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AIDA-2020

Advanced European Infrastructures for Detectors at Accelerators

Presentation

State-of-the-art and evolution of UFSD sensors design at FBK

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State-of-the-art and evolution of UFSD sensors design at FBK

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12th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking detectors (HSTD12)

The UFSD project: brief history

Project goal: develop a silicon detector with excellent time and space resolution, able to achieve concurrently

Timing resolution ~ 10's ps
Space resolution ~ 10's of μm

suitable for tracking in 4 Dimensions
baseline: LGADs optimized for timing

The UFSD project: brief history

2010: LGAD proposed & developed at CNM within RD50 collaboration

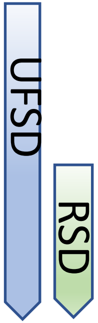
2012: First 4" wafer 300 µm thick, LGAD produced by CNM

2016: UFSD1 First 300 µm thick LGAD **(FBK 6" wafer)**

2017: UFSD2 First 50 µm thick LGAD (FBK 6" wafer)
Gain layer doping: Boron, Gallium, Boron + Carbon, Gallium+Carbon

Fall 2018: UFSD3 50 µm LGAD (FBK 6" wafer), produced with the stepper (many Carbon levels, studies of interpad design)

June 2019: UFSD3.1 50 µm LGAD (internal FBK) interpad design.
RSD1 Resistive AC-LGAD

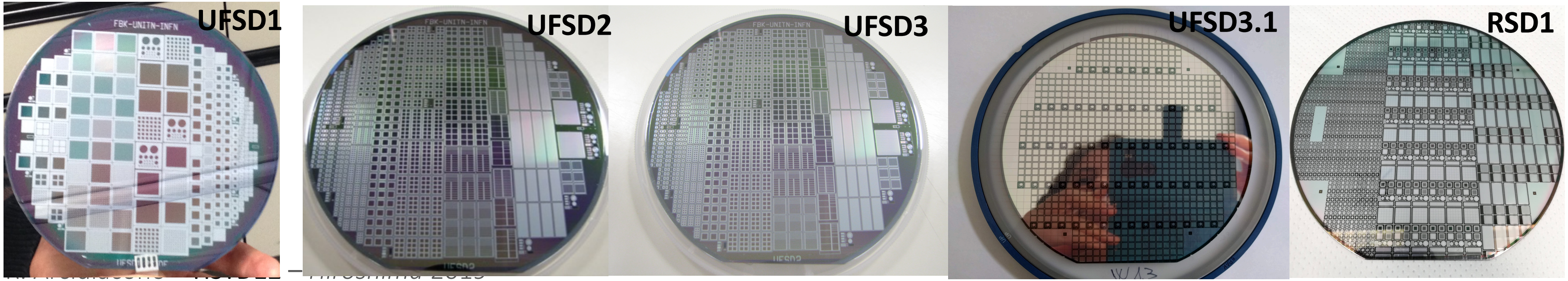


Let's start with big pads

[for timing applications - CMS ETL /ATLAS HGTD]

...

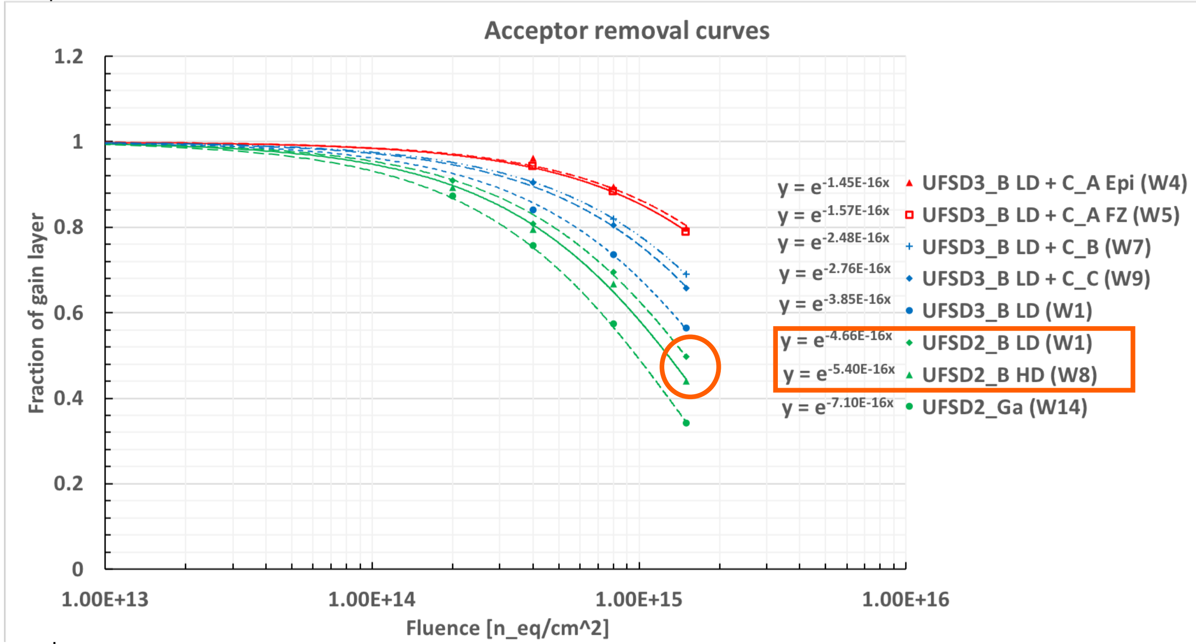
while working towards to ultimate small pixel matrix



On radiation hardness

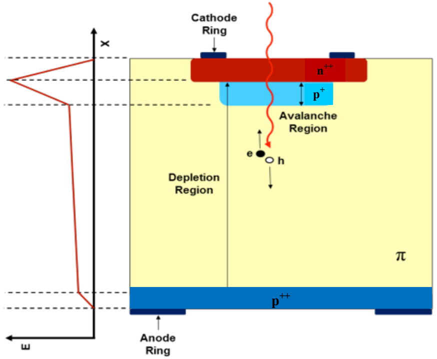
Radiation level changes the doping concentration of the gain layer, so it changes the way the device works

$$\frac{N_A(\Phi)}{N_A(0)} = e^{-c(NA(0))\Phi/\Phi_0}$$



Smaller c, better resistance

- Gain layer Low Diffusion (LD - narrower) are more radiation resistant than the High Diffusion HD type



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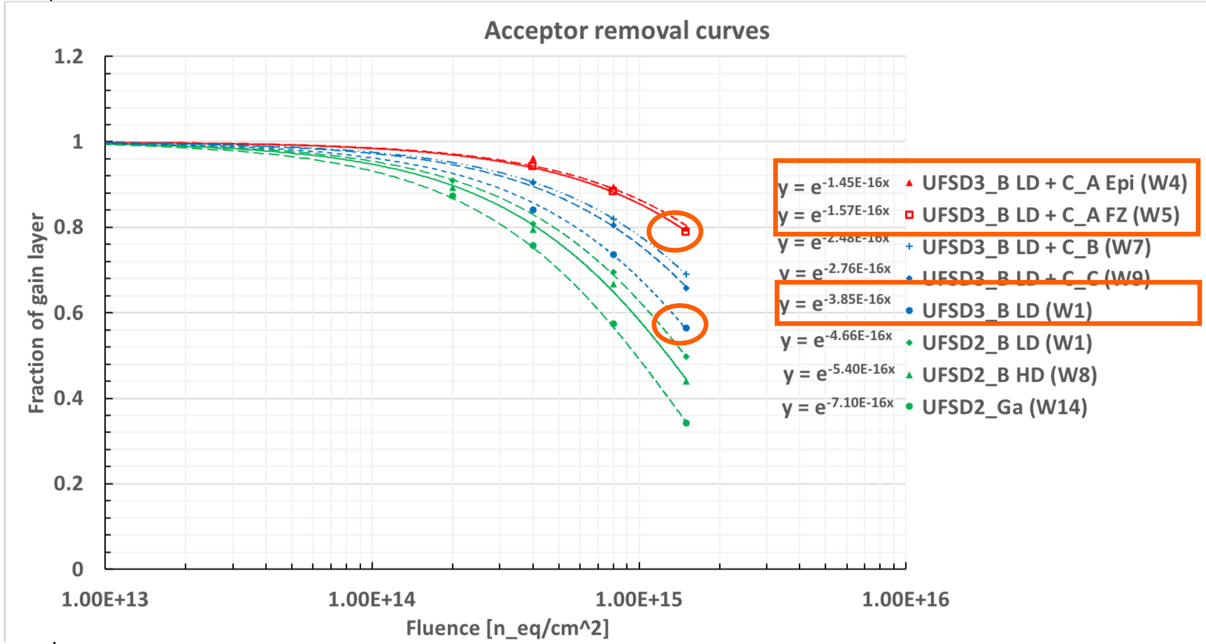

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- Gain layer Low Diffusion (LD - narrower) are more radiation resistant than the High Diffusion HD type
- the addition of carbon improves by a factor of ~2 the radiation resistance

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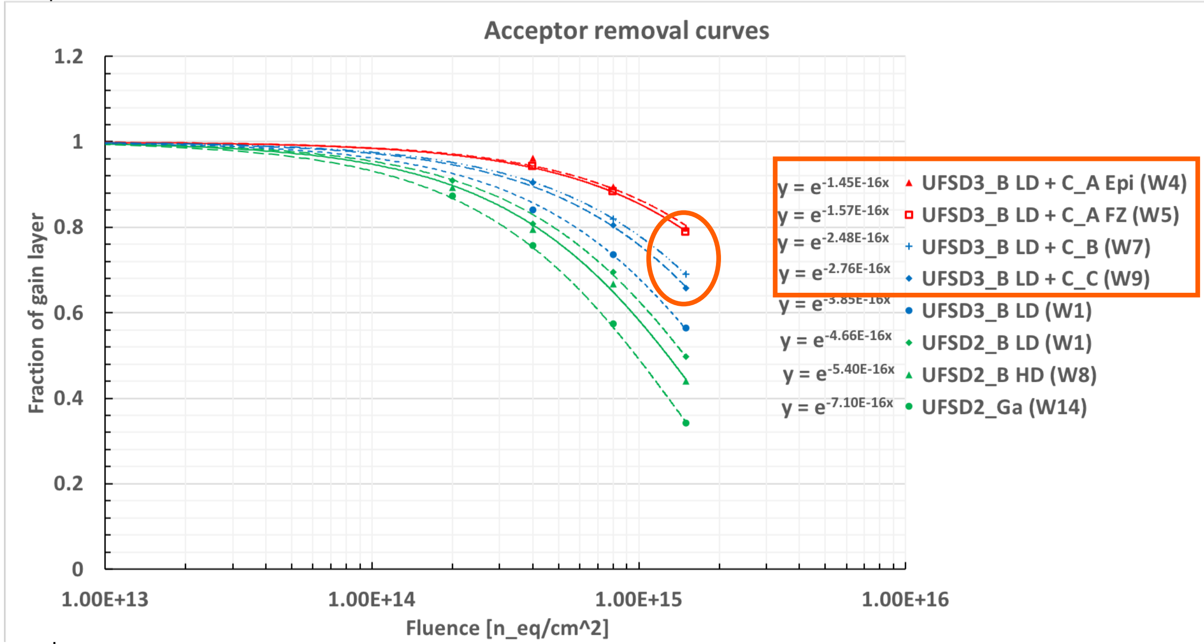


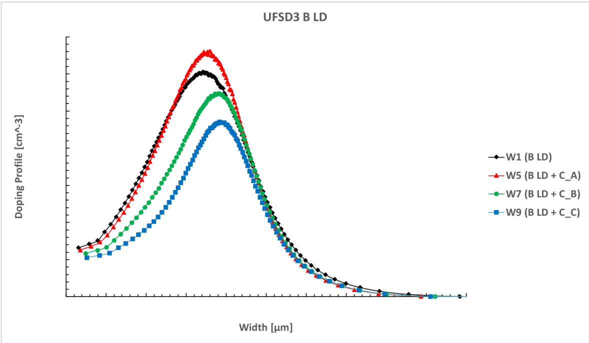
Smaller c, better resistance

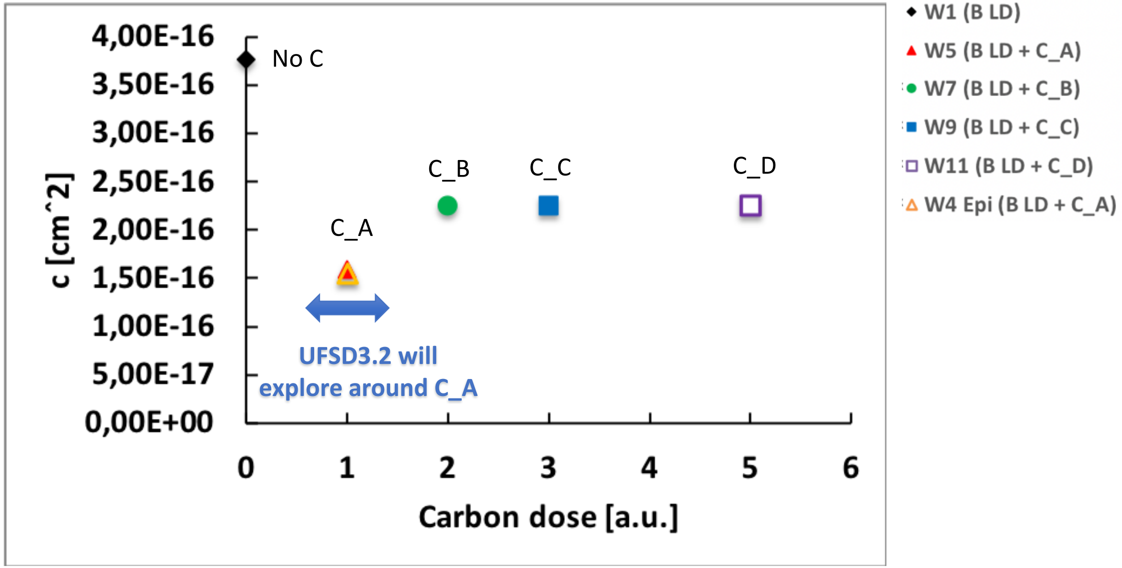
- Gain layer Low Diffusion (LD - narrower) are more radiation resistant than the High Diffusion HD type
- the addition of carbon improves by a factor of ~2 the radiation resistance
- dose C_A shows the best radiation resistance (both Epi and FZ are the same)
- increasing the carbon dose does not necessarily improves the rad. hardness

Acceptor removal coefficients "c"

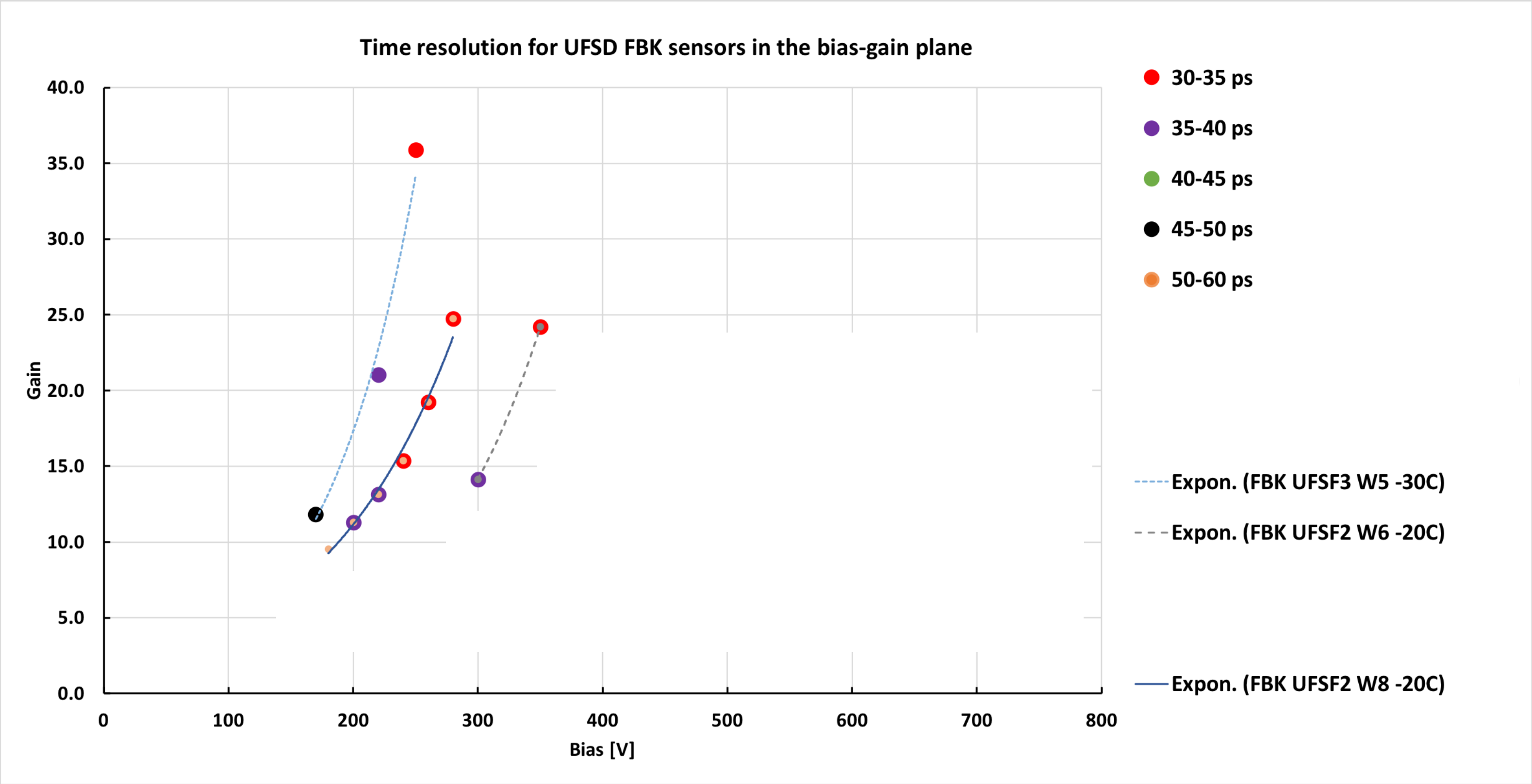
In UFSD3 the radiation hardness **degrades** as a function of the **Carbon doses.**
Carbon also reduces the amount of active gain layer, when co-implanted.
After correcting for the different initial Boron density:

- C_A shows the best radiation resistance (both Epi and FZ are the same)
- C_B, C_C, and C_D doses are equally radiation hard





Present time resolution (best of UFSD2/3)



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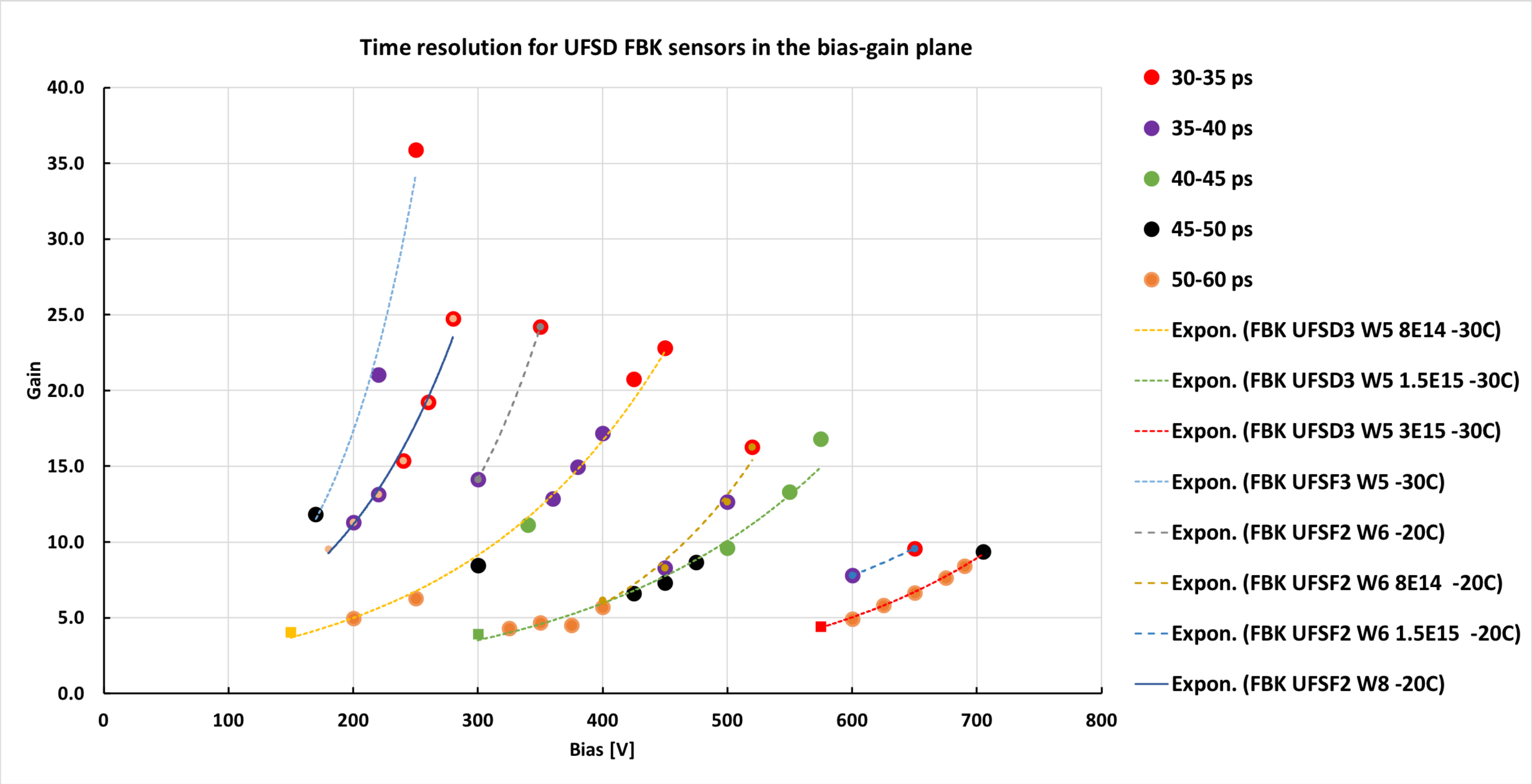
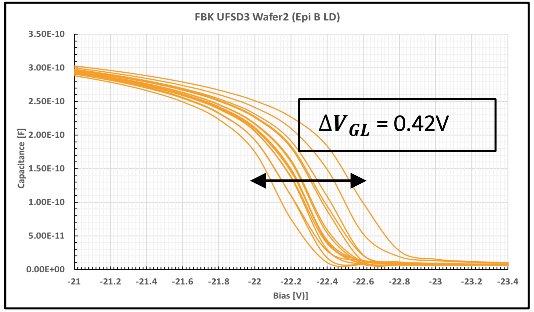


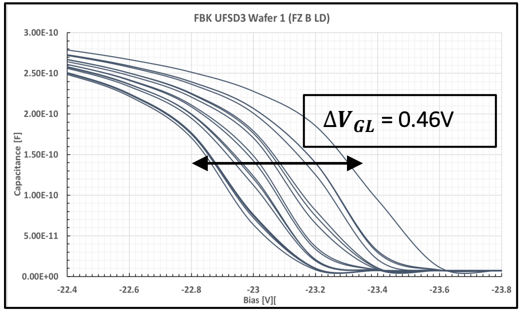
Time resolution depends upon the gain and the holes drift velocity (∝ Vbias)

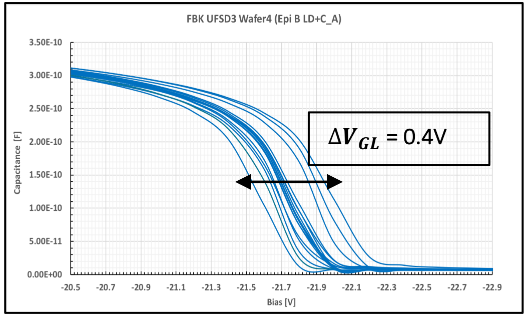
On the gain layer uniformity

Study of the gain layer uniformity on UFSD3 wafers by measuring CV of several pads.

V_{GL} is proportional to the amount of active doping in the gain layer.







The three wafers tested show a non-uniformity of depletion voltage of gain layer of about 2%

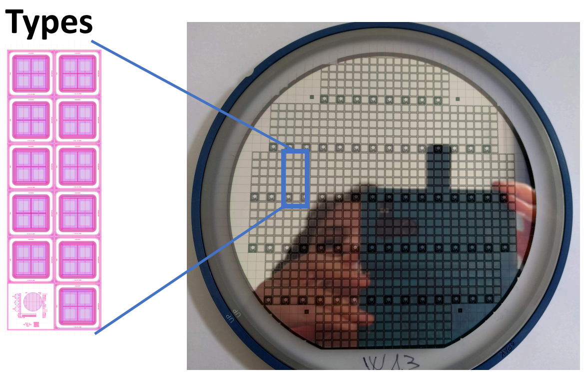
$$\Delta V_{GL}/V_{GL} \sim 2\%$$

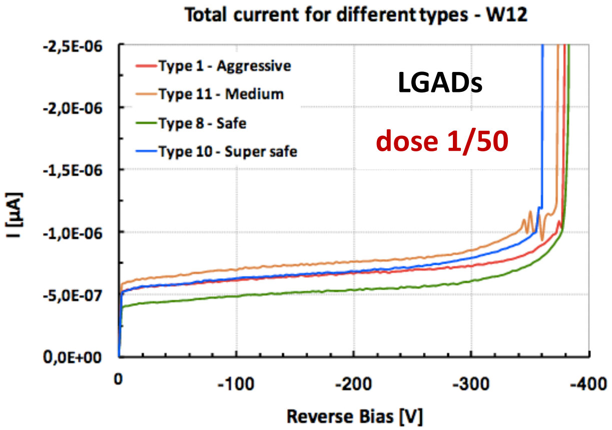
The non-uniformity is lower than 2% when excluding sensors at the periphery of the wafers

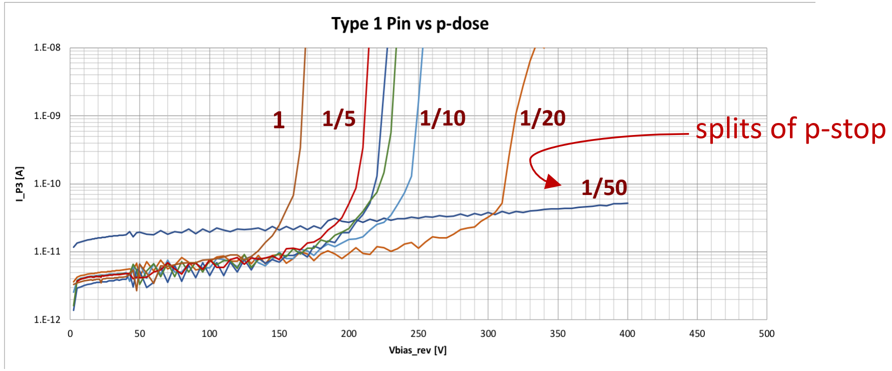
UFSD 3.1: internal FBK run

Production designed to understand/fix some problems of **early breakdown and "pop-corn" noise observed in UFSD3,** due to a combination of very aggressive edge design and incorrect p-stop doping

- 7 wafers – LGADs param. as W12 (different splits of p-stop – in units of UFSD3 p-stop dose)
- 11 different types of 2x2 matrices (pad size 1.3x1.3 mm^2)







Clear dependence of the BD from p-stop doping -> appropriate p-stop doping range identified. Pop-corn noise absent in the three lowest p-stop doses. Now sent to irradiation…

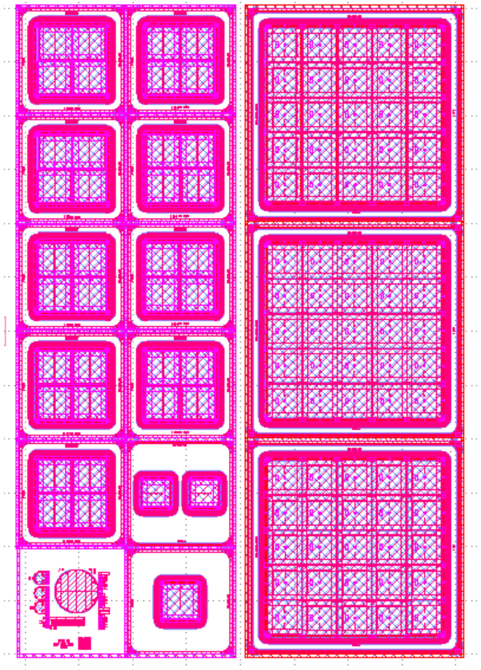
The next step: UFSD3.2

Goal of UFSD3.2 (R&D and CMS ETL oriented production)

- On radiation hardness of the sensor:
  - explore lower carbon levels (gain layer)
  - explore gain layer deep implant combined with Carbon
- study performance of aggressive interpad solutions on small matrices
- validate the p-stop dose selected
- provide 3 conservative version of 5x5 matrices (“ALTIROC” – like)

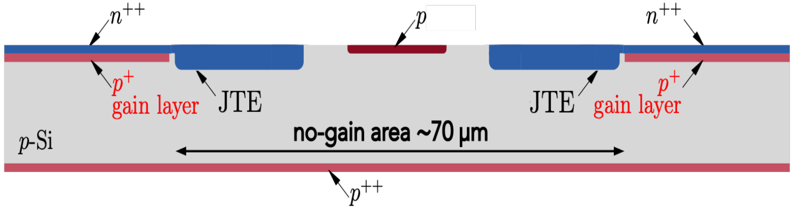
19 different splits (wafers)

Expected delivery: Q1/2020



4D tracking sensors and Fill Factor

In the current UFSD design, isolation structures between readout pads represent a no-gain area for signal collection



present size of no-gain area is in the 40-100 µm range

measured with TCT laser setup and @Beam Test

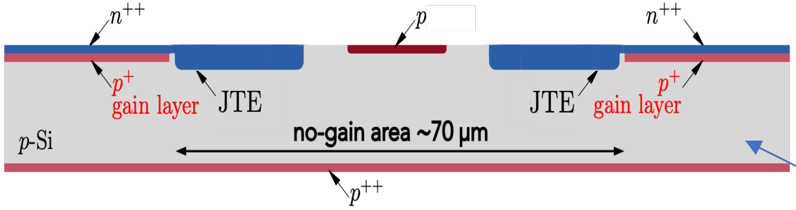
Vendor	Prod	no-gain area (microns)
FBK	2018 (UFSD2)	70
FBK	2019 (UFSD3)	40
HPK	2019	75
CNM	2018	70

Fill Factor for a 1.3 mm pitch pad matrix = 94%

Fill Factor for a 100 µm pitch pixel matrix = 36%

4D tracking sensors and Fill Factor

In the current UFSD design, isolation structures between readout pads represent a no-gain area for signal collection



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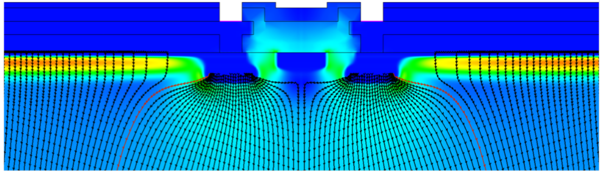
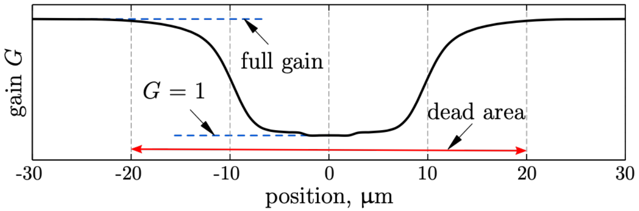
qualitative sketch





TCAD simulations performed on 50-µm UFSD sensors show that a no-gain area of about 20 µm could be reached with aggressive designs of the LGAD pad isolation structure and JTE

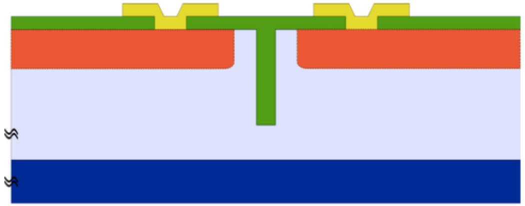
NEW technological developments:

- Trench-Isolated LGAD (TI-LGAD FBK internal run)
- Resistive AC-coupled LGAD (RSD project)

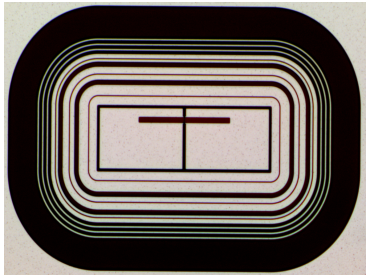
see G. Paternoster's talk today for more technical details

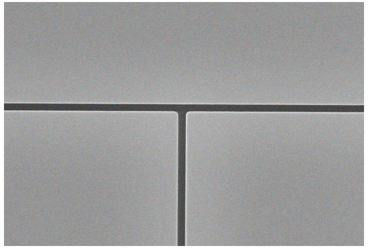
Towards 100% Fill Factor: TI-LGAD

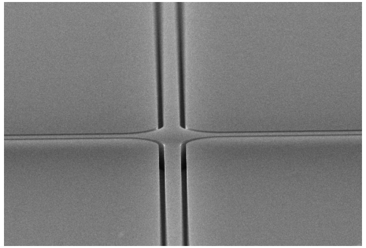
Trench-Isolated LGADs: pad isolation design substituted by shallow tranches (Deep Trench Isolation technology, < 1 µm wide)



Courtesy G. Paternoster







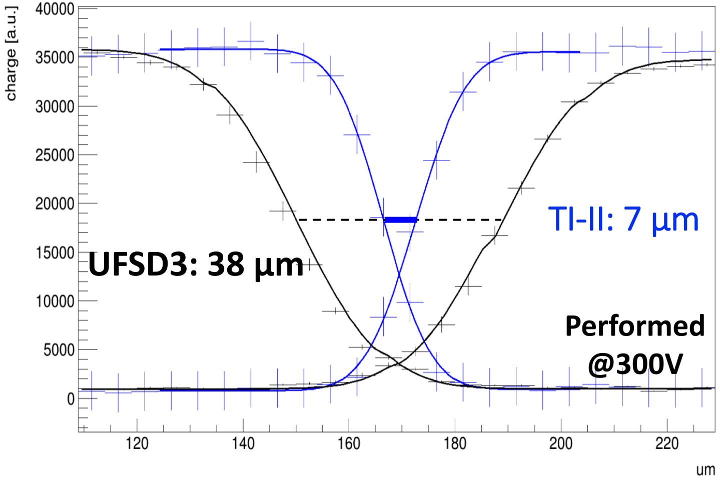
First test run produced at FBK in 2019 ("proof of concept" run)
structures: 2x1 pixels (250 µm × 375 µm) with single-trench and 2-trenches isolation

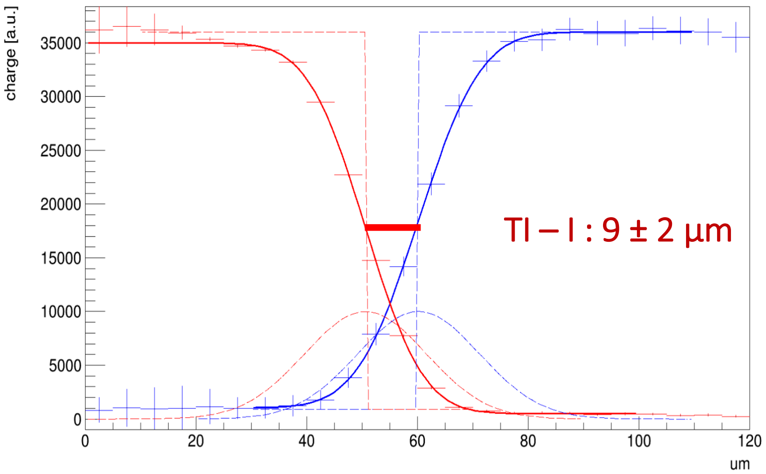
Tested so far:

- pad isolation ✓
- Breakdown and Gain measurements (behave as standard LGADs) ✓
- Interpad distance with TCT laser scan on the optical window ↩

TI-LGAD: performances

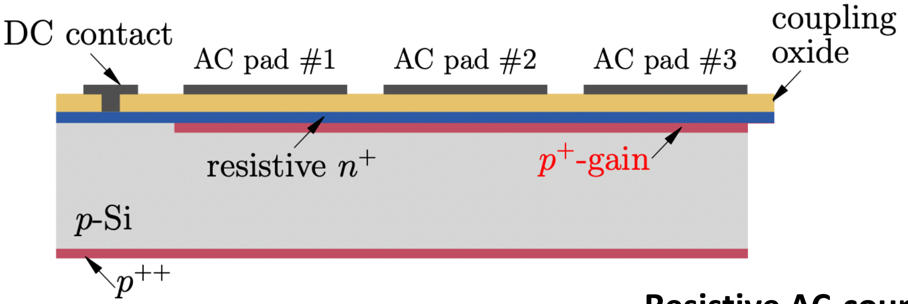
Inter-pad*: Comparison of UFSD3 vs Trench-Isolated (2 trenches) and Trench-Isolated (1 trench) W5*

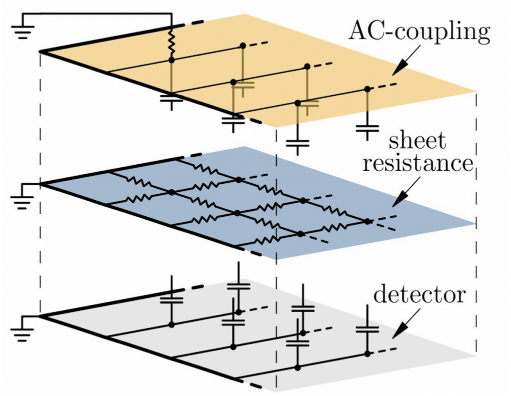




Detailed studies of the full production (30 split of wafers) still ongoing.
Preliminary results on noise at high voltage, and on time resolution show no problem.
Structures sent to irradiation…
New TI-LGAD production (RD50 project) will be ready in Q2/2020.

Towards 100% Fill Factor: AC coupled-LGAD





Resistive AC-coupled LGAD (RSD) are designed as detectors with 100% Fill Factor

- **One continuous gain layer**
- **Segmentation of read-out pads defines spatial resolution**
- **Easy structure with a reduced number of edges, more resistant**

First FBK RSD production delivered in May 2019.

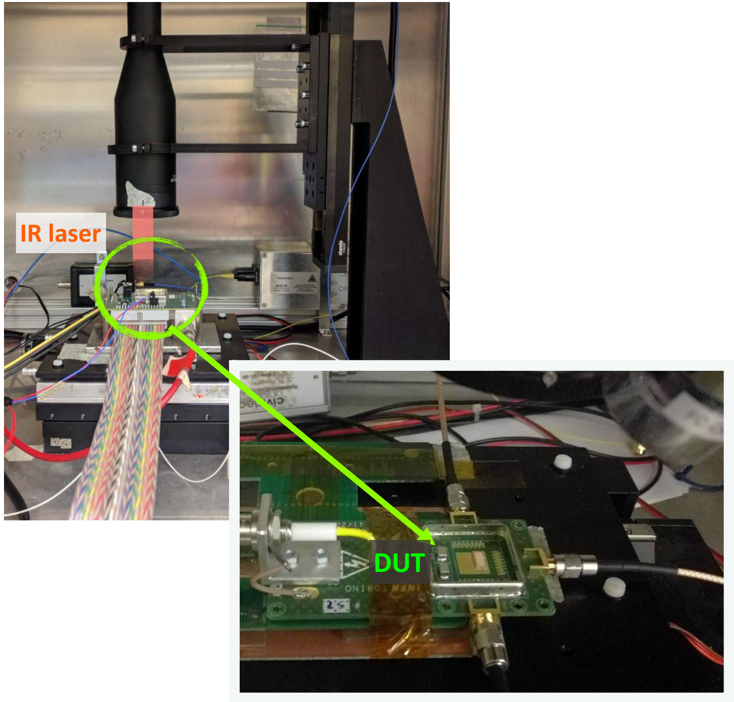
- 15 wafers (different splits in resistive sheet dose, gain dose and oxide thickness)
- several structures designed (for testing purposes or specific application oriented)

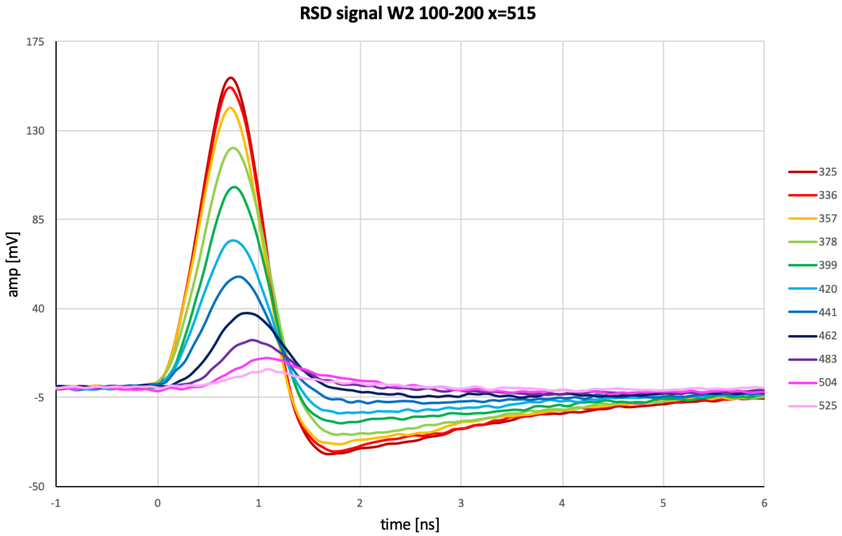
naming convention ***W2 3X3 100-200***

wafer ID ***matrix type*** ***AC pad size*** ***pitch***

TCT measurements for space and time resolution

TCT picosecond Laser setup, 1064 nm
spot size 10 µm
Stages with micrometrical precision



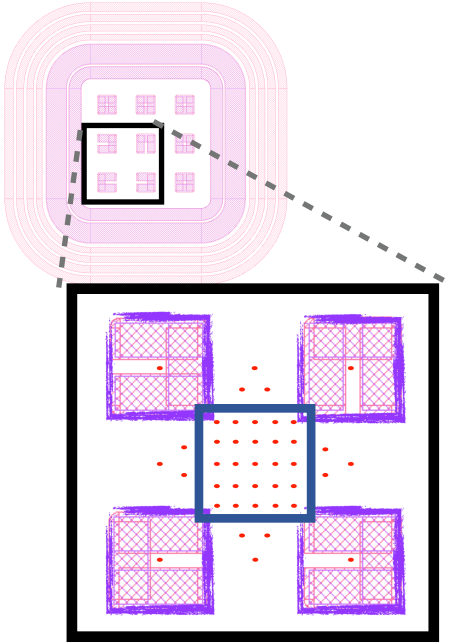


RSD signals reach their maximum when the laser is shot in the middle of the AC pad, and get smaller (and delayed) moving away from the pad: **the signal created by a particle is visible in several pads.**

We can exploit this feature to obtain excellent space and time resolution

Space resolution extraction

RSD W2 3X3, (operated to have gain=17) on multi-channel amplifier board
Laser shot on red dots, intensity ~ 1 MIP - 4 AC pads read out, ~500 triggers in each point
Reconstruction of hits position is obtained as amplitude-weighted centroid



$$x_{reco} = \frac{\sum_{i=1}^{i=4} x_{pad}(i) * Amp(i)}{\sum_{i=1}^{i=4} Amp(i)}$$

Space resolution is obtained as the sigma of the Gaussian distribution of $x_{laser} - x_{reco}$

Very recent measurements and analysis.
NB: the amplifier outputs still need to be calibrated to give the same amplification -> possible offsets of central values

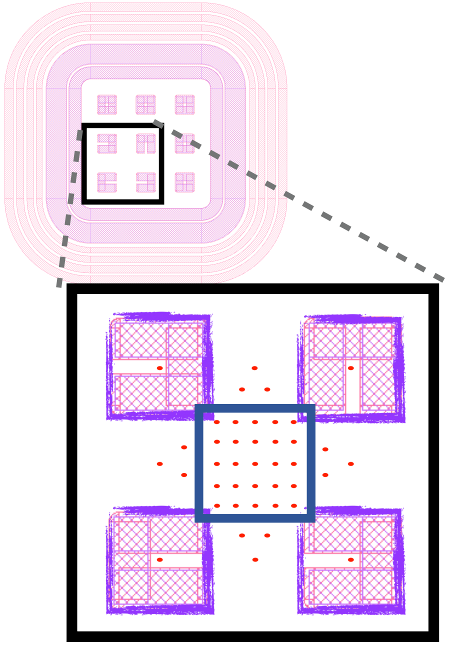
RSD: space resolution

RSD W2 3X3, (operated to have gain=17) on multi-channel amplifier board

Very Preliminary

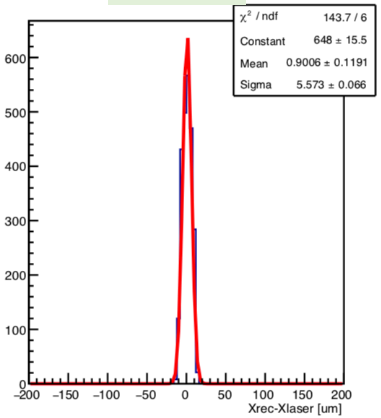
Laser shot on red dots, intensity ~ 1 MIP - 4 AC pads read out, ~500 triggers in each point

Reconstruction of hits position is obtained as amplitude-weighted centroid



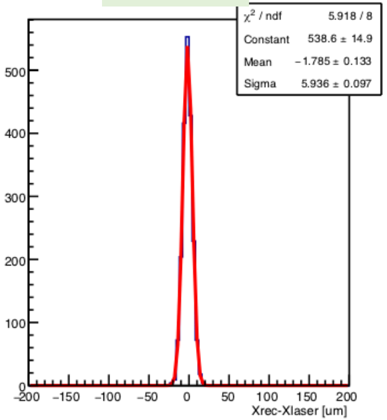
Considering only the shot positions where you have a good signal from at least 4 pads, the following space resolutions are obtained

50-100



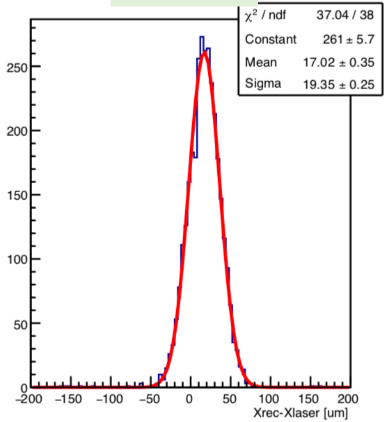
$\sigma_x \sim$ 6 µm

100-200



$\sigma_x \sim$ 6 µm

200-500



$\sigma_x \sim$ 20 µm

much better than the sensor pitch/√12 (29, 58, 144)

Time resolution extraction

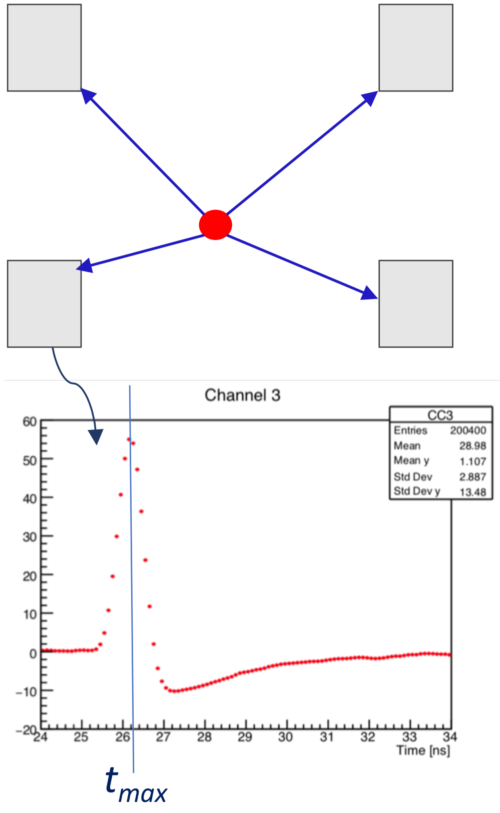
Using the same data from TCT laser scans (as described before) **the time reconstruction is obtained as an amplitude-weighted centroid of the t_{max} seen by the 4 pads:**

$$t_{hit} = \frac{\sum_{i=1}^{i=4} t'_{max}(i) * Amp(i)}{\sum_{i=1}^{i=4} Amp(i)}$$

where the $t'_{max}(i)$ is the time corrected for:

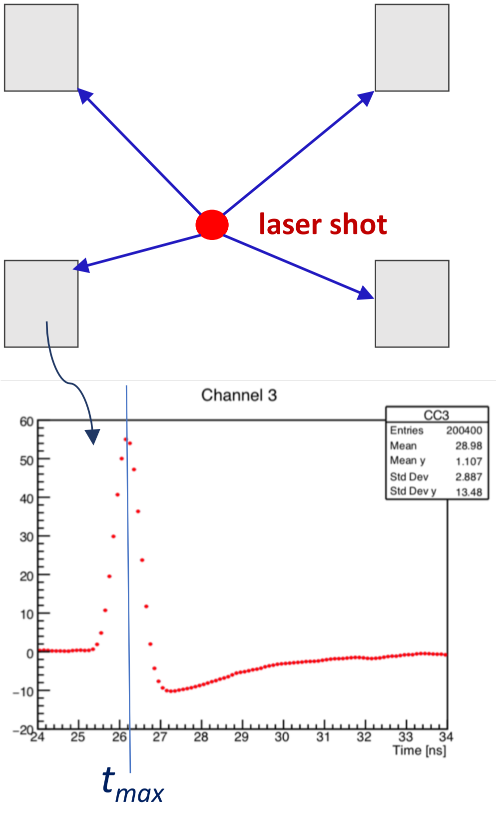
- delay due to propagation time to the read-out pad $dist(i)/speed$
- a time offset $t_{offset}(i)$ due to difference in the connection length of the read-out channel

$$t'_{max}(i) = t_{max}(i) - t_{offset}(i) - dist(i)/speed$$



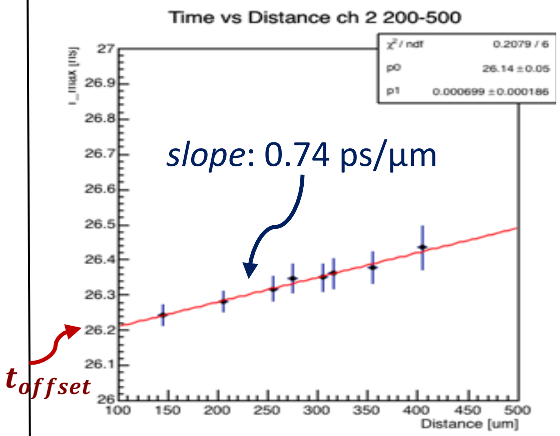
Time resolution extraction

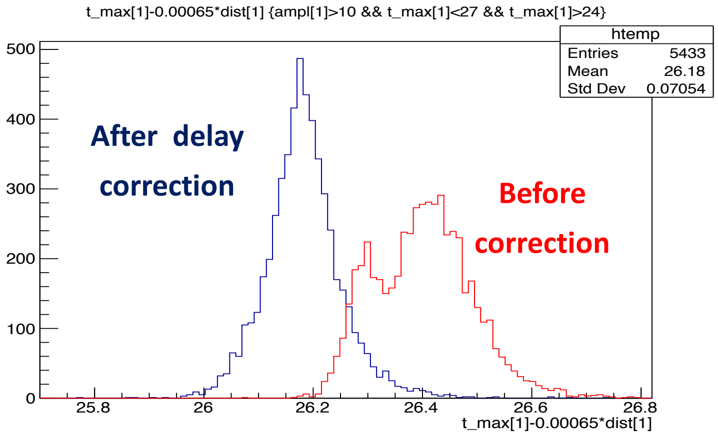
Using the same data from TCT laser scans (as described before) **the time reconstruction is obtained as an amplitude-weighted centroid of the t_{max} seen by the 4 pads:**



$$t_{hit} = \frac{\sum_{i=1}^{i=4} t'_{max}(i) * Amp(i)}{\sum_{i=1}^{i=4} Amp(i)}$$

$$t'_{max}(i) = t_{max}(i) - t_{offset}(i) - dist(i)/speed$$



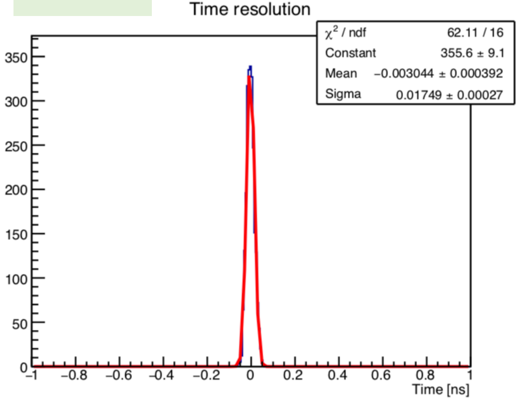


RSD: time resolution

Very Preliminary

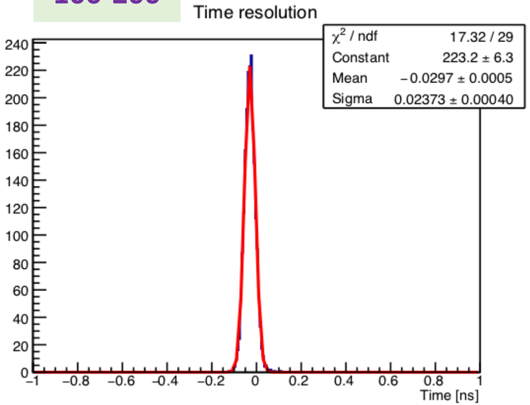
Considering only the shot positions where you have a good signal from at least 4 pads (amplitude>10 mV), the following time resolutions are obtained

50-100



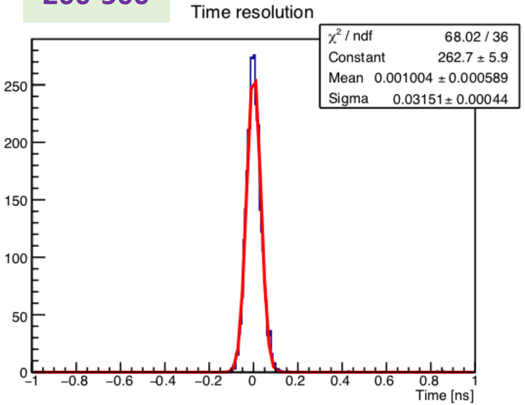
$\sigma = 17\ ps$

100-200



$\sigma = 24\ ps$

200-500



$\sigma = 31\ ps$

NB: the amplifier outputs still need to be calibrated to give the same amplification -> possible offsets of central values

Conclusion and Outlook

- The **UFSD project was started in 2015 with the goal of designing sensors for 4D tracking**:
  - 5 sensor productions have been completed so far
  - the 6th is expected in Q1/2020.
  - The project is fully funded to continue for at least 3 more years.
- Achieved so far:
  - **Excellent time resolution**
  - Very good production uniformity and yield
  - Optimization of the gain layer design to **enhance reliability and radiation hardness**
- R&D towards smaller pads:
  - Exploration of **aggressive inter-pad structures** (standard LGADs)
  - Promizing results from the first production using trenches (TI-LGAD) and the first resistive AC-LGAD (RSD)

Many plans on the list: looking forward to presenting them at HSTD13!

THANK YOU for YOUR ATTENTION

Acknowledgments

We kindly acknowledge the following funding agencies, collaborations:

- INFN - Gruppo V RSD
- Horizon 2020, grant UFSD669529
- H2020 project AIDA-2020, GA no. 654168
- U.S. Department of Energy grant number DE-SC0010107
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)
- RD50 Collaboration, CERN

BACK-UP slides

LGAD tailored for low energy photons detection

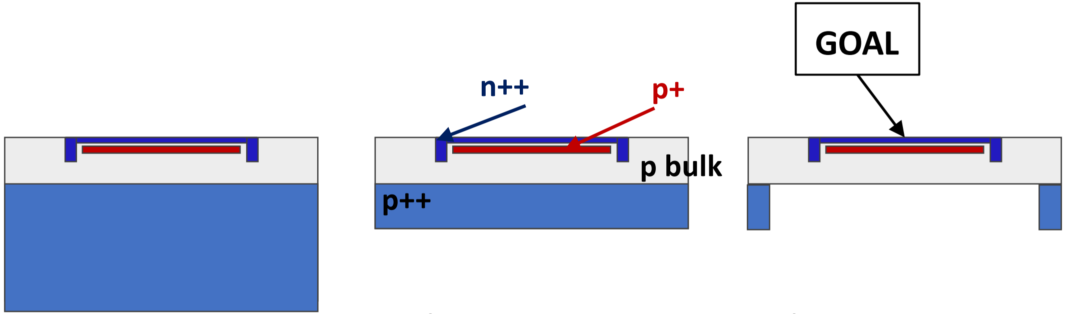
In the future plans:
3 years R&D project for very thin LGAD (20-30 microns), characterized by very thin rear entrance window, suitable for detection of low energy X-ray and very low material budget applications.

Very soft x-rays (energy of ~ 1-10 keV):

- barely penetrate the silicon volume
- energy released is very low, ~300 electron-hole pairs per 1 keV.

Back-illuminating the sensor on the p-side requires the absence of the support wafer:

- study feasibility of manufacturing LGAD with a double-sided process with the gain layer on one side and the thin entrance window on the other side

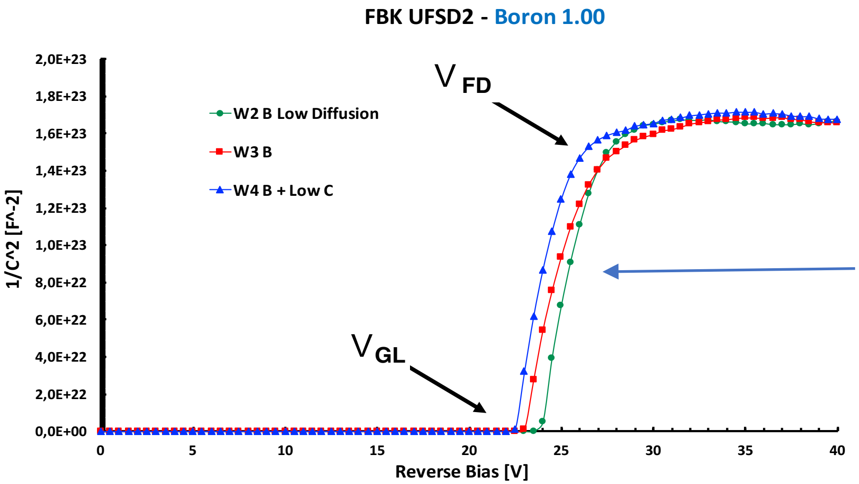


a) Thin LGAD on a thick support wafer

b) Thin LGAD on a thinned support wafer

c) Thin LGAD on ribs

How do we measure the Acceptor density?



V_{GL} = depletion voltage for gain layer

V_{FD} = full depletion voltage

slope $\propto$**1/N$_{bulk}$**

V_{GL} is proportional to the amount of active doping **in the gain layer**

- The **foot** in the 1/C^2 - V curves **indicates the depletion of the gain layer**
- Evolution of active acceptor density with fluence

$$N_A(\Phi) = g_{eff}\,\Phi + NA(0)\,e^{-c(N_A(0))\,\Phi/\Phi_0}$$

UFSD2/3 productions

UFSD2 production

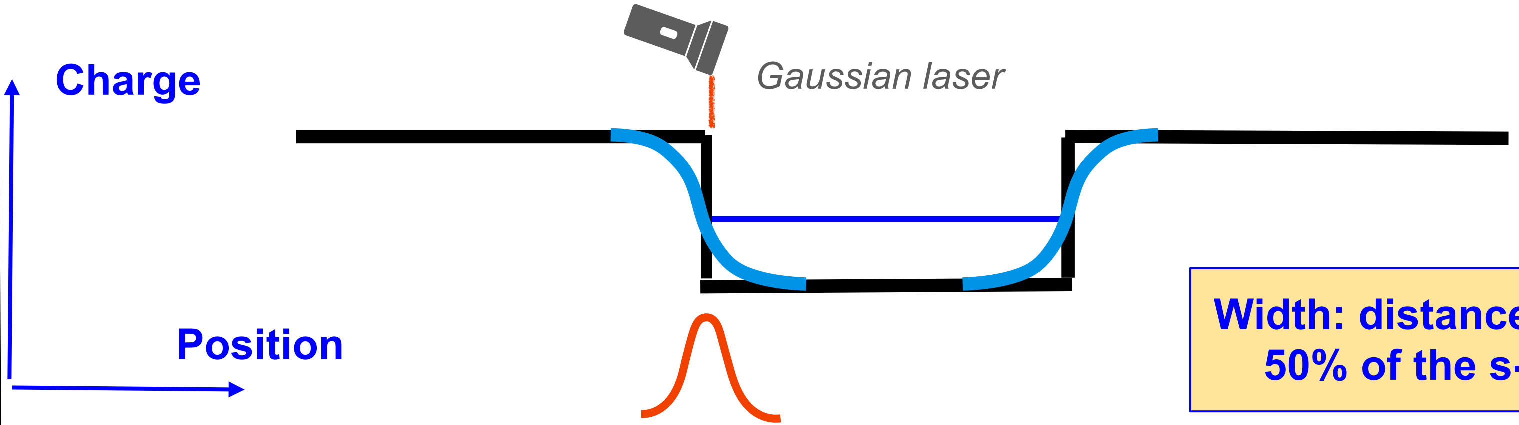
Wafer #	Dopant	Gain dose	Carbon	Diffusion
1	Boron	0.98		Low
2	Boron	1.00		Low
3	Boron	1.00		HIGH
4	Boron	1.00	Low	HIGH
5	Boron	1.00	HIGH	HIGH
6	Boron	1.02	Low	HIGH
7	Boron	1.02	HIGH	HIGH
8	Boron	1.02		HIGH
9	Boron	1.02		HIGH
10	Boron	1.04		HIGH
11	Gallium	1.00		Low
12	Gallium	1.00		
13	Gallium	1.04		Low
14	Gallium	1.04		
15	Gallium	1.04	Low	Low
16	Gallium	1.04	HIGH	Low
17	Gallium	1.08		Low
18	Gallium	1.08		

UFSD3 production

Wafer #	UFSD2	Dose Pgain	Carbon	Diffusion
1	W1	0.98		L
2	W1-Epi	0.96		L
3		0.96	A	L
4	Epi	0.96	A	L
5		0.98	A	L
6		0.96	B	L
7		0.98	B	L
8		0.98	B	L
9		0.98	C	L
10		1.00	C	L
11		1.00	D	L
12	W8	1.02		H
13	W8-Epi	1.00		H
14	W6	1.02	A	H
15	W6-Epi	1.00	A	H
16		1.02	B	H
17		1.02	B	H
18		1.04	B	H
19		1.02	C	H
20		1.04	C	H

TCT: Interpad measurement

- We measured the inactive area width of the tested sensors with the TCT
- **Get the width** by scanning two nearby pads → **charge vs position**



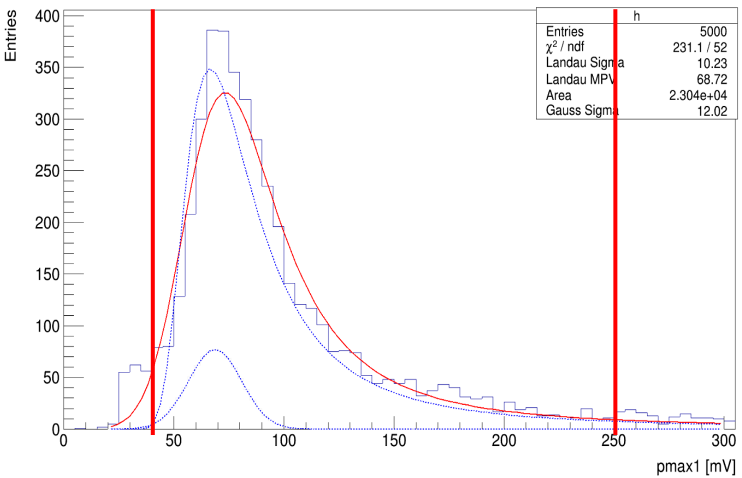
Width: distance between 50% of the s-curves

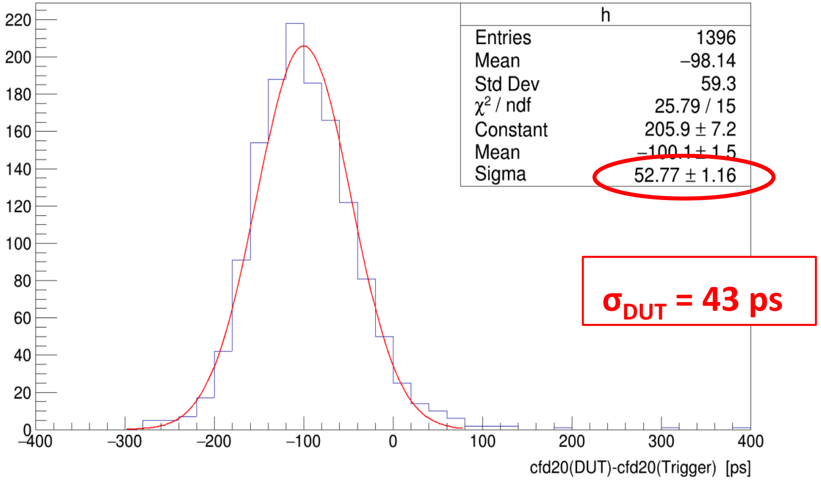
→ The profile is a convolution of the step function with a gaussian (= **s-curve**)

TI-LGAD: performances (II)

To measure the time resolution:

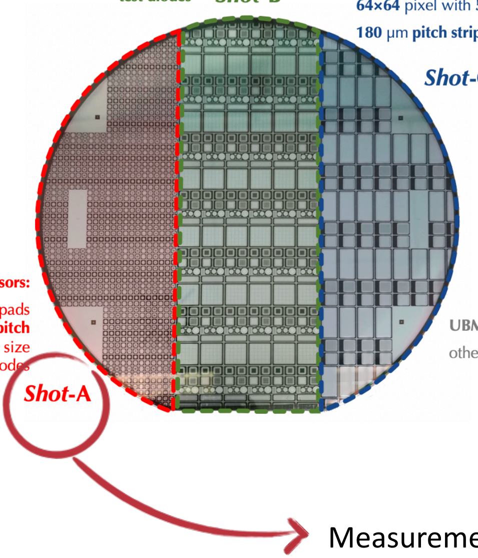
- Times of passage of the particle in DUT and Trigger are measured → t_{DUT} , $t_{Trigger}$
- Define the time difference: $\Delta t = t_{DUT} - t_{Trigger}$ → Δt has a gaussian distribution
- $\sigma_{Measured}$ of Δt distribution is the squared sum of DUT and trigger resolutions
    - $\sigma_{Trigger}$ = 30ps is known and fixed → $\sigma_{DUT} = \sqrt{(\sigma_{Measured}^2 - \sigma_{Trigger}^2)}$





2-trenches TI-LGAD (W5) @300V

RSD project: RSD1 production



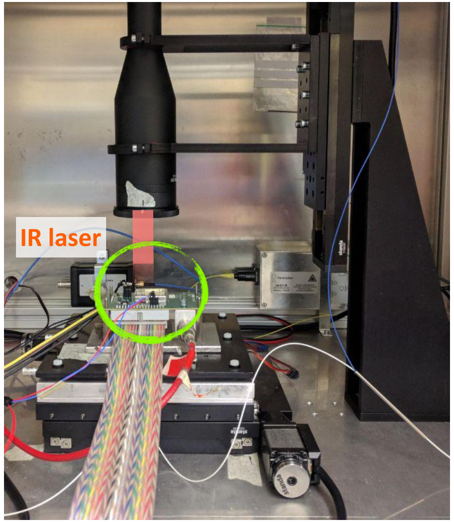
Measurements on devices belonging to this shot are presented

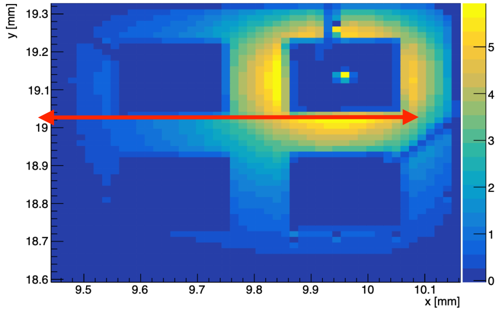
RSD 1 production at FBK

wafer	*n-plus dose*	*p-gain dose*	dielectric thickness	*p-stop dose*	substrate
1	A	0.92	L	B	Si-Si
2	A	0.94	L	A	Si-Si
3	A	0.94	L	B	Epi
4	A	0.94	H	B	Si-Si
6	B	0.92	L	B	Epi
7	B	0.94	L	A	Si-Si
8	B	0.94	L	B	Si-Si
10	B	0.96	H	B	Si-Si
11	C	0.92	L	B	Si-Si
12	C	0.94	L	B	Epi
13	C	0.94	L	B	Si-Si
15	C	0.96	H	C	Si-Si

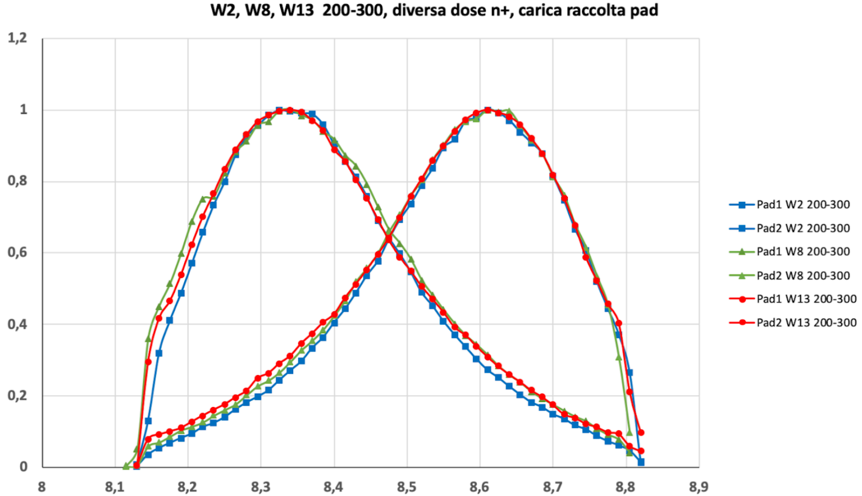
TCT measurements: time and space resolution

TCT picosecond Laser setup, 1064 nm
spot 10 µm
Stages with micrometrical precision

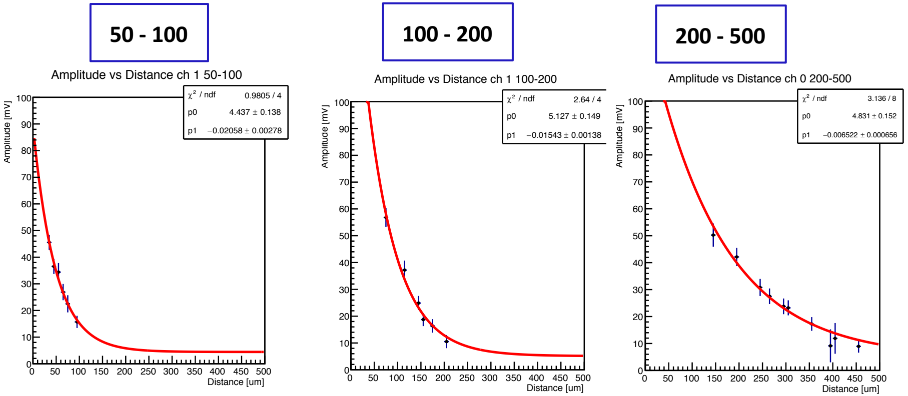




Study of charge projections along a scan line (in red) for two neighboring pads
The induced charge shape doesn't depend on the oxide thickness or on the n+ dose
The induced charge shape depends on the pitch and the AC pad size in the DUTs

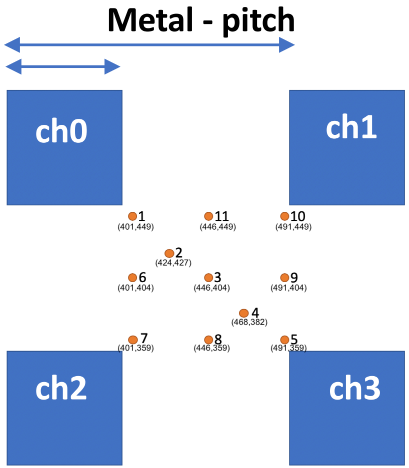


AC-LGAD: Amplitude vs distance from the particle position

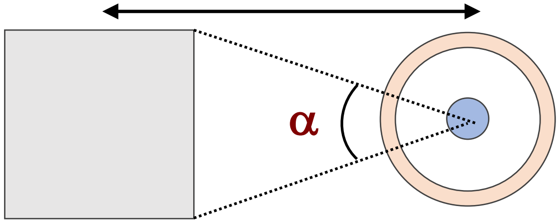


RSD W2 3X3, (operated to have gain=17) on multi-channel amplifier board.
1 MIP ~ 8 fC

$$A(z) = cost + A(0)e^{-cz}$$



The amplitude becomes negligible when the distance is twice the metal pad size: **the angle α is about 15% of the total 2pi angle**



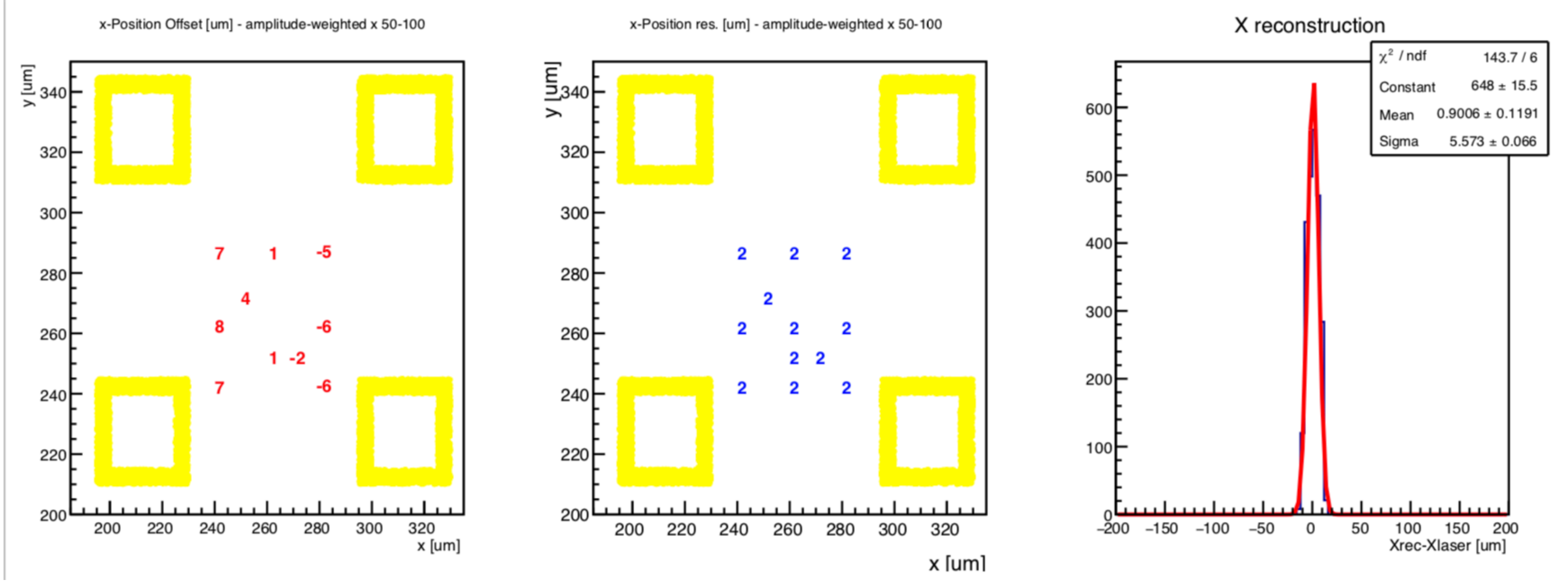
AC-LGAD: position reconstruction 50-100

The position of the hit is obtained as:

(amplitude>10 mV)

$$x_{reco} = \frac{\sum_{i=1}^{i=4} x_{pad}(i) * Amp(i)}{\sum_{i=1}^{i=4} Amp(i)}$$

$x_{reco} - x_{Laser}$

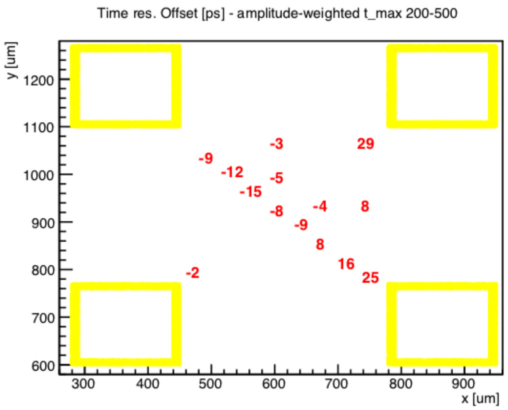


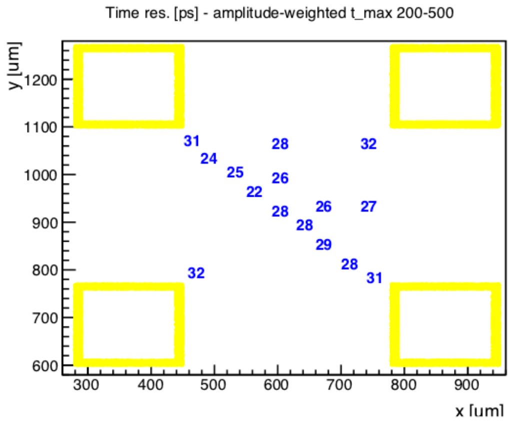
Offsets: due to non-calibrated amplifiers, or other systematic effects

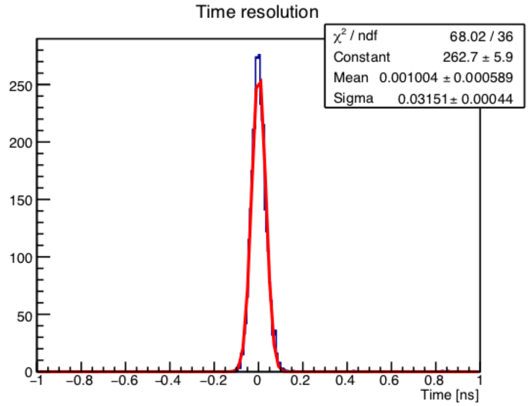
The single point resolution is 2 um

x resolution: 6 um, with an offset of -2 um

AC-LGAD: time reconstruction 200-500







$$\sigma = 31\, ps$$

$$t_{hit} = \frac{\sum_{i=1}^{i=4} t'_{max}\,(i) * Amp(i)}{\sum_{i=1}^{i=4} Amp(i)}$$