4D tracking with thin Resistive Silicon Detectors (RSD2): recent performance studies and future potentials

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State of the art of 4D-tracking with RSD (FBK)

What is an RSD? Resistive read-out AC-LGAD Silicon Detector

⇛ 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

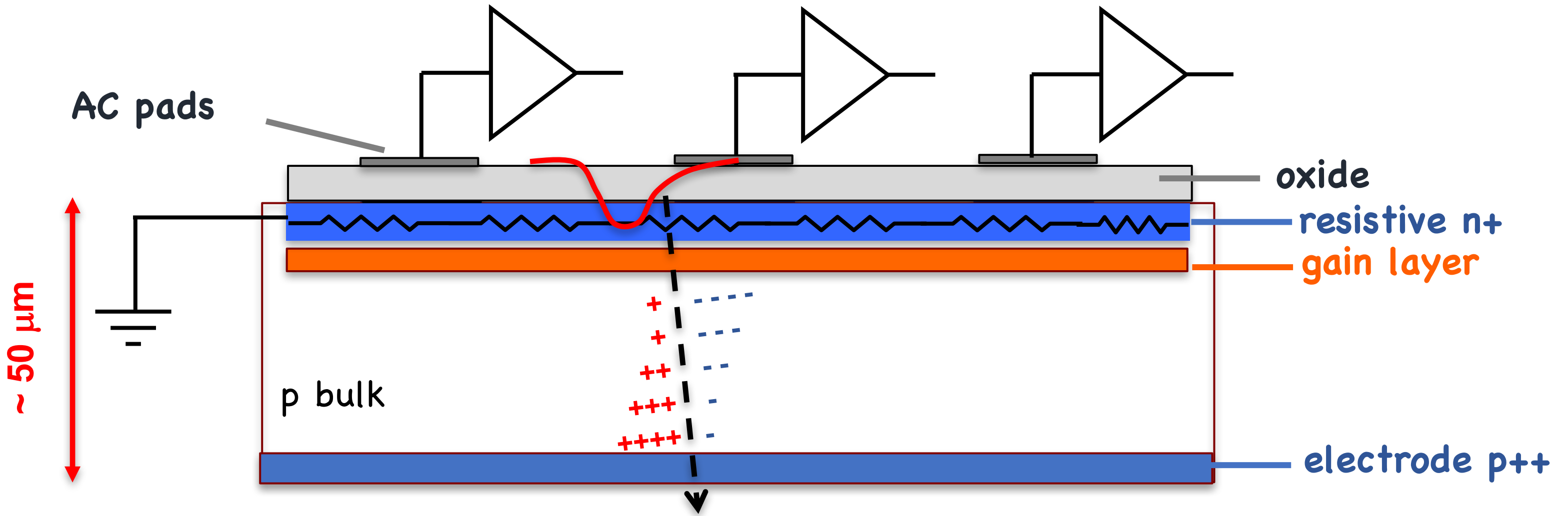
⇛ 100% Fill Factor (continuous gain), reduced material budget and enhanced timing performance by design

⇛ spatial resolutions better than $\sigma_x = k \frac{\text{pitch}}{\sqrt{12}}$, k ~ 0.5 - 1

Reminder: resistive AC-LGAD devices

Intrinsic signal sharing is realized thanks to a resistive read-out, AC-coupled

- **Charge is induced on the n+ layer ==> very fast process (1 ns)**



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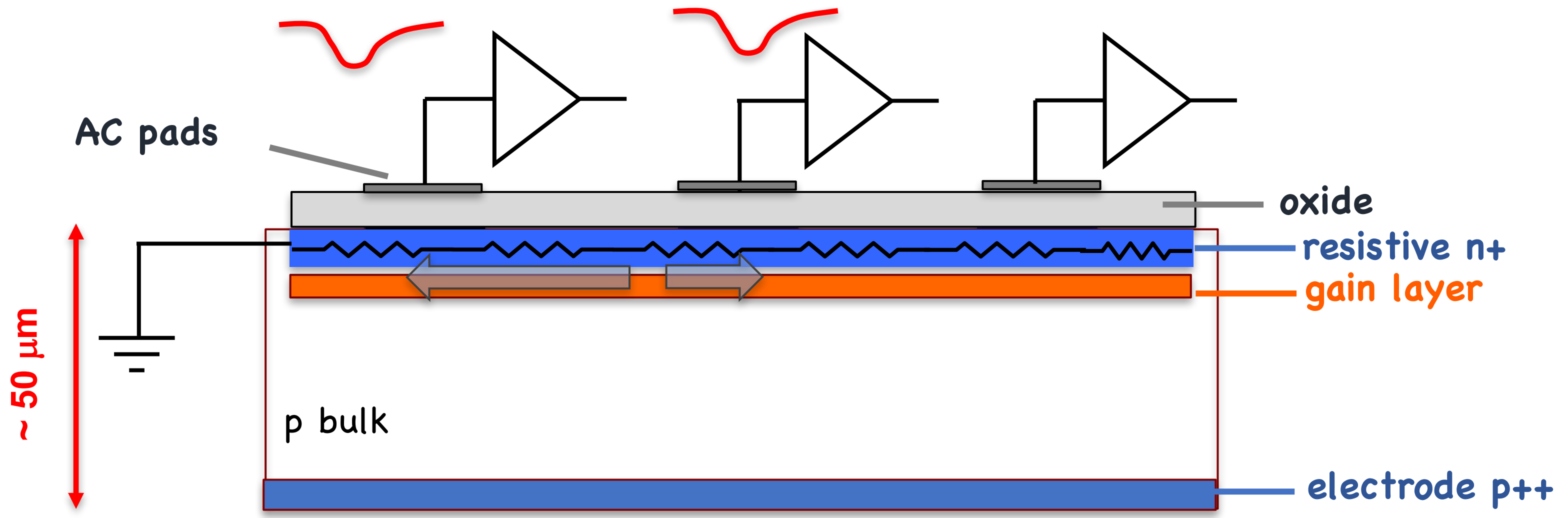

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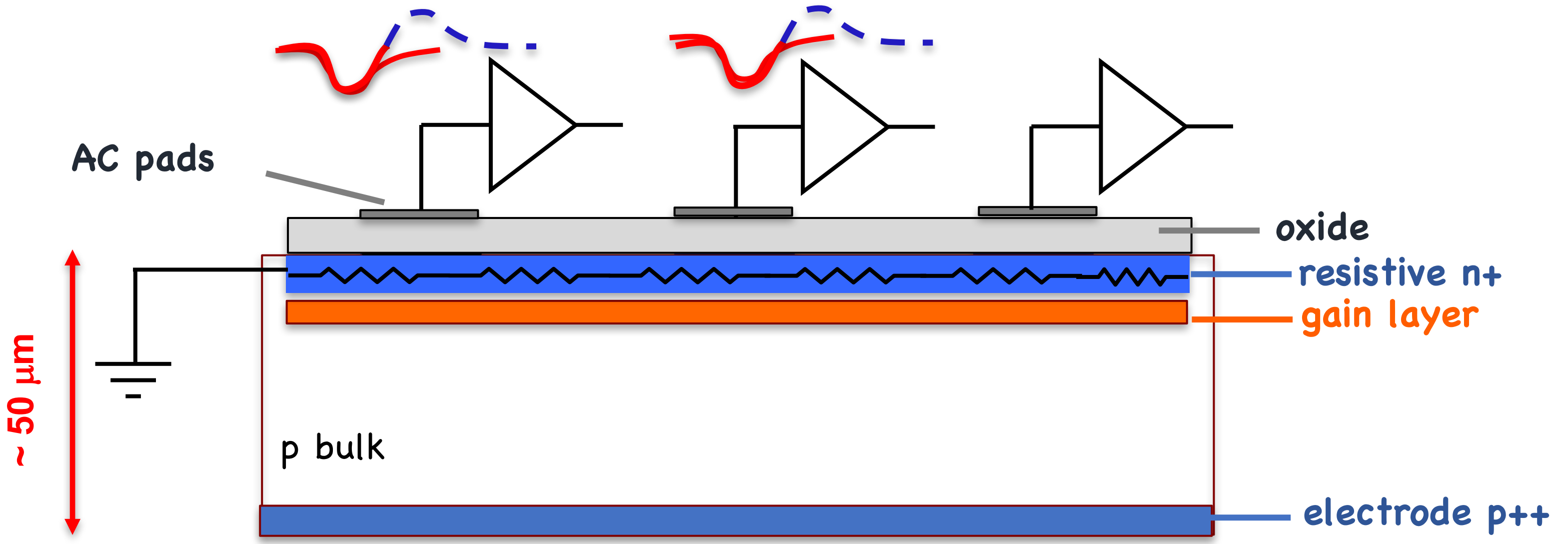
- **The charge flows to ground (slow component)**



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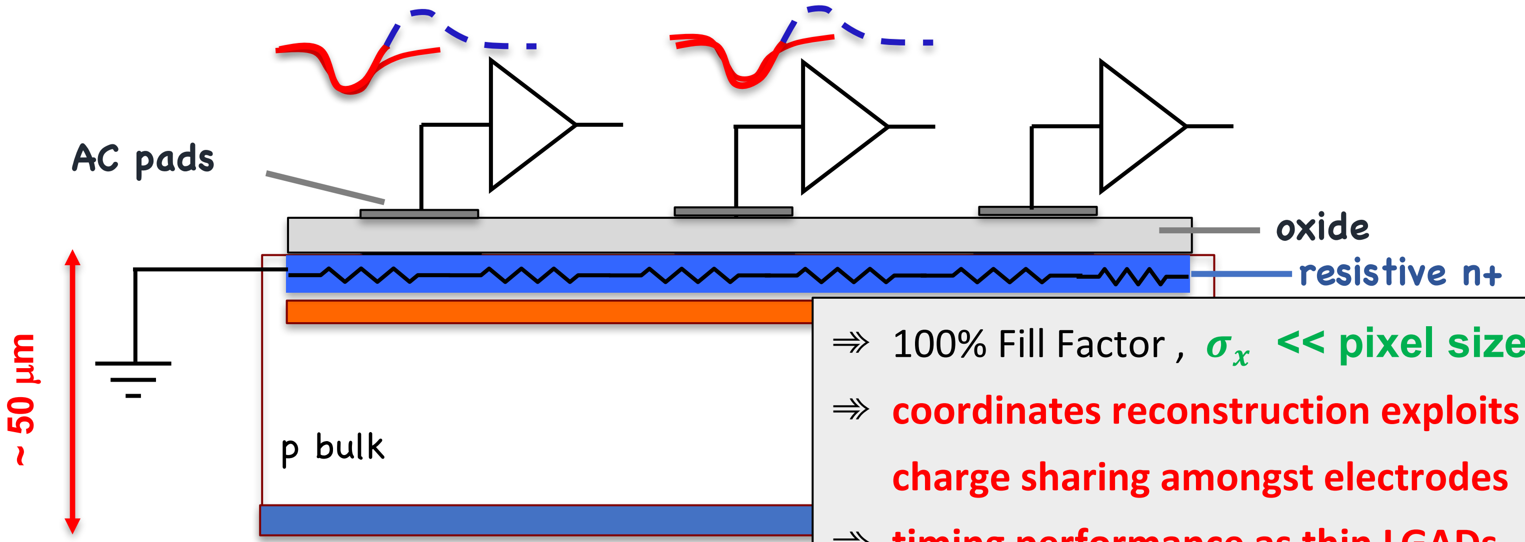

⇛ 100% Fill Factor , σ_x **<< pixel size**

⇛ **coordinates reconstruction exploits the charge sharing amongst electrodes**

⇛ **timing performance as thin LGADs**

RSD productions at FBK

- **RSD1 production (2019) demonstrated the soundness of the idea. Several lessons learned:**
  - *reconstruction is biased when the sharing involves too many pads*
  - *variable number of pads compromises the uniformity of the response*
  - *metal of read-out pads should be minimized*
  - *leakage current collected by the DC contact at the periphery of the device may create baseline fluctuation in large devices*

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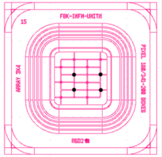
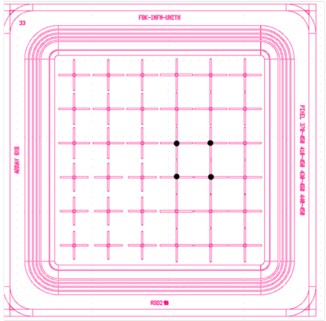
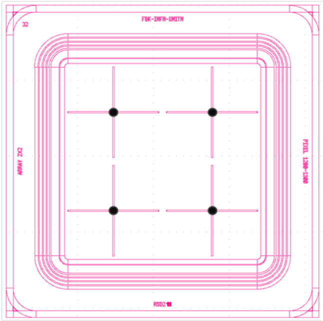
  - *metal of read-out pads should be minimized*
  - *leakage current collected by the DC contact at the periphery of the device may create baseline fluctuation in large devices*
- **RSD2 production (2021) optimized the design (parameters that drive the sharing) and improved performance: various non-conventional electrodes shapes implemented**



200 x 340 μm^2



Pitch = 450 μm



Pitch = 1300 μm

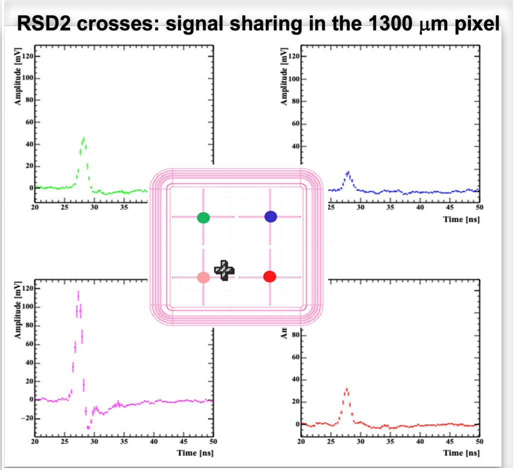
Our best so far (and most recent) results **have been obtained** with the **crosses.**

RSD2 with crosses: Lab and testbeam 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 ($\sigma_{x\text{ -laser}} \sim 2\ \mu m$).

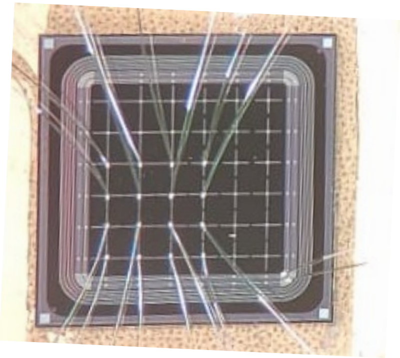
16 electrodes read out (FNAL read-out board + digitizer)

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



A few devices have been tested at DESY (3-6 GeV electrons), on testbeam lines equipped with a EUDET pixel telescope (2-15 micron of spatial resolution) -> analysis ongoing. **Today some preliminary results**

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

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- 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 electronics
  ~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.

Reconstruction method for the position (1)

SPACE RESOLUTION

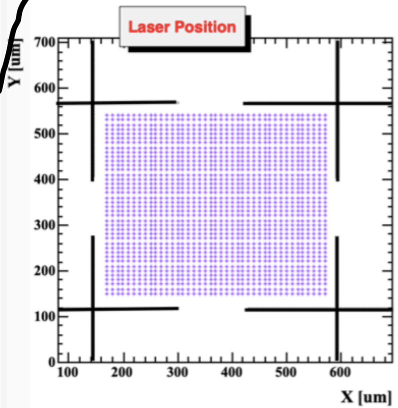
x-y coordinates reconstructed using only **4 neighboring electrodes with the larger signals.**

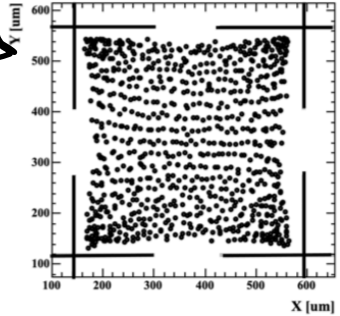
Method: "charge asymmetry"

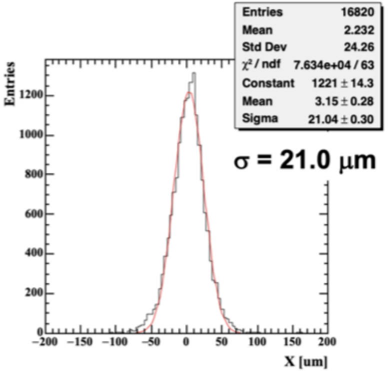
$$x_i = x_{center} + k_x \frac{pitch}{2} * \frac{Q_3 + Q_4 - (Q_1+Q_2)}{Q_{tot}}$$

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

$$\sigma_x \sim \frac{pitch}{\sqrt{12}} \sim 130\ micron$$







σ = 21.0 µm

reconstructed positions for the 450 × 450 μm^2

Reconstruction method for the position (2)

SPACE RESOLUTION

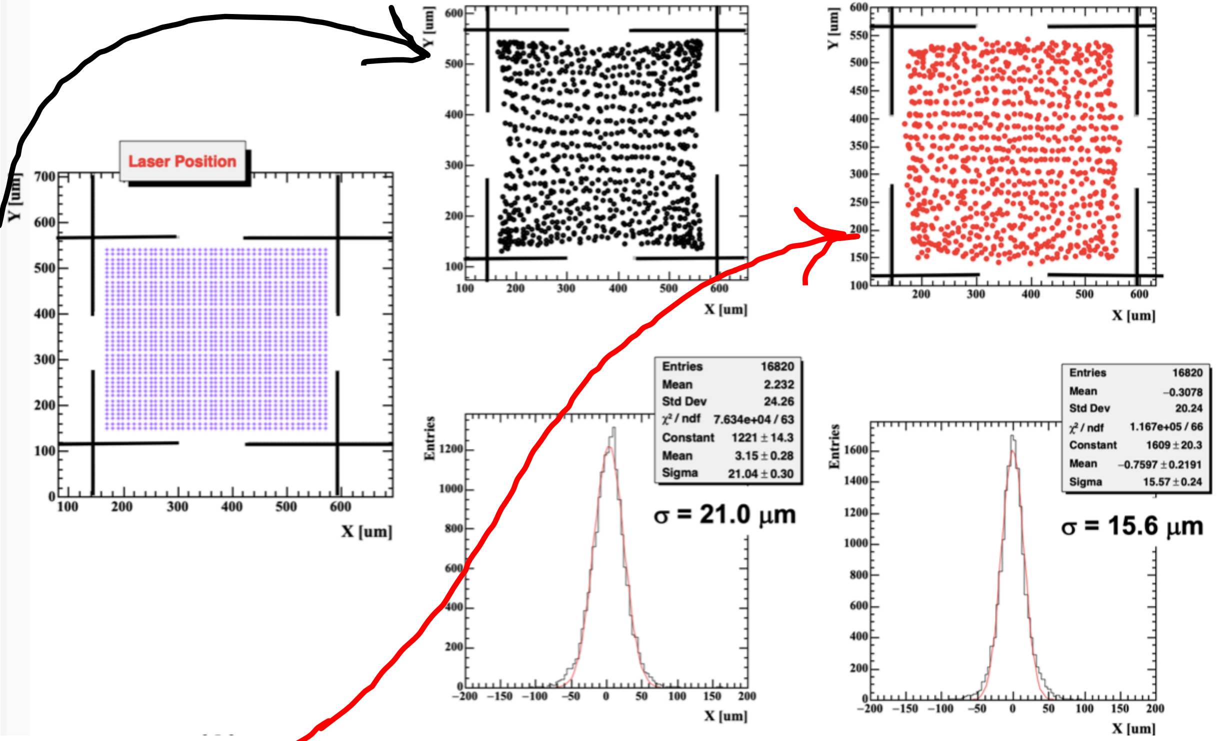
x-y coordinates reconstructed using only **4 neighboring electrodes with the larger signals.**

Method: “charge asymmetry”

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

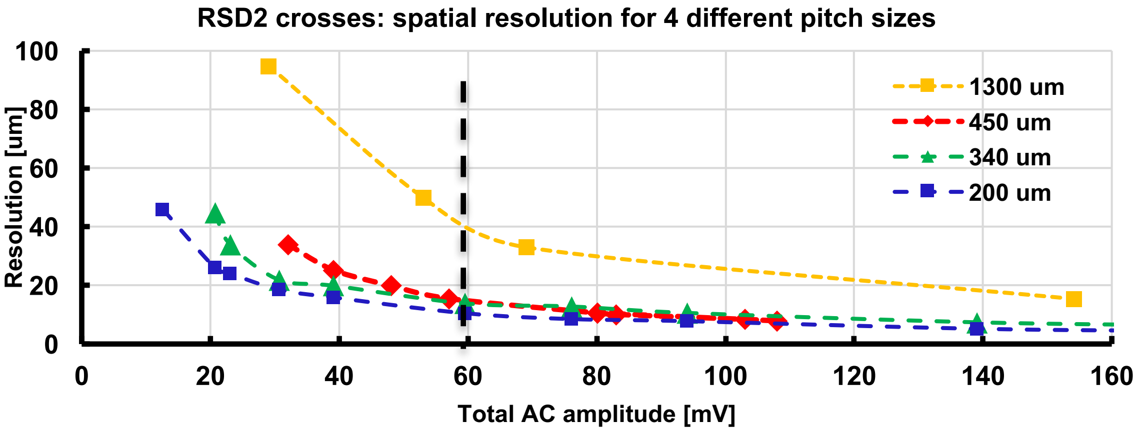
$$y_i = y_{center} + k_y \frac{pitch}{2} * \frac{Q_1 + Q_3 - (Q_2+Q_4)}{Q_{tot}}$$

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

Spatial resolution from the TCT measurements



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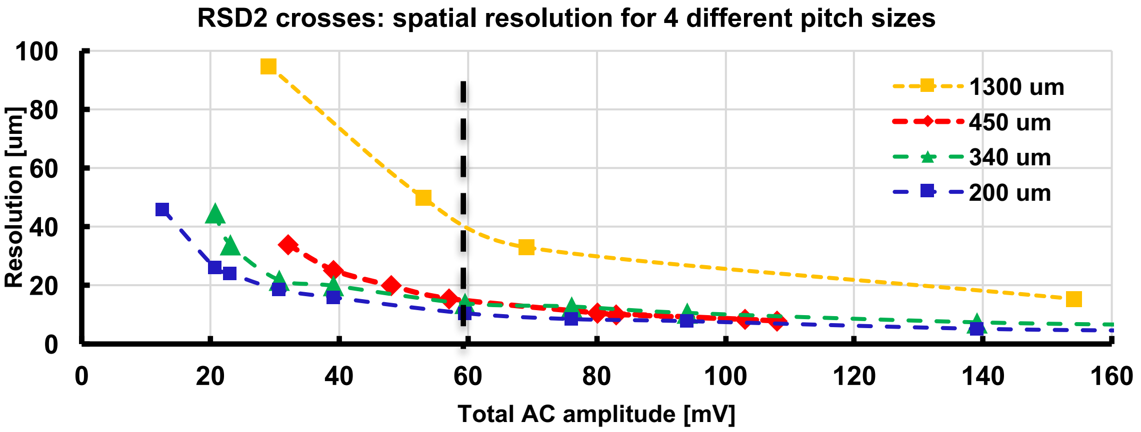
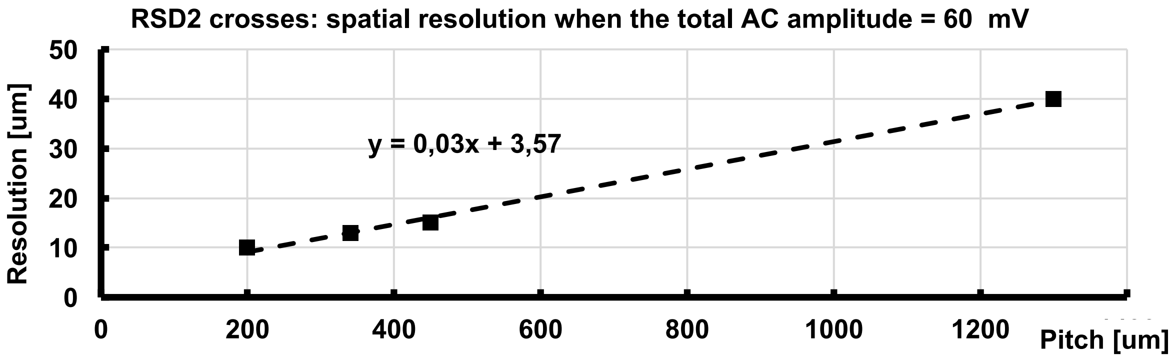
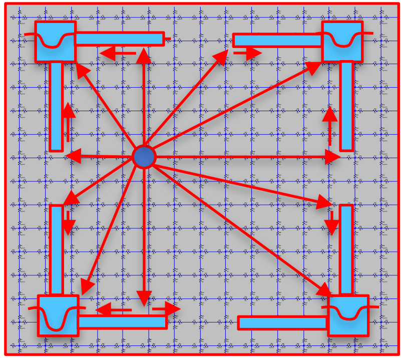
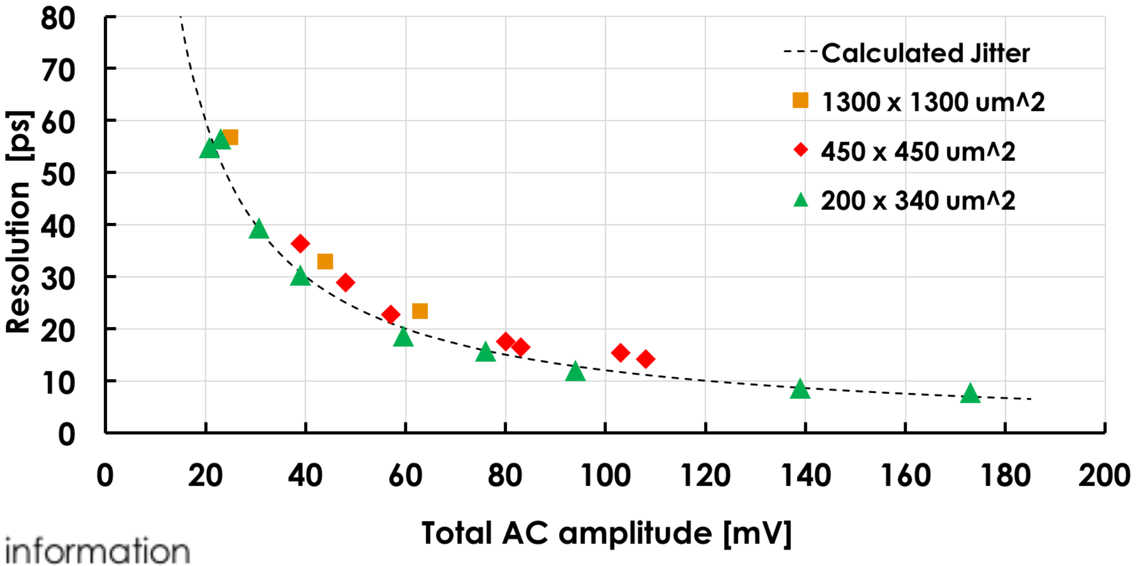




Spatial resolution versus pitch size when the total AC amplitude equals 60 mV.
At a fixed amplitude, the resolution depends linearly on the pixel size (terms σ_setup, σ_sensor are zero)

Time resolution from the TCT measurements





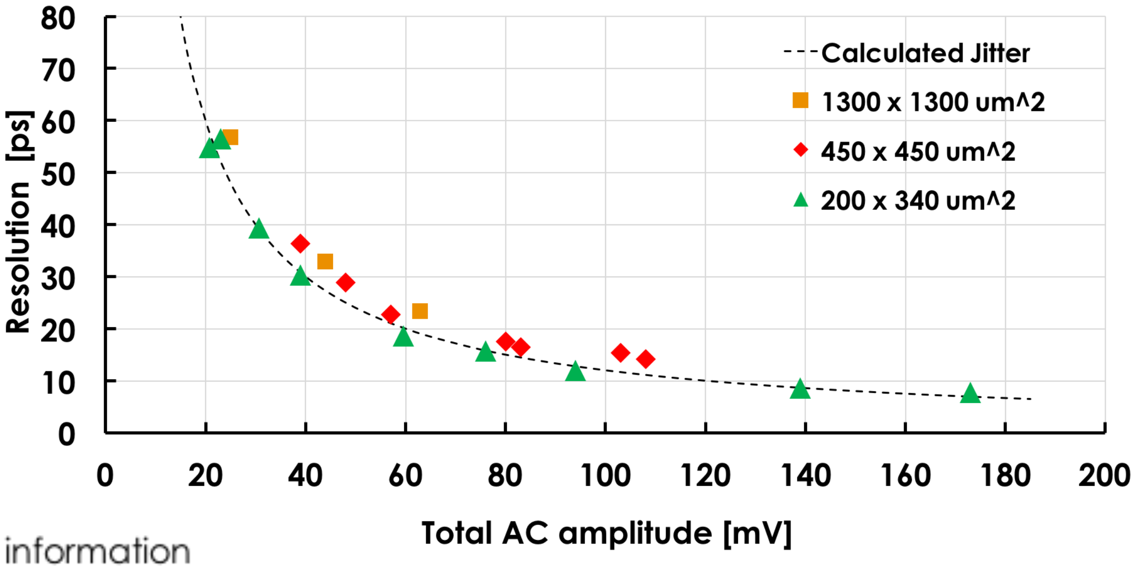
The time is obtained combining the information from the 4 read-out pads, minimizing the chi 2

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

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

Time resolution from the TCT measurements

Landau fluctuations not present in this measurement



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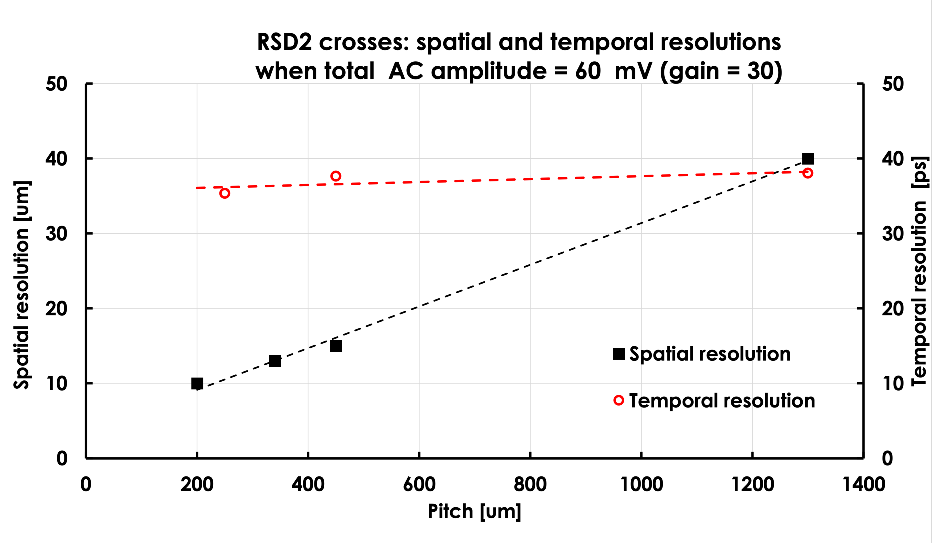
The resolution (jitter + delay term) depends mostly upon the signal size and **weakly on the pixel size**

σ_{delay} **is very small**

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

RSD2 extrapolated performance

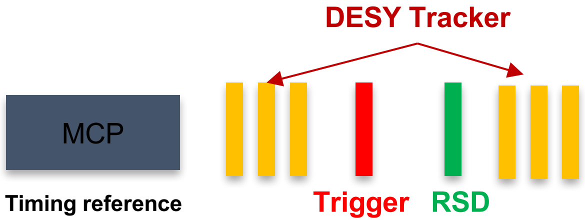
- Extrapolated resolutions for the determination of the position and time coordinates
- **time resolution**: computed by adding the Landau noise term ($\sigma_{\text{Landa noise}}$ = 30 ps)
- **spatial resolution**: computed adding $\sigma_{\text{setup}} + \sigma_{\text{sensor}}$ = 5 µm in quadrature



Spatial resolution is about 3% of the pixel size

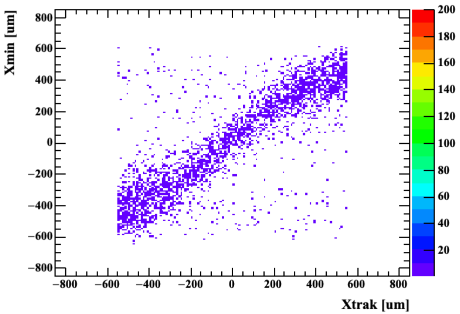
Time resolution is fairly constant at about 38 ps as a function of the pixel size

Test beam @ DESY, 1.3 x 1.3 mm^2 crosses



Read-out: 16 ch CAEN Digitizer

Correlation x_tracker and x_RSD



very preliminary

Hit position reconstructed using the method explained (with correction)

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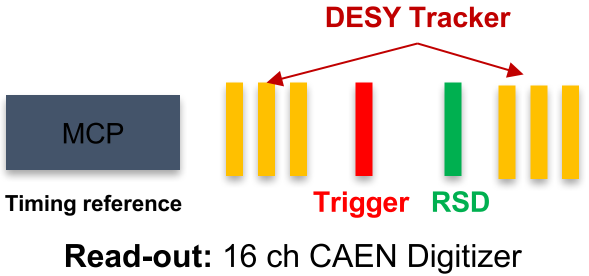

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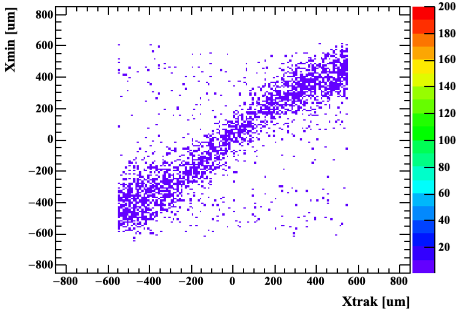

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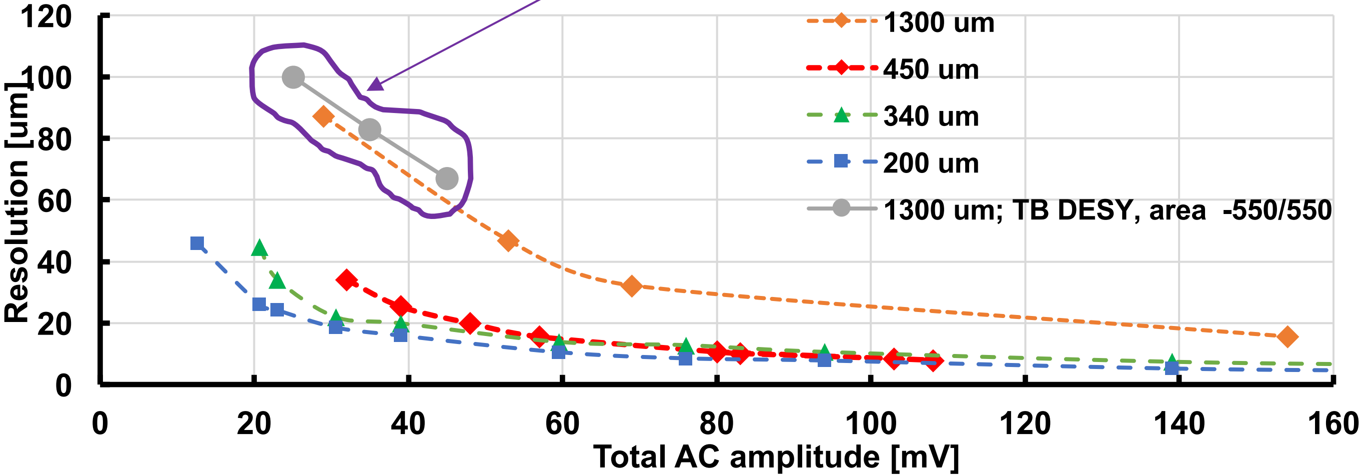


- max gain obtained with this device ~15
- using high part of Landau distribution
- **work just started…**

Next step: DC-coupled resistive LGAD

DC-RSDs

- studies started within the Italian project PRIN 2017 (2017L2XKTJ – 4DinSiDe)
- now supported by INFN CSN5 project 4DSHARE
- **see Tommaso Croci's talk "**A two-prong approach to the simulation of DC-RSD: TCAD and Spice"

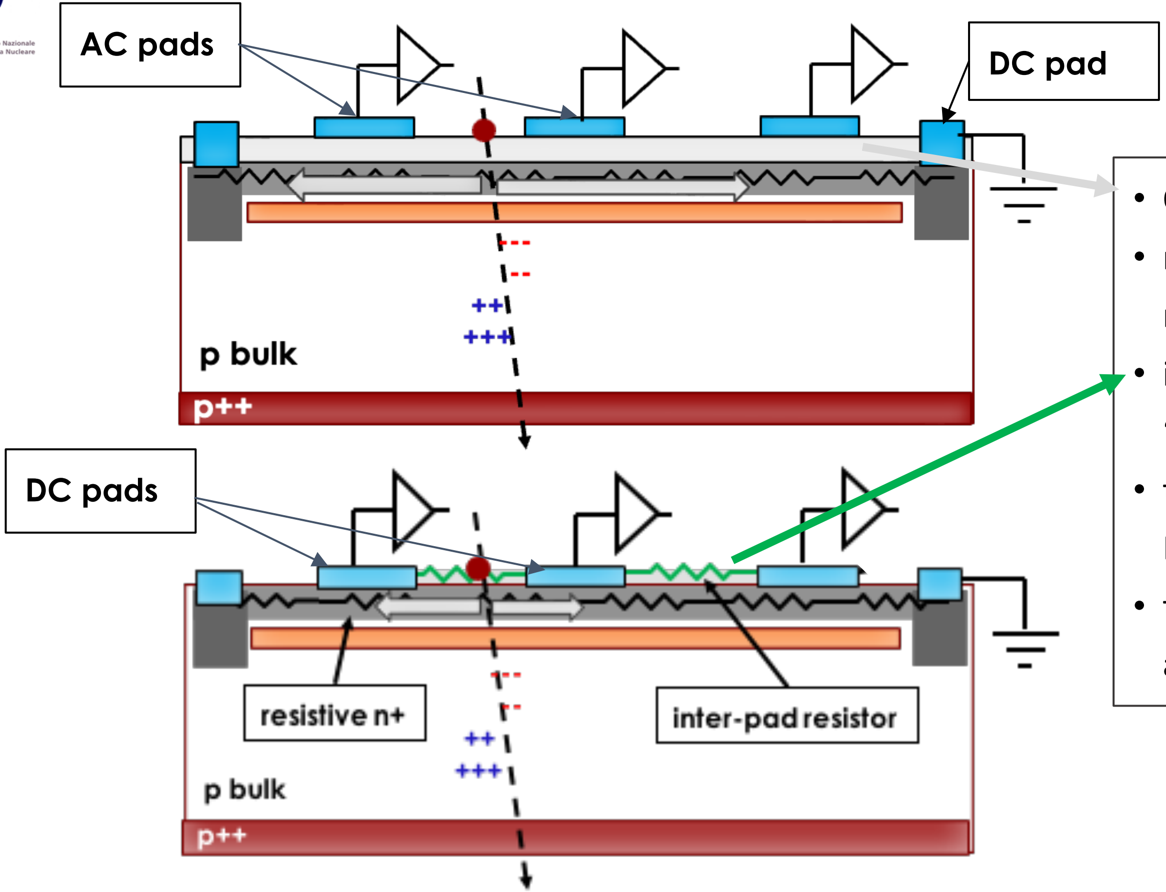
main objectives for the DC-coupled resistive read-out LGADs

➢ **overcome the limitations or drawbacks** observed studying the resistive AC-LGADS

key points:

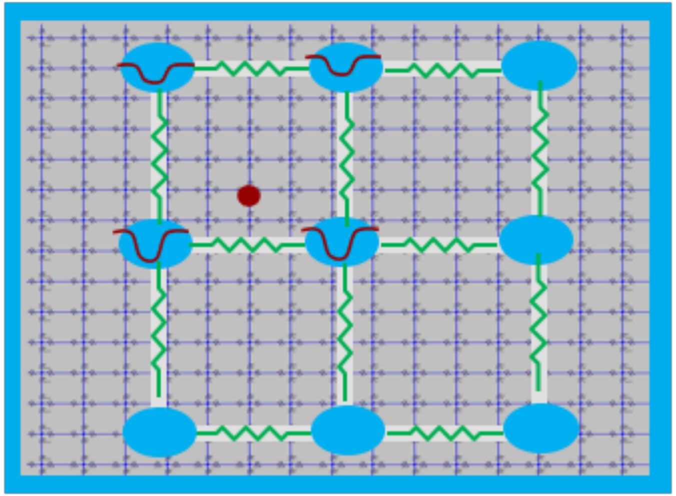
- **obtain intrinsic controlled signal sharing**, in a predetermined (not too large) number of pads
- **avoid** the collection of the **leakage current only at the periphery** of the sensor

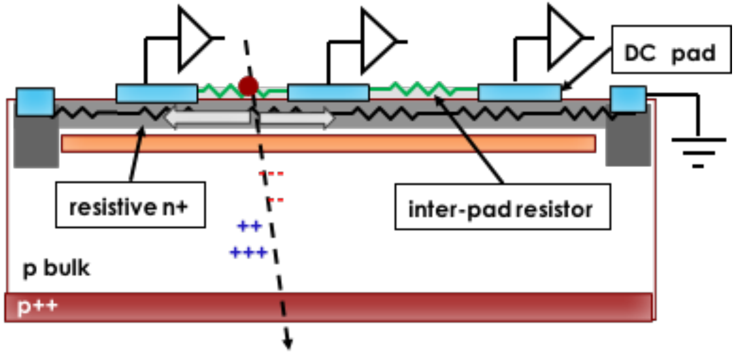
From AC to DC-coupled LGAD: what's new



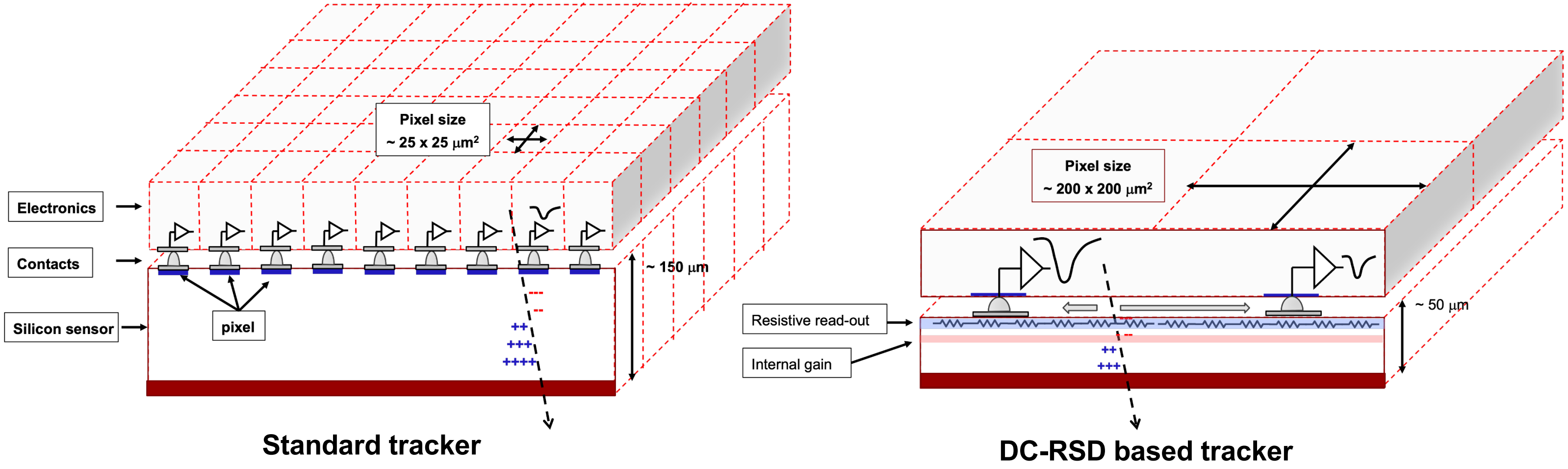
- Oxide layer for AC-coupling removed
- read-out electrodes implanted on the resistive layer
- inter-pad resistors added to create a "cage" where the signal is confined
- the signals are read out via the closest DC electrodes
- the leakage currents is removed locally at each electrodes

DC-RSD from above





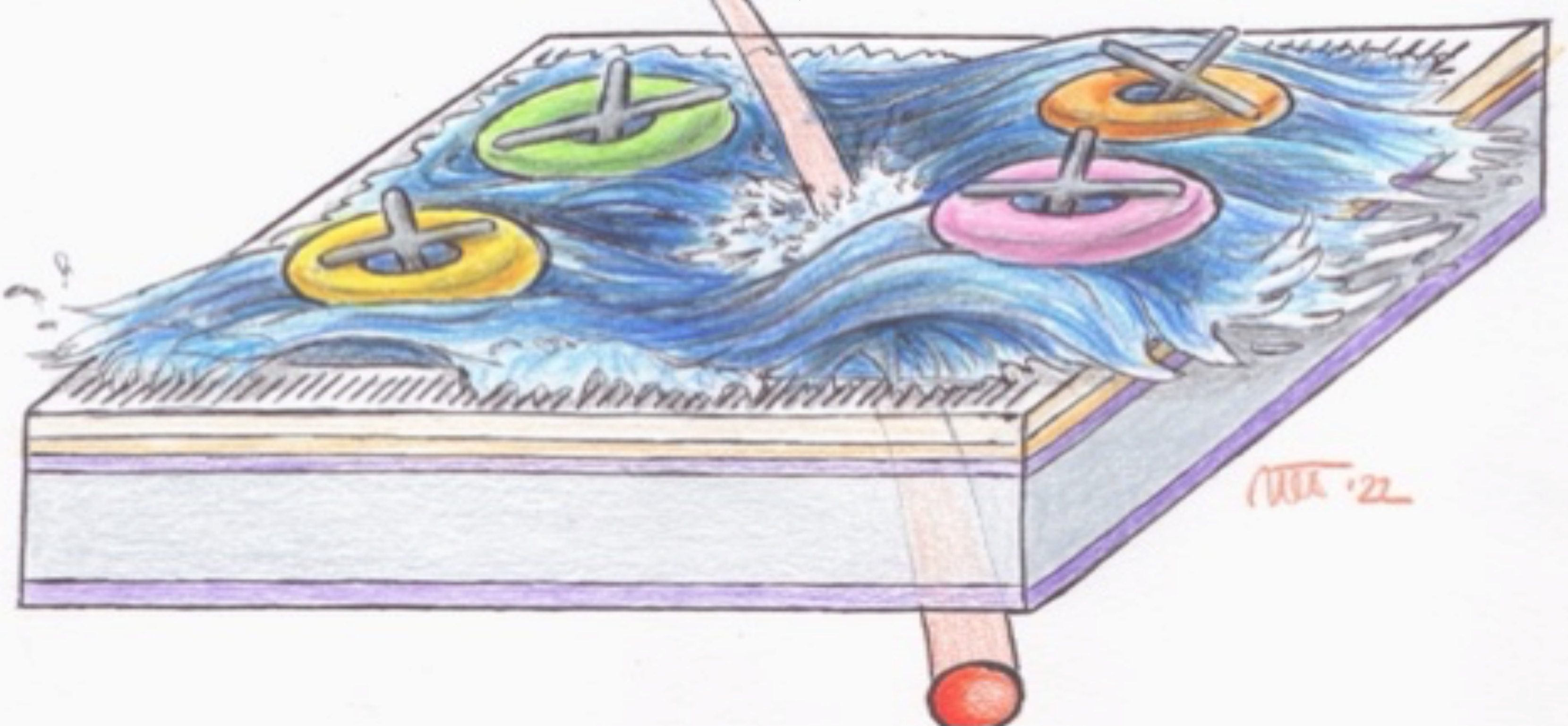
A look at the next generation 4D-trackers?



The design of a tracker based on RSD:

- Delivers ~ 30 ps time resolution
- Can easily deliver position resolution of a few microns, but with much larger pixels (number of pixel is reduced by 50-100)
- The electronic circuitry can be easily accomodated (power consumption ~ 0.1-0.2 W/cm²)
- The sensors can be really thin

Thanks for your attention



Acknowledgments

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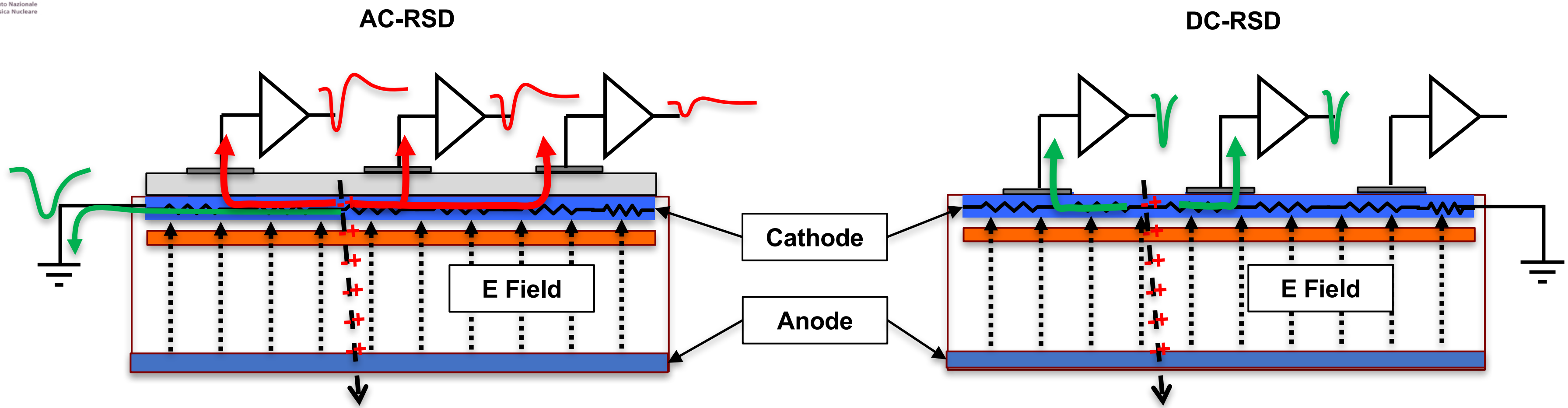
- INFN - Gruppo V RSD
- H2020 project AIDA-2020, GA no. 654168
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)
- Ministero della Ricerca, Italia , PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- RD50 Collaboration, CERN
- INFN - Gruppo V 4DSHARE
- Compagnia San Paolo,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

BACK-UP

From RSD to DC-RSD



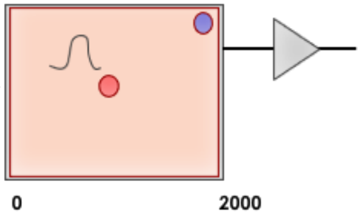
DC-RSD wants to improve the RSD design:

- Move to DC-coupled read-out
  - DC signal
  - Remove the leakage current at each node and not at the periphery
- Limit the signal sharing to the closest neighboring pads
- Improve reconstruction accuracy

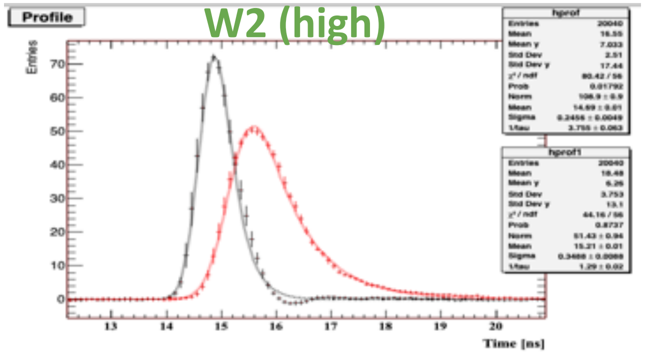
Study of the propagation on the resistive layer

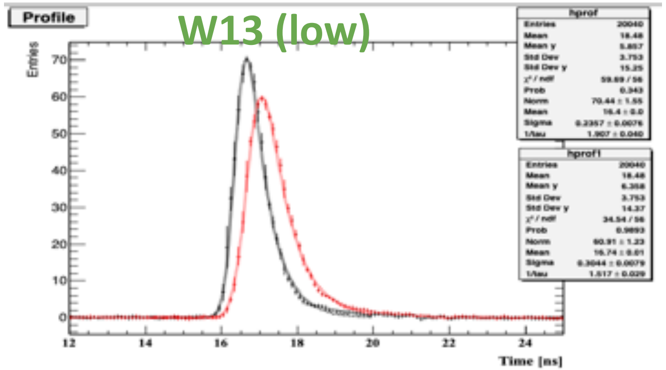
In RSD1 there is a device without electrodes, ideal for this study:

an area 2x2 mm^2 read out only at the DC contact only



Study of the signal (laser induced) propagation/deformation as a function of position on the surface, for wafers with different resistivities





Read= shot in the center

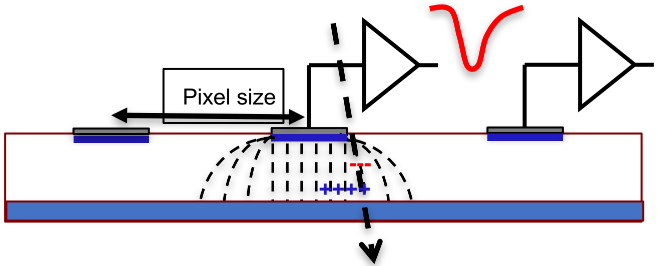
Blue = shot on one side

Even a propagation over a large pixel (O(mm)), and on the most resistive n+ surface, does not degrade the signal significantly → key point to pursue the DC-RSD idea --> this device represent well one DC-RSD pixel

Position measurement: Single and Multi Pixels Read-out

Single pixel

where the signal is induced on one pixel



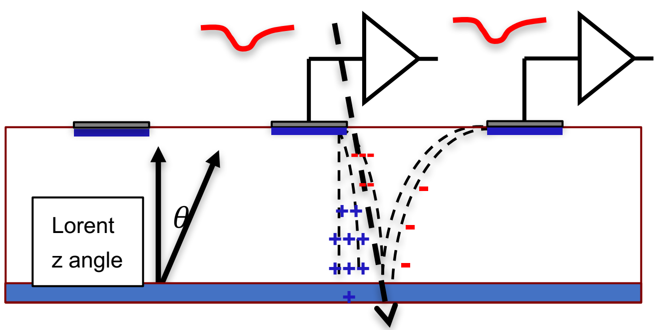
$$\sigma_x = k \frac{pitch}{\sqrt{12}}, k \sim 0.5 - 1$$

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

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

Multi pixels

where the signal is induced on a few pixels

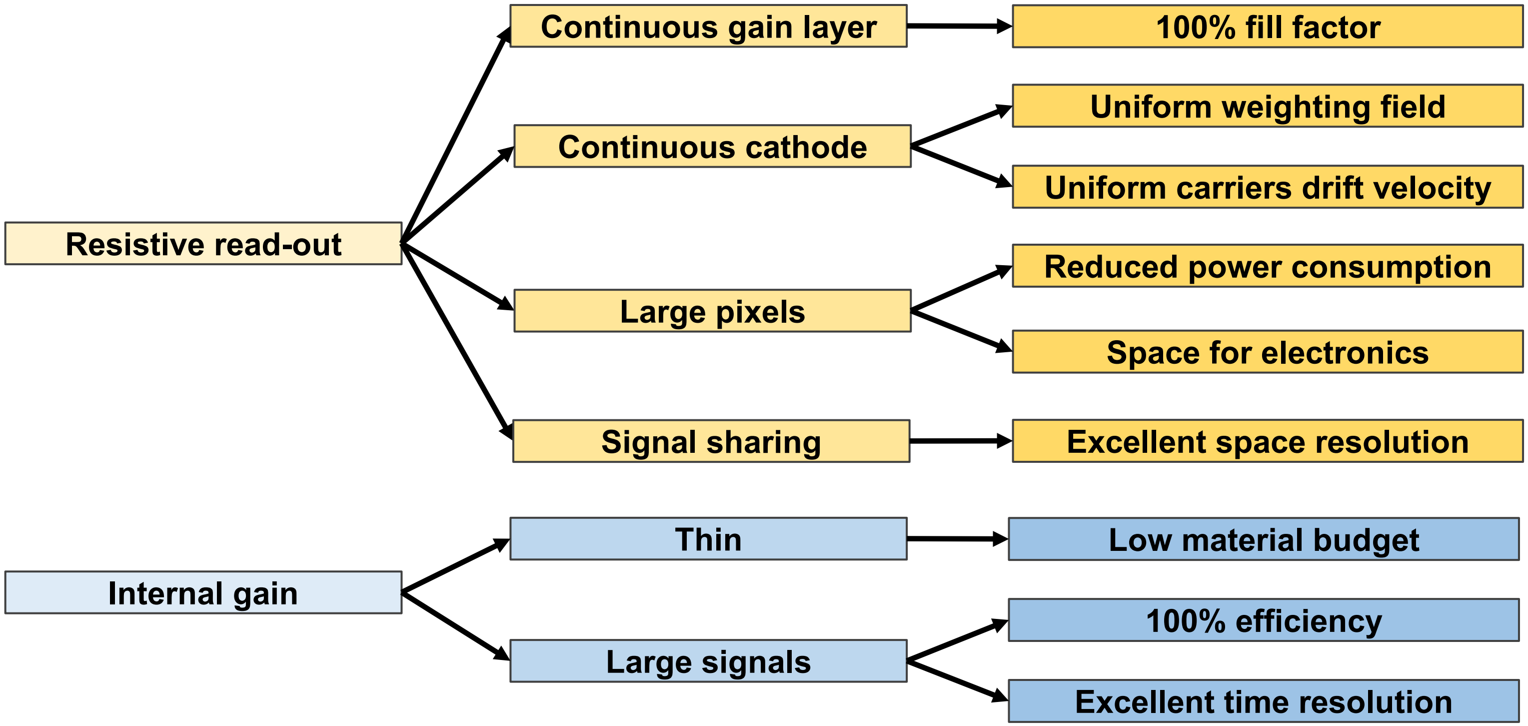


$$x = \frac{\sum_i x_i Ai}{\sum_i A_i}$$

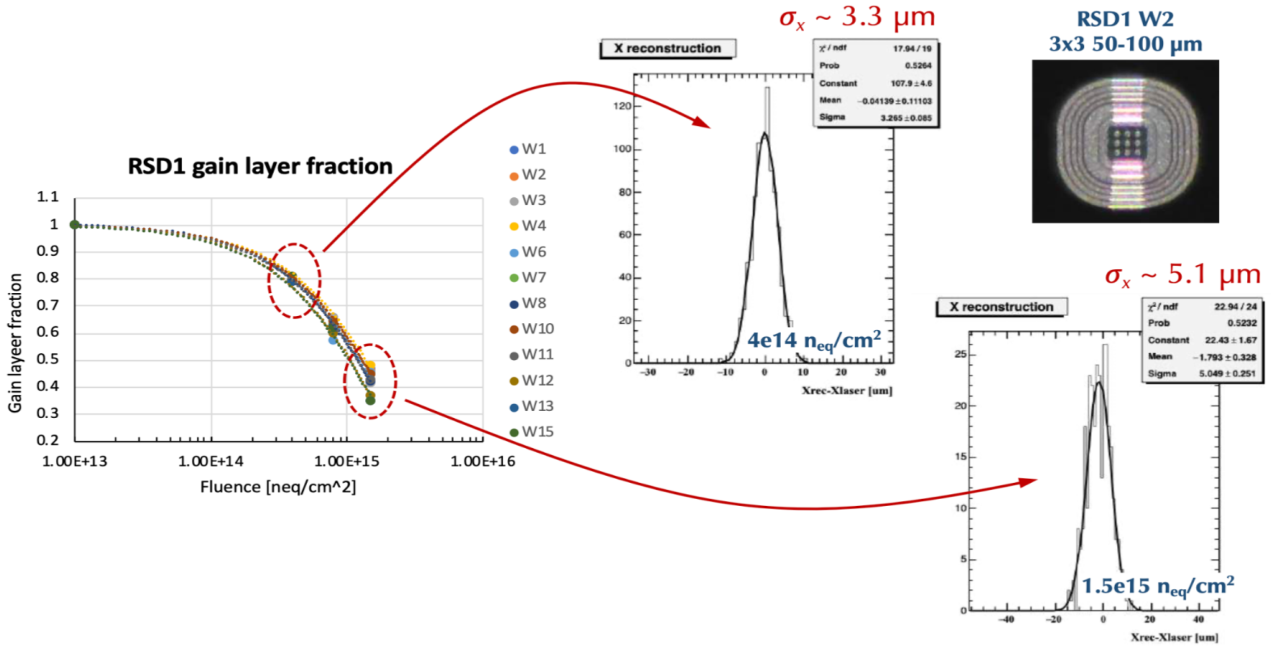
- $\boldsymbol{\sigma_x}$ **<< pixel size**
- **Same** σ_x **can be obtained with larger pixels**

Properties of optimized RSDs

Innovation | **Sensor property** | **Experimental feature**

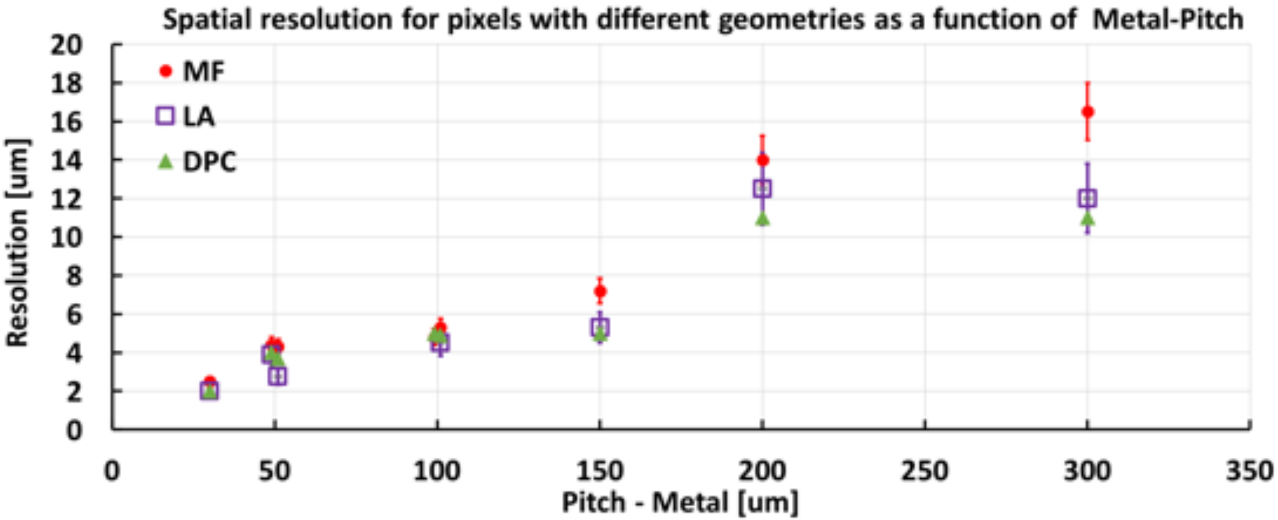


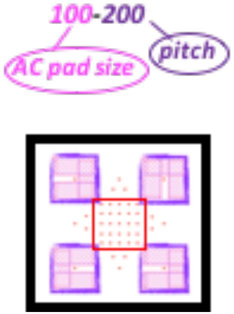
RSD1 radiation resistance



- The radiation resistance of RSD1 is similar to that of standard LGAD
- The space and time resolutions decrease due to the signal being smaller
- No “RSD specific” effects have been found, **resistive read-out is not sensitive to radiation damage up to 1E15 n/cm² → Study to be extended to check the limits**

RSD1- position resolution





- In RSD1 Position resolution (within the red square) is about 5% of the distance between electrodes