IV Streaming Readout workshop, Camogli, May 22-24 2019

Ultra-Fast Silicon Detector for Timing and Tracking

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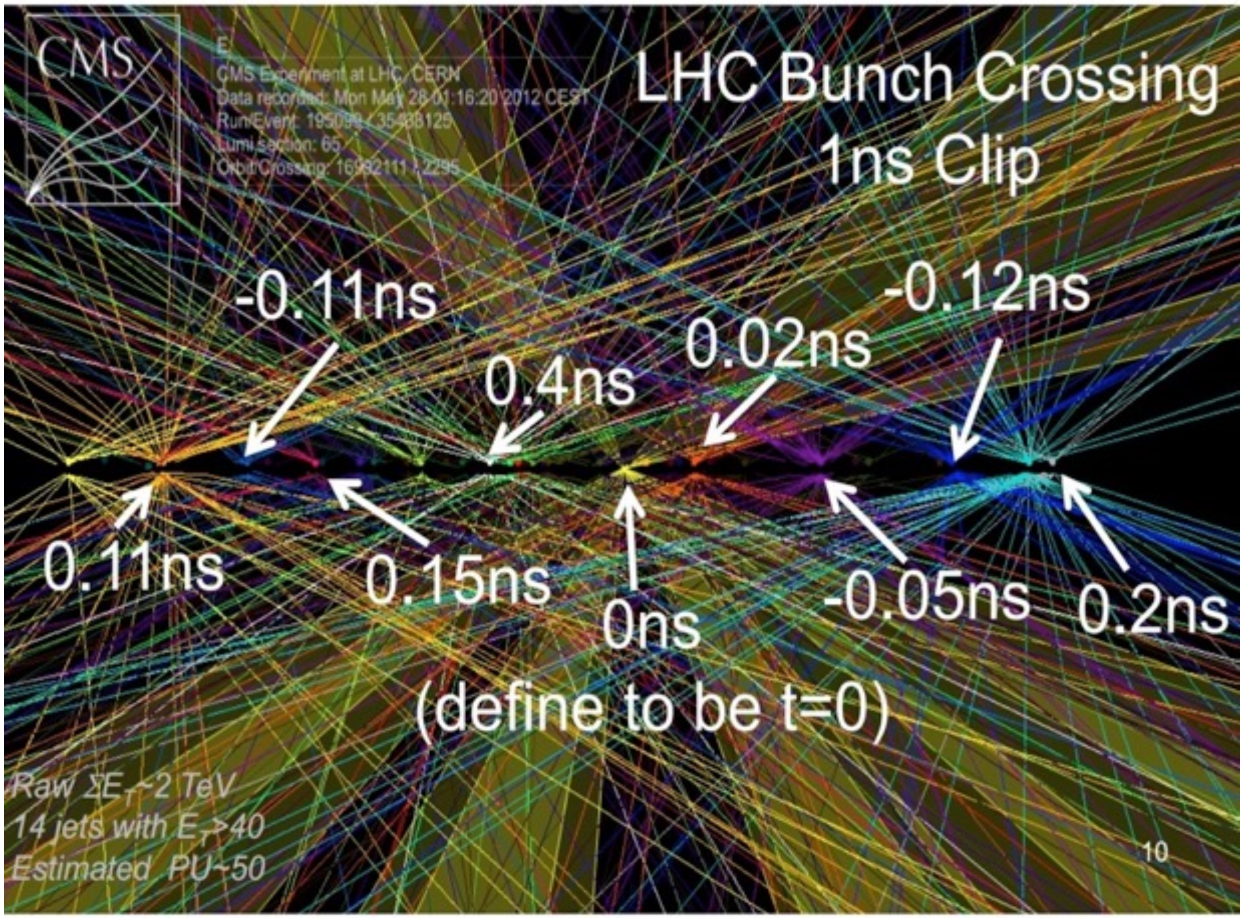
Current situation at LHC: no real need for timing

Proton



Proton

Time

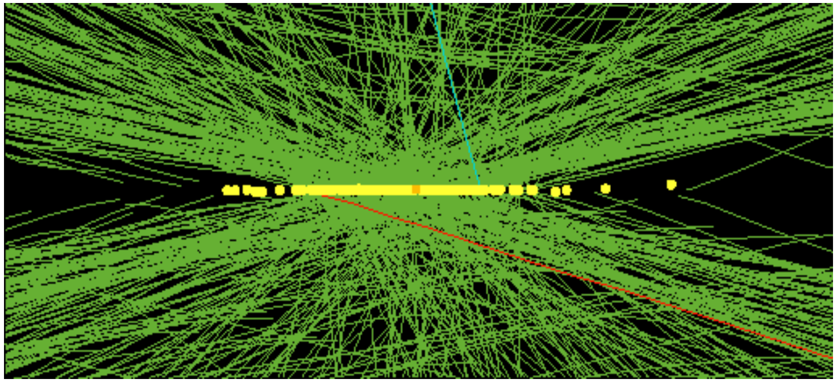
Why 4D tracking?

4D tracking has recently become one of the most interesting area of R&D for future detectors

Timing-Tracking capability is strongly motivated by high dense environments in future hadron collider

HL-LHC experiments condition:

- **150-200 events per bunch crossing**
- **Time RMS between vertices ~ 150ps**
- **Average distance between two vertex: 500µm**
- **Fraction off overlapping vertices ~10-20%** **(due to tracker limit)**
  - Of those events, a large fraction will have significant degradation of the quality of the reconstruction



Bunch crossing simulation

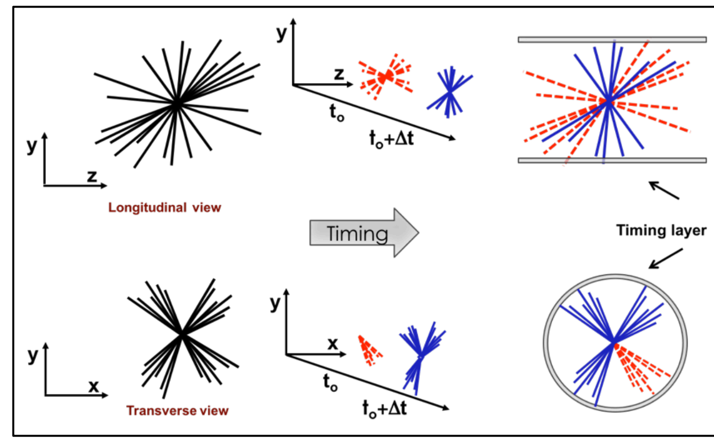
@ HL-LHC Timing is equivalent to additional luminosity

The effect of timing information

The inclusion of timing-tracking in the events information has the capability to change radically the experiment design

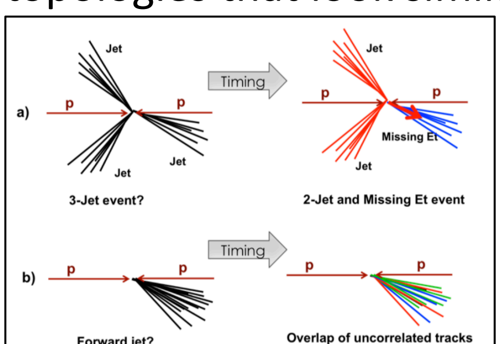
Timing can be available at different levels of the event reconstruction:

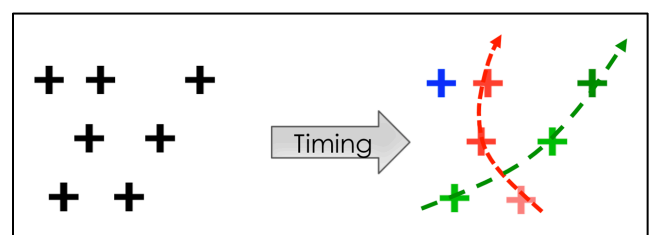
- Track timing in the event reconstruction:
  Timing allows distinguishing overlapping events



- Timing at each point along the track:
  Massive simplification in pattern recognition
  Use only compatible time

- Timing at the trigger level:
  Timing at the trigger decision allows reducing the trigger rate and rejecting topologies that look similar





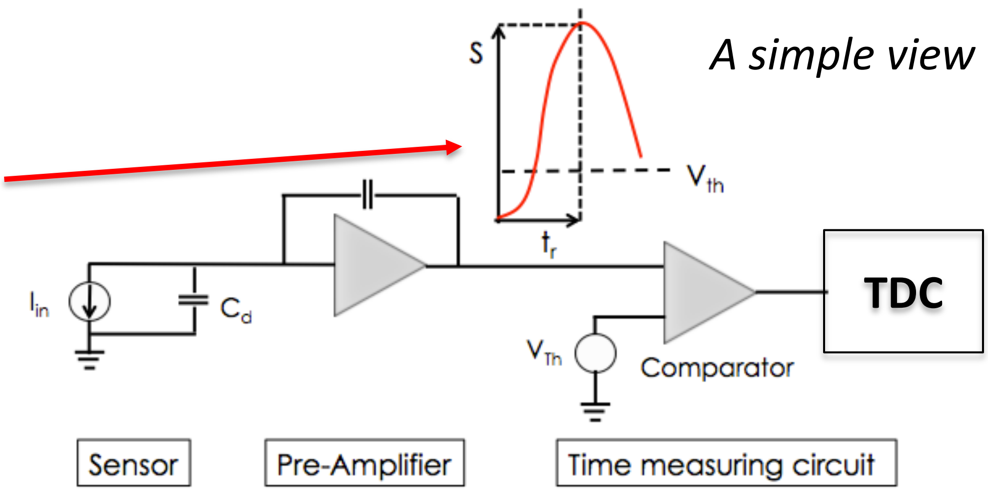
4D tracking ingredients

Position measurement: fine segmentation of electrodes

Time measurement
Time is set when the signal crossed the comparator threshold.

Time performances depends by the characteristic of the signal at the output of the preamplifier and by the binning of the TCD

A simple view



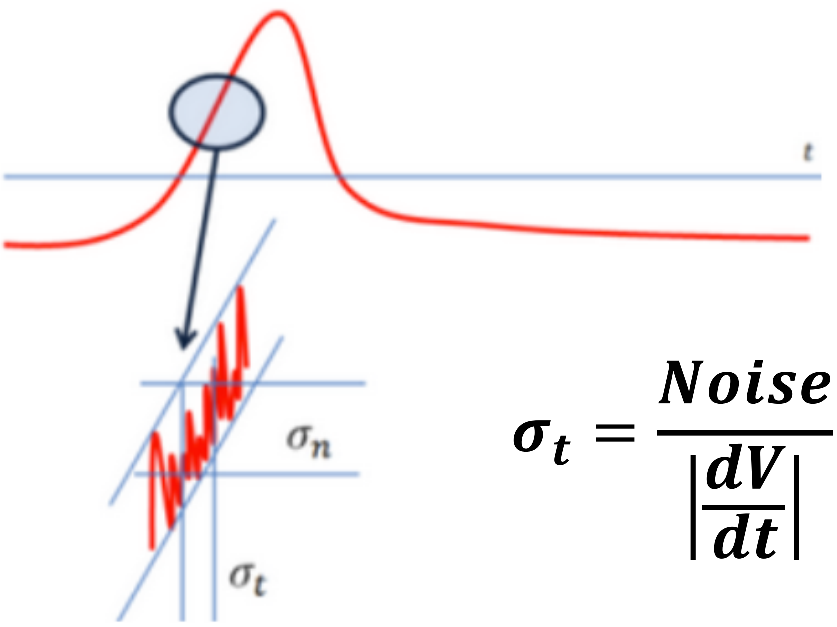
Strong interplay between sensor and electronic is necessary

Time resolution ingredients

$$\boldsymbol{\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{Time-Walk}^2 + \sigma_{Landau}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2}$$

Time resolution ingredients - Jitter

$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{Time-Walk}^2 + \sigma_{Landau}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$



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

Jitter: Noise is summed to the signal, causing amplitude variations around the comparator threshold

Mostly due to electronic noise

Reducible by sensor and electronic optimization

Time resolution ingredients – Time Walk and Landau

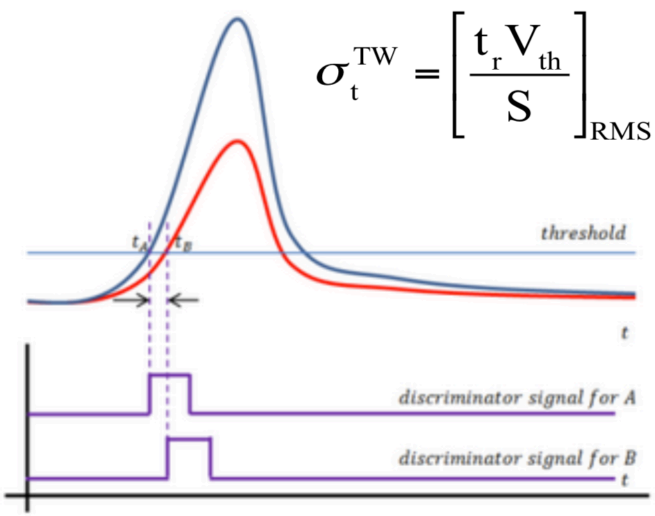
$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{Time-Walk}^2 + \sigma_{Landau}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$

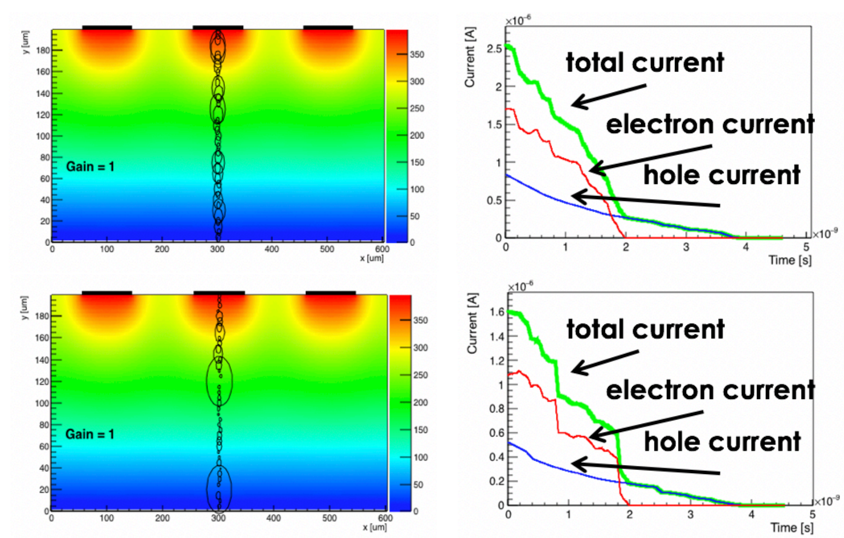
Time walk: change in signal amplitude due to variation in energy deposition

Correctible in appropriate electronic

Landau Noise: signal shape variation due to non homogeneous energy deposition

Mitigated by optimization of sensor design





Time resolution ingredients – Distortion

$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{Time-Walk}^2 + \sigma_{Landau}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$

Signal Distortion: signal shape formation

Type equation here.

Signal shape is determine by Ramo's theorem $\longrightarrow$ $I \propto qvE_w$

Drift velocity

Weighting field

The key to good time measurement is the uniformity of signal

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

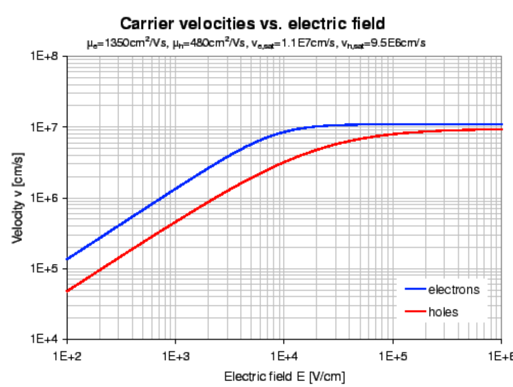
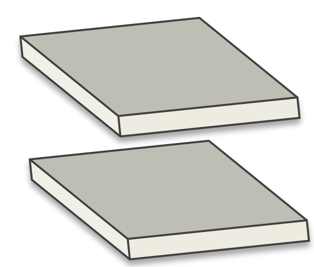


Figure: Electron and hole velocities vs. the electric field strength in silicon.



Parallel plate capacitor

Time resolution ingredients – TDC

$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{Time-Walk}^2 + \sigma_{Landau}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$

TDC: Negligible using an appropriate High Precision TCT

Considering 25ps binning of HPTDC $\sigma_{TDC} = \frac{25ps}{\sqrt{12}} \sim 7ps$

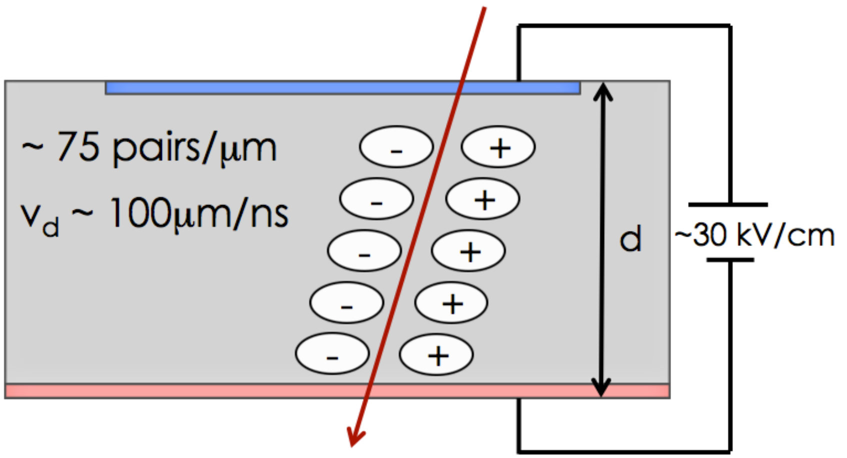
Signal requirements

A good time resolution requires fast and large signal (high slew rate)

How can you get fast and large signal in a silicon sensor?

What is controlling the slew rate?

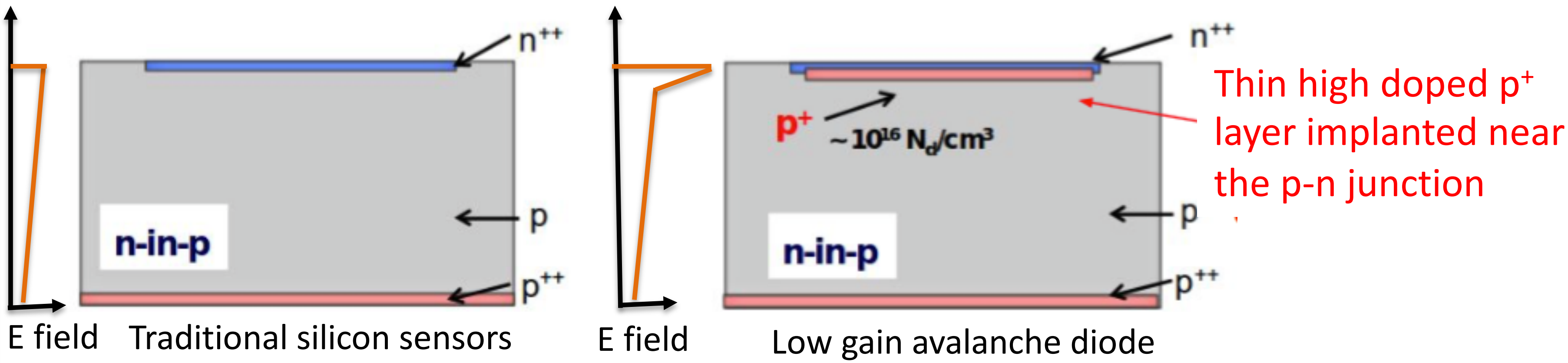
$$\frac{dV}{dt} \propto ?$$



Thin sensor→ fast signal (slew rate in 50µm thick sensor less than 1ns)

Gain→ large signal (electric field of 300kV/cm activate charge multiplication)

Low Gain Avalanche Diode(LGAD)



p^+ implant create an **high electric field** near the Junction (**~300kV/cm**), that accelerates electrons enough to start **avalanche multiplication** (same principle of APD but with much lower gain)

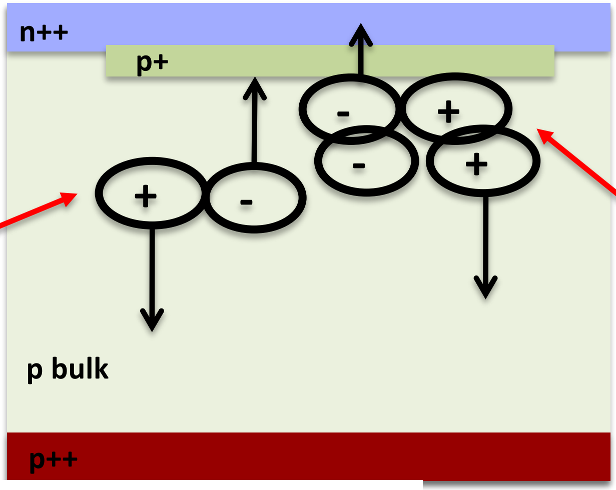
UFSD is a thin LGAD with an active width of ~50μm:

- Thin to maximize the slew rate
- Parallel plate geometry for more uniform weighting field
- High electric field to maximize the drift velocity
- Highest possible resistivity to have uniform electric field
- Small size to keep the capacitance low
- Small volume to keep the leakage current low (shot noise)

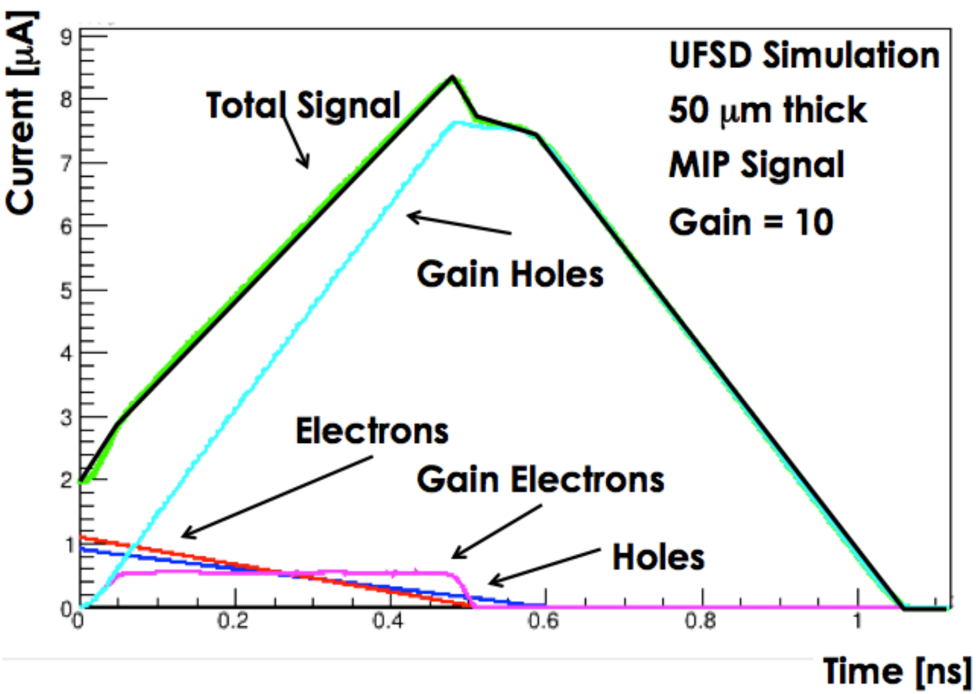
LGAD sensors proposed and produced for the first tine by CNM (2015) (National Center for Micro-electronics, Barcelona)

How gain shape the signal

Initial electron/hole:
- Electron activates the avalanche multiplication mechanism in **p+ layer**
- Hole drift to the p++ electrode



Gain electron:
Immediately collected by n++ electrode
Gain hole:
Long drift to the p++ electrode



Electrons multiply and produce additional electrons and holes
- Gain electrons negligible
- Gain holes dominate the signal

Holes do not multiply

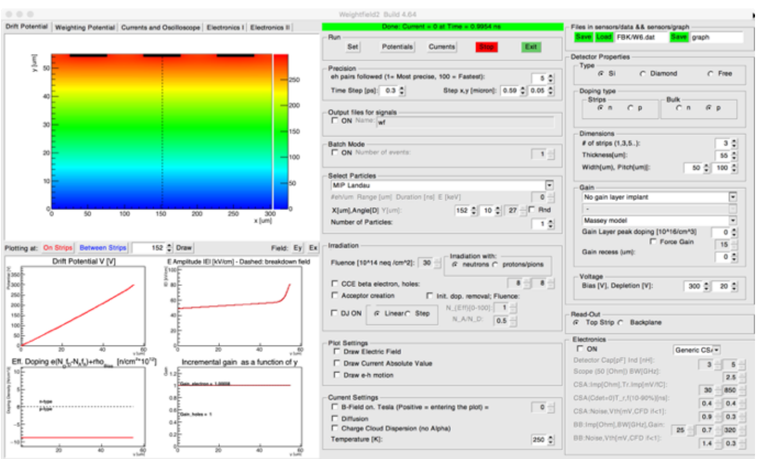
Simulator Weightfield2

Waightfiel2 useful tool for simulation of UFSD and parallel plate silicon sensors

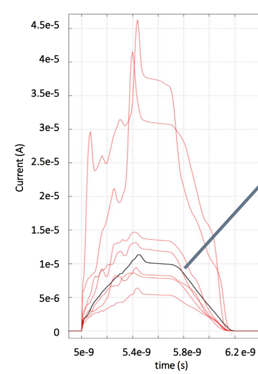
Available at:
http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html

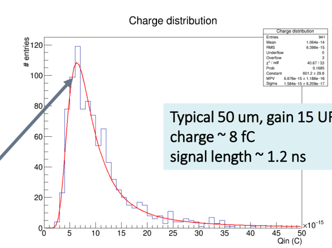
It requires Root build from source, it is for Linux and Mac.

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



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

Ultra Fast Silicon Detector (UFSD)

UFSD design based on the Low Gain Avalanche Diode (LGAD) technologies

UFSDs are sensors suitable for 4D tracking

- **Tracking**
  - Segmentable electrodes
  - Position resolution ~ 10 µm
  - Fast signal (rise time ~ 500 ps) and large signal (~ 10-20 higher than traditional silicon sensors)
  - Time resolution ~ 30 ps

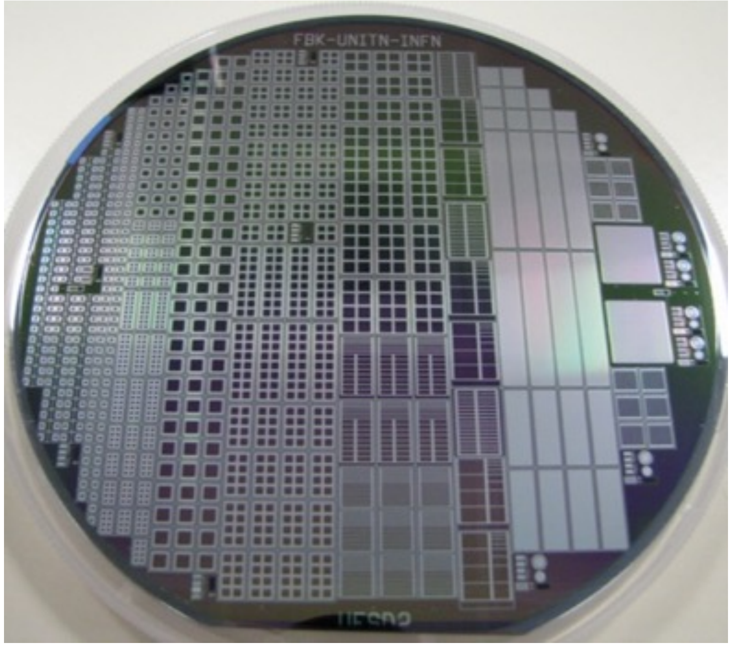
- **Radiation resistance:**
  - Performances maintained at fluences $\emptyset > 10^{15}\, {}^{n_{eq}}/_{cm^2}$
  - Suitable for future experiments at HL-LHC

UFSD group: FBK-Trento Uni- INFN-Torino

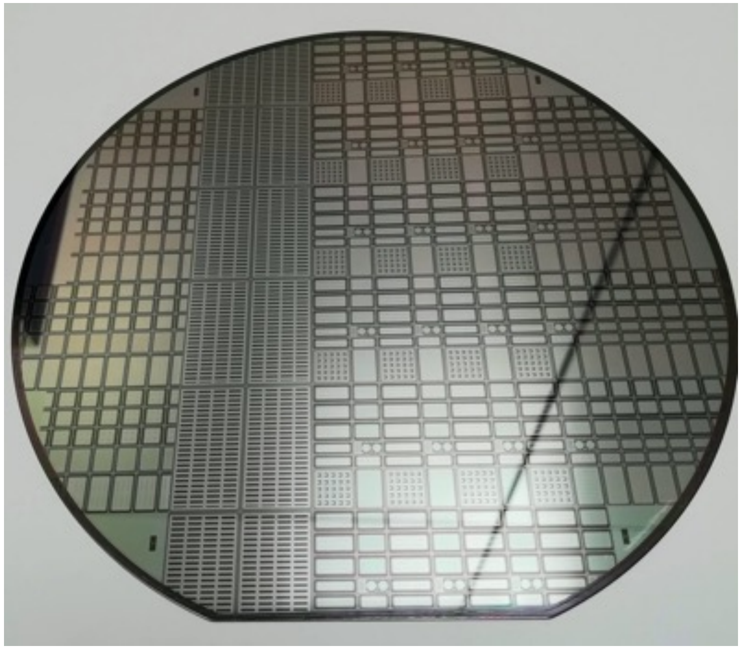
Torino has a privileged relationship with FBK in sensors development

FBK productions:

- **UFSD1 (2016)**: **300μm** thick. First LGAD production at FBK. Gain layer study, edges
- **UFSD2 (2017): 55μm** thick. First UFSD production by FBK. Excellent time resolution and radiation hardness study
- **UFSD3 (2018): 55μm** thick. Produced with the stepper. Radiation harness and segmentation study
- **UFSD4: 45μm** thick. Available next years



UFSD2



UFSD3

UFSD development process flow

Production Work Flow

4 mount

Simulation & layout design

- TCAD simulation
- Keep to technological rules
- Selection of device geometry

UFSD development process flow

Production Work Flow

4 mount

Simulation & layout design
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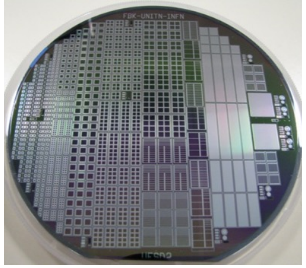
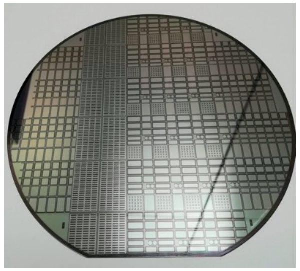
- Selection of device geometry

4 mount

Manufacturing
- Wafers supplying
- Hundreds stage of manufacturing





UFSD development process flow

Production Work Flow

~ 1 year

4 mount

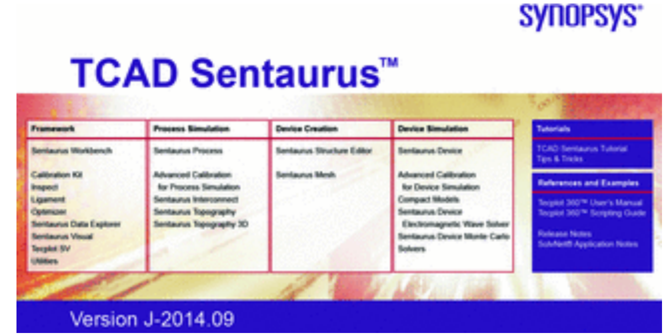
Simulation & layout design
- TCAD simulation
- Keep to technological rules
- Selection of device geometry

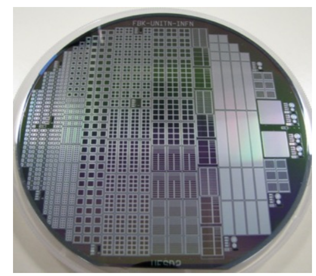
4 mount

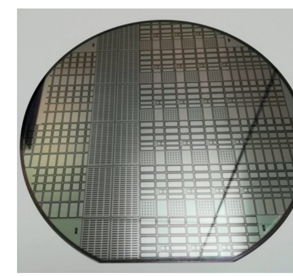
Manufacturing
- Wafers supplying
- Hundreds stage of manufacturing

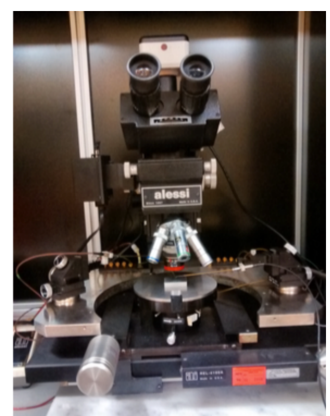
4 mount

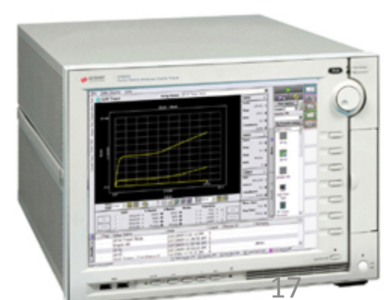
Testing
- Electrical test pre-irradiation
- Irradiation Campaign
- Electrical test post-irradiation
- Beam test







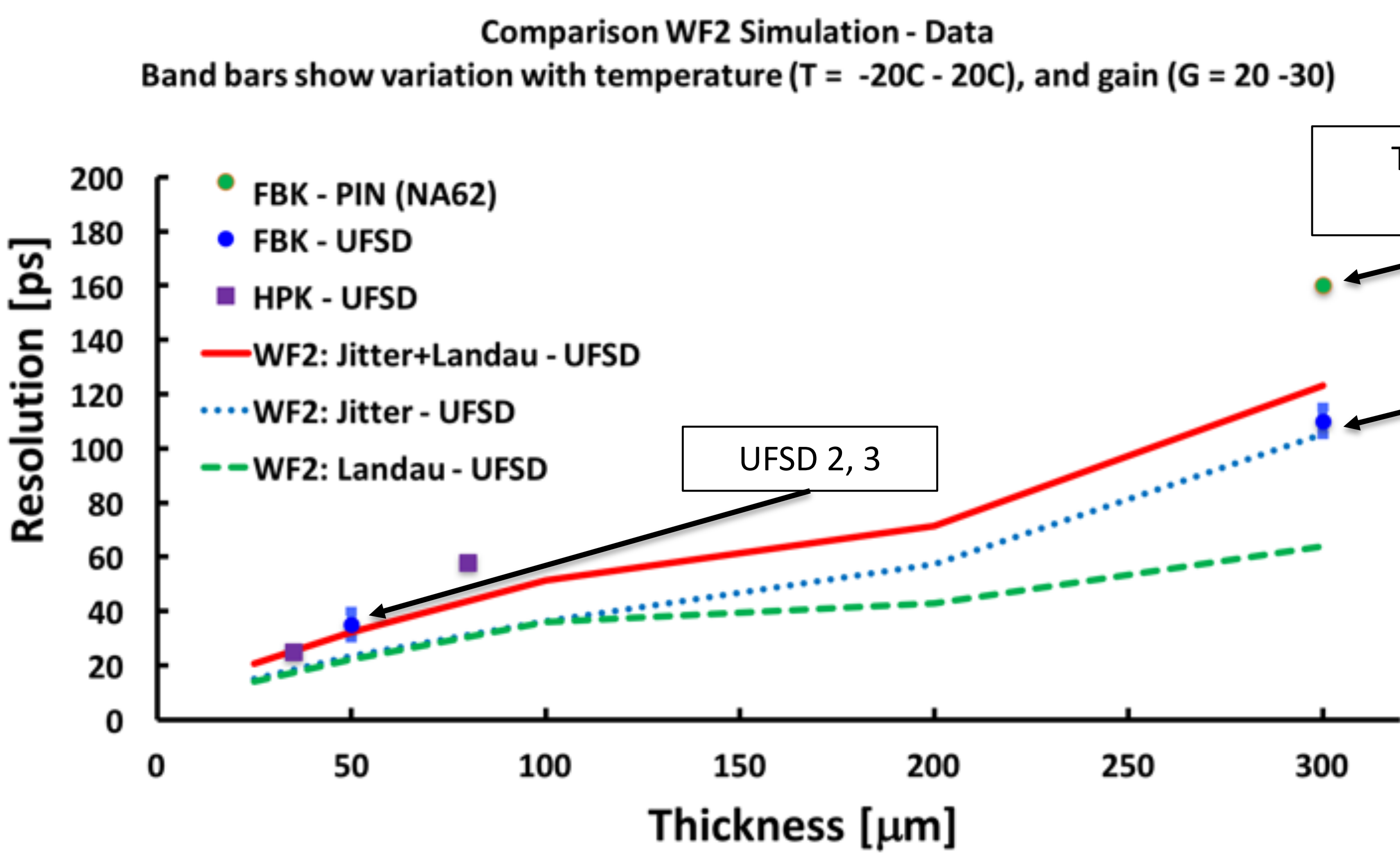




UFSD performances
time resolution summary

UFSD project progress through a series of productions.
The goal is to obtain the intrinsic time resolution for each sensor thickness:

- **20 ps for 25µm**
- **30 ps for 50µm**



Irradiation effect on UFSD

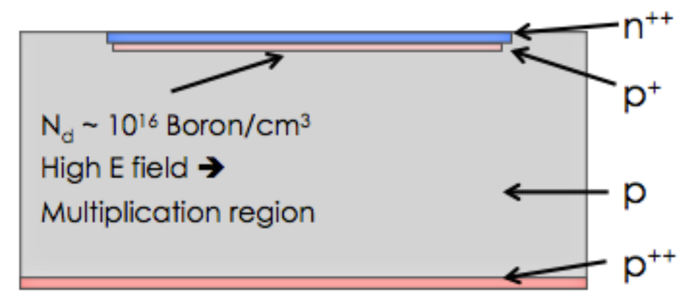
3 main effects by irradiation:
- Decrease of charge collection efficiency due to trapping
- Doping creation and **removal**
- Increasing leakage current and shot noise

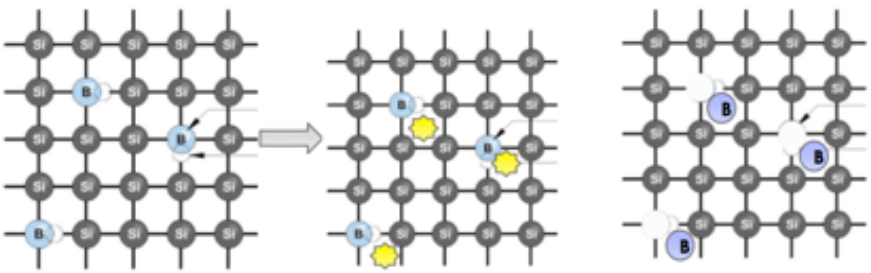
UFSDs maintain their performance at a fluence 10^{15} n_{eq}/cm^2

Acceptor removal

Irradiation de-activate p-doping removing active boron from the reticle

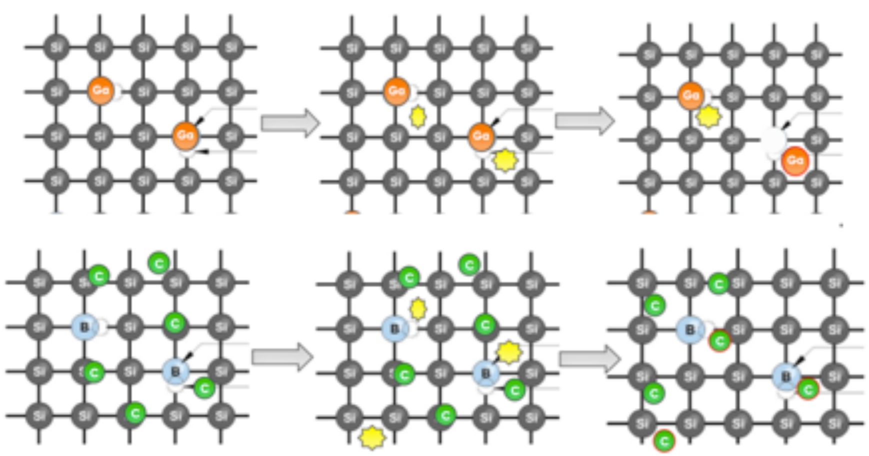
$$N(\emptyset) = N(0)e^{-c\emptyset}$$





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

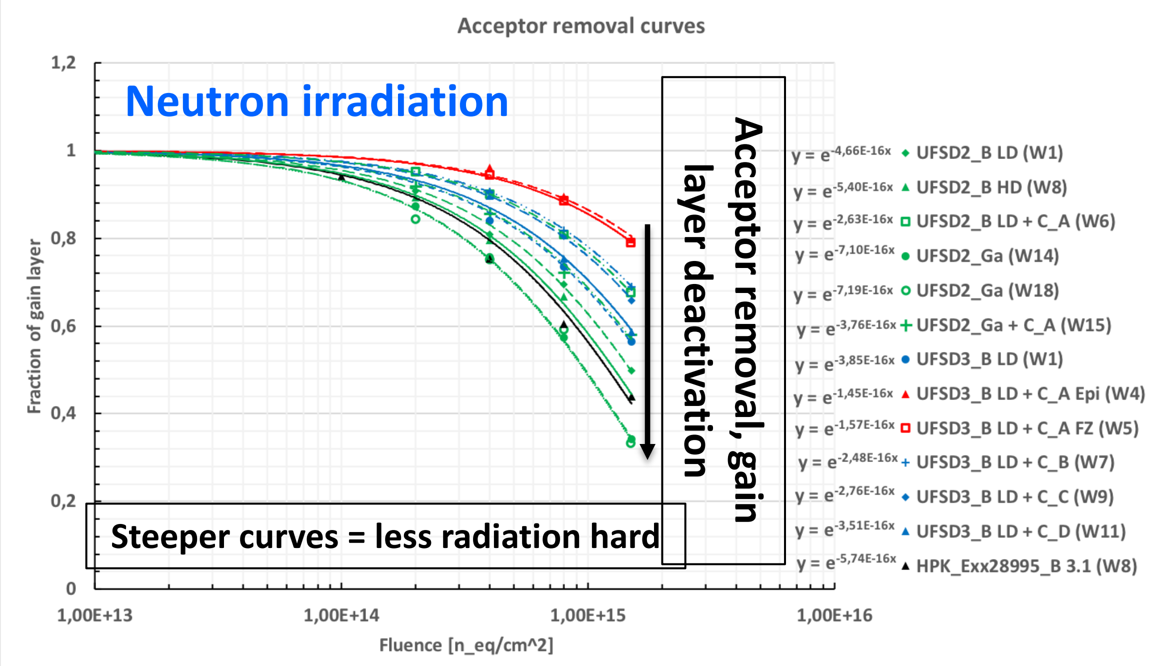
Two possible solution



Use Gallium
Gallium is substitutional
From literature, Gallium has a lower possibility to become interstitial

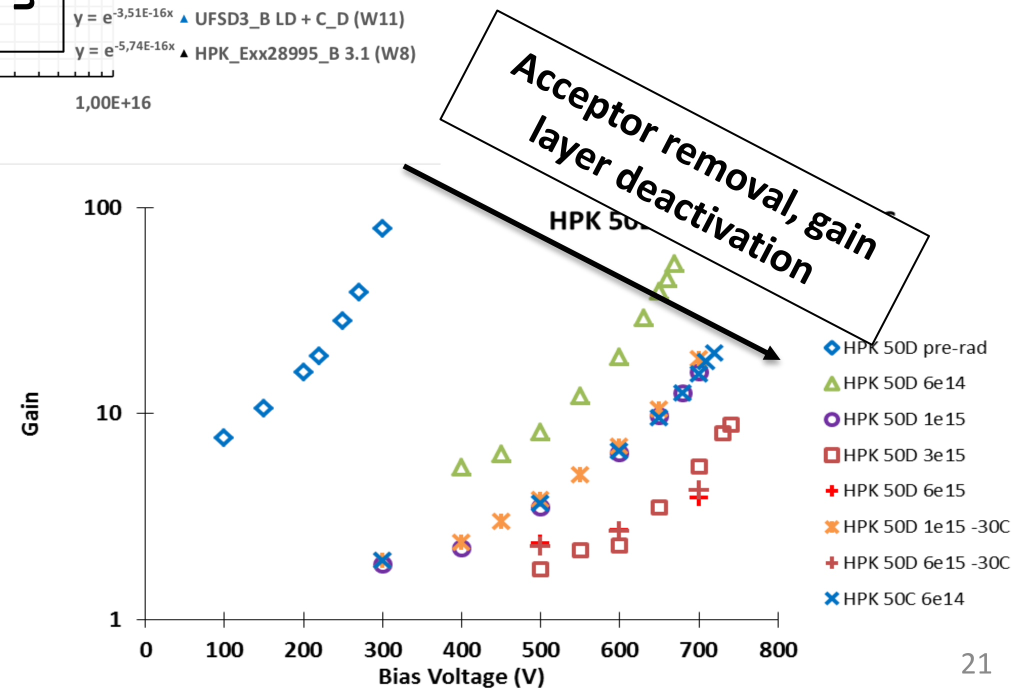
Co-implant Carbon
Interstitial Si interact with Carbon instead of with Boron and Gallium

Effect of acceptor removal

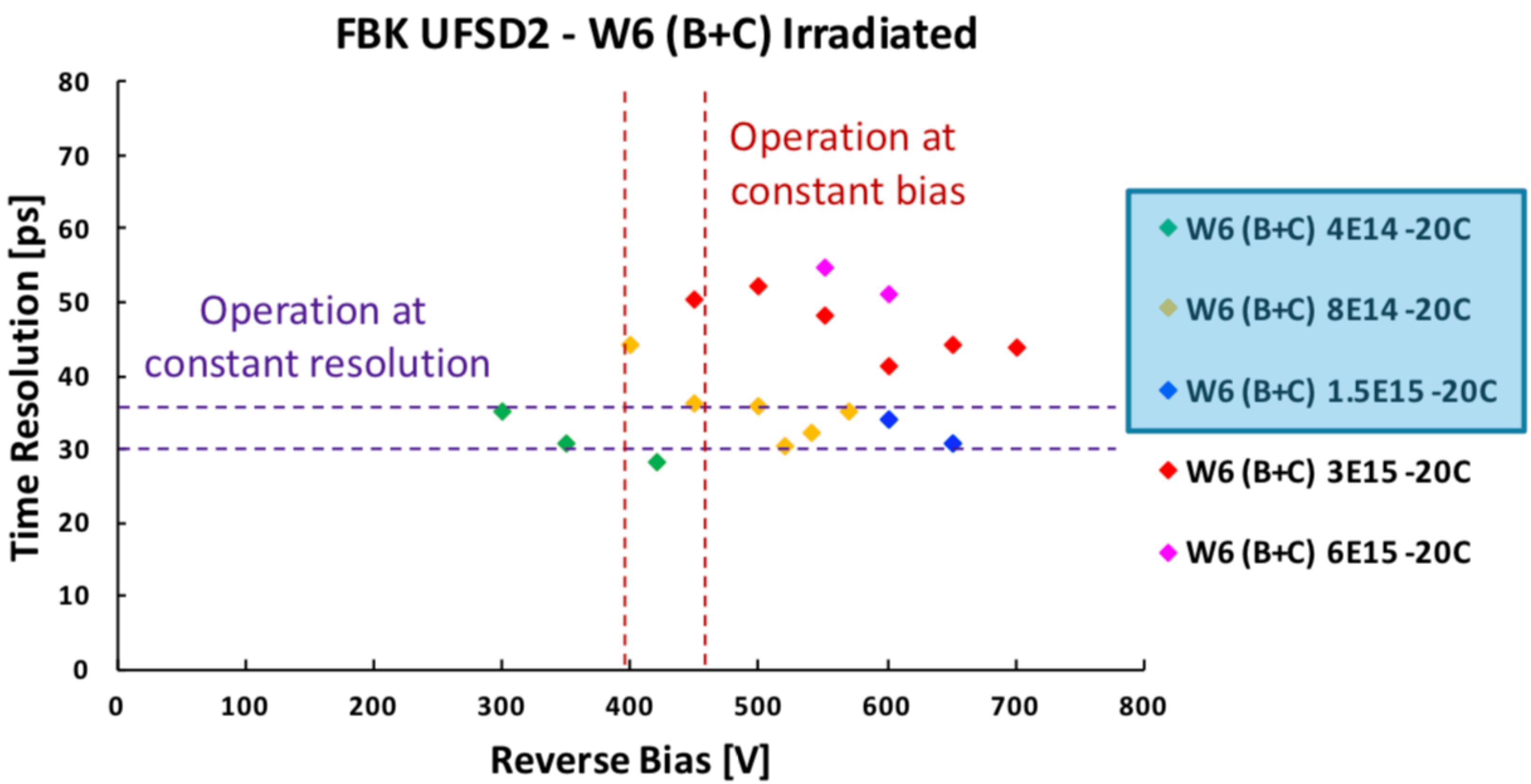


- **Carbon addition work very well, increase by a factor 2-3 the radiation hardness**
- **Gallium is same radiation hardness than boron**

Disappear of the gain layer might be compensated by the increasing of the bias voltage



Irradiated UFSD, performances



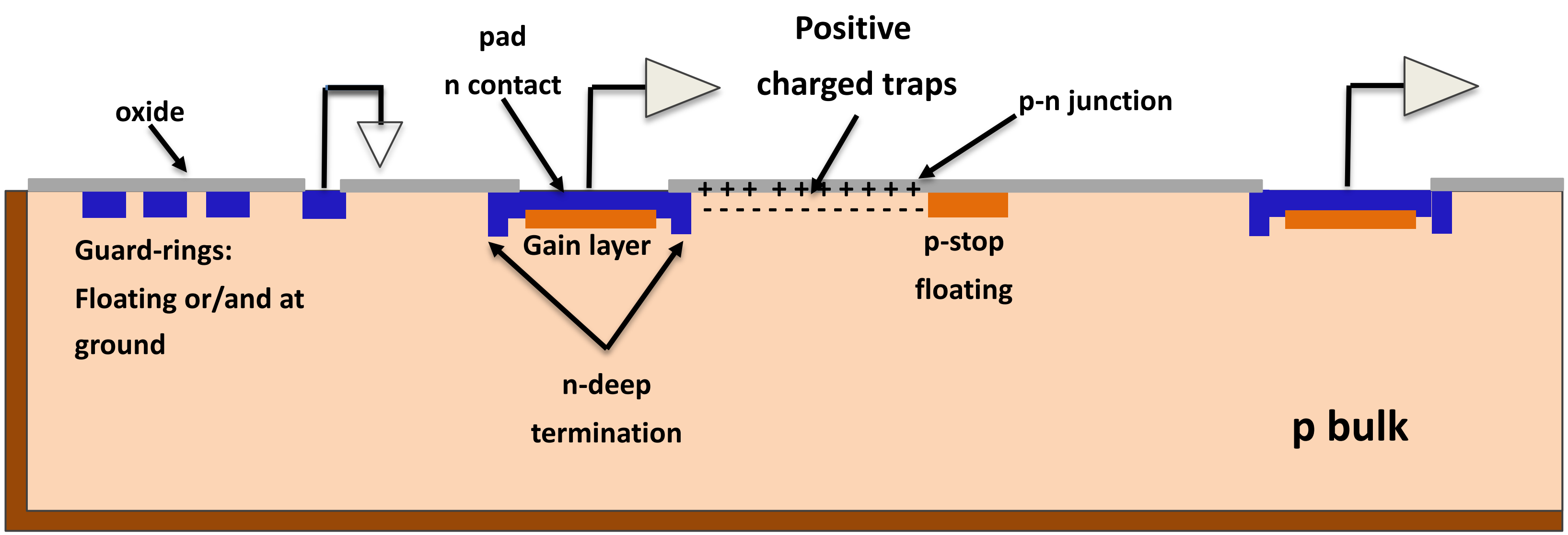
Time resolution of 30-35 ps @ 1.5E15 n_{eq}/cm^2

From single pad to a 4D tracker

A large variety of of single pads and small array with many geometries, thickness and gain have been successfully produced

To produce a full large tracker we should develop sensors with large uniformity area and high fill factor (fraction of active area)

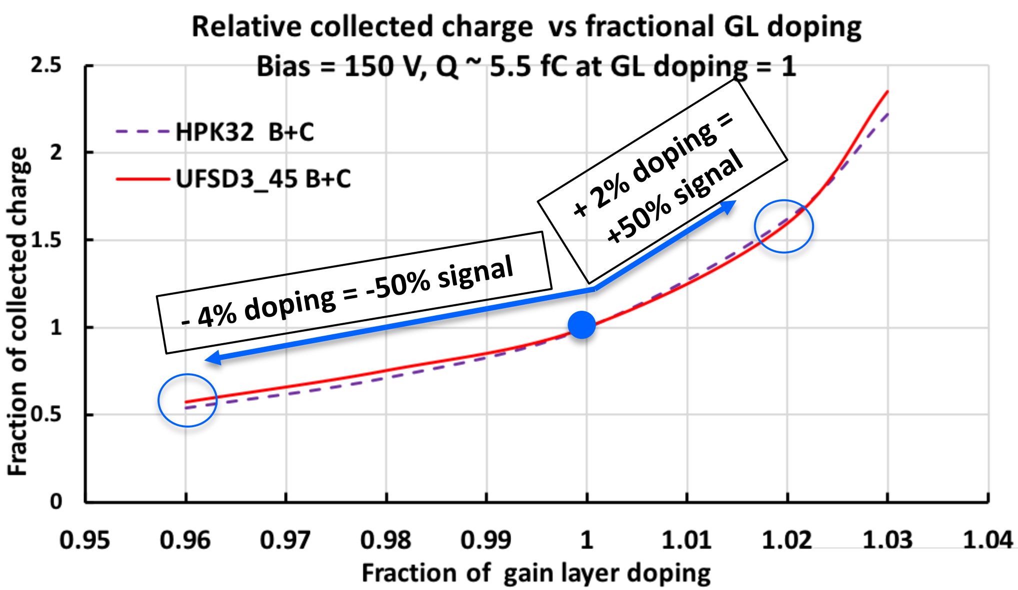
Multi-pad sensor building block



Transversal cut of a generic multi pad UFSD sensor

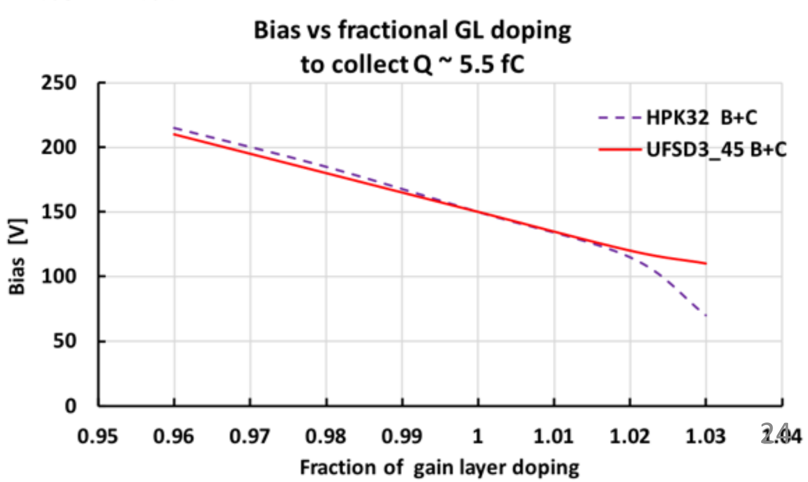
Gain uniformity

The gain uniformity is a critical point



Gain uniformity requires a very accurate manufacturing capability

The bias can adjust the gain variation keeping a constant collected charge



Marco Ferrero, INFN, IV Streaming Readout workshop, Camogli 22-24 May 2019

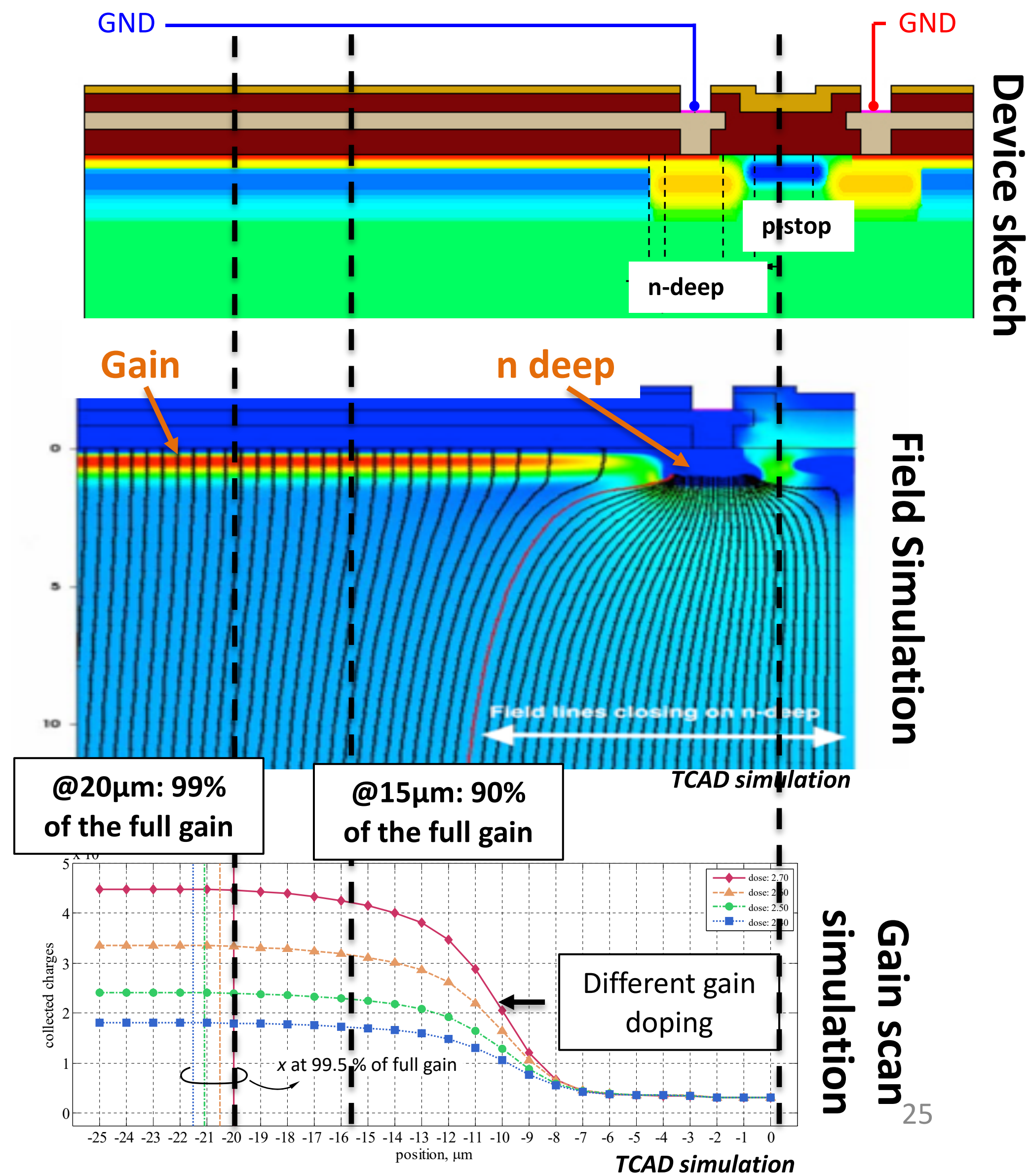
Segmentation-fill factor TCAD simulation

In Multi-pad sensors adjacent pads need to be isolated by termination structure **(n-deep and p-stop)**

termination structures between readout pads **(n-deep, p-stop)** represent a **no-gain area**, where the collected charges determine a **lower signal**

In a very aggressive design:

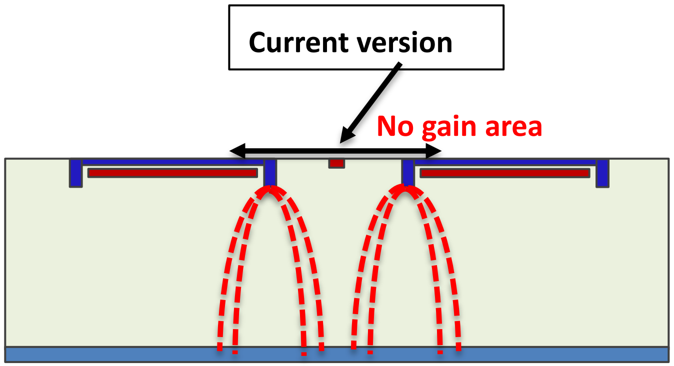
- nominal inactive area per side < 10 µm
- 99% of full gain @20µm from p-stop



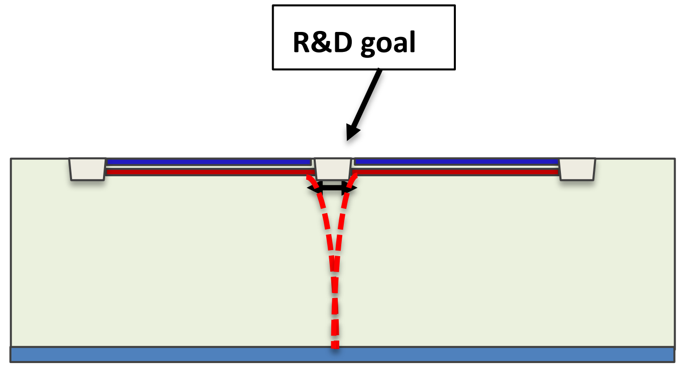
fill factor improvement: trenches

Trenches (same techniques used in SiPM)

No excess inactive area due to **p-stop** and **n-deep** implants



JTE + p-stop design

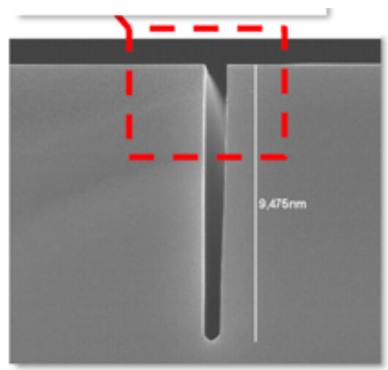


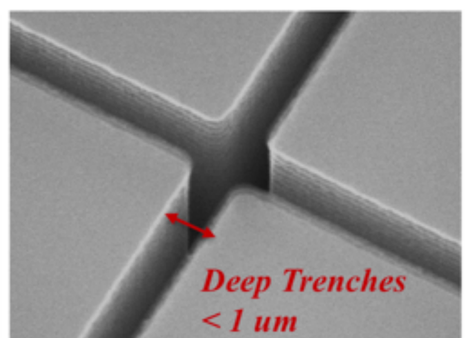
Trench design

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



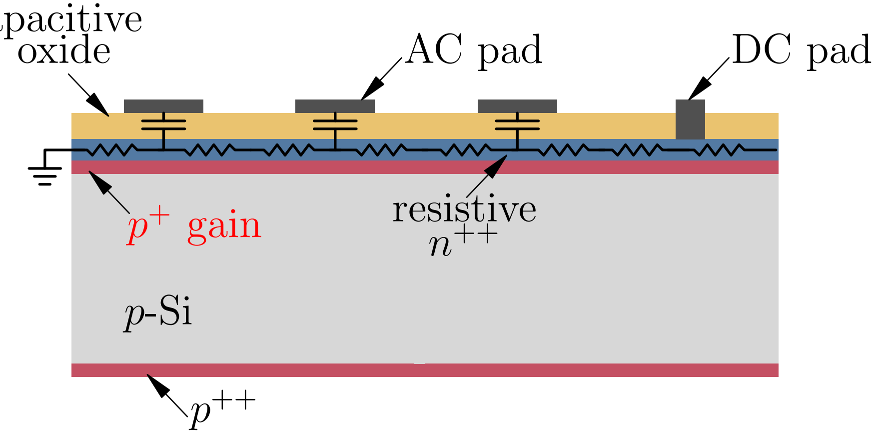


FBK project (High Density LGAD) funded by RD50 CERN Collaboration

RD50

fill factor improvement: Resistive AC-Couple Silicon Detectors (RSD)

The new readout paradigm to have a 100% fill-factor



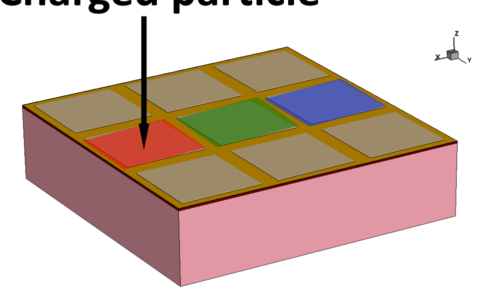
RSD Figures of merit:

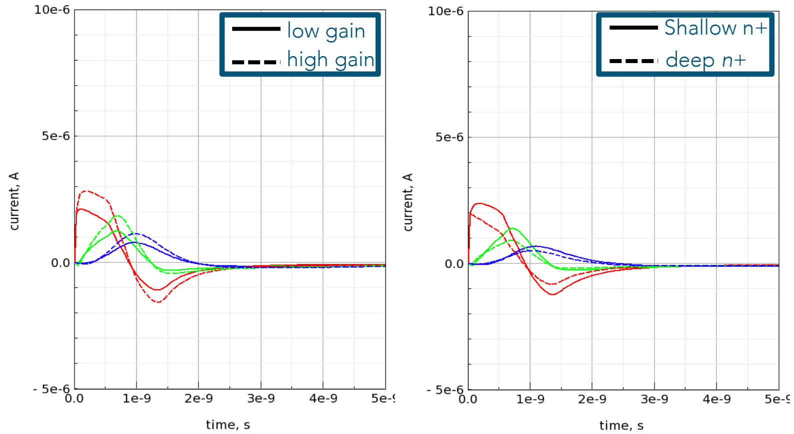
- Continuous gain layer (LGAD technology);
- Resistive n++ electrode: tens to hundreds of Ω
- Dielectric coupling: few 100s of nm

RSD sensors are designed to have a **readout characteristic time** short enough for the signal to be seen and long enough to minimize pile-up

TCAD Simulation of signal induced by charge particle

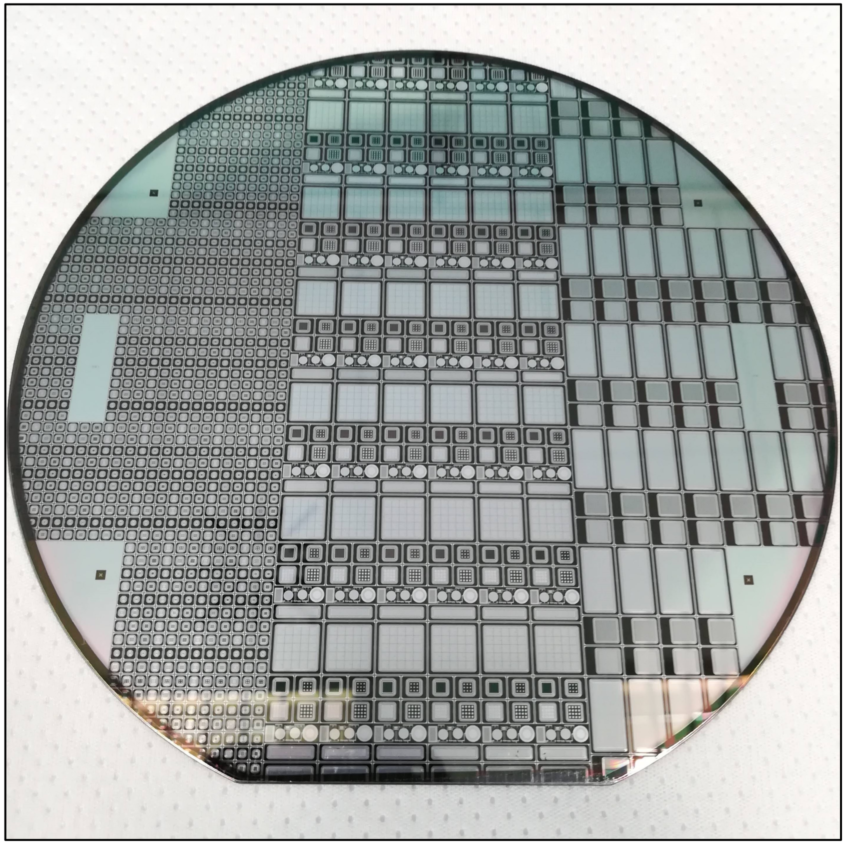
Charged particle





Signal expected: bipolar signal

Resistive AC-Couple Silicon Detectors (RSD) Simulation



First RSD production by FBK (RSD1) has been completed two week ago.

Goals of first RSD production:
- AC couple technology exploration
- Feasibility of manufacturing process

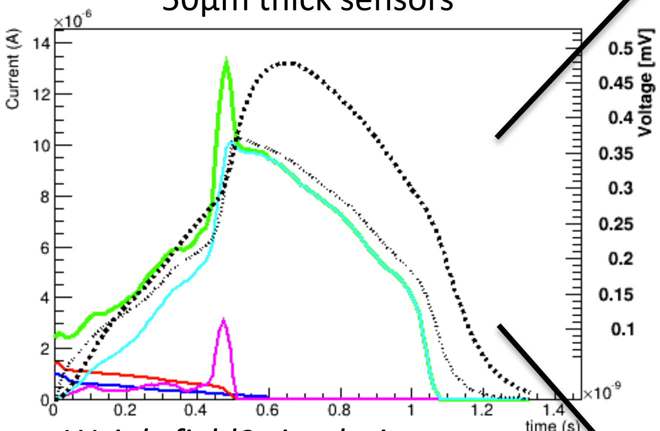
A wide variety of devices: matrix modules, strip and RD53A sensor;
Most **aggressive device** with a **pitch of 50µm**

A second RSD production will be available in 2020

RSD is a INFN project of Mandurrino Marco in collaboration with FBK

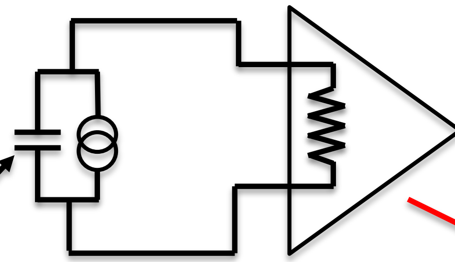
Electronic: best pre-amp choice for UFSD readout

Current signal in 50µm thick sensors

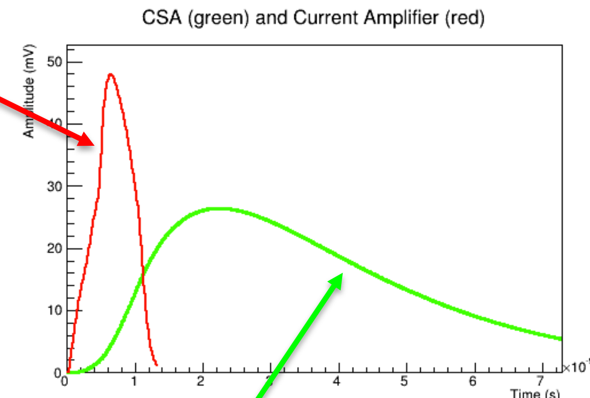


Weightfield2 simulation

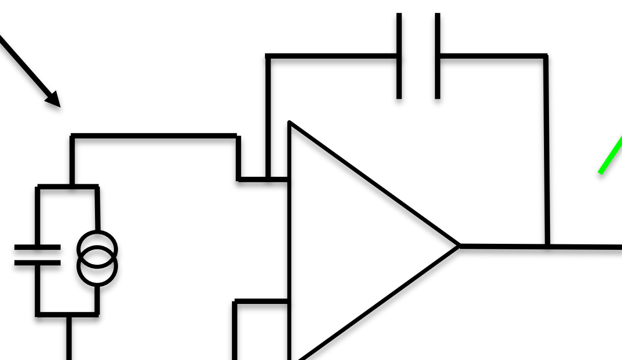
Current Amplifier



- Faster slew rate
- Higher noise
- Sensitive to landau fluctuation



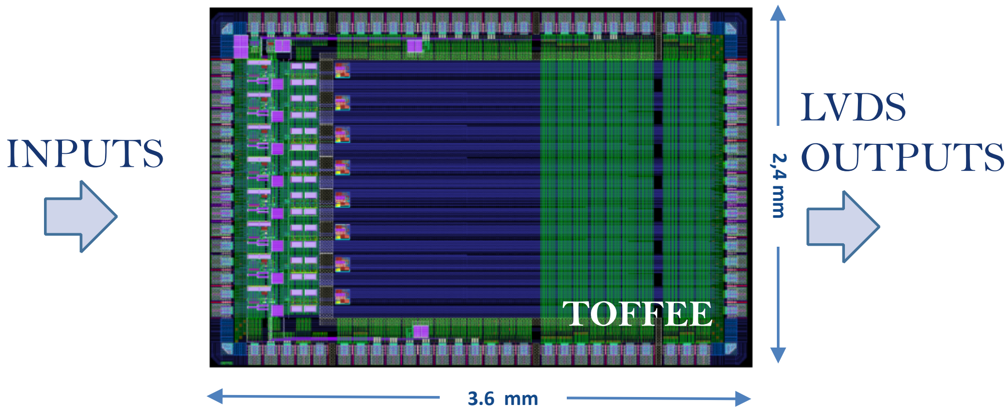
Charge Sensitive Amplifier



- Slower slew rate
- Less noise
- Integration help the signal smoothing

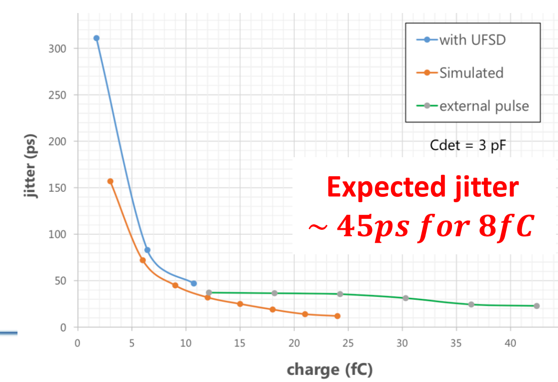
Readout electronic for timing: TOFFEE

TOFFEE is the first read out electronic chip designed and produced in 2016/17 for UFSD readout

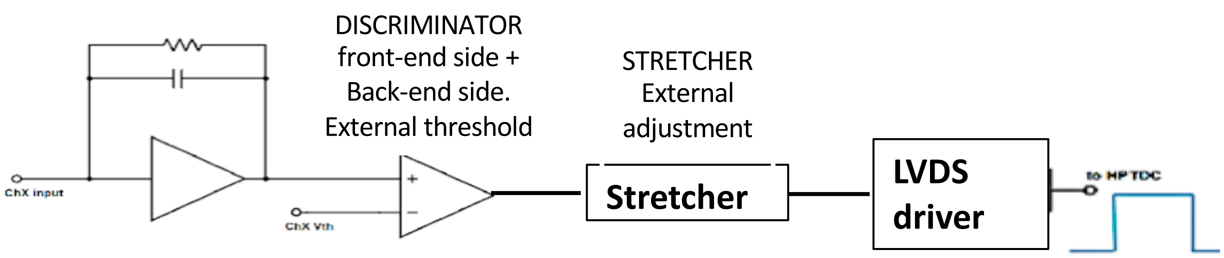


Technology	CMOS 110 nm
Channels	8
Sensor capacitance	5-10 pF
Input dynamic range	3 fC – 60 fC
Analog gain	7 mV/fC
GBW	14 GHz
RMS noise (C=6pF)	800 µV
Discriminator output	2 – 14 ns
Power consumption	< 20 mW/ch
AVDD/DVDD	1.2 V/2.5 V

Measured Jitter

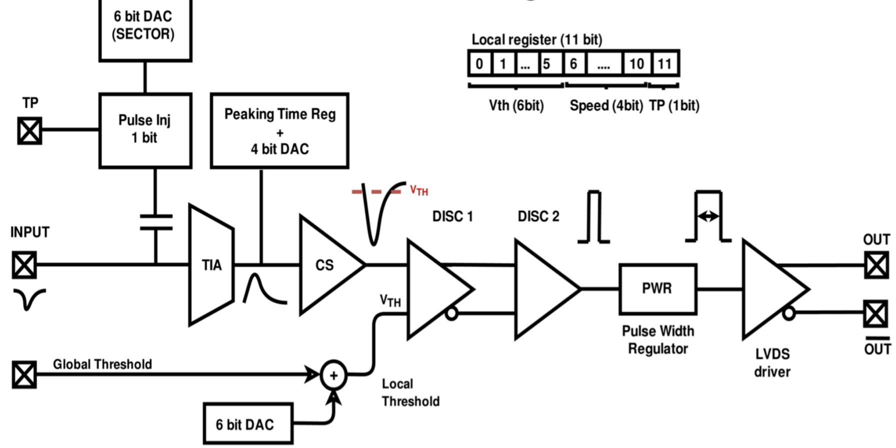


The channel architecture

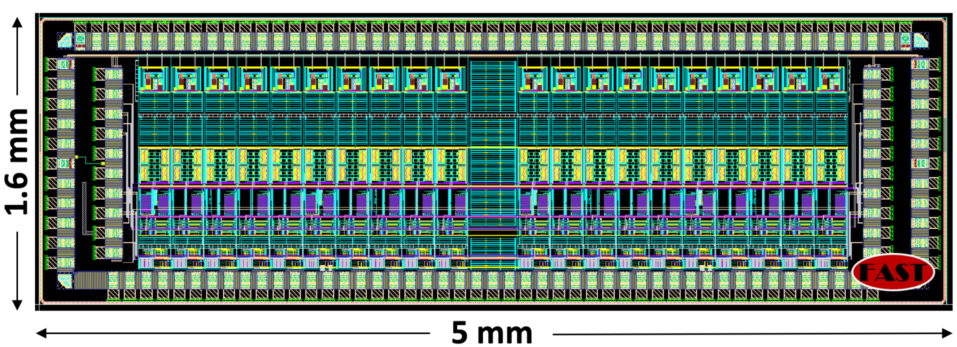


Readout electronic for timing: FAST

channel block diagram



Technology	CMOS 110 nm
Channels	20
Sensor capacitance	6 pF
Input dynamic range	3 fC – 60 fC
S/N	60
RMS noise (C=6pF)	700 µV
Power budget	< 2 mW/ch
AVDD/DVDD	1.2 V/2.5 V
Jitter (MPV)	25 ps



- Resistive feedback preamplifier stage
- ToA vs ToT based TW correction

ASIC submission date 22nd April, 2019

ASIC designers: Federico Fausti fausti@to.infn.it Jonhatan Olave olave@to.infn.it

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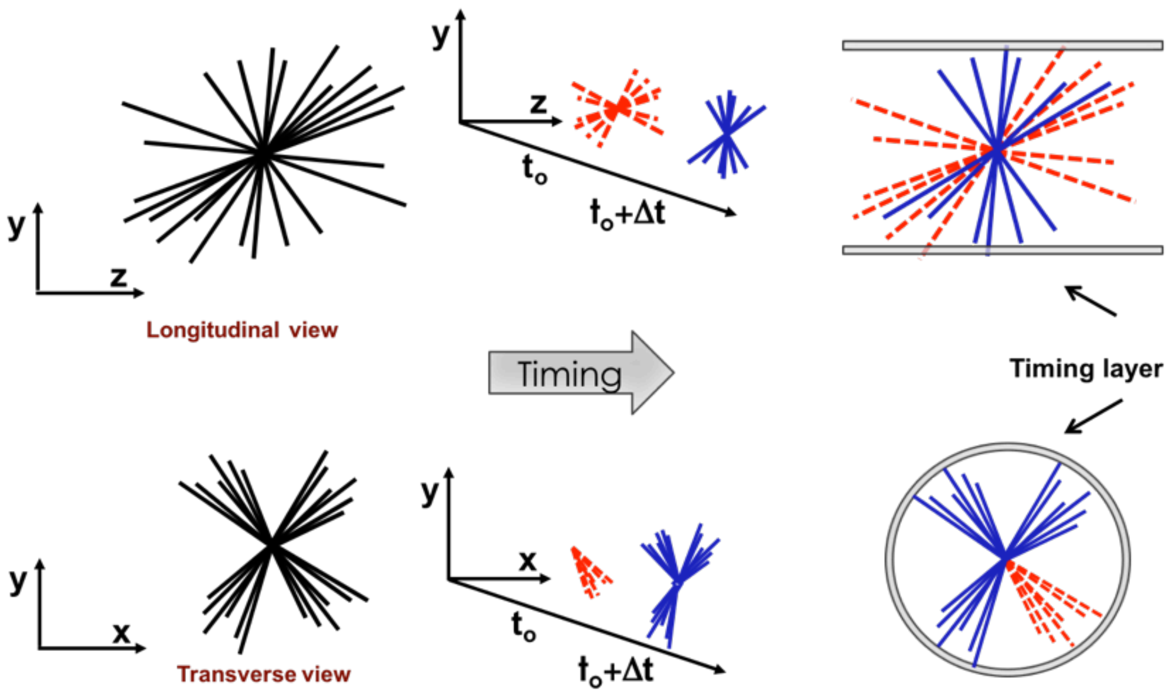
- Grant Agreement no. 654168 (AIDA-2020)
- Dipartimenti di Eccellenza, Torino Physics Dep. (ex L. 232/2016, art. 1, cc. 314, 337)

Backup

Timing in the event reconstruction

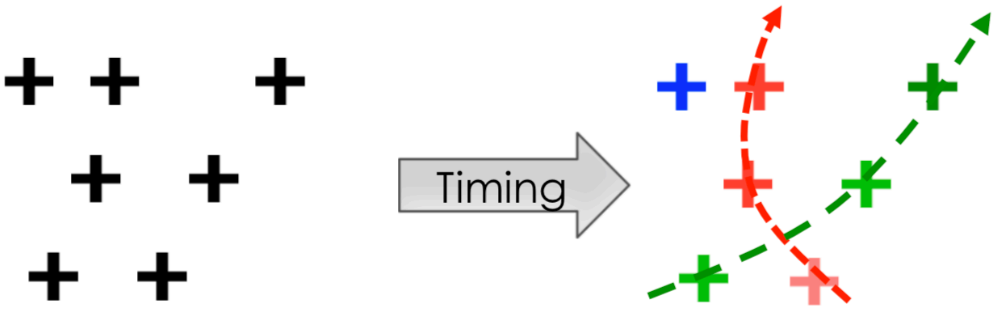
Timing allows distinguishing overlapping events



Timing at each point along the track

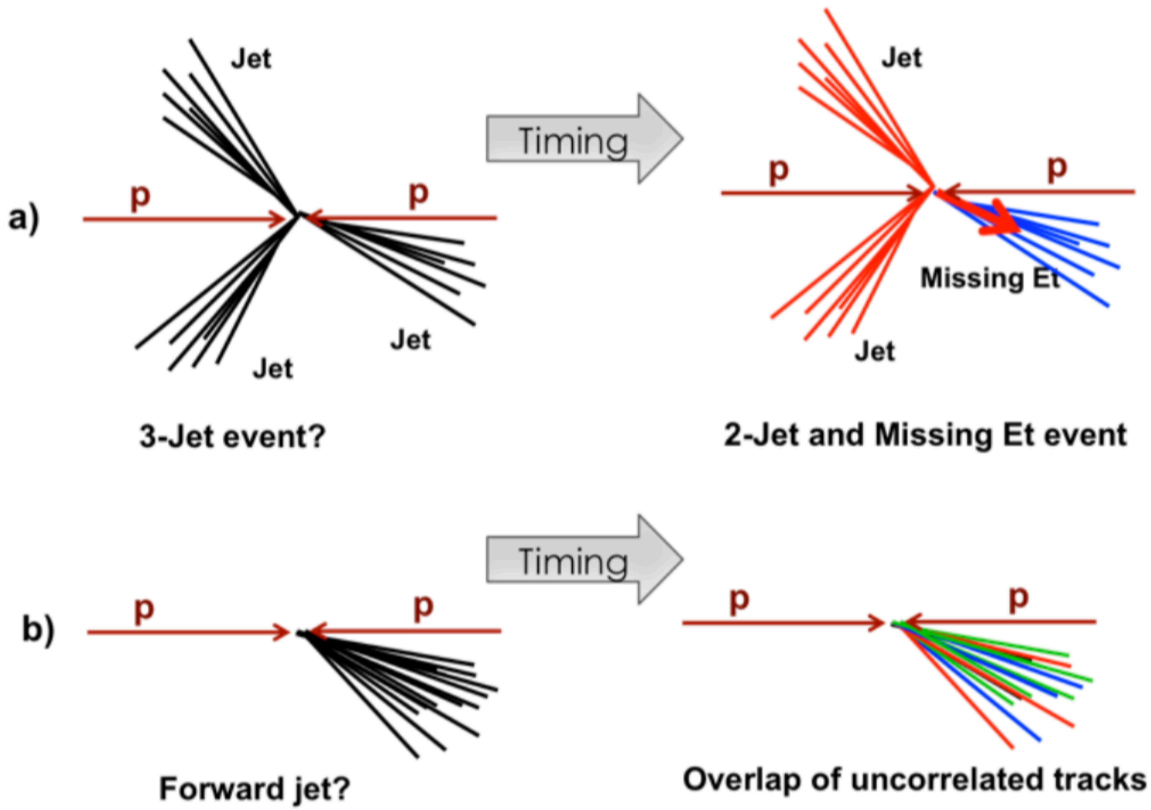
- Massive simplification in pattern recognition, new tracking algorithms will be faster even in high dense environments

- Use only compatible time



Timing at the trigger level

➢ Timing at the trigger decision allows reducing the trigger rate and rejecting topologies that look similar



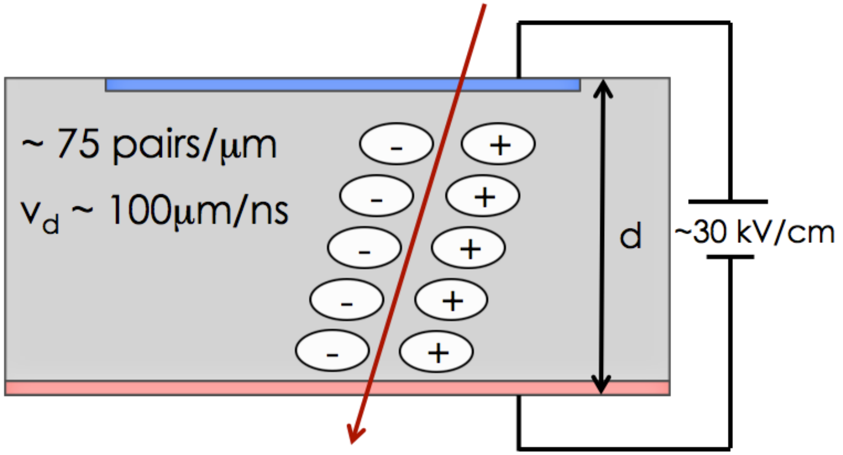
Signal formation in silicon sensors

A good time resolution requires fast and large signal (high slew rate)

How can you get fast and large signal in a silicon sensor?

What is controlling the slew rate?

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



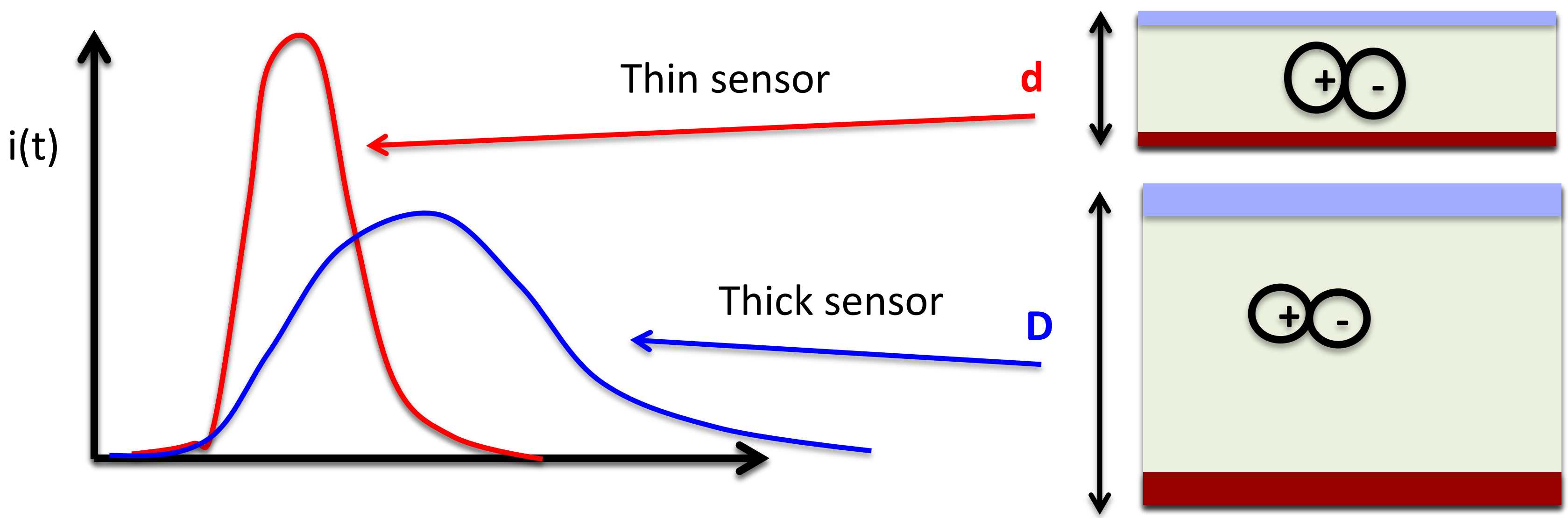
Signal formation in silicon sensor:
- Particle creates couple electrons/holes
- The charges star moving under the effect of an external bias
- The motion of the charge induce a current on the electrode
- Signal ends when the last charge is collected by the electrodes

Signal of one e^-/h^+ pair

Single electron and hole pair
The integral of their current is equal to the electric charge, **q**

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

Therefore the **signal shape** depends to the sensors thickness **d**



One e^-/h^+ pair generate faster signal in thin sensors

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

Weighting field

Signal in thick sensors

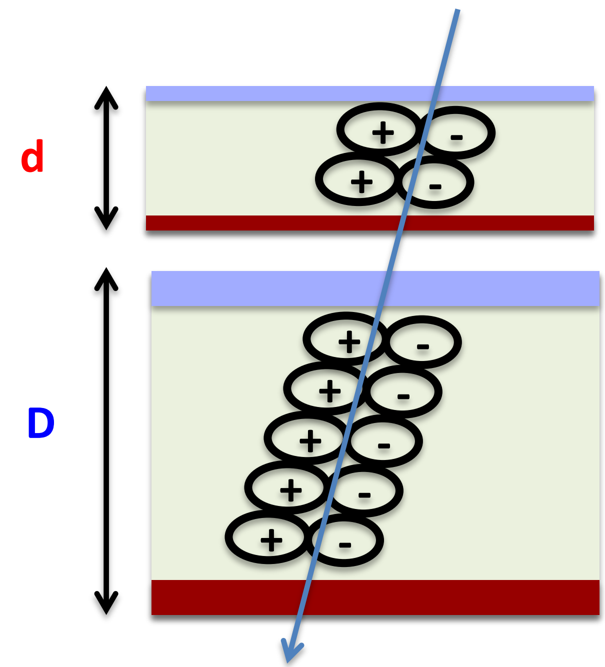
Thick sensors have higher number of charge:

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

Each charge contributes to the initial current as:

$$i \propto q * v * \frac{1}{d}$$

The initial current for a sensor does not depend to the thickness of the sensor



$$i = Nq * \frac{k}{d} v = (75 * d * q) \frac{k}{d} v = 75kqv$$

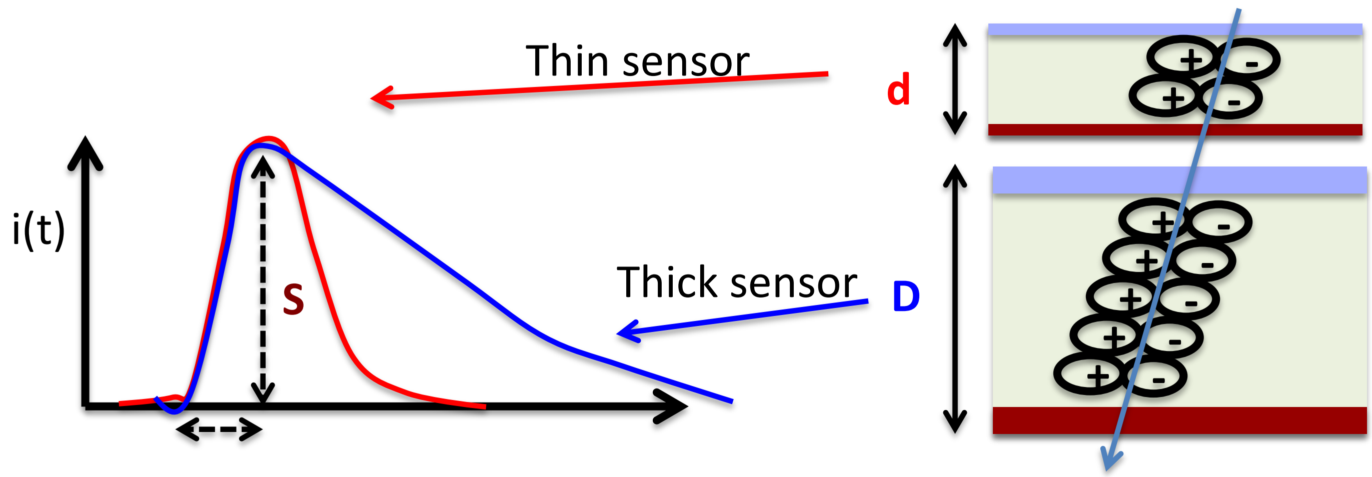
Number of e⁻/h⁺ (75/micron)

Weighting field

Drift velocity

Initial current is constant

Signal in thin and thick sensors



$$\boxed{\frac{dV}{dt} \sim \frac{Signal}{Rise\ time} \sim const}$$

Thick sensors have larger signal not higher signal

To have a higher signal we need to add gain

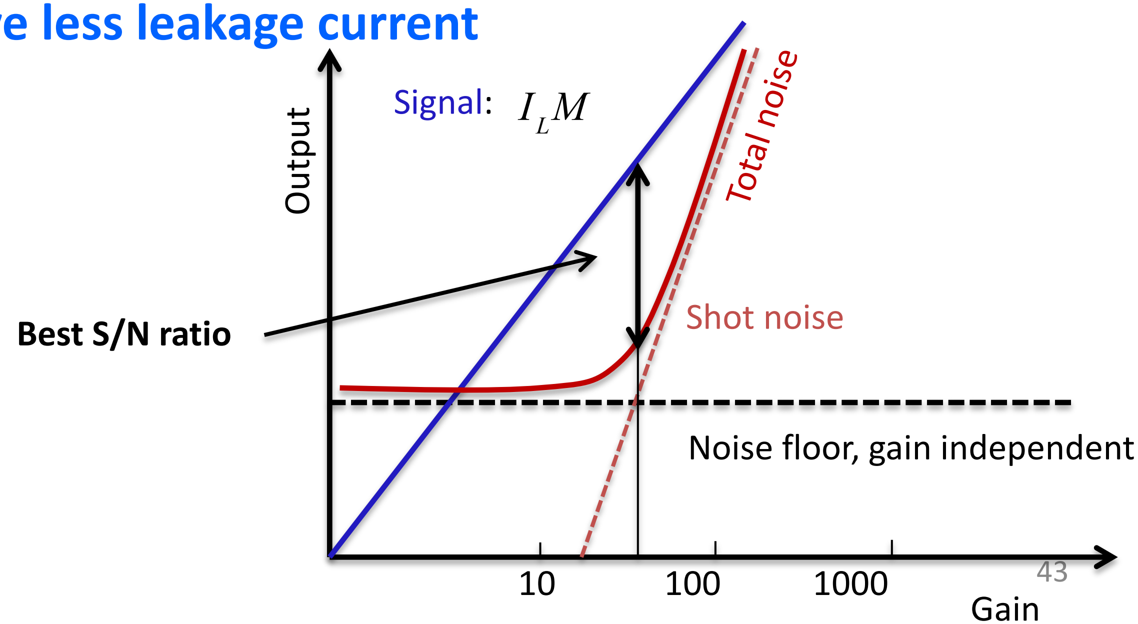
Shot Noise

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

Shot noise increases faster than the signal
The ratio S/N becomes worse at high gain

To minimize the shot noise:

- **Low gain (G = 10-20)**
- ☞ **Cool the detector**
- ☞ **Use small pads to have less leakage current**



Marco Ferrero, INFN, IV Streaming Readout workshop, Camogli 22-24 May 2019

Gain in silicon detectors

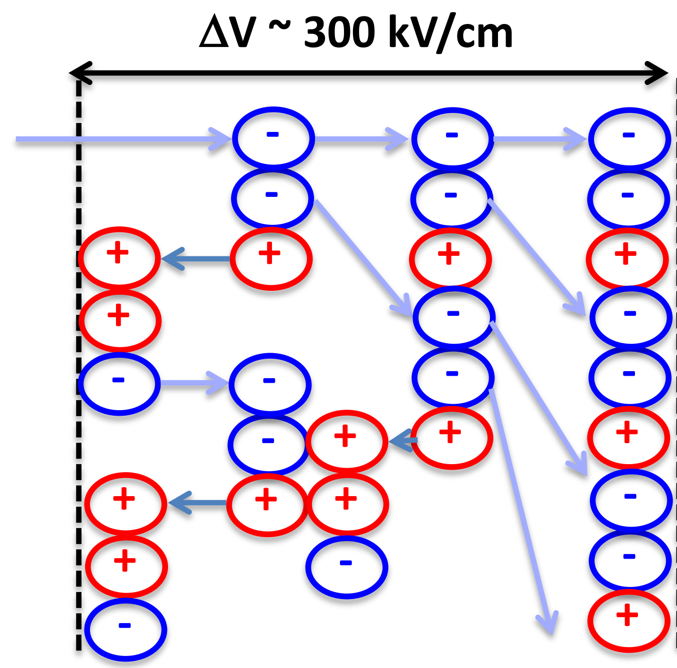
It’s based on the avalanche mechanism that starts in high electric fields: V ~ 300 kV/cm

Gain definition:

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

α = it is the inverse of a distance, strong function of E

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

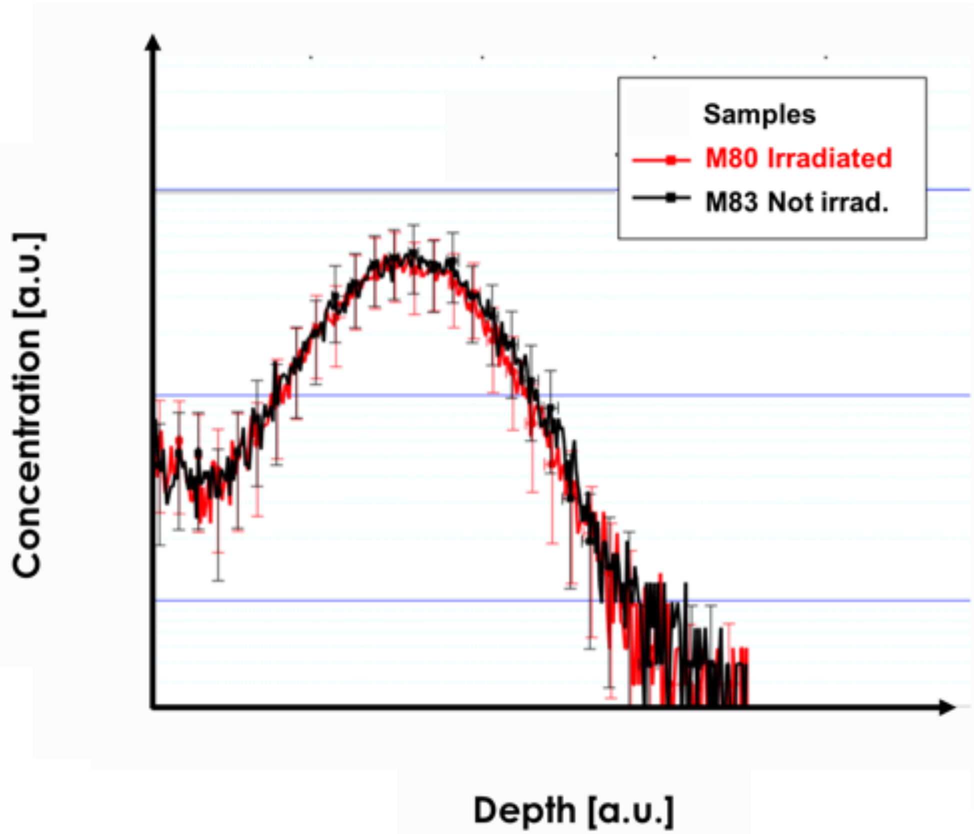


Concurrent multiplication of electrons and holes generate very high gain

Silicon devices with gain:

- **APD: gain 50-500**
- **SiPM: gain ~ 10^4**

What happened to the boron



SIMS measurement of Boron concentration into the gain layer on irradiated and not irradiated sensor

The Boron is still into the gain layer but is not active, instead of **being substitutional** (in the place of silicon atoms, electrically active) become **interstitial** (in the middle of the lattice, not electrically active)

Acceptor removal, methodology of measurement

Evolution of active acceptor density with fluence

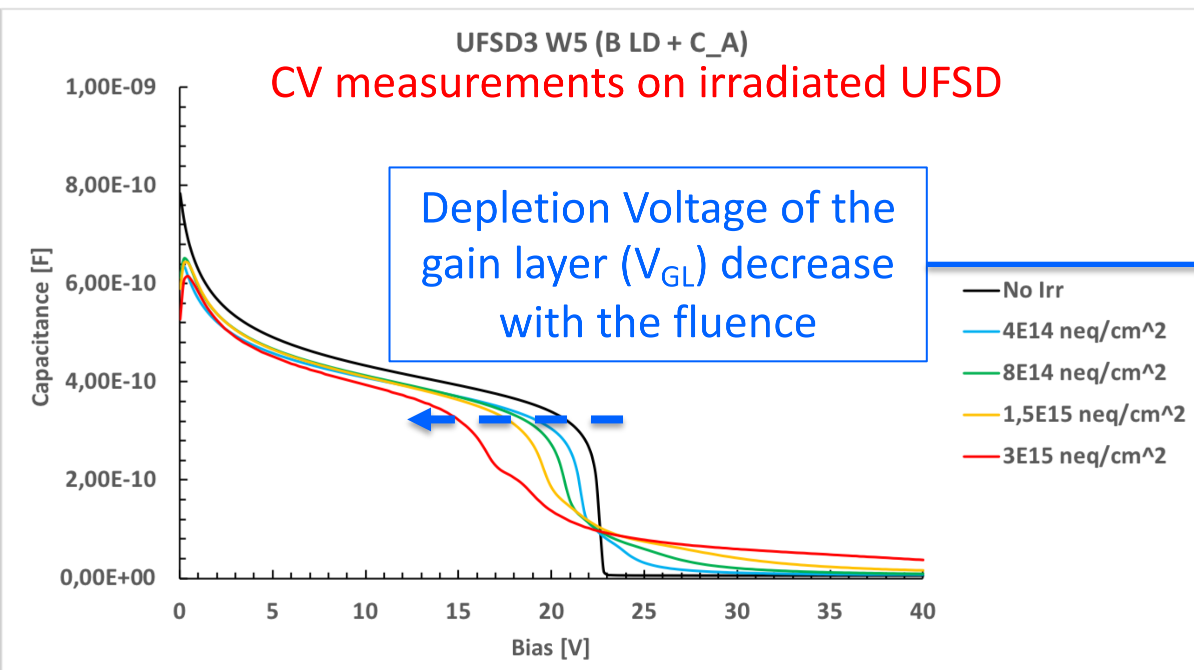
$$\boxed{N_A(\emptyset) = \underbrace{geff * \emptyset}_{\text{Acceptor creation}} + \underbrace{N_A(0)e^{-c\emptyset}}_{\text{Acceptor removal}}}$$

$\emptyset$ = fluence

$N_A(\emptyset)$, $N_A(0)$ = active acceptor density at fluence $\emptyset$ or initial

$geff$ = empirical constant (~0,02 cm^{-1})

c = initial acceptor removal coefficient



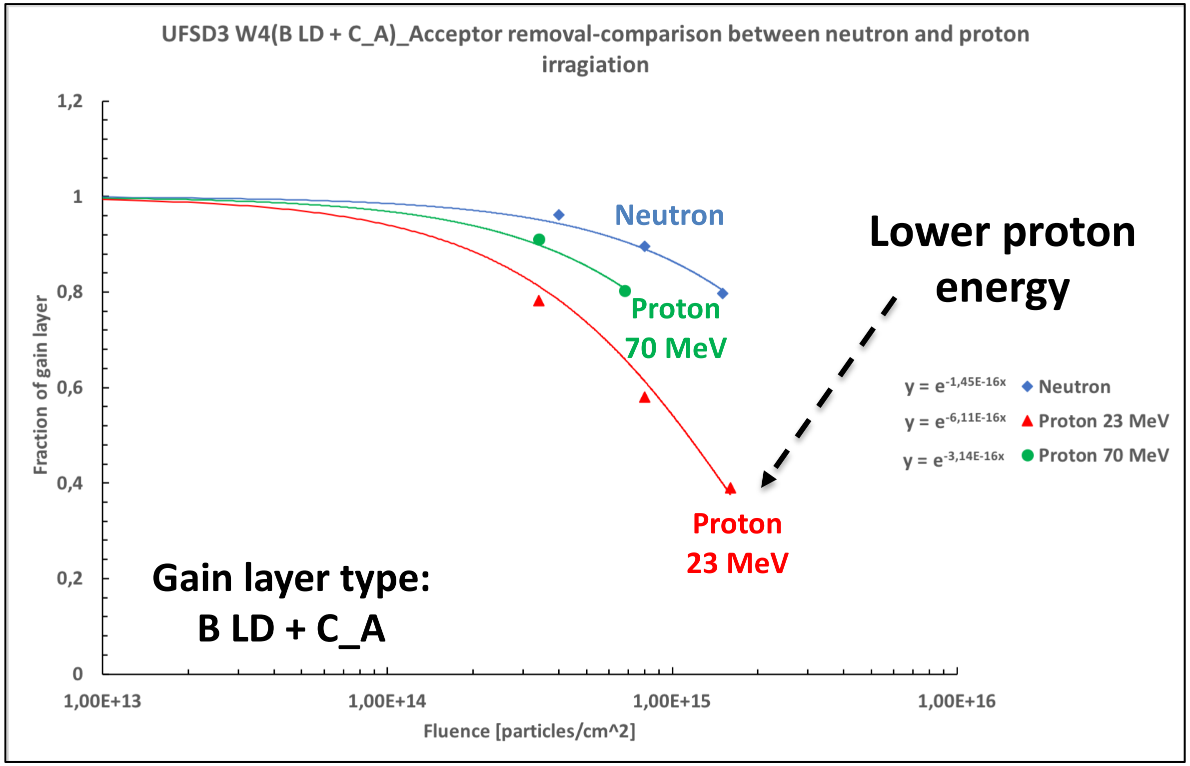
Depletion voltage of the gain layer is proportional to the amount of the active doping

$$V_{GL} = \frac{qN_A}{2\varepsilon_{SI}} * w^2$$

$$\boxed{\frac{N_A(\emptyset)}{N_A(0)} = \frac{V_{GL}(\emptyset)}{V_{GL}(0)} e^{-c\emptyset}}$$

Acceptor removal: comparison between neutron and proton irradiation

Low Energy proton (E_p < 100 MeV)

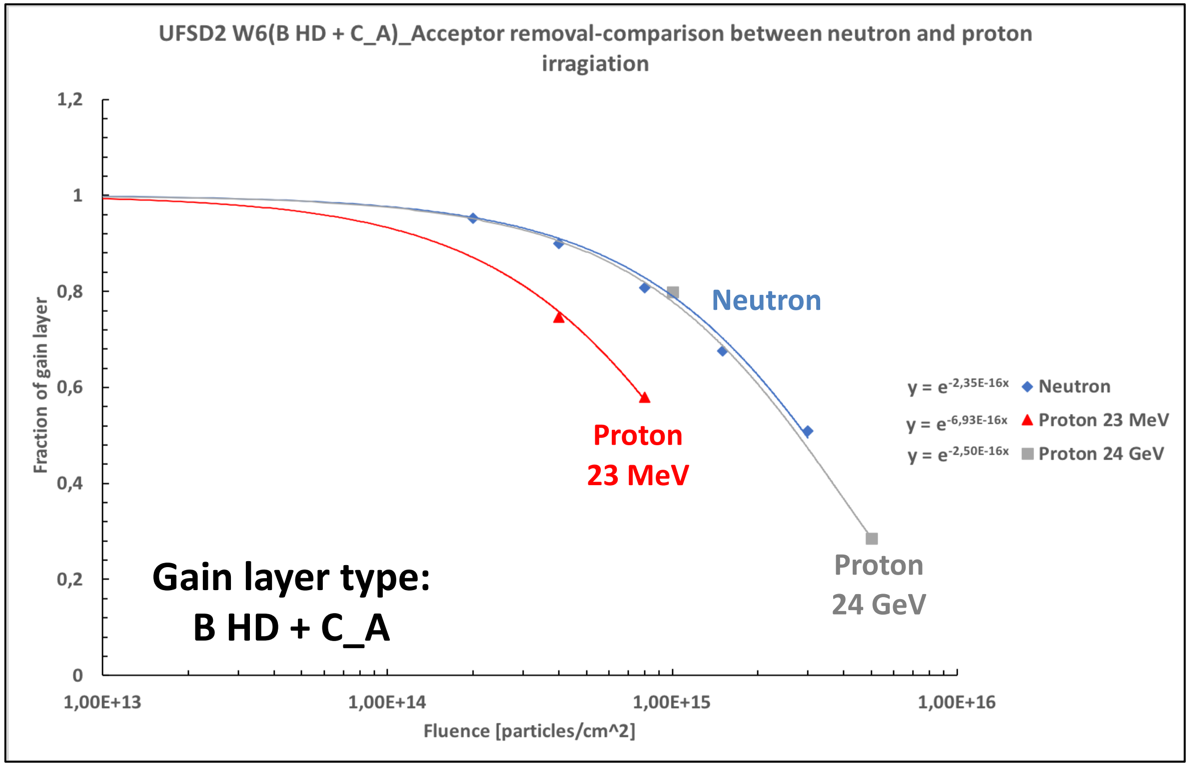


Fluence on the x axes expressed in Particle/cm²

- **Effect of proton energy**: low energy protons deactivate the gain layer faster than high energy protons
- The acceptor removal from protons of tens MeV is faster than that neutrons
- At a fluence of **1,5E15 particle/cm²**: the **fraction of gain layer** for proton at 23MeV is **half** than Neutron

Acceptor removal: comparison between neutron and proton irradiation

High Energy proton (E_p > GeV)



Fluence on the x axes expressed in Particle/cm^2

- Acceptor removal by 24 GeV/c protons and 1 MeV neutrons is very similar
- The damage induces into the gain layer by high energy proton (E_p>GeV) and neutron are similar.

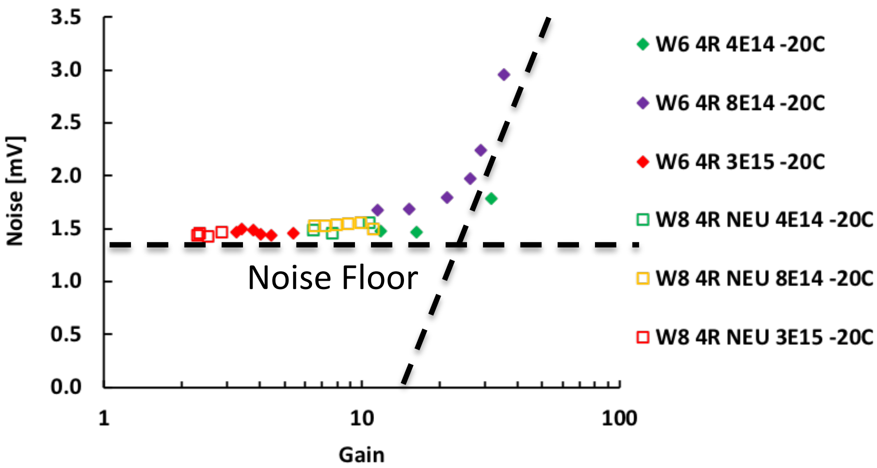
Noise of irradiated sensors

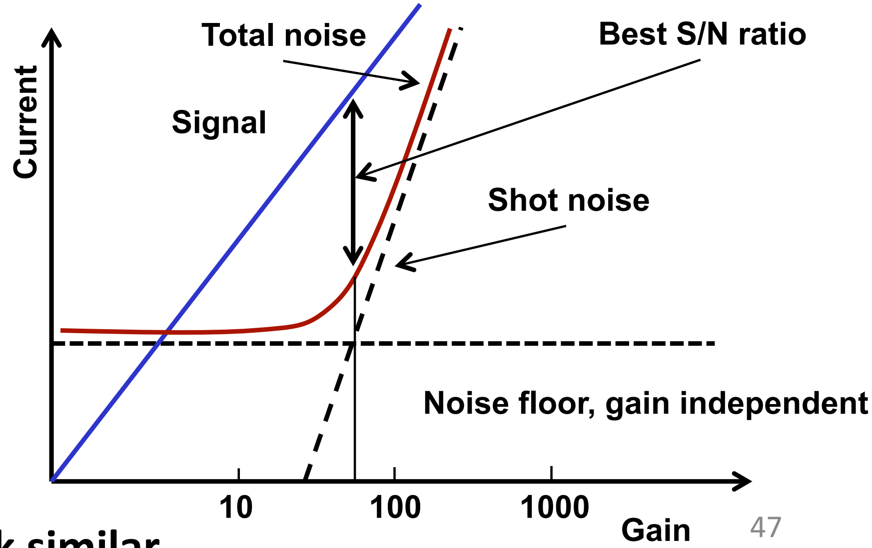
Jitter term contain electronic noise and Current noise

Current Noise due to the combination of **high leakage current** (shot noise) and **randomness of multiplication mechanism** (excess noise factor)

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

Goal: the noise from silicon current should stay below the noise of electronic



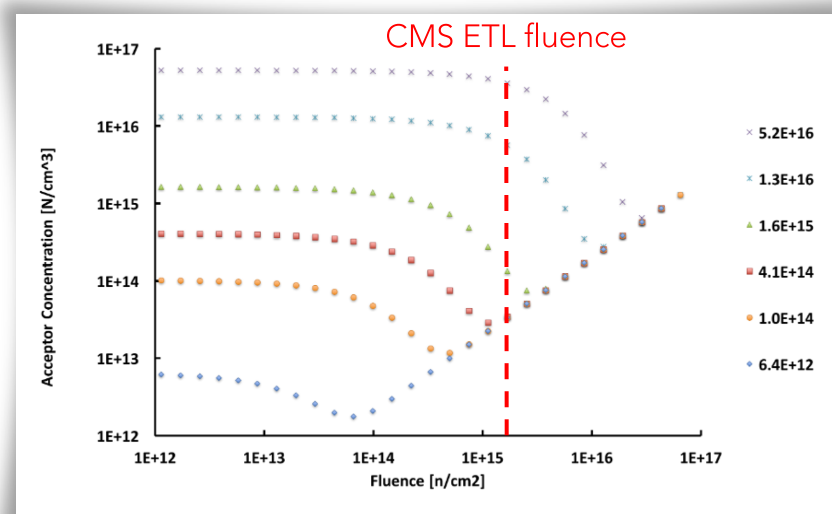


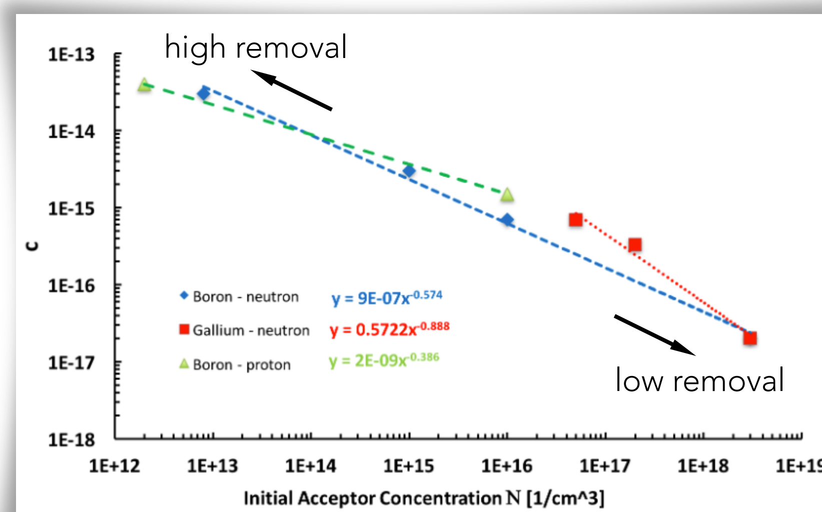
Data and model look similar

Empirical acceptor removal and creation

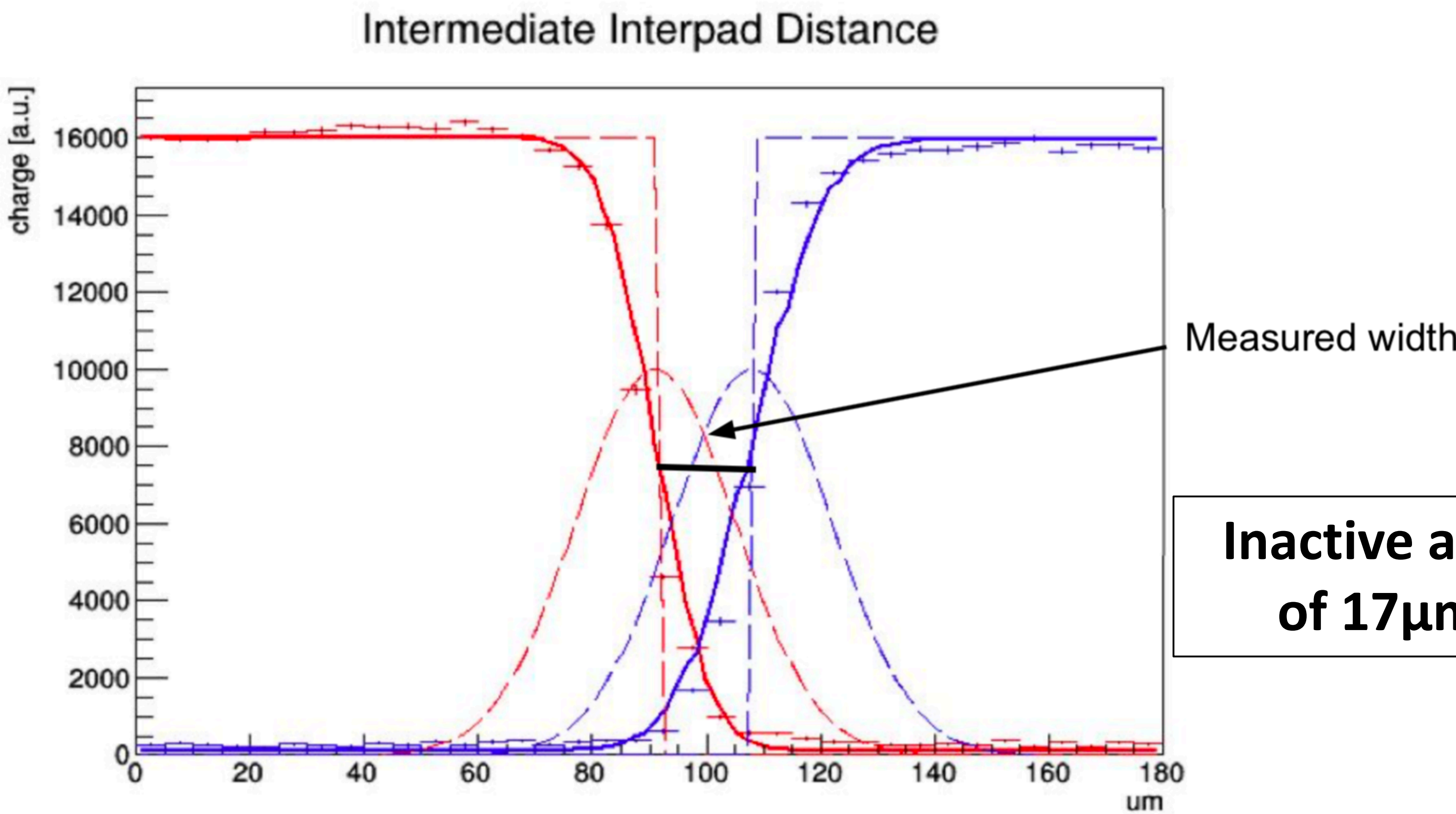
$$N_A(\phi, x) = g_{eff}\,\phi + N_A(0,x)\, e^{-c(N_A(0,x))\phi}$$

$$c\,(N_A(0,x)) = \alpha\, N_A(0,x)^{-\beta}$$





Laser measurement of inactive area in more aggressive UFSD design



Inactive area of 17µm