Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Latest results on RSD2 performances, a lab update

18th Trento Workshop on Advanced Silicon Radiation Detectors

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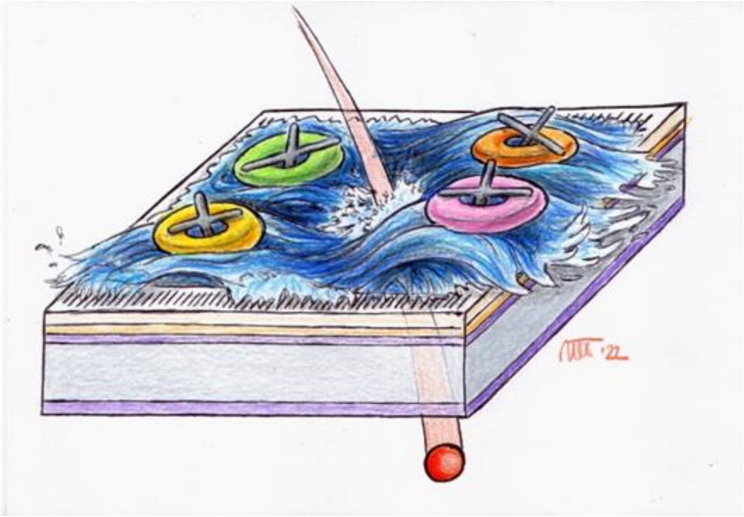
Outline

- Introduction
  - Motivations
  - Resistive Silicon Detectors
  - RSD 2 production by FBK
- Experimental setup
- Analysis and results
  - Spatial Resolution
  - Temporal Resolution
- Conclusions

Introduction



Motivations

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Need for spatial information in future HEP experiments(1)

Facility:	FCC-ee	ILC	CLIC
$\sigma_{hit\ pos}$ [μm]	~ 5	< 3	< 3
Thickness [μm of Si]	~ 100	~ 100	~ 100
Hit rate [10^6/s/cm^2]	~ 20	~ 0.2	~ 1
Power dissipation [W/cm^2]	0.1 -0.2	0.1	0.1

Plus timing information, 5-25 ps depending on the facility.

Traditional sensors have difficulties in fulfilling these tasks:

- 5 µm obtainable with 25x25 µm^2, but the number of channels is too high
- Better resolutions are possible with charge sharing due to external magnetic field, but sensors become too thick

A new solution is needed

Resistive Silicon Detectors

Change in silicon sensors paradigm: **R**esistive **S**ilicon **D**etector (RSD)

Charge sharing over silicon surface
+
Internal gain (LGAD)

→ Excellent position resolution with large pads
→ Timing

With

- Contained channels number
- Thin sensors
- Low power consumption
- Low material budget

+ **100 %** intrinsic fill factor!

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Resistive Silicon Detectors

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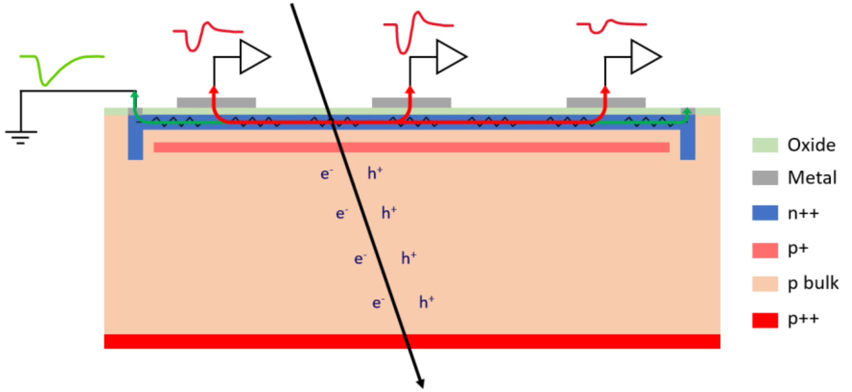
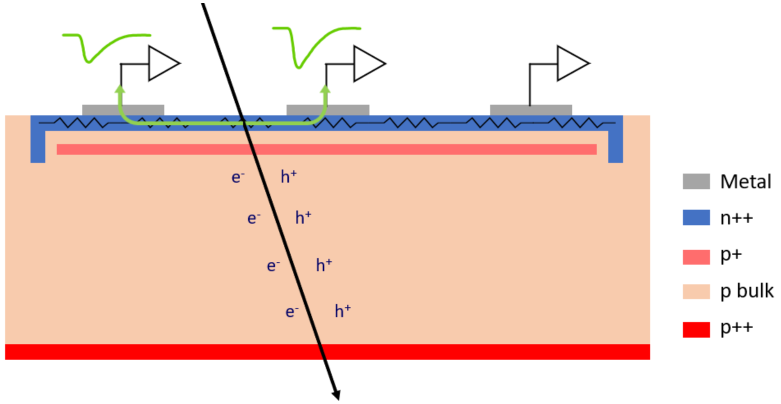
RSD can be AC or DC coupled to their readout



(AC-)RSD



DC-RSD

Productions by FBK

- RSD 1
- RSD 2

Focus of his talk

Propedeutic for

- DC-RSD 1

(AC-)RSD Principles of Operation

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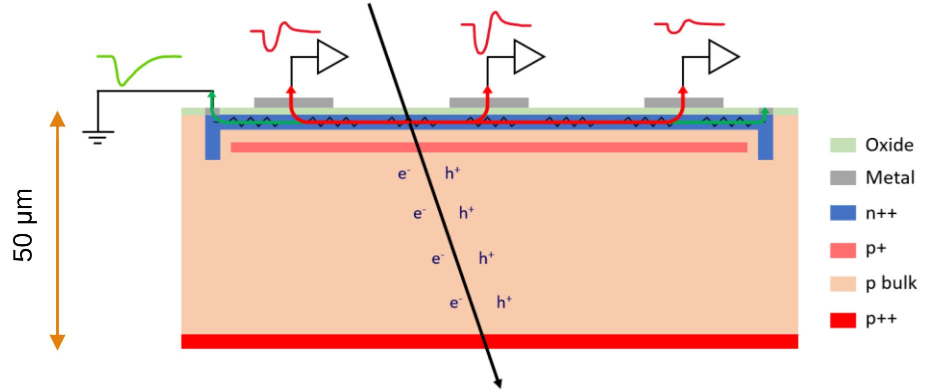
e-h pairs are produced by the impinging particle in the sensor volume



- Charge is induced in the n+ layer (1 ns)
- Nearby AC pads see a fast signal thanks to capacitive coupling
  ↳ **Signal sharing**
- Charges in the n+ flow to ground

In normal pixel detectors $\sigma_x = k\frac{pitch}{\sqrt{12}}$ with $k \sim 0.5 - 1$

(AC-)RSD have

- $\sigma_x \ll \text{pitch}$
- Time resolution proper of thin LGADs

Standard Silicon Detector vs RSD

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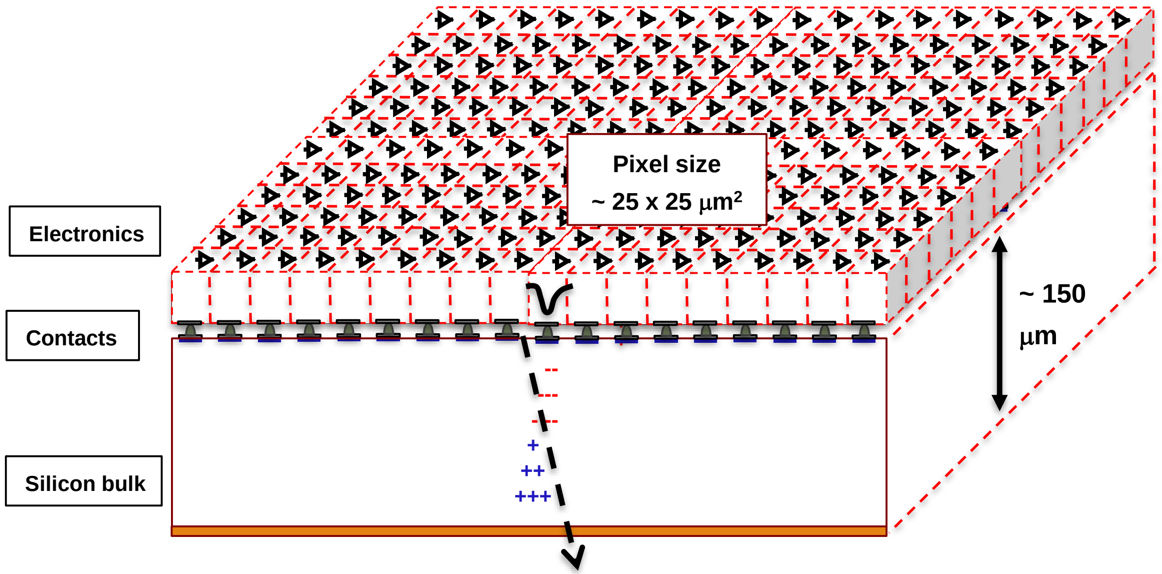
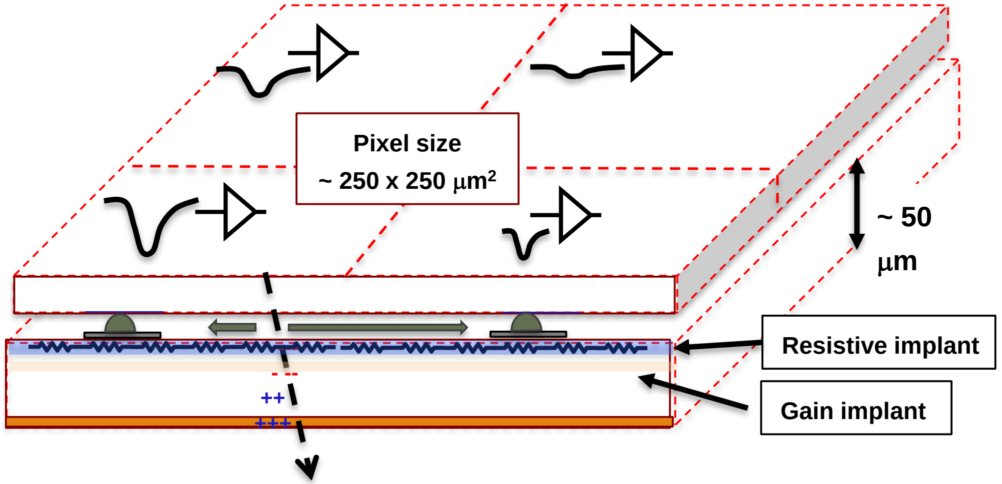


Standard Silicon Detector



Resistive Silicon Detector

Devices Under Test

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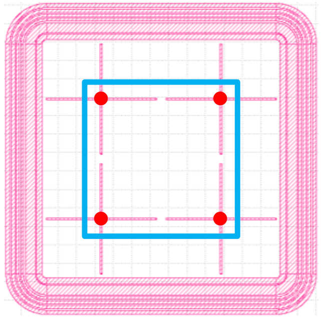
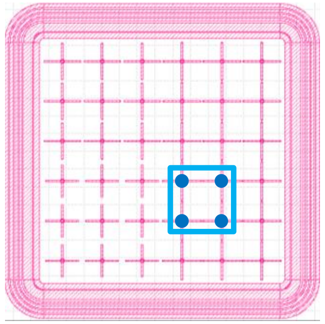
From the RSD 1 production, we learned that for optimal results:

- Not too many pads should be involved – S/N ratio worsens
- The number of pads involved should be the same over the sensor surface
- Careful tuning of the pads capacitance – less metal on the pads

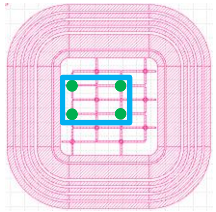
Ideas implemented in RSD 2 and various electrodes shapes implemented



1.3 x 1.3 mm^2

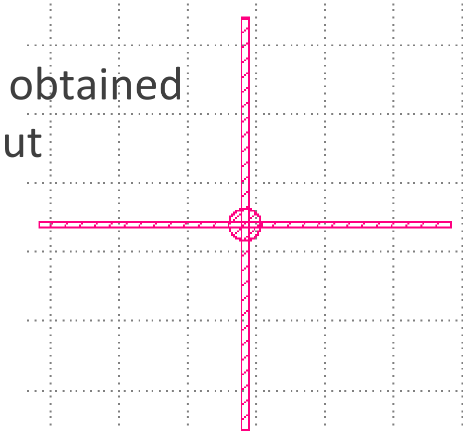


450 x 450 μm^2



200 x 340 μm^2

Our best results have been obtained employing the **crosses** layout



RSD 2 DUTs in Photos

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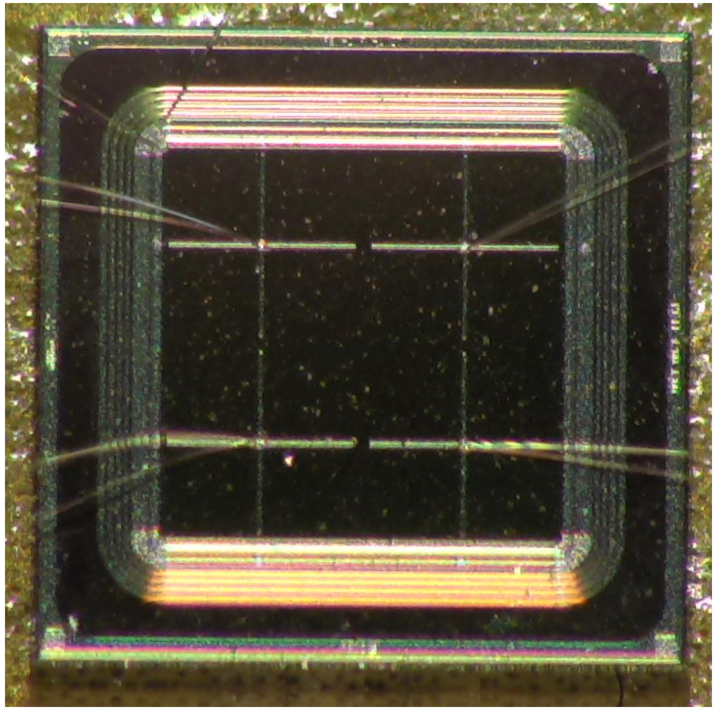

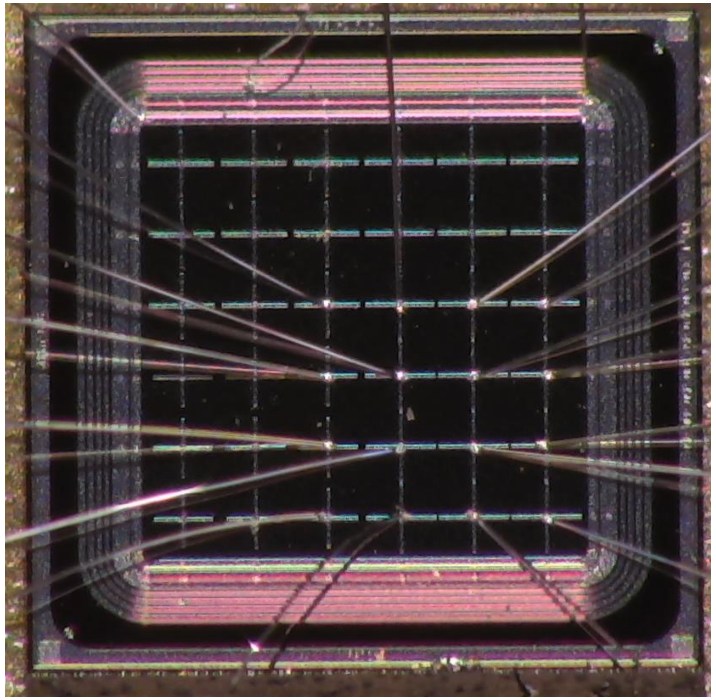

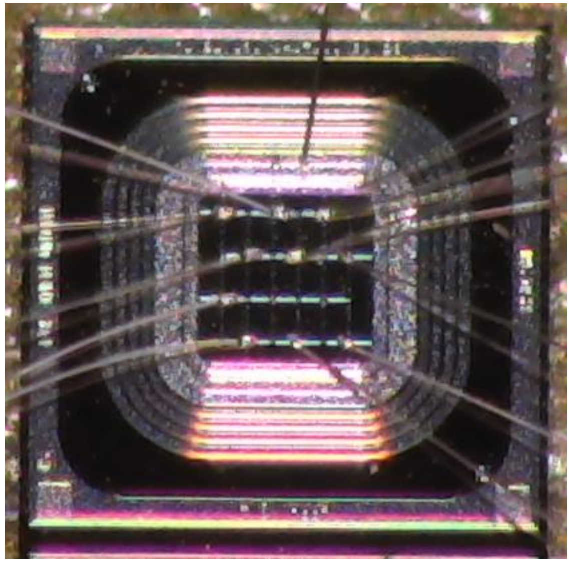

RSD 2 by FBK

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RSD 2 consists of 15 wafers with different characteristics.

Wafer #	Type	Carbon	n^+ dose	p gain dose
1	Si-Si 55 µm	N	A	0.96
2	Si-Si 55 µm	N	A	0.96
3	Si-Si 55 µm	N	A	0.98
4	Si-Si 55 µm	N	A	1
5	Si-Si 55 µm	N	A	1
6	Epi 45 µm	N	B	1
7	Si-Si 55 µm	N	B	0.98
8	Epi 45 µm	N	B	0.96
9	Epi 45 µm	N	B	0.96
10	Epi 45 µm	Y (1)	B	0.96
11	Epi 45 µm	N	C	0.96
12	Epi 45 µm	Y (0.8)	C	0.96
13	Si-Si 55 µm	N	C	0.98
14	Epi 45 µm	N	C	0.98
15	Si-Si 55 µm	N	C	0.94

- n^+ dose (A < B < C)
- Gain
- Wafer type (Epitaxial and Floating Zone)
- Pad capacitance

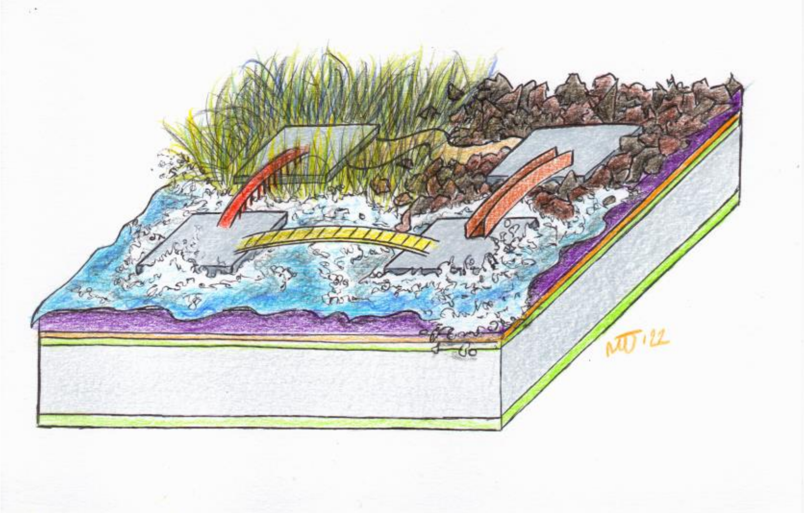
Electrostatics measurements were performed on all wafers(2)

On a selection of these

- Fine TCT inspection — **This presentation**
- Test beam @ DESY — **F. Siviero (next talk)**

3	Si-Si 55 µm	N	A	0.98

Experimental Setup



Experimental Setup

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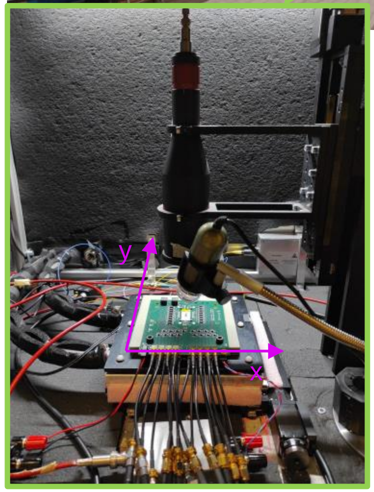
All measurements were performed in the Torino Laboratory for Innovative Silicon Sensors (LISS)



The setup consists of a TCT by Particulars equipped with a

- IR laser simulating the passage of 1-3 MIP(s)
- Laser spot size of ~10 µm FWHM

A precise x-y stepper provides reference positions of the laser on the sensor surface

- σ_{step} ~ 2 µm

Multiple signals (50-100) are produced and recorded at each point

The whole active area is scanned with 10-20 µm steps

Experimental Setup

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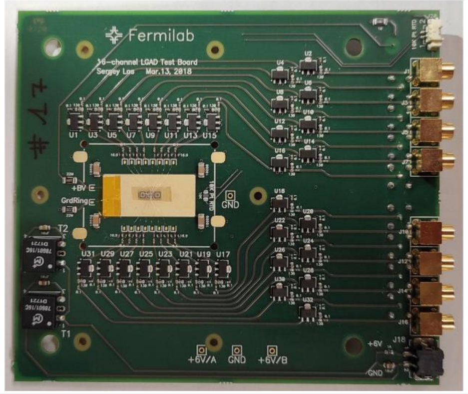
All sensors were bonded on a 16-ch Fermilab board

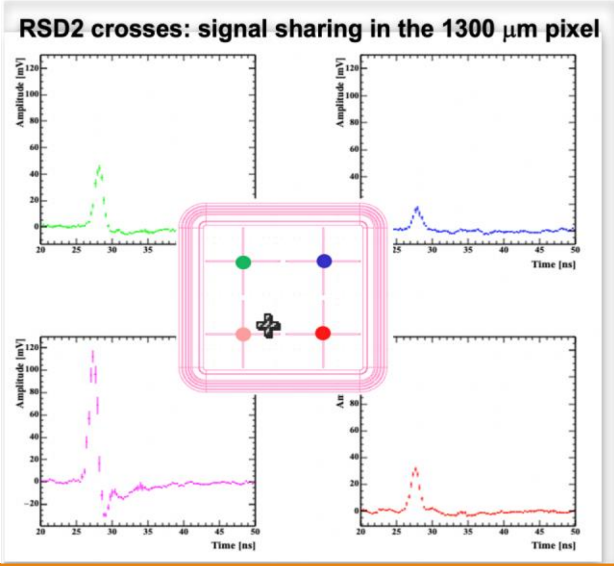
- Double-stage amplifiers
- RMS noise @roomT ~ 2-3 mV

The output signals are read out employing a 5 GS/s 16-ch digitizer

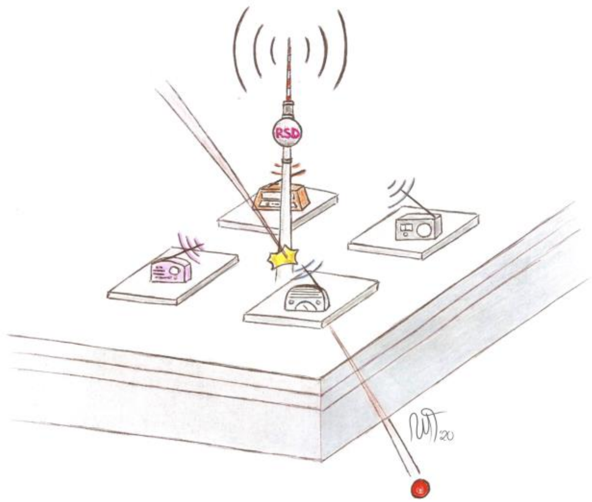
An output rootfile containing positions and sampled waveforms is produced and undergoes

- "standard" c++ analysis[3]
- Machine Learning-based approach[4,5]





Analysis and Results



Resolutions parametrization

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Space

$$\sigma^2_{pos} = \sigma^2_{jitter} + \sigma^2_{rec} + \sigma^2_{setup} + \sigma^2_{sensor}$$

- σ^2_{jitter} due to the variation in the signal amplitude caused by the electronic noise ~ noise/amplitude
- σ^2_{rec} accuracy of the reconstruction method
- σ^2_{setup} related to eventual variations in the signal sharing due to the experimental setup (i.e. amplifiers)
- σ^2_{sensor} all sensor imperfections that could contribute to differences in signal sharing

Time

$$\sigma^2_{time} = \sigma^2_{jitter} + \sigma^2_{Landau} + \sigma^2_{delay}$$

- σ^2_{jitter} similar as before, ~ noise/(dV/dt)
- σ^2_{Landau} non-uniform ionization contributes with ~30 ps in 50 µm thick sensors
- σ^2_{delay} propagation time from the impact point to the read-out pad. It is correlated to the precision of the hit position reconstruction

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Space Reconstruction

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Considering a sensor with 450 µm pitch

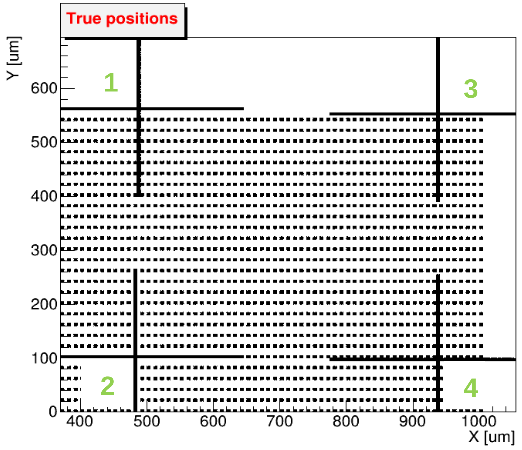
$$\sigma_{pos} \sim \frac{pitch}{\sqrt{12}} \sim 130\ \mu m$$

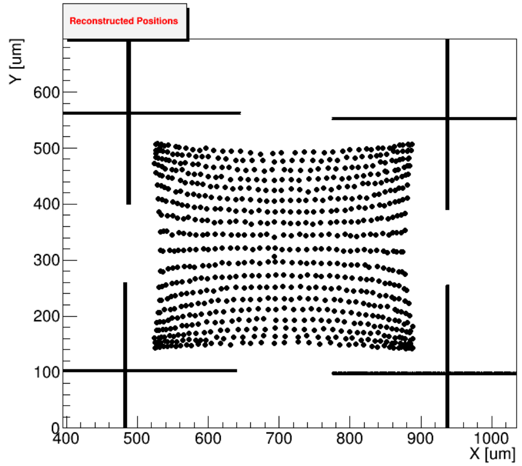
In RSD 2, spatial coordinates (x-y) are reconstructed with the method of the “charge asymmetry”

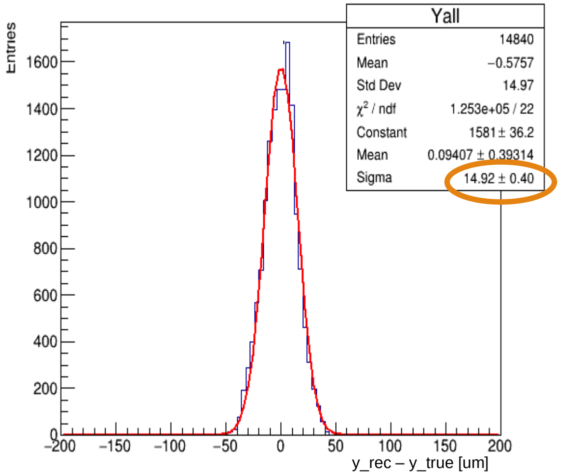
$$x_i = x_{center} + k_x \frac{pitch}{2} \frac{A_3 + A_4 - (A_1 + A_2)}{\sum A_j}$$

$$y_i = y_{center} + k_y \frac{pitch}{2} \frac{A_1 + A_3 - (A_2 + A_4)}{\sum A_j}$$

We employed the amplitude *A*







15 µm

Correction Matrix

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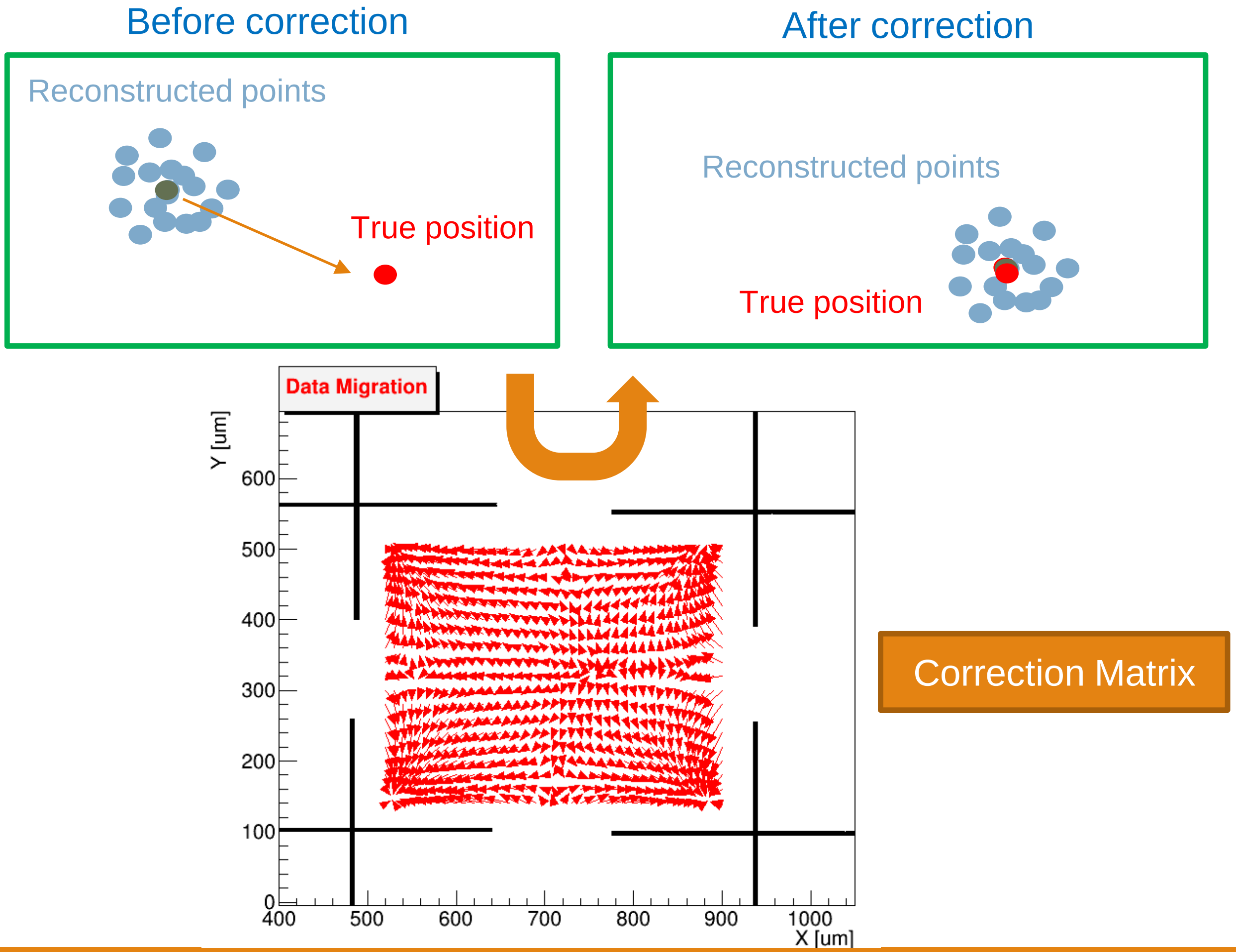
A correction matrix is generated with the highest amplitudes dataset.

The migration of the data is then applied to all datasets, bringing the average point position to (almost) overlap with the true one.

This correction drastically improves the accuracy of the reconstruction method, especially in cases of low amplitudes



Space Reconstruction

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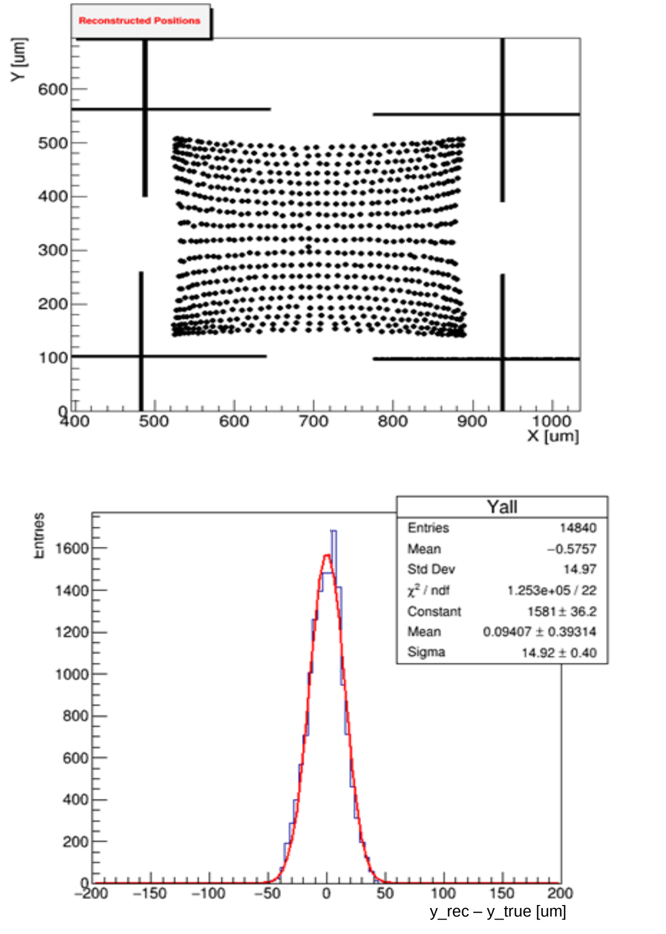
After the correction with the migration matrix, the results improve

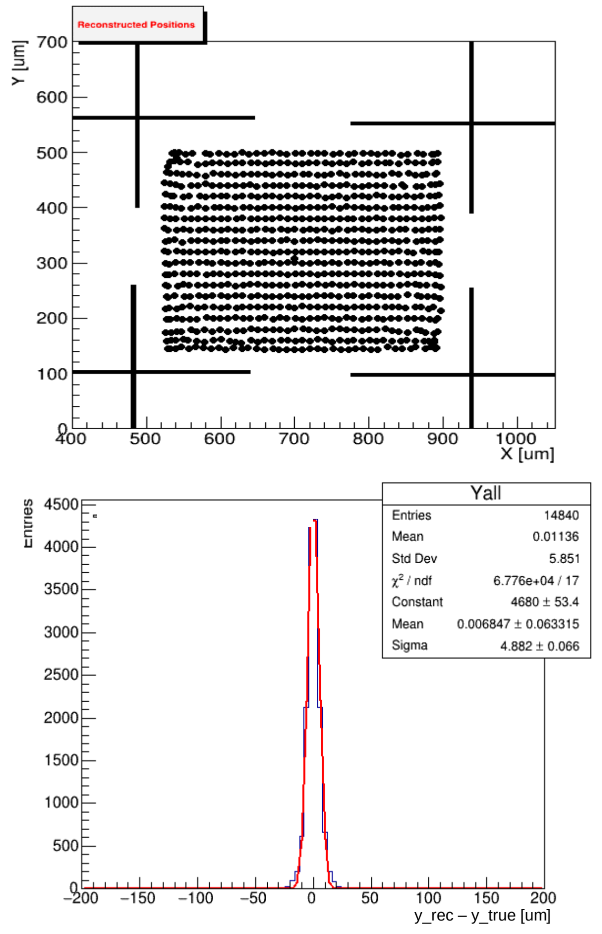
The same correction matrix is applied to the lower-gain datasets.

~ 15 µm → ~ 5 µm

Before correction



After correction



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Space Reconstruction Results

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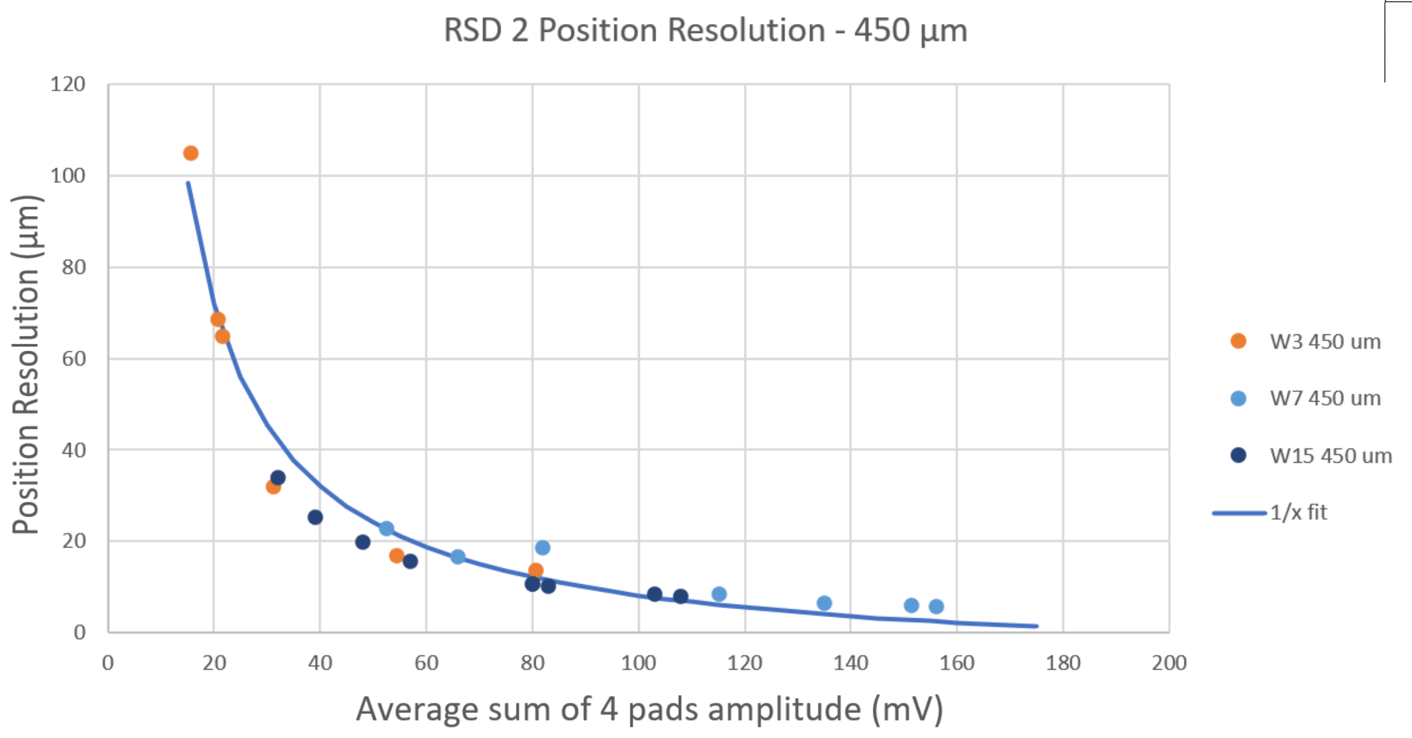
Different wafers can be studied with a fixed geometry – 450 µm pitch

Wafer #	Type	Carbon	n^+ dose	p gain dose
3	Si-Si 55 µm	N	A	0.98
7	Si-Si 55 µm	N	B	0.98
15	Si-Si 55 µm	N	C	0.94



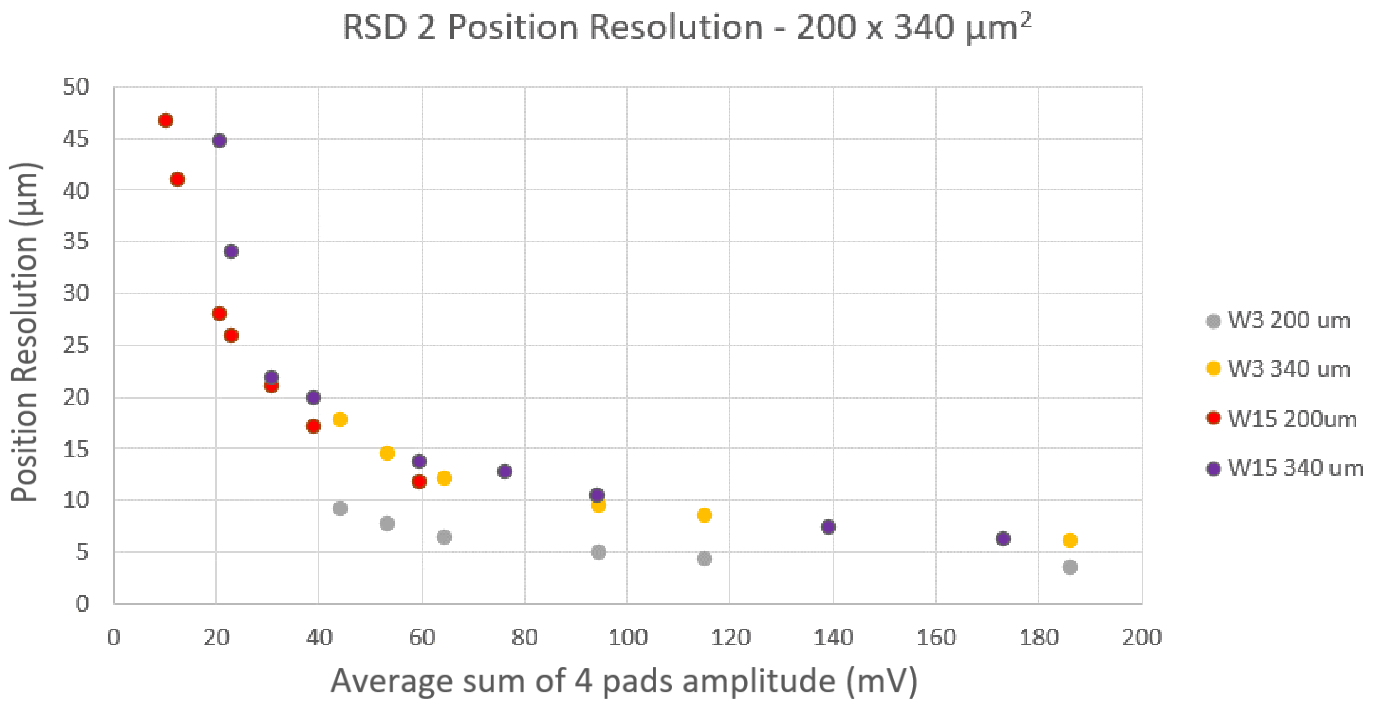
The different wafers behave in the same way

The jitter term depends on the amplitude as 1/A.

Since the data agrees quite well with the 1/A behavior, the resolution is dominated by the jitter term

Space Reconstruction Results

The smallest DUT - 200 x 340 μm^2



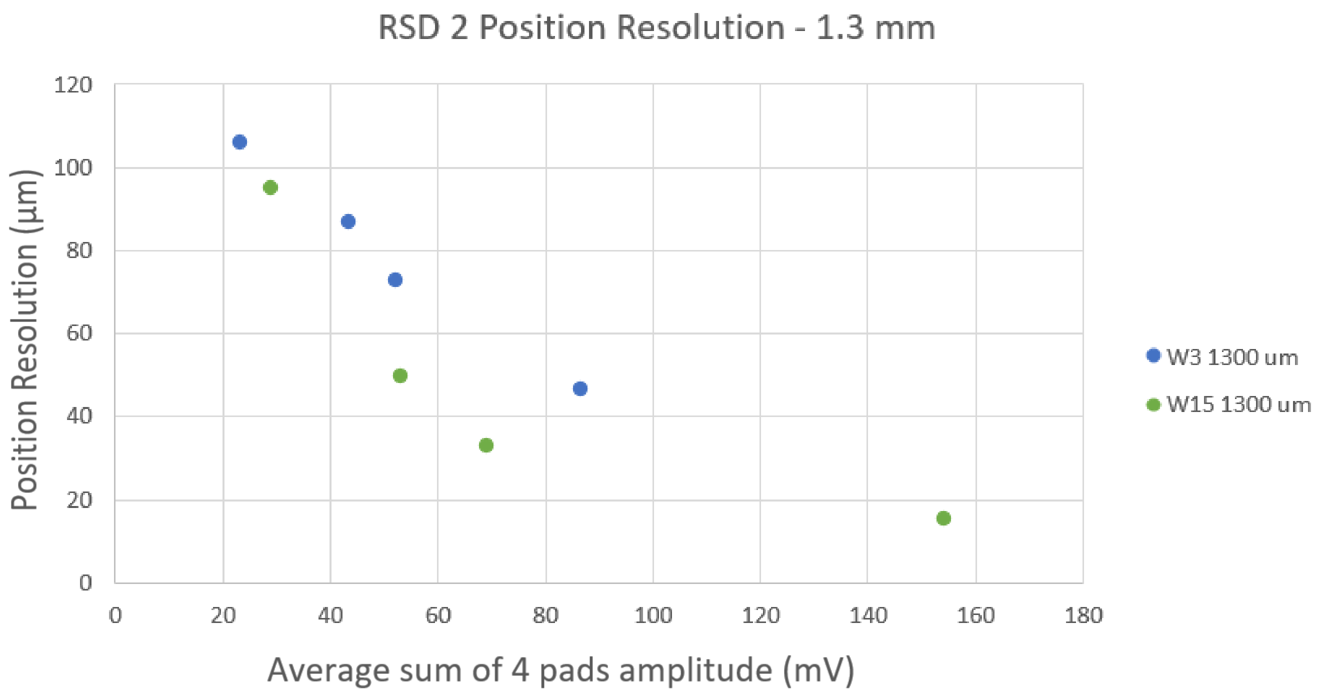
Wafer #	Type	Carbon	n^+ dose	p gain dose
3	Si-Si 55 μm	N	A	0.98
7	Si-Si 55 μm	N	B	0.98
15	Si-Si 55 μm	N	C	0.94

For the smallest pitch, the wafer with the highest n+ resistivity (W3) achieves the best resolution.

This is expected since at lower resistivities the signal is spread on too many electrodes

Space Reconstruction Results

Largest DUT - 1.3 mm pitch



Wafer #	Type	Carbon	n^+ dose	p gain dose
3	Si-Si 55 µm	N	A	0.98
7	Si-Si 55 µm	N	B	0.98
15	Si-Si 55 µm	N	C	0.94

Resistivity seems to play an important role also in big sensors

Lower resistivity helps the signal travel longer distances

W7 measurements are currently undergoing

Time Reconstruction

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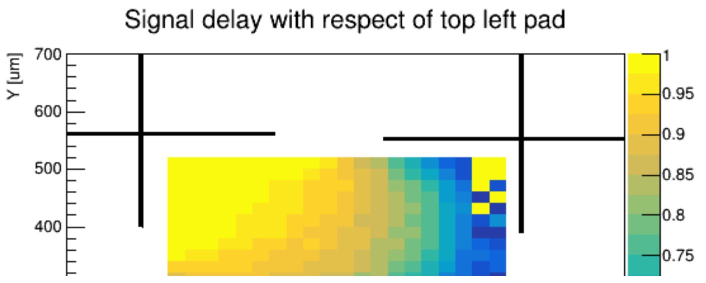
Each pad signal is an estimator of the time coordinate, weighted on its amplitude

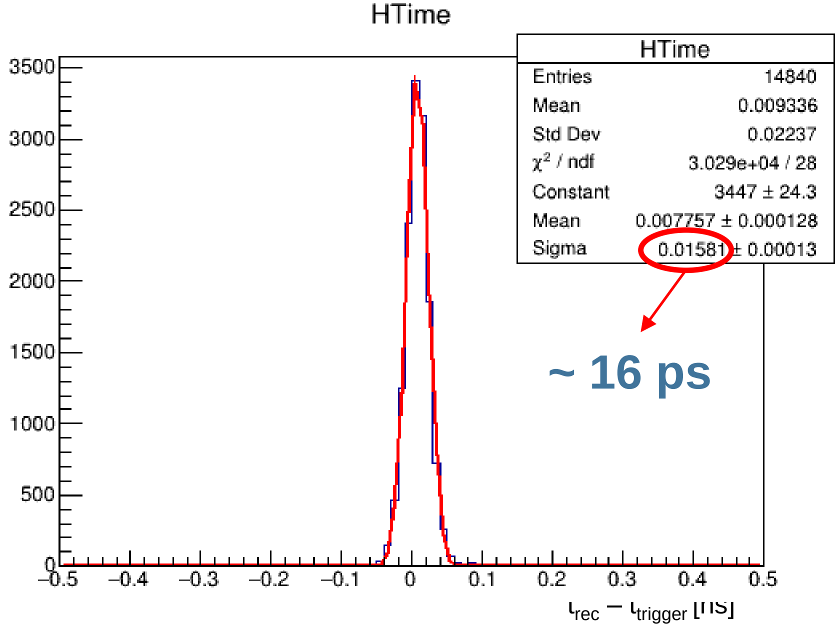
$$t_i = \frac{\sum_j^4 t_j^{rec} A_j^2}{\sum_j^4 A_j^2}$$

Where $t_j^{rec} = t_j^{meas} + t_j^{delay}$, the delay is computed from the correction matrix and t_j^{meas} corresponds to the time at the signal maximum.

To the obtained value is subtracted the trigger contribution (~ 10 ps)

In the case of TCT measurements, the Landau term is not present.





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Time Resolution Results

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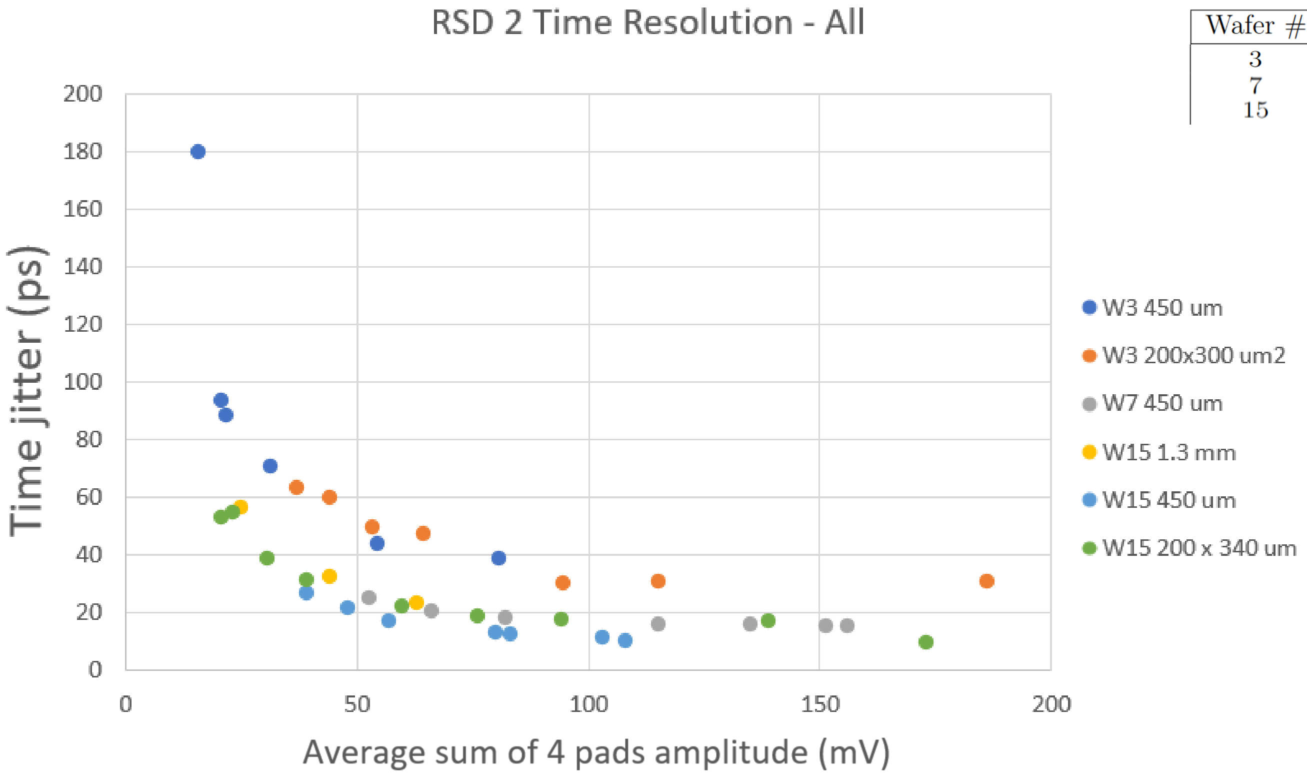
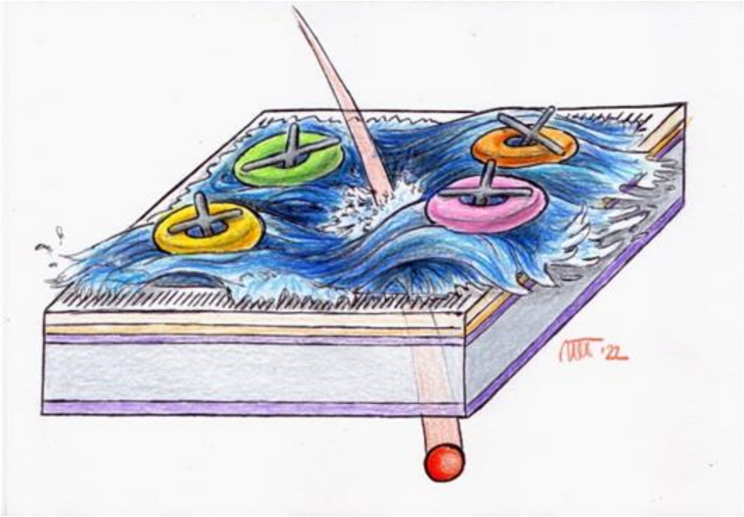
Very uniform performance



Wafer #	Type	Carbon	n^+ dose	p gain dose
3	Si-Si 55 µm	N	A	0.98
7	Si-Si 55 µm	N	B	0.98
15	Si-Si 55 µm	N	C	0.94

W3 has worse timing due to the broader signal shape and the choice of t^{meas}

Conclusions



Conclusions

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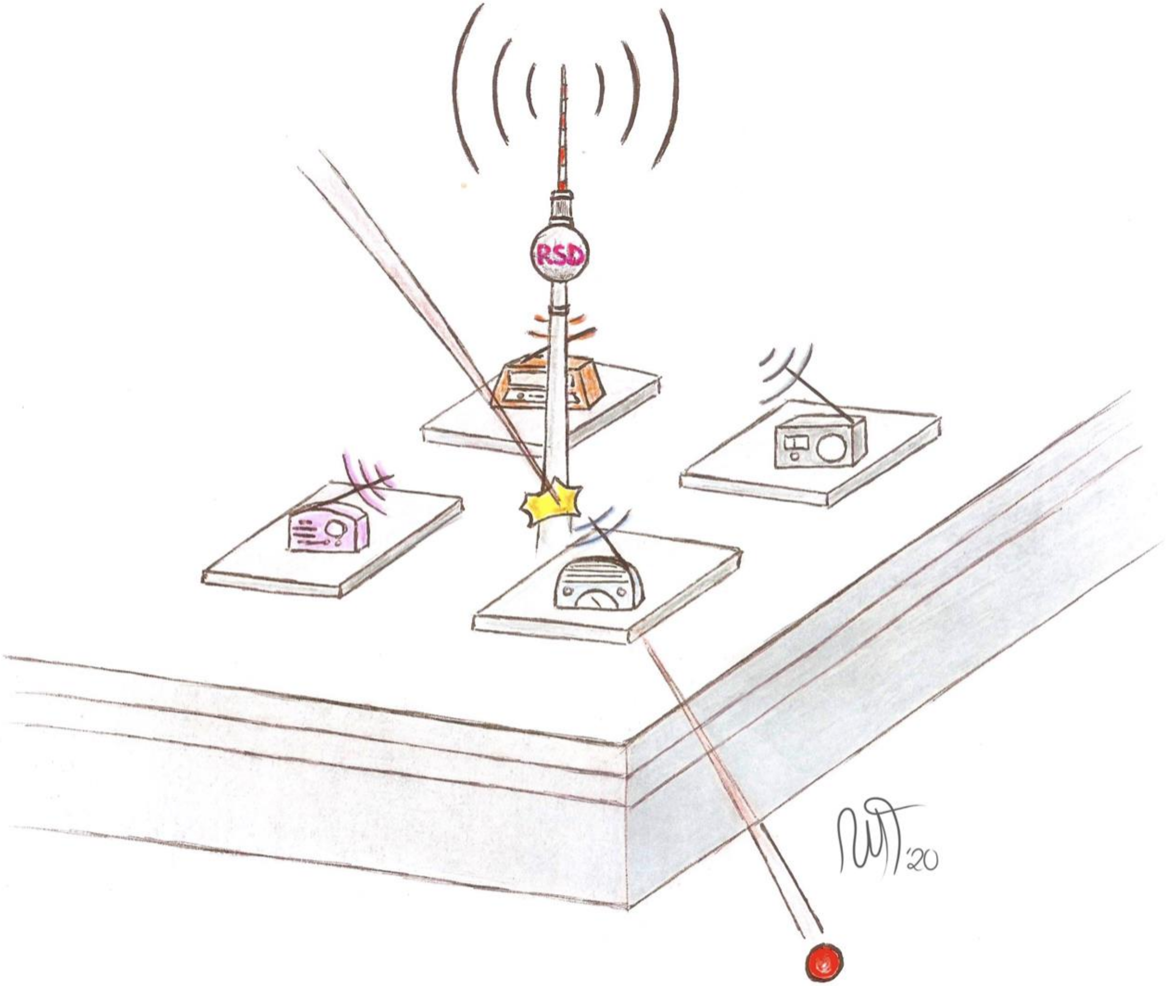
RSD technology has proven to be a promising candidate as a 4D detector, combining LGADs timing and the innovative charge sharing in silicon for position reconstruction

- Position resolution is better than in standard sensors
  - The n+ layer resistivity is to be tuned on the pixel size
- Time resolution of “standard” LGADs is maintained
  - Time jitter is lower for sensors with lower resistivity due to the signals shape

Very useful information for future developments on DC-RSD

More on RSD 2 results (test beam @Desy) in the next talk



Thank you!

Special Thanks to

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- INFN - Gruppo V, UFSD and RSD projects
- INFN – FBK agreement on sensor production (convenzione INFN-FBK)
- Horizon 2020, grant UFSD669529
- 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
- Marta Tornago for all the nice drawings

References

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2. M. Mandurrino, et al., The second production of RSD (AC-LGAD) at FBK, JINST 17 (08) (2022) C08001. arXiv:2111.14235, doi:10.1088/1748-0221/17/08/C08001.
3. "High precision 4D tracking with large pixels using thin resistive silicon detectors". R. Arcidiacono et al.
4. "First experimental results of the spatial resolution of RSD pad arrays, readout wit a 16-ch board", F. Siviero et al., arxiv.org/abs/2204.06388.
5. "Silicon sensors with resistive read-out: ML techniques for ultimate spatial resolution", M. Tornago et al.

Space Reconstruction Results

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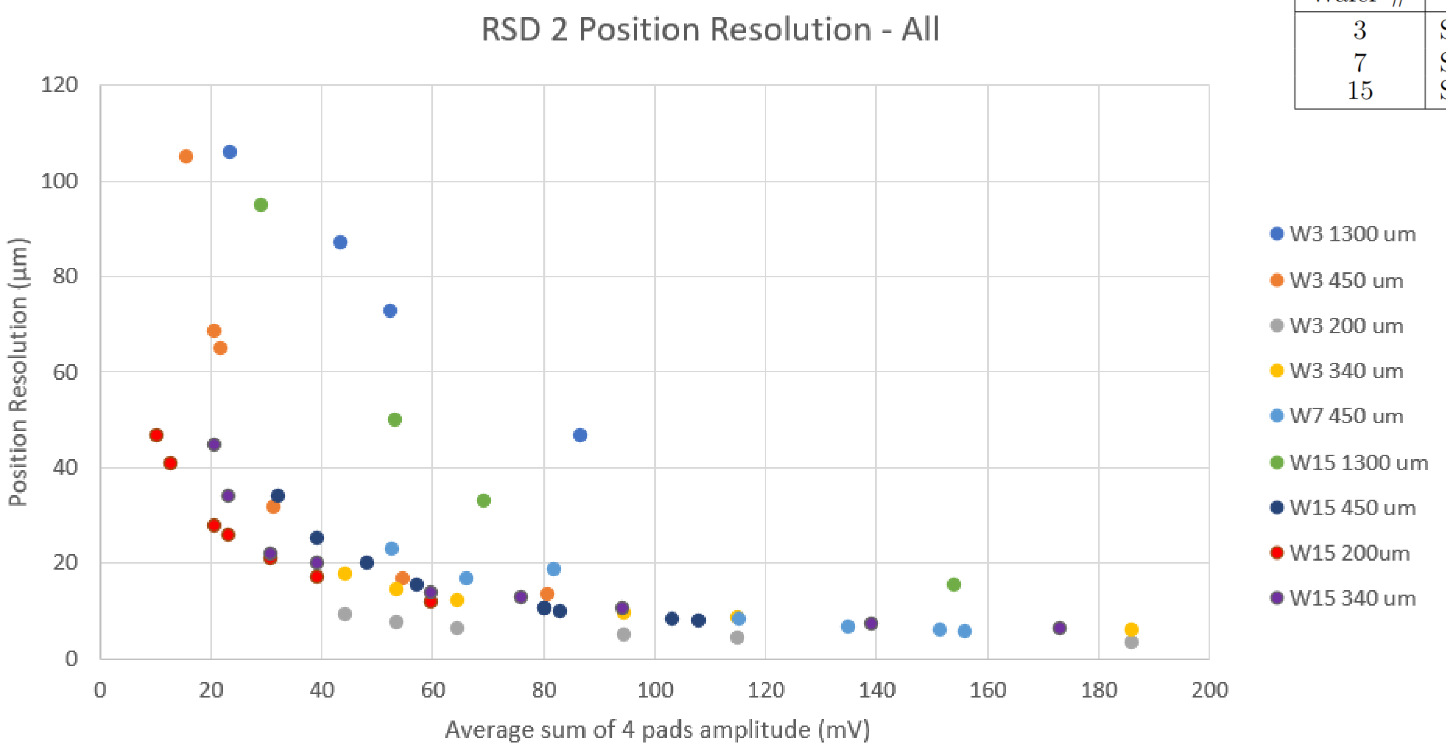
Different wafers can be studied with a fixed geometry

Wafer #	Type	Carbon	n^+ dose	p gain dose
3	Si-Si 55 µm	N	A	2.45
7	Si-Si 55 µm	N	B	2.45
15	Si-Si 55 µm	N	C	2.35



Performances at a fixed amplitudes sum

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