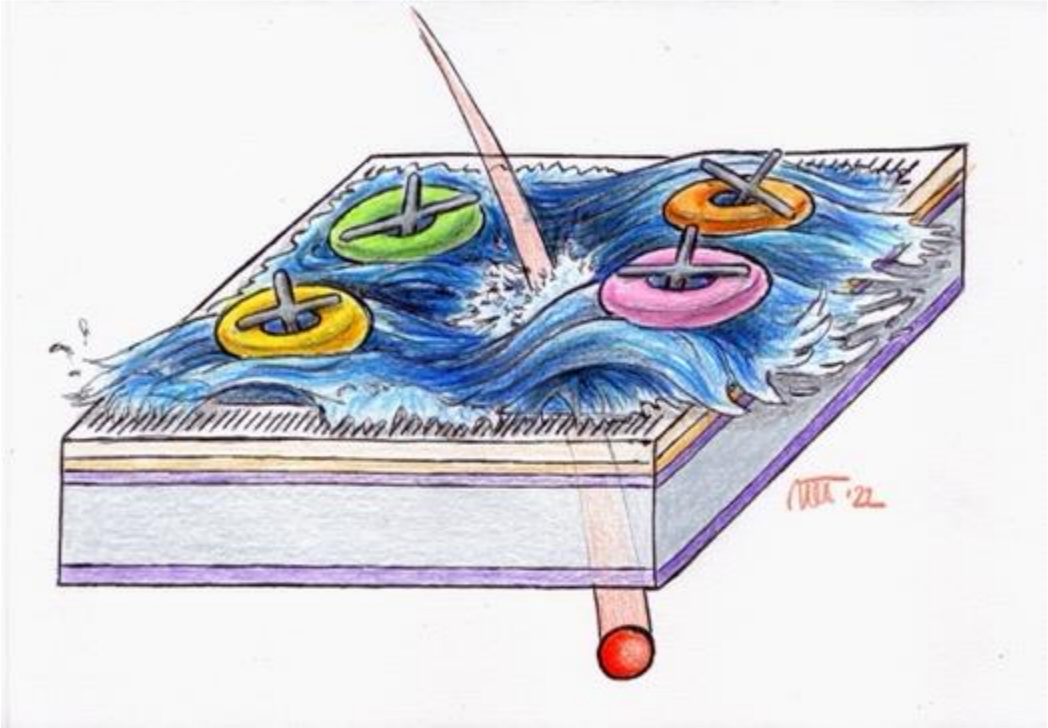
High-Precision Tracking with Large Pixels using Thin Resistive Silicon Detectors



This talk focuses on the spatial resolution of RSD sensors

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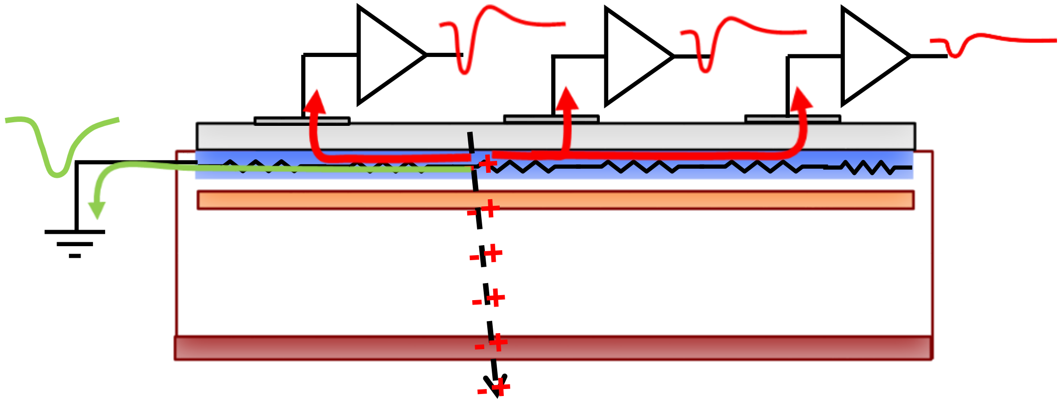
UFSD group

Image courtesy of M. Tornago

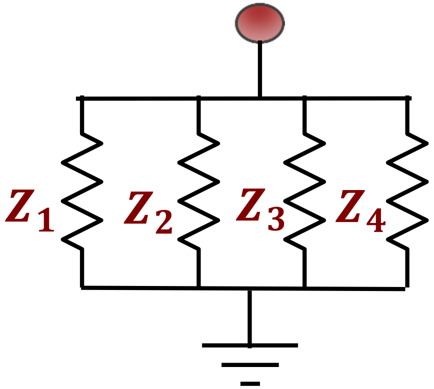
Aide memoire: RSD principle of operation

AC signals (red) are measured on the pads
DC signal (green) on the resistive layer

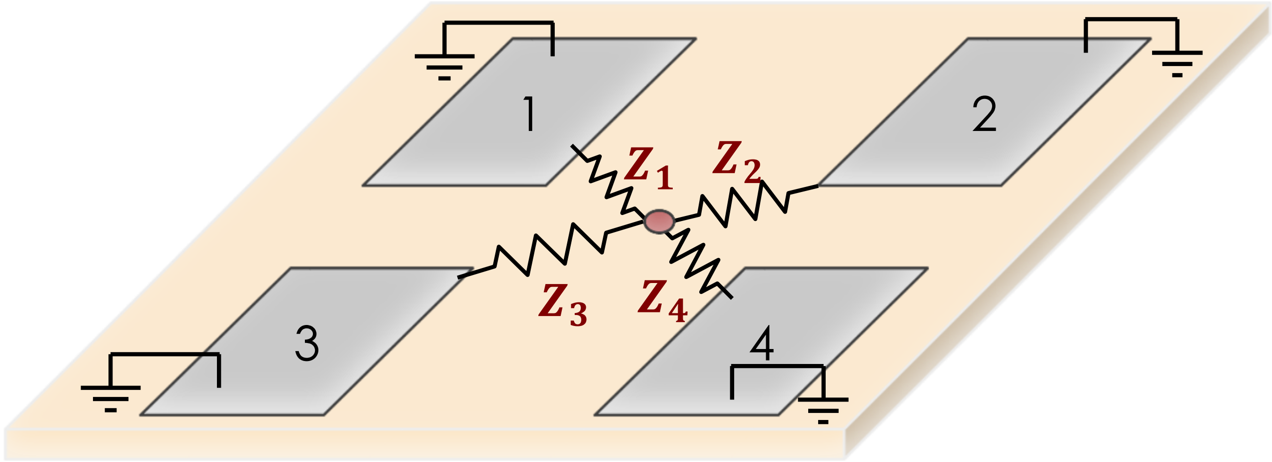


The signal sees several impedances $\boldsymbol{Z_i}$ in parallel, and it is split according to Ohm's law.

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



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

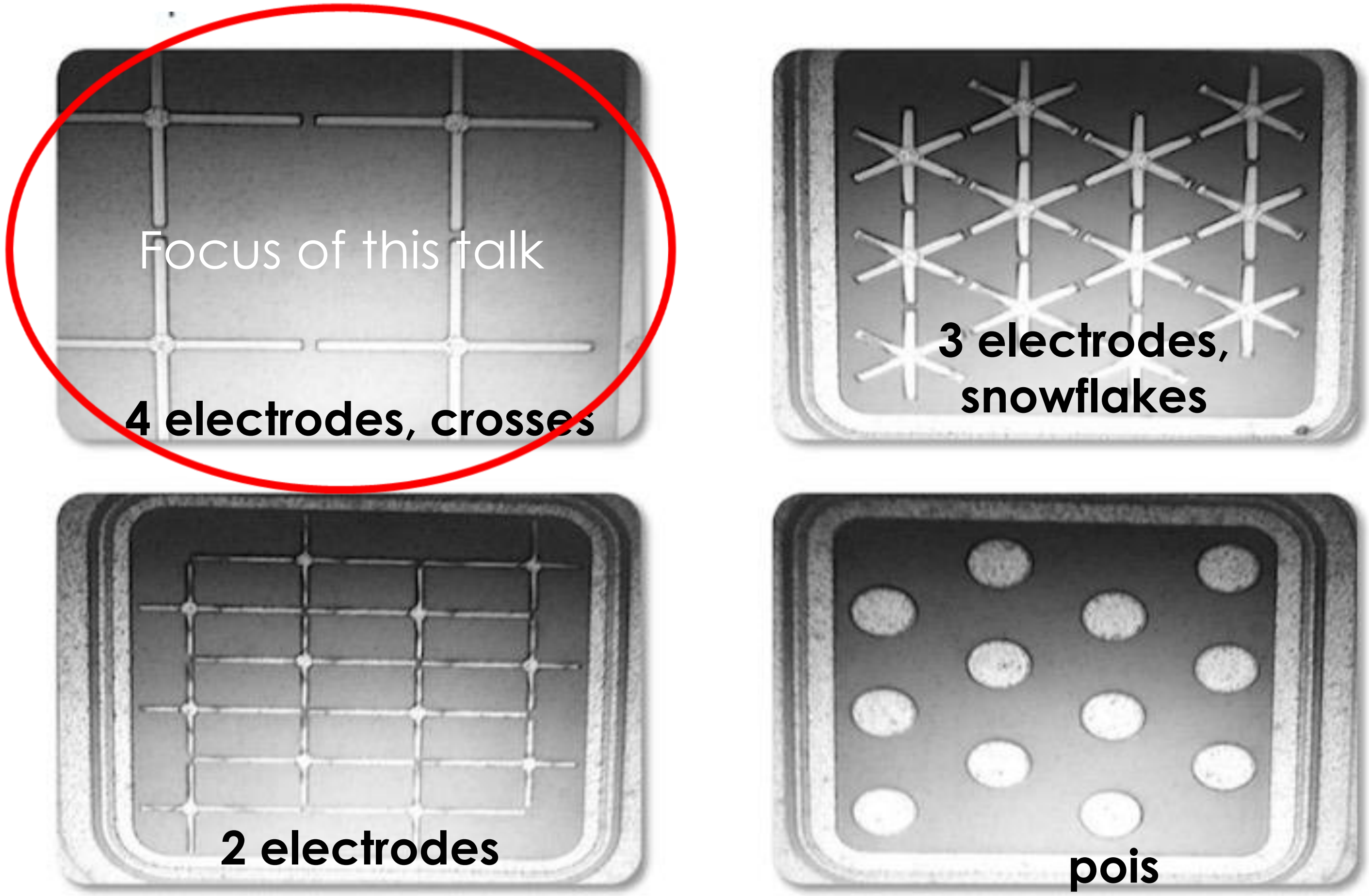


The FBK RSD2 production

Goals for RSD2:

Optimized signal sharing for uniform performance

- Optimize the fabrication parameters (resistivity, oxide, gain layer)
- Reduce as much as possible the metal area of the pads
- Design electrodes shape that would maximize the response uniformity obtained with the collected charge



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

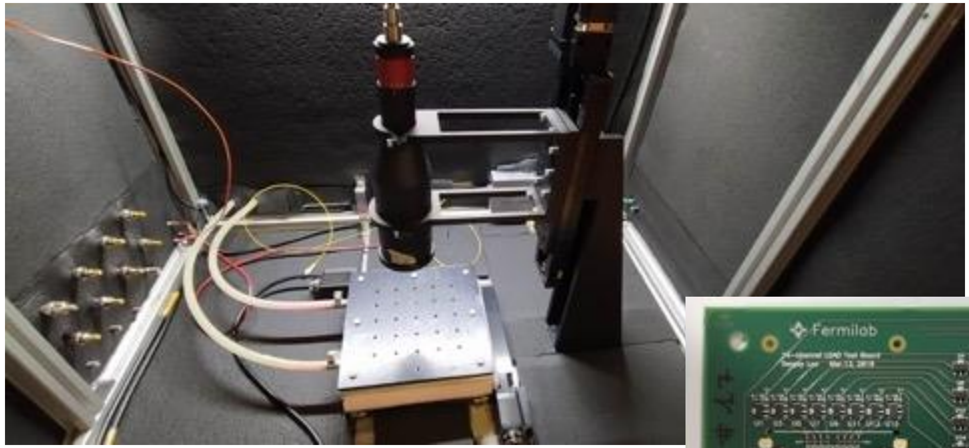
Experimental set-up

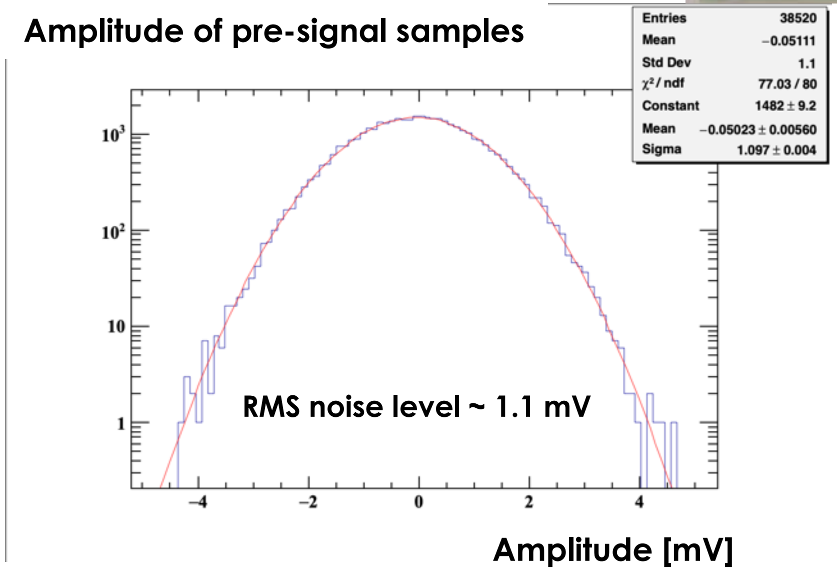
The **Particulars TCT laser setup** has been used:

- 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

Sensors are read out with 16-ch fast analogue board, developed at FNAL

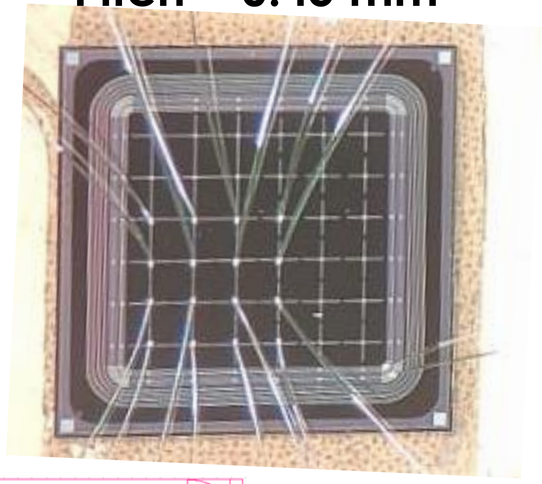
The signals are recorded with16-ch CAEN Digitizer (5 Gs)





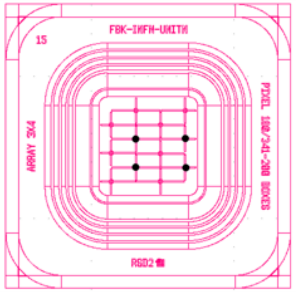
RSD2 sensors with cross-shaped electrodes

Pitch = 0.45 mm

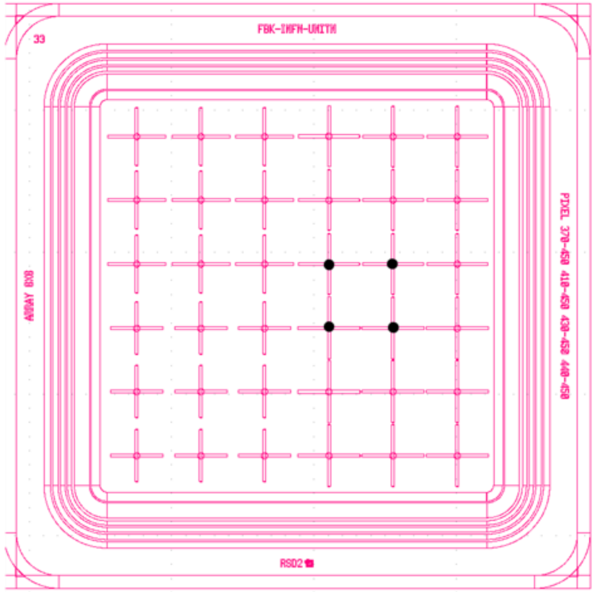


In this study, the perfomance of sensors with electrodes shaped as crosses is presented.

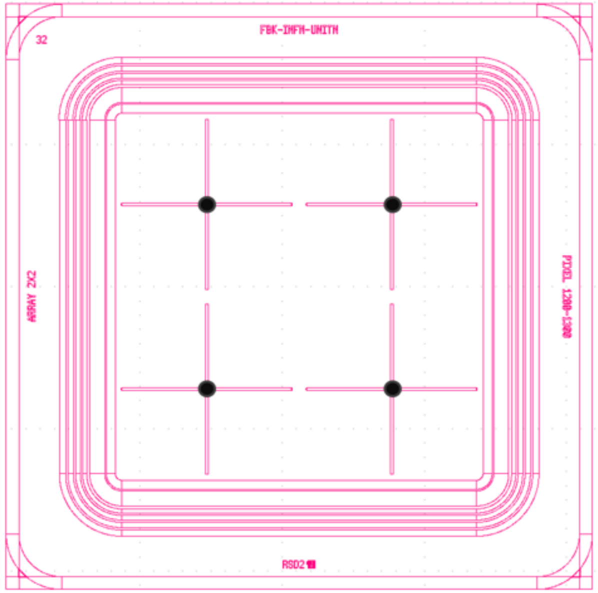
4 different dimensions: 200, 340, 450, and 1300 μm



(A)
200 x 340 μm^2



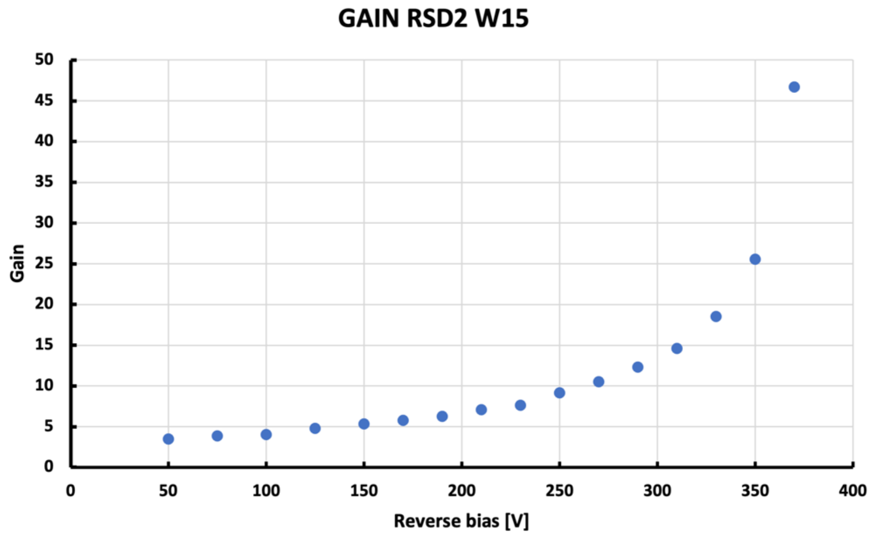
(B)
Pitch = 450 μm



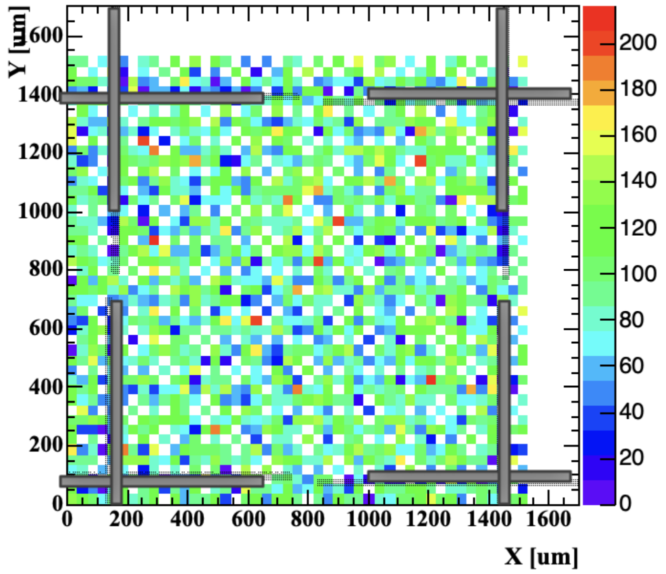
(C)
Pitch = 1300 μm

RSD2 W15 gain

All structures belong to W15,
For reference, this is the gain curve



Area of the DC-signal in the 1300 x 1300 μm² pixel.



The amount of charge injected by the laser has been measured using the area of the DC-signal.

Note: in some plots, values of gain > 30 are reported.
These are achieved by increasing the laser intensity to about 3 MIP while keeping the bias in the range 250V-330V.
This feature is indicated as "**gain equivalent**"

Hit position resolution

$$\sigma^2_{hit} = \sigma^2_{jitter} + \sigma^2_{signal} + \sigma^2_{reconstruction} + \sigma^2_{sensor}$$

σ^2_{jitter} : contribution due to the electronic noise. **This term determines the measurement precision**. See next slide

σ^2_{signal} : systematic error in the reconstruction of the signal amplitude. For example, the amplitude, due to the fitting method to determine the maximum of the gaussian, has a 1% systematic error.

$\sigma^2_{reconstruction}$: Possible systematic errors in the reconstruction program, the position is always shifted in x or y. **This determines the measurement accuracy.**

σ^2_{sensor}: **this term groups all sensor imperfections.** For example, uneven n+ resistivity

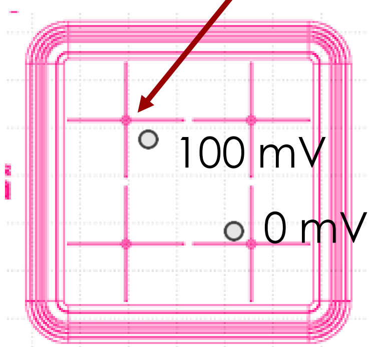
Position Jitter

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

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

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 ~1 mV (as in our lab)

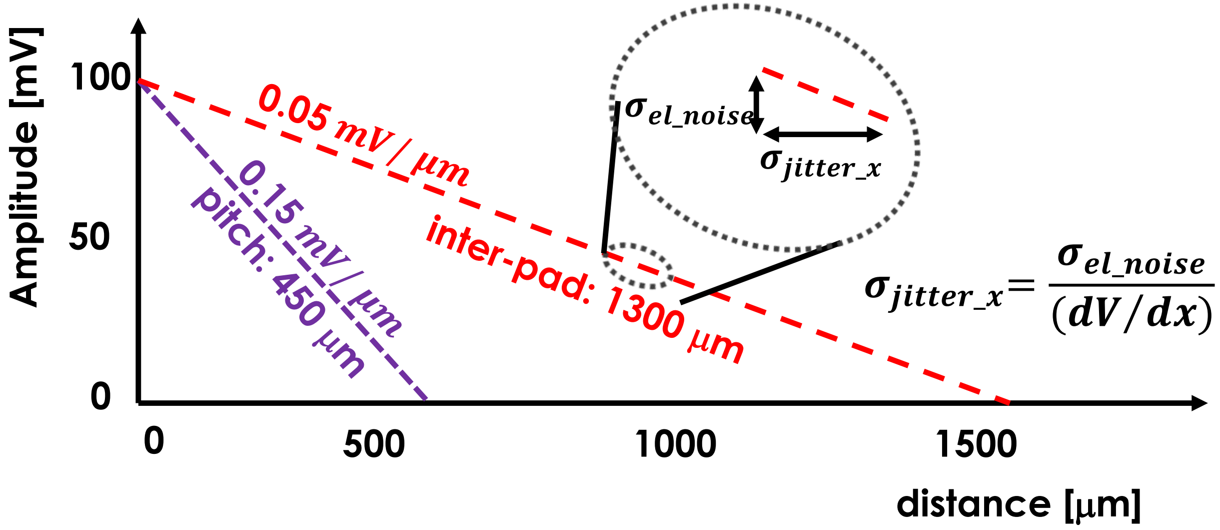


In this simplified system, the signal decreases by:

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

So, the jitter is:

- **Pitch 1300 μm: 1 mV/(0.05 mV/μm) = 20 μm**
- **Pitch 450 μm: 2 mV/(0.15 mV/μm) = 7 μm**

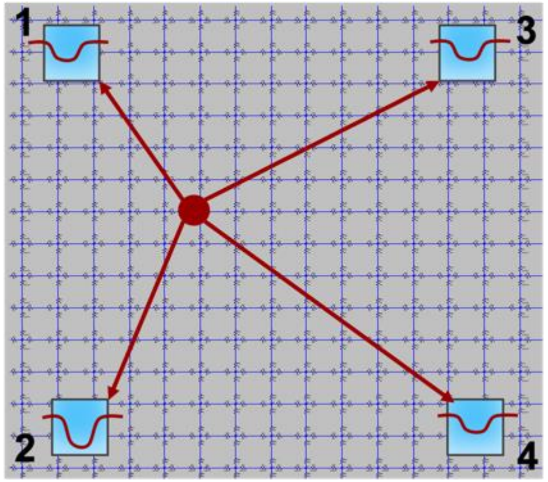


With increasing number *n* of AC-read-out pads, the jitter becomes larger as $\sigma_{jitter} \propto \sqrt{n}$

==> keep the number of read-out pads involved as small as possible

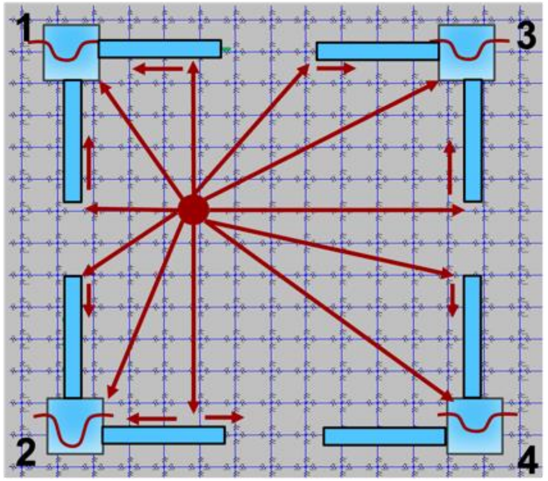
Reconstruction method

In RSD1 we develop an analytical reconstruction method.
This was efficient since there were well defined paths between the hit point and the read-out pads



In RSD2, this is quite difficult as there are multiple paths to a given read-out pad.

For this reason, we use a data-driven approach



Step 1: position reconstruction using charge imbalance

In this analysis, **the 4 pads with the highest signals are used.**

4 pads are readout, all others connected to gnd

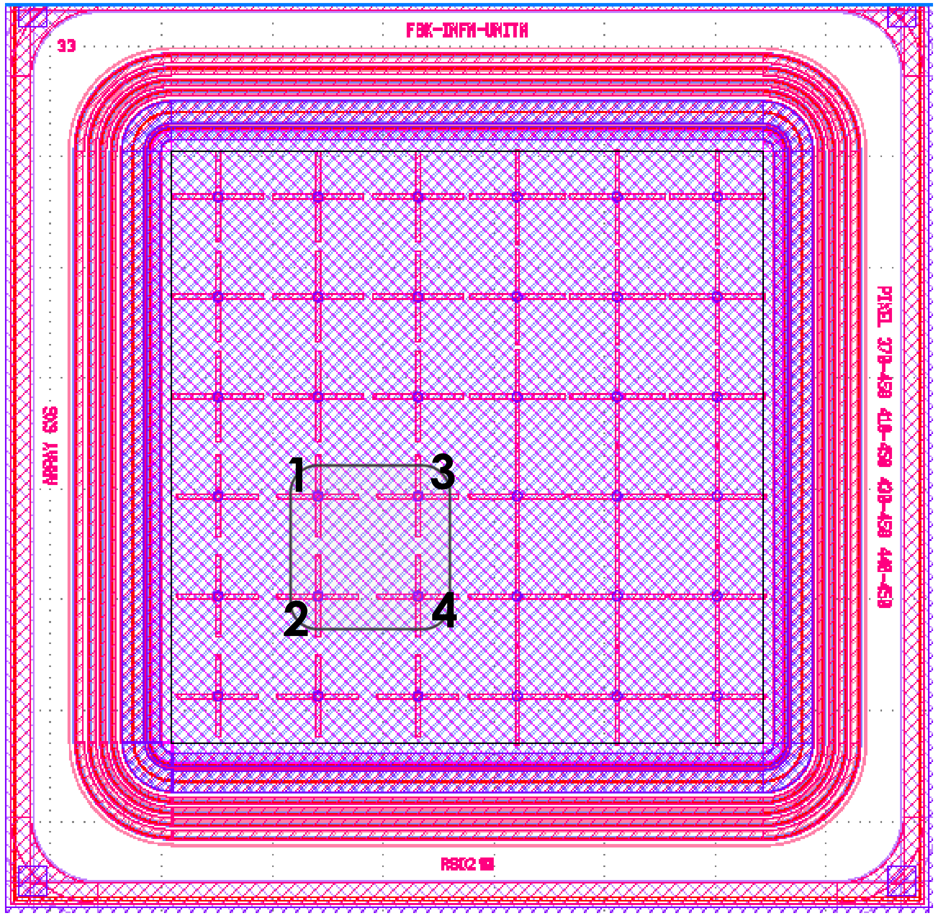
Reconstruction method via charge imbalance:

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

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

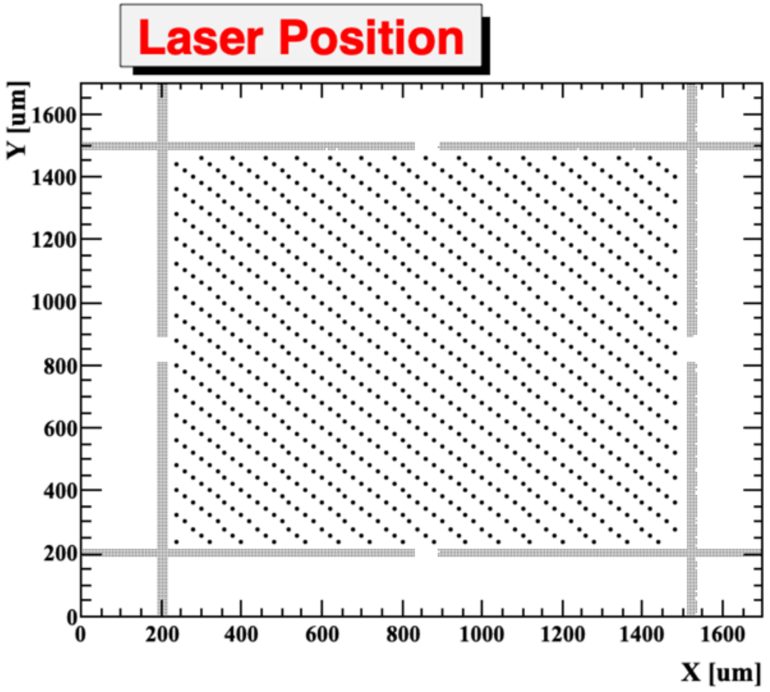
$$k_x = \frac{Q_{tot}}{Q_3 + Q_4 - (Q_1+Q_2)} |_{x@edge}$$

$$k_y = \frac{Q_{tot}}{Q_1 + Q_3 - (Q_2+Q_4)} |_{y@edge}$$

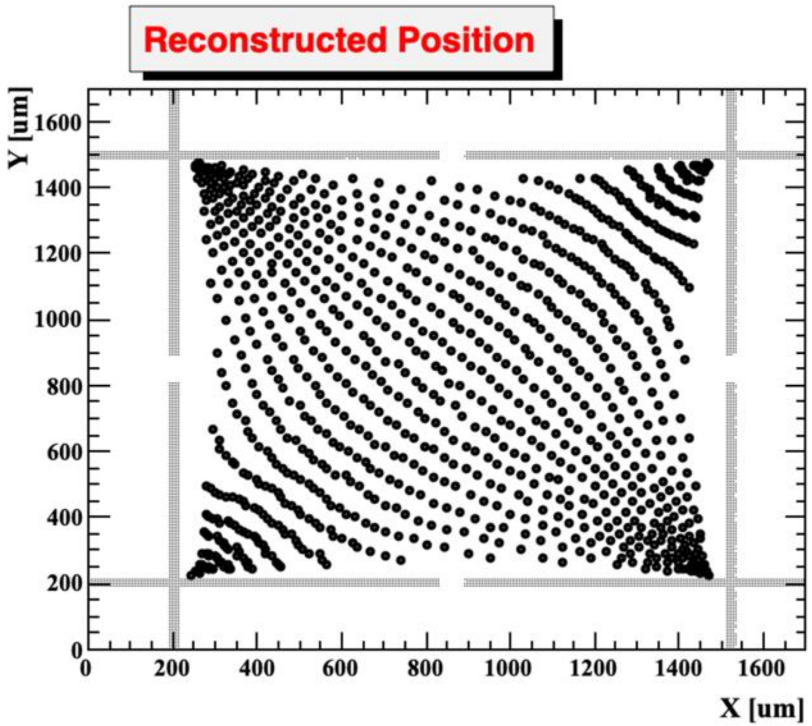


Step 2: evaluate the performance of the reconstruction

Shoot the laser in a grid of points



Reconstruct the hit position with the equations on pag 7



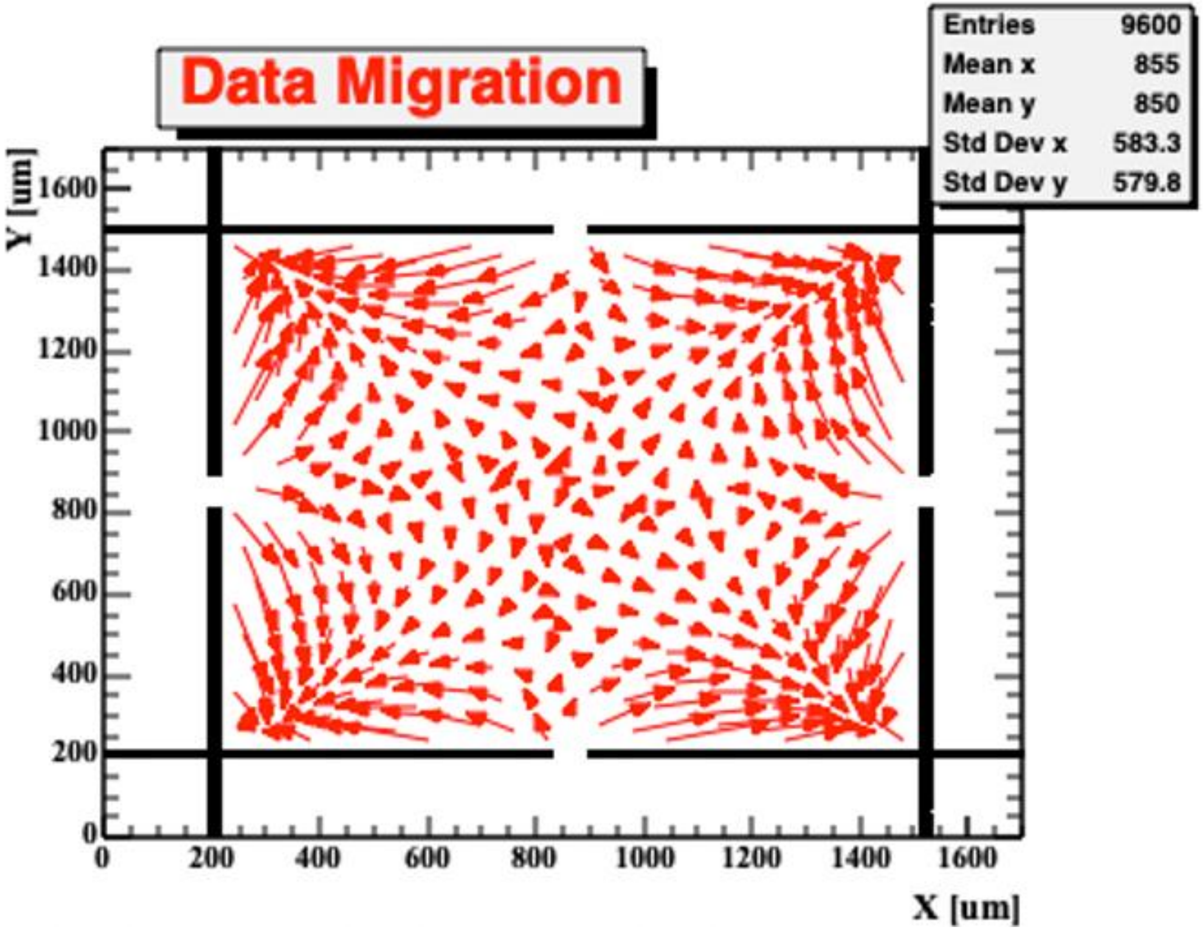
First take-home result: even without any additional correction, the cross-shaped electrodes provide a fairly accurate reconstruction

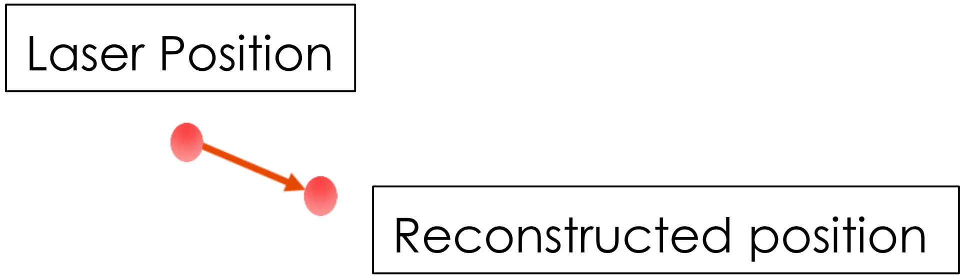
Second take-home result: near the pads, the reconstructed positions are systematically shifted with respect to true positions

Step 3: measure the migration map

Compute the migration map:

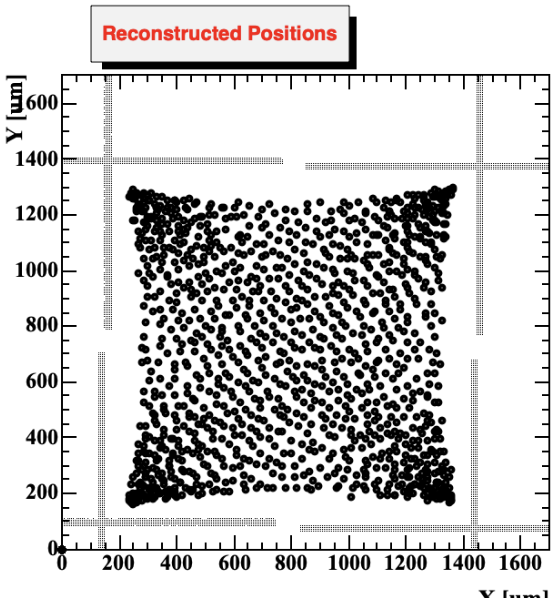
For each laser position, connect the true and reconstructed positions.

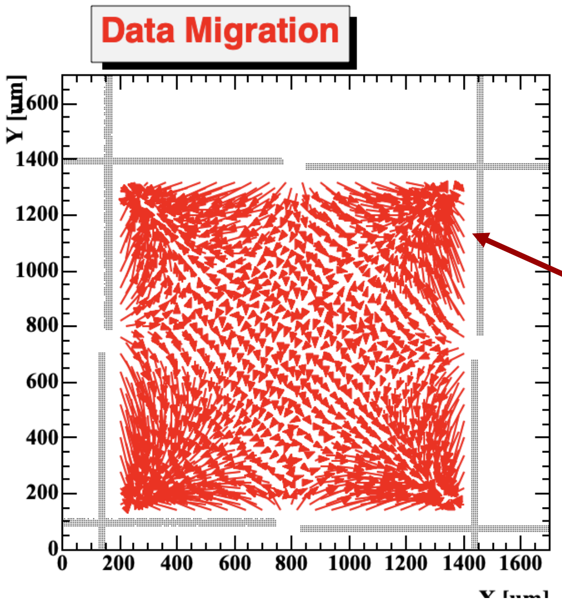




Step 4: apply the correction

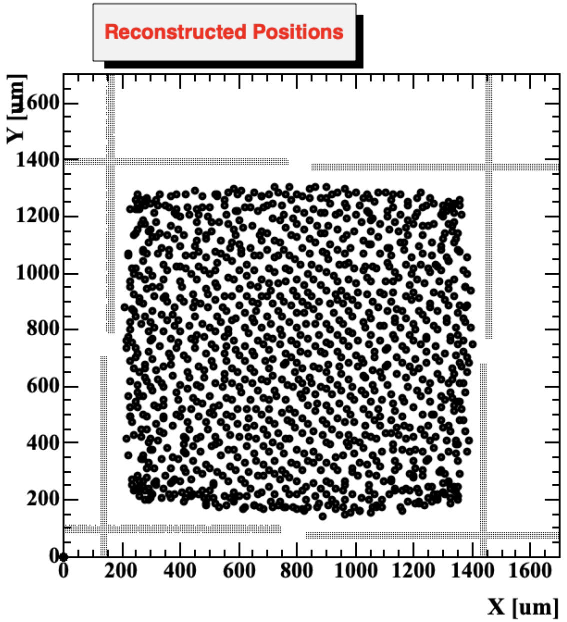
Raw data

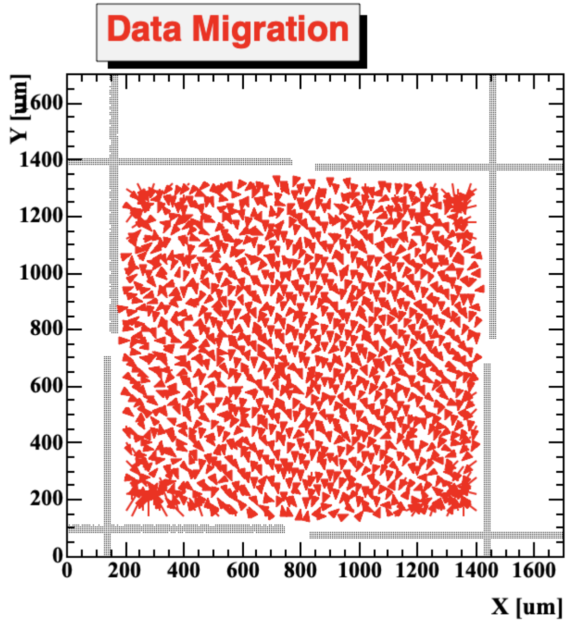




Note: a 30 microns minimum distance from the metal electrodes has been used to ensure the laser shot is fully on the open silicon.

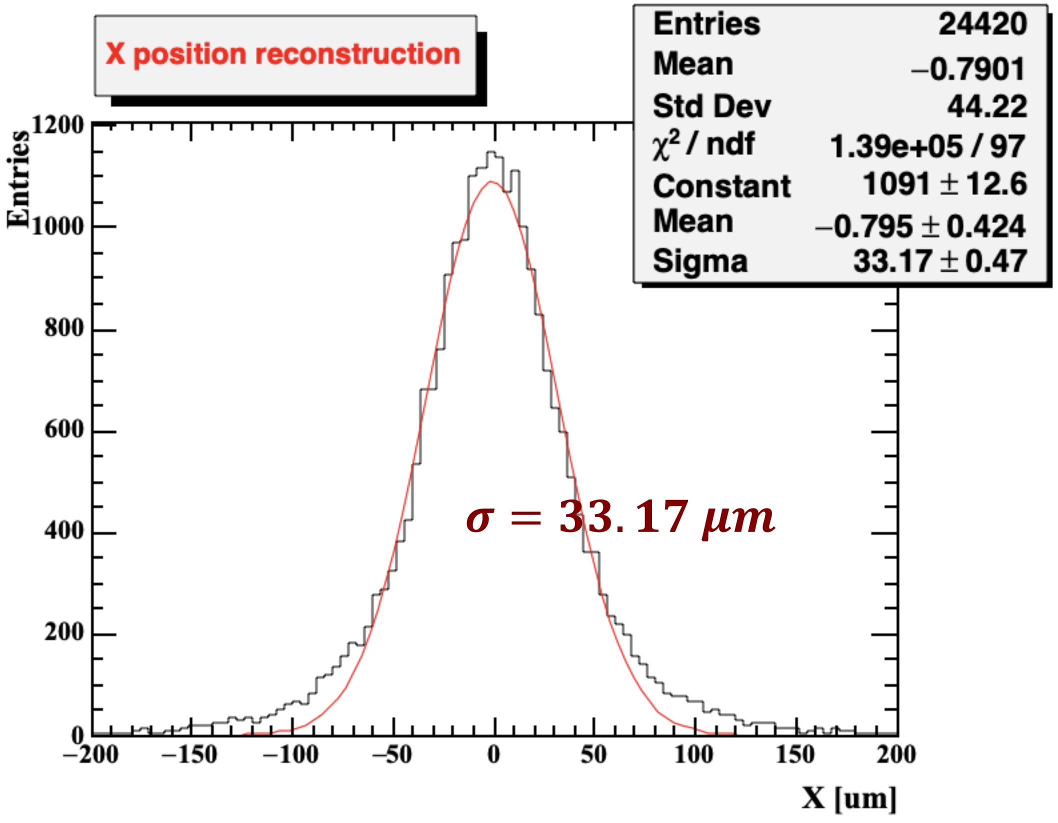
Corrected data

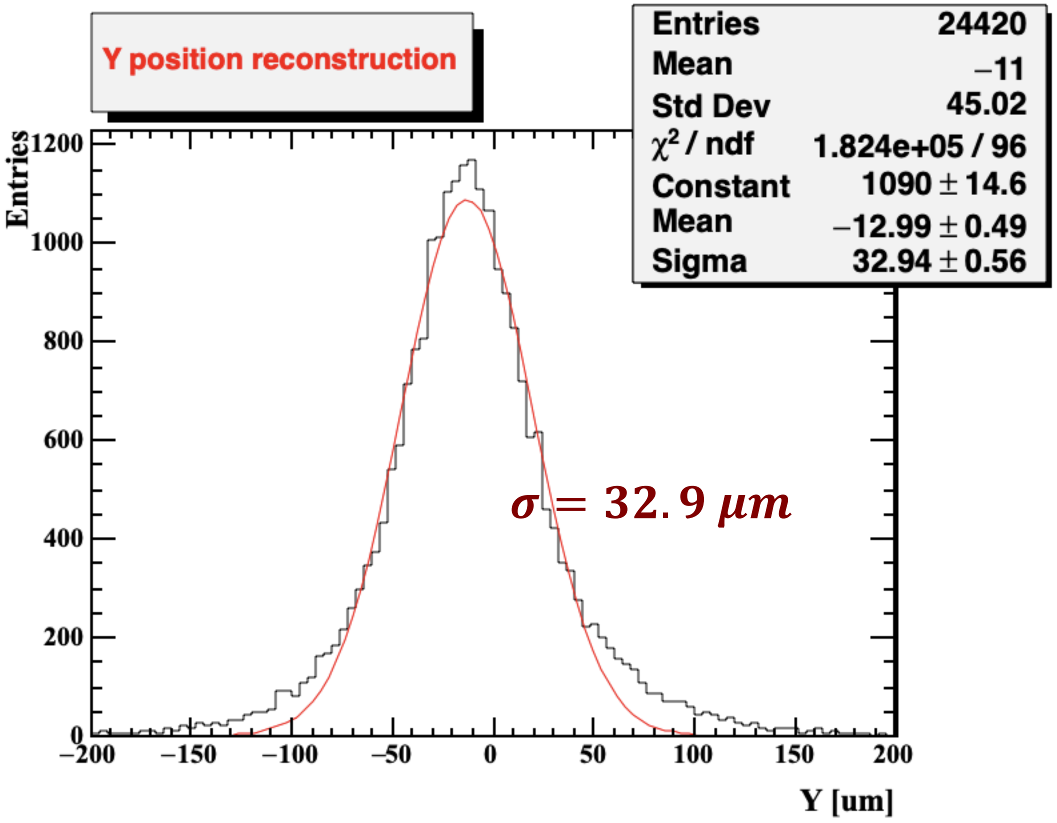




Migration, after correction, is limited

Example: 1300x1300 μm^2, gain = 33

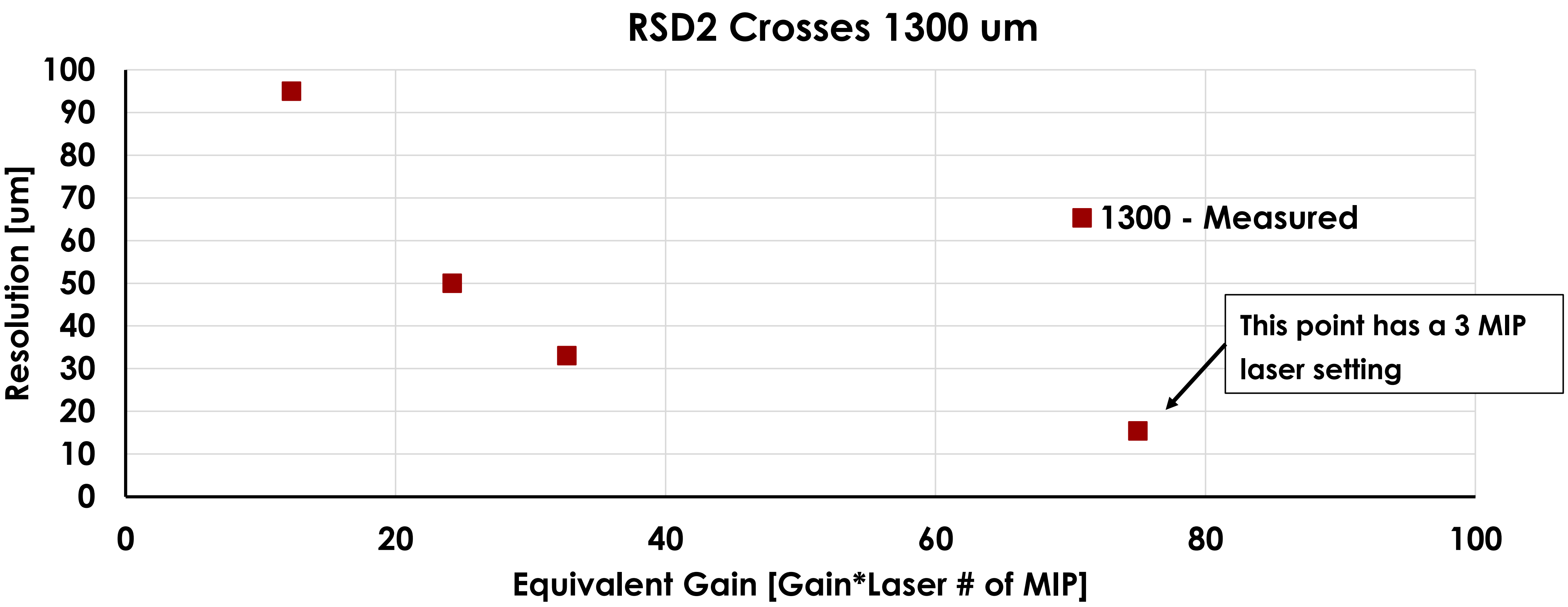




(True-reconstructed) x,y coordinates for the 1300 x1300 μm^2 sensor, gain = 33

The non-gaussian tails are due to the reconstruction near the corners, where migration is the highest

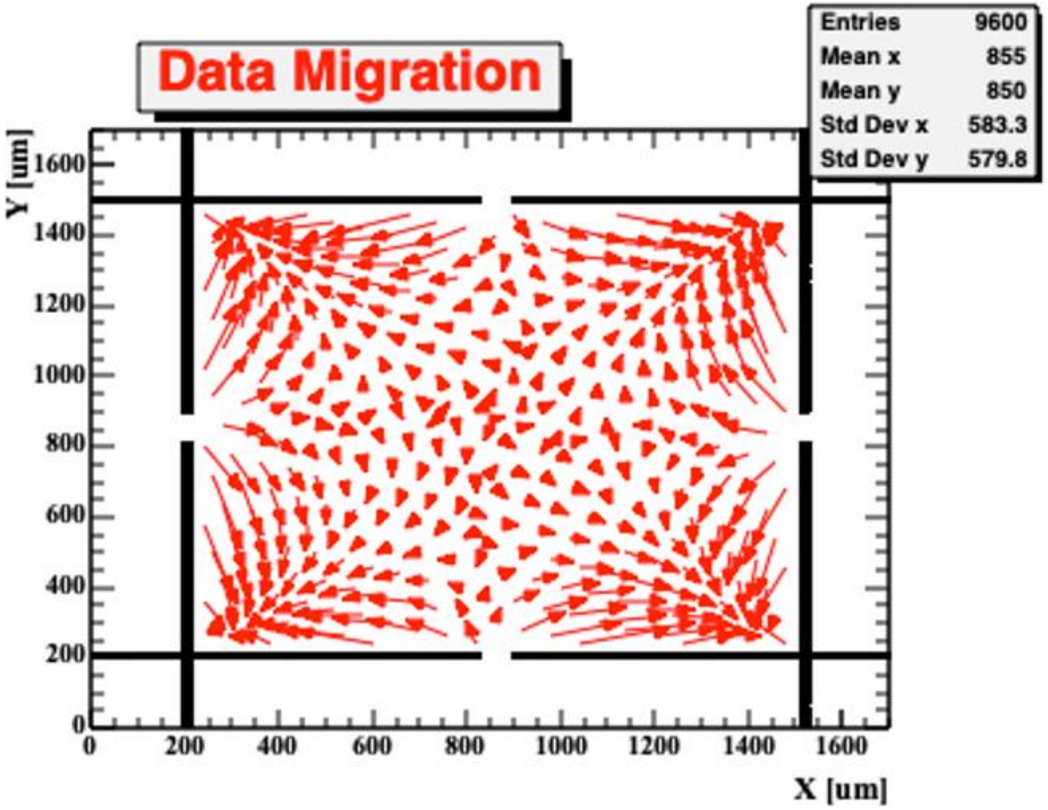
Result for 1300x1300 μm^2

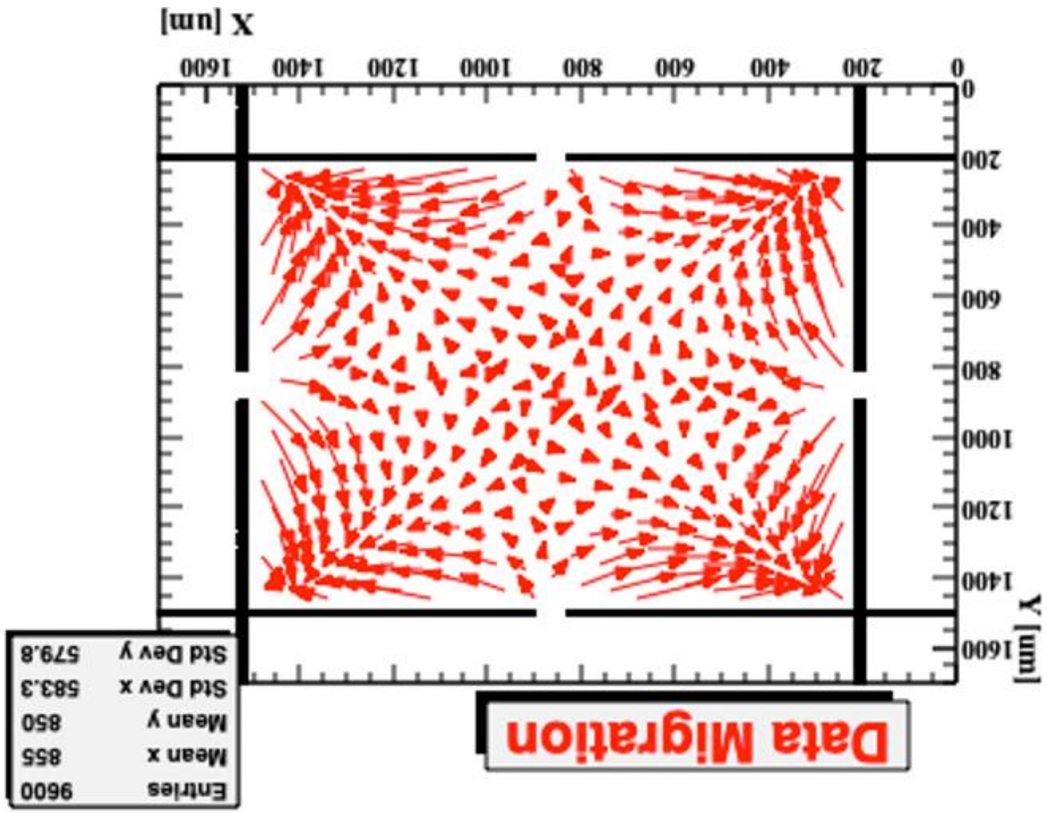


- The position resolution is dominated by the jitter term
- Other contributions are sub-leading
- **At gain ~ 30, $\sigma_{jitter} \sim 35\ \mu m$**

Systematic check: rotate the migration matrix

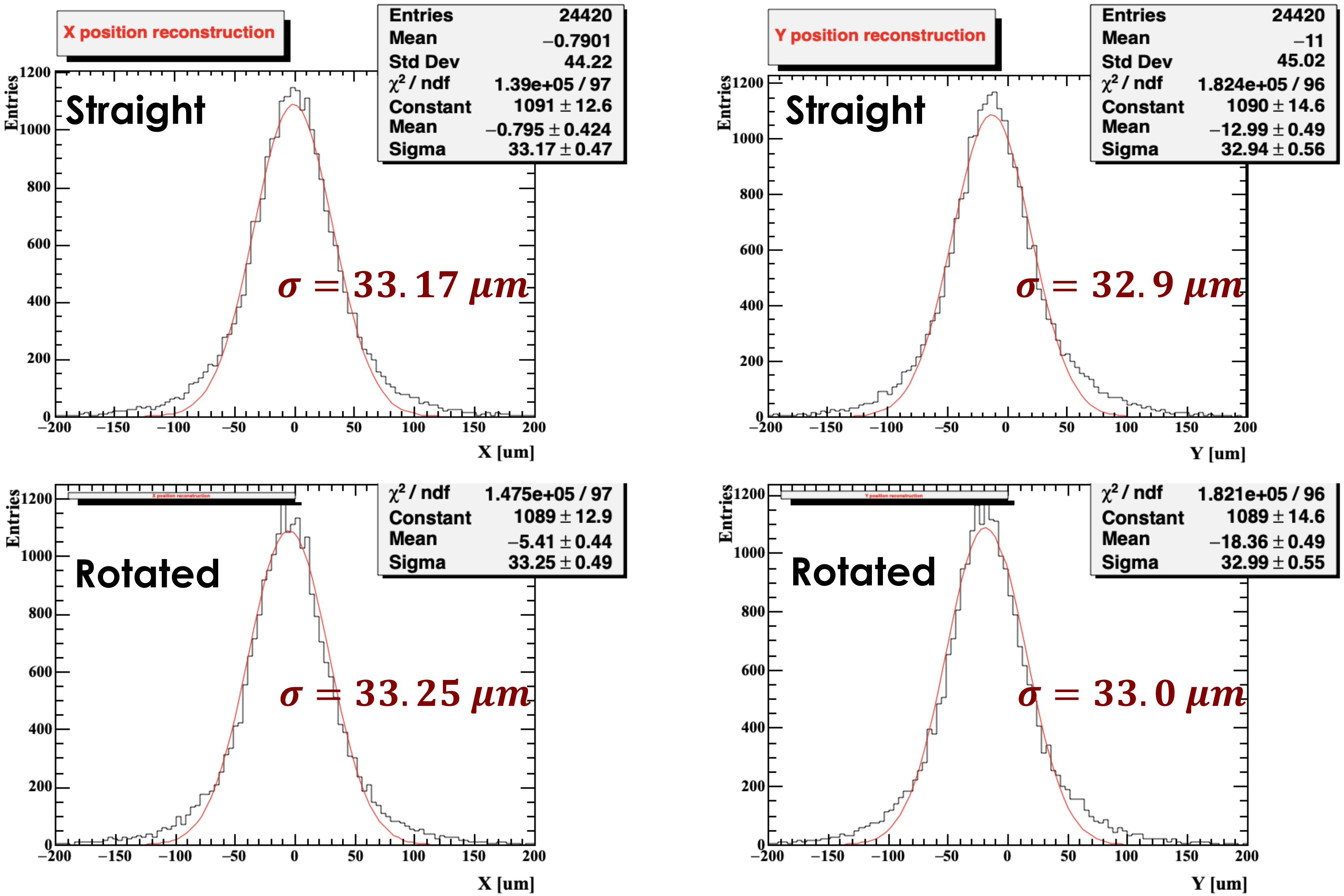
Apply to the data the migration matrix straight and rotated by 180 degrees





This procedure checks the sensor uniformity and differences in the read-out amplifiers

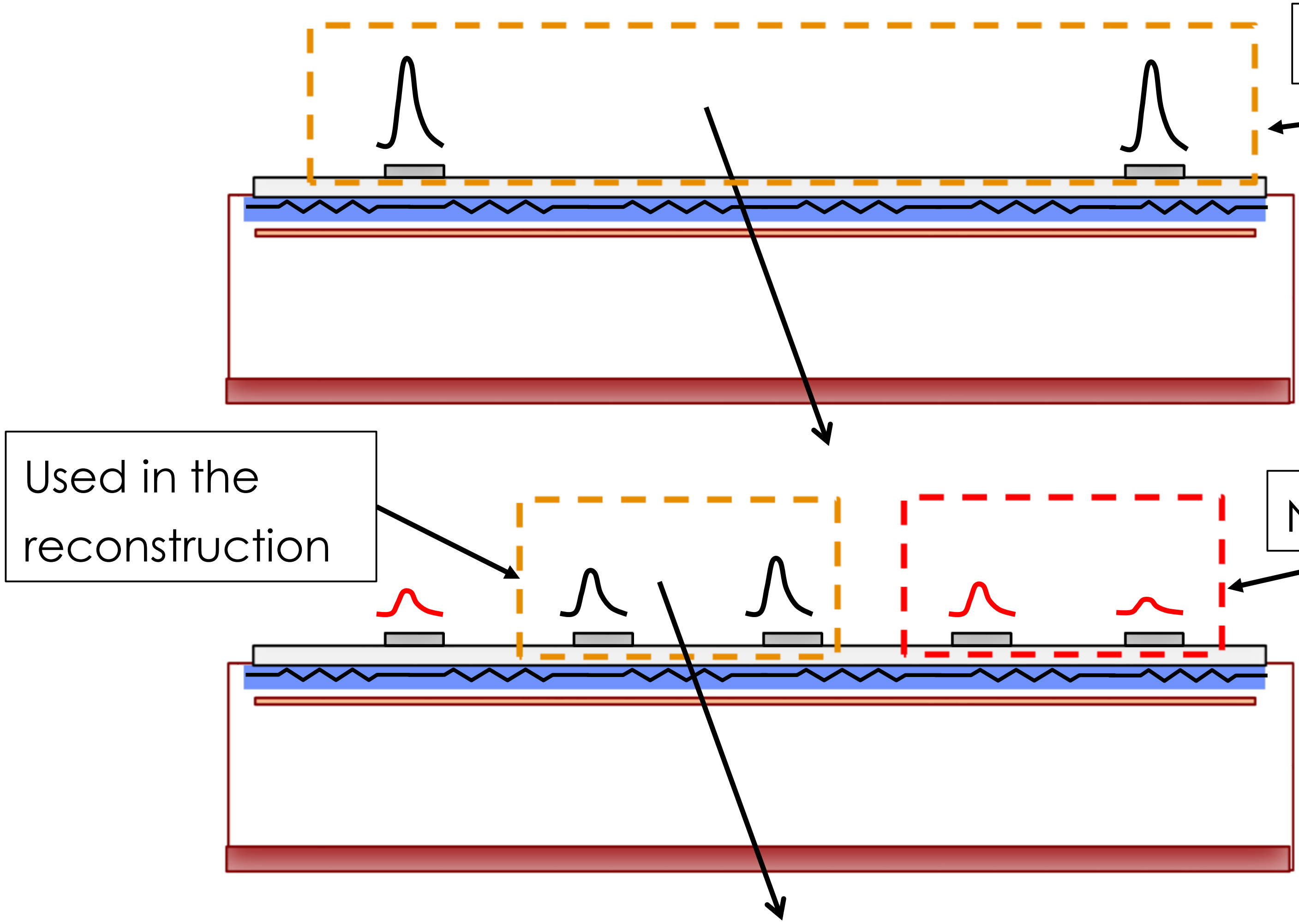
Resolution of straight and rotated migration matrix



The resolution using the straight or rotated matrix is the same, indicating that

$\sigma^2_{signal} + \sigma^2_{reconstruction} + \sigma^2_{sensor}$ are all sub-leading with respect to the jitter term

Signal spread vs pixel size

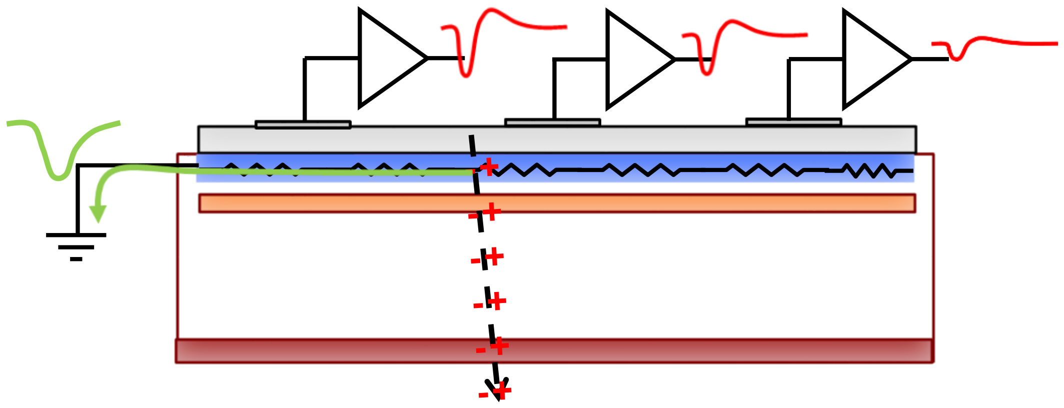


In large pixels, the signal is visible only on the nearest pads.
The full signal is used in the reconstruction

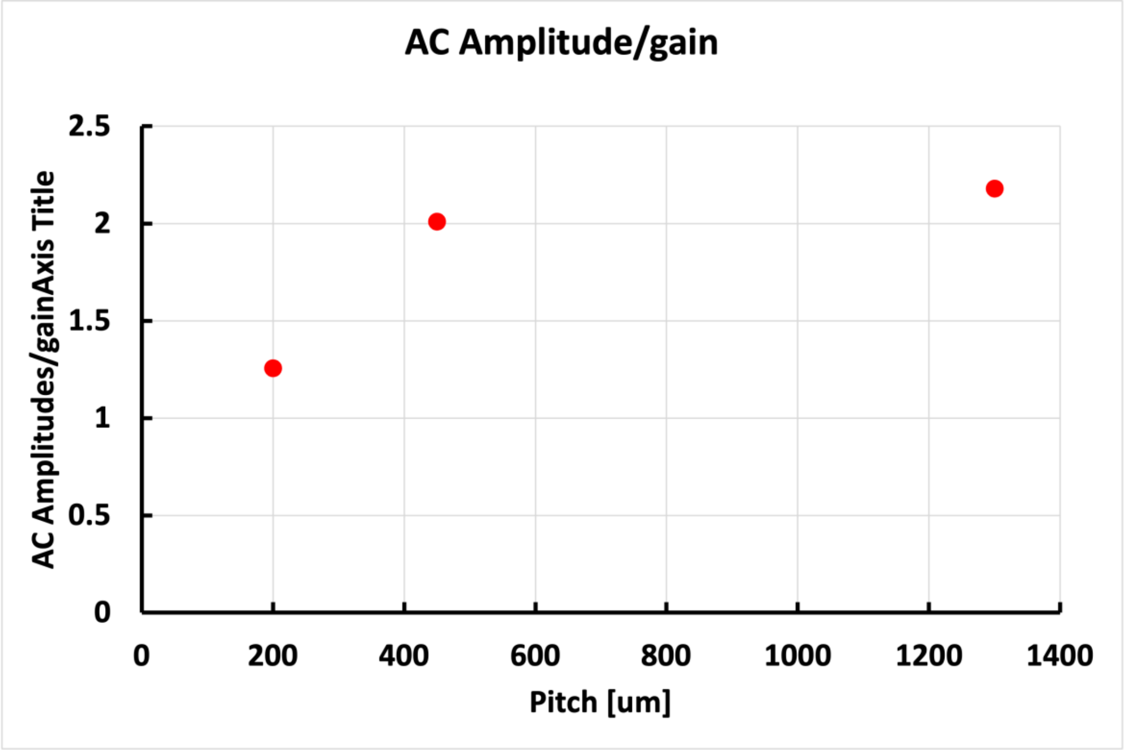
In small pixels, the signal is visible on many pads.
When only 4 pads are used, only a part of the total signal is used in the reconstruction

In small pixels, for equal gain, the signal-to-noise ratio is worse since part of the signal leaks to pads not used in the reconstruction

AC Signal and DC Signals

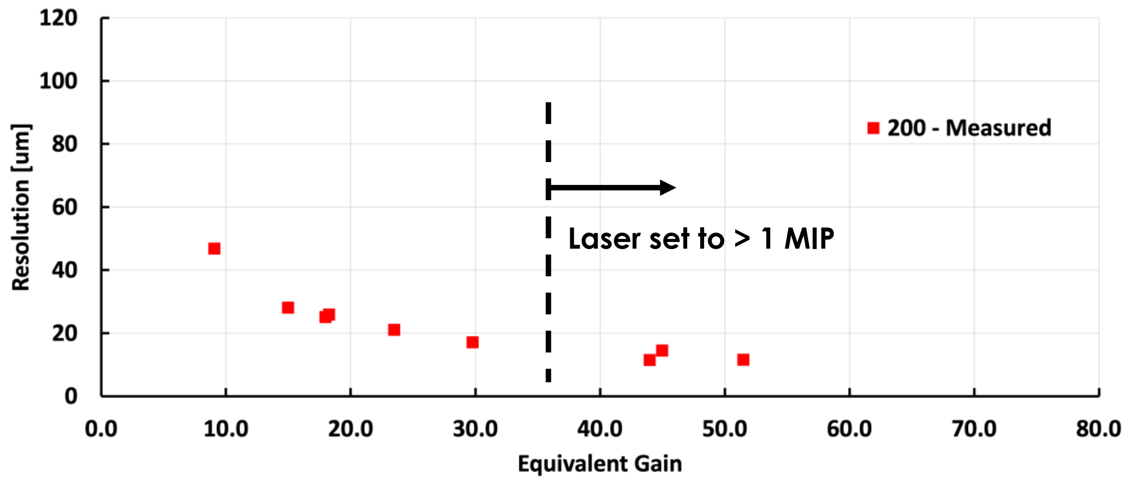


In small pixels, the sum of the AC signals the closest 4 read-out pads contains only about 60% of the total AC-signal (with respect of large pixels).

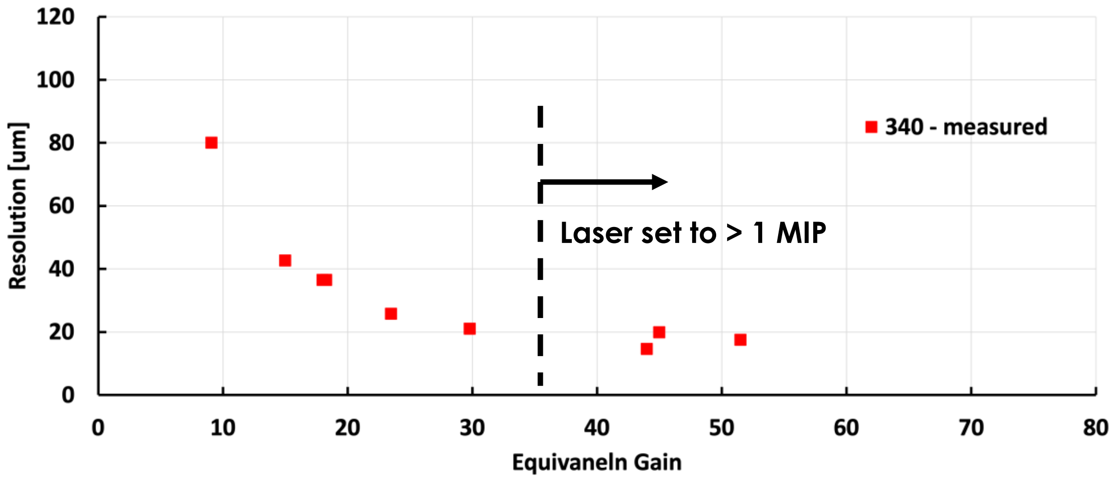


Results: resolution vs gain (4 different pitches)

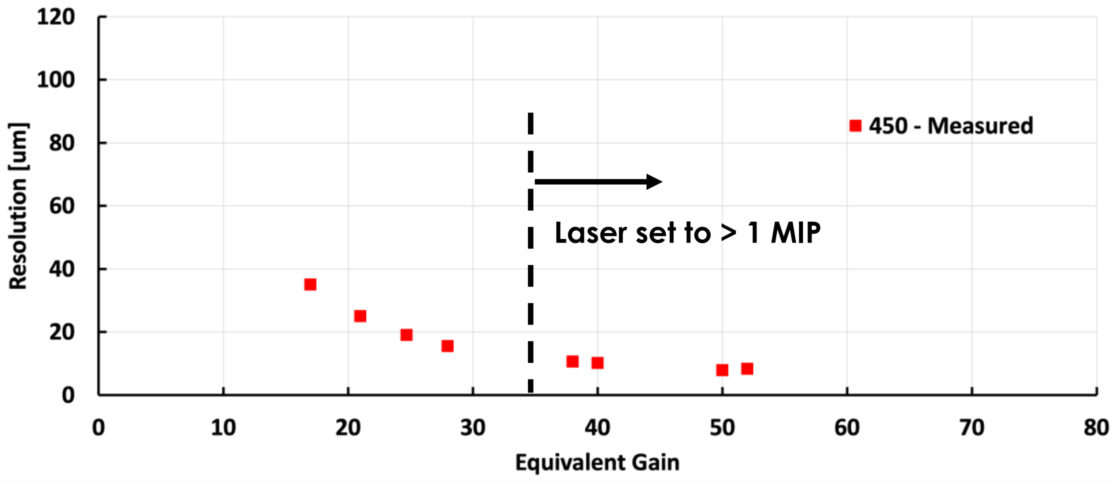
RSD2 Crosses 200 um



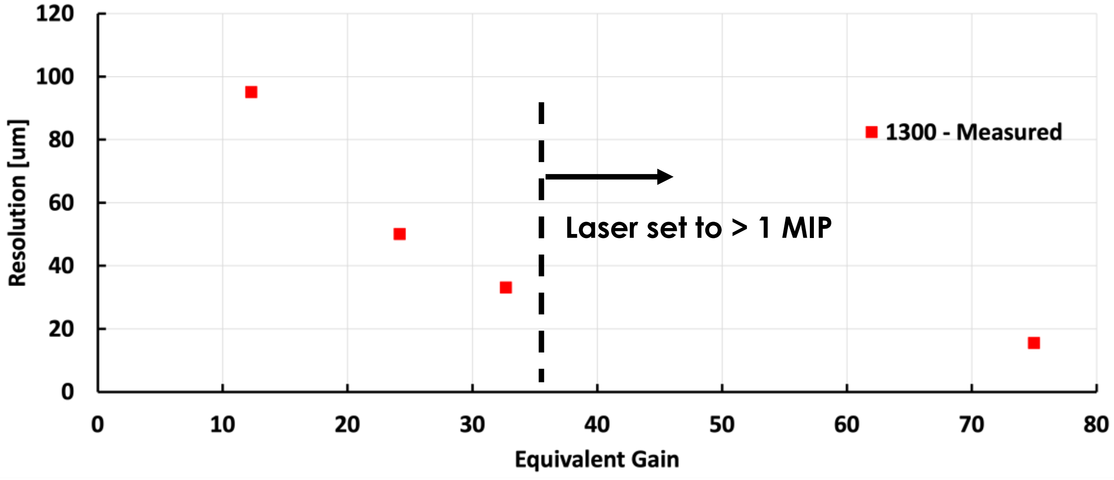
RSD2 Crosses 340 um



RSD2 Crosses 450 um

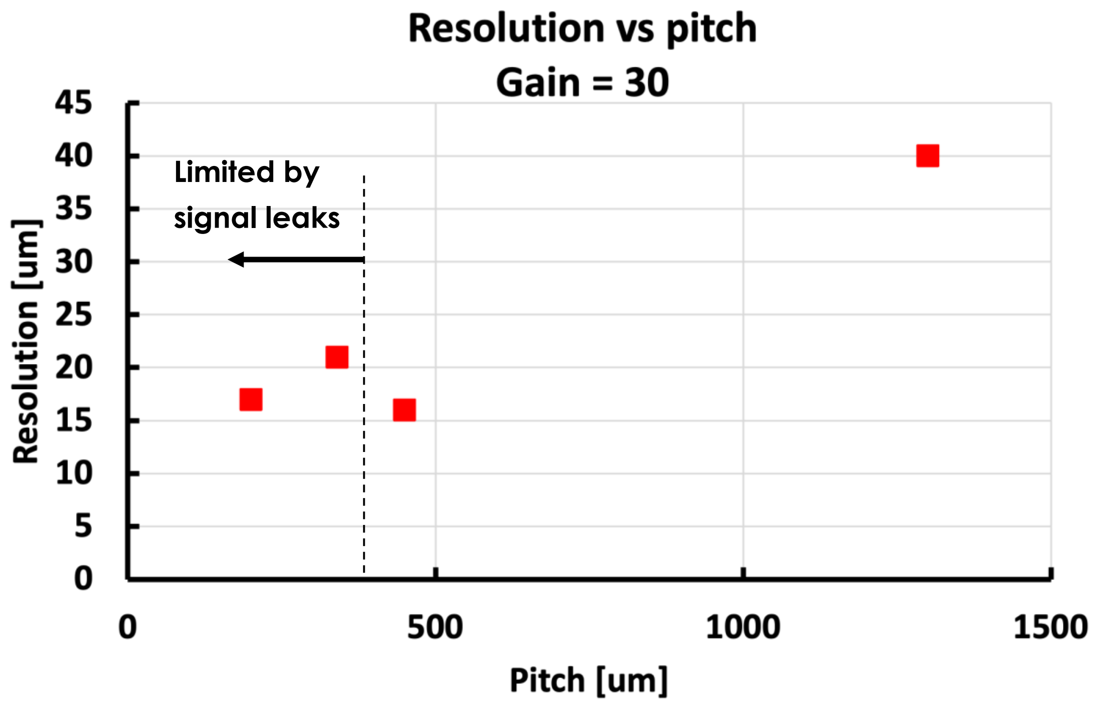


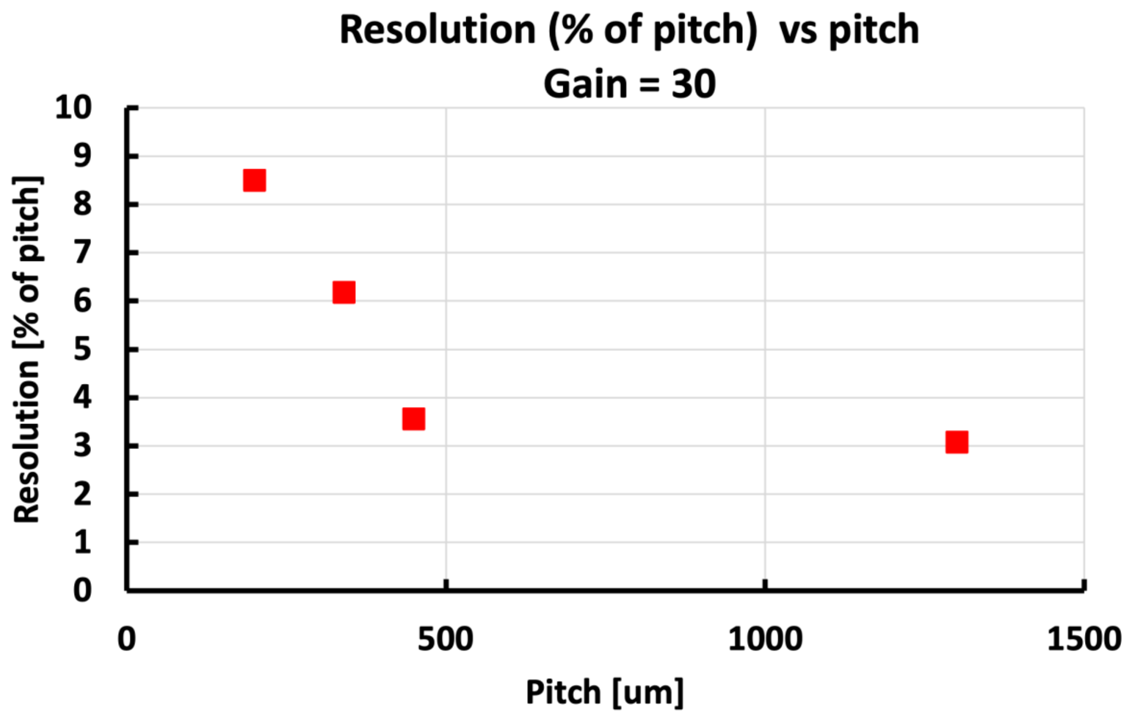
RSD2 Crosses 1300 um



Note: high-gain signals are obtained using a 3 MIP laser setting

Summary: resolution vs pitch





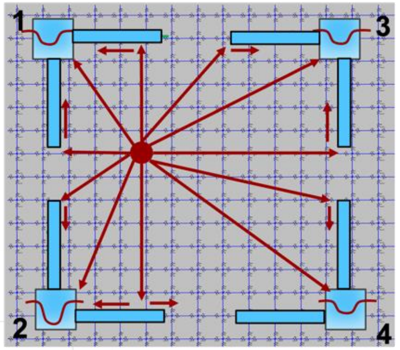
The position resolution is very good

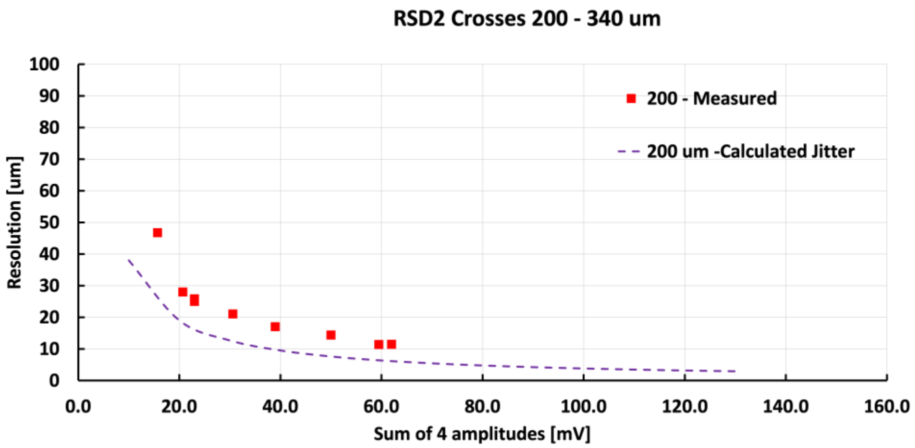
- Using only 4 read-out pads, the resolution in small structures is limited by the excessive signal spread
- The best relative resolution is about 3% of the pitch

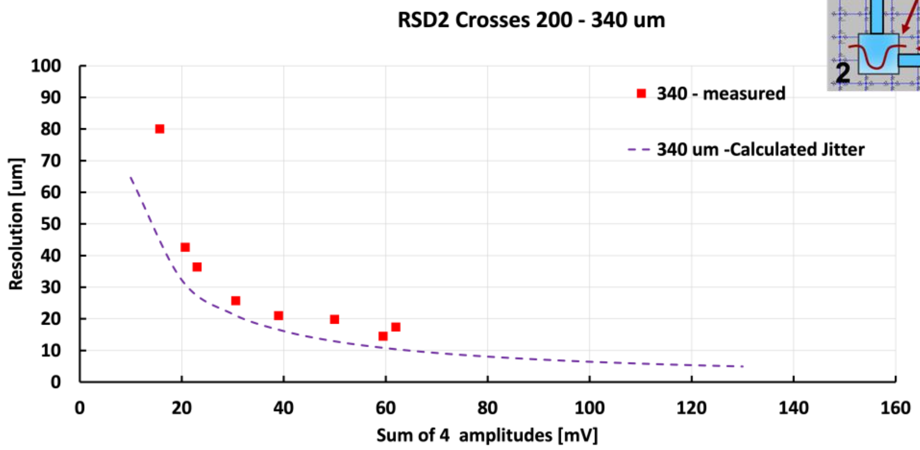
Resolution vs Sum of 4 amplitudes (4 different pitches)

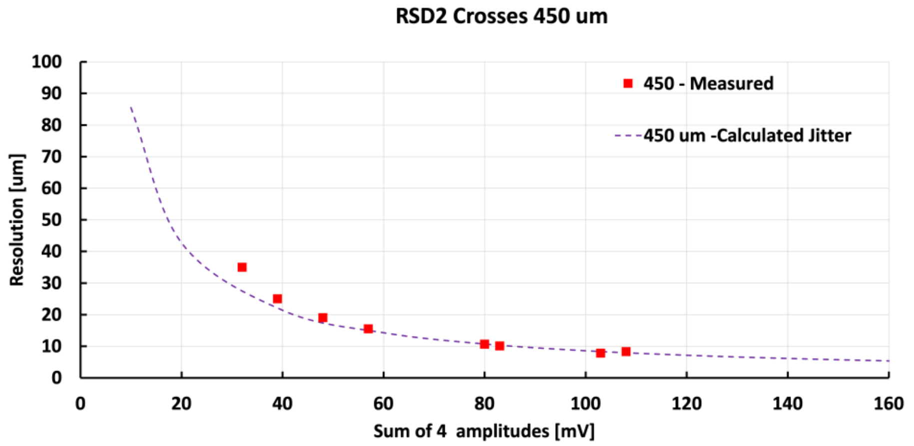
The jitter reproduces quite well the overall resolution vs amplitude trend

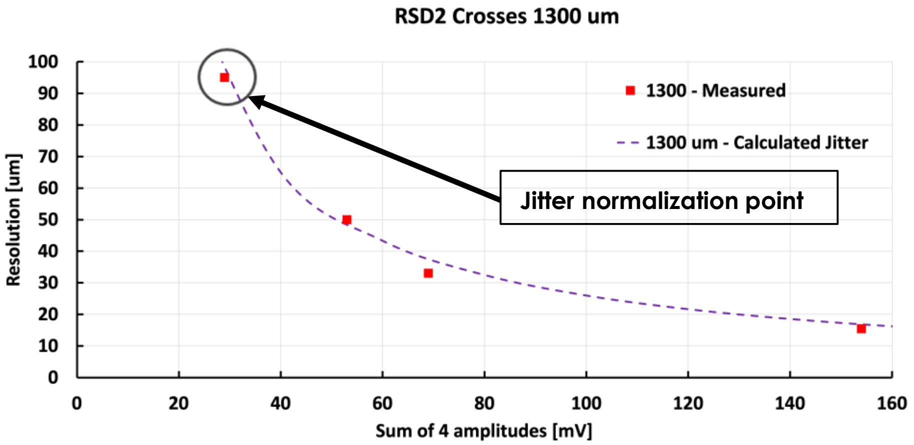
$$\sigma_{jitter} = \frac{\sigma_{el\_noise}}{\frac{\sum A}{pitch}}$$











Note: one single normalization for the 4 pitch sizes

How to improve performances

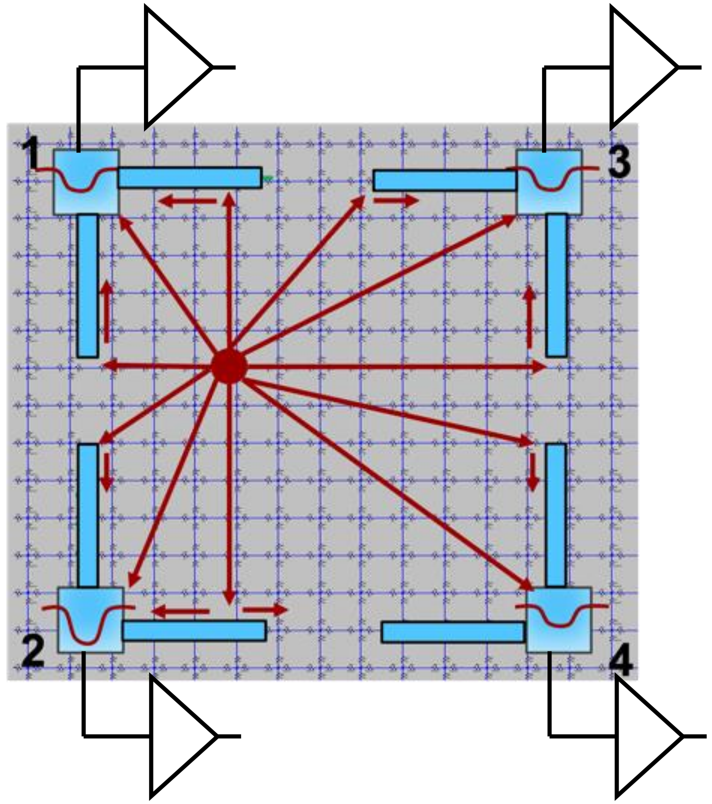
The resolution is dominated by the jitter term

==> limited by the electronic noise.

The electronics used for this study is "fast electronics":

large bandwidth, high noise

Clearly, the wrong choice if you simply want the amplitude



Low-noise small bandwidth electronics might lead to significant improvements.

If shaping time increases by 10 ns, the noise decreases by about 3

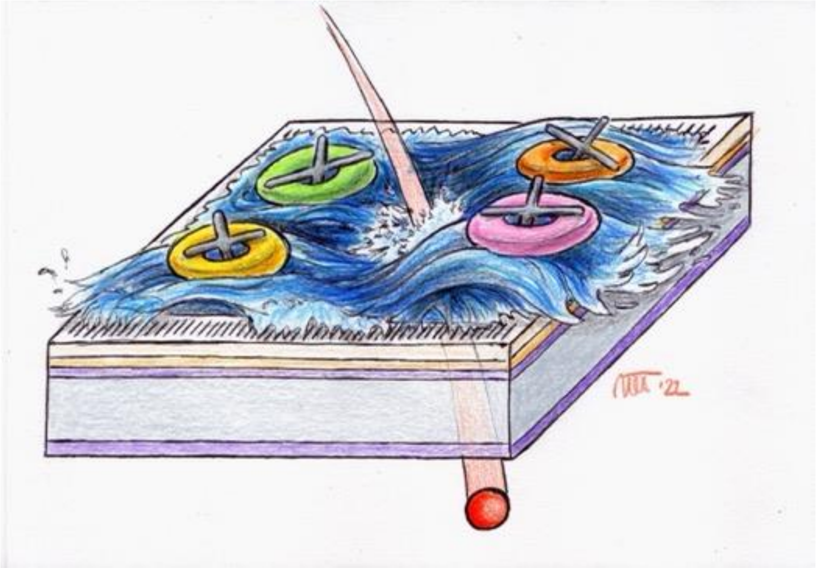
Conclusions

The FBK – RSD2 production has been designed to:

- Have uniform spatial resolution over the pixel surface
- Explore different read-out layouts.

This analysis explores the spatial resolution of sensors with crossed-shaped electrodes.

4 pitch sizes: 200, 340, 450, and 1300 microns



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

For all pitch sizes, the resolution is dominated by the jitter term

==> Improvement with low-noise electronics

At gain = 30, the spatial resolution is:

- Pitch = 200 μm ==> σ_x ~ 17 μm; σ_x/pitch ~ 8%
- Pitch = 340 μm ==> σ_x ~ 21 μm; σ_x/pitch ~ 6%
- Pitch = 450 μm ==> σ_x ~ 16 μm; σ_x/pitch ~ 3%
- Pitch = 1300 μm ==> σ_x ~ 40 μm; σ_x/pitch ~ 3%

Using only 4 read-out pads, in small-pitch sensor,
the signal leakage to neighboring pixels limits the resolution.

This effect can be lowered by increasing the surface resistivity: next round of tests…