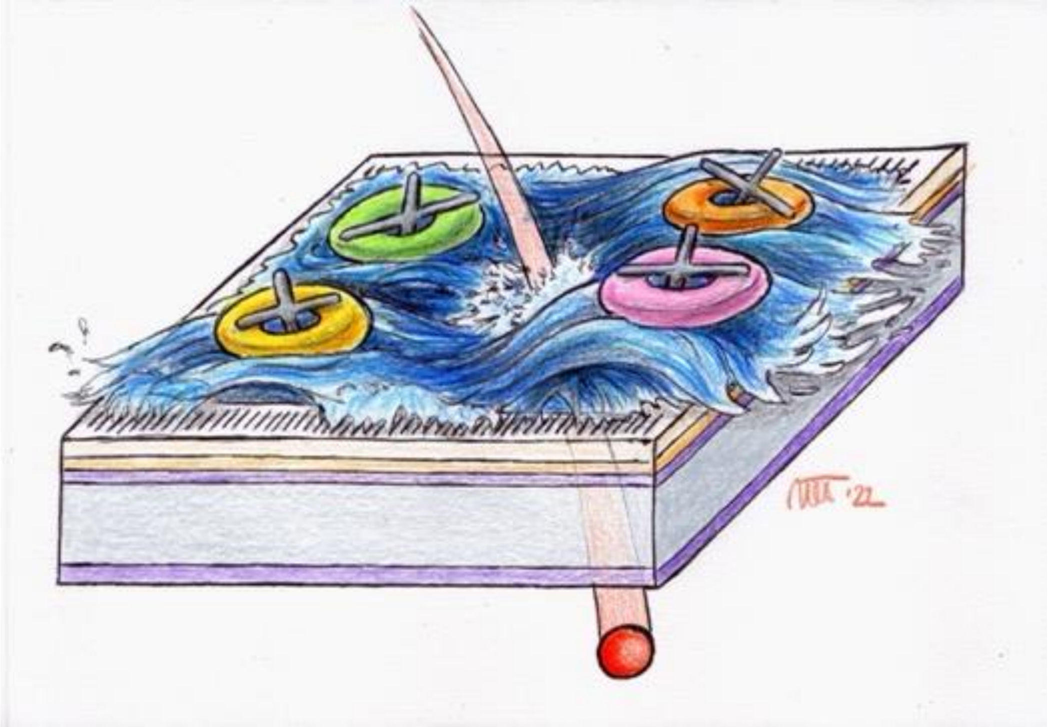
Spatial and temporal resolution of FBK RSD2 sensors



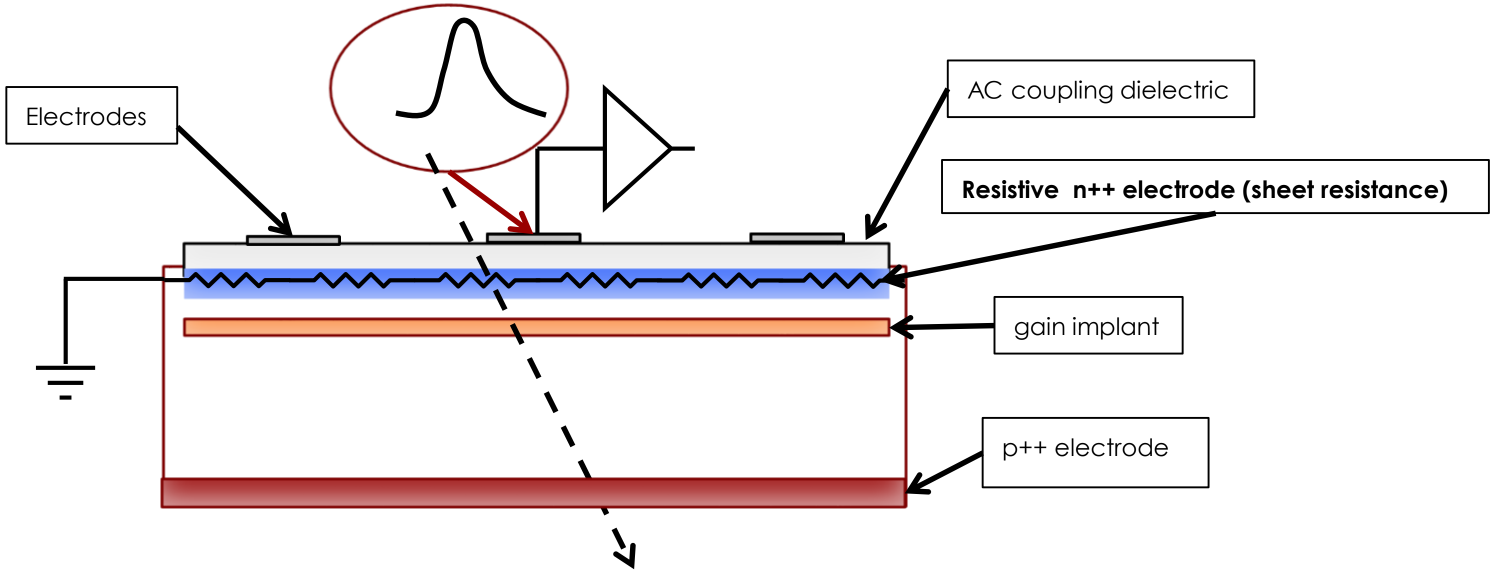
N. Cartiglia
UFSD group

Image courtesy of M. Tornago

TREDI and resistive silicon detectors

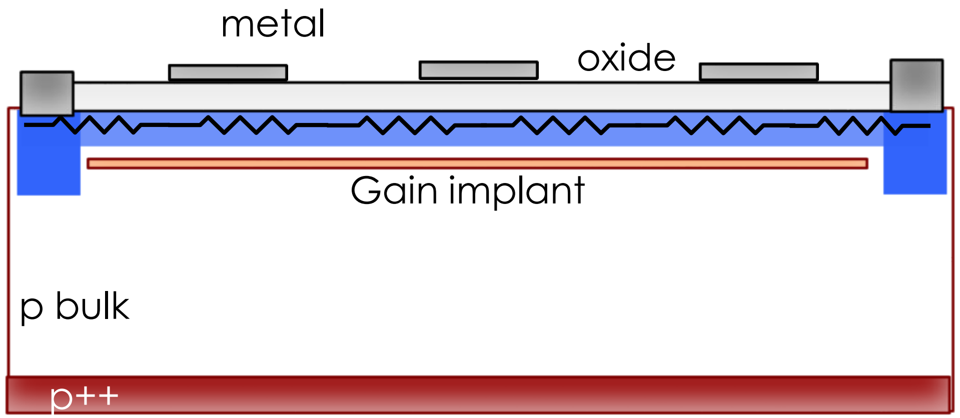
- Resistive silicon detectors (aka AC-LGAD) were presented at **TREDI 2015**
- At **TREDI 2020**, we presented the first results on the properties of silicon sensors with resistive read-out
- Now, at **TREDI 2022,** we present the results obtained with the second FBK RSD production, RSD2.

AC-RSD building blocks:



Digress: nomenclature

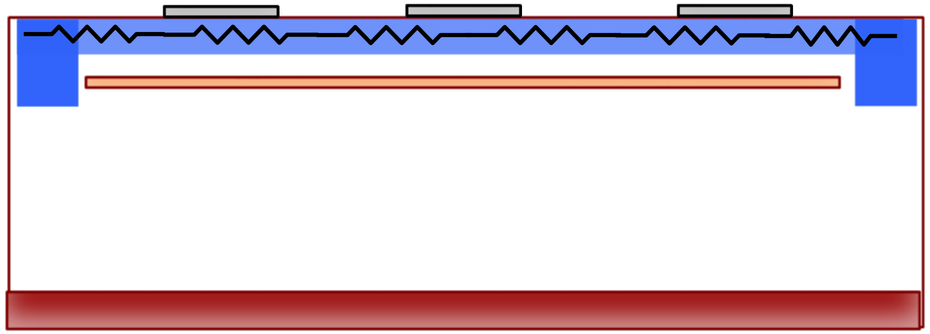
LGAD (also UFSD)



RSD (also AC-LGAD),

==> AC-RSD

FBK RSD1, RSD2 are AC-RSDs



New design: DC – RSD

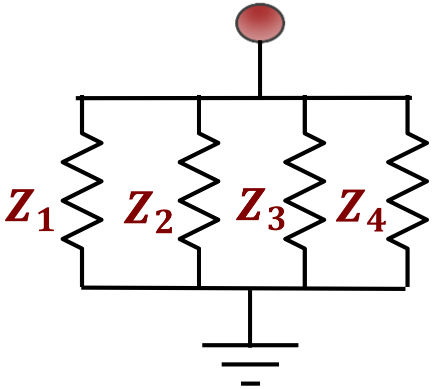
(see L. Menzio, Thursday afternoon)

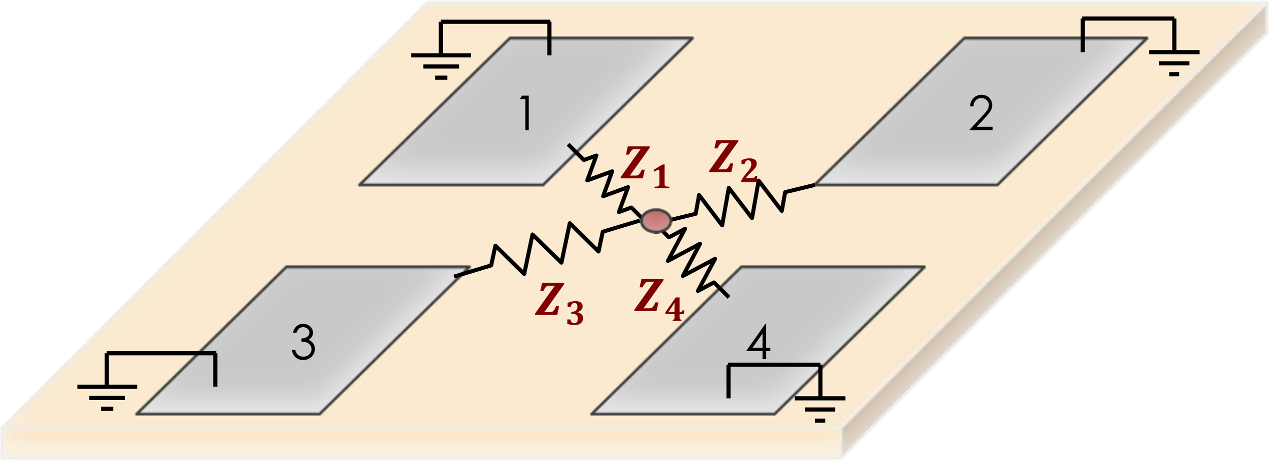
Aide memoire: RSD principle of operation

The signal sees several impedances $\boldsymbol{Z_i}$ in parallel, and it is split according to Ohm's law.

Each pad gets a share $\boldsymbol{S_i}$ of the total signal, exactly as in a current divider

$$S_i \propto \frac{\frac{1}{Z_i}}{\sum_1^n \frac{1}{Z_j}}$$



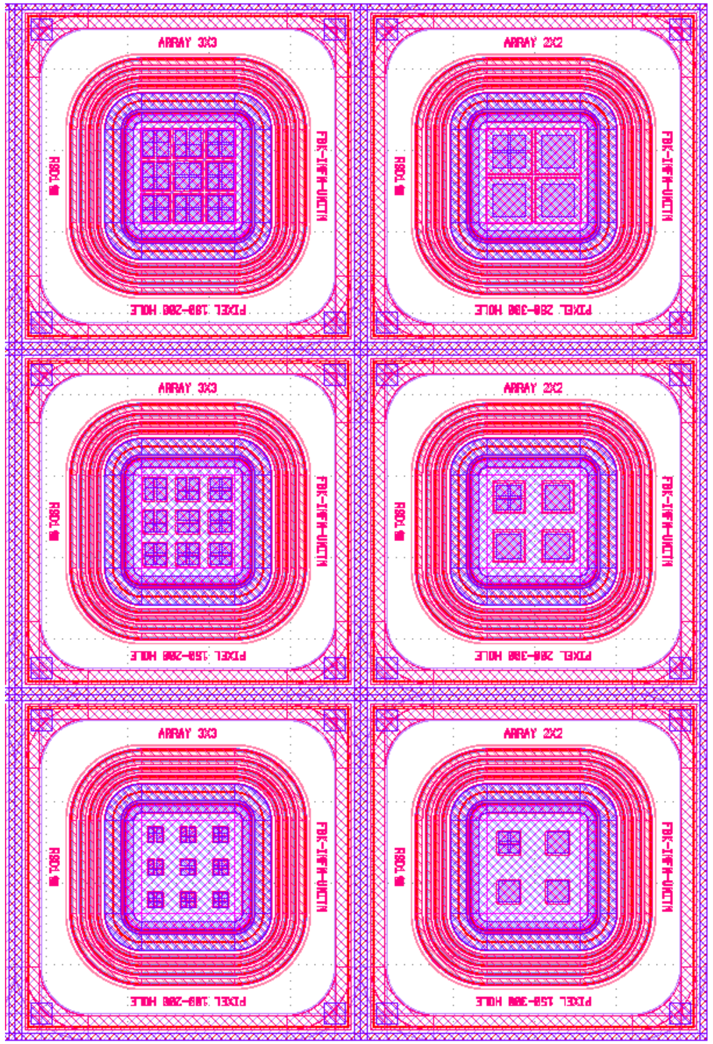


FBK RSD1 lessons learnt

Signal sharing

- **allows reaching excellent spatial resolutions,**
- **does not spoil the temporal resolution proper of the LGAD technology.**

Example of RSD1 structures



- Hits on the metal generate (mostly) a signal only in that pad

  ==> no signal sharing if the metal pad is large, the resolution is spoiled
- Sharing to many pads leads to signals so small that are not considered in the reconstruction

  ==> reconstruction is biased
- Sharing should involve a “fixed” number of pads

  ==> otherwise non-uniform response and performance
- Floating pads do not contribute,

  ==> be aware during testing, you can get to the wrong conclusions

The FBK RSD2 production

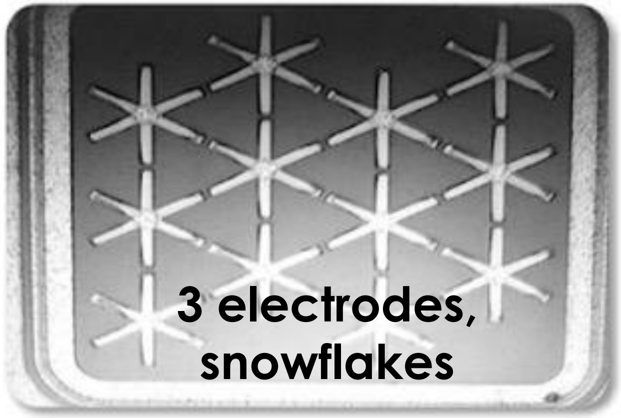
Goals for RSD2:

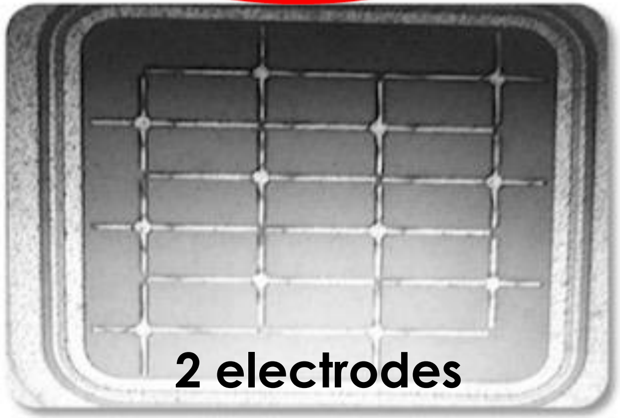
Uniform and controlled signal sharing

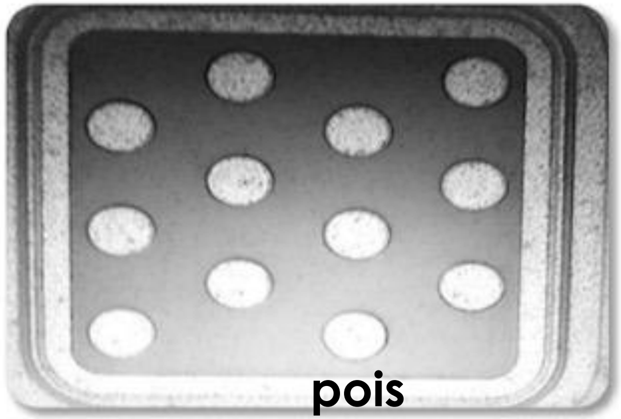
- Optimize the fabrication parameters (resistivity, oxide, gain layer)
- Reduce as much as possible the metal area of the pads
- Design the electrodes to contain the signal
- Split the signal into a well defined set of pads


Focus of this talk

4 electrodes, crosses


3 electrodes, snowflakes


2 electrodes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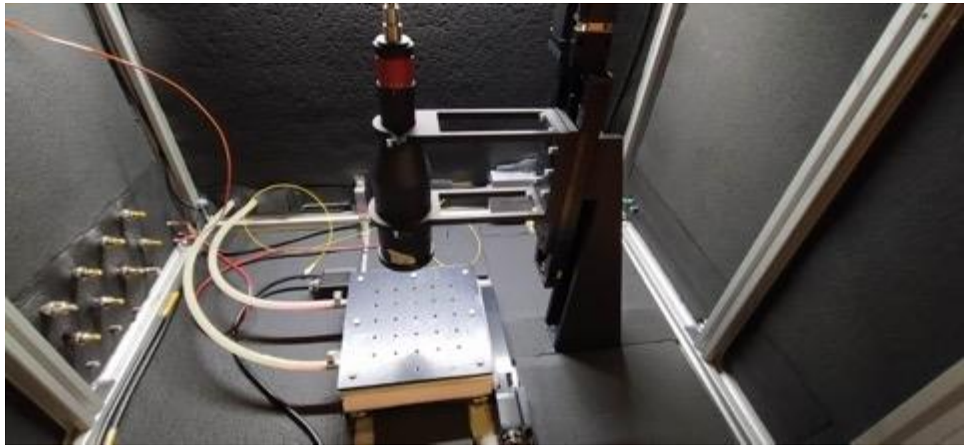
Details on RSD2:
- M. Mandurrino, “RSD2, the new production of AC-LGADs at FBK”, 39th RD50,
- F. Siviero, “First experimental results of the spatial resolution of RSD pad arrays …” VCI2022

Experimental set-up

The **Particulars TCT laser setup** has been used:

- IR laser generates a signal in the RSD,
- simulating the passage of a MIP
- laser spot size ~ 8 μm
- Laser temporal precision: ~ 8 ps
- movable x-y stage provides reference positions of the laser shots, precision: σ_{Laser}~ 2 μm



All pads are read out with an oscilloscope

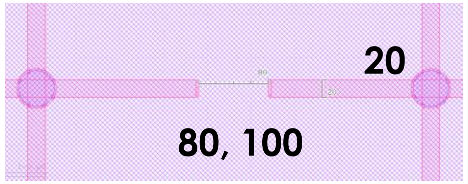
We used a 16-ch fast analog board, developed at FNAL, with an **RMS noise ~ 2 mV.**

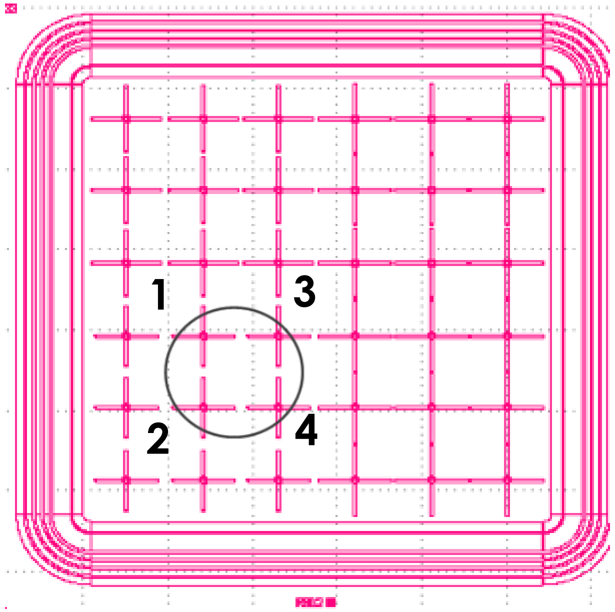
Minimum signal level ~ 8 mV

RSD2 sensors with 4 electrodes

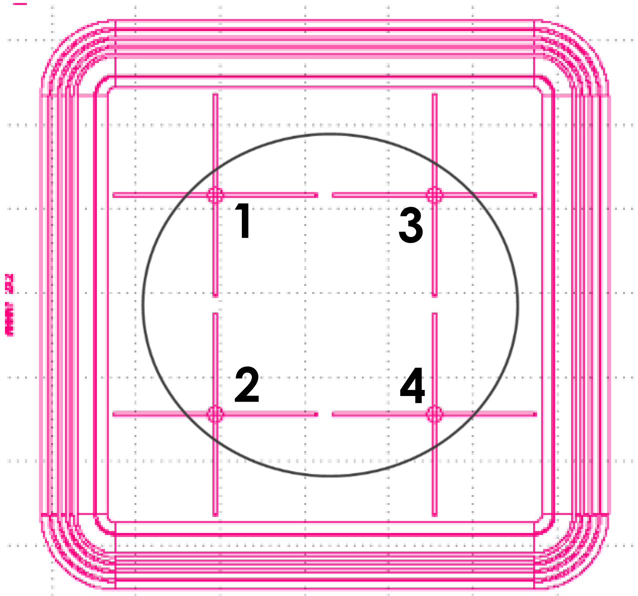
In this study, the perfomances of sensors with electrodes shaped as crosses are presented.

- Two different pitches: 450 μm and 1300 μm
- Electrode width: 20 μm
- Gap: 80 μm (pitch = 450 μm) and 100 μm (pitch = 1300 μm)



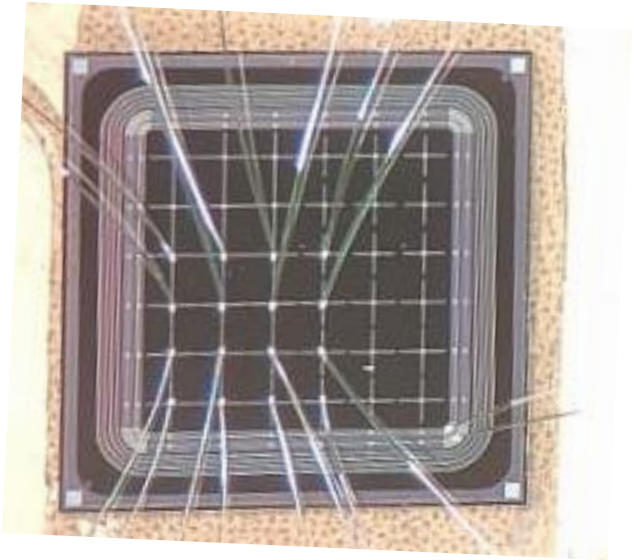


Pitch = 0.45 mm



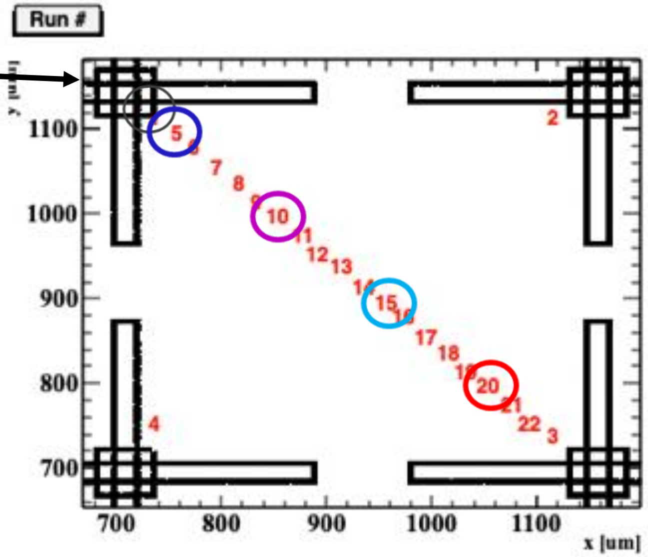
Pitch = 1.3 mm

Pitch = 0.45 mm

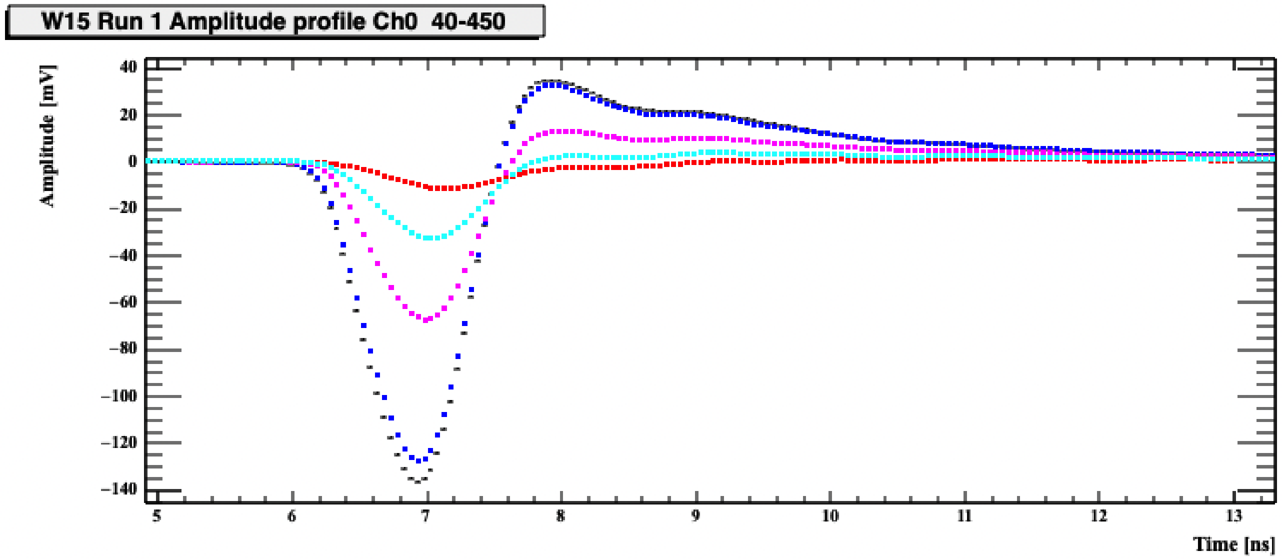


Signal shape and propagation – 450 μm pitch

The effects of propagation on the signal shape have been studied by shooting laser signals along the diagonal, and measuring the signals seen in a given read-out pad

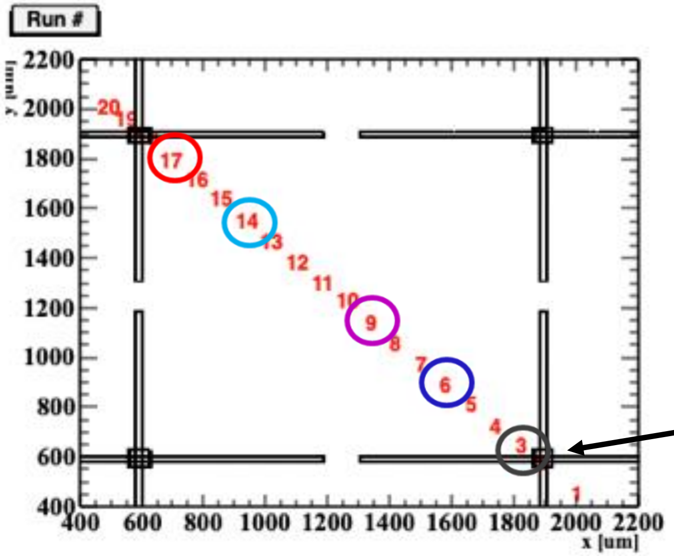

Read-out pad

- **The signal is very similar to that of a standard LGAD when the hit is near the pad.**
- The signal decreases in amplitude and it is shifted in time as the hit position is moved away



Signal shape and propagation – 1300 μm pitch

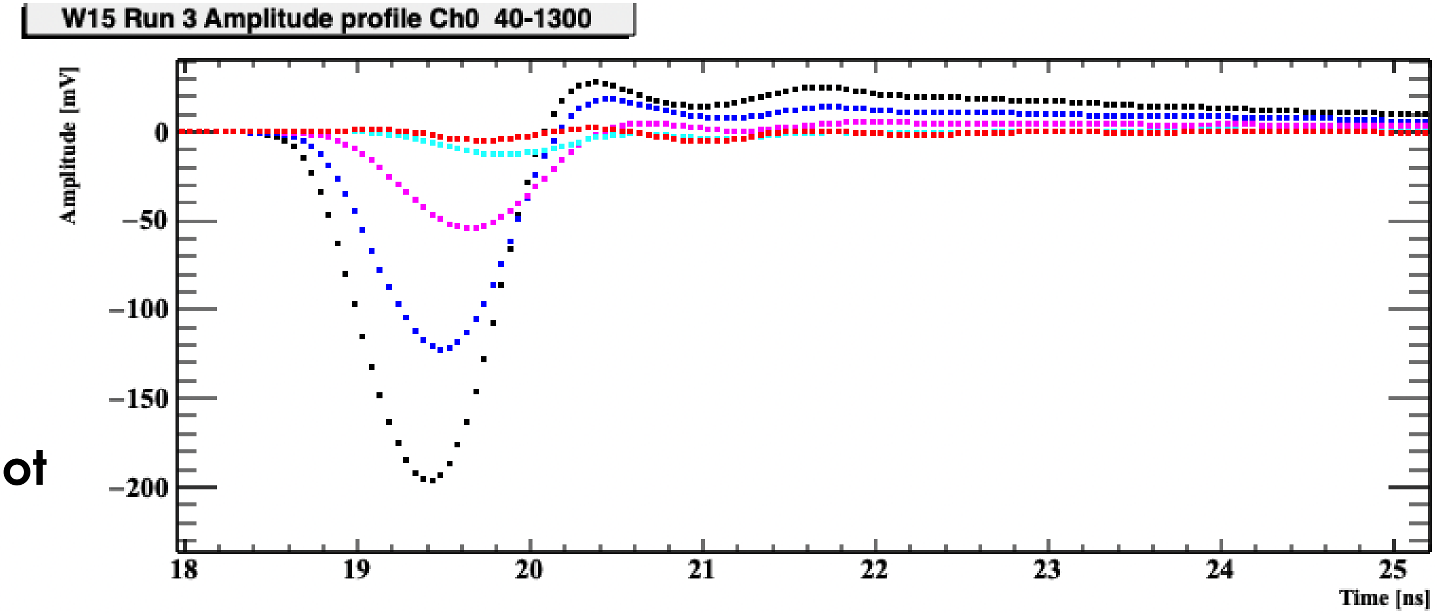
- The overshoot is smaller in the 1300 μm pitch, as the RC is longer (the capacitance is larger)
- When the hit is at the opposite corner of the square, the signal is barely visible ==> distortion in the reconstruction



Read-out pad

The signals measured in sensors with pitch either 450 μm or 1300 μm are very similar

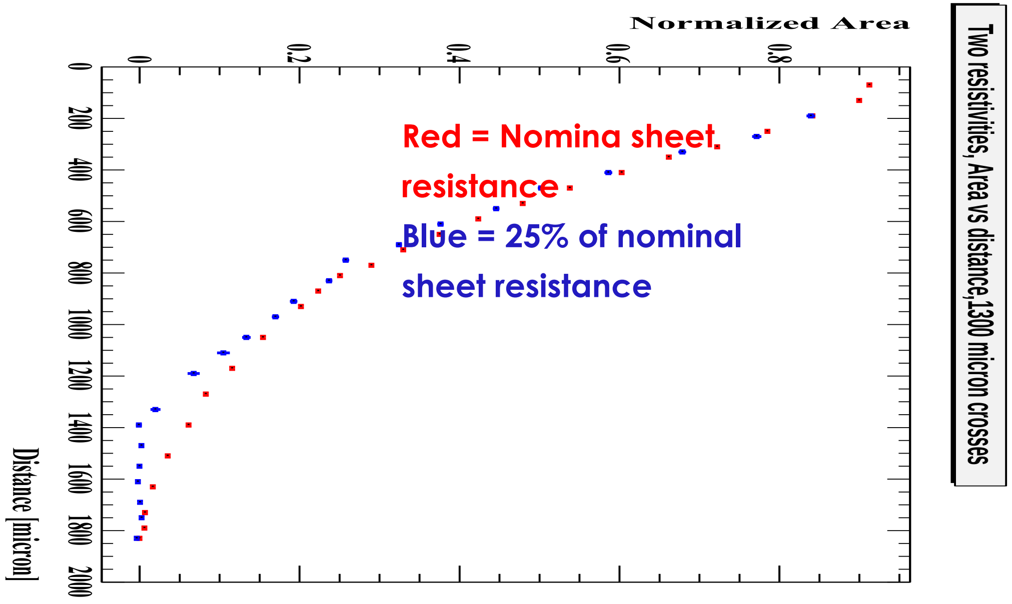
- **The major difference is in the overshoot**



Signal attenuation in 1300 μm pitch: 2 different sheet resistances

How does the sheet resistance influence signal attenuation & sharing?

Signal area vs distance for two RSDs with different sheet resistance:

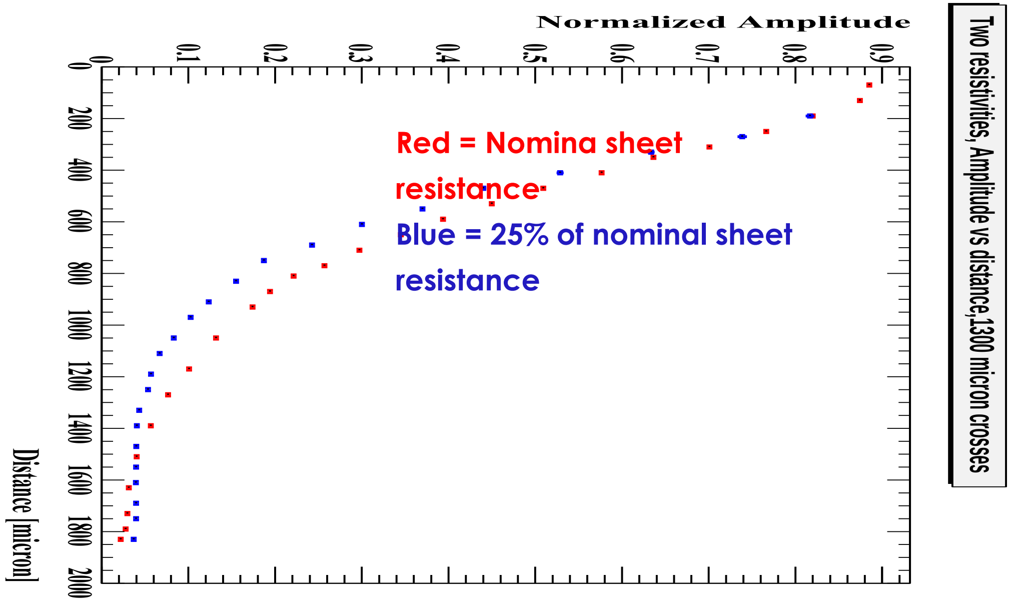


Red = Nomina sheet resistance

Blue = 25% of nominal sheet resistance

No significant difference in signal attenuation.
As expected, the sheet resistance does not influence signal sharing

Signal amplitude vs distance for two RSDs with different sheet resistance:



Red = Nomina sheet resistance

Blue = 25% of nominal sheet resistance

On the more resistive sheet, the signal becomes smaller and wider with distance, so the amplitude decreases more rapidly.

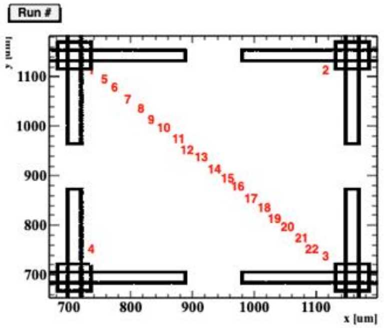
Signal amplitude vs distance for 450 μm and 1300 μm pitch

How signal sharing is affected by the size of the pixel?

For the two geometries, compare the signal attenuation seen while shooting along the diagonal.

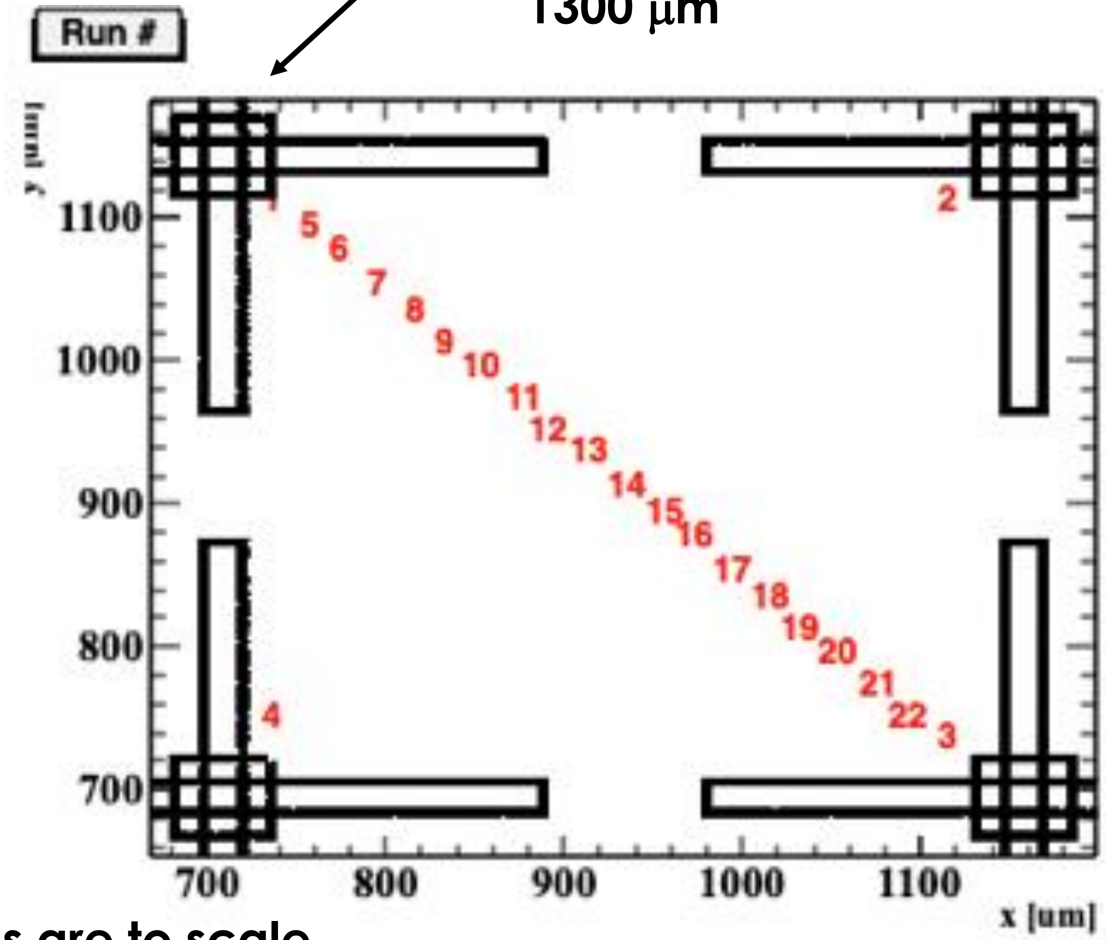
Read-out pad

450 μm



Read-out pad

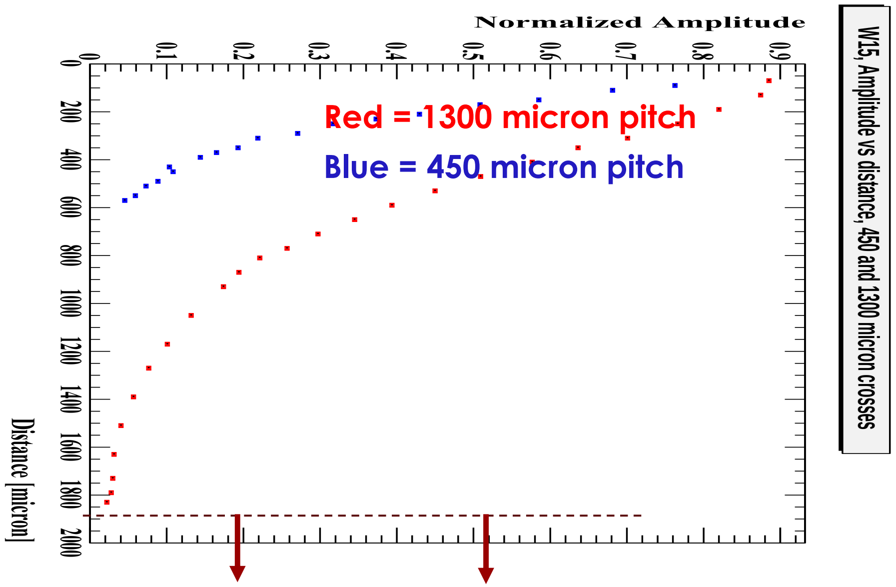
1300 μm

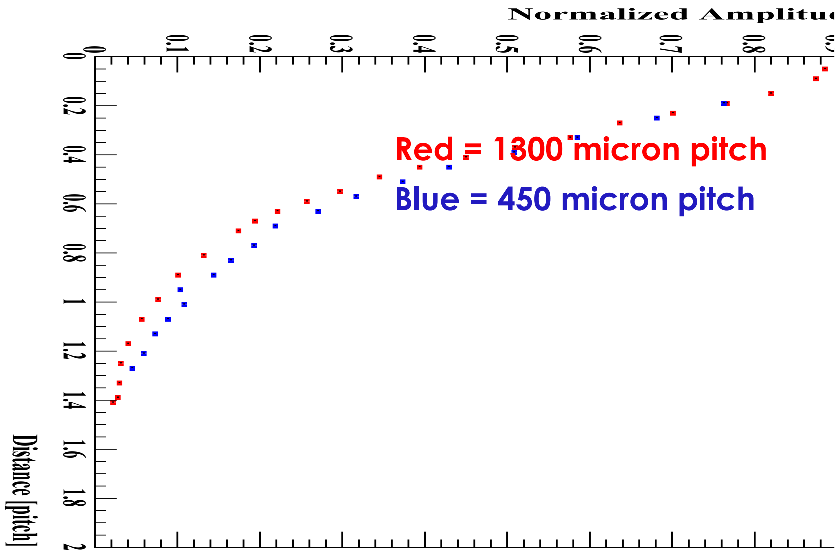


The two pixel sketches are to scale.

Signal attenuation vs distance for 450 μm and 1300 μm pitch

- **For equal electrode design, sharing is identical, regardless of the pitch size**
- The absolute distance (450 μm vs 1300 μm) does not matter in the attenuation





Example: a pad sees 10% of the signal when the hit is about 1 pitch away along the diagonal

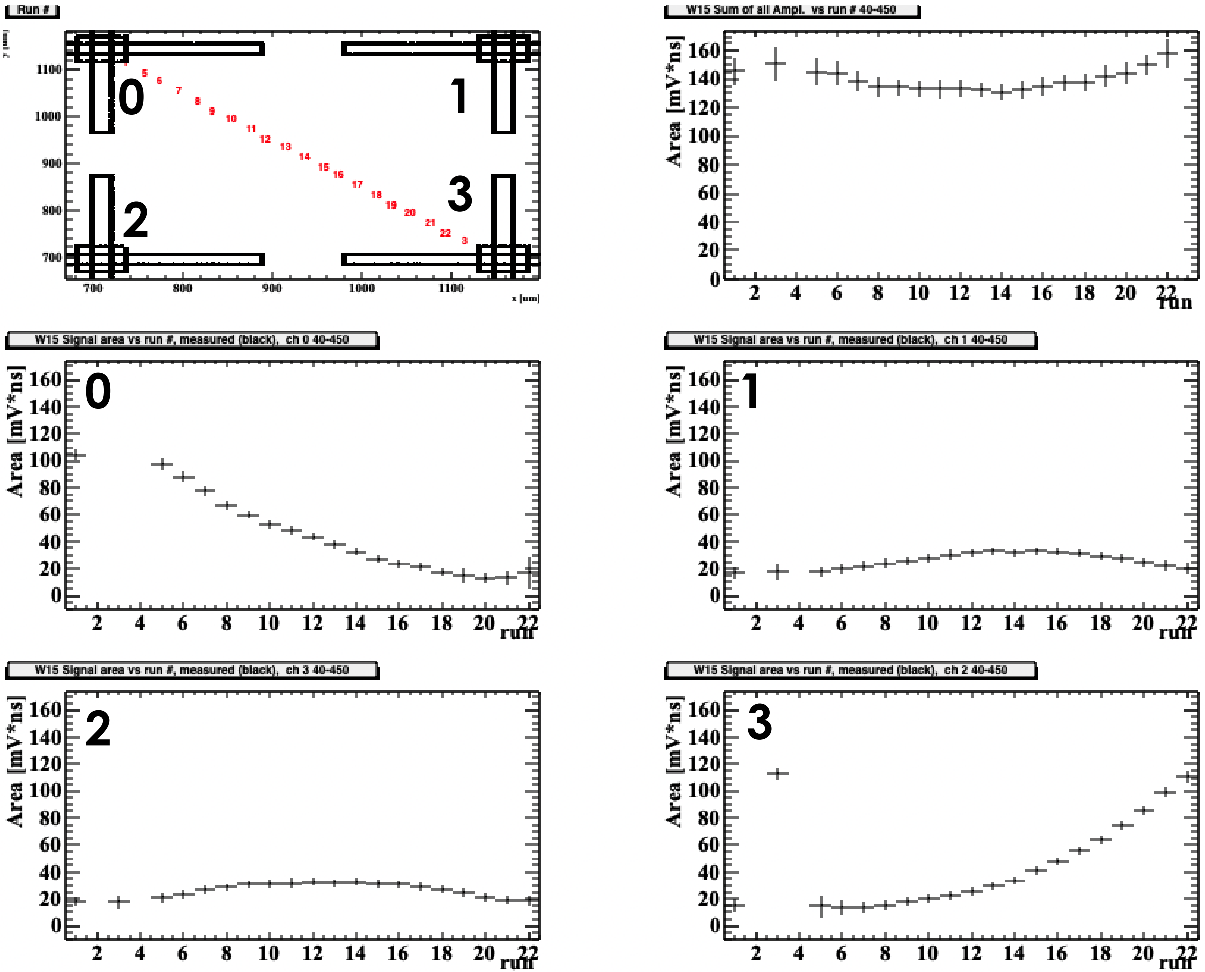
The curves “amplitude vs distance” for the two pitches are almost identical if the distance is expressed in unit of pitch

Note: the signal is almost contained within a pixel, even if they have very different sizes

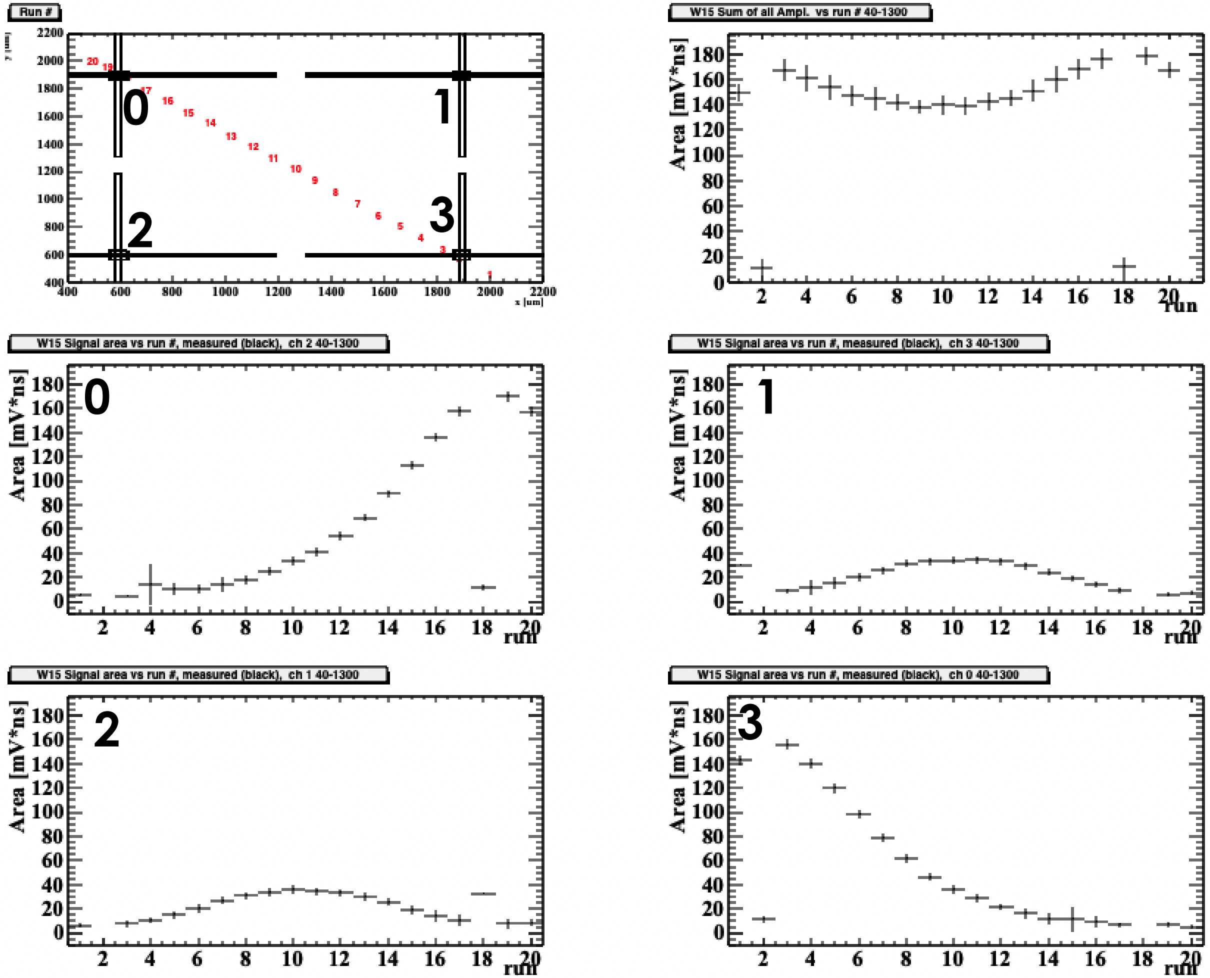
==> the cross geometry behaves as envisioned.

Signal sharing among the 4 pads vs run

450 μm pitch



1300 μm pitch



This is the complete signal splits for signals shot along the diagonals

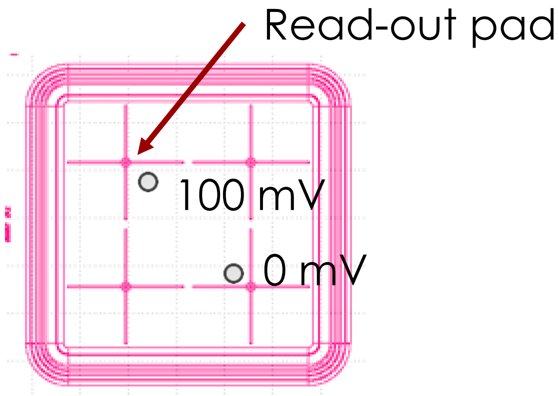
Position resolution

The main component of the position resolution is the position jitter, defined as:

$$\sigma_{jitter} = \frac{\sigma_{el\_noise}}{\frac{dV}{dx}}$$

Imagine a system with a single read-out pad where a hit generates:

- A signal of 100 mV when shot near a pad
- A signal of 0 mV when shot at the opposite corner
- Noise – 2 mV (as in our lab)

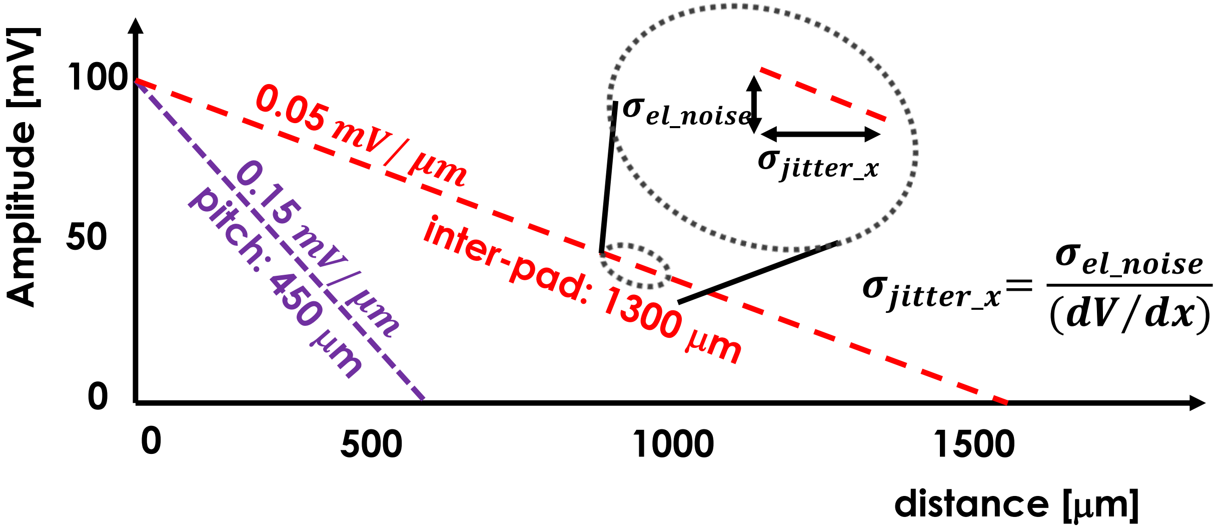


In this simplified system, the signal decreases by:

- Pitch 1300 μm: 0.05 mV/μm
- Pitch 450 μm: 0.15 mV/μm

So, the jitter is:

- **Pitch 1300 μm: 2 mV/(0.05 mV/μm) = 40 μm**
- **Pitch 450 μm: 2 mV/(0.15 mV/μm) = 14 μm**



$$\sigma_{jitter\_x} = \frac{\sigma_{el\_noise}}{(dV/dx)}$$

Obviously the real reconstruction is more complex, 4 pads are contributing

Position reconstruction

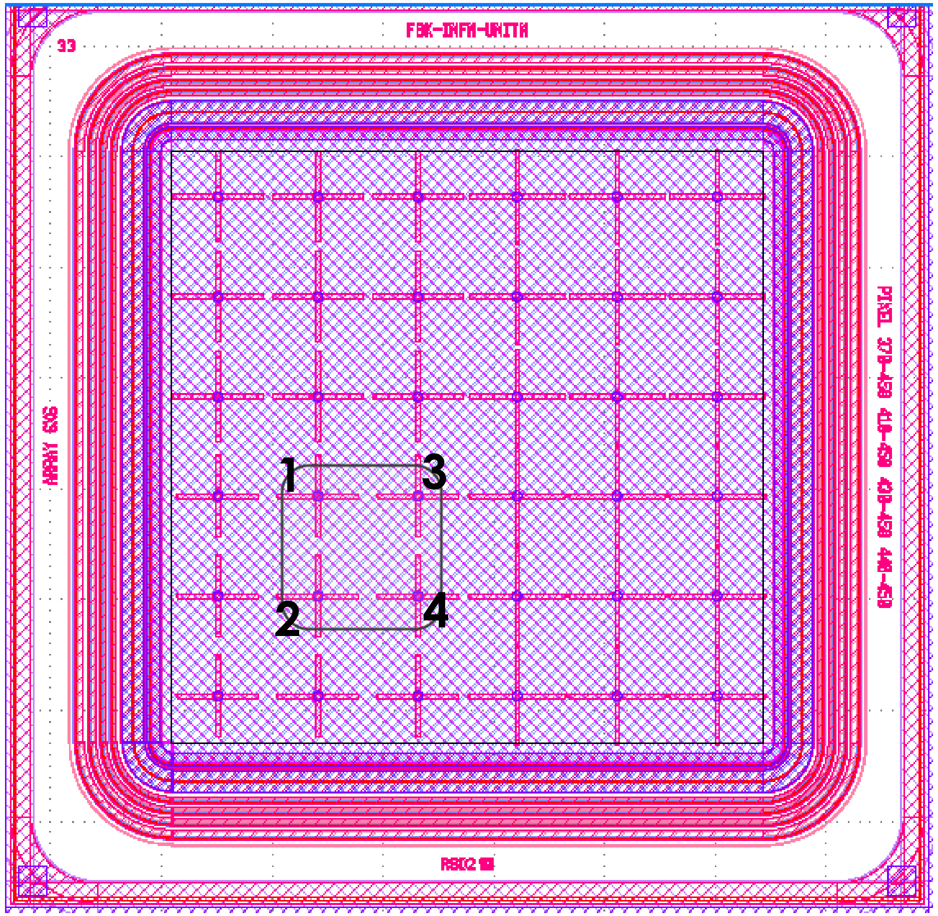
4 pads are readout, all others connected to gnd

Reconstruction method via charge imbalance (aka charge-weighted position centroid):

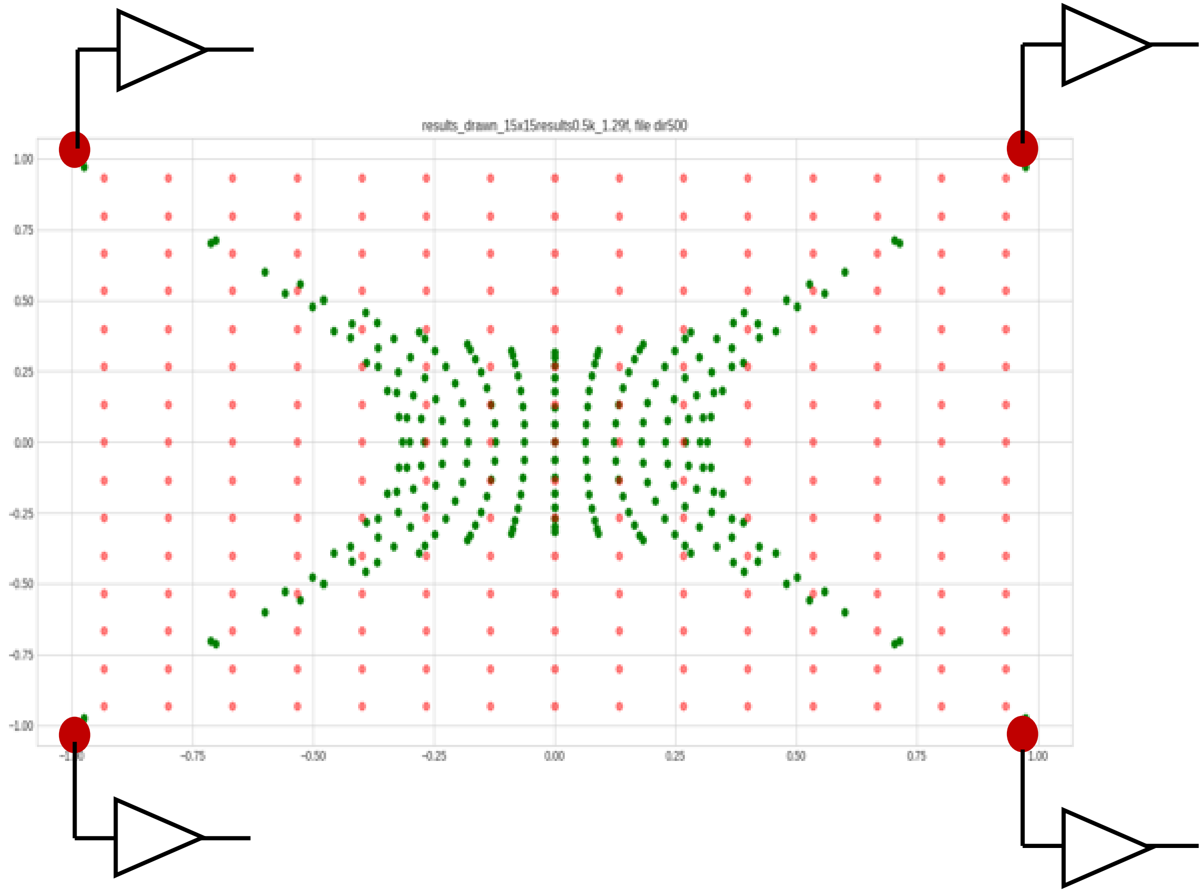
$$x_i = x_{center} + \frac{pitch}{2} * \frac{Q_3 + Q_4 - (Q_1+Q_2)}{Q_{tot}}$$

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

This is the simplest alghoritms for position reconstruction.



Simulation results



Shoot in a grid of points, and see where the position is reconstructed:

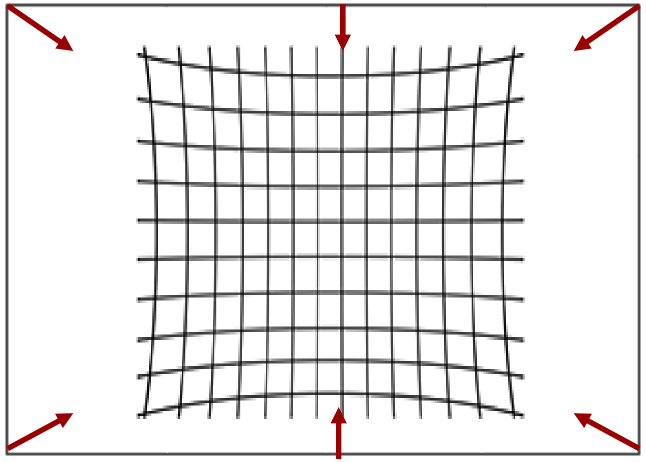
Red: points where the signals are injected

Green: reconstructed points

The reconstructed points (in green) show a distortion effect called "pincuschion" (very common in other resistive surfaces)

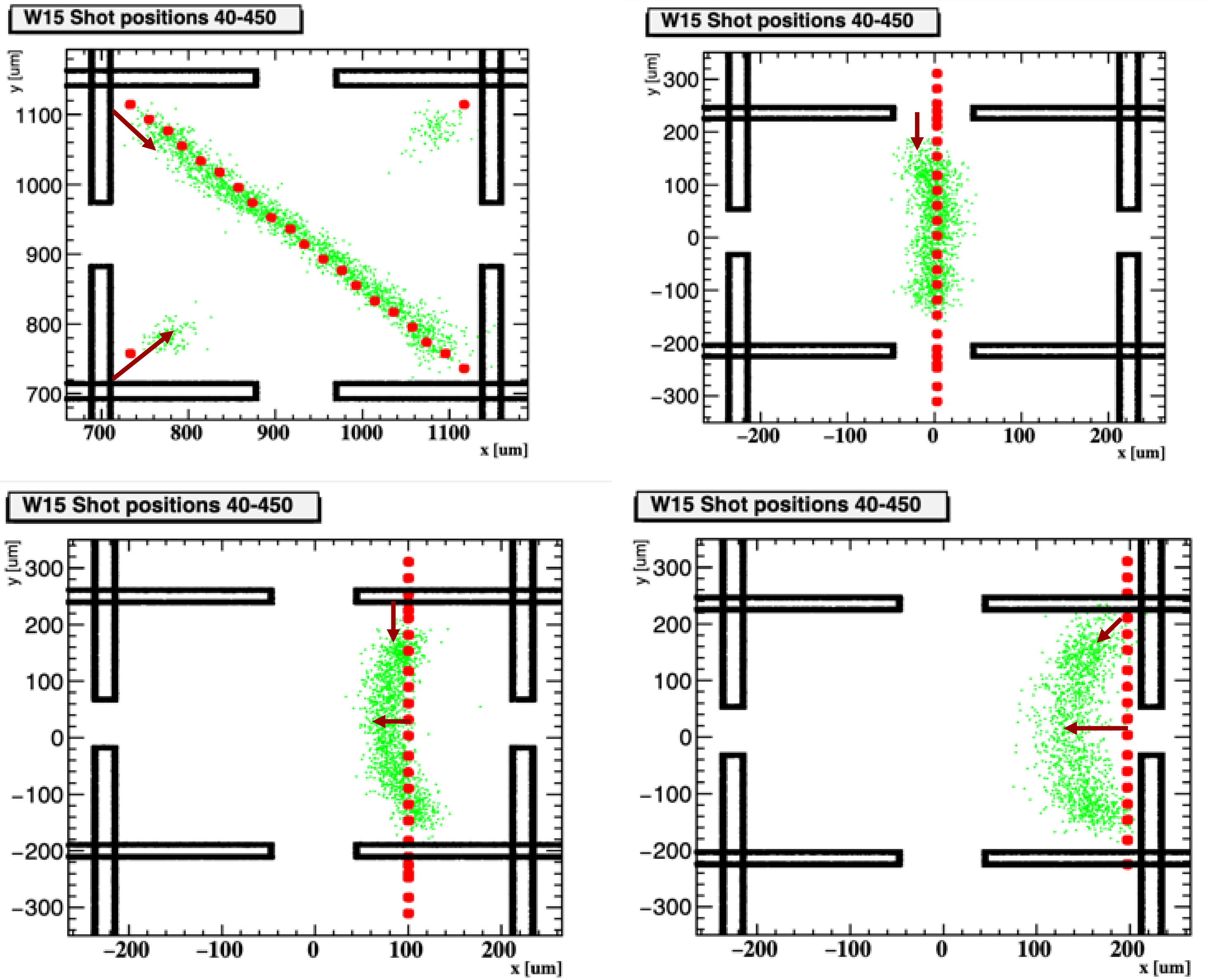
Reconstruction results: 450 μm pitch

In the geometry with crosses the "pincuschion" distortion is present, but not very pronounced



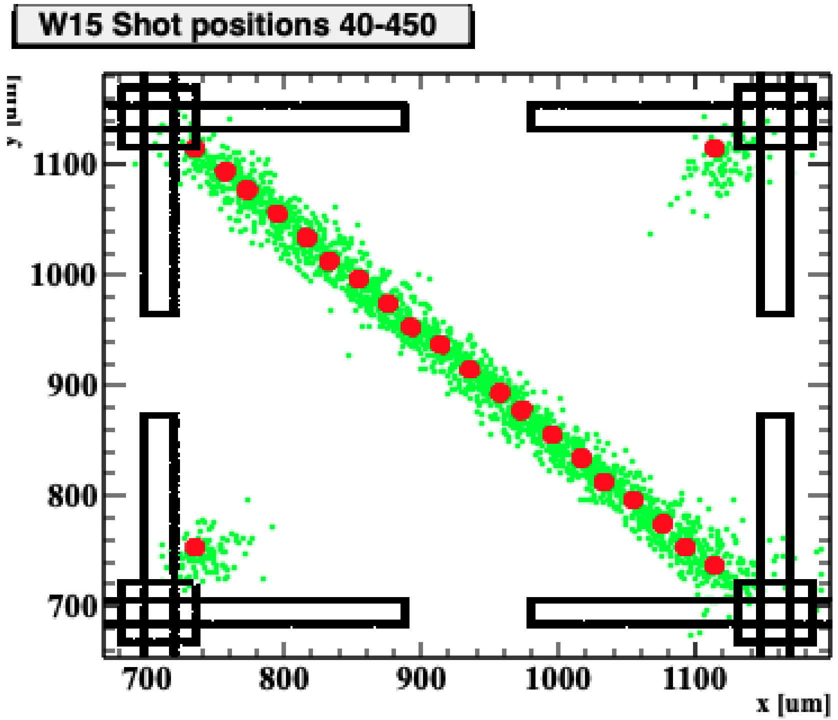
The points are "compressed" towards the center.
It is possible to correct this distortion, either with an analytic law or a map.

Laser position **red**, reconstructed position **green**



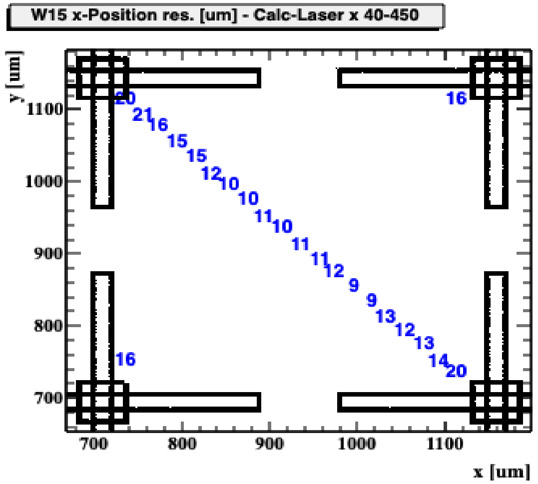
Position resolution for 450 μm pitch, gain = 10

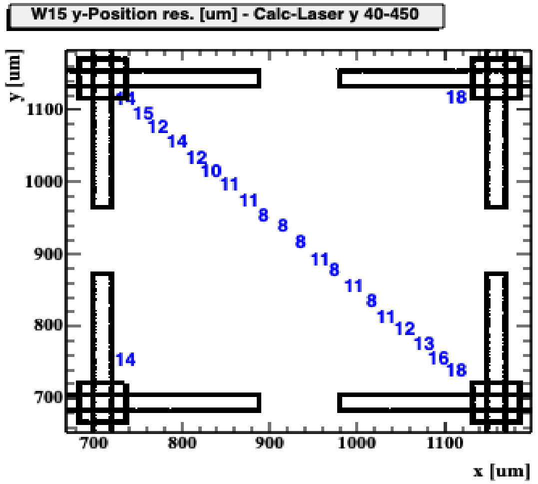
After correcting for the distortion, the position resolution is about **13 μm** (gain ~10)



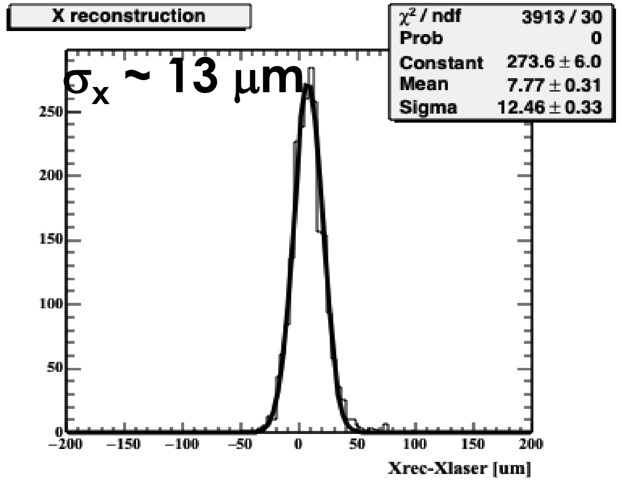
Laser position **red**, reconstructed position **green**

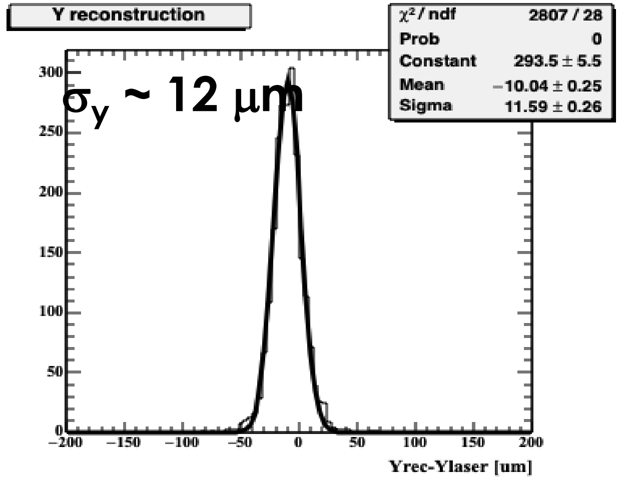
Resolution at various positions





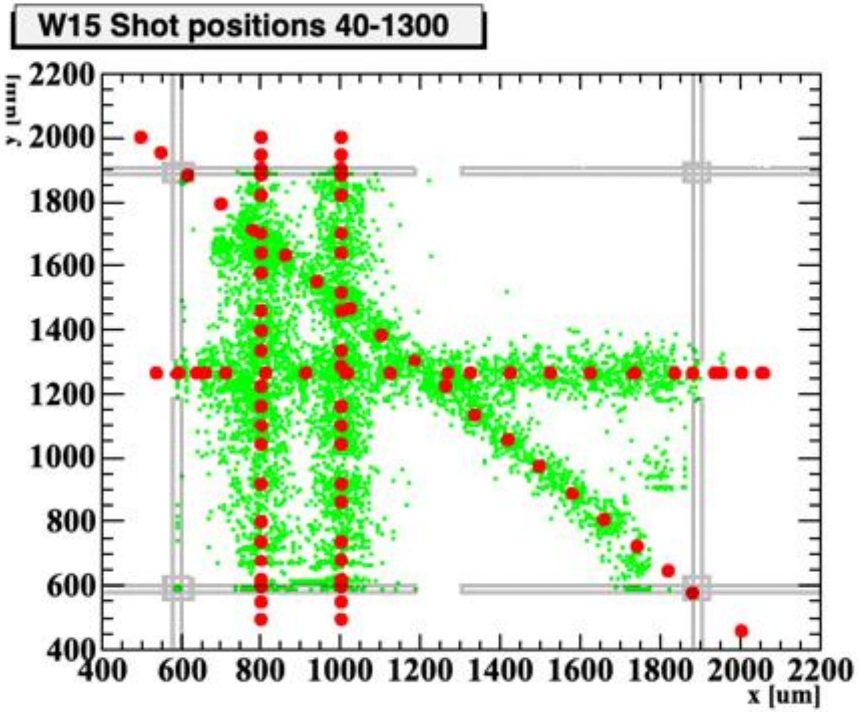
Resolution at all positions





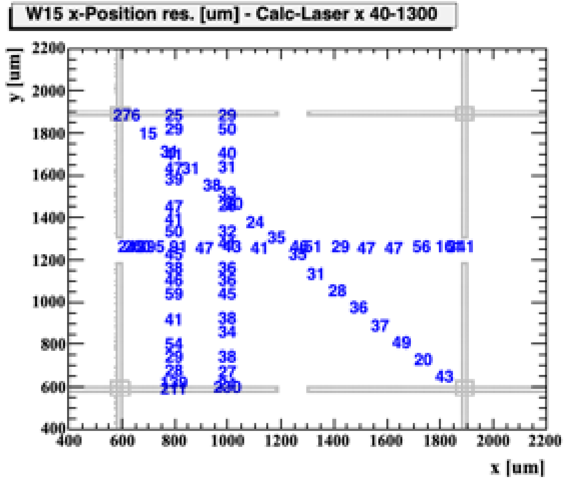
Position resolution for 1300 μm pitch, gain = 10

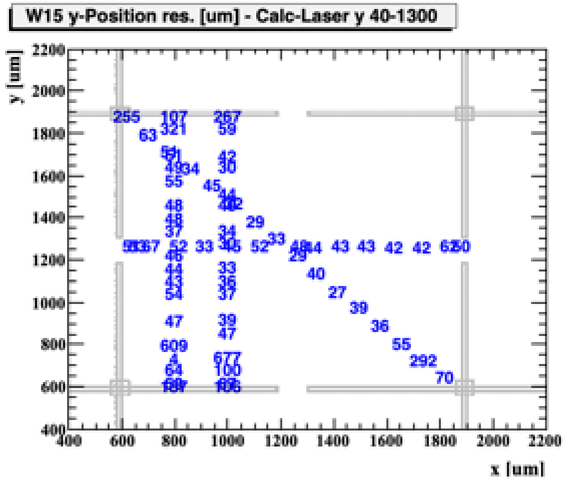
After correcting for the distortion, the position resolution is about **40 μm** (gain ~10)



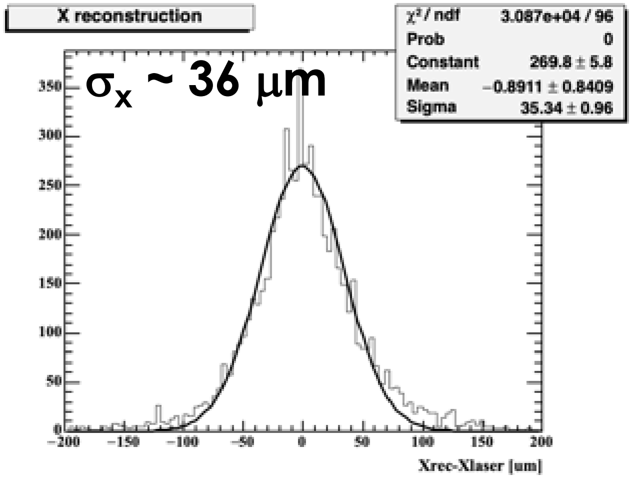
Laser position **red**, reconstructed position **green**

Resolution at various positions

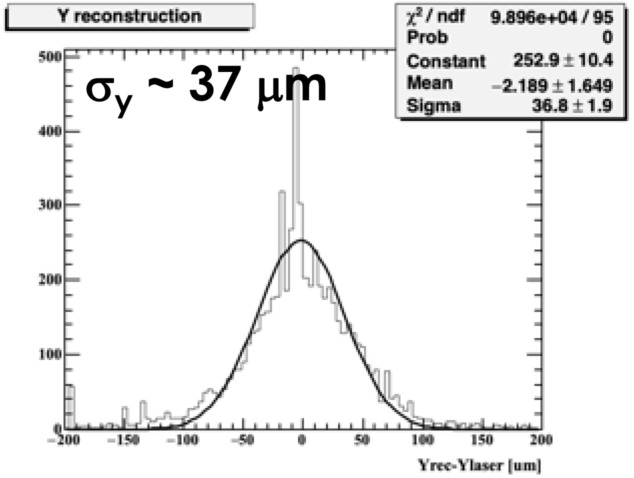




Resolution at all positions



σ_x ~ 36 μm

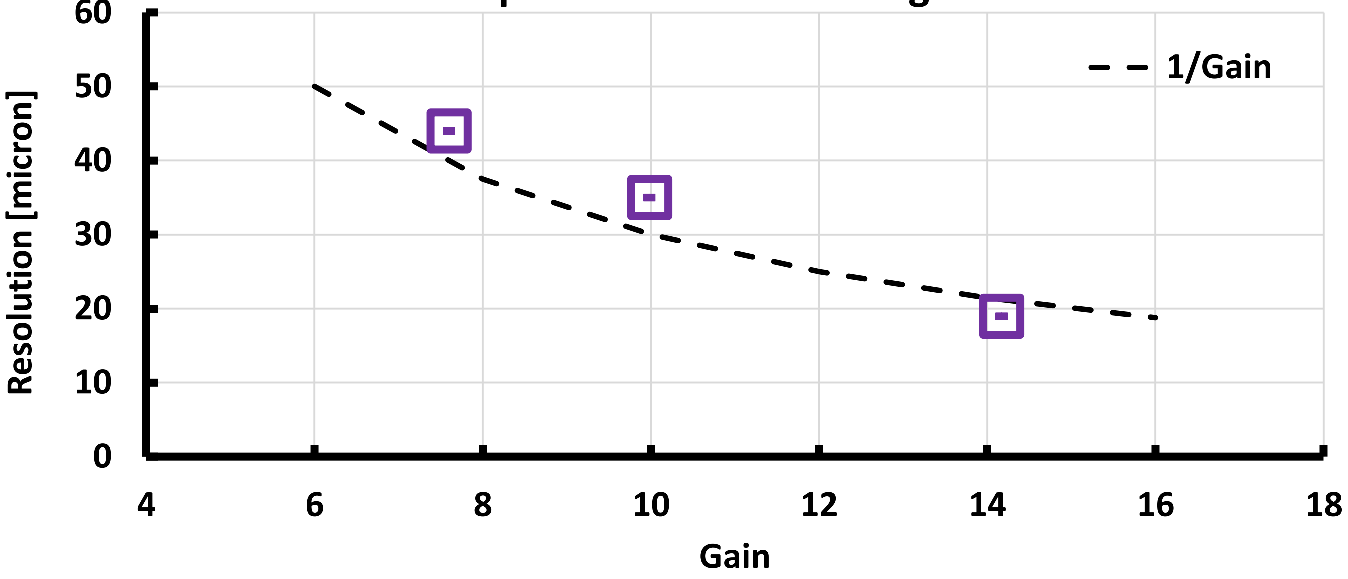


σ_y ~ 37 μm

Position resolution vs gain or pitch

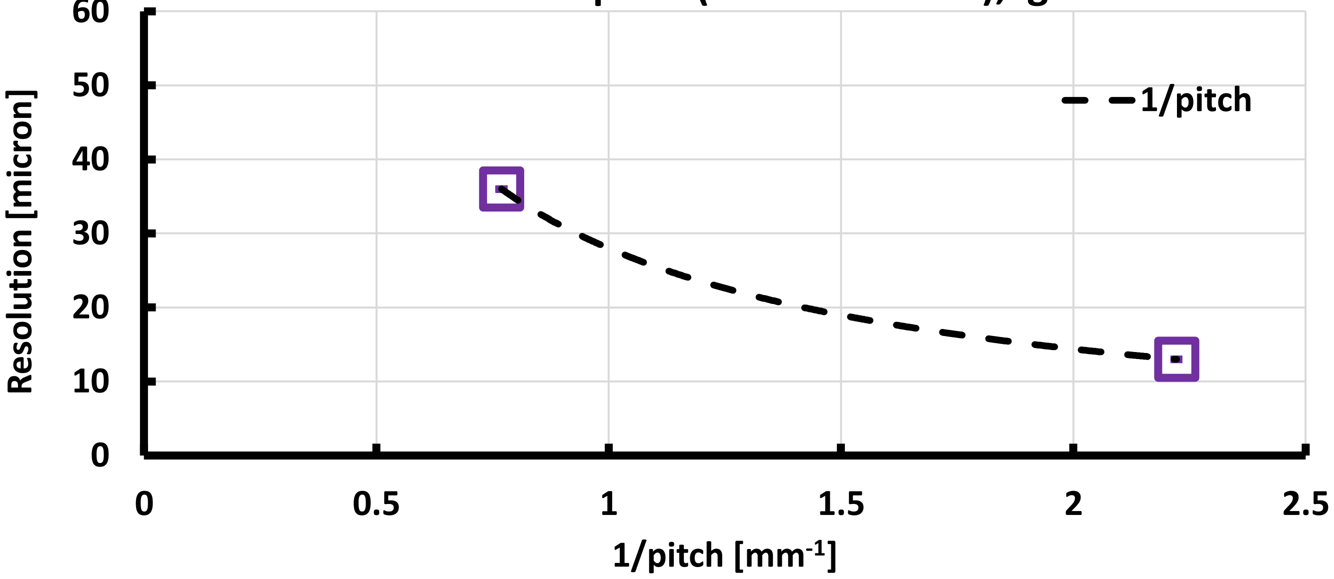
The position resolution is a strong function of the signal amplitude, reaching about **σ_x ~ 20 µm** for a gain ~14

Pitch 1.3 mm: position resolution vs gain



For equal gain, the position resolution improves as 1/pitch

Position resolution vs pitch (0.45 & 1.3 mm), gain = 10



Note:

σ_x follows quite well the behaviour 1/(dV/dx)

(equivalent to 1/gain or 1/pitch)

as predicted by the jitter formula

Signal delay

The signal delay increases with distance, however, given the shape of the electrodes, the determination of ”distance” it is not straightforward: the vertex? the closest metal?

Along the diagonal, the delay for this specific structure is about 0.3 ps/ µm

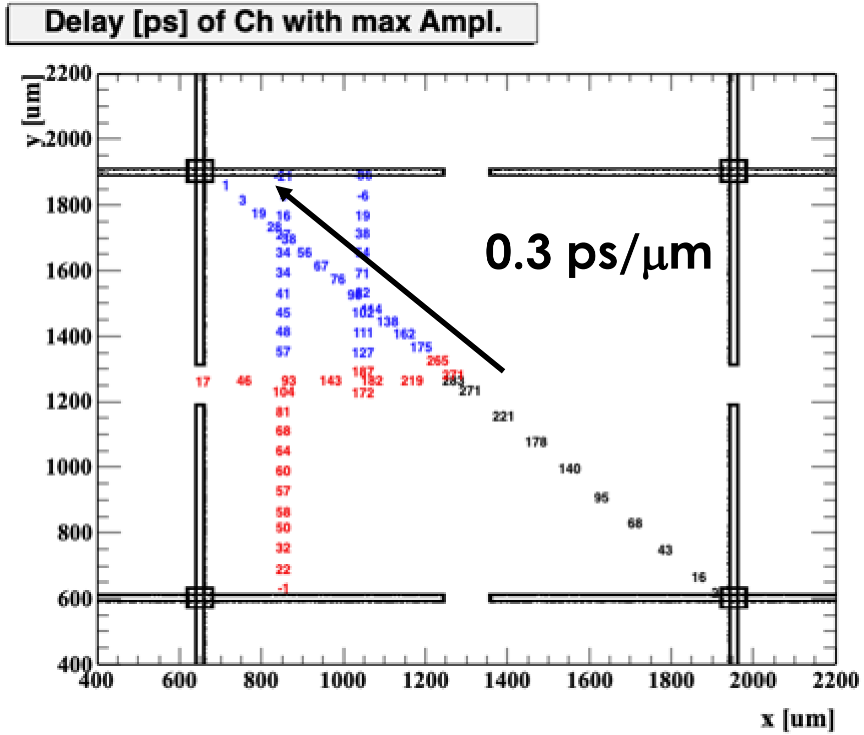
==> the delay is the same for 450 µm and 1300 µm pitch

==> the delay increases in wafer with a higher sheet resistance

The time of each pad ***i*** is defined as:

$$t_i^{True} = t_i^{Meas} - delay$$

Using the laser, a delay map has been created



Signal delay of the channel with the maximum amplitude for different hit positions

Hit time

The time of the hit can be defined in several ways.

For examples:

1) Amplitude-weighted

(leads to uniform precision on the pixel surface):

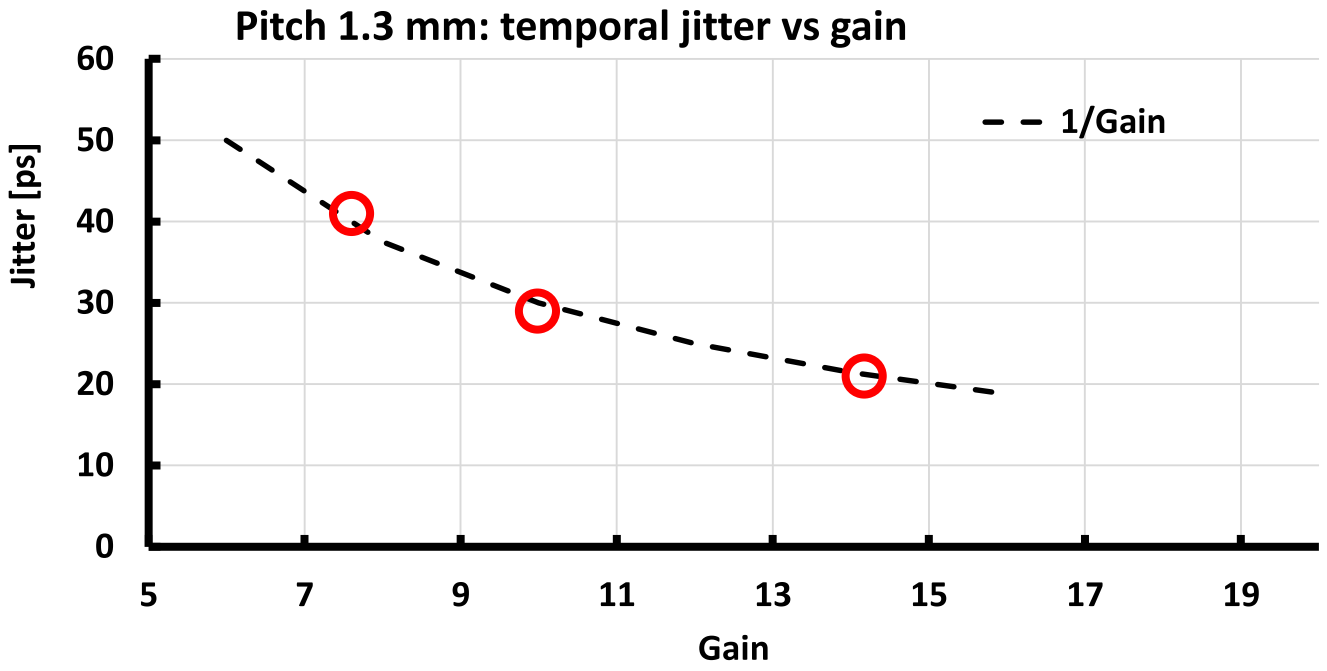
$$Hit_{Time} = \sum_{1}^{4} \frac{A_i t_i^{True}}{A_i}$$

2) Time of the channel with the maximum amplitude:

(works best when one amplitude is much larger than the other 3, not uniform on the pixel surface)

$$Hit_{Time} = t_{ChMax}^{True}$$

The jitter is quite good, similar to that of an LGAD with equivalent gain



Amplitude weighted temporal resolution (jitter component) vs gain

(laser contribution not subtracted)

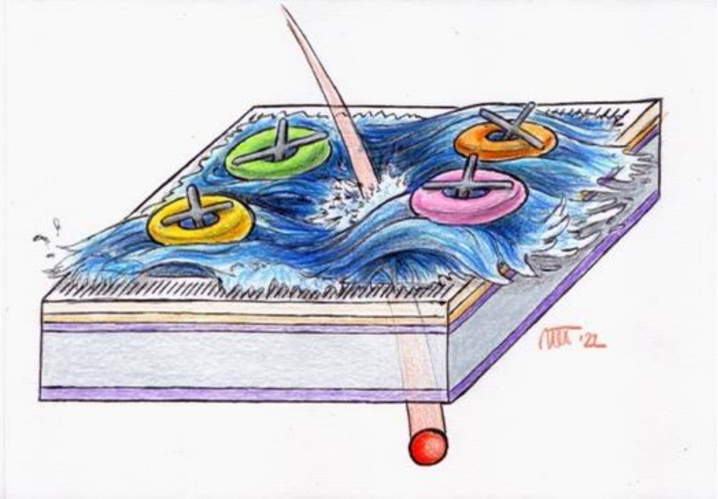
Conclusions

The FBK – AC-RSD2 production has been designed to:

- Have uniform signal sharing on the pixel surface
- Limit sharing to a well defined set of electrodes

Electrodes shaped as crosses are very effective in reaching both goals

- Sharing happens on the whole pixel surface
- The signal is mostly contained within 4 electrodes



In our studies, we reached a spatial resolution about 3% of the pitch at gain = 10

- Pitch = 450 μm ==> σ_x ~ 13 μm; σ_x/pitch ~ 3%
- Pitch = 1300 μm ==> σ_x ~ 37 μm; σ_x/pitch ~ 3%

Spatial resolution depends upon ~ 1/gain, ~ 1/pitch, and ~noise

Temporal resolution similar to LGAD with equivalent gain

Acknowledgement

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- RD50 collaboration
- INFN - Gruppo V, RSD projects
- INFN – FBK agreement on sensor production (convenzione INFN-FBK)
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)
- Ministero della Ricerca, Italia , PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare