Properties of signal sharing in Resistive Silicon Detectors

- **Interplay of the surface resistivity and pixel size in determining RSD performance**
  - Amplitude
  - Propagation time
- **Optimization of the read-out bandwidth**
- **Results**
  - Spatial and temporal resolution of low-resistivity DC-RSD1 pixel matrices (300, 500, and 1000 micron pitch)

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for the 4DShare group

DRD3 week – CERN – November 11th 2025

Sensors used in the study

This study uses FBK DC-RSD1 pixel matrices from the first 4DSHARE production run.

- **Low surface resistivity**, R = 0.75 **kΩ/□ (Wafer 15):**
  - 300 um
  - 500 um
  - 1000 um
- **High surface resistivity**, R = 1.8 **kΩ/□ (Wafer 3):**
  - 500 um
  - 1000 um

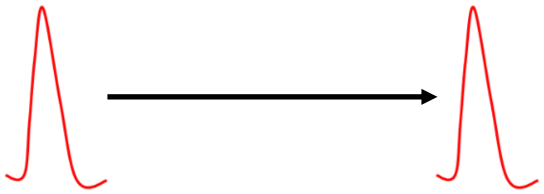
The measurements shown in the following slides were collected during two test beams at the DESY beam line.

Interplay of the surface resistivity and pixel size in determining RSD performance

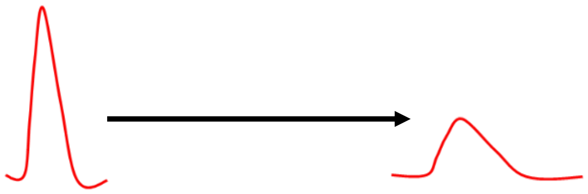
RSDs are characterized by a **resistive surface** that forms an **RC system with the backplane. This RC system might decrease the signal amplitude.**

Detector performance is determined by the sum of the **signal amplitudes reaching the 4 electrodes**, therefore **RSDs should be designed to preserve the signal amplitude as much as possible**

Good design

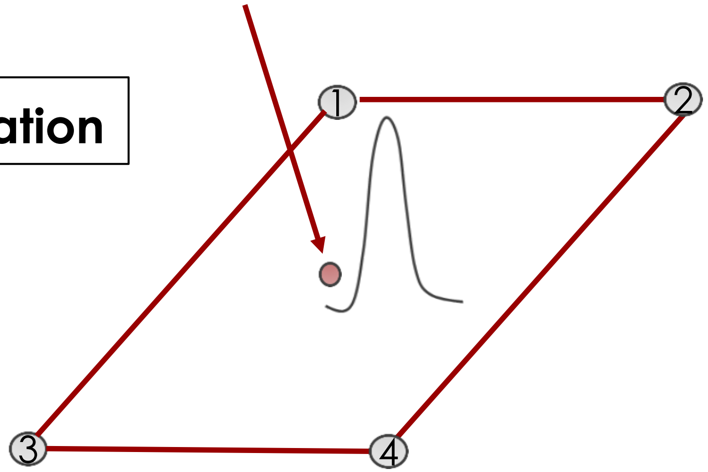


Not so good design



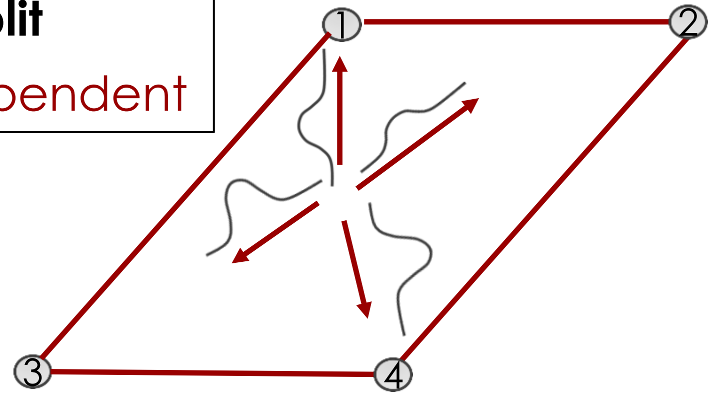
Chain of events

Step 1: Signal creation



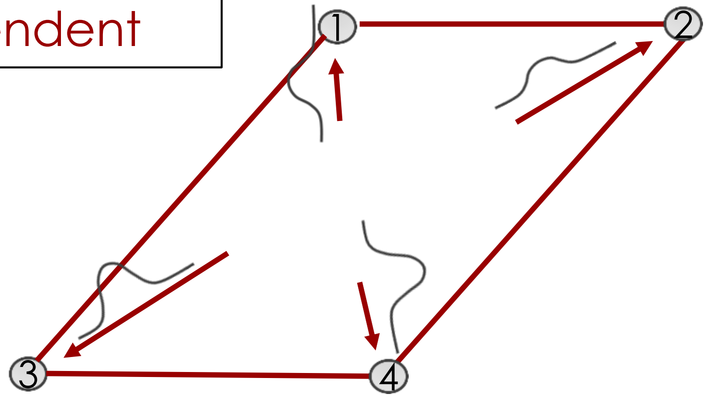
Step 2: Signal split

- Frequency dependent



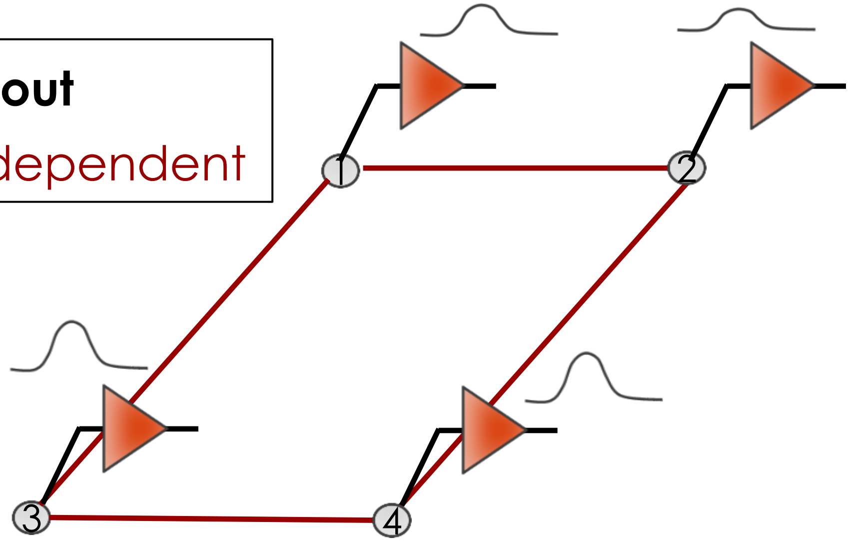
Step 3: Signal propagation

- Frequency dependent



Step 4: Read-out

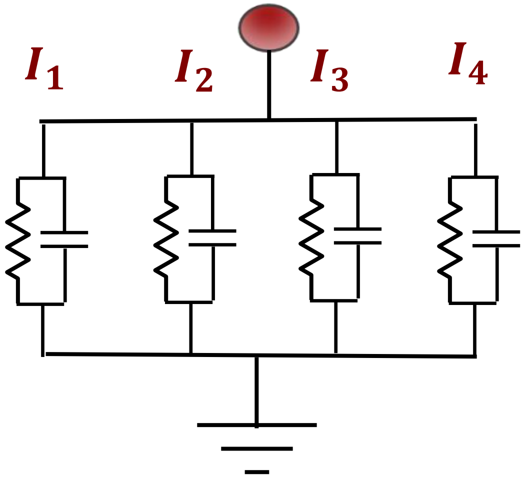
- Frequency dependent

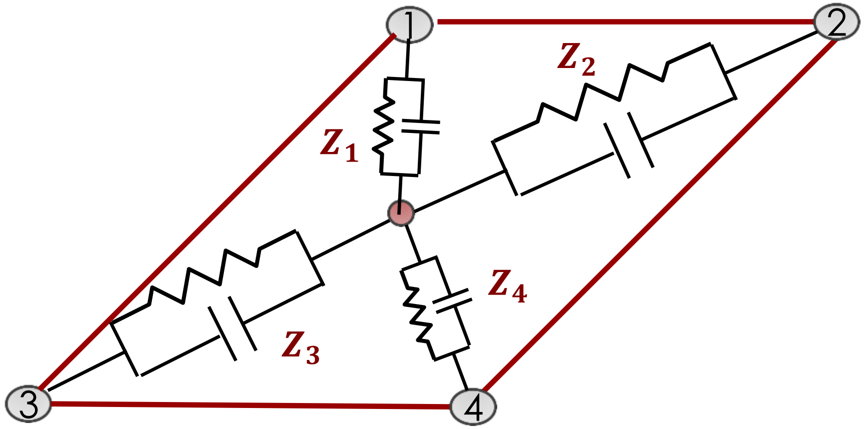


Step 2: Signal split

The amplitude split depends on the impedance toward each electrode, determined by:

- the absolute size of the pixel
- the relative electrode positions
- the sensor thickness
- the surface resistivity





Simplified model:

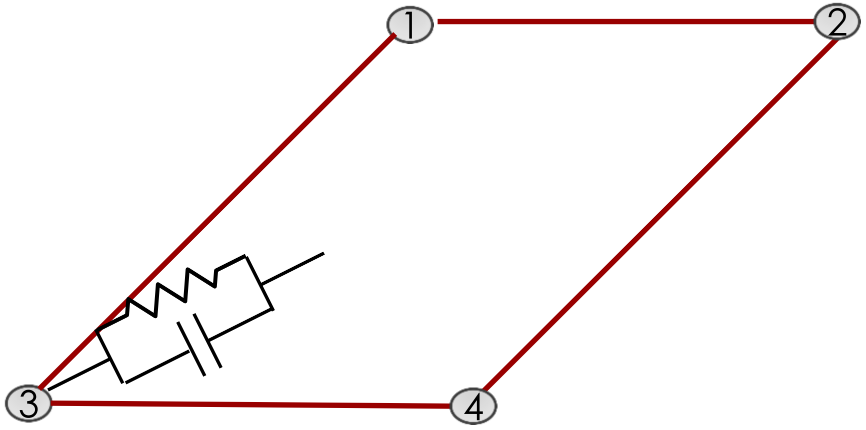
$$S_i\,(d,f) \propto \frac{\frac{1}{Z_i}}{\sum_1^n \frac{1}{Z_i}}$$

$\mathrm{S_i}\,(\mathrm{d},\mathrm{f})$ is the fraction of a signal with frequency f going to one electrode at the split point

Step 3: Signal propagation

The amplitude attenuation depends on:

- the sensor thickness
- the surface resistivity



Simplified model:

The amplitude of a sinusoidal signal of frequency *f* falls exponentially with distance:

$$S(w,d) \approx S(w,0)\, e^{-d/L_w^{Prop}}$$

- S(w,0) is the initial value at $d = 0$
- Propagation length: $L_w^{Prop} = \sqrt{\frac{2}{2\pi f RC}}$

with $D = \frac{1}{R_S C}$; $C = \frac{\varepsilon_{Si}}{d}$.

Frequency [MHz]	W15 L_ω [mm] R = 0.75 kΩ/□	W3 L_ω [mm] R = 1.8kΩ/□
300	0.83	0.53
400	0.72	0.46
600	0.58	0.38

In our set-up, the highest signal frequency f_{eff}

(rise time $t_r \sim 0.5\, ns$) $f_{max} \approx \frac{0.35}{t_r} \sim 700$ MHz.

Step 4: Read-out

In our set-up, the highest frequency f_{eff} is the **minimum** between

- the frequencies contained in the signal (0.35/$\mathrm{t_r} \sim 700\ \mathrm{MHz}$)
- the read-out BW, 400 MHz:

$$\boldsymbol{f_{\mathbf{max}} \approx min\left(\frac{0.35}{t_r}, 400\right)}.$$

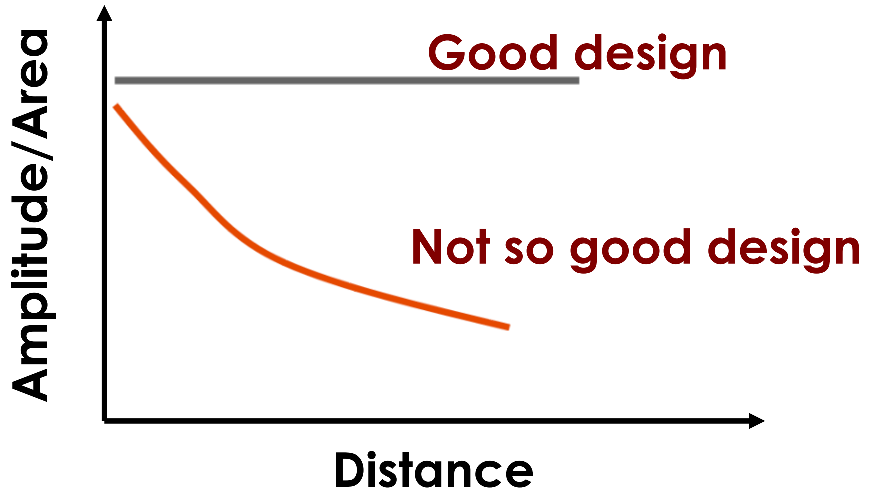
$$R_s(W15) = 0.75\ k\Omega/\square\text{:}\quad L_{400} \approx \mathbf{0.72\ mm}$$

$$R_s(W3) = 1.8\ k\Omega/\square\text{:}\quad L_{400} \approx \mathbf{0.46\ mm}$$

How to measure frequency-dependent effects

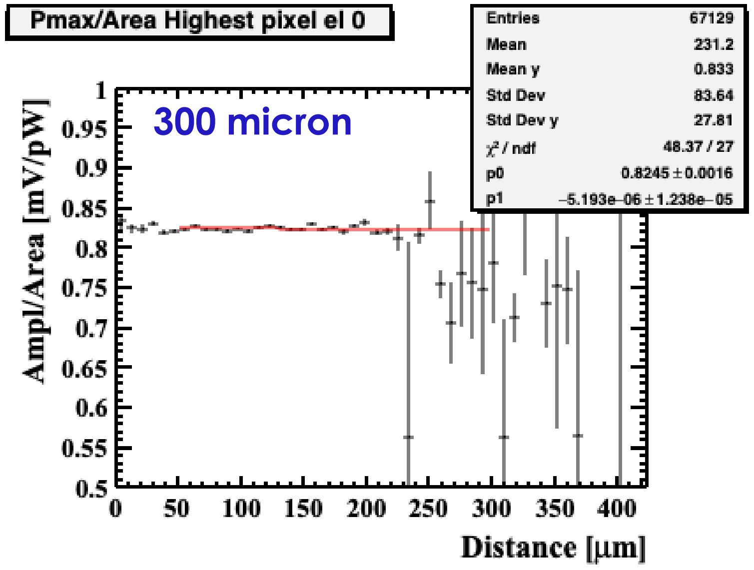
In a RC extended system:

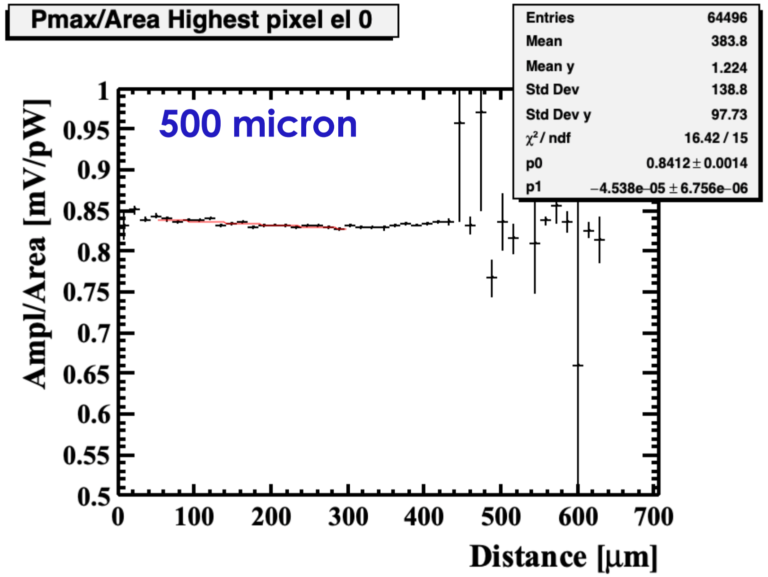
- **The total signal amplitude might decrease** due to frequency-dependent effects
- **The total signal area does not change**

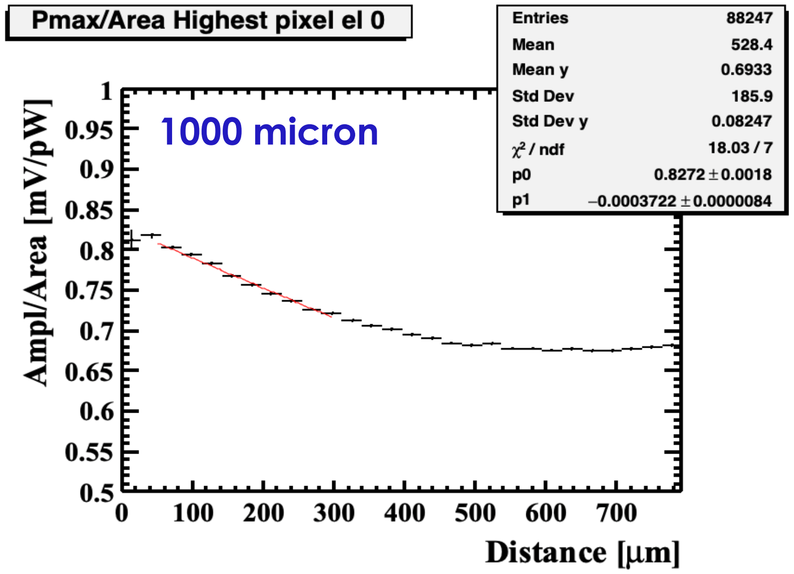


The ratio **Amplitude/Area vs distance** is a good indicator to measure how a signal is affected by the RC system

Measurements: **low** surface resistivity



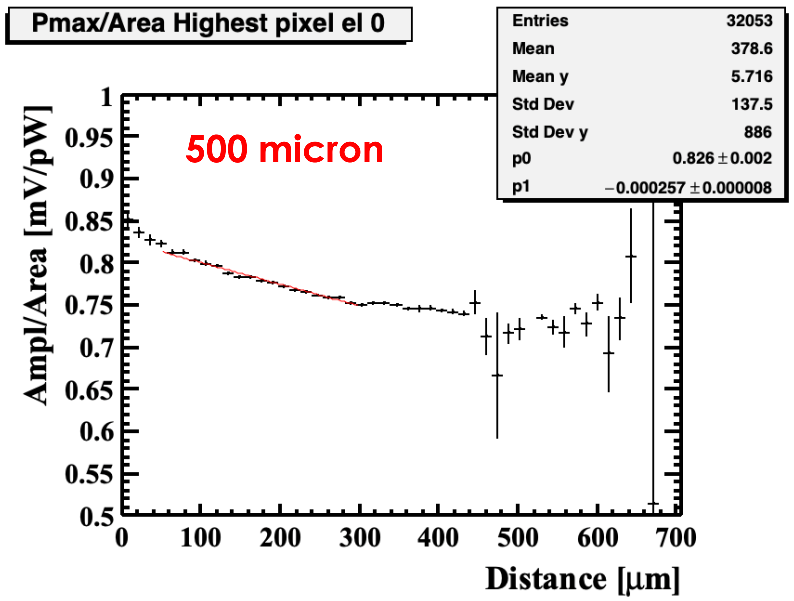


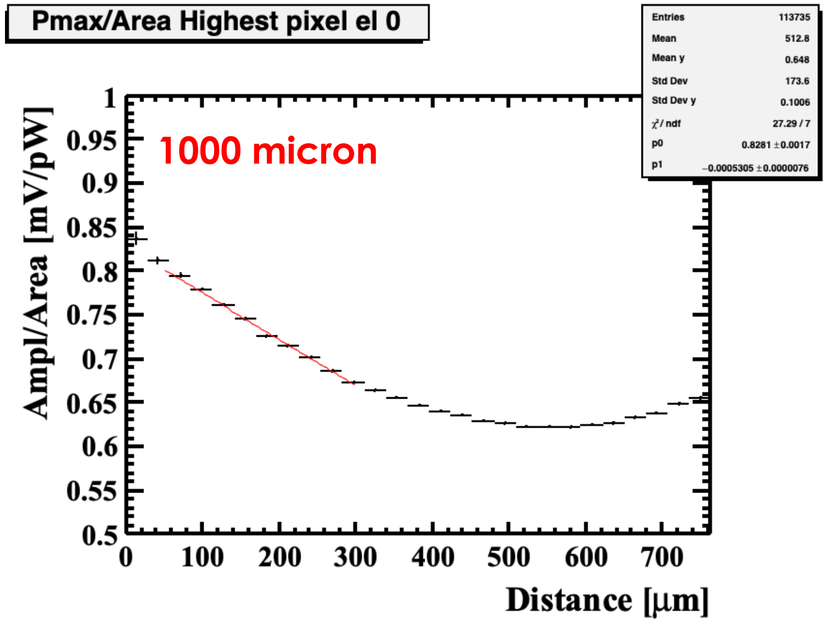


- Among these 3 detectors, **only the 1000 micron** has a clear drop with distance
- Amplitude attenuation due to propagation leads to the same slope

==> **attenuation due to signal split, not propagation**

Measurements: **high** surface resistivity

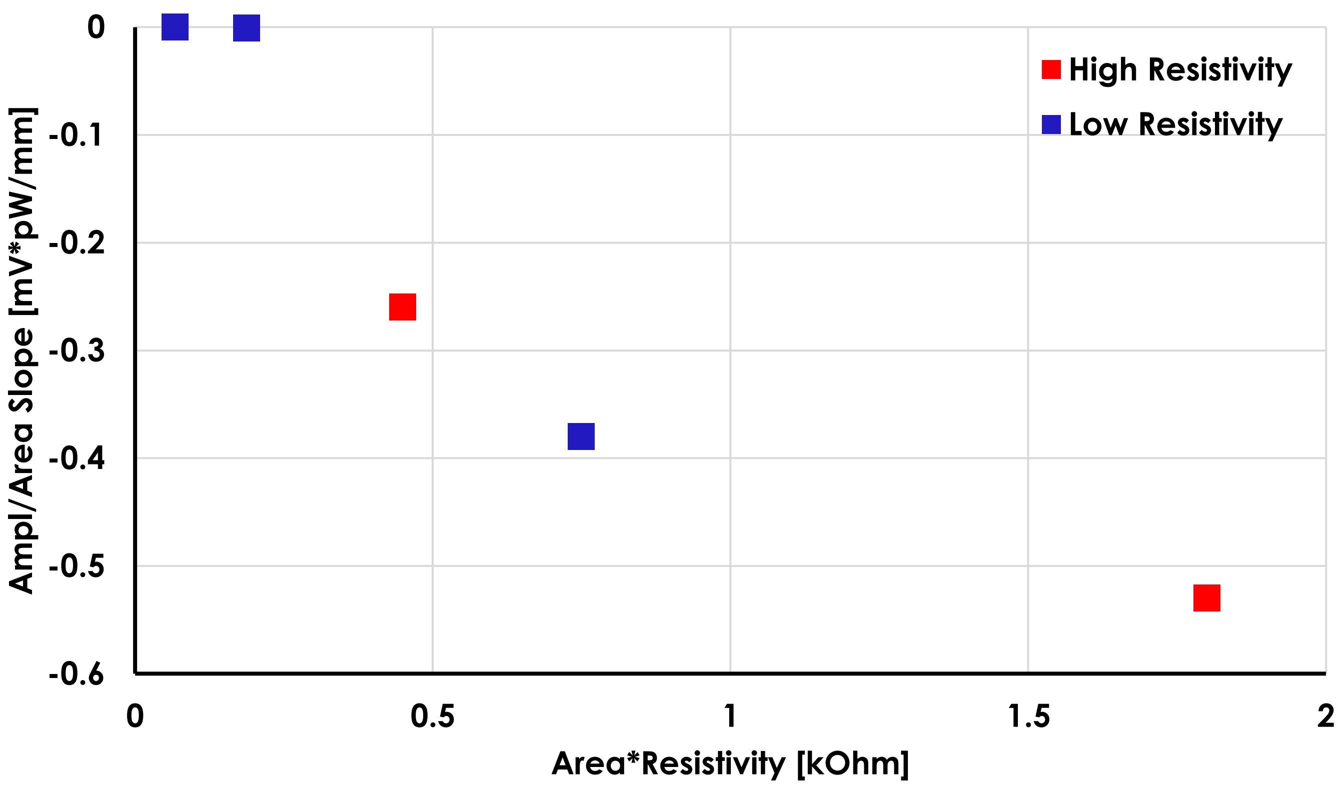




- For these two high resistivity detectors the slope decreases with pixel size

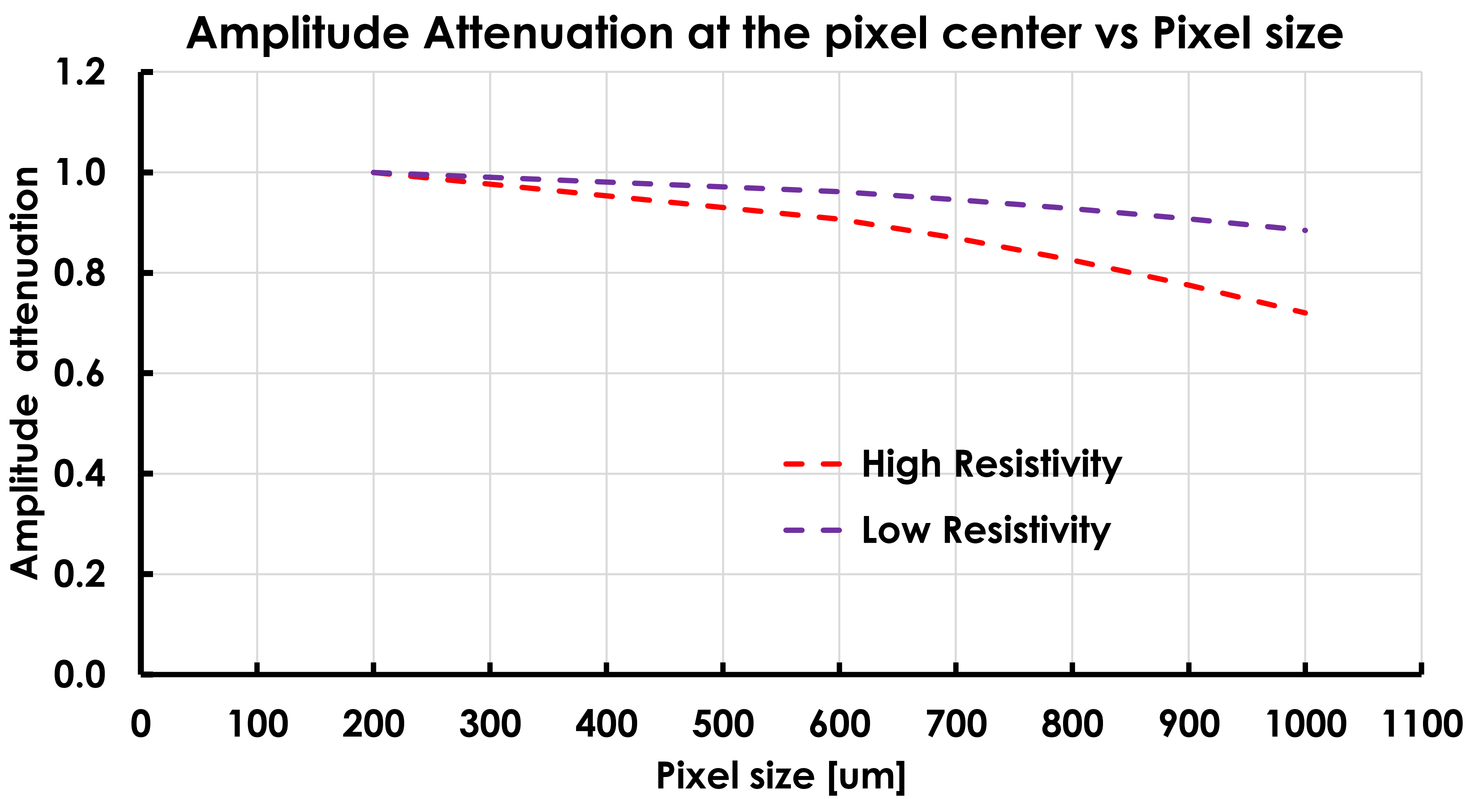
==> **attenuation due to signal split and, possibly, propagation**

Summary of measurements



The slope (Amplitude/Area) decreases as the product (Pixel Area × Surface Resistivity) increases.

Take-home message



When designing an RSD, the pixel size and the surface resistivity need to be evaluated togheter.

- **For pixel sizes up to ~ 500 micron, resistivities up to 1.5 – 2 $k\Omega/\square$ are fine**
- **For pixel sizes up of 500 -1000 micron, the resistivities should be below 1 $k\Omega/\square$**

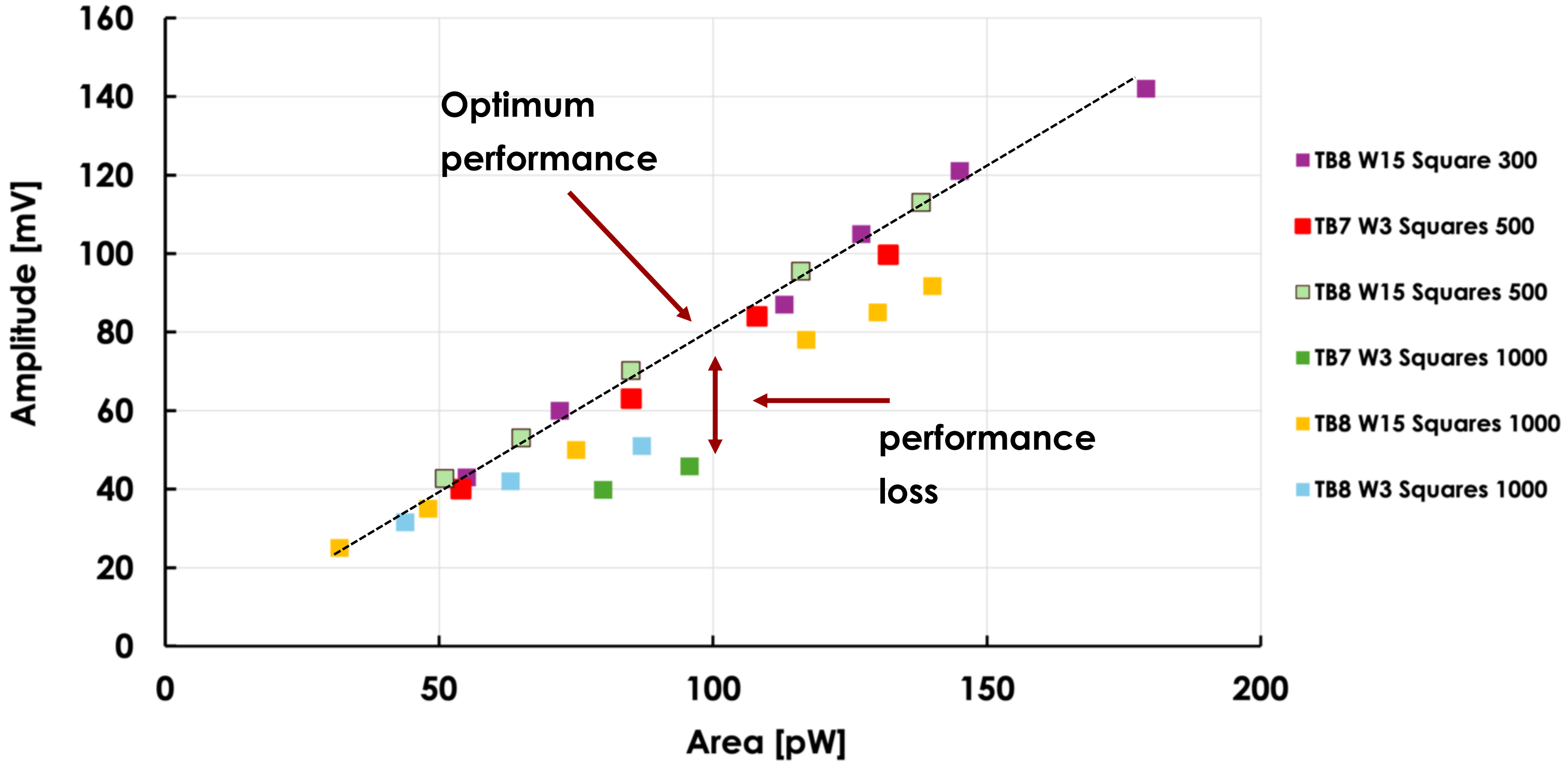
Amplitude vs Area (Gain)

If there are no losses, the Amplitude/Area ratio remains constant (about 0.8 mV/pW)

- **Optimum performance**

For larger pixels and/or higher resistivity, for equal gain the measured amplitude is lower

- **Loss of performance**



Reconstruction of the hit time

The standard algorithm is based on two steps

Step 1:

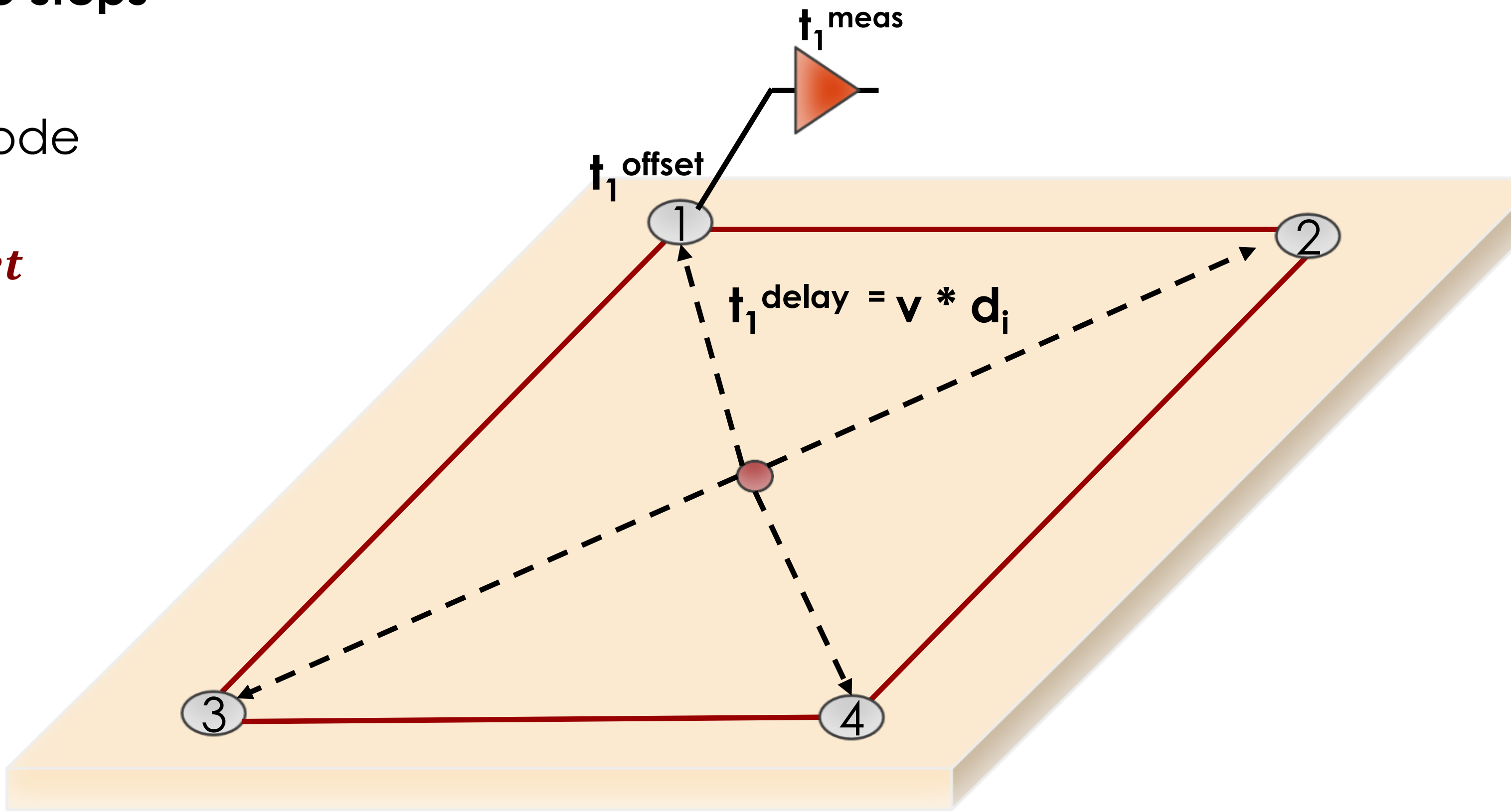
- Estimate the hit time at each electrode

$$t_i^{hit} = t_i^{meas} + t_i^{delay} + t_i^{offset}$$

Step 2:

- Combine the estimators

$$t^{hit} = \frac{\sum_1^4 t_i^{hit} A_i^2}{\sum_1^4 A_i^2}$$



The calculation of the propagation time, t_i^{delay}, is very important to reach good results

Calculation of the signal delay

Simplified model:

If the distance hit-electrode is

- > signal diffusion length, delay $\propto d^2$
- < signal diffusion length, delay $\propto d$

Low resistivity:

- **delay $\propto d^2$ for distances > 0.7-0.8 mm**

High resistivity:

- **delay $\propto d^2$ for distances > 0.4-0.5 mm**

Diffusion length:

$$L_\omega = \sqrt{\frac{2D}{\omega}} = \sqrt{\frac{2}{R_s C\, \omega}} \approx \sqrt{2D\, \tau}.$$

Frequency [MHz]	W15 L_ω [mm] R = 0.75 kΩ/□	W3 L_ω [mm] R = 1.8kΩ/□
300	0.83	0.53
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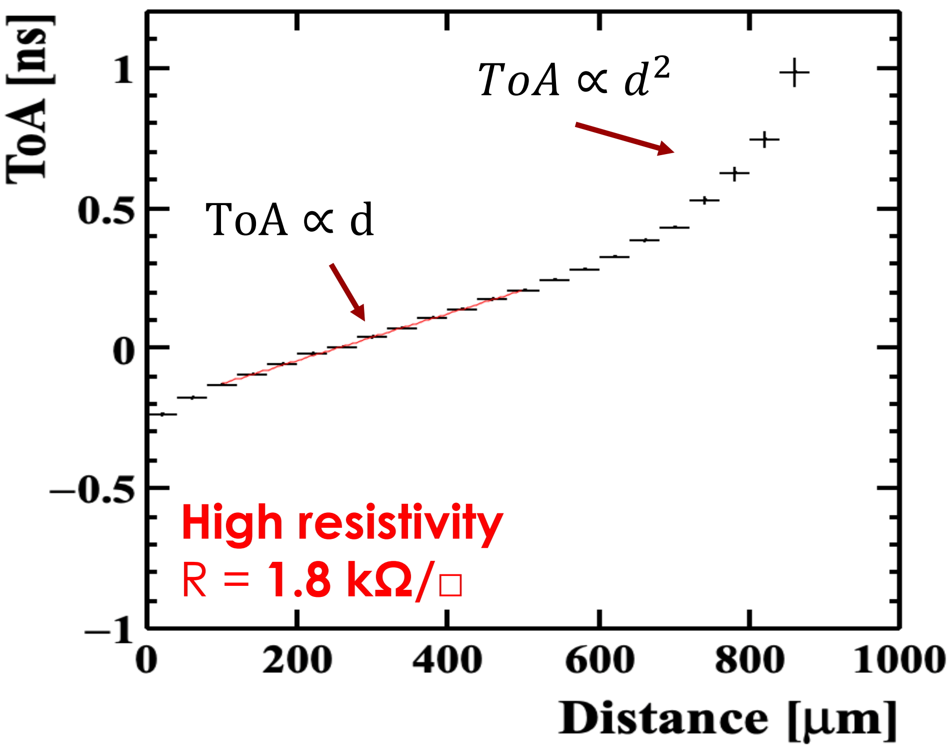
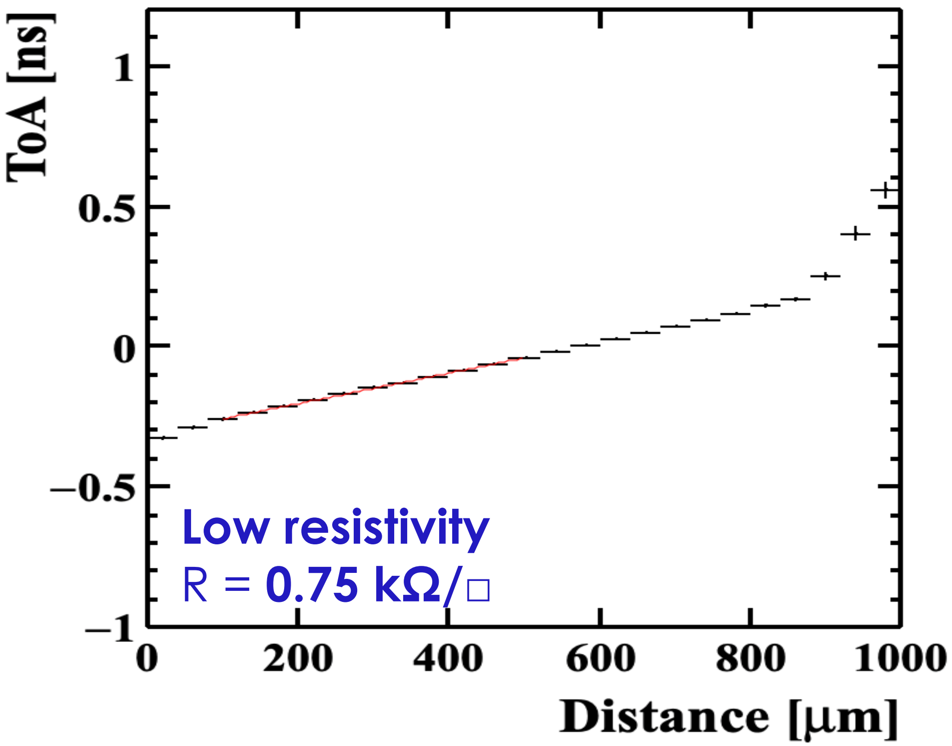
Summary of measurements



High resistivity

R = **1.8 kΩ/□**



Low resistivity

R = **0.75 kΩ/□**

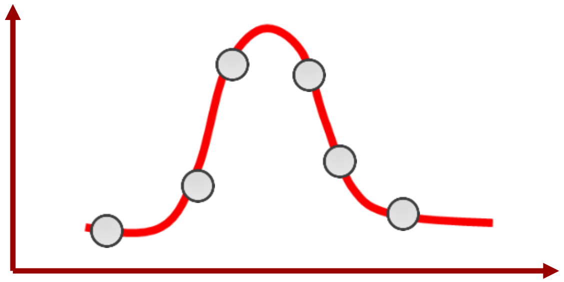
In **high-resistivity** sensors the delay becomes quadratic at about 0.7-0.8 mm.

- **Non-linear delays are more difficult to account for and degrade the temporal resolution**

In **low-resistivity** sensors the delay stays linear for a longer distance.

- **If the delay is proportional to the distance, the correction is trivial**

Optimization of the read-out bandwidth - I

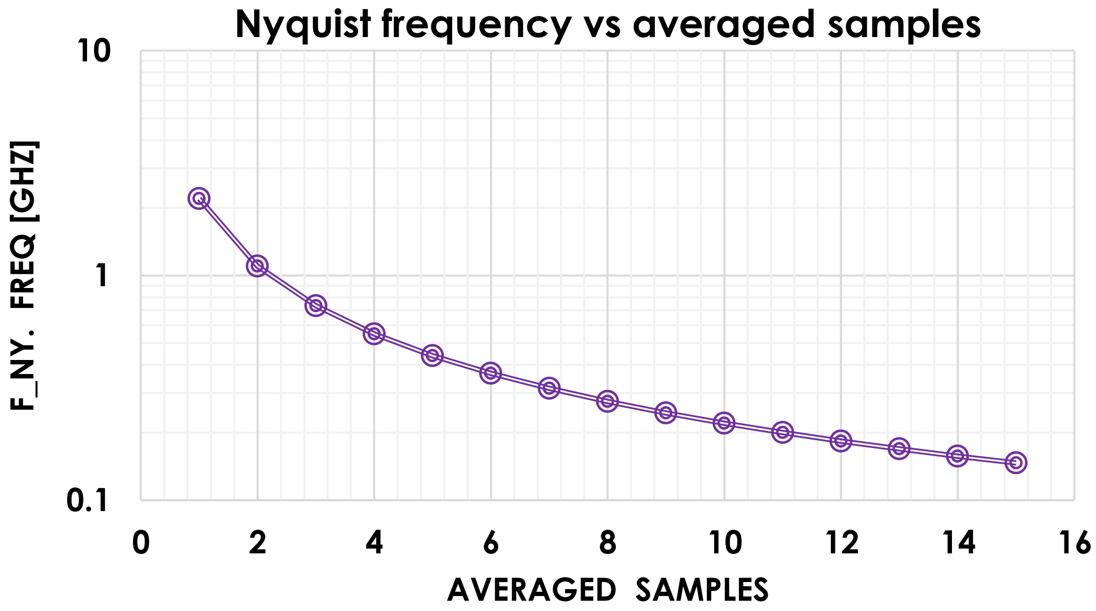


Data are collected with 5 GS/s CAEN digitizer, 500 MHz analog Bandwidth

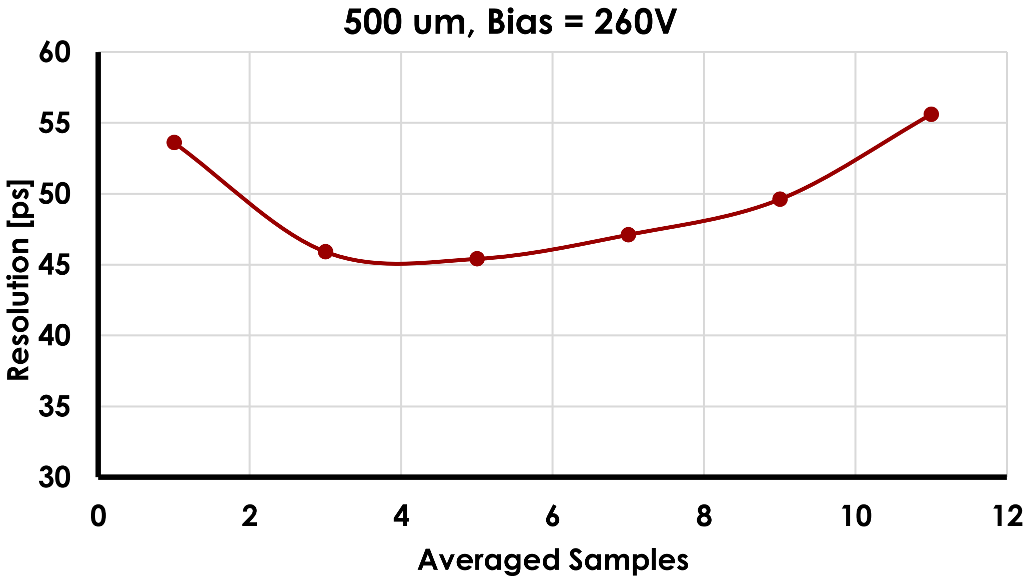
- a sample each 200 ps

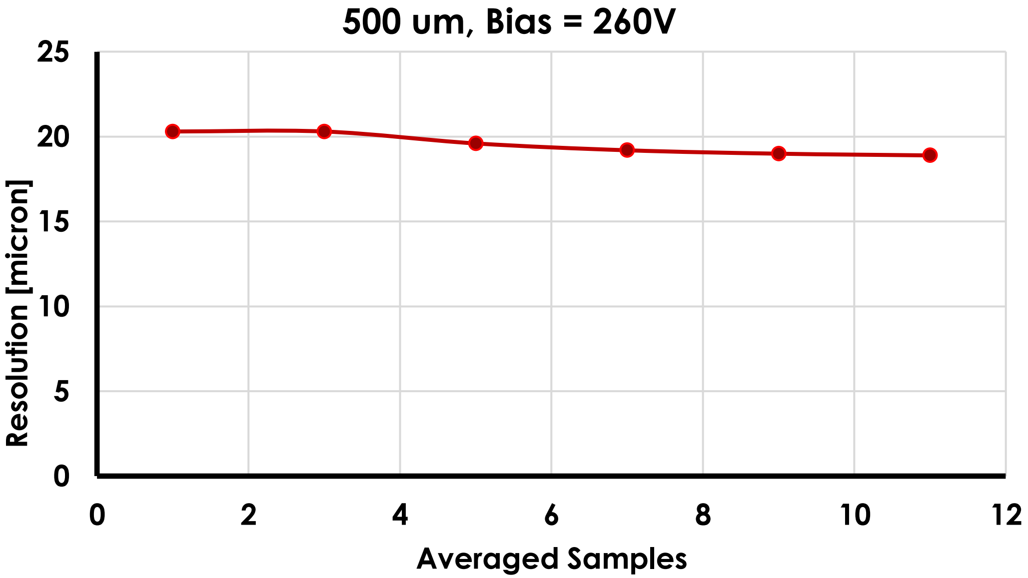
A “**running average**” over n samples is a simple way to implement a low pass filter

$$f_{Ny} = \frac{0.443}{N}\frac{1}{200\,ps}$$



Optimization of the read-out bandwidth - II





Optimum performance is found with a 5-sample average,

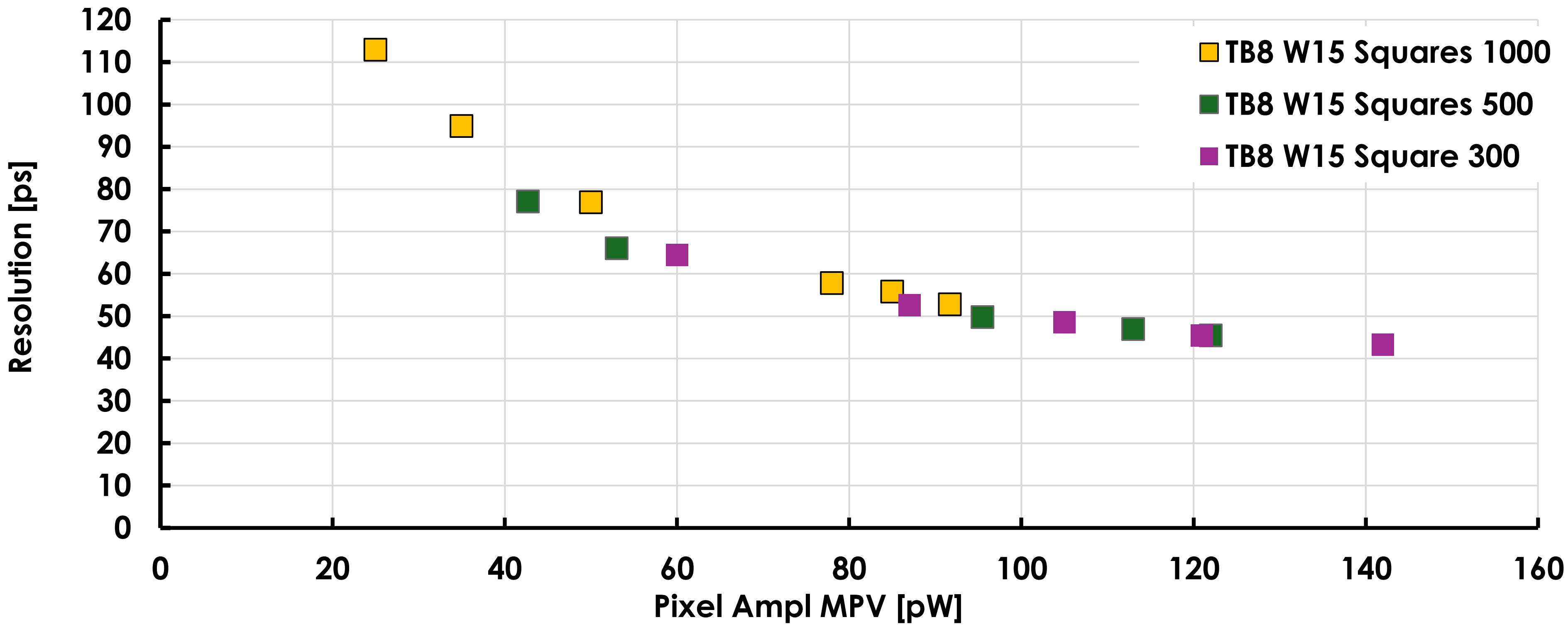
corresponding to a f_{Ny} ~ **400 MHz**

Results

The following two slides presents the summary of the results obtained at a DESY test beam on a low-resistivity RSD

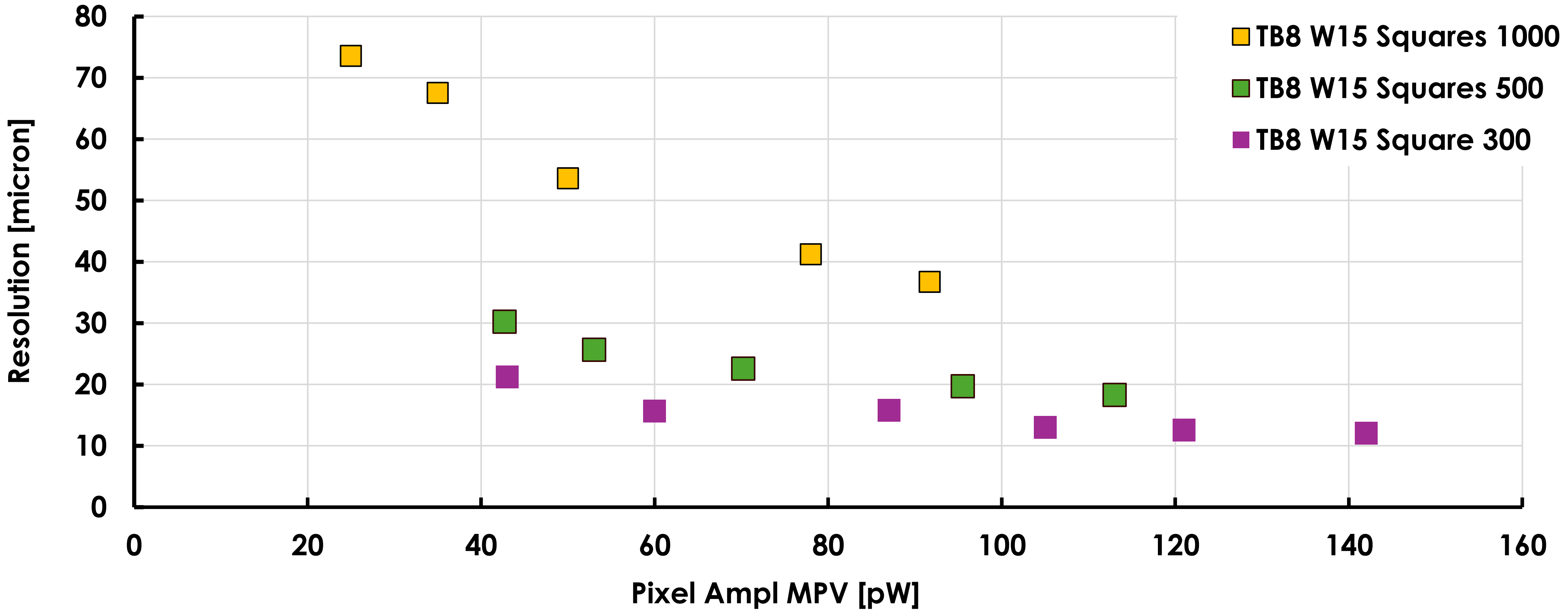
- Pixel pitch 300, 500, and 1000 micron
- Data collected with a CAEN digitizer
- 5-sample averaging
- Position reconstruction performed using the template method
- Delay calculated assuming a linear dependance on the hit distance

Temporal Resolution



- Remarkably, **pixel size does not affect the result**; only signal amplitude matters.
- Excellent resolution also for large pixels
- MCP time reference
- CAEN digitizer contribution not subtracted
- Delay calculated assuming a linear dependence on the hit distance

Spatial Resolution



- Resolution below 5% of the pixel size
- Tracker contribution (8 micron) subtracted

Summary

RSDs are an extended RC system

- A too high resistivity for a given pixel size leads to **amplitude loss** and **non-linear delay corrections**
    - **Both effects decrease the sensor performance**
- **A read-out with a tailored bandwitdh significantly improves the temporal resolution**

We performed comprehensive studies on low resistivity sensors of pixel size 300, 500, and 1000 microns

In a subsequent testbeam we have extensivley measured a high-resistivity 500-micron pixel matrix, results coming soon.

A model to predict the optimal resistivity as a function of the pixel size has been provided

Acknowledgment

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF). This project has received funding from the European Union Horizon Europe research and innovation program under grant agreement No 101057511.

We kindly acknowledge the following funding agencies and collaborations:
INFN – FBK agreement on sensor production;
Dipartimento di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337);
Ministero della Ricerca, Italia, PRIN 2022, 4DShare;
INFN Gruppo V project 4DShare

extra

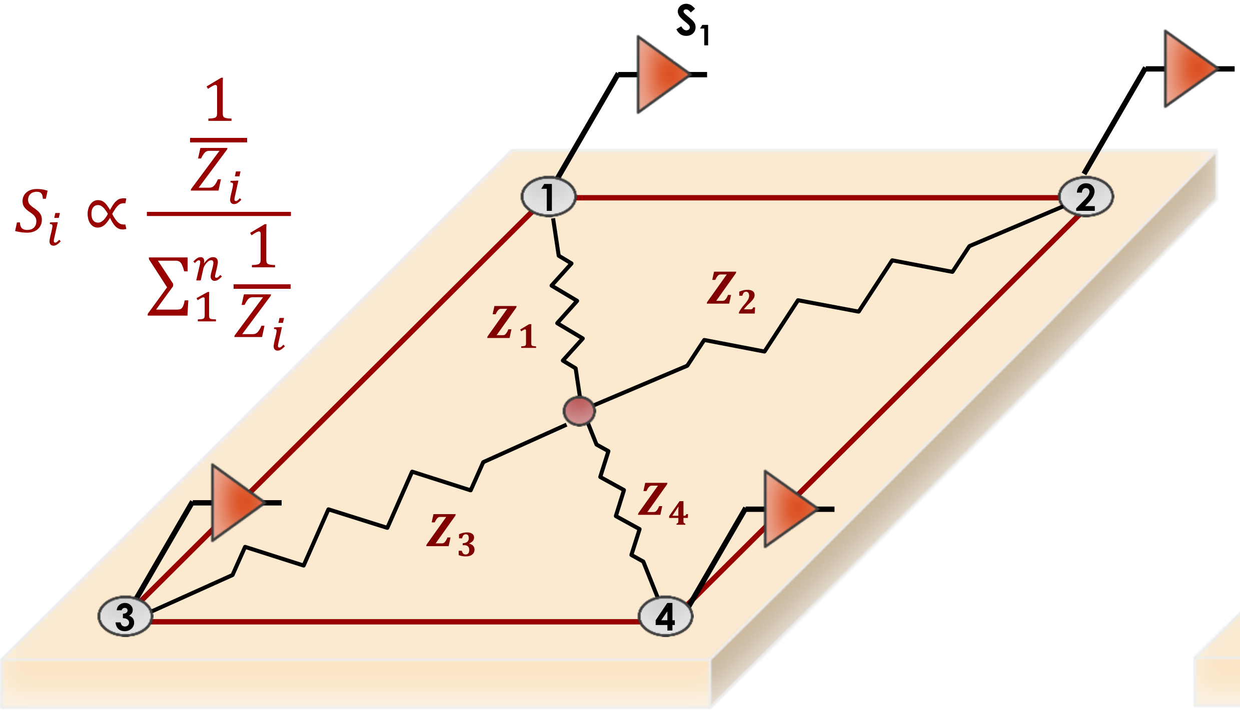
Square pixel DC-RSD properties

DC-RSD square pixels are very easy systems

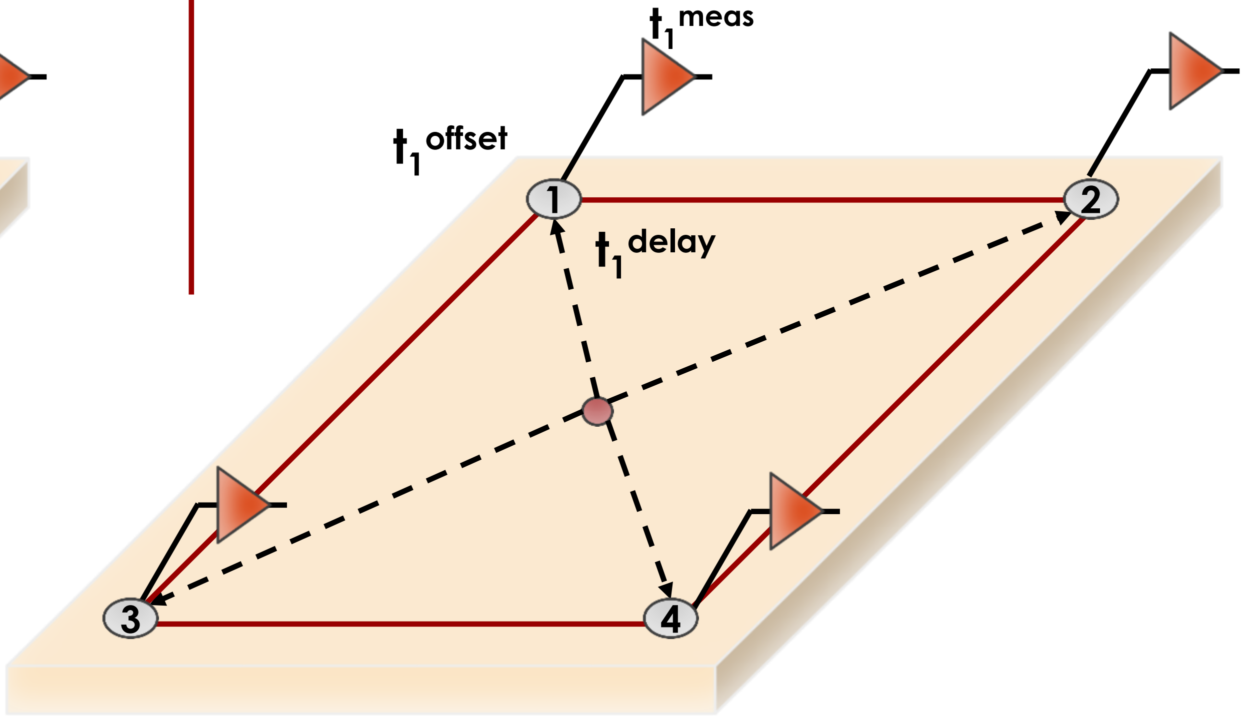
Signal sharing works like a current divider.

In the 500- and 1000-micron pitch square geometry, the **resistors are, to a good approximation, proportional to the distance hit-electrode.**

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



Signal delay depends linearly on the distance hit-electrode

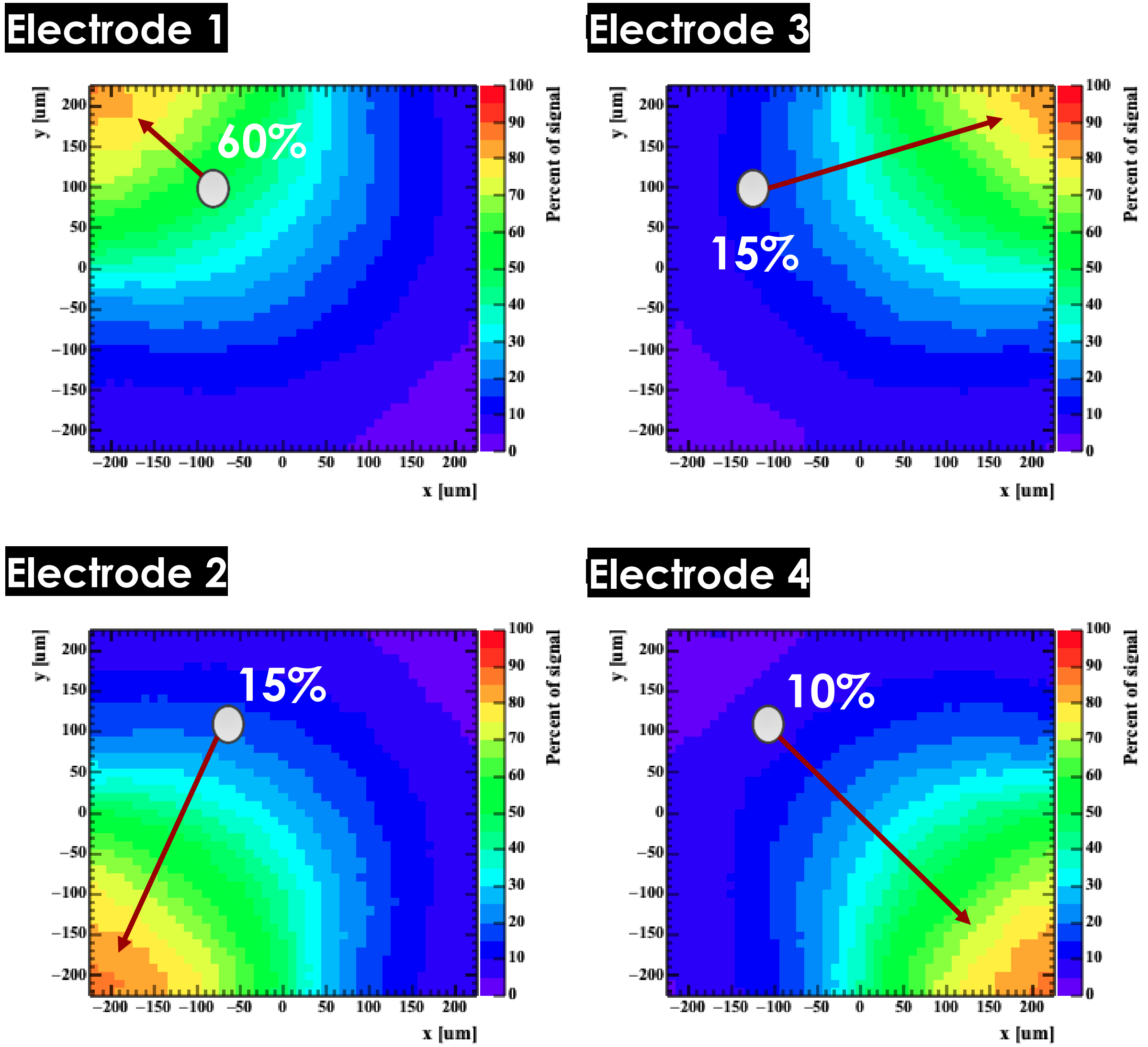


Sharing and delay can be computed analytically

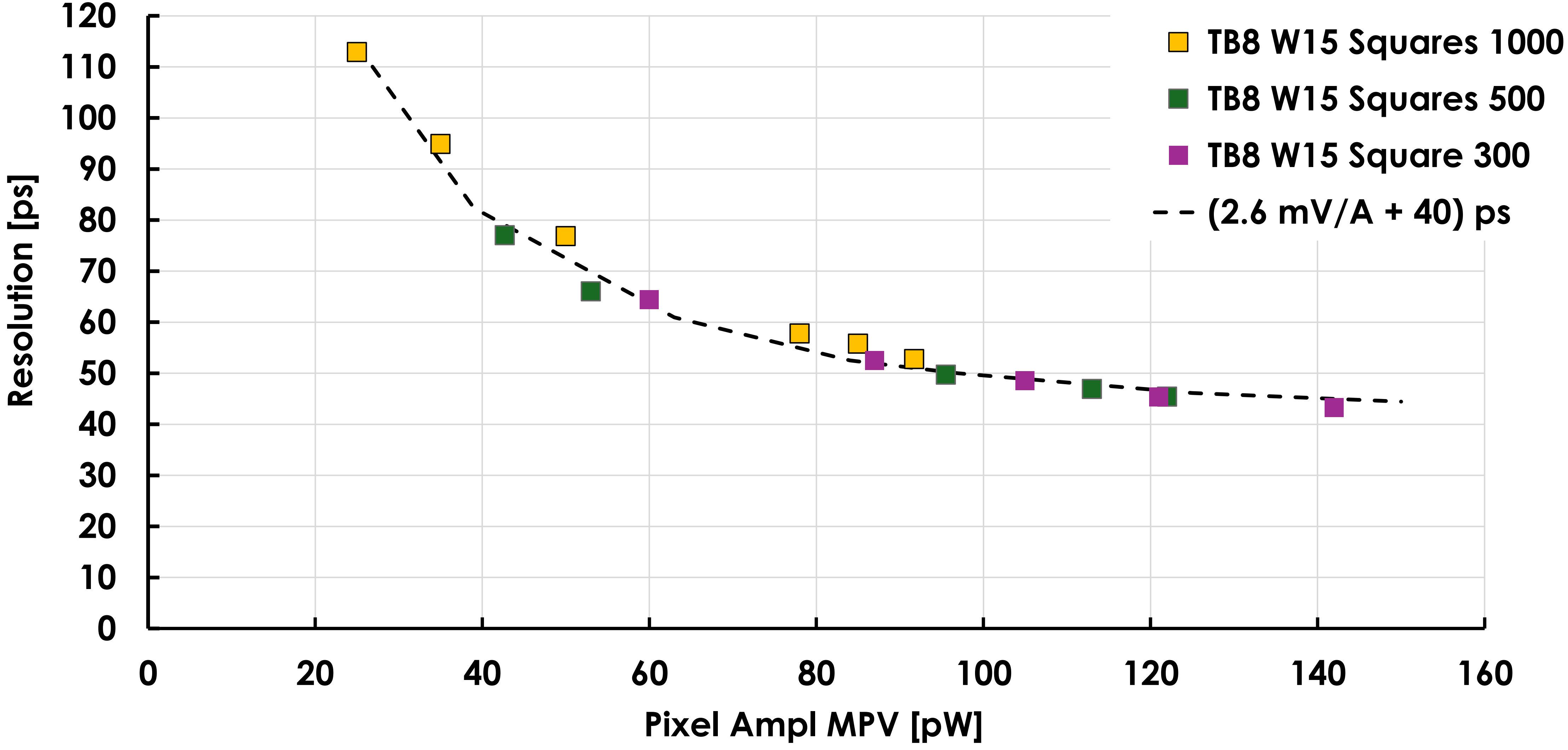
Position reconstruction method: sharing template

Step 1:
Produce look-up tables (2D histrograms) with the signal-sharing pattern among the 4 electrodes (done with test beam data)

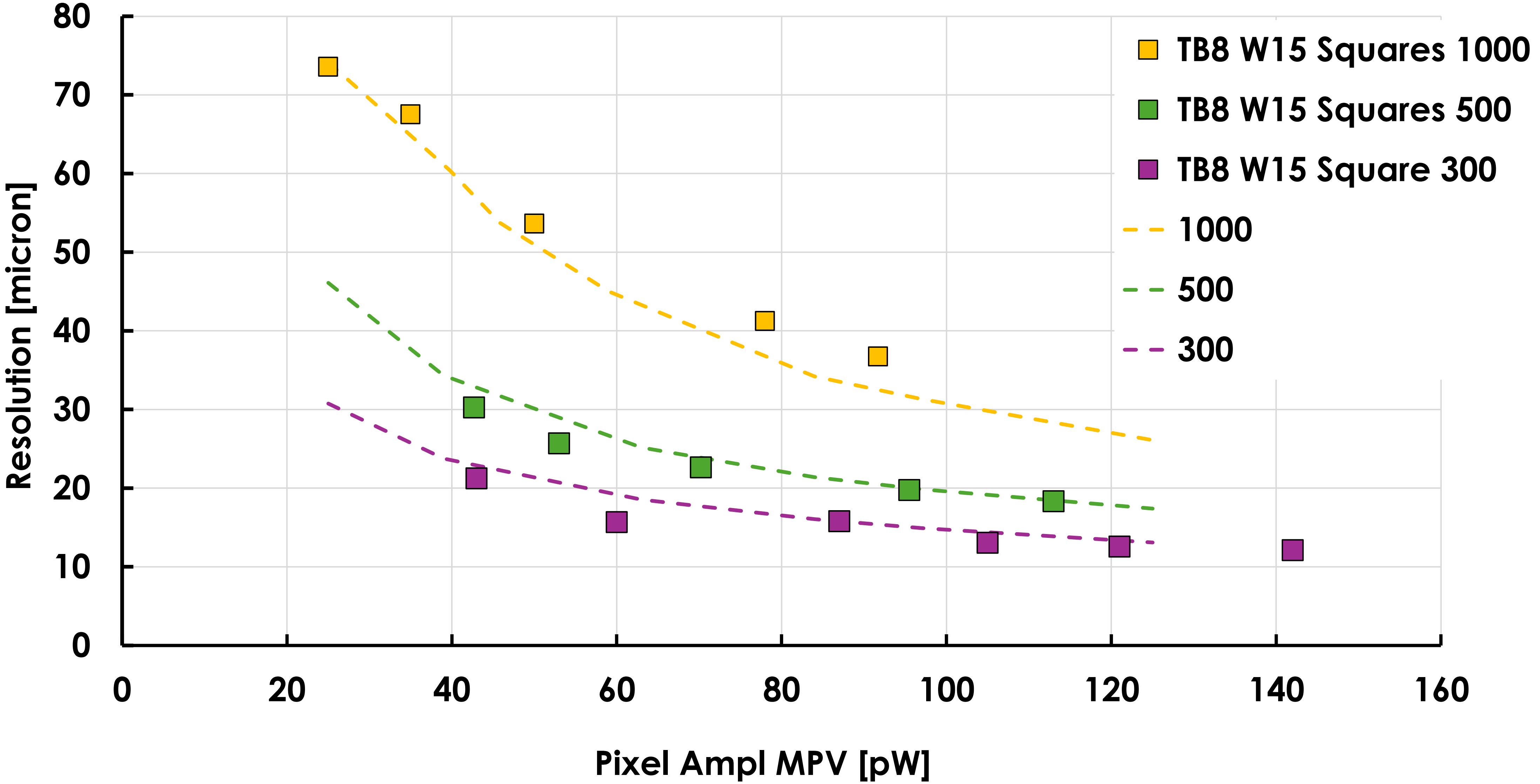
Step 2:
For each event, compare the measured signal sharing with the look-up table to find the location that best reproduces the measured sharing



Temporal resolution + Model



Spatial resolution + Model



Calculation of the delay

2-D RC diffusion equation on a resistive medium:

$$\partial V/\partial t = D\nabla^2 V$$

with $D = 1/(R_s C)$

where

- Rs is the sheet resistance (Ω/□),
- C is the capacitance to the backplane per unit area (F/m²)
- The expected delay with distance is:

$$t_{Delay} \approx \frac{d^2}{4D} = \frac{R_s C}{4} d^2$$

Note:

- The **pixel size** does *not* directly enter the diffusion delay formula
- The **signal delay** **grows quadratically** with the distance d between the hit point and the readout electrode:

$$t_{peak} \propto d^2$$

This is the IDEAL case,

in practice you need to account for the BW of your system