# The power of resistive read-out in silicon sensor

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MINISTERO DELL'ISTRUZIONE DELL'UNIVERSITA' E DELLA RICERCA

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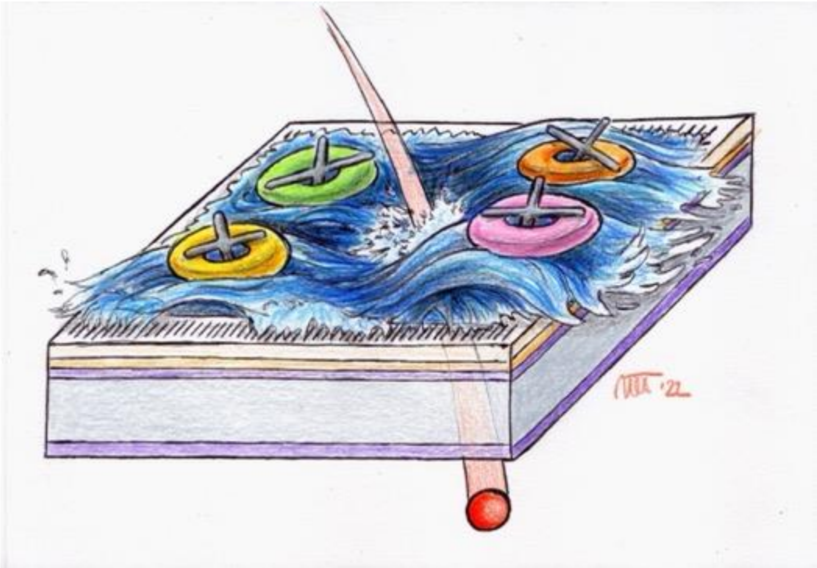
# Motivations

In recent years, two design innovations have been introduced in the design of silicon detectors:

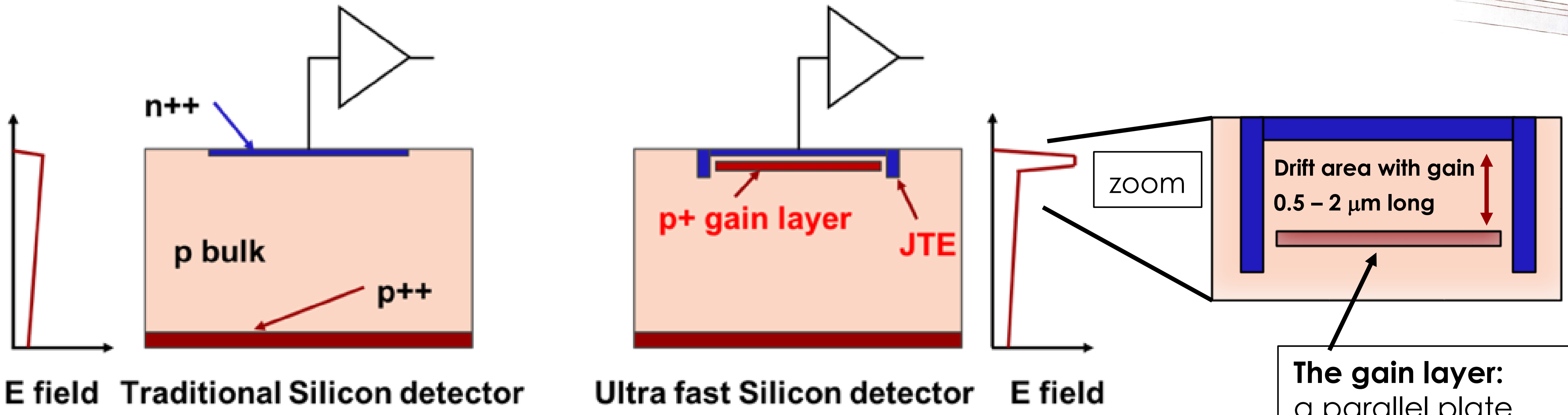
- **Low-Gain Avalance Diode (LGAD)**
  - It provides large signals and low noise, ideal for timing

- **Resistive read-out (RSD)**
  - It shares the signal among neighbouring pads, ideal for position resolution

In this talk, I will review the possibilities opened by these two innovations



# First design innovation: low gain avalanche diode (LGAD)




**The gain layer:** a parallel plate capacitor with high field

**The LGAD sensors, as proposed and first manufactured by CNM**

(National Center for Micro-electronics, Barcelona):

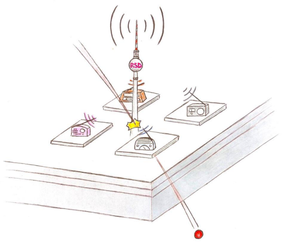
**High field obtained by adding an extra doping layer**

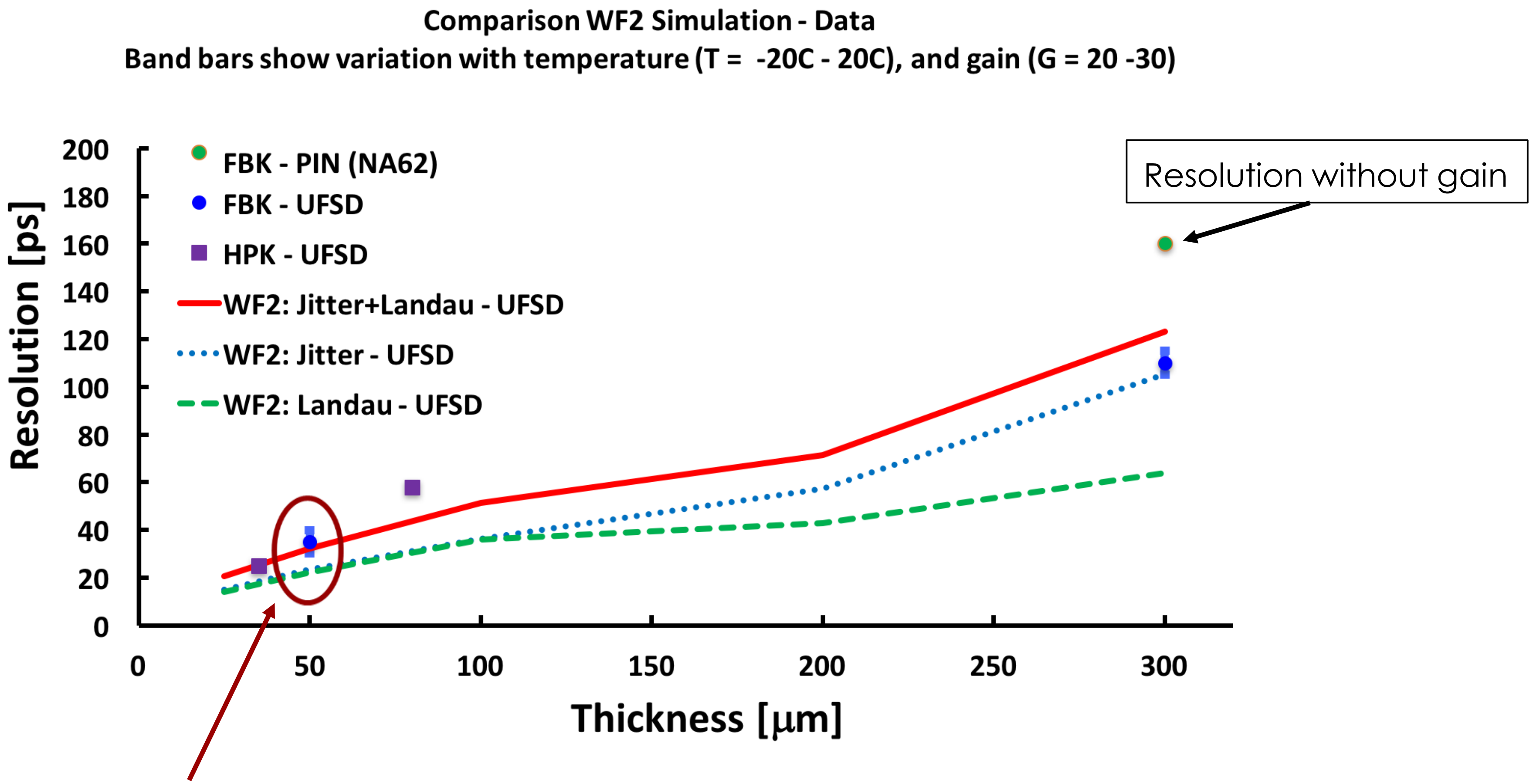
E ~ 300 kV/cm, closed to breakdown voltage

- The low-gain mechanism, obtained with a moderately doped p-implant, is the defining feature of the design.

**Low gain is the key ingredient to good temporal resolution**

# Summary of LGAD temporal resolution

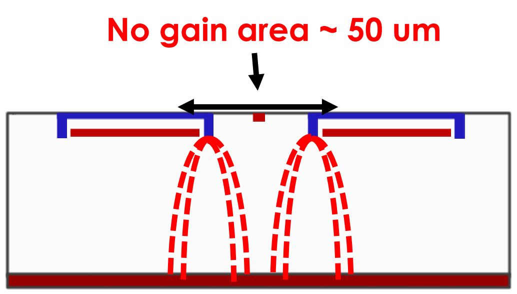





**There are now hundreds of measurements on 45-55 μm-thick LGADs**

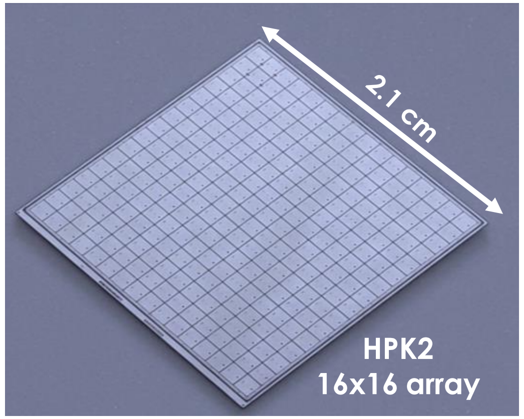
**➔ Current sensor choice for the ATLAS and CMS timing layers**

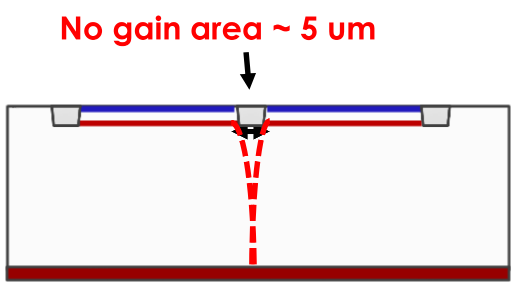
# LGAD: State-of-the art




### JTE + p-stop design

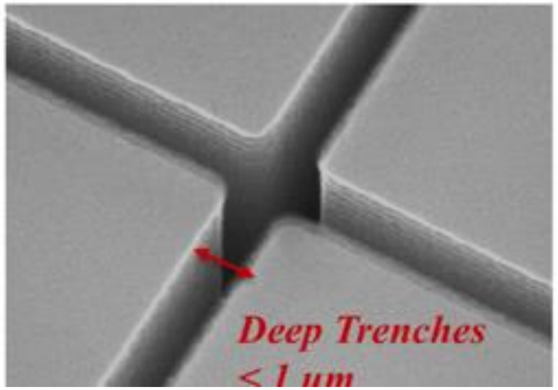
- CMS && ATLAS choice
- Not 100% fill factor
- Very well tested
- High Occupancy OK
- Rate ~ 50-100 MHz
- Rad hardness ~ 2-3E15 n/cm2



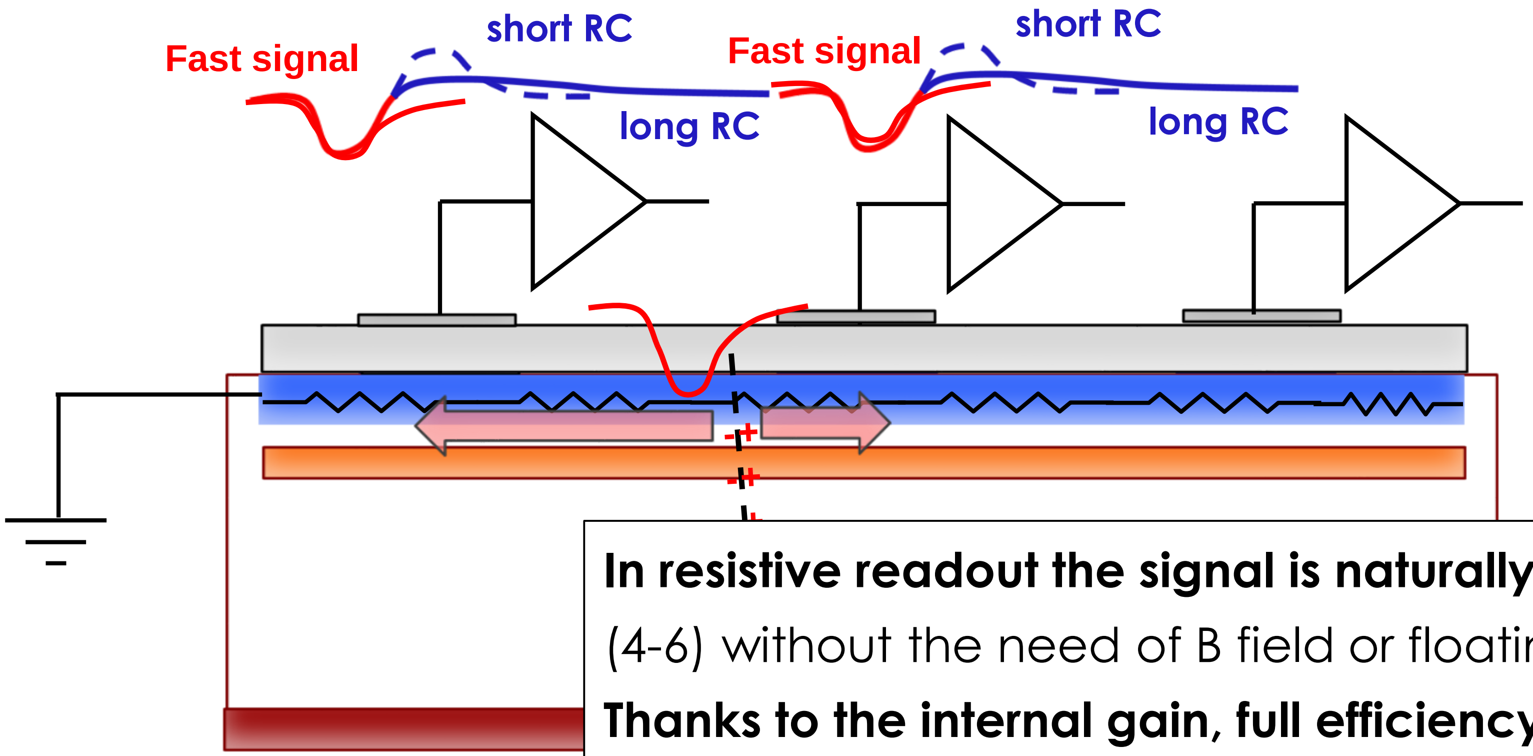

### Trench-isolated design

- Almost 100% fill factor
- Temporal resolution (50 μm) : 35-40 ps
- High Occupancy OK
- Rate ~ 50-100 MHz
- Rad hardness: to be studied



# **Second design innovation**: resistive read-out (Tredi conf. 2015)

- **The signal is formed on the n+ electrode ==> no signal on the AC pads**
- **The AC pads offer the smallest impedance to ground for the fast signal**
- **The signal discharges to ground**

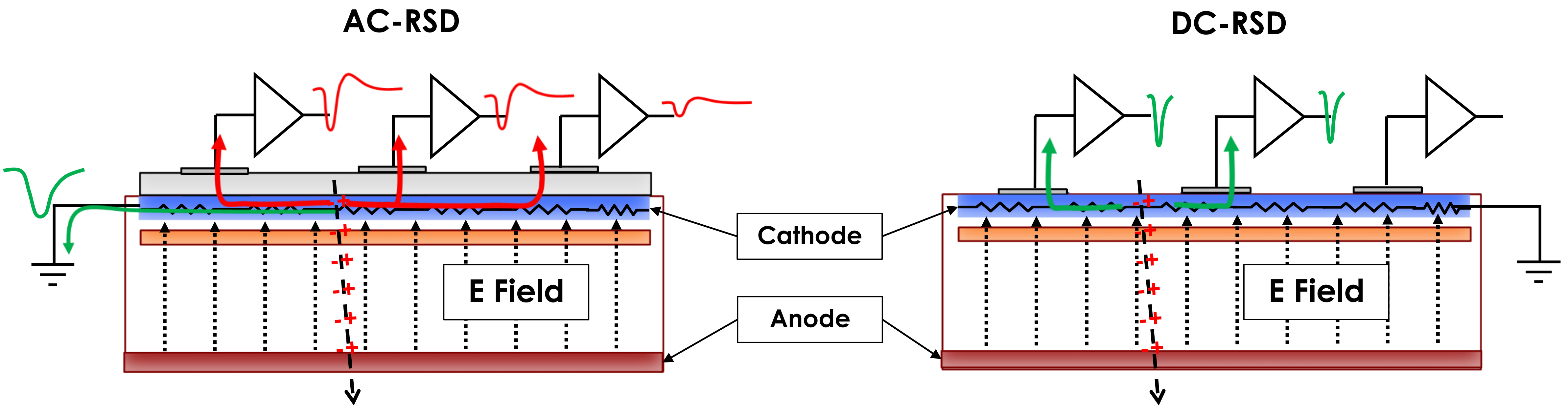



**In resistive readout the signal is naturally shared among pads** (4-6) without the need of B field or floating pads

**Thanks to the internal gain, full efficiency even with sharing**

**Results presented here are from the FBK RSD2 production**

# RSD and DC-RSD




This design has been manufactured in several productions by FBK, BNL, and HPK

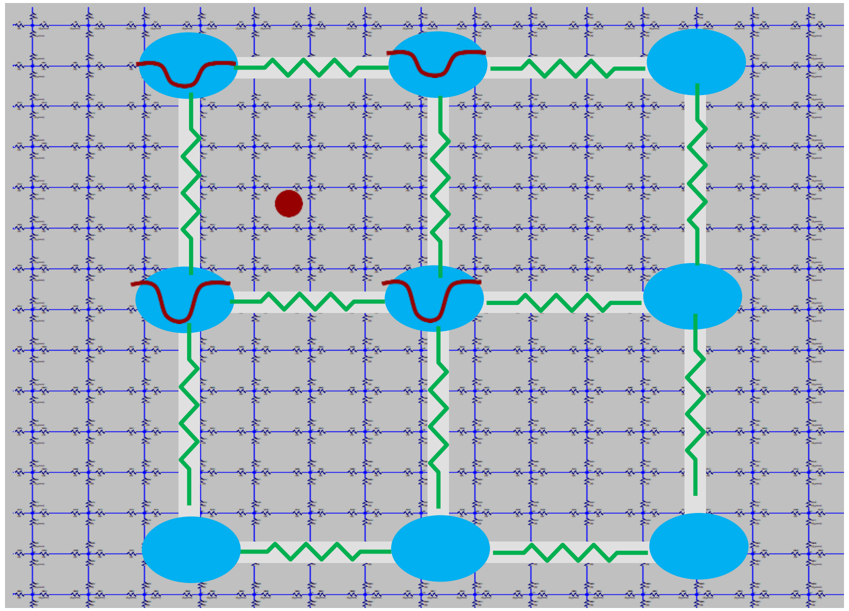
This design is presently under development by FBK

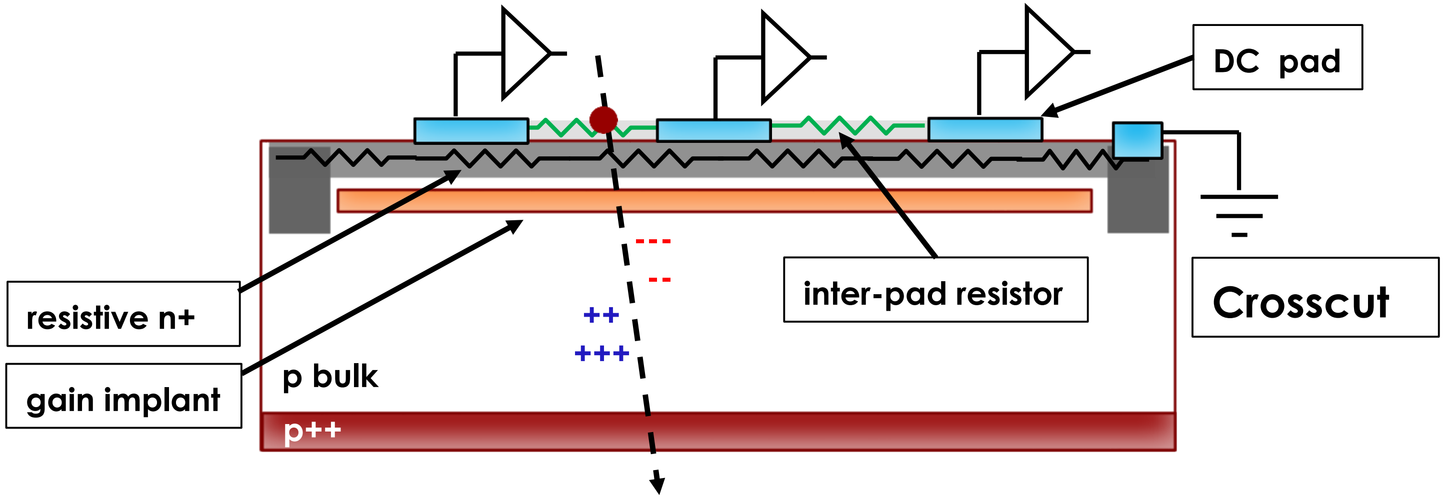
The main advantage of the DC-RSD design is to limit the signal spread

# DC-RSD with resitors

The DC-RSD design can also be done **including resistors** between the read-out electrodes.

According to simulation, **these resistors are improving the position resolution of the sensors**




**Simulation results in talk: "TCAD simulations of innovative Low-Gain Avalanche Diodes for particle detector design and optimization "**

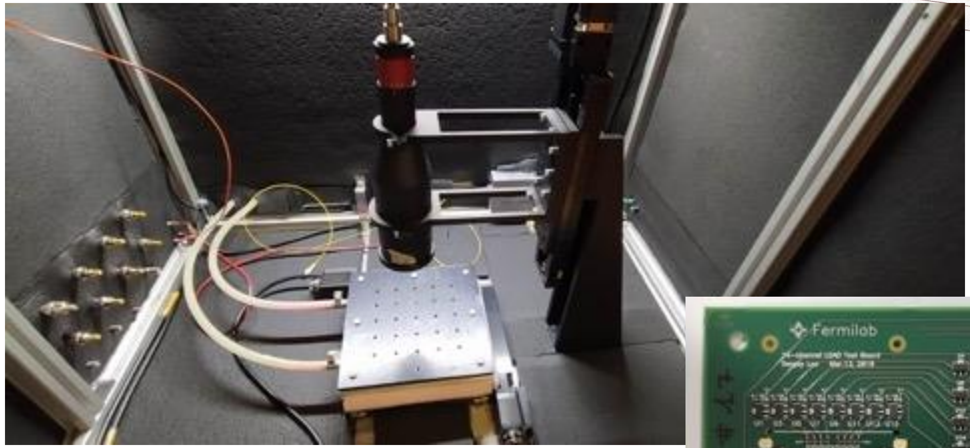
# Experimental set-up

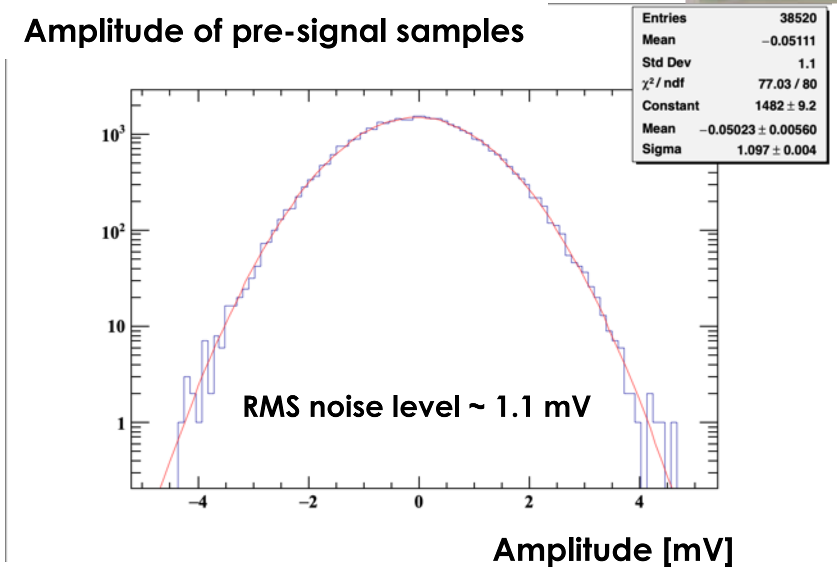
The **Particulars TCT laser setup** has been used:

- 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: $\sigma_{Laser}$~ 2 μm

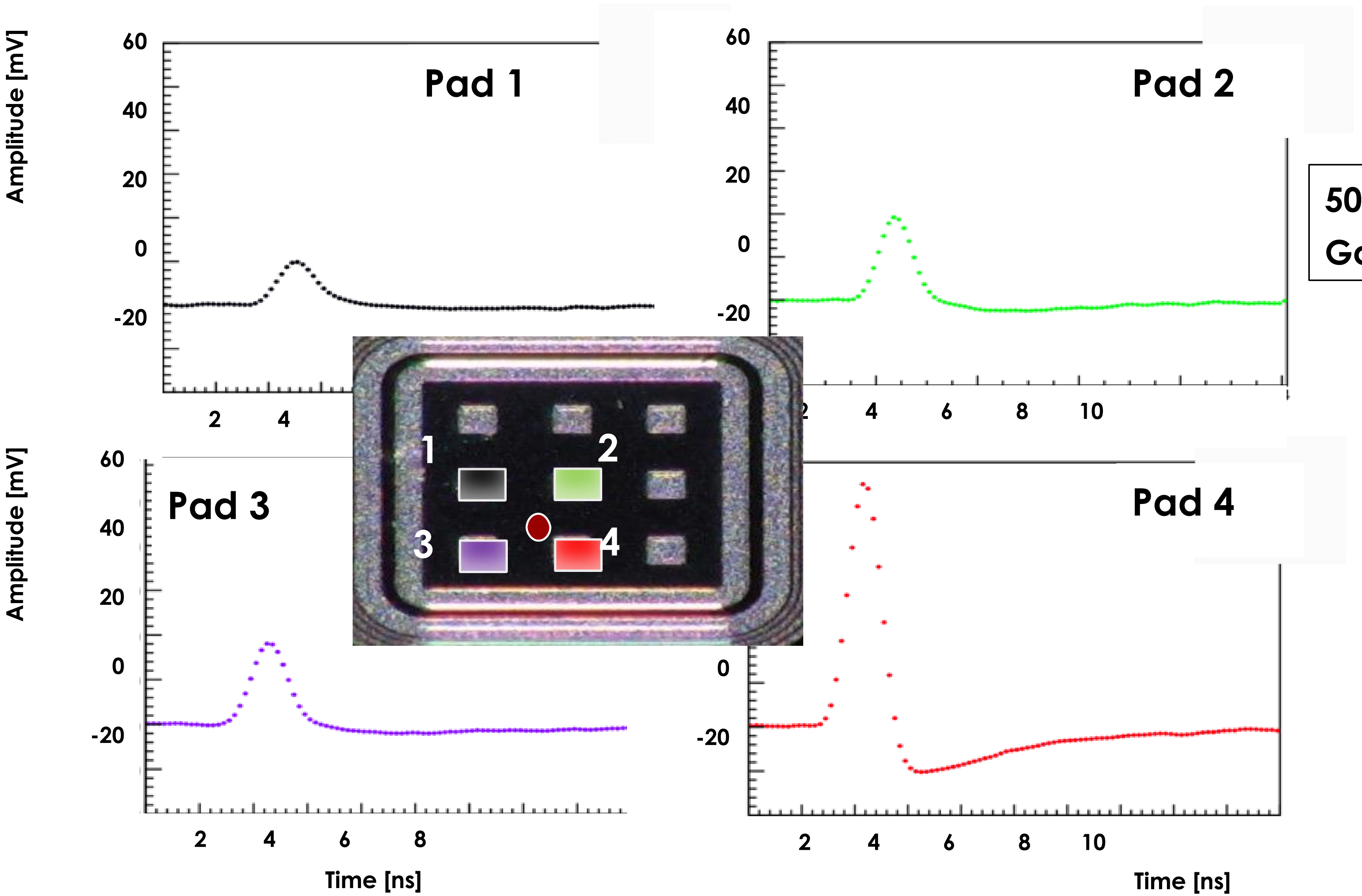
**Sensors are read out with 16-ch fast analogue board, developed at FNAL**

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



# Example of signal sharing

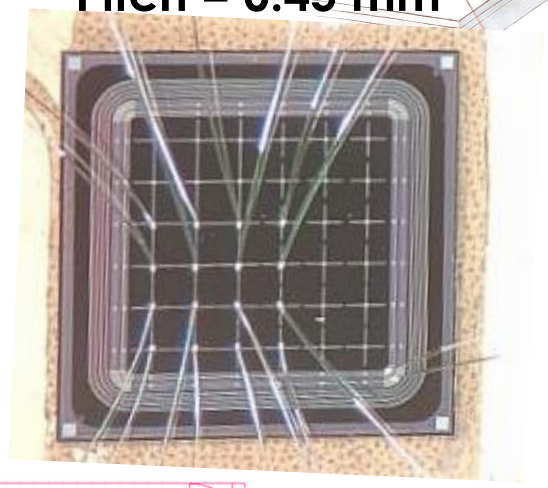



50-mm thick RSD,
Gain ~ 20

**The laser is shot at the position of the red dot: the signal is seen in 4 pads**

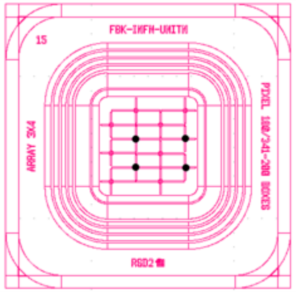
# RSD2 structures used in this analysis (FBK - RSD2 production)

Pitch = 0.45 mm

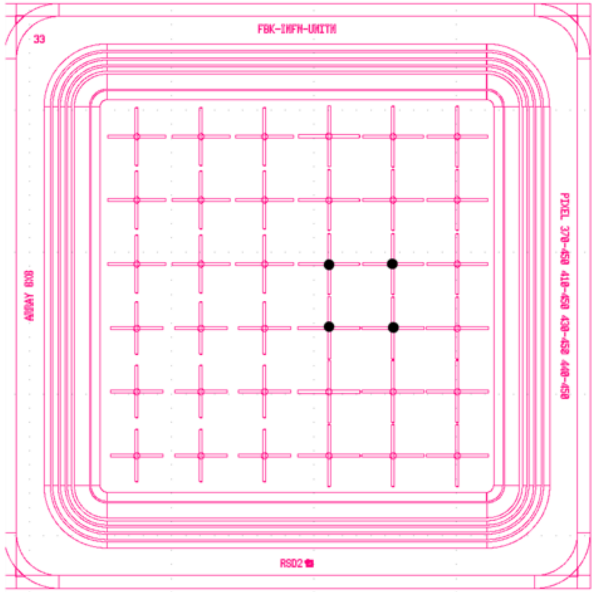


In this study, the perfomance of sensors with electrodes shaped as crosses is presented.

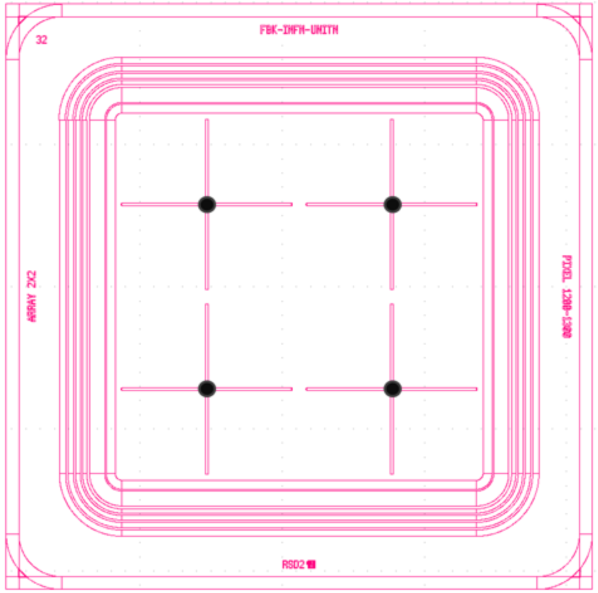
**4 different dimensions: 200, 340, 450, and 1300 μm**



**(A)**
**200 x 340 μm²**



**(B)**
**Pitch = 450 μm**



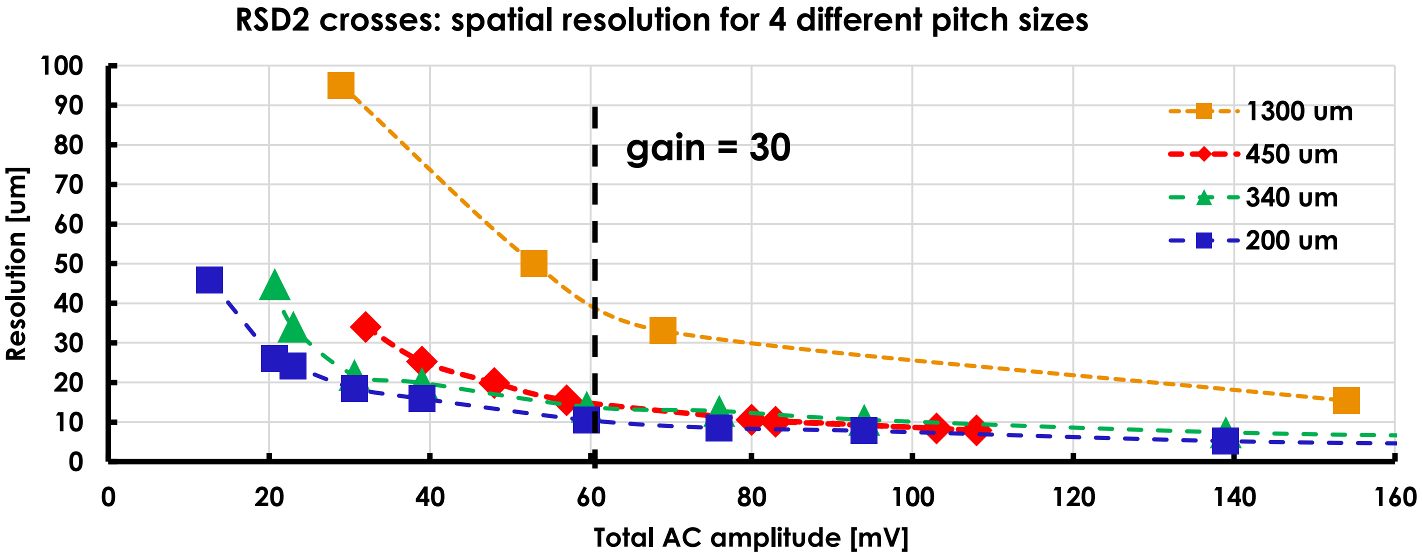
**(C)**
**Pitch = 1300 μm**

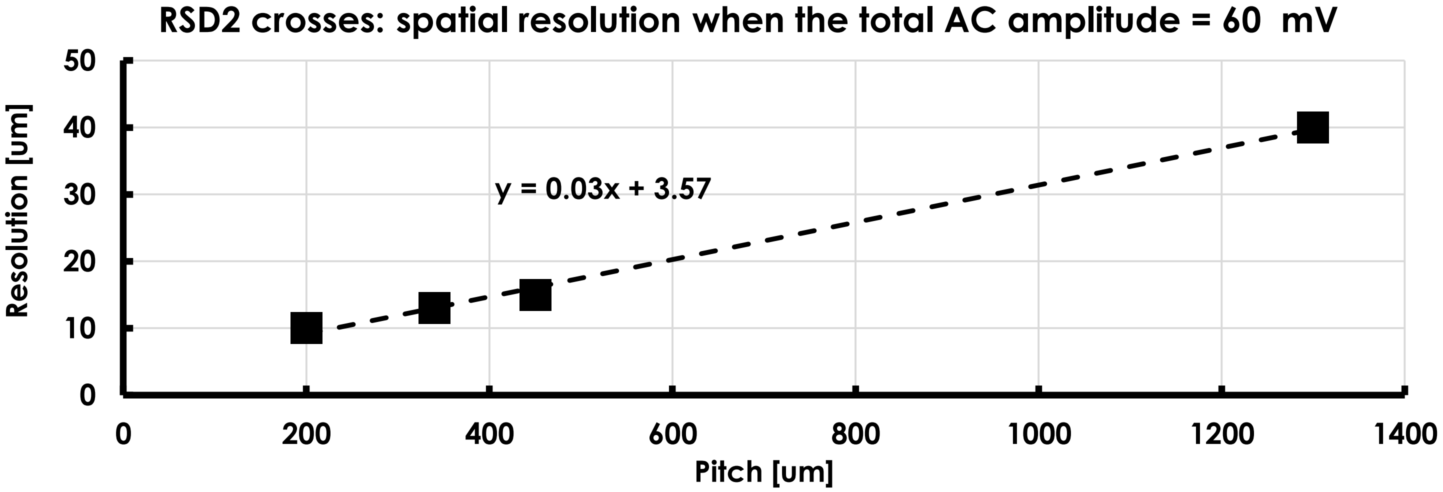
# RSD position resolution (FBK RSD2 production)

RSDs at gain = 30 achieve a spatial resolution of about 3% of the pitch size:

**RSD:**

- **1300 x 1300 $\mu m^2$: $\sigma_x$ ~ 40 $\mu$m**
- **450 x 450 $\mu$ $m^2$: $\sigma_x$ ~ 15 $\mu$m**

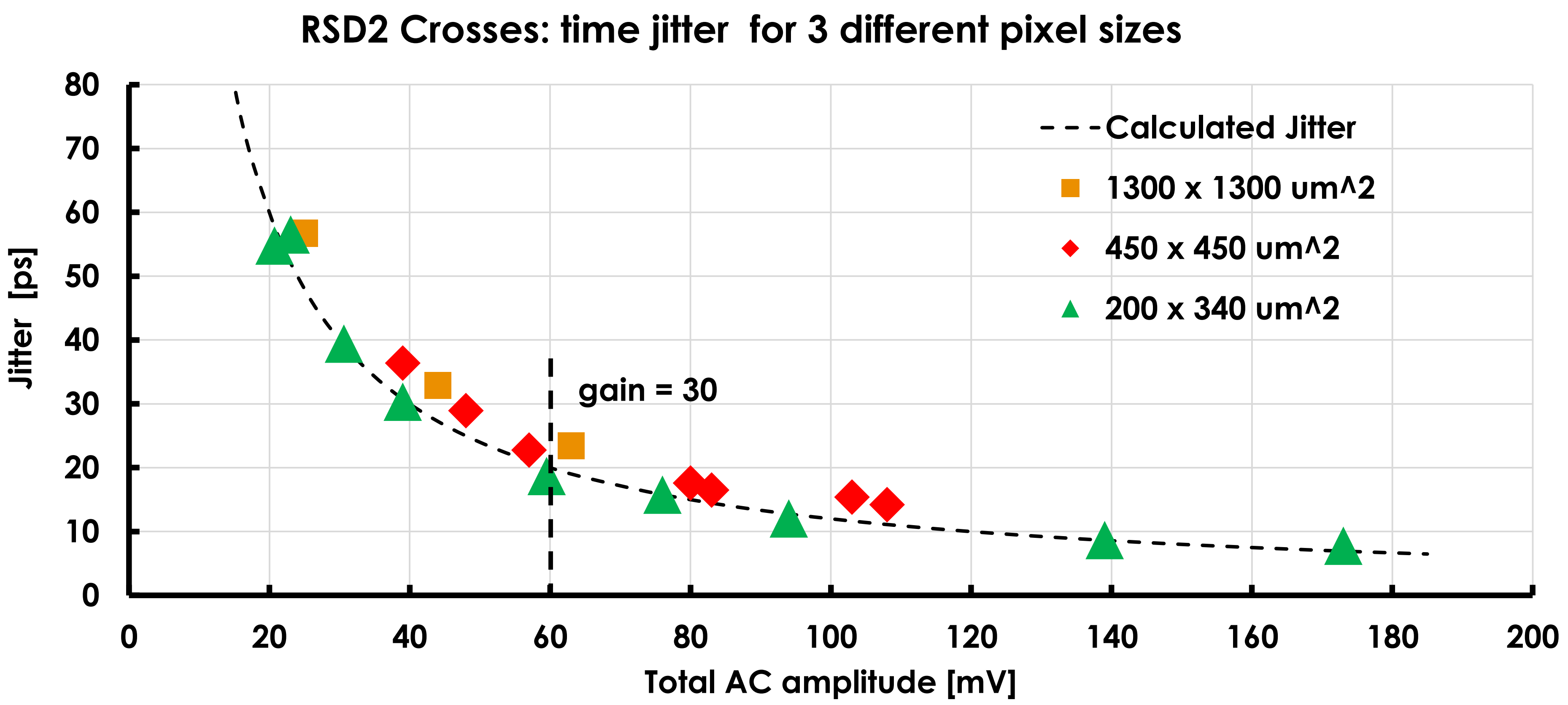


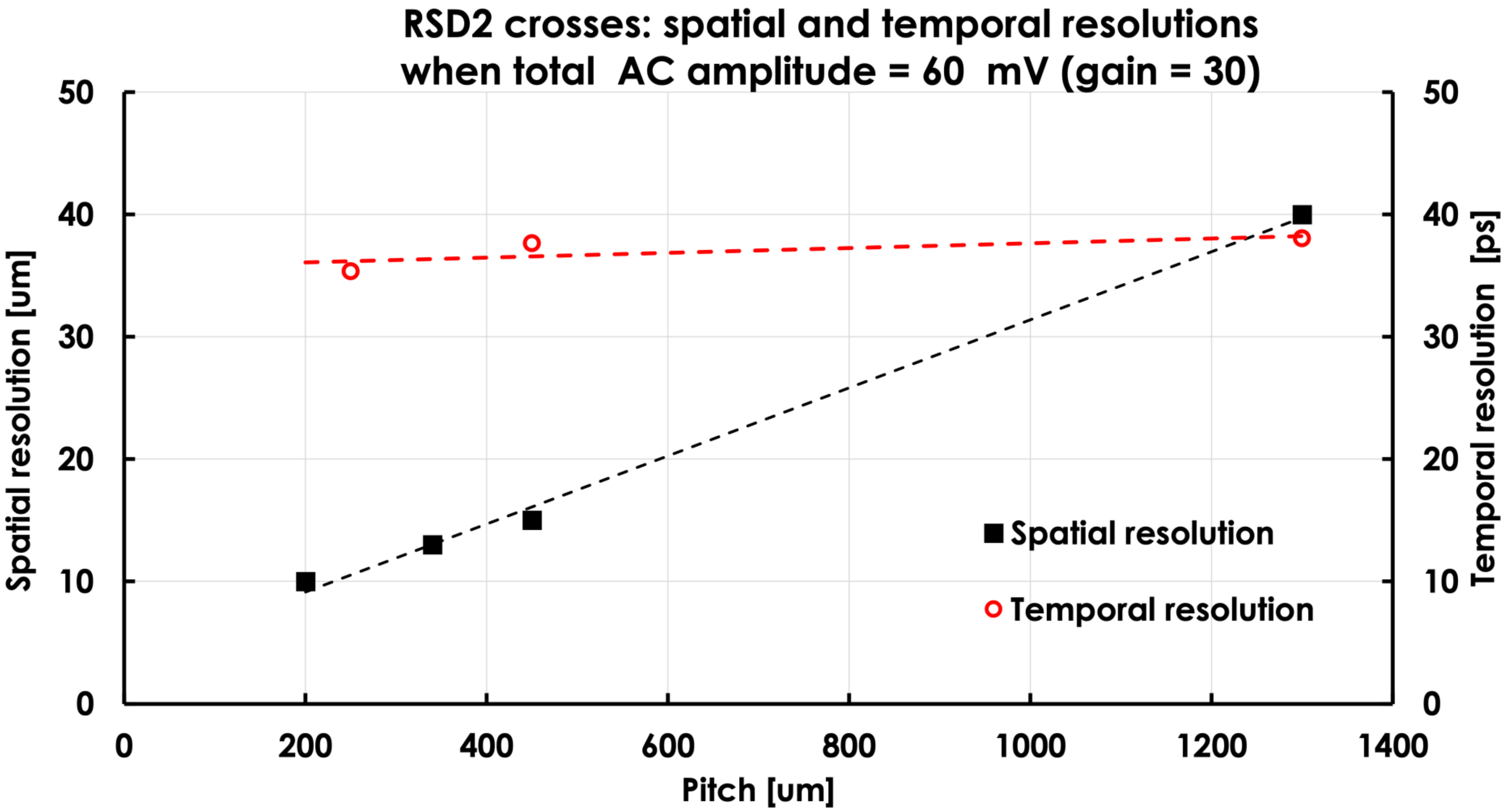
# RSD temporal resolution (FBK RSD2 production)

**The resolution** depends mostly upon the signal size and **weakly on the pixel size**

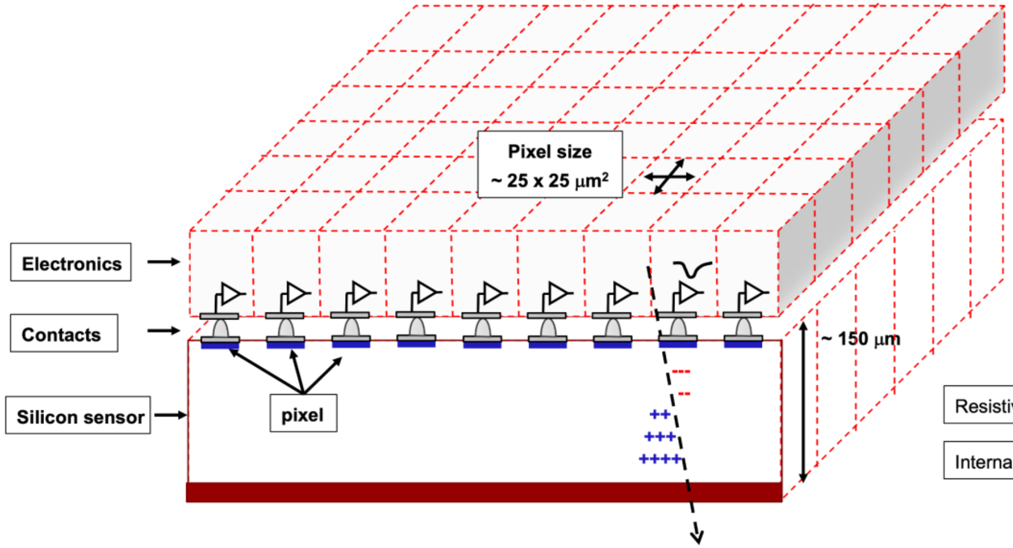
RSDs at gain = 30 achieve a temporal jitter of about 20 ps



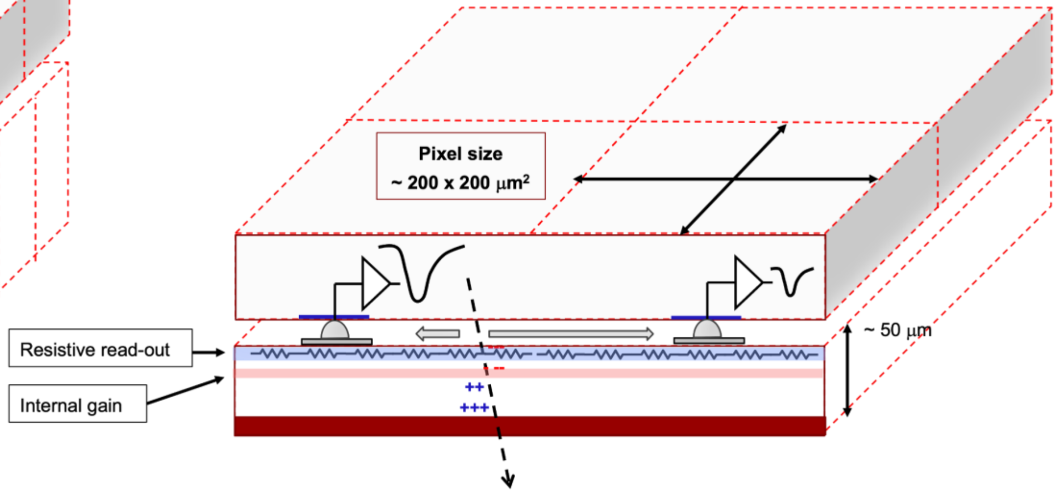
# RSD2 performance summary



# Final goal of RSD R&D: a completely new tracker




**Standard tracker**




**RSD-based tracker**

**The design of a tracker based on RSD is truly innovative**:

- It delivers ~ 20 -30 ps temporal resolution
- For the same spatial resolution, the number of pixel is reduced by 50-100
- The electronic circuitry can be easily accomodated
- The power consumption is much lower, it might even be air cooled (~ 0.1-0.2 W/cm$^2$)
- The sensors can be really thin

# 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 and temporal resolutions 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

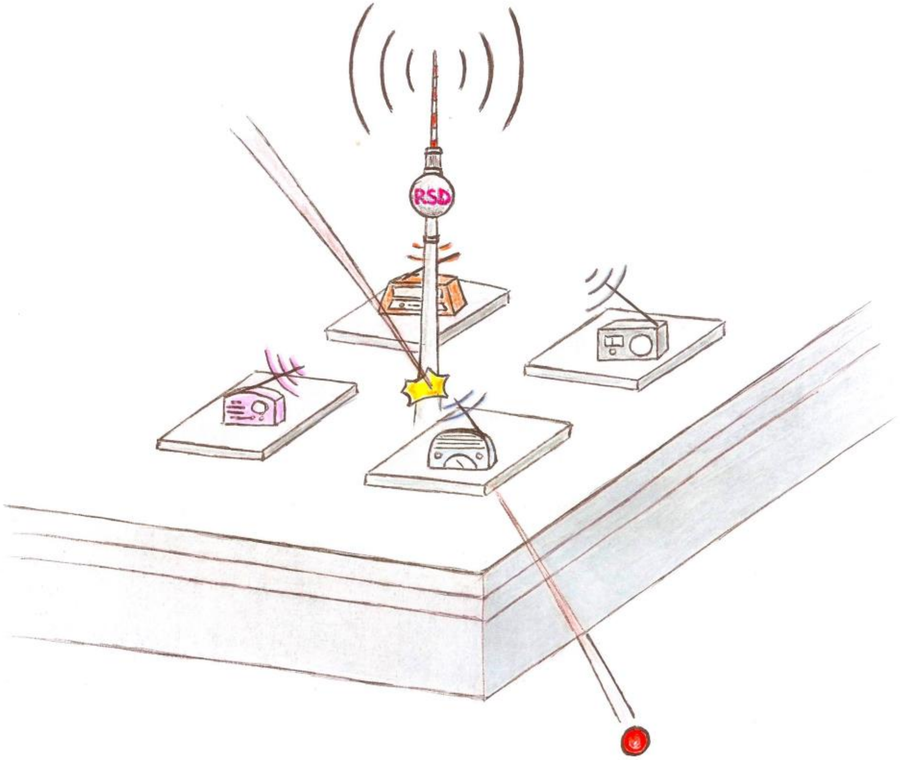
==> Improvement with low-noise electronics

**Temporal resolution depends upon ~ 1/gain, and ~noise**

The resolution does not depend on the pitch size

==> Improvement with low-noise electronics

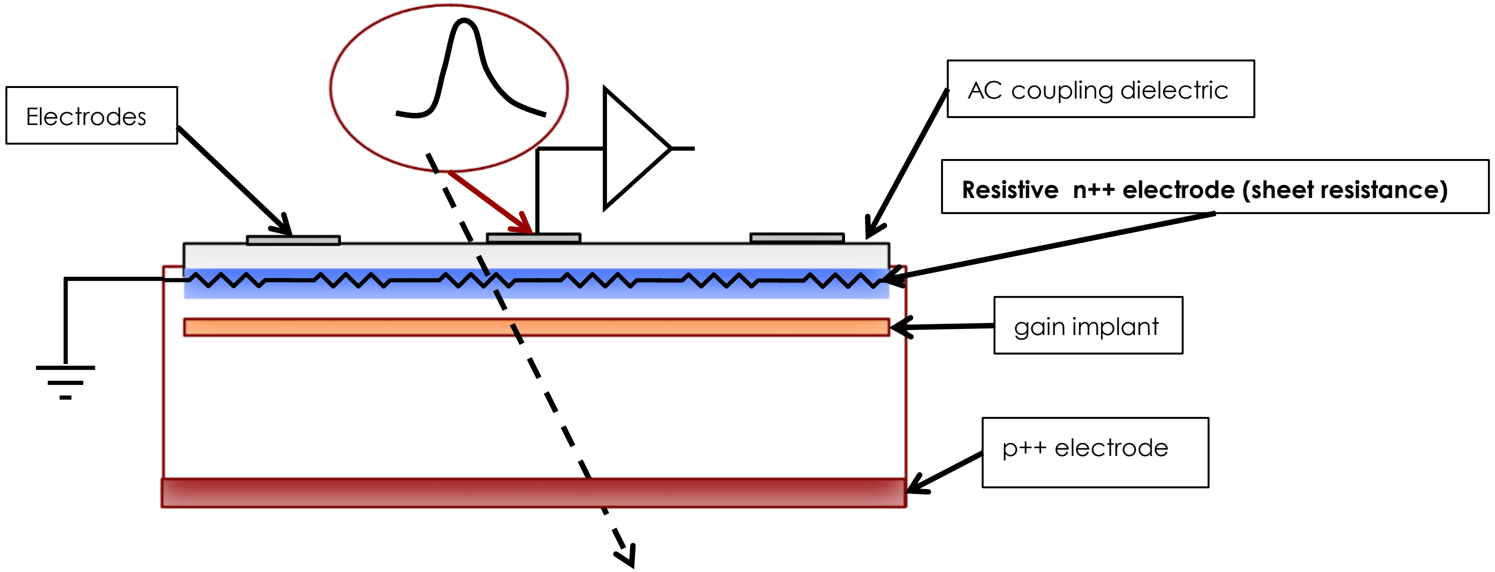
# Back-up



# Resistive silicon detectors

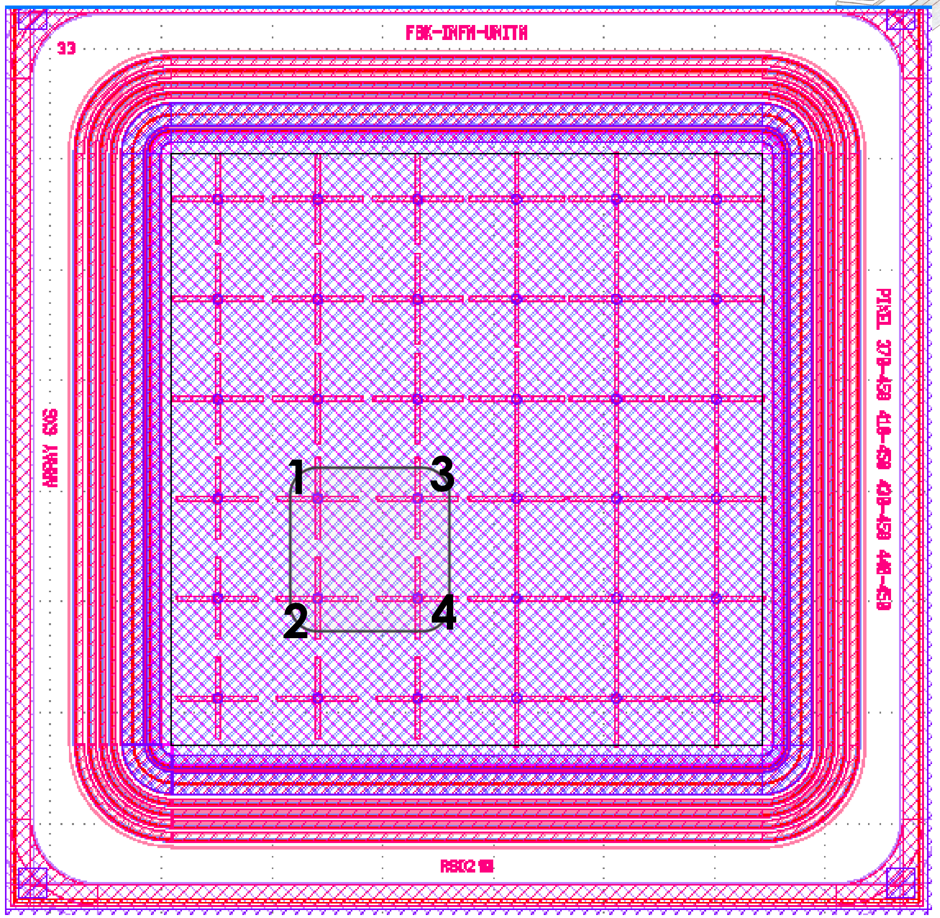
- Resistive silicon detectors (aka AC-LGAD) were presented at **TREDI 2015**
- At **TREDI 2020**, we presented the first results on the properties of silicon sensors with resistive read-out
- Now, at **TREDI 2022,** we present the results obtained with the second FBK RSD production, RSD2.

**RSD building blocks:**



# 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:

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

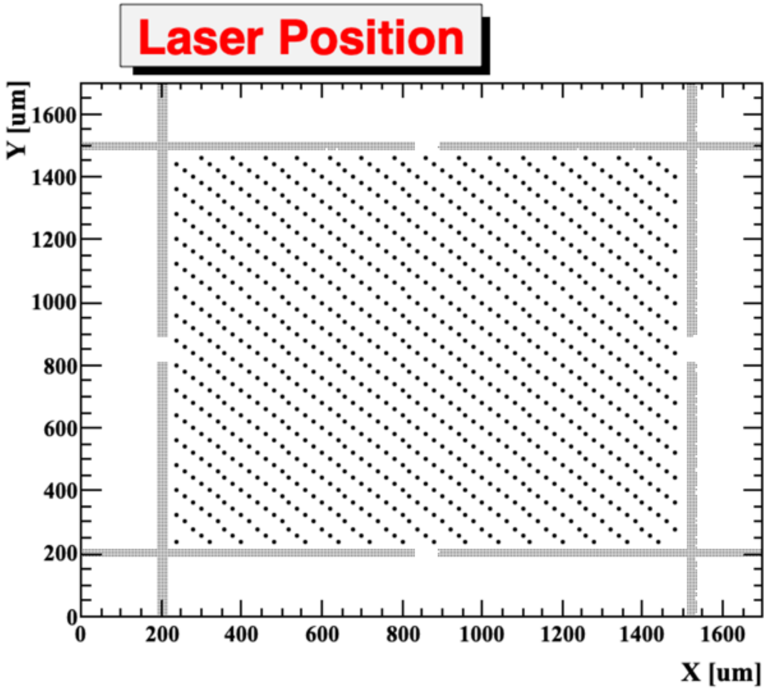
$$y_i = y_{center} + k_y \frac{pitch}{2} * \frac{Q_1 + Q_3 - (Q_2+Q_4)}{Q_{tot}}$$

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

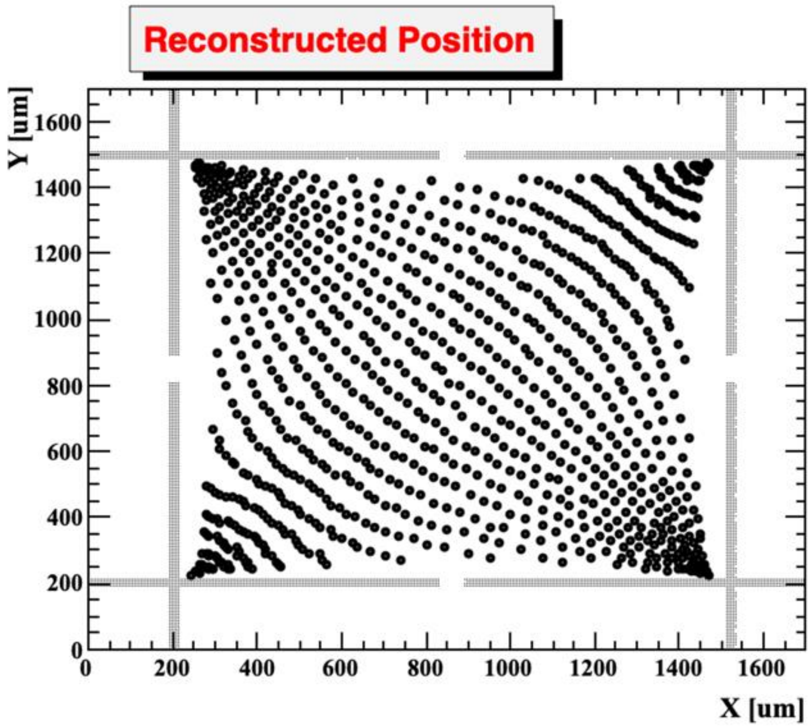
$$k_y = \frac{Q_{tot}}{Q_1 + Q_3 - (Q_2+Q_4)}|_{y@edge}$$

# Reconstruction 1: evaluate the performance

**Shoot the laser in a grid of points**




**Reconstructed hit position**



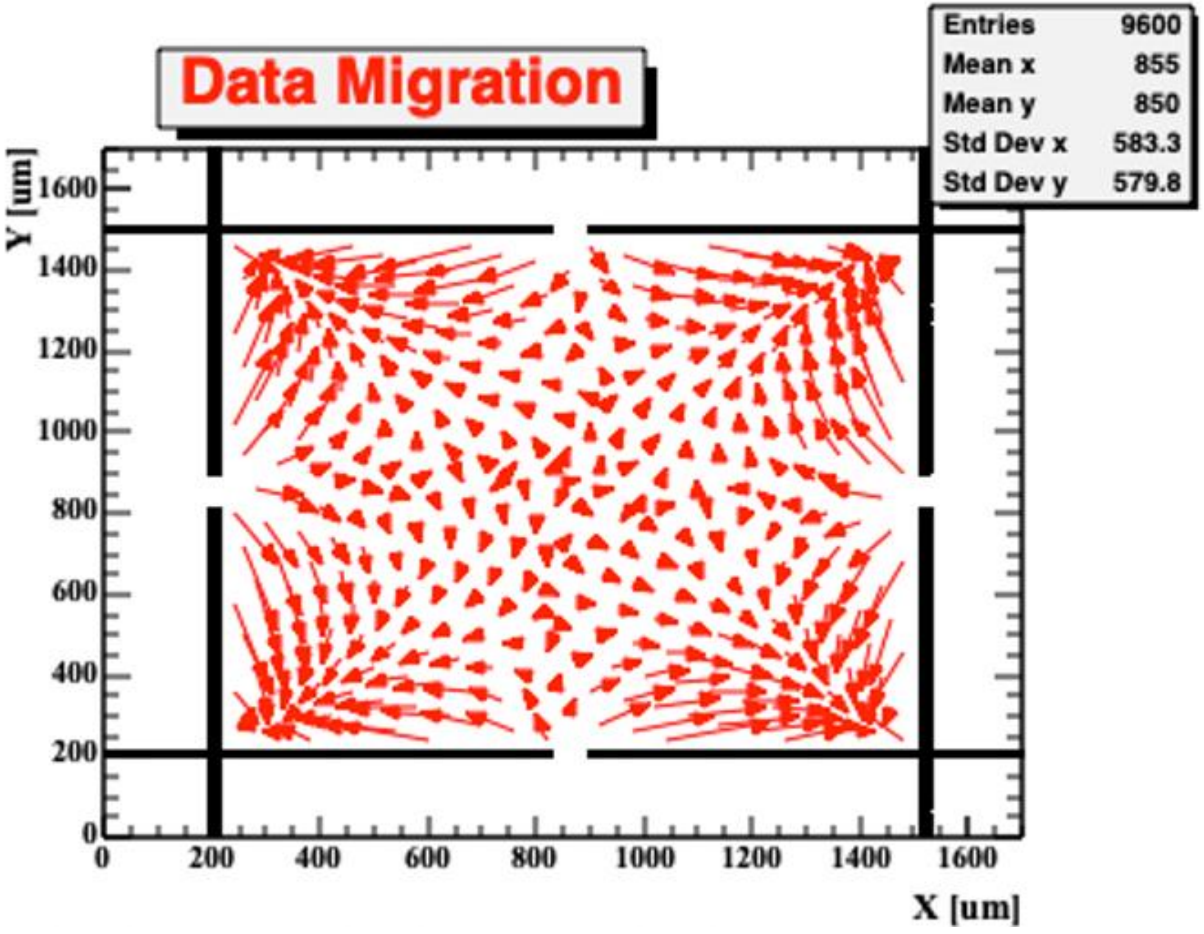

**First take-home result:** even without any additional correction, the cross-shaped electrodes provide a fairly accurate reconstruction

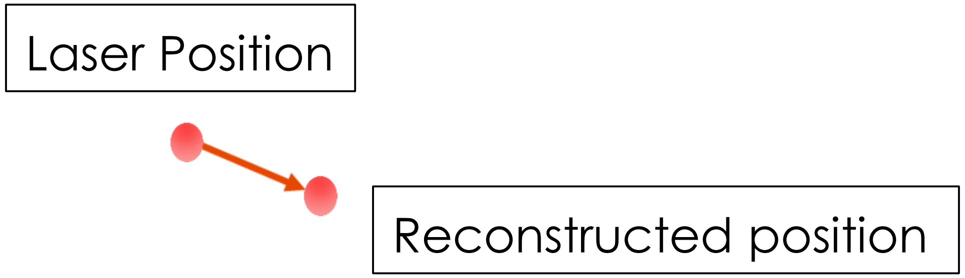
**Second take-home result:** near the pads, the reconstructed positions are systematically shifted with respect to true positions

# Reconstruction 2: measure the migration map

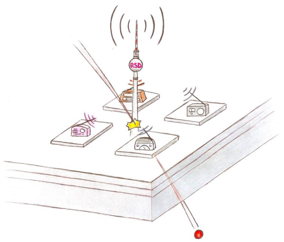
Compute the migration map:

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

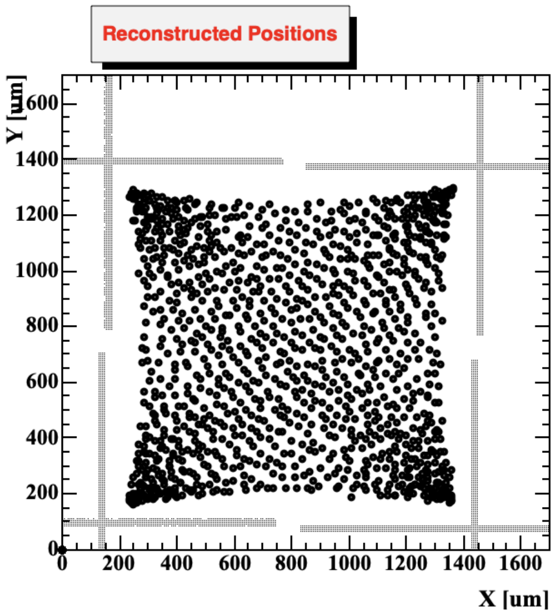


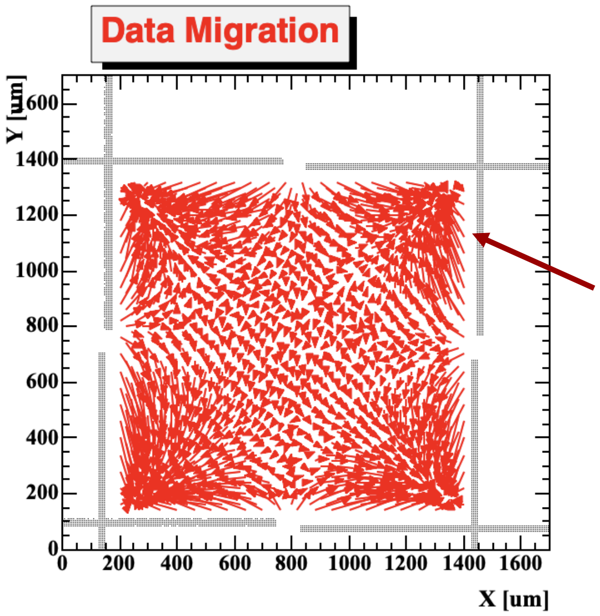



# Reconstruction 2: apply the correction



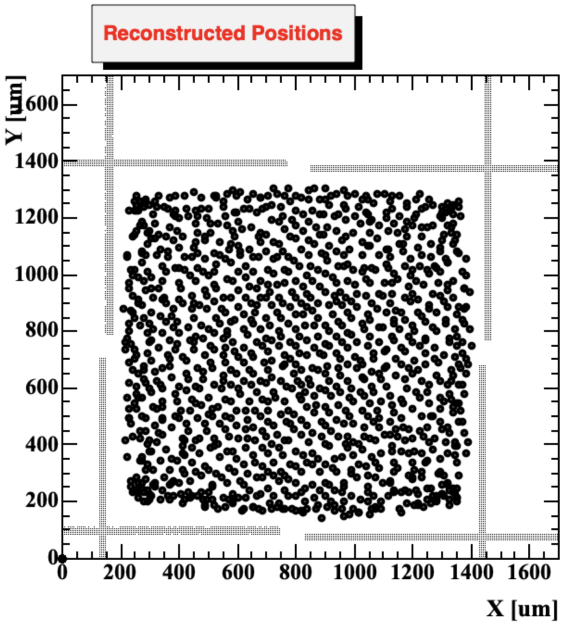
Raw data



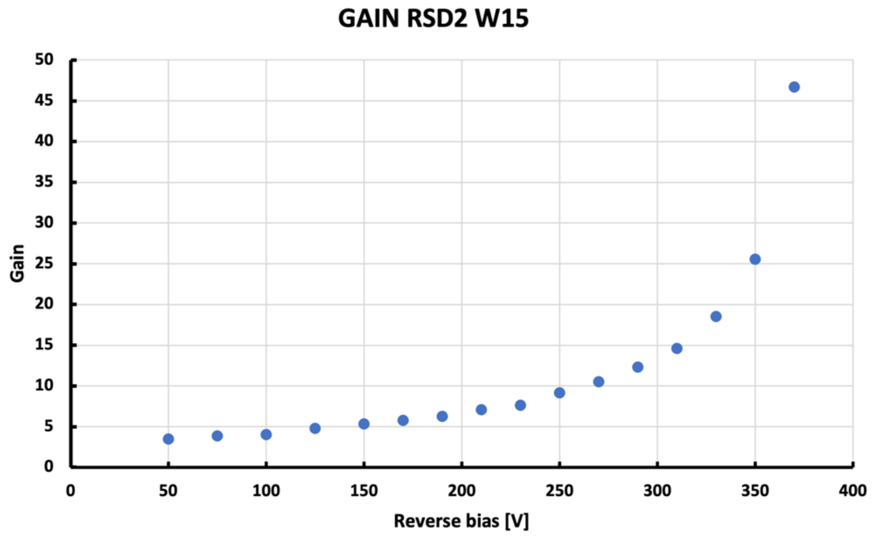

**Note:** a 30 microns minimum distance from the metal electrodes has been used to ensure the laser shot is fully on the open silicon.

Corrected data



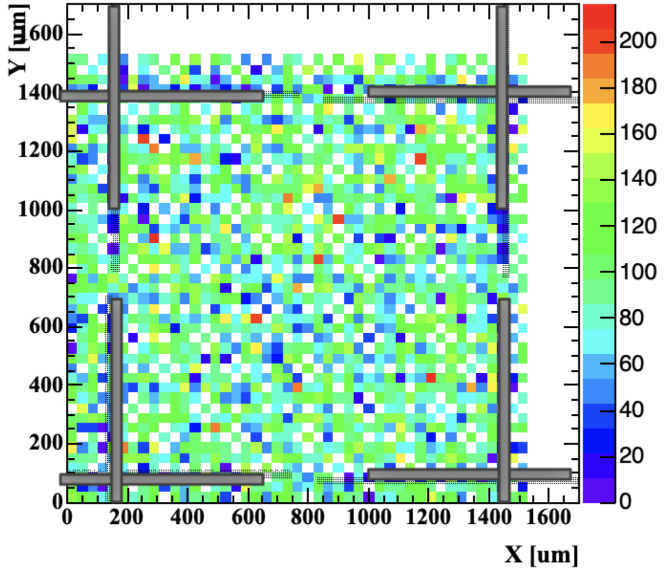
# RSD2 response uniformity

this is the gain curve →



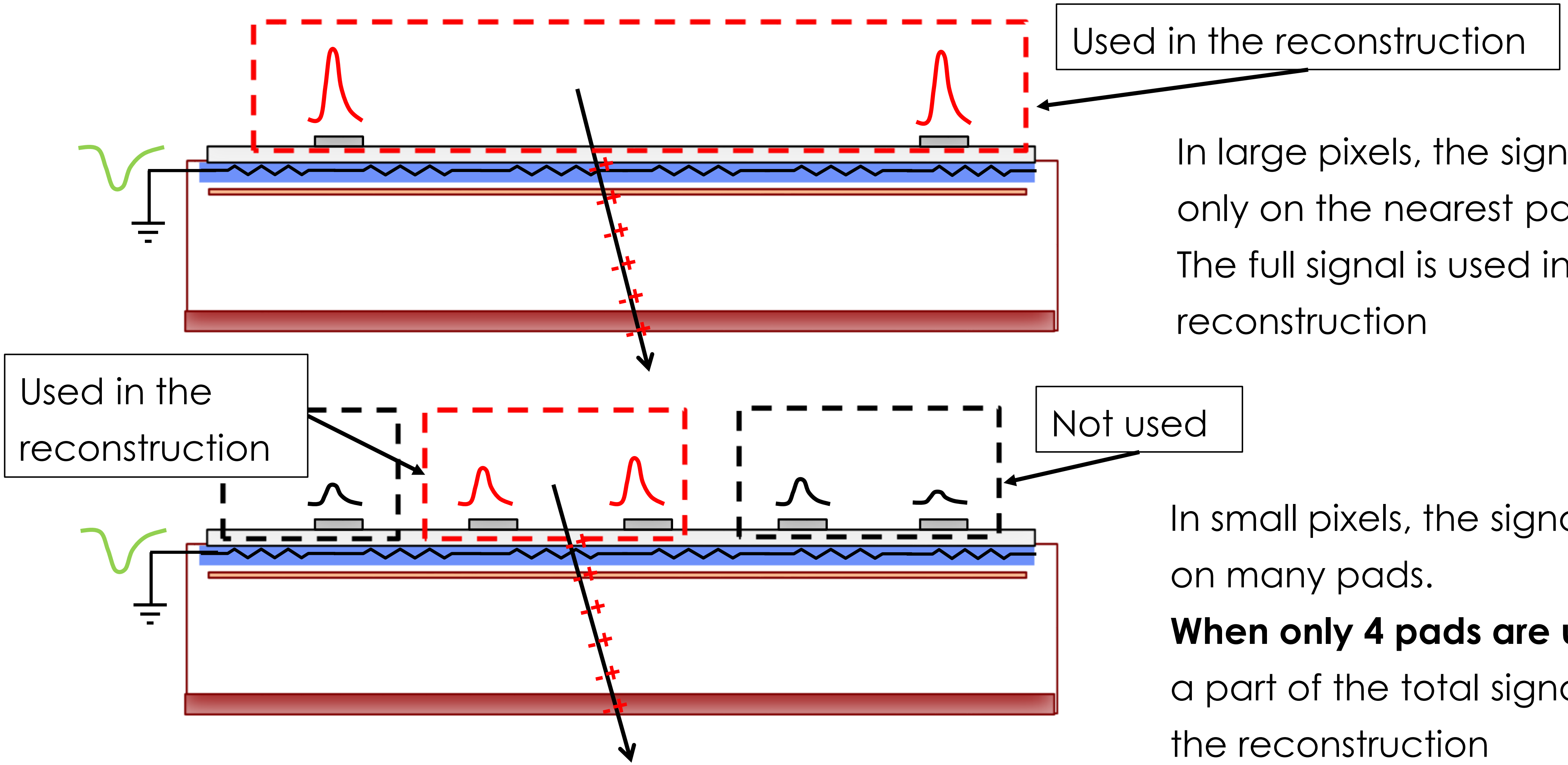

**Area of the DC-signal in the 1300 x 1300 $\mu m^2$ pixel.**

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




**The response is very uniform over the pixel area**

# Signal spread vs pixel size



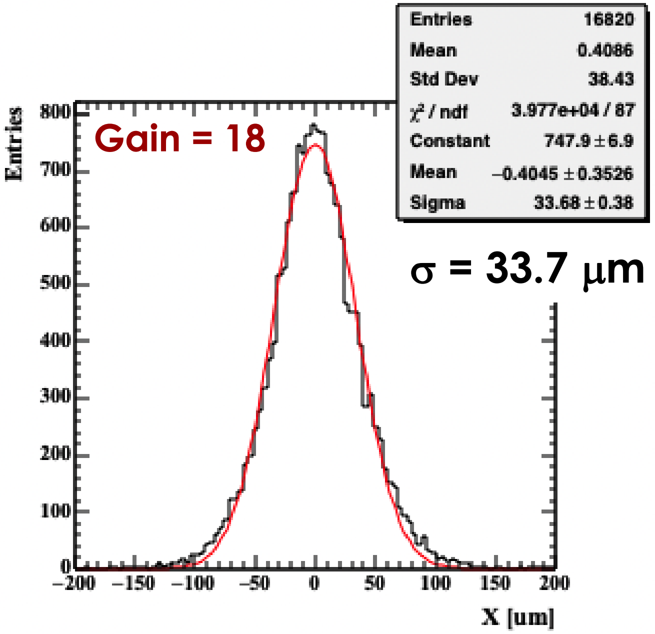

In large pixels, the signal is visible only on the nearest pads.
The full signal is used in the reconstruction

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

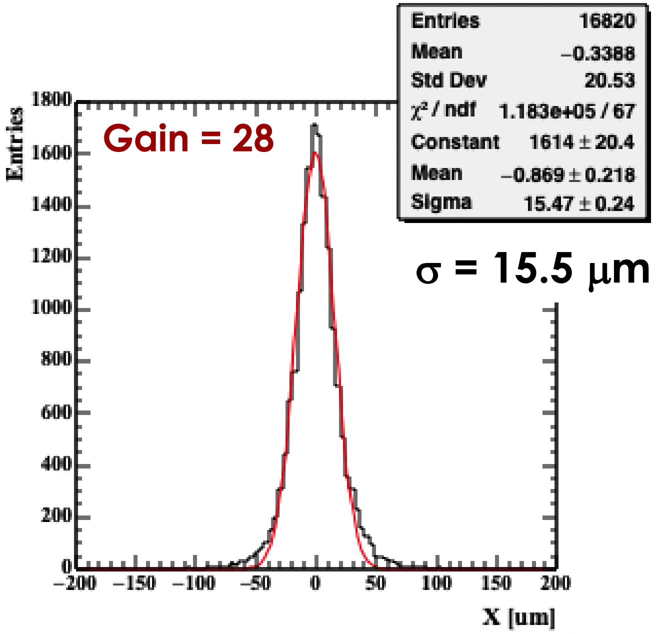
**In small pixels, for equal gain, the signal-to-noise ratio is worse since part of the signal leaks to pads not used in the reconstruction**

# Example of position resolution

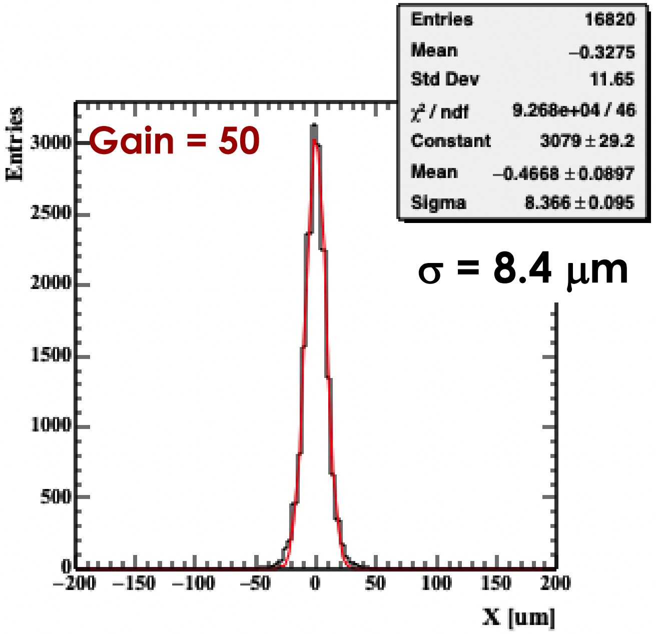
**RSD2 crosses: spatial resolution at 3 different gains in the 450 μm pixel**




**(A)**




**(B)**

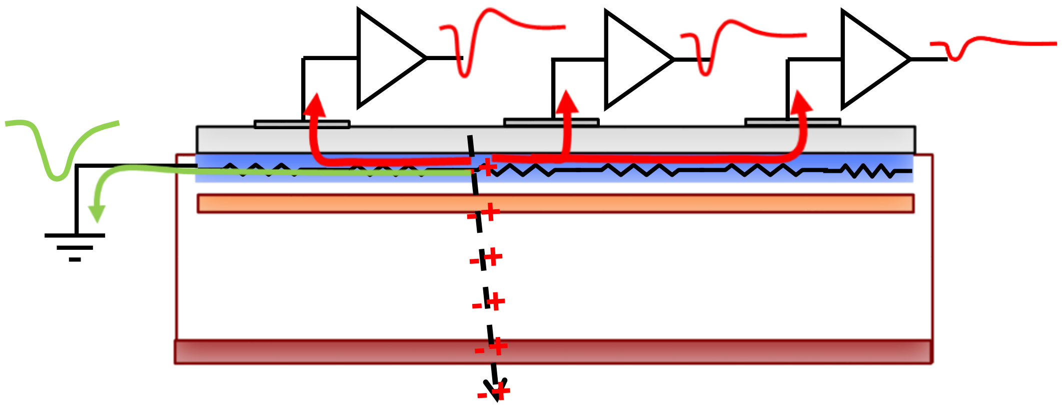



**(C)**

# Aide memoire: RSD principle of operation

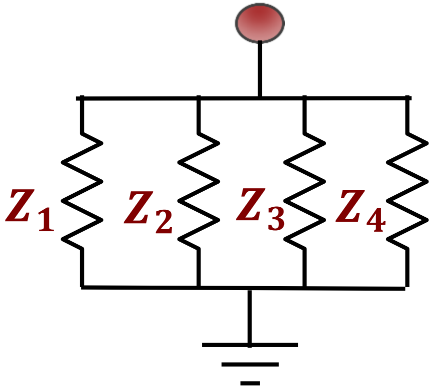
**AC signals (red)** are measured on the pads

**DC signal (green)** on the resistive layer

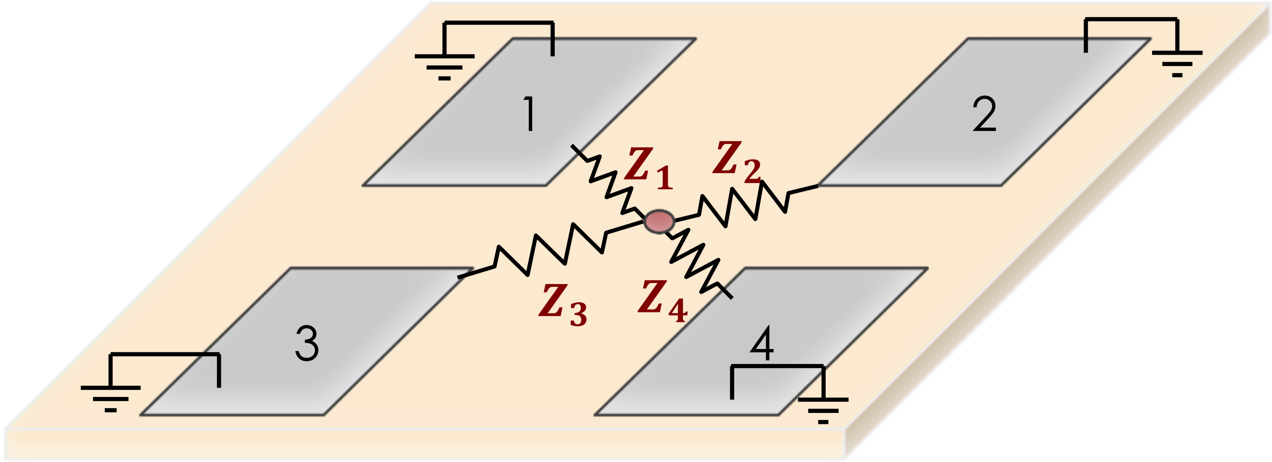


The signal sees several impedances $\boldsymbol{Z_i}$ in parallel, and it is split according to Ohm's law.

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




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

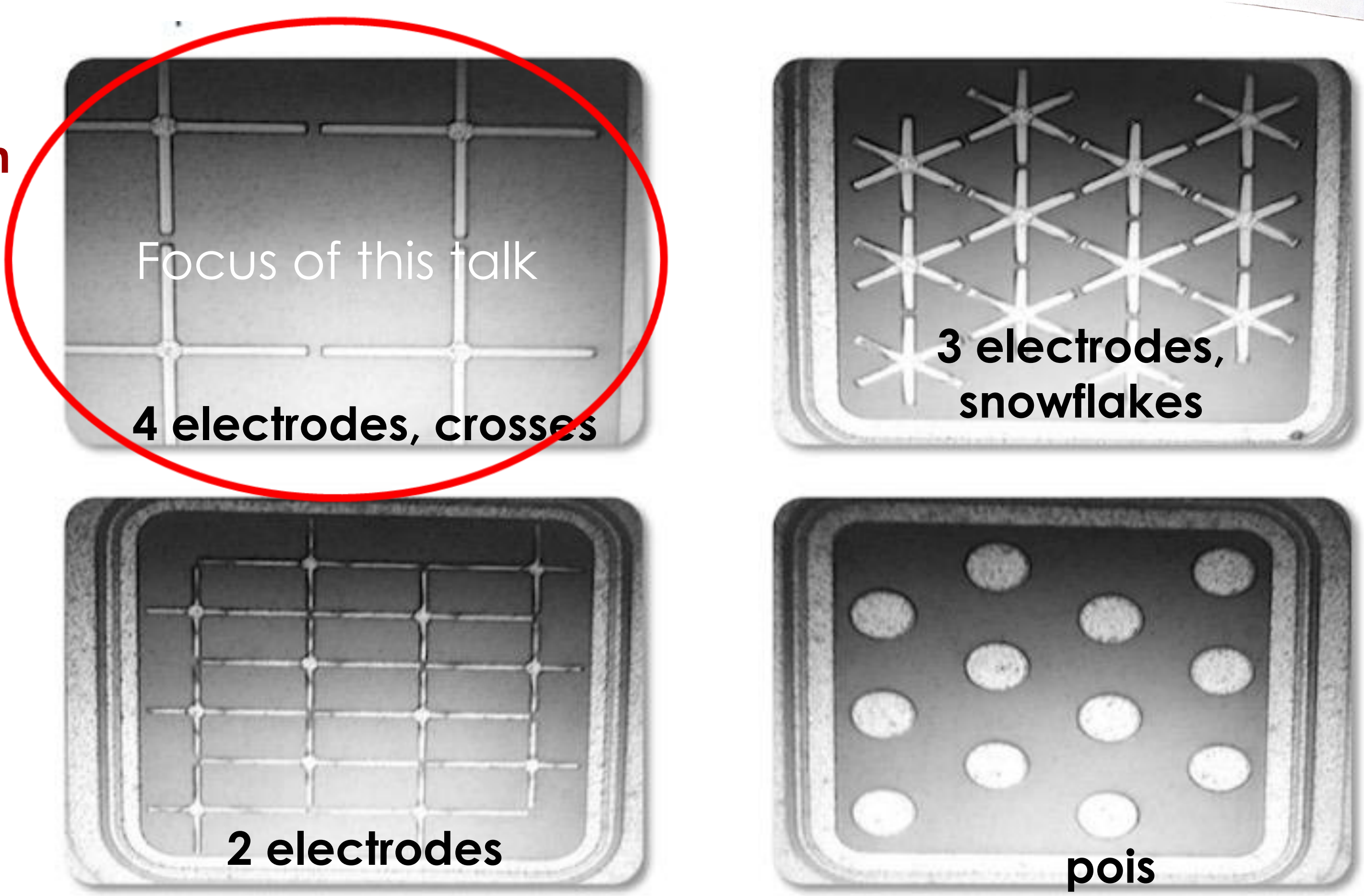


# The FBK RSD2 production

**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

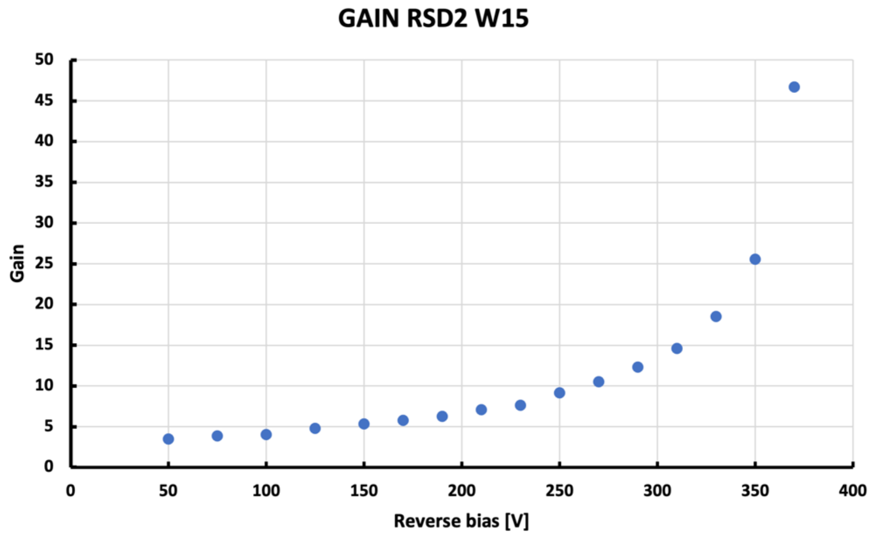



Details on RSD2:

- 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

# 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 $\mu m^2$ pixel.**

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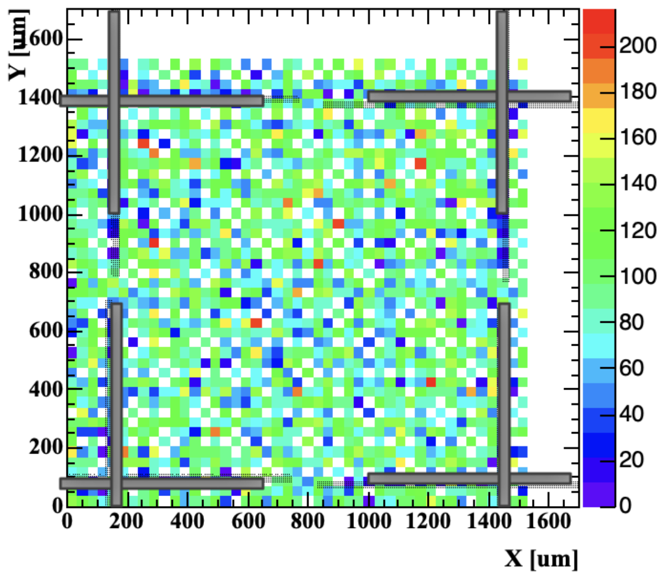



**Note:** in some plots, values of gain > 30 are reported.
These are achieved by increasing the laser intensity to about 3 MIP while keeping the bias in the range 250V-330V.
This feature is indicated as "**gain equivalent**"

# Hit position resolution

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

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

$\boldsymbol{\sigma^2_{signal}}$ : 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.

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

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

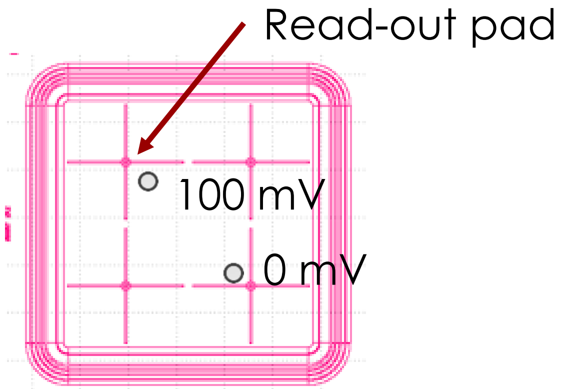
# Position Jitter

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)

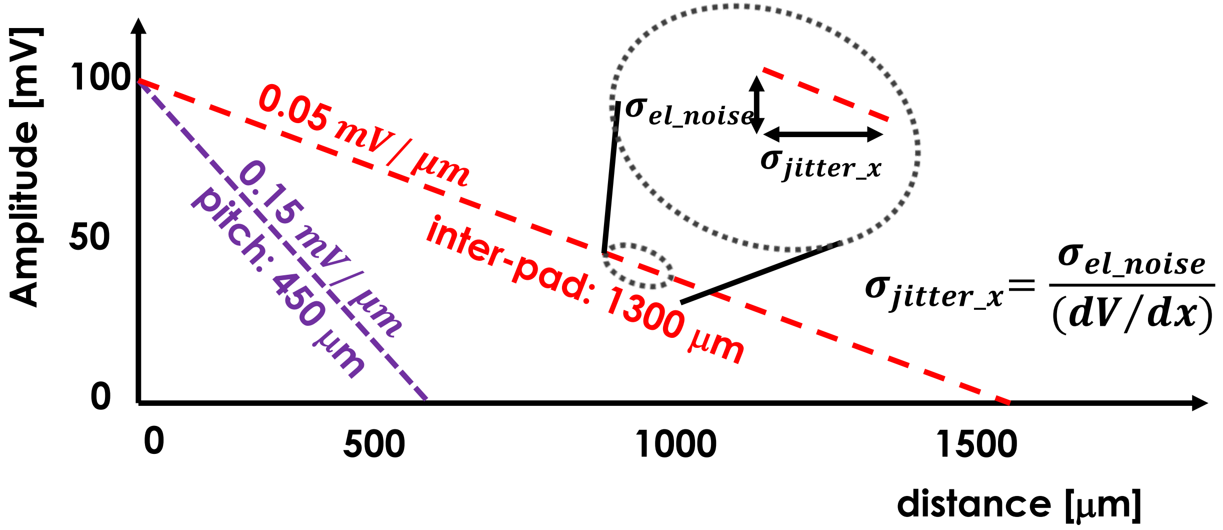



In this simplified system, the signal decreases by:

- 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: 1 mV/(0.15 mV/μm) =** **7 μm**

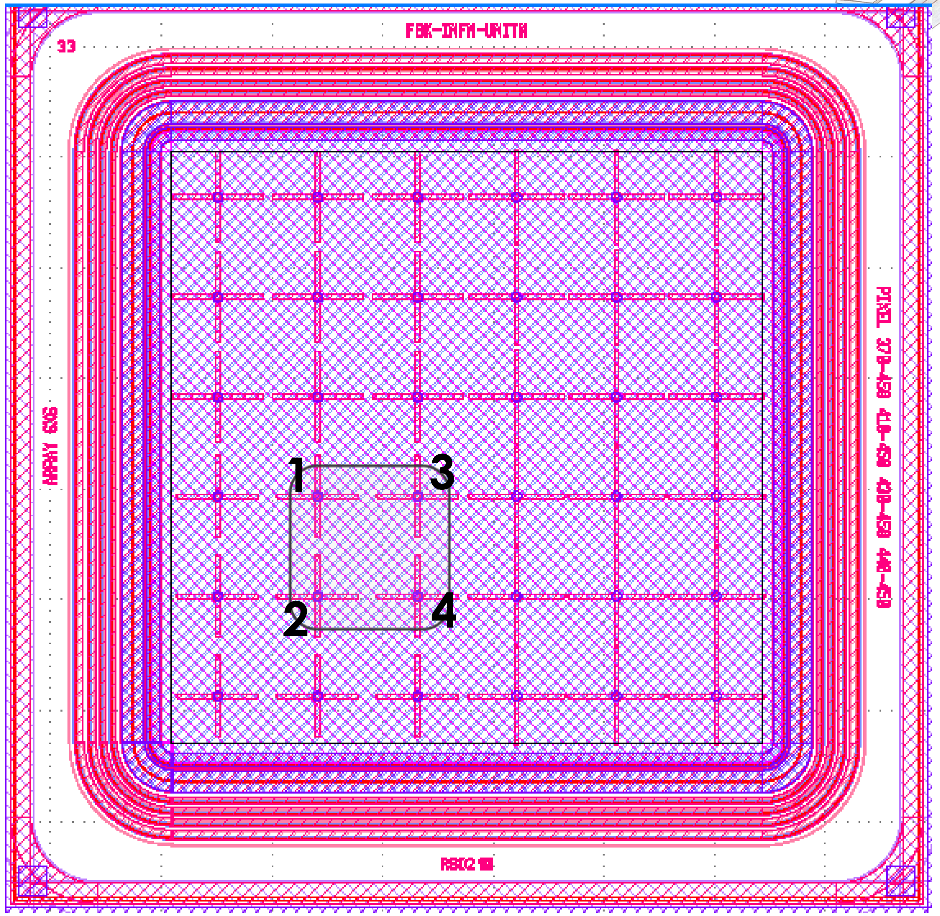



**With increasing number *n* of AC-read-out pads, the jitter becomes larger as $\sigma_{jitter} \propto \sqrt{n}$**

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

# 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:

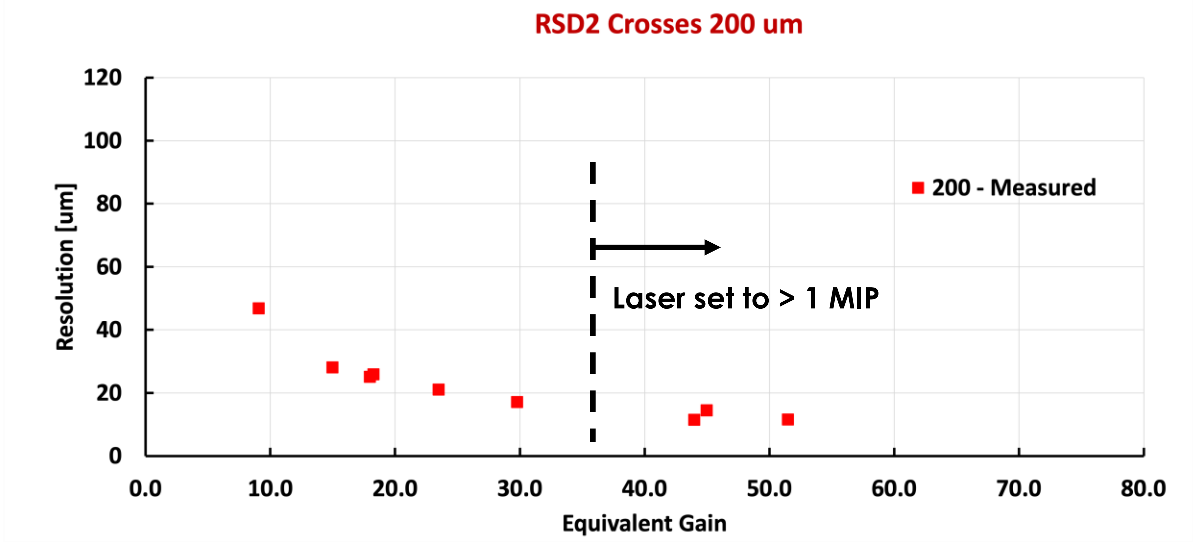
$$x_i = x_{center} + k_x \frac{pitch}{2} * \frac{Q_3 + Q_4 - (Q_1+Q_2)}{Q_{tot}}$$

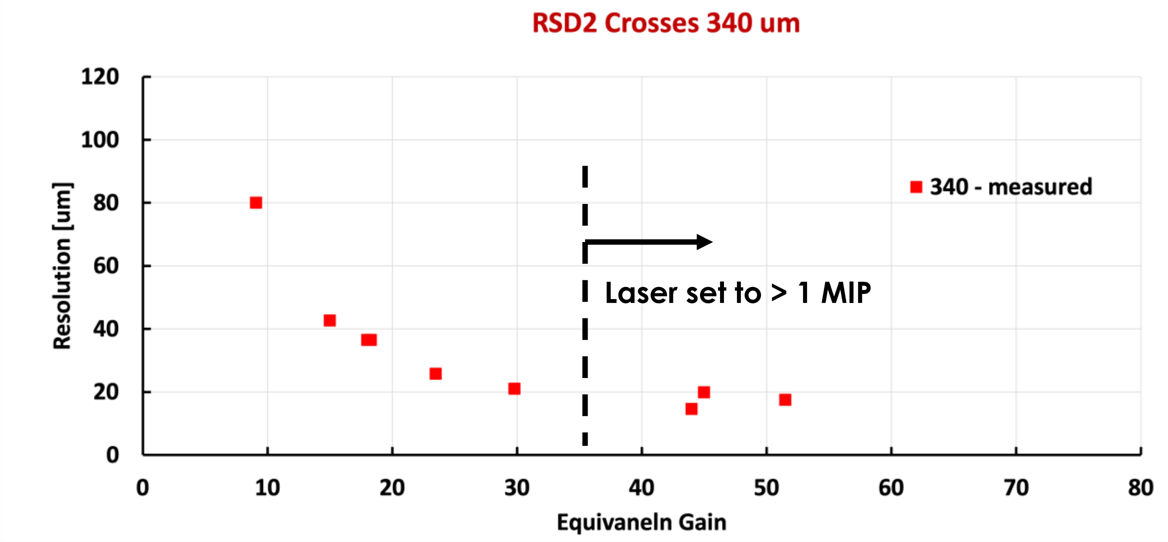
$$y_i = y_{center} + k_y \frac{pitch}{2} * \frac{Q_1 + Q_3 - (Q_2+Q_4)}{Q_{tot}}$$

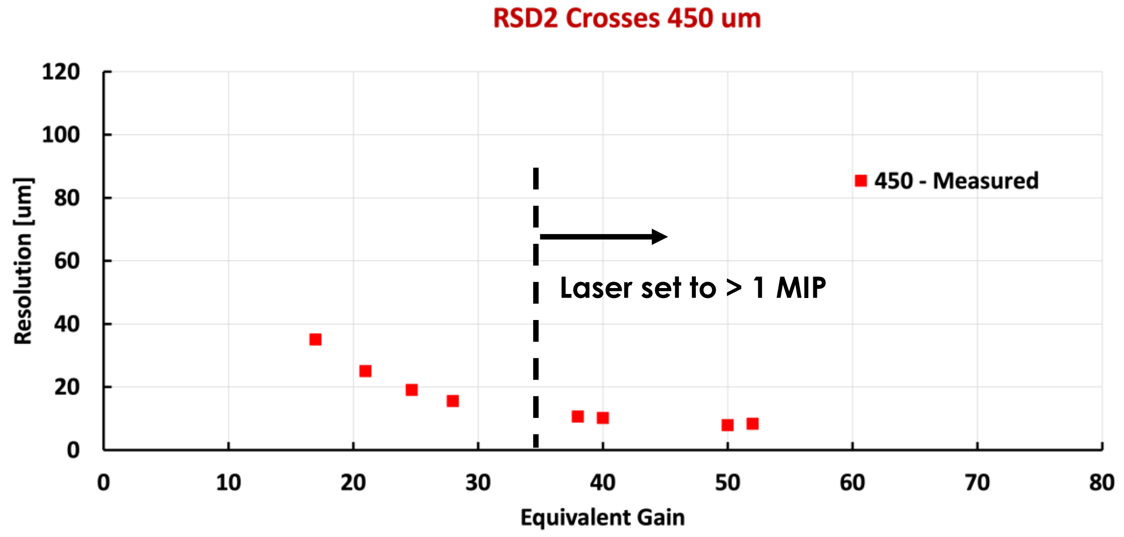
$$k_x = \frac{Q_{tot}}{Q_3 + Q_4 - (Q_1+Q_2)}\Big|_{x@edge}$$

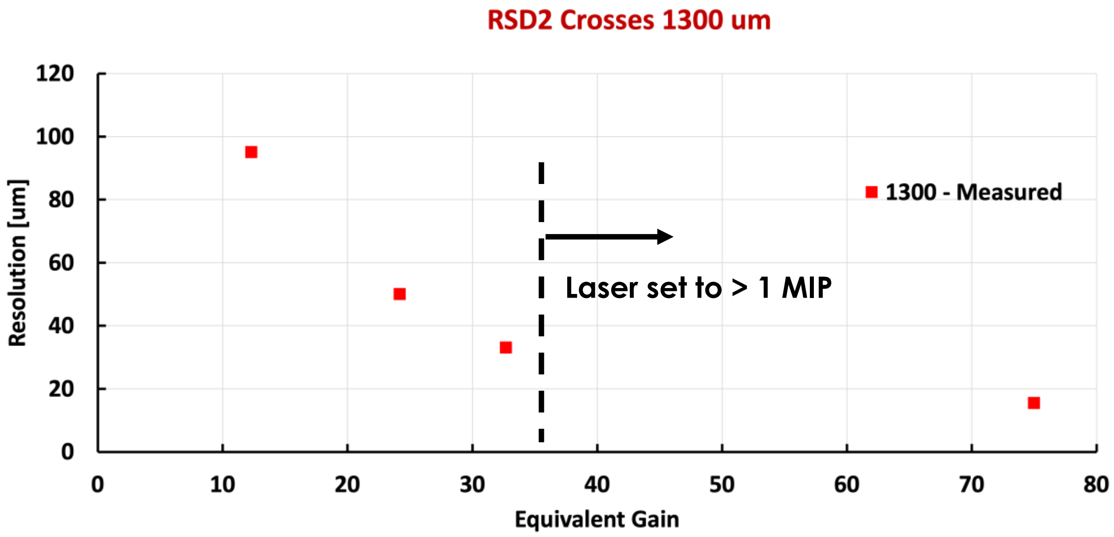
$$k_y = \frac{Q_{tot}}{Q_1 + Q_3 - (Q_2+Q_4)}\Big|_{y@edge}$$

# Results: resolution vs gain (4 different pitches)



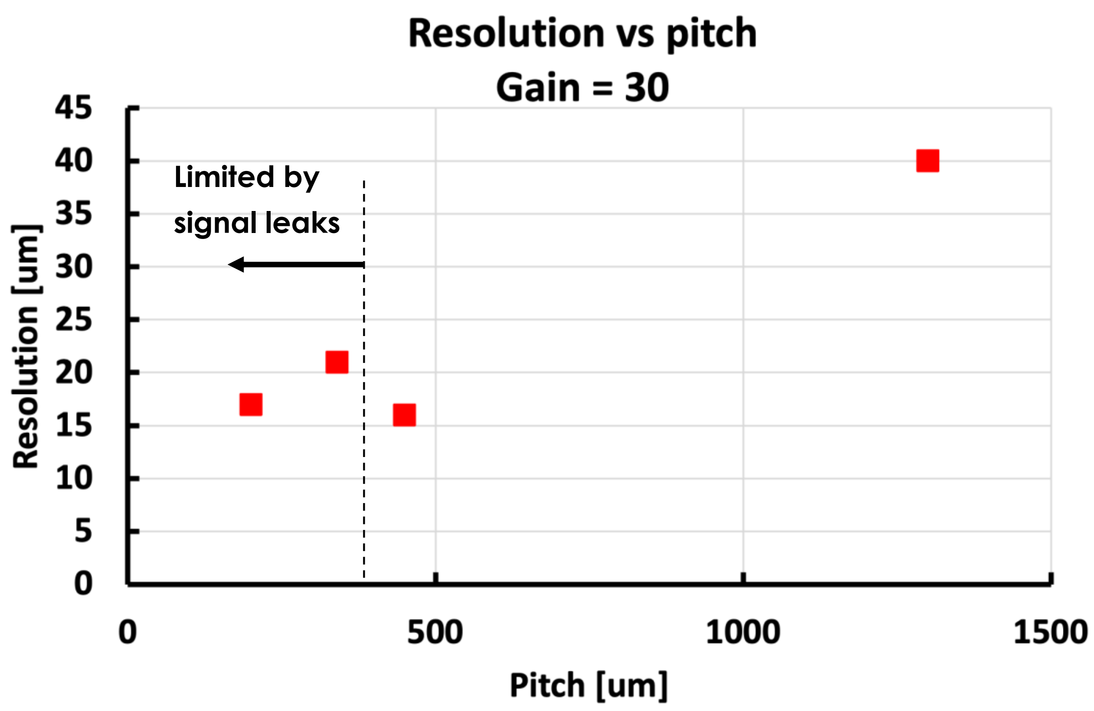



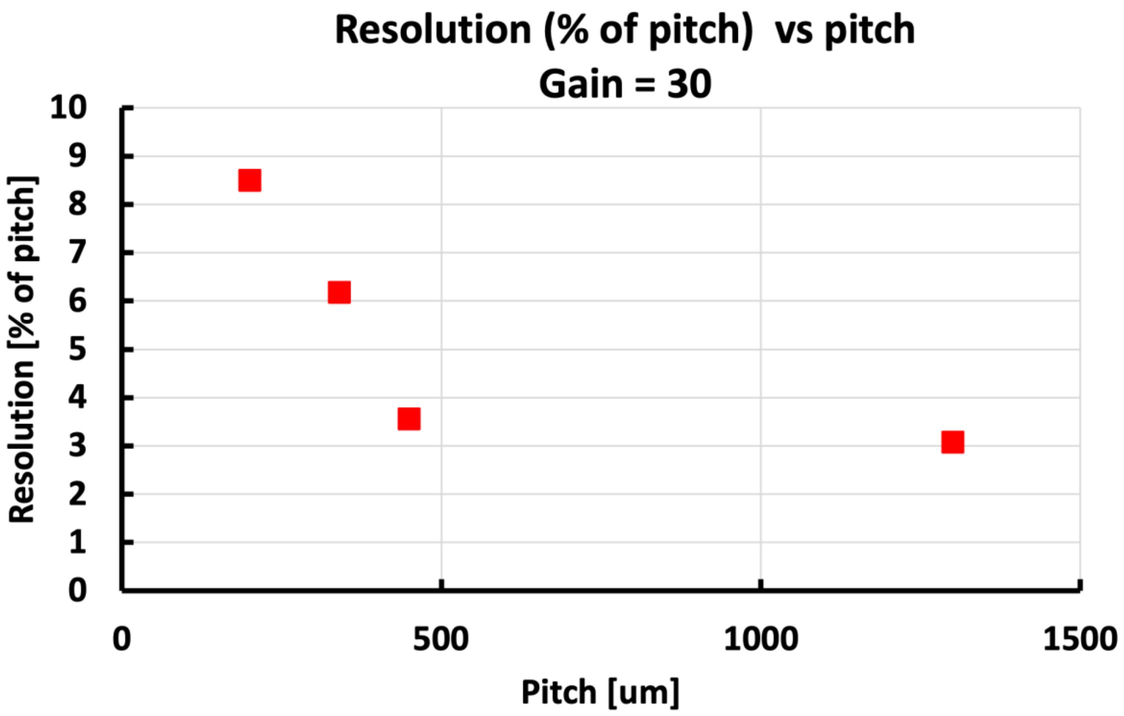




Note: high-gain signals are obtained using a 3 MIP laser setting

# Summary: resolution vs pitch



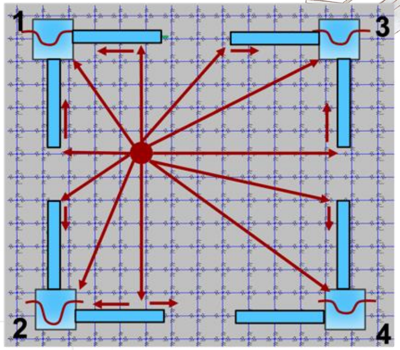

**The position resolution is very good**

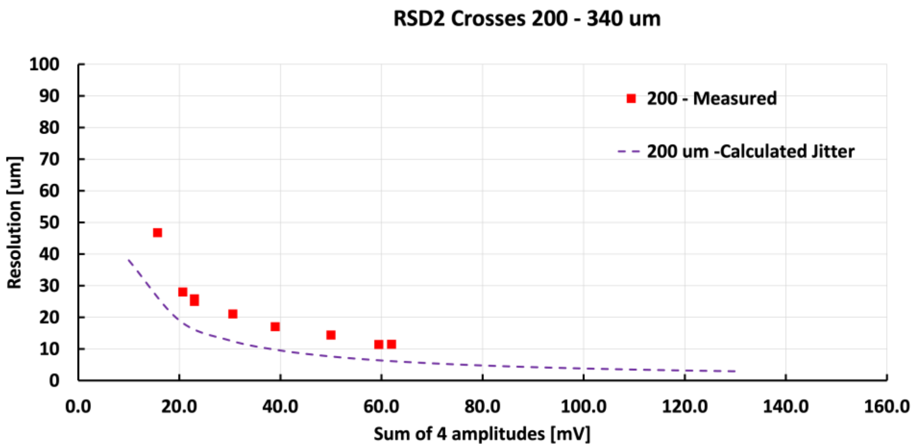
- Using only 4 read-out pads, the resolution in small structures is limited by the excessive signal spread
- The best relative resolution is about 3% of the pitch

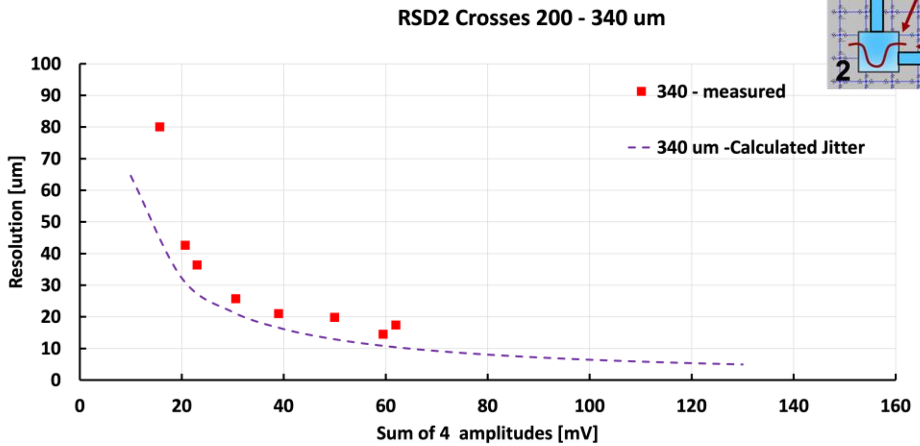
# Resolution vs Sum of 4 amplitudes (4 different pitches)

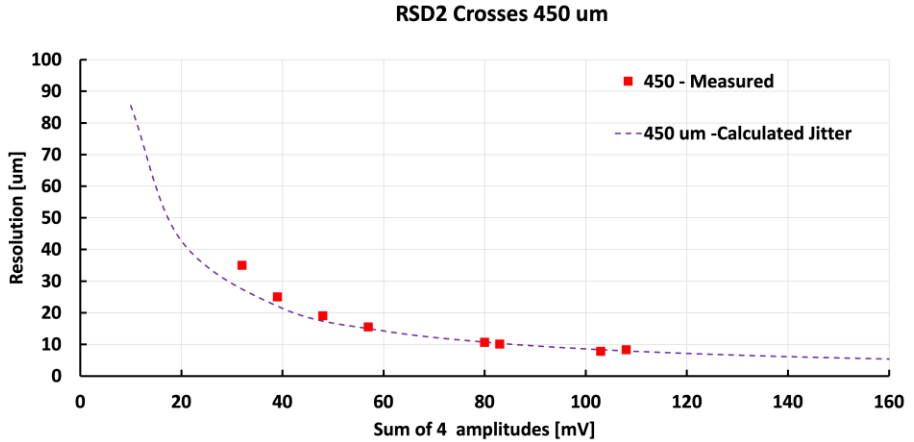
The jitter reproduces quite well the overall resolution vs amplitude trend

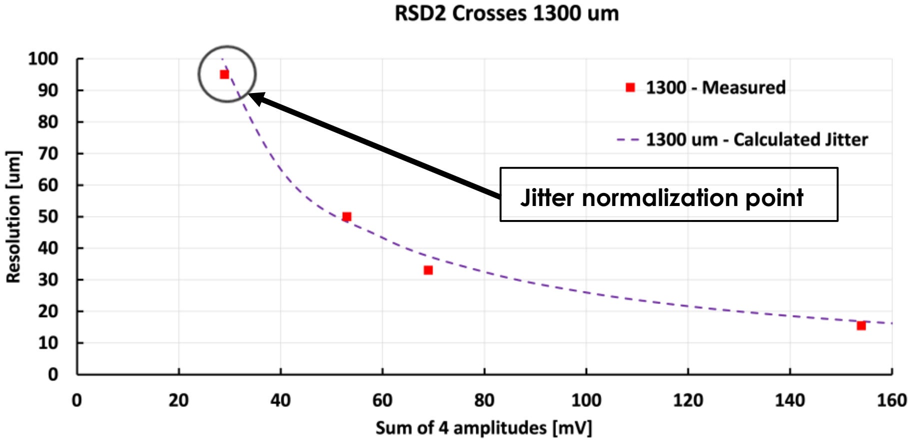
$$\sigma_{jitter} = \frac{\sigma_{el\_noise}}{\frac{\sum A}{pitch}}$$




Note: one single normalization for the 4 pitch sizes

# How to improve performances

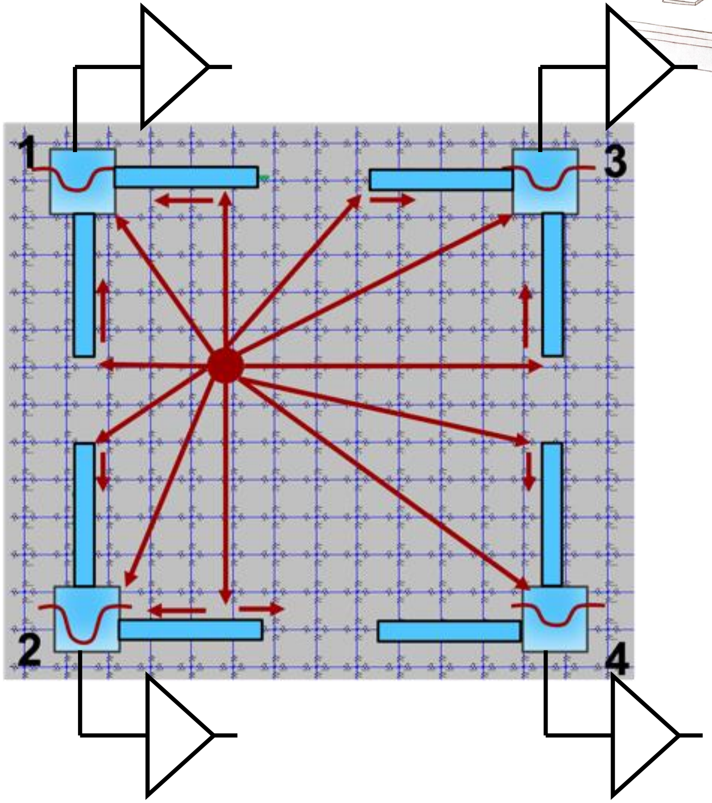
**The resolution is dominated by the jitter term**

==> limited by the electronic noise.

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

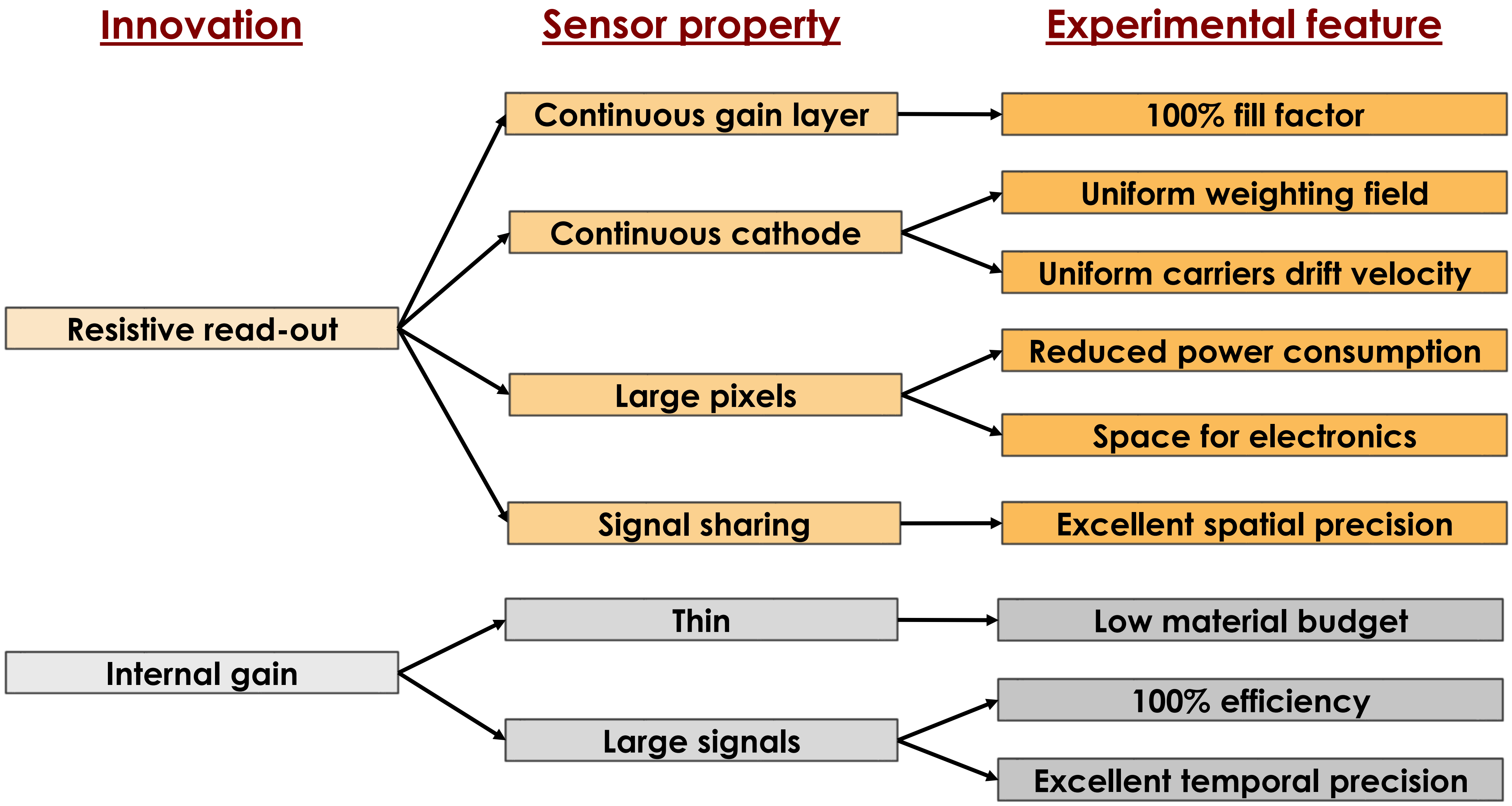
large bandwidth, high noise

**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


Innovation
Sensor property
Experimental feature
Resistive read-out
Continuous gain layer
100% fill factor
Continuous cathode
Uniform weighting field
Uniform carriers drift velocity
Large pixels
Reduced power consumption
Space for electronics
Signal sharing
Excellent spatial precision
Internal gain
Thin
Low material budget
Large signals
100% efficiency
Excellent temporal precision