The 1-μm project

Preamble:

- **First design innovation: low gain avalanche diode (LGAD)**
- **Second design innovation: resistive read-out in silicon detectors (joining RPC, GEM..)**
  - Two names for one solution: RSD or AC-LGAD

Plan:

- **Exploit these two innovations to design sensors with 1 μm spatial resolution, large pixels, low material budget, and the "usual" LGAD temporal resolution**

UFSD group

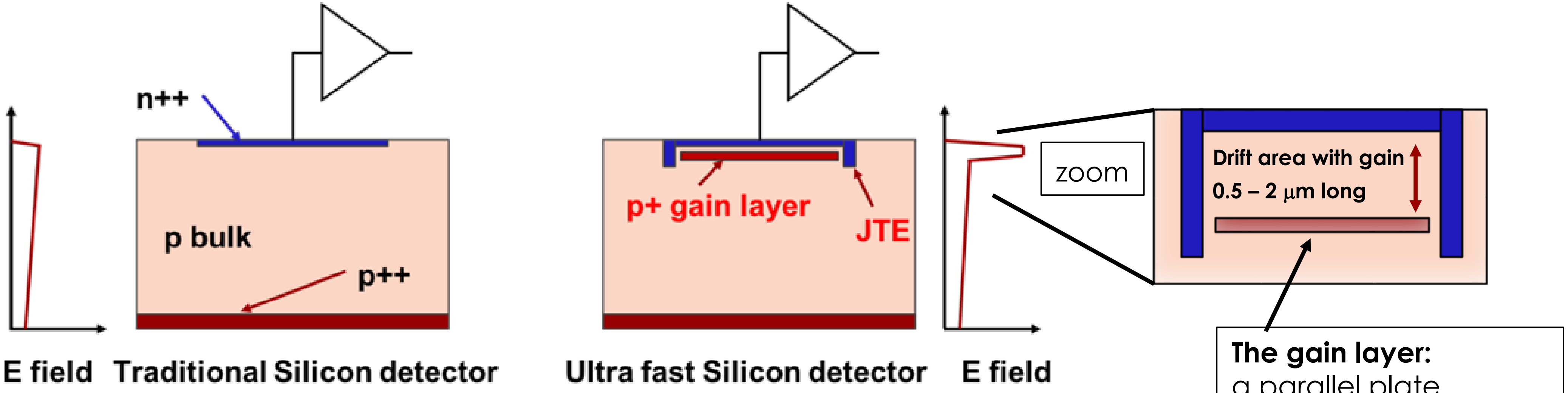
INFN - Torino, Univ. of Turin, Univ. of Piemonte Orient,
FBK-Trento, Univ. of Trento, Univ. of California at Santa Cruz.

Extensive collaborations with other groups and within the RD50 CERN collaboration

erc
UFSD

PRIN
4DInSiDe

First design innovation: low-gain avalanche diodes



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

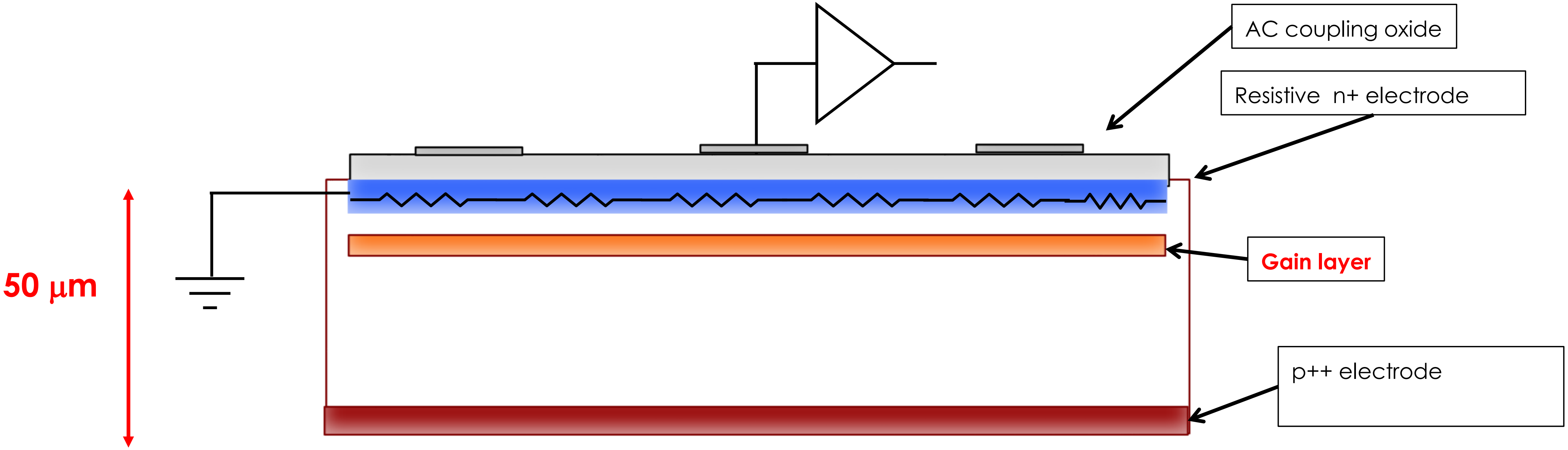
- The low-gain mechanism, obtained with a moderately doped p-implant, is the defining feature of the design.
- The low gain allows segmenting and keeping the shot noise below the electronic noise, since the leakage current is low.

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

1) Continuous 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

Results presented here are from the FBK RSD1 production

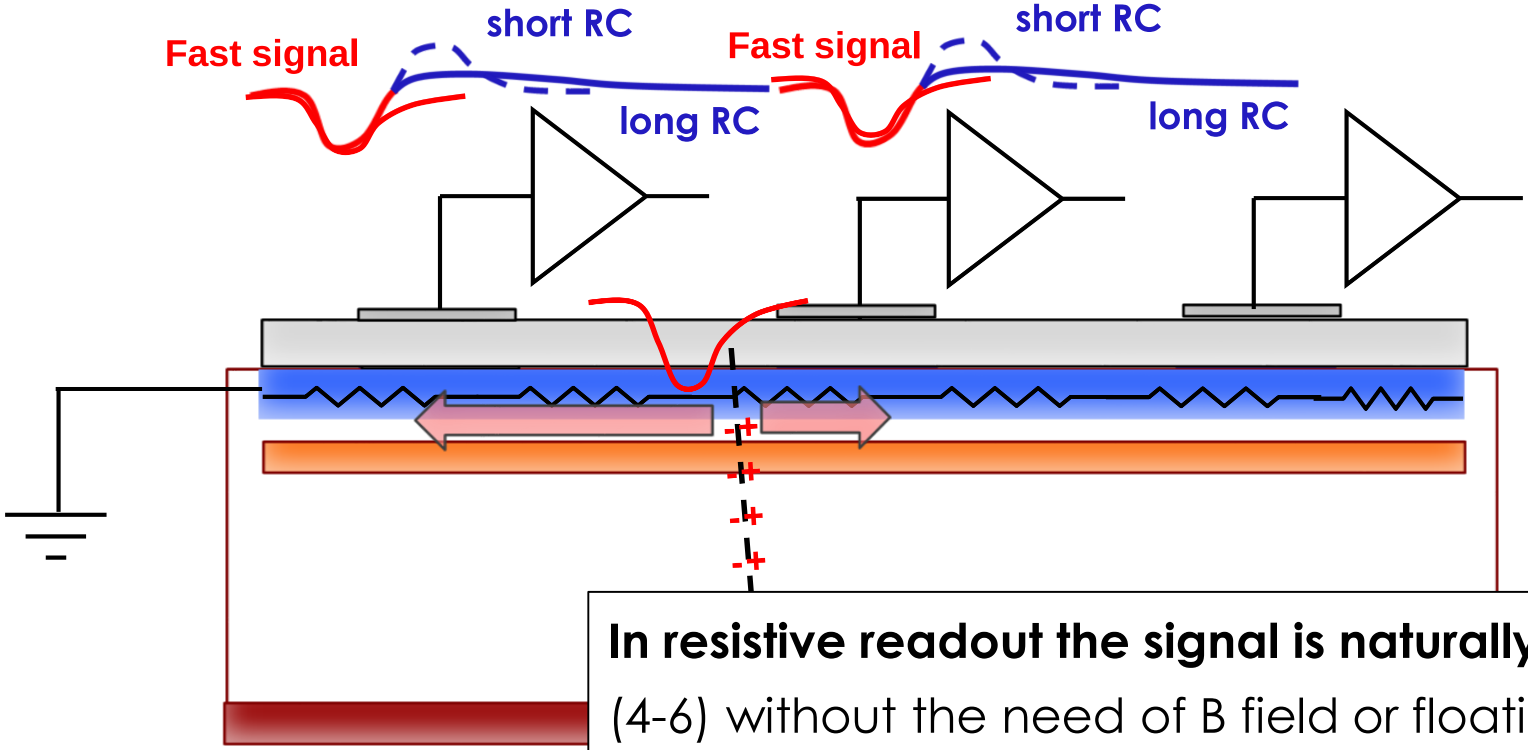
(INFN grant "giovani" RSD, PI M. Mandurrino)



Resistive readout club: GEM, RPC, and RSD

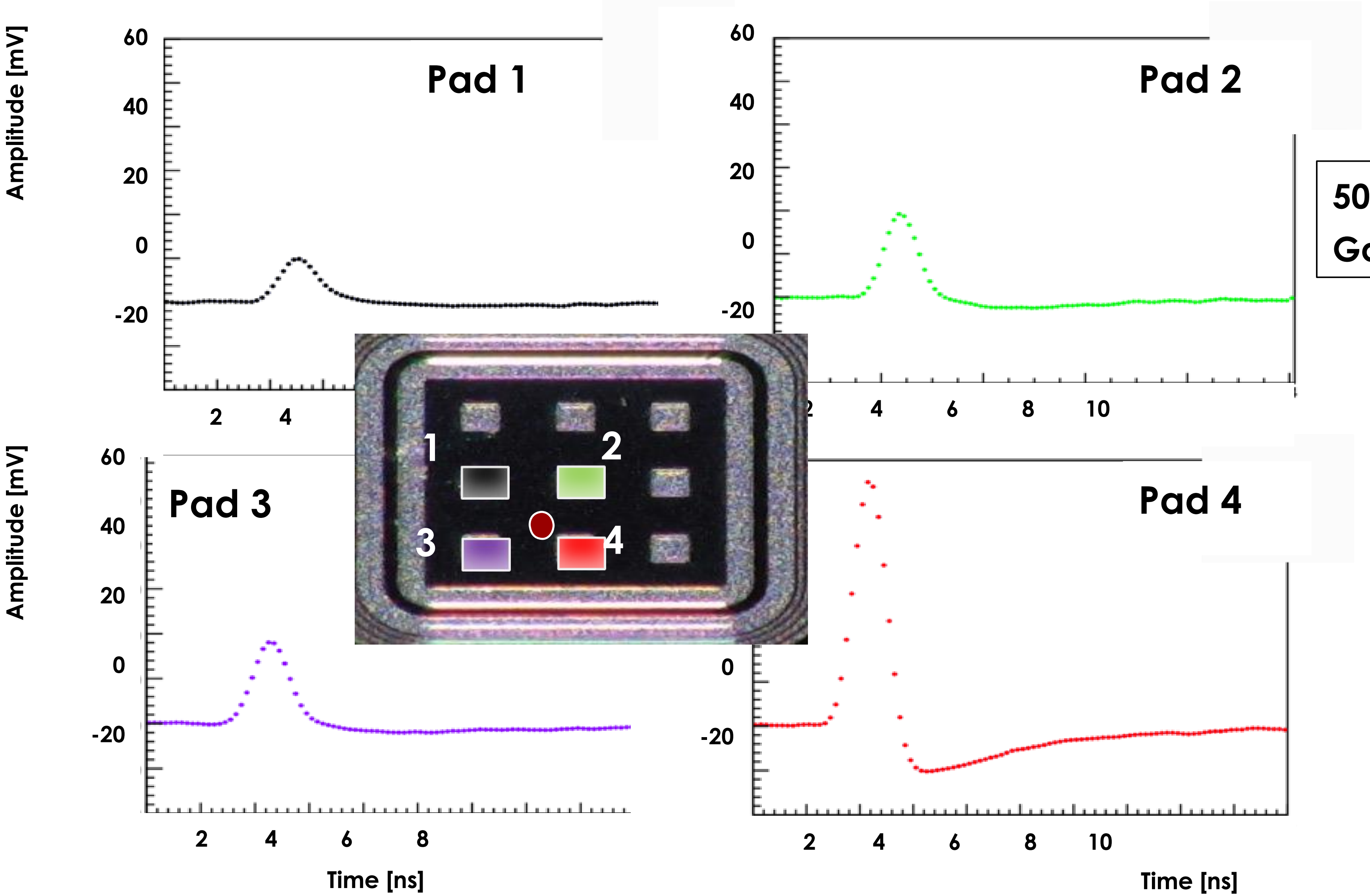
Signal formation in resistive readout

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

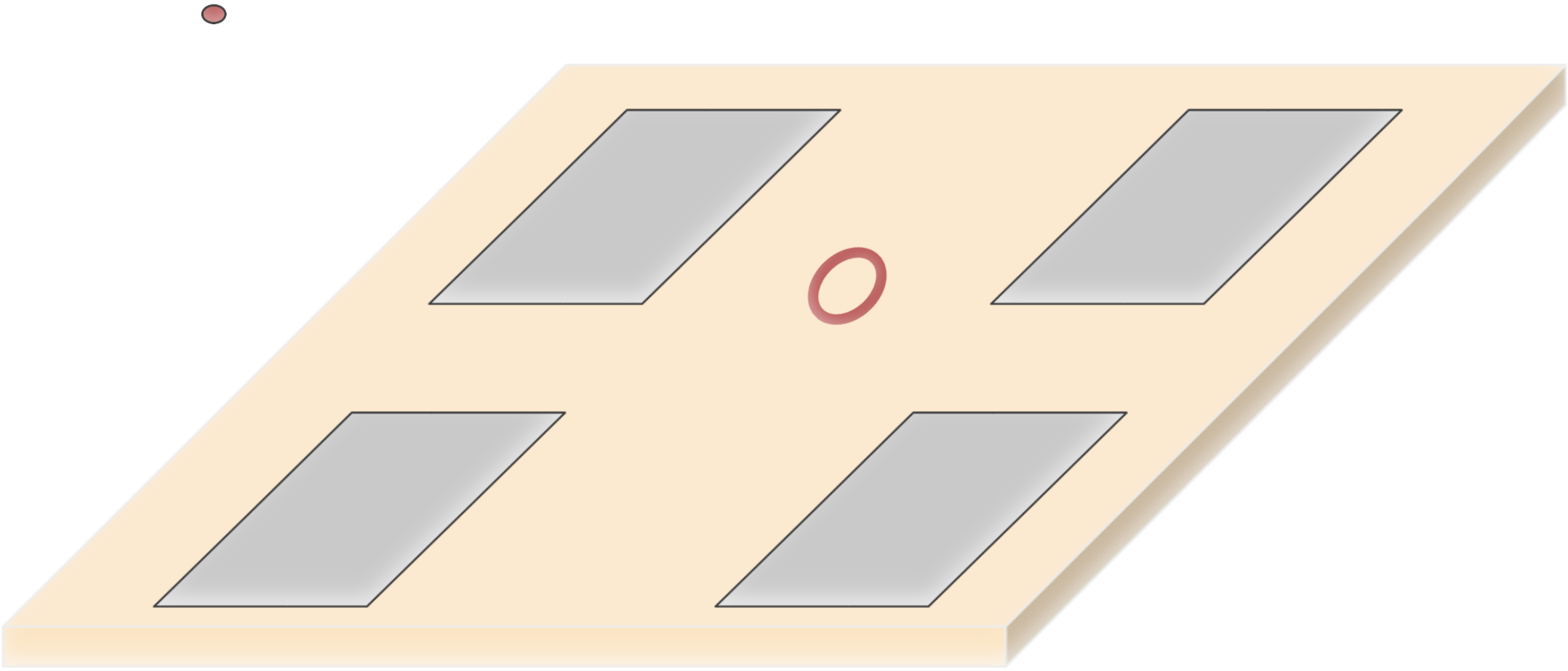
Example of signal sharing



50-mm thick RSD, Gain ~ 20

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

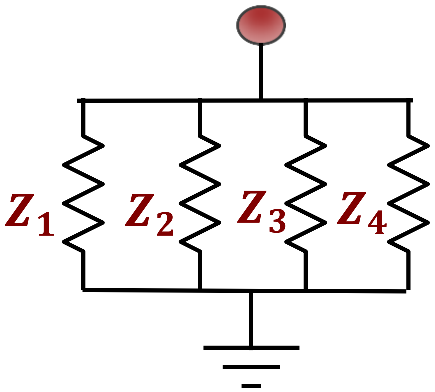
RSD principle of operation



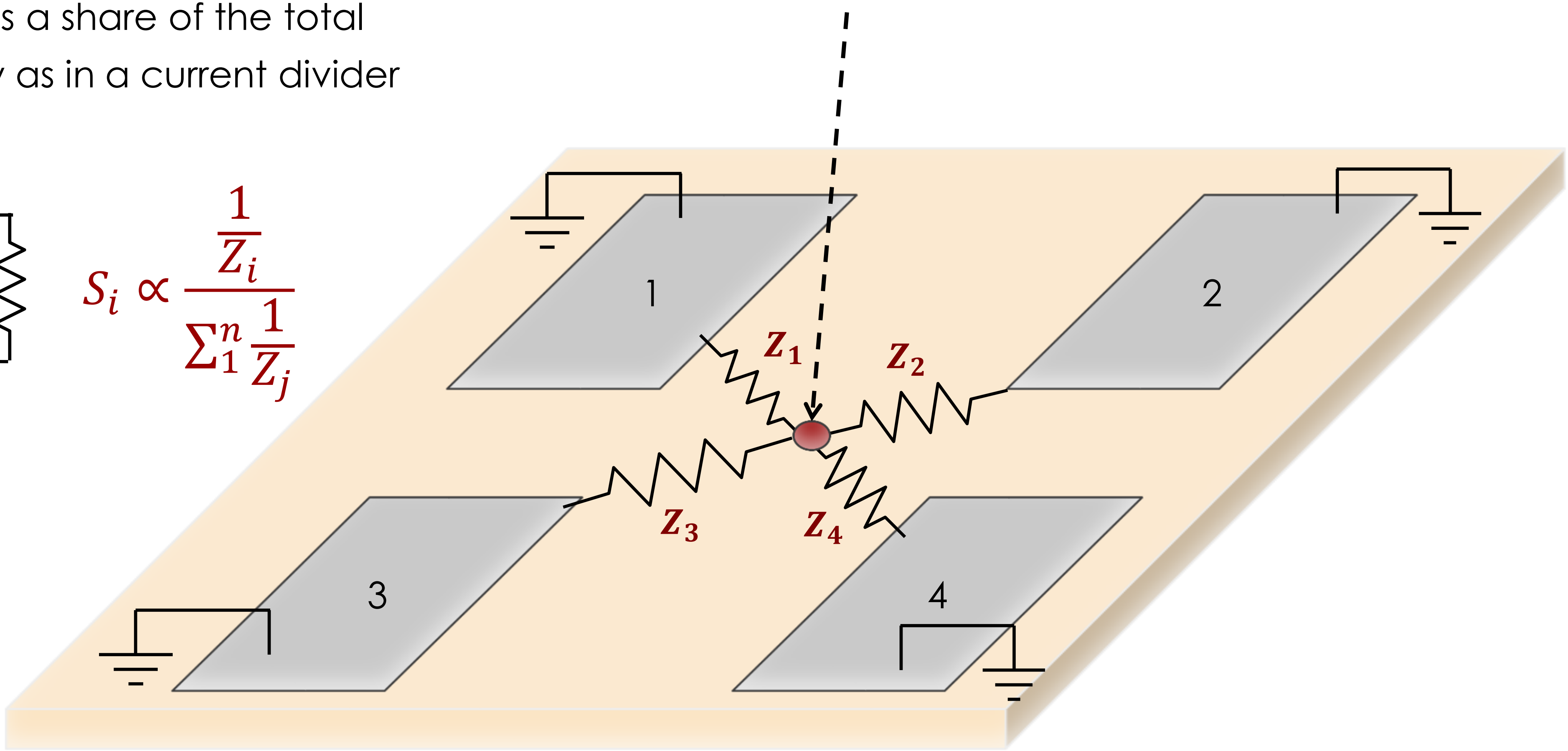
Charge sharing in RSD

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



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

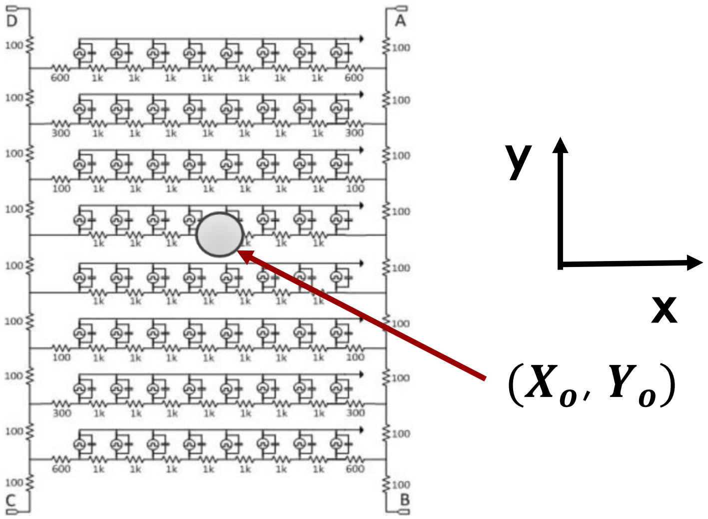


Discretized Positioning Circuit

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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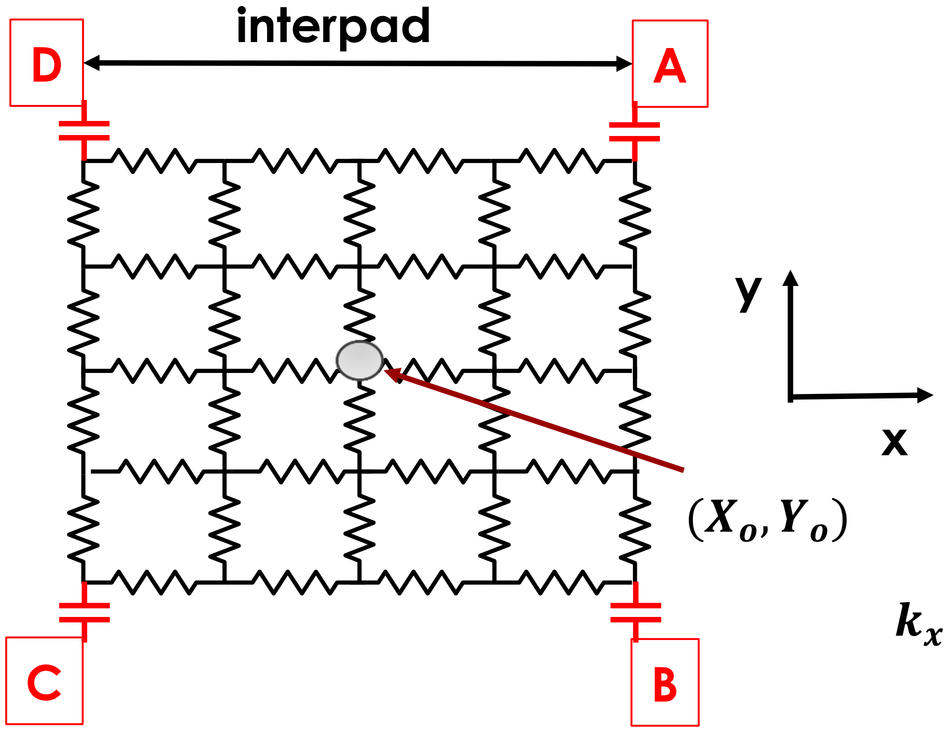
RSD as a Discretized Positioning Circuit



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

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

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

RSD is a hybrid resistors/capacitors DPC circuit

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

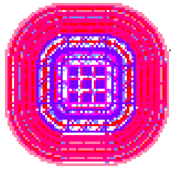
➔ no need for a analytical sharing law.

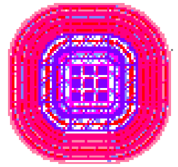
➔ $k_{x,y}$ = imbalance parameter along x or y

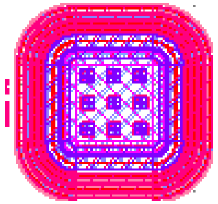
- Maximum value of the charge imbalance within the pixel
- Needs to be determined experimentally for each geometry

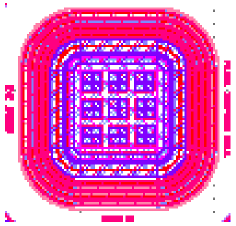
Structures tested (metal-pitch)

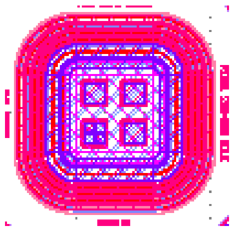
The FBK production RSD1 yielded many samples, of several geometries, exploring the interplay of n+ resistivity, dielectric thickness, metal pad, and pitch

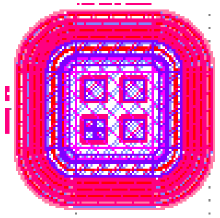

50-100

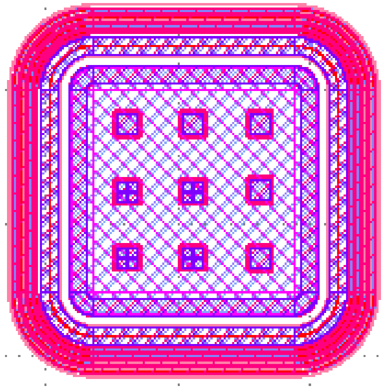

70-100

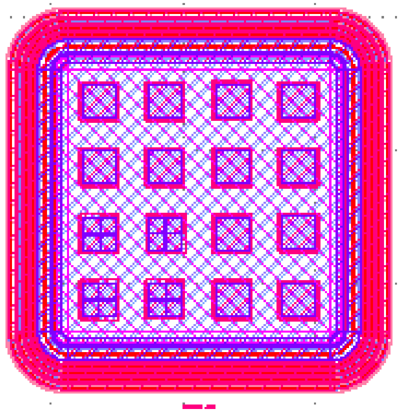

100-200


150-200

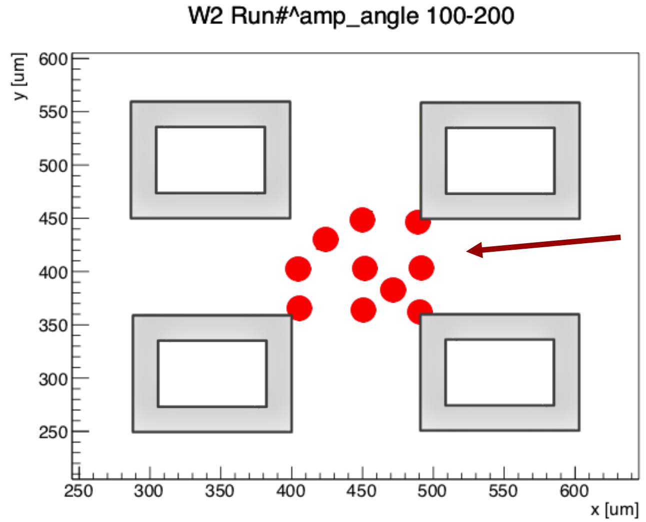

150-300


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



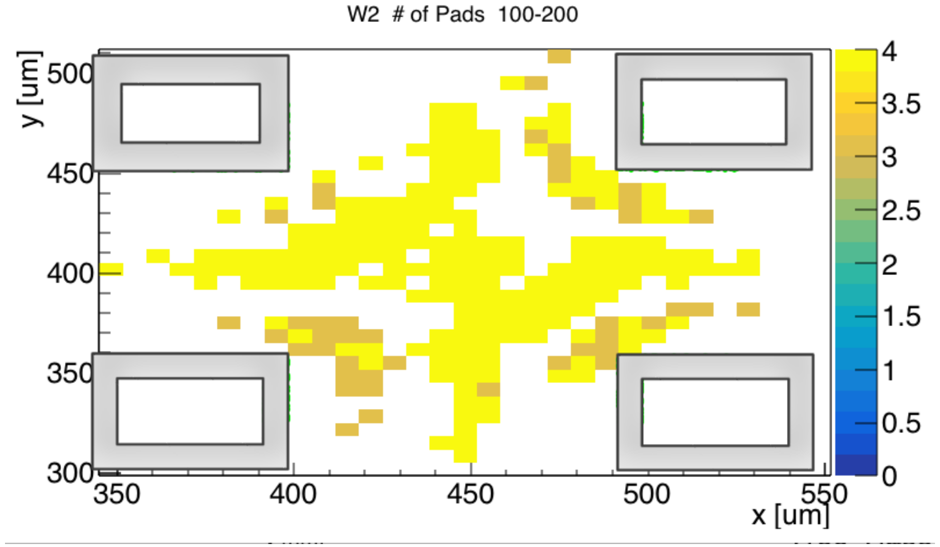
Example of laser positions

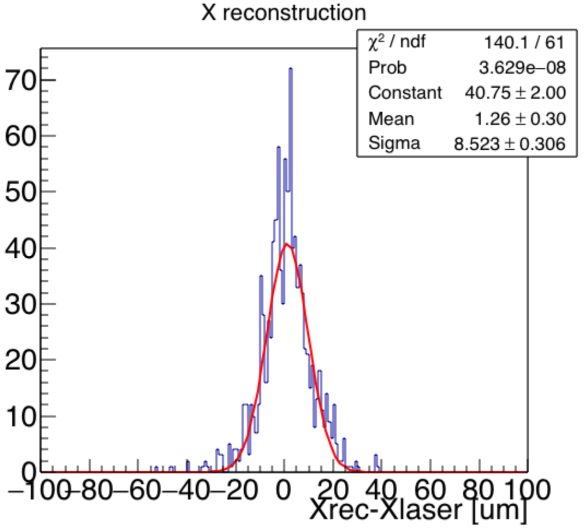
Laser study: position resolution

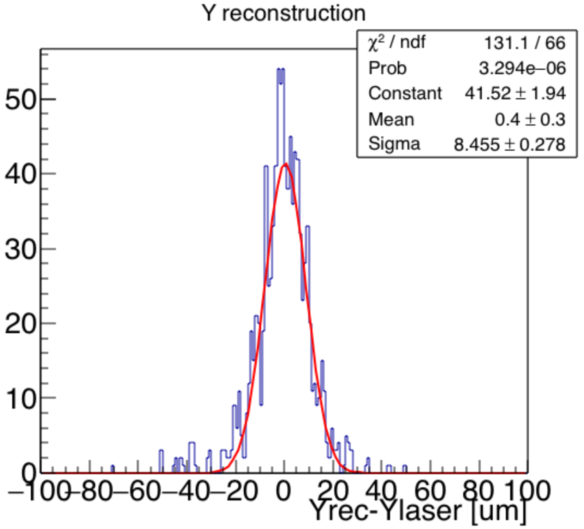
Shooting the laser in many positions, the **spatial precision** can be evaluated. This is done by comparing the position reconstructed using the look-up table to the known laser position.

Geometry: 100 Metal, 200 pitch

Shooting position and# of pads used in the reconstruction



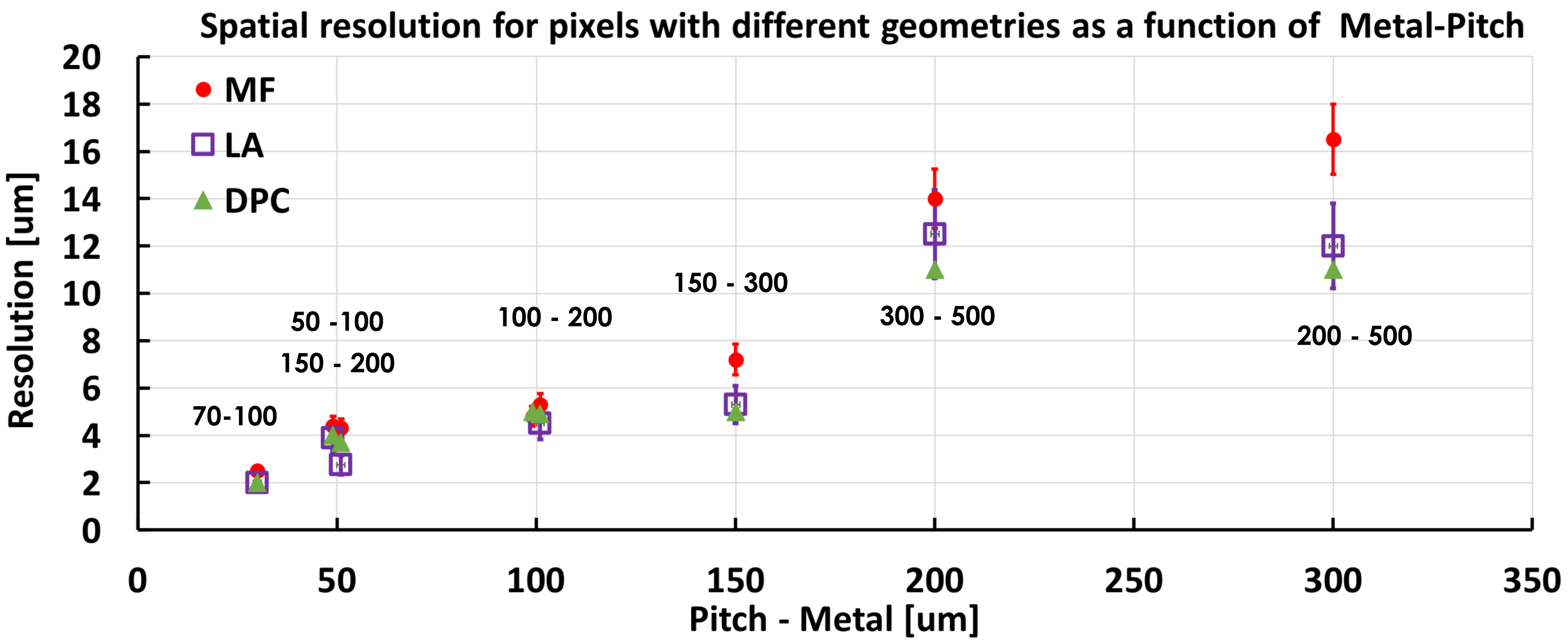




Resolution ~ 8.5 um

Gain ~ 17

Laser study: position resolution as a function of pixel geometry



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

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

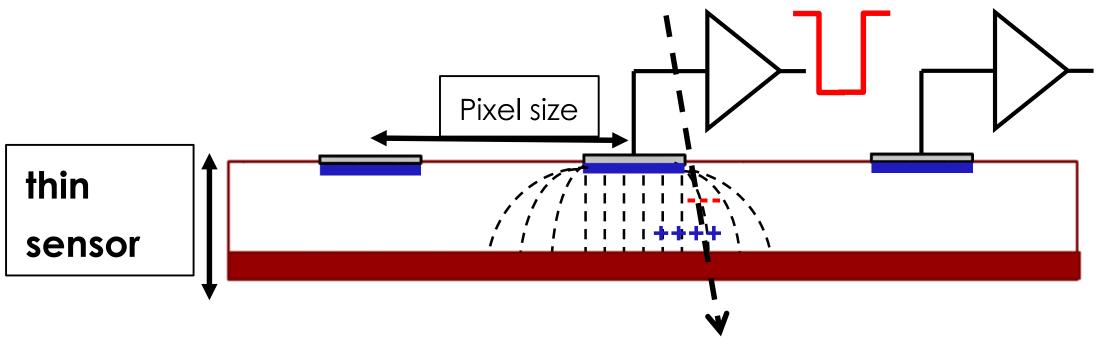
Sensor accuracy σ_x and readout

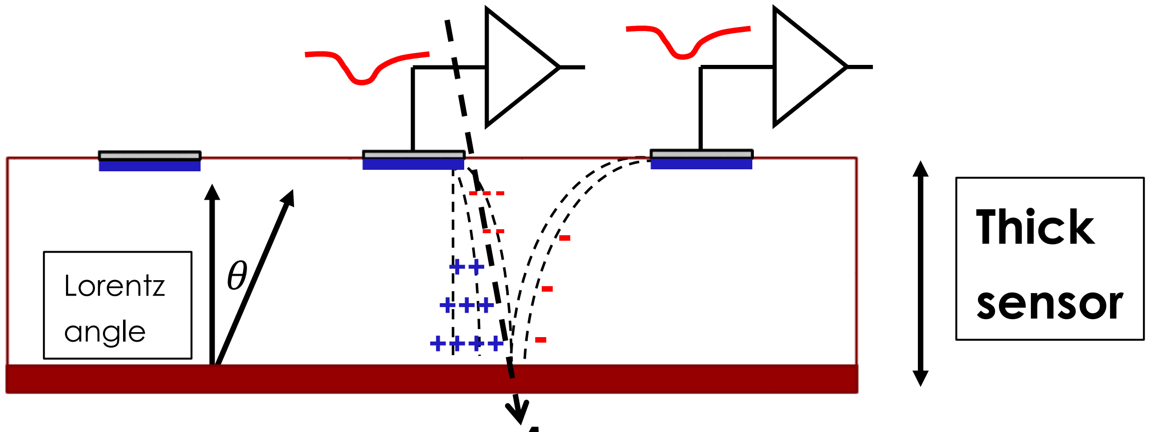
Binary readout

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

Analog readout

where the amplitude of the signal is recorded





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

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

- σ_x << pixel size
- σ_{MS} large

  Sensors have to be thick to maintain efficiency

  rodes)

  thin

- σ_x depend on the pixel size

  pixel = 100 μm ➔ $\sigma_x = 20\ \mu m$

- σ_{MS} sn

The sensors are either very accurate OR very thin

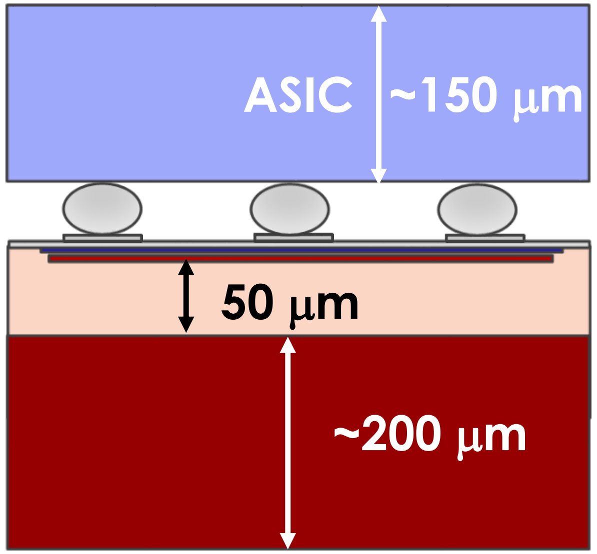
RSDs are both thin and accurate

RSD material budget and time resolution

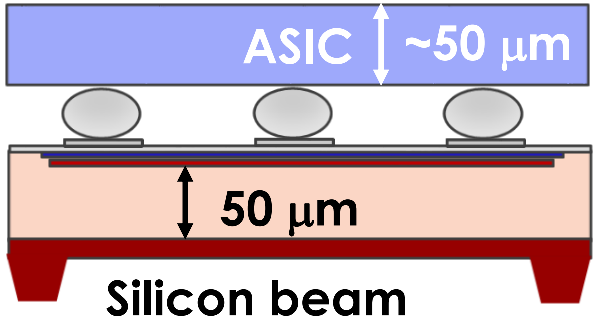
The active thickness of RSD sensor is rather small ~ 50 um.

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

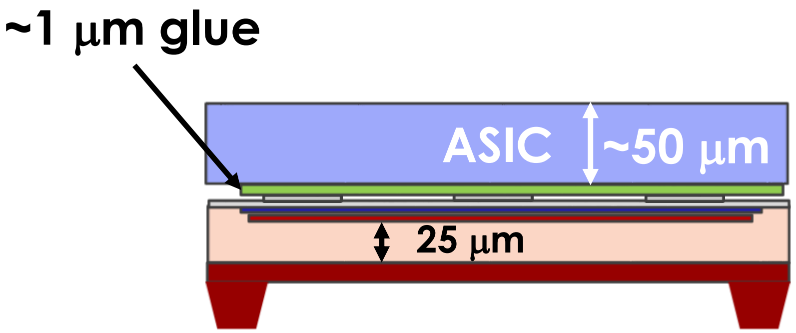
There is a clear path leading to < 100 μm material:



Present design: no material budget optimization



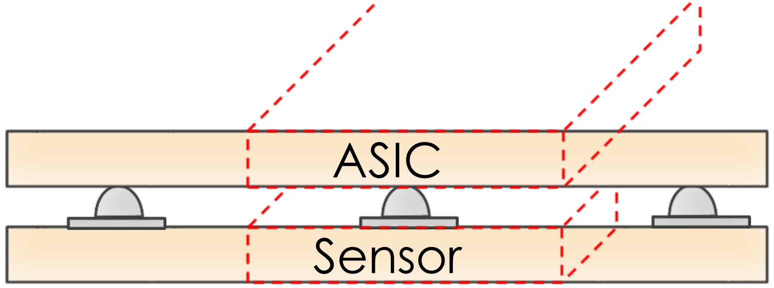
- Thinned handle wafer:
  500 um ➔ 10-20 um



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

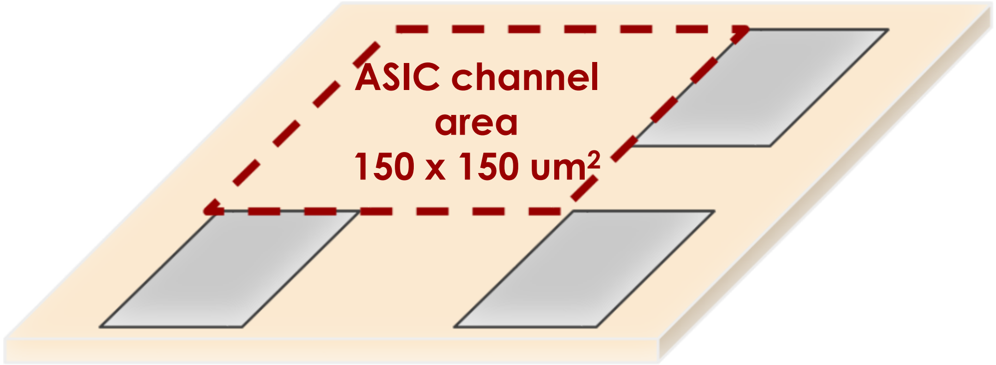
ASIC for RSD

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

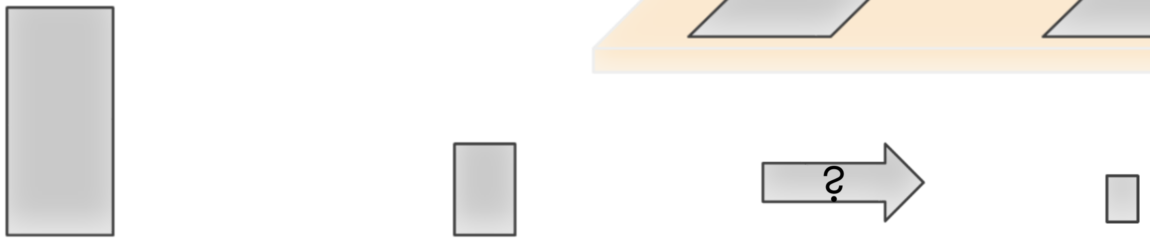


Assuming a goal of ~ 5 mm spatial resolution,
the RSD pitch can be 150-200 μm

- ➔ 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

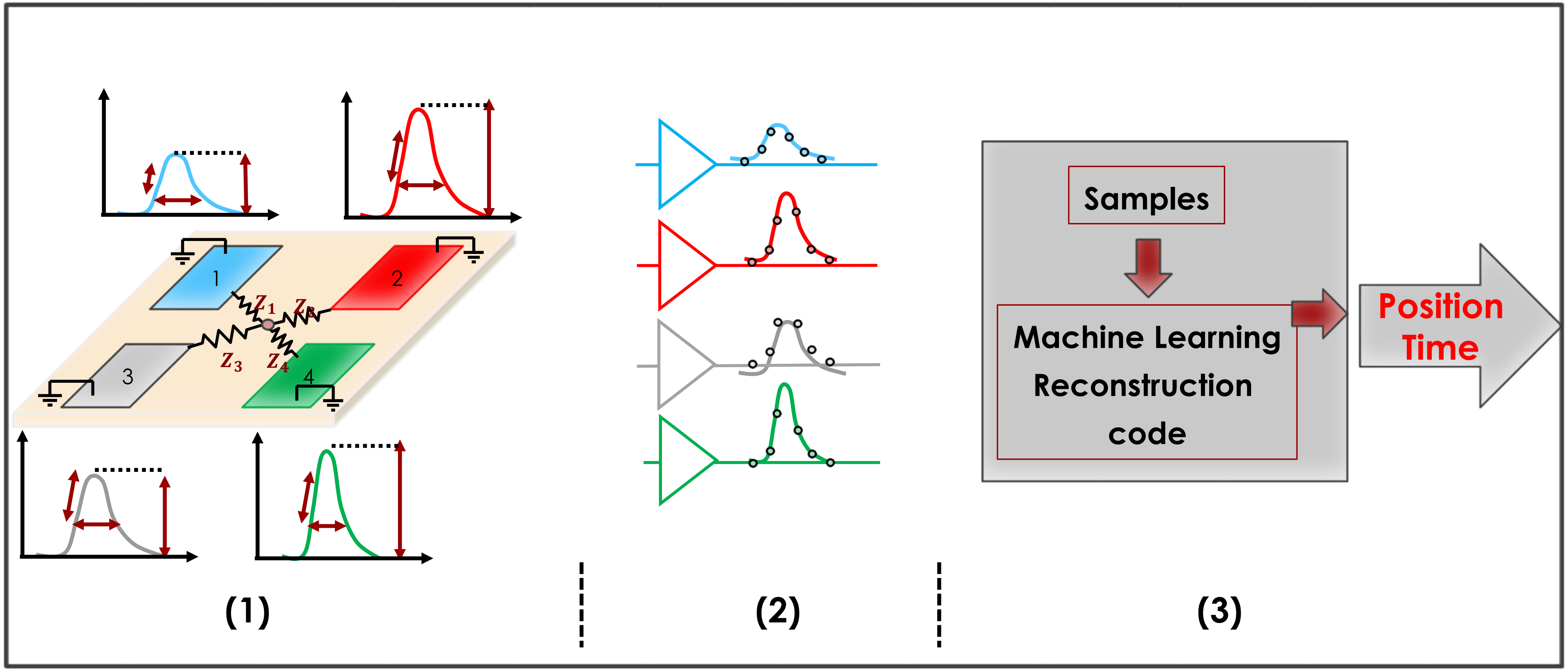


130 nm:
70 x 150 micron

65 nm:
40 x 60 micron

28 nm:
~20 x 30 micron

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

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

RSDs are truly remarkable detectors:

- **Initial small applications**: ideal beam monitor, providing position and time.
- **Your beta source telescope**: they provide time and position
- **In your future experiments**: they might meet the crazy requirements of FCC-ee, EIC, CMS LS3…

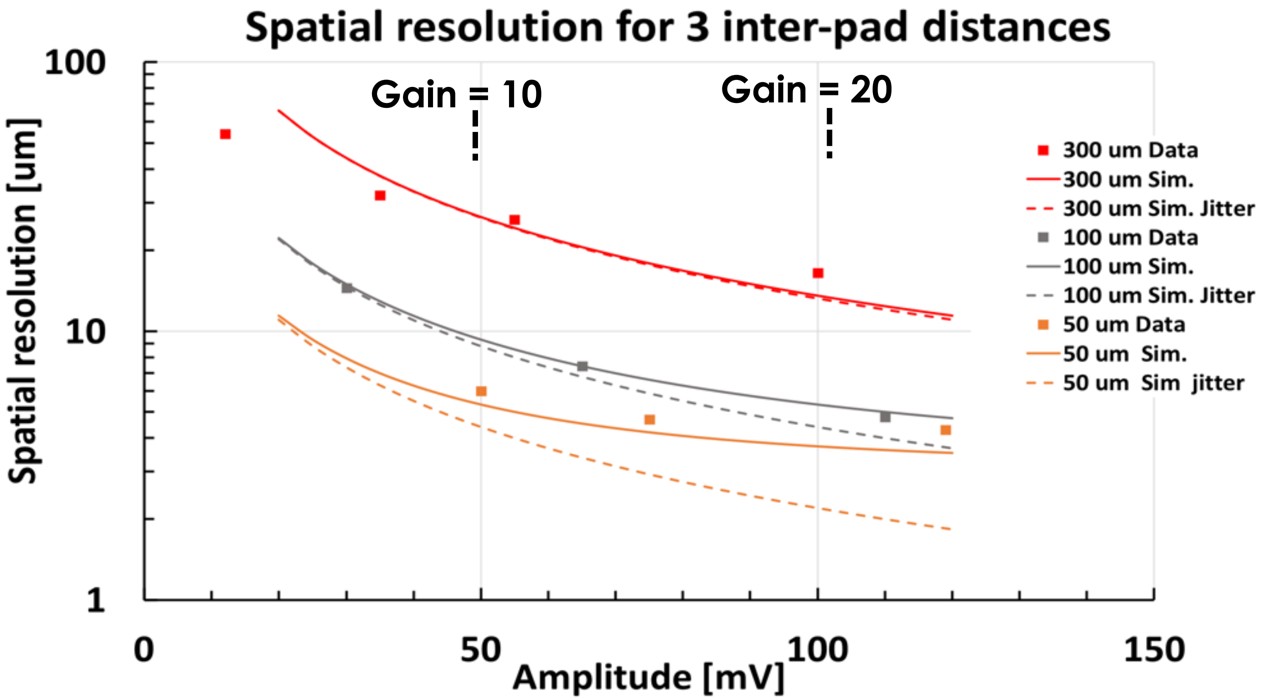
Extra

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

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:

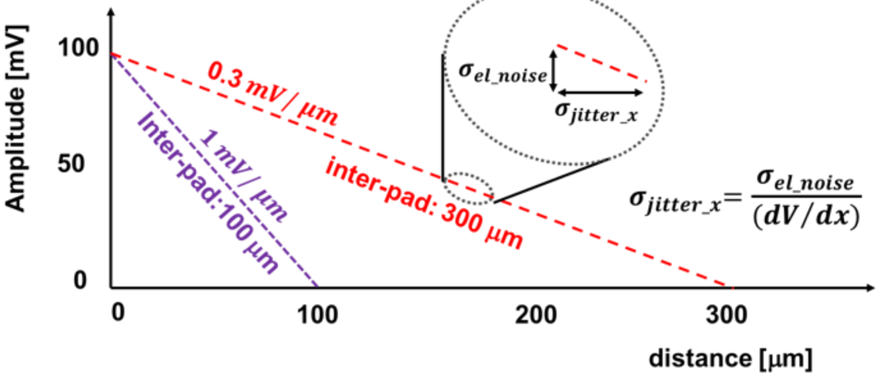
- 100 μm and 300 μm apart
- 100mV signal
- 3 mV electronic noise

100 μm: the signal changes by 1 mV/ μm

➔ σ_{Jitter} **= 3 μm**

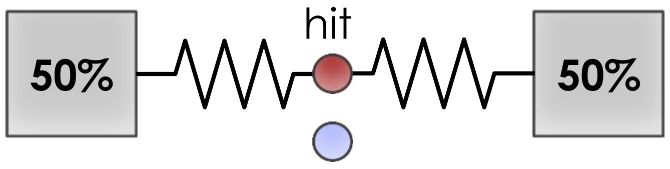
300 μm: the signal changes by 3 mV/ μm

➔ σ_{Jitter} **= 9 μm**

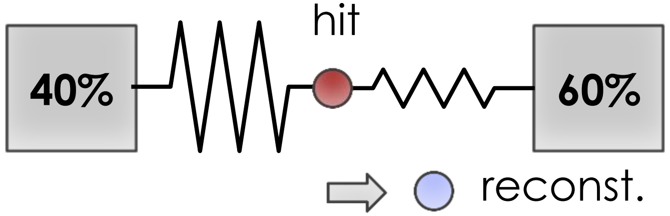


$$\sigma_{Sensor}$$

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

$$\sigma_{Recontruction}$$

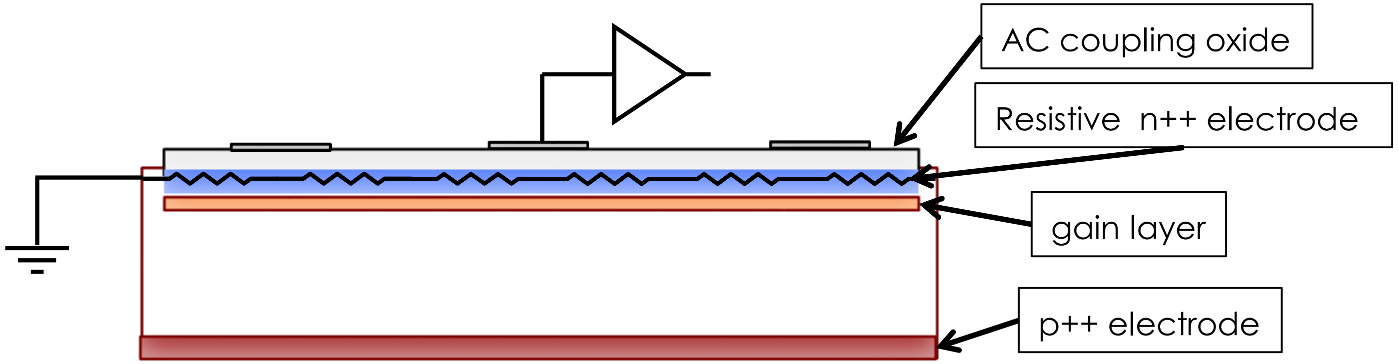
Algorithm

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

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

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

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]

Bibliography

[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

Temporal resolution limit: non uniform ionization

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

Large dV/dt,
➔ small jitter

Non uniform ionization:

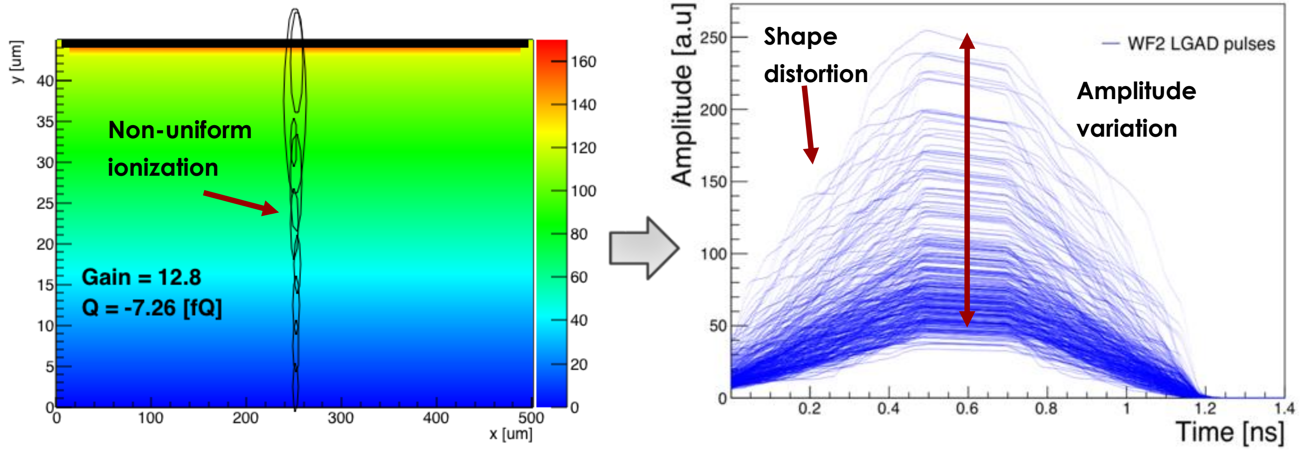
Physical limit of UFSD sensors

UFSD 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

Simulation of signals in 50-um UFSD



WF2 Simulation
Minimum temporal resolution vs sensor thickness using CDF = 50%