Sensori RSD: stato delle produzioni e risultati dai test

FCC WP-Silicon Workshop - Torino

23.4.2024

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Outline

- ➢ The RSD design
  - ○ Tuning the parameters
  - ○ Different paths to position reconstruction
- ➢ The FBK RSD2 production
  - ○ DESY Test Beam results
- ➢ Other AC-LGAD productions
- ➢ The DC-RSD

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  - Different paths to position reconstruction
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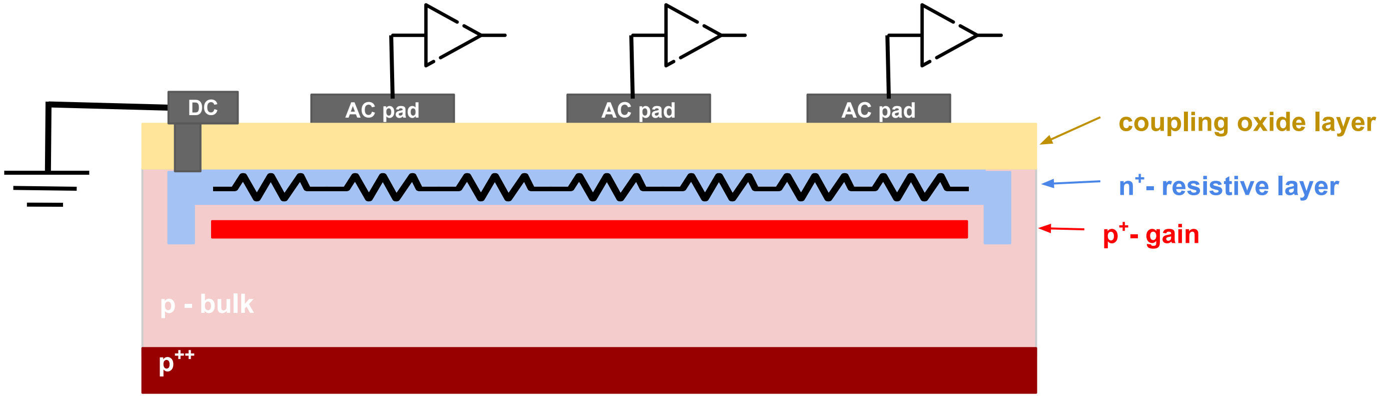
  - DESY Test Beam results
- Other AC-LGAD productions
- The DC-RSD

Resistive Silicon Detectors (RSDs, aka AC-LGAD)

- Silicon sensors based on the **LGAD technology**, implementing **AC-coupled resistive read-out:**
  - **Metal read-out pads** coupled to the sensor through an **oxide layer**
  - **Resistive n^+ layer**
  - **Continuous gain layer** spreading across the active area

~ 50 µm active thickness



cross section of an RSD

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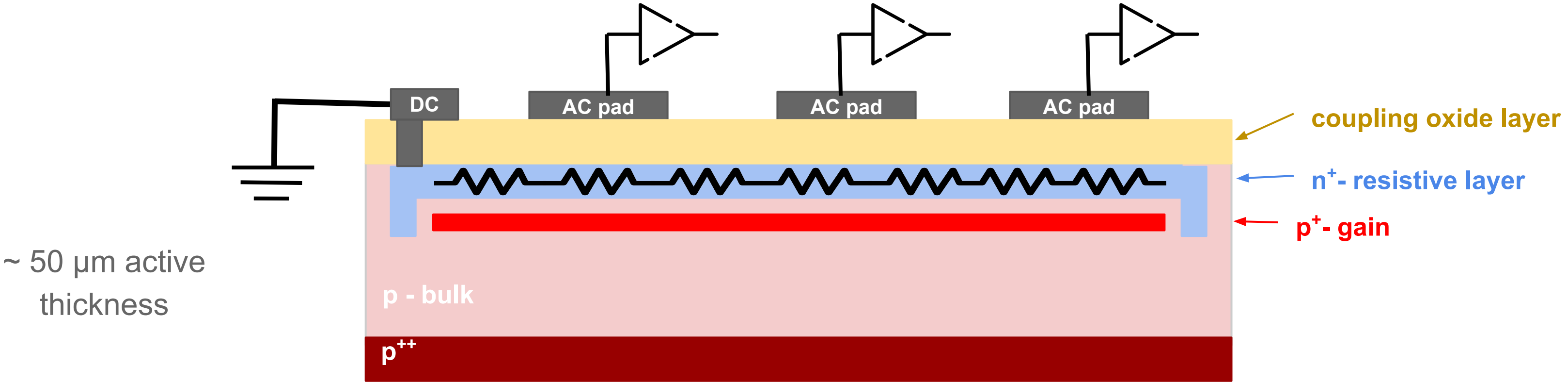
internal charge multiplication



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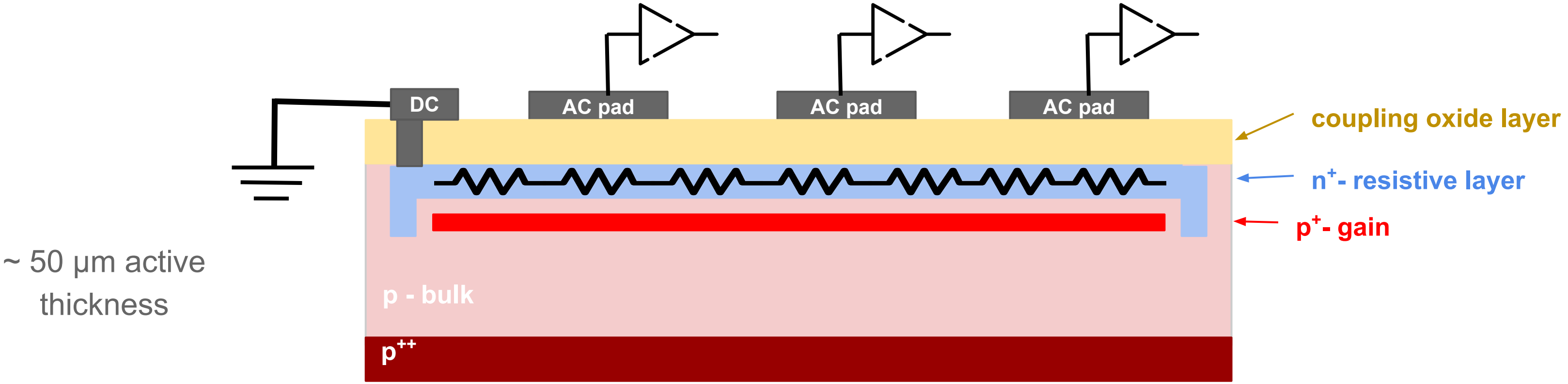
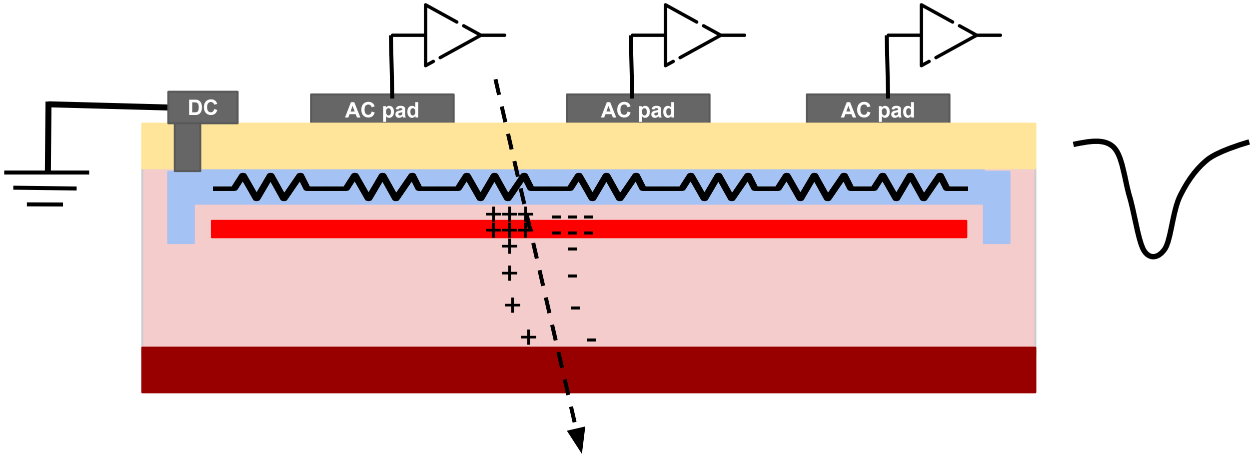


Large signals shared among several read-out channels → the key for enabling 4D-tracking

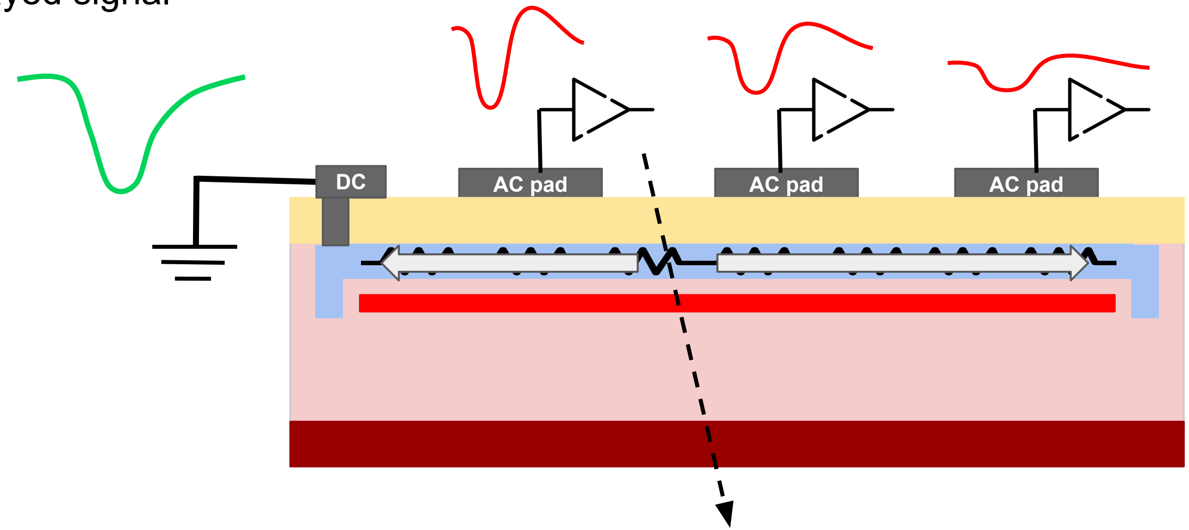
The RSD design principle

- An impinging particle creates *e-h* pairs → electrons multiplied in the gain region → direct charge induction on the resistive layer
  - Large (> 5 fC, gain 10-30) & fast (~1 ns) signal
  - No Lateral spread, vertical drift lines (just like an LGAD)



The RSD design principle

- The signal spreads through the resistive layer, which acts as a current divider
- AC-coupled metal pads connected to the electronics offer the lowest impedance path to the high-frequency part of the signal → pads further away from the hit position see a smaller, wider and more delayed signal



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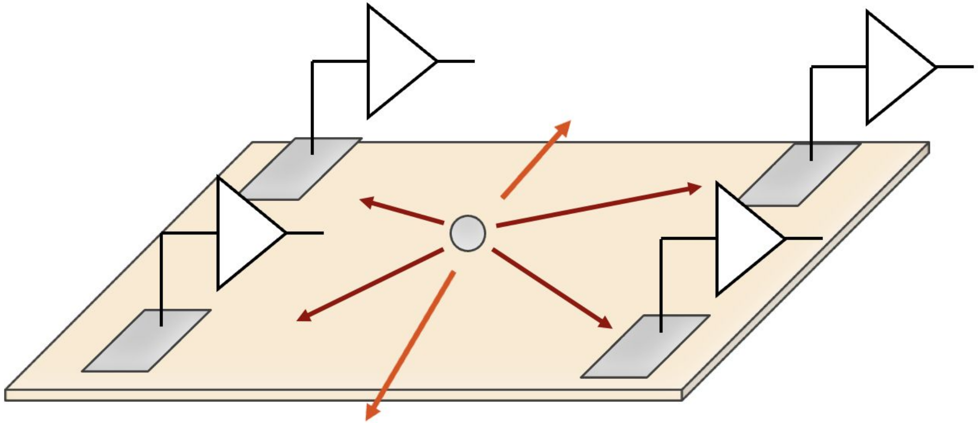
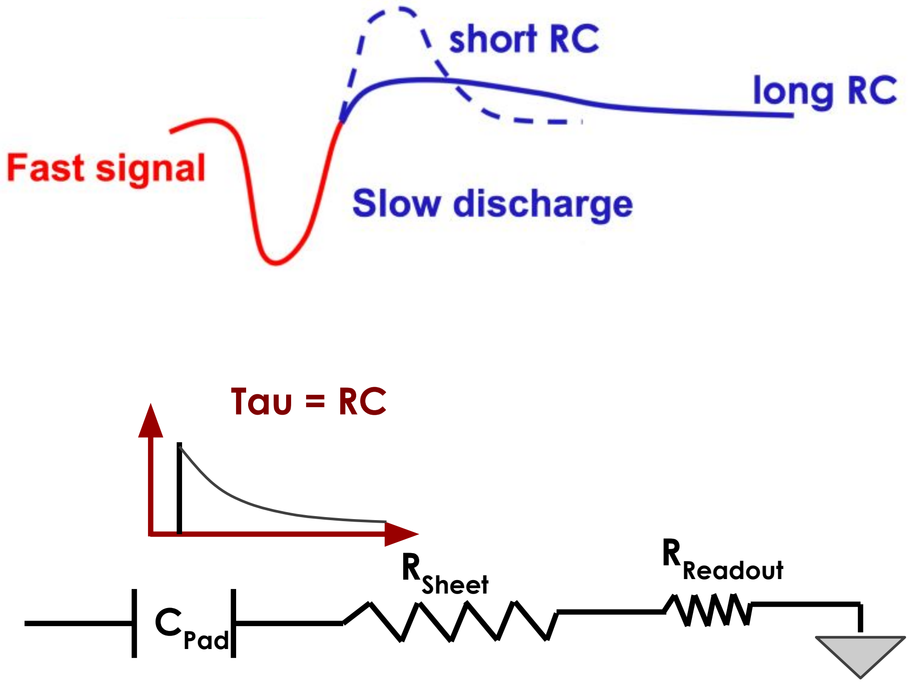
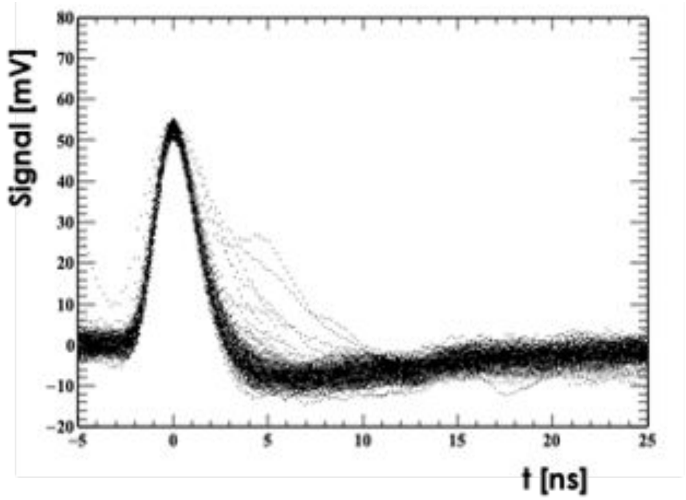
A fraction of the signal may escape
→ effect minimized by careful choice of design parameters and electrodes geometry (next slides)



The RSD design principle

- The signal discharges according to the read-out RC → small RC: large and short positive lobe



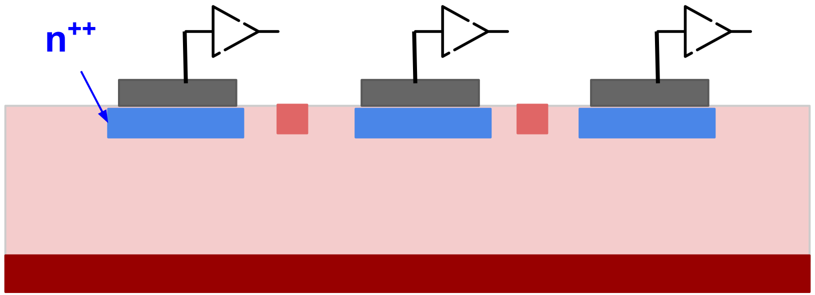


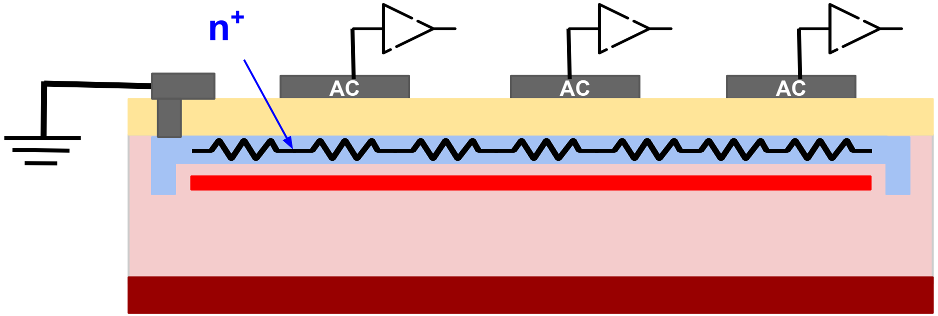
Typical RSD signal, as measured at a test beam (inverted polarity)

A change of paradigm

Standard read-out: many *pn* diodes interleaved with *p*-stops

Resistive read-out: single, uninterrupted diode





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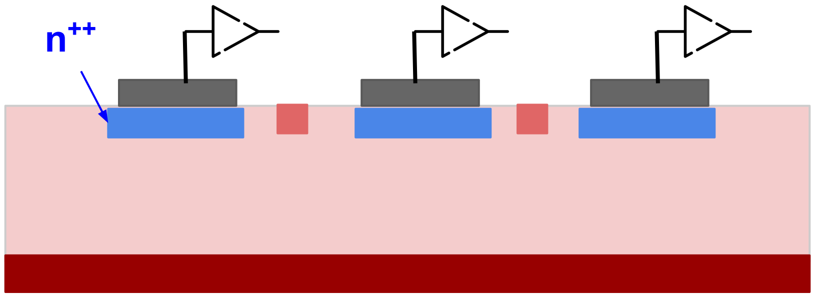
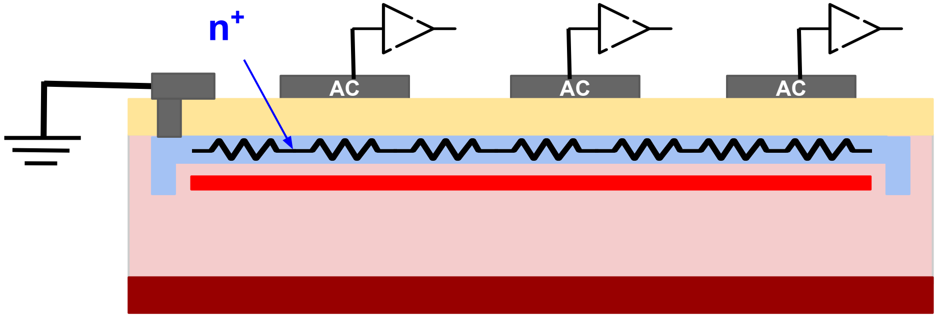
- Sharing not effective if read-out signals are small → **internal gain** (LGAD) to achieve large signals





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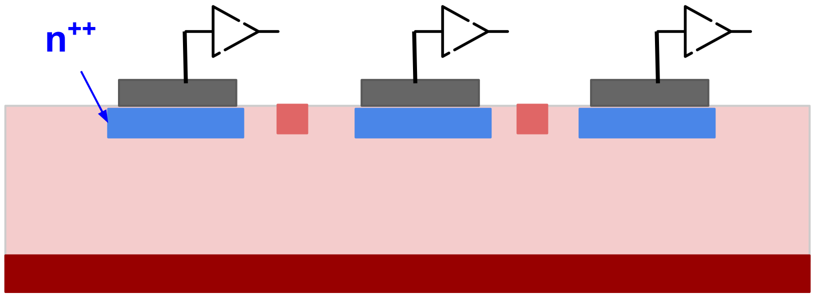
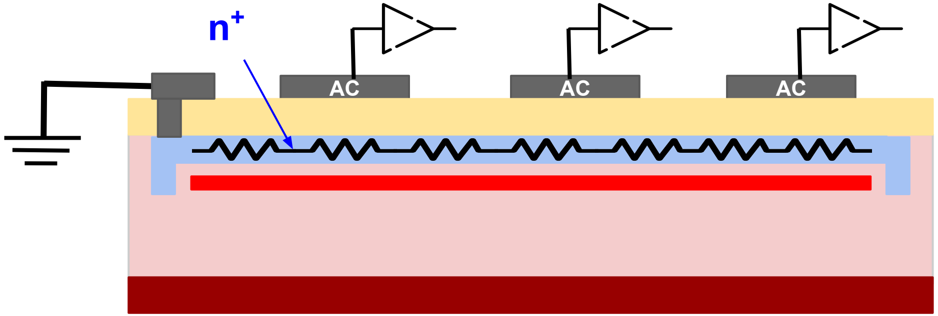
→ that's the **RSD "recipe"** to achieve accurate reconstruction of the hit position

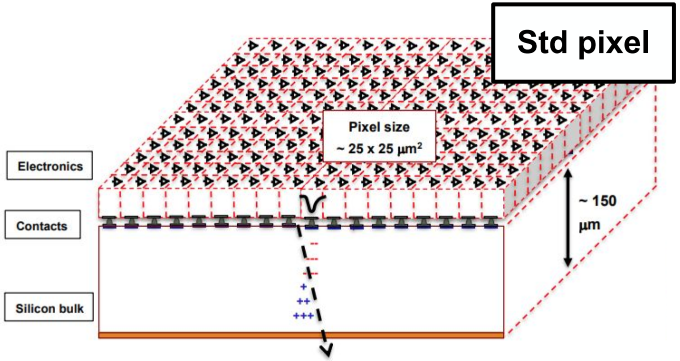


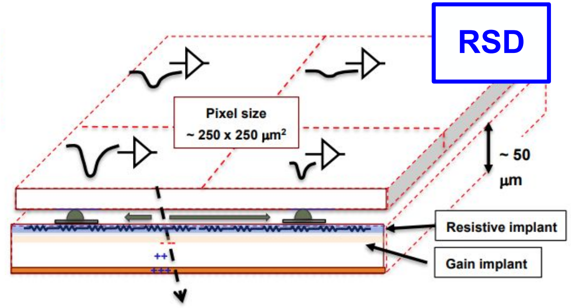


A change of paradigm

- **Binary read-out: σ_{Pixel} ~ 0.3·pitch***
- **RSD: σ_{RSD} ~ 0.03·pitch**

RSDs need fewer read-out channels to achieve same $\sigma_{Spatial}$





*may reach σ_{Pixel} ~ 0.15·pitch with B field and tilted sensor

A change of paradigm

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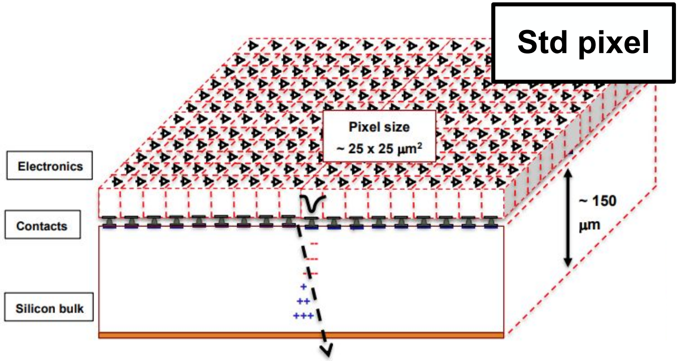

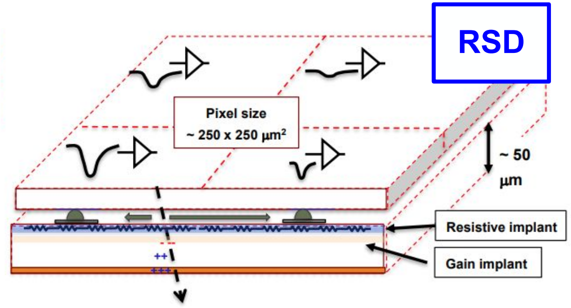

➢ **100% fill factor** by design

➢ RSDs are LGAD sensors → **30-40 ps time resolution** (link)

A change of paradigm

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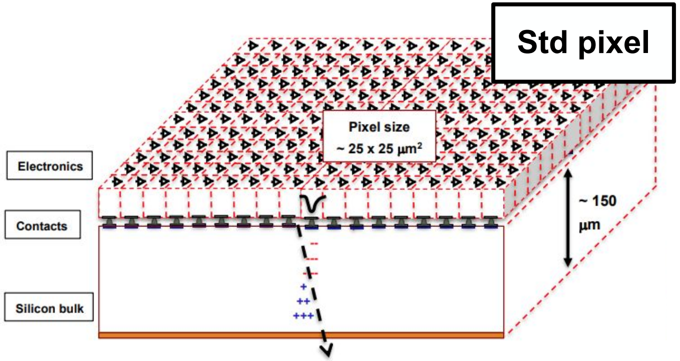

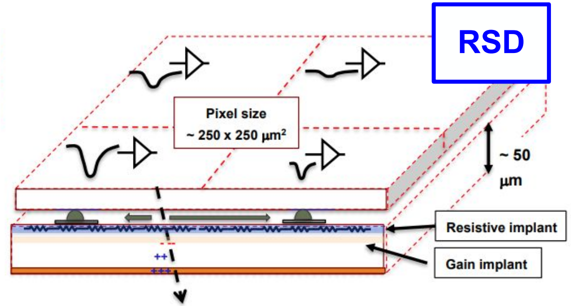

- ➢ **100% fill factor** by design
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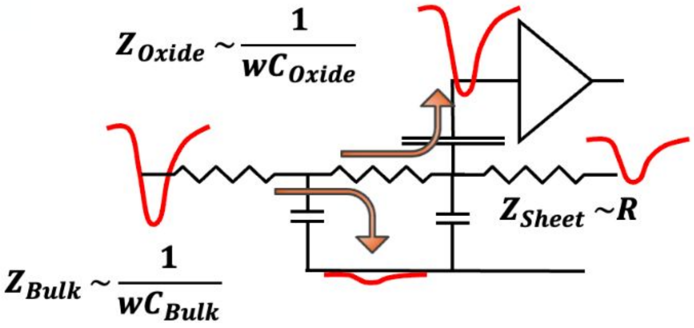
RSDs are suited as 4D-trackers for future experiments

Tuning the parameters

- Sharing controlled by Z_{Oxide}, Z_{Sheet} , Z_{Bulk}
  - Usually Z_{Oxide}, Z_{Sheet} << Z_{Bulk}
- Signals choose the lowest-impedance path



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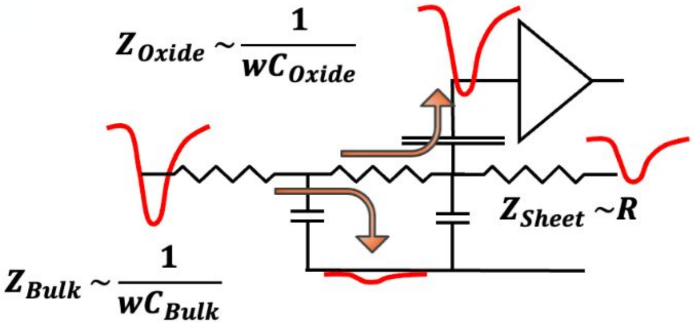
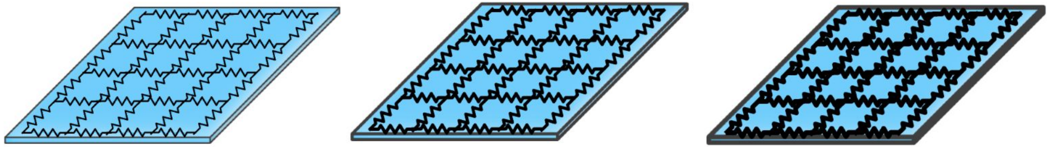


Increase resistivity → Z_{Sheet} increases

→ less signal spread



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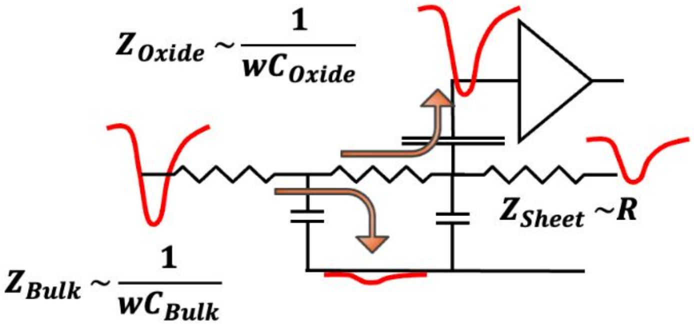

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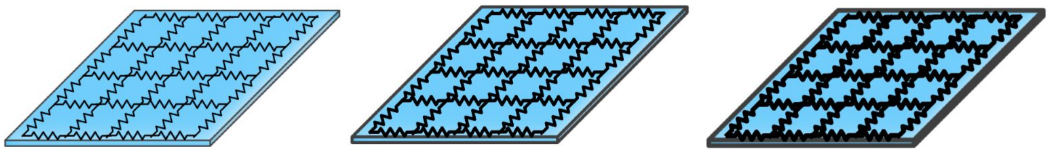
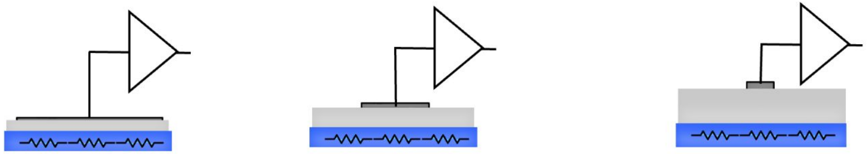


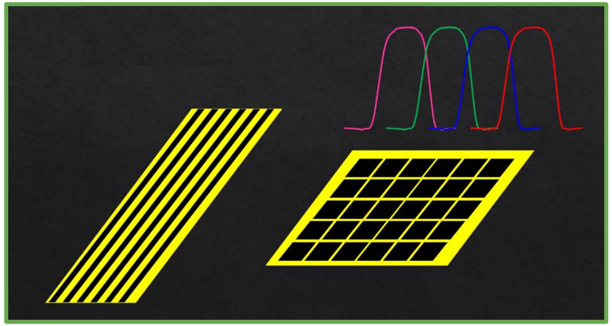


Increase oxide thickness and/or decrease pad size

→ Z_{Oxide} increases → more signal spread

Two approaches to have good spatial resolution

- ***Charge sharing* with large electrodes**
  - Fully exploit charge sharing to reconstruct hit position (relatively low Z_{Sheet})
  - Low power consumption, plenty of space on the pixel to accommodate the electronics
  - Large capacitance, smaller signal amplitude
  - Ideal for low-occupancy colliders, such as lepton colliders



- ***Fine pitch* with small electrodes and binary read-out**
  - Reduced sharing (high Z_{Sheet})
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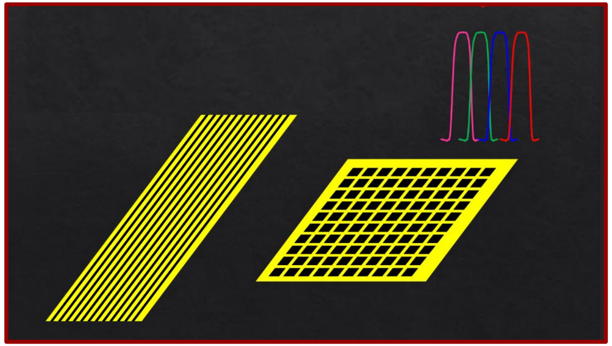

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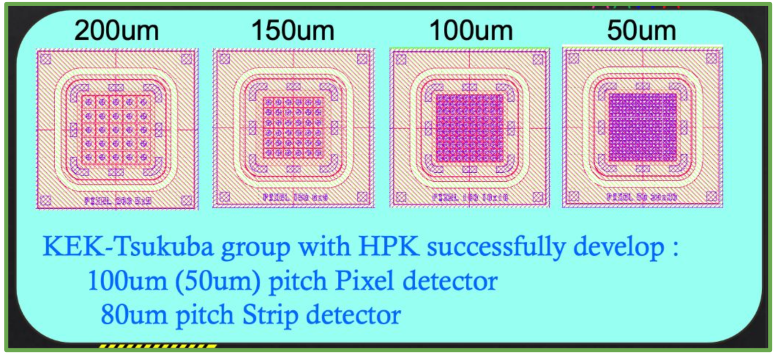

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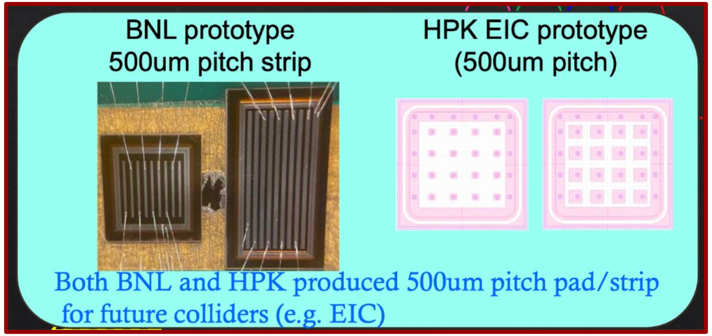

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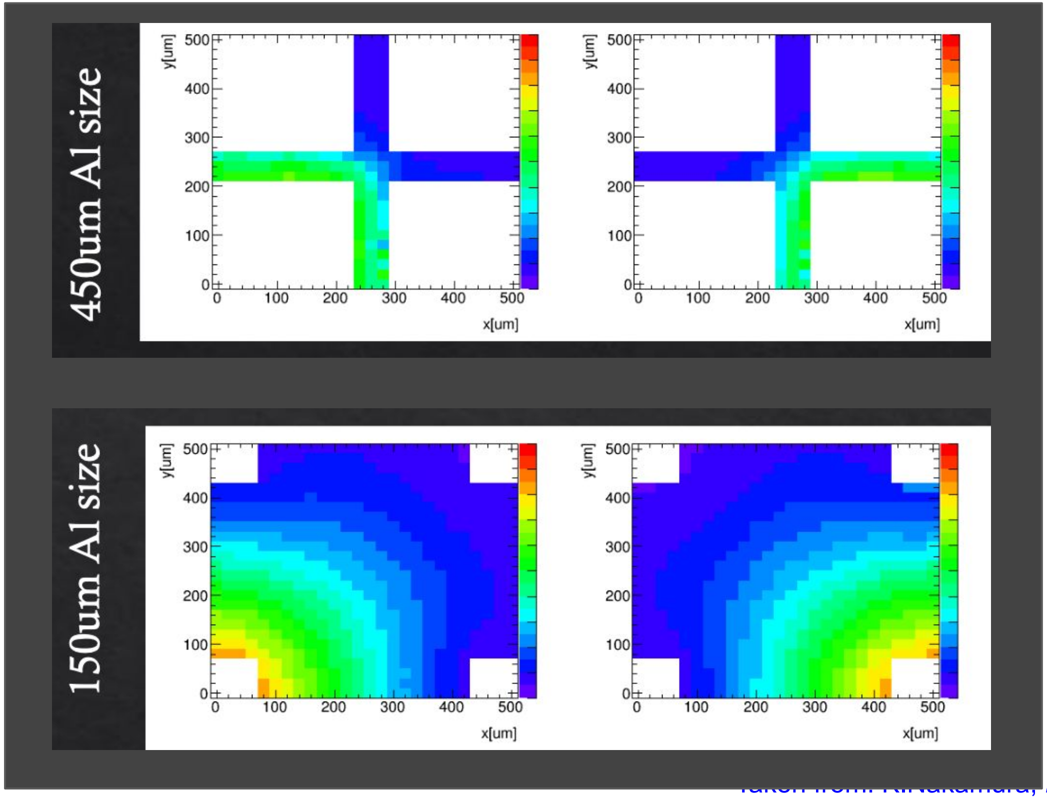

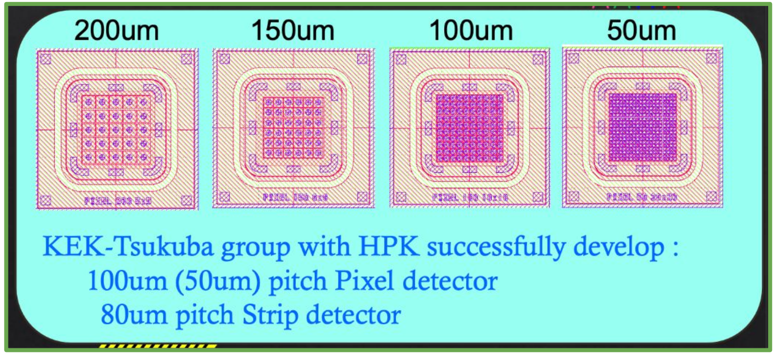

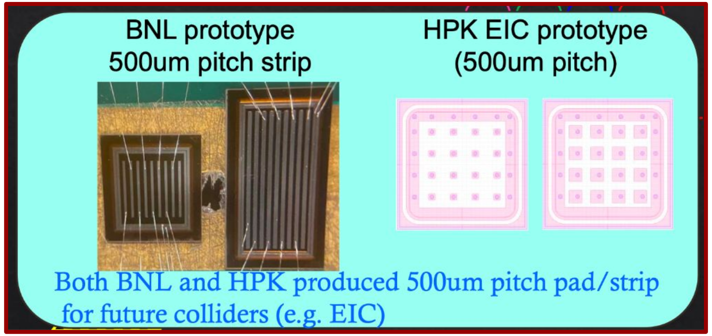

Development of tracking detector with capability of precise time and spatial resolution for future collider experiments, INFN Seminar, Torino (2024)

Two approaches to have good spatial resolution

Today I will focus on this

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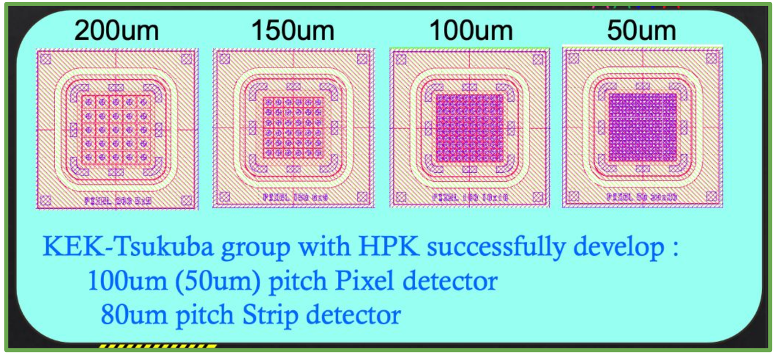

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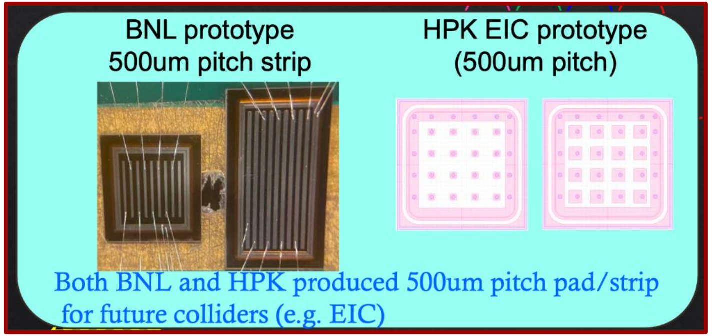

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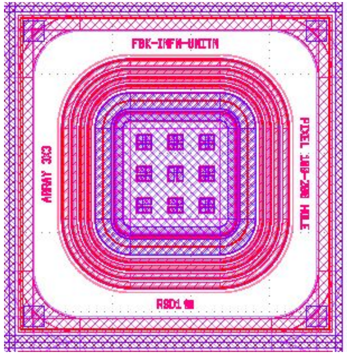
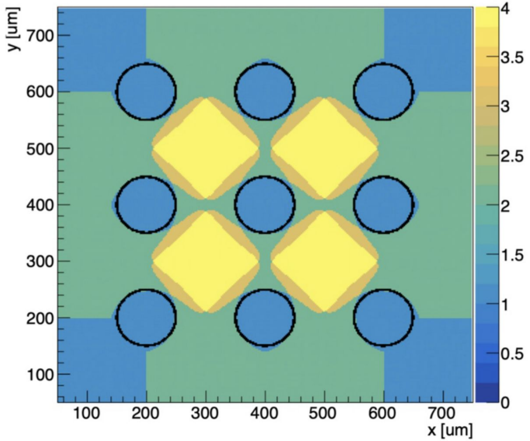
FBK RSD productions

- In RSD1 we explored the properties of resistive read-out
  - Large squared metal pads, sensors with different pitch & number of pads
- Lessons learnt:
  - If sharing involves too many pads, reconstruction is biased
  - Sharing should involve a fixed number of pads to achieve uniform response
  - Little or no sharing underneath a metal



 # electrodes involved strongly position-dependent



- Number of pads seeing a signal above noise threshold, as a function of x-y position
- Reconstruction is biased, response non-uniform

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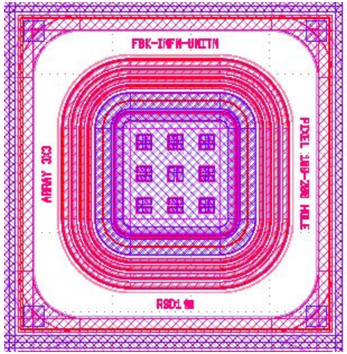
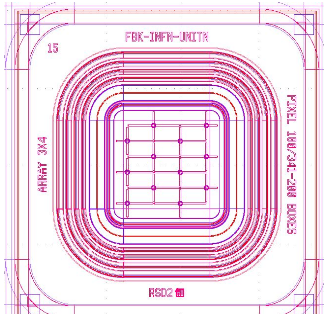
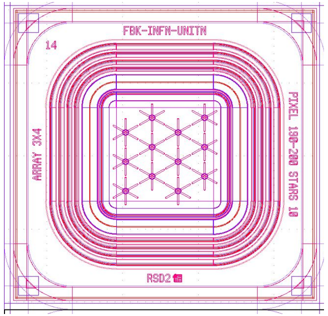
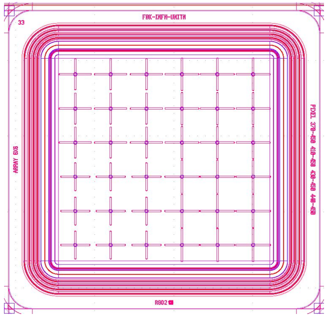


 # electrodes involved strongly position-dependent

- In RSD2, we improved the electrodes design
- Many geometries included:
  - **minimum metal coverage**
  - **extended electrode to limit signal dispersion (pad design with "arms")**





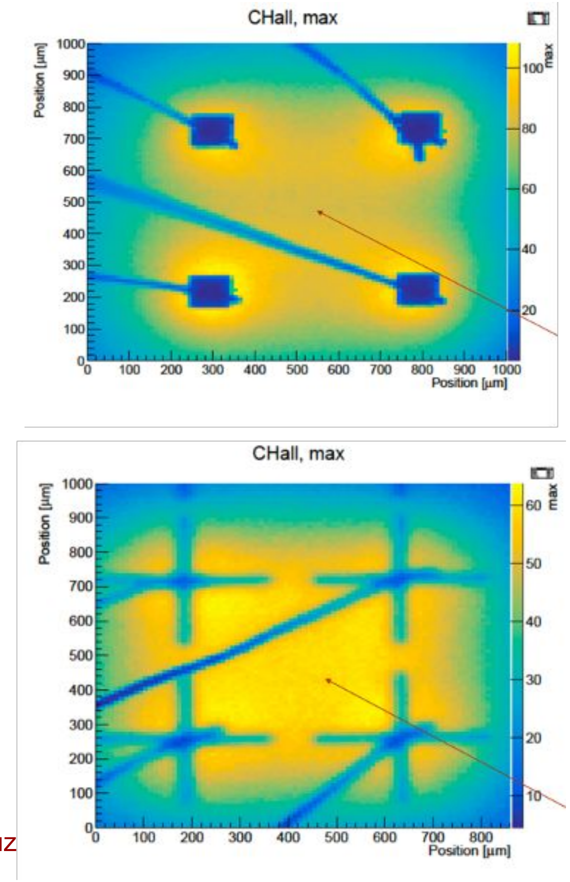


Sharing among a predetermined number of electrodes ⇨ *2 electrodes* *3 electrodes* *4 electrodes*

RSD1 vs RSD2

- 2D-maps showing the sum of 4 pad amplitudes, obtained with TCT laser setup
- Qualitative measurement of the signal fraction escaping from the pixel ("full" signal is observed when shooting close to the electrodes)
- Pmax in the bottom plot is ~constant across the whole pixel, whereas large differences are seen in the top plot

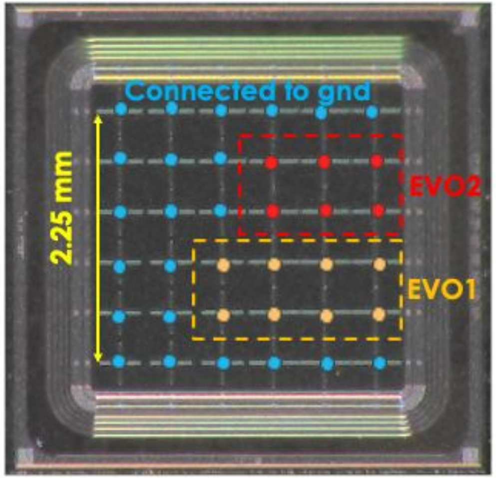
→ Extended cross-shaped electrodes are ideal to achieve very uniform response within the pixel

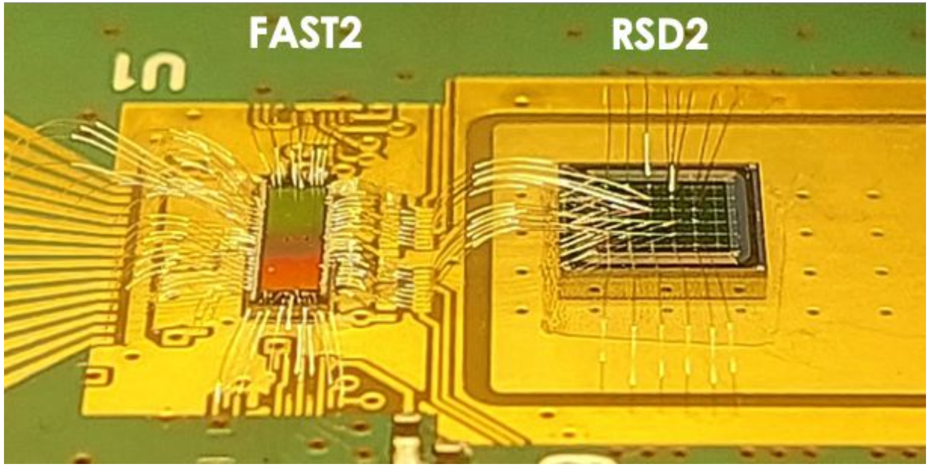


Courtesy of UC Santa Cruz

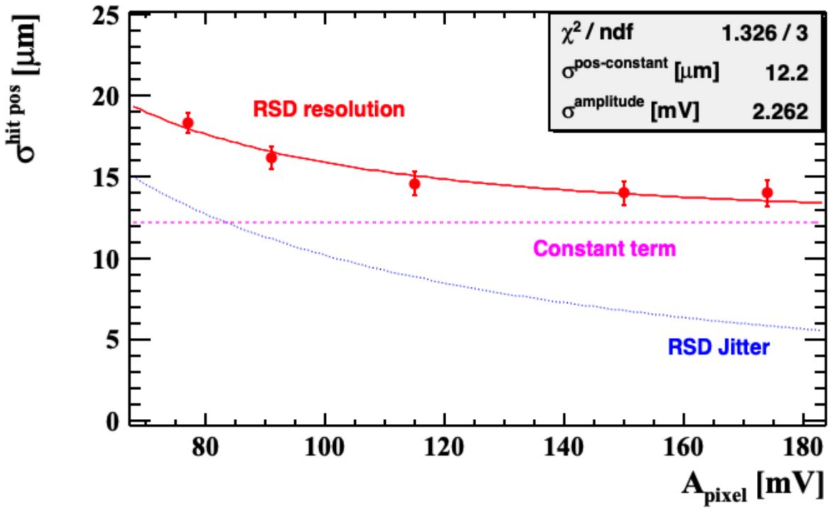
Results on RSD2 from a DESY Test Beam

- 6x6 RSD2 matrix with cross-shaped electrodes, 450um pitch
  - 14 pads read out, the others grounded
- Read-out with FAST2 ASIC (EVO1, EVO2 are slightly different front-ends)
- Measured with 5 GeV/c electrons





Results on RSD2 from a DESY Test Beam: spatial resolution



subtracted $\sigma_{Tracker}$ ~ 8 um

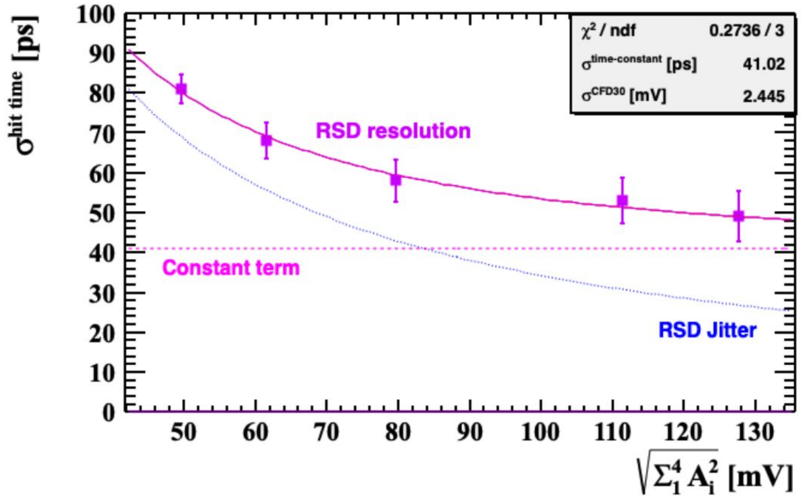
$$\sigma^{\text{hit pos}} = \sqrt{(\sigma^{\text{pos-constant}})^2 + \left(\frac{\sigma^{\text{amplitude}} \times \text{pitch}}{\Sigma_i^4 A_i}\right)^2}$$

Reconstruction method + experimental setup + sensor non uniformity → Leading term

Jitter

- **Achieved $\sigma_{\text{Spatial, RSD}}$ = 15 um with a 450um-pitch** pixel sensor (gain~35)
- With binary read-out this is achieved with ~45um pitch → 100 less read-out channels
- Brief description of reconstruction method in the backup

Results on RSD2 from a DESY Test Beam: time resolution



subtracted σ_{MCP} ~ 38 ps

$$\sigma^{\text{hit time}} = \sqrt{(\sigma^{\text{time-constant}})^2 + (\frac{\sigma^{\text{CFD30}} \times t^{\text{rise}}}{\Sigma_i^4 A_i^2})^2}.$$

Landau noise + not perfect delay correction + sensor non uniformity + ASIC non linearity → Leading term

Jitter

- **Achieved $\sigma_{\text{Time, RSD}}$ = 49 ps** (gain~35)
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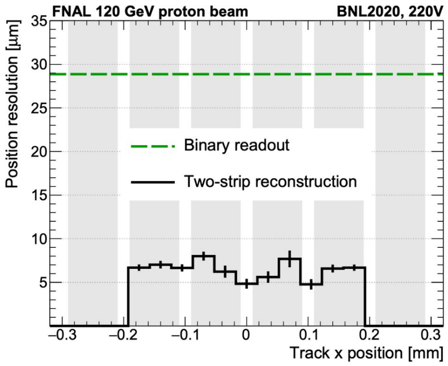
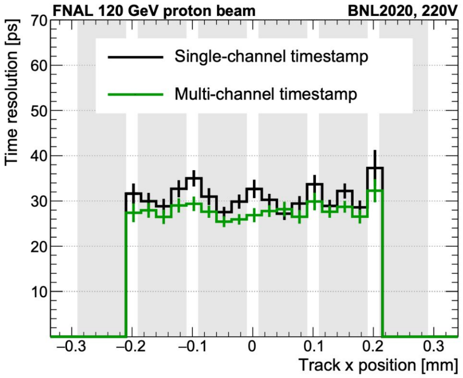
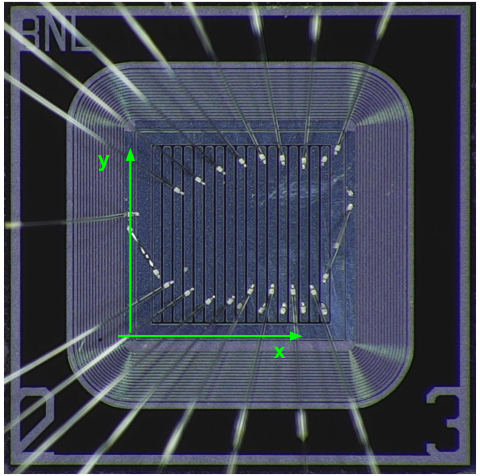
Developed for EIC

Other AC-LGAD productions

- Results from a FNAL test beam ([link]()) on **BNL production**







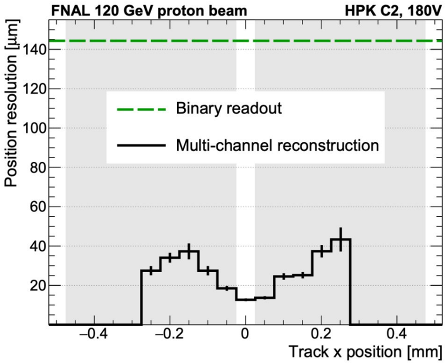
BNL sensor:
1.7mm strip, 100um pitch
(80um metal - 20um interpad)

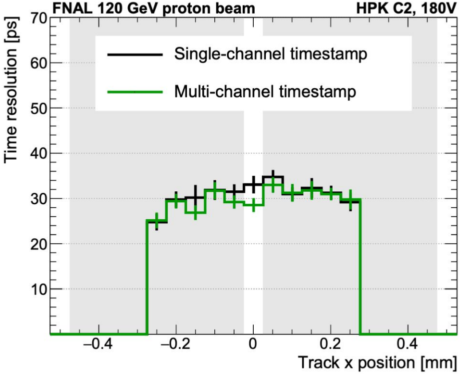
- $\boldsymbol{\sigma_{Spatial}}$ **= 5-10 um** along x-axis (much larger along y)
- $\boldsymbol{\sigma_{Time}}$ **= 30-40 ps**
- Only ~30% of active area (central part) used for the reconstruction

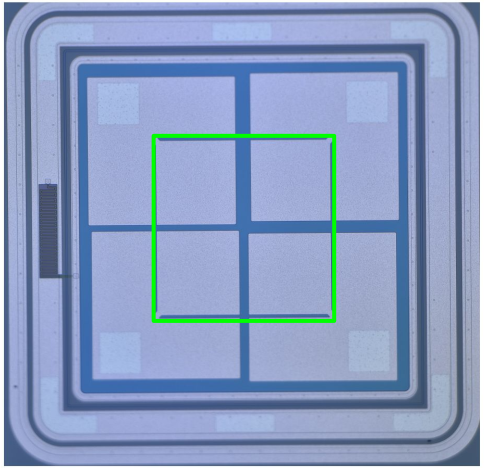
Developed for EIC

Other AC-LGAD productions

- Results from a FNAL test beam (link) on **HPK production**





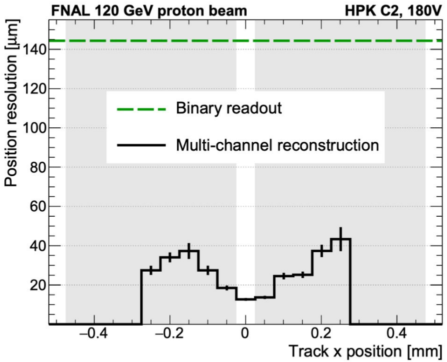


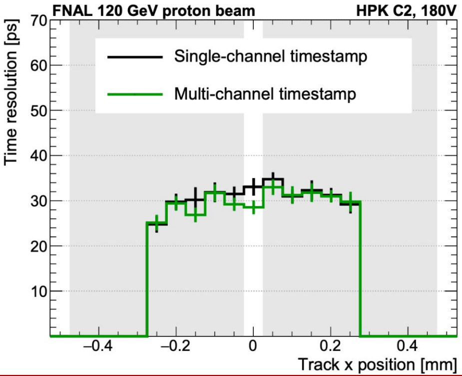
HPK sensor:
500x500 um^2 pads,
variable interpad gap

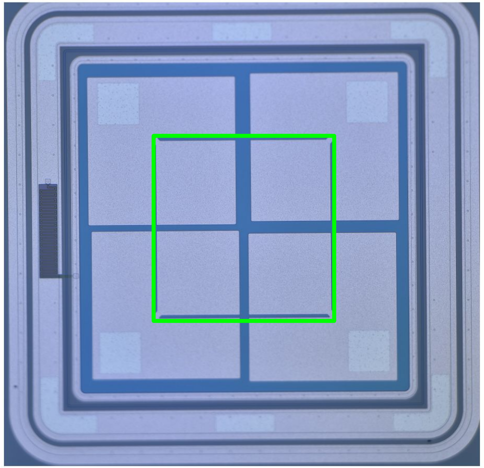
- $\sigma_{Spatial}$ **= 15-40 um** (strongly position-dependent)
- σ_{Time} **= 30-40 ps**
- Only the area framed used in the reconstruction (binary read-out elsewhere)

Other AC-LGAD productions

- Results from a FNAL test beam (link) on **HPK production**







HPK sensor:
500x500 um^2 pads,
variable interpad gap

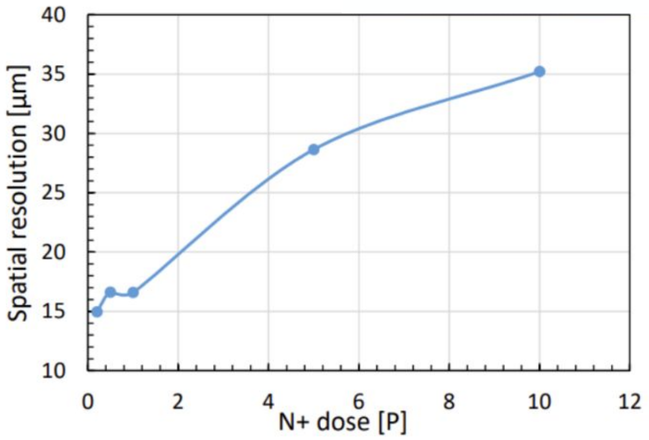
➢ HPK adopted a different philosophy compared to FBK: use large pads fully covered with metal, to keep the signal confined in 2-3 pads

  - Main drawback: if pad is large signal sharing may not occur in the central part of the electrode, getting back to binary read-out (+ non-uniform response)

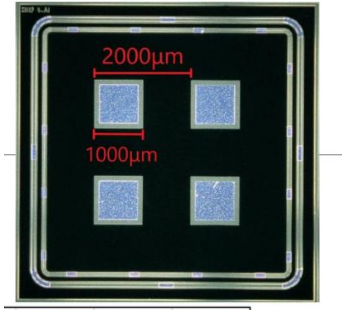
  - ..but, more suited for environments with high occupancy (basically no signal escaping beyond the first neighboring pads)

Other AC-LGAD productions

- AC-LGAD producers are growing more and more
- FBK, BNL, HPK, IHEP, CNM (maybe others) have produced or are going to produce these sensors
- EIC has an ambitious program to develop and use the RSD, based on US-Japan collaboration
- CMS is considering to use RSDs in the tracker forward disks (upgrade for Phase3 HL-LHC)



IHEP
AC-LGAD



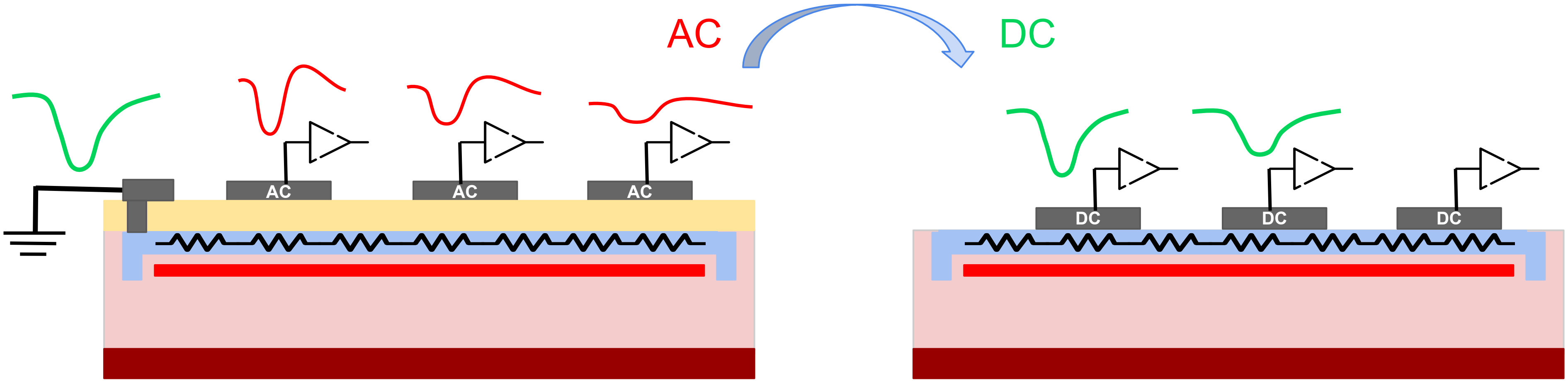
…and of course FCC

Outline

- The RSD design
  - Tuning the parameters
  - Different paths to position reconstruction
- The FBK RSD2 production
  - DESY Test Beam results
- Other AC-LGAD productions
- The DC-RSD

DC-RSD

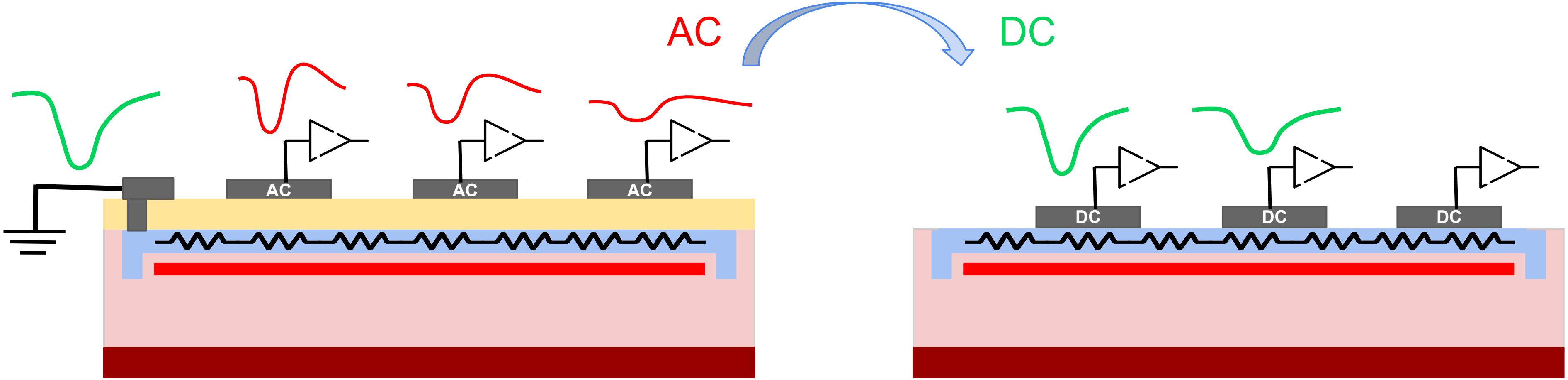
- Future production devoted to upgrading the RSD design, addressing some weaknesses of the AC design:
  - Possible baseline fluctuations on large devices
  - The bipolar nature of the signals, with rather long tails during the discharge
  - The fact that is not possible to 100% confine the signal
- In DC-RSD, the coupling oxide is removed → DC-coupling of the electrodes to the resistive layer
  - Single diode, signal sharing and 100% fill factor are still there, just like the AC-RSD



DC-RSD

*AC-design likely not ideal for high-occupancy

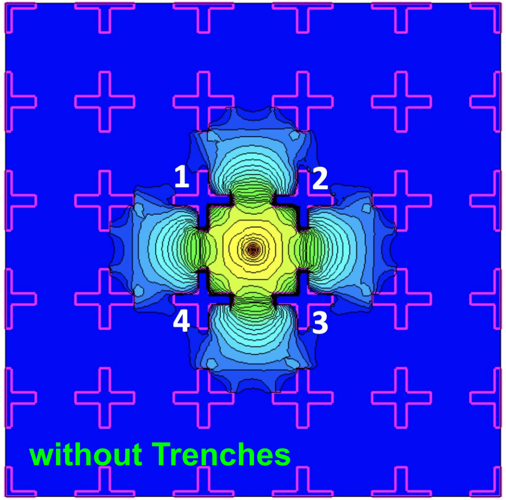
- DC-RSD may be suited for either low- and high-occupancy tasks*
  - Multiple hits should not affect the baseline
  - No signal dispersion, reconstruction of a particle hit involves a predetermined number of pads
  - No bipolar signal (i.e. slow discharge) → 1 ns-long pulses
- No signal dispersion + No baseline fluctuations → improved SNR ratio
- Due to their characteristics, DC-RSD with $O(\text{cm}^2)$ active surface are feasible



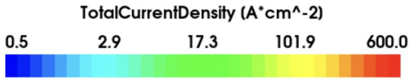
DC-RSD…with Trenches!

- In a slightly different version of the DC-RSDs, trenches would be implemented to confine the signals:
  - Fill factor < 100%, but signal completely confined within a pixel, further pushing the sensors performance in terms of position reconstruction
  - FBK TI-LGAD productions clearly showed that trenches of a few um are feasible without affecting device operation

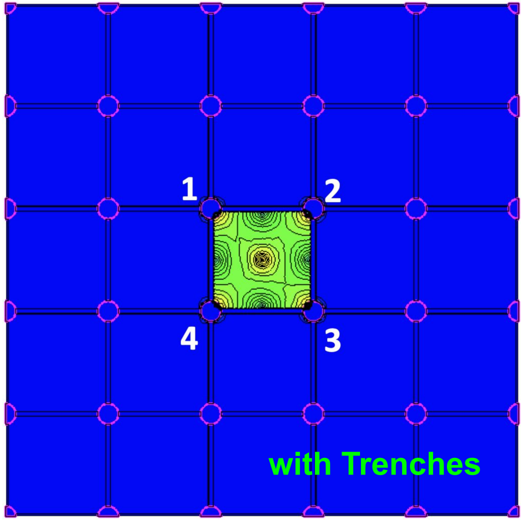
96% signal confinement in the pixel



3D-TCAD simulation comparing DC-RSD with (right) and without (left) trenches



100% signal confinement in the pixel

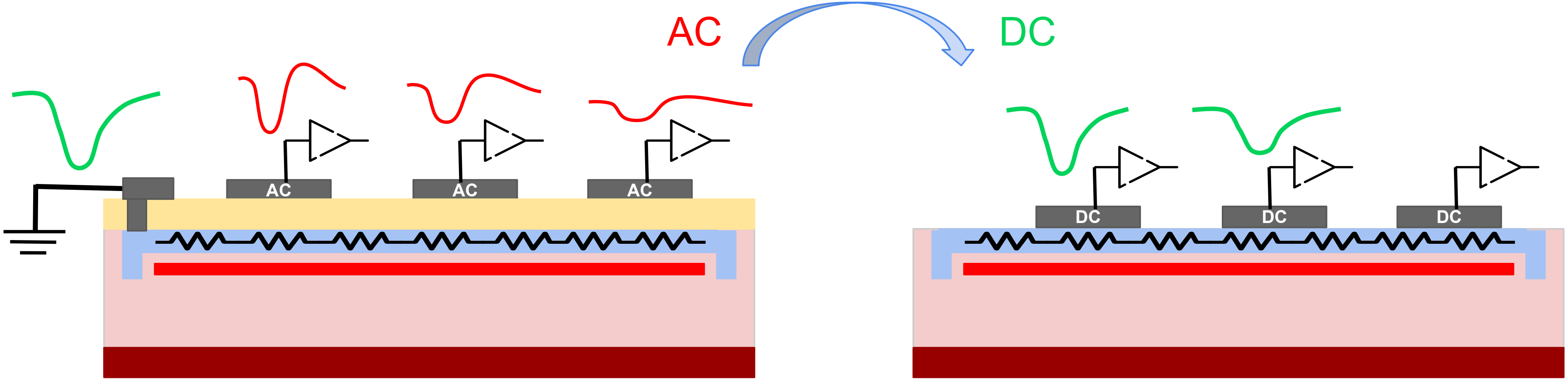


DC-RSD

- DC-RSD development started in the framework of the 4DinSiDe (PRIN, 2017) and is now supported by INFN Gruppo 5 (4DSHARE experiment) and PRIN project 4DSHARE (started October ‘23)

- FBK is currently manufacturing the first production of DC-RSD (w and w/o trenches)
  - reticle design completed, production just started: we expect first sensors in Fall 2024

→ **stay tuned…DC-RSD are coming soon!**



Summary & Outlook

- The principle of resistive read-out coupled to the LGAD technology can enable accurate 4D-tracking
  - Large & fast signals shared among a constant number of pads
  - 100% fill factor
  - An exciting R&D field for future colliders, included FCC
- Resistive Silicon Detectors (RSDs) are one example of this promising technology
  - Achieved 15 um spatial resolution and 50 ps time resolution when measured with 5 GeV/c electrons
  - Large, cross-shaped electrodes → ideal for low-occupancy applications
- Many other AC-LGAD / RSD producers out there!
  - HPK, BNL are working hard on AC-LGADs for EIC, for instance
  - Using large metalized strip/pixel sensors and achieving < 20 um spatial resolution and < 40 ps time resolution
  - CNM and IHEP are also developing their own resistive sensors
- CMS is considering RSDs for the Phase3 Upgrade of HL-LHC
- What’s next: DC-RSD, opening the way to high-occupancy applications with RSDs

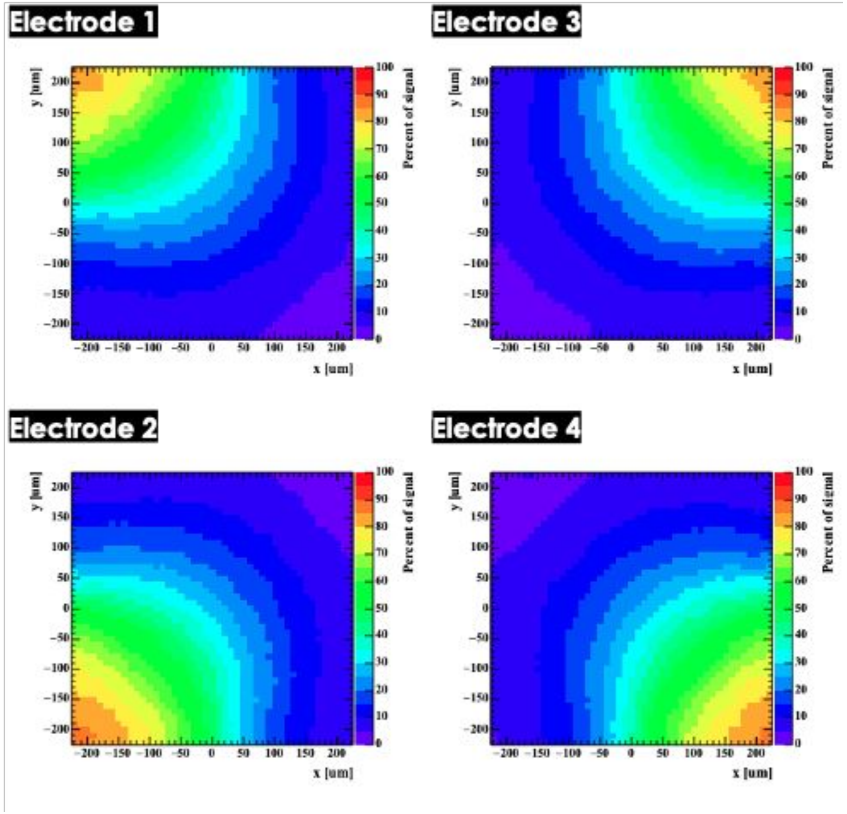
BACKUP

Position reconstruction: Sharing Template method

Step 1:
Produce a look-up table with a 10x10 micron[2] cell granularity of the sharing pattern among the 4 electrodes.
The look-up table is computed with test beam data, summing up the data from the 7 pixels.

Step 2:
For each event, compare the measured signal sharing with the look-up table to find the cell that best reproduces the measured sharing

Step 3:
A local fit centered on the cell determines the hit location.



Time reconstruction

- Each electrode measures an arrival time
  - $t_{hit} = t_{delay} + t_{setup} + t_{meas}$
- The t_{hit} estimators can be combined in a Chi-2 distribution

$$t^{hit} \sim \frac{\sum_i^4 t_i^{hit} * A_i^2}{\sum_i^4 A_i^2}$$