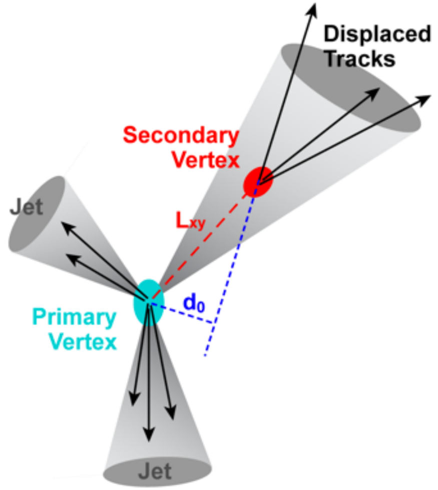
The “1 μm” project

Resistive Read-out in Silicon Detector offers the possibility to reach unprecedented position resolution using large pixels and thin sensors

- Impact parameter resolution, sensor accuracy, material budget
- Requests at future colliders
- Resistive readout in silicon detectors
- Charge sharing: RSD main formula
- Reconstruction method
- Results: laser, beam test ➔ All results obtained using RSD1 from FBK
- Read-out electronics
- Application of Machine learning algorithms
- Future directions
- Publications, contributors
- Extra topics (not for the presentation)

Impact parameter resolution in silicon detector

The capability of distinguishing secondary vertexes is often expressed by the impact parameter resolution $\boldsymbol{\sigma_{d_0}}$



$$\sigma_{d0}^2 = \sigma_{Geom}^2 + \sigma_{MS}^2$$

The geometrical precision $\boldsymbol{\sigma_{Geom}}$ depends on the **accuracy of the single sensor** $\boldsymbol{\sigma_x}$

The average multiple scattering $\boldsymbol{\sigma_{MS}}$ depends on the material budget of the sensors and services

- First layer as close as possible to the beam line
- Last layer as far as possible
- **Smallest possible $\boldsymbol{\sigma_x}$: very accurate sensors**

- Low mass beam pipe
- Place services far away
- **Smallet possible $\boldsymbol{\sigma_{MS}}$: very thin sensors**

The sensors need to be very accurate and very thin

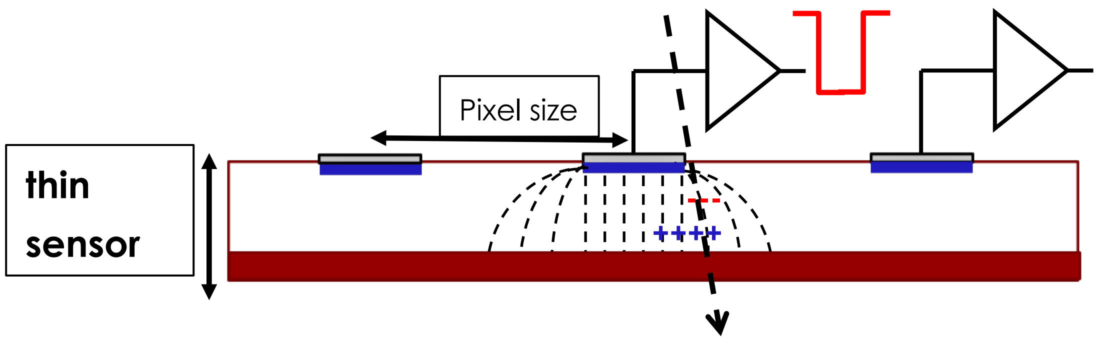
Sensor accuracy σ_x and readout

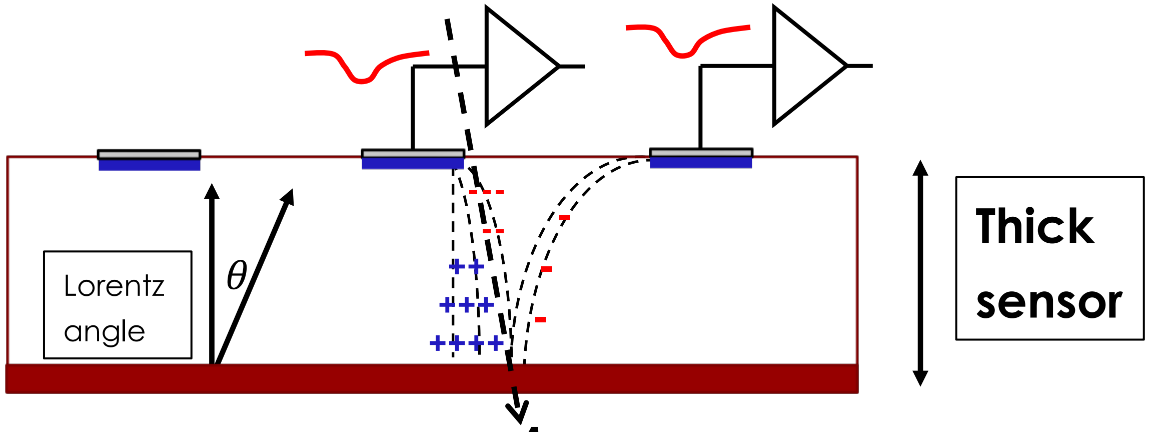
Binary readout

where the only information is hit/miss (0,1)

Analog readout

where the amplitude of the signal is recorded





$$\sigma_x = k \frac{pitch}{\sqrt{12}}, k \sim 0.5 - 1$$

- σ_x depend on the pixel size

  pixel = 100 μm ➔ $\sigma_x = 20\ \mu m$
- σ_{MS} small : sensors might be thin

Thin, NOT accurate

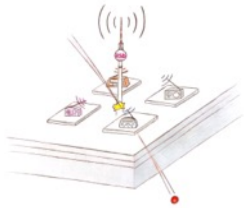
$$x_i = \frac{A_i x_i}{\sum_1^2 A_l x_l}$$

- σ_x << pixel size
- σ_{MS} large

  Sensors have to be thick to maintain efficiency
- Need B field (or floating electrodes)

Accurate, NOT thin

The sensors are either very accurate OR very thin



Request at future accelerators

Facility:	FCC-ee	ILC	CLIC
σ_x [μm]	~ 5	<3	< 3
Thickness of tracker material [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
Pixel size [μm ^{2}]	25 x 25	25 x 25	25 x 25

$$\boldsymbol{\sigma_x = 5\ \mu m\ \&\&\ \sigma_{MS} \sim 100\ \mu m\ \&\&\ air\ cooled}$$

Very difficult to achieve

➔ tiny pixels with binary readout: technologically very difficult (power, bumps, services)

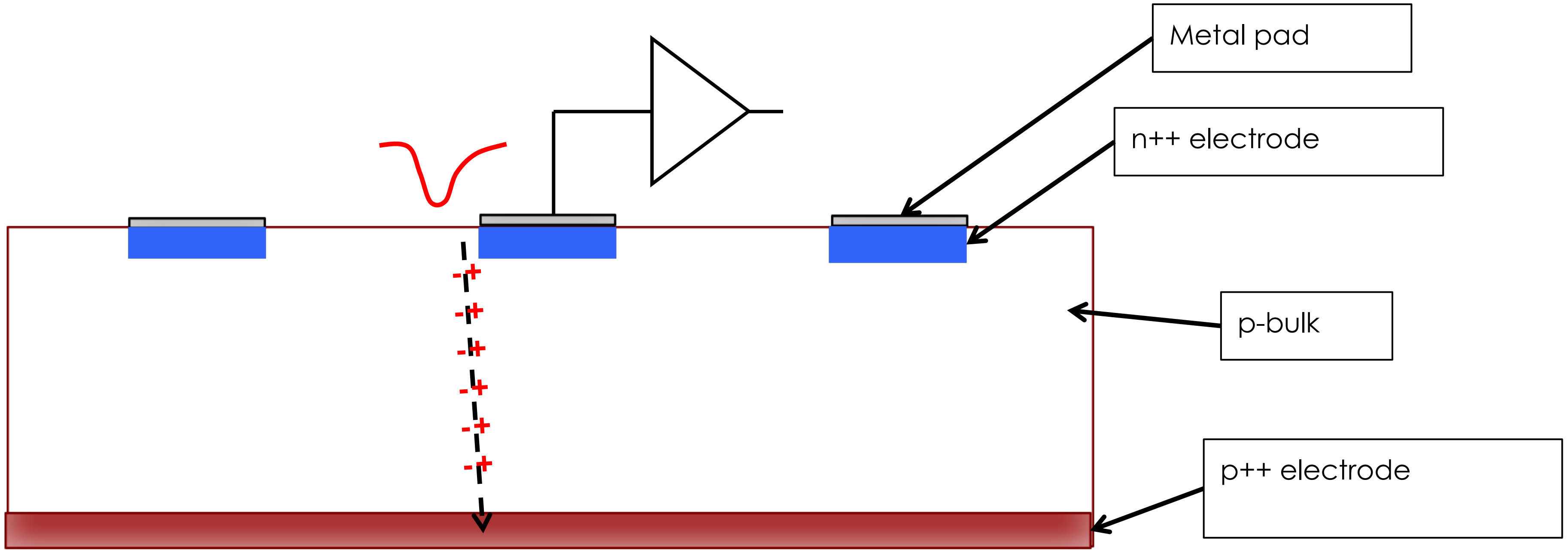
Monolithic (MAPS…)?

➔ The reason for small pixels is the position accuracy not occupancy ➔ almost empty detector

Good temporal resolution is also very challenging with so many pixels and not enough power

Signal formation in DC-coupled silicon sensor

The e/h are drifting, producing direct charge induction in the n++ layer (Ramo's theorem)

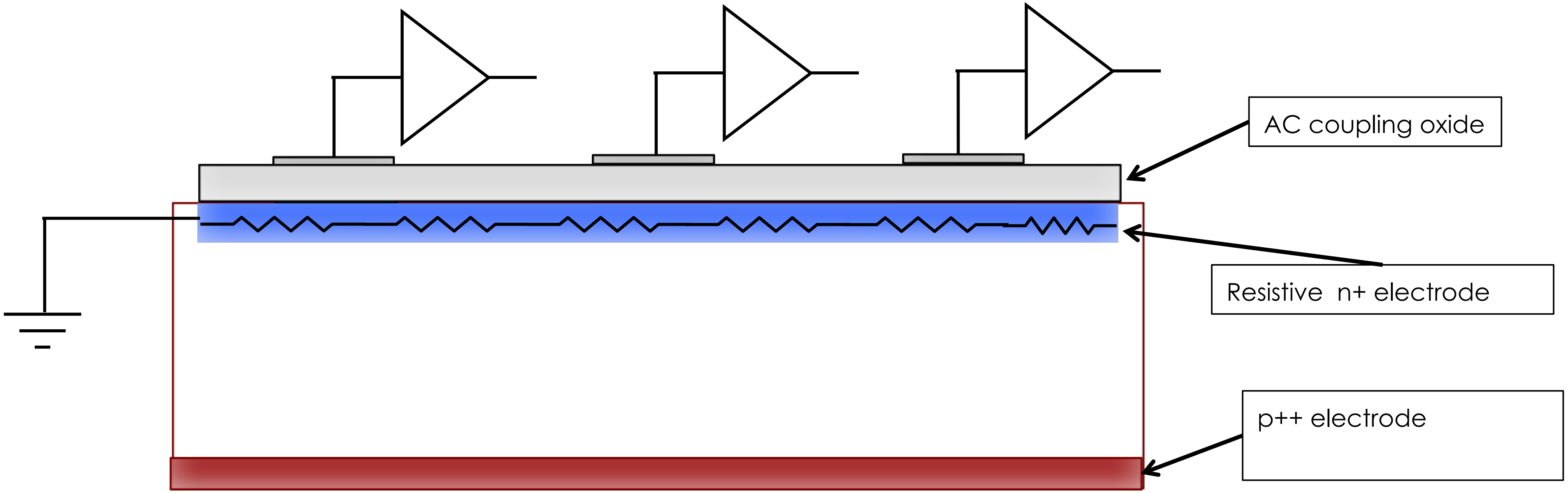


Resistive readout

1) Extended the n++ electrode over the whole Si surface

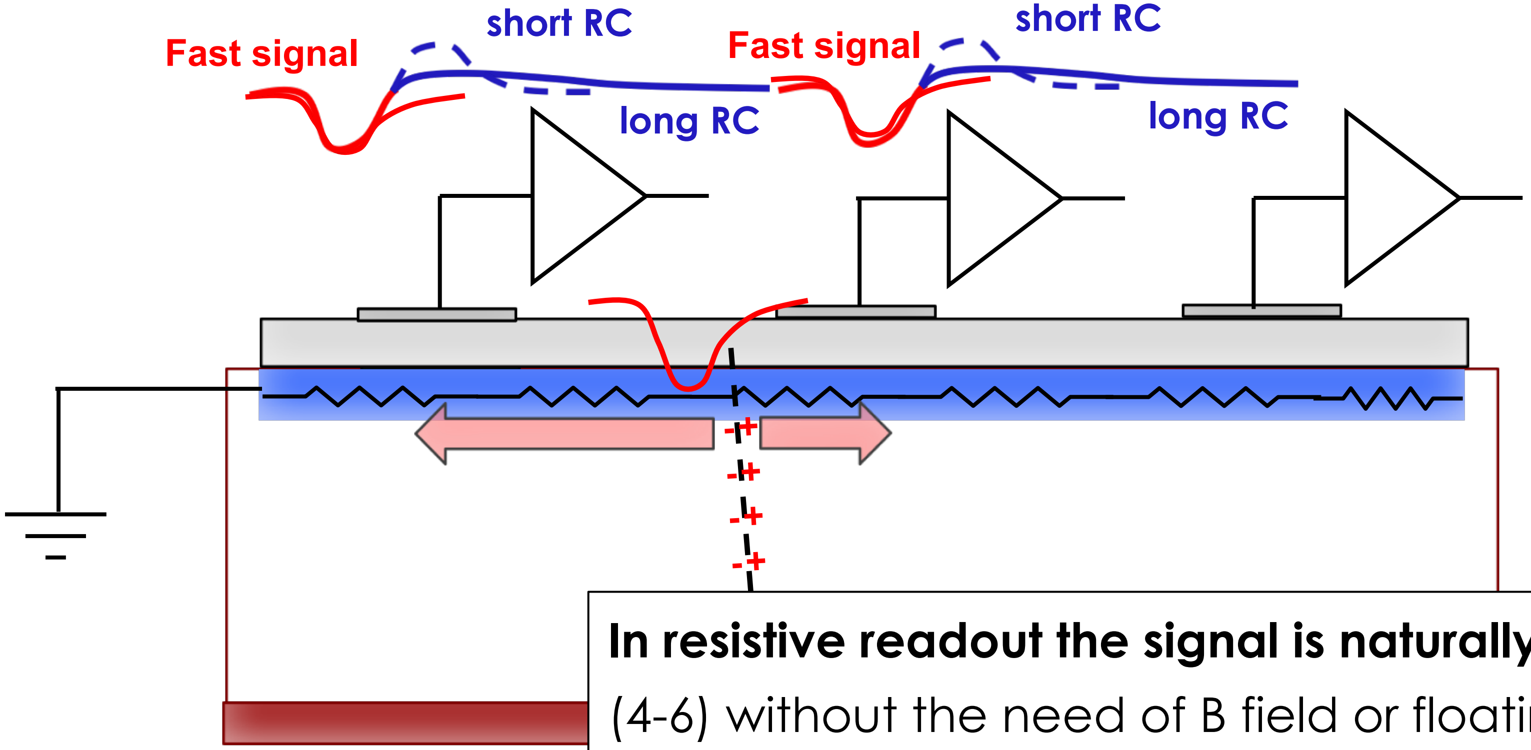
2) Make the n++ electrode resistive ➔ n+

3) Add AC-coupling readout



Signal formation in resistive readout

- **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
Problem: sharing a small signal leads to inefficiency

Combining internal sharing and internal gain

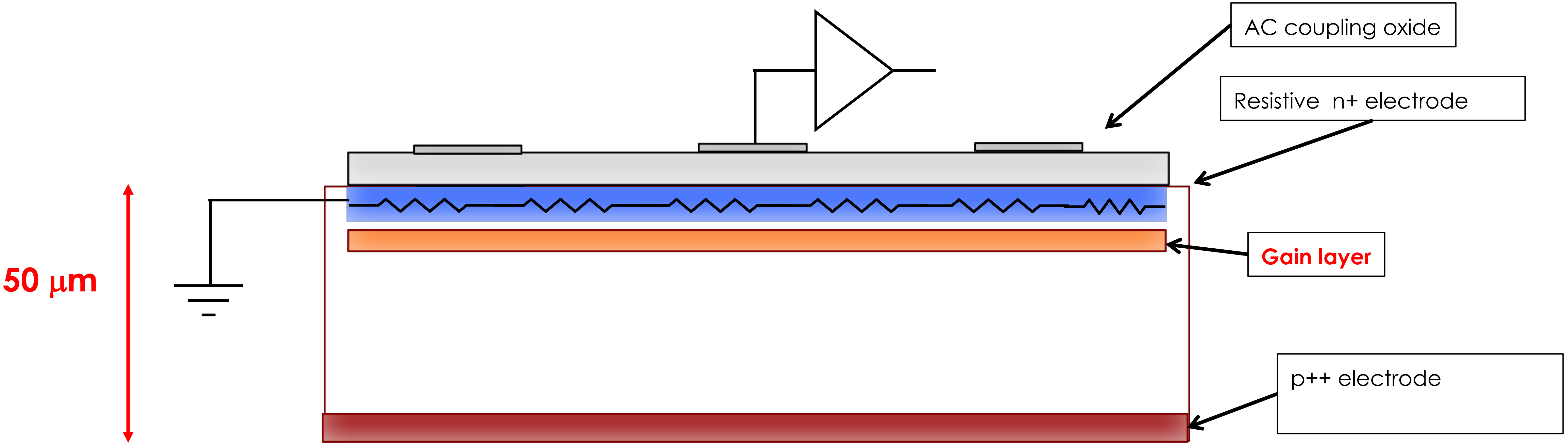
1) **Extended the n++ electrode over the whole Si surface**

2) **Make the n++ electrode resistive ➔ n+**

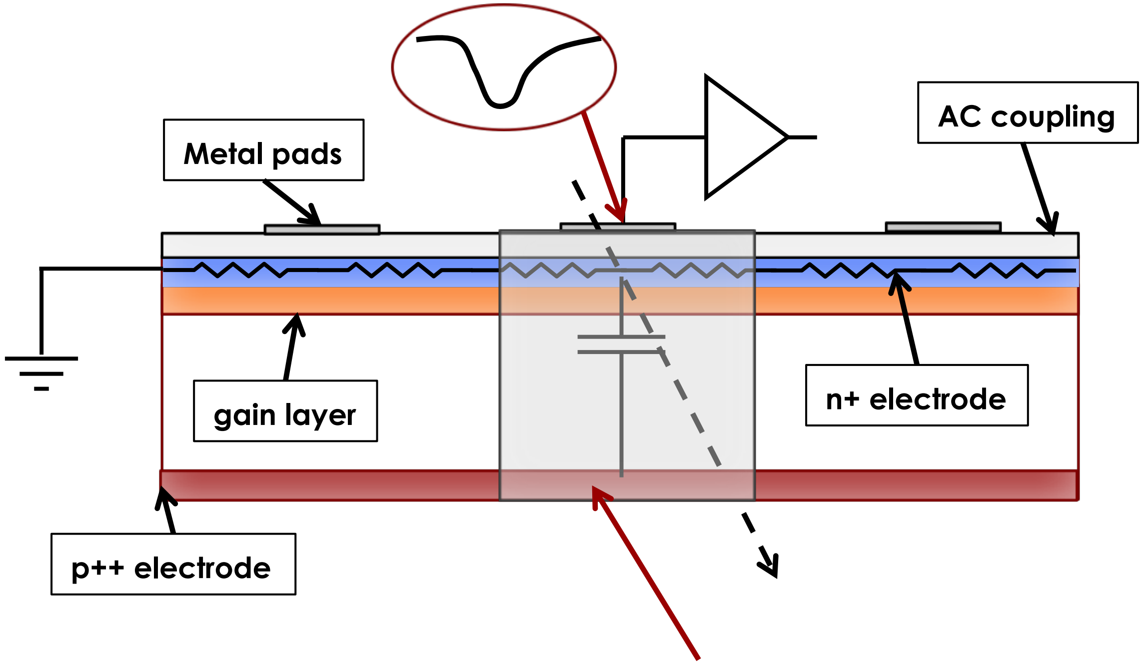
3) **Add AC-coupling readout**

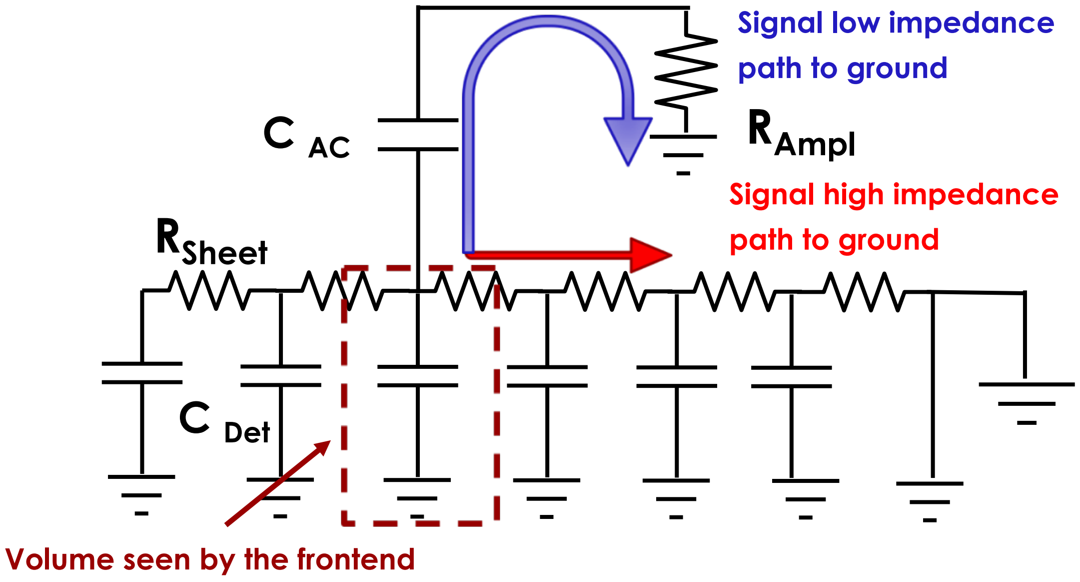
4) **Add internal gain to maintain 100% efficiency even with signal sharing**

5) **Make the sensor thin to reduce material budget and enhance timing performance**



Resistive readout: why does it work?

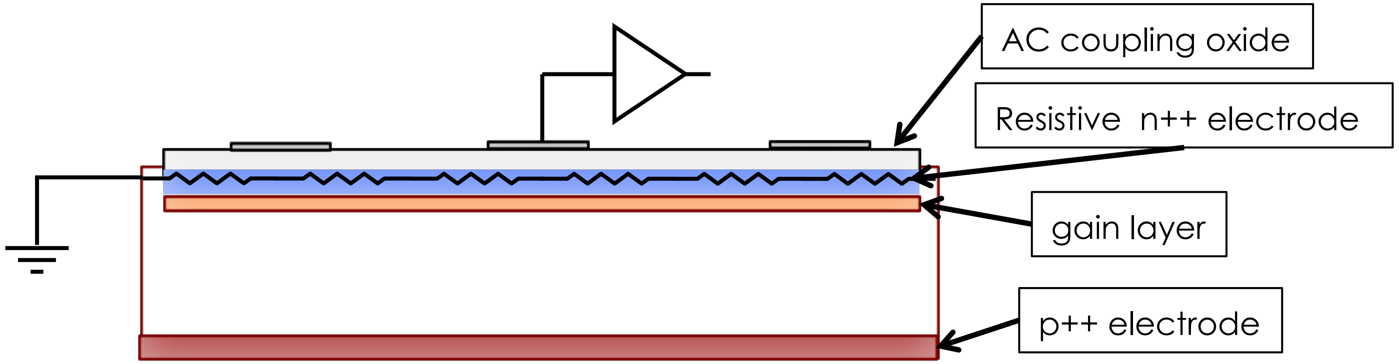




The resistive n+ electrode limits the geometrical volume seen by the read-out: given the high frequencies involved, the capacitive path to ground is more favorable than the resistive path

- Rather small capacitance: $\frac{1}{C_{Tot}} = \frac{1}{C_{AC}} + \frac{1}{C_{Det}} \sim \frac{1}{C_{Det}}$
- The AC pad discharge time is: $R_{Sheet} * C_{AC}$~ 2 kΩ ∗ 3 pF ~ 4 ns
- The signal rise time is increased by: $R_{Ampl} * C_{Det}$~ 100 Ω ∗ 1pF ~ 100 ps

Timeline of the Resistive readout sensor: AC – LGAD / RSD

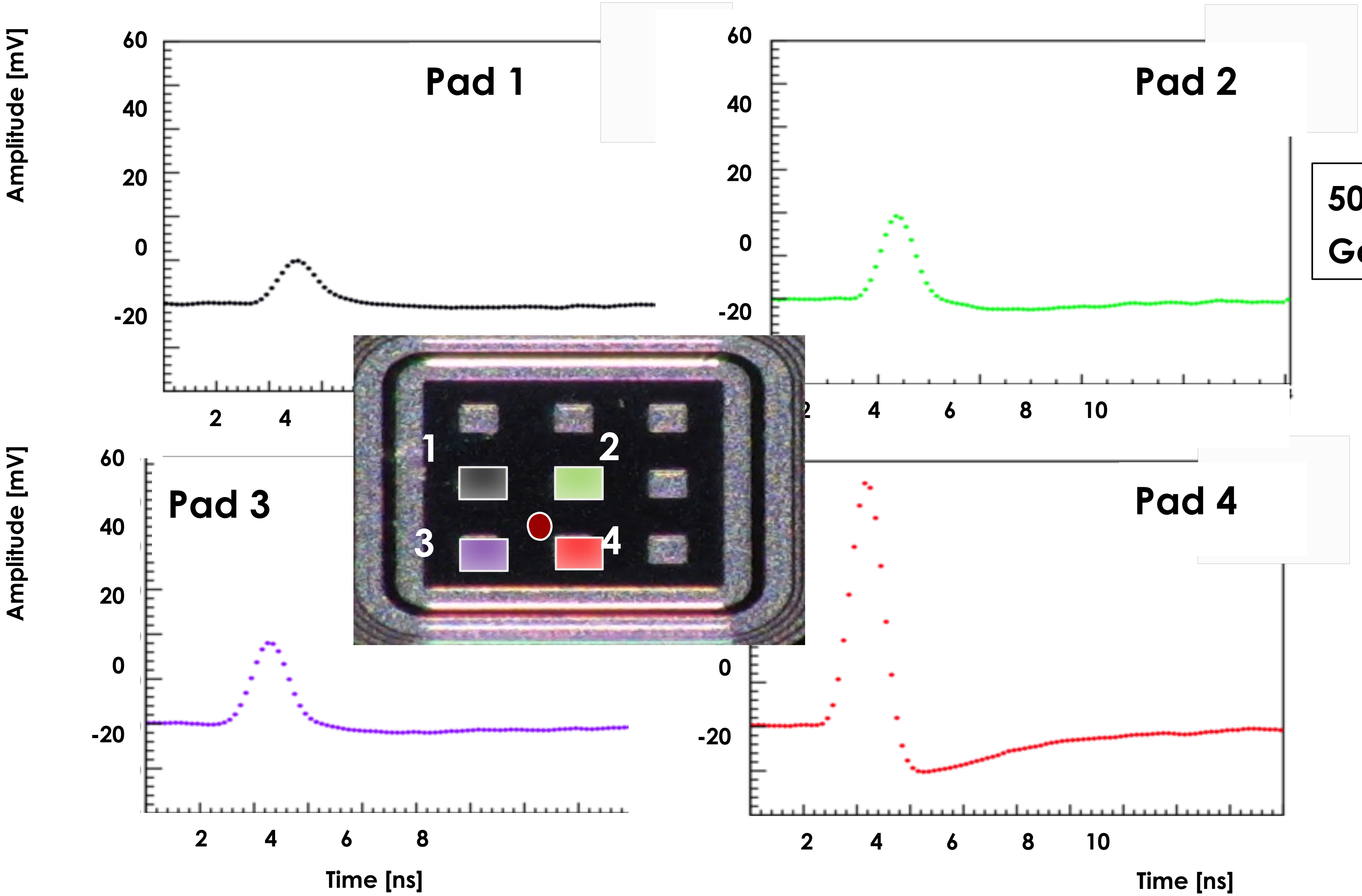


These sensors enjoy a double name: the **key technological features are** the **“resistive n+ layer”**, necessary to produce the local AC coupling, and **gain** to avoid inefficiency and allow small material budget.

AC-LGAD (AC-coupled Low-Gain Avalanche Diode) or **RSD** (Resistive Silicon Detector).

- AC-LGAD were proposed at the TREDI 2015 conference [1].
- The sensors presented here are manufactured at FBK within the RSD project (INFN) [2],[3].
- CNM produced AC-LGAD sensors in 2017 [4]
- BNL produced AC-LGAD in 2019 [5].
- Results shown from beamtest are from [6]
- The application of Machine Learning is [7]
- First results on AC-LGAD strips at beam test [8]

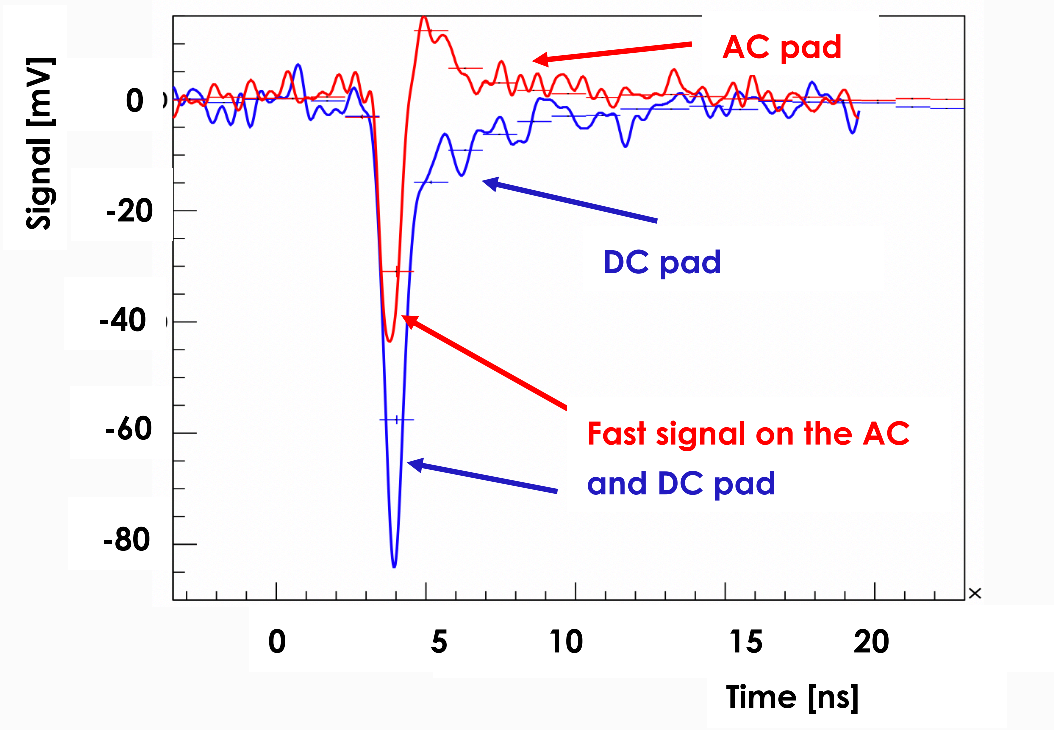
Example of signal sharing



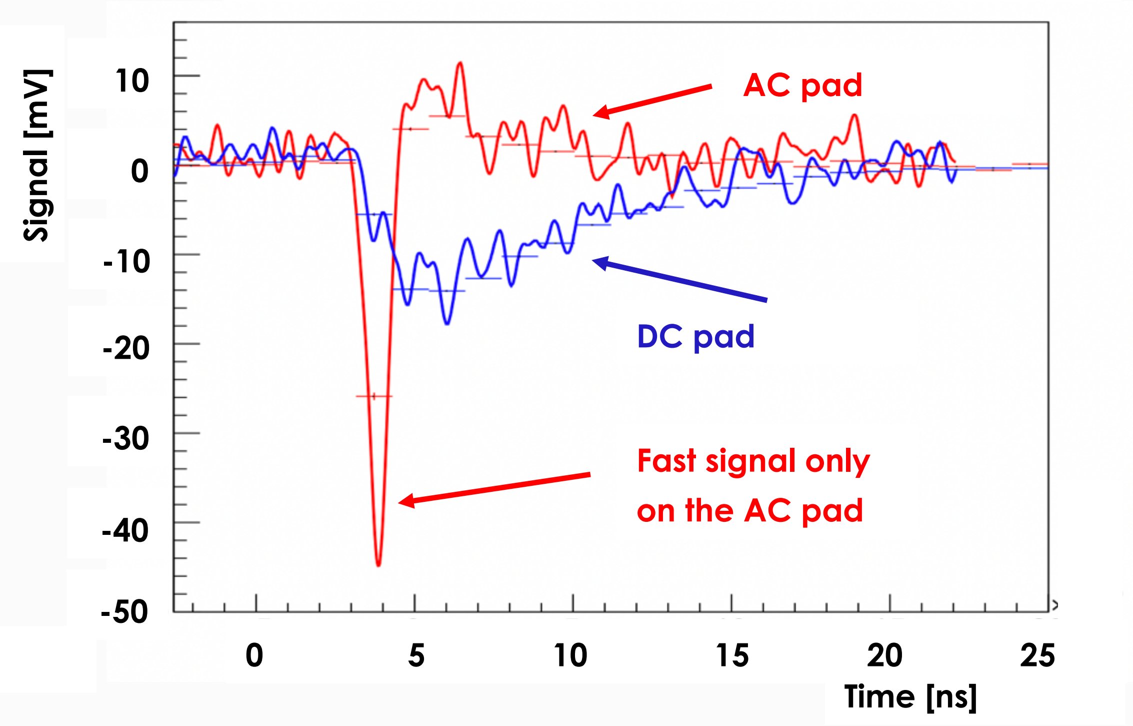
50-mm thick RSD,
Gain ~ 20

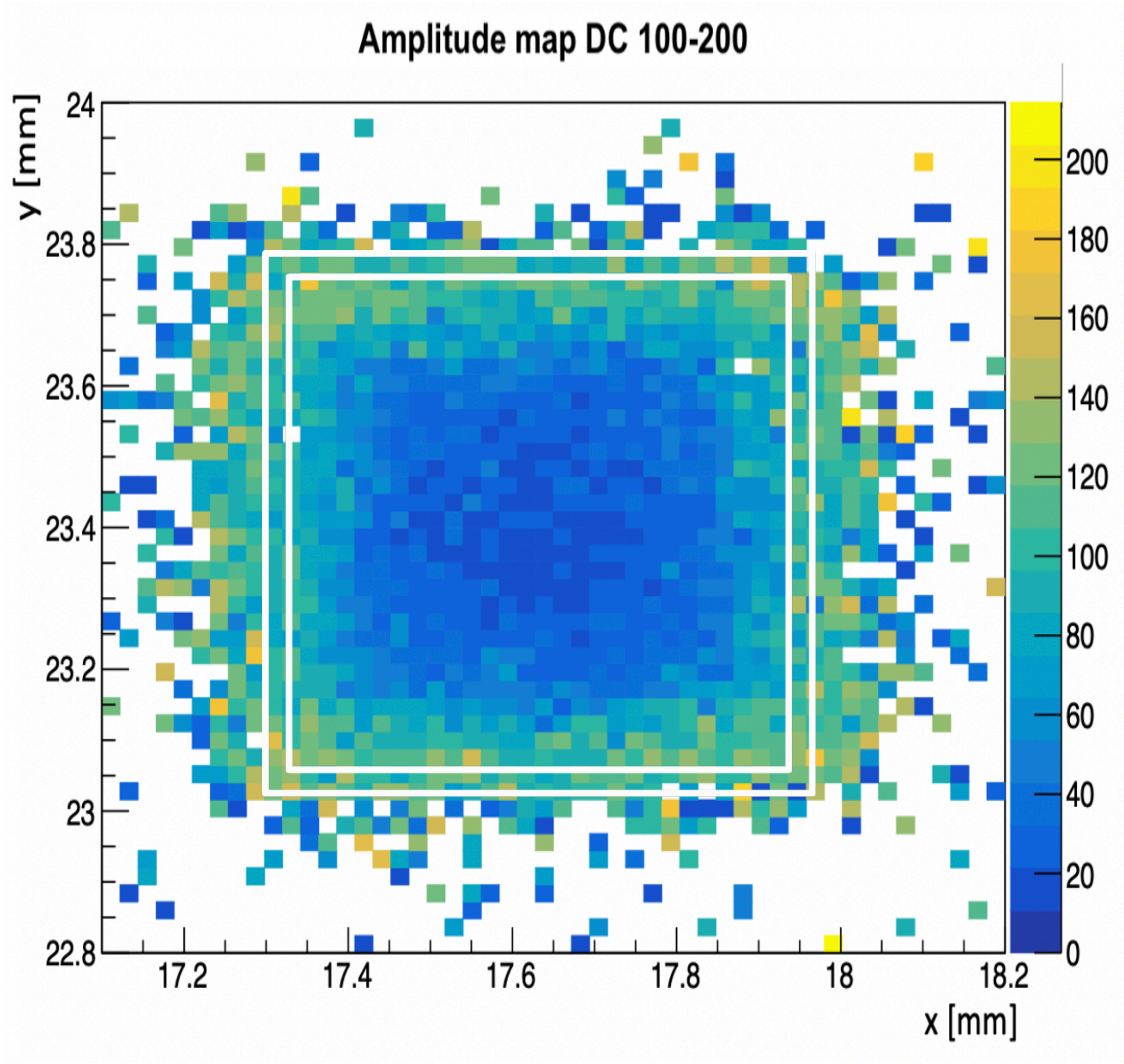
The laser is shot at the position of the red dot: the signal is seen in 4 pads

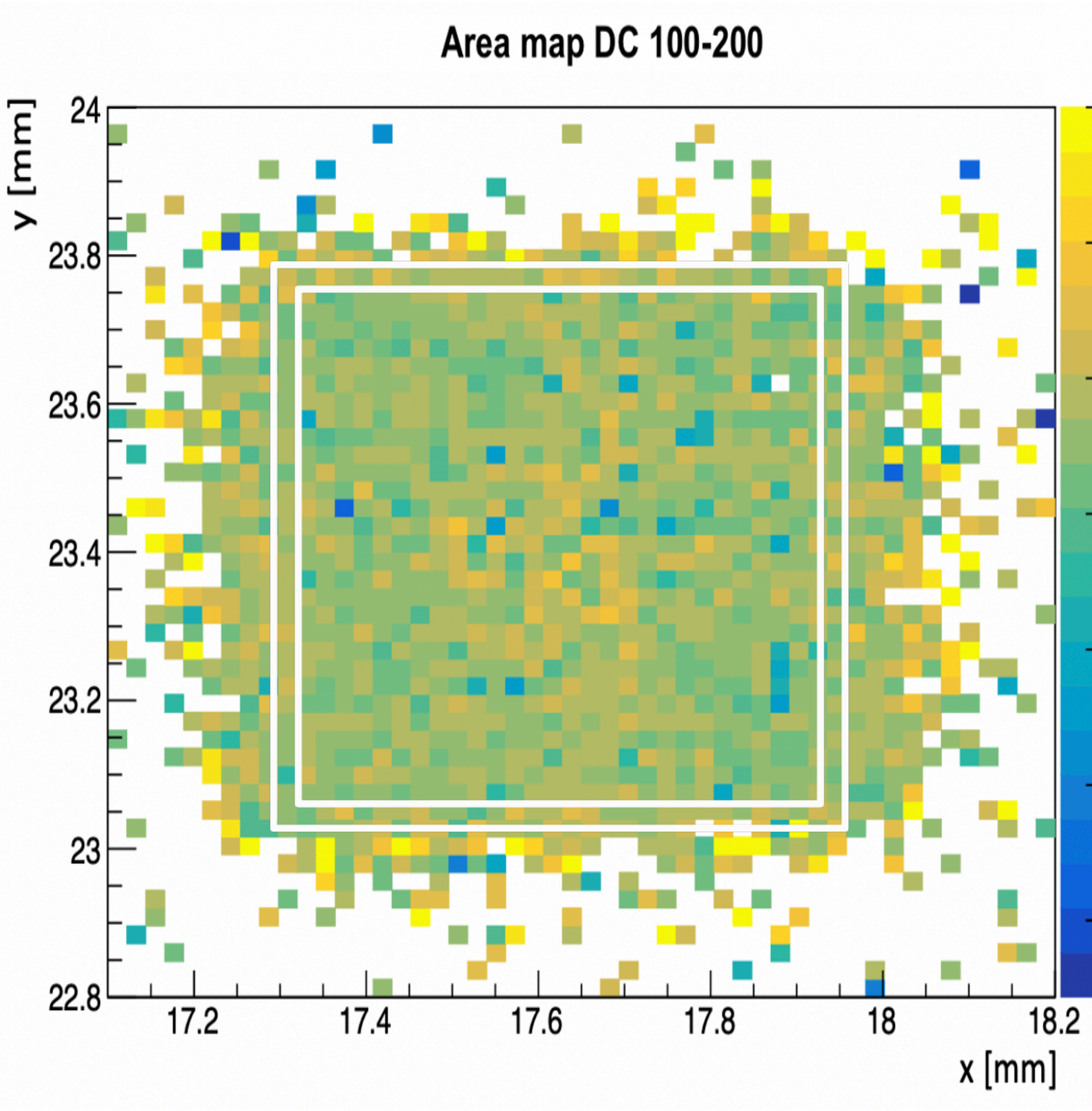
Particle impact point in the outer sensor region



Particle impact point in the inner sensor region



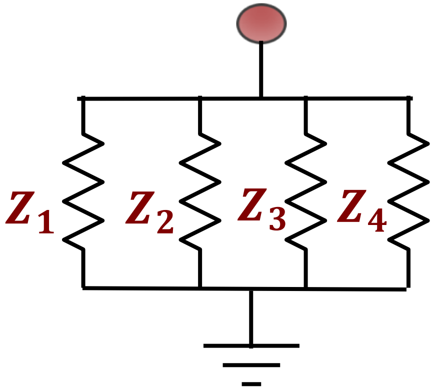

Amplitude map DC 100-200
y [mm]
24
23.8
23.6
23.4
23.2
23
22.8
17.2
17.4
17.6
17.8
18
18.2
x [mm]
0
20
40
60
80
100
120
140
160
180
200
Amplitude [mV]


Area map DC 100-200
y [mm]
24
23.8
23.6
23.4
23.2
23
22.8
17.2
17.4
17.6
17.8
18
18.2
x [mm]

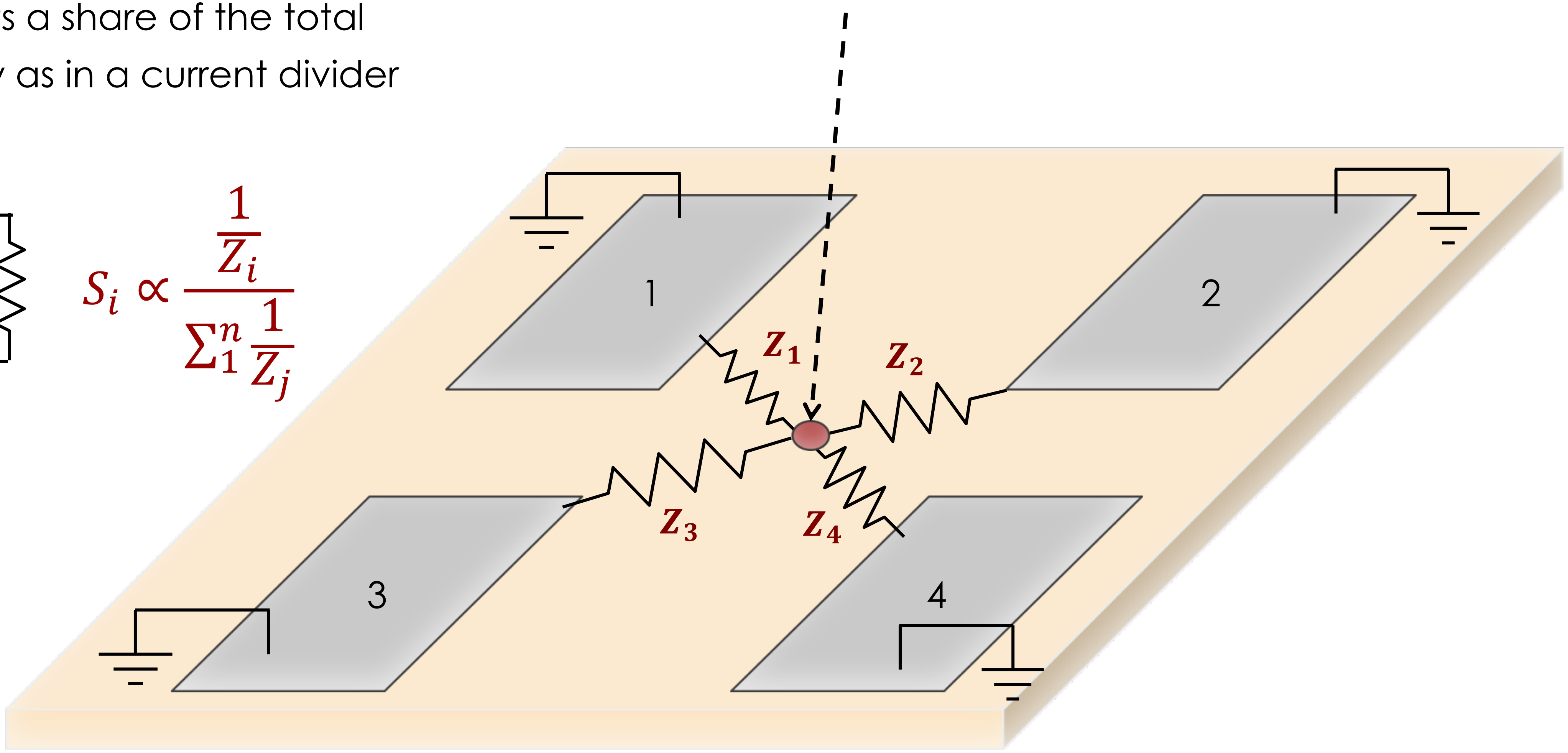
Charge sharing in RSD

The signal sees several impedances in parallel, and it is split according to Ohm’s law.

Each pad gets a share of the total signal, exactly as in a current divider



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



How to calculate Z_i

The impedance Z seen by a propagating signal does not increase linearly with the distance r since the signal spreads on a larger area

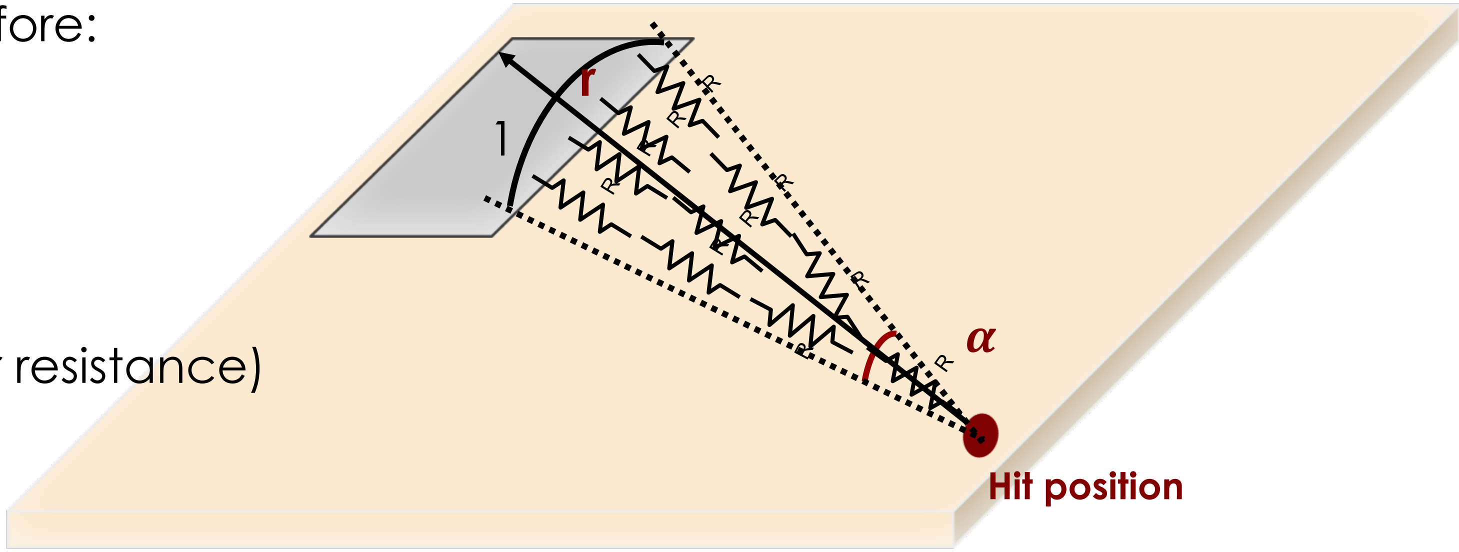
The resistance R per unit distance decreases as the circumference C becomes larger

$$Z(r) \propto \frac{dr}{\alpha r}$$

The impedance Z up to radius r is therefore:

$$Z(d) \propto \frac{1}{\alpha}\int_1^d \frac{1}{r} \propto \frac{ln(d)}{\alpha}$$

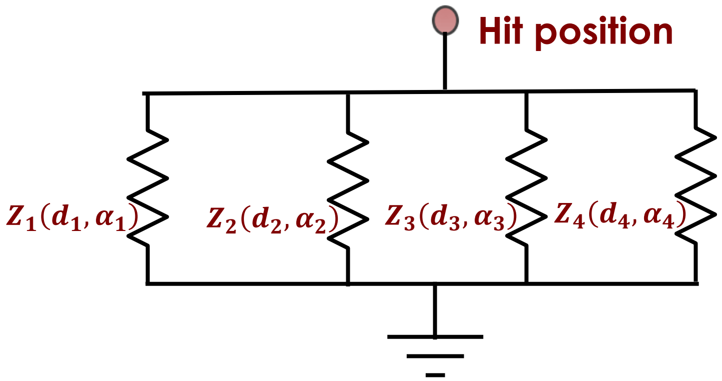
where α is the angle (larger pad, smaller resistance)



RSD main formula

The fraction of signal seen in each pad is:

$$S_i(\alpha_i, d_i) = \frac{\frac{\alpha_i}{\ln(d_i)}}{\sum_1^n \frac{\alpha_j}{\ln(d_j)}}$$

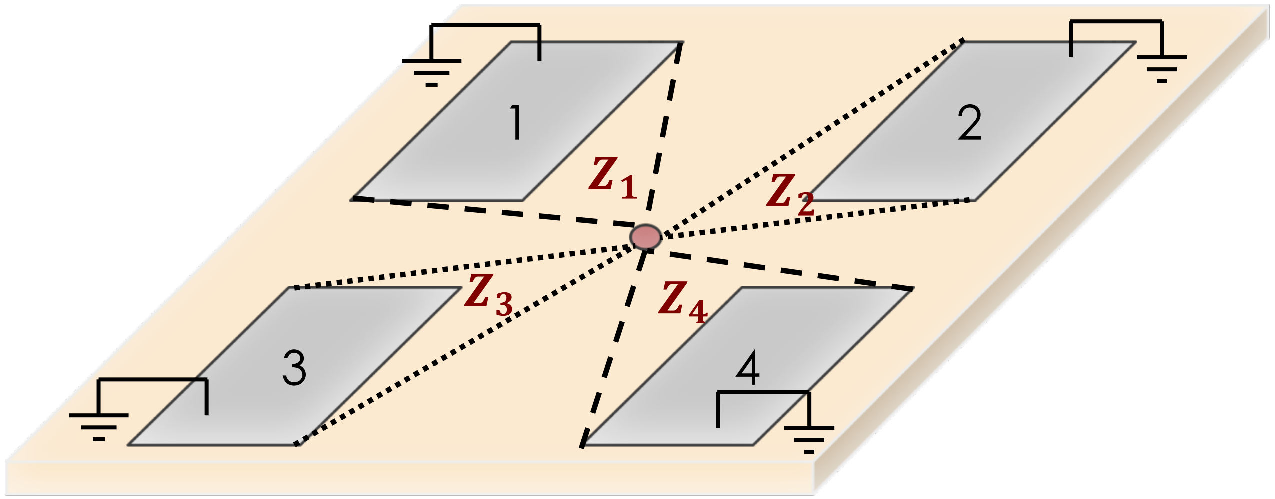


where:

- d_i= distance hit-pad
- α_i= angle of view hit-pad

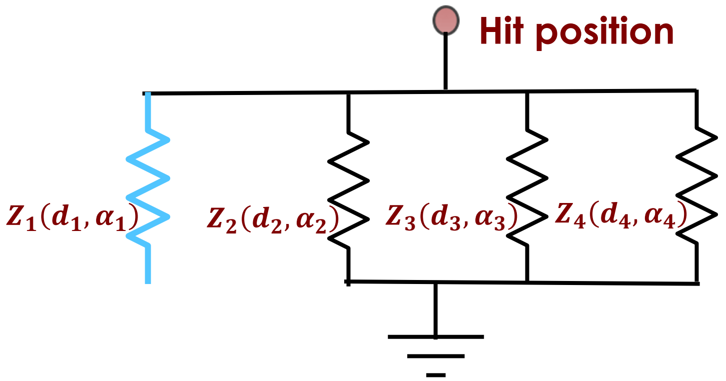
Important points:

- The signal seen in a pad depends upon how many other pads are nearby
- A signal can be seen by 2,3 or 4 pads, depending on the hit location

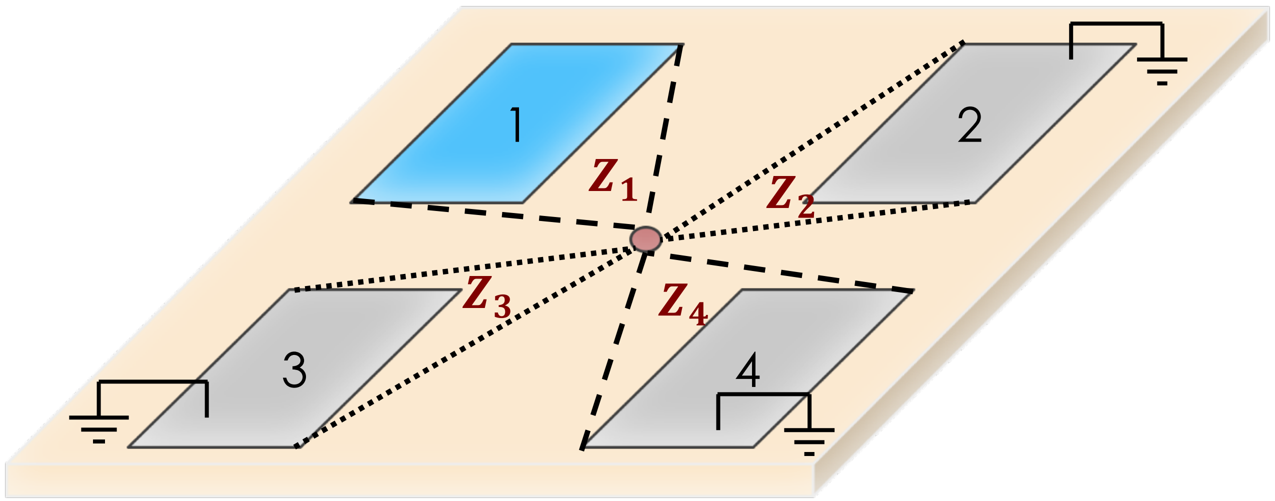


RSD main formula – floating pads

$$S_1(\alpha_1, d_1) = \frac{\frac{\alpha_1}{\ln(d_1)}}{\sum_1^n \frac{\alpha_j}{\ln(d_j)}} = 0$$

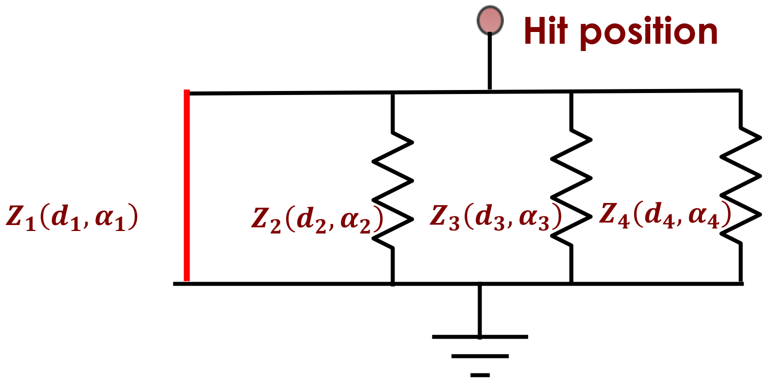


A floating pad does not contribute to the signal sharing, there is no path to ground, i.e., no current flow.

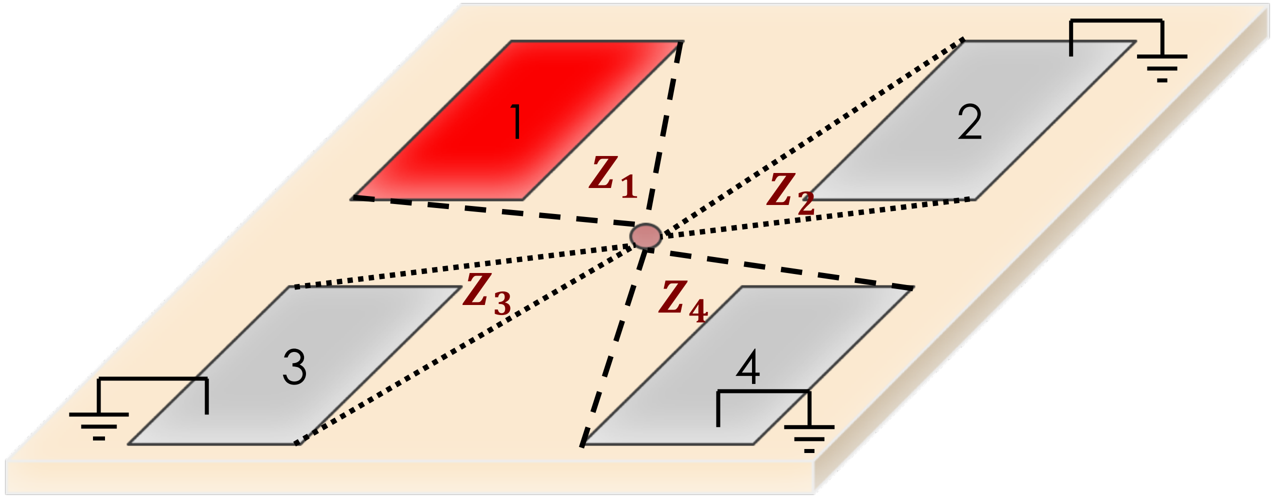


RSD main formula – Hit on metal

$$S_1(\alpha_1, d_1) = \frac{\frac{\alpha_1}{\ln(d_1)}}{\sum_1^n \frac{\alpha_j}{\ln(d_j)}} \sim S_{tot}$$



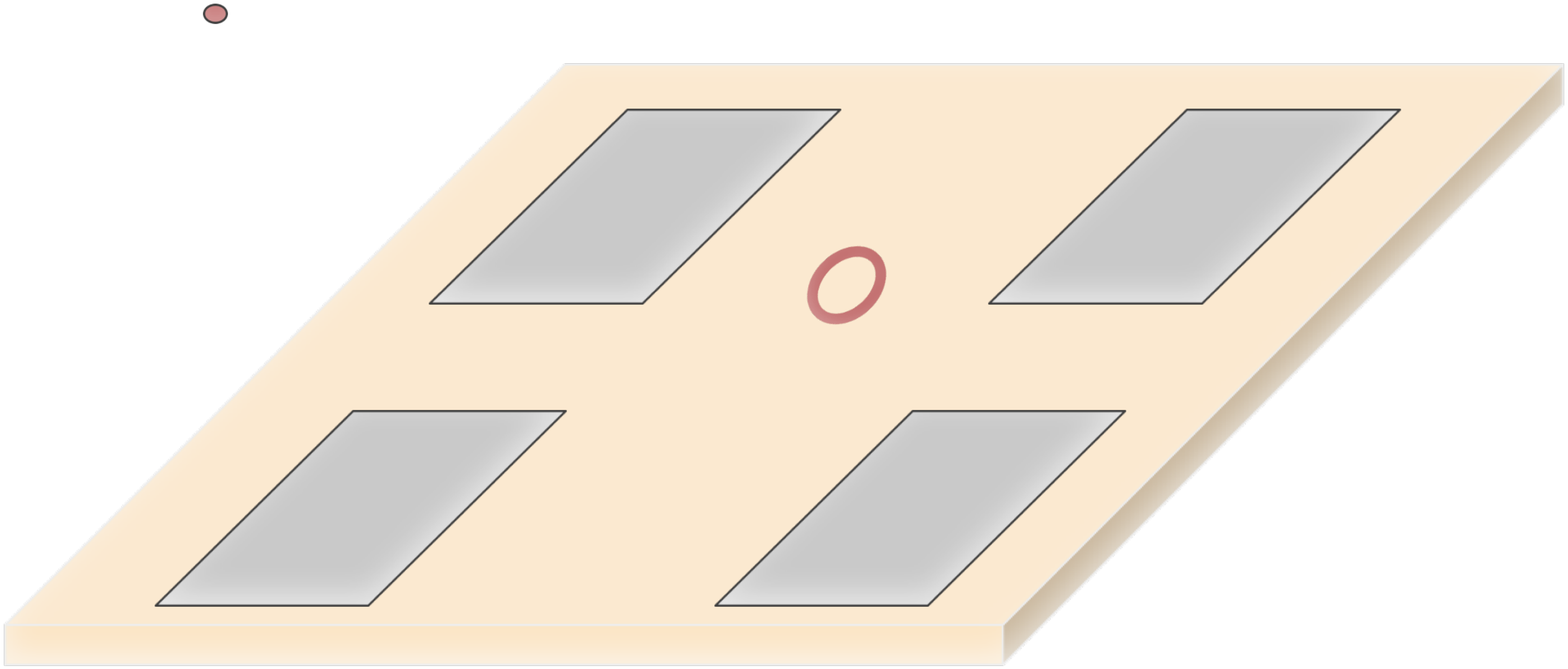
When the hit is on the metal, the impedance to that pad is ~ zero, so the whole signal is in one pad.



Consequences:

- In the following, signal sharing refers to the area without metal
- Metal pads need a special design

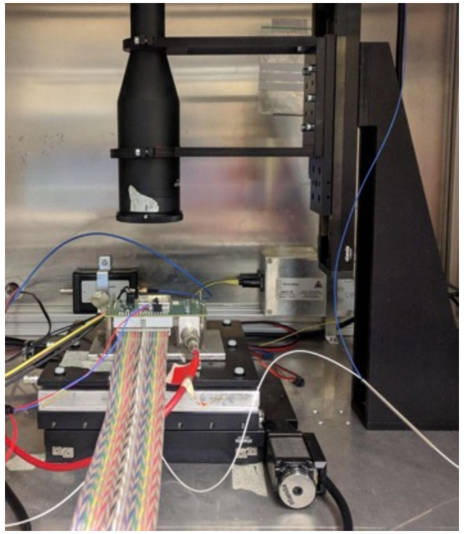
RSD main formula in motion



Experimental data: Laser and beam test

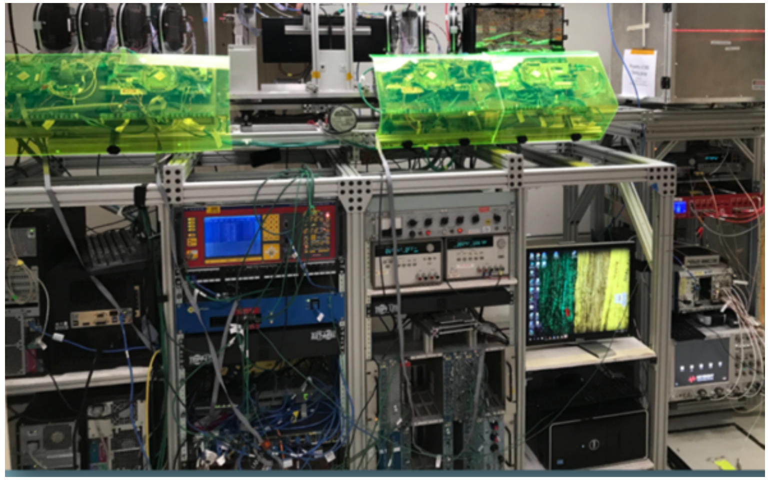
The laser studies presented here are obtained using a "Particular" laser TCT set-up

- Sensors are glued on a 16-channel read-out board.
- The laser is shot in various position via an x-y-z micrometric stage



The beam test results have been obtained at FNAL, in collaboration with the FNAL CMS-Timing ETL team

- 120 GeV/c proton beam
- Precise timing determination (~ 10 ps)
- Fairly precise tracking system (~ 35-40 um)



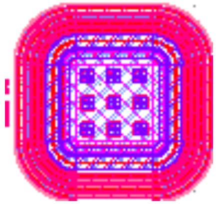
The signals are recorded with a digital oscilloscope (20-40 GS/s, 2-4 GHz BW) for offline analysis

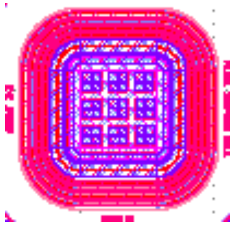
Structures tested (metal-pitch)

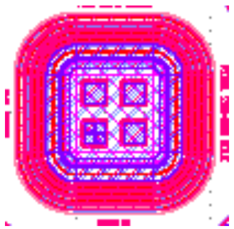
The FBK production RSD1 yielded many samples, of several geometries, exploring the interplay of n+ resistivity, dielectric thickness, metal pad, and pitch

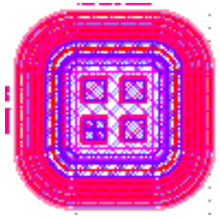

50-100

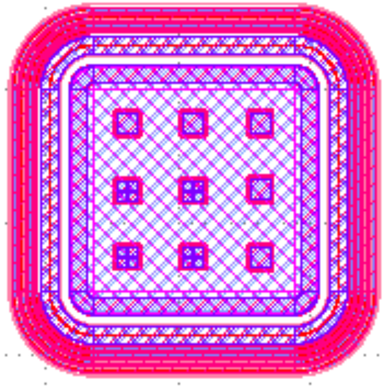

70-100

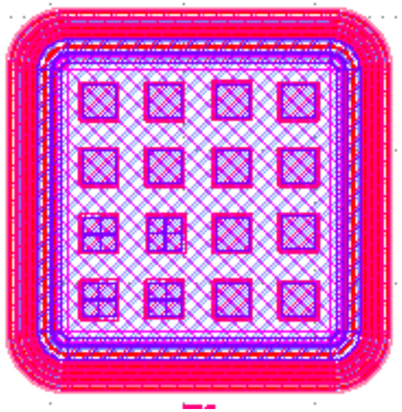

100-200


150-200

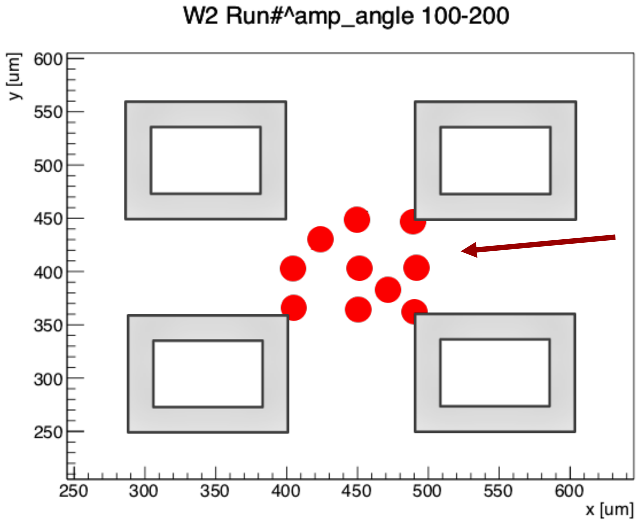

150-300


200-300


200-500


300-500

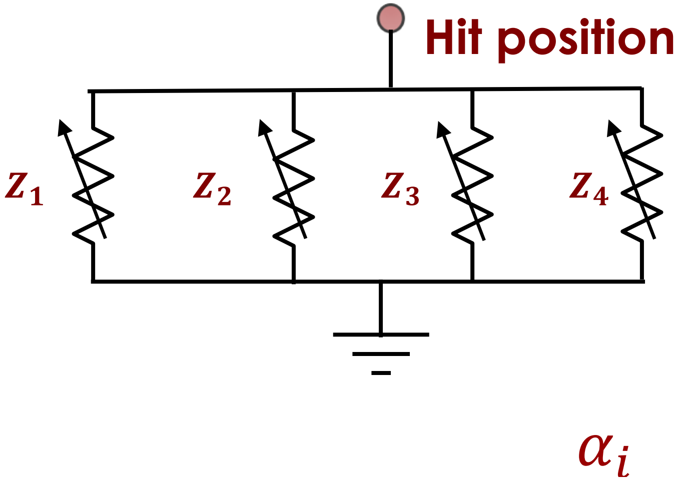
Each sensor was tested with the laser TCT set-up, shining the laser spot (~ 10 um) in several positions and recording the signals seen by the 4 adjacent pads. The runs were repeated at 3-4 values of gain for each geometry

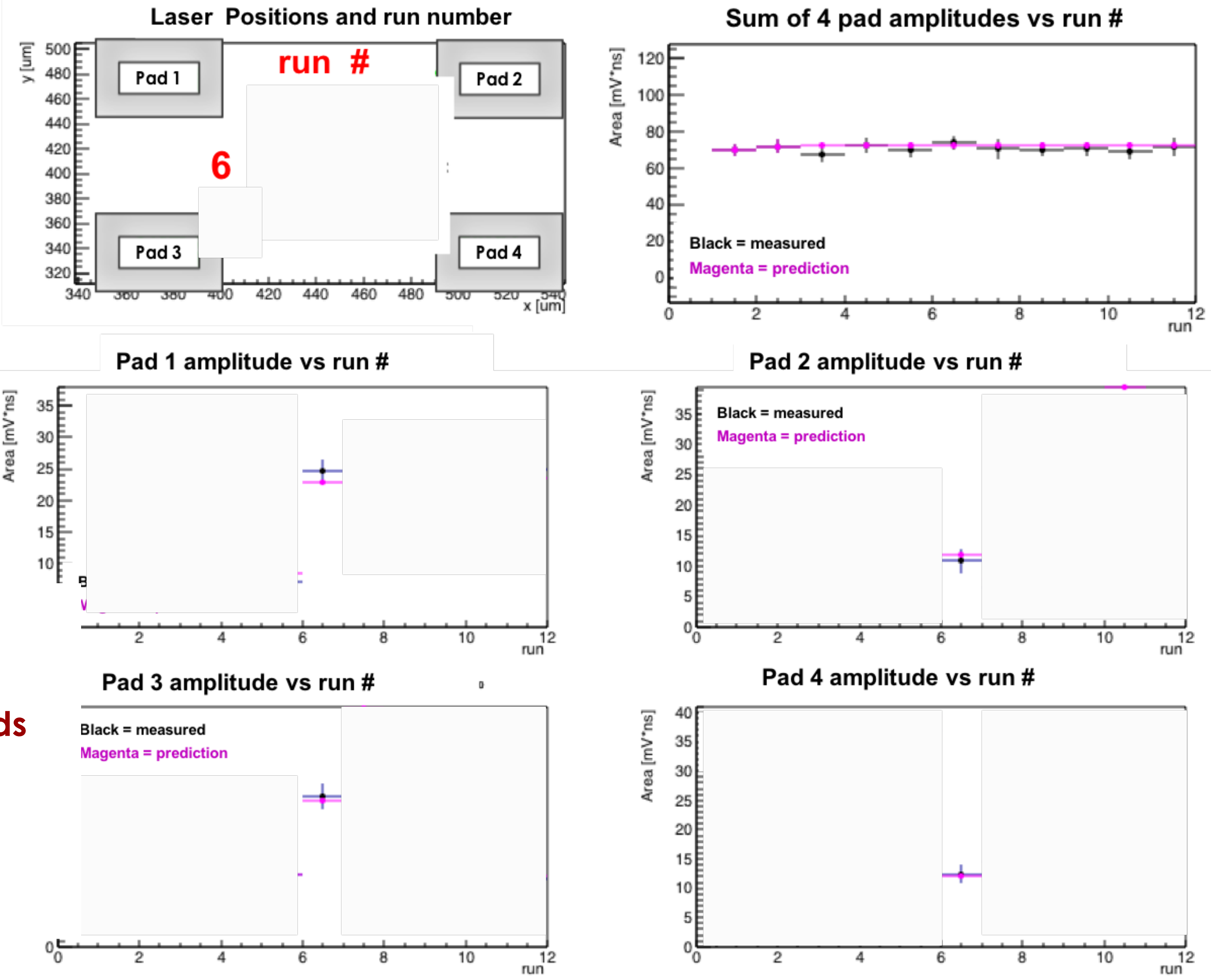


Example of laser positions

Signal amplitudes as a function of positions – 4 pads

The amplitudes in the 4 pads change together, in a "coordinated way", as they should in a current divider.





Wrap-up:

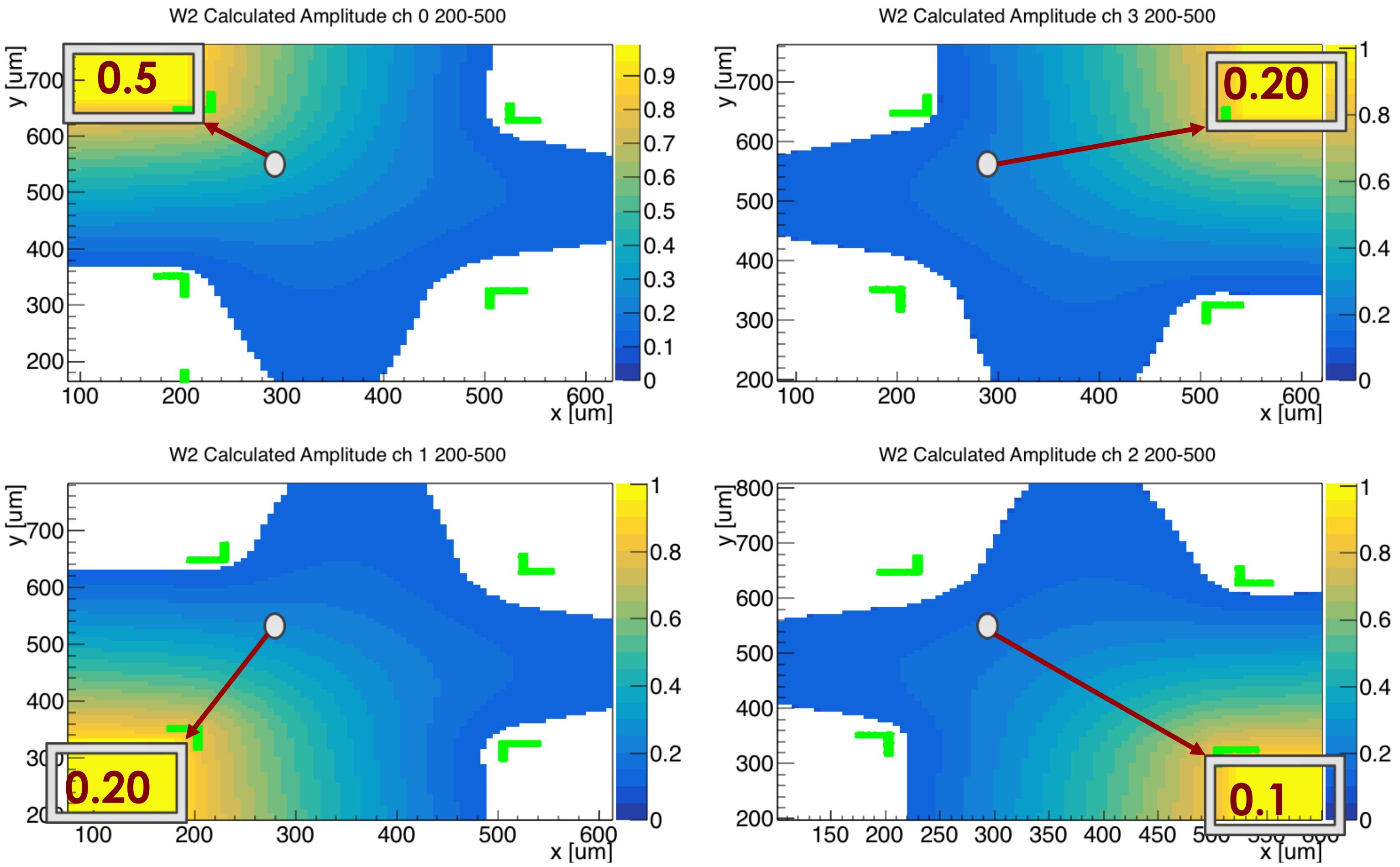
- **RSD works as a current divider**
- **The signal is naturally shared among pads**
- **The RSD main formula works well**

  ➔ **no free parameters, the magenta points are an absolute prediction**
- **The total amplitude is fairly constant**

Position reconstruction method

Basic principle: the amplitudes seen by the pads define a unique x-y point

The RSD main formula allows computing for each x-y point the 4 amplitudes seen by the pads



A particle hits in a given position, with relative amplitude in the 4 pads **0.5,0.2,0.1,0.2**

How the hit position is determined?

The x-y positions of a measured hit are the **coordinates of the bin that minimize the difference between the measured and calculated amplitudes of the 4 pads.**

Minimize the quantity:

$$\chi^2 = \sum_{1}^{4} \frac{\left[S_i^{Meas} - S_i^{Calc}\right]^2}{\sigma}$$

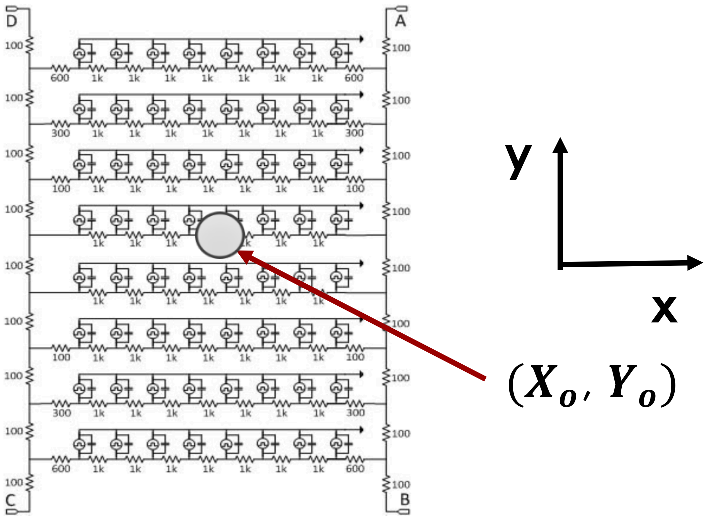
Discretized Positioning Circuit

The readout of an arrays of SiPMs in PET detectors is often performed by connecting them in a matrix of resistors and/or capacitors and measuring the signals at the 4 corners.

This technique, called Discretized Positioning Circuit (DCP), is used to reduce the number of readout channel

DPC uses the charge imbalance between the two opposite sides of a square to determine the hit position.

64 SiPM read out by 4 pads



Charge imbalance in the x, y direction

$$X = X_o + \frac{X_A - X_B}{2} \frac{Q_A + Q_B - Q_C - Q_D}{Q_A + Q_B + Q_C + Q_D}$$

$$Y = Y_o + \frac{Y_A - Y_D}{2} \frac{Q_A + Q_D - Q_B - Q_C}{Q_A + Q_B + Q_C + Q_D}$$

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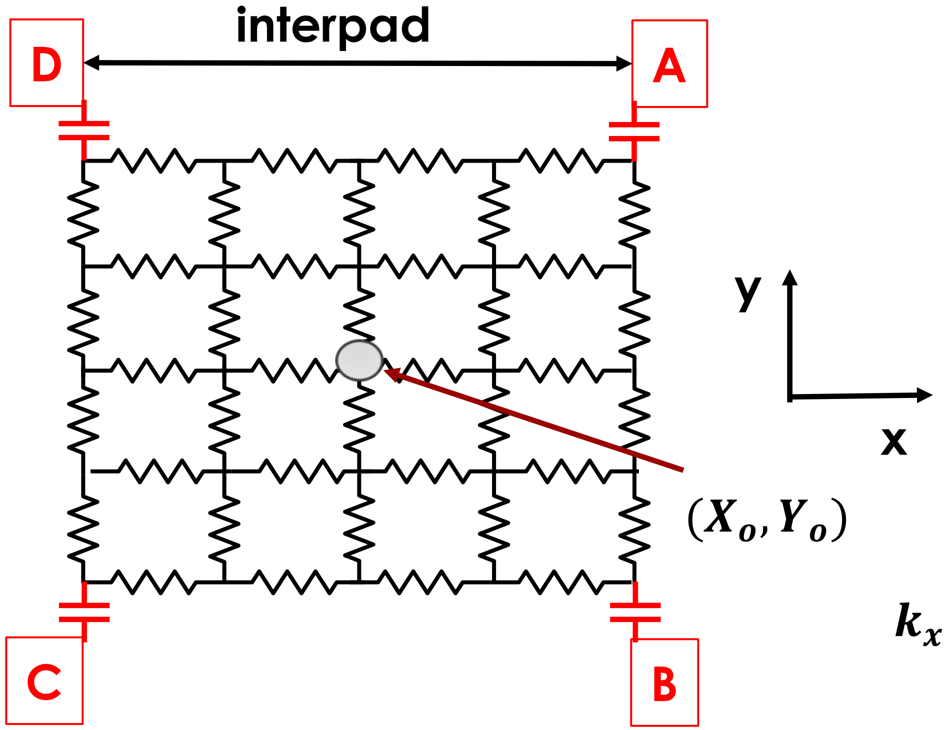
RSD as a Discretized Positioning Circuit



$$X = X_o + k_x \left(\frac{Q_A + Q_B - Q_C - Q_D}{Q_A + Q_B + Q_C + Q_D}\right)$$

$$Y = Y_o + k_y \left(\frac{Q_A + Q_D - Q_B - Q_C}{Q_A + Q_B + Q_C + Q_D}\right)$$

$$k_x = \frac{interpad}{2} * \frac{\alpha_x}{\left(\frac{Q_A + Q_D - Q_B - Q_C}{Q_A + Q_B + Q_C + Q_D}\right)_{x=X_0+\frac{Interpad}{2},y=Y_o}}$$

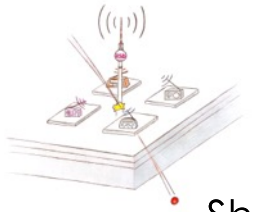
RSD is a hybrid resistors/capacitors DPC circuit

The reconstruction method uses only the signals in the 4 pads to reconstruct the hit position

➔ no need for a analytical sharing law.

➔ $k_{x,y}$ = imbalance parameter along x or y

- Maximum value of the charge imbalance within the pixel
- Needs to be determined experimentally for each geometry

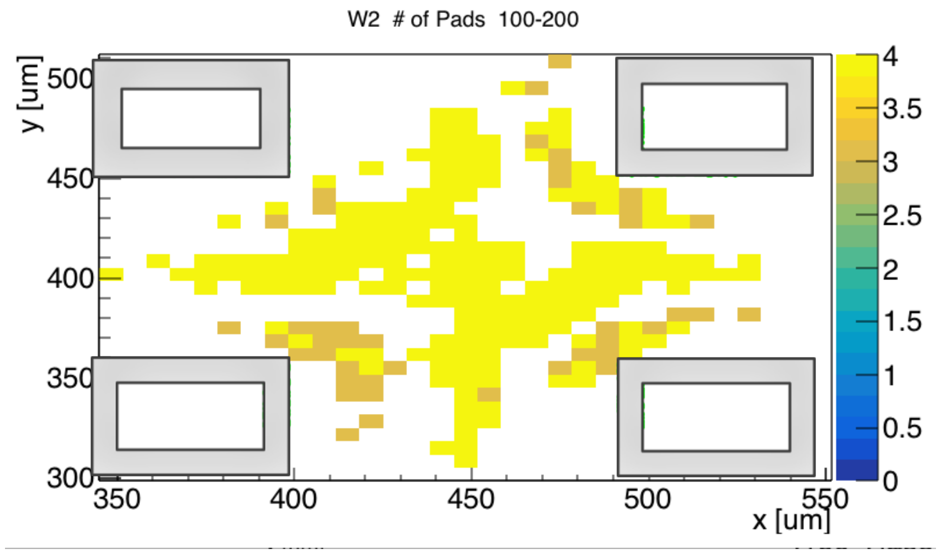


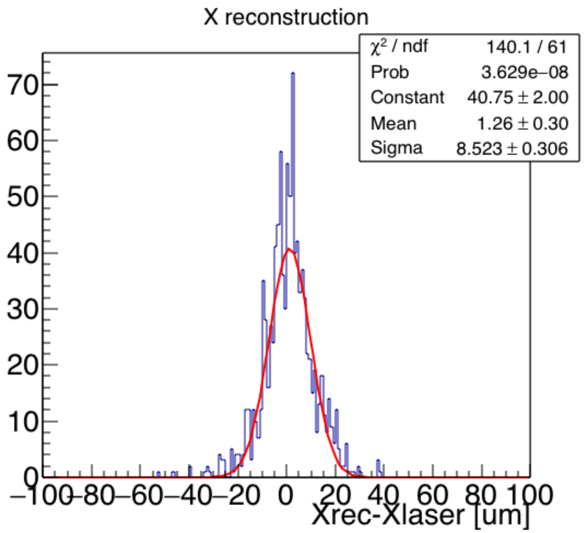
Laser study: position resolution

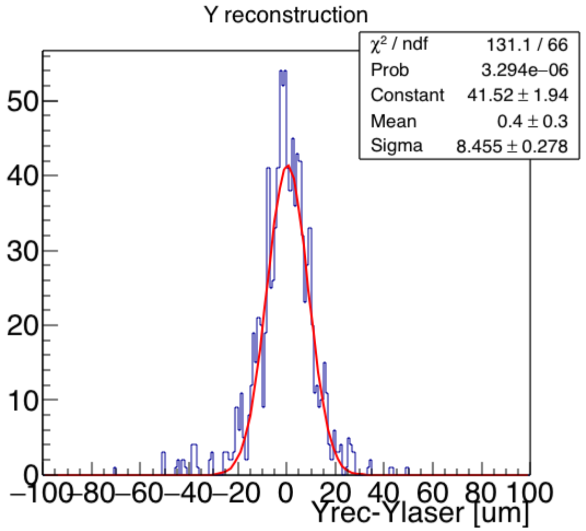
Shooting the laser in many positions, the **spatial precision** can be evaluated. This is done by comparing the position reconstructed using the look-up table to the known laser position.

Geometry: 100 Metal, 200 pitch

Shooting position and# of pads used in the reconstruction







Resolution ~ 8.5 um

Gain ~ 17

Spatial resolution in resistive readout

$$\sigma_x^2 = \sigma_{Jitter}^2 + \sigma_{Sensor}^2 + \sigma_{Reconstruction}^2$$

$$\sigma_{Jitter} = \frac{\sigma_{El\_noise}}{\frac{dV}{dx}}$$

Electronic noise

Assume a geometry with only 2 pads:

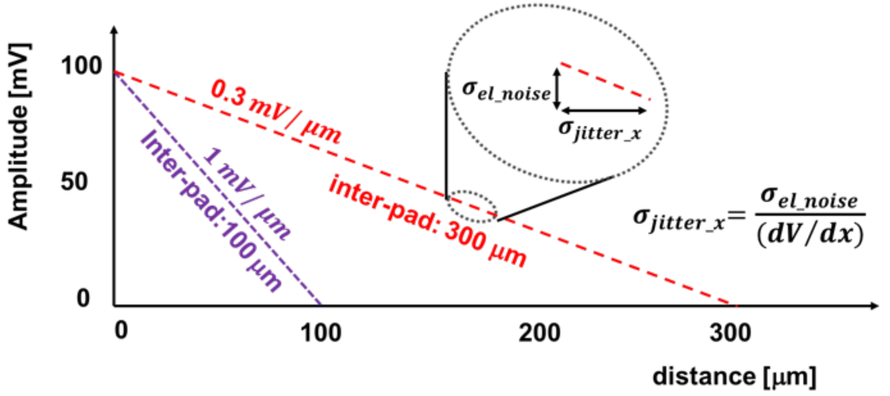
- 100 μm and 300 μm apart
- 100mV signal
- 3 mV electronic noise

100 μm: the signal changes by 1 mV/ μm

➔ σ_{Jitter} **= 3 μm**

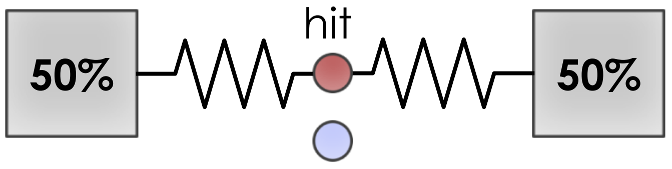
300 μm: the signal changes by 3 mV/ μm

➔ σ_{Jitter} **= 9 μm**

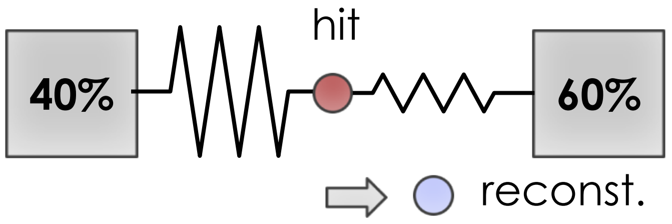


$$\sigma_{Sensor}$$

Sensor non-uniformity



For equal resistivity, 50%-50% sharing indicates the hit is in the middle



If the resistivity is not uniform, the reconstruction shifts the point closer to the smaller resistivity

$$\sigma_{Recontruction}$$

Algorithm

$$S_i(\alpha_i, r_i) = \frac{\frac{\alpha_i}{\ln(r_i)}}{\sum_1^n \frac{\alpha_j}{\ln(r_j)}}$$

If the predicted sharing is incorrect, the reconstructed position is shifted.

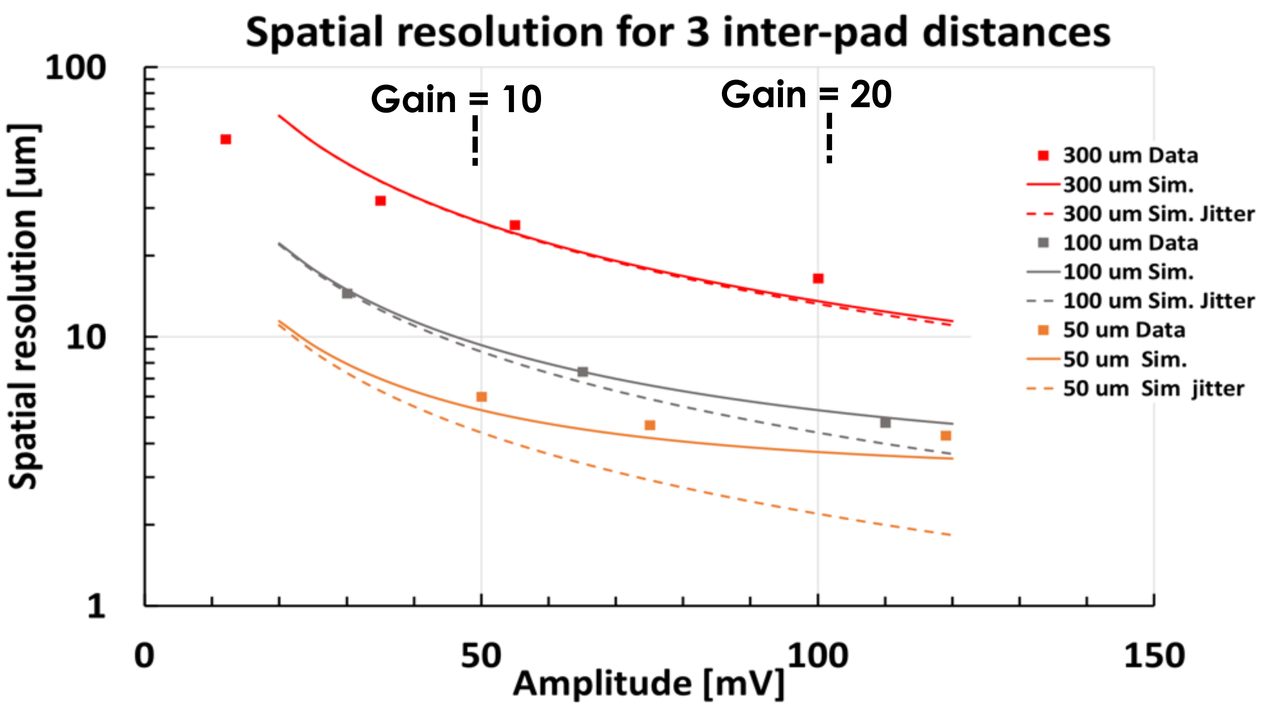
DPC: RSD might not be a perfect DPC, yielding to systematic errors.

Laser study: position resolution as a function of amplitude

The spatial resolution improves with signal amplitude, plateauing at about 5 um

Important points:

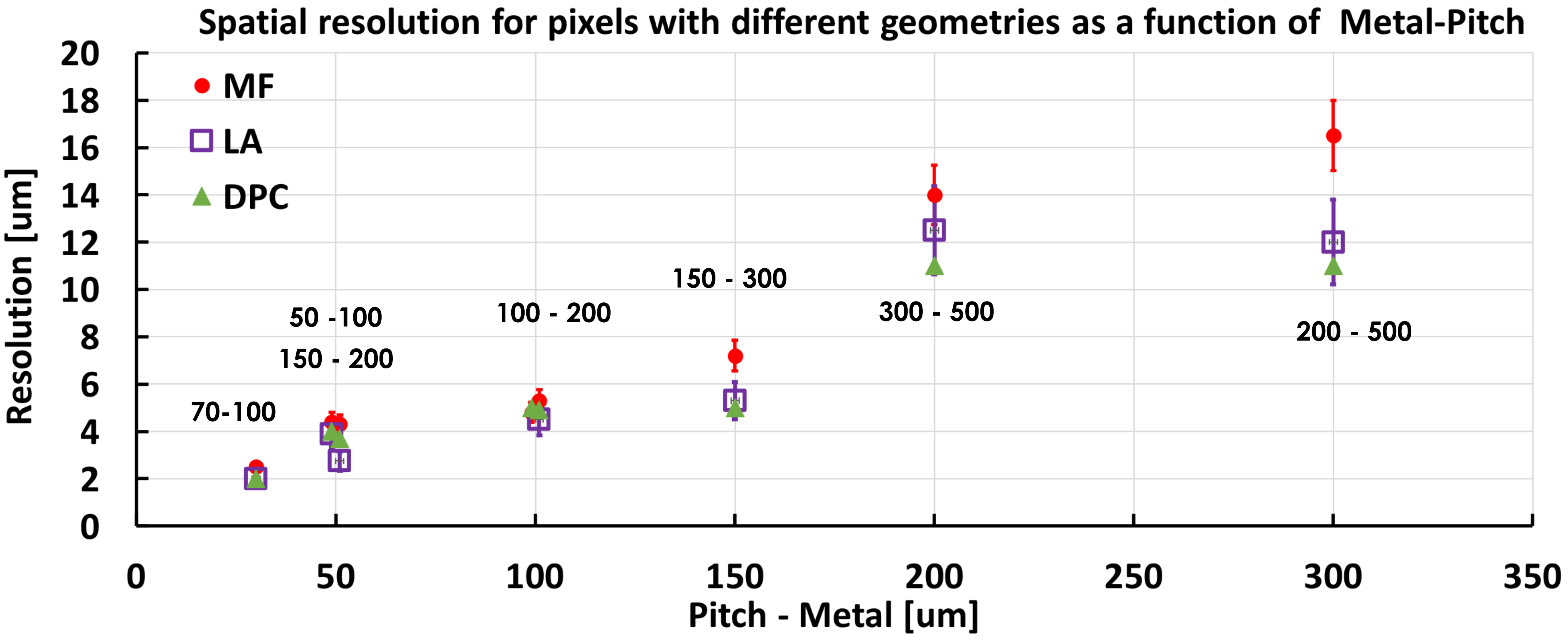
- At low signal amplitude, the resolution is dominated by jitter
  - ➔ Low noise electronics
- Larger geometries have worse position resolution
  - ➔ need high gain
- At high amplitude, the resolution is limited by systematics such as the precision of the amplitude reconstruction and the use of the RSD main formula.



$$\sigma_x^2 = \sigma_{Jitter}^2 + \sigma_{Sensor}^2 + \sigma_{Reconstruction}^2$$

Interpad	Measured Resolution
300 um	17 ± 0.1 (exp.) ± 3.5 (syst.) um
100 um	5.5 ± 0.1 (exp.) ± 3.5 (syst.) um
50 um	4 ± 0.1 (exp.) ± 3.5 (syst.) um

Laser study: position resolution as a function of pixel geometry

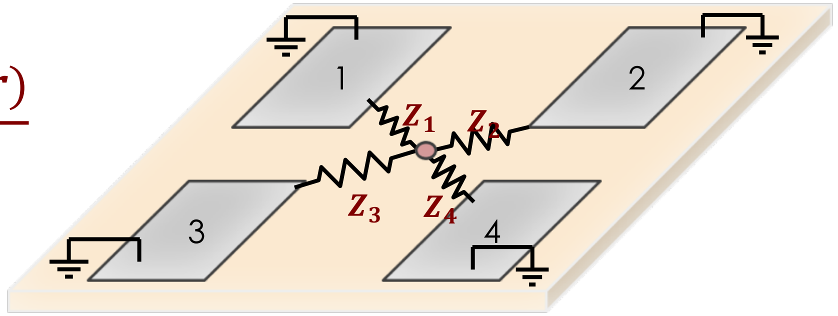


RSDs reach a spatial resolution that is about 5% of the inter-pad distance

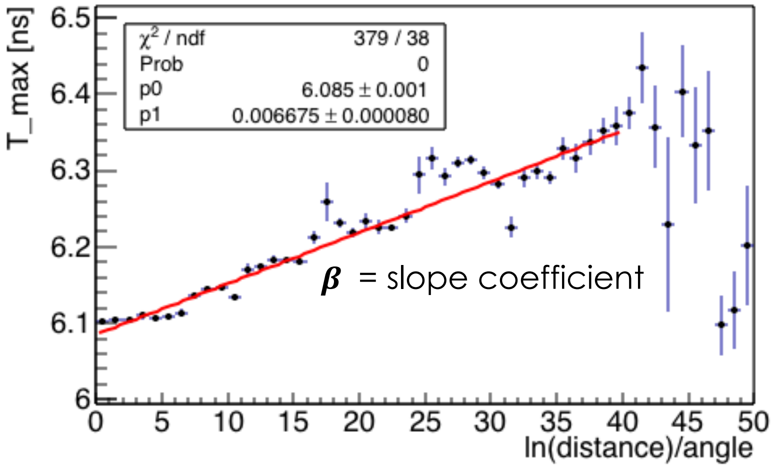
Laser study: signal delay

Each pad sees the signal with a delay proportional to the resistance from the impact point to the pad

$$delay \propto \frac{ln(r)}{\alpha}$$



T_{max} vs $\frac{ln(r)}{\alpha}$ for the geometry 200-500

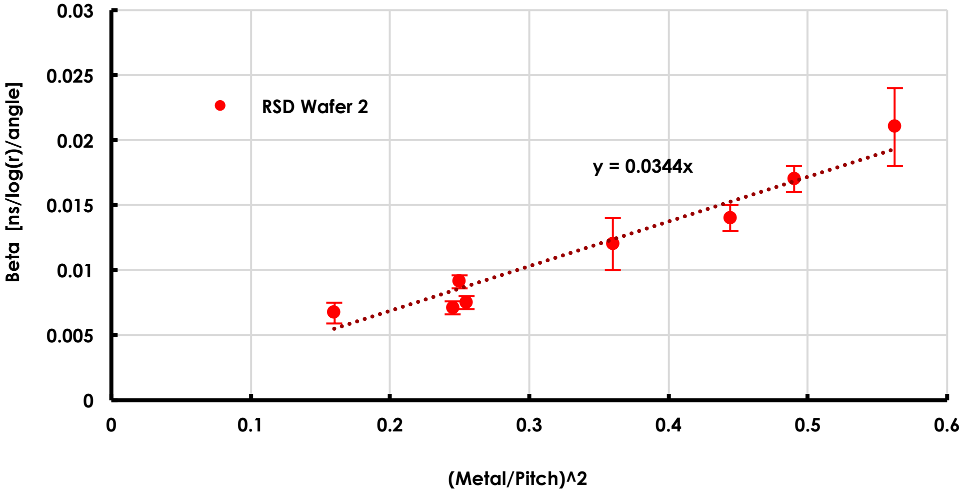


β = slope coefficient

The time of each pad is defined as:

$$t_i^{True} = t_i^{Meas} - \beta \frac{ln(r_i)}{\alpha_i}$$

Coefficient β for different geometries



β depends linearly from (metal/pitch)^2

(related to the detector capacitance)

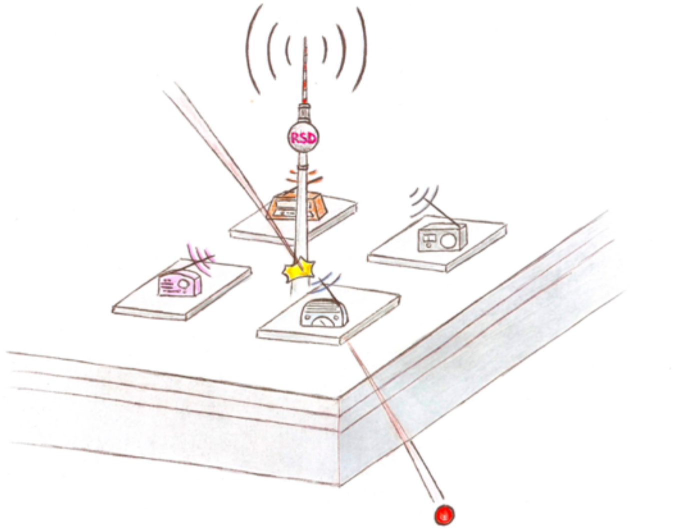
FNAL beam test results

All details in: M. Tornago, 36th RD50 "Latest results on RSD spatial and timing resolution https://indi.to/2cGQy

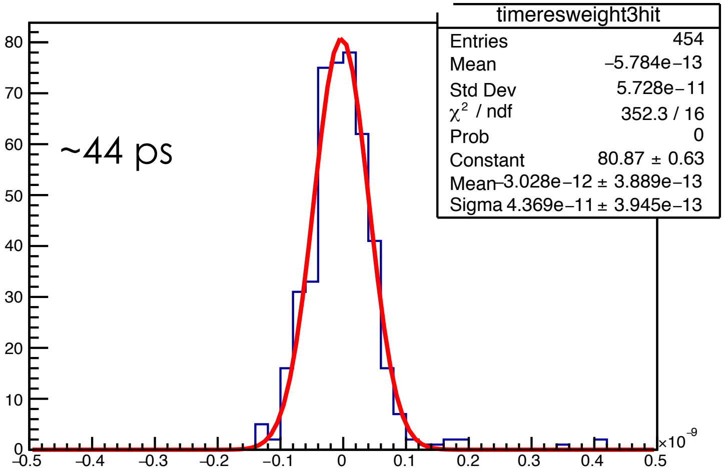
Data taken with RSD 3x3 100-200 and 190-200 geometries

Lesson learnt:

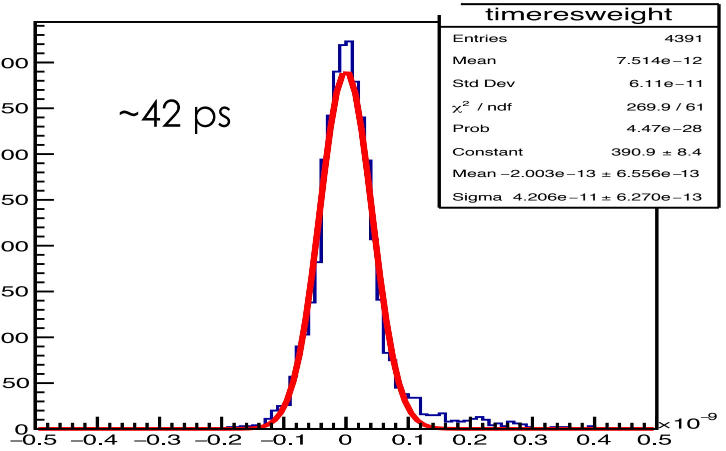
- RSD are ~ 100% efficient
- The RSD x-y hit reconstruction worked very well
- The time resolution is $\boldsymbol{\sigma_{t\ 100-200} = 44\ ps, \sigma_{t\ 190-200} = 42\ ps}$
- The metal size (100 vs 190 um) does not influence the time resolution



100 - 200



190 - 200



Interesting fact: the combination of n pads does not lead to a $1/\sqrt{n}$ improvement since the effects of non-uniform ionization are fully correlated

➔ pads see a copy of the same signal

RSD main formulas

RSD signals are therefore controlled by two equations:

1. the signal sharing among pads

$$S_i(\alpha_i, r_i) = \frac{\frac{\alpha_i}{ln(r_i)}}{\sum_1^n \frac{\alpha_i}{ln(r_i)}}$$

2. the signal delay

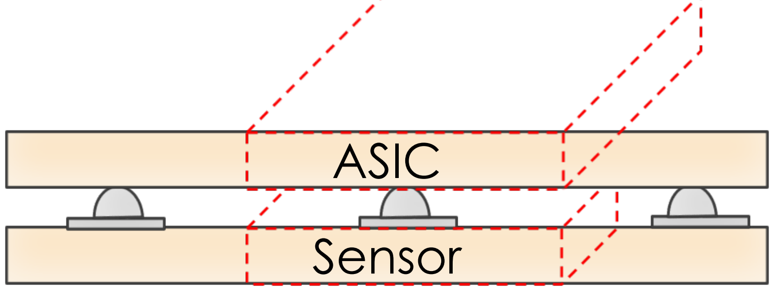
$$t_i^{True} = t_i^{Meas} - \gamma \left(\frac{Metal}{pitch}\right)^2 \frac{ln(r_i)}{\alpha_i}$$

where γ is wafer-specific (n+ resistivity, dielectric thickness)

ASIC for RSD

Very important point: in hybrid technology (sensor bump-bonded to the ASIC),

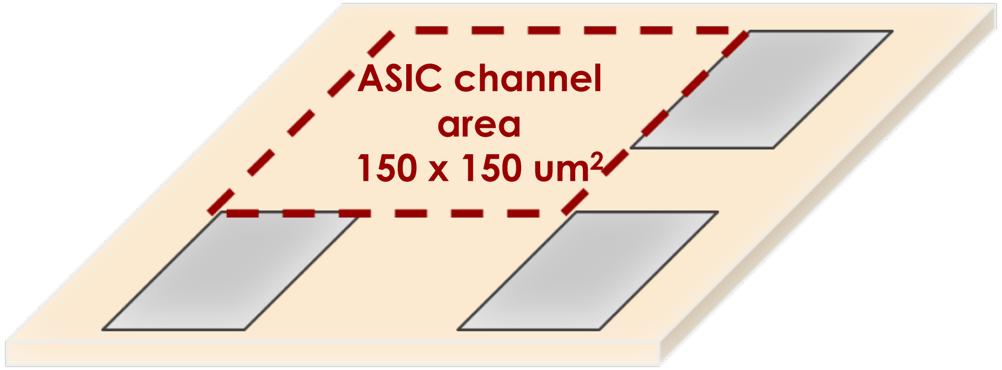
the area available for each read-out channel is identical to the pixel area



Assuming a goal of ~ 5 mm spatial resolution,

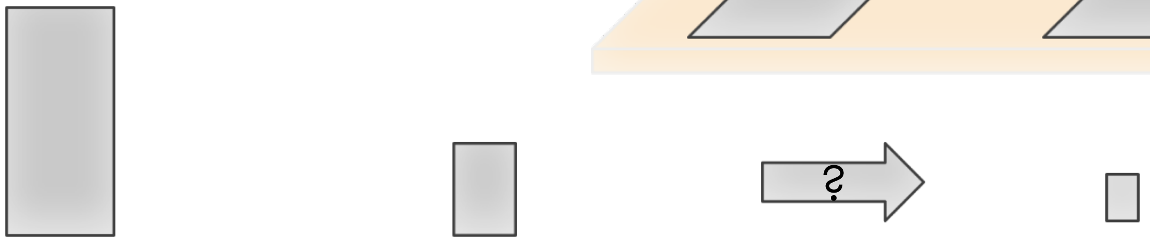
the RSD pitch can be 150-200 μm

- ➔ At least a factor of 10-20 more space than using binary readout
- ➔ Can concentrate the power available for that area into a single channel
- ➔ The needed circuits for timing might actually fit



Example:

TDC evolution



130 nm:
70 x 150 micron

65 nm:
40 x 60 micron

28 nm:
~20 x 30 micron

RSD Read-out scheme - II

Signal characteristics:

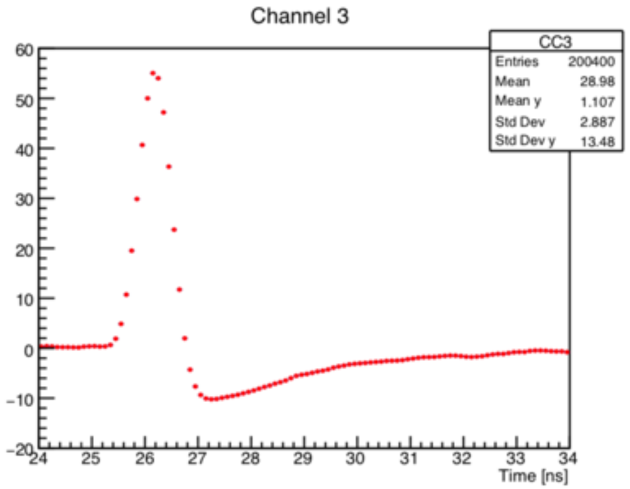
- Short and fast, very similar to standard UFSD
- Bipolar (do not integrate)

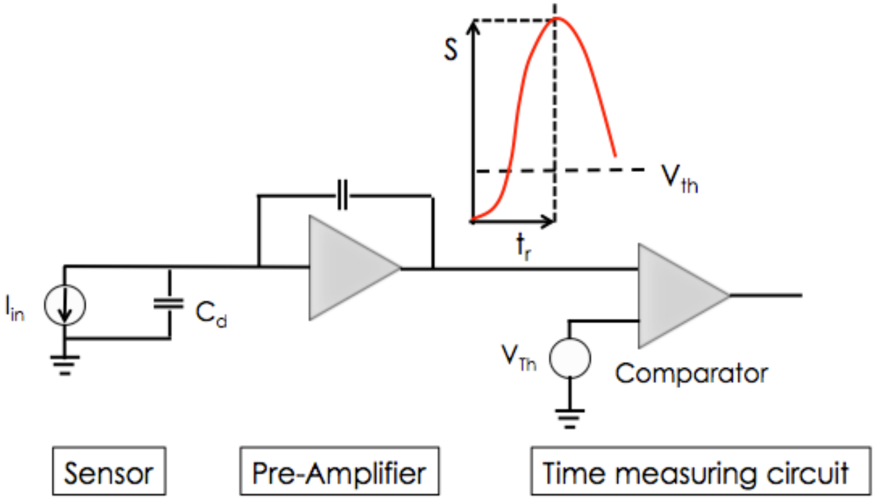
Read-out characteristics:

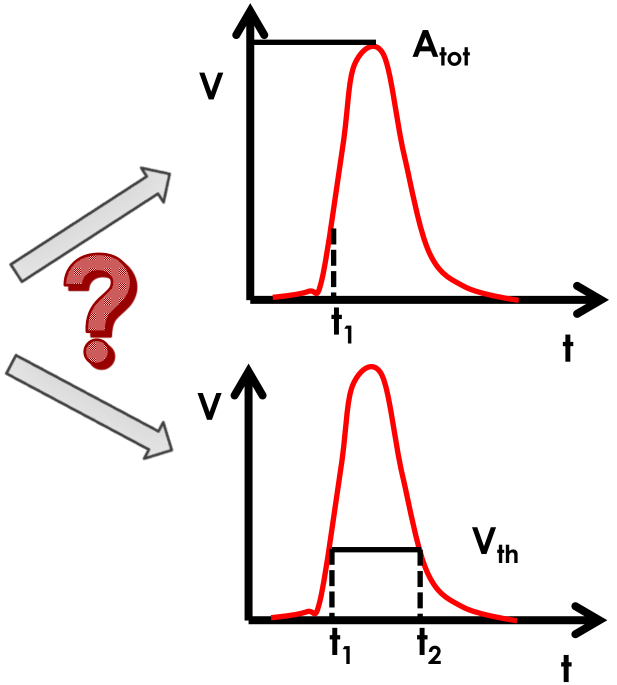
- Record signal amplitude with good precision
- Timing capabilities: keep the jitter below the Landau floor

BW ~ 500 MHz, $Q_{in} \sim 5\ - 10\ fC$

➔ A Leading edge discriminator with linear Time-over-Threshold information or/and a DAC for amplitude measurement







Time of Arrival and Amplitude:

$t_{1,} A_{tot}$

TDC for $t_{1,}$

ADC for A_{tot}

Time over Threshold:

$ToT = t_2 - t_1$

Need TDC for $t_{1,} t_2$

RSD intrinsic time resolution

The AC readout scheme does not change the basic timing properties of UFSD:

$$\sigma_t^2 = \left(\frac{Noise}{dV/dt}\right)^2 + (\Delta ionization)^2$$

“Jitter” term

Here enters everything that is “Noise” and the steepness of the signal

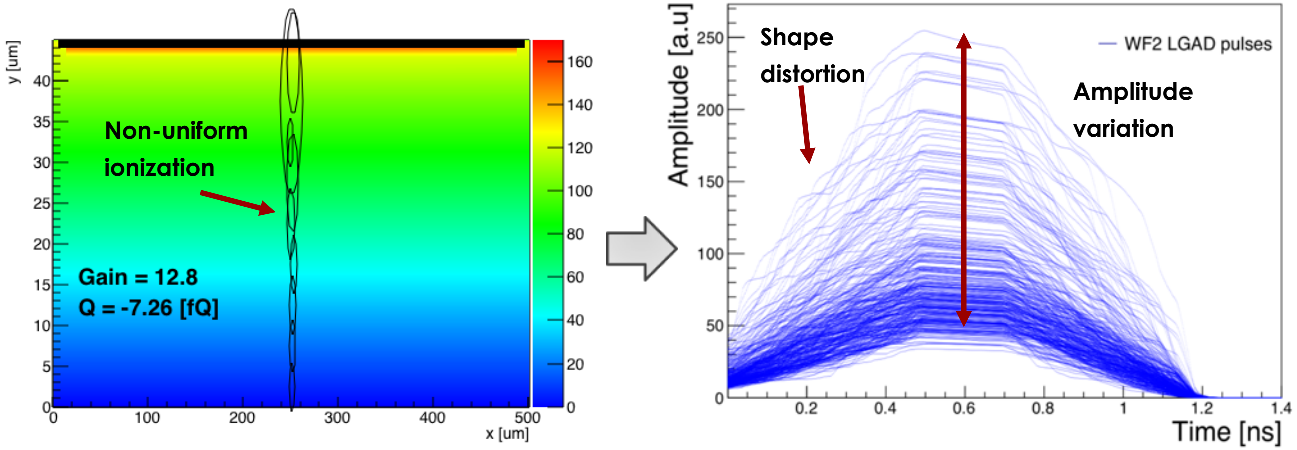
Non uniform ionization:

1) Amplitude variation:

variation in the total charge

2) Shape distortion:

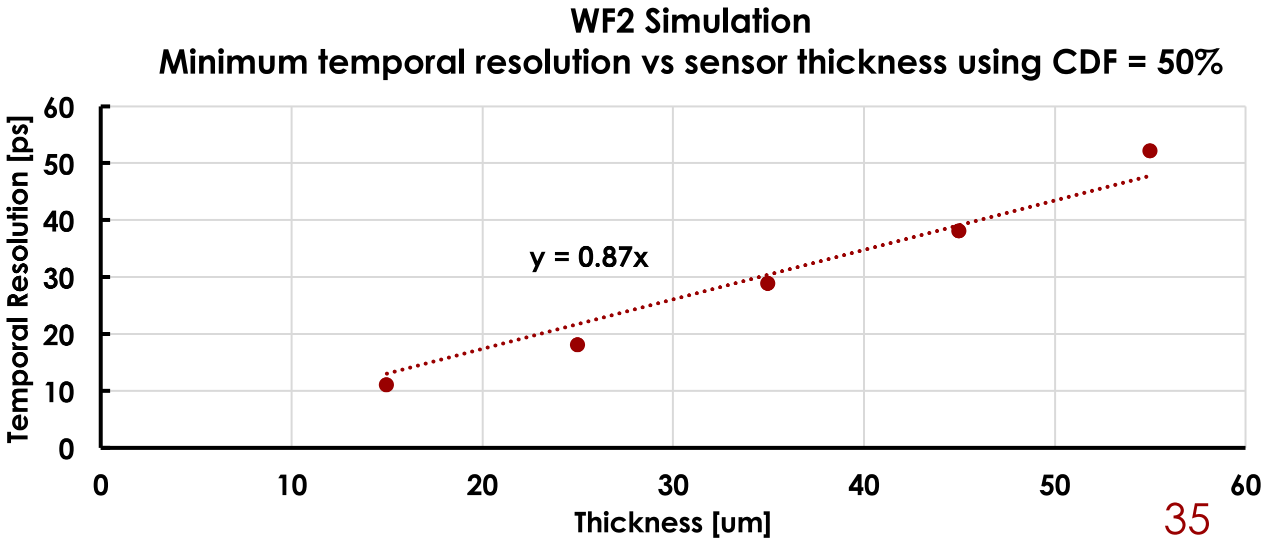
Signal Shape distortion ➔Minimum time resolution



RSD minimum temporal resolution improves for thinner sensors:

40 ps @ 45 um ➔ 20 ps @ 25 um

However, the total charge is less (10fC➔5 fC) and the electronics might not be able to exploit this improvement

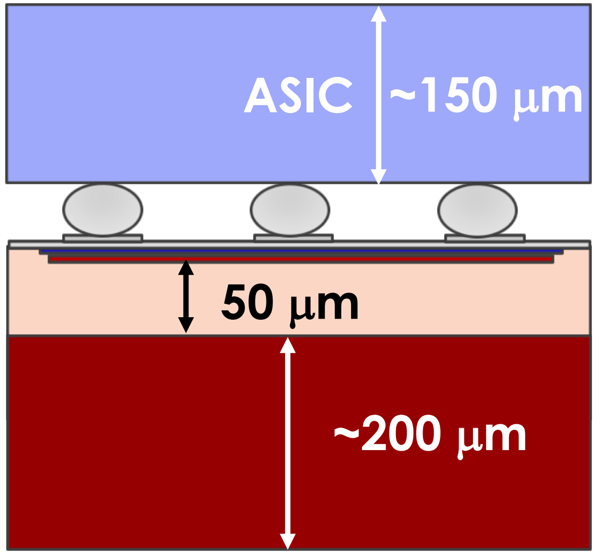


RSD material budget and time resolution

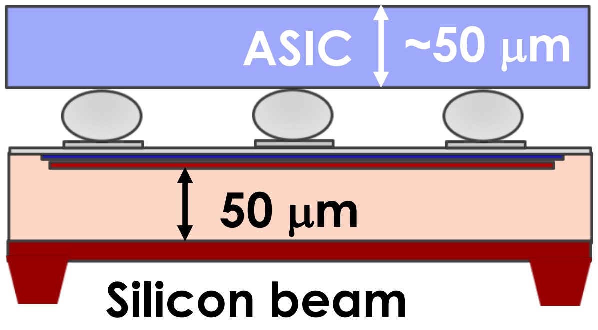
The active thickness of RSD sensor is rather small ~ 50 um.

In the present prototypes, the active part is attached to a thick "handle wafer"

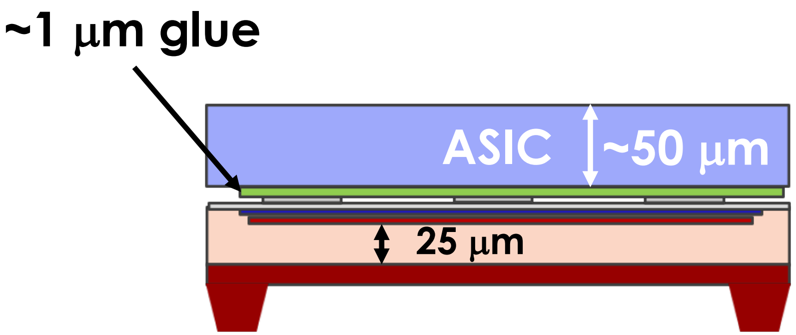
There is a clear path leading to < 100 μm material:



Present design: no material budget optimization



- Thinned handle wafer:
  500 um ➔ 10-20 um



- Thinned handle wafer:
  500 um ➔ 10-20 um
- Thinned active area:
  50 um ➔ 25 um
  50 ps ➔ 25 ps

Summary of RSD characteristics

In AC-LGAD/RSD signal sharing happens on the surface, in the n+ layer, and not during the e/h drift, opening the possibility of having very small σ_{MS} and σ_x

1. The AC-LGAD/RSD design combines internal signal sharing with internal gain
2. RSDs have:
    - Very good position resolution due to internal sharing (< 5 μm)
    - Very good temporal resolution due to internal gain (~20-30 ps)
    - 100% fill factor due to the continuous n+ implant
3. RSDs can be made very thin (~ 30 μm)
4. The pixel size can be kept large: 200x200 μm^2 achieves 5 μm position resolution

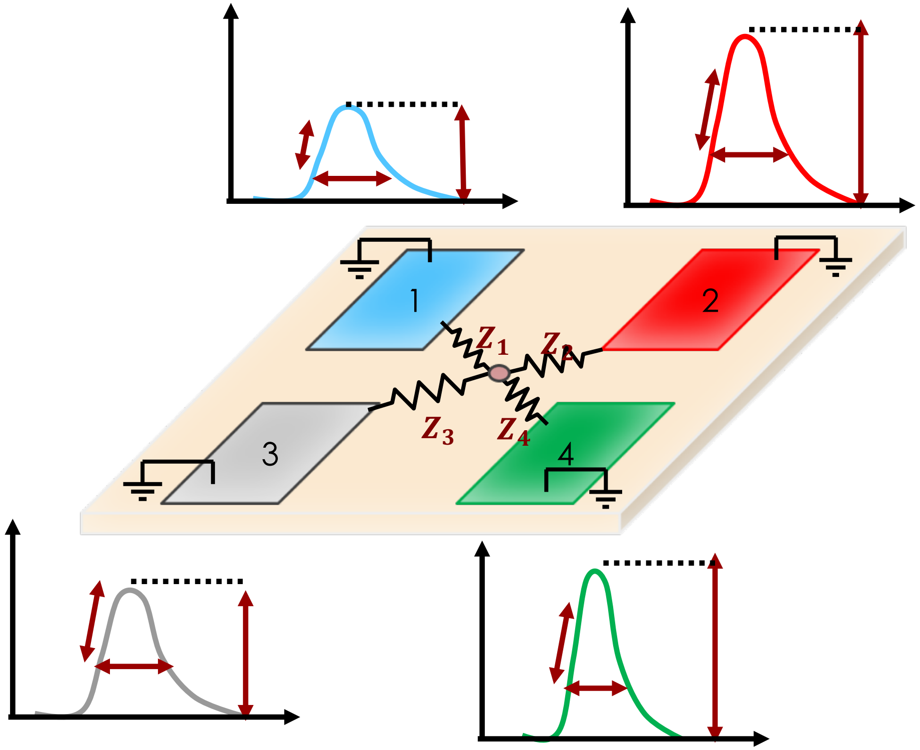
Future directions

- **Reconstruction algorithm:** use of machine learning
- **Position resolution**: design optimization
- **RSD strip detector**: design optimization
- **Far out designs**: where the wild things are
- **RSD field of applications**

Machine Learning applied to RSD

All details in: F. Siviero, 36th RD50 "Position reconstruction using machine learning algorithms applied to Resistive Silicon Detectors (RSD)"

Each of the signals in an RSD event carries a lot of information (**amplitude, derivative, width**) that can be exploited to perform very accurate x-y-t reconstruction.

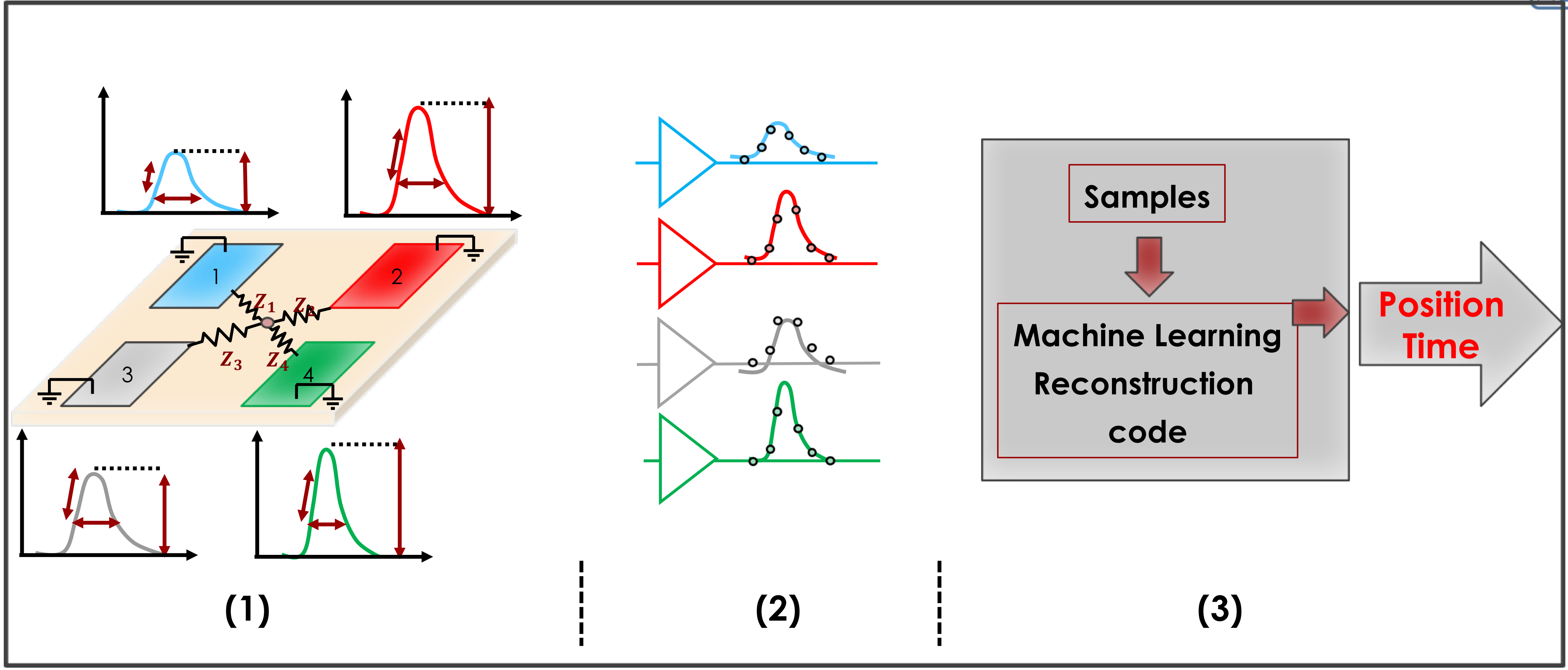


Analytic sharing laws are not able to capture all this information

Need to use

- **➔ Multiple sampling front-end**
- **➔ Machine learning algorithm trained with real data, no need to have a "sharing law"**

The “1 µm” project



Samples

Machine Learning Reconstruction code

Position
Time

(1) **(2)** **(3)**

RSD sensor

Multiple sampling frontend

Simplest design:

Time-over-threshold

Multi-inputs regression task

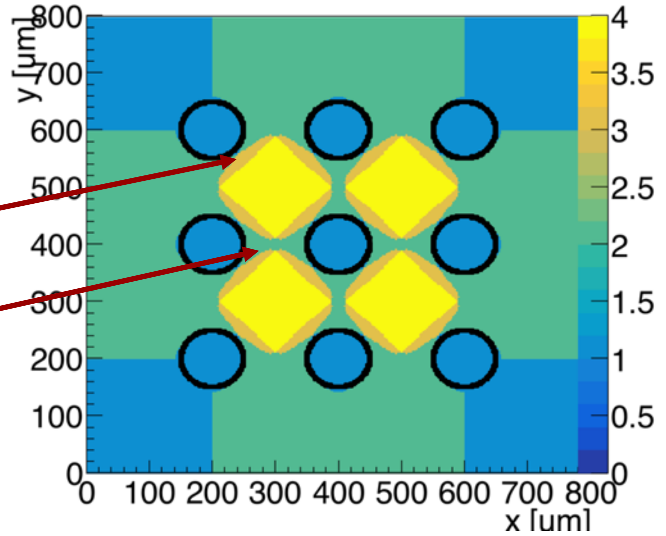
Trained using laser and beam test data

Position resolution: the geometry problem

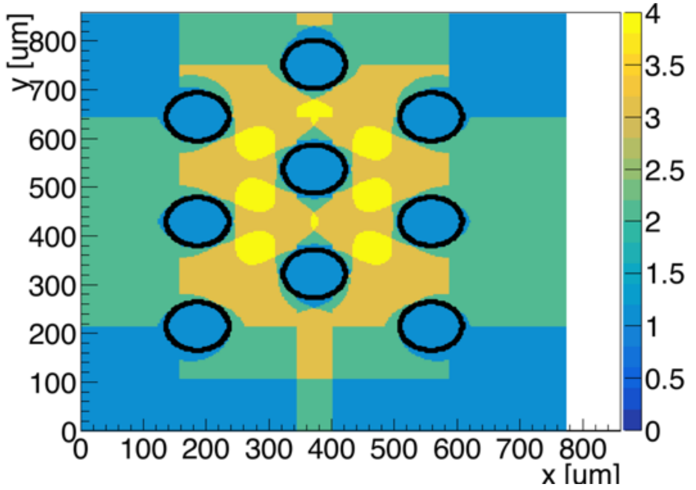
In a squared pixel geometry, **4 pads are necessary to obtain optimal resolution**

- **When only 3 pads are used**, the reconstructed position is “pulled away” from the missing pad
- **When 2 pads are used**, the hit position cannot be determined

100 – 200 Number of pads used in reconstruction
Amplitude = 120 mV, min amplitude = 15 mV



100 – 200 Number of pads used in reconstruction
Amplitude = 120 mV, min amplitude = 15 mV



Solution:

➔ Use triangular geometry, with equidistant pads

➔ In triangular geometry, **3 pads are necessary to obtain optimal resolution**

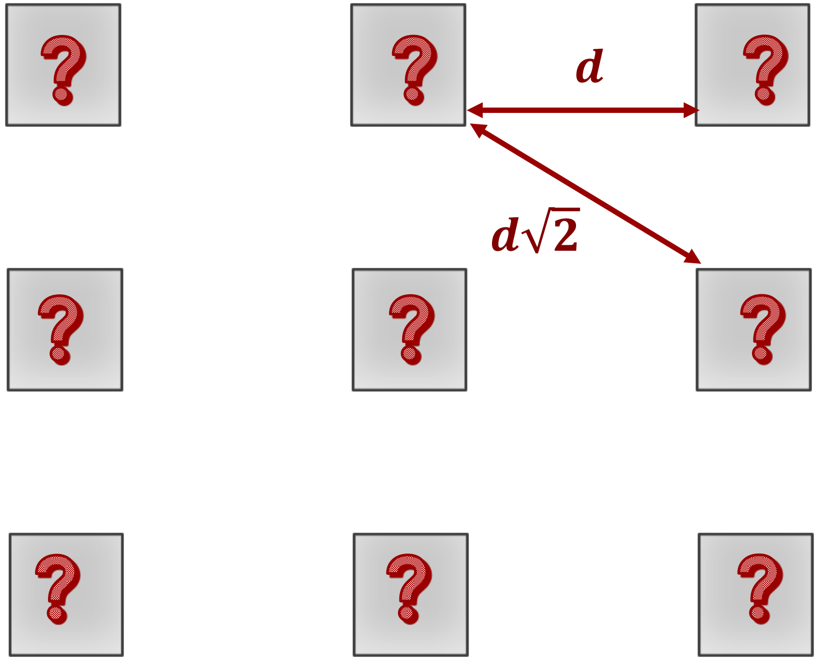
➔ **No region with 2 pads**

Position resolution: the metal problem

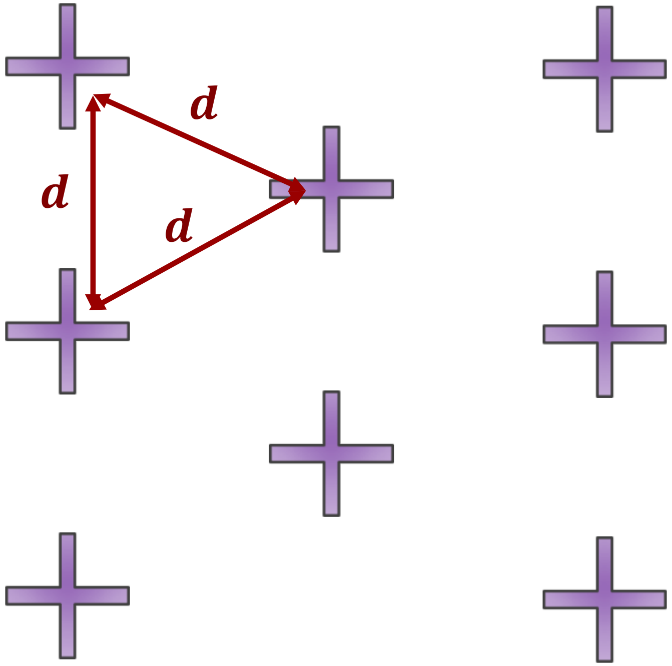
Lessons learnt:

- Very good position resolution (~ 3-5 um) even with large pixels (~100 – 200 um) can be achieved exploiting charge sharing
- The traditional "squared geometry" leads to a position-dependent space resolution
- Large metal pads prevent good hit localization
- **Uniform read-out is obtained when the distance between neighboring pad is the same**
- **The metal pads should be redesigned, using less metal**

Present design



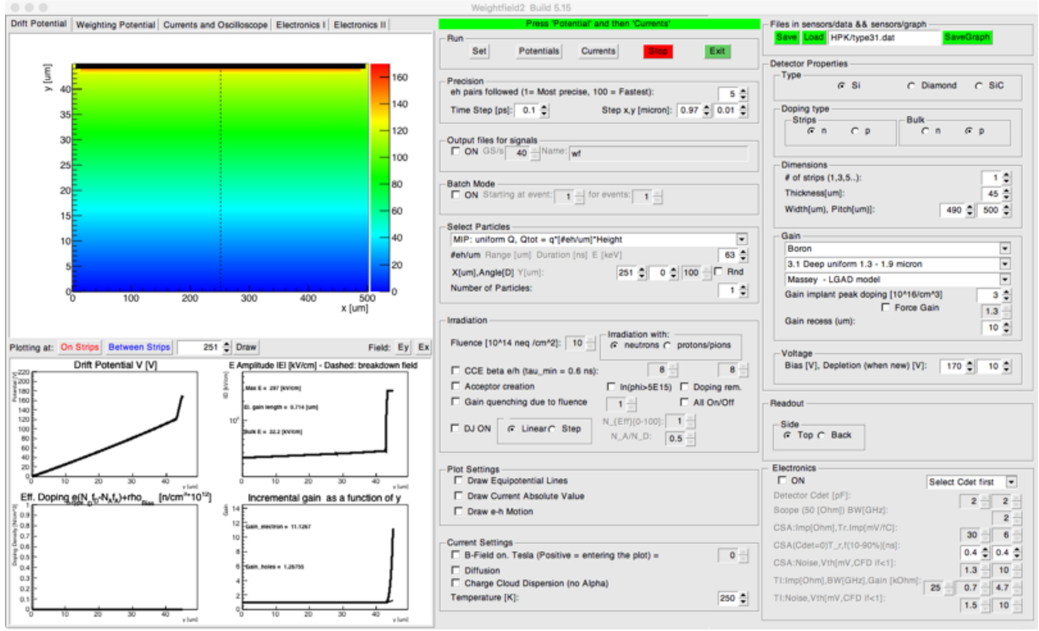
Better design



RSD Simulator: WF2$_{RSD}$

In the development of Ultra Fast Silicon Detectors we have written and extensively used a simulator, Weightfield2.

- http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html
- WF2 emulates the current signals produced in a UFSD.
- It includes non-uniform ionization, radiation damage, B field, temperature
- It requires Root build from source, it is for Linux and Mac.
- It will not replace TCAD, but it helps in understanding the sensors response


Weightfield2 Build 5.15

Press 'Potential' and then 'Currents'

Plotting at: On Strips Between Strips 251 Draw

Precision: eh pairs followed (1= Most precise, 100 = Fastest): 5; Time Step [ps]: 0.1; Step x,y [micron]: 0.97 0.01

Output files for signals: ☐ ON GS/s 40 Name: wf

Batch Mode: ☐ ON Starting at event: 1 for events: 1

Select Particles: MIP: uniform Q, Qtot = q*[#eh/um]*Height; #eh/um 63; X[um],Angle[D] Y[um]: 251 0 100 ☐ Rnd; Number of Particles: 1

Irradiation: Fluence [10^14 neq /cm^2]: 10; Irradiation with: ● neutrons ○ protons/pions; ☐ CCE beta e/h (tau_min = 0.6 ns): 8 8; ☐ Acceptor creation ☐ ln(phi>5E15) ☐ Doping rem.; ☐ Gain quenching due to fluence 1 ☐ All On/Off; ☐ DJ ON ● Linear ○ Step N_{Eff}[0-100]: 1 N_A/N_D: 0.5

Plot Settings: ☐ Draw Equipotential Lines; ☐ Draw Current Absolute Value; ☐ Draw e-h Motion

Current Settings: ☐ B-Field on. Tesla (Positive = entering the plot) = 0; ☐ Diffusion; ☐ Charge Cloud Dispersion (no Alpha); Temperature [K]: 250

Files in sensors/data && sensors/graph: HPK/type31.dat

Detector Properties: Type ● Si ○ Diamond ○ SiC; Doping type: Strips ● n ○ p, Bulk ○ n ● p

Dimensions: # of strips (1,3,5..): 1; Thickness[um]: 45; Width[um], Pitch[um]]: 490 500

Gain: Boron; 3.1 Deep uniform 1.3 - 1.9 micron; Massey - LGAD model; Gain implant peak doping [10^16/cm^3] 3; ☐ Force Gain 1.3; Gain recess (um): 10

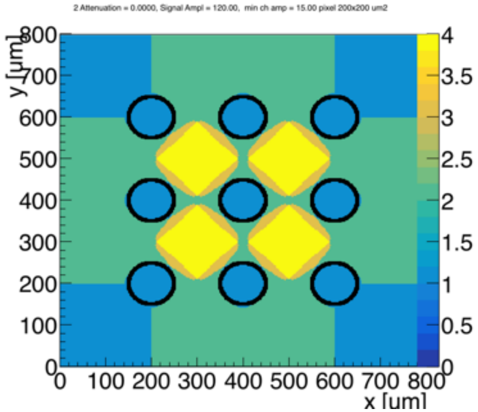
Voltage: Bias [V], Depletion (when new) [V]: 170 10

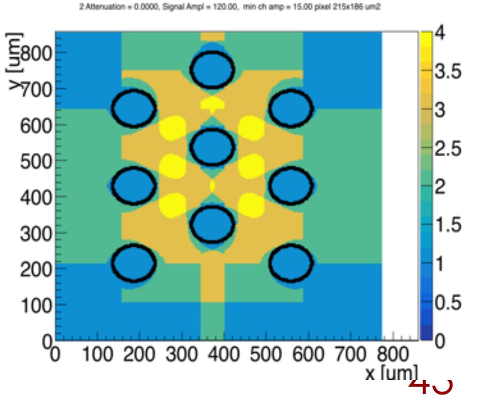
Readout: Side ● Top ○ Back

Electronics: ☐ ON Select Cdet first; Detector Cdet [pF]: 2 2; Scope (50 [Ohm]) BW[GHz]: 2; CSA:Imp[Ohm],Tr.Imp[mV/fC]: 30 6; CSA(Cdet=0)T_r,f(10-90%)[ns]: 0.4 0.4; CSA:Noise,Vth[mV,CFD if<1]: 1.3 10; TI:Imp[Ohm],BW[GHz],Gain [kOhm]: 25 0.7 4.7; TI:Noise,Vth[mV,CFD if<1]: 1.5 10

We has expanded WF2 to include RSD, incorporating the RSD main formula and the signal sharing among pads placed with any array geometry.

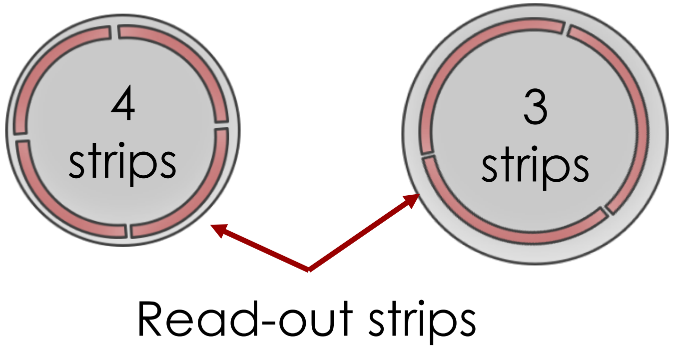
WF2$_{RSD}$ emulates the charge sharing among pads and provide the current signals from each pad.



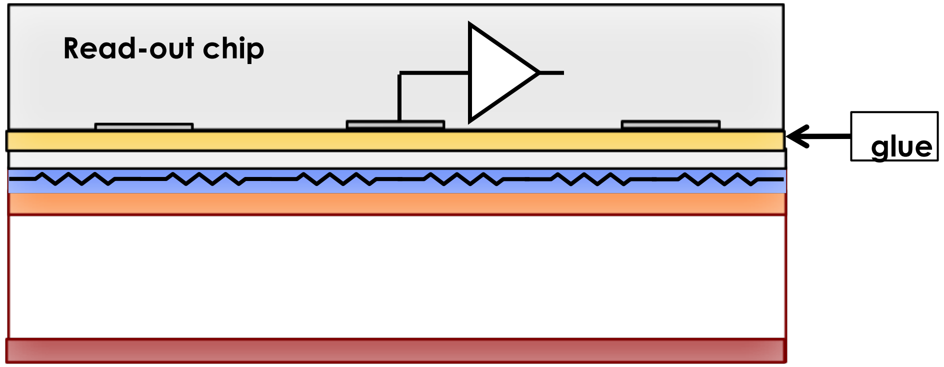


Where the wild things are

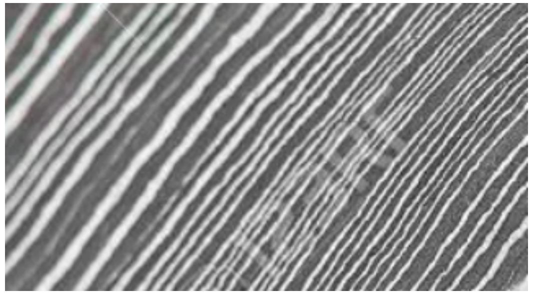
A circular RSD with 3 or 4 electrodes should be very accurate providing with a few channels excellent position (~ 5 um) and time (~ 35 ps) resolution. Looks promising for beam test apparatuses



Universal RSD: no metal pad, glued to the ASIC.
In RSD the signal is large, 5-10 fC, so it can be seen across a thin layer of glue.
The metal pads are provided by the read-out chip, no need to deposit metal pad on the RSD side.



Any metal pattern: as there is no implant underneath, the AC metal can be shaped into any pattern



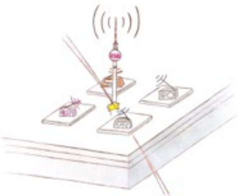
It takes a village

Very special thanks to the UFSD group, for enduring endless weeks of measurements in the lab and many many meetings

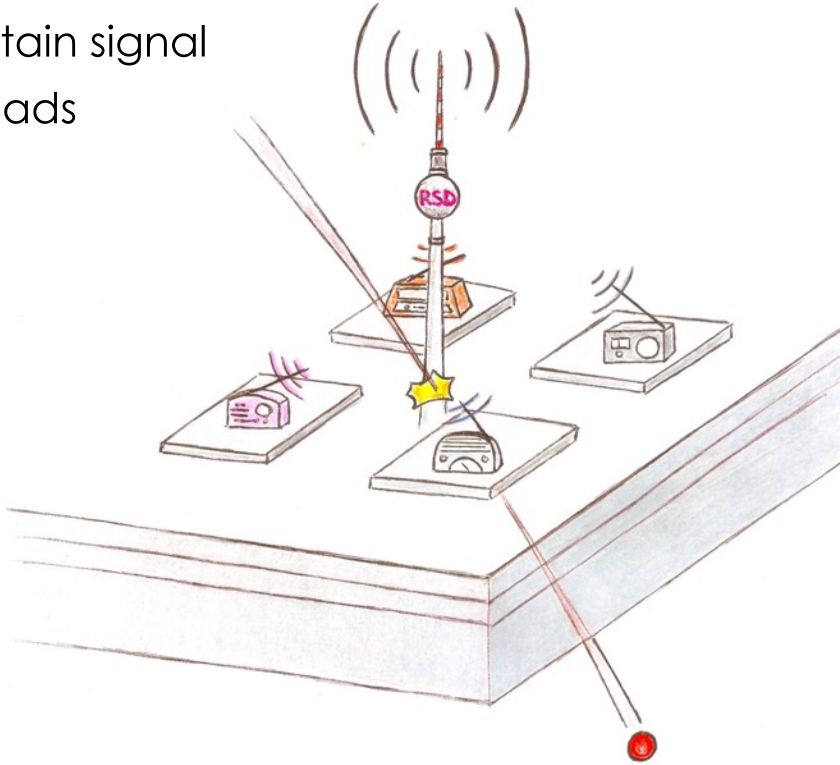
R. Arcidiacono[ab] , G-F Dalla Betta[ae], G. Borghi[fa], M. Boscardin[fa], M. Costa[ac], F. Fausti[ac], F. Ficorella[fa], M. Ferrero[ab], M. Mandurrino[a], J. Olave[a], L. Pancheri[ae], F. Siviero[a], V. Sola[a], M. Tornago[ac,] ,G. Paternoster[f], H. Sadrozinski[d], A. Seiden[d,] M. Centis Vignali[fa]

[a] INFN, [b] Università del Piemonte Orientale, [c] Università di Torino,
[d] University of California, Santa Cruz , [e] Università di Trento, [f] FBK

Fermilab beam test team: A. Apreysan, R. Heller, K. Di Petrillo, S. Los.



Thank you for your attention



RSD are a novel n-in-p silicon device that evolves the LGAD design to obtain signal amplification with 100% fill factor and very strong signal sharing among pads

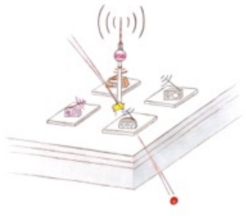
The RSD design maintains the excellent temporal resolution of UFSD sensors,: **$\sigma_t \sim 40\ ps$ for $50\ \mu m$ thick sensors at gain ~ 15.**

RSD exploits the resistive n+ layer to achieve charge sharing among pads. The spatial resolution is about 5% of the inter-pad distance:

Geometry	50 -100	100-200	150 - 300	200-500
σ_x [um]	4	5.5	5.9	15

The multiple signals germane to RSD are well suited for reconstruction algorithms based on machine learning. We expect that this technique will provide the ultimate spatial and temporal resolution

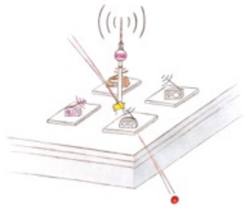
The extended signal sharing in RSD is a drawback in environment with high density of tracks and high irradiation. Most likely RSD and FCC-hh don't go together



Acknowledgement

We kindly acknowledge the following funding agencies, collaborations:

- ➢ INFN - Gruppo V, UFSD and RSD projects
- ➢ INFN – FBK agreement on sensor production (convenzione INFN-FBK)
- ➢ Horizon 2020, grant UFSD669529
- ➢ U.S. Department of Energy grant number DE-SC0010107
- ➢ 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



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[1] N. Cartiglia, Tredi 2015,"Topics in LGAD Design" https://indico.cern.ch/event/351695/contributions/828366/attachments/695875/955507/TREDI_Cartiglia.pdf, N. Cartiglia, A. Seiden, H. Sadrozinski, *US Patent 9613993*

[2] M. Mandurrino *et al*., "Demonstration of 200-, 100-, and 50- micron Pitch Resistive AC-Coupled Silicon Detectors (RSD) With 100% Fill-Factor for 4D Particle Tracking," in *IEEE Electron Device Letters*, vol. 40, no. 11, pp. 1780-1783, Nov. 2019.

[3] M. Mandurrino et al. "Analysis and numerical design of Resistive AC-Coupled Silicon Detectors (RSD) for 4D particle tracking" https://doi.org/10.1016/j.nima.2020.163479

[4] H. Sadrozinski, HSTD11, "Time resolution of Ultra-Fast Silicon Detectors", https://indico.cern.ch/event/577879/contributions/2740418/attachments/1575077/2487327/HSTD1--HFWS1.pdf

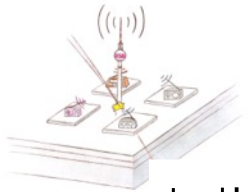
[5] G. Giacomini, W. Chen, G. D'Amen, A. Tricoli, Fabrication and performance of AC-coupled LGADs, JINST 14 (09) (2019)

[6] M. Tornago et al, "*Resistive AC-Coupled Silicon Detectors principles of operation and first results from a combined laser - beam test analysis*", https://arxiv.org/abs/2007.09528

[7] F. Siviero et al, "Application of machine learning algorithms to the position reconstruction of Resistive Silicon Detectors", paper in preparation

[8] A. Apresyan, "Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam", https://arxiv.org/abs/2006.01999

Extra topics



Calculation of signal sharing

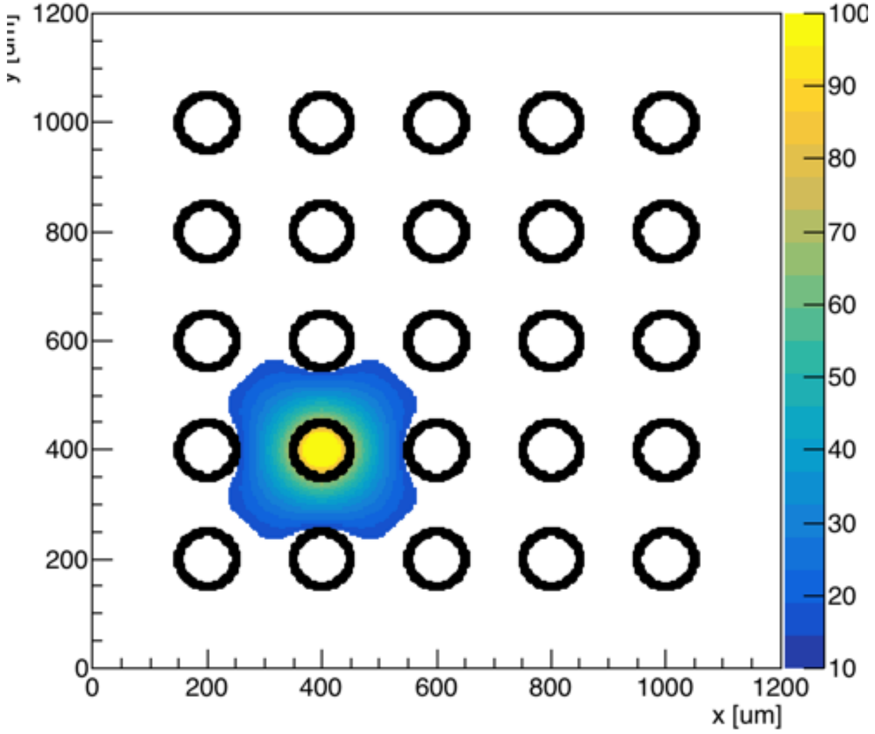
Let’s use the RSD main formula to explore the following geometry (analytic calculation):

- Pixel matrix (round metal for simplicity) with metal – pitch = 100 – 200 micron
- Signal amplitude = 100 mV
- Min amplitude = 15 mV

Blue = 1 active pad: when the hit is on the pad, the signal does not spread much

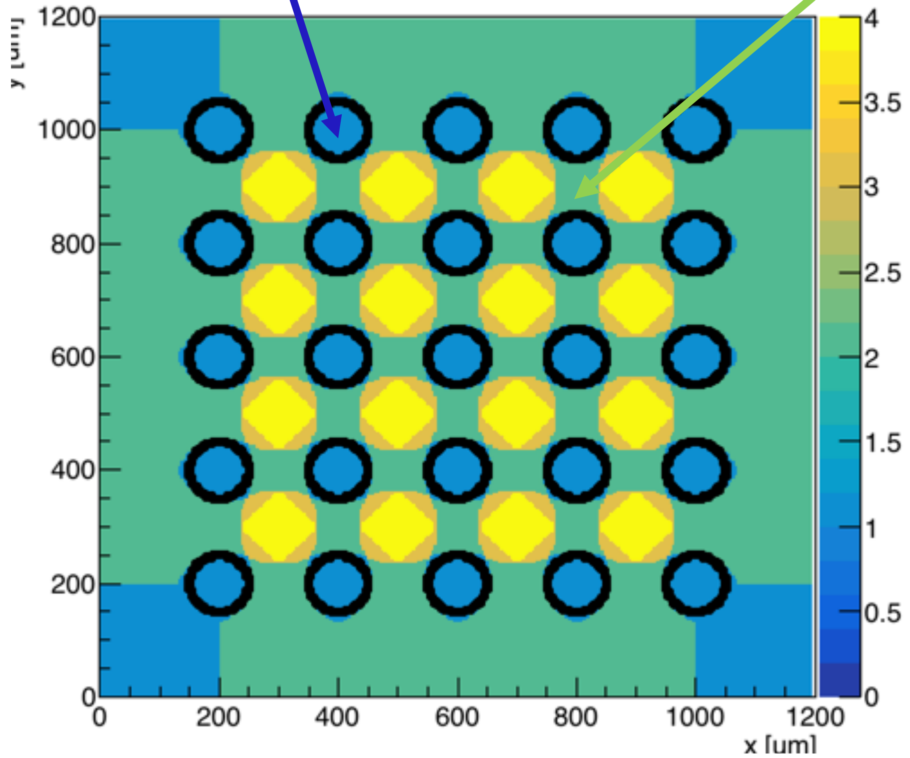
Green = 2 active pads: in between 2 pads

Signal seen by a pad as a function of distance



Good localized signal

Number of pads (1,2,3, or 4) with signal > 15 mV

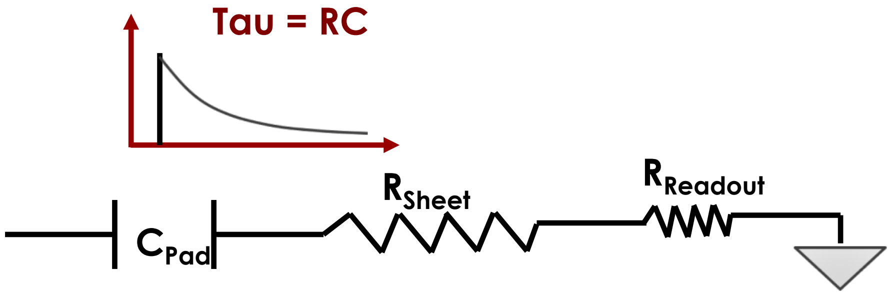


Not very uniform readout pattern

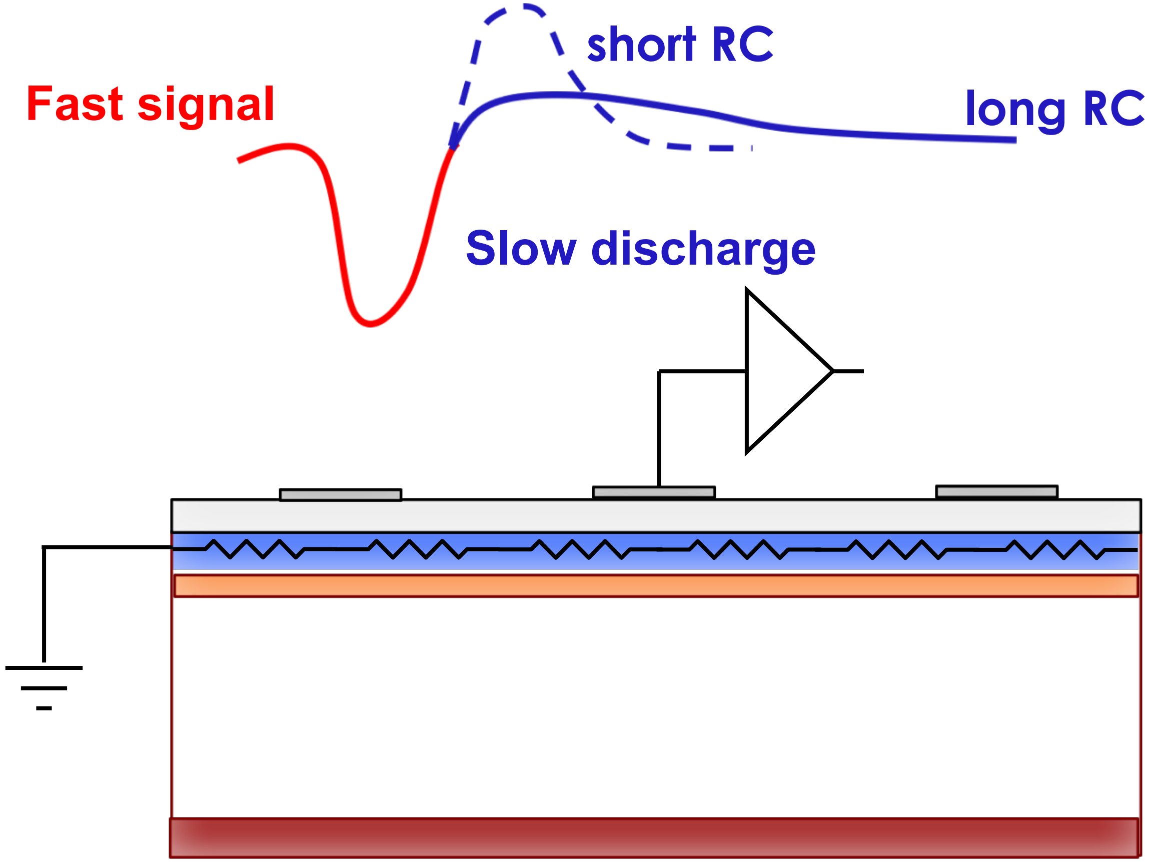
Signal discharge

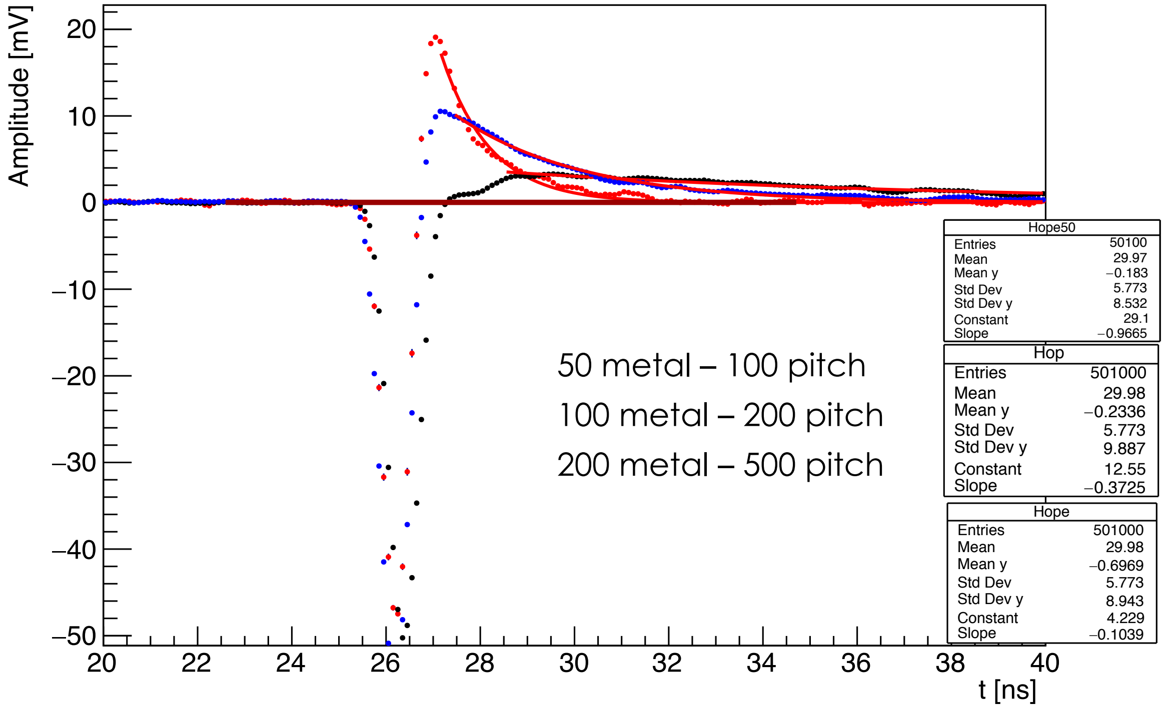
The signal discharges, according to the read-out RC.

Small RC have larger and shorter positive lobes (need to discharge the same charge in a shorter time)



50-100 (red) 100-200 (blue) 200-500 (black)



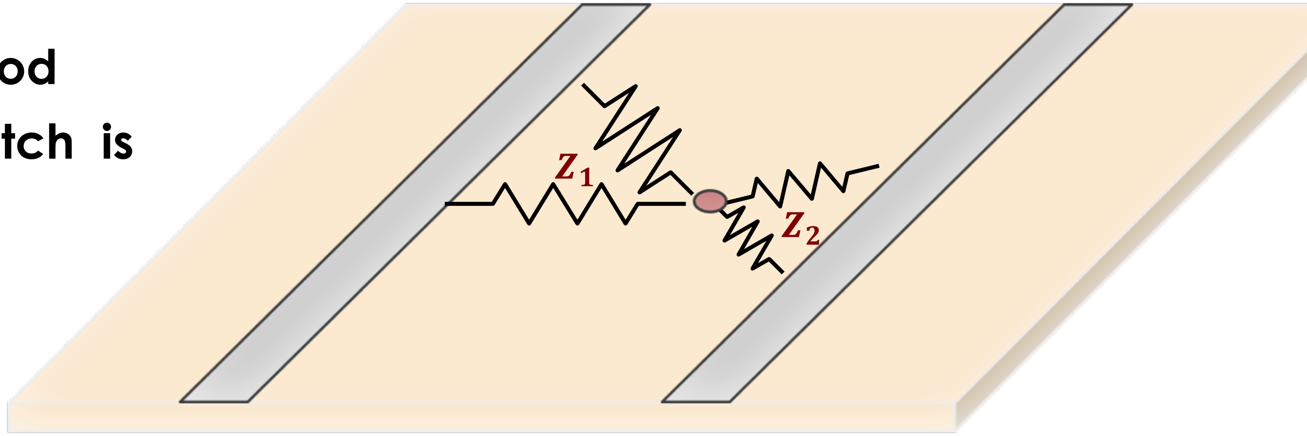


RSD strip detectors

The FBK RSD1 sensor production included 2 type of strip designs.
We tested them with the TCT laser and they work fine.
This first design did no exploit completely the charge sharing capability

In the next productions, several strip pitch and metal width will be explored, using thin metal strips (~ 20-30 um) at increasing distance (50,100, 200, 500 um).

Given the very favorable geometry, very good position resolution (~ 5 – 10 um) with large pitch is expected



RSD strips should have small metal and large intergapd

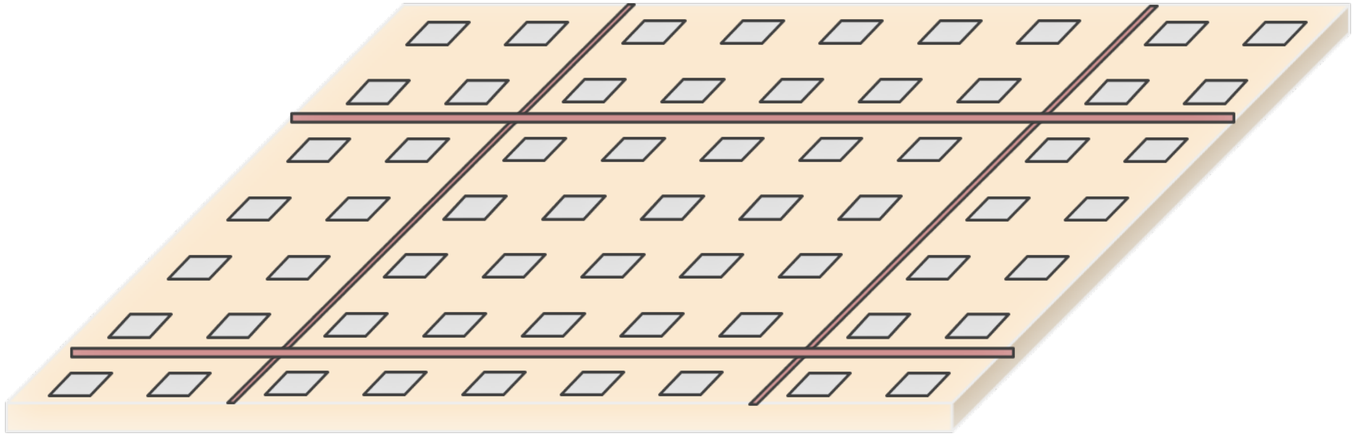
Results on AC-LGAD strips manufactured by BNL was shown here: K. Di Petrillo, https://indico.cern.ch/event/918298/contributions/3880513/attachments/2050888/3437589/2020.06.04.kdp.ACstrips_RD50.pdf

RSD large sensors

Pixellated RSD sensor have a single n-in-p diode.

This can be a problem in large detectors (in 6'' wafers they can be~ 10x10 cm^2)

Possible solution: insert a macro grid of ground contacts connected to the guard ring.



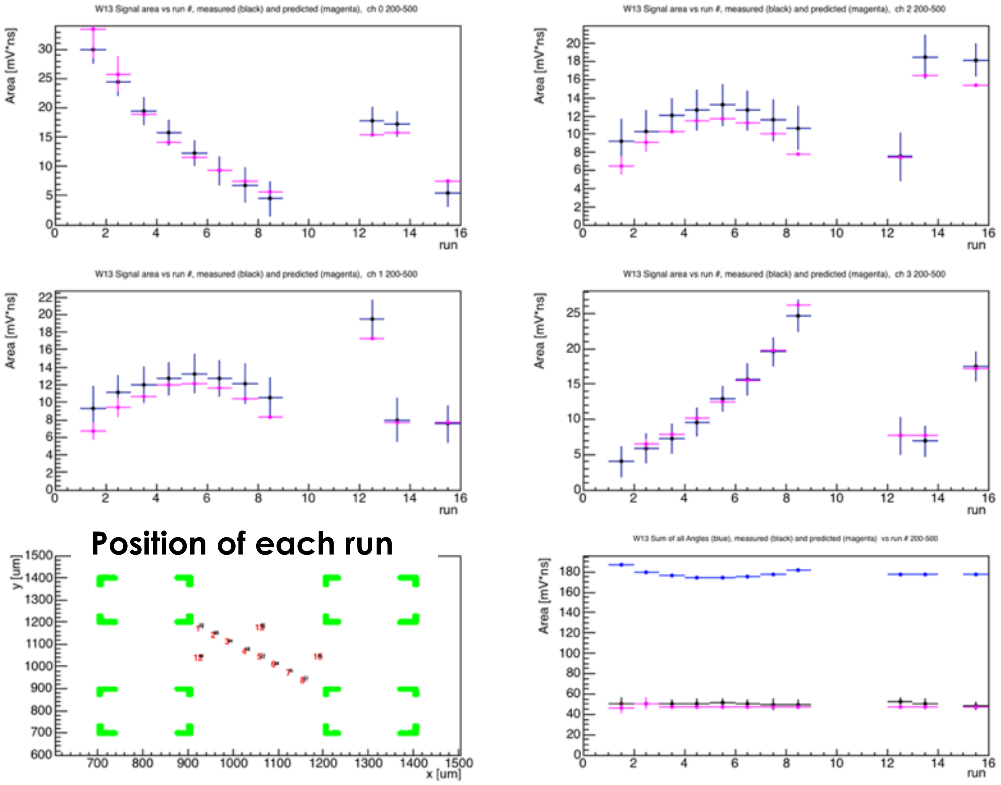
This grid isolates the macro area from each other, making the detector look like a sequence of smaller units

The RSD main formula vs n+ resistivity

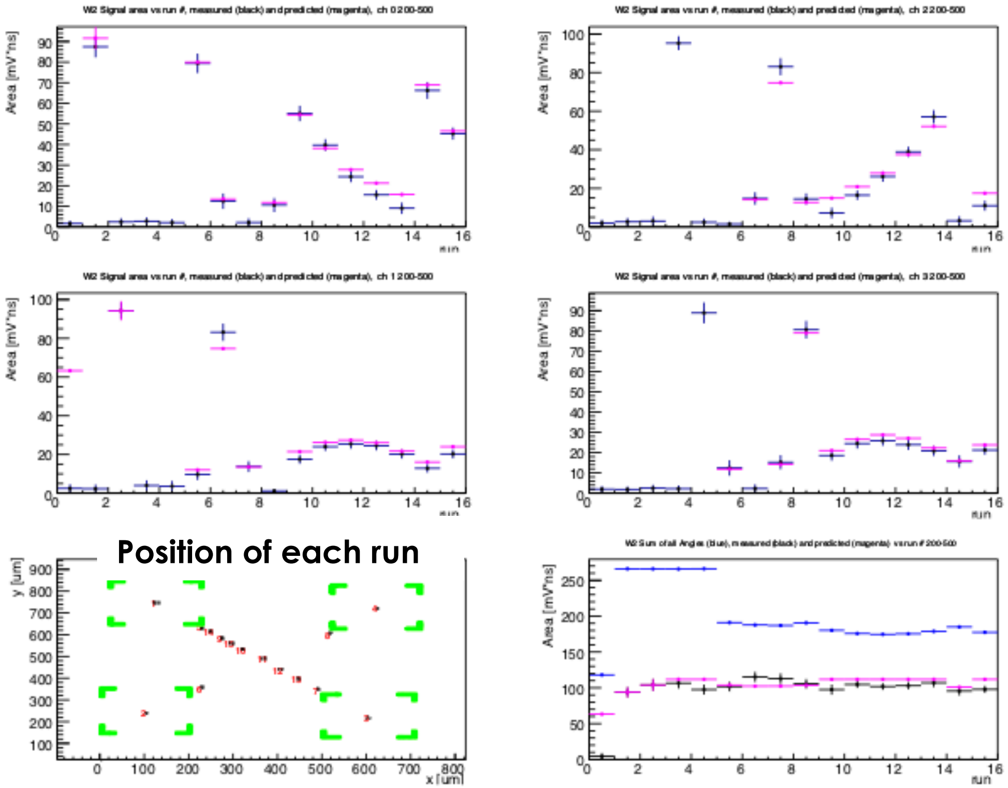
The RSD main formula does not depend on the n+ resistivity since **it predicts the relative split** of signals among the pads.

$$S_i(\alpha_i, r_i) = \frac{\frac{\alpha_i}{\ln(r_i)}}{\sum_1^n \frac{\alpha_i}{\ln(r_i)}}$$

Signal split among pads as a function of run number (black = measured, magenta = predicted)

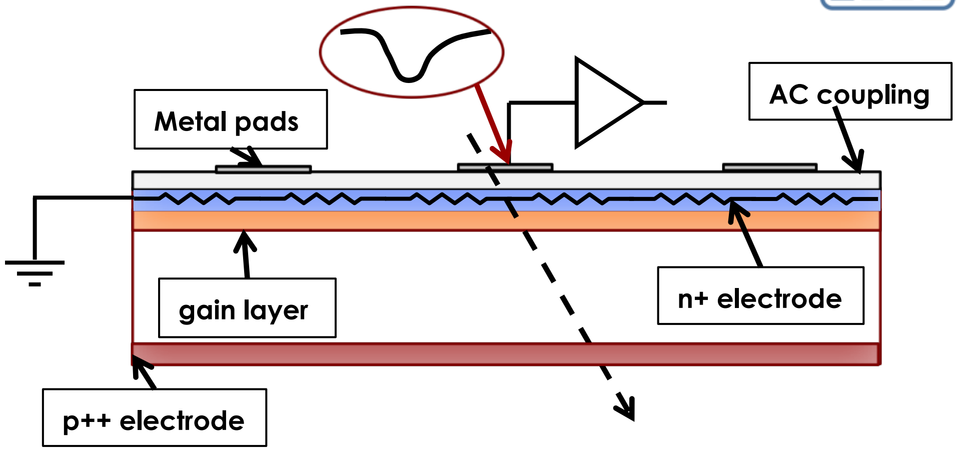


RSD1 W13: low resistivity n+ implant



RSD1 W2: high resistivity n+ implant

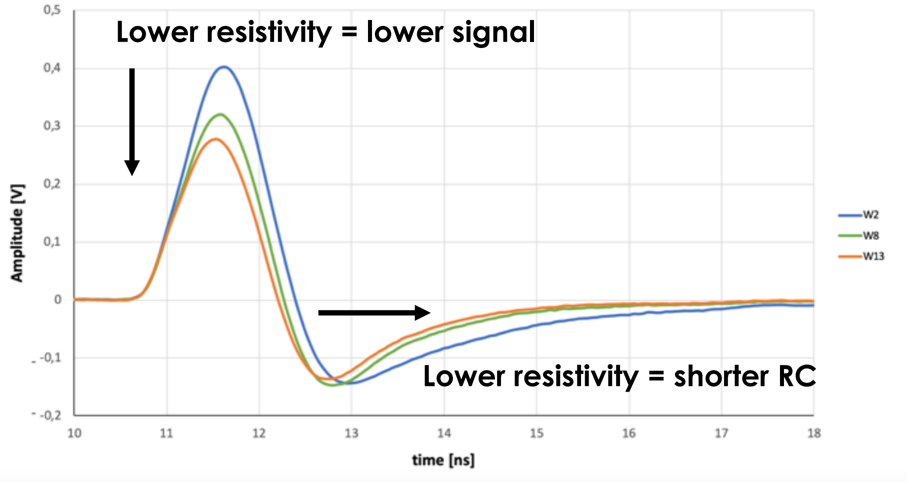
The effect of n+ resistivity



What are the effects of n+ resistivity on the signal?

The signal is formed on the n+ layer, and it is coupled to the AC metal pad.
If the n+ is too conductive, it will not couple the charges to the AC metal pad

Signals RSD 70-100 different n+ dose



➔ the AC amplitude decreases with increasing n+ doping.
In the limit of very conductive n+, there is no AC signal.

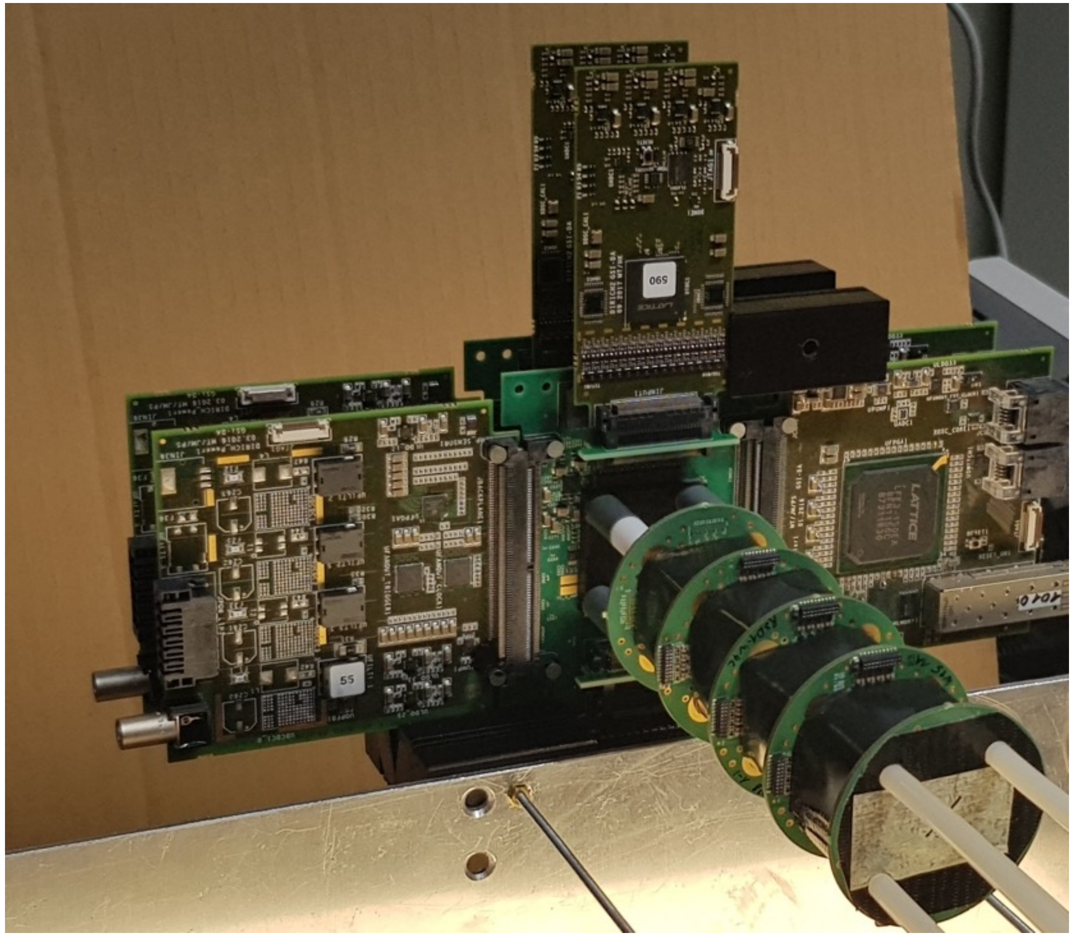
➔ Additional effects, studied on RSD1 wafers (W13, W2) with $\frac{Doping\ W13}{Doping\ W2} \sim 3$

- RC discharge time is shorter at lower resistivity, $(\frac{\tau_{W13}}{\tau_{W2}} \sim 0.5)$
- The $\beta\ \ [\mathrm{ns}/\frac{ln(r)}{\alpha}]$ coefficient, the delay, decreases at lower resistivity $(\frac{\beta_{W13}}{\beta_{W2}} \sim 0.8)$

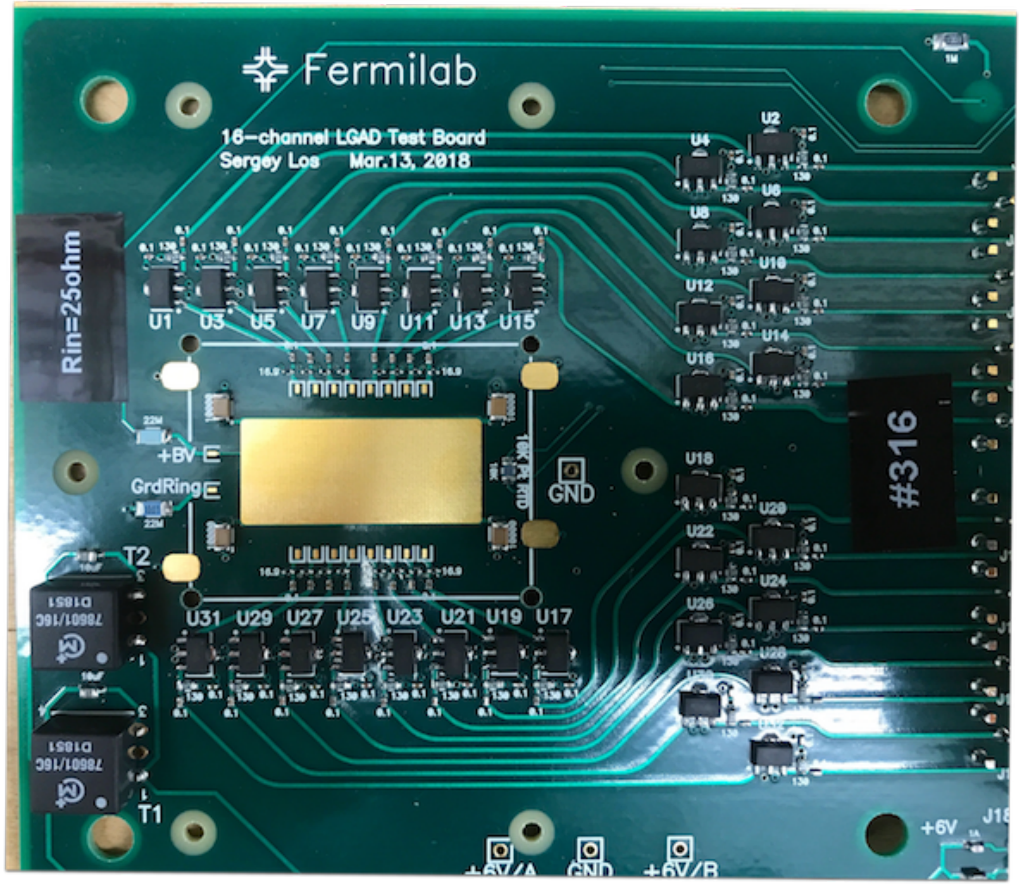
RSD use in HADES

The HADES collaboration (GSI) has completed a beam test with a combination of UFSD and RSD strips.

2.5 GeV/c protons, 1.2 MHz/ strip, results in the near future



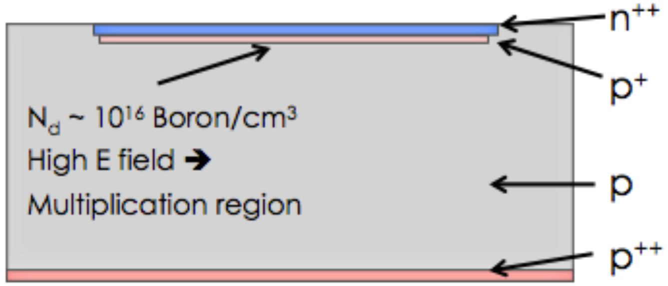
FNAL 16-ch board



RSD radiation resistance

The effect of irradiation on RSD is similar to that of the other LGAD-based devices:

- Decrease of charge collection efficiency due to trapping
- Doping creation/removal
- Increased leakage current, shot noise



Most important fact: irradiation de-activate the gain layer

➔ the electric field decreases, and the multiplication stops.

RSD has been irradiated, albeit not yet tested after irradiation.

Possible outcome: RSD will behave as the other LGAD-based devices, working well up to fluences of about ~ 1E15 n_{eq}/cm^2

Unknown: effect of enhanced oxide charges due to radiation to the AC coupling mechanism

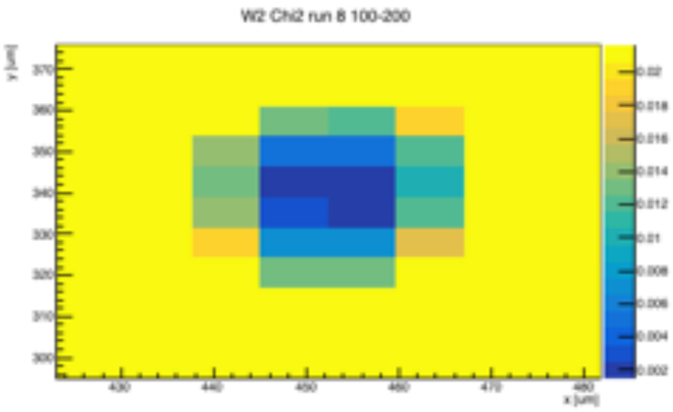
Position reconstruction method: the recipe

Recipe:

- For each position, using the RSD main formula, calculate S_i^{Calc}
- Find which x-y bin minimize the quantity:

$$\chi^2 = \sum_1^4 \frac{[S_i^{Meas} - S_i^{Calc}]^2}{\sigma}$$

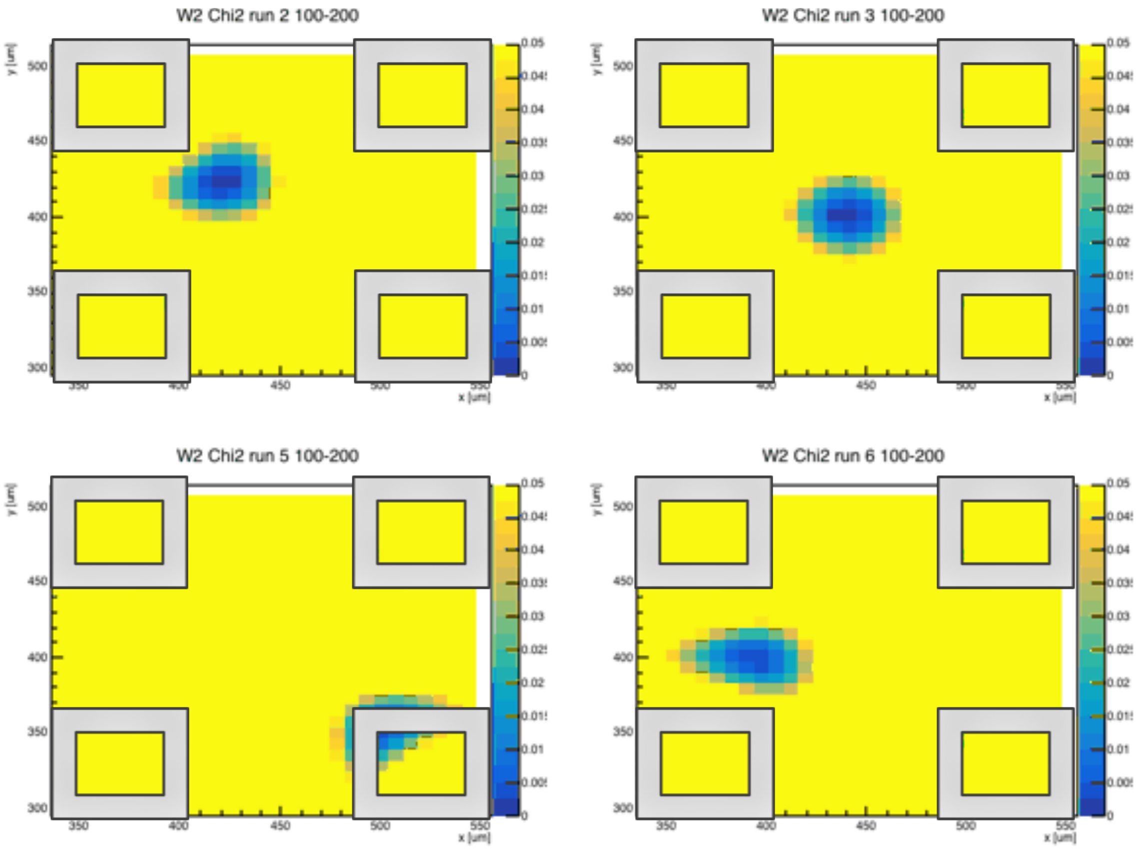
- Perform a local interpolation around the minimum.



χ^2 values for 4 different laser shots

(sensor geometry:100-metal 200-pitch)

The reconstructed position is the bin with the minimum χ^2 value

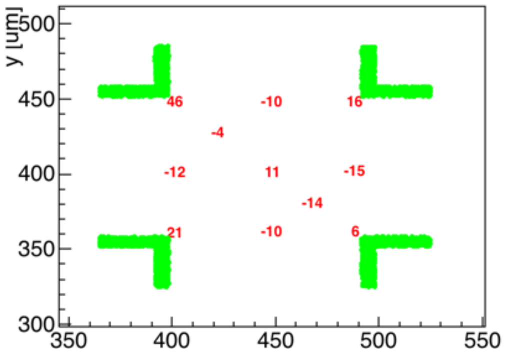


Laser study: time resolution

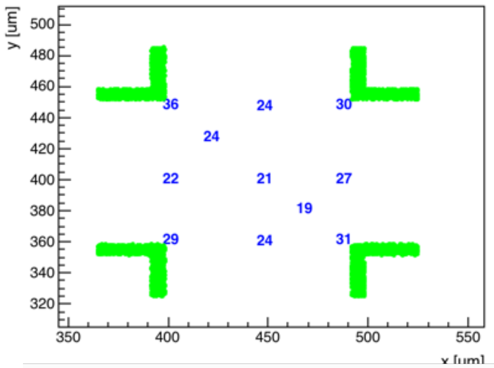
The **hit time** is obtained combining the timing information from each pad, after correcting for delay

Geometry:	**100 Metal, 200 pitch**	**200 Metal, 500 pitch**
Temporal precision:	**28 ps**	**35 ps**

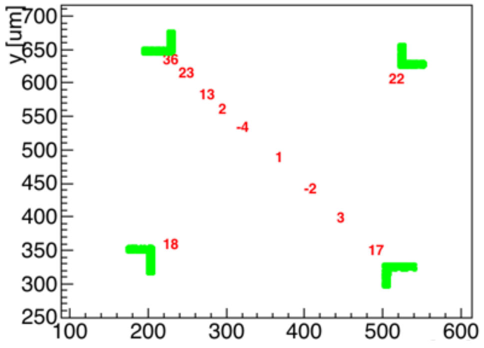
Offset at each point



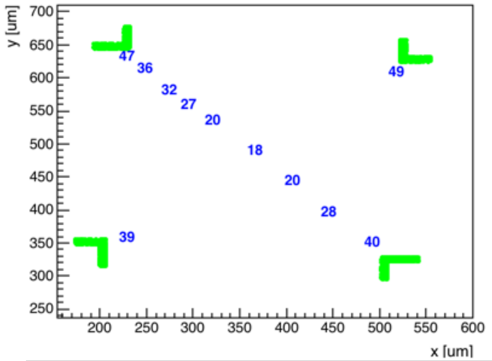
Resolution at each point



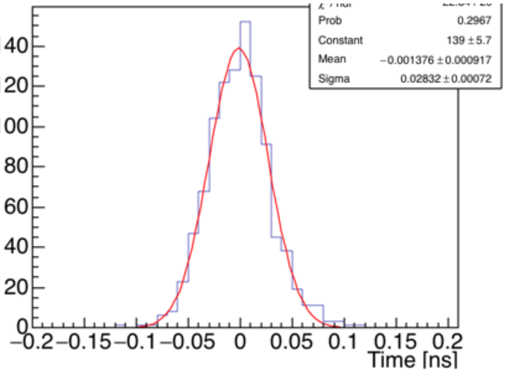
Offset at each point



Resolution at each point

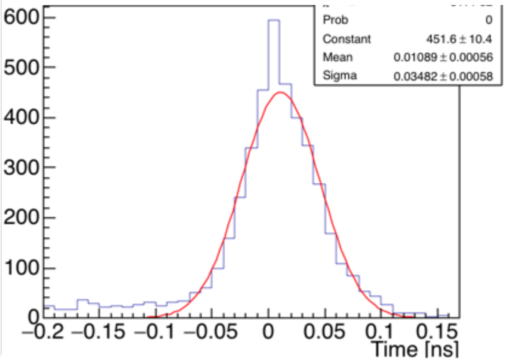


Total resolution



RSD maintain the "usual" excellent temporal resolution of standard UFSD

Total resolution



N. Cartiglia, INFN Torino, CEA Saclay, Detector Seminar, 26/10/2020

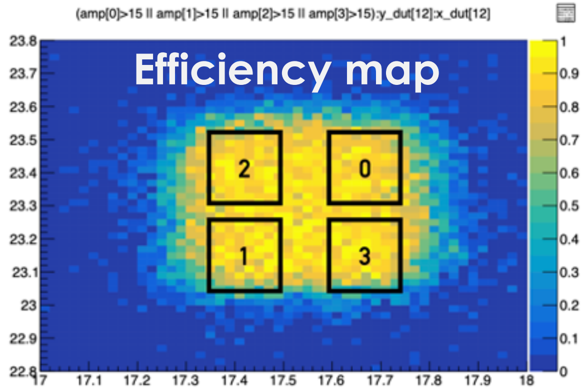
Fermilab beam test results

All details in: M. Tornago, 36th RD50 “Latest results on RSD spatial and timing resolution https://indi.to/2cGQy

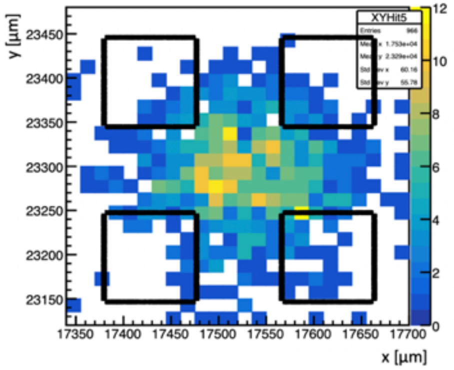
Data taken with RSD 3x3 100-200 and 190-200 geometries

Lesson learnt:

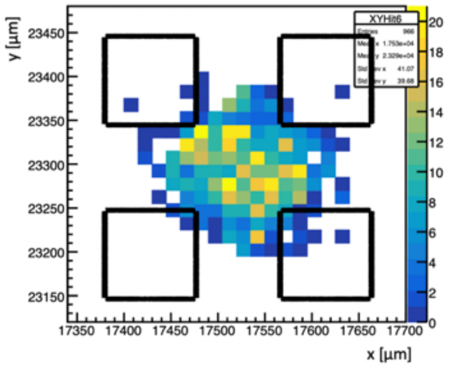
- RSD are ~ 100% efficient
- The RSD x-y hit reconstruction worked very well
- The time resolution is $\boldsymbol{\sigma_{t\,100-200} = 44\ ps, \sigma_{t\,190-200} = 42\ ps}$ similar to UFSD results, limited by non-uniform ionization
- The metal size (100 vs 190 um) does not influence the time resolution



	single pad	3 pad	4 pad
100-200 laser	45 ps	Improves as $1/\sqrt{n}$ →	22 ps
100-200 test beam	50 ps →	44 ps	-
190-200 test beam	35 ps $\cancel{1/\sqrt{n}}$ →	42 ps	-



x-y tracker reconstruction



x-y RSD reconstruction

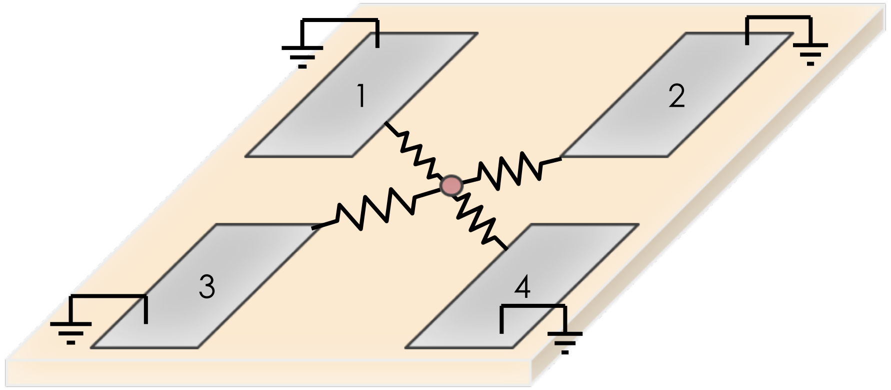
Small improvement combining pads in beam test:
resolution limited by the effects of non-uniform ionization that are fully correlated

Laser study: signal delay

There is one more interesting point.

Let's compute the time of the event as the average time seen by the 4 pads:

$$RSD_{Time} = \frac{1}{4}\sum_{1}^{4} t_i^{True} = \frac{1}{4}\sum_{1}^{4} t_i^{Meas} - \beta\frac{1}{4}\sum_{1}^{4}\frac{ln(r_i)}{\alpha_i}$$



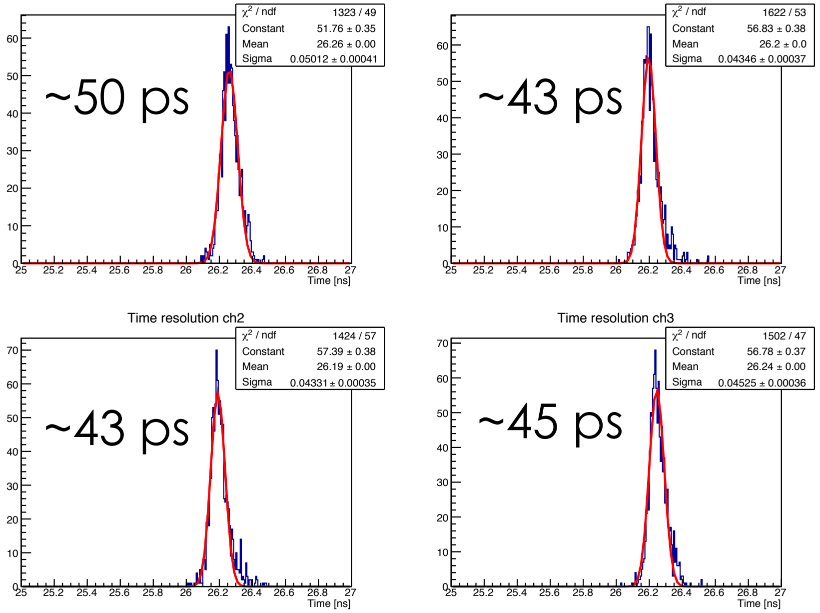
The sum of the resistivity, $\sum_1^4 \frac{ln(r_i)}{\alpha_i}$**, is actually a constant** (it is equivalent of the signal amplitude) for every point of the sensor, **so it does not contribute to the time resolution**, it is just an offset ➔ **no need to know accurately the delay**

$$\sigma_{tot}^2 = \sigma_{Trigger}^2 + \sigma_{RSD}^2 = \sigma_{Trigger}^2 + \frac{1}{4}\sqrt{\sum_{1}^{4}\sigma_{t_i^{Meas}}^2}$$

Laser study: time resolution

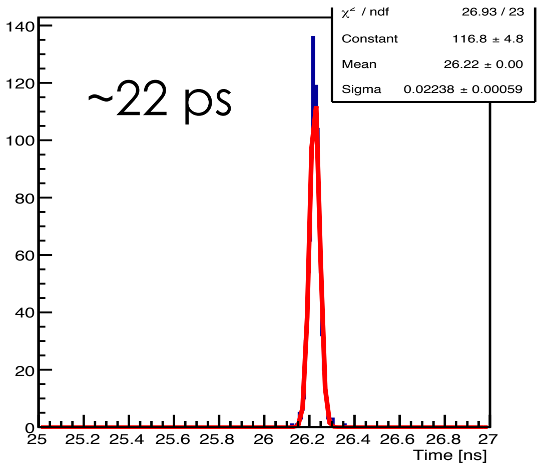
The **hit time** is obtained combining the timing information from each pad, after correcting for delay

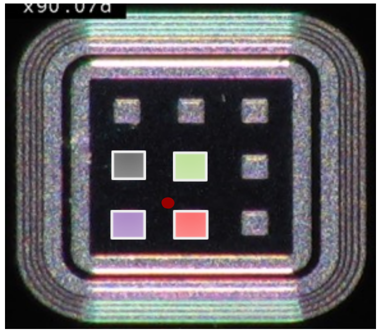
Temporal resolution of each pad



~45ps/√4

4-pads combined temporal resolution





RSD show excellent temporal resolution and the combination of multiple signals yields to $\sim \frac{1}{\sqrt{n}}$ **improvements**