Ultra-Fast Silicon Detectors & Beyond: a Decade of Developments Chasing Accurate 4D Tracking.

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Introduction

Facility:	FCC-ee	ILC	CLIC
σ_x [μm]	~ 5	< 3	< 3
σ_t [ps]	10's	10's	10's
Thickness of tracker material [μm of Si]	~ 100	~ 100	~100
Hit rate [10^6/s/ cm^2]	~ 20	~ 0.2	1
Power dissipation [W/cm^2]	0.1 – 0.2	0.1	0.1
Pixel size [μm ^{2}]	25 x 25	25 x 25	25 x 25

air cooled?

Very difficult to achieve

- Dimension of the pixels is driven by the position resolution, not occupancy
- Tiny pixels technologically very difficult (power, bumps, services)
- **Time resolution** is also very challenging with so many pixels and not enough power

Introduction

Requests for the trackers at the next generation colliders

- *very low material budget* ***for accurate measurement of low momentum particles***
- *very small pixels to reach the desired* ***spatial resolution*** *(5-10 microns)*
- *very good* ***time resolution*** *(few tens of ps)*

Emerging technology -> **resistive read-out LGAD silicon sensors**

first implementation realized as AC-coupled (also called AC-LGAD or RSD)

It all started with this question

Can we achieve a concurrent accurate time and space measurement using the same silicon sensor device?

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2014: INFN CSN5 and ERC Advanced Grant fueled this R&D

UFSD project goal: develop a **silicon detector** able to achieve concurrently

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

suitable for tracking in 4 Dimensions

baseline technology: Low Gain Avalanche Diodes

Chasing 4D tracking with silicon sensors

Can we achieve a concurrent accurate time and space measurement using the same silicon sensor device?

2014: INFN CSN5 and ERC Advanced Grant fueled this R&D

Within the UFSD project/RD50 collaboration

- **working on thin LGAD sensors, optimized for timing - big pad size** - before addressing the ultimate small pixel matrix ***(eventually we took a detour)***
- steady progress from ~ 2015:
  - Institutes/companies initially involved: CNM first, followed by FBK (2016) and then HPK, Micron (2017)
  - R&D focused on timing applications - CMS ETL /ATLAS HGTD
- Now a booming field: several new designers/producers developing LGADs (Micron, Teledyne, IHEP-IME, IHEP-NDL, BNL …)

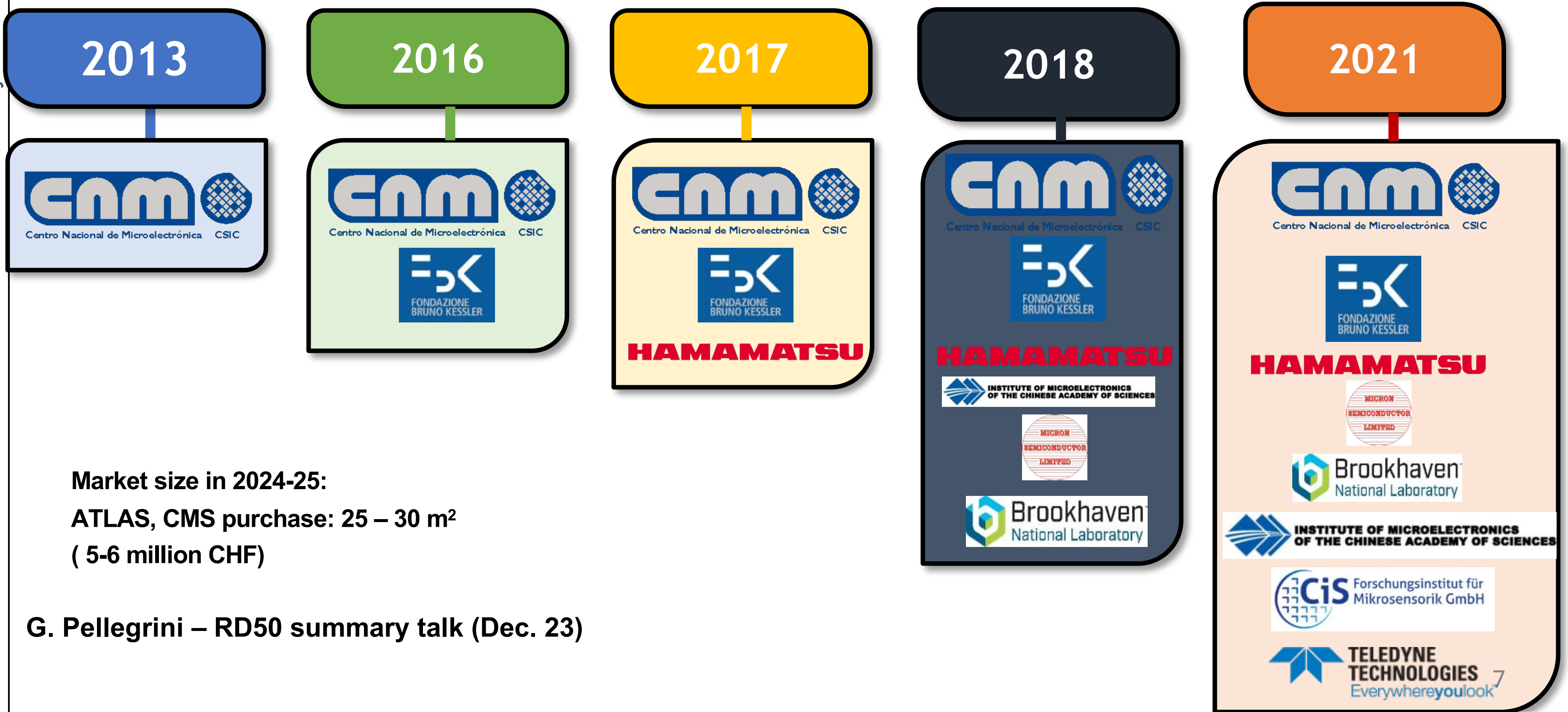
Chasing 4D tracking with silicon sensors

Can we achieve a concurrent accurate time and space measurement using the same silicon sensor device?

Within the RSD INFN project/RD50 collaboration/FBK R&D/4DInside team **(from 2018)**
- addressing the "pad-size issue" to improve the spatial resolution in LGADs

Working on two fronts:
- **Trench-Isolated LGADs**
- **Resistive AC-coupled LGADs (also known as RSDs – Resistive Silicon Detectors)**
- Several Foundries now developing AC-LGADs (FBK, HPK, CNM, BNL, IHEP …)

Clean Rooms developing LGAD technology



Market size in 2024-25:
ATLAS, CMS purchase: 25 – 30 m^2
(5-6 million CHF)

G. Pellegrini – RD50 summary talk (Dec. 23)

Some FBK remarkable productions

2017: UFSD2 First 50 µm-thick LGAD (FBK 6” wafer)

Late 2022: UFSD4 50 µm-thick LGAD (FBK 6” wafer, deep and shallow optimized carbonated gain layer) CMS ETL prototype run

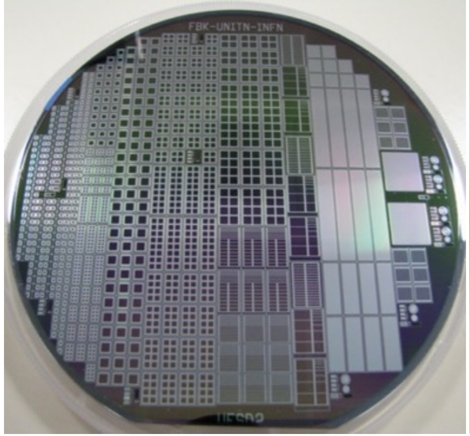
UFSD

RSD

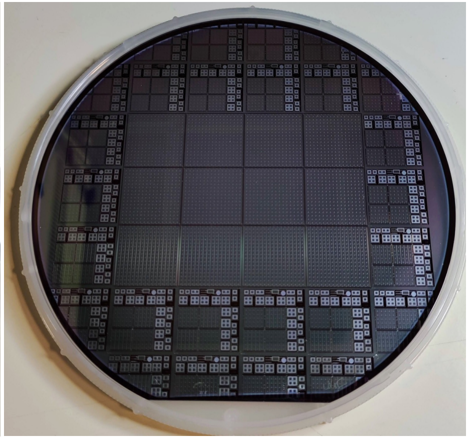
2019: RSD1 Resistive AC-LGAD

2021: RSD2 Resistive AC-LGAD

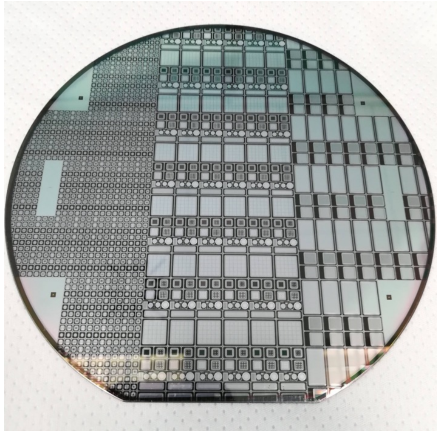
UFSD2



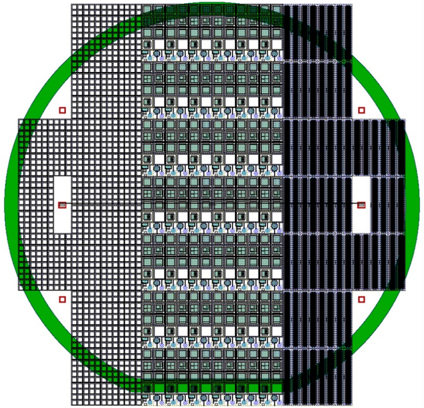
UFSD4



RSD1



RSD2

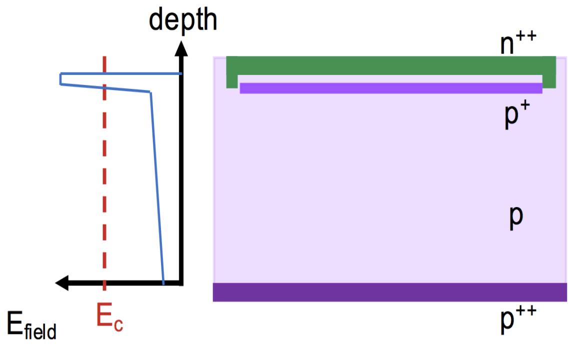


Design innovations

Two design innovations have **radically changed the performance** of silicon sensors:

- The introduction of **internal moderate gain:**

  Low-Gain Avalanche Diode (LGAD)
  - It provides large signals with short rise time and low noise, ideal for timing



Standard silicon sensor
+ thin gain layer (p+)

Design innovations

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- The introduction of **internal moderate gain:**

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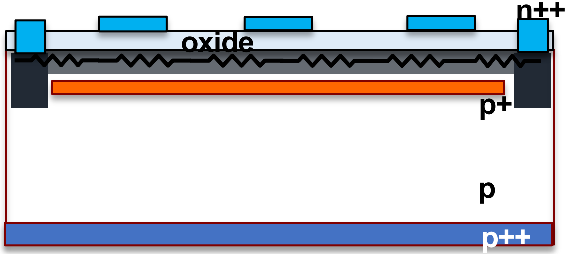
  - It provides large signals with short rise time and low noise, ideal for timing

- The introduction of **intrinsic charge sharing:**

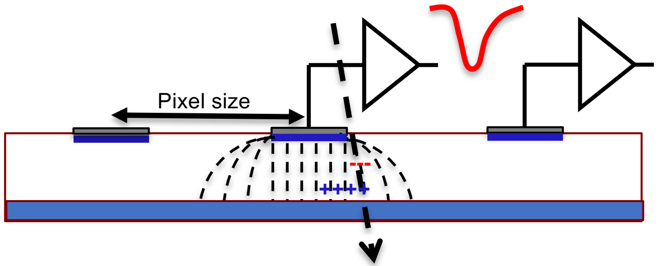
  Resistive AC-coupled read-out LGAD (AC-LGAD or RSD)
  - It provides intrinsic signal sharing, which is a **key ingredient to excellent spatial resolution using large pixels**



Standard silicon sensors in single or multi-pixels read-out

Single pixel

where the signal is induced on one pixel



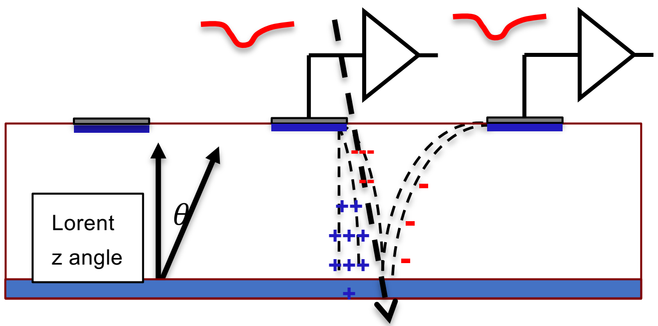
$$\sigma_x = k \frac{pitch}{\sqrt{12}}, k \sim 0.5 - 1$$

- $\boldsymbol{\sigma_x}$ **depend on the pixel size**

  pixel = 100 μm → $\sigma_x = 20\ \mu m$

Multi pixels

where the signal is induced on a few pixels



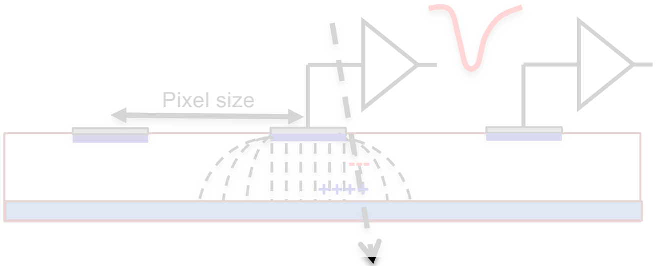
$$x = \frac{\sum_i x_i Ai}{\sum_i A_i}$$

- $\boldsymbol{\sigma_x}$ **<< pixel size**
- **Same σ_x can be obtained with larger pixels**

Adding Precise Time Measurement to Single Pixels Read-out

Single pixel

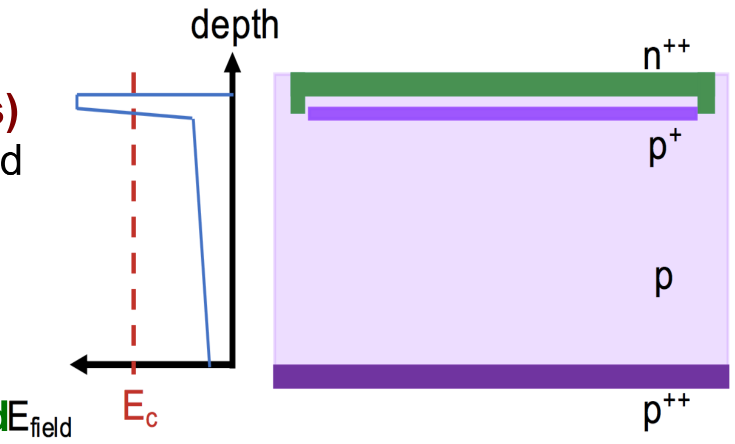
where the signal is induced on one pixel



development of thin LGAD sensors (~50ish microns)

- thin layer of doping element to produce low controlled multiplication **(the gain layer)** close to the n++ electrode

- Several years of R&D to improve the **timing performance, radiation hardness, uniformity and yield of large area devices** (driving force → ATLAS/CMS timing layers)



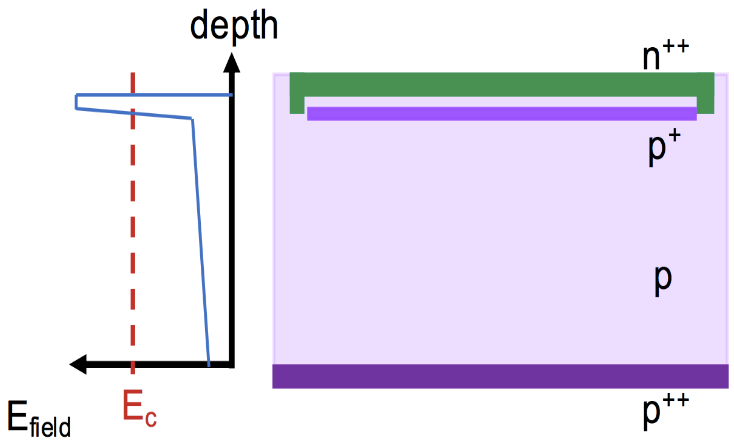
Adding Precise Time Measurement to Single Pixels Read-out

Single pixel

where the signal is induced on one pixel

- The low-gain mechanism, obtained with a moderately doped p-implant, is the defining feature of the design.
- The low gain allows segmenting and keeping the shot noise below the electronic noise, since the leakage current is low.

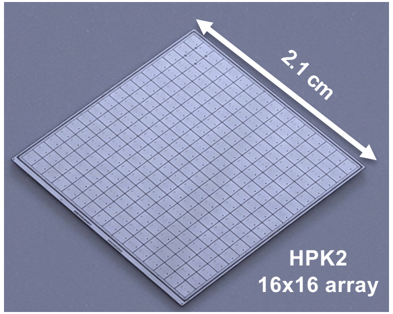
performance, radiation hardness, uniformity and yield of large area devices
(driving force → ATLAS/CMS timing layers)

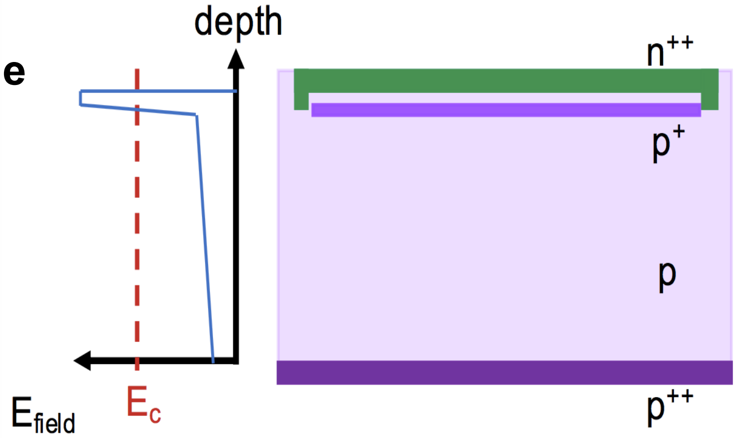


State-of-the-art LGADs for timing

State-of-the-art (ATLAS/CMS timing layers LGADs)

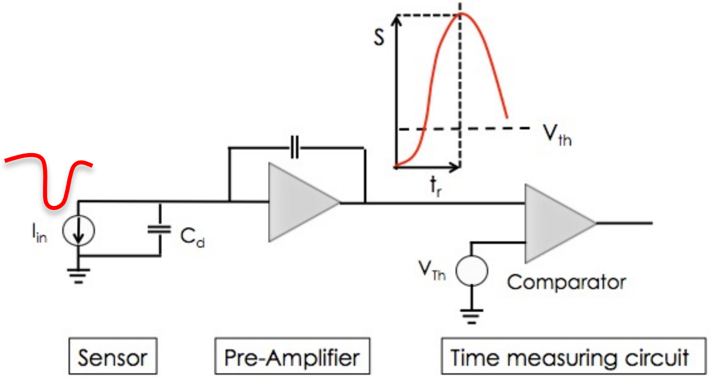
- "pixel" size = 1.3 x 1.3 mm^2
- time resolution: **25-40 ps (new-irradiated)**
- well characterized in lab and testbeams
- **gain layer uniformity ~1% or better**
- **rad hardness:** still able to deliver **>=5 fC of charge up to ~ 2E15 n_{eq}/cm^2**





Why do LGADs allow good time measurement?

- Sensors produce a current pulse
- The read-out measures the time of arrival



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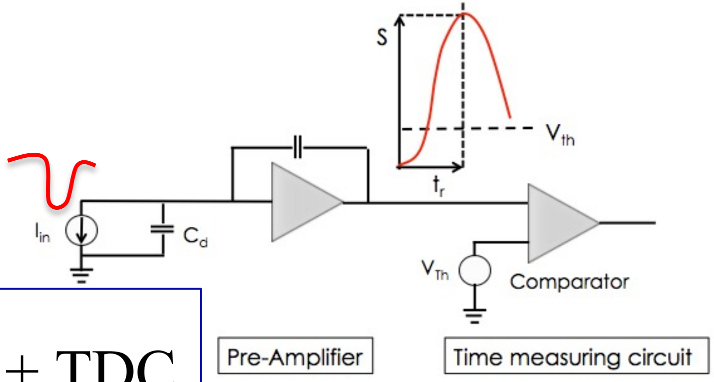
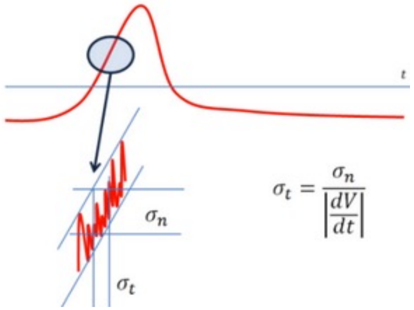


$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \text{TDC}$$

Usual “Jitter” term



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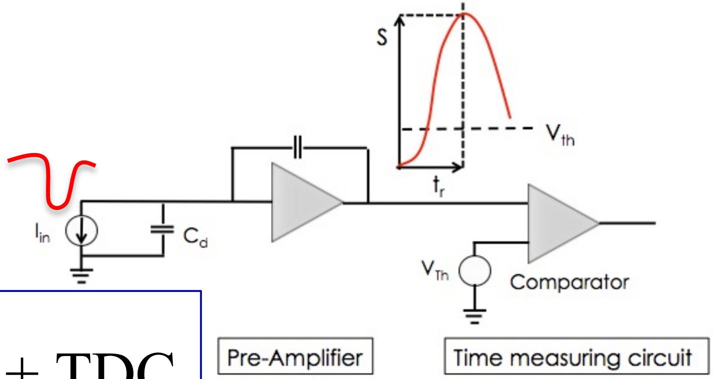
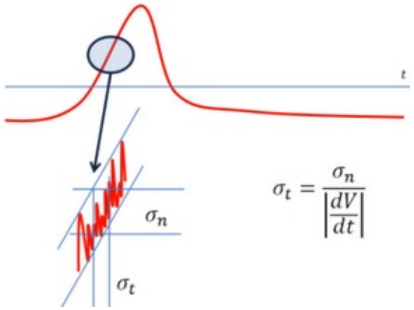


$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \text{TDC}$$

Time walk: time correction circuitry

Shape variations: non homogeneous energy deposition

Usual “Jitter” term



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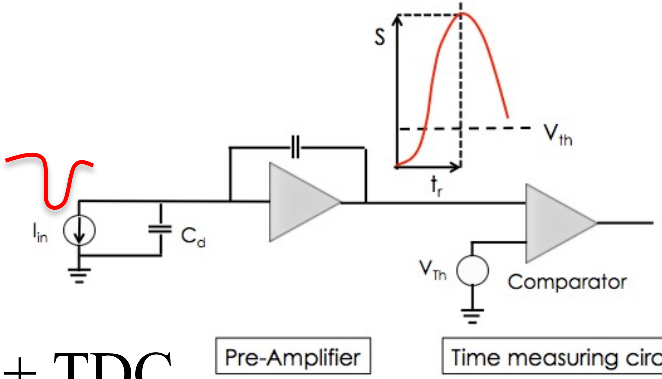

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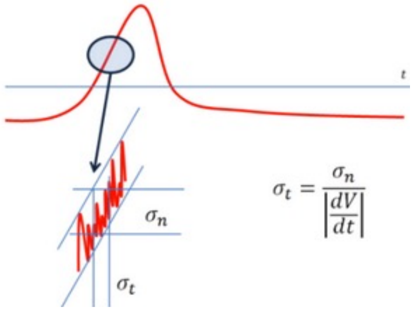
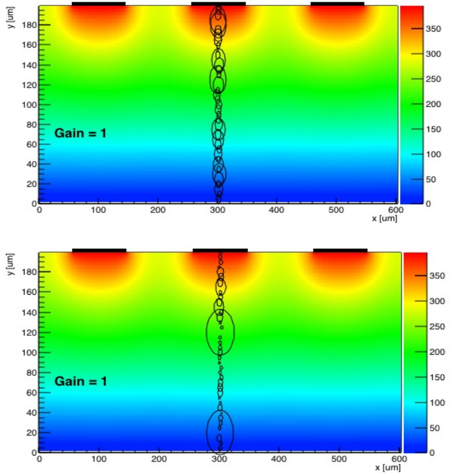
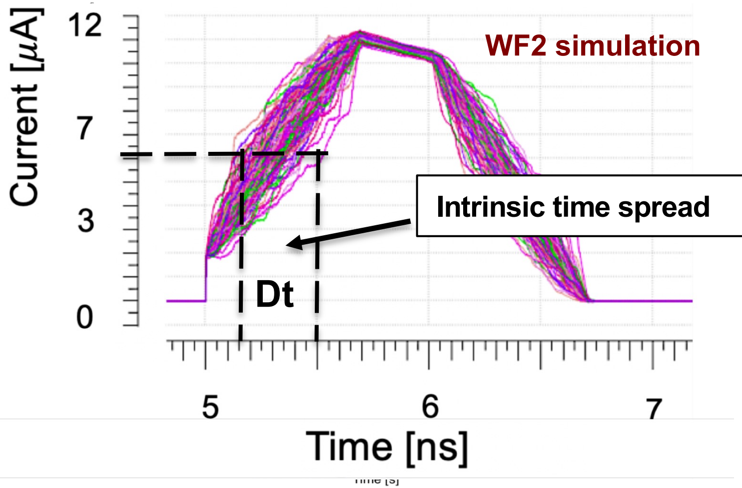


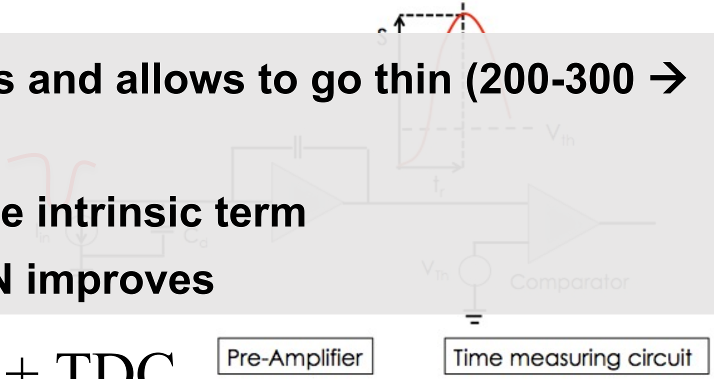




Why do LGADs allow good time measurement?

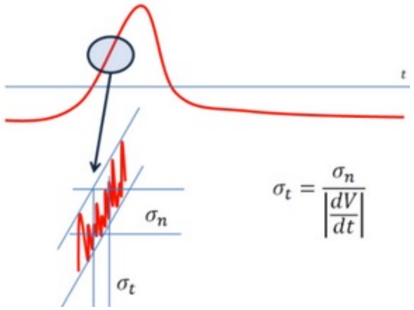
- Sensors produce a current pulse
- The read-out measures the time of arrival

- **The gain gives high amplitude signals and allows to go thin (200-300 → 50 um)**
- **Thin sensors gives steeper signals**
- **Thin sensors reduce the Landau noise intrinsic term**
- **There is a gain range in which the S/N improves**

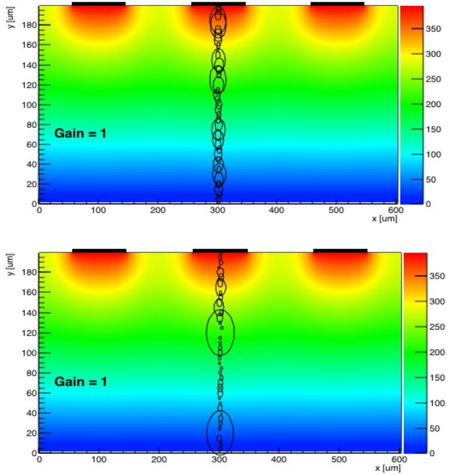


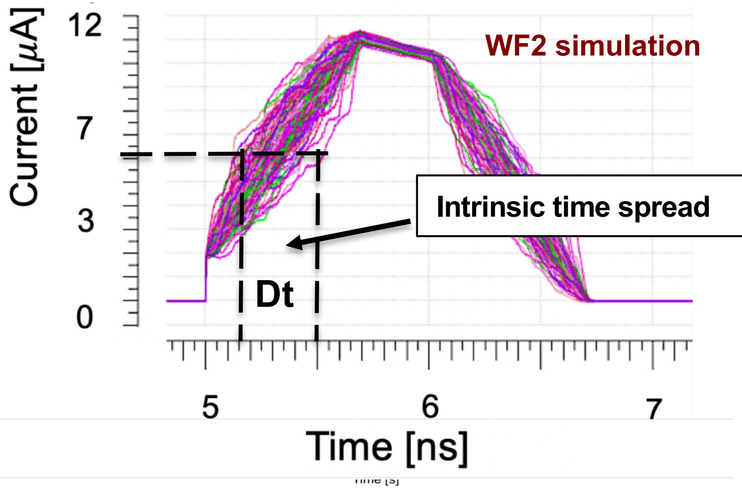
$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \text{TDC}$$

Usual "Jitter" term



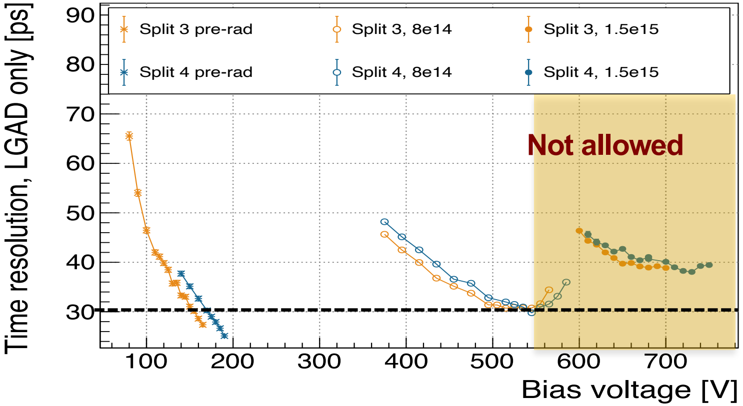
$$\sigma_t = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|}$$

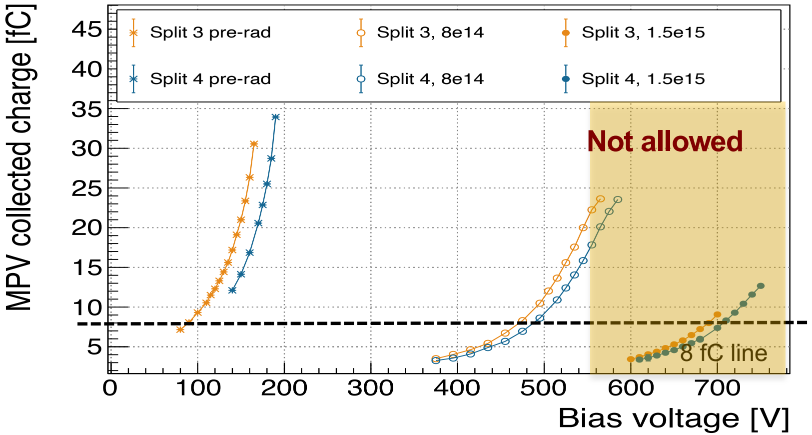




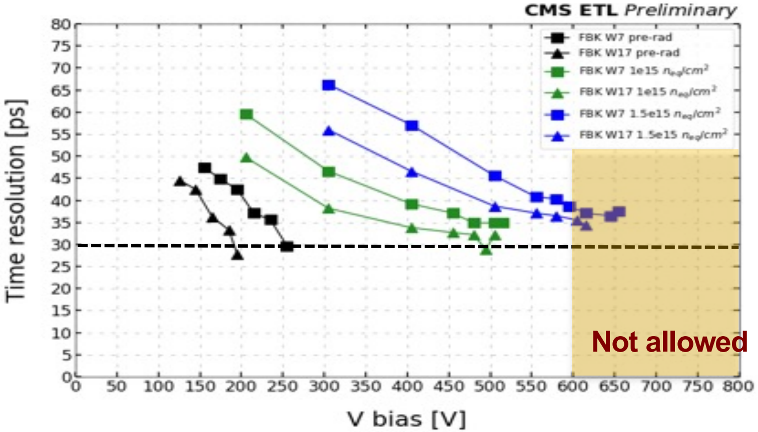
Timing performance

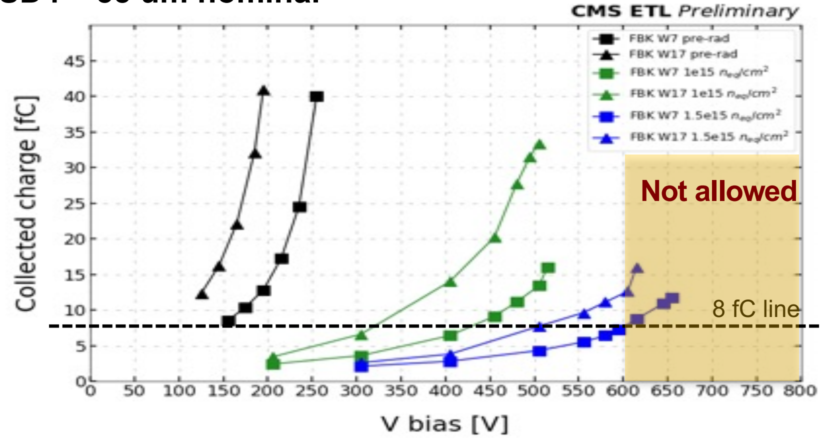
HPK MS samples – HPK2 – 50 um nominal





FBK MS samples – UFSD4 – 55 um nominal

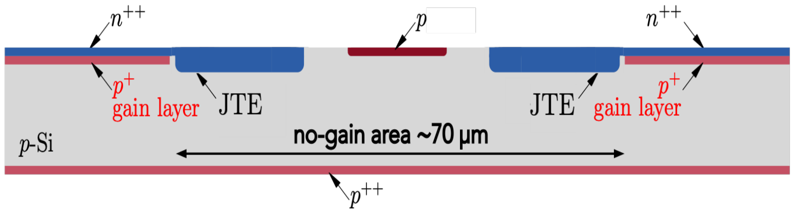




Pad size: how small can it be? (PIXEL?)

In the ”standard” UFSD design, **isolation structures between read-out pads represent a no-gain area for signal collection (inter-pad area)**

example of pixel/gain isolation structure (FBK)



size of inter-pad area is in the 40-120 µm range
measured with TCT laser setup and @Beam Test

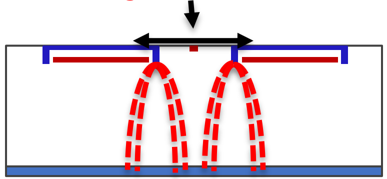
Table with smallest no-gain area for FBK, HPK, CNM

Vendor	Production	no-gain area (microns)
FBK	2020 (UFSD3.2)	40
HPK	2020 (HPK2)	65
CNM	2020 (AIDA2020)	40

Fill Factor for a 1.3 mm pitch pad matrix = 94%
Fill Factor for a 100 µm pitch pixel matrix = 36%

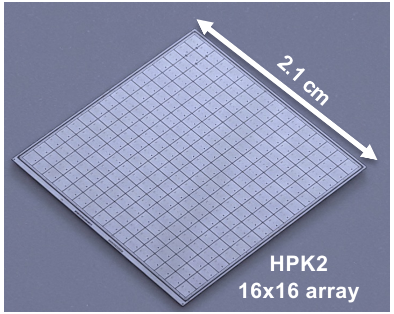
A new technology for the inter-pad area

No gain area ~ 50 um

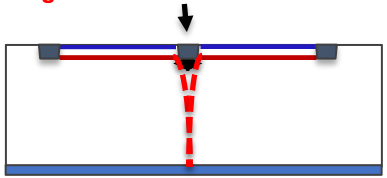


JTE + p-stop design

- **CMS && ATLAS choice**
- **Not 100% fill factor**
- **Very well tested**



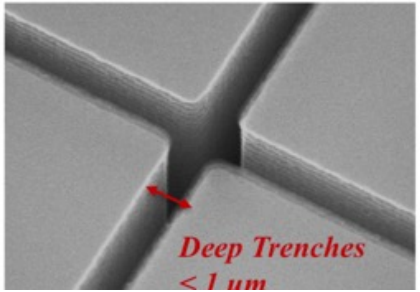
No gain area ~ few micrometers



Trench-isolated design

pad isolation structures are substituted by shallow tranches (Deep Trench Isolation technology, < 1 μm wide) – FBK development

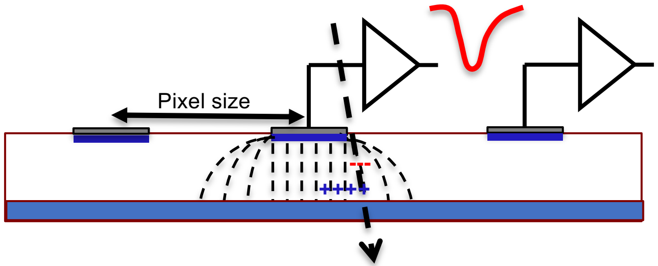
- **Almost 100% fill factor (depends upon the pad size)**
- **Trench-isolated LGADs produced by FBK: 3 productions**
- **Now (2023!) this technology is mature**
- **R&D on TI-LGADs pixelated matrices (50,100 um) are ongoing**



Focusing on Position: Single and Multi Pixels Read-out

Single pixel

where the signal is induced on one pixel



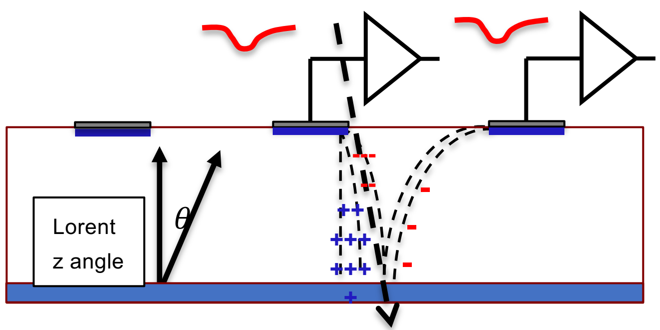
$$\sigma_x = k\,\frac{pitch}{\sqrt{12}},\; k \sim 0.5\text{ - }1$$

- $\boldsymbol{\sigma_x}$ **depend on the pixel size**

  pixel = 100 $\boldsymbol{\mu m} \rightarrow \boldsymbol{\sigma_x = 20\ \mu m}$

Multi pixels

where the signal is induced on a few pixels



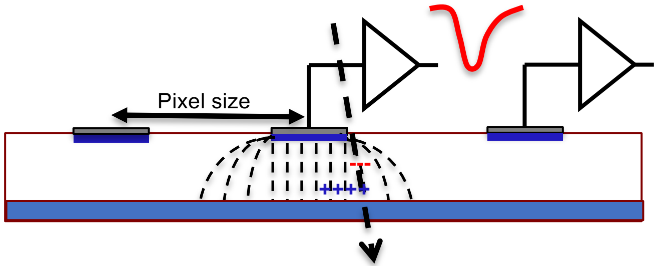
$$x = \frac{\sum_i x_i\, Ai}{\sum_i A_i}$$

- $\boldsymbol{\sigma_x}$ **<< pixel size**
- **Same** σ_x **can be obtained with larger pixels**

Focusing on Position: Single and Multi Pixels Read-out

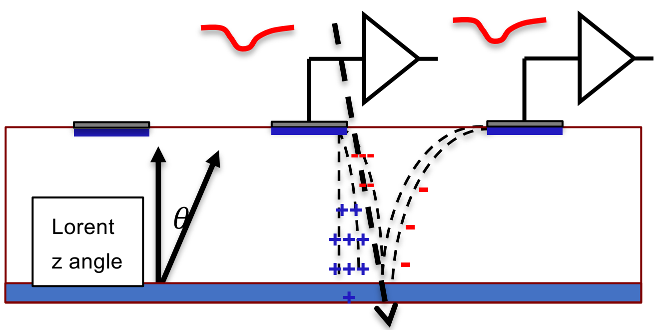
Single pixel

where the signal is induced on one pixel



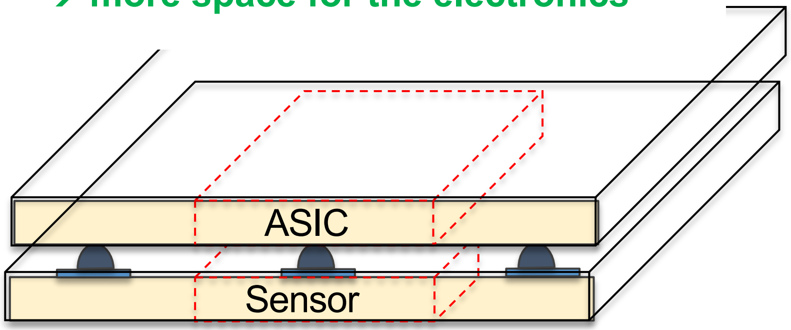
Multi pixels

where the signal is induced on a few pixels



Small pixels: very important **constraints on the design of the electronics and on the power consumption**

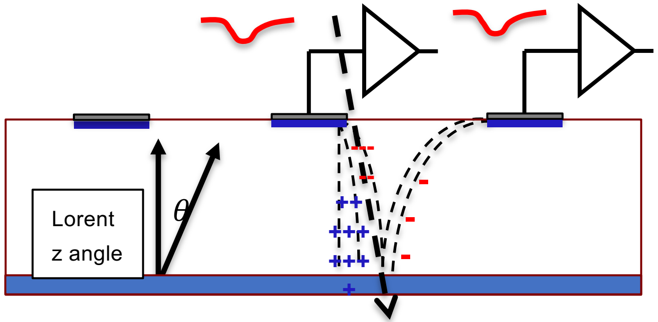
→ **more space for the electronics**



Focusing on Position: Single and Multi Pixels Read-out

Multi pixels

where the signal is induced on a few pixels



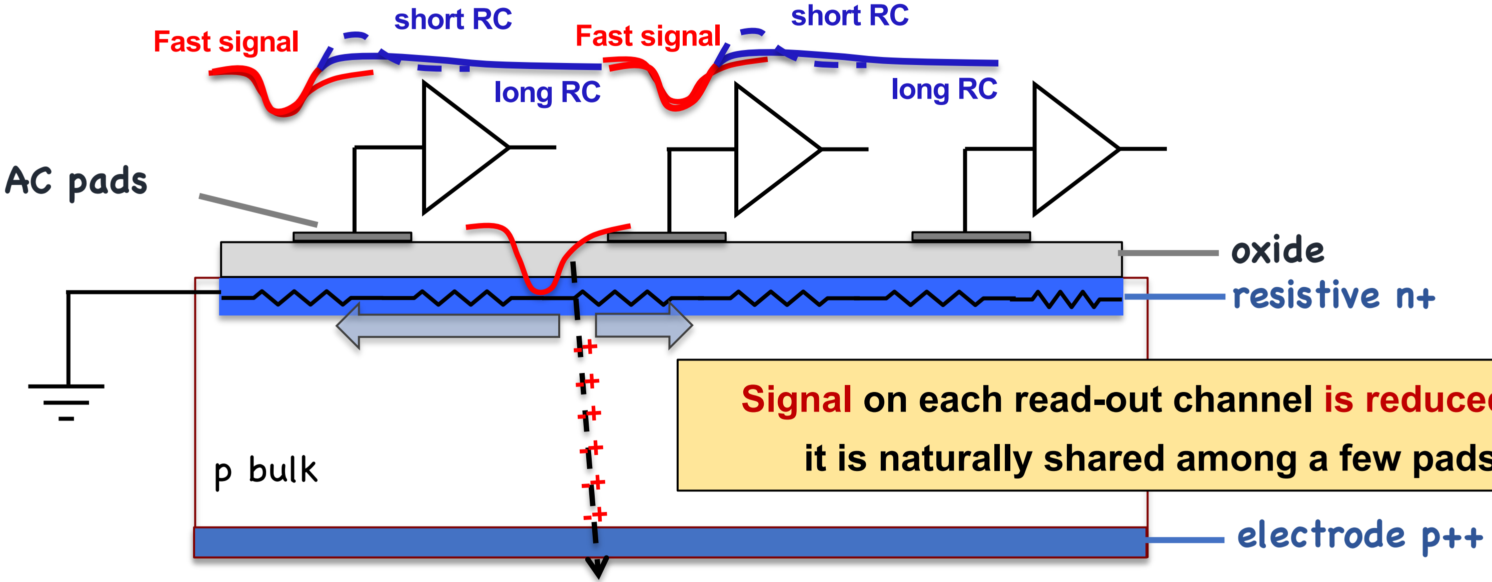
To be noted:

- **the charge is divided among 2 or more pixels:** sensor needs to be thicker to maintain efficiency
- need B field (or floating electrodes) to obtain sharing

Resistive AC-coupled Silicon Sensors

Another way of achieving signal sharing among pads is the AC-coupled resistive read-out

- Charge is induced on the n+ electrode ==> very fast process (1 ns)
- This generates signals on the near-by AC pads (fast component – capacitive coupling)
- The charge flows to ground (slow component)



Signal on each read-out channel is reduced as it is naturally shared among a few pads

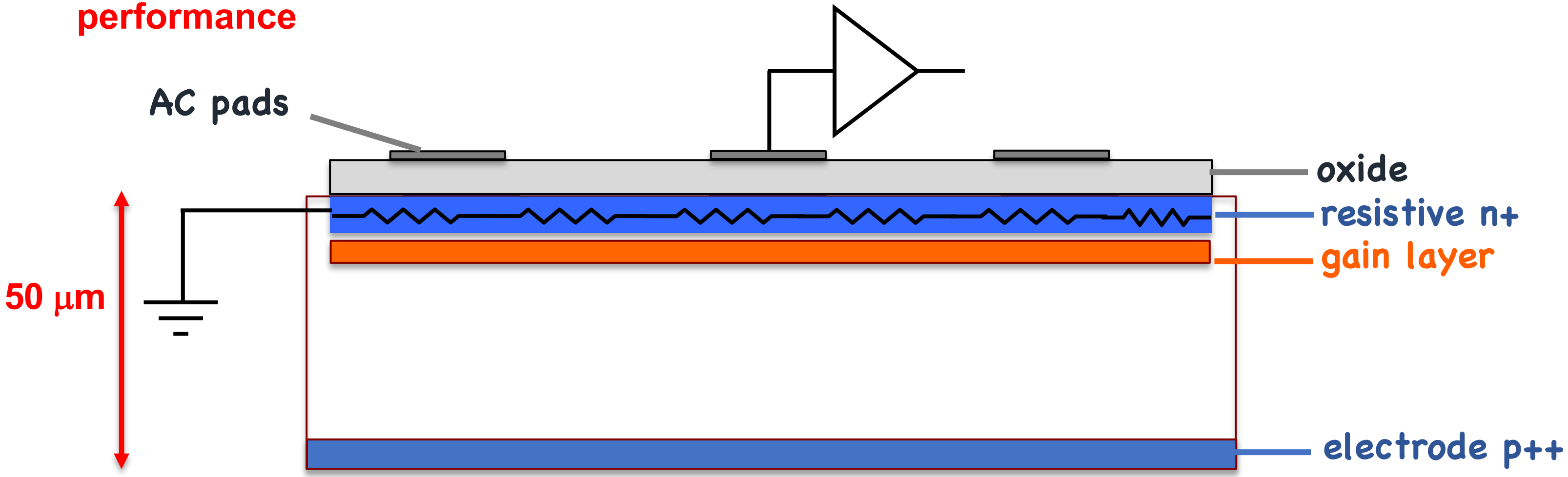
Resistive AC-coupled LGADs

To overcome this limit: adding a continuous gain layer (moderate gain) to amplify the signal

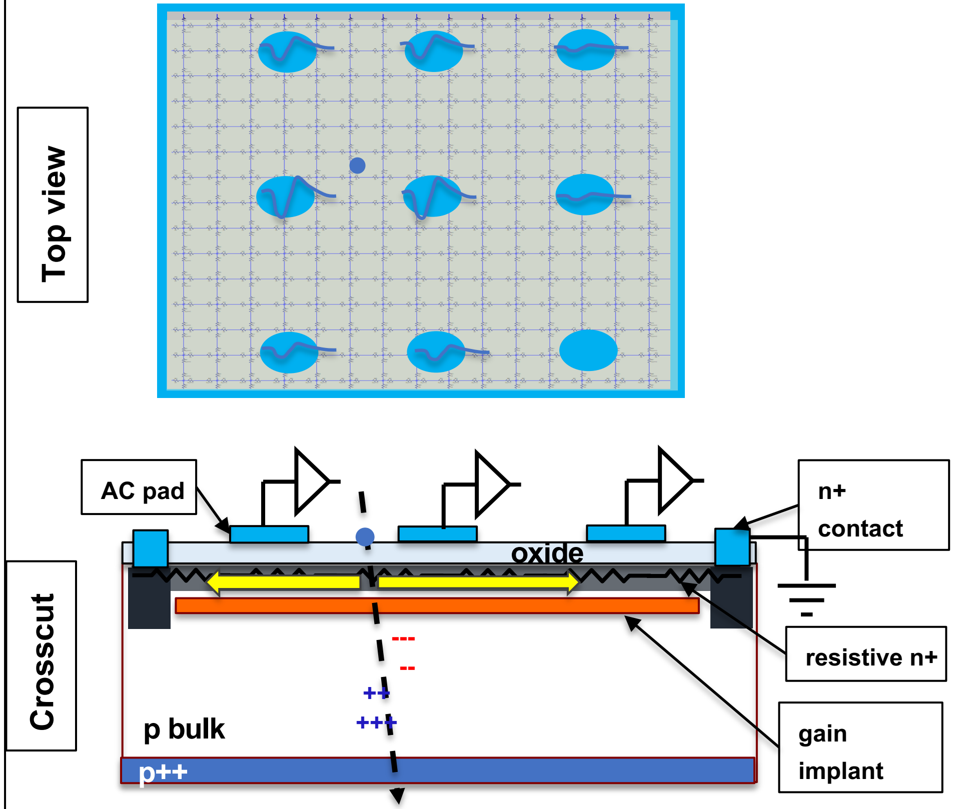
resistive AC-LGAD (or Resistive Silicon Detector)

⇒ Thin LGAD with a resistive AC read-out, where the **design of the read-out pads** (shape and segmentation) adapts easily to any geometry and defines spatial resolution

⇒ **100% detector efficiency**, 100% Fill Factor, reduced material budget and **enhanced timing performance**



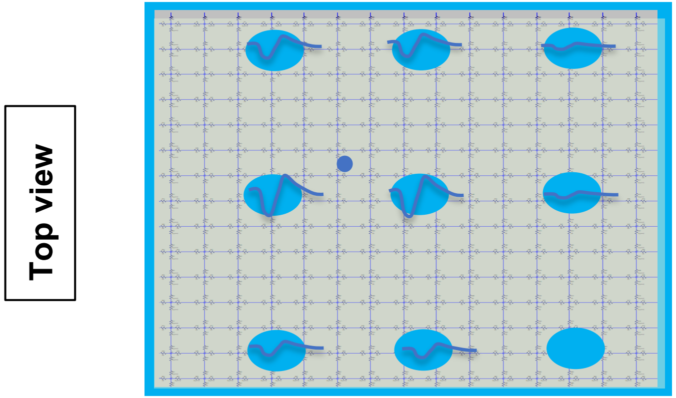
AC-coupled resistive read-out LGAD (RSD)

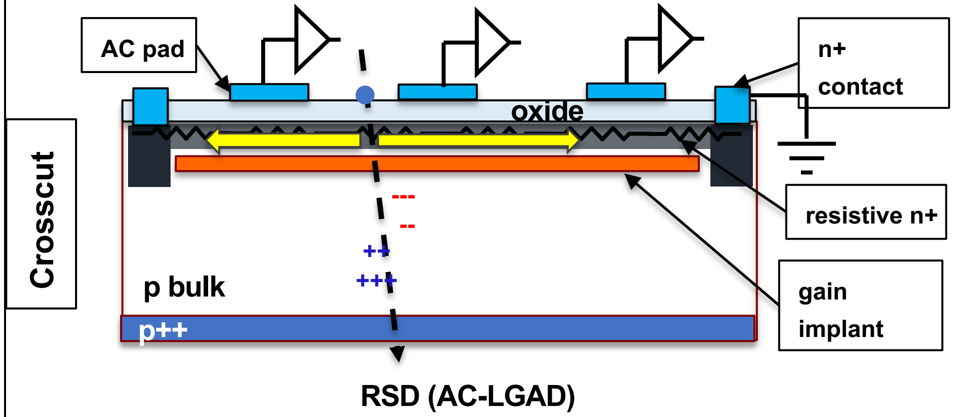


RSD (AC-LGAD)

⇛ Thin LGAD with a resistive read-out AC-coupled, where the design of the read-out pads (shape and segmentation) defines the segmentation and can easily adapt to many geometries

AC-coupled resistive read-out LGAD (RSD)



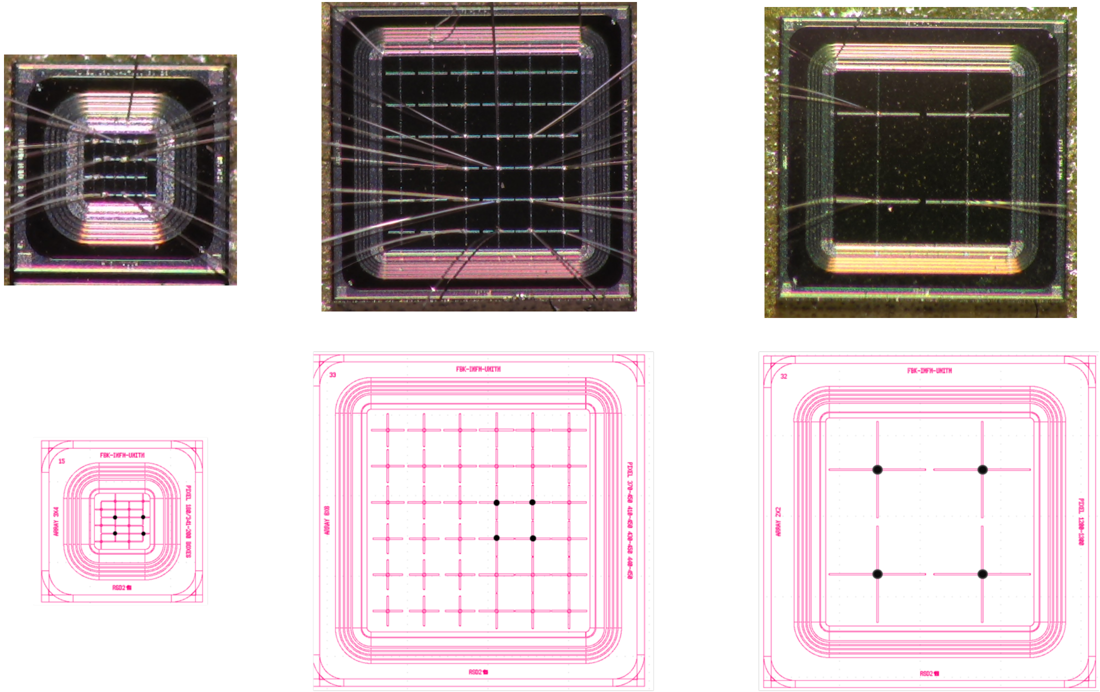


⇛ the coordinates are reconstructed exploiting the charge sharing amongst neighboring electrodes: spatial resolutions better than

$\sigma_x = k \frac{\text{pitch}}{\sqrt{12}}$, k ~ 0.5 - 1

RSD spatial resolution: results with TCT

Results from FBK RSD2 production (2021): second RSD production with optimized design (parameters that drive the sharing) and optimized electrode shapes



(A) (B) (C)

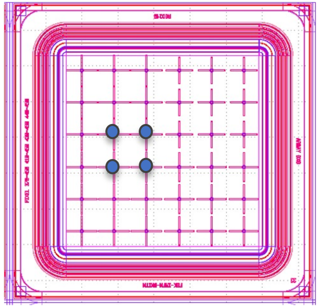
R. Arcidiacono – UFSD & beyond

RSD spatial resolution: results with TCT

Results from FBK RSD2 production (2021): second RSD production with optimized design (parameters that drive the sharing) and optimized electrode shapes

x-y coordinates reconstructed using the "charge asymmetry" method + correction

Using only the 4 electrodes of the cell with the highest signal (sum of the 4)



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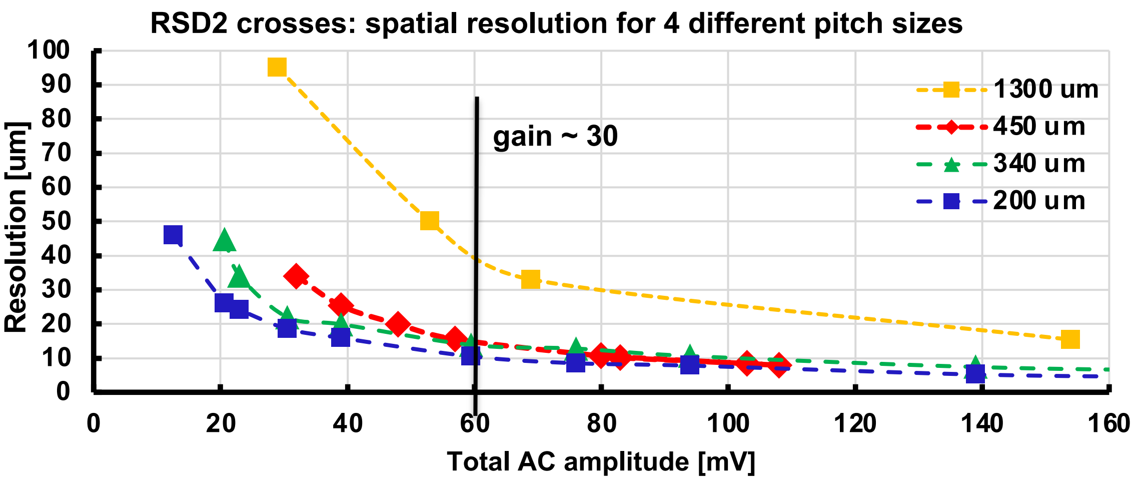
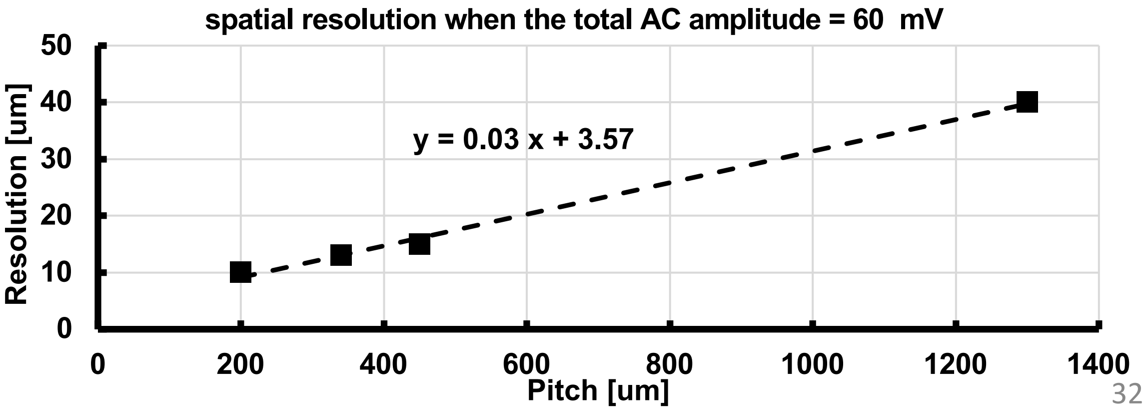
Results from FBK RSD2 production (2021): second RSD production with optimized design (parameters that drive the sharing) and optimized electrode shapes

***x-y coordinates reconstructed using the "charge asymmetry" method + correction* [3]**

RSDs at gain = 30 achieve a spatial resolution of about 3% of the pitch size

- **1300 x 1300 mm²: s_x ~ 40 μm**
- **450 x 450 mm²: s_x ~ 15 μm**

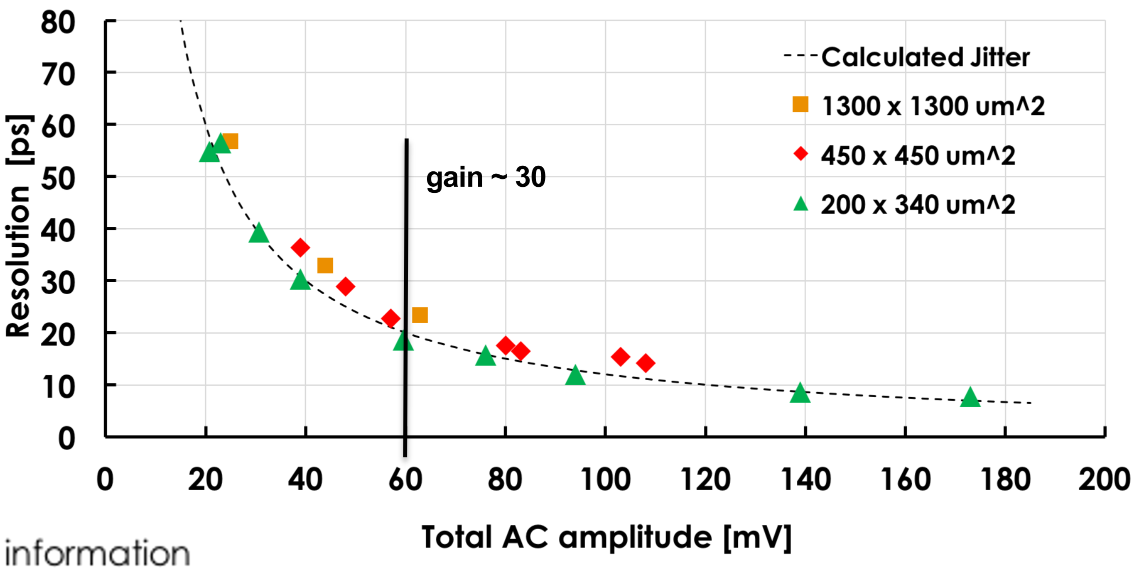




RSD time resolution: jitter term

Results from FBK RSD2 production (2021)

NB: Landau fluctuations NOT present



The time is obtained combining the information from the 4 read-out pads, minimizing the chi 2

$$t_{rec} = \frac{\sum_i^4 t_{rec}^i * A_i^2}{\sum_i^4 A_i^2}$$

where $t_{rec}^i = t_{meas}^i + t_{delay}^i$

The resolution (jitter + delay term) depends mostly upon the signal size and **weakly on the pixel size**

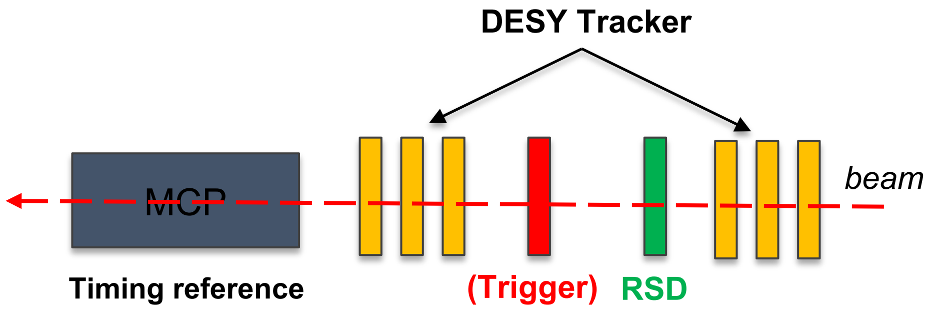
σ_{delay} **is very small**

RSD2 crosses at gain = 30 achieve a time jitter of 20 ps

RSD performance with real particles

Performed two successful testbeams in DESY in the past 12 months: DUT data synchronized with EUDET tracker

EXPERIMENTAL SETUP



DUTs: **RSD2-1300**, pixel 1300 x 1300 um^2 4 electrodes

RSD2-450, pixel 450 x 450 um^2 16 electrodes

Read-out methods

- 16ch FNAL Board + CAEN Digitizer
- 16ch FAST2 Board (INFN Torino) + CAEN Digitizer

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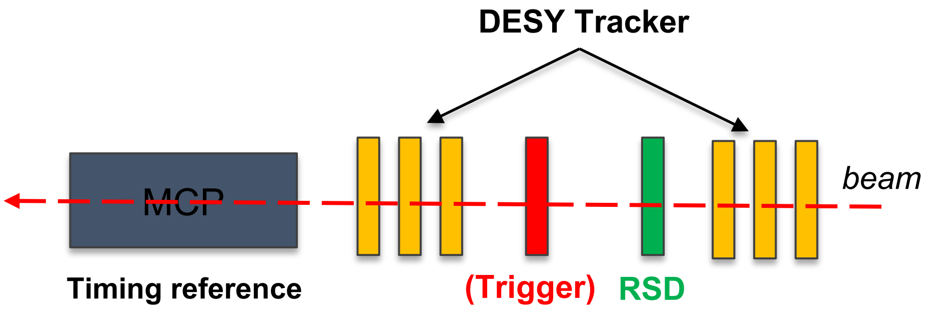

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FIRST TESTBEAM:

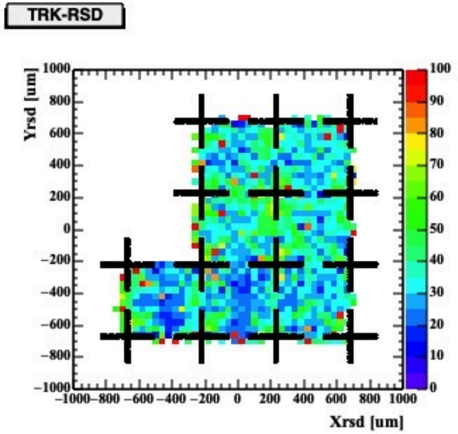
- FNAL Board +16ch CAEN Digitizer
- max gain obtained with DUTs ~15
- using high part of Landau distribution to study performance

SECOND TESTBEAM (Oct 2023)

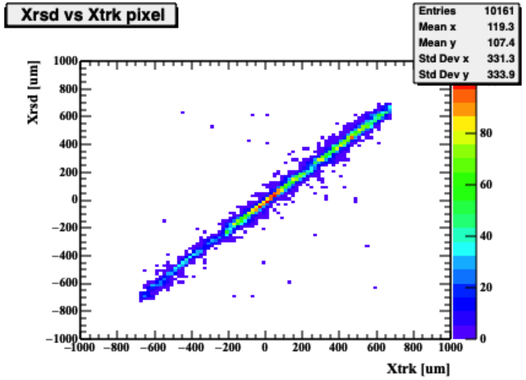
- FAST2 (custom ASIC) Board +16ch CAEN Digitizer
- lower electronic noise, higher amplification
- higher signal amplitudes obtained
- exploring up to gain ~40 with the RSD2-450

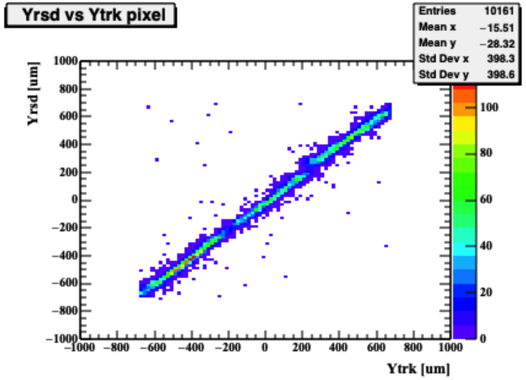
RSD@testbeam: RSD2-450 at 200 V

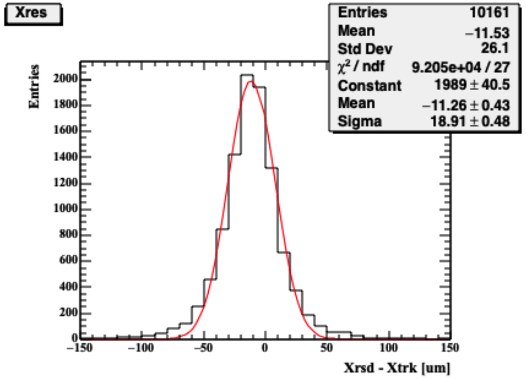
At 200 V this device has a gain close to ~ 50

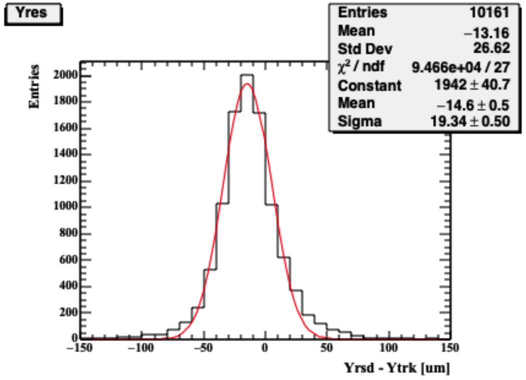


2D map of the average distance hit_RSD – hit_tracker



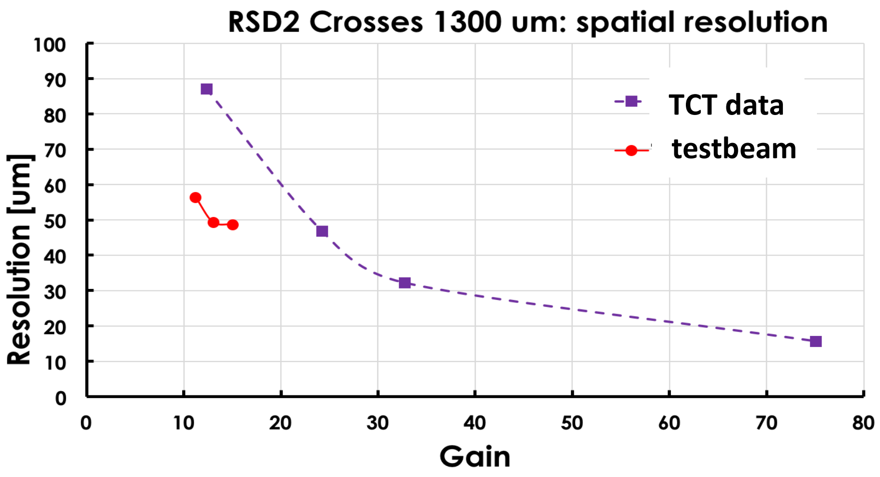






Sigma ~ 19 microns, tracker resolution to be removed (8 ± 2 μm)

RSD@testbeam: preliminary results using FAST2



Very good results with low amplitude signals.

This DUT had high noise at higher gain

at the testbeam setup

For equivalent gain, FAST2 yields better results

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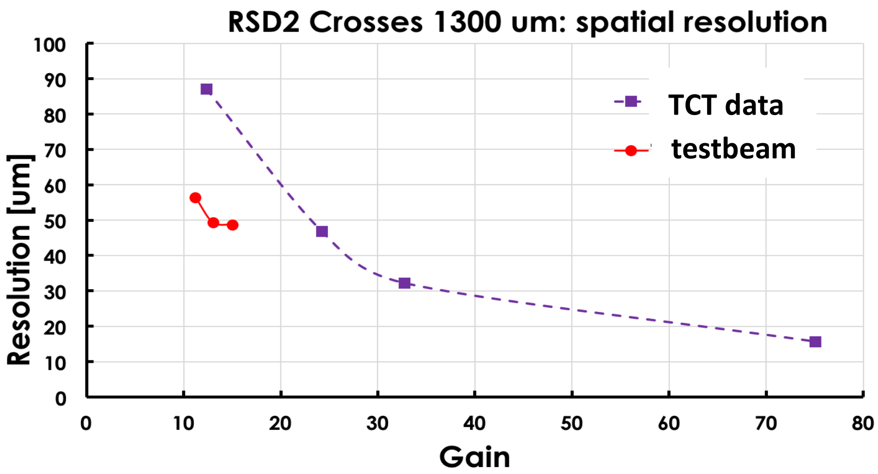
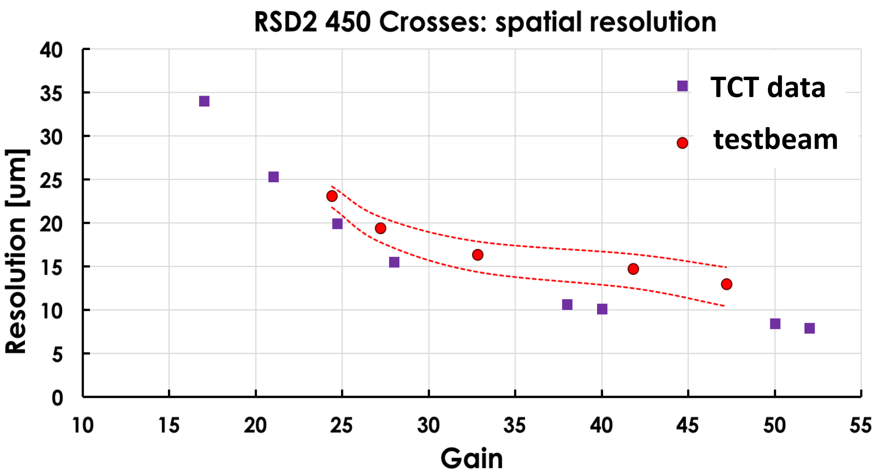




Very good results with low amplitude signals.

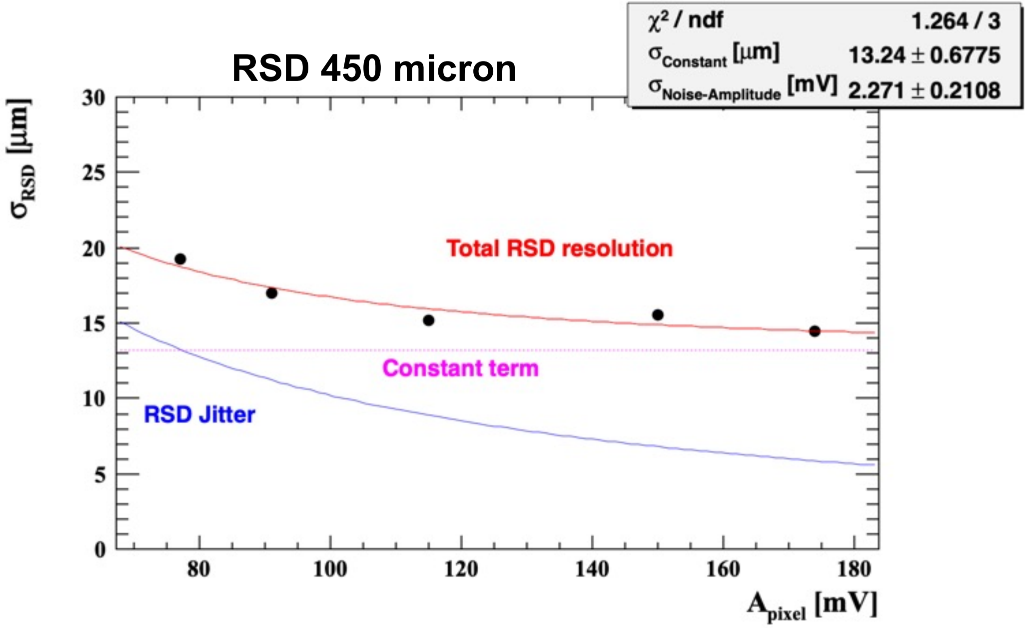
This DUT had high noise at higher gain at the testbeam setup

For equivalent gain, FAST2 yields better results.

Here, **the spatial resolution** measured with particles, at higher amplitudes, **is dominated by the constant term**: residual mis-alignment, uncertainty on the tracker resolution, read-out chain non-uniformities

Lastest results obtained RSD2+FAST2

$$\sigma_{RSD}^2 = \sqrt{\text{constant}^2 + \left(\frac{\text{Noise}}{\text{Gain}}\right)^2}$$



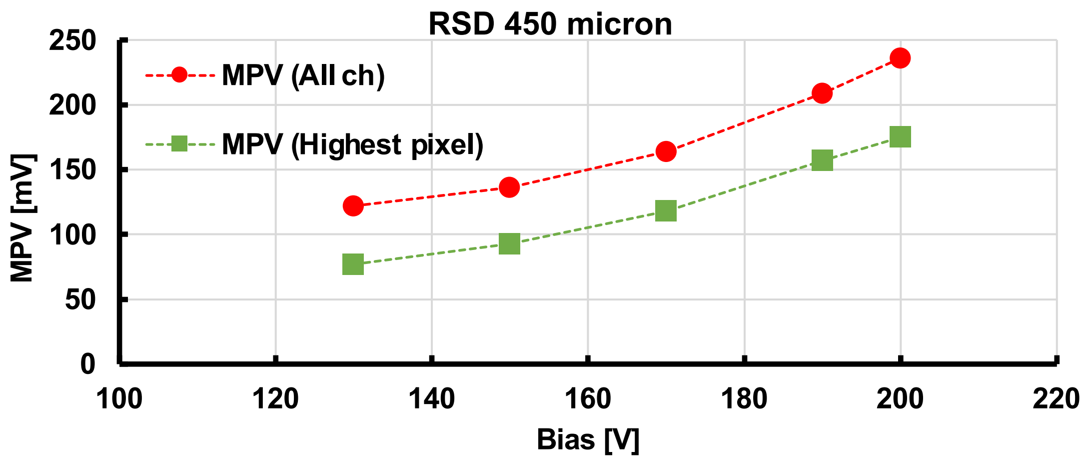
- The constant term dominates the resolution, about $\sigma_{constant} \sim 13\ \mu m$
- The constant term includes mis-alignement RSD-Tracker, sensor and electronics non uniformity, etc…

Take away message from AC-LGAD (RSD)

To be noted:

- signal spread may involve a larger (>4) and variable number of electrodes, leading to slight deterioration and a spatial resolution which is position-dependent.
- performance of these device with cross shape electrodes is computed using only four electrodes, method which leads to the best results. **On average 30% of the signal leaks outside the area read by the four electrodes**
- the leakage current of the whole device is read out at the periphery of the device: baseline fluctuations in large or in highly irradiated devices

→ the resolution should further improve with the full containment of the signal in a predetermined area



The next level evolution: DC-coupled RSD

DC-RSD: DC-coupled Resistive readout Silicon Detectors

Development started in the framework of the project 4DInSide (Italian National project) in collaboration with FBK, and now supported by the 4DSHARE Grant (Italian National project)

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Goal: evolve the resistive AC-LGAD design, improving the performance and scalability to large devices

Key points: achieve controlled signal sharing in a predetermined number of pads and drain the device leakage current at every pixel

The DC-coupled resistive read-out LGAD (DC-RSD)

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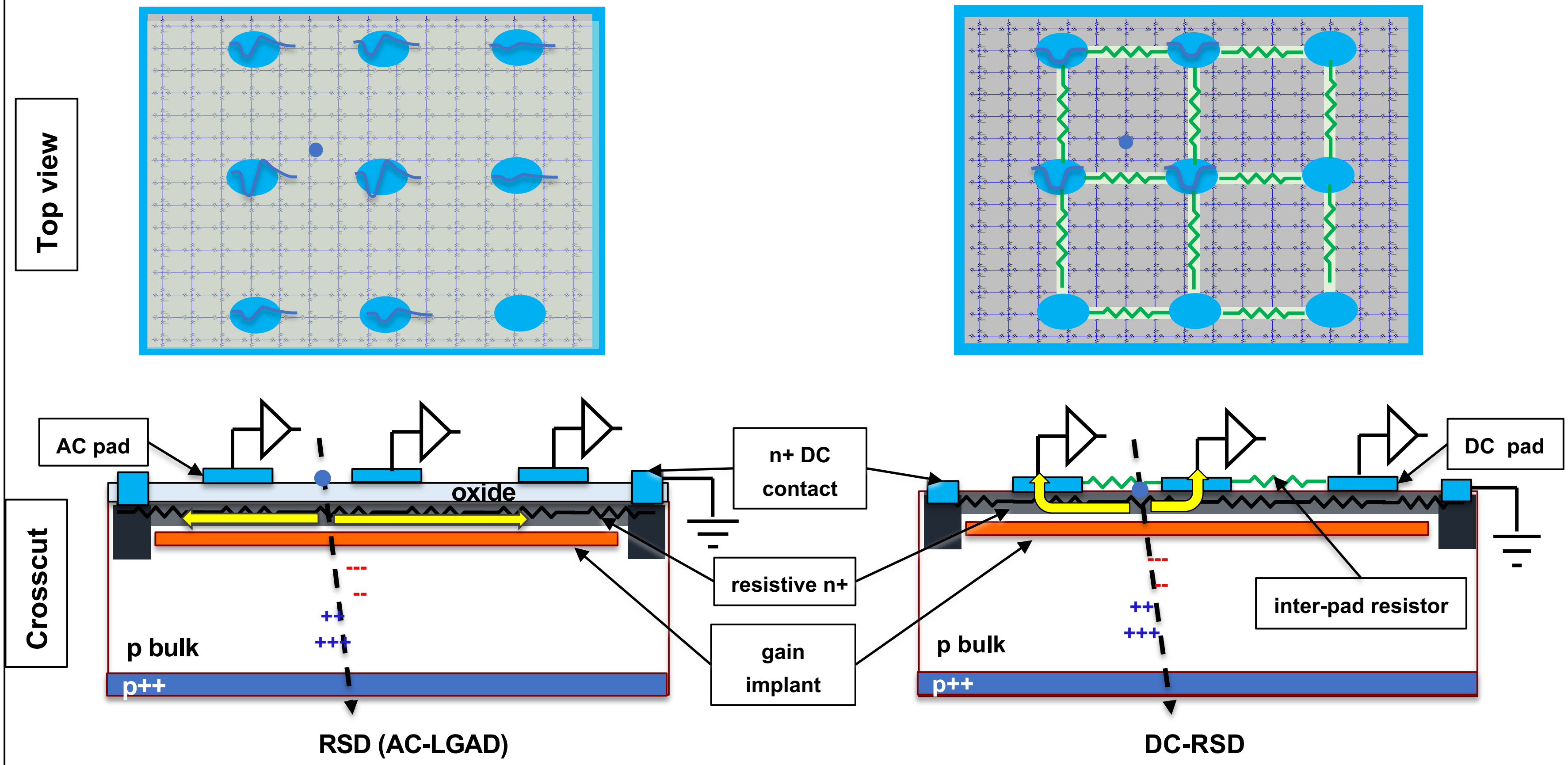
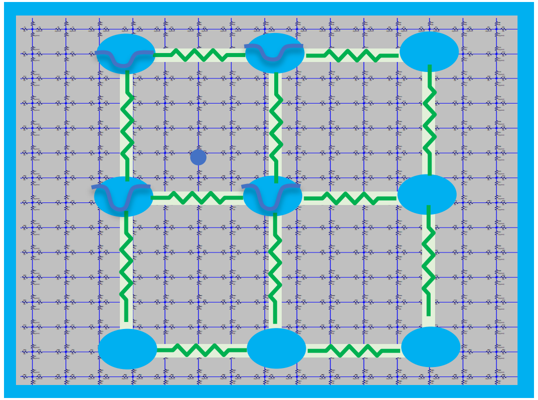


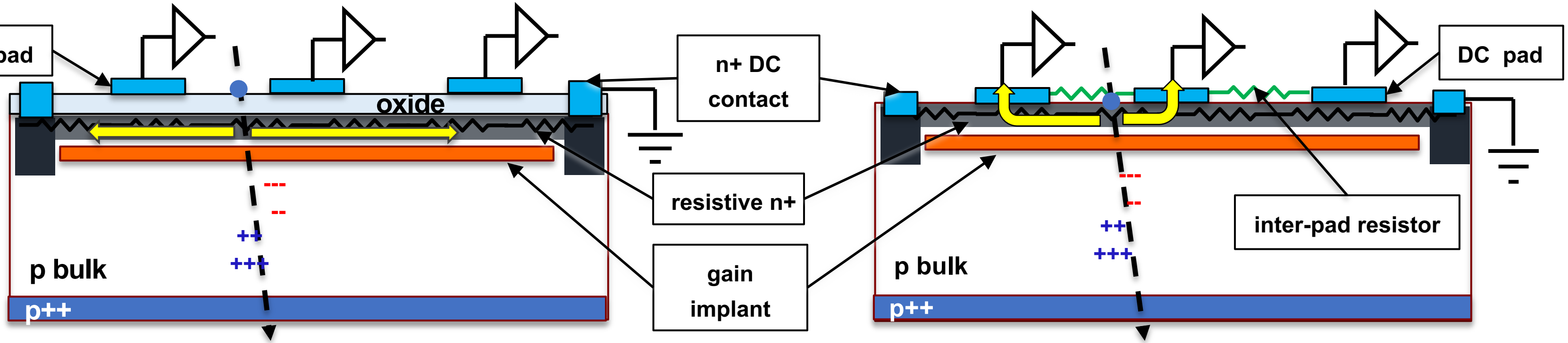
The DC-coupled resistive read-out LGAD (DC-RSD)

Top view

- Oxide layer for AC-coupling removed
- read-out electrodes implanted on the resistive layer
- inter-pad resistors added to create a "cage" where the signal is confined
- the signals are read out via the closest DC electrodes
- the leakage currents is removed locally at each electrodes



Crosscut

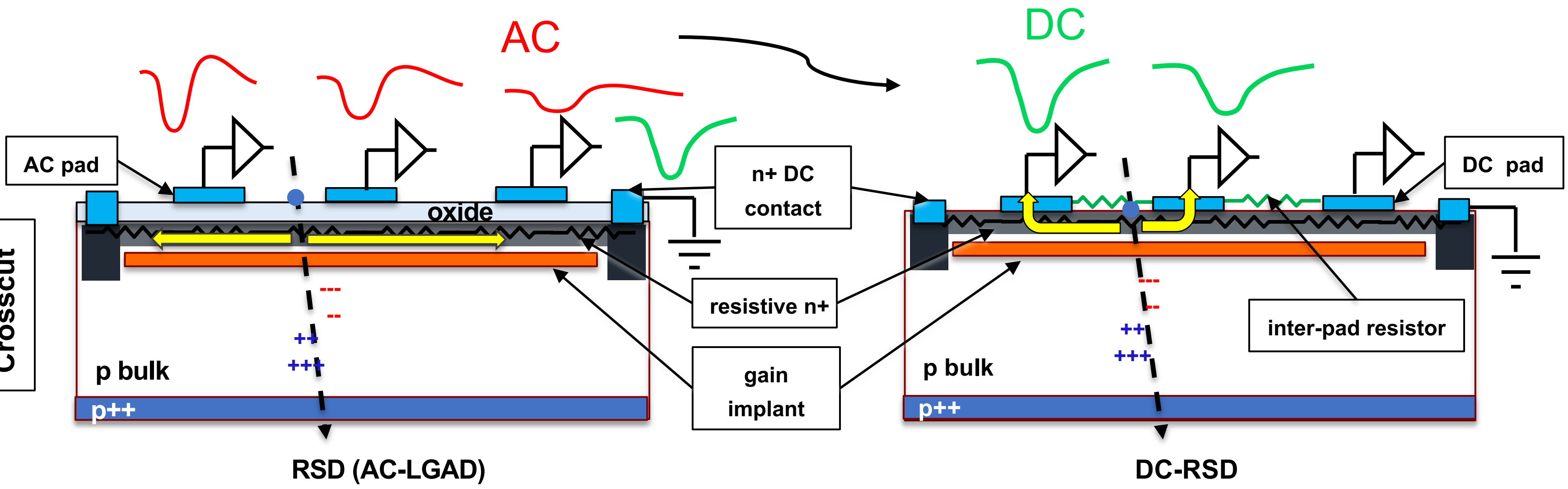


RSD (AC-LGAD)

DC-RSD

The DC-coupled resistive read-out LGAD (DC-RSD)

- No signal dispersion, reconstruction of a particle hit involves a predetermined number of pads
- No bipolar signal (i.e. slow discharge) → 1 ns-long pulses
- No signal dispersion + No baseline fluctuations → improved SNR ratio
- Due to their characteristics, DC-RSD with O(cm^2) active surface are feasible



Crosscut

Status of the R&D: production process flow

Working on two fronts: development of the production process flow (exploration of technological solution to manufacture the device - FBK) and simulation of the device

FBK technological studies

- completed a few short-loops to acquire the necessary technical skills needed for DC-RSD:
  - learn how to achieve a “zero-resistivity” Al - Si substrate contact
  - Resistors with Ti-TiN: study properties of the contact with Si substrate, which resistivity are obtainable and so forth

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- “zero-resistivity” Al - Si substrate contact achieved

- “zero-resistivity” contact with Si substrate achieved
- work ongoing to master the art of implementing the inter-pad resistors with controllable, and uniform values

We recently explored the possibility of using trenches (like in SiPM or TI-LGADs) to contain the signal, instead of inter-pad resistors

Status of the R&D: 3D TCAD simulations

Working on two fronts: development of the production process flow (exploration of technological solution to manufacture the device - FBK) and simulation of the device

The DC-RSD concept and the sensor design have been guided by simulations [4]

We performed detailed simulation studies on the signal spread characteristics (sharing, amplitude variations, delays between electrodes) in different conditions:

- Use of crossed-shaped or bar-shaped electrodes
- Use of floating electrodes to contain the signal
- Use of a squared or hexagonal matrix of electrodes (dot-like), effect of electrode diameter
  - Use of resistive strips between electrodes
  - Use of trenches of different length between electrodes

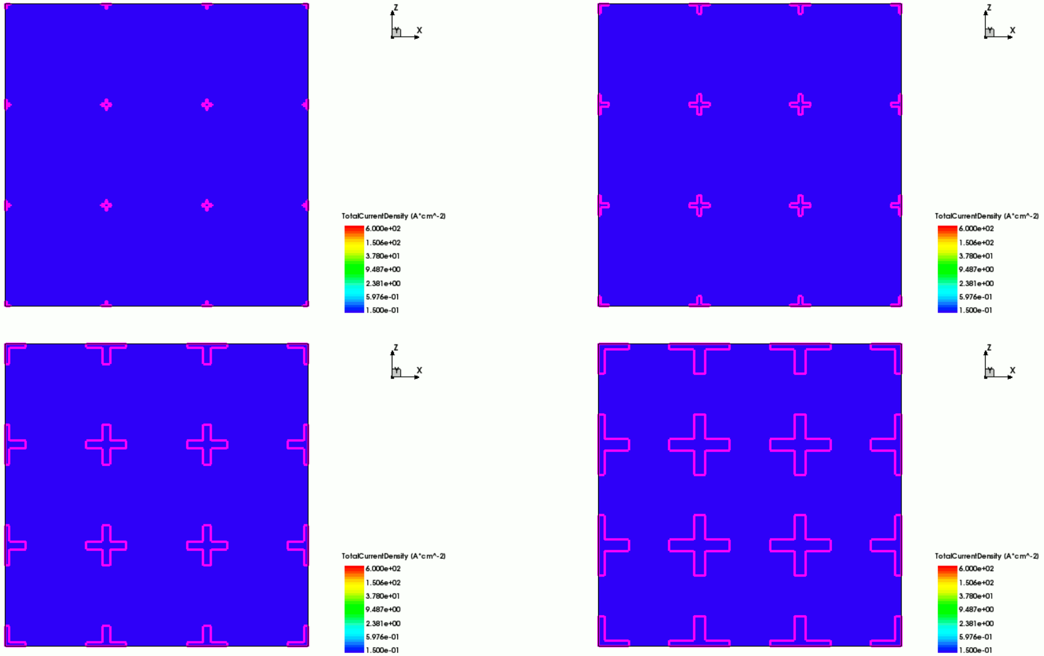
Signal spread with cross-shaped electrodes in DC-RSD

3x3 pixel DC-RSD structure, evolution of the current density over the resistive layer

Different cross shape dimensions were considered:

when the electrodes are an important fraction of the pitch, the signal is well-confined inside the cell

however, if the particle hits one electrode not in its center, the information about the impact position is altered (located in the center), so it is not appropriate to implement electrodes with long arms.



3D TCAD simulations with MIP stimulus

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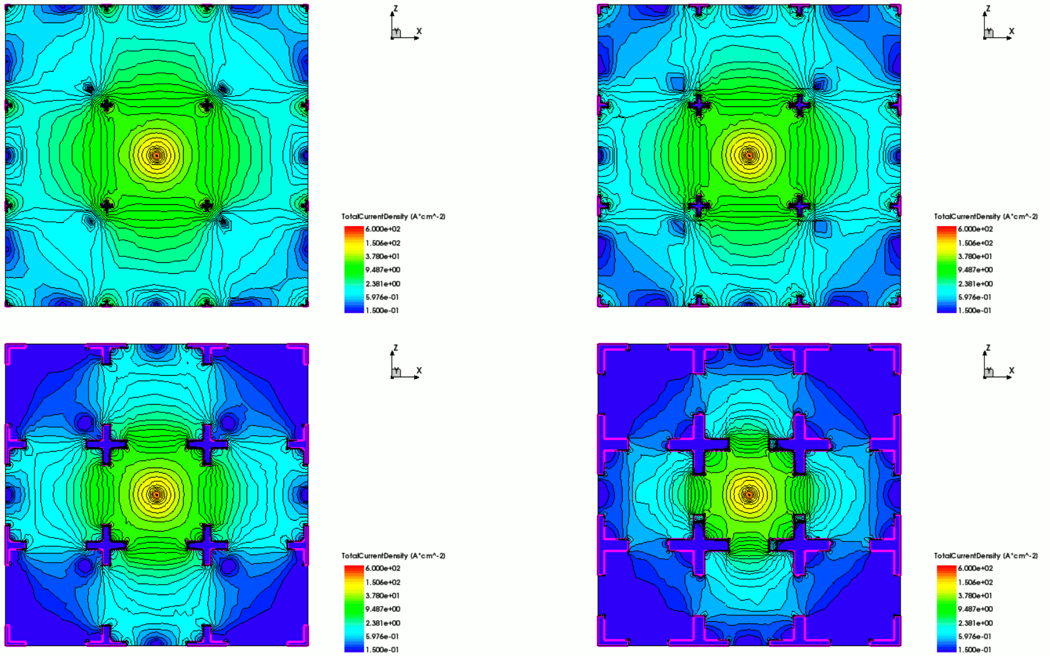

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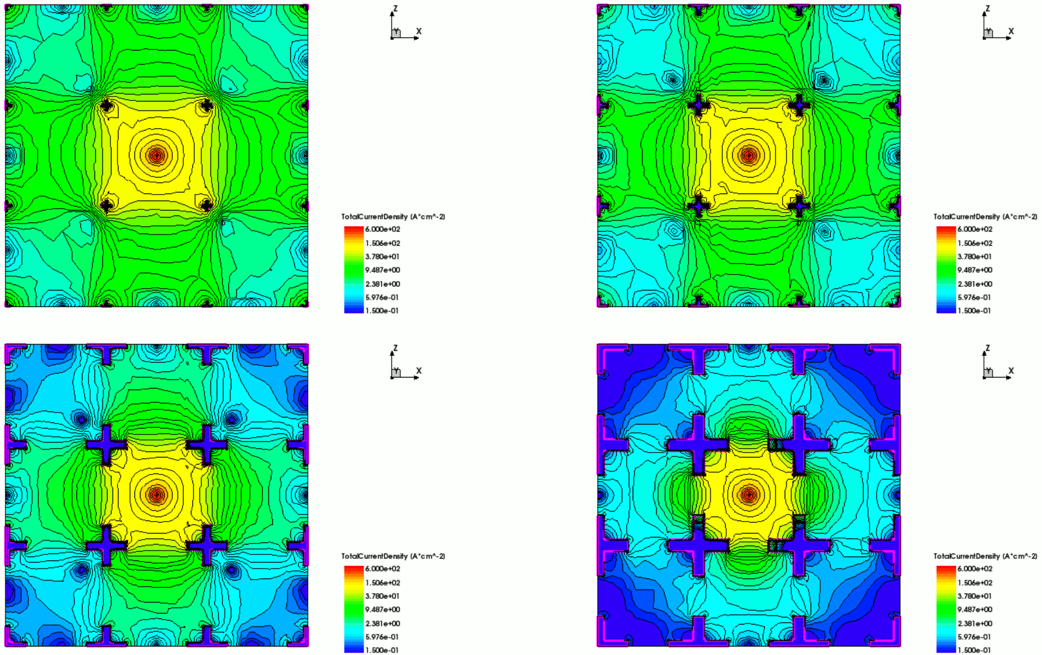

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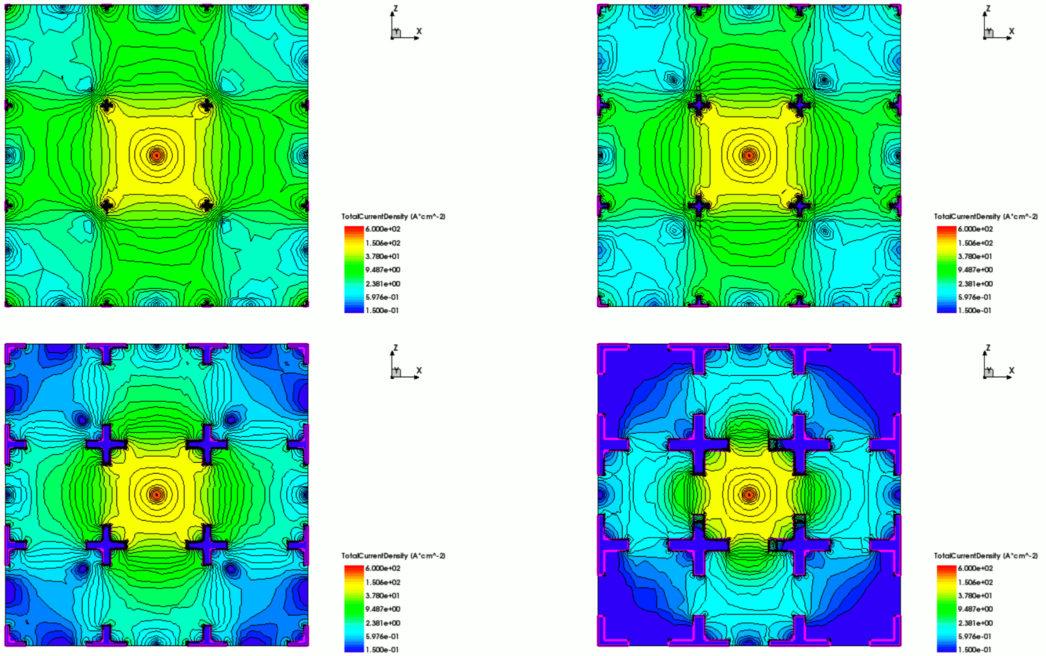

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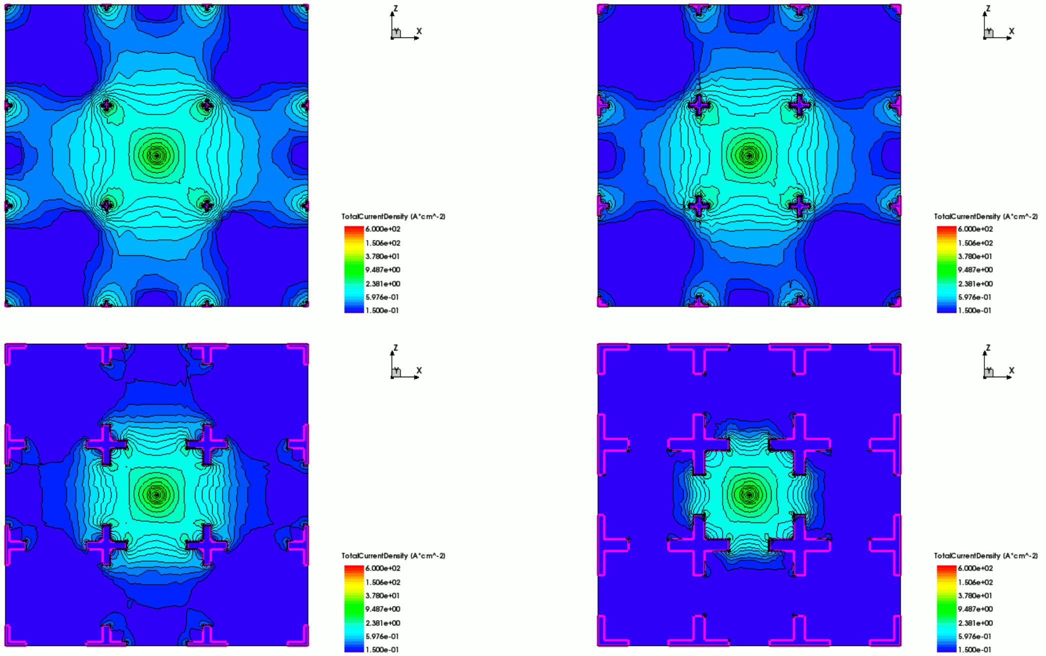

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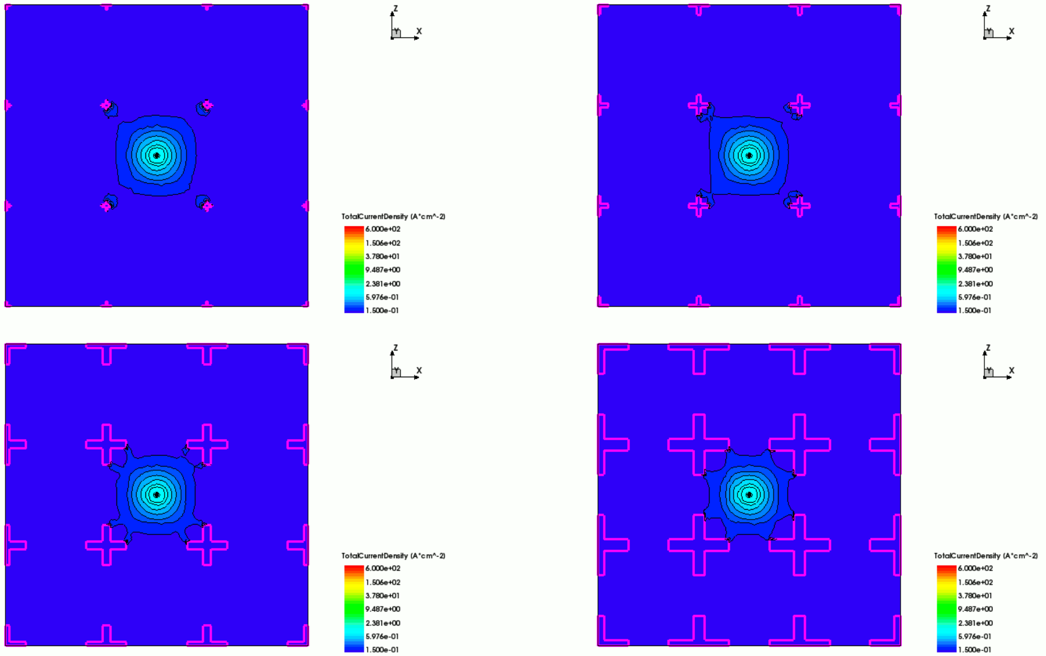

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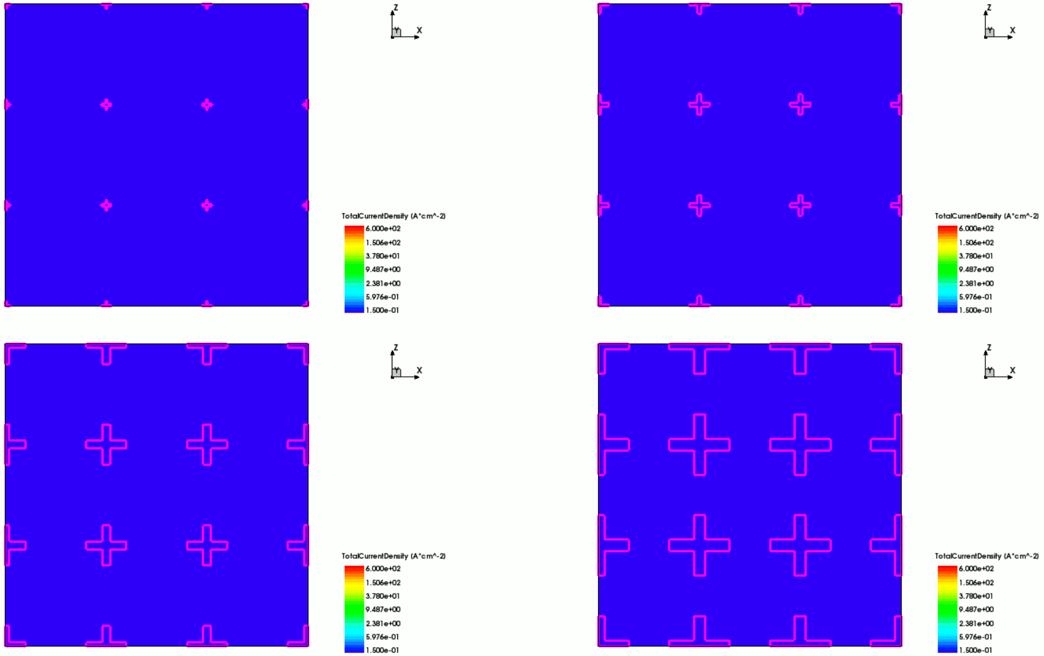
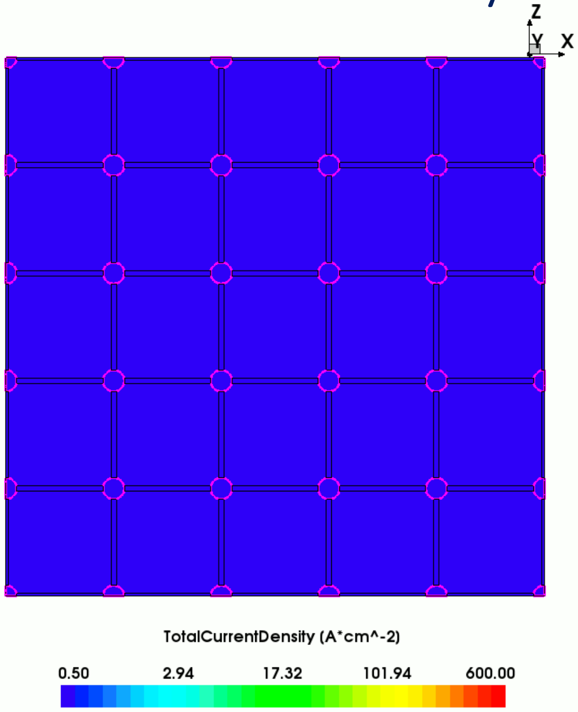


Signal spread with inter-pad resistors or isolating trenches

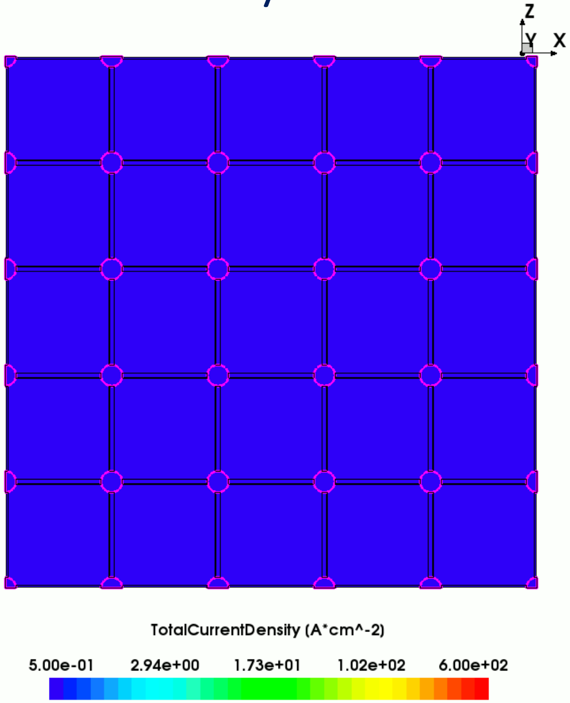
5x5 pixel structure, evolution of the current density over the resistive layer

Pixels with inter-pad resistors or isolating trenches, connecting 100% of the gap within electrodes, have a signal well confined

The cause of the small signal spill outside the hit pixel, 1 or 2 orders of magnitude smaller than the central signal, is related to the dimension of the simulated pixel



inter-pad resistors



isolating trenches

3D TCAD simulations with MIP stimulus

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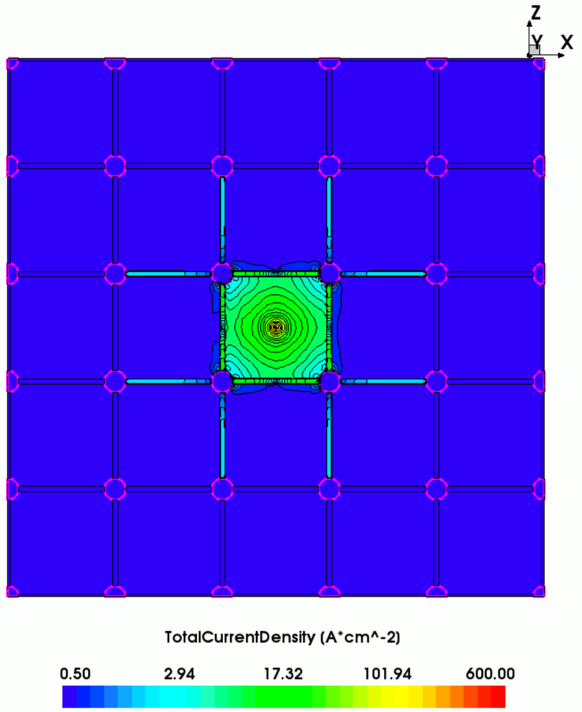

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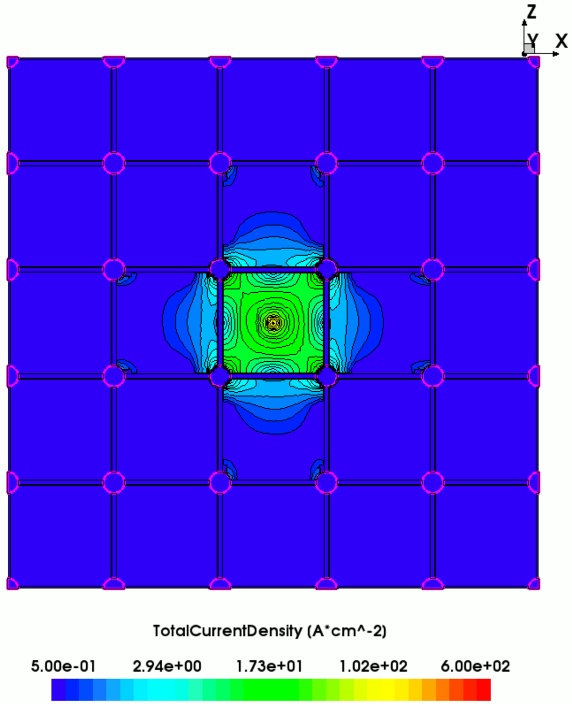

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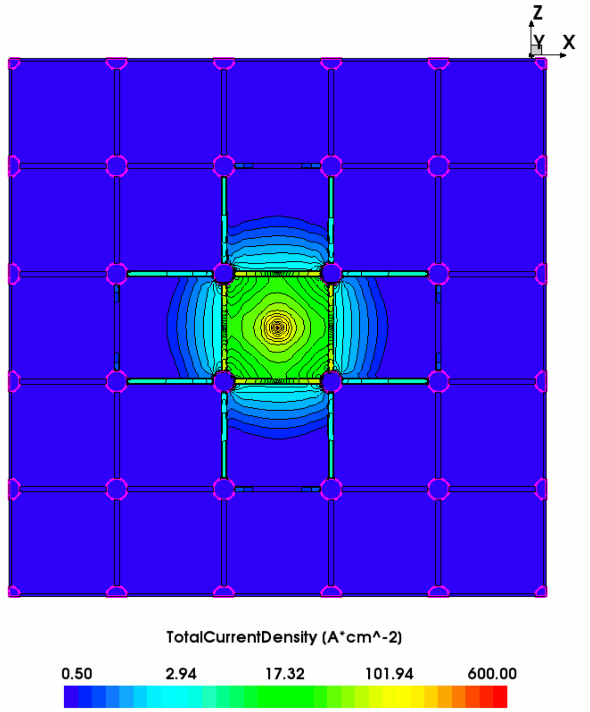

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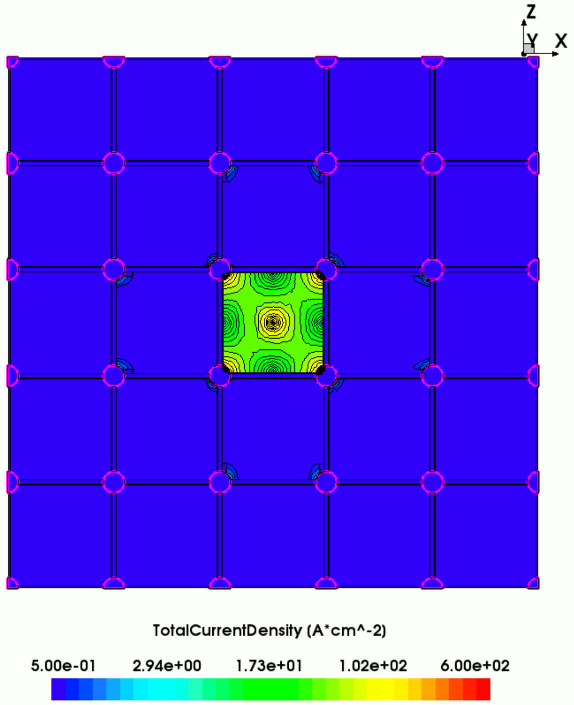

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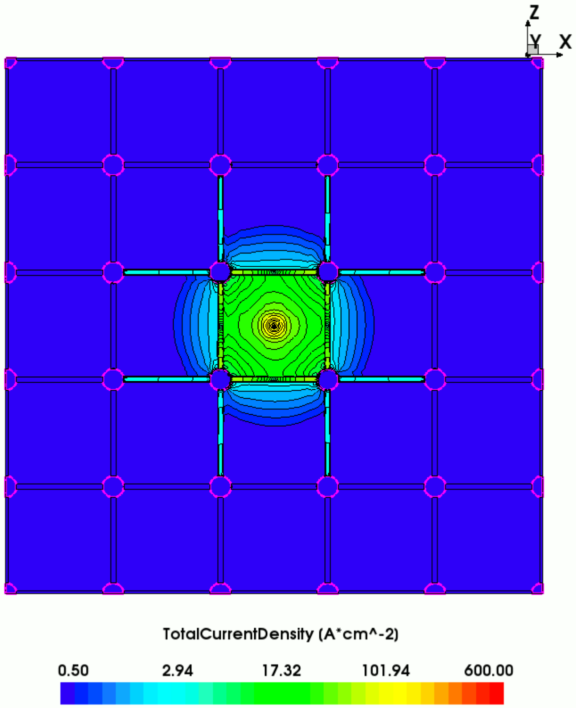

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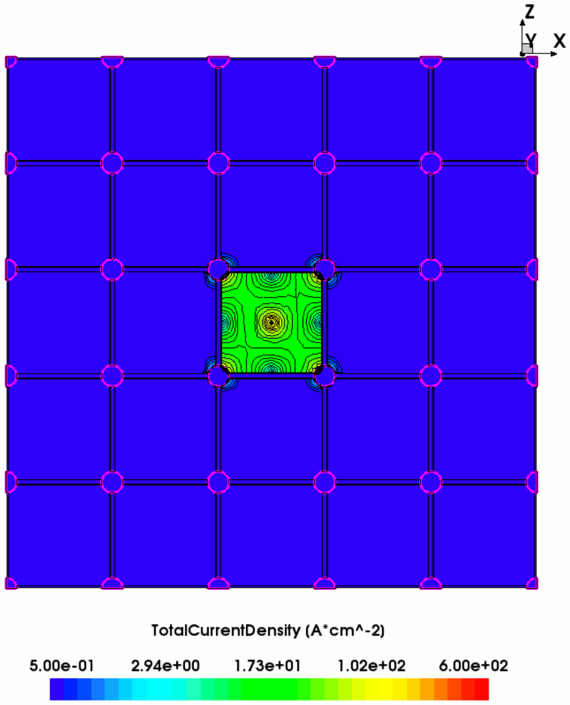

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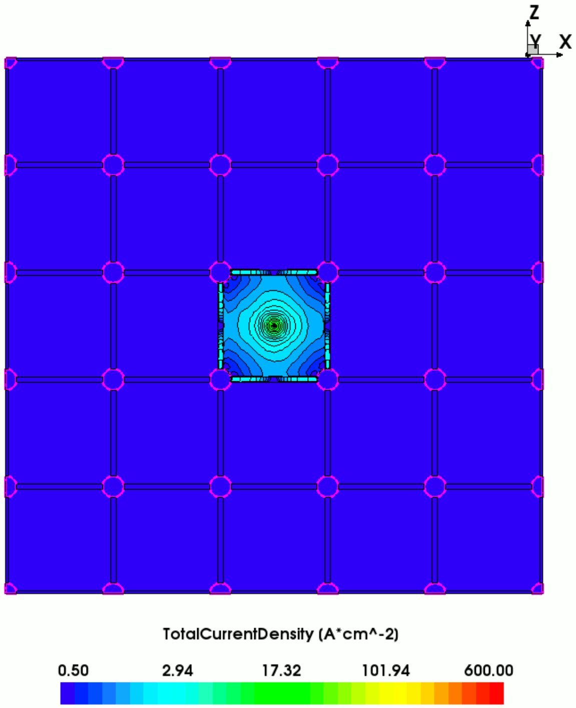

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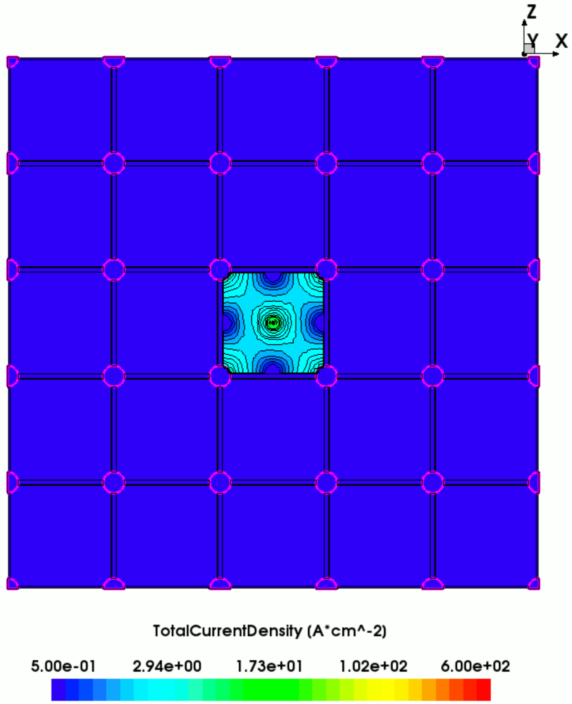

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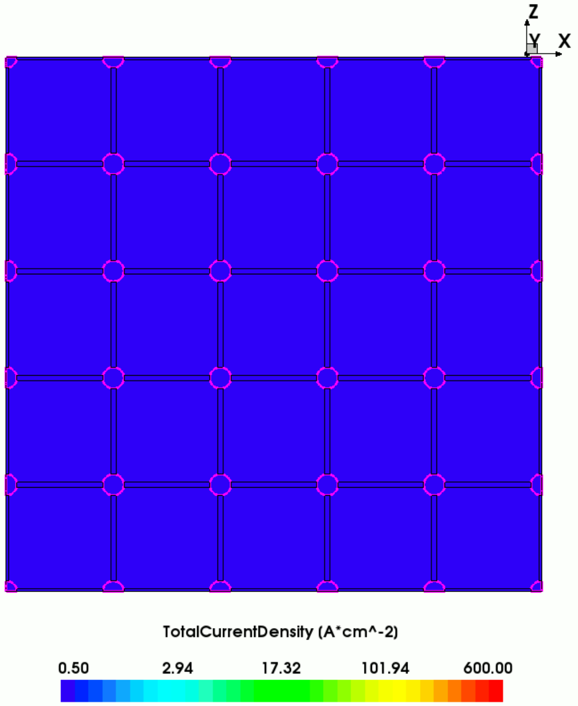

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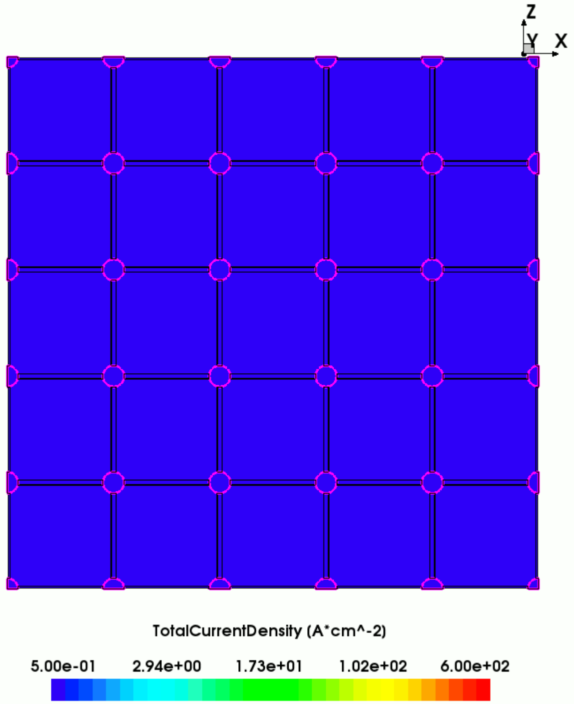

isolating trenches

Outlook on the first DC-RSD prototype run

The solution selected to achieve the containment: **Isolating Trenches**
→ the design will be implemented with this technology

The design of the reticle (area of ~ 2.1 x 2.1 cm^2), hosting several test structures, has been finalized:

- structures with squared or hexagonal matrix of electrodes (dot-like), without and with isolating trenches

The gain layer type will be shallow and not-carbonated

The production has started. First sensors ready for characterization in Fall 2024

Conclusions

The existing resistive read-out LGAD sensors (AC-coupled RSD) are demonstrating unprecedented performance in terms of combined space and time resolutions.

The characteristics of the shared signales carry a wealth of information well suited for reconstruction algorithms based on machine learning. This technique will probably provide the ultimate position and time resolution.

This innovative sensor concept looks very promising for the future 4D-tracking detectors.

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The **DC-coupled** version of the **RSD** should provide **improved performance and scalability to larger devices. The first proof-of-concept DC-RSD production is in progress… Stay tuned!!**

I hope we will have as much fun in the next 10 years!

Acknowledgements

We kindly acknowledge the following Funding Agencies and collaborations:

- INFN - CSN V – RSD project
- Horizon 2020, ERC-advanced grant UFSD669529
- H2020 project AIDA-2020, GA no. 654168
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)
- Ministero della Ricerca, Italia , PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia , PRIN 2022, progetto 2022KLK4LB – 4DShare
- RD50 Collaboration, CERN
- INFN - CSN V - 4DSHARE project
- Compagnia San Paolo, Bando TRAPEZIO 21, Italy

Some References

- G.Pellegrini,et al., **Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications**, Nucl. Inst. Meth. A 765 (2014) 12.

- M. Mandurrino et al., “First production of resistive AC-coupled silicon detectors (RSD) at FBK,” presented at the 34th RD50 Workshop, Jun. 2019. [Online]. Available: https://indico.cern.ch/event/812761/ contributions/3459062

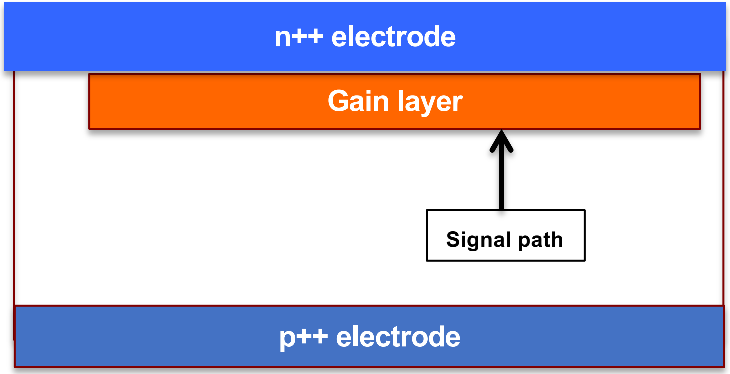
- F. Siviero et al , "Optimization of the gain layer design of Ultra-Fast Silicon Detectors”, https://arxiv.org/abs/2112.00561, NIMA 1033

- R. Arcidiacono et al, “High precision 4D tracking with large pixels using thin resistive silicon detectors”, NIM A 1057 (2023) https://doi.org/10.1016/j.nima.2023.168671
- L. Menzio et al., “DC-coupled resistive silicon detectors for 4D tracking”, NIMA 1041 (2022) 167374

- F. Siviero et al, “Machine learning for Precise Hit Position reconstruction in resistive Silicon Detectors”, JINST 19 C01028

BACK-UP material

Signal, noise in LGAD



First concept: gain (G) increases the signal (I):

$$Signal = G * I_{signal}$$

Second concept: gain increases noise more than increases the signal

$$\sigma_{Signal} = G * I_{signal}\sqrt{F}$$

Excess noise factor: noise of the multiplication process

$$F = Gk + \left(2 - \frac{1}{G}\right) * (1 - k)$$

k = e/h ionization rate

G = gain

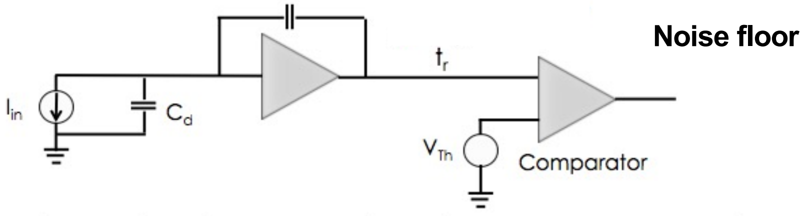
Conclusion:
internal gain decreases the signal-to-noise ratio of the signal BUT…we need to consider also the electronics noise

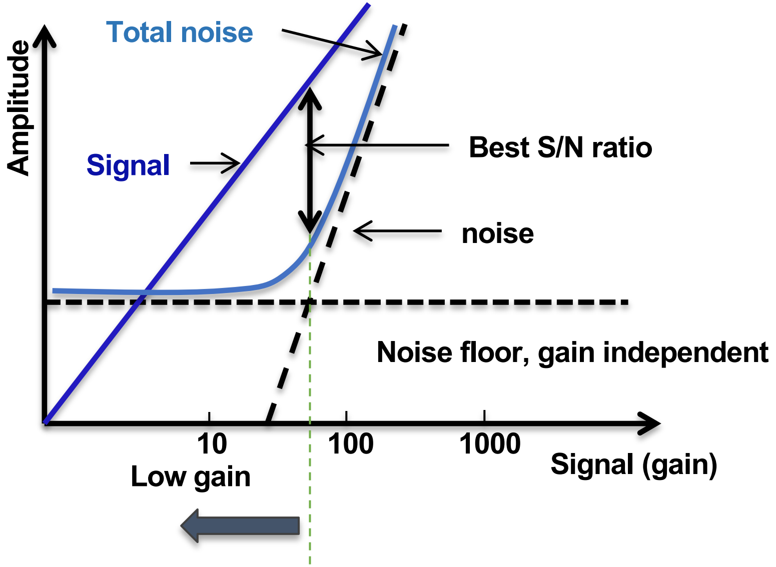
Signal, noise in LGAD + Electronics

1) The electronics has a noise floor
2) The signal increases with gain
3) The noise increases with gain with steeper characteristics
4) **The total noise is flat at low gain, and then it increases fast**

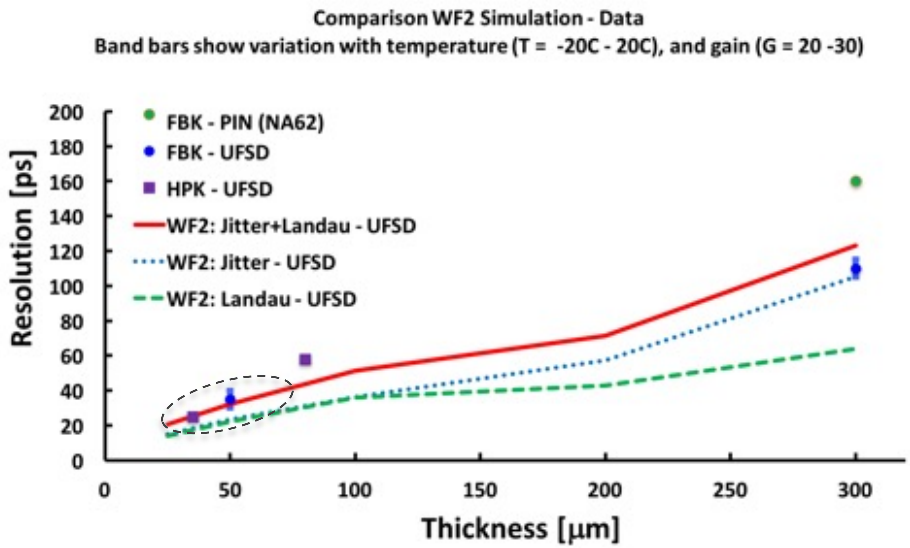
"Low gain" needs to be understood in connection with the noise of the electronics: it is the range of gain with an improved signal-to-noise ratio.

The success of LGADs rests on the fact that the sensor noise is hidden by the electronic noise





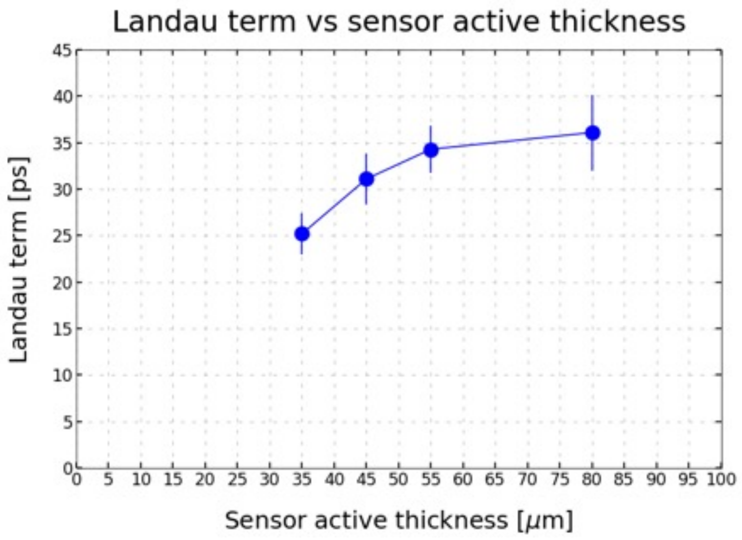
UFSD temporal resolution in thinner sensors



resolution improves in thinner sensors:

==> reasonable to expect 10-20 ps for 10-20 μm thick sensors.

Be aware: very difficult to do timing with small signals… power consumption increases

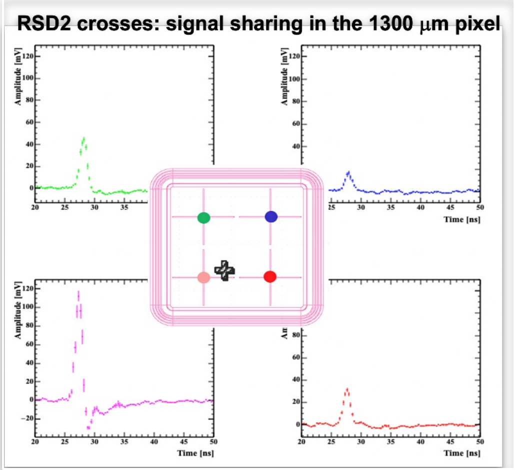


RSD2 with crosses: TCT Lab studies

Signal formation and performance studied in the lab using a TCT-setup with **picosecond laser** (spot ~ 8 um; Intensity 1-3 MIPs), mounted on a movable x-y stage ($\sigma_{x\text{-laser}} \sim 2\ \mu m$).

16 electrodes read out (FNAL read-out board + digitizer)

Typically signals from 4 adjacent electrodes are used in the reconstruction.



Position and time coordinates are reconstructed with the methods briefly described in the following.

More details in this paper http://arxiv.org/abs/2211.13809

RSD: reconstruction method in TCT measurements

SPACE RESOLUTION

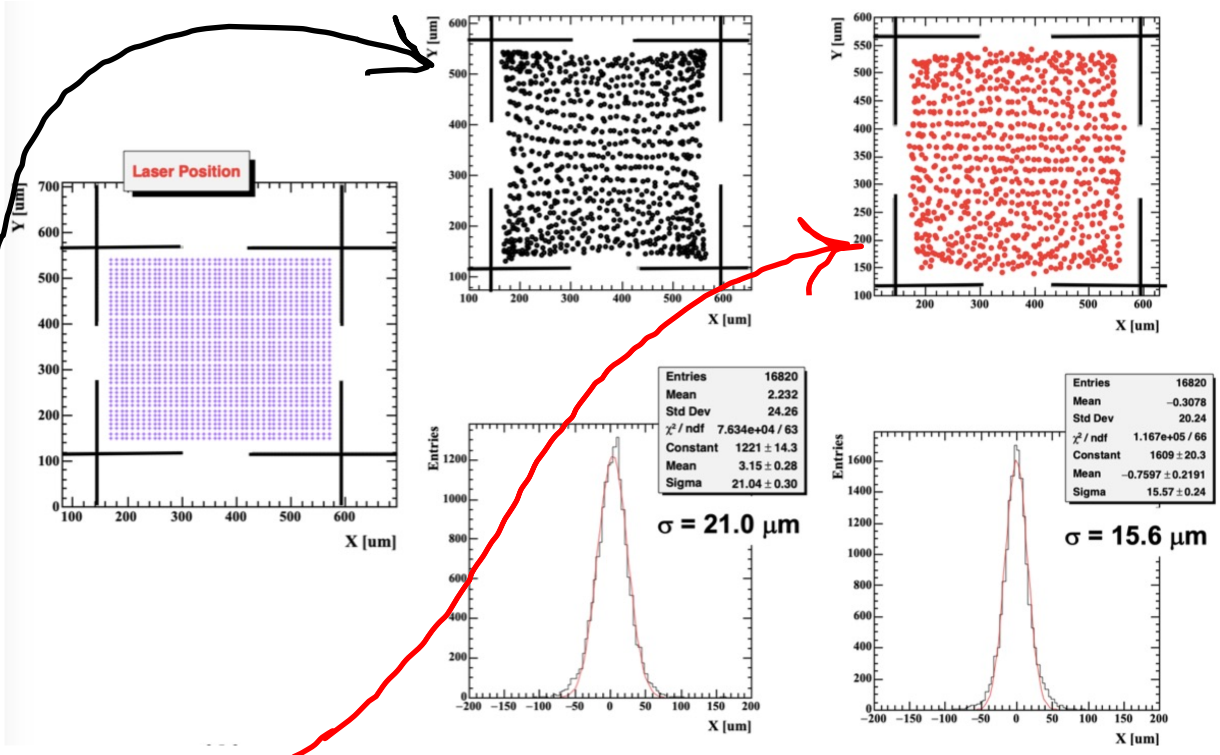
x-y coordinates reconstructed using only **4 neighboring electrodes with the larger signals.**

Method: “charge asymmetry”

$$x_i = x_{center} + k_x \frac{pitch}{2} * \frac{Q_3 + Q_4 - (Q_1+Q_2)}{Q_{tot}}$$

$$y_i = y_{center} + k_y \frac{pitch}{2} * \frac{Q_1 + Q_3 - (Q_2+Q_4)}{Q_{tot}}$$

The coordinates are then corrected using a migration matrix (measured always with the laser setup – independent set of data)



reconstructed positions for the 450 × 450 μm^2

Parametrization of the resolutions

SPACE

$$\sigma^2_{hit\ pos} = \sigma^2_{jitter} + \sigma^2_{rec} + \sigma^2_{setup} + \sigma^2_{sensor}$$

- ***jitter term***: related to the variation of signal amplitude induced by the electronic noise (this biases the space-amplitude correlation) **~Noise/(dV/dx)**
- σ_{rec} : accuracy of the reconstruction method used, which might have a position-dependent systematic offset
- σ_{setup} **:** related to changes in the relative signal sharing due to the experimental set-up.
- σ_{sensor} **:** all sensor imperfections contributing to an uneven signal sharing among pads

TIME

$$\sigma^2_{hit\ time} = \sigma^2_{jitter} + \sigma^2_{Landau} + \sigma^2_{delay}$$

Uncertainty on hit time seen by a single pad

- ***jitter term***: due to the electronic noise **~Noise/(dV/dt)**
- ***Landau term***: due to non-uniform ionization, about ~30 ps for a 50 µm thick sensor
- σ_{delay} : the delay, due to the propagation time to the read-out pad, has un uncertainty induced by the hit position reconstruction.
- uncertainties due to variation of signal amplitude are corrected (time walk corrections)