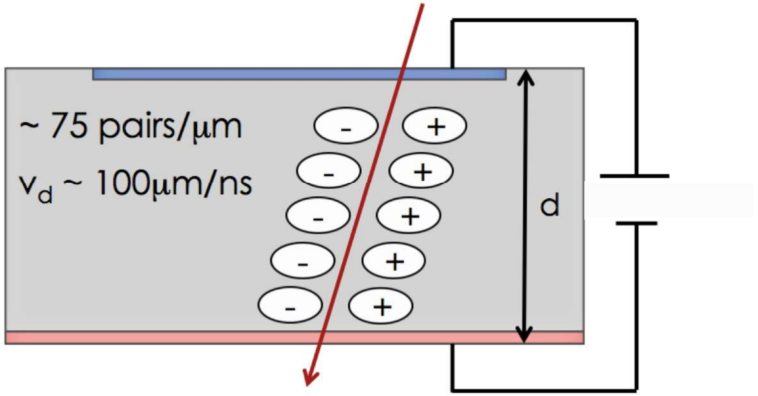
$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim \text{const}$$

Thick detectors have longer signals, not higher signals

We need to add gain

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

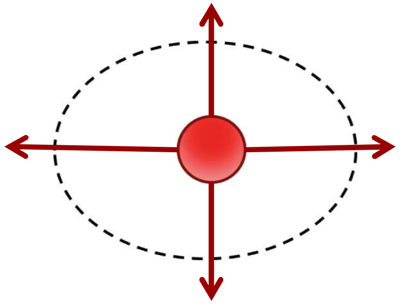
1) Use external bias: assuming a 50 micron silicon detector, we need **V_{bias} = ~ 600 - 700 V**



Difficult to achieve

2) Use Gauss Theorem:

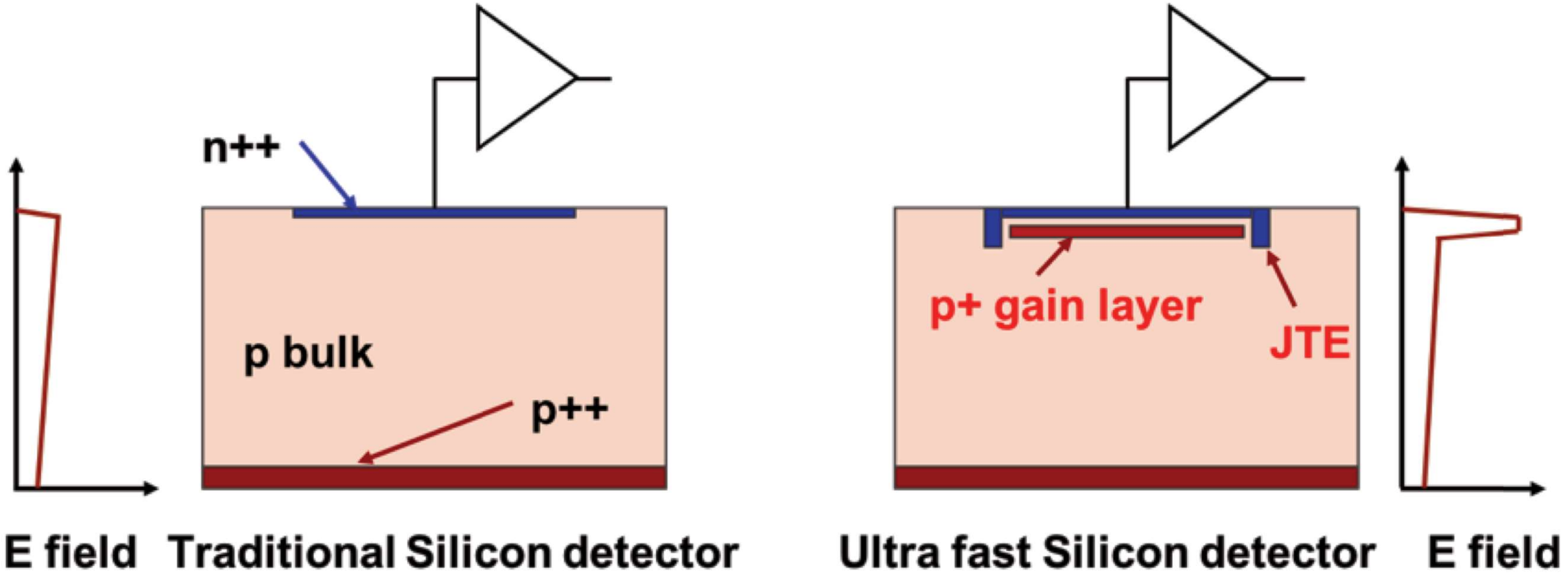
$$\sum q = 2\pi r * E$$



E = 300 kV/cm ➔ q ~ 10^{16} /cm^3

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

Standard vs Low Gain Avalanche Diodes



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

Fields in UFSD and PiN sensors

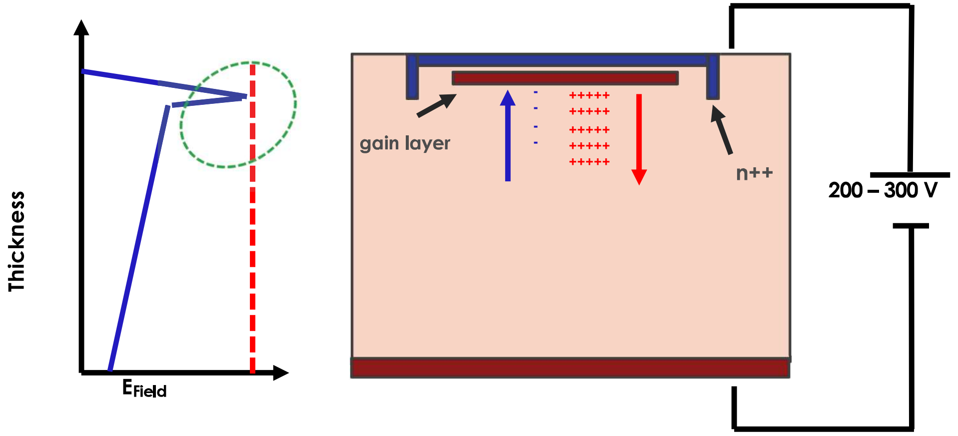
Gain happens when the E_{field} is near the critical values

Two methods to increase Efield:

1. Gain layer
2. Bias

➔ **Gain due to Interplay between gain layer and bias**

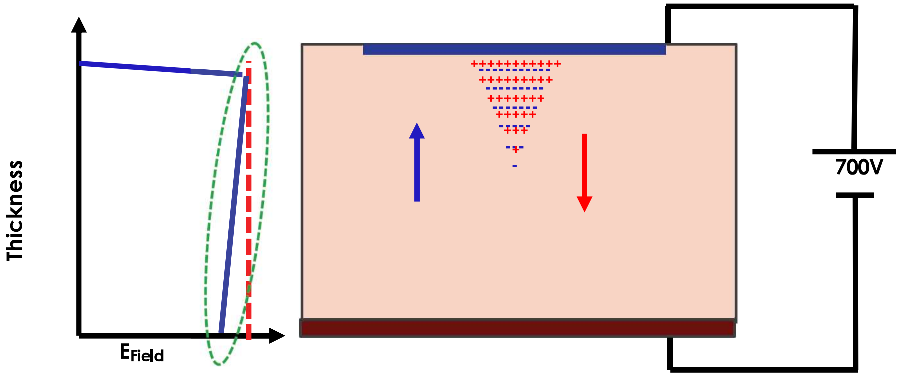
UFSD sensors

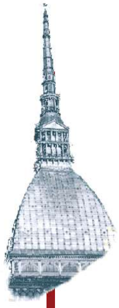


One method to increase Efield:

1. Bias

Standard Silicon sensor

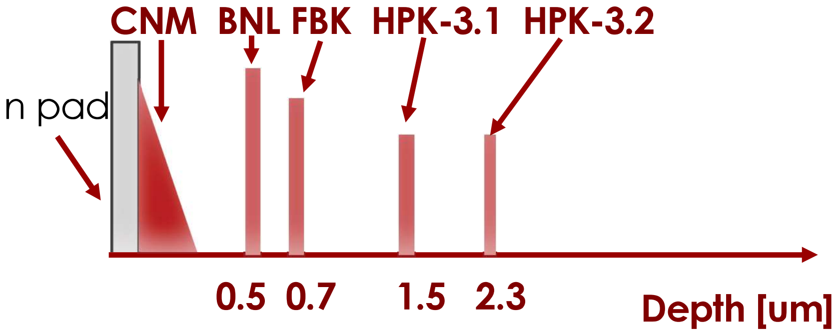




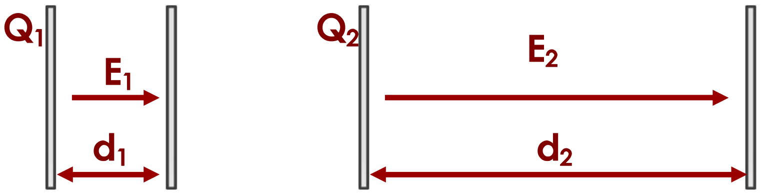
Gain layer position: a detail of great importance

Different producers use different designs

Latest HPK R&D prod. has delivered several different types of implant, both rather deep. Is this good or bad?



In a parallel plate capacitor, the field **E** does not depend on the distance **d**, only on the charge **Q**



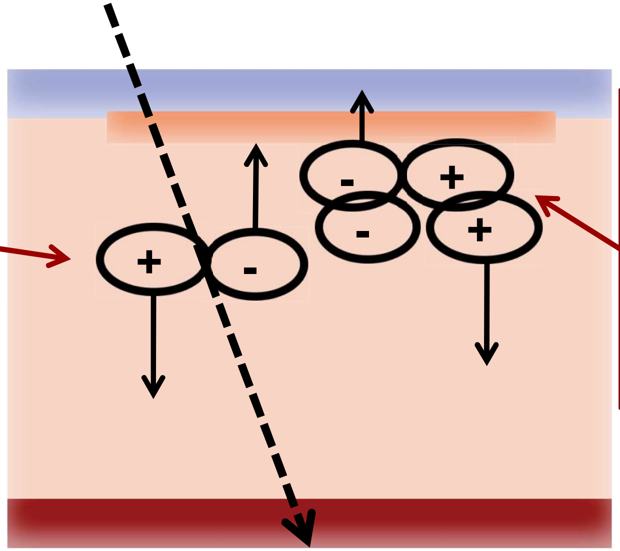
If $Q_1 = Q_2$, then $E_1 = E_2$

$$G \propto e^{\alpha * d}$$

Gain: exp(field * distance)

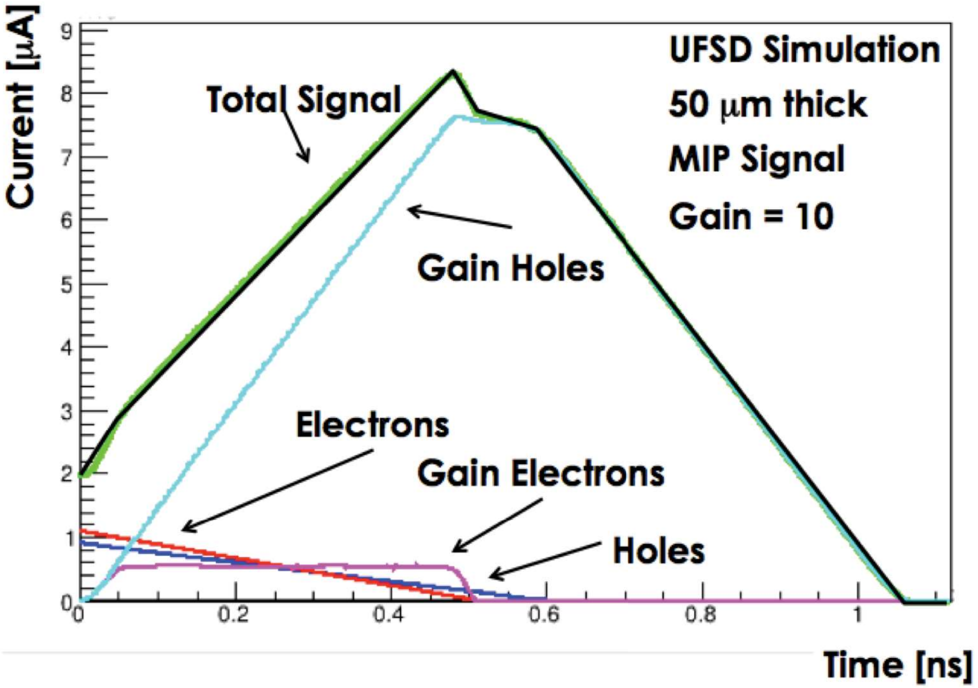
➔ **If depth increases, doping should decrease to keep the same gain**

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.

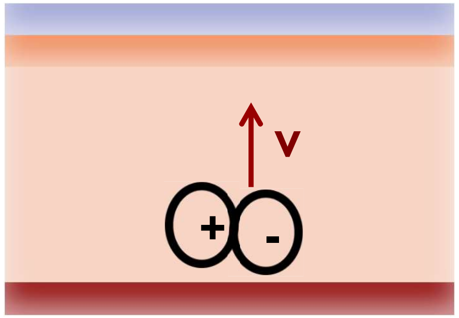
- **Gain electrons have almost no effect**
- **Gain holes dominate the signal**

➔ **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})

Gain →



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)

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

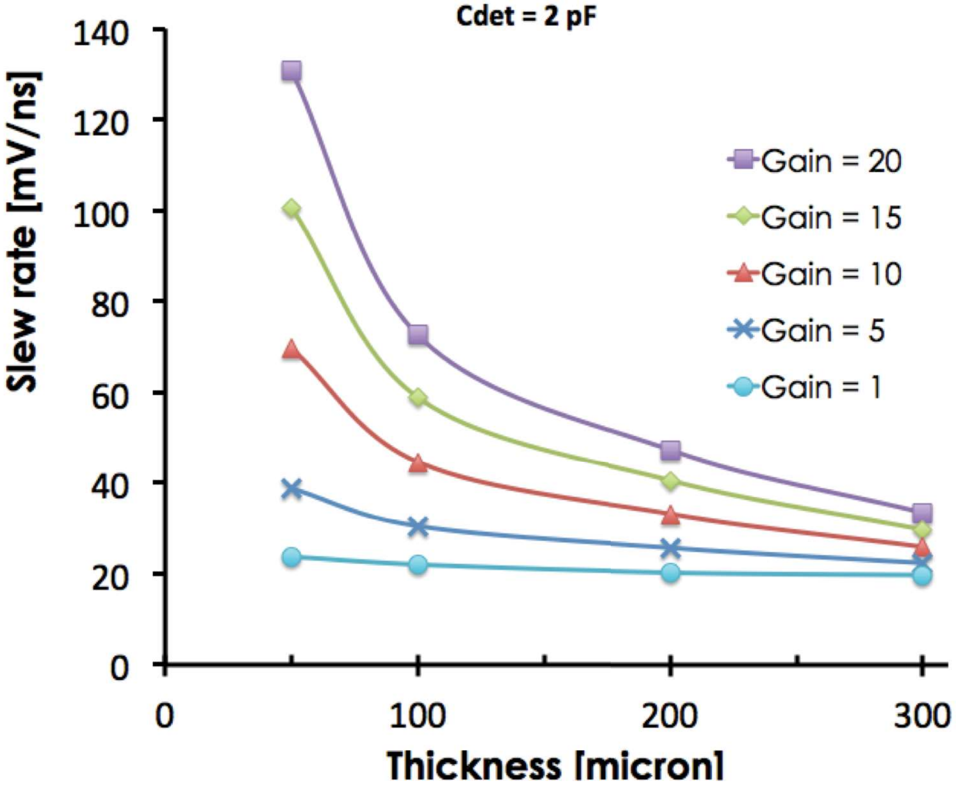
➔ **Gain current ~ 1/d**

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

Gain current vs Initial current

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

➔ Go thin!!



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

Full simulation

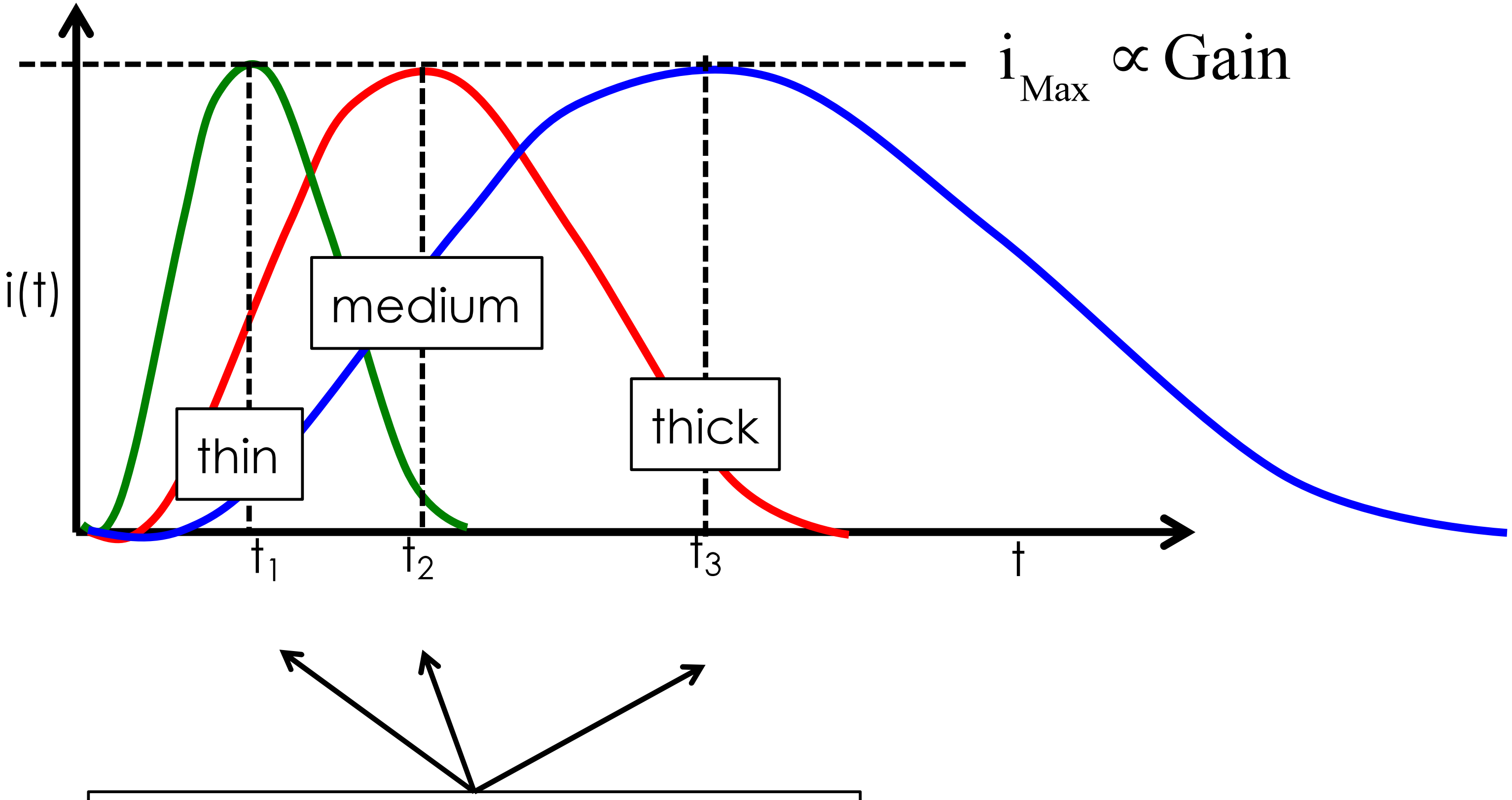
(assuming 2 pF detector capacitance)

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

Significant improvements in time resolution require thin detectors

Gain and Signal 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

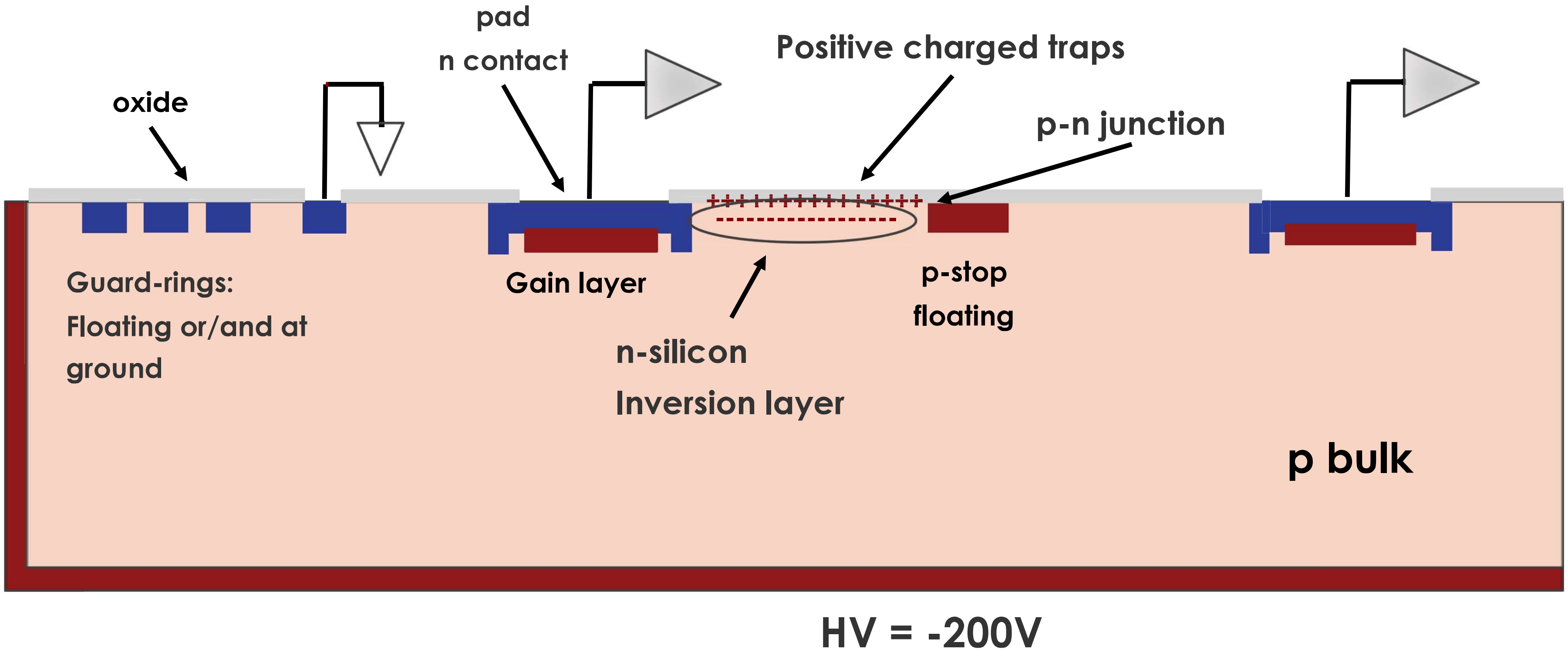
Specifically:

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 Multi-pad sensors

Basic building block for a generic UFSD sensor.

Vendors use proprietary technical variations



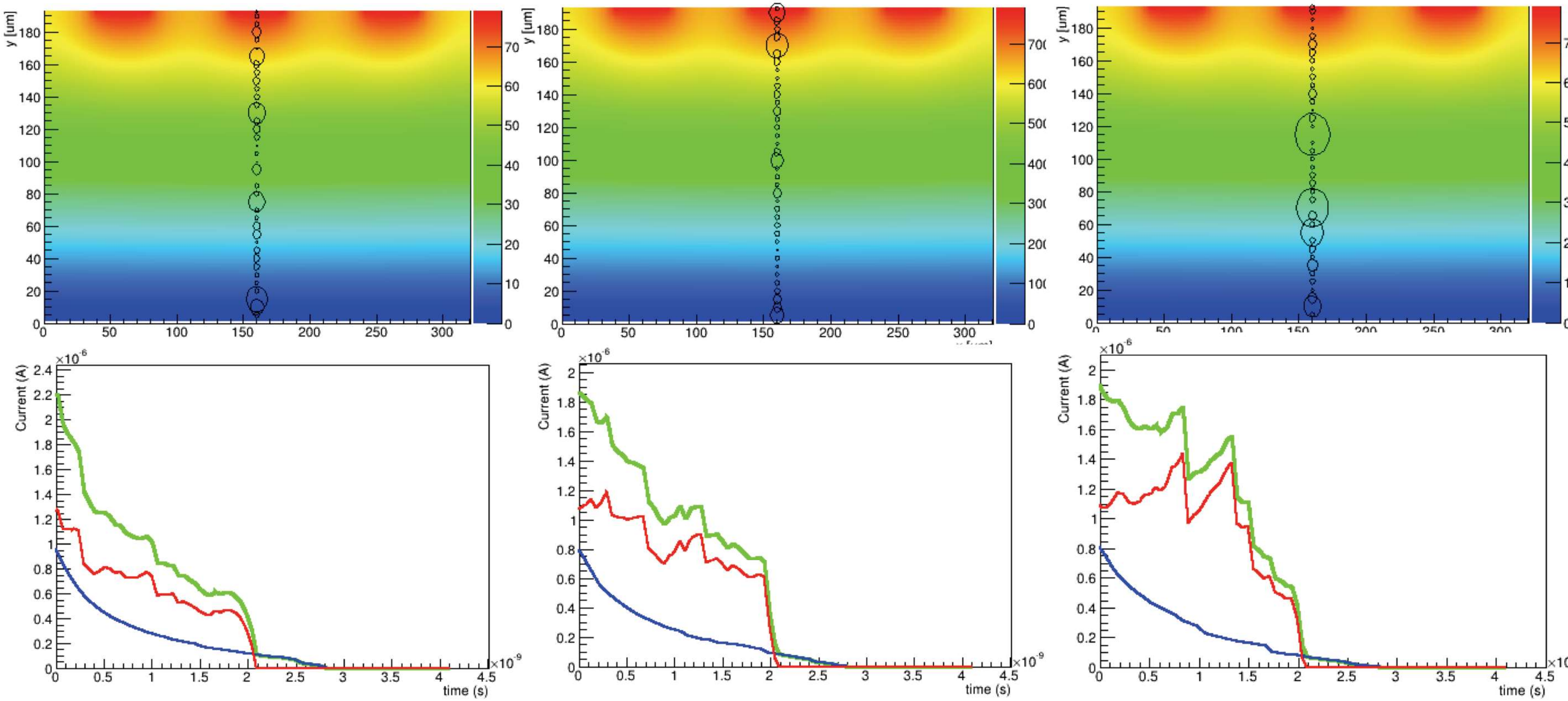
Many years of R&D to define the best geometry

Physical limit to time precision: Non-Uniform Energy deposition

Fluctuations in ionization 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:



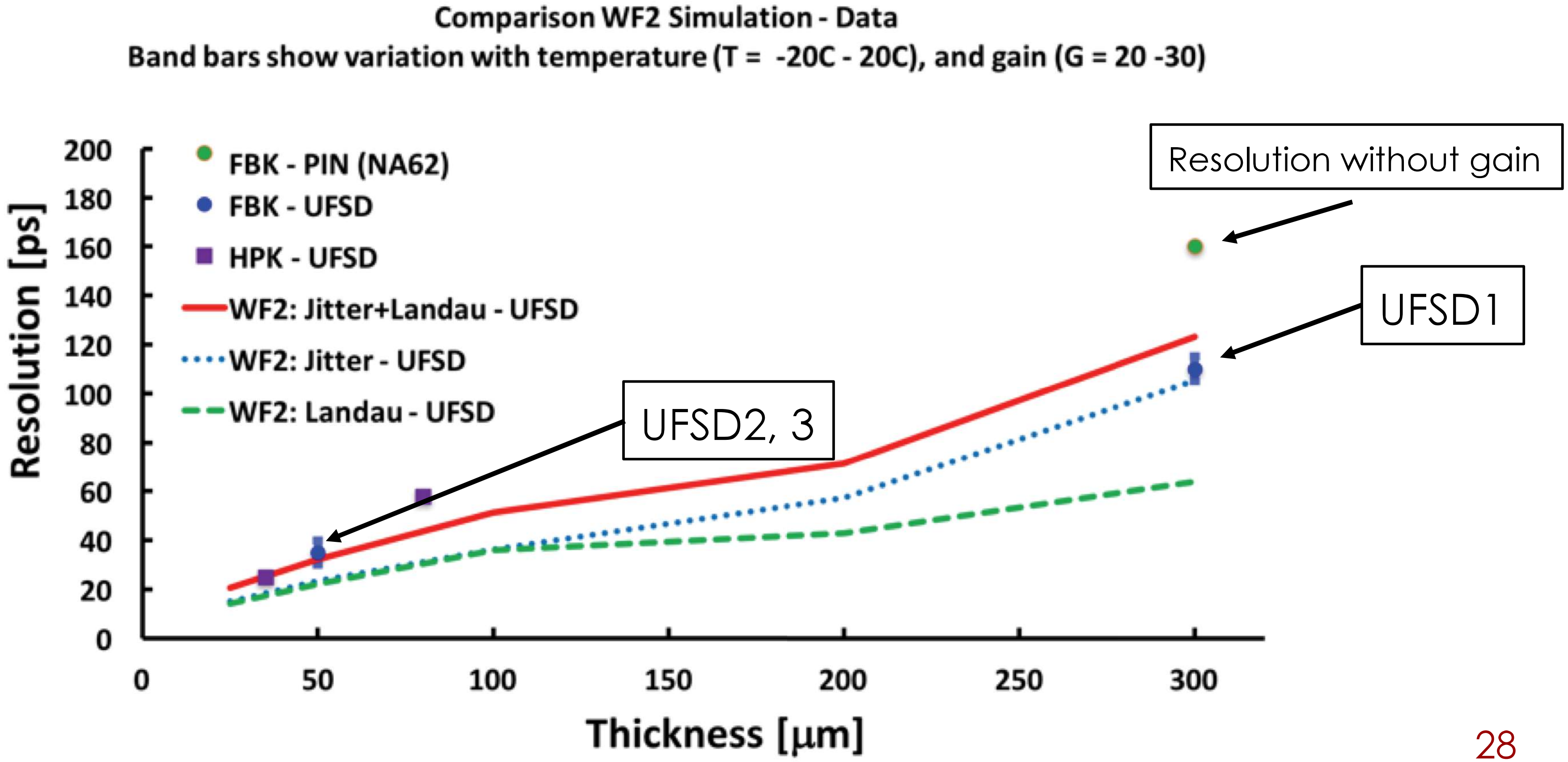
UFSD time resolution summary

The UFSD advances via a series of productions.

For each thickness, the goal is to obtain the intrinsic time resolution

Achieved:

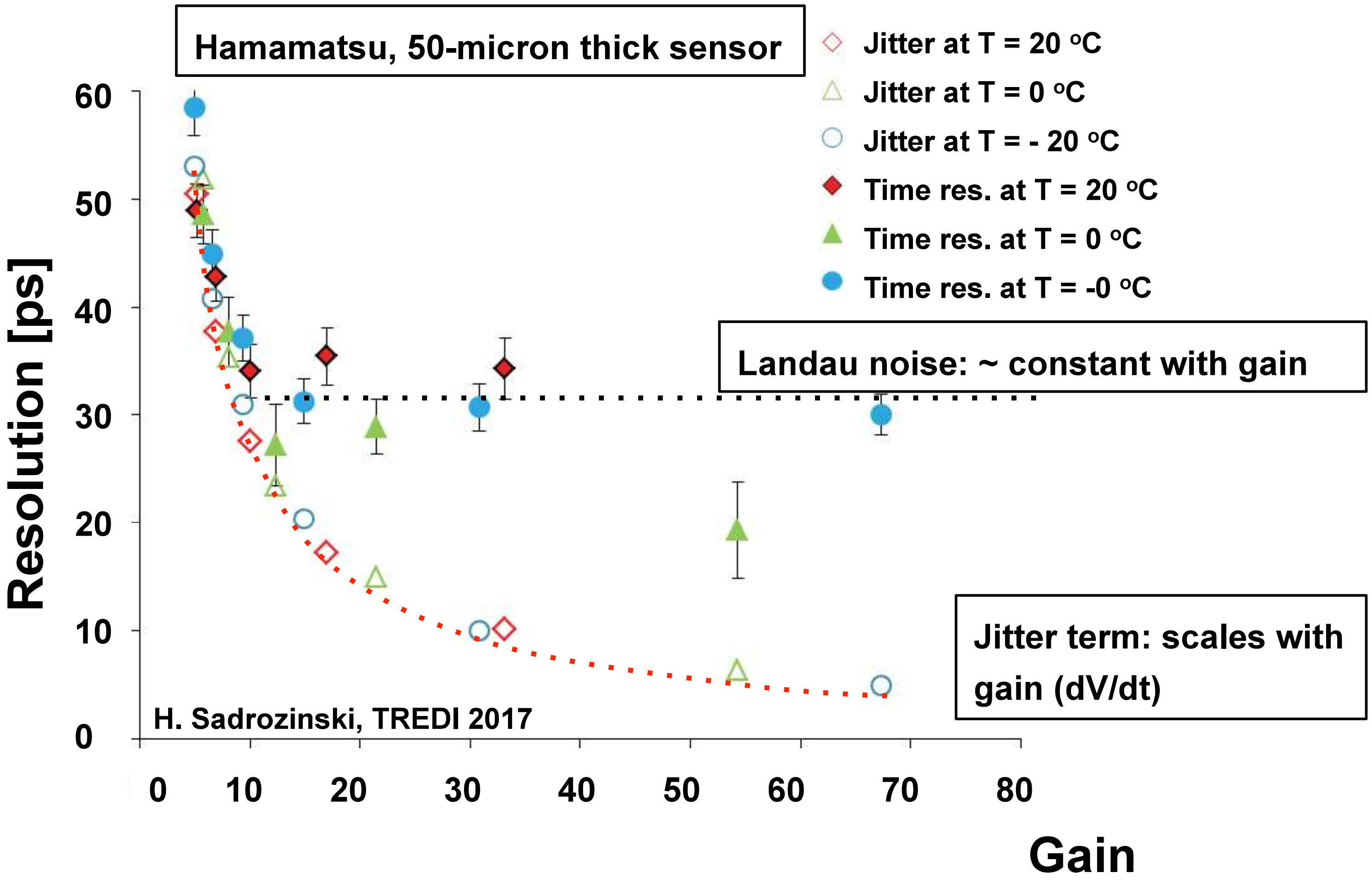
- **20 ps for 35 micron**
- **30 ps for 50 micron**



UFSD time resolution

UFSD from Hamamatsu: 30 ps time resolution,

Value of gain ~ 20



Landau noise: ~ constant with gain

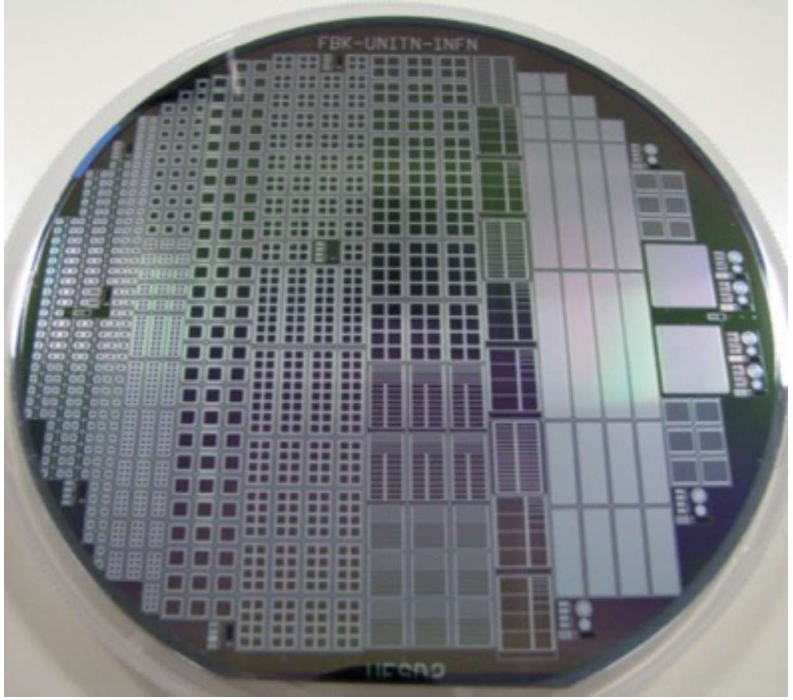
Jitter term: scales with gain (dV/dt)

UFSD group: FBK – Trento Uni – INFN-To

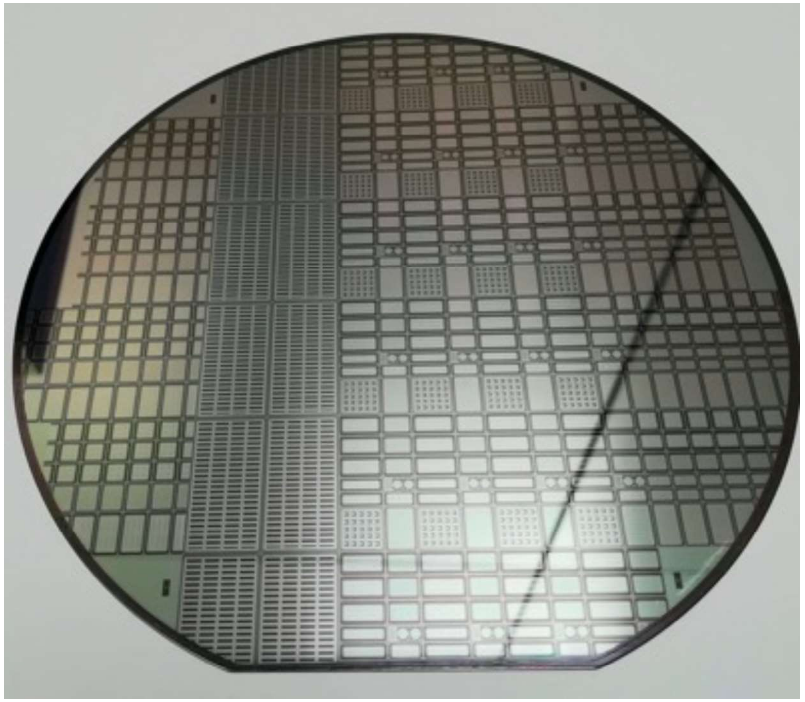
UFSD1: 300-micron. First LGAD production at FBK. Gain layer study, edges

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

UFSD3: 50-micron, produced with the stepper, many Carbon levels, small dead space



UFSD2



UFSD3

Irradiation effects

Irradiation causes 3 main effects:

- Decrease of charge collection efficiency due to trapping
- Gain layer disappearance
- Increased leakage current, shot noise

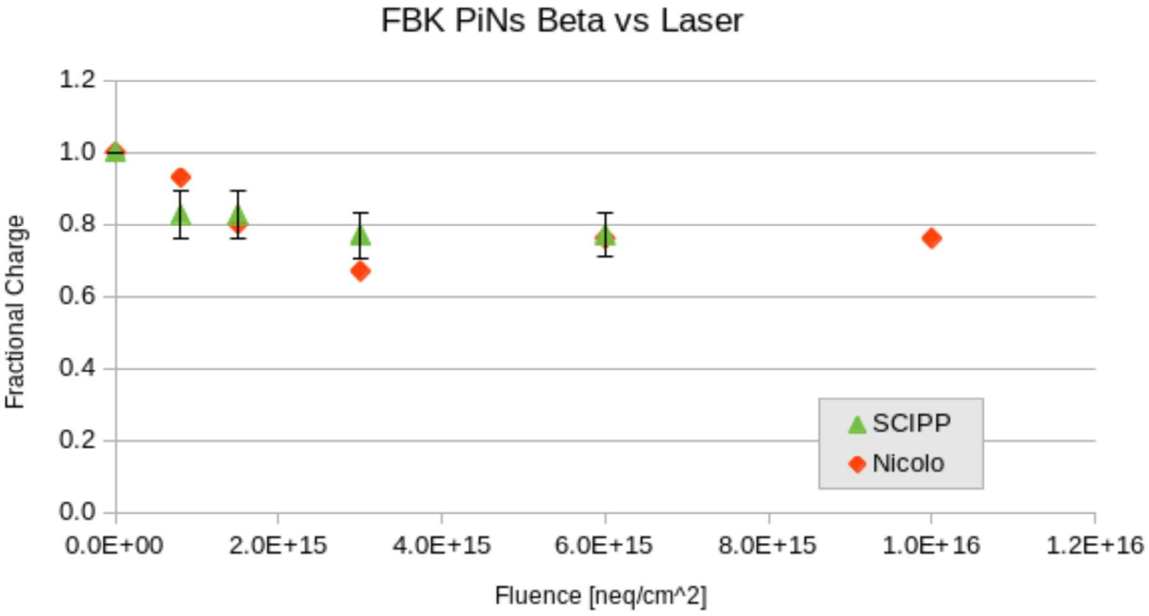
(1) Charge Collection efficiency

Traditionally, the e/h lifetimes decreases as a function of the fluence:

$$Q(\emptyset) = Q(0)e^{-t/\tau} \qquad \tau = 1/(\beta\emptyset)$$

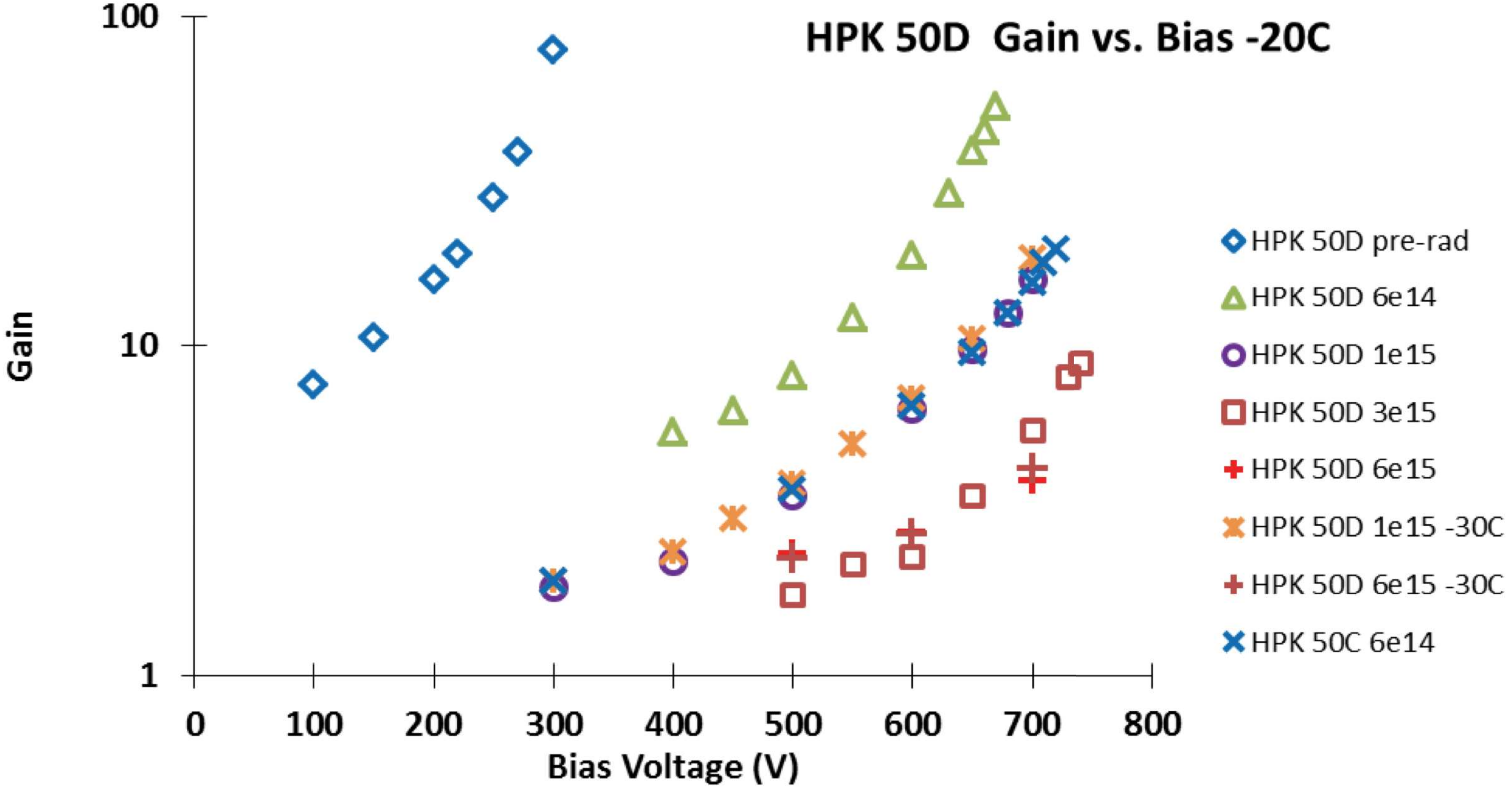
➔ For some unknown reason, after an initial decrease, the lifetime in thin sensors remains constant

This is a common problem in our understanding of how Silicon sensors work:


FBK PiNs Beta vs Laser

Silicon sensors after heavy irradiation behaves better than what is expected by extrapolating from lower fluence data

(2) Gain in irradiated sensors



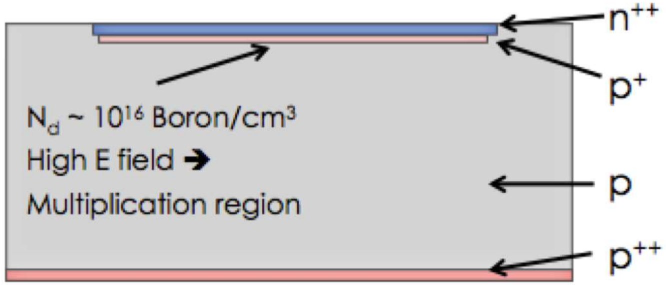
The gain decreases with fluence. Why?

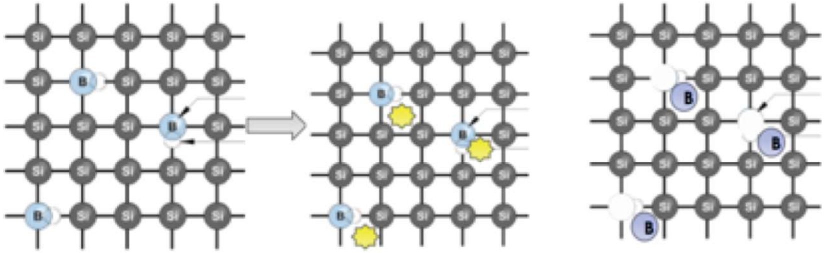
To some extent, the gain layer disappearance might be compensated by increasing the bias voltage

Gain layer de-activation

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

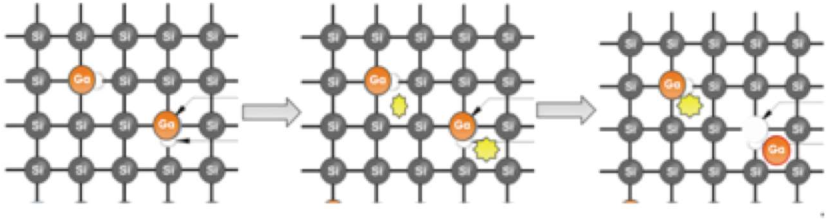
$$N(\emptyset) = N(0) * e^{-c\emptyset}$$



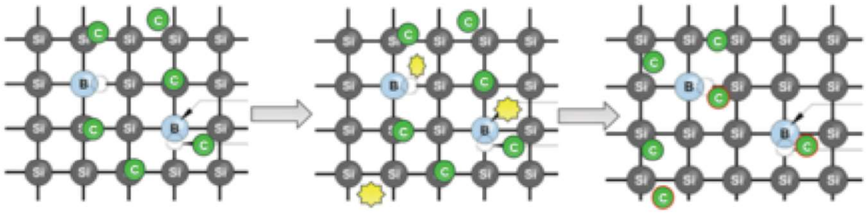


Boron
Radiation creates interstitial defects that inactivate the Boron: Si_i + B_s ➔ Si_s + B_i

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

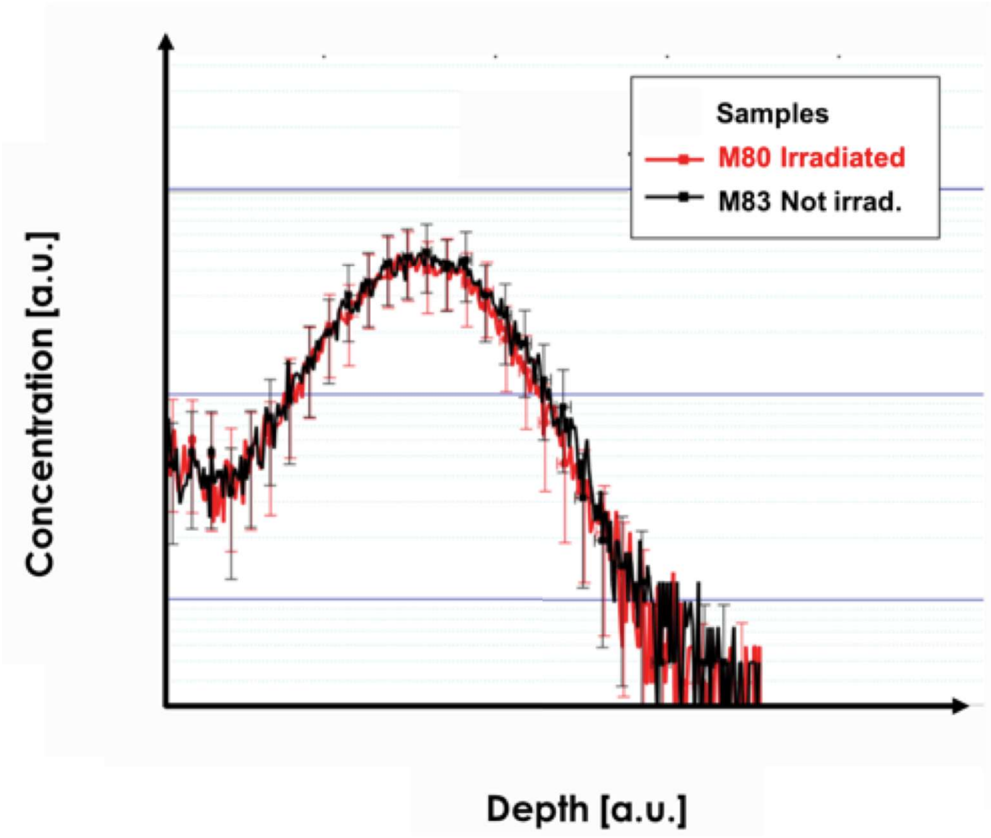


Gallium
From literature, Gallium has a lower possibility to become interstitial



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…

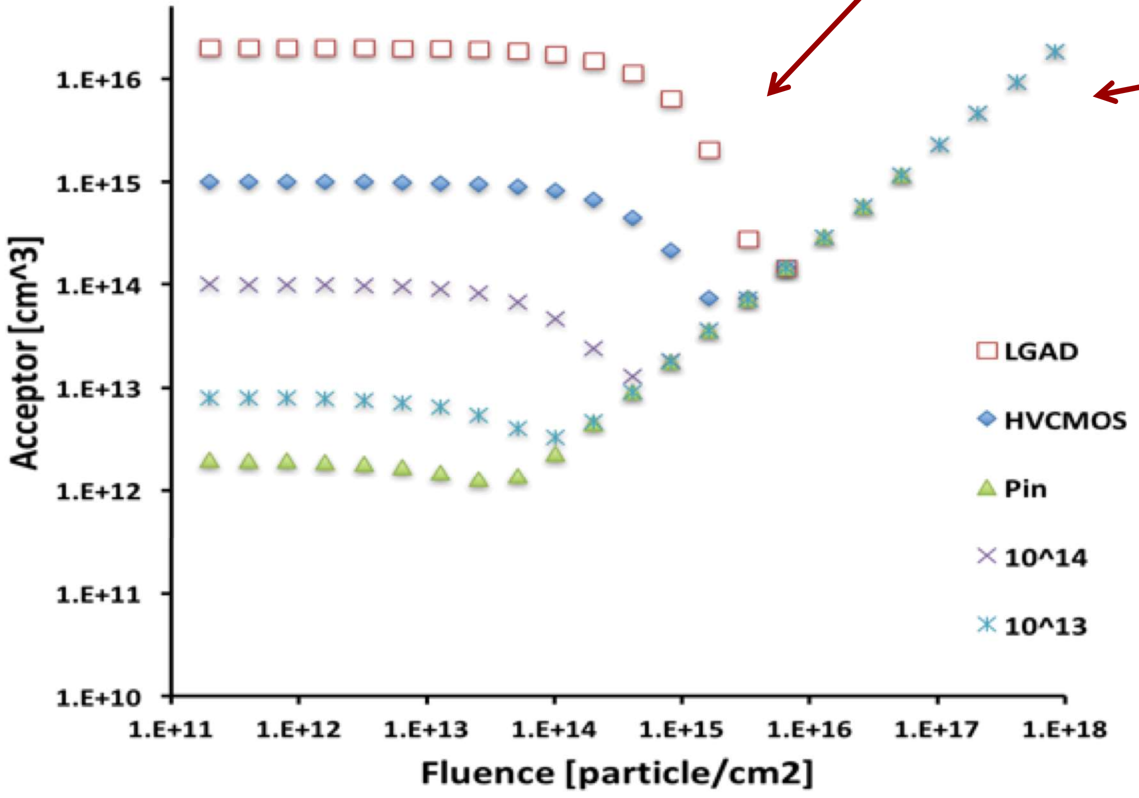
Instead of being "substitutional" (i.e. in the place of a Silicon atom) **is "interstitial"** (i.e. In the middle of the lattice, not electrically active)

Initial acceptor (Boron) removal

Density of the boron doping vs irradiation:

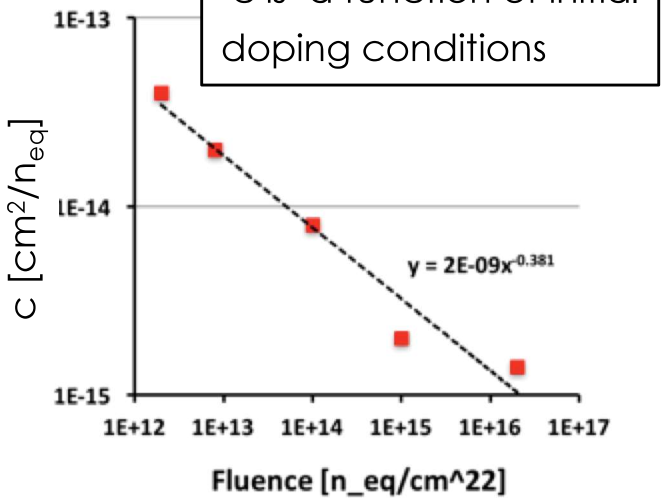
$$N_D = N_0 e^{-c\phi} + \beta\phi$$

Initial acceptor removal

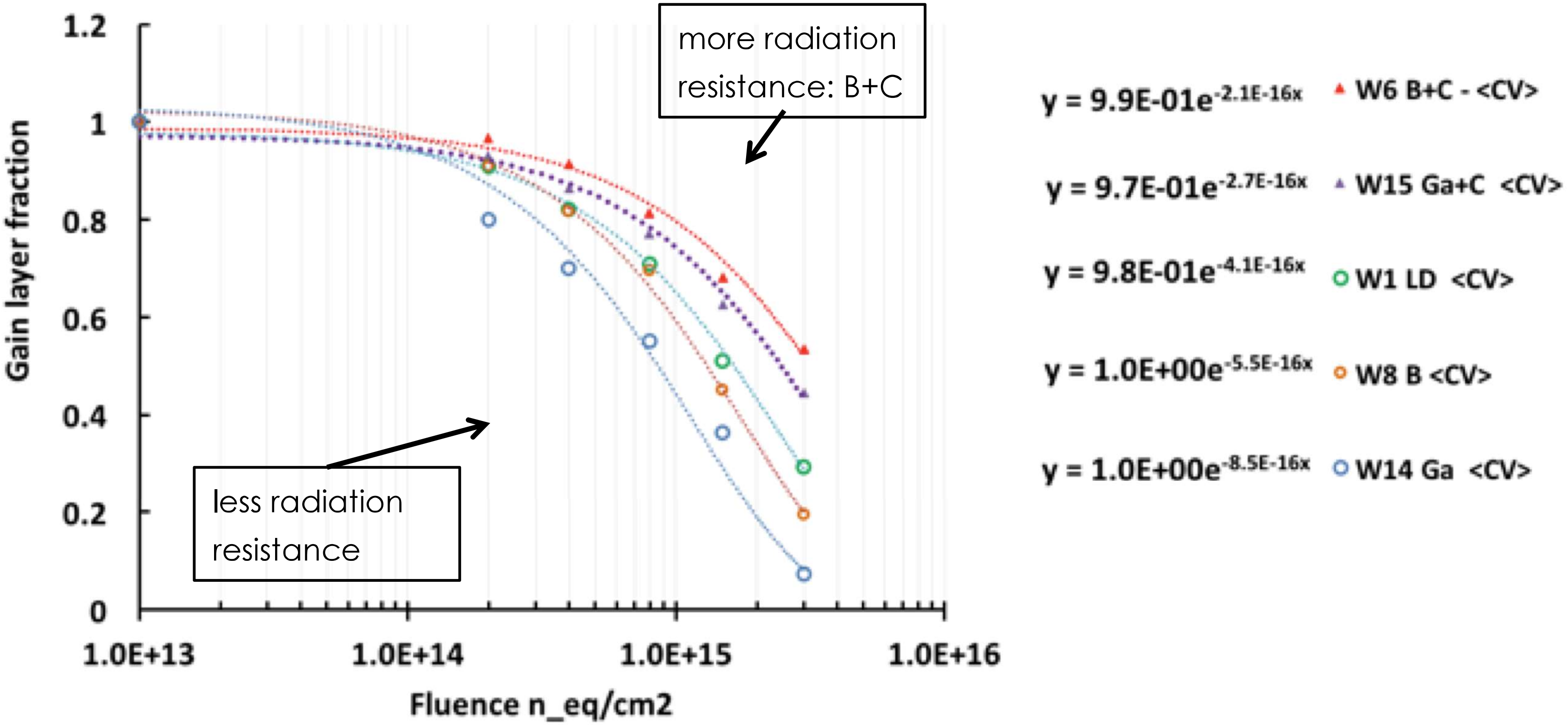


Deep level creation
p-doping lookalike

c is a function of initial
doping conditions



Study of radiation resistance



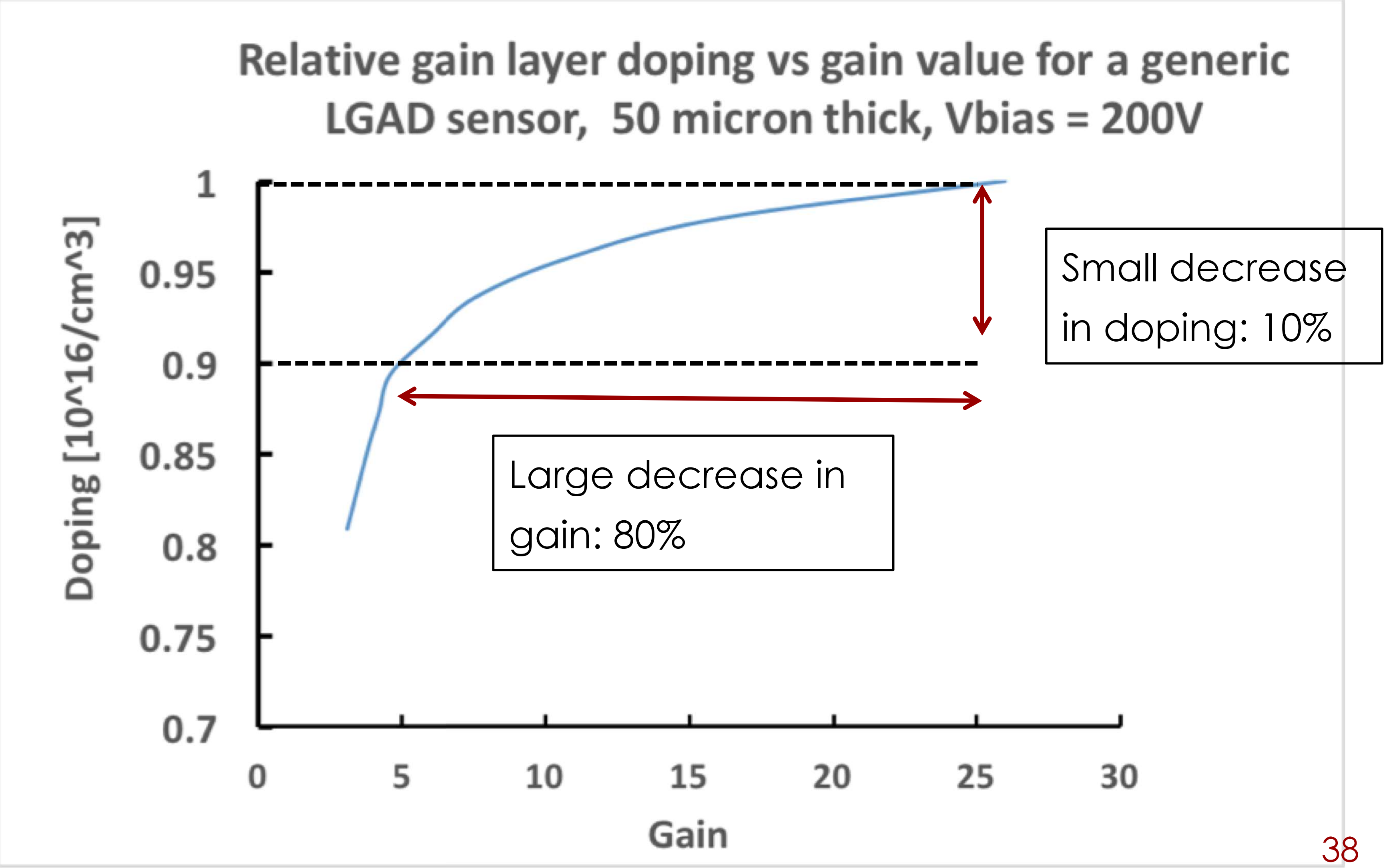
more radiation resistance: B+C

less radiation resistance

1) Gallium is actually is not more rad-hard than Boron
2) Carbon addition works really well, increasing by a factor of 2-3 the radiation hardness

Gain vs gain layer doping

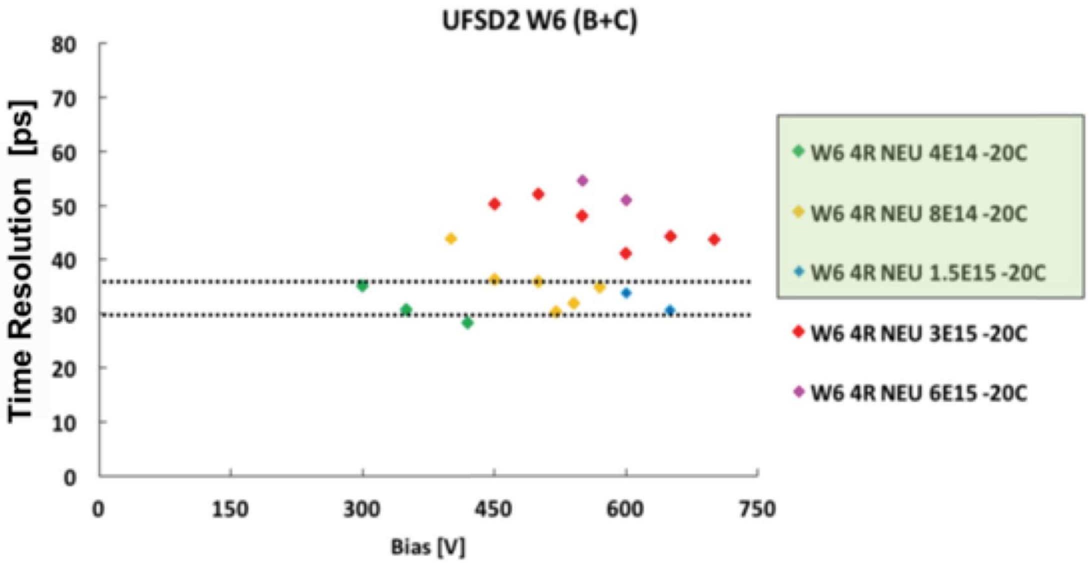
Unfortunately, the gain is very sensitive to the doping level

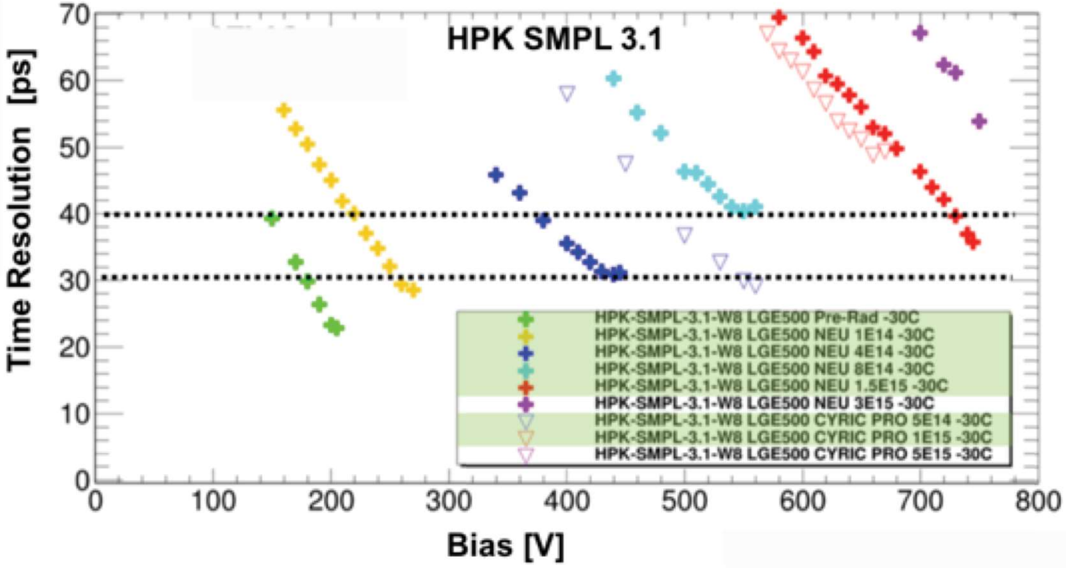


Small decrease in doping: 10%

Large decrease in gain: 80%

FBK and Hamamatsu time resolution





(3) Noise in irradiated sensors

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

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

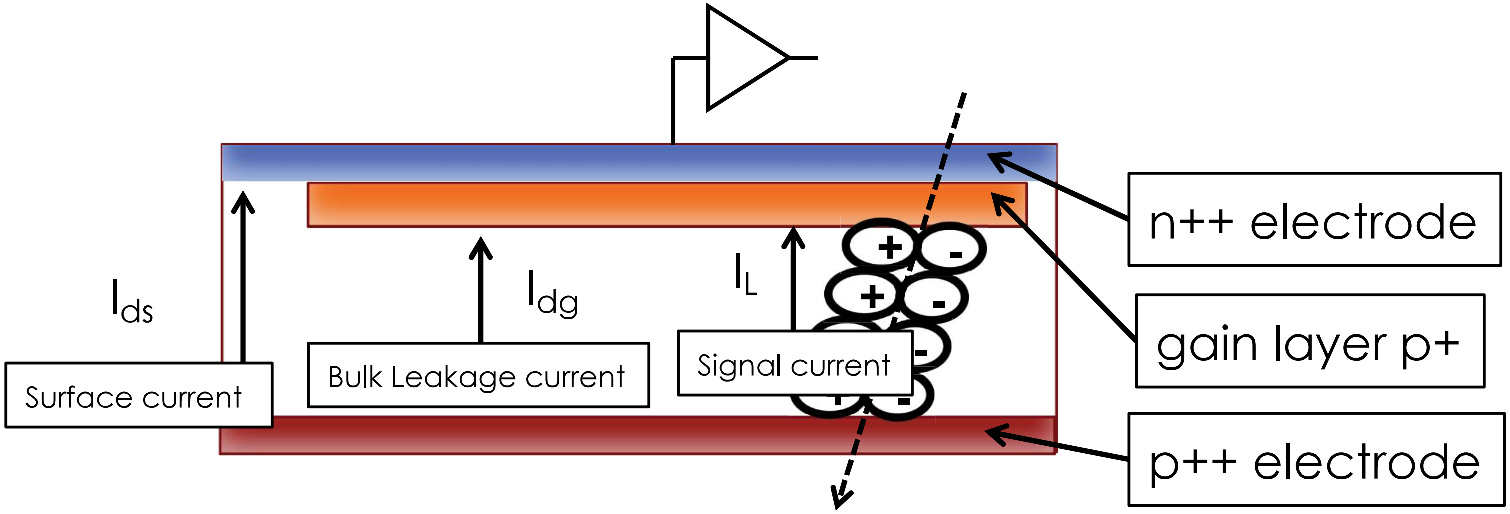
The jitter term contains electronic noise and Current noise:

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

Current noise: noise due to the combination of

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

Current noise in UFSD



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

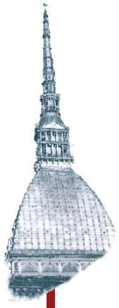
Excess noise factor:
Correction factor to the standard Shot noise,
due to the noise of the multiplication mechanism

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

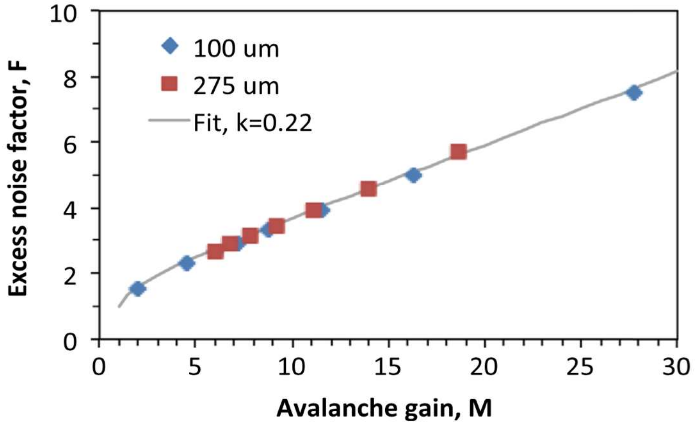
$$F \sim M^x$$

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



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

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

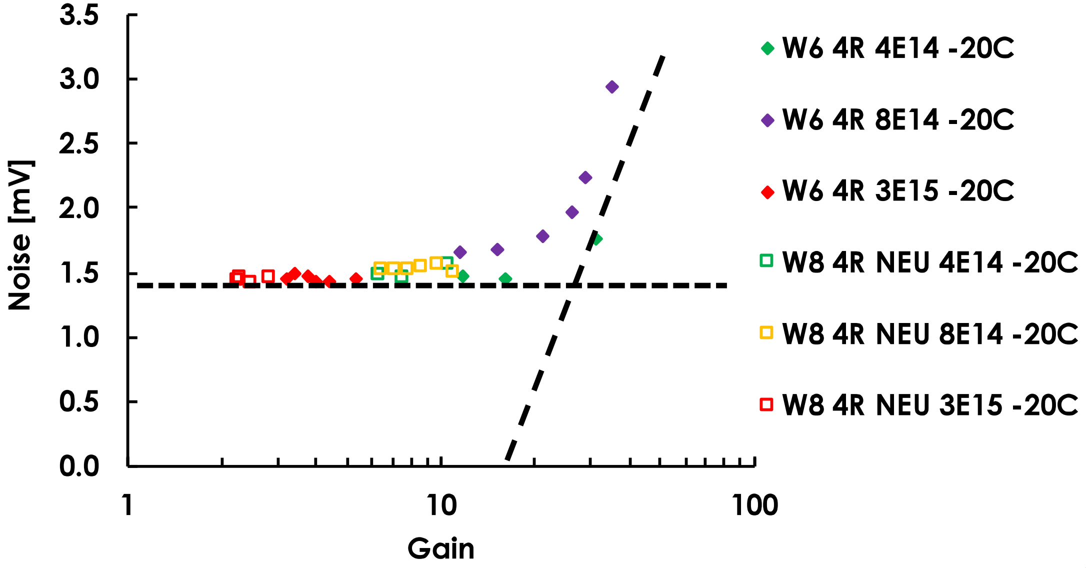
k = e/h ionization rate

x = excess noise index

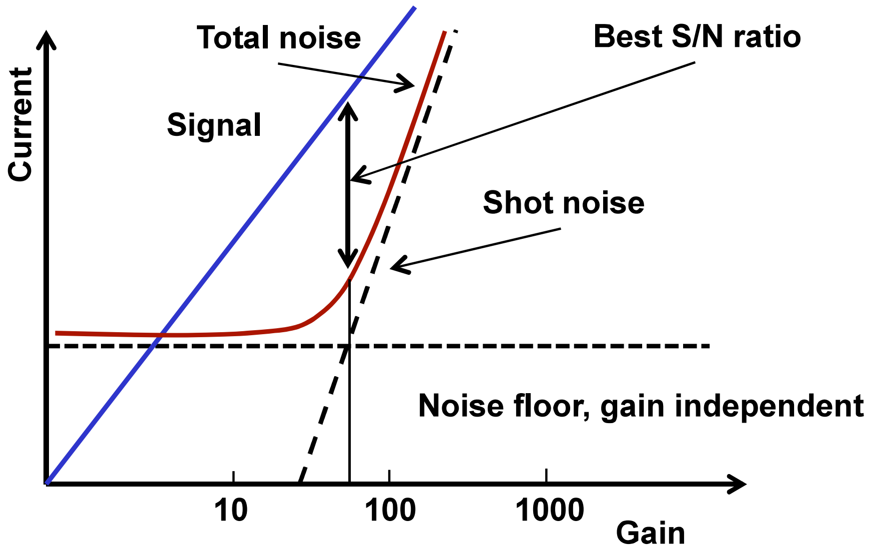
M = gain

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

Noise increase as a function of fluence and gain

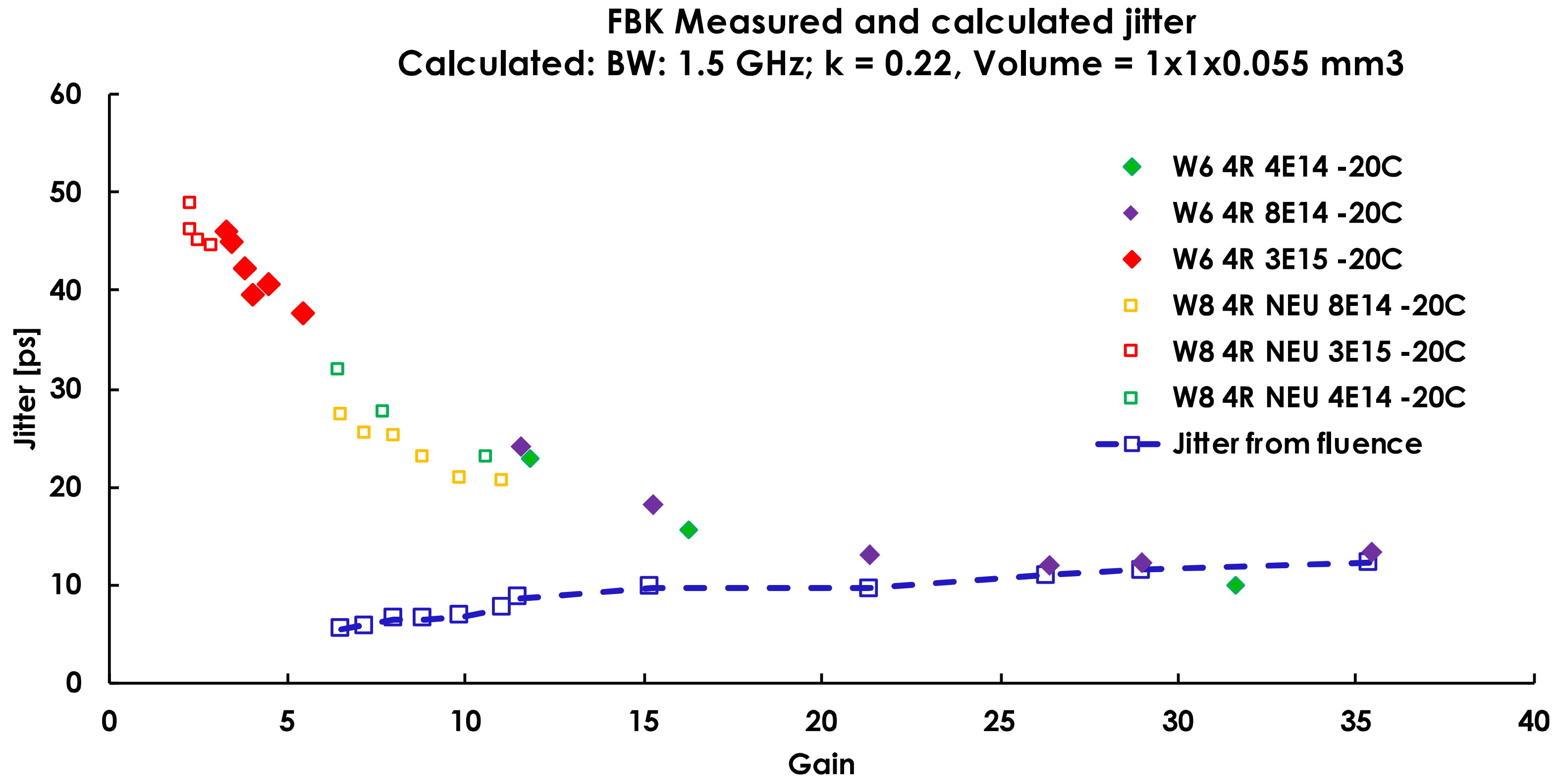


Data and model look similar.

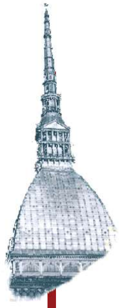


Goal: the noise from Silicon current should stay below that of the electronics

Current noise and Jitter



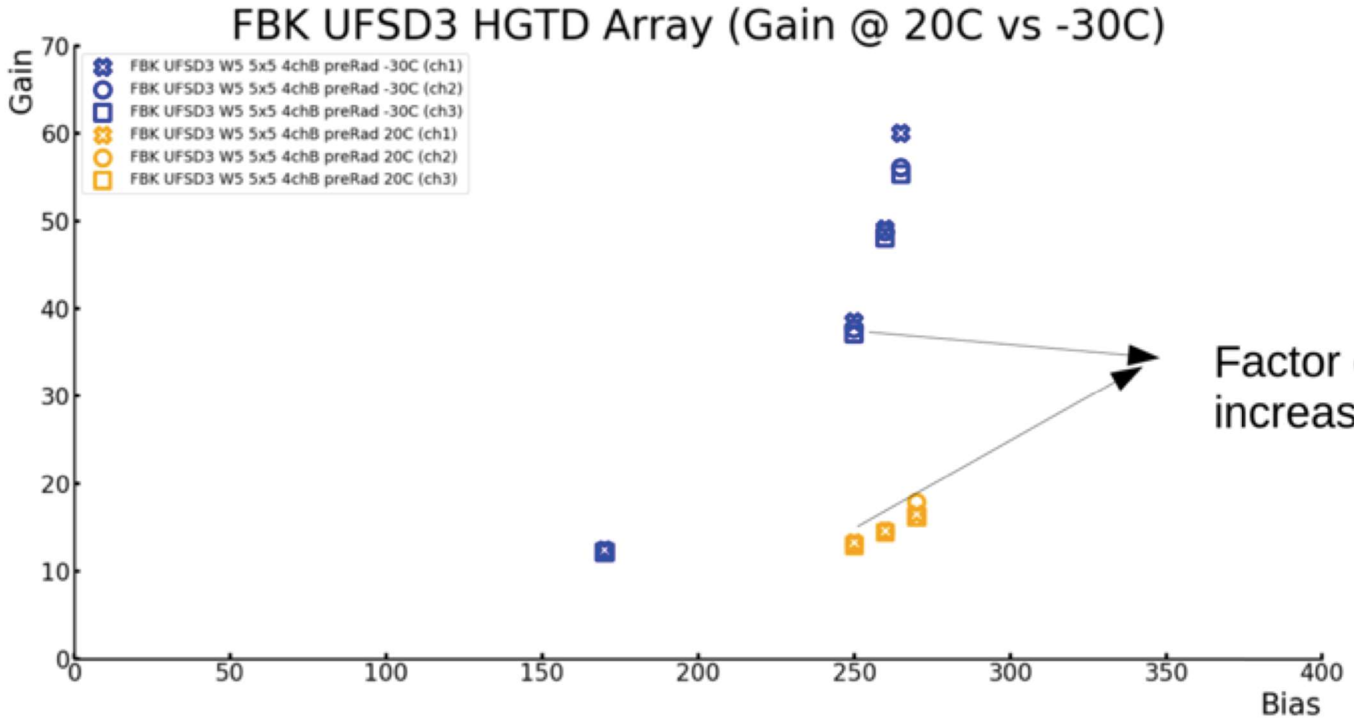
The Jitter, instead of decreasing, is becoming constant due to the contribution of the current noise.



Effect of Temperature: excellent

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

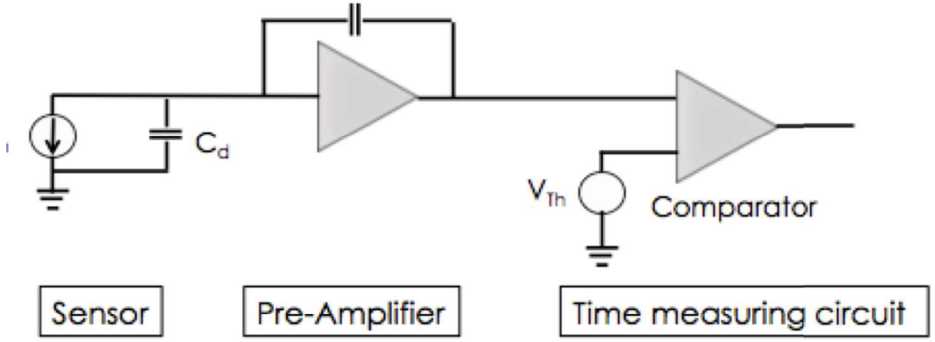
- More gain due to longer mean path between collisions
- Less noise, the leakage current is lower (a factor of 2 every 7 C



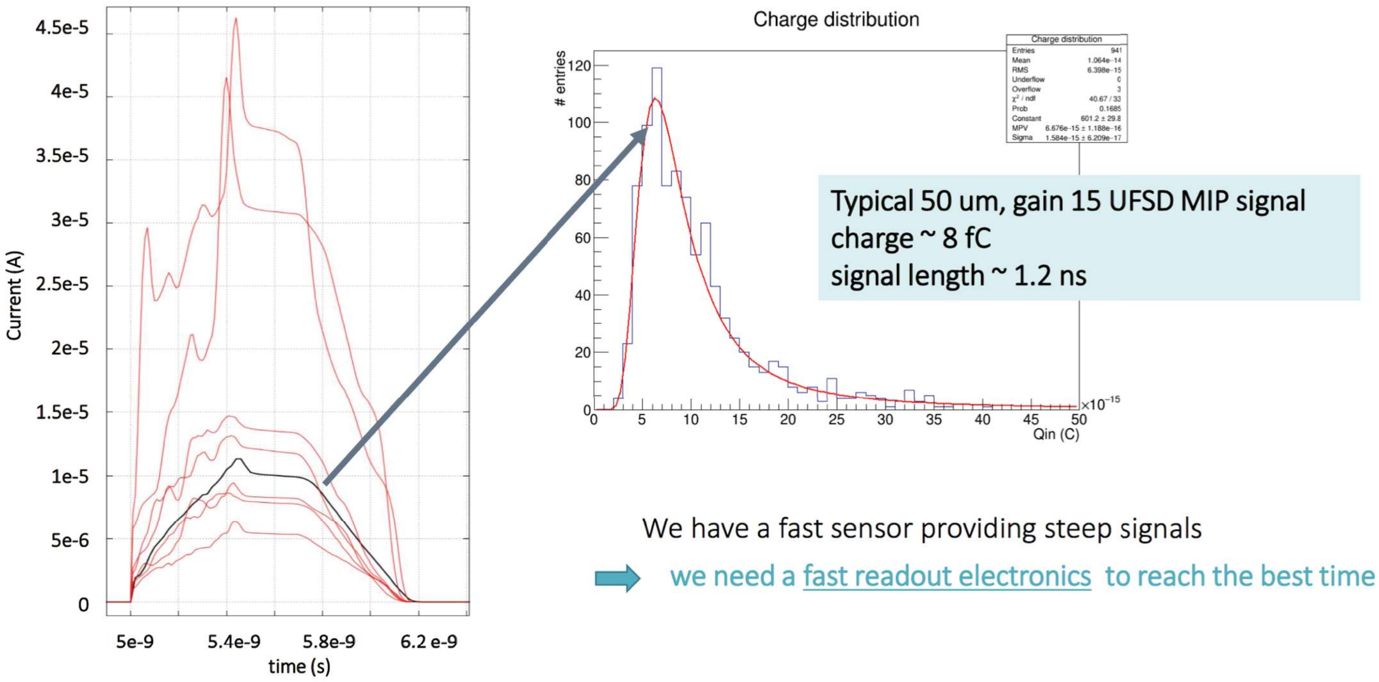
Factor of ~ 3 to 4 increase in gain

Electronics

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



50 um UFSD signals

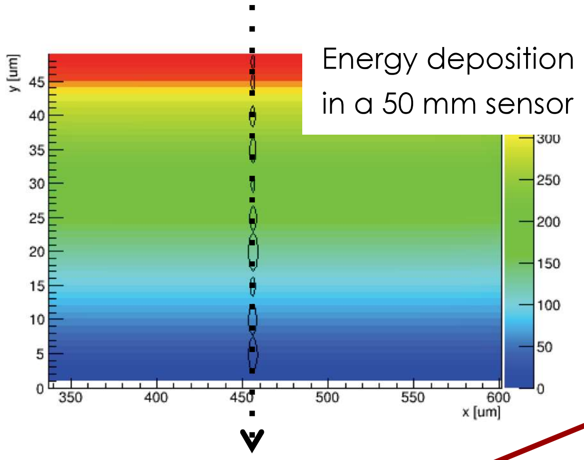


Typical 50 um, gain 15 UFSD MIP signal
charge ~ 8 fC
signal length ~ 1.2 ns

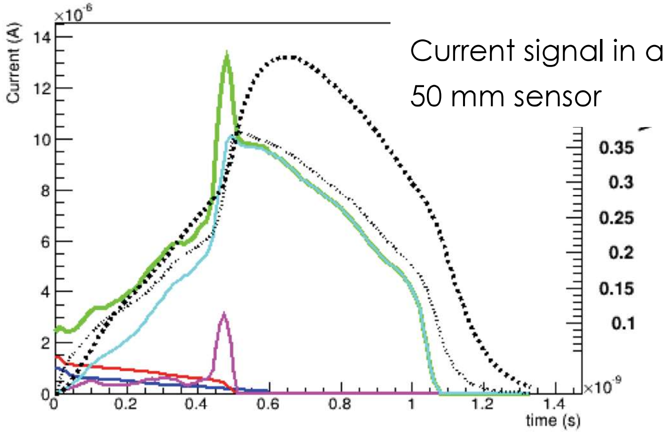
We have a fast sensor providing steep signals

➡ we need a fast readout electronics to reach the best time re

Electronics: What is the best pre-amp choice?

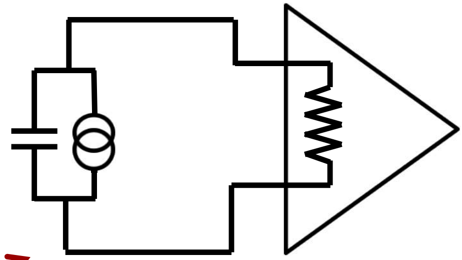


Energy deposition in a 50 mm sensor



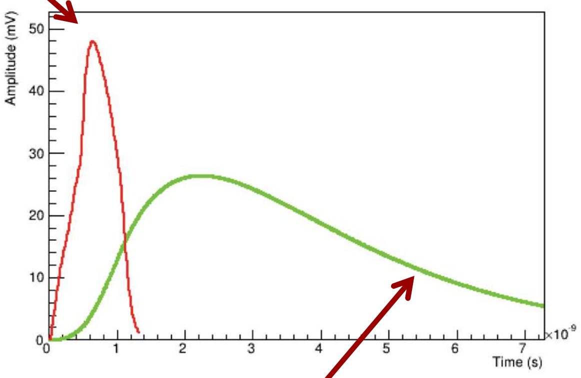
Current signal in a 50 mm sensor

Current Amplifier

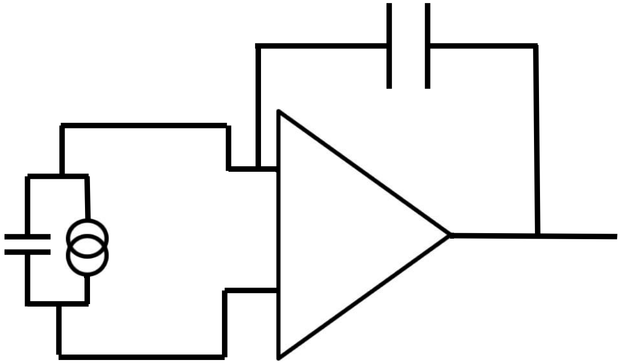


- Fast slew rate
- Higher noise
- Sensitive to Landau bumps

CSA (green) and Current Amplifier (red)

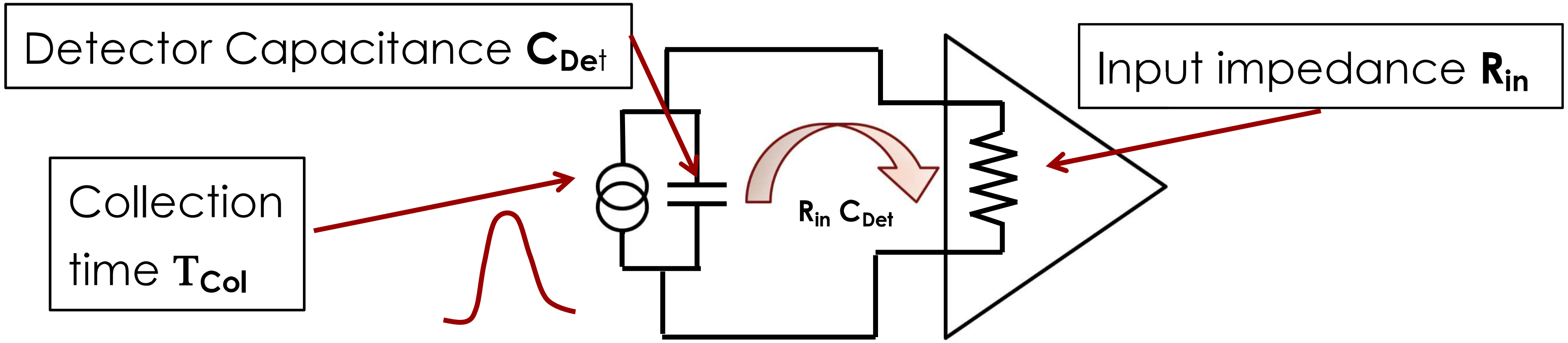


Charge Sensitive Amplifier



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

Interplay of T_{Col} and $\tau = R_{in} C_{Det}$



Detector Capacitance C_{Det}

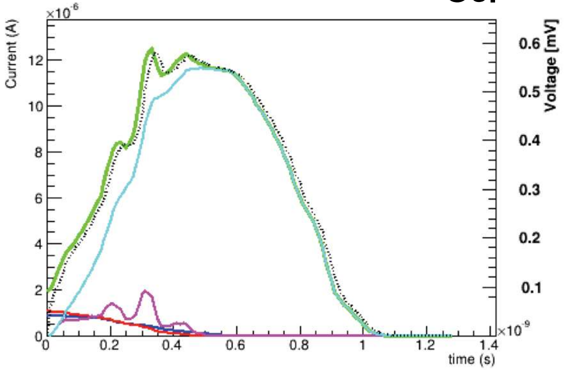
Collection time T_{Col}

Input impedance R_{in}

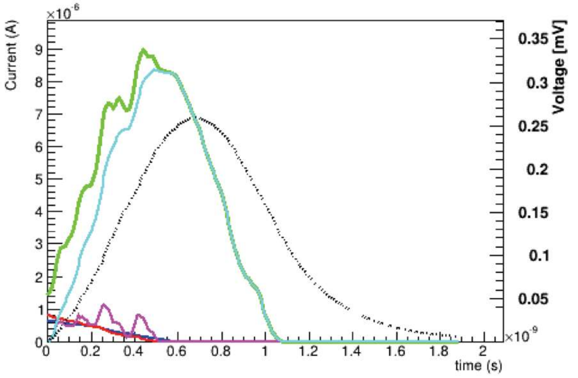
There are two time constants at play:

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

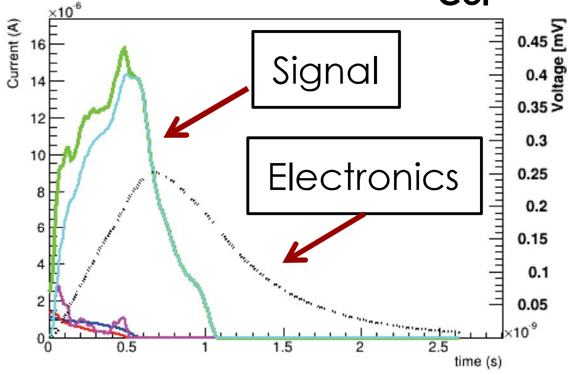
$\tau < T_{Col}$



$\tau \sim T_{Col}$



$\tau > T_{Col}$



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

➔ Smoother current

Need to find the optimum balance

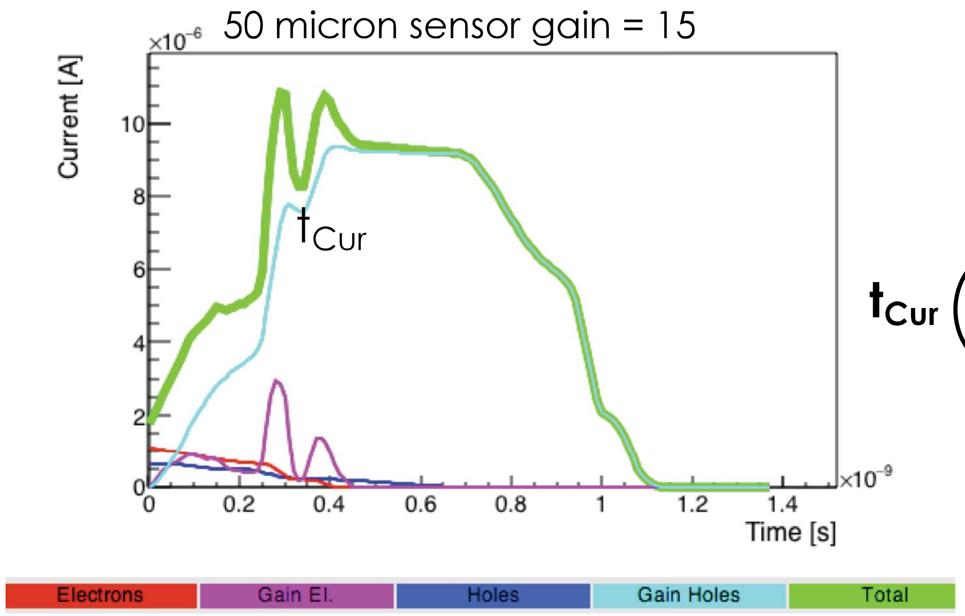
The players: signal, noise and slope

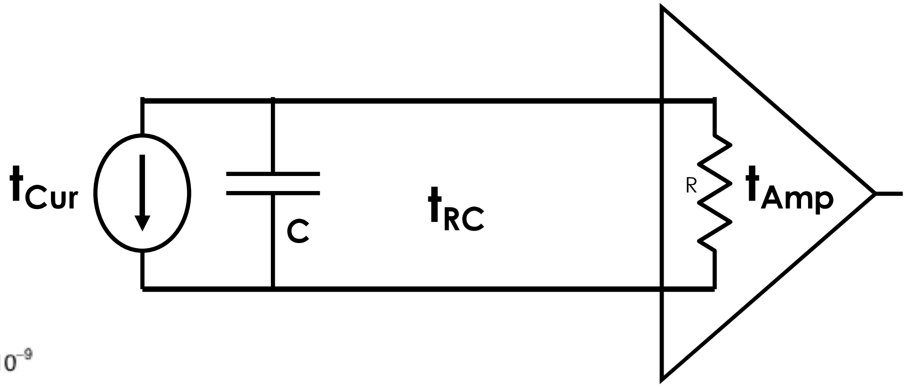
Signal dV/dt

Landau Noise

Shot Noise

Electronic Noise





The current rise time (t_{Cur})

The RC circuit (t_{RC})

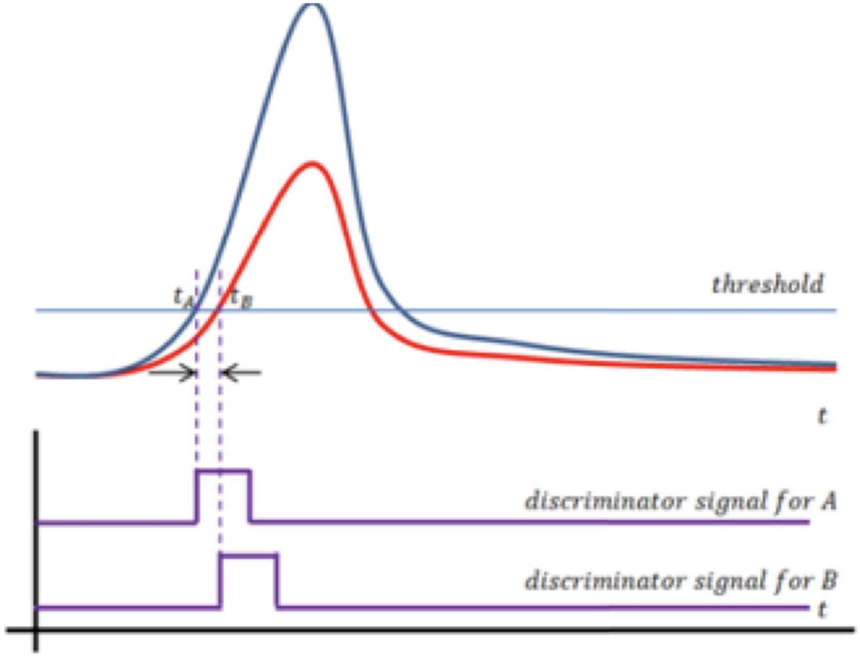
Amplifier rise time (t_{Amp})

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})

Time walk

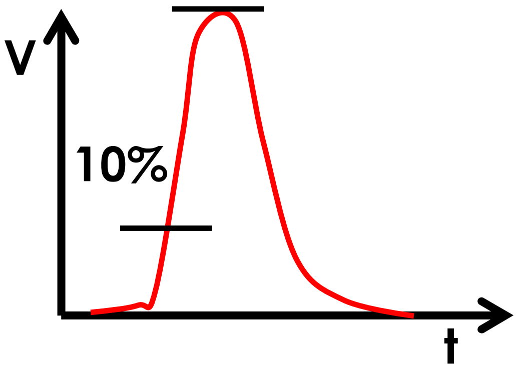
Time walk: the voltage value V_{th} is reached at different times by signals of different amplitude



Time walk effect

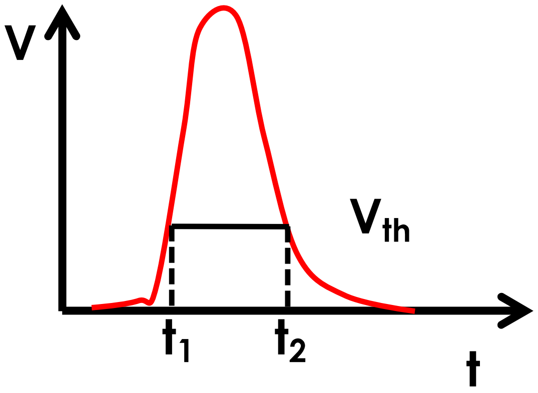
In order to correct for this effect we need to measure the signal amplitude

After the preamp: What is the best “time measuring” circuit?



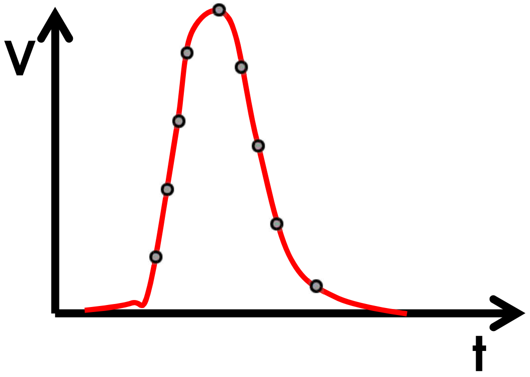
Constant Fraction Discriminator

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



Time over Threshold

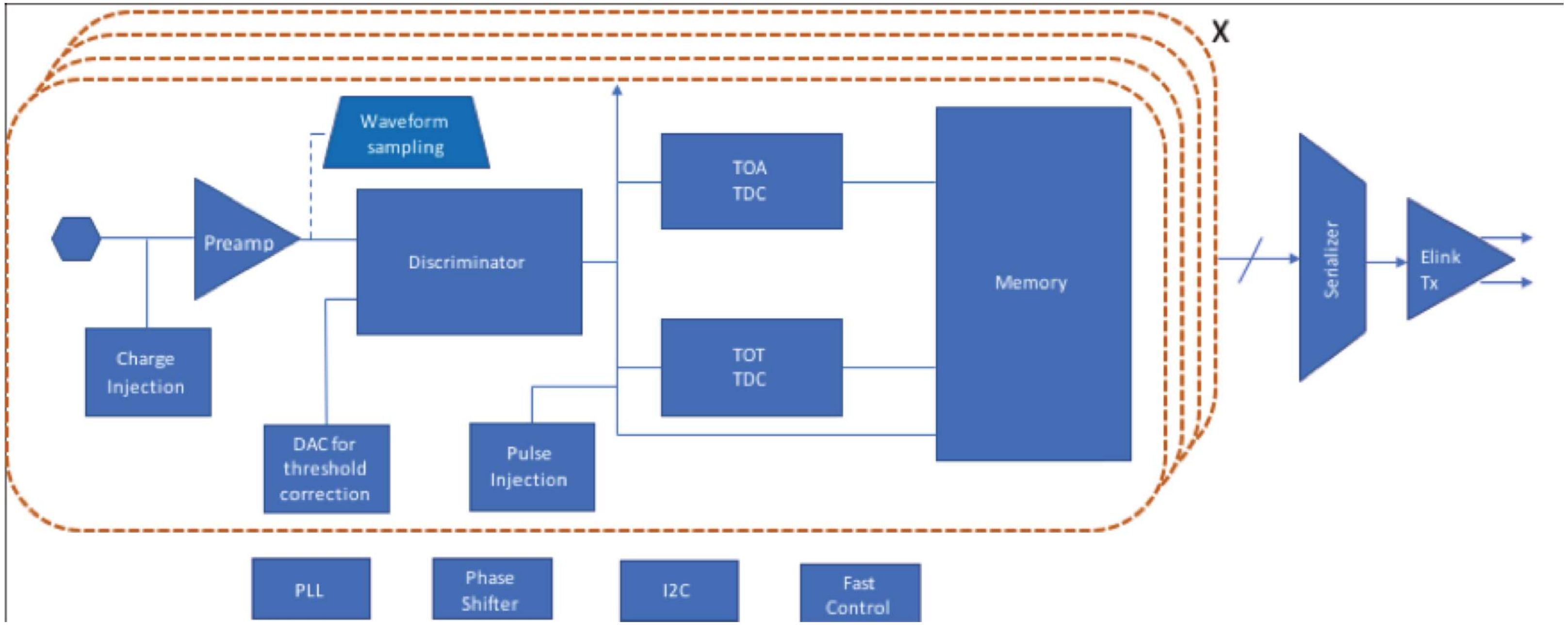
The amount of time over the threshold is used to correct for time walk



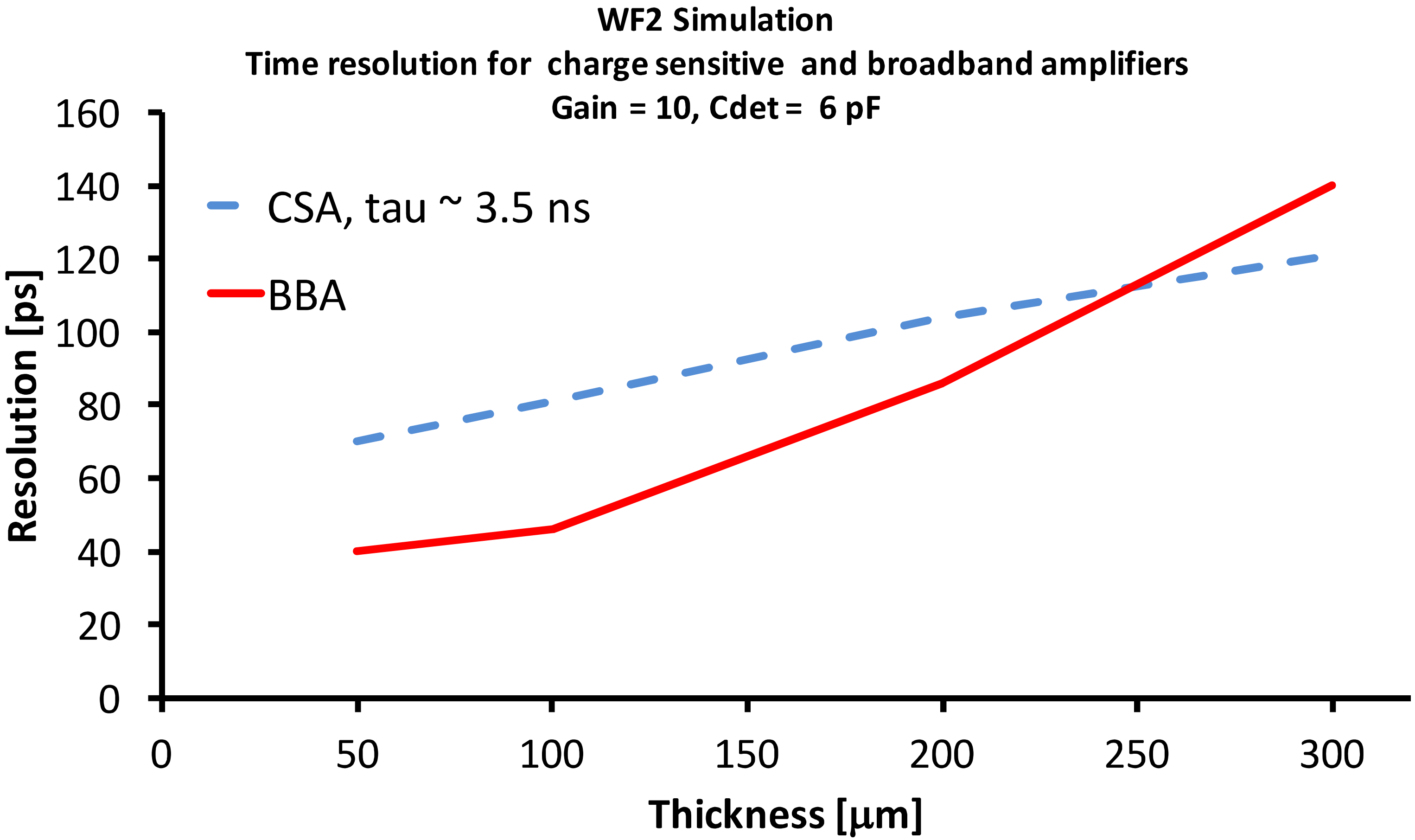
Multiple sampling

Most accurate method, needs a lot of computing power.

A complete chip



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

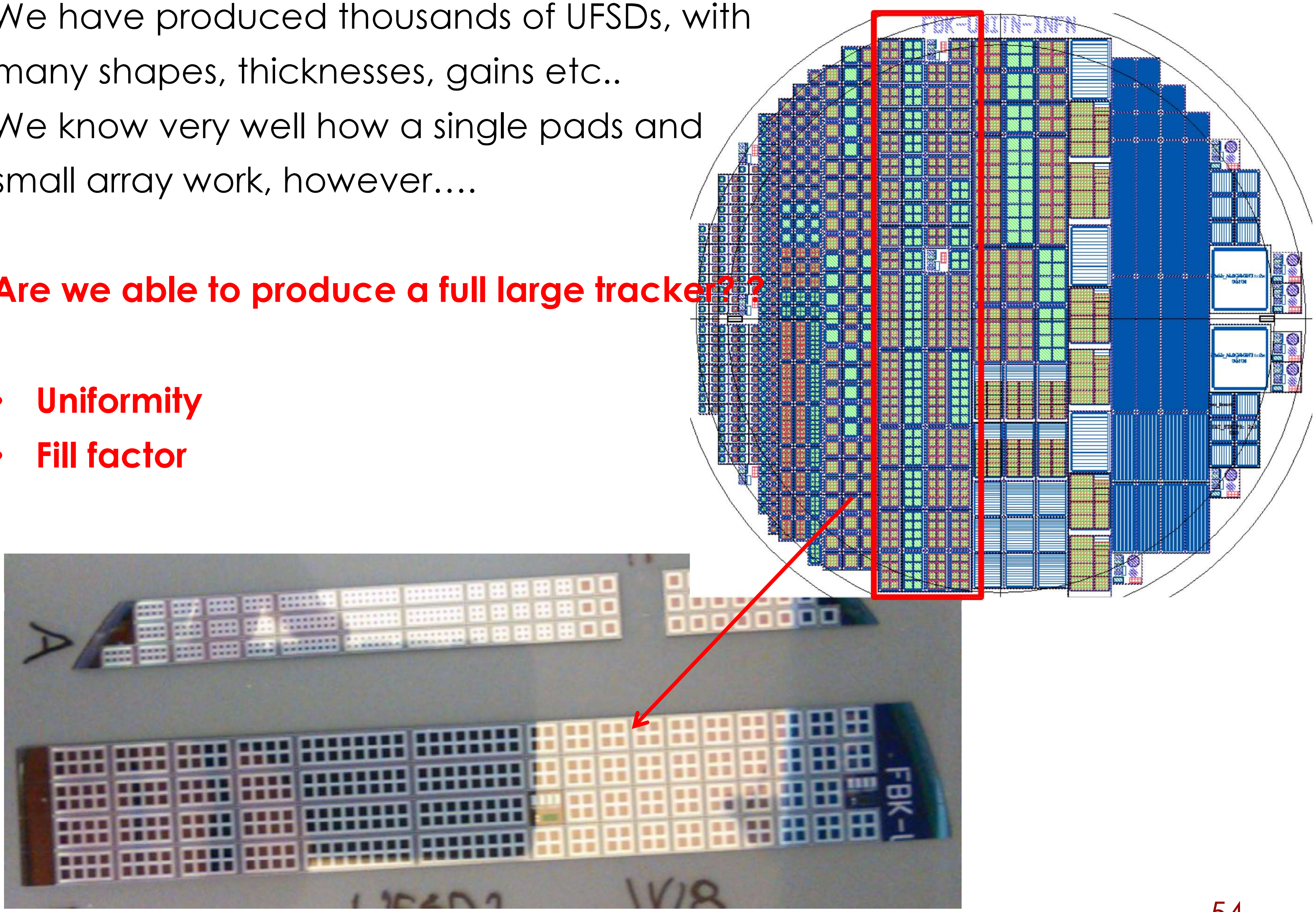
From one pad to a Timing Layer

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? ?

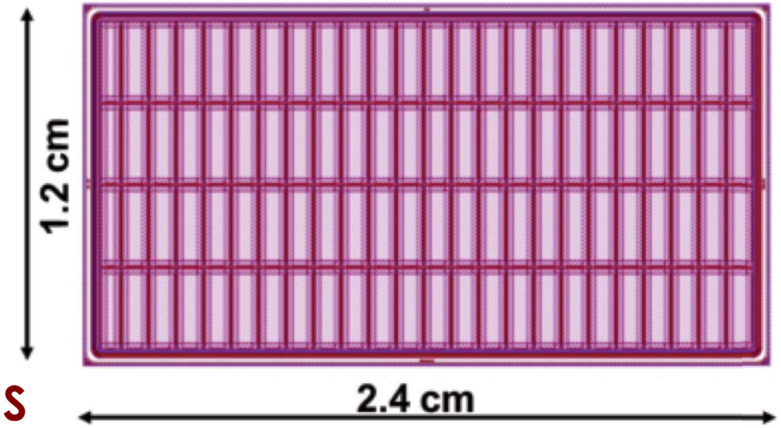
- **Uniformity**
- **Fill factor**



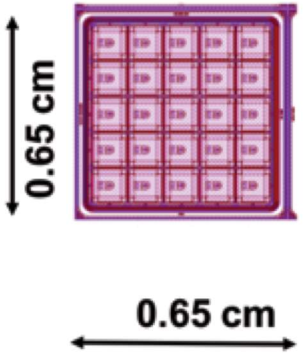
ATLAS-CMS path to construction

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

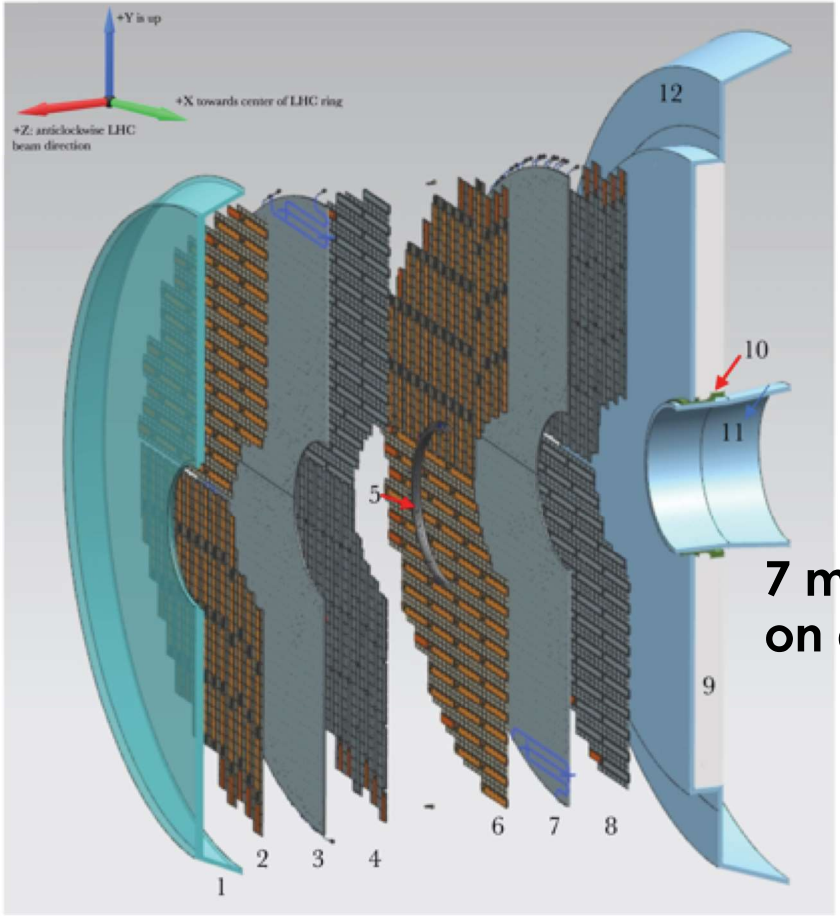


CMS



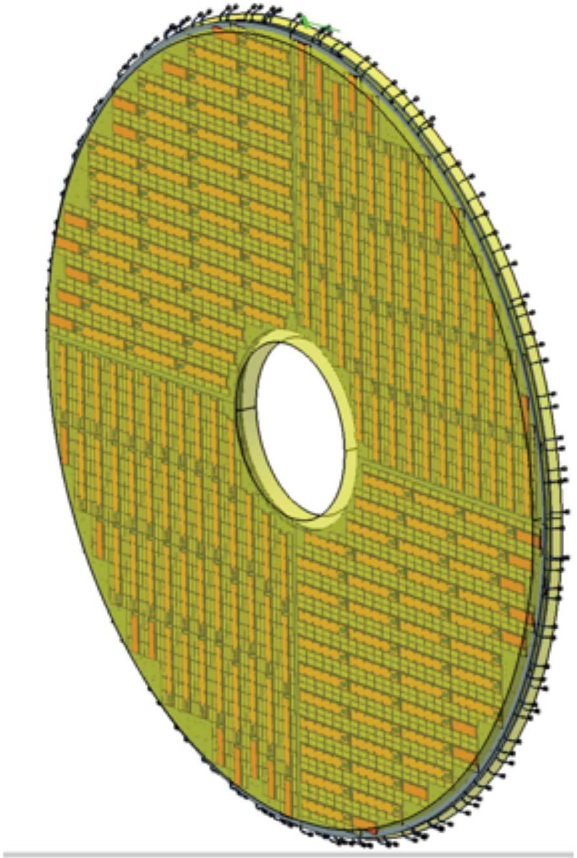
ATLAS

ETL: Endcap Timing Layer



1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

7 m^2 of sensors on each side



A circle obtained with long staves

~ 16000 sensors:

- 2x4 cm^2 --- small sensors
- Thickness of active area: 40-50 microns
- Pad size: 1.3 x 1.3 mm^2 (512 pads)

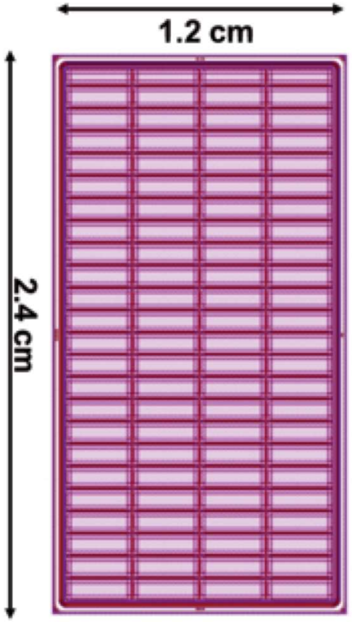
Wafer uniformity and sensor yield

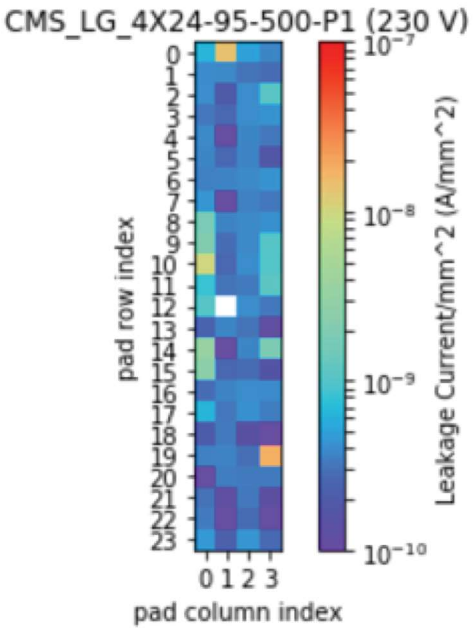
Overall, very good uniformity and yield from HPK and FBK.

This is great news in view the production for CMS and ATLAS

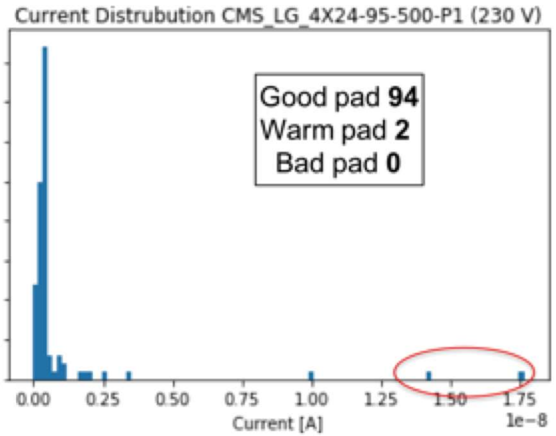
Table 3.4: Summary of the uniformity studies on the latest sensor productions.

Foundries	Sensor type	# Sensor tested	# Warm pads	# Hot pads	Comments
FBK	4x24 pads	152	14 (0.1%)	0	bias = 100V
FBK	5x5 pads	23	4 (0.7%)	0	bias = 300V
HPK	4x24	15	20 (1.3%)	0	bias = 250V



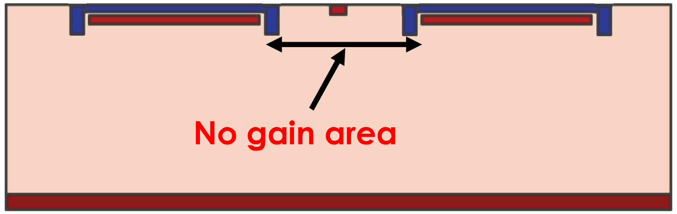


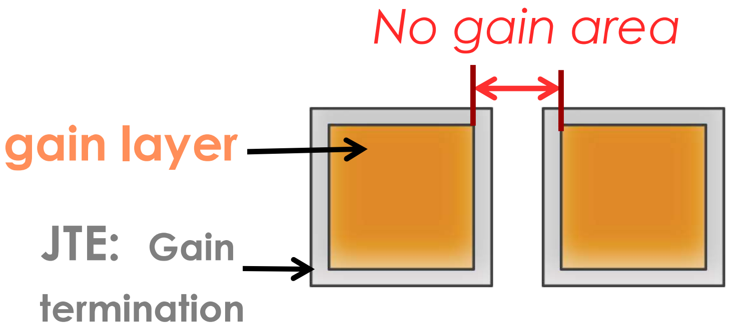
BD Voltage ~ 240/250 V



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

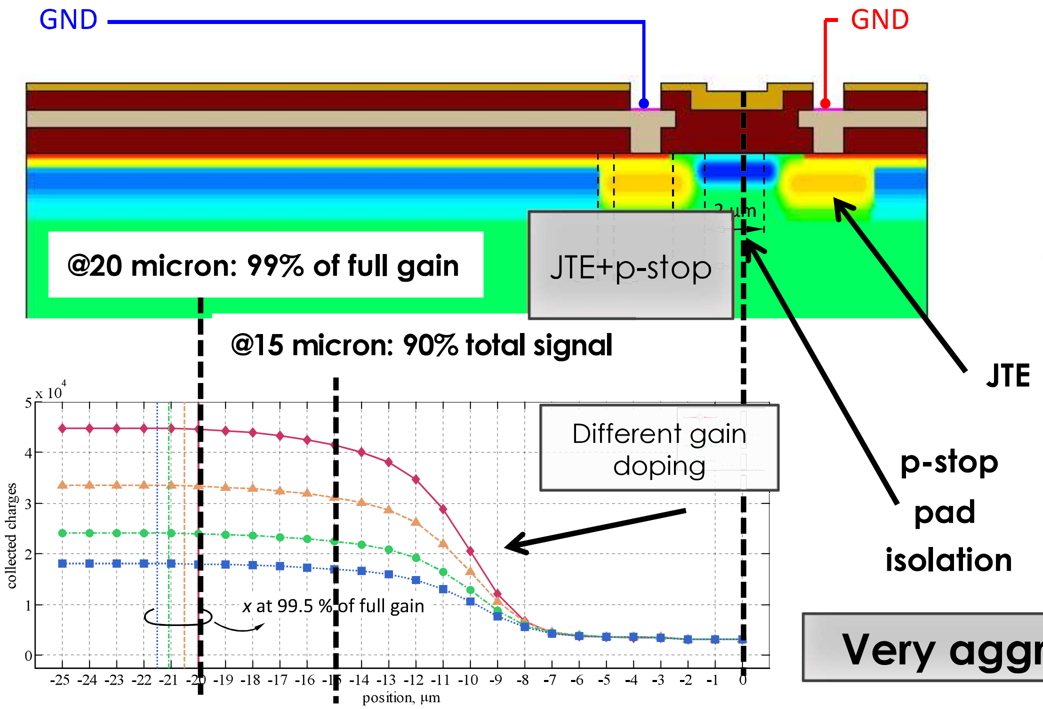
The gap is due to **two components**:

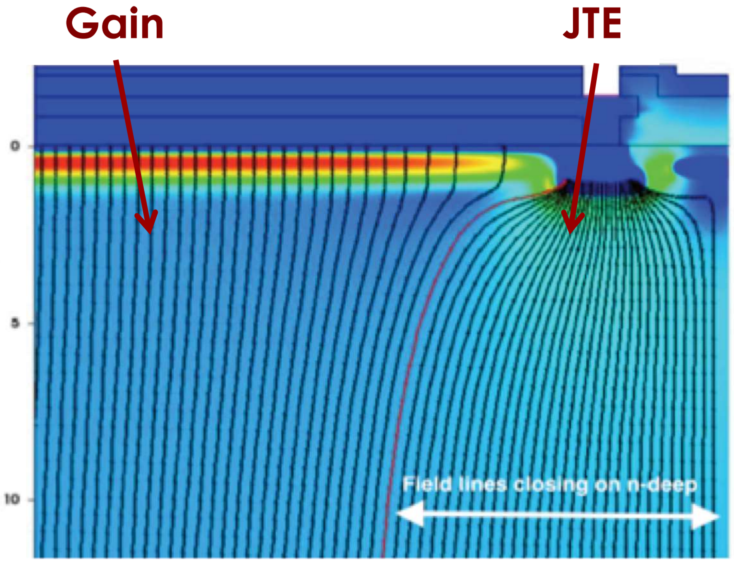
1) Adjacent gain layers need to be isolated (**JTE & p-stop**)

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**

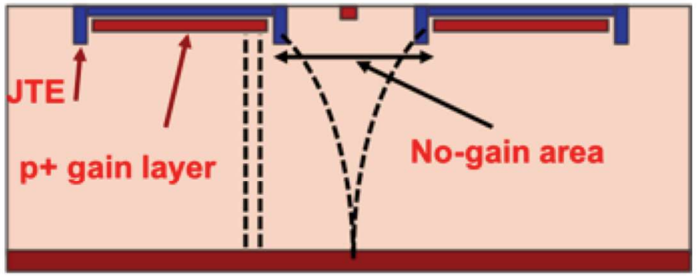


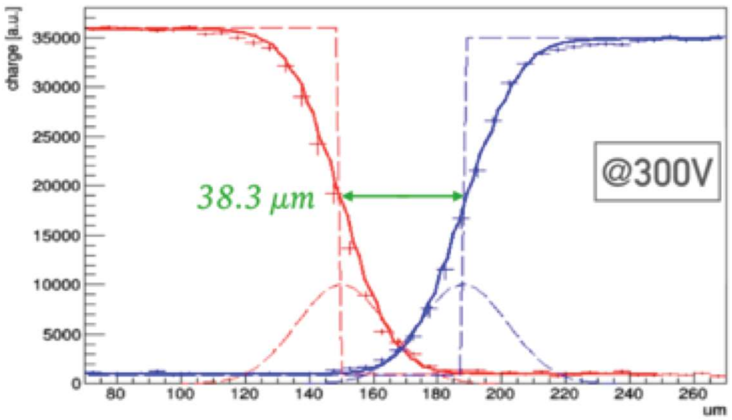


Very aggressive design: <10 micron per side

Fill factor in CMS: higher than 85%

Foundries	No-gain distance [μm]	Comments
CNM	100	The latest production with smaller distances has very high leakage current and cannot be used. A new production is expected in August 2019
FBK	40, 70	In the latest production much smaller distances were attempted but the sensors go into early breakdown. A dedicated new production is expected in April 2019.
HPK	75, 90, 135	Even the shortest separation works well, most likely HPK can obtain even smaller distances.



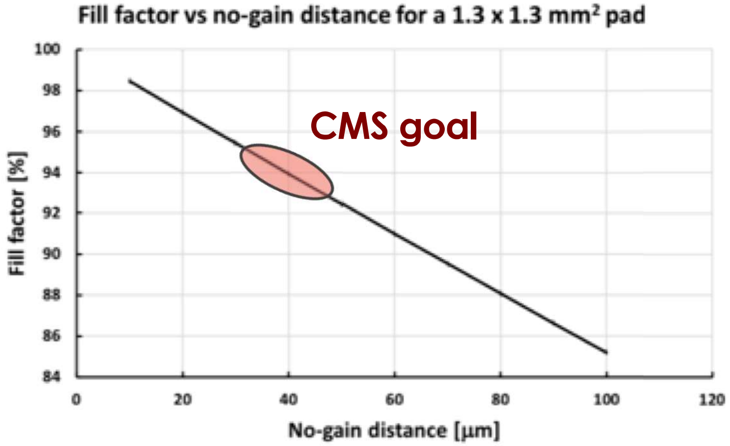


Our TDR stated goal is to have a fill factor of 85% per layer (1.3 x 1.3 mm² pad)

- 5% comes from the sensors placements
- 2-3 % dead area comes from the butting of sensors in the module
- 7-8% comes from the no-gain area

➔ **Keep no-gain distance below 40-50 um**

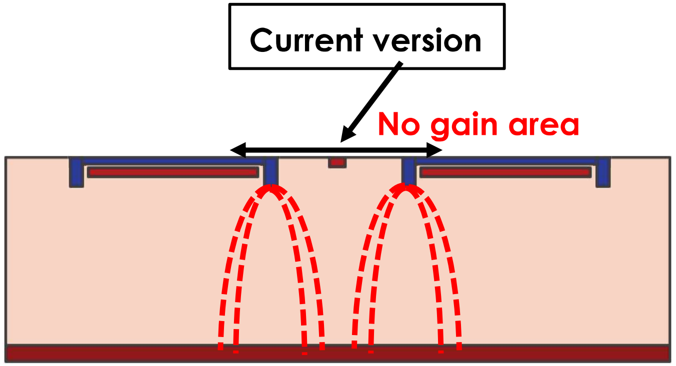
Not achieved yet



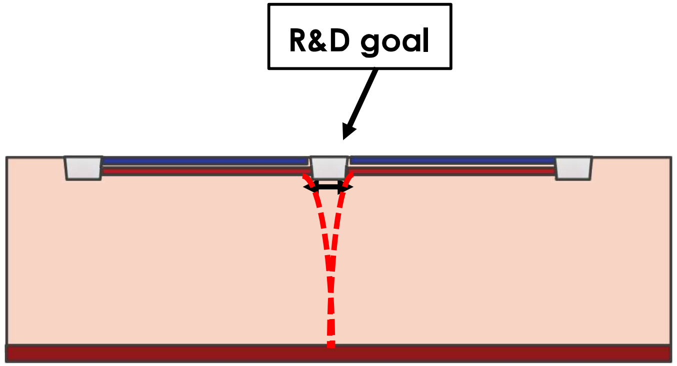
Fill factor solution: trenches

Trenches (the same technique used in SiPM):

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



JTE + p-stop design

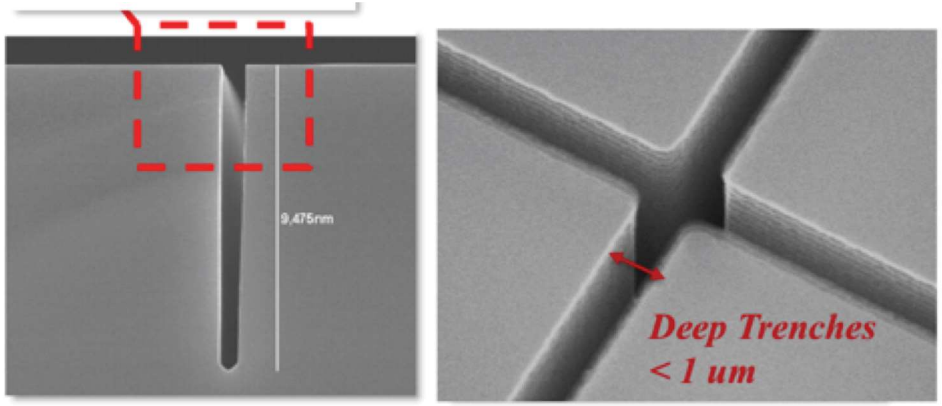


Trench design

Trench isolation technology

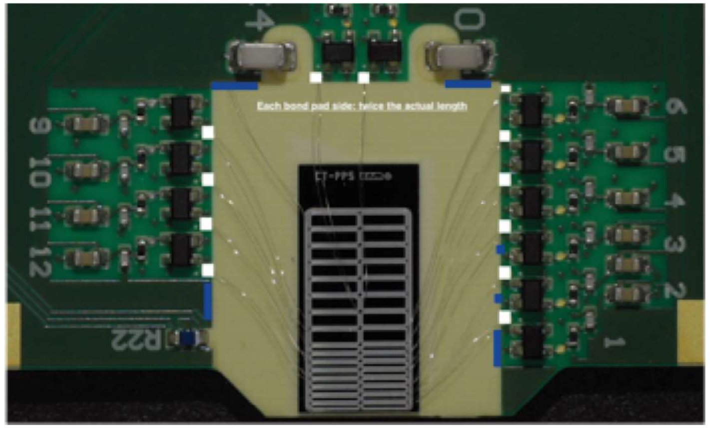
- Typical trench width < 1 um
- Max Aspect ratio: 1:20
- Trench filling with: SiO_2, Si_3N_4, PolySi

CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS



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:

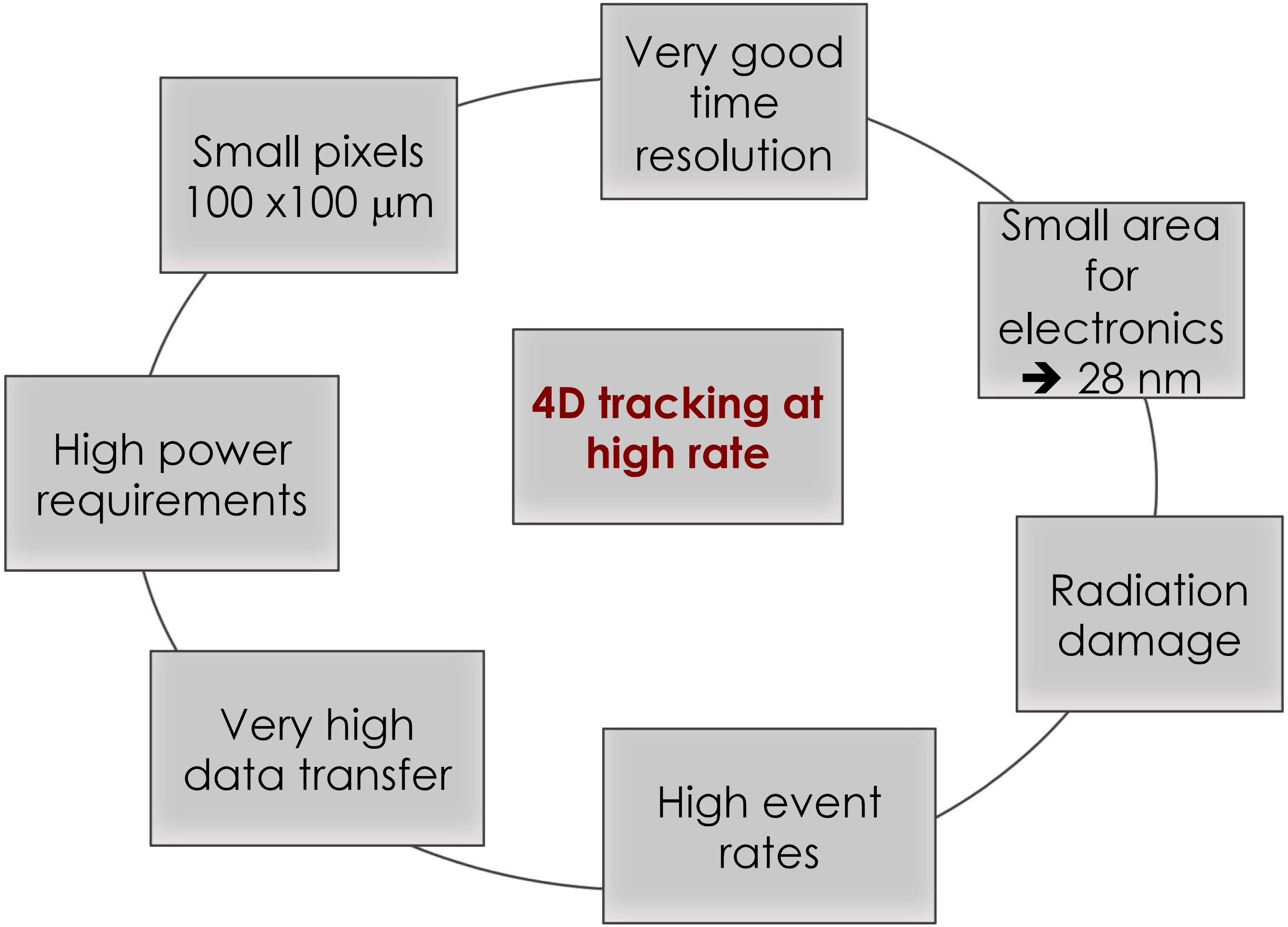
- keep the power consumption low:
  ALTIROC chip for the ATLAS timing layer: 2.5 mW/mm2
  Only 0.5 mA for the front end (< 1 mW), almost impossible
  If used in CMS (sensors ~8 m2 per side) ➔ 20 kW !! Very large

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

From a Timing Layer to a 5D tracker

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

This situation is the pinnacle of complications..



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

4D tracking at high rate

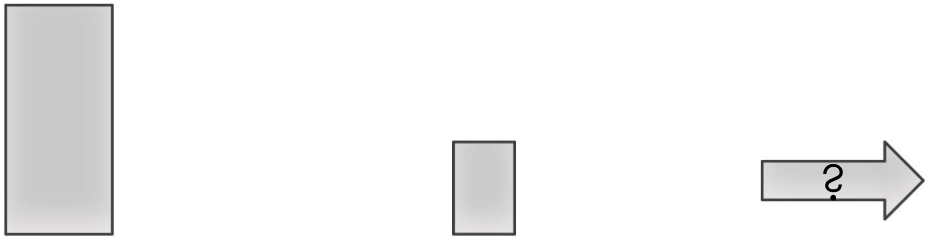
5D tracking: sensors and electronics

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

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:

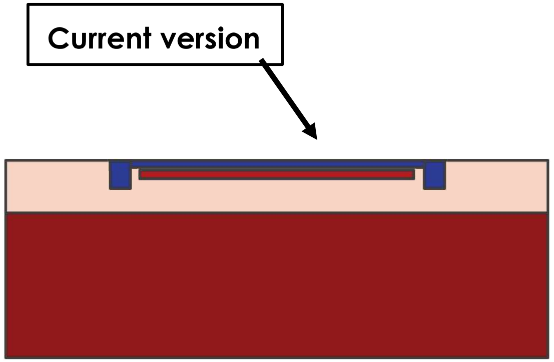
Very fast data transfer

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

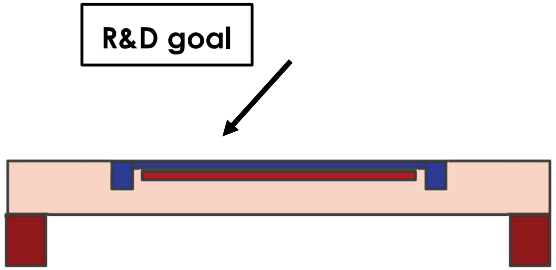
➔ Sometimes called "retina", being pursued by several groups.

R&D in the next 5 years

Reduce material budget:

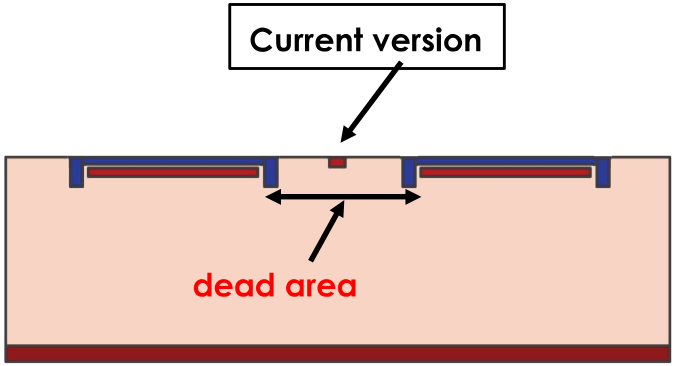


Thin LGAD on a thick support wafer

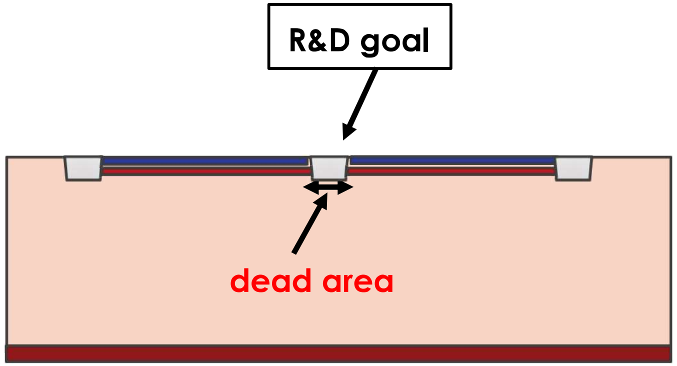


Thin LGAD on ribs

Reduce dead area between pads:



JTE + p-stop design



Trench design

Alternatives Silicon Sensors for timing

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

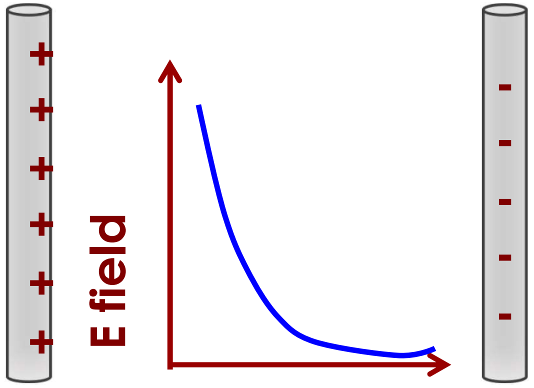
3D sensors for timing applications

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

Can they be used in 4D-tracking?

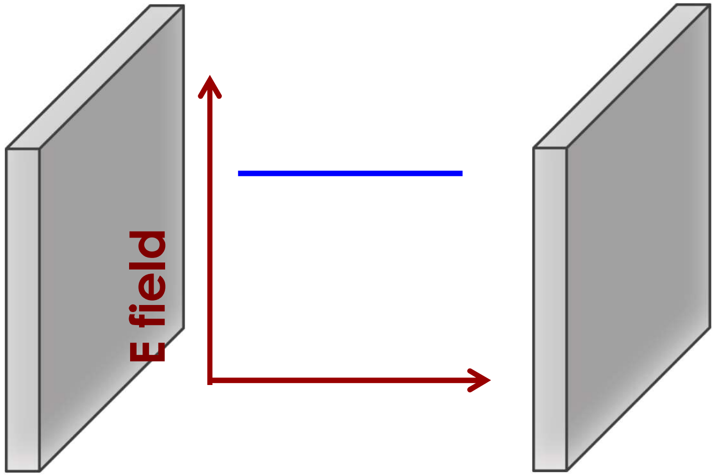
Can diamond 3D work?

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:

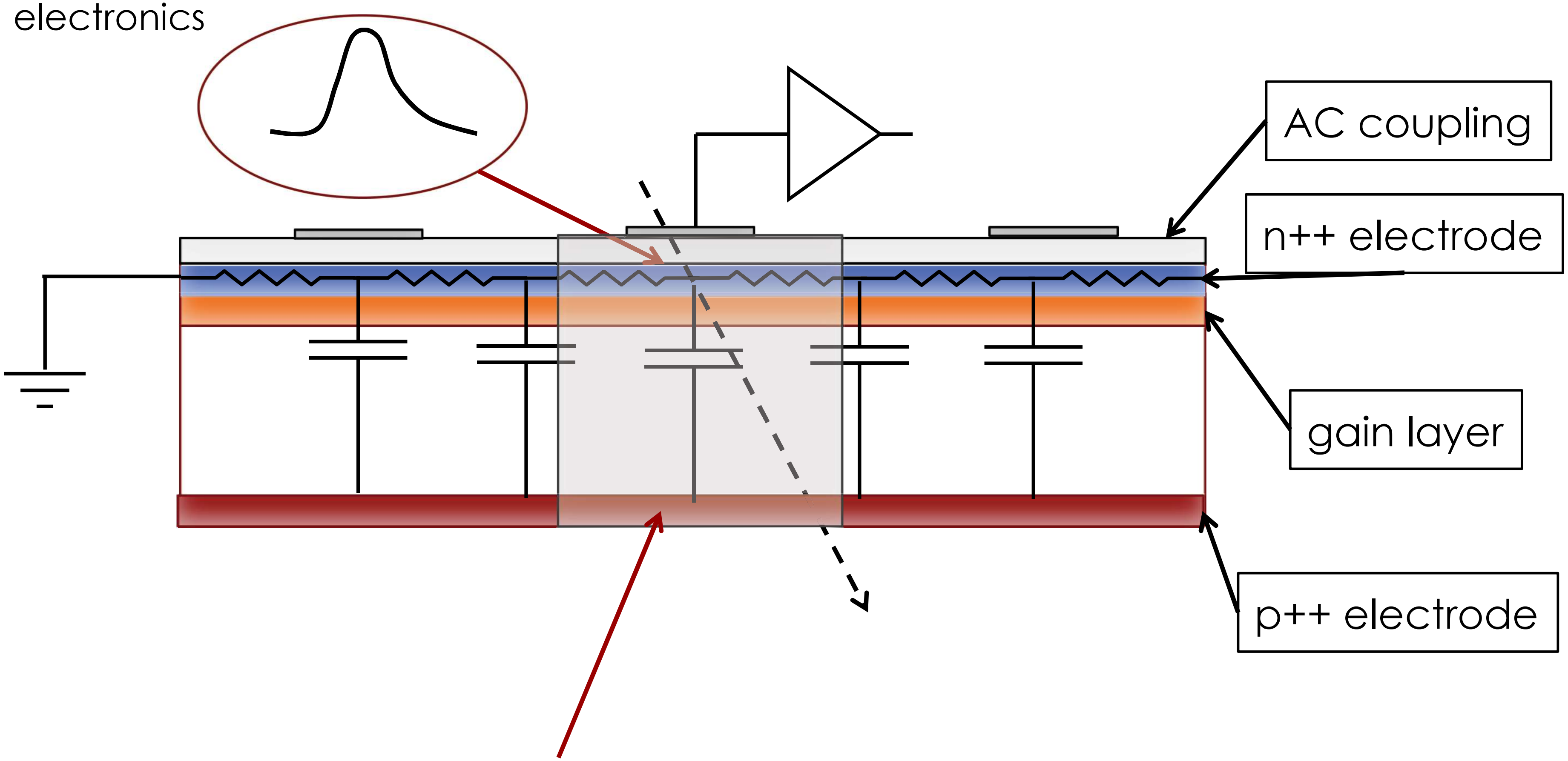
- Position dependent current shape
- Strong signal reduction with irradiation

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

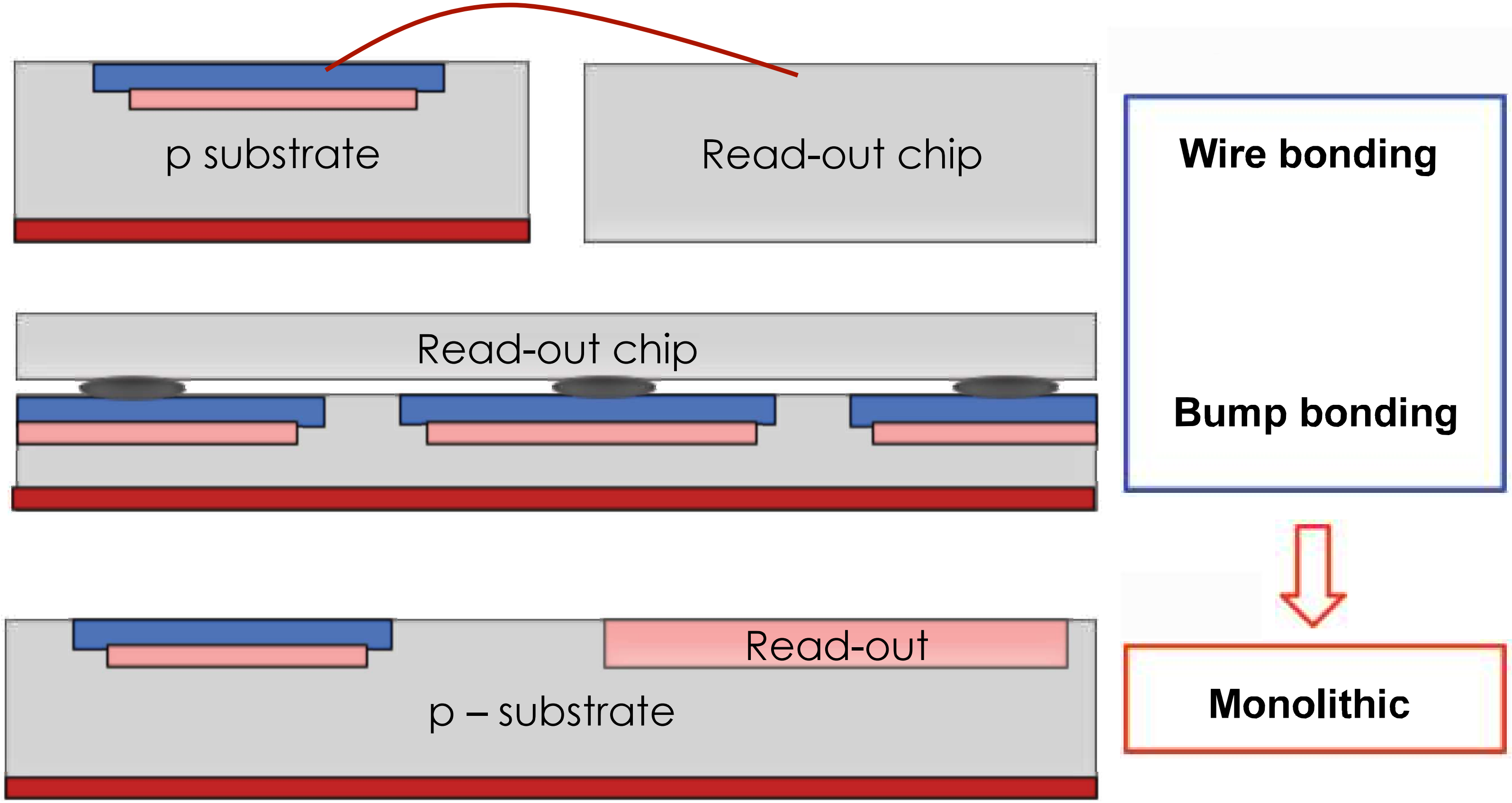
➔Segmentation is achieved via AC coupling



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

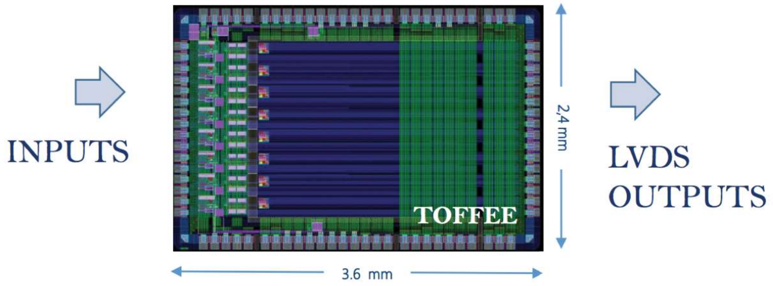
Two examples of UFSD and read-out chips

Single pad + TOFFEE

Multipad + TDCPix

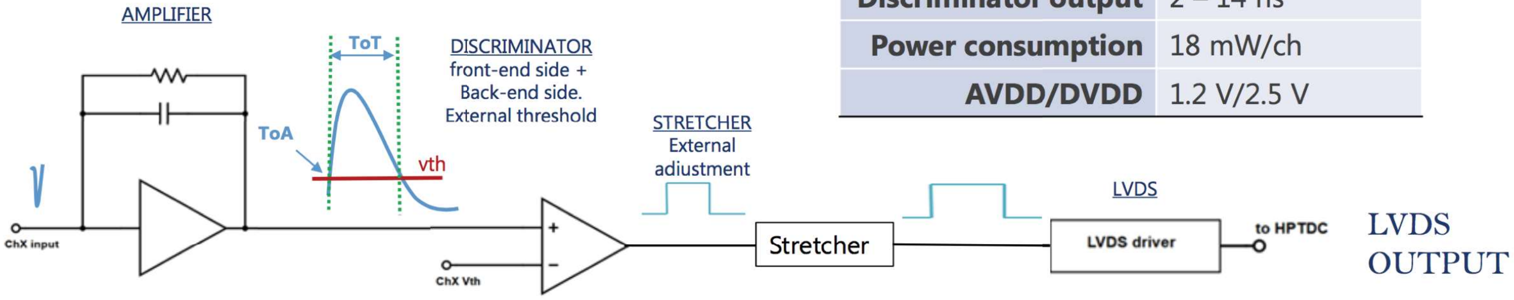
Bonus material

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

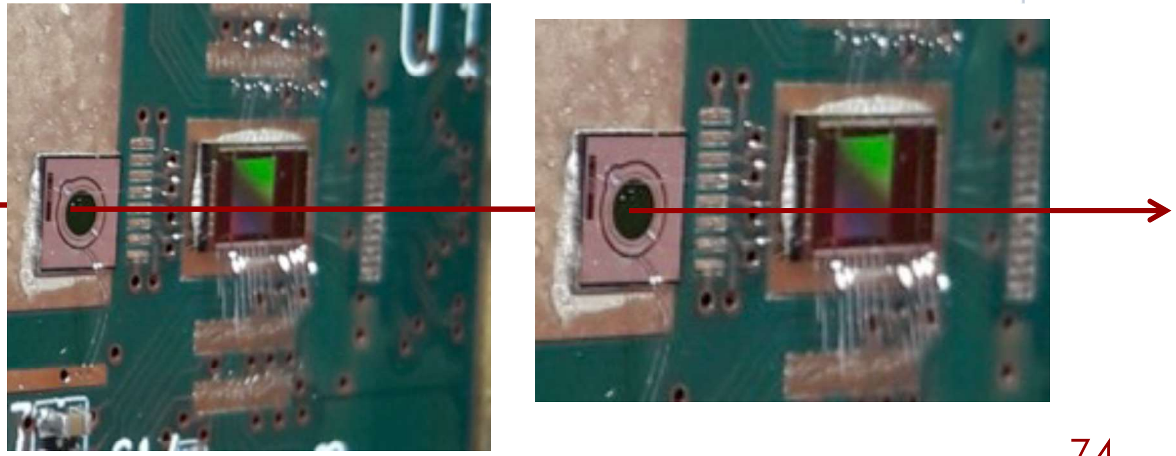
The channel architecture



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

Beam test at

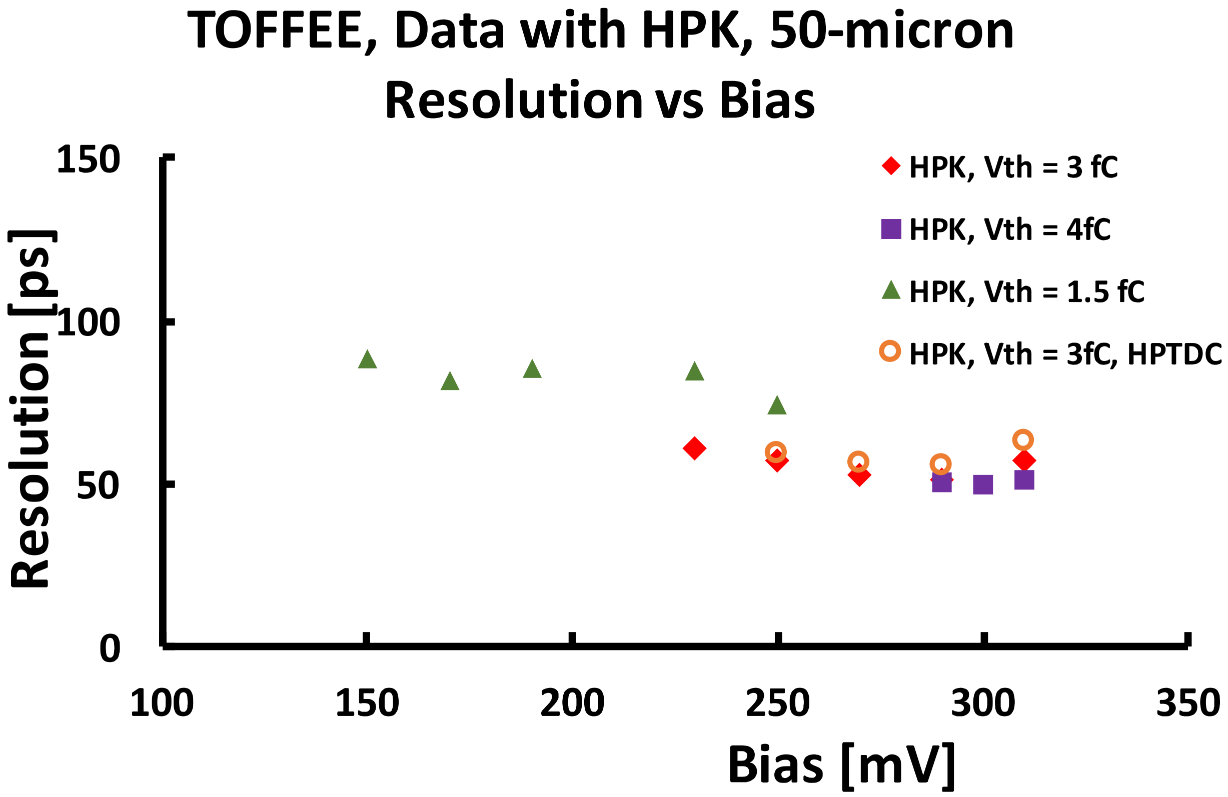
CERN north area



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.

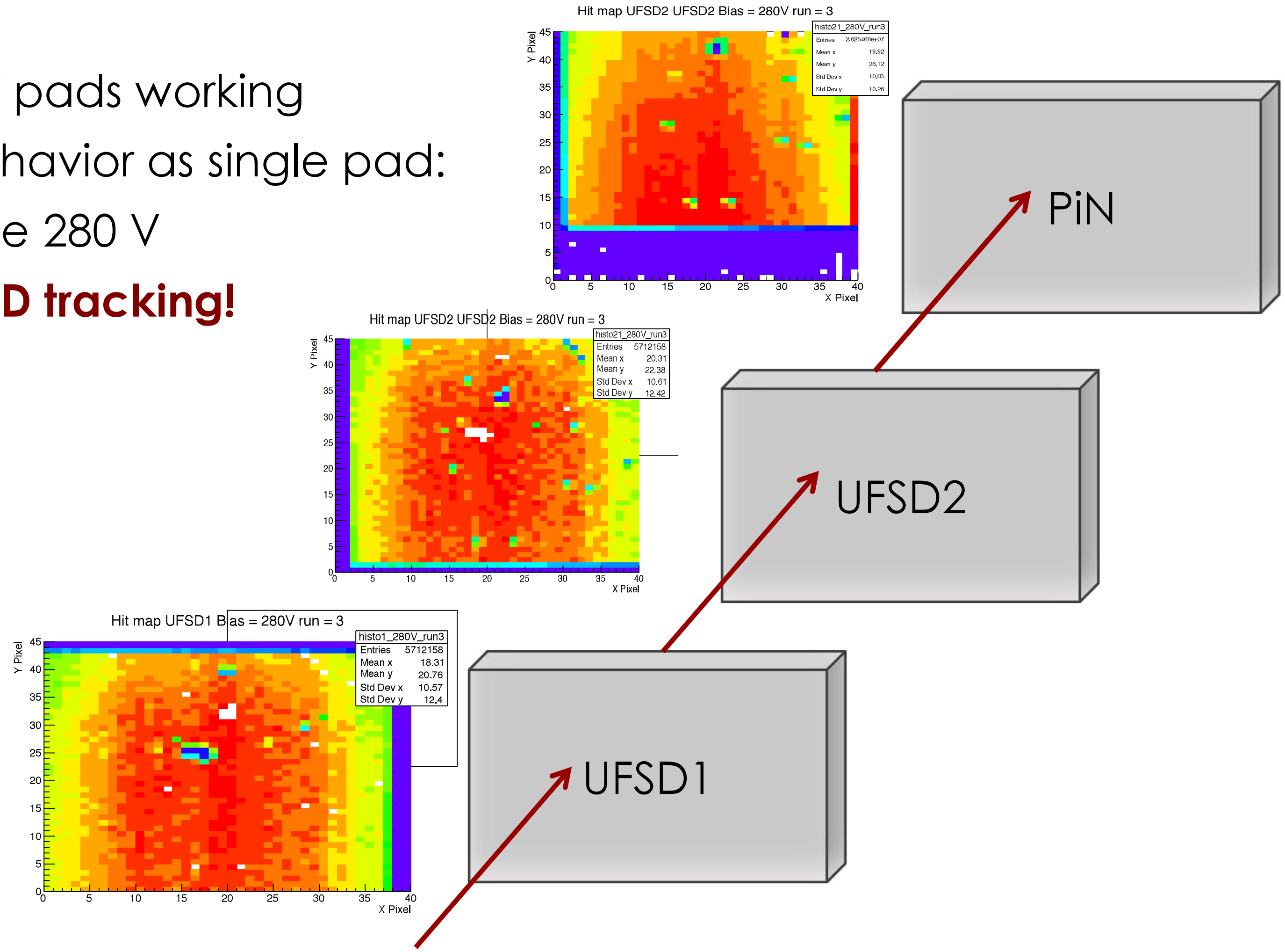


Multi-pad sensors: TDCpix & FBK-UFSD

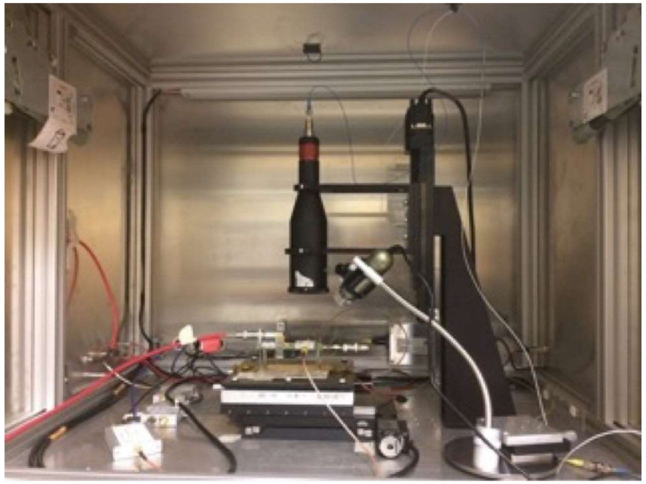
Bump-bonded NA62 TDCpix ROC to FBK-UFSD sensor

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

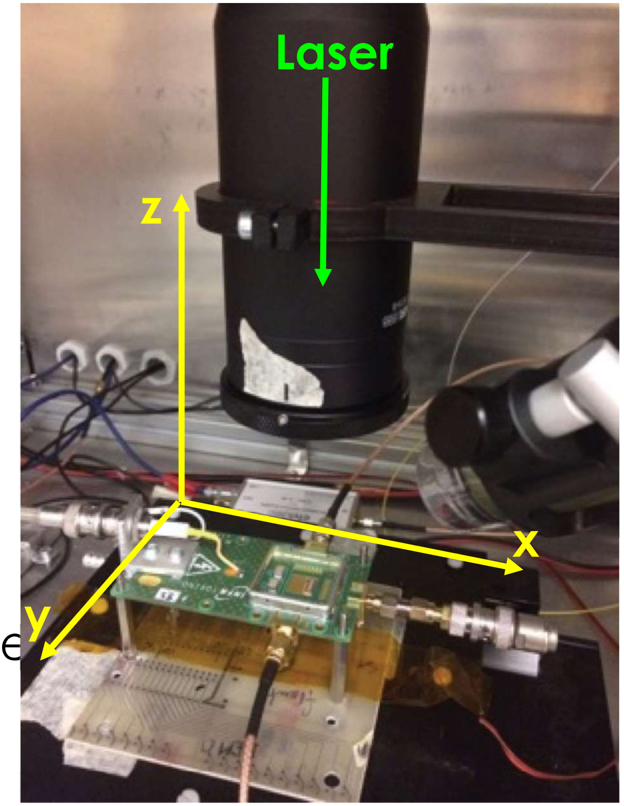
- More than 99% of pads working
- Same voltage behavior as single pad: breakdown above 280 V
- **First example of 4D tracking!**



Special Tools: TCT



TCT Setup in Torino



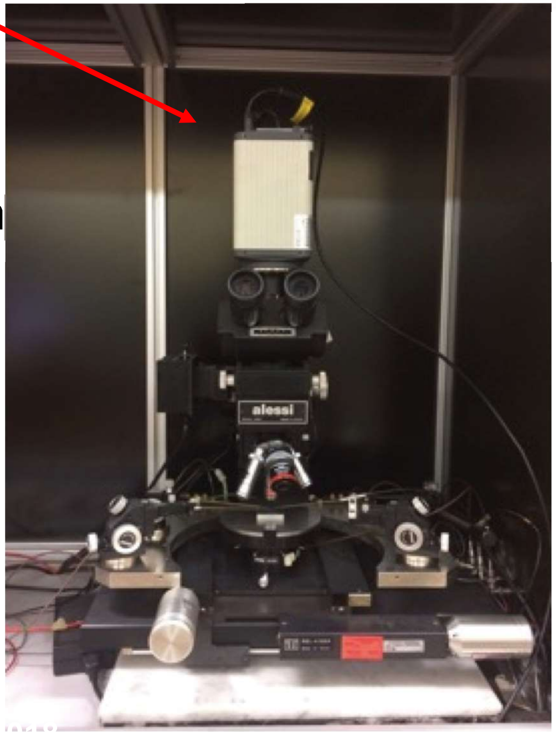
Particulars TCT setup:

- IR pulsed **laser** (1060 nm) → **10-15 μm spot**
- xy-stage with sub-μm precision
- Stage control and DAQ via Labview software
- **Automatic xy-scan + Small laser spot:**

➔ **Very precise mapping of the DUT**

Special Tools: Thermal Camera

Hamamatsu C11090-22B



- The camera is mounted on a probe station
- 2 pictures of the sensor are taken:
  - A conventional picture taken with an external source of light
  - A picture taken in complete darkness (probe station closed) with the DUT in BD

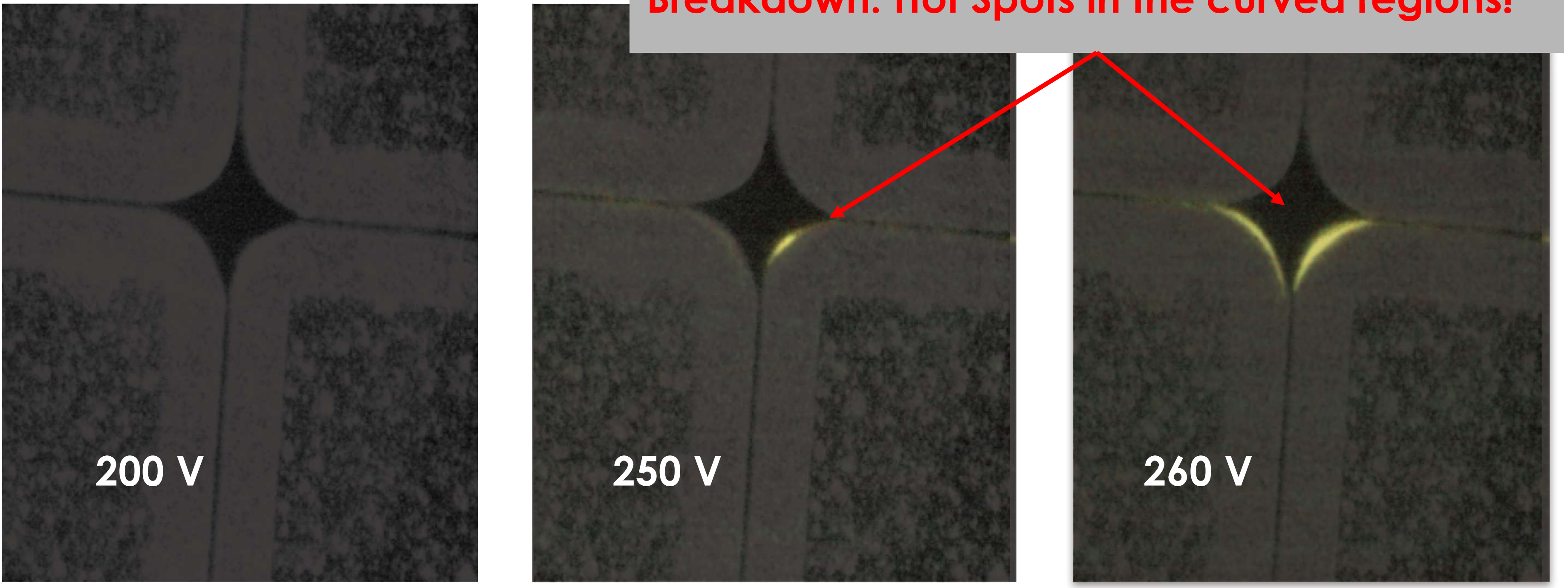
➔ The 2 pictures are then overlapped to show in which area the hot spots come out

We focused on the corners of the inactive area

F. Siviero, INFN Torino

Not so good design: current hot spot

Breakdown: Hot Spots in the curved regions!



F. Siviero, INFN Torino