4D-tracking with silicon detectors: a Decade of Developments Chasing Accurate 4D Tracking.

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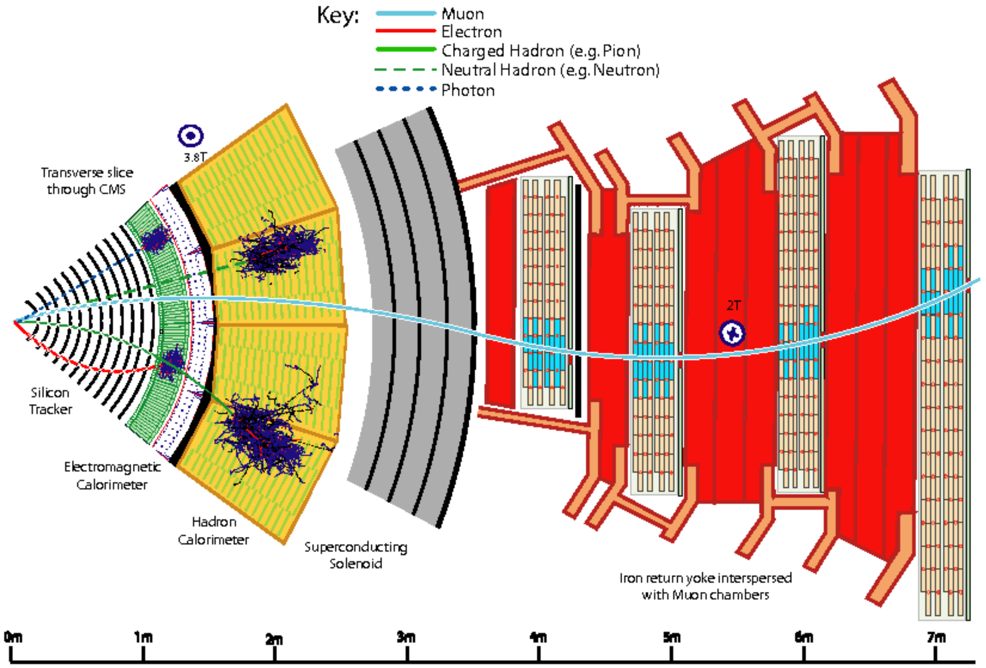
The XXXIII Bonaudi-Chiavassa International School on Particle Detectors

4D tracking?? let's start with 3D trackers…

Particle trackers are traditionally placed in the inner part of a detector.

Trackers: they can "see" the charged particles tracks

Principle of operation: detection of the ionisation induced by the particle traversing the sensitive medium, leaving measurable signals (hits) in multiple layers of the detector.



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Coupled with a calibrated magnetic field, it provides the measurement of the charge and momentum of the particle

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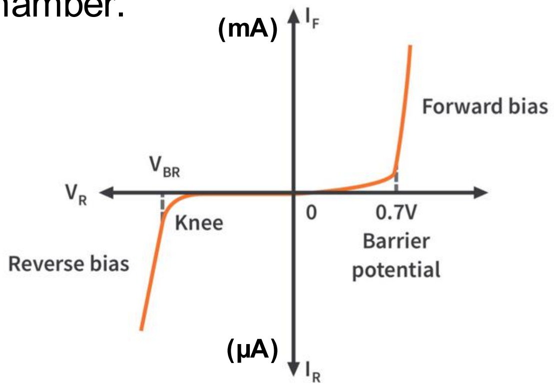
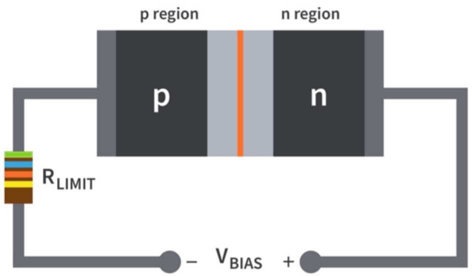
For their excellent spatial resolution, flexibility, and reliability, **silicon-based sensors have been the preferred technology for more than 40 years**.

These sensors are fabricated using thin layers of silicon, approximately 300 micrometres thick: **diodes of various geometries are operated applying a reverse-bias voltage** → the sensor (p-n junction) is depleted of free charge carriers and effectively behaves as a solid-state ionization chamber.





https://www.circuitbread.com/study-guides/basic-electronics/diodes-and-diode-circuits

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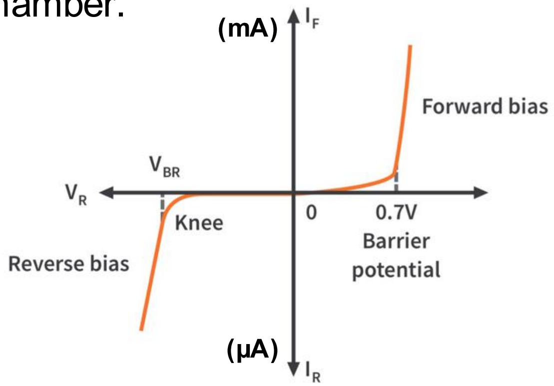

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Some characteristics of Silicon crystals

– Small band gap Eg = 1.12 eV -> E(e-h pair) = 3.6 eV (~30 eV for gas detectors)
– 106 e-h/μm (average) produced by a M.I.P.
– High carrier mobility μ_e = 1450 cm^2/Vs, μ_h = 450 cm^2/Vs
→ fast charge collection (<10 ns)
– Rigidity of silicon allows thin self supporting structures
– Detector production by microelectronic techniques
→ well-known industrial technology, relatively low price, small structures easily possible

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4.5×10^8 free charge carriers in this volume → reduce number of free charge carriers, i.e. deplete the detector

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Silicon tracking detectors underwent a remarkably fast evolution, enabling many key discoveries in the fields of nuclear and particle physics. Their applications extend across diverse fields, including solid-state physics, astrophysics, biology, and medicine.

the 4th dimension… Time

Detectors for particle time measurement, mostly aiming at time-of-flight measurement for particle identification or to time tag reconstructed particles, have been **traditionally based on Multigap Resistive Plate Chambers (MRPC), scintillator counters, and Cherenkov-based detectors**.

The feasibility of using **silicon sensors for precision time measurements** has been recently demonstrated, particularly in the development of timing detectors for pile-up mitigation at LHC, enabled by the development of the **low-gain avalanche diode (LGAD) technology**.

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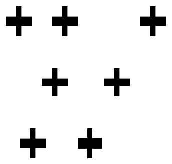
The introduction of silicon sensors with high-precision timing capabilities has opened the way to **R&Ds oriented to measuring position and time of passage of a charged particle using the same silicon-based sensitive device,**
to achieve high-resolution **4D-tracking detectors.**

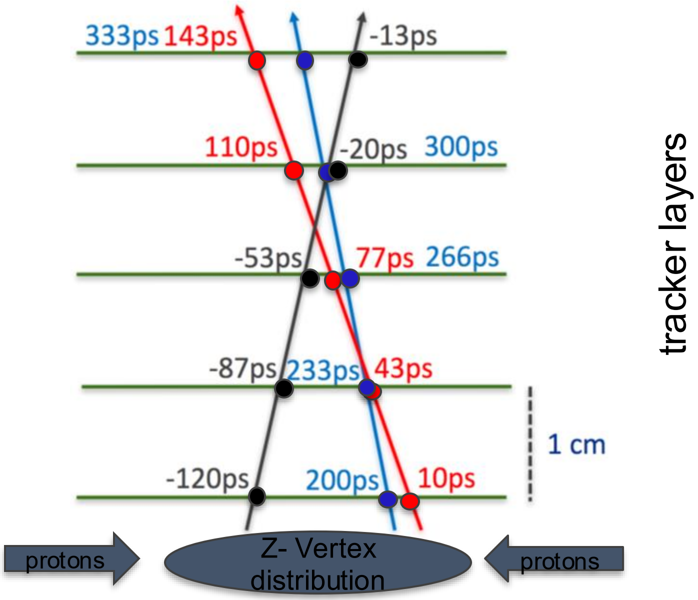
4D tracking: how to make use of timing information

The inclusion of track-timing in the event information may change radically how we design experiments.

The time information can be available:

1) At each point along the track
2) At track level
3) At the trigger level





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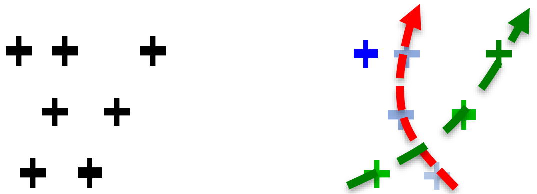
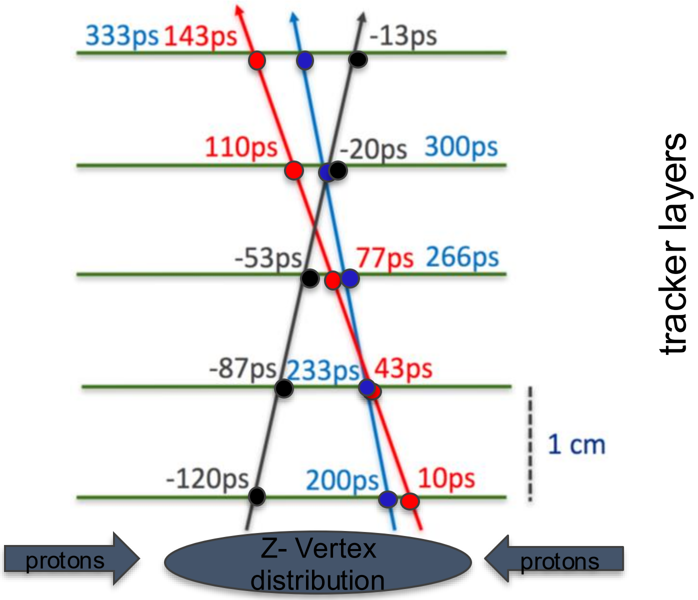


Massive simplification of patter recognition using only "time compatible points"



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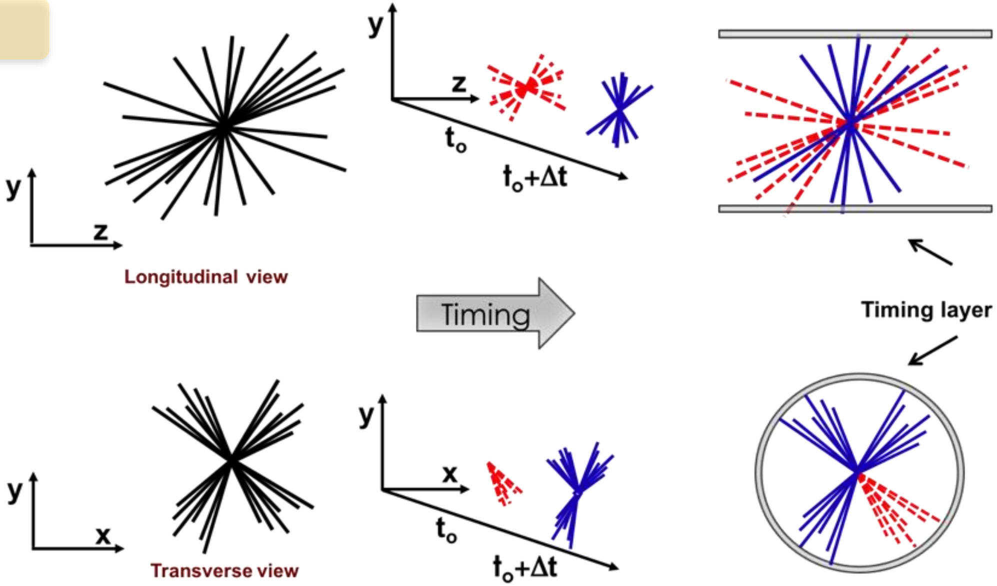
Timing allows distinguishing overlapping events by means of the time information.



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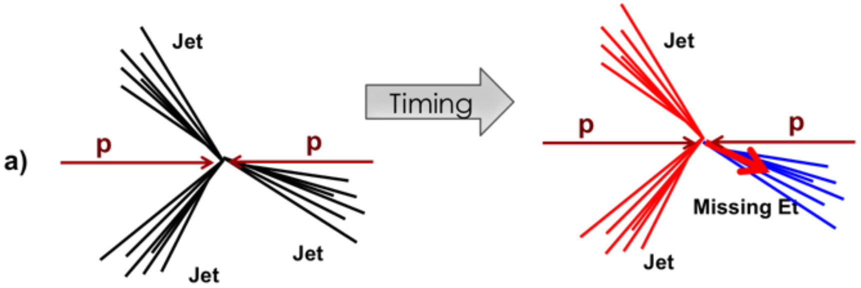
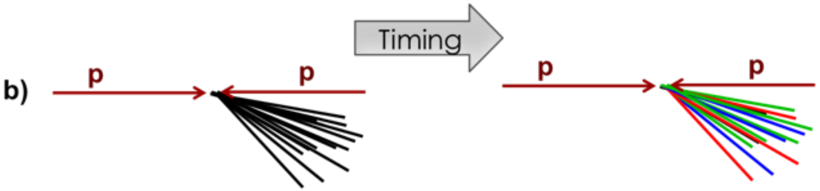
trigger rate reduction: time can be used to better identify the different topologies already at trigger level



3-Jet event?

2-Jet and Missing Et event



Forward jet?

Overlap of uncorrelated tracks

In our future…

Facility:	FCC-ee	ILC	CLIC
$\sigma_{x,y}$ [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?

pixelated binary read-out

$$\sigma_x = k \frac{pitch}{\sqrt{12}}$$

$k \sim 0.5 - 1$

From **"The 2021 ECFA detector research and development roadmap"**, ECFA Detector R&D Roadmap Process Group

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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

Key point

Precise time measurement in a 4D-tracker is a matter of two:
sensor and front-end electronics

During this decade the front-end design evolved towards low-power.

The primary optimization factor for a practical 4D tracking system (millions of readout channels) is power consumption (scales with # of channels not with the detector area).

In our future…

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 resistive read-out LGADs

(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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in 2014/2015: INFN CSN5 and ERC Advanced Grant fueled this R&D

UFSD “Ultra-Fast Silicon Detectors” 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

Very first conception - November 2012 - RD50 project "detectors with enhanced multiplication”

Chasing 4D tracking with silicon sensors

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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:
  - Foundries involved: CNM first, followed by FBK (2016) and then HPK, Micron (2017)

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- steady progress from ~ 2015:
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  - **R&D focused on timing applications** → CMS ETL /ATLAS HGTD
- Now a booming field: several new designers/producers developing LGADs (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?

starting in 2018… how do we get a pixelated, small-size, matrix?

Within the RSD INFN project/FBK R&D/4DInside team
- addressing the *"pad-size" parameter* 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

2013
- Centro Nacional de Microelectrónica CSIC

2016
- Centro Nacional de Microelectrónica CSIC
- FONDAZIONE BRUNO KESSLER

2017
- Centro Nacional de Microelectrónica CSIC
- FONDAZIONE BRUNO KESSLER
- HAMAMATSU

2018
- Centro Nacional de Microelectrónica CSIC
- FONDAZIONE BRUNO KESSLER
- HAMAMATSU
- INSTITUTE OF MICROELECTRONICS OF THE CHINESE ACADEMY OF SCIENCES
- MICRON SEMICONDUCTOR LIMITED
- Brookhaven National Laboratory

2021
- Centro Nacional de Microelectrónica CSIC
- FONDAZIONE BRUNO KESSLER
- HAMAMATSU
- MICRON SEMICONDUCTOR LIMITED
- Brookhaven National Laboratory
- INSTITUTE OF MICROELECTRONICS OF THE CHINESE ACADEMY OF SCIENCES
- CiS Forschungsinstitut für Mikrosensorik GmbH
- TELEDYNE TECHNOLOGIES Everywhereyoulook

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

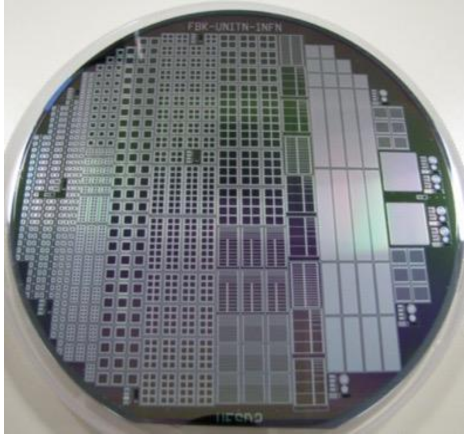
DC-RSD

2019: RSD1 Resistive AC-LGAD

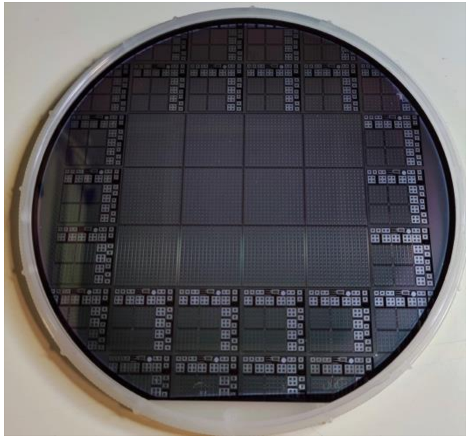
2021: RSD2 Resistive AC-LGAD

2024: DC-RSD1 Resistive DC-coupled LGAD

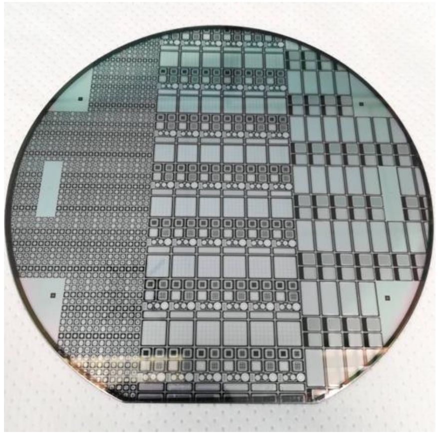
UFSD2



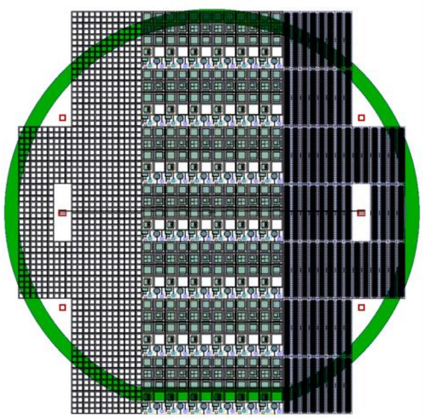
UFSD4



RSD1



RSD2



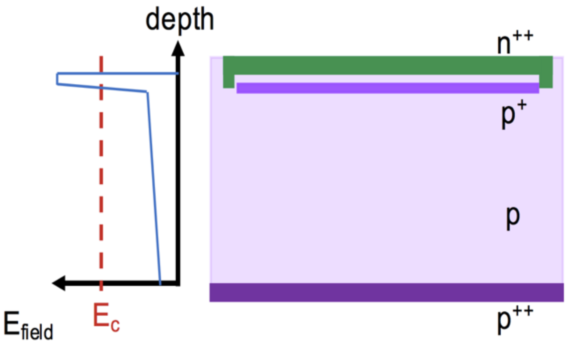
Design innovations

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

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

Low-Gain Avalanche Diode (LGAD)

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



Standard *n-i-p* silicon sensor
+ **thin gain layer (p+)**

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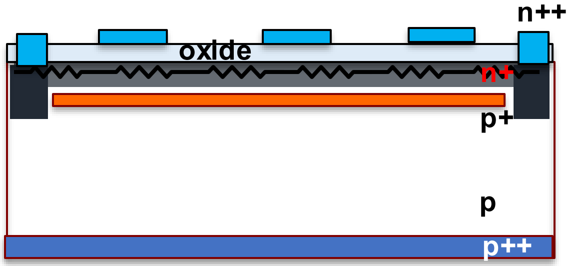
  - It provides large signals with short rise time and low noise, ideal for timing

- 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**

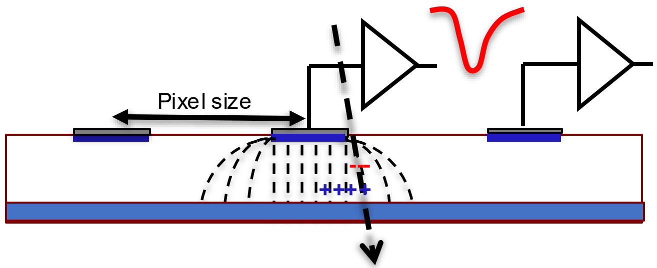


Standard *n-i-p* silicon sensor + **thin gain layer (p+)** where the "n++" layer is a resistive layer --> n+

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 → $\sigma_x = 20\ \mu m$

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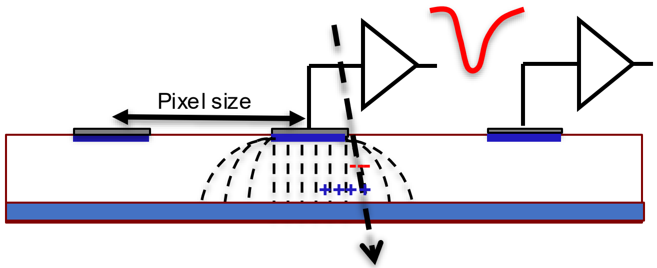

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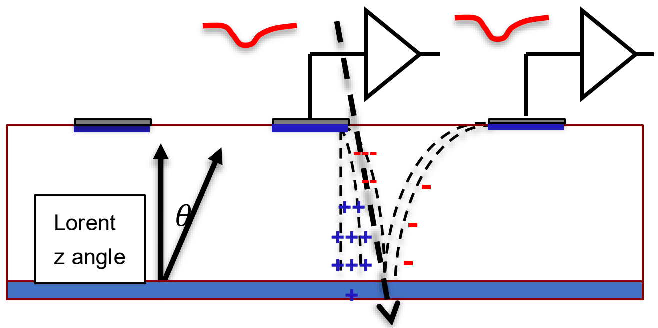
Multi pixels

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

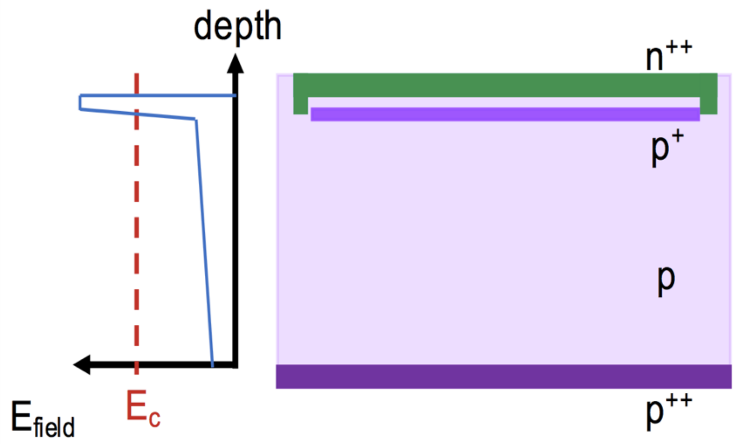
Single pixel

where the signal is induced on one pixel

development of thin LGAD sensors (~50ish microns)

- thin layer of doping element (Boron) to produce low controlled multiplication **(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)



~ 0.5 fC of charge in 50 µm with no gain

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.

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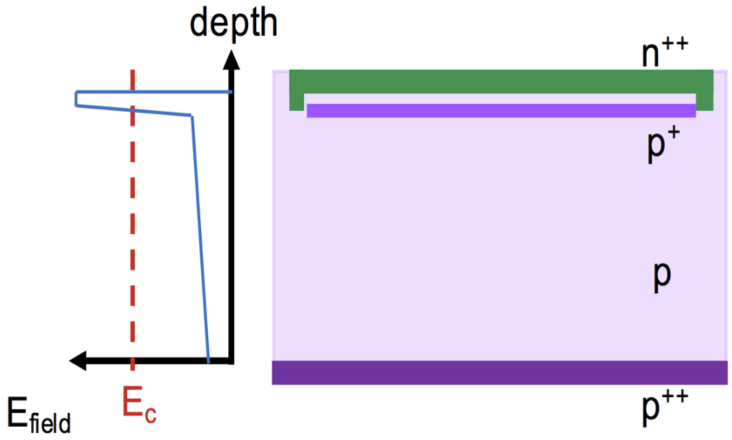
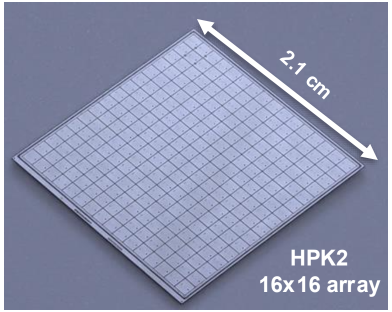


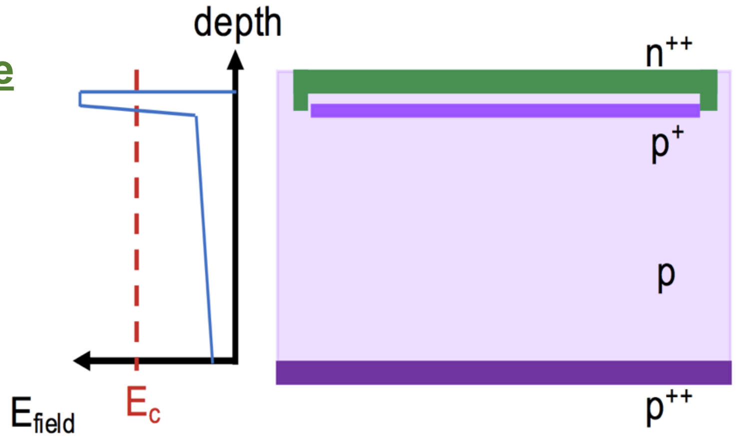
State-of-the-art LGADs for timing

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 known characterization in lab and at testbeams
- **gain layer uniformity ~1% or better**
- **rad hardness:** still able to deliver **>=5 fC of charge** **up to ~ 2E15 n_{eq}/cm^2**

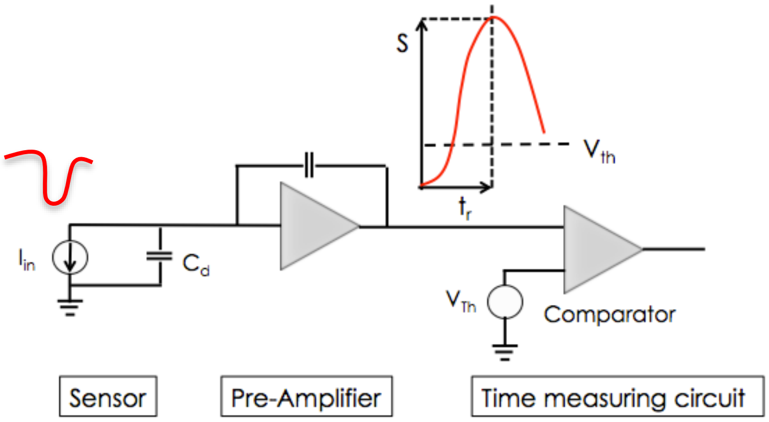
Gain ~ 10





Why do LGADs allow good time measurement?

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



Time is set when the signal crosses the comparator threshold

The time resolution is determined by the characteristics (shape, shape variations) of the signal at the output of the pre-Amplifier and by the TDC binning

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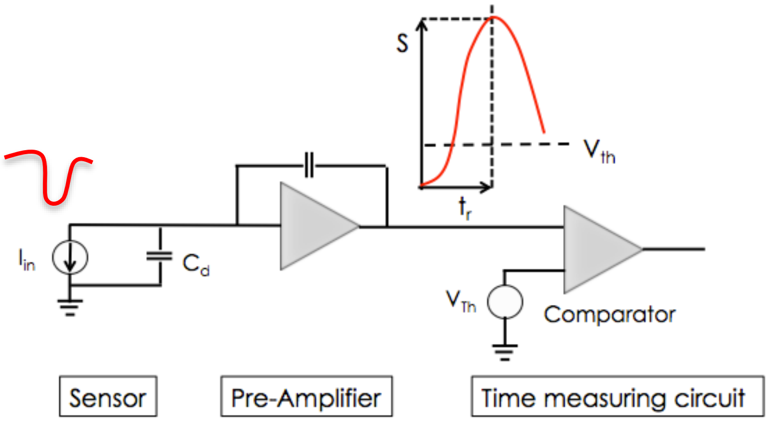

$$\sigma^2_t = \sigma^2_{Jitter} + \underbrace{\sigma^2_{\text{Time Walk}} + \sigma^2_{\text{Landau Noise}}}_{} + \sigma^2_{Distortion} + \cancel{\sigma^2_{TDC}}$$

Minimized by optimized RO electronics

Terms related to variation of signal shape (Landau distribution)

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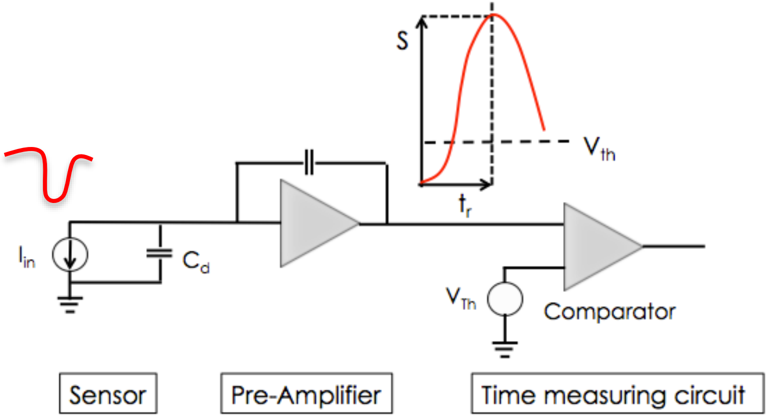

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$I_{Ramo} \approx q\, v_{drift}\, E_w$

Requires **uniform v_{drift} and E_w**

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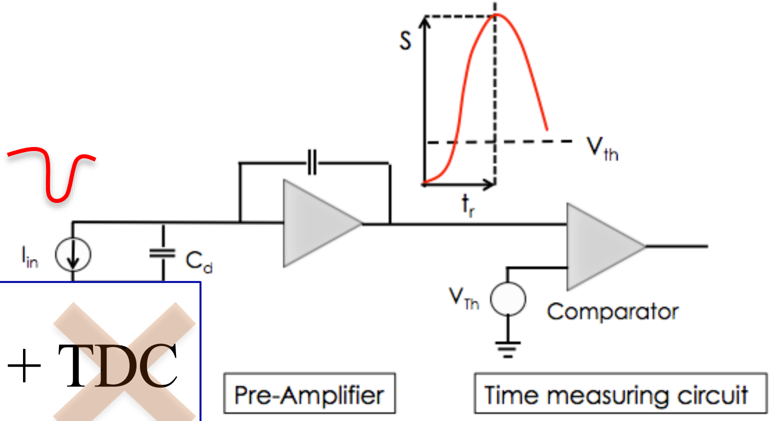
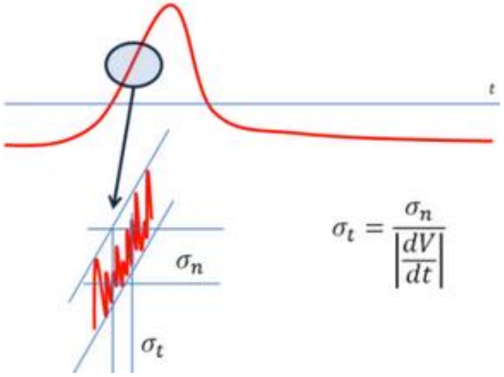


$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \cancel{\text{TDC}}$$

"Jitter" term



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

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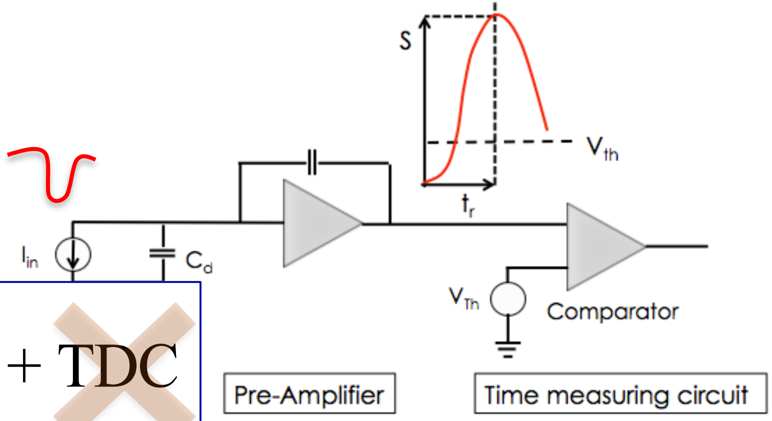
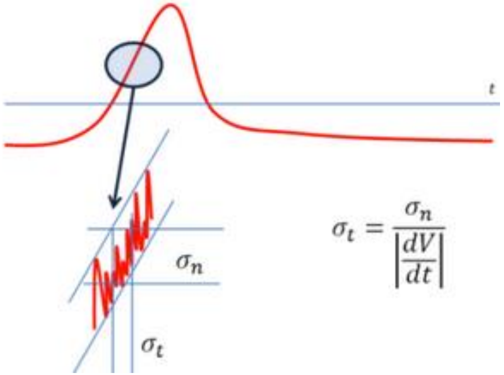


$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \cancel{\text{TDC}}$$

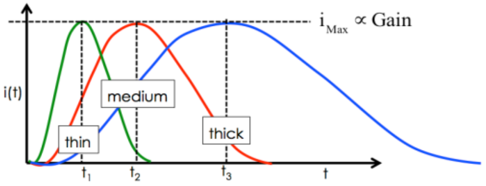
"Jitter" term



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

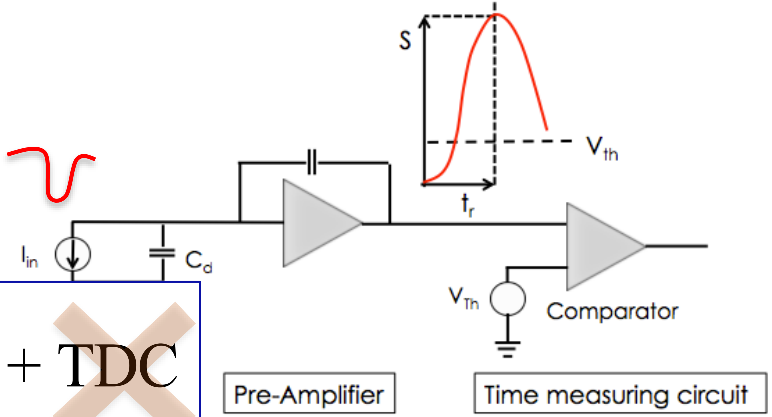
$\sigma_{Jitter} \approx N/(dV/dt) \approx t_{rise}/(S/N)$

- need **gain** to increase S
- need **thin detector** to decrease t_{rise}



Why do LGADs allow good time measurement?

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



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

1 - Time walk: minimized by time correction circuitry

Why do LGADs allow good time measurement?

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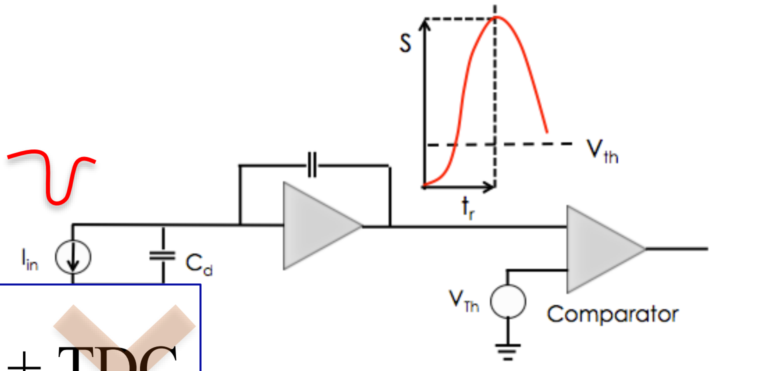
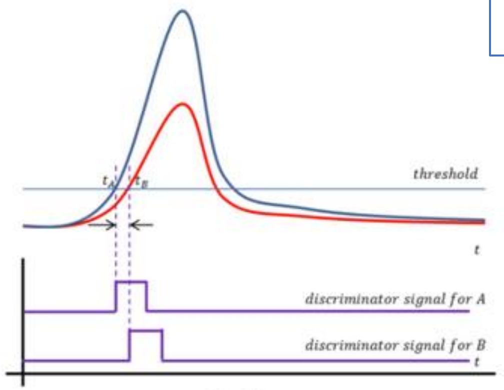


$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \cancel{\text{TDC}}$$

1 - Time walk: minimized by time correction circuitry



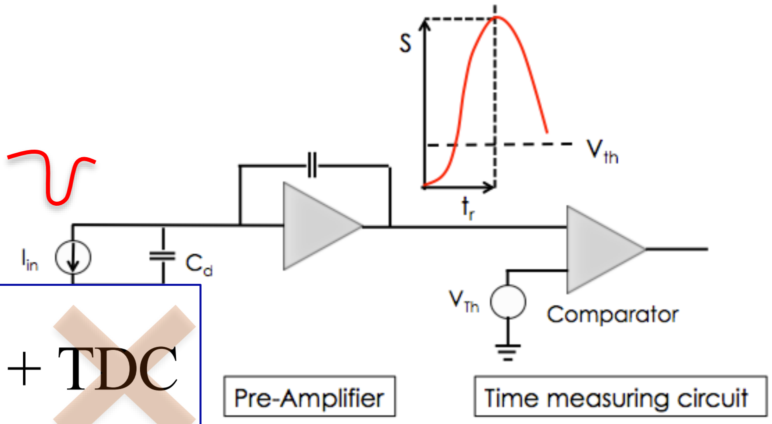
Time walk effect

Time walk: the comparator threshold V_{th} is reached at different times by signals of different amplitude, and it is **due to the physics of signal formation**

$$\sigma_t^{TW} = \left[\frac{t_r V_{th}}{S}\right]_{RMS}$$

Why do LGADs allow good time measurement?

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



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

2- Shape variations:
nonhomogeneous energy deposition

Why do LGADs allow good time measurement?

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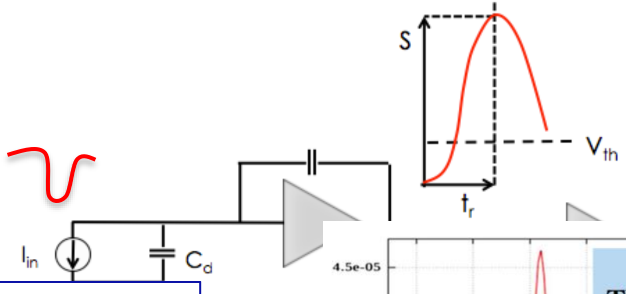
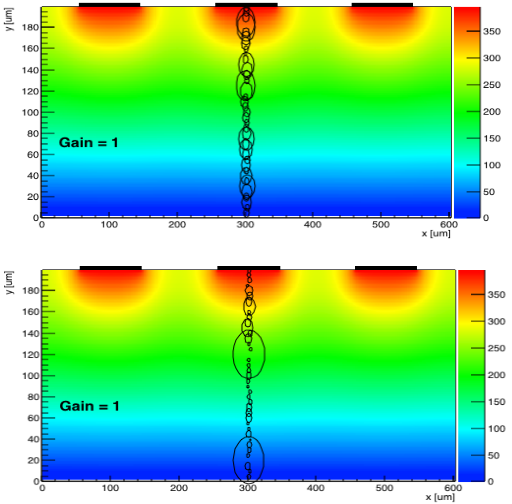
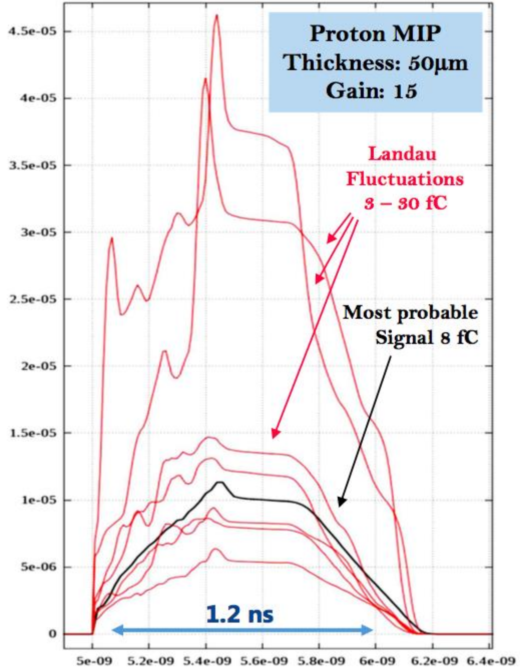


$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \cancel{\text{TDC}}$$

2- Shape variations:
nonhomogeneous energy deposition

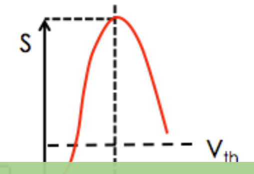




R. Arcidiacono – 4D-tracking

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**

$$\sigma^2_t = \sigma^2_{Jitter} + \underbrace{\sigma^2_{Time\ Walk} + \sigma^2_{Landau\ Noise}}_{\text{Terms related to variation of signal shape (Landau distribution)}} + \sigma^2_{Distortion} + \cancel{\sigma^2_{TDC}}$$

Minimized by optimized RO electronics

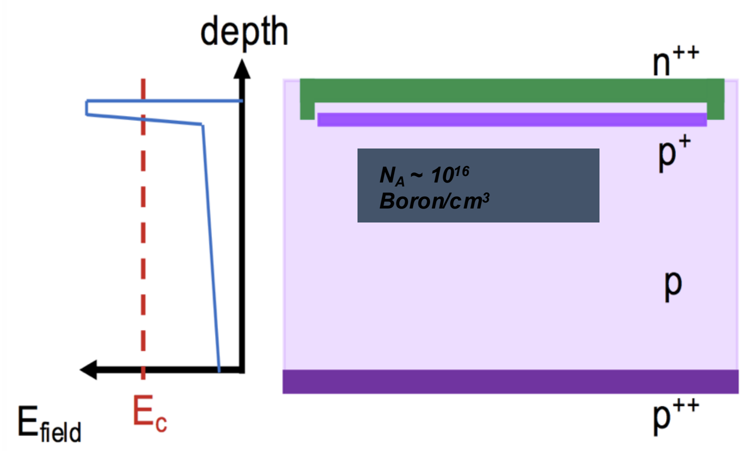
Radiation hardness

Evolution of the active acceptor density with fluence

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

Φ = fluence   *(Φ_0 is a constant)*
N_A *(Φ)* **, N_A** *(0)***=** *active acceptor density at fluence Φ ,*
g_{eff} = *empirical constant* *(~ 0.02 cm^{-1})*

*The **c** coefficients to be determined depend upon the irradiation type, the acceptor type and the initial acceptor density*

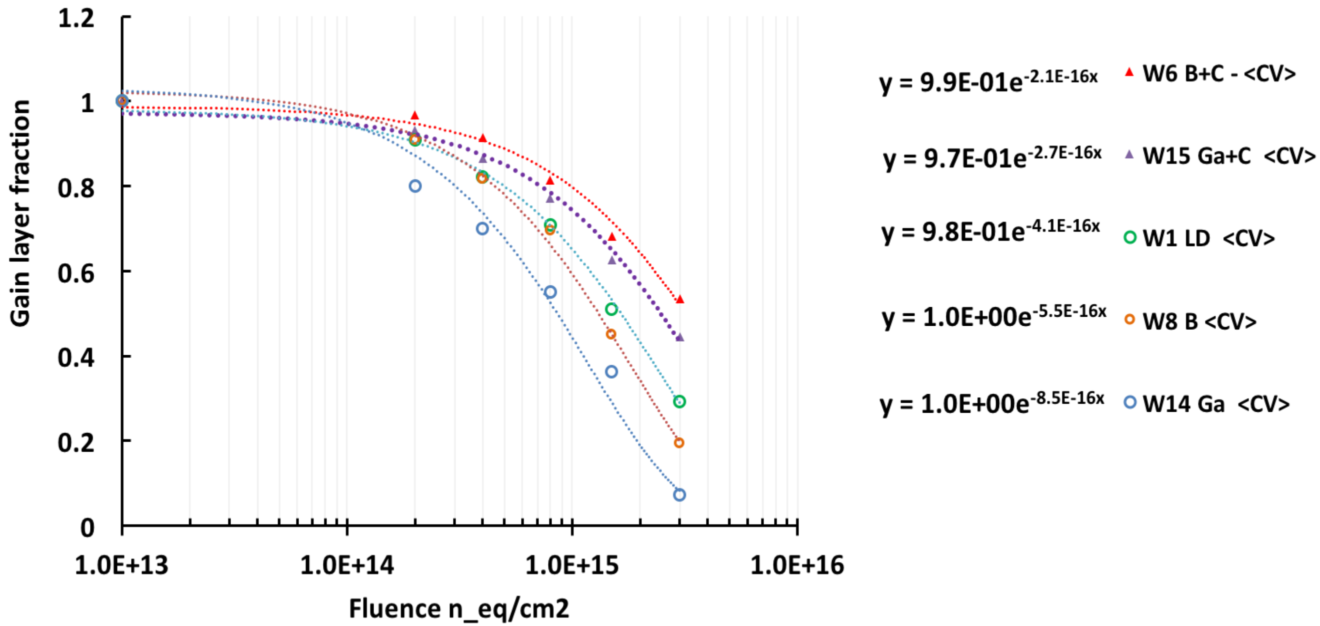


R. Arcidiacono – 4D-tracking

Radiation hardness: acceptor removal

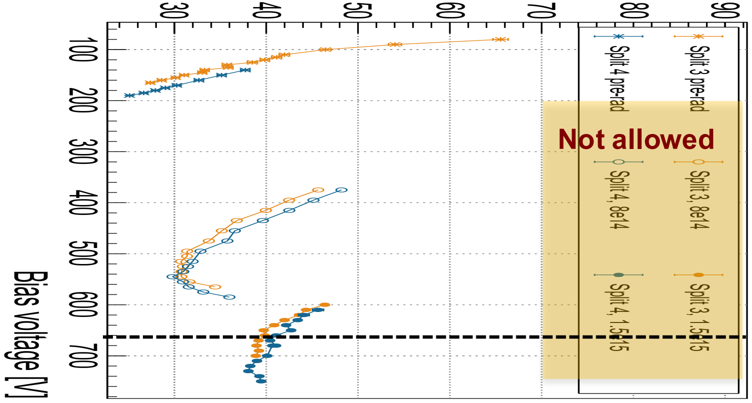
$$\frac{N_A(\Phi)}{N_A(0)} = \frac{V_{GL}(\Phi)}{V_{GL}(0)} = e^{-c(NA(0))\Phi/\Phi_0}$$

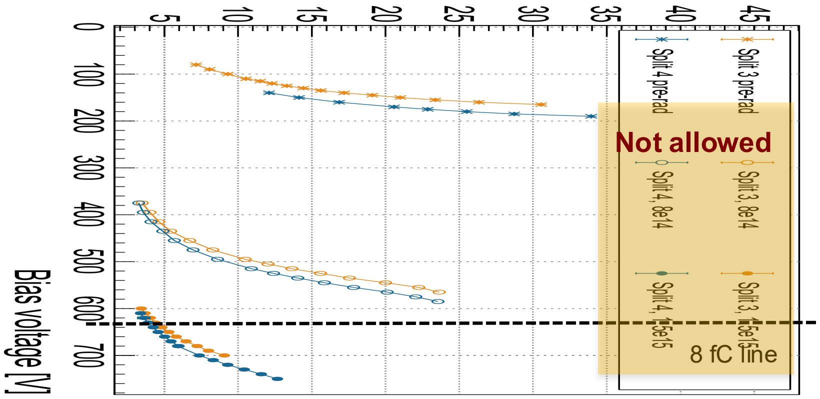
1MeV-neutrons irradiation



LGAD Timing performance

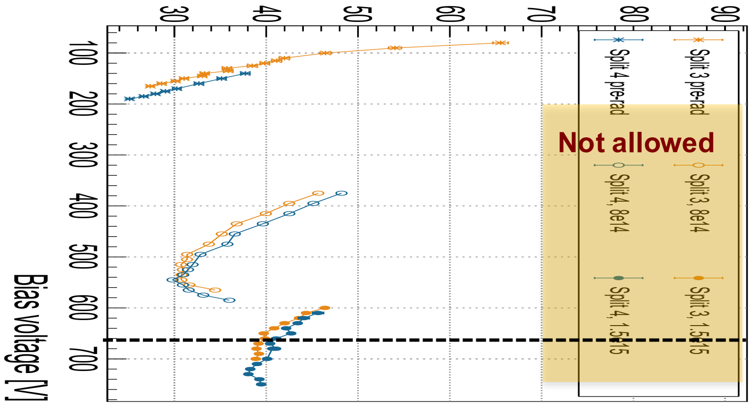
HPK – HPK2 – 50 um nominal – T= -25ºC

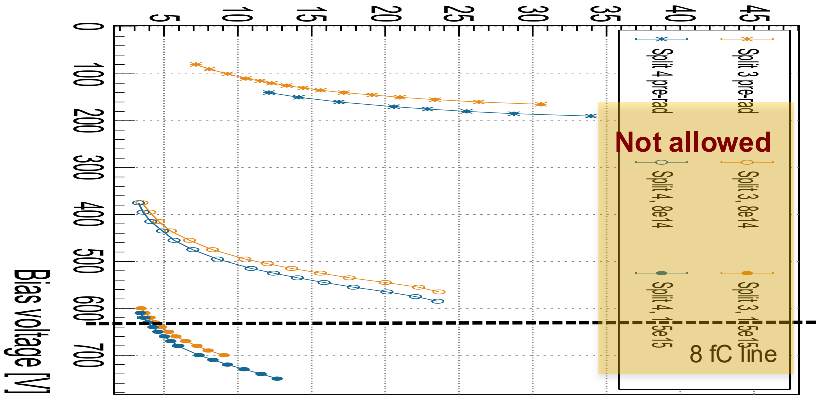




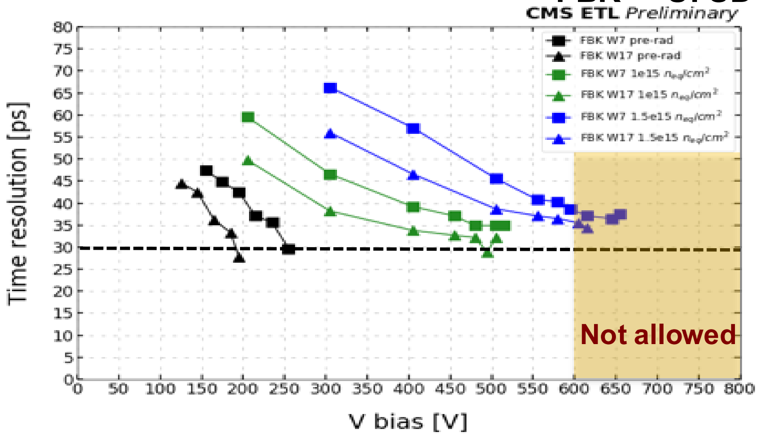
LGAD Timing performance

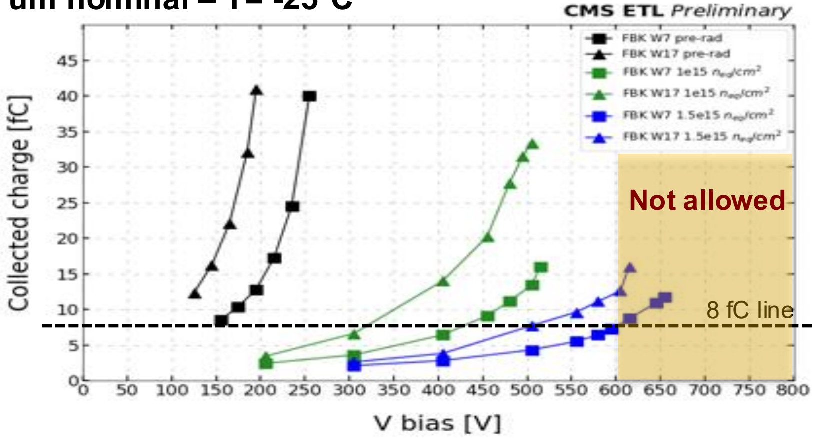
HPK – HPK2 – 50 um nominal – T= -25ºC





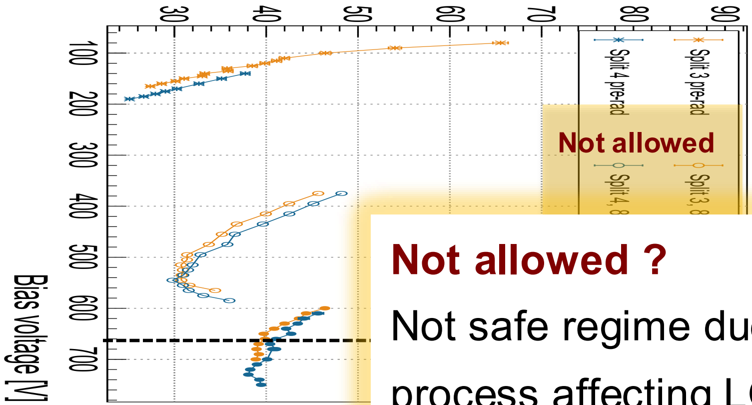
FBK – UFSD4 – 55 um nominal – T= -25ºC

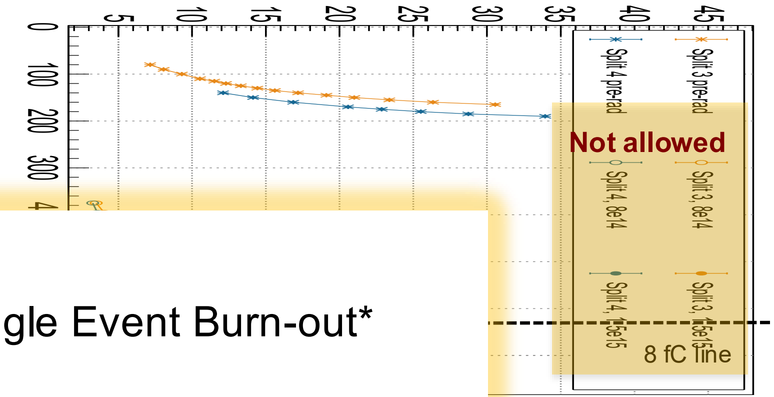




LGAD Timing performance

HPK – HPK2 – 50 um nominal – T= -25ºC





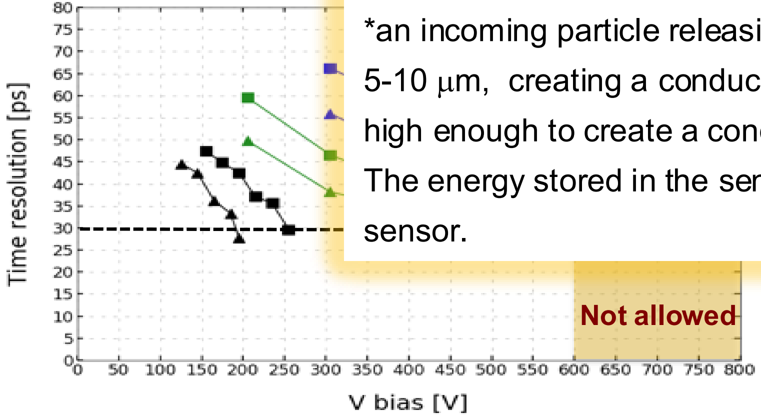
Not allowed ?

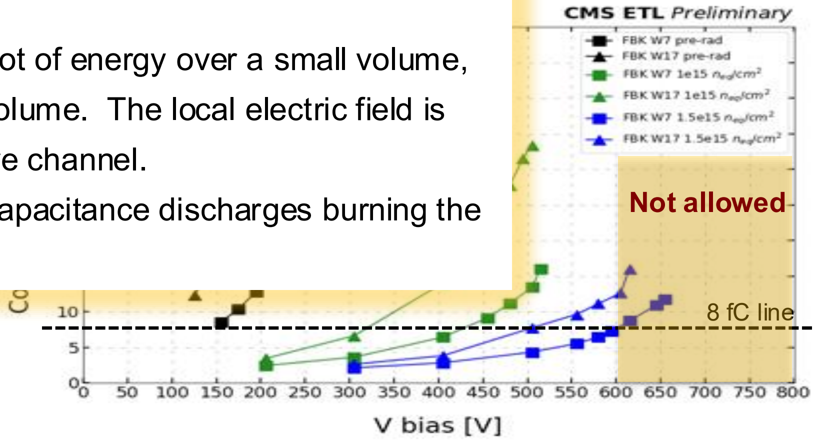
Not safe regime due to Single Event Burn-out* process affecting LGADs

E bulk < 11 V/μm

*an incoming particle releasing a lot of energy over a small volume, 5-10 μm, creating a conductive volume. The local electric field is high enough to create a conductive channel.

The energy stored in the sensor capacitance discharges burning the sensor.

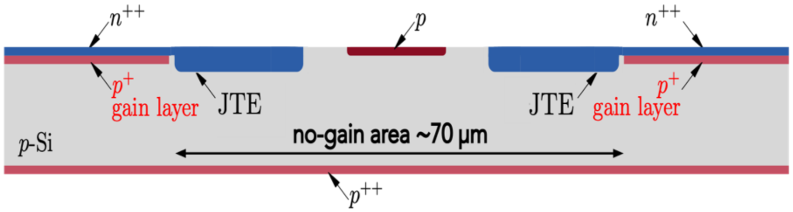




Pad size: how small can it be? (PIXEL?)

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

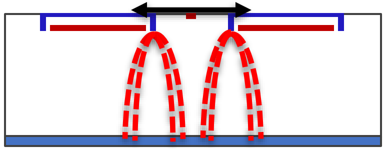
Table with smallest no-gain area for FBK, HPK, CNM

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%

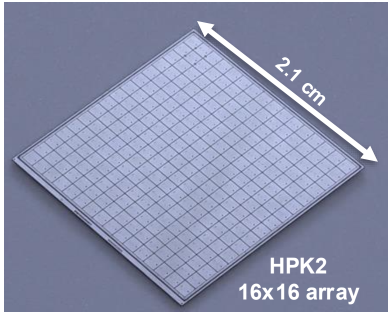
A new technology for the inter-pad area

No gain area ~ 50-70 um



JTE + p-stop design

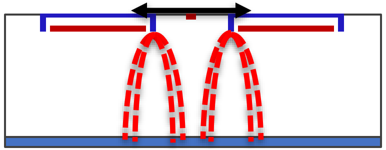
- **CMS && ATLAS choice**
- **Not 100% fill factor**
- **Very well tested**



R. Arcidiacono – 4D-tracking

A new technology for the inter-pad area

No gain area ~ 50-70 um



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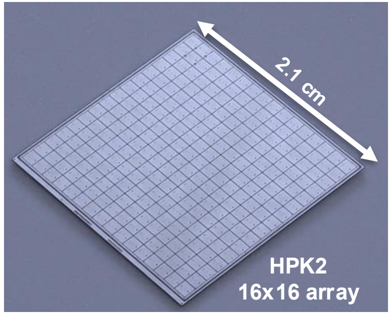
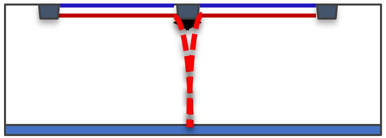


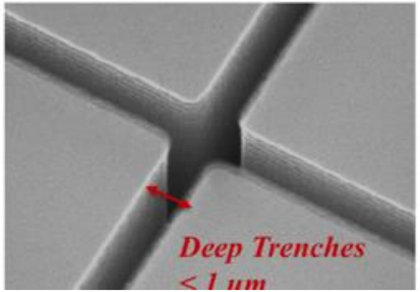
No gain area ~ few micrometers



Trench-isolated design

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

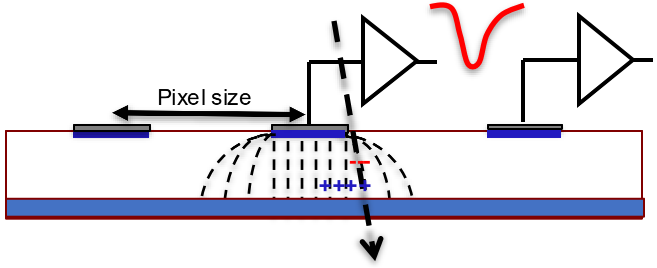
- **Almost 100% fill factor (depends upon the pad size)**
- **Trench-isolated LGADs produced by FBK: 3 productions**
- **Now this technology is mature**
- **R&D on TI-LGADs pixelated matrices (50,100 um) are ongoing**



Focusing on Position: Single and Multi Pixels Read-out

Single pixel

where the signal is induced on one pixel



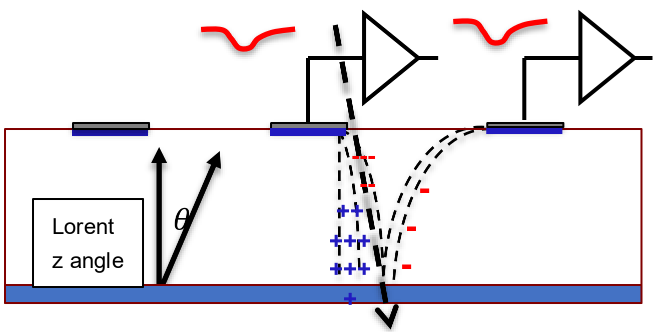
$$\sigma_x = k\,\frac{pitch}{\sqrt{12}},\ k \sim 0.5 - 1$$

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

  pixel = 100 μm **→** $\boldsymbol{\sigma_x = 20\ \mu m}$

Multi pixels

where the signal is induced on a few pixels



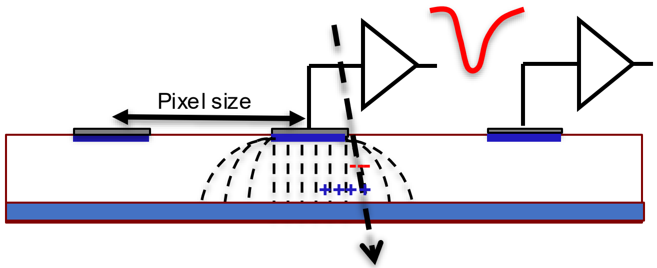
$$x = \frac{\sum_i x_i\, Ai}{\sum_i A_i}$$

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

Focusing on Position: Single and Multi Pixels Read-out

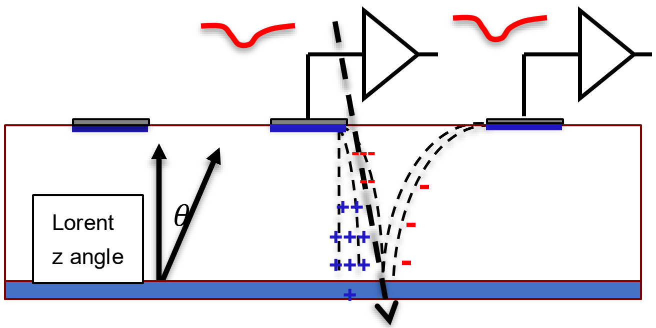
Single pixel

where the signal is induced on one pixel



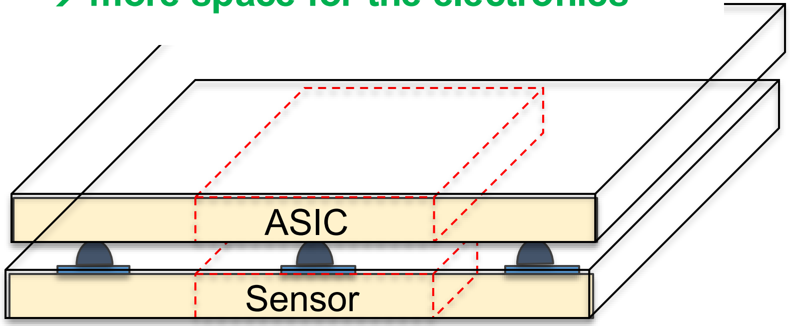
Multi pixels

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

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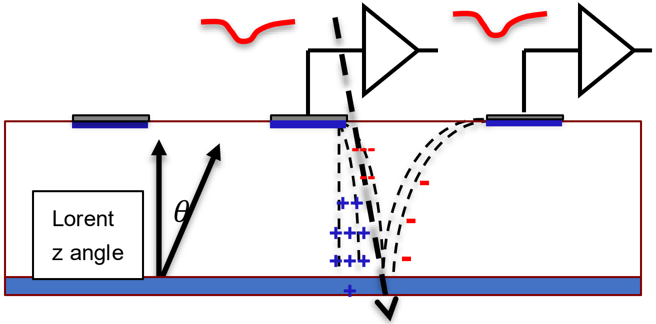
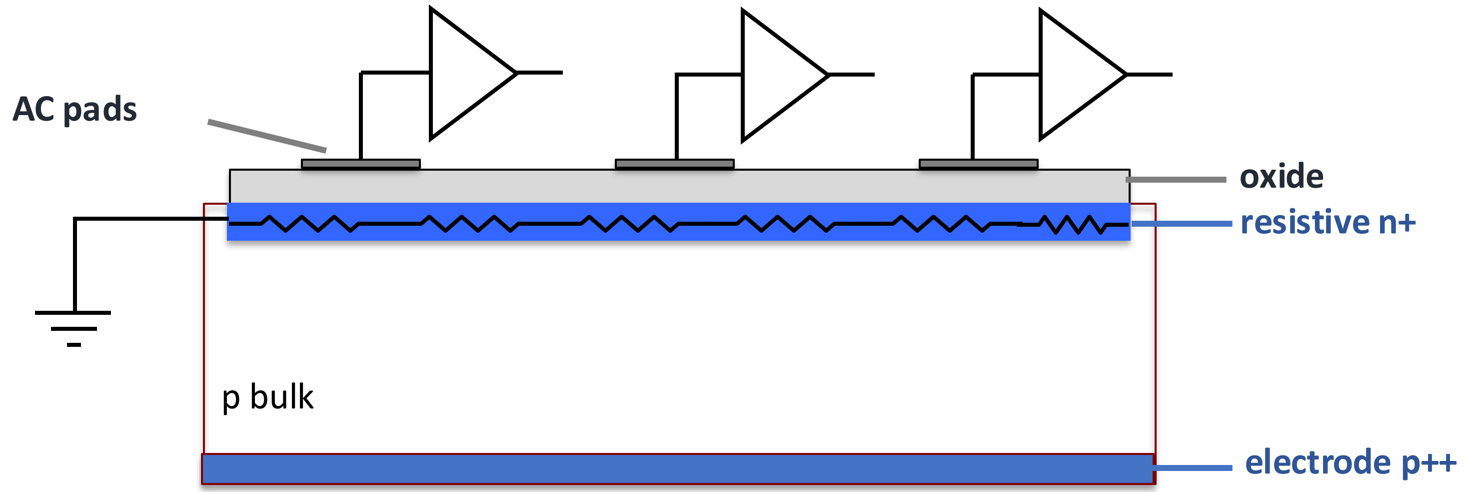


To be noted:

- **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

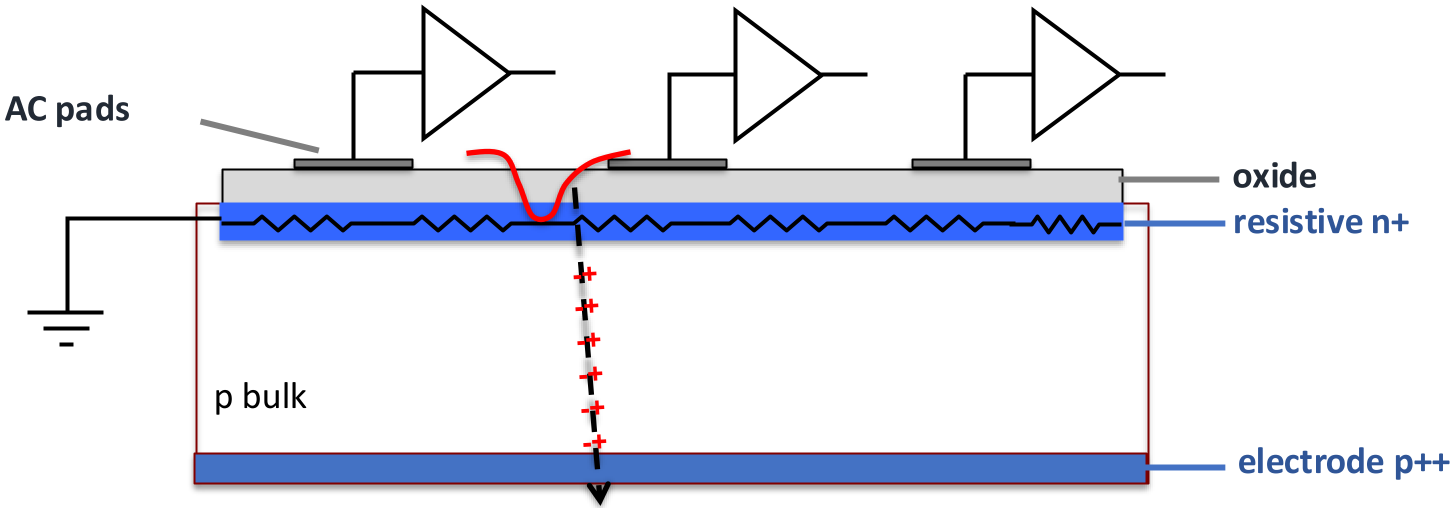
Another way of achieving signal sharing among pads is the AC-coupled resistive read-out



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)**

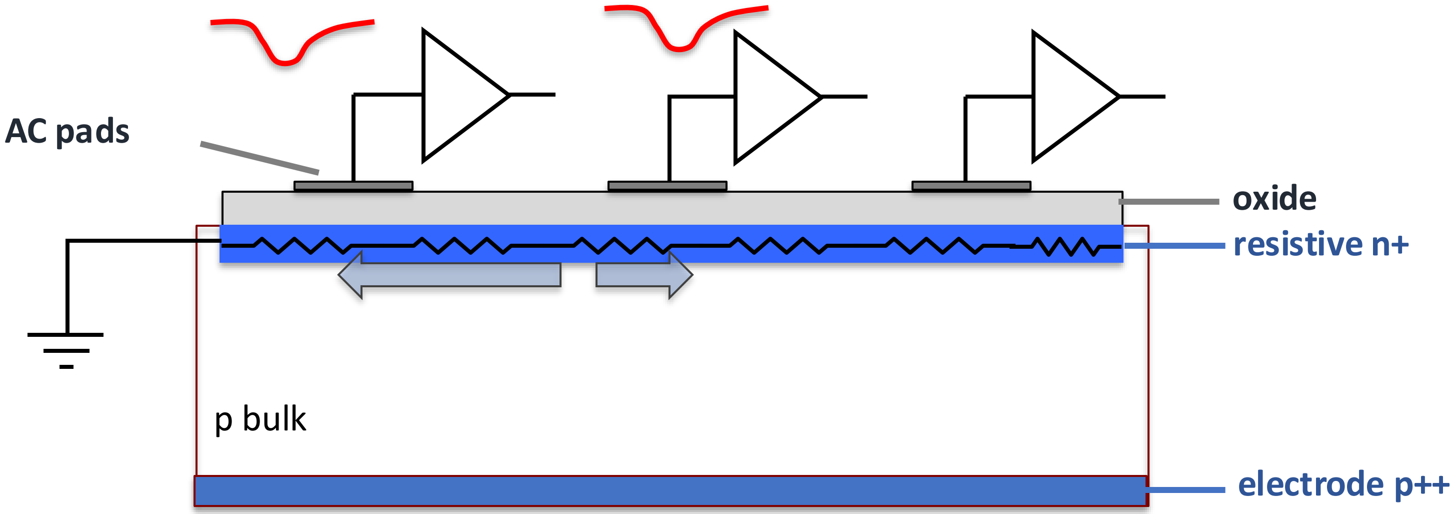


Resistive AC-coupled Silicon Sensors

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)**

  (spread controlled by n+ resistivity, metal pad capacitance, pitch, system inductance)



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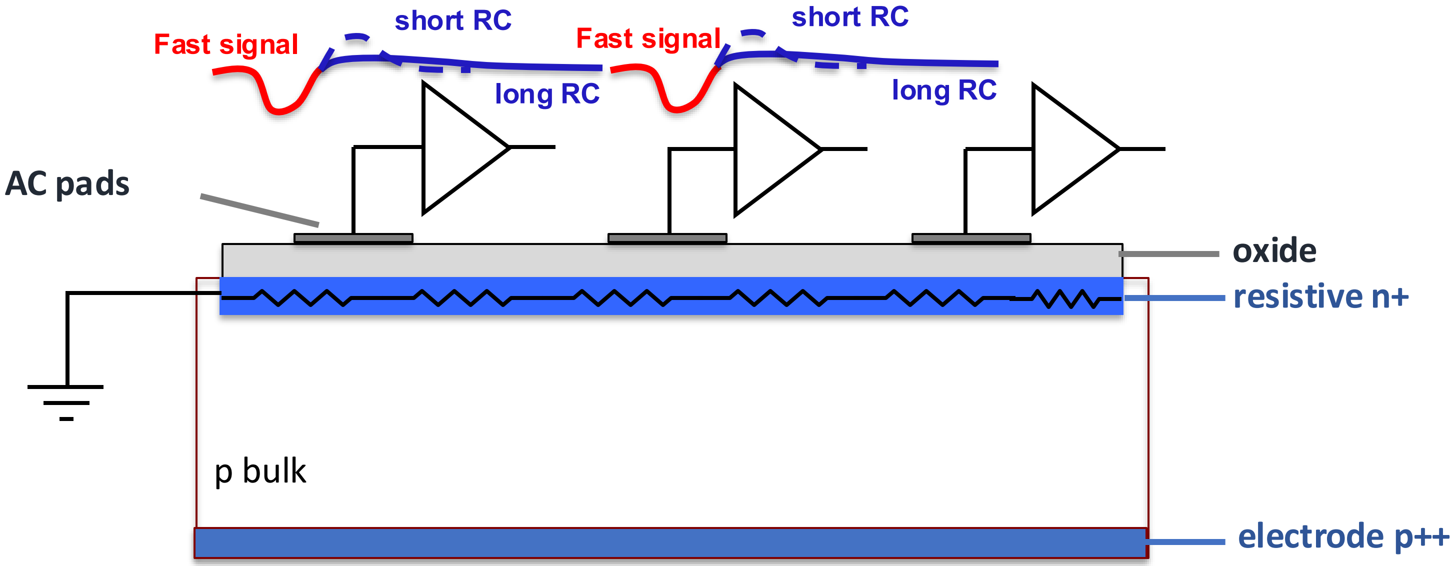
- **The charge flows to ground (slow component)**



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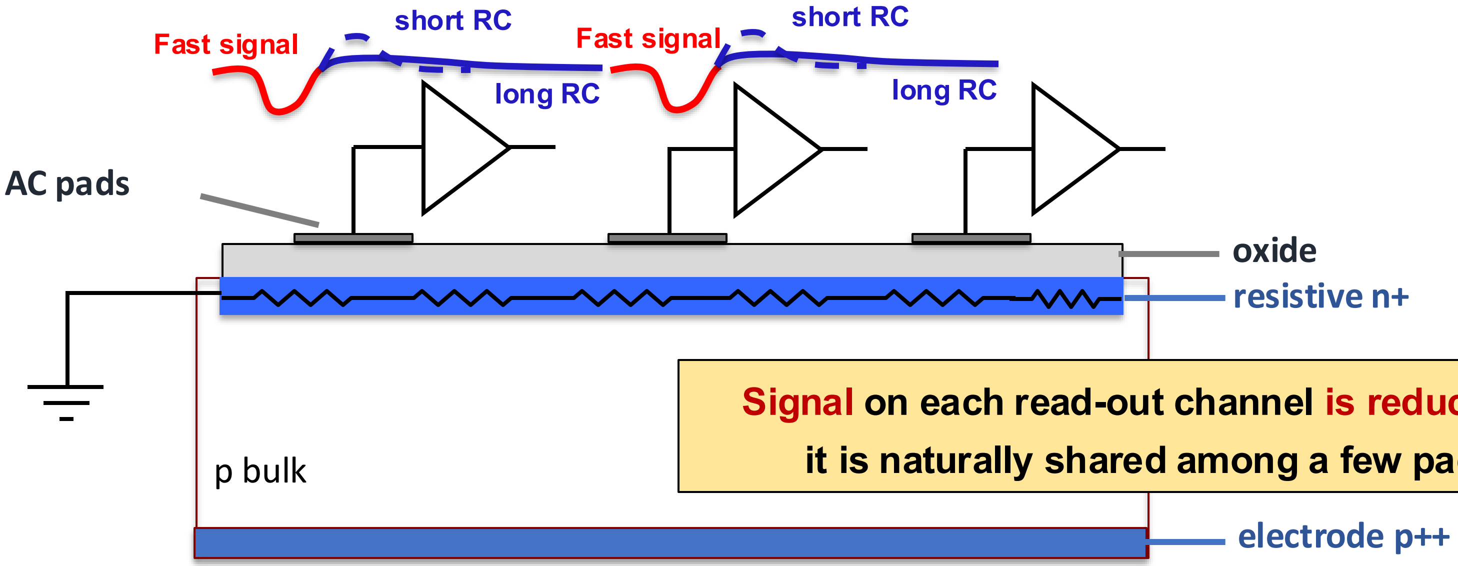


Signal on each read-out channel is reduced as it is naturally shared among a few pads

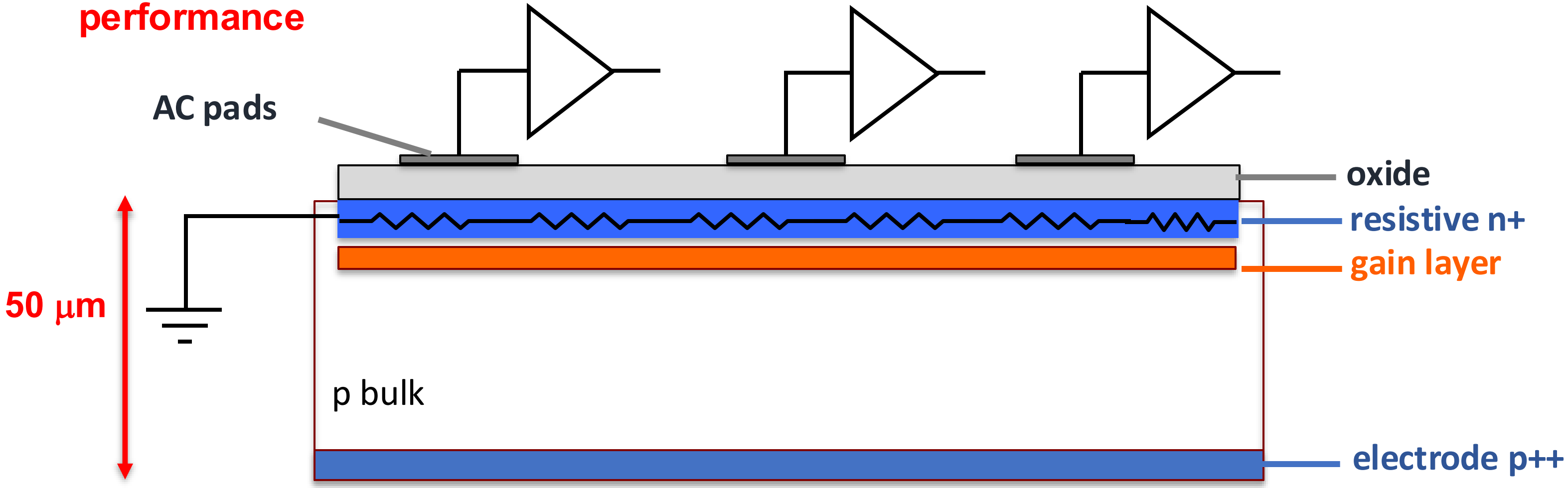
Resistive AC-coupled LGADs

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

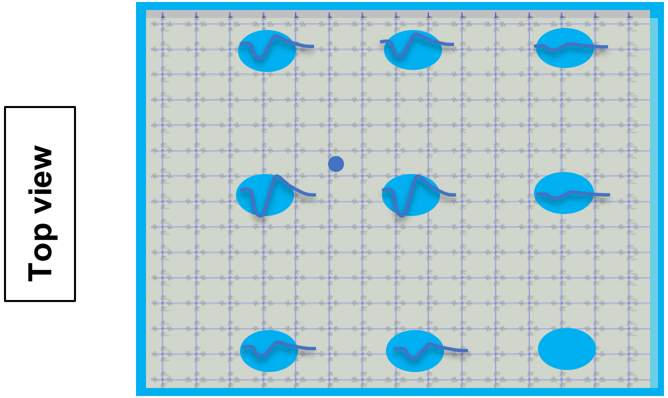
resistive AC-LGAD (or Resistive Silicon Detector)

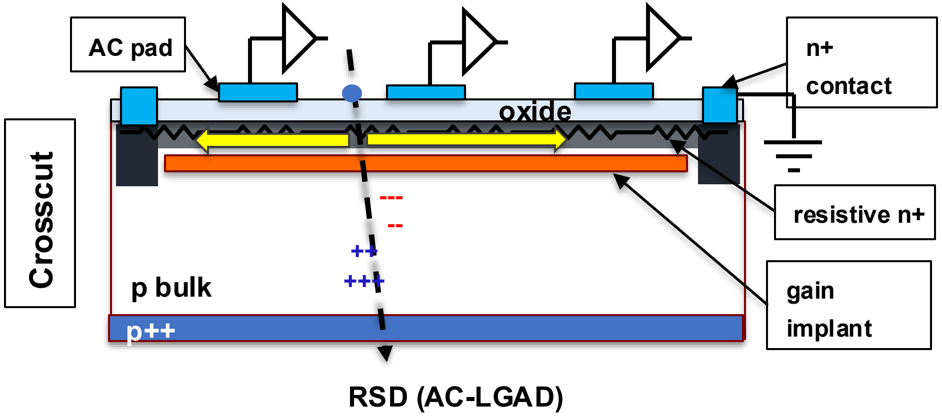
⇒ Thin LGAD with a resistive AC read-out, where the **design of the read-out pads** (shape and segmentation) adapts easily to any geometry and defines spatial resolution

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



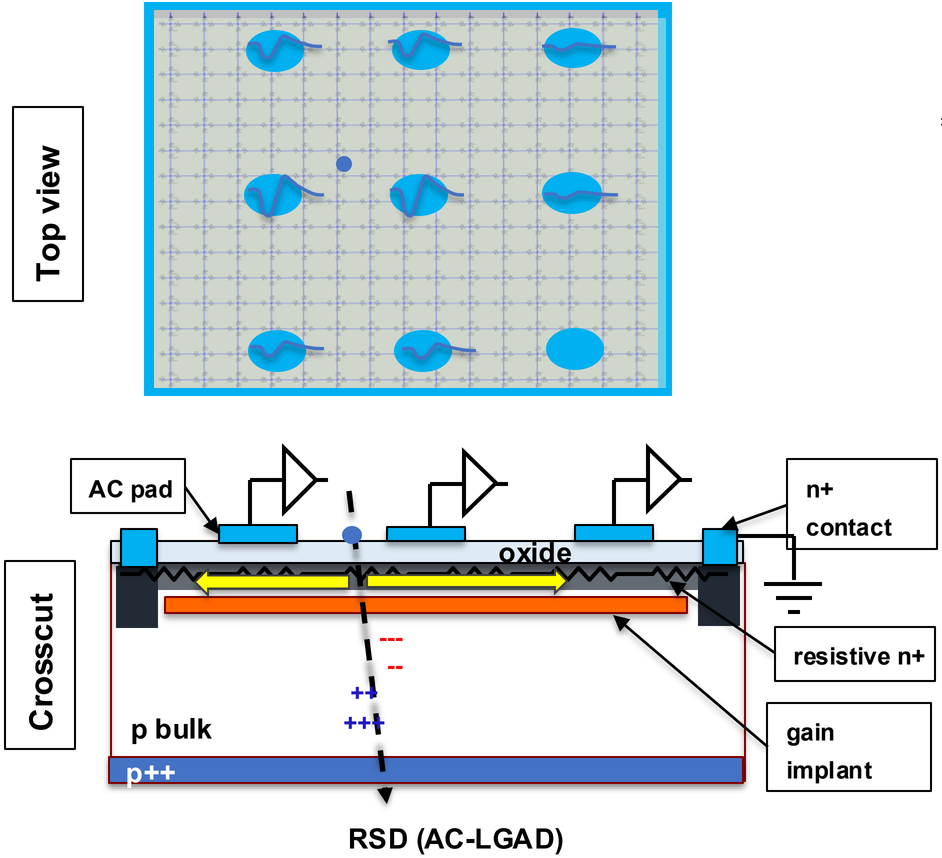
AC-coupled resistive read-out LGAD (RSD)





⇛ 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)



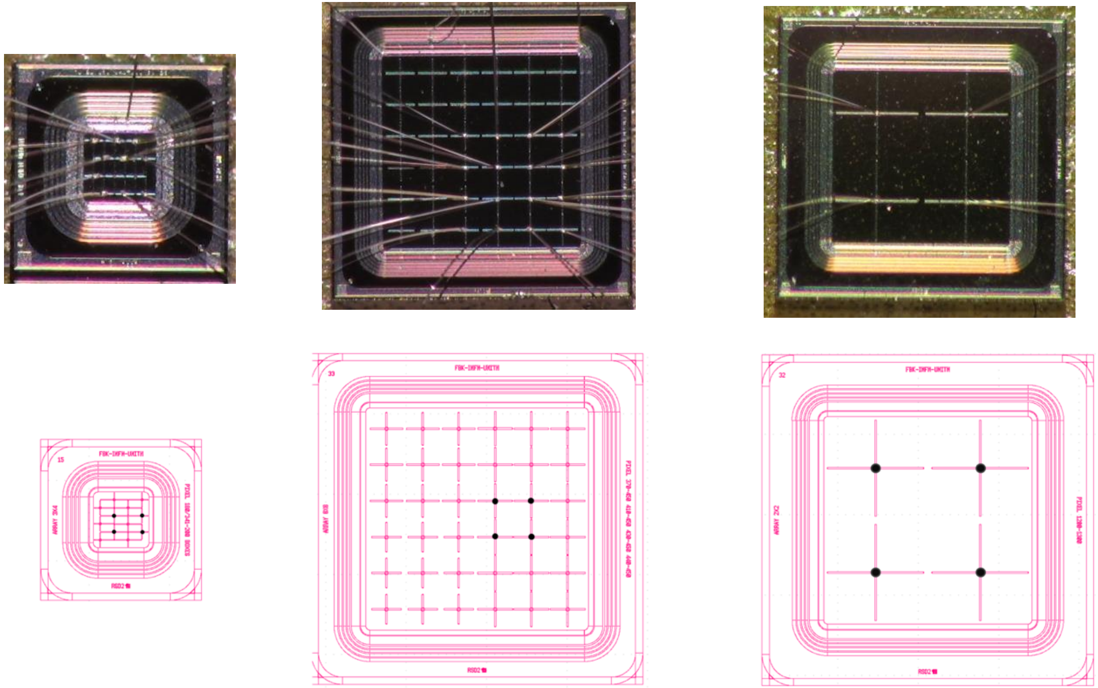
⇒ the coordinates are reconstructed exploiting the **charge sharing amongst neighboring electrodes**:

spatial resolutions much better than

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

RSD spatial resolution: results with laser TCT

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



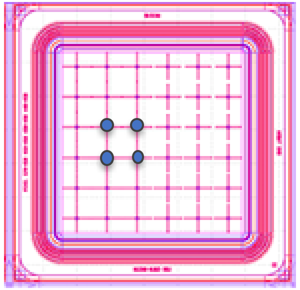
(A) (B) (C)

RSD spatial resolution: results with laser 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)



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

RSD spatial resolution: results with laser TCT

Results from FBK RSD2 production (2021): second RSD production with optimized design (parameters that drive

Method: "charge asymmetry"

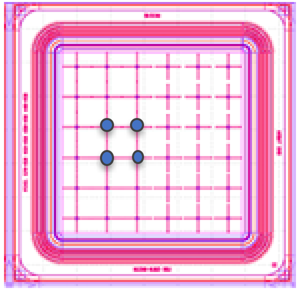
$$x_i = x_{center} + k_x \frac{pitch}{2} * \frac{Q_3 + Q_4 - (Q_1+Q_2)}{Q_{tot}}$$

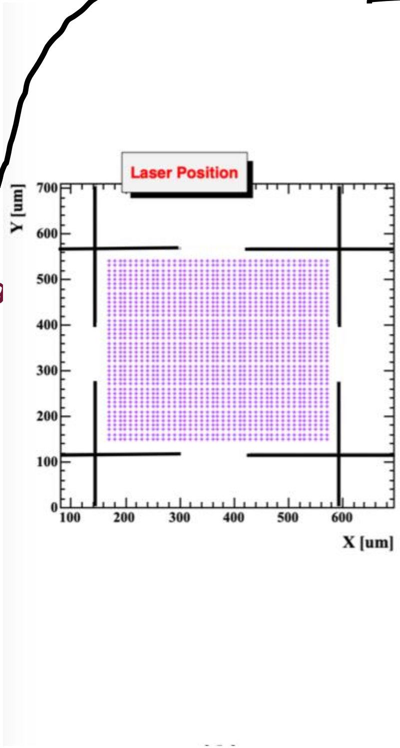
$$y_i = y_{center} + k_y \frac{pitch}{2} * \frac{Q_1 + Q_3 - (Q_2+Q_4)}{Q_{tot}}$$

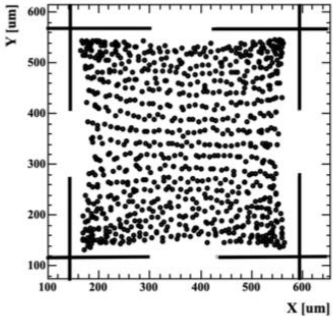
harg

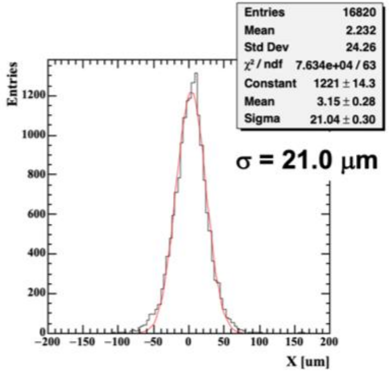
he

highest signal (sum of the 4)









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

RSD spatial resolution: results with laser TCT

Results from FBK RSD2 production (2021): second RSD production with optimized design (parameters that drive

Method: "charge asymmetry"

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

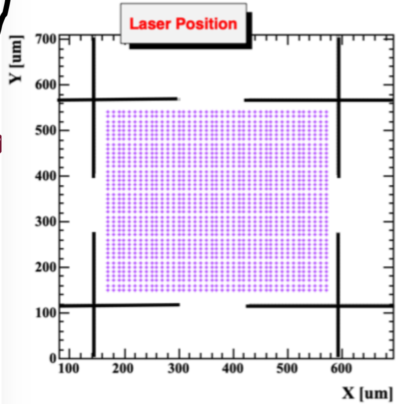
$$y_i = y_{center} + k_y \frac{pitch}{2} * \frac{Q_1 + Q_3 - (Q_2+Q_4)}{Q_{tot}}$$

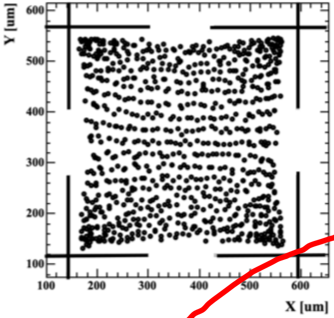
harg

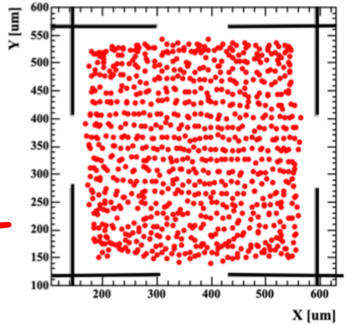
he

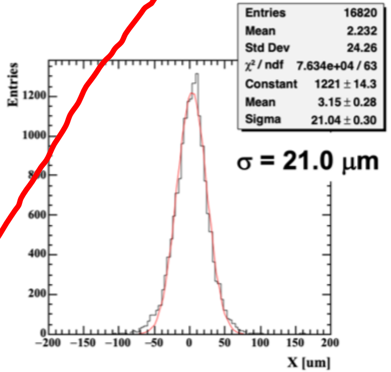
highest signal (sum of the 4)

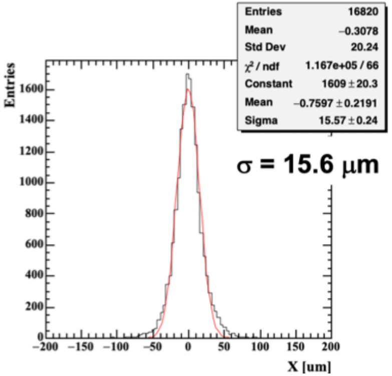
The coordinates are then corrected using a migration matrix (measured always with the laser setup – independent set of data)











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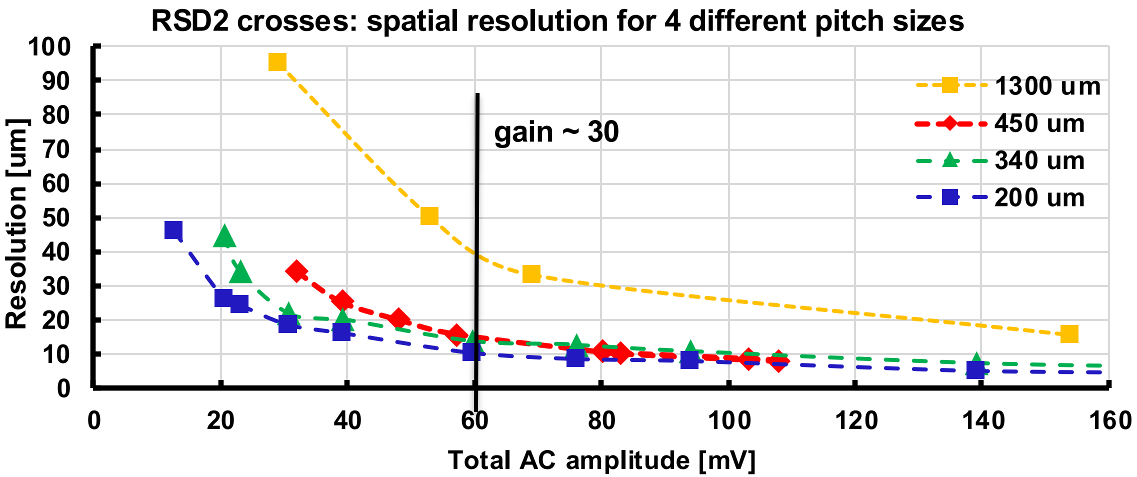
RSD spatial resolution: results with laser TCT

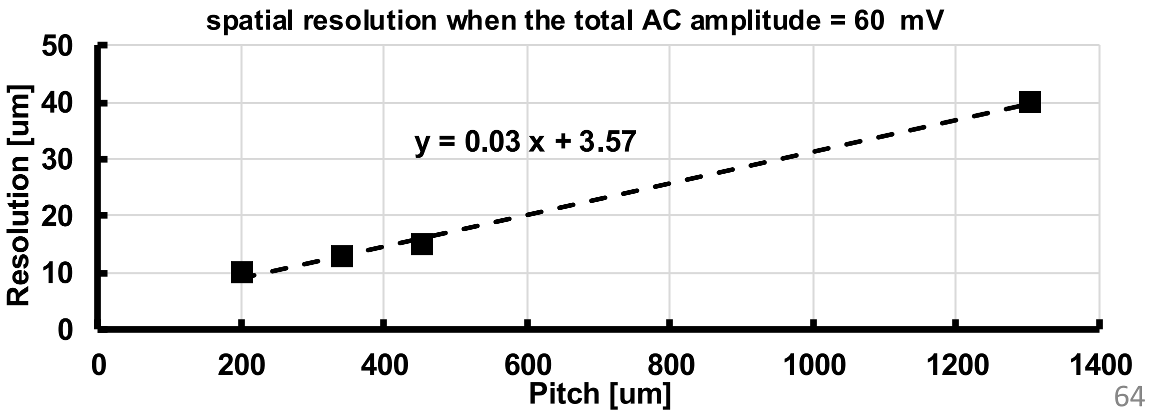
Results from FBK RSD2 production (2021): second RSD production with optimized design (parameters that drive the sharing) and optimized electrode shapes

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

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**

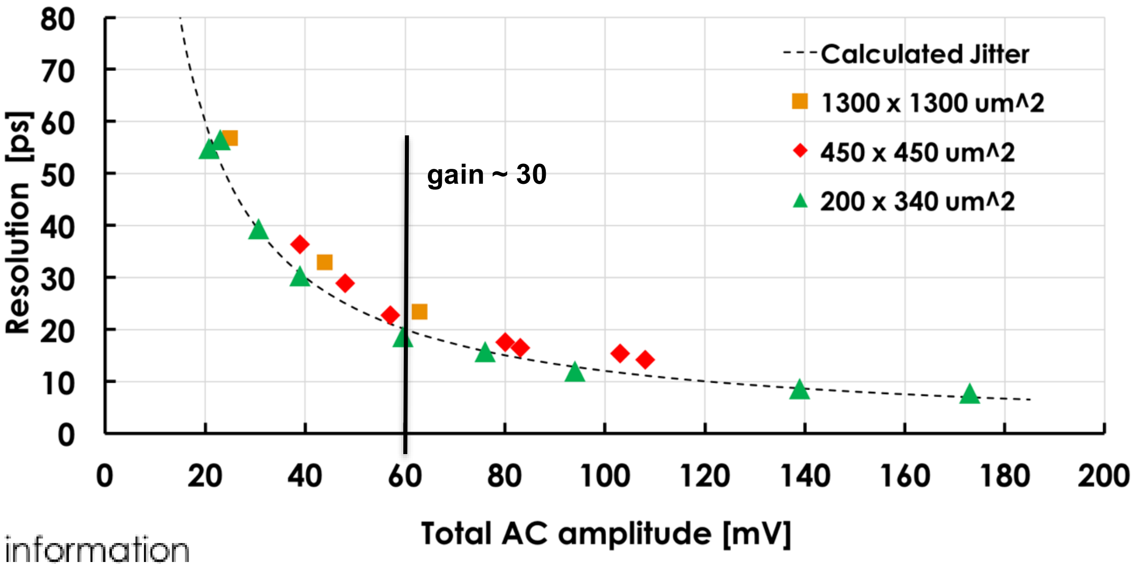




RSD time resolution: jitter term

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**

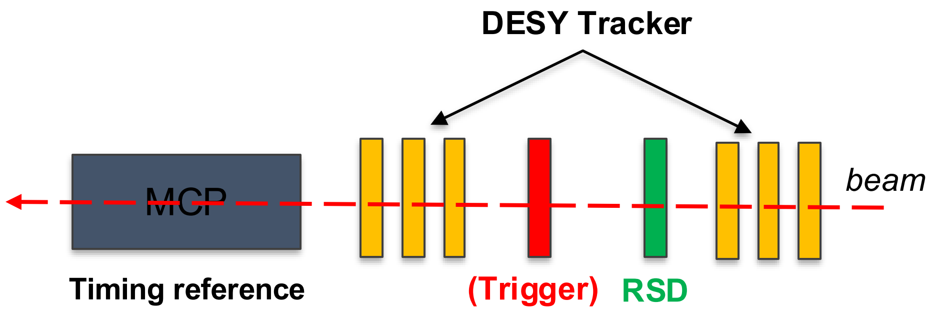
σ_{delay} **is very small**

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

RSD performance with 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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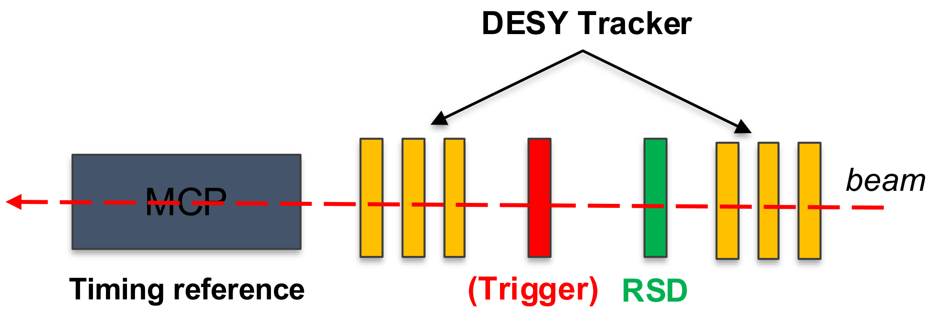

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FIRST TESTBEAM:

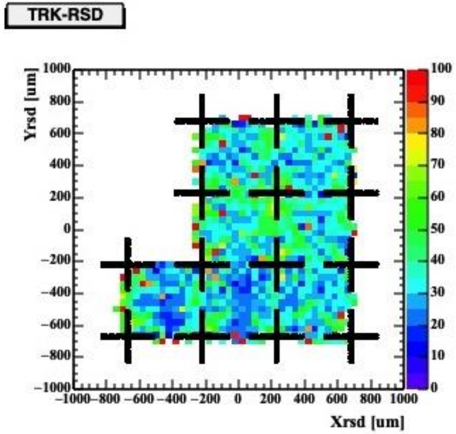
- FNAL Board +16ch CAEN Digitizer
- max gain obtained with DUTs ~15
- using high part of Landau distribution to study performance

SECOND TESTBEAM (Oct 2023)

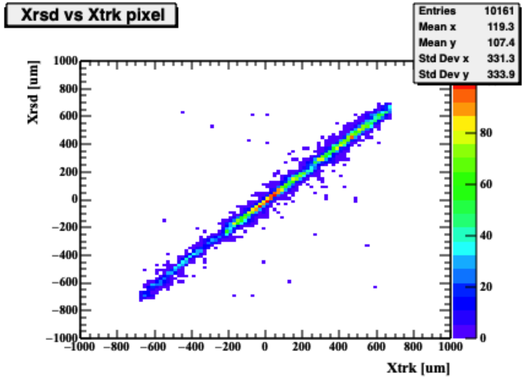
- FAST2 (custom ASIC) Board +16ch CAEN Digitizer
- lower electronic noise, higher amplification
- higher signal amplitudes obtained
- exploring up to gain ~50 with the RSD2-450

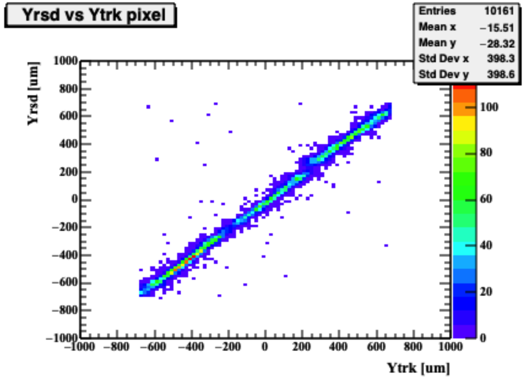
RSD@testbeam: RSD2-450 at 200 V

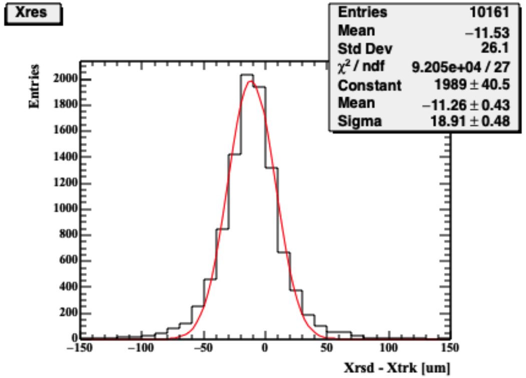
At 200 V this device has a gain close to ~ 50

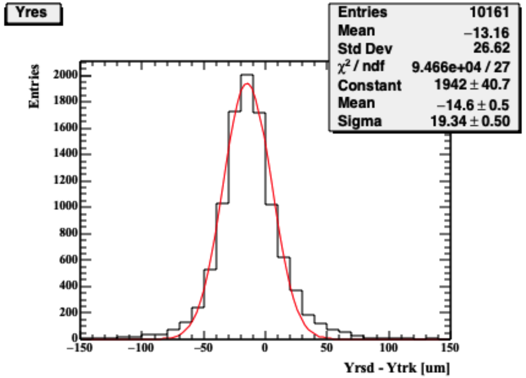


2D map of the average distance hit_RSD – hit_tracker



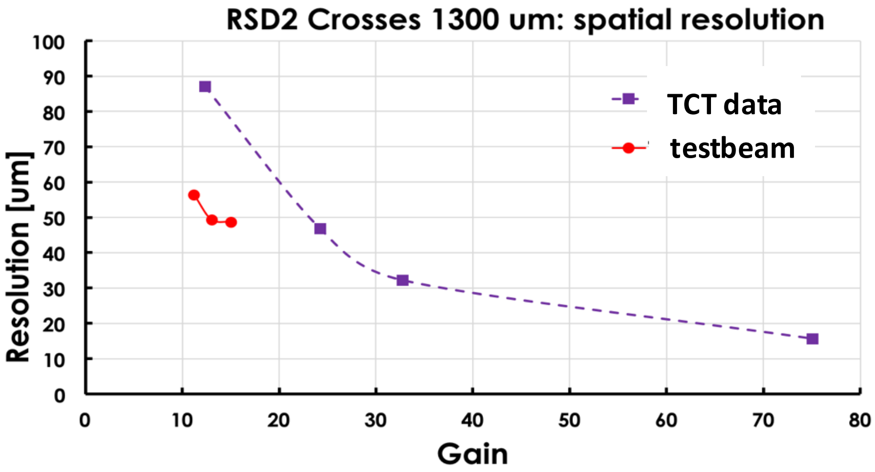






Sigma ~ 19 microns, tracker resolution to be removed (8 ± 2 μm)

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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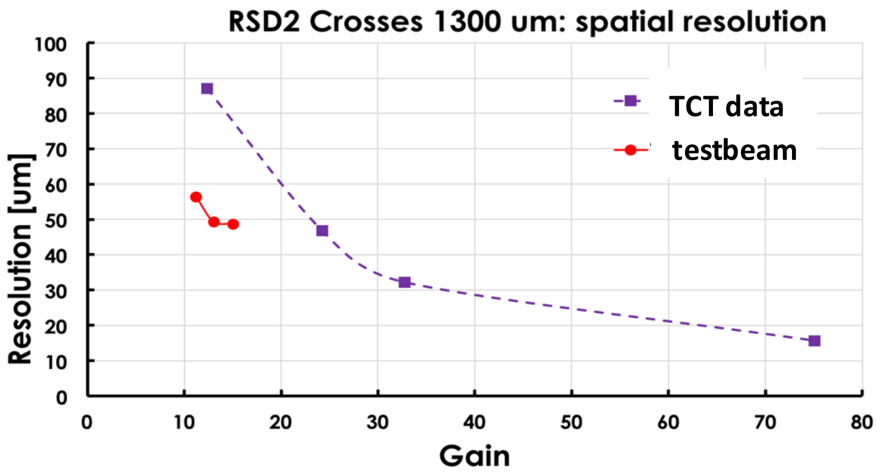

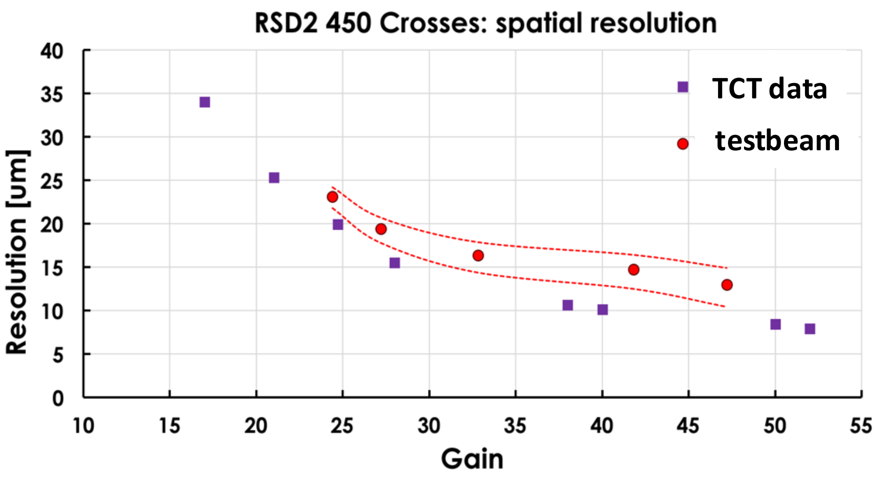

Very good results with low amplitude signals.

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at the testbeam setup

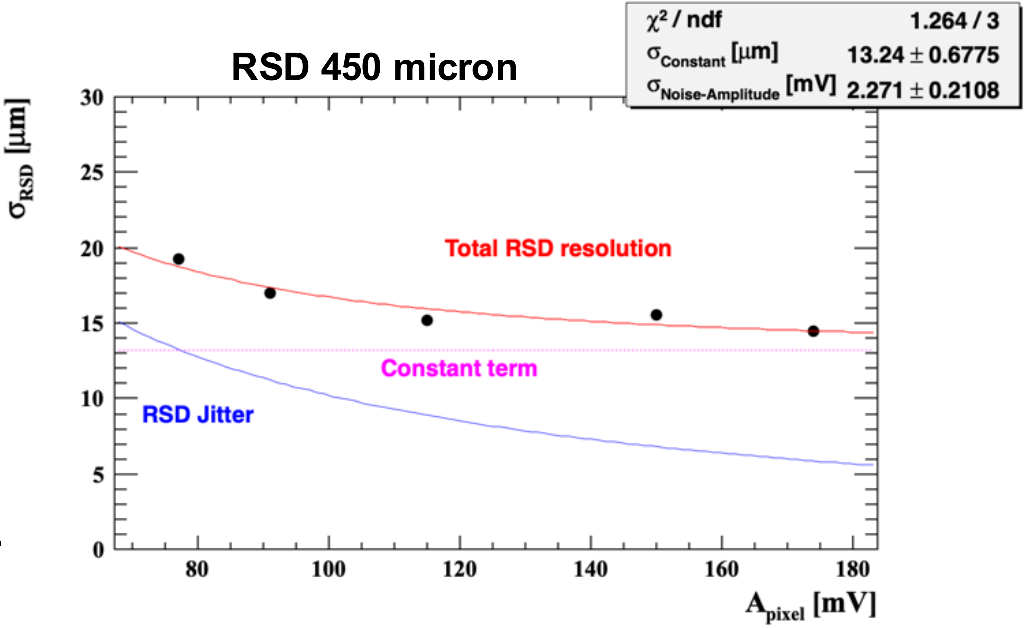
For equivalent gain, FAST2 yields better results.

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

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

Resolution around **3%-4%** **of the pitch.**



- 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…

L. Menzio et al, "First test beam measurement of the 4D resolution of an RSD 450 microns pitch pixel matrix connected to a FAST2 ASIC",)NIMA 1065 (2024), 169526

Take away message from AC-LGAD (RSD)

To be noted:

- signal spread may involve a large (>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
- Signals are bipolar with rather long tails during the discharge

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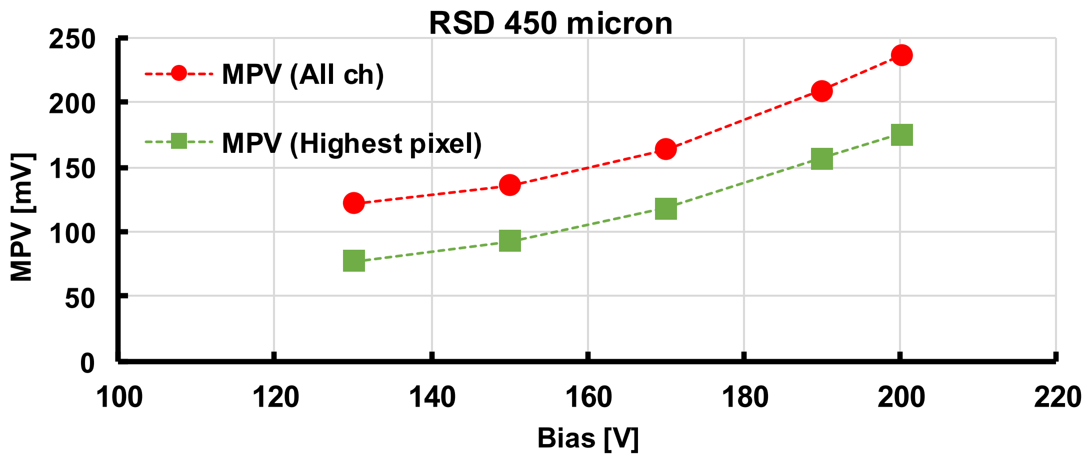
→ the resolution should further improve with the full containment of the signal in a predetermined area



The evolution: DC-coupled RSD

DC-RSD: DC-coupled Resistive read-out 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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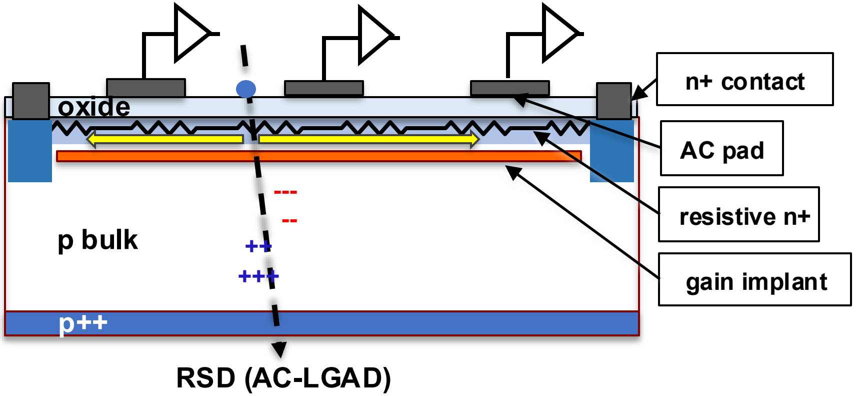
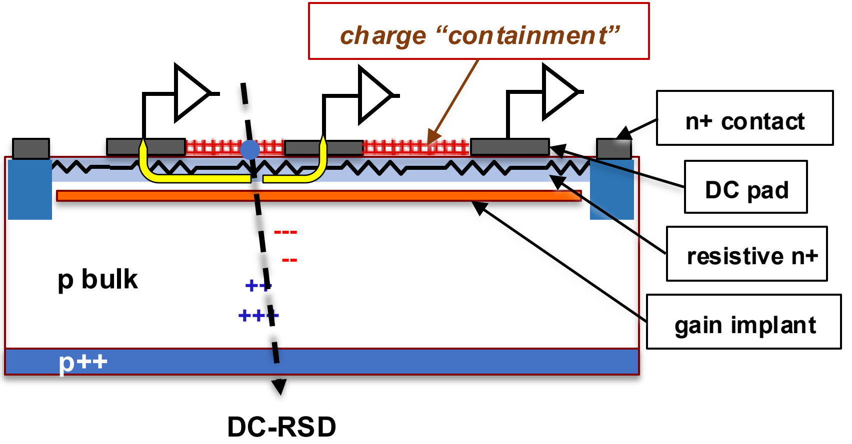
Development started in the framework of the project 4DInSide (Italian National project) in collaboration with FBK, and now supported by the 4DSHARE Grant (Italian National project)

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)



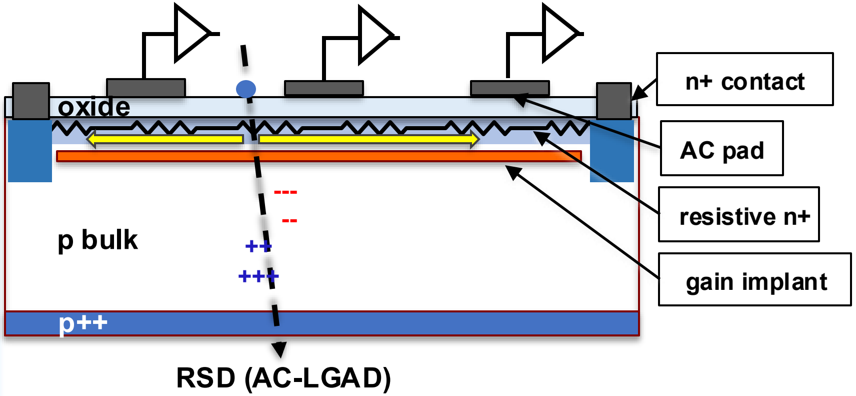


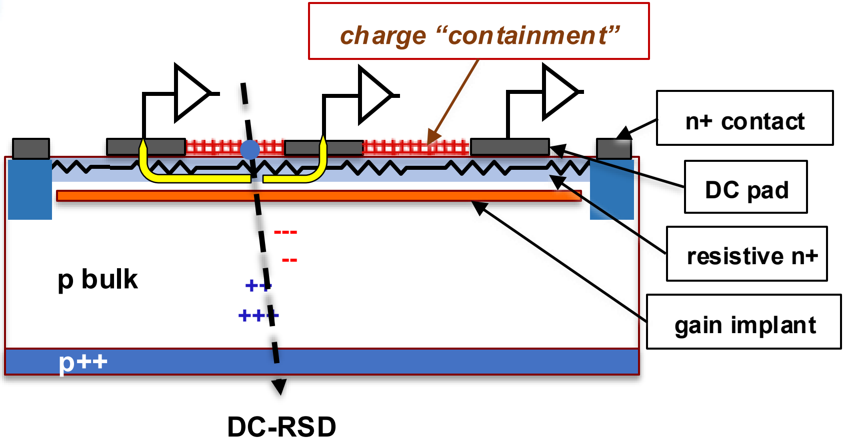
Evolution of the RSD design:

DC collection of signals, with low resistivity paths to read-out pads **+ charge "containment"** structures (isolating trenches for now) $\Longrightarrow$ **DC-RSD design**

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

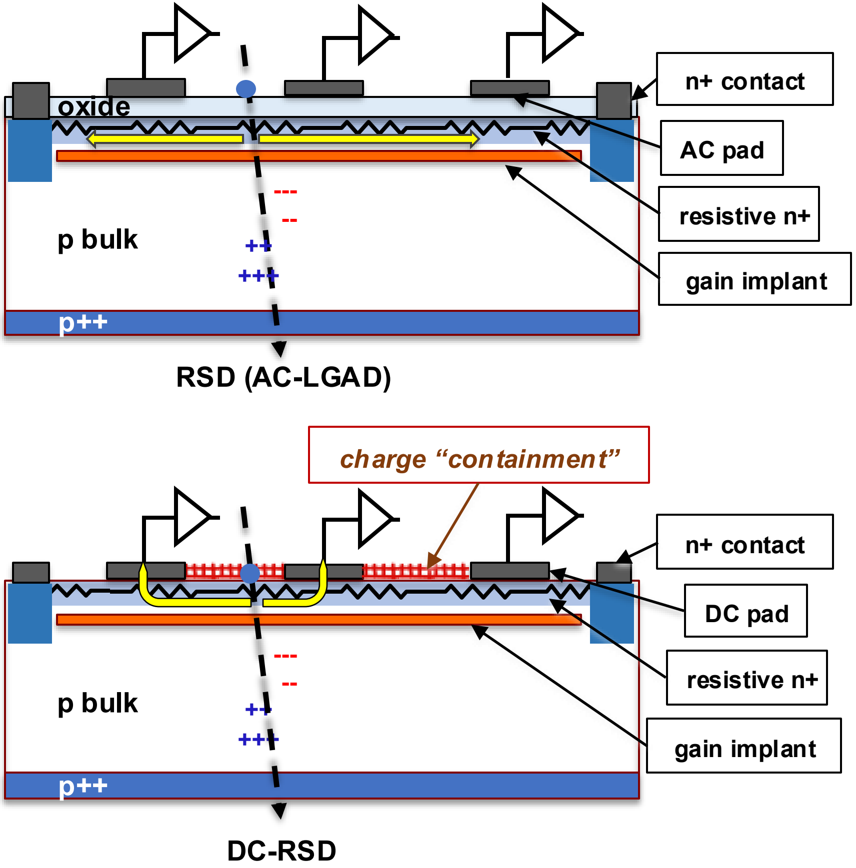
- Oxide layer for AC-coupling removed
- read-out electrodes implanted on the resistive layer
- the signals are read out via the closest DC electrodes
- the leakage currents is removed locally at each electrodes





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



Status of the R&D: production process flow

– TWO YEARS of work!

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
  - Investigated the possibility of introducing inter-pad resistors (Ti-TiN) as charge sharing containment

- “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

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

– TWO YEARS of work!

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

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

F. Moscatelli et al, https://www.sciencedirect.com/science/article/pii/S0168900224003061

A. Fondacci's talk at Pixel2024

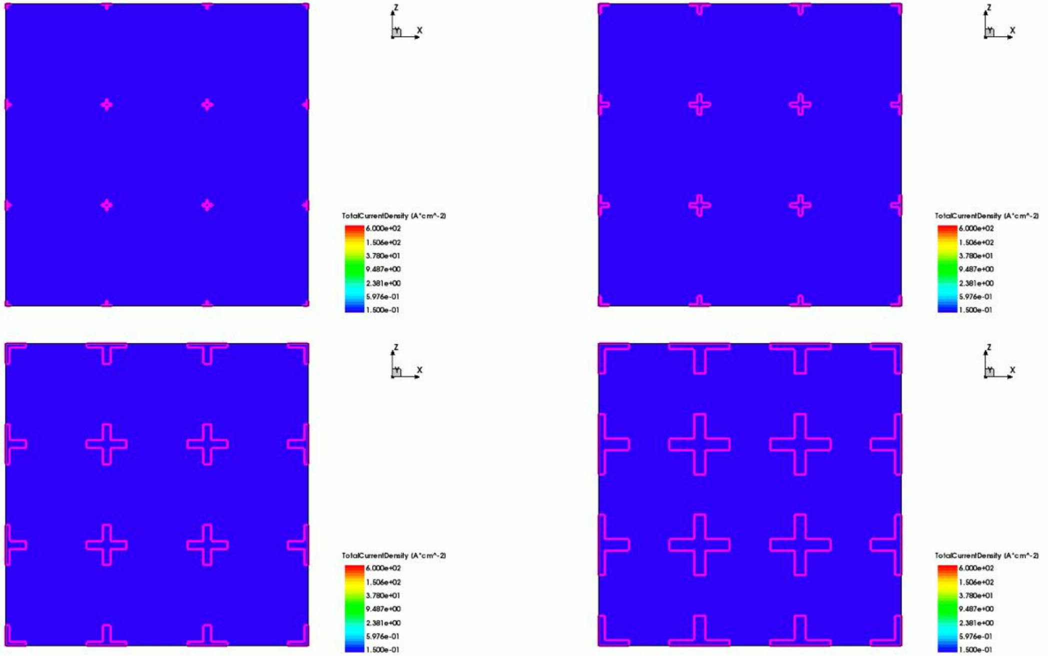
Signal spread with cross-shaped electrodes in DC-RSD

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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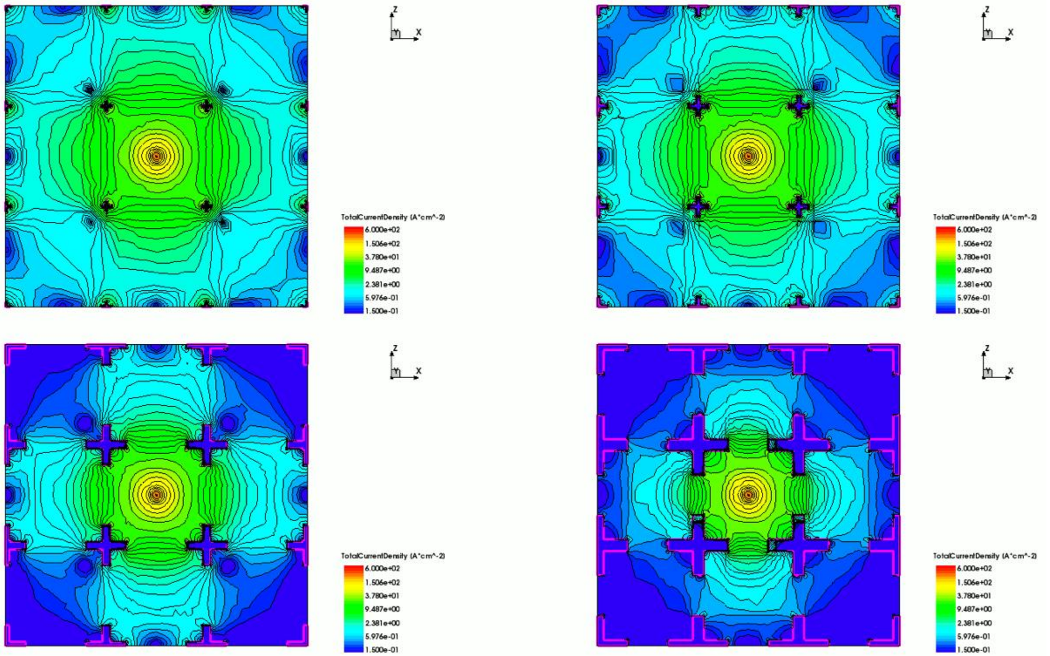

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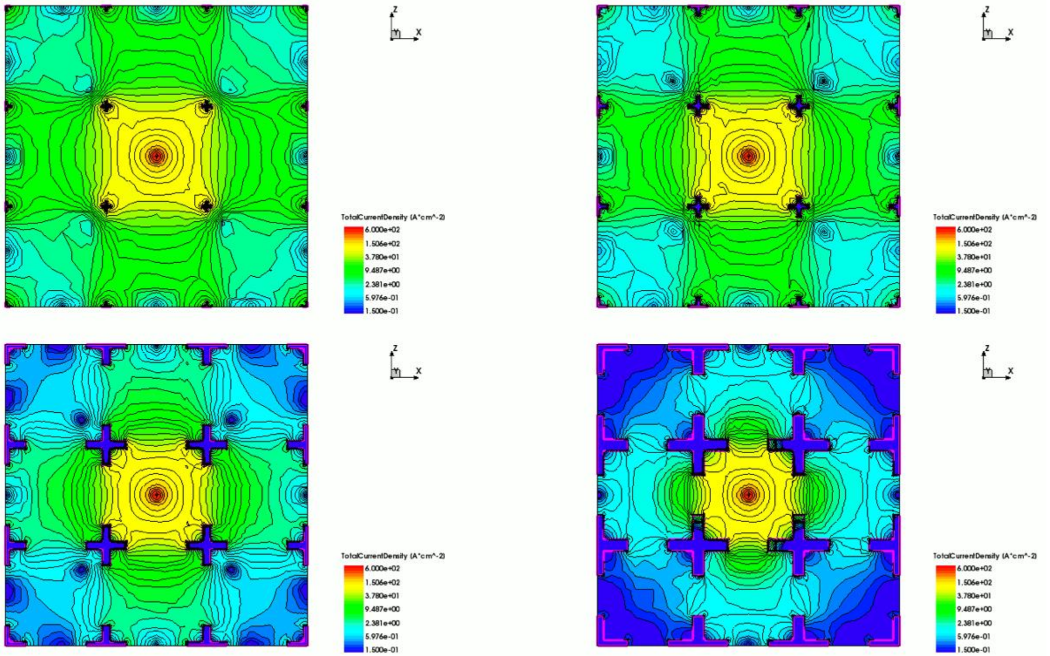

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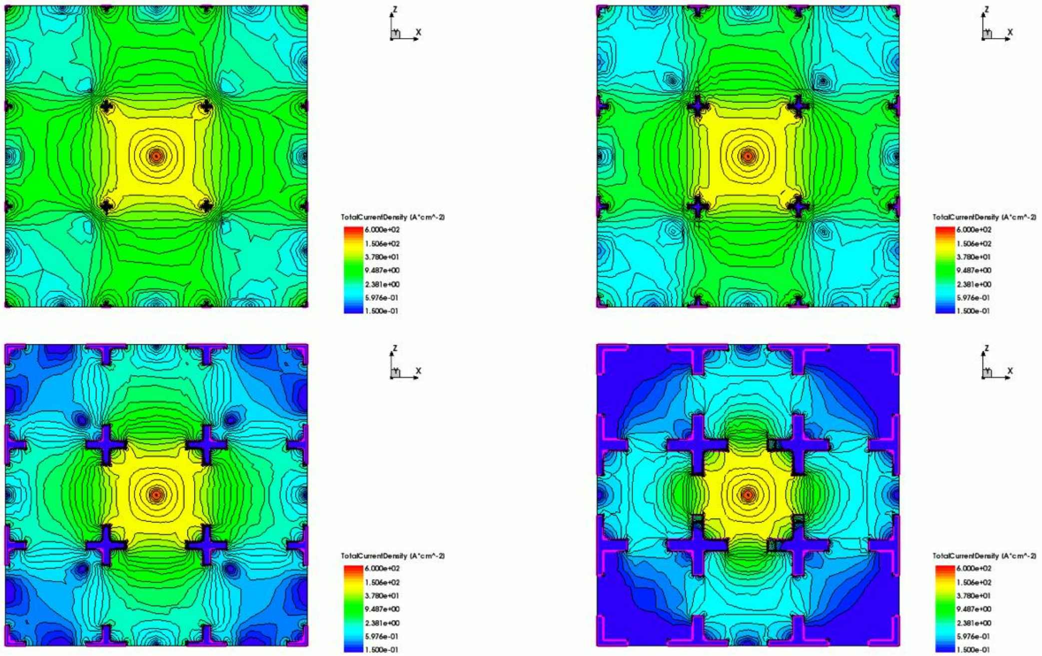

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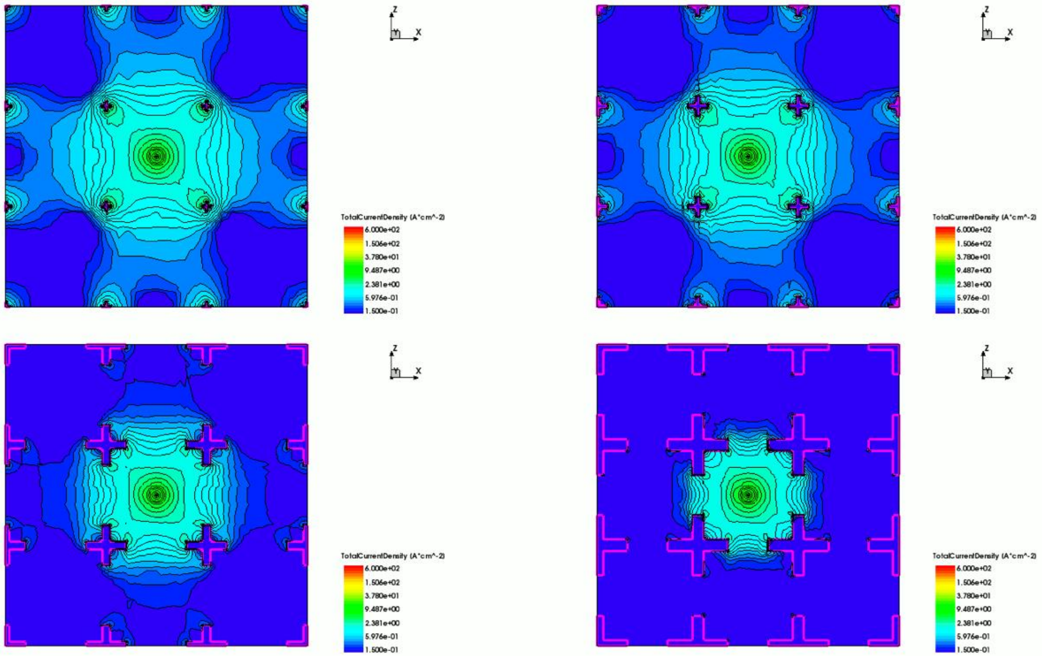

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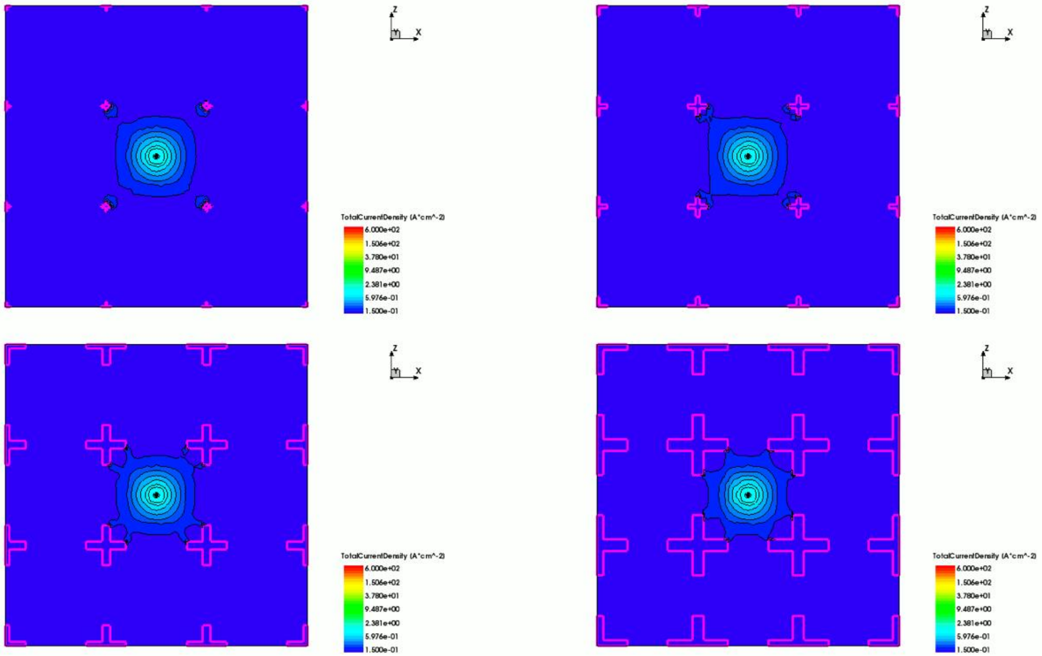

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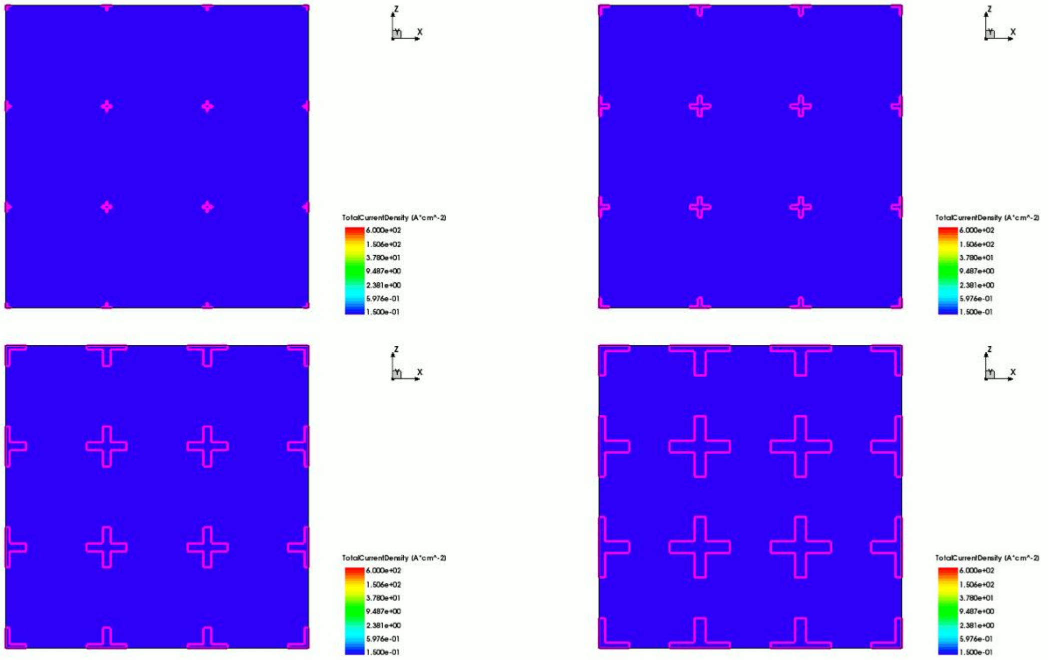
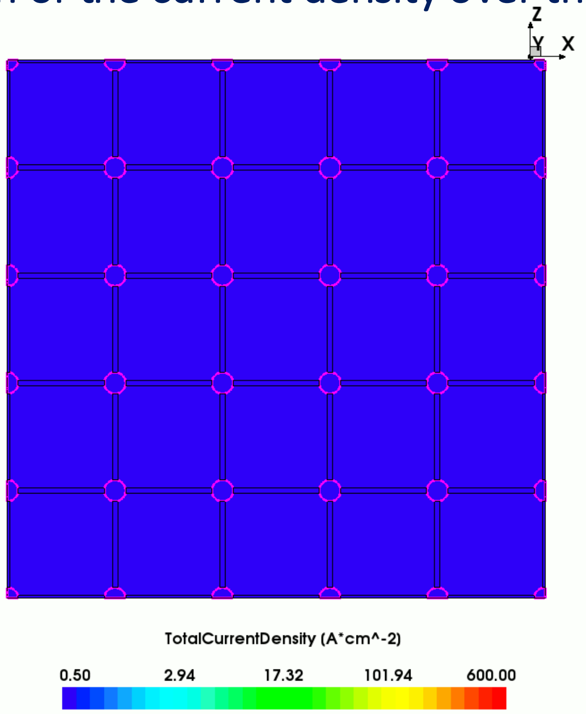


Signal spread with inter-pad resistors or isolating trenches

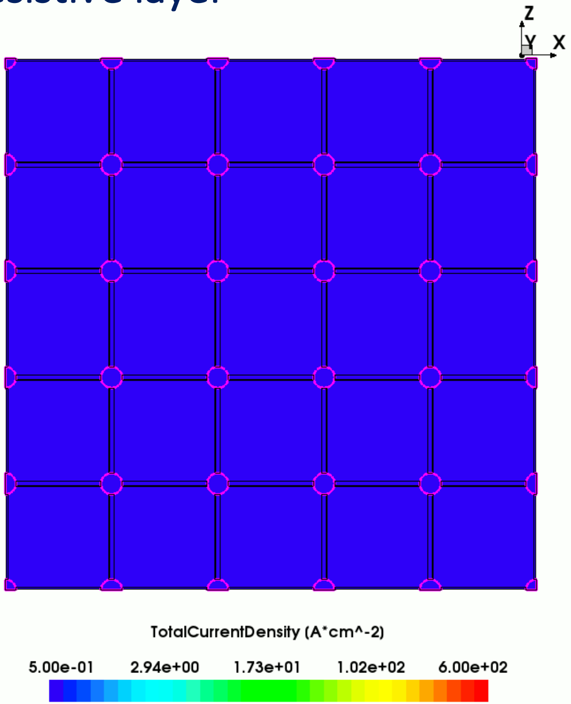
5x5 pixel structure, evolution of the current density over the resistive layer

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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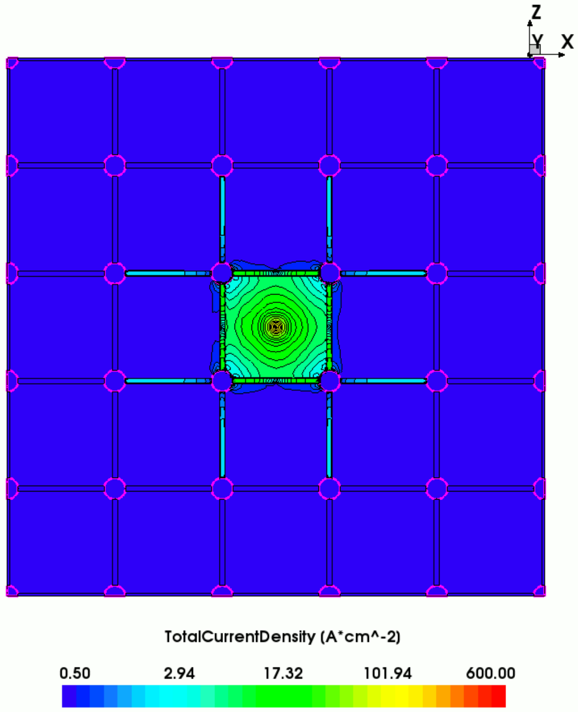

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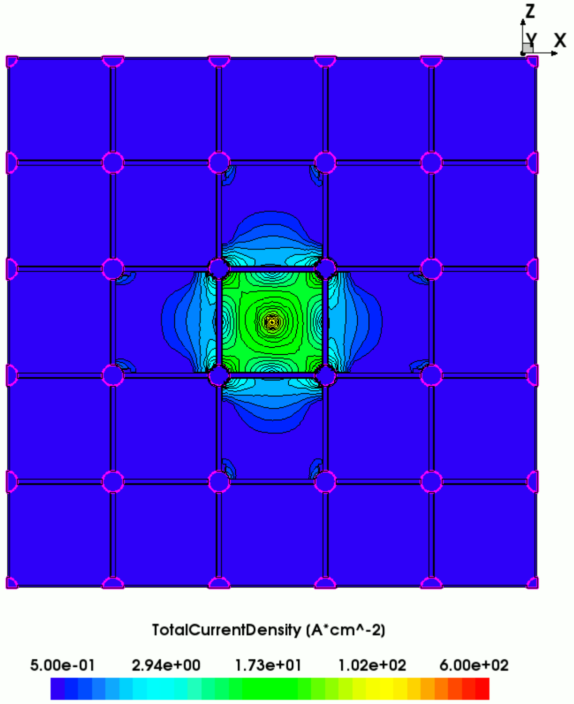

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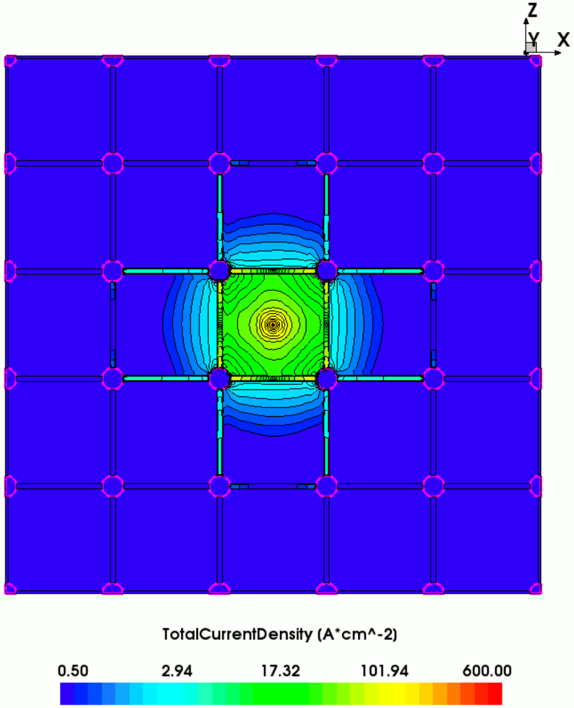

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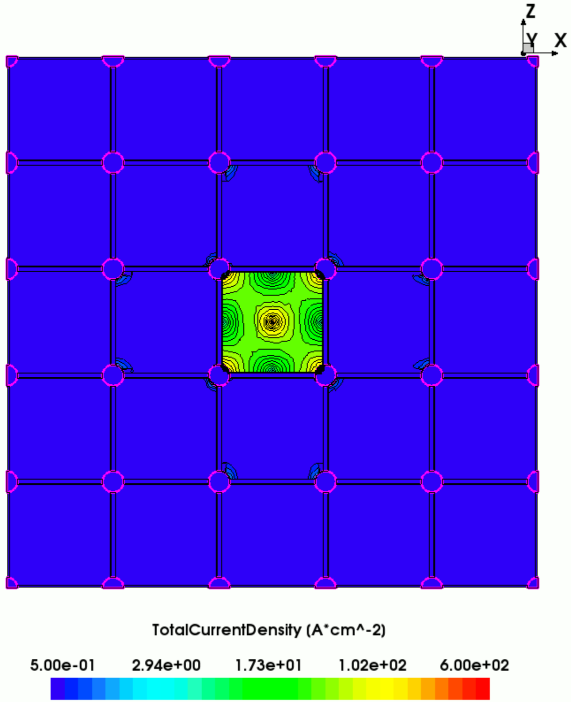

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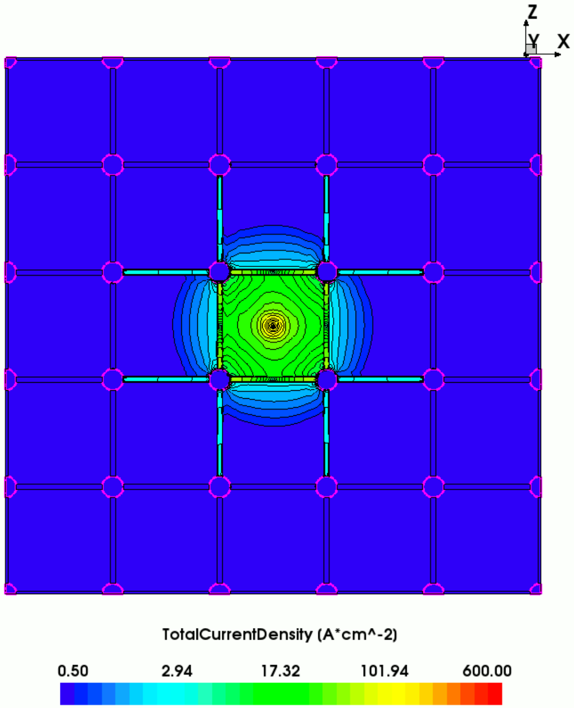

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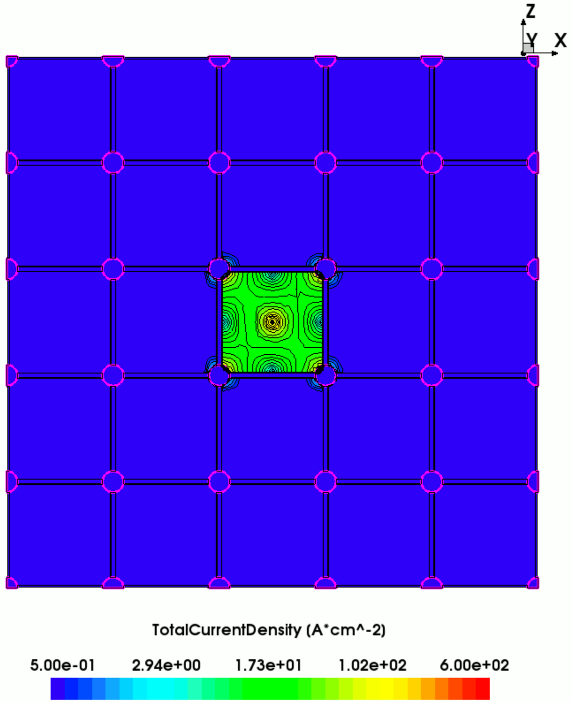

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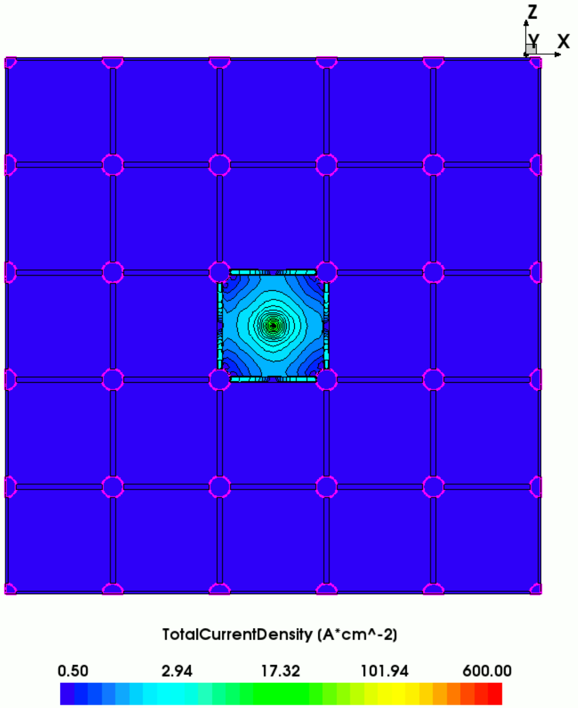
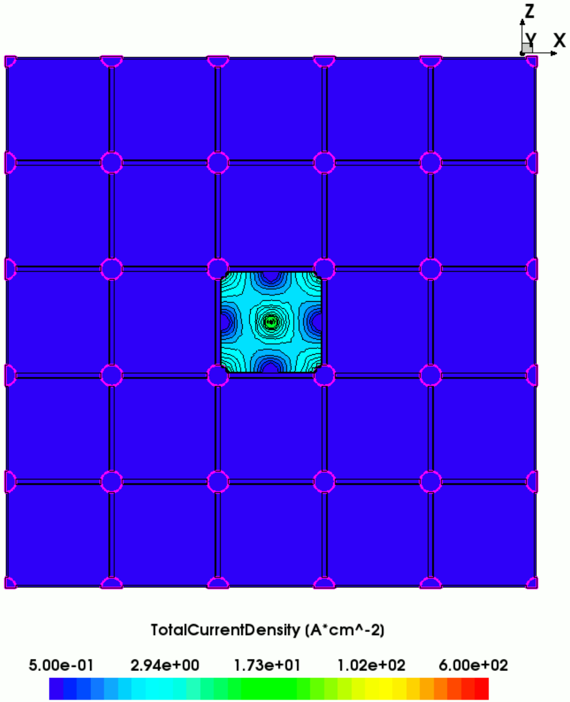


inter-pad resistors

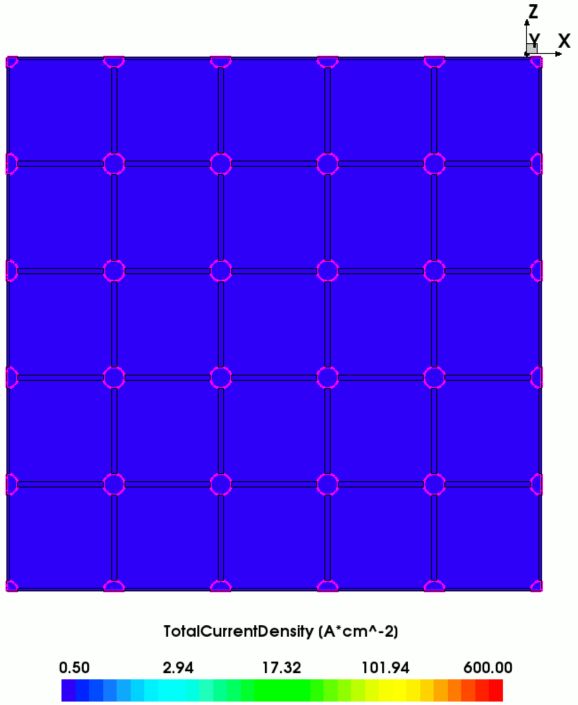


isolating trenches

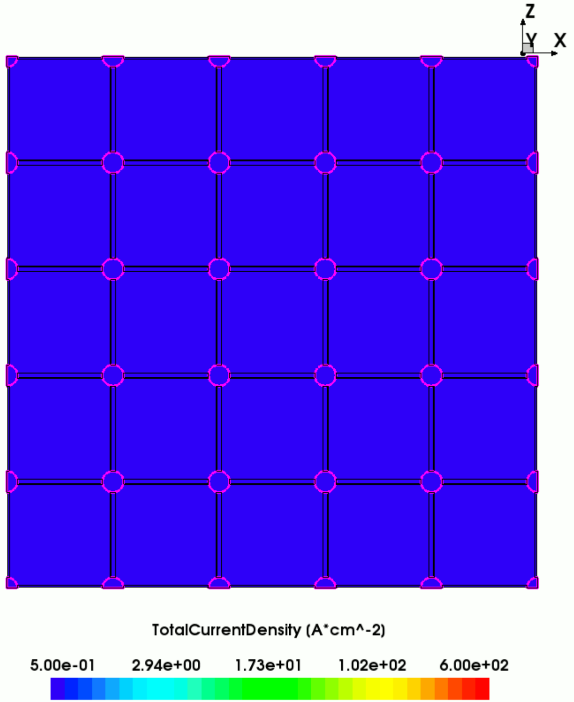
Signal spread with inter-pad resistors or isolating trenches

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

DC-RSD1: “proof-of-concept” production

The first production was completed @FBK in November 24: **DC-RSD1**

- The solution selected to achieve **charge containment**: use of Isolating Trenches (like TI-LGADs or SiPM)

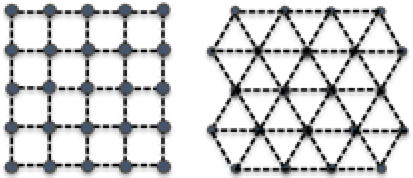
DC-RSD1: "proof-of-concept" production

The first production was completed @FBK in November 24: **DC-RSD1**

- The solution selected to achieve **charge containment**: use of Isolating Trenches (like TI-LGADs or SiPM)

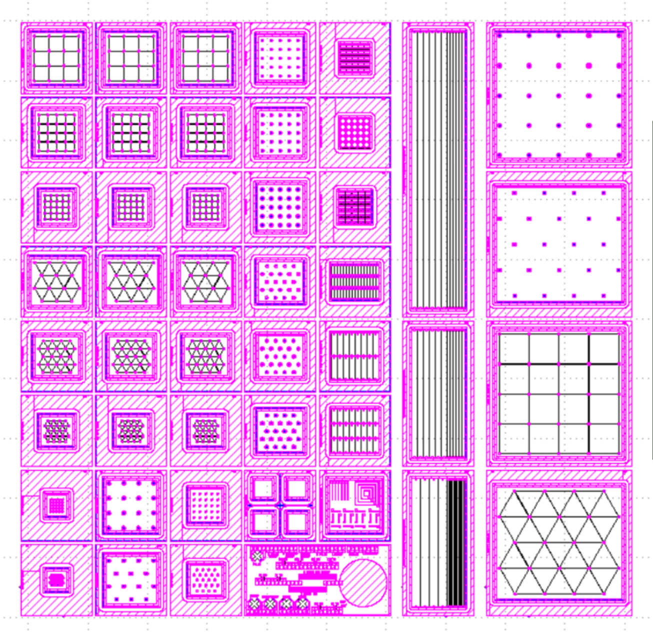
Several test structures implemented:

- devices with squared or hexagonal matrix of electrodes (dot-shaped), with and without isolating trenches, multiple pitch options
- strips with multiple pitch options and multiple length



"square" or "triangle" pixel shape

- devices without isolating trenches have been implemented to allow comparison with the equivalent designs in AC-LGADs



DC-RSD1 reticle

DC-RSD1: “proof-of-concept” production

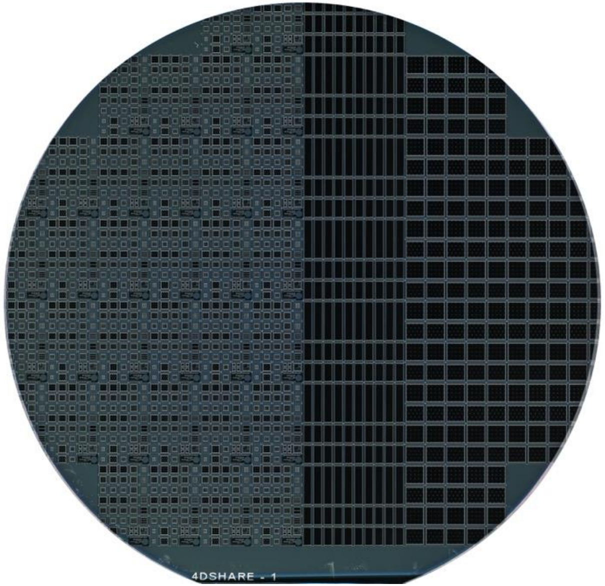
The first production was completed @FBK in November 24: **DC-RSD1**

- The solution selected to achieve **charge containment**: use of Isolating Trenches (like TI-LGADs or SiPM)

Split table:

Wafer	NPLUS dose	CONHO IMP	Trench depth	Trench process	PGAIN dose	Thickness
1	0,25		D2	P2	1.02	55
2	0,25	Y	D2	P2	1.02	55
3	0,25	Y	D2	P2	1.06	55
4	0,25	Y	D2	P2	1.06	55
5	0,5		D2	P2	1.02	55
6	0,5		D2	P2	1.06	55
7	0,5	Y	D2	P2	1.06	55
8	0,5	Y	D2	P2	1.02	55
9	1		D2	P2	1.02	55
10	1		D2	P2	1.06	55
11	1	Y	D2	P2	1.02	55
12	1	Y	D2	P2	1.06	55
13	0,25	Y	D2	P2	1.06	55
14	0,5	Y	D2	P2	1.02	55
15	1	Y	D2	P2	1.06	55

wafer selected for lab and testbeam measurements



DC-RSD1 wafer

see M. Centis Vignali’s Talk at TREDI2025 for more information on the DC-RSD1 production

DUTs @DESY testbeam

Preliminary results on space and time resolutions of these devices

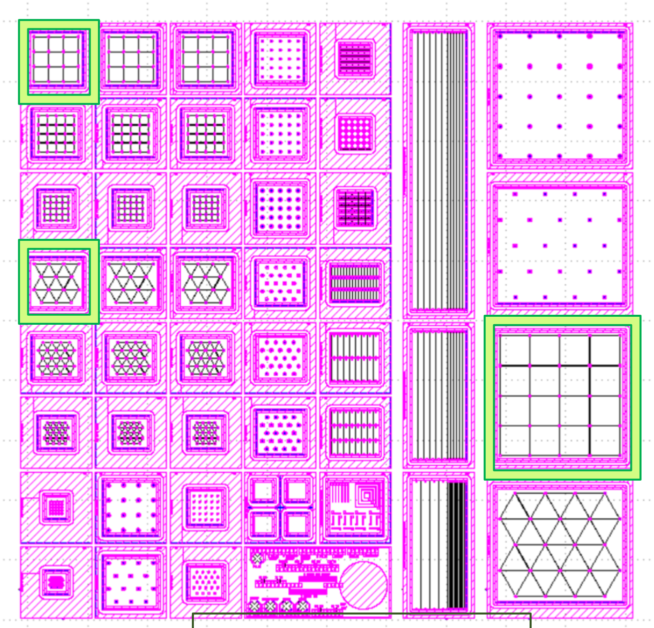
measured with a 5 GeV electron beam (DESY)

“Square” pixels

- 3x3 pixel matrix
- 16 electrods
- 500- and 1000-micron pitch

“Triangle” pixels

- 5x3 pixel matrix
- 14 electrodes
- 500-micron pitch



DC-RSD1 reticle

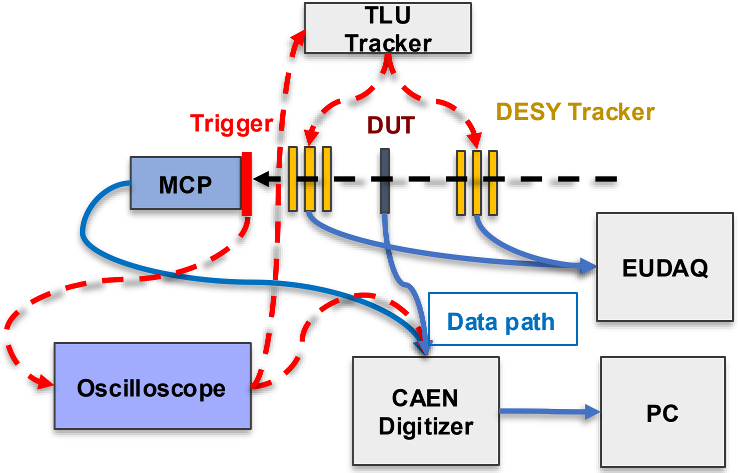
The DESY test beam set-up

Two different data taking modes

Studies of spatial resolution

Read many pixels using a CAEN digitizer

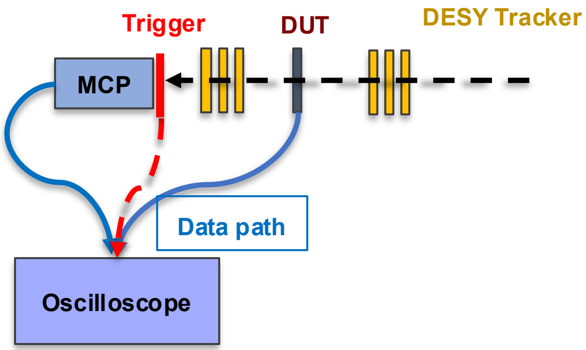
- Up to 16 electrodes



Studies of time resolution

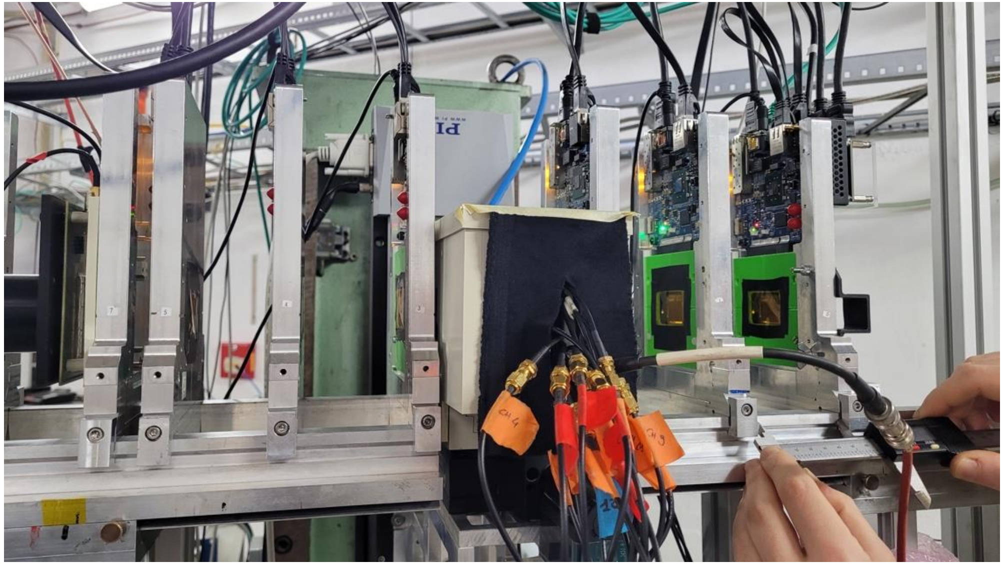
Read 2 pixels using an 8-ch oscilloscope

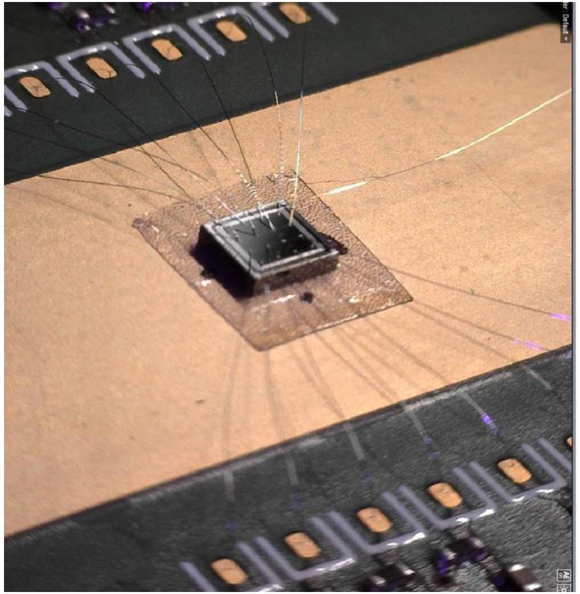
- Up to 7 electrodes + MCP (time reference)
- High time resolution



The DESY test beam set-up

in pictures….



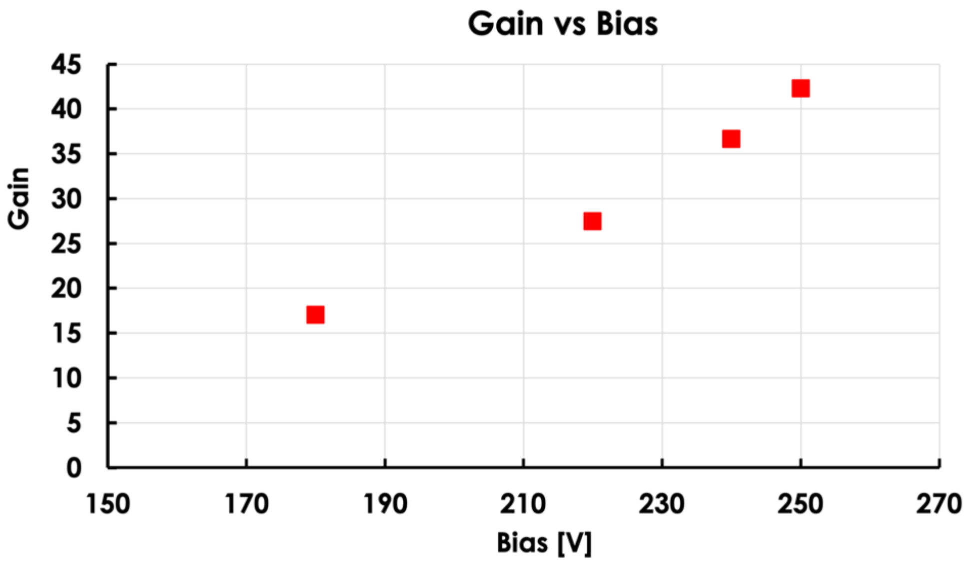


DC-RSD1 W3: gain studies

Wafer 3: "high" p-gain dose, highest n+ resistivity ("slower" propagation on the resistive layer)

High-statistics runs taken at different reverse bias voltages.

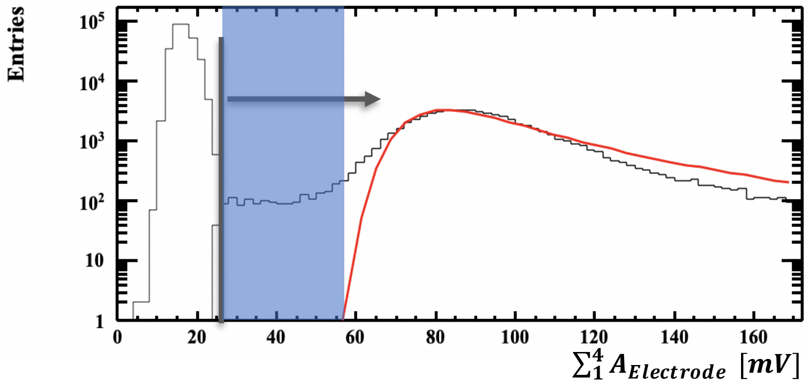
Gain estimated by comparing the signal area measured at a given bias, with the theoretical signal area in a PIN (uncertainty ~10%)



Gain range used in the analysis: 15 - 45

Signals collected by a pixel

The signal collected by a "pixel" is estimated **summing the amplitudes seen by the four** (three) **electrodes** defining the squared (triangular) pixel



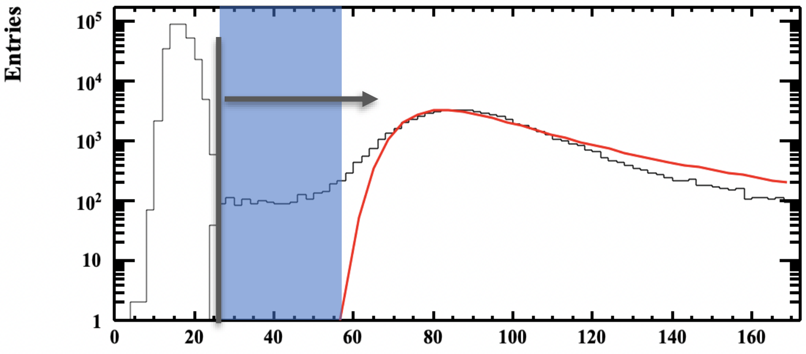
Clear separation between signal (Landau in red) and noise.

Event Selection criteria: $A_{pixel} > 25\,mV$

Events with lower amplitudes are located close to trenches

Signals collected by a pixel: inefficiencies?

The signal collected by a "pixel" is estimated **summing the amplitudes seen by the four** (three) **electrodes** defining the squared (triangular) pixel



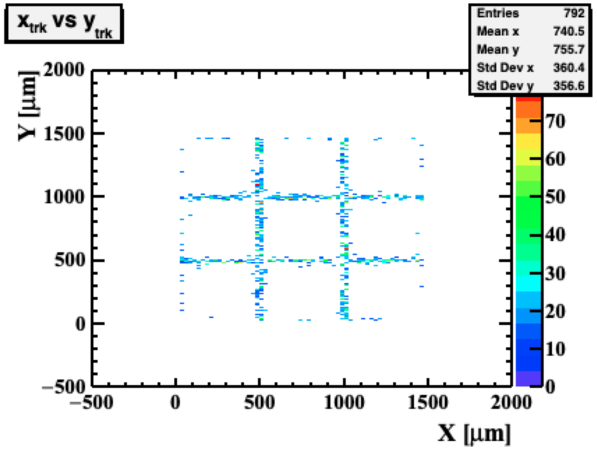
Clear separation between signal (Landau in red) and noise.

Event Selection criteria: $A_{pixel} > 25\,mV$

Events with lower amplitudes are located close to trenches

Is the DUT inefficient?

Events with tracks inside the active area and $A_{pixel} < 25\,mV$

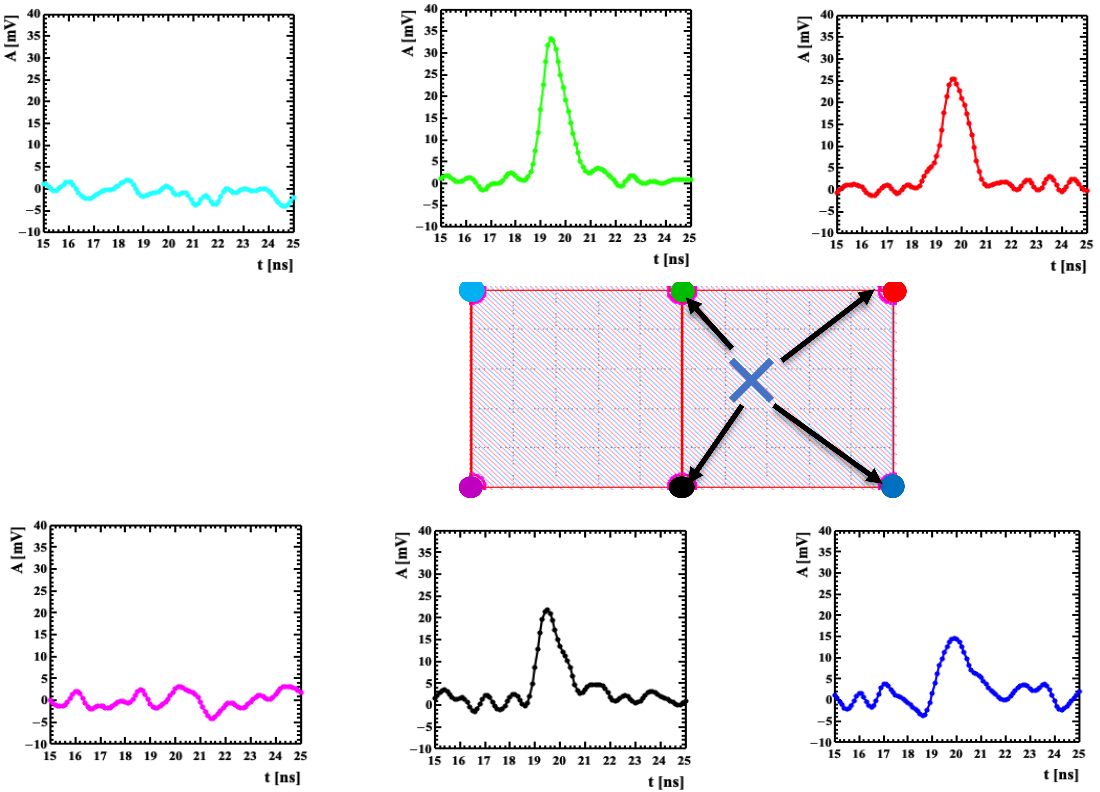


mostly aligned with the trenches!
this is not inefficiency but acceptance (fill factor ~ 99%)

Signal shape: square pixel, 500-micron pitch

Amplitudes recorded by 6 electrodes (see sketch)

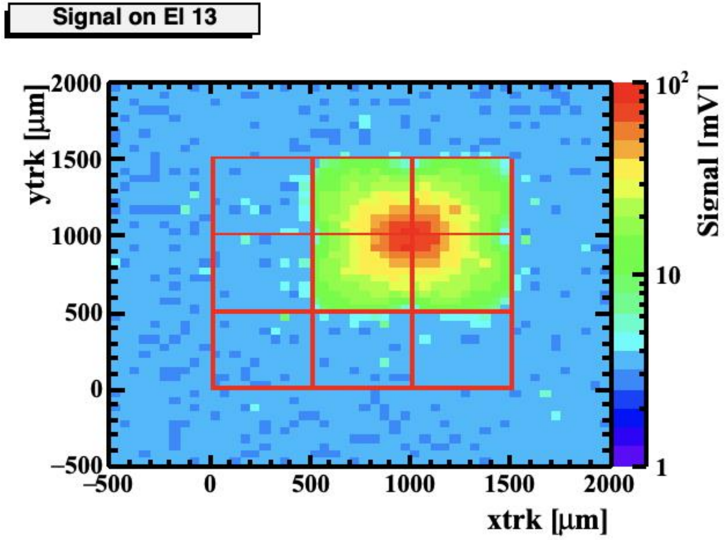
- **The signal is fast**, unipolar, same shape of a standard LGAD.
- **Perfect isolation**: the signal is seen only in the electrodes belonging to the hit pixel.

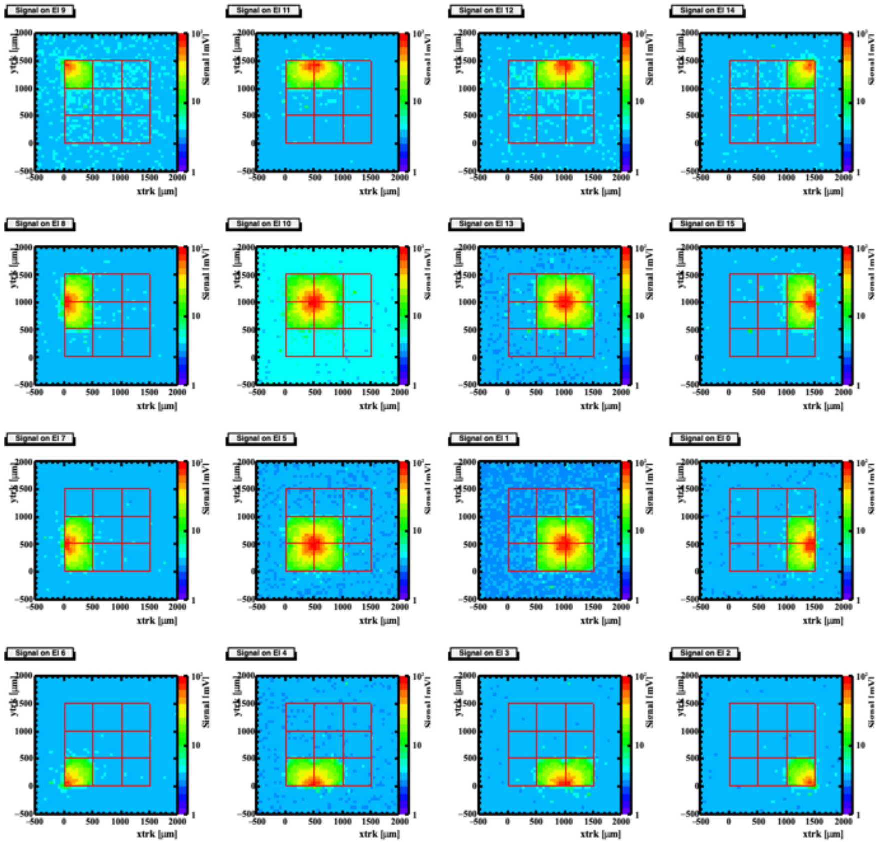


DC-RSD signal containment

Average signal amplitude seen by each electrode as a function of the $(X,Y)_{TRACKER}$

(Square pixels 230V)

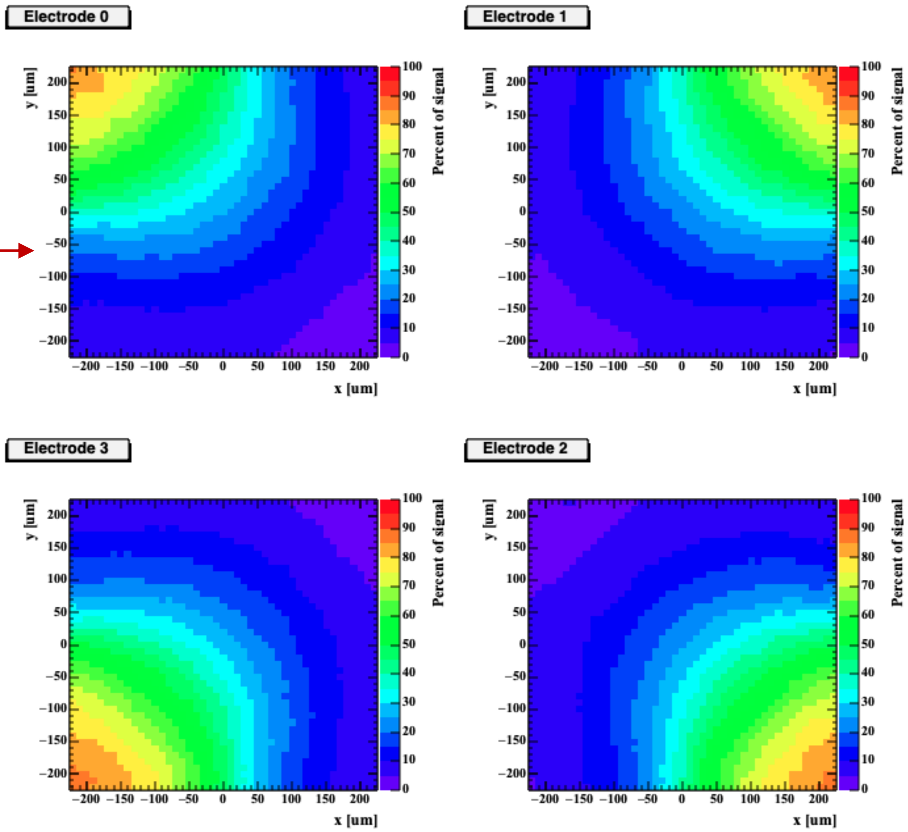




Position reconstruction method: sharing template

Position reconstruction procedure:

1) Produce look-up tables with the signal-sharing pattern among the 4 electrodes (done with test beam data).
   These plots show the signal percentage seen by a given electrode as a function of position (tracker)
2) For each event, compare the measured signal sharing with the look-up table to find the location that best reproduces the measured sharing



NB:

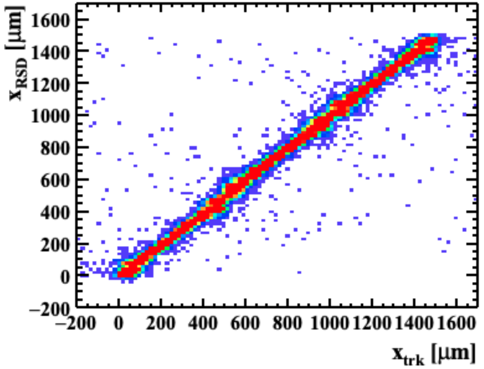
- **DUTs** have been **aligned w.r.t. the tracker**
- **Rotations** have been estimated and **corrected for**
- **electrodes amplification** (FNAL board) **inter-calibrated**, equalizing the MPV of the amplitude distributions

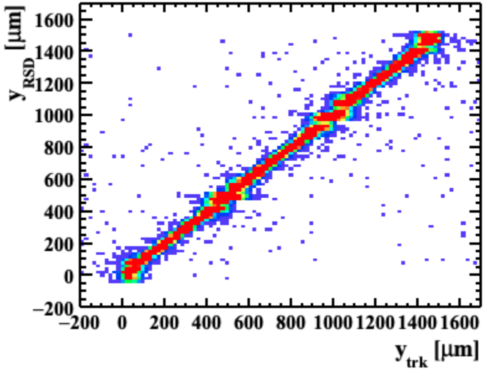
DC-RSD position resolution

Square matrix, 500-micron

Bias = 240 V (gain ~37)

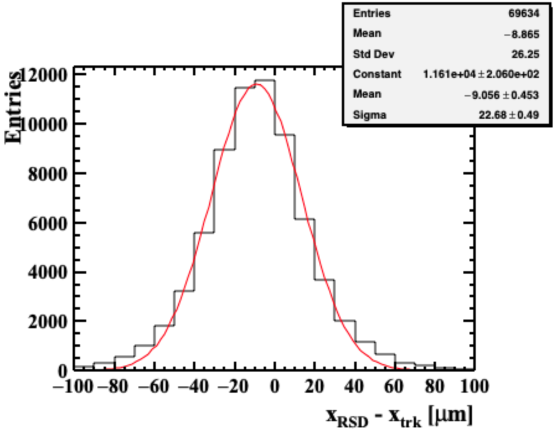
Correlation between the positions of tracker and DC-RSD over the whole 3x3 matrix.

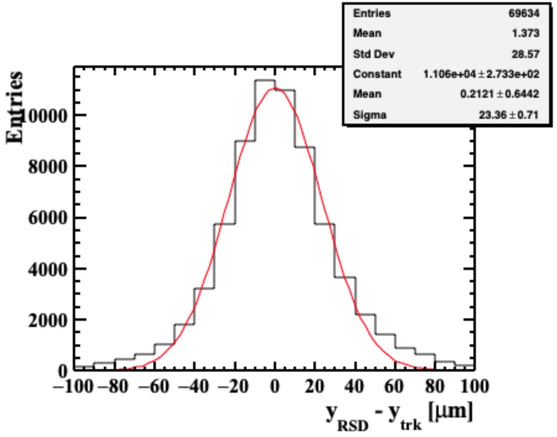




Measurement of the position resolution $(X, Y)_{DC\text{-}RSD} - (X, Y)_{TRK}$

$$\sigma_{x,y} \sim 23\ \mu m$$

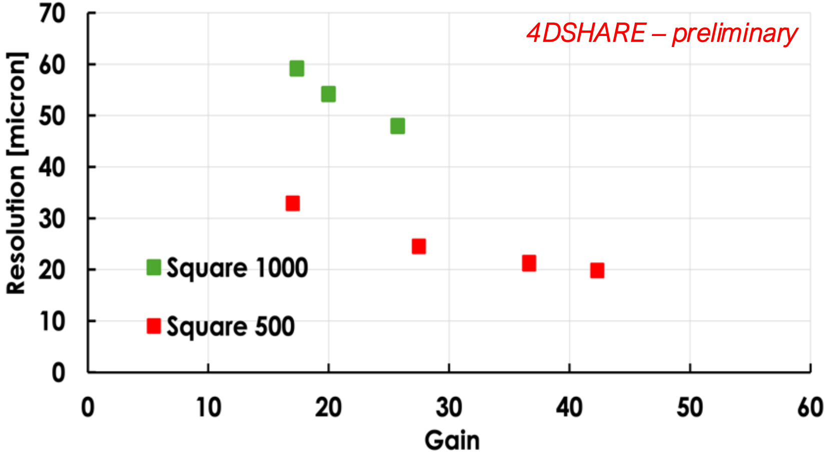




Position resolution: summary of results

Resolution for the 500- and 1000-micron pitch squared pixel matrix

(tracker resolution ~8 micron subtracted)



Position resolution: summary of results

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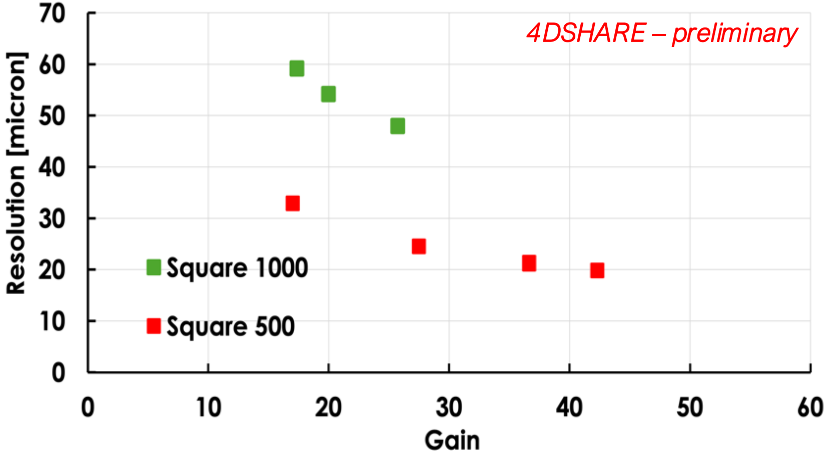
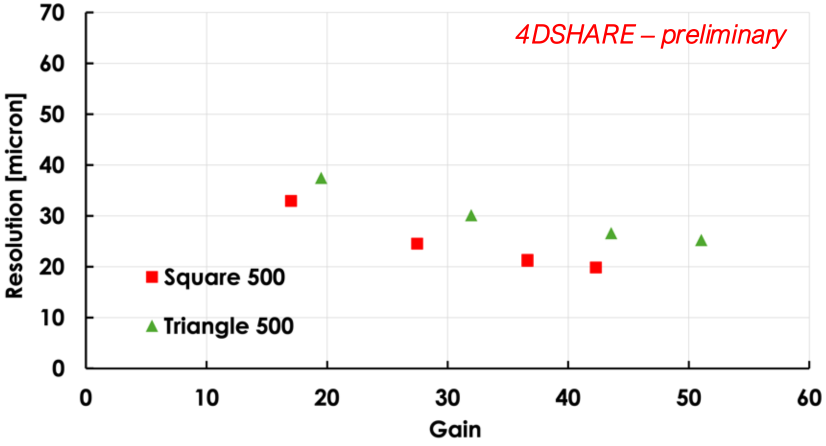


Resolution for the 500-micron pitch squared and triangular pixel matrix

(tracker resolution ~8 micron subtracted)



Both sensors reach very good position resolution, below 5% of their pitch

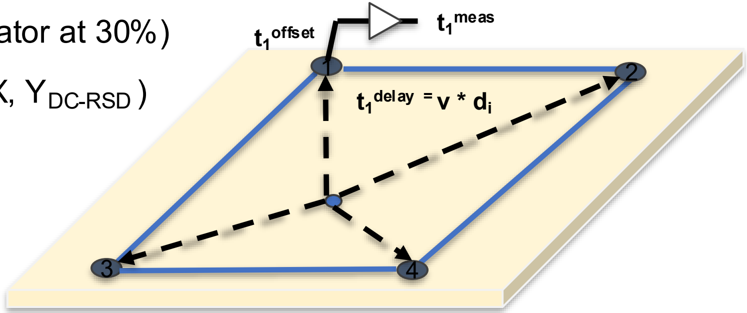
Square pixels are better performing than triangular pixels

Time reconstruction procedure

For each electrode, estimate the time of the hit t_i^{hit}

- Measure the time of arrival t_i^{meas} (constant fraction discriminator at 30%)
- Correct for signal delay $t_i^{delay} = v * d_i$ (d computed using X, $Y_{DC\text{-}RSD}$)
- Correct for set-up offset t_i^{offset}

$$t_i^{hit} = t_i^{meas} + t_i^{delay} + t_i^{offset}$$



The delays are calculated assuming a given signal propagation velocity on the n+ layer

The **particle time is computed combining the 4 measurements**, weighted with the squared amplitude

$$t^{hit} = \frac{\sum_1^4 t_i^{hit} A_i^2}{\sum_1^4 A_i^2}$$

Time reconstruction procedure

For each electrode, estimate the time of the hit t_i^{hit}

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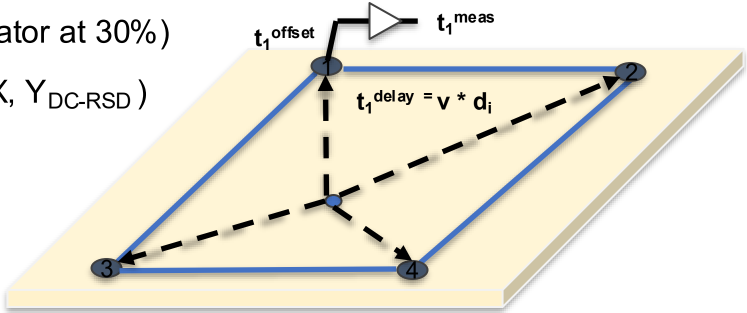
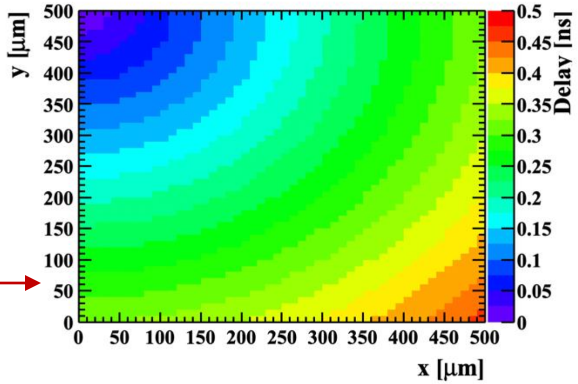


The delays are calculated assuming a given signal propagation velocity on the n+ layer, **which can also be measured using the data**

The **particle time is computed combining the 4 measurements**, weighted with the squared amplitude

$$t^{hit} = \frac{\sum_1^4 t_i^{hit} A_i^2}{\sum_1^4 A_i^2}$$

signal delay as a function of the hit position

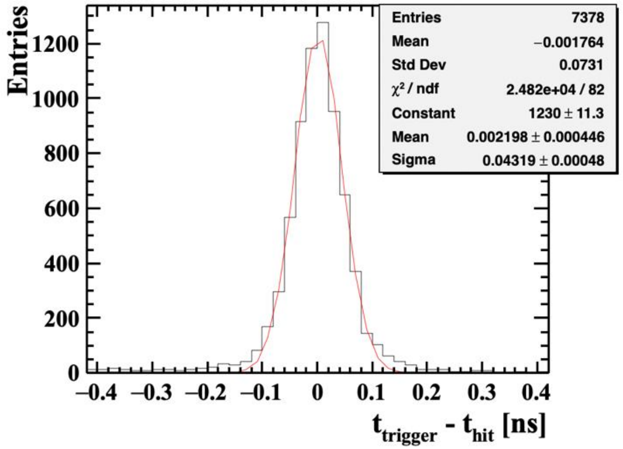


DC-RSD Time resolution

$$t^{hit} = \frac{\sum_1^4 t_i^{hit} A_i^2}{\sum_1^4 A_i^2}$$

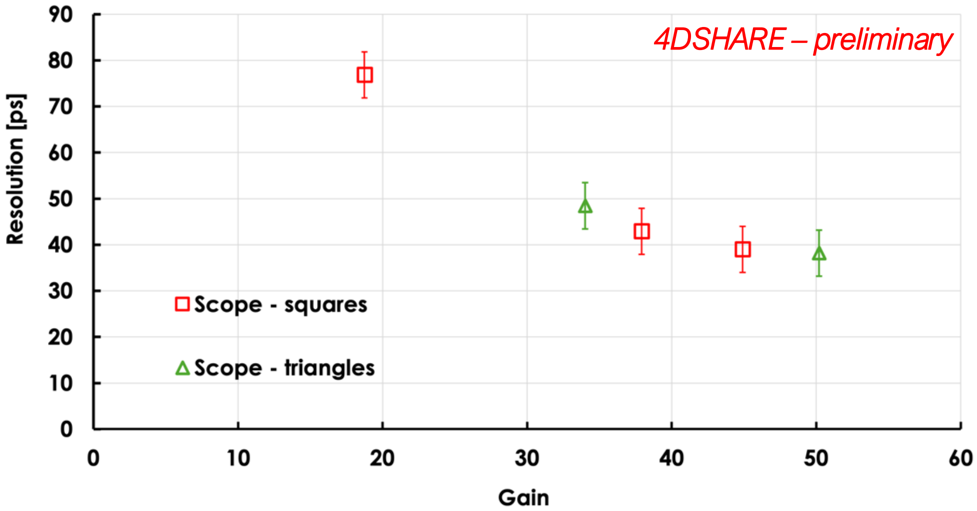
Distribution of $t^{MCP} - t^{hit}$ for 500-micron square matrix, bias = 240 V

$\sigma_t \sim 43\ ps$



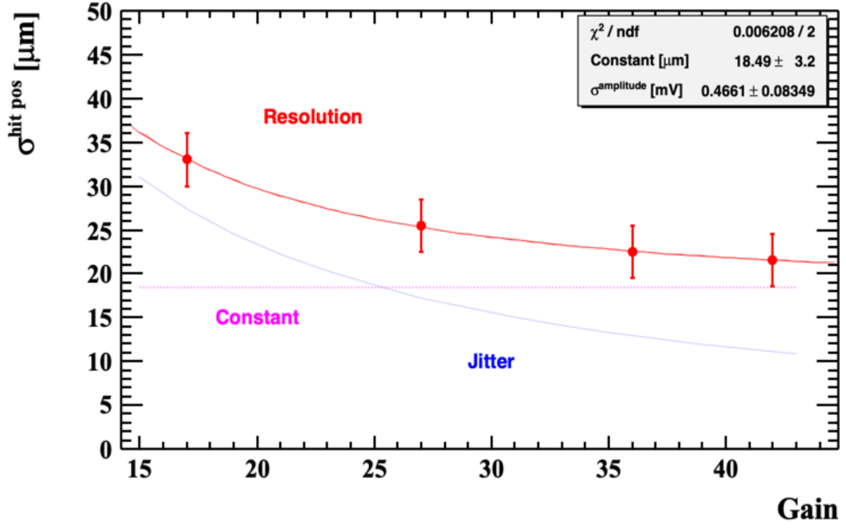
Time resolution for the 500-micron pitch squared and triangular pixel matrix

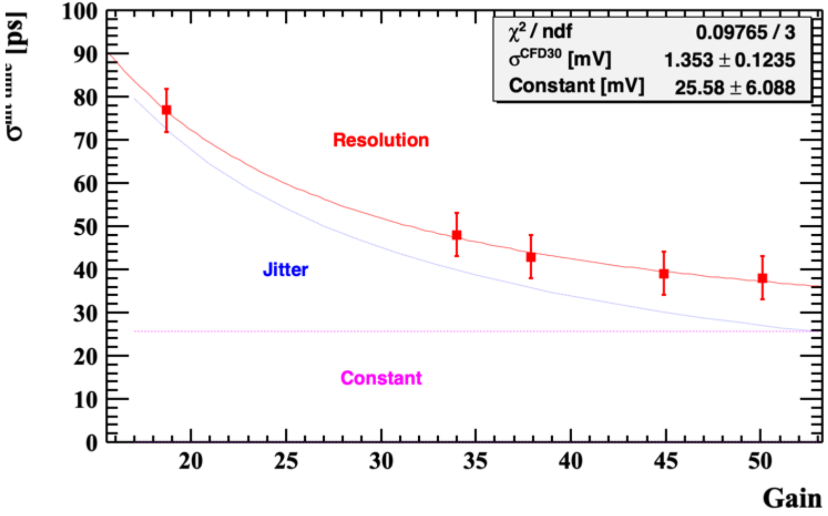
(time resolution MCP estimated to be 5 ps – subtracted)



Performance DC-RSD “squares” pitch 500

20 micron – 40 ps





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 signals 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 with low power consumption!

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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 signals 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 with low power consumption!

The DC-coupled version of the RSD is alive, the charge is contained by the trenches. The main goal of the production has been achieved: need more time to refine/complete the studies and assess its full potential.

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

BACK-UP material

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

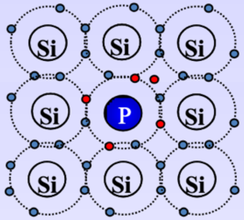
- F. Siviero et al , "Optimization of the gain layer design of Ultra-Fast Silicon Detectors”, https://arxiv.org/abs/2112.00561, NIMA 1033

- 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

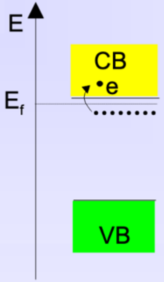
- F. Siviero et al, “Machine learning for Precise Hit Position reconstruction in resistive Silicon Detectors”, JINST 19 C01028

Doping, resistivity and p-n junction

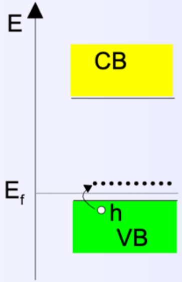
e.g. Phosphorus



- **Doping: n-type silicon**
  - add elements from Vth group
    ⇒ **donors** (P, As,..)
  - electrons are majority carriers



- **Doping: p-type silicon**
  - add elements from IIIrd group
    ⇒ **acceptors** (B,..)
  - holes are majority carriers

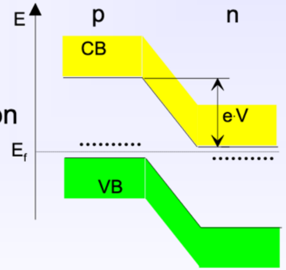


- **resistivity ρ**
  - carrier concentration n, p
  - carrier mobility μ_n, μ_p

$$\rho = \frac{1}{q_0(\mu_n n + \mu_p p)}$$

	detector grade	electronics grade
doping	$\approx 10^{12}$ cm^{-3}	$\approx 10^{17}$ cm^{-3}
resistivity ρ	$\approx$ 5 k$\Omega\cdot$cm	$\approx$1 $\Omega\cdot$cm

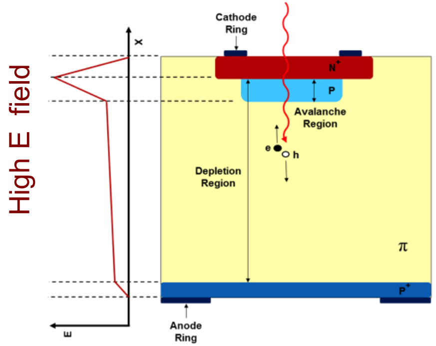
- **p-n junction**
  There must be a single Fermi level!
  ⇒ band structure deformation
  ⇒ potential difference
  ⇒ depleted zone

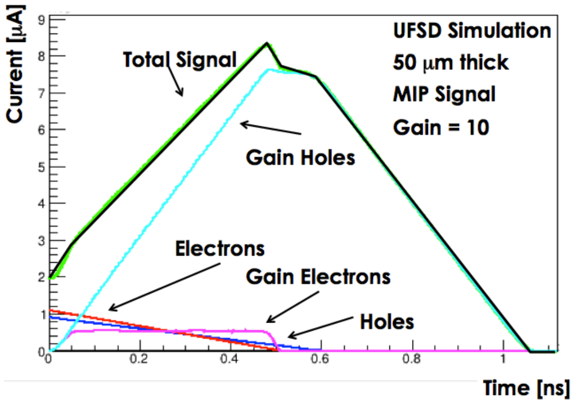


Ultra Fast Silicon Detectors

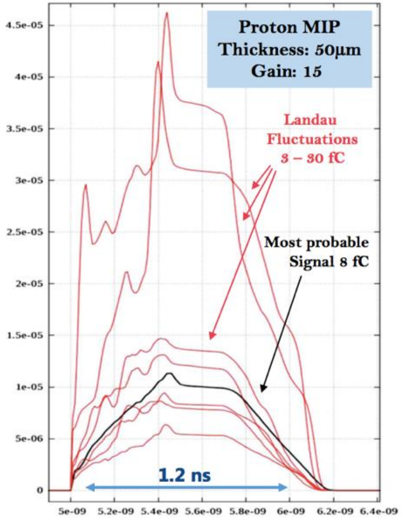
LGAD (Low Gain Avalanche Diodes) technology sensors optimized for timing measurements

The idea: add a thin layer of doping to produce low controlled multiplication (the gain layer)



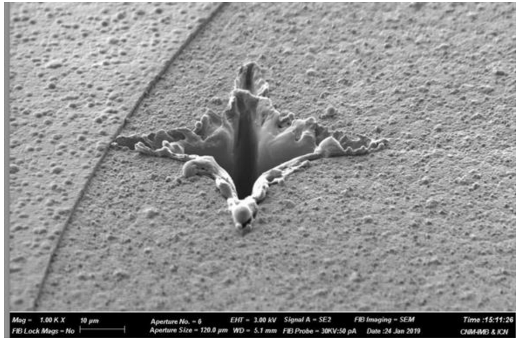


The main contribution to the signal comes from gain holes. The signal shape depends on the sensor thickness and gain



Sensors Single Event Burn-out

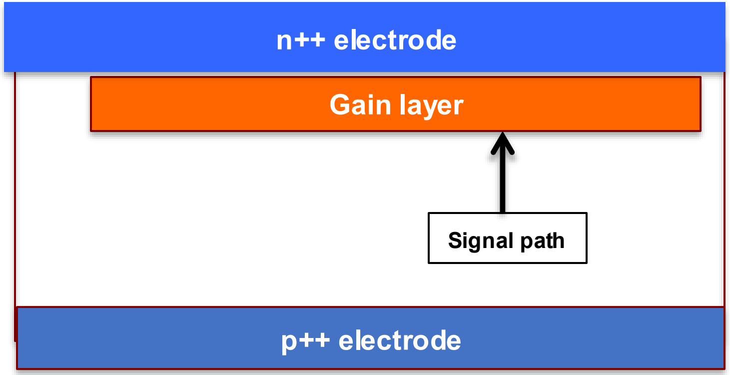
- **50 μm thick LGAD** sensors exposed to 120 GeV/c protons, when biased at 625 V or higher (**12.5 V/μm**) , break down permanently.
- The break-down happens rather quickly, in 5-10 minutes.
- Sensors' irradiation level does not seem to influence the outcome
- The same sensors, previously tested with a β source at much higher voltages and for many hours, did not break.
- The burnt mark position is consistent with the position predicted by the beam-test tracker ==> burn out due to a single particle.



- **After many investigations and measurements done at testbeams by the CMS and ATLAS collaborations, the current understanding of the process is that the effect is proportional to the bulk electric field value**
- **Sensors break down are observed for E => 12 V/μm**
- **Sensors biased such to achieve E = 11 V/μm** are considered operated in a SAFE REGIME

R. Arcidiacono – 4D-tracking

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

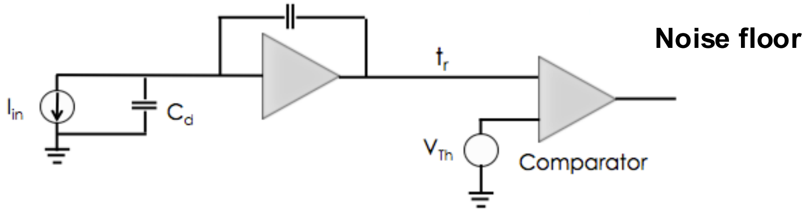
Conclusion:
internal gain decreases the signal-to-noise ratio of the signal BUT…we need to consider also the electronics noise

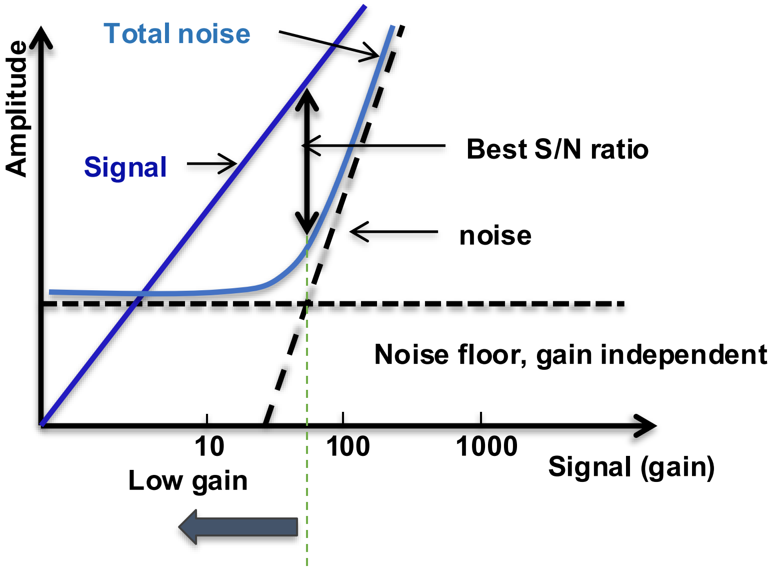
Signal, noise in LGAD + Electronics

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**

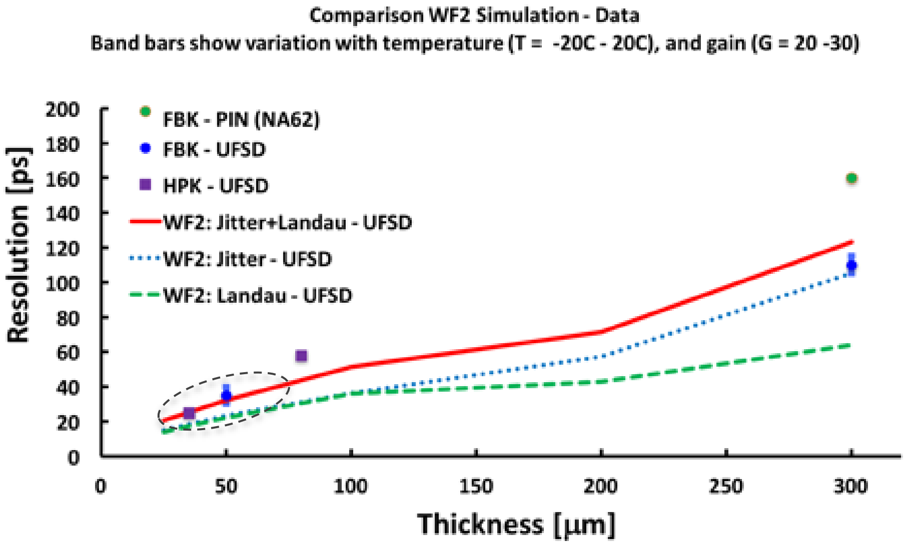
"Low gain" needs to be understood in connection with the noise of the electronics: it is the range of gain with an improved signal-to-noise ratio.

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





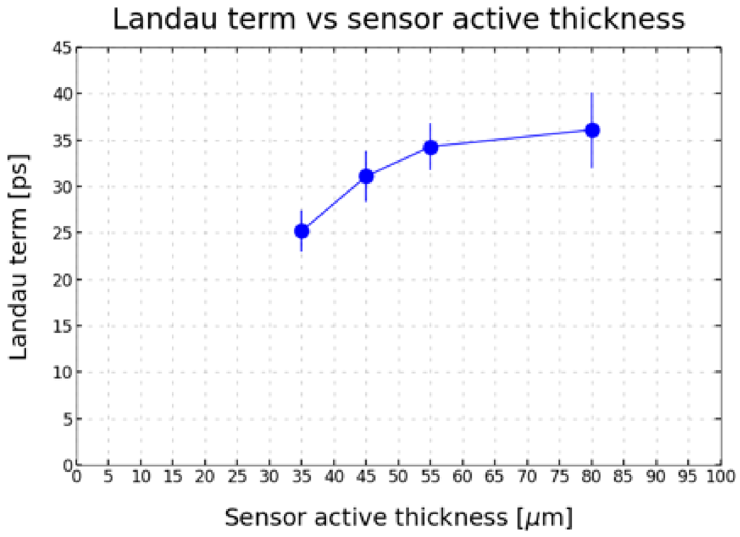
UFSD time resolution in thinner sensors



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



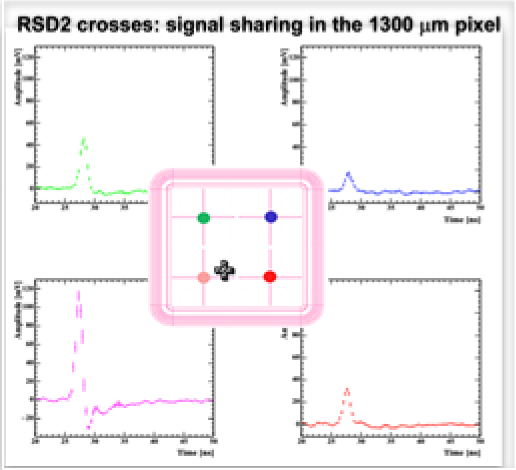
R. Arcidiacono – 4D-tracking

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 ($\sigma_{x\text{ -laser}}$~ 2 μm).

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

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)**
- $\boldsymbol{\sigma_{rec}}$: accuracy of the reconstruction method used, which might have a position-dependent systematic offset
- $\boldsymbol{\sigma_{setup}}$ **:** related to changes in the relative signal sharing due to the experimental set-up.
- $\boldsymbol{\sigma_{sensor}}$ **:** 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
- $\boldsymbol{\sigma_{delay}}$: 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)