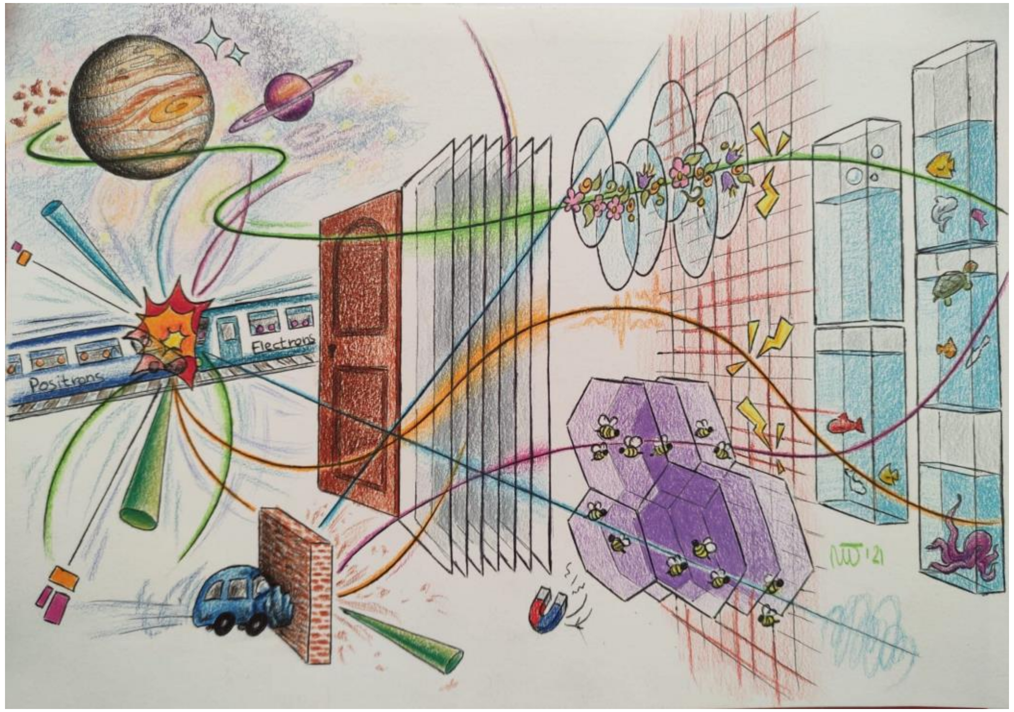
Tracking particle in space and time

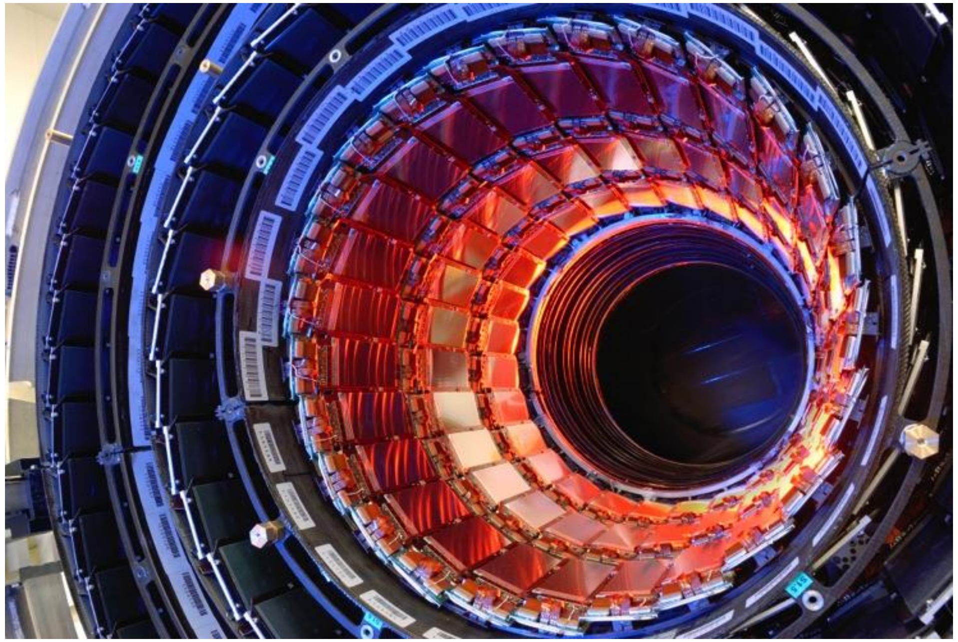
New trends in silicon sensors design



N. Cartiglia
INFN Torino,

Silicon life in 2010

Very mature silicon systems, very large silicon trackers



Millions of channels, very reliable, very radiation hard

Two simple facts in 2010:

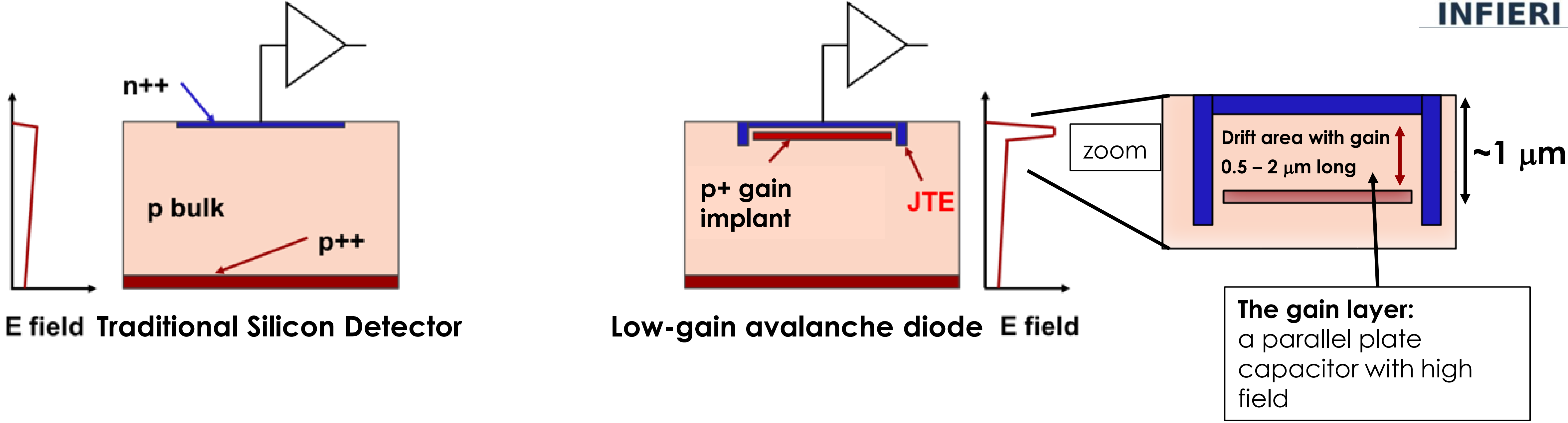
1. Silicon sensors are not suitable timing detectors
2. Silicon sensors cannot be used efficiently to detect 1-5 keV XRay

One nagging problem: radiation damage causes charge trapping, reducing the signal in heavily irradiated sensors.

Solution: add moderate gain, just enough to compensate for charge trapping
"to control and optimize the charge multiplication effect, **in order to fully recover the collection efficiency of heavily irradiated silicon detectors**" [1]

[1] G.Pellegrini,et al., **Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications**, Nucl. Inst. Meth. A 765 (2014) 12.

First design innovation: low gain avalanche diode (LGAD)



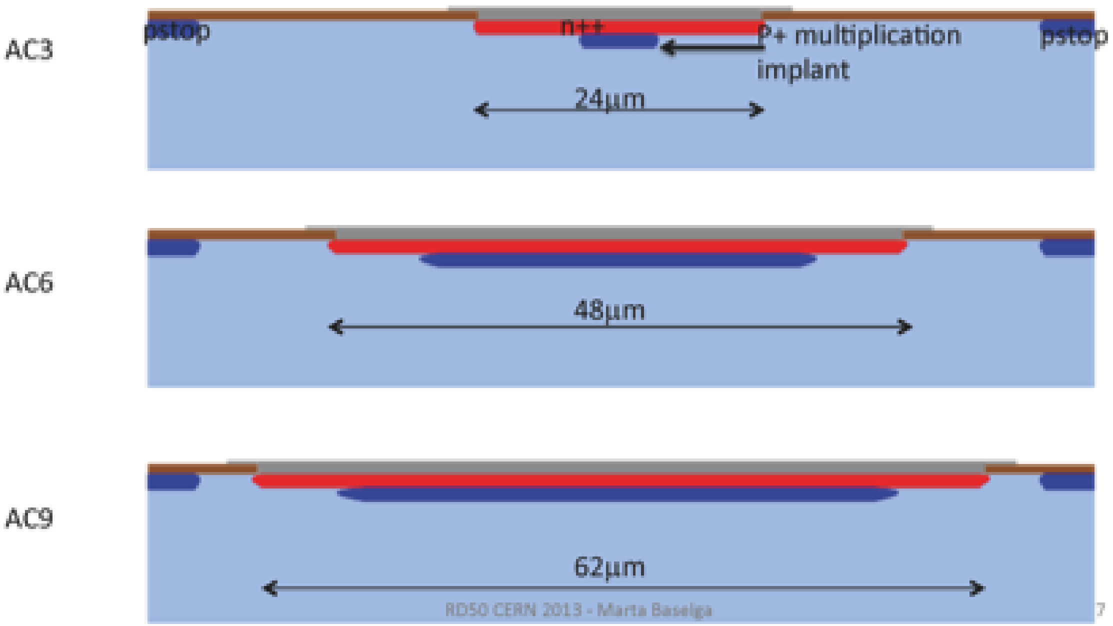
The gain layer:
a parallel plate capacitor with high field

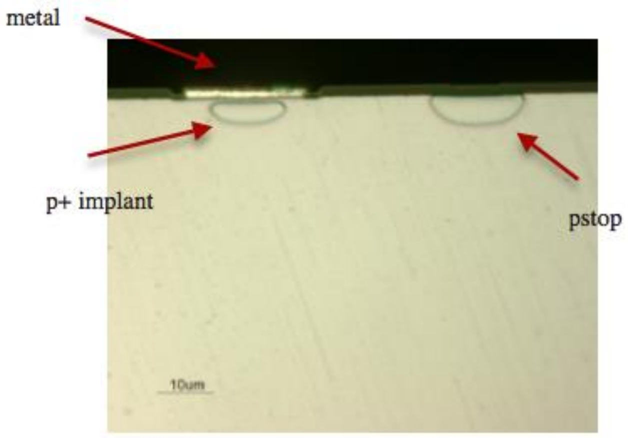
- In LGAD, a moderately p-doped implant creates a volume of high field, where charge multiplication happens.
- **This "extra charge" was supposed to compensate for charge trapping in irradiated silicon sensors**

LGADs Pads, Pixels and Strips

The LGAD approach can be used in any silicon structure,

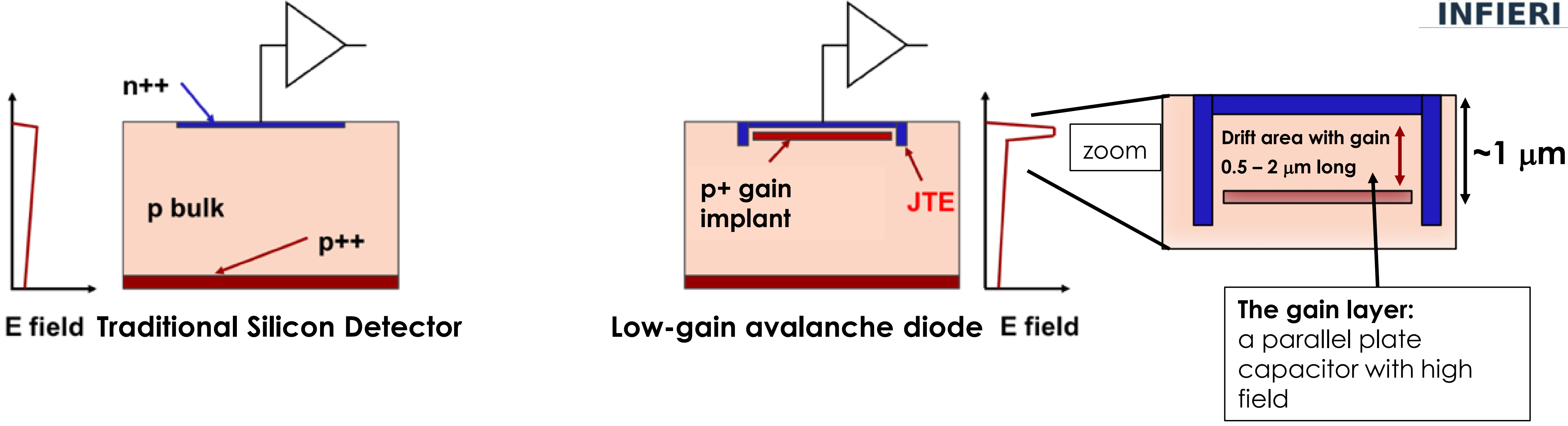
This is an example of LGAD strips





LGAD strips are considered in space application, as they allow to have longer strips while keeping constant the ratio Charge/Capacitance

First design innovation: low gain avalanche diode (LGAD)



E field Traditional Silicon Detector

Low-gain avalanche diode E field

The gain layer:
a parallel plate capacitor with high field

- **It turned out that the LGAD design does not solve the charge-trapping problem as the LGAD mechanism does not work well in high radiation environments (above 2-3E15 1-MeV n_{eq}/cm^2)**

In the meantime, other challenges were becoming important….

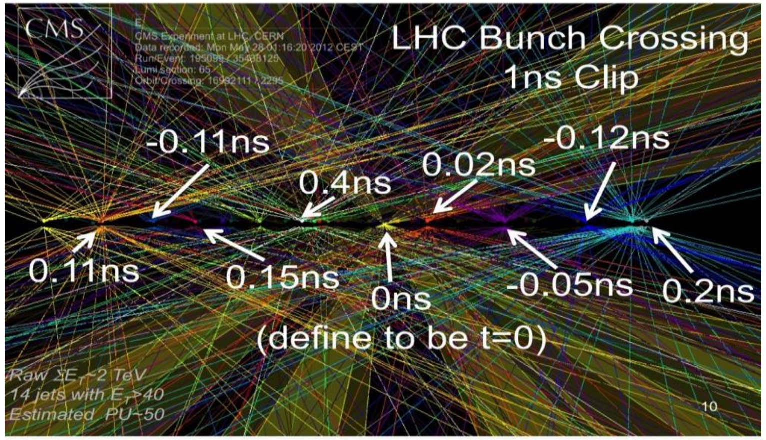
Scattering density in the HL-LHC upgrade

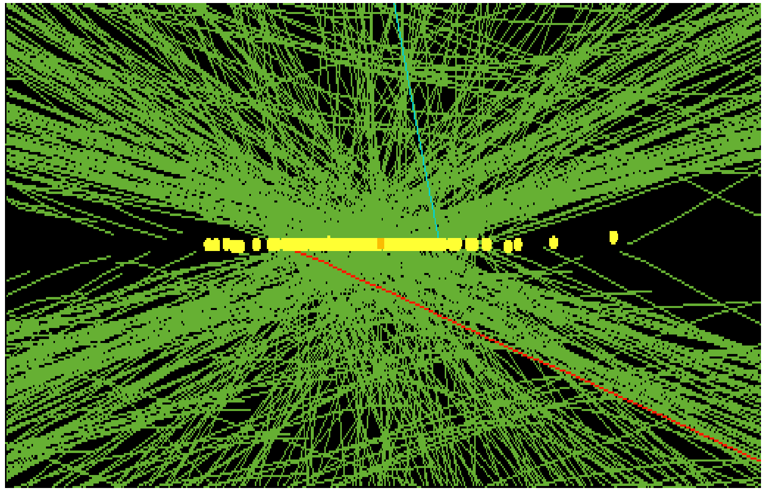
protons

protons

LHC situation:

the collisions are separated in space and time



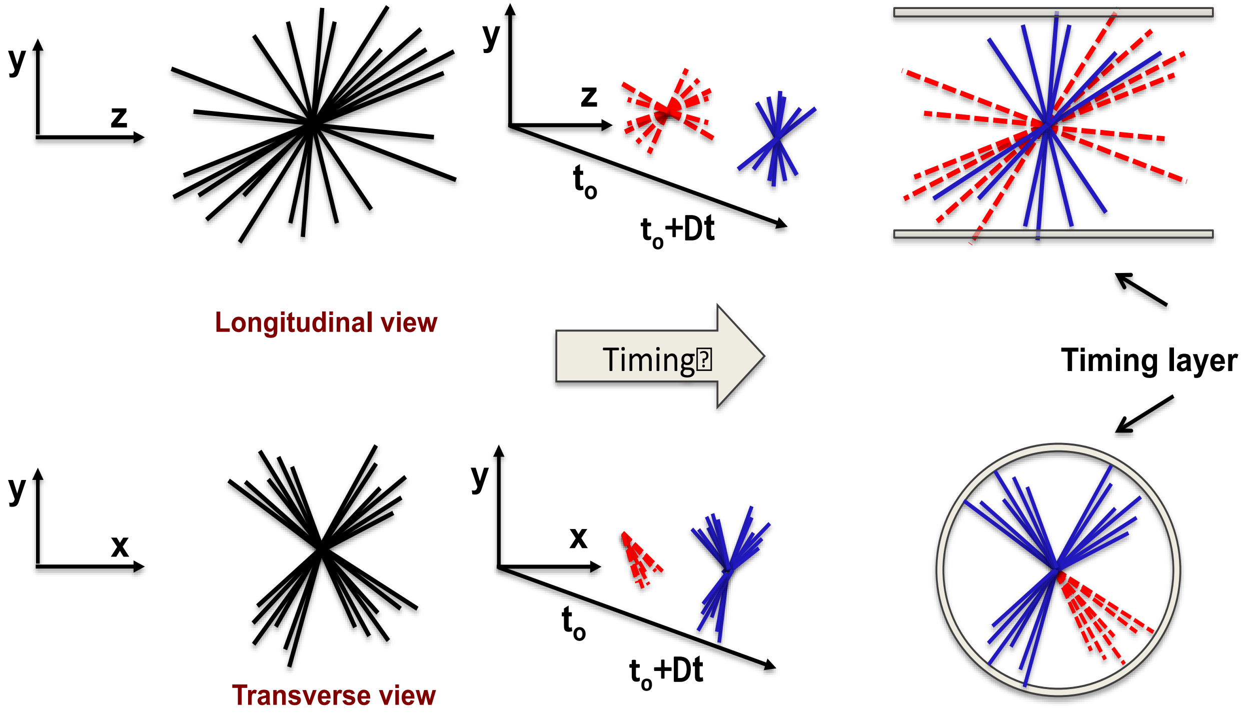


HL-LHC situation:

the collisions are so dense that they overlap in space and time.

This leads to error in the reconstruction of the event

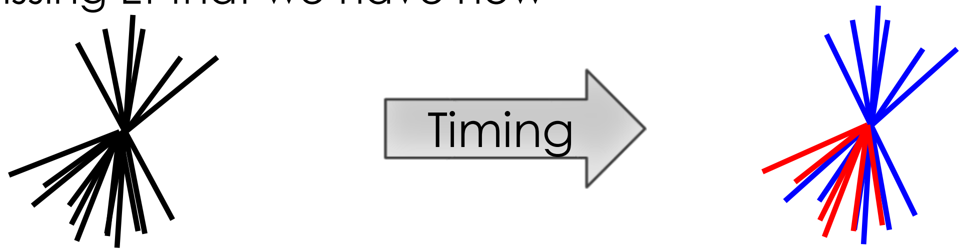
New concept: Tracking in 4Dimension



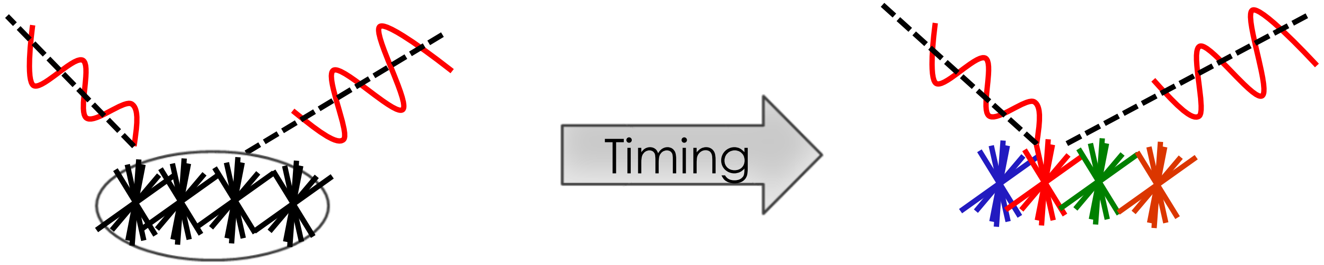
The introduction of timing allows separating collisions that happen in the same location

Timing in the event reconstruction - II

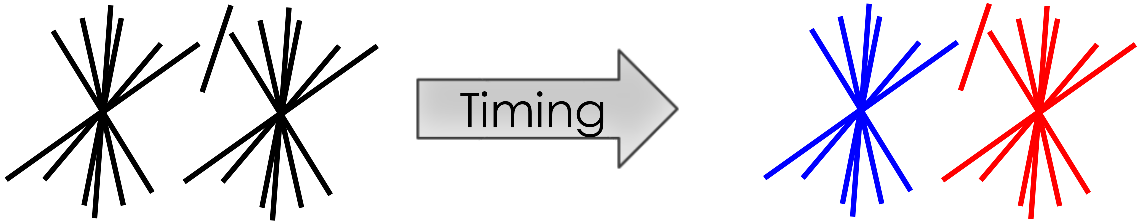
Missing Et: consider overlapping vertexes, one with missing Et: Timing allows obtaining at HL-LHC the same resolution on missing Et that we have now



H ➔ γ γ : The timing of the γγ allows to select an area 1 cm) where the vertex is located. The vertex timing allows to select the correct vertex within this area

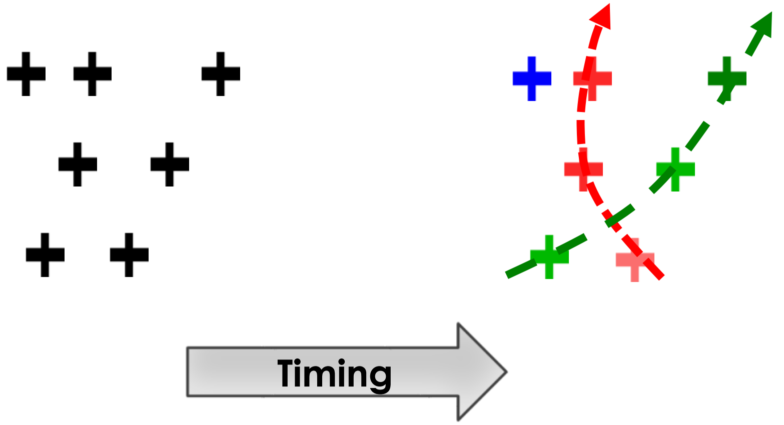


Displaced vertexes: The timing of the displaced track and that of each vertex allow identifying the correct vertex



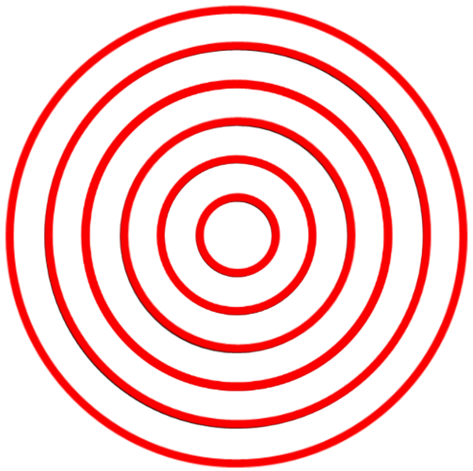
Timing layers and 4D tracking

By "**4D tracking**" we mean the process of assigning a space and a time coordinate to a hit.



Timing can be available at different levels of the event reconstruction:

1) Timing in a single point (timing layer ATLAS,CMS)
2) Timing at some points along the track
3) Timing at each point along the track



Timing layers and 4D tracking

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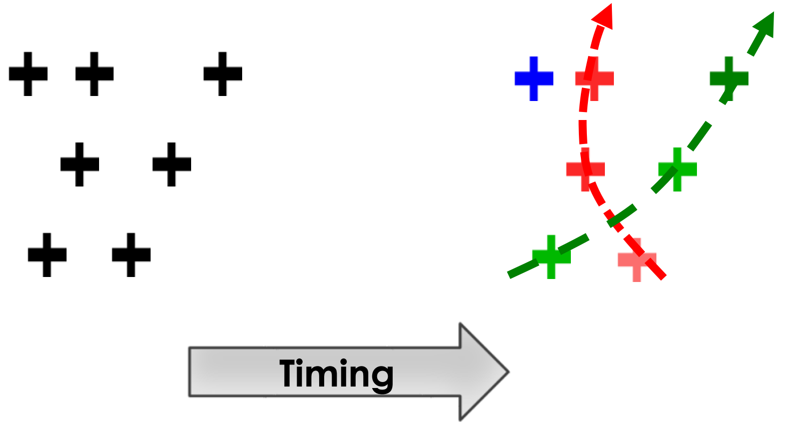


Timing can be available at different levels of the event reconstruction:

1) Timing in a single point (timing layer ATLAS,CMS)
2) Timing at some points along the track
3) Timing at each point along the track

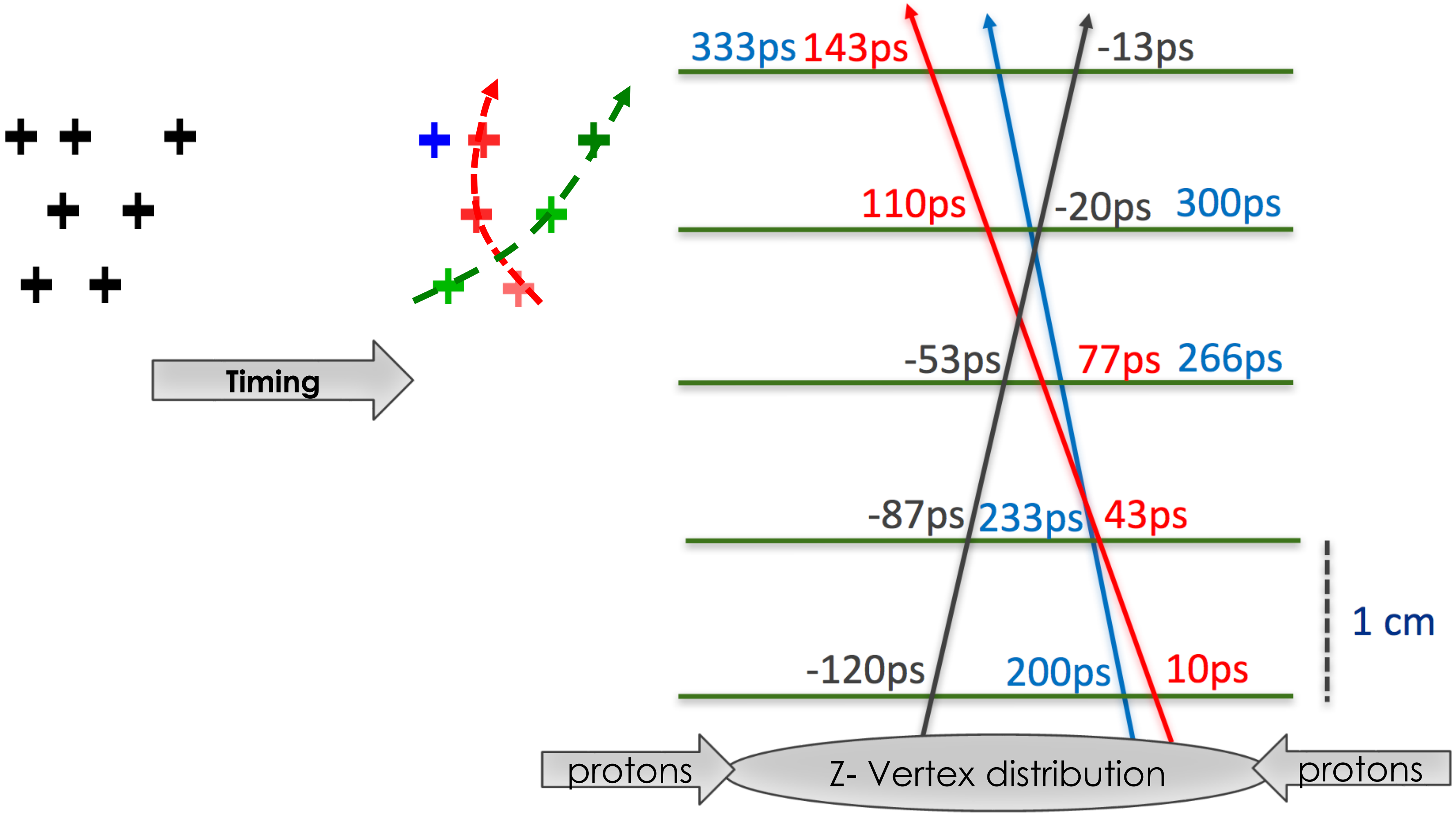
More timing coordinates yields to more performing systems, but require a much more complex read-out system.

Some projects will be perfectly fine with having a limited set of timing points

4D tracking: Timing at each point

➔Massive simplification of patter recognition, new tracking algorithms will be faster even in very dense environments

➔ Use only “time compatible points”



Systems designed for accurate timing

In a large detector system, good temporal resolution has many parts:

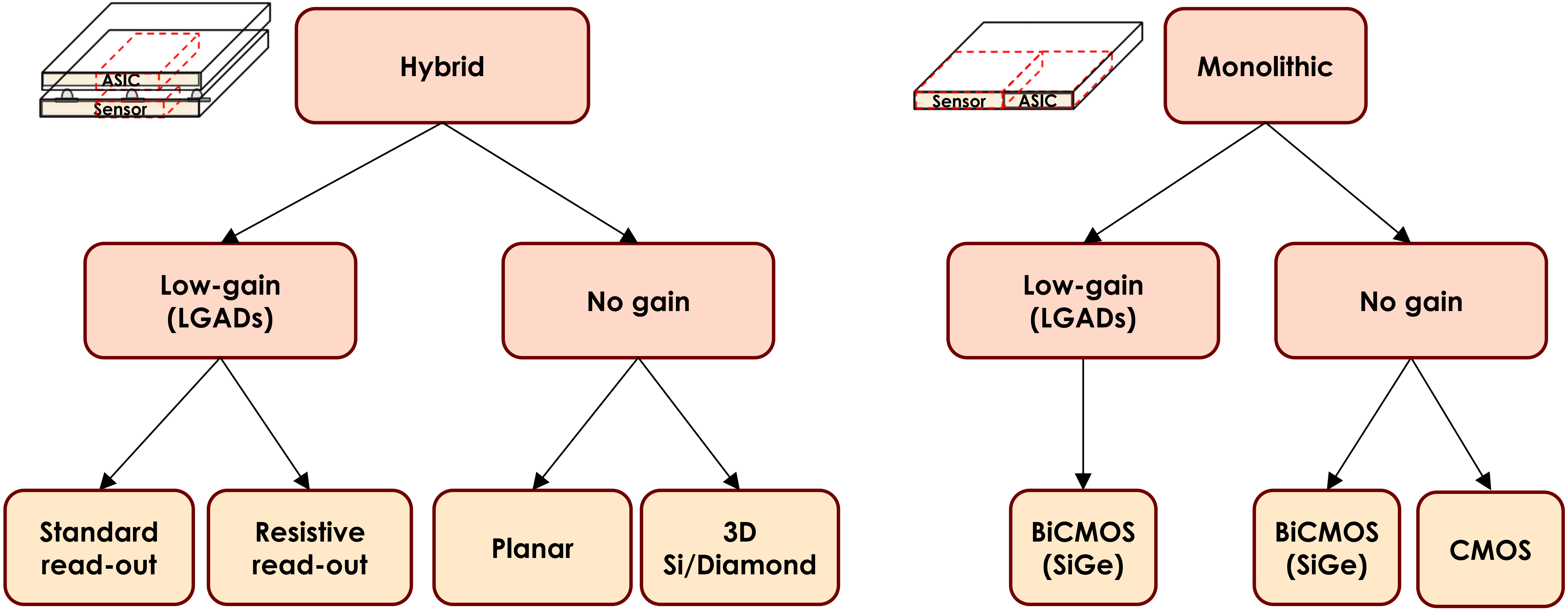
1. **The sensor**
2. **The design of the ASIC:**
   - Technology (process, BW..)
   - Money
   - Power available
2. **Detector design:**
   - Cabling, module quality, noise rejection
   - quality of power supply etc
3. **Infrastructure:**
   - Clock distribution
   - Cooling
   - Data transfer

A detector for timing needs very strong R&Ds in many additional aspects

(these challenges are now faced by the ATLAS and CMS timing layers)

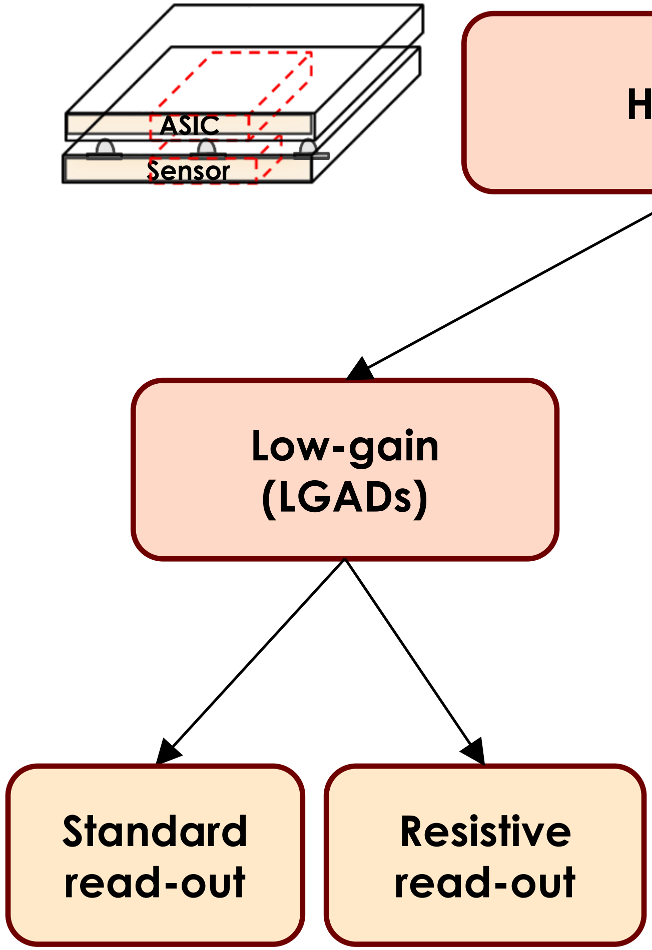
Tracking in 4-dimensions

The present R&Ds in position-sensitive timing detectors is very diverse



- Hybrid
  - Low-gain (LGADs)
    - Standard read-out
    - Resistive read-out
  - No gain
    - Planar
    - 3D Si/Diamond
- Monolithic
  - Low-gain (LGADs)
    - BiCMOS (SiGe)
  - No gain
    - BiCMOS (SiGe)
    - CMOS

The LGAD R&D



Hybrid

Low-gain
(LGADs)

Standard
read-out

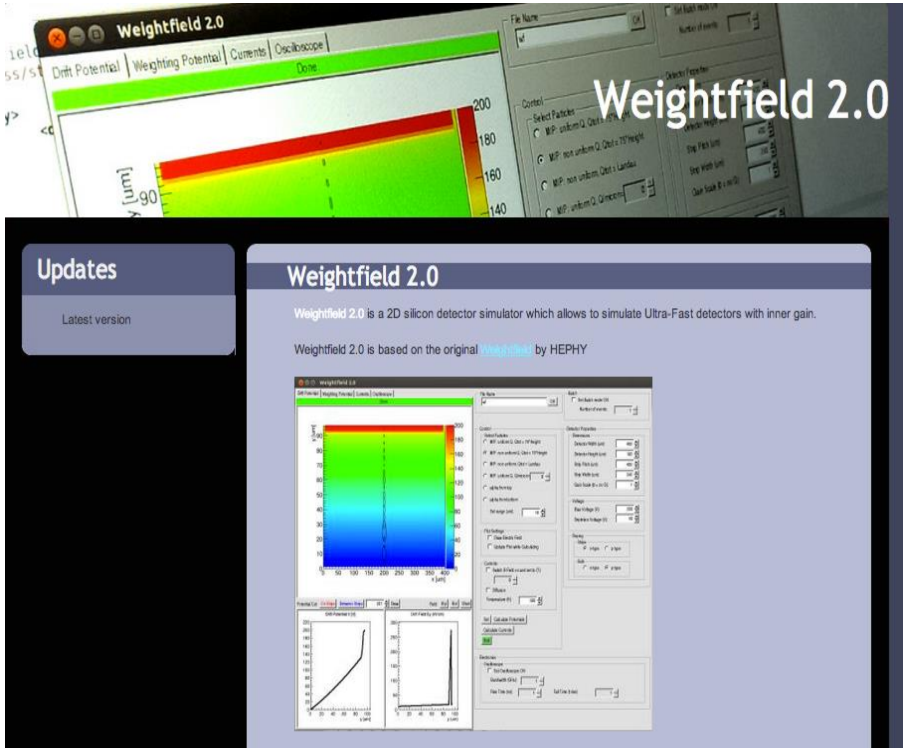
Resistive
read-out

In the past 10 years, the developments of LGAD have reached a very mature phase.
LGAD are now used in ATLAS and CMS, and considered in many future experiments.

Key tool: WF2 sensor simulation

The design of pico-second front-end electronics needs to know what type of current signals the front end will receive.

For this reason, we designed a simulator able to simulate the current pulse generated by silicon sensors accurately



Weightfield 2.0 is a 2D silicon detector simulator which allows to simulate Ultra-Fast detectors with inner gain.

Weightfield 2.0 is based on the original Weightfield by HEPHY

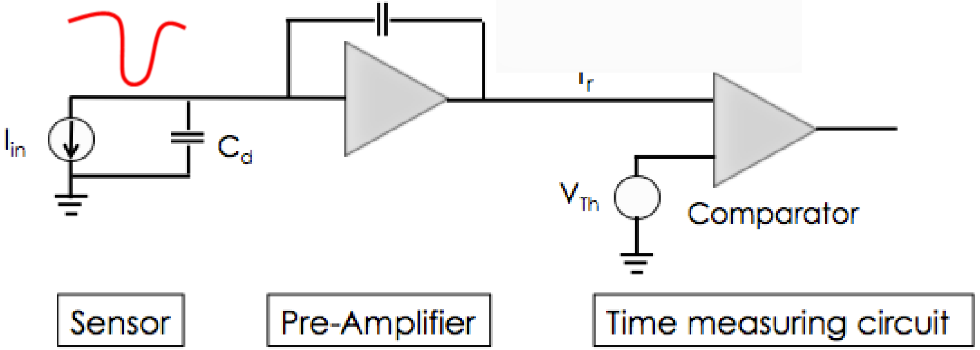
It includes:

- Custom Geometry
- Calculation of drift field and weighting field
- Currents signal via Ramo’s Theorem
- Gain
- Diffusion
- Temperature effect
- Non-uniform deposition
- Electronics

WeightField2, Available at
http://personalpages.to.infn.it/~cartigli/weightfield2

Silicon time-tagging detector

- Sensors produce a current pulse
- The read-out measures the time of arrival



Sensors and read-out are two parts of a single object, sometimes even on the same substrate (monolithic option).

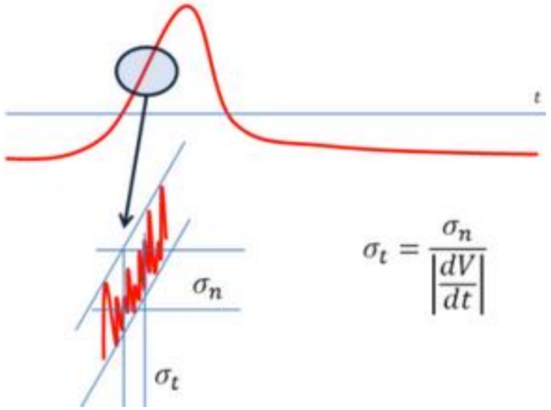
Sensors and electronics succeed (or eventualy fail) together

In “timing circuits”, things can go wrong very rapidly (quote stolen from a chip designer)

==> this is not a simple evolution of what we know how to do.

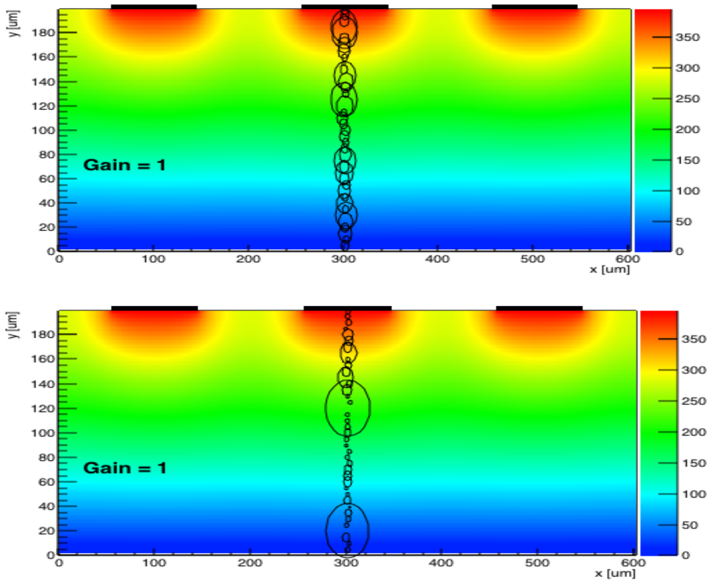
Time resolution

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

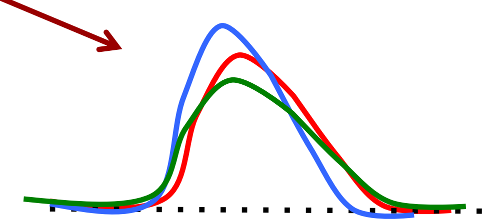


“Jitter” term

Small noise ==> choice of electronic technology
Large dV/dt ==> use sensors with internal gain

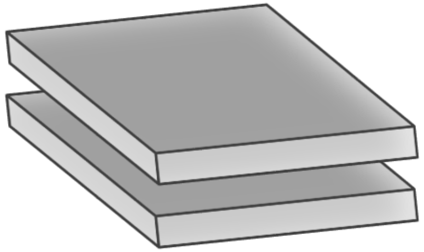


Amplitude variation ==> corrected offline (time walk)
Non-homogeneous energy deposition ==> signal change variation. Cannot be corrected, =minimized by design



Signal shape is determined by Ramo’s Theorem

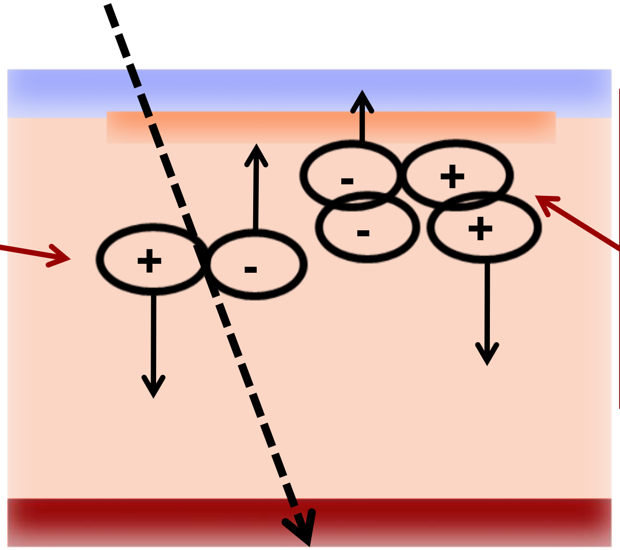
$i \, \mu \, qvE_w$



Saturated drift velocity v everywhere in the sensor volume
Uniform weighting field E_w

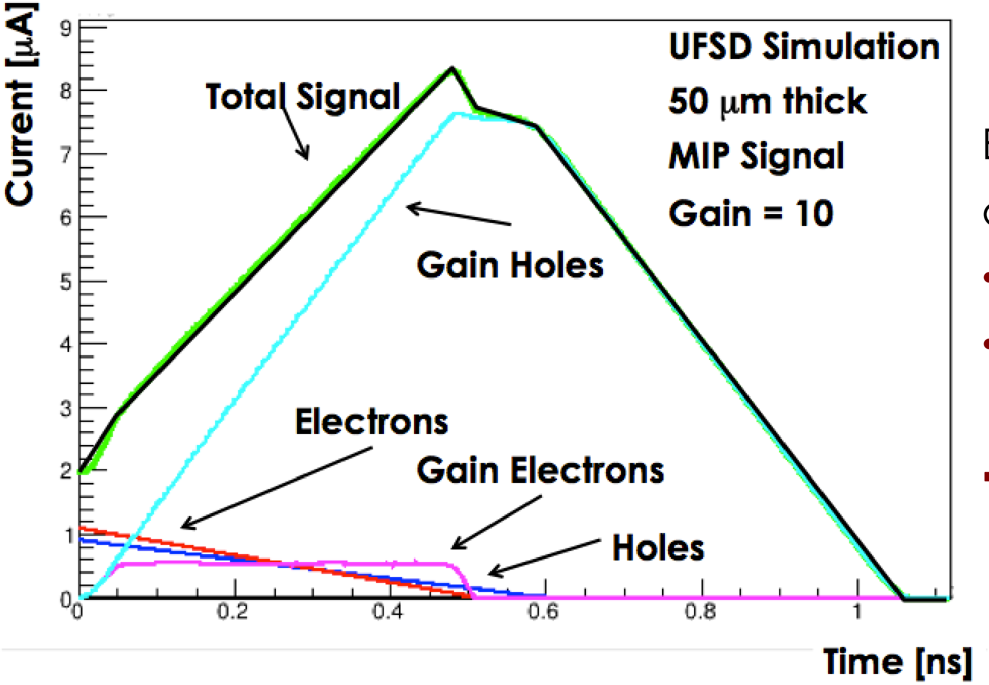
==> Needs parallel plate geometry

Minimize jitter: LGADs have large signals!



Initial electron, holes

Gain electron:
absorbed immediately
Gain holes:
long drift home



Electrons multiply and produce additional electrons and holes.

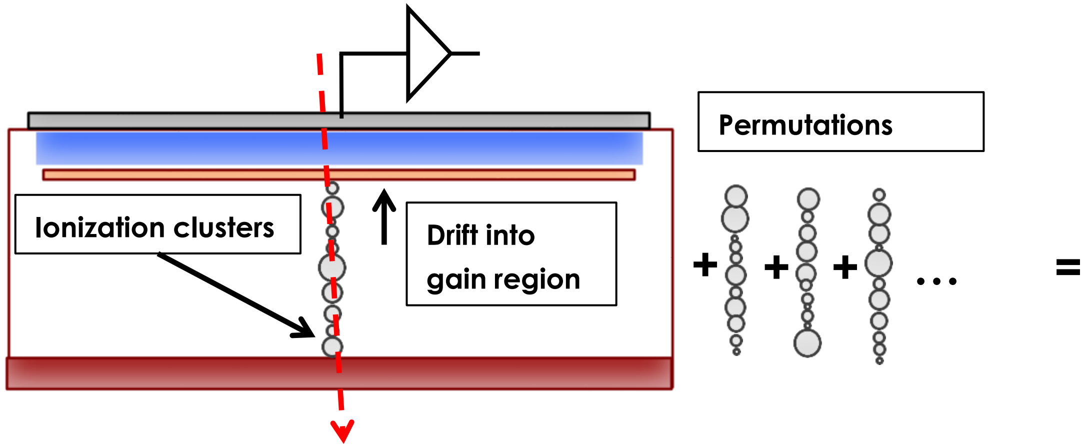
- **Gain electrons have almost no effect**
- **Gain holes dominate the signal**

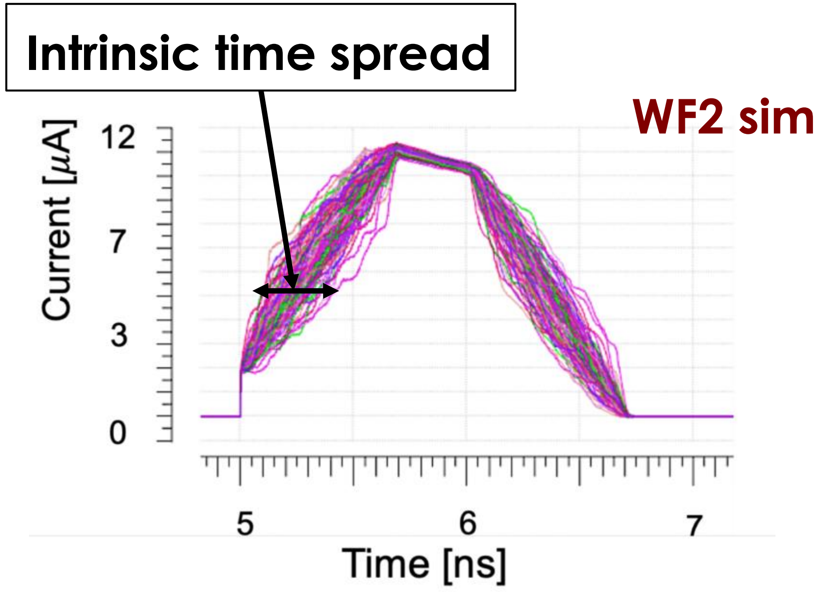
➔ **No holes multiplications**

Intrinsic LGAD time resolution

Why LGAD have an "intrinsic" time resolution?

It is a combinatorial problem: how many different ways are there to produce a given amplitude summing up individual ionization clusters (imagine there is 1 cluster every 1 micron) ?





WF2 simulation

50 microns thick ==> 50! Permutations…

10 microns thick ==> 10! Permutation

The thinner the sensor, the smaller the intrinsic time resolution

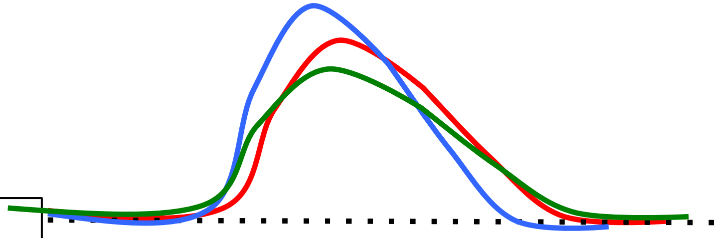
Sensor geometry: how to minimize its contribution to σ_t^2

Signal shape is determined by Ramo's Theorem:

$$i\ \mu\ qvE_w$$

Drift velocity

Weighting field



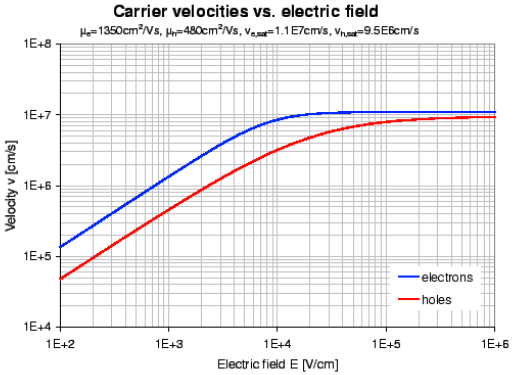
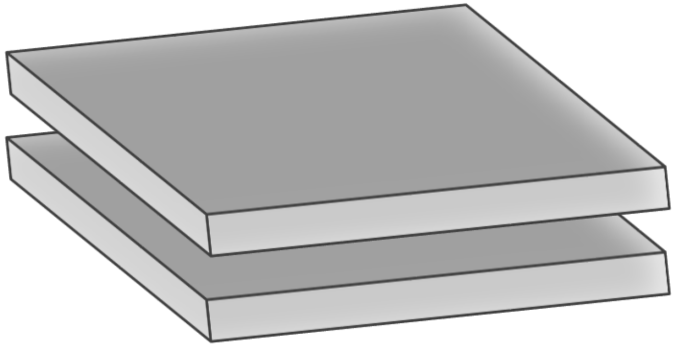


Figure: Electron and hole velocities vs. the electric field strength in silicon.



The key to good timing is the uniformity of signals:

Drift velocity and Weighting field need to be as uniform as possible

Basic rule: **parallel plate geometry**

What is the signal of one e/h pair?

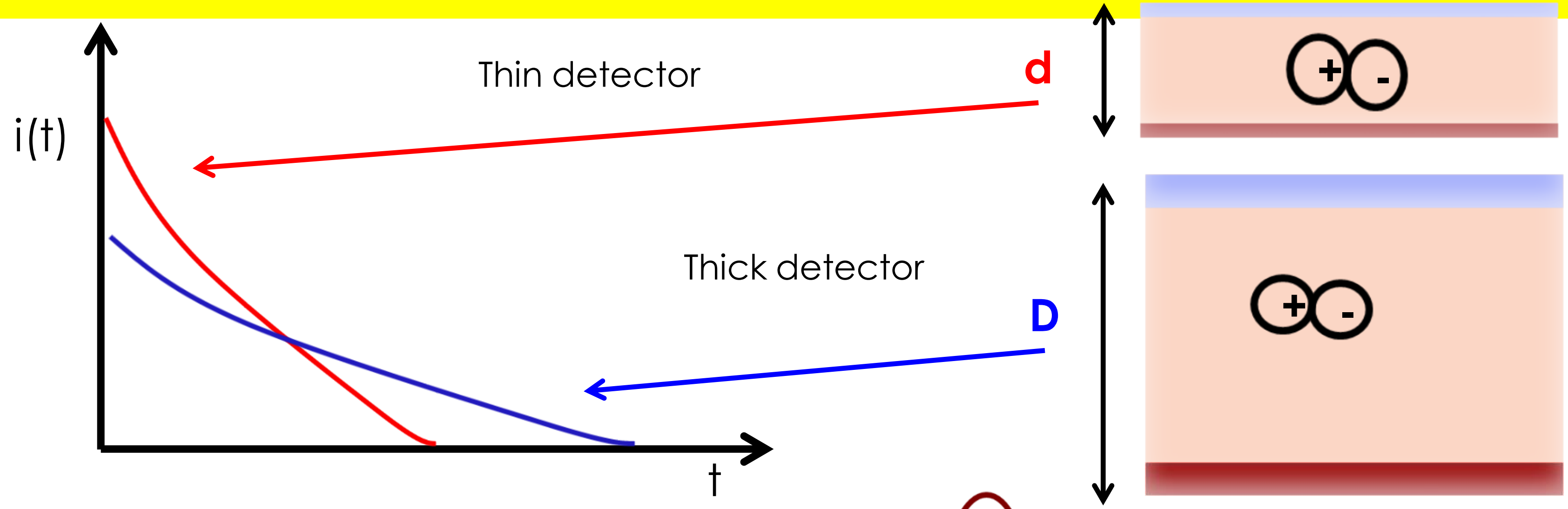
(Simplified model for pad detectors)

Let's consider **one single electron-hole pair.**

The integral of the current is equal to the electric charge, q:

$$\int [i_{el}(t)+i_h(t)]dt = q$$

However, **the shape of the signal depends on the thickness d:**
Thinner detectors have a higher slew rate

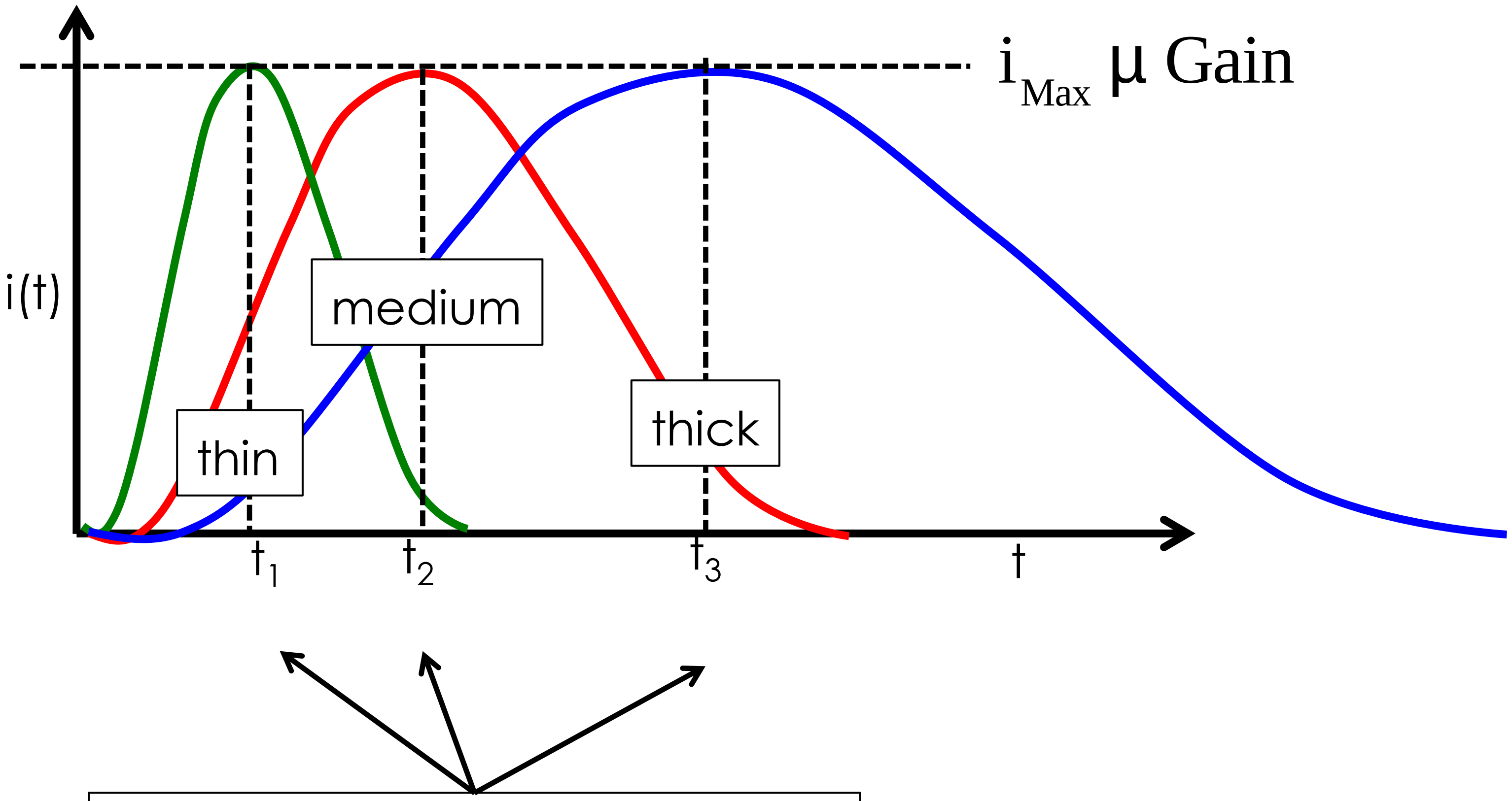


➔ **One e/h pair generates a higher current in thin detectors**

$$i \propto qv\boxed{\frac{1}{d}} \leftarrow \text{Weighting field}$$

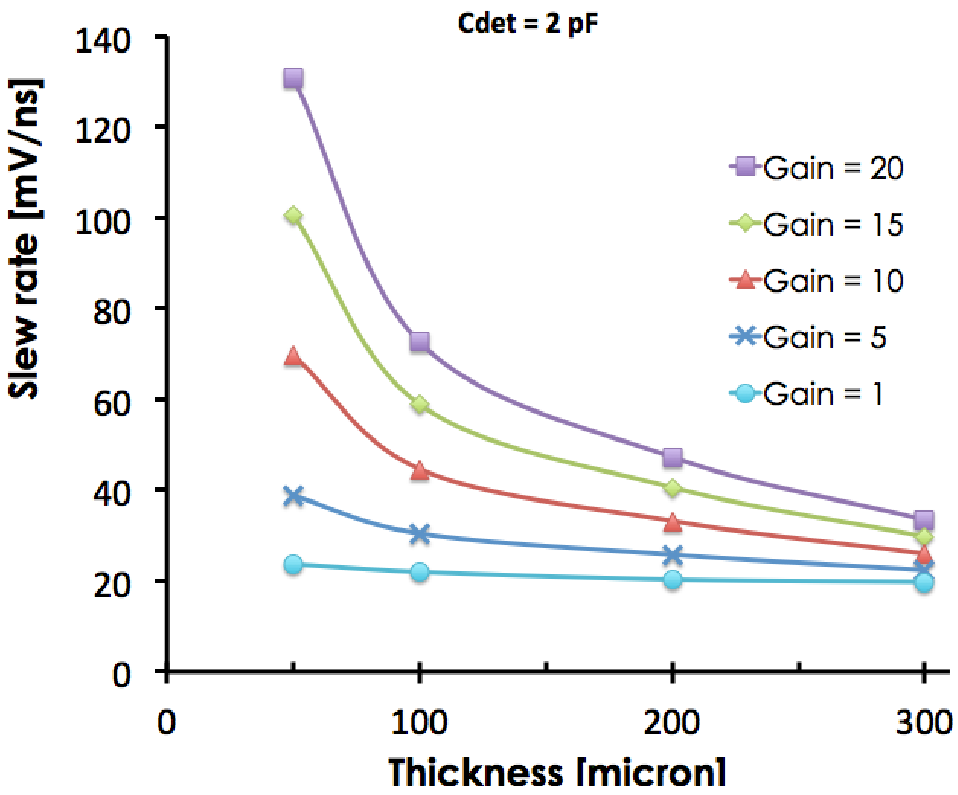
Slew rate dV/dt

$$\frac{dV}{dt} \mu \frac{G}{d}$$



The rise time depends only on the sensor thickness ~ 1/d

Slew rate vs sensor thickness



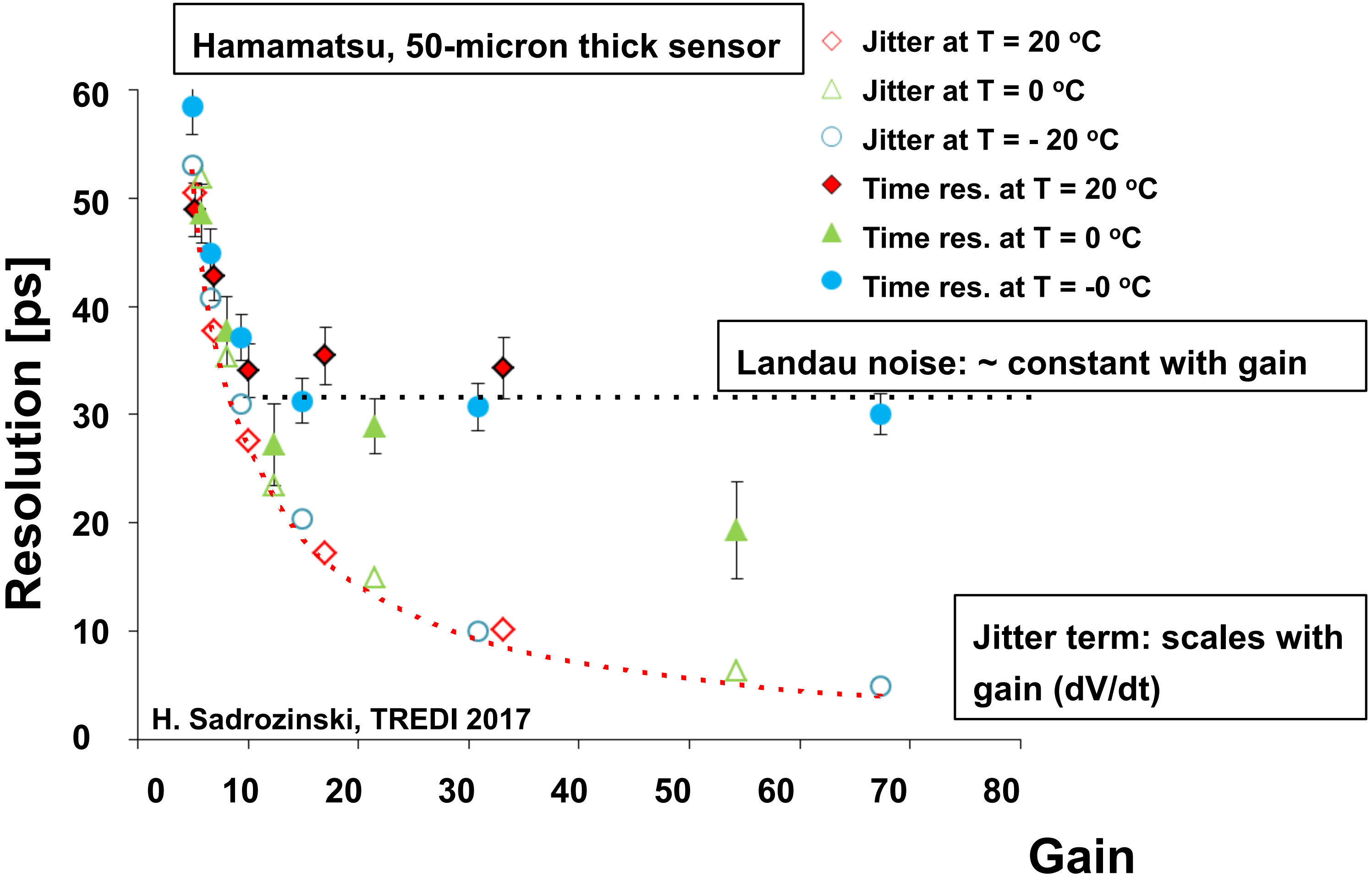
300 micron:
~ 2-3 improvement
with gain = 20

Significant improvements in time resolution require thin detectors

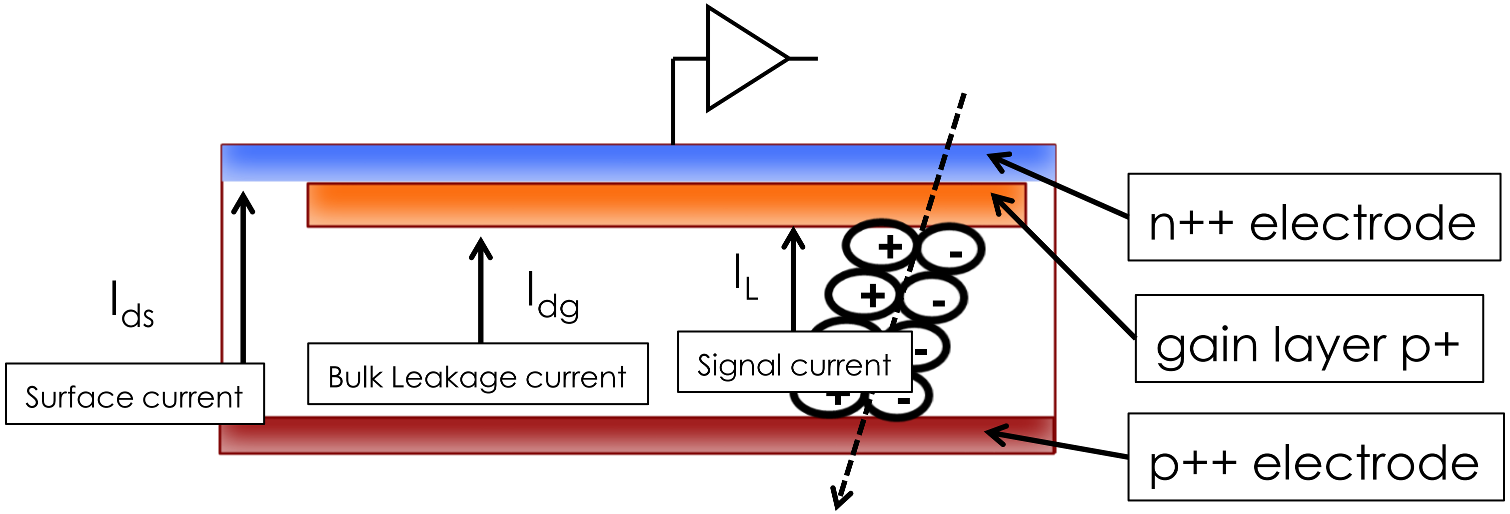
An example ofLGAD Hamamatsu’s time resolution

UFSD from Hamamatsu: 30 ps time resolution,

Value of gain ~ 20



Why low gain? Shot noise in LGAD - APD



I_{ds}

Surface current

I_{dg}

Bulk Leakage current

I_L

Signal current

n++ electrode

gain layer p+

p++ electrode

$$i^2_{Shot} = 2eI_{Det} = 2e\left[I_{Surface} + (I_{Bulk} + I_{Signal})M^2F\right]$$

Correction factor to the standard Shot noise, due to the noise of the multiplication mechanism

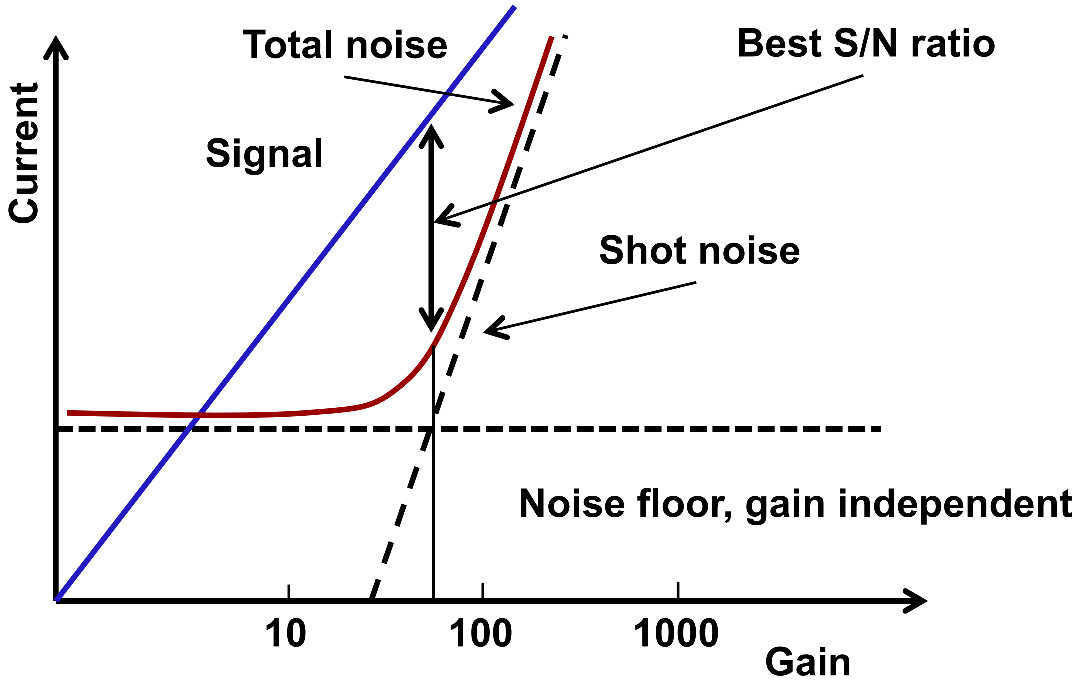
$$F = Mk + \left(2 - \frac{1}{M}\right)(1 - k)$$

$$F \sim M^x$$

k = e/h ionization rate
x = excess noise index
M = gain

$$F = \frac{\langle M^2 \rangle}{\langle M \rangle^2} \Rightarrow \langle M^2 \rangle = \langle M \rangle^2 F$$

Noise increase as a function of gain



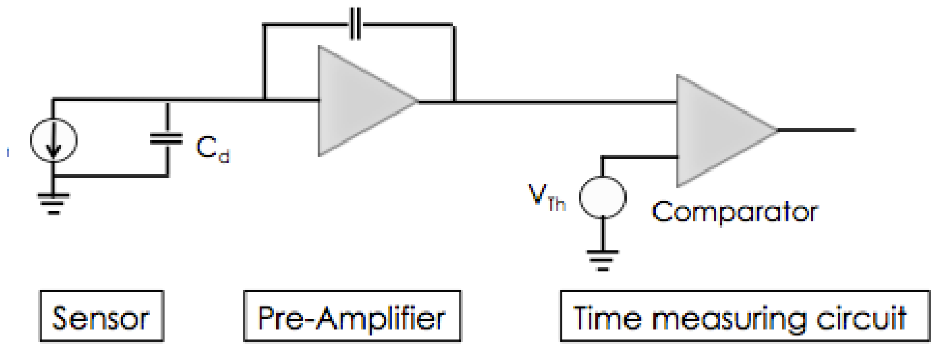
Goal:

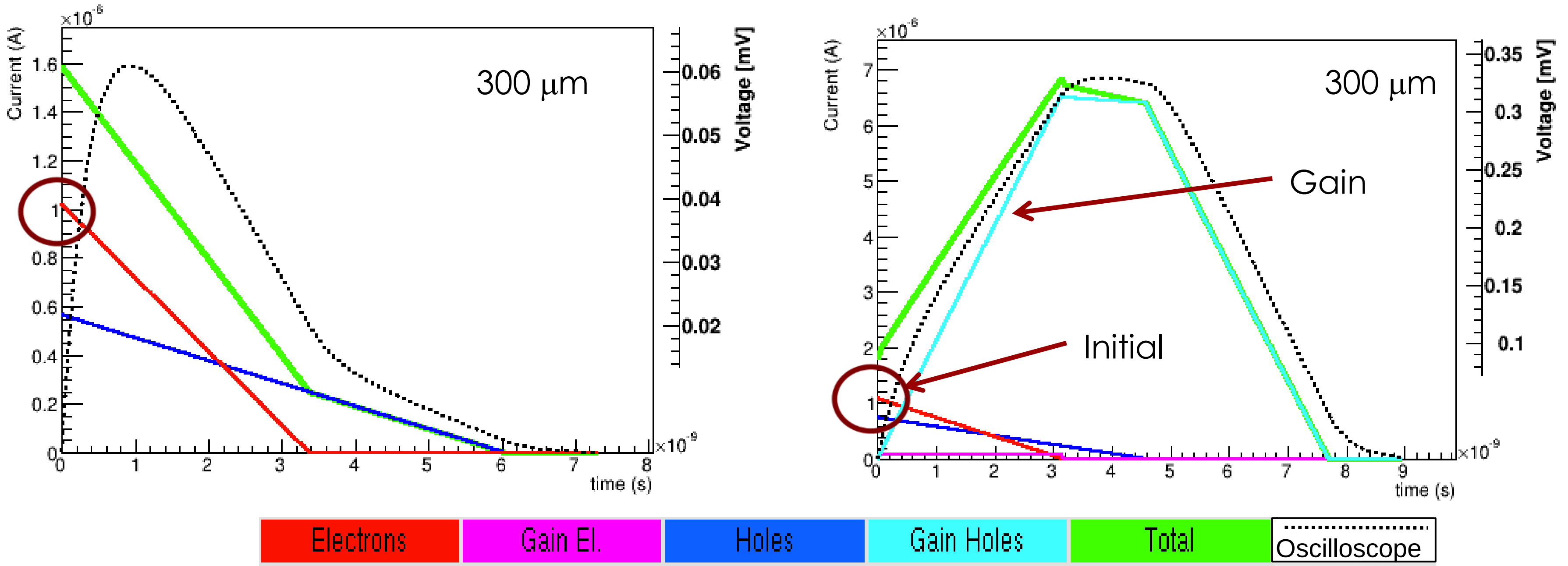
The noise from silicon current should stay below that of the electronics

Electronics

To fully exploit UFSDs, dedicated electronics needs to be designed.

The signal from UFSDs is different from that of traditional sensors





Simulated Weightfield2

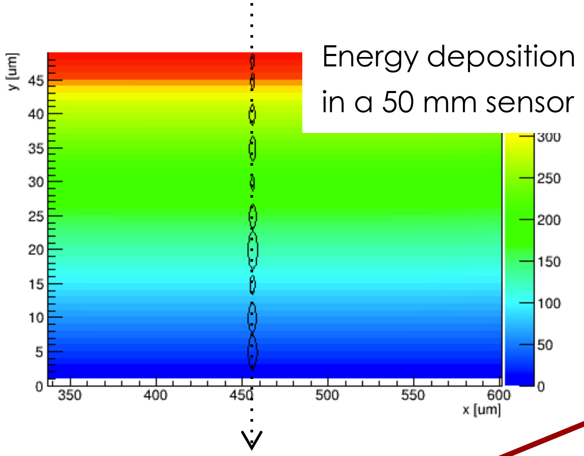
Pads with no gain

Charges generated uniquely by the incident particle

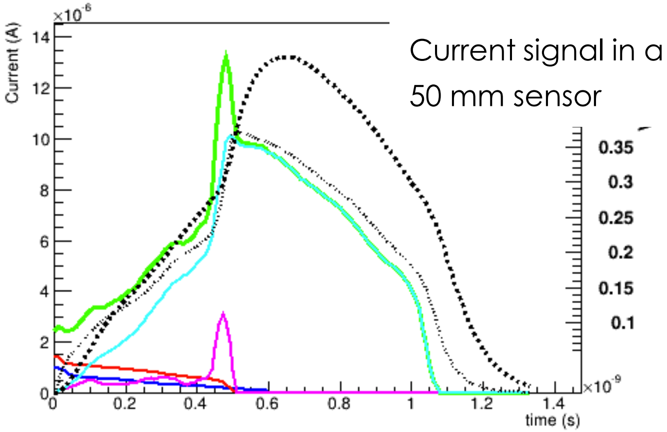
Pads with gain

Current due to gain holes creates a longer and higher signal

Electronics: What is the best pre-amp choice?

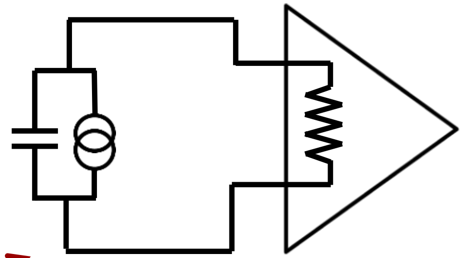


Energy deposition in a 50 mm sensor

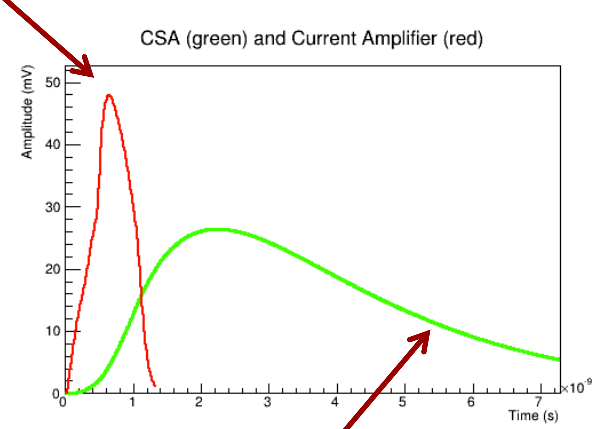


Current signal in a 50 mm sensor

Current Amplifier

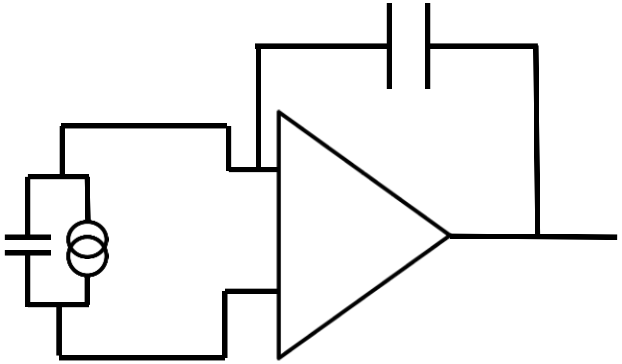


- Fast slew rate
- Higher noise
- Sensitive to Landau bumps



CSA (green) and Current Amplifier (red)

Charge Sensitive Amplifier



- Slower slew rate
- Quieter
- Integration helps the signal smoothing

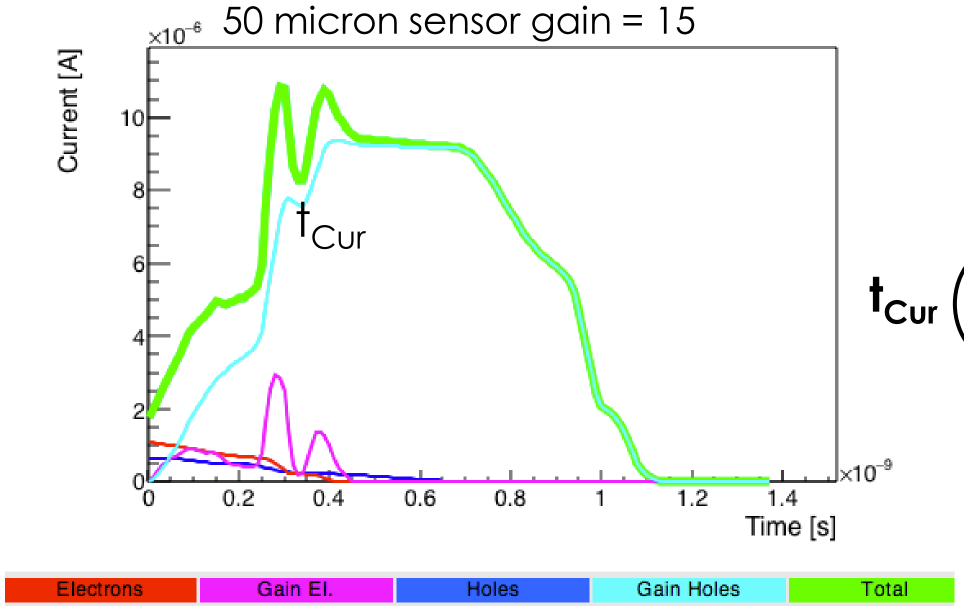
The players: signal, noise and slope

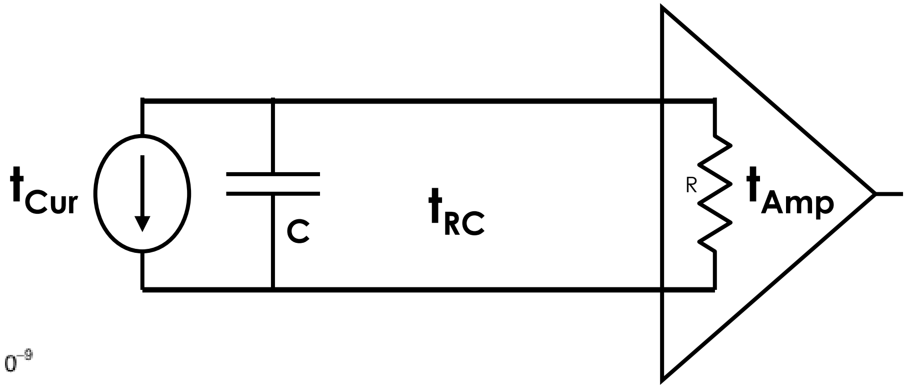
Signal dV/dt

Landau Noise

Shot Noise

Electronic Noise





The current rise time (t_{Cur})

The RC circuit (t_{RC})

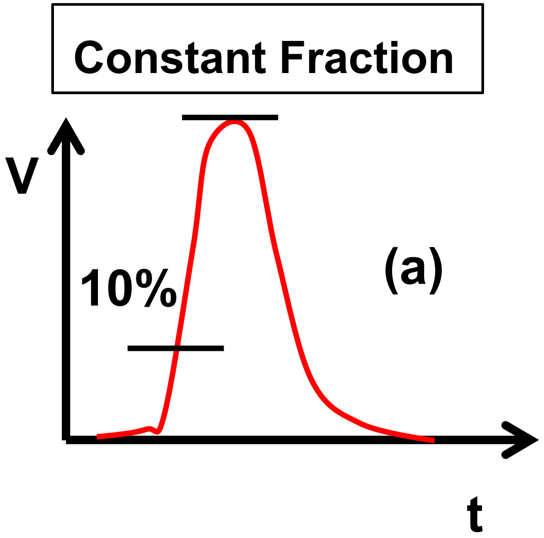
Amplifier rise time (t_{Amp})

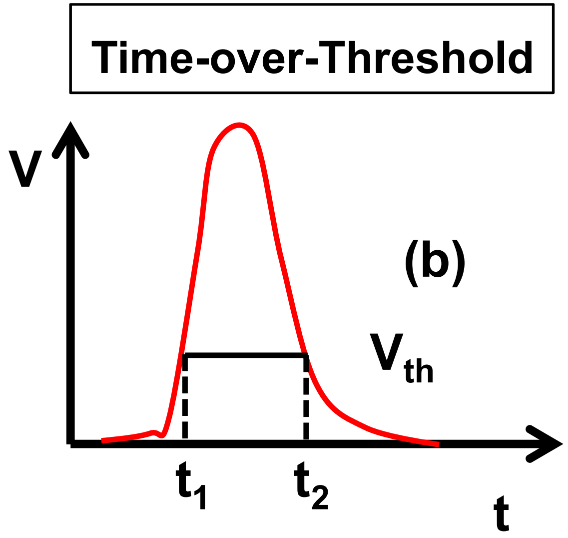
There are 3 quantities determining the rise time after the amplifier:

1. The signal rise time (t_{Cur})
2. The RC circuit formed by the detector capacitance and the amplifier input impedance (t_{RC})
3. The amplifier rise time (t_{Amp})

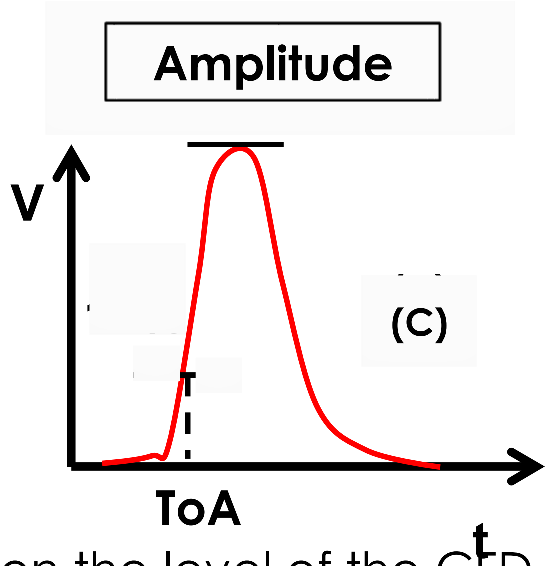
Time walk corrections

On paper both seem feasible, in practice **ToT is much easier to implement**





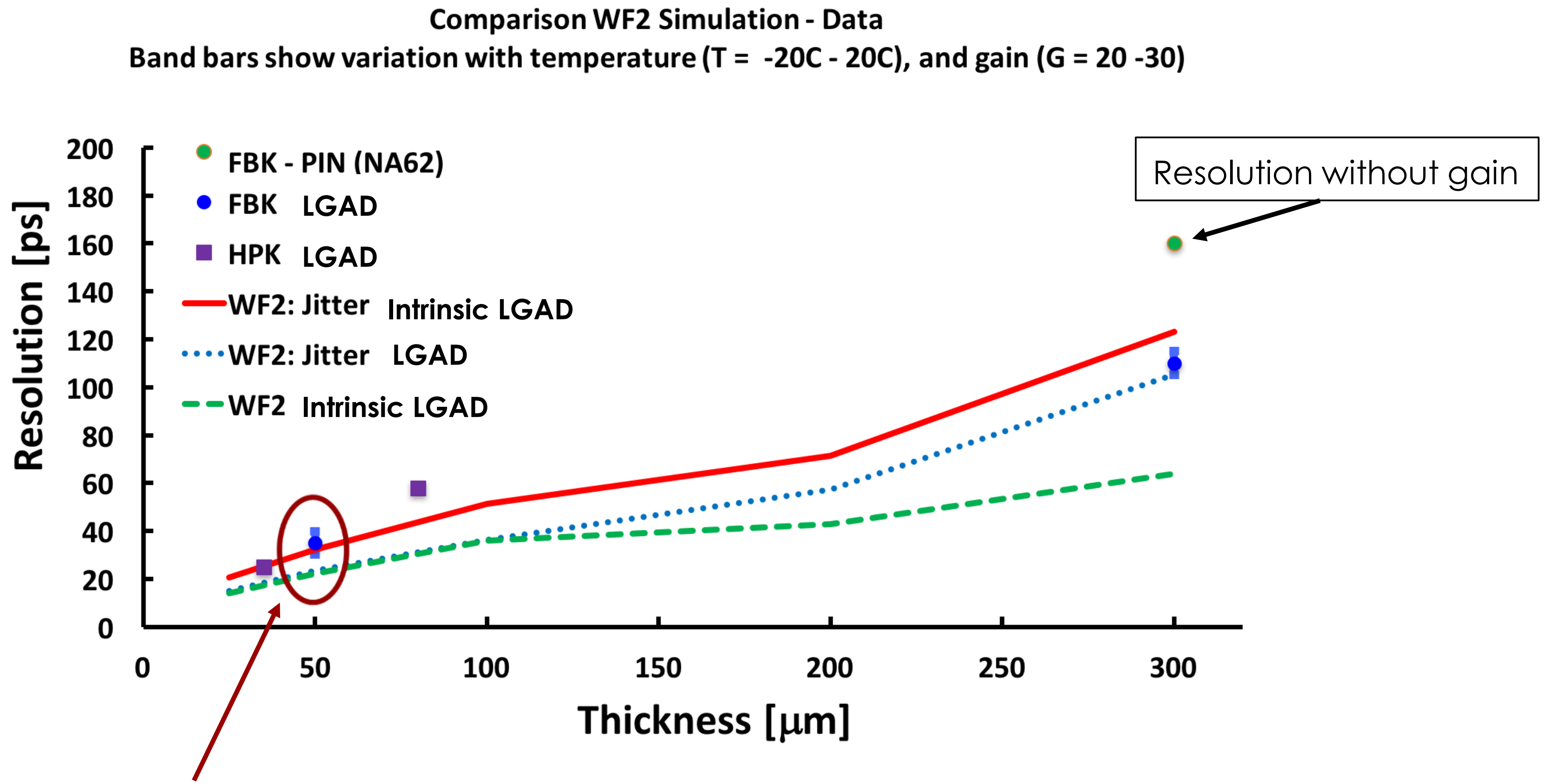
My favorite: **ToA and Amplitude**
➔ The tail of the signal is prone to large changes due to charge trapping



What is the influence of the sensor on the level of the CFD or of V_{th}?

LGAD temporal resolution vs sensor thickness

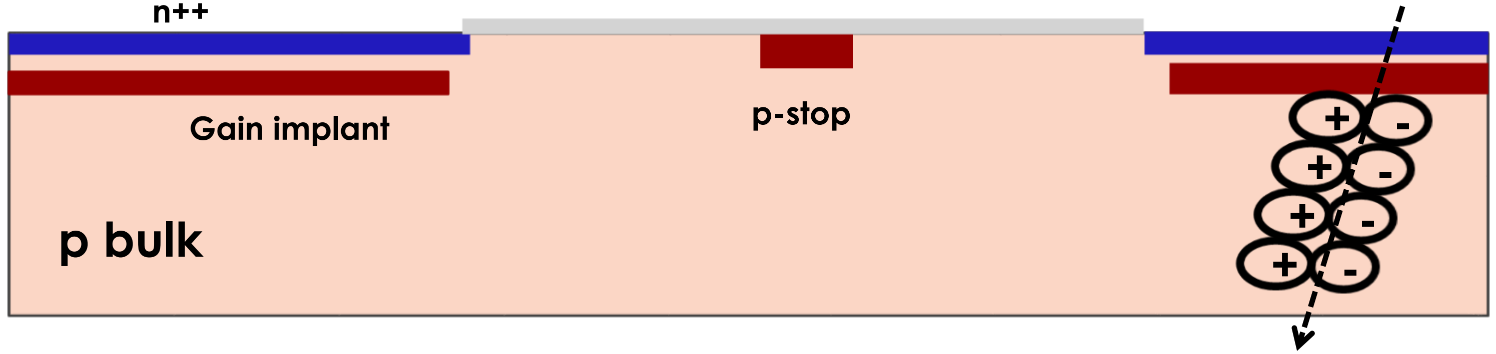
Note: LGADs have an intrinsic resolution that depends on the thickness



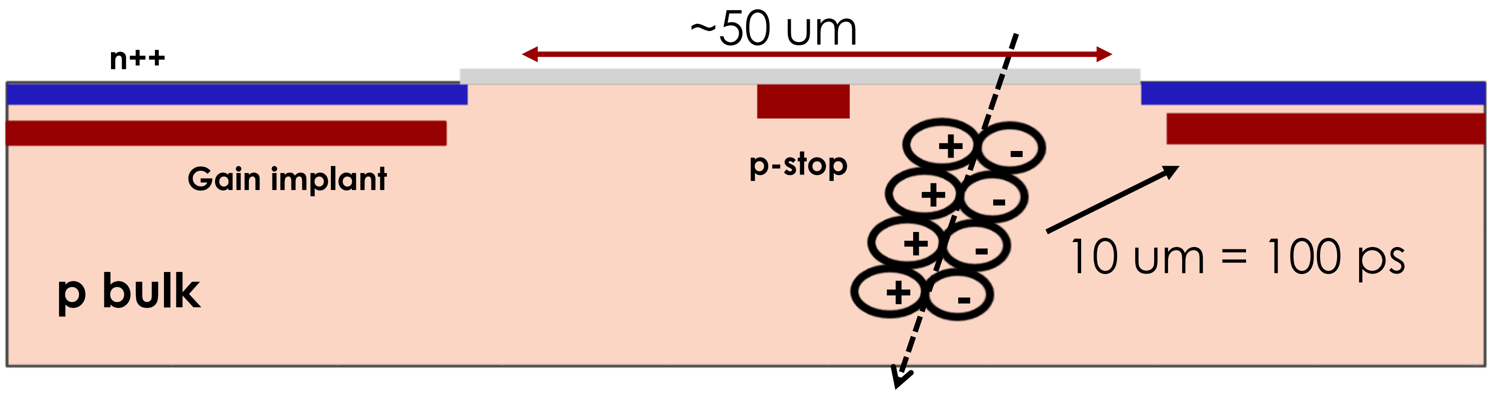
Both CMS and ATLAS have opted for 50 µm thick LGAD,
(intrinsic time resolution of about 30 ps)

Signals from inter-pad region

Particles hitting a pad create charges underneath the timing layer: no delay between the passage of the particle and the start of multiplication

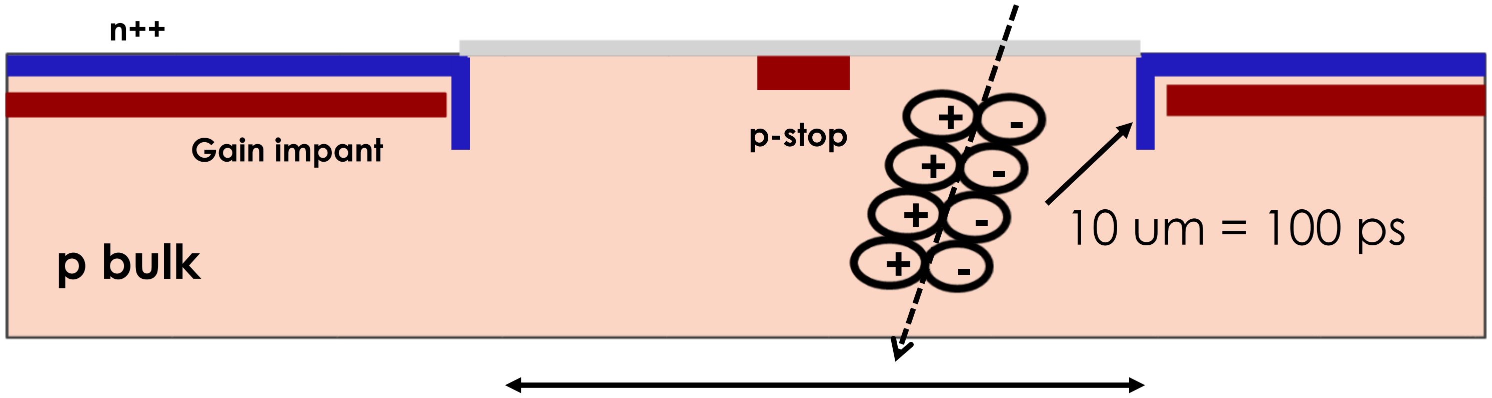


Particles hitting between pads create charges far from the multiplication layers: they generate late signals



Signals from inter-pad region

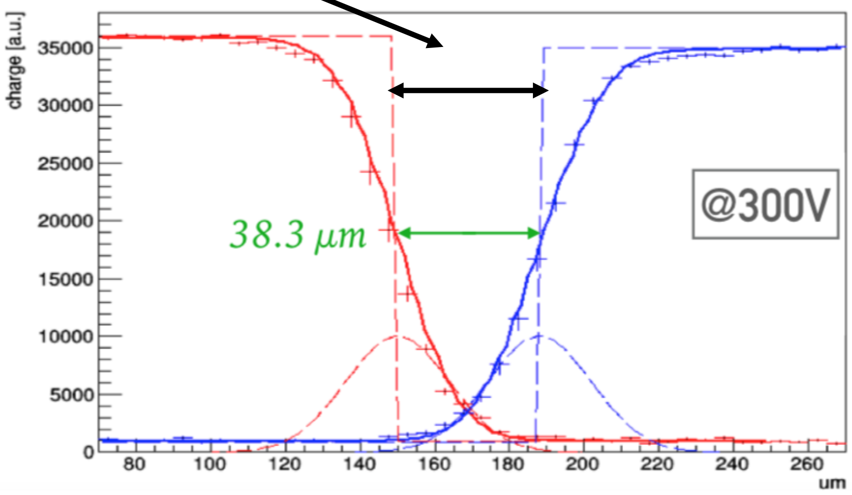
Solution: add a deep n implant to collect the charges in the interpap



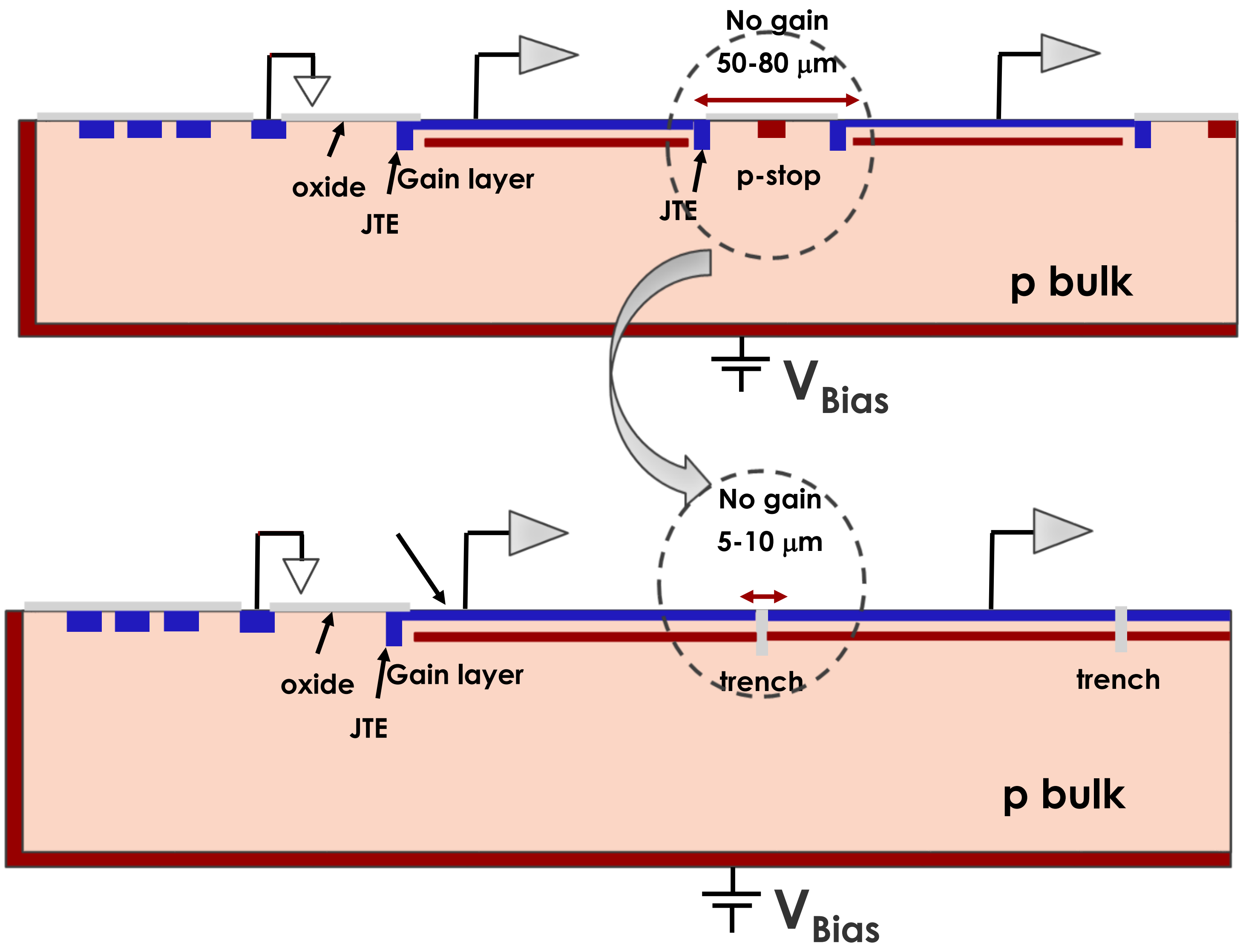
Deep implants collect the charge carriers the preventing their multiplications:

- signals that are “out of time” are not multiplied
- Setting a threshold high enough allows to be blind to the interpad signals

No gain area



LGAD Trench Isolated: enabling small UFSD pixels



No-gain region ~ 50-80 μm

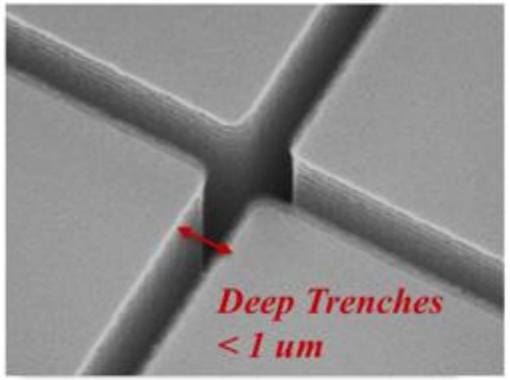
➔ cannot use for small pixels

Solution: use trenches for pad isolation

➔ No-gain region ~ 0 – 10 μm

RD50-TI production

Interpad design	Interpad distance [μm]
V1_1TR	2.7 ± 0.2
V2_1TR	6.5 ± 0.2
V3_1TR	7.9 ± 0.1
V4_1TR	10.6 ± 0.2
V2_2TR	8.9 ± 0.2
V3_2TR	10.3 ± 0.1



➔ The R&D to achieve small pixels is clear

Irradiation effects in LGADs

Irradiation causes 3 main effects:

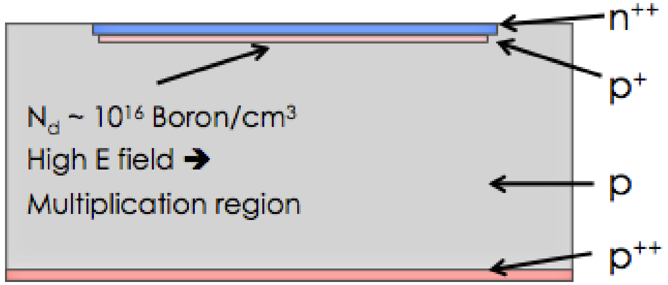
- Decrease of charge collection efficiency due to trapping
- Doping creation/removal
- Increased leakage current, shot noise

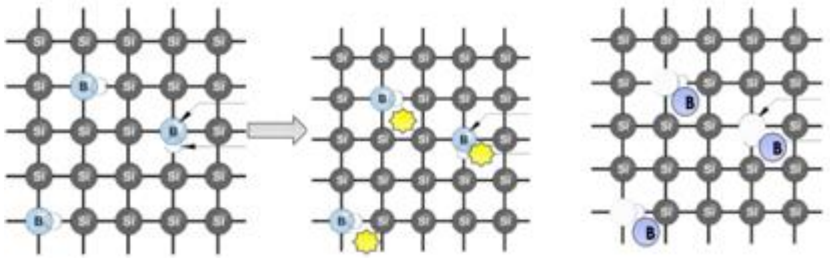
We need to design a detector that is able to survive large fluences, up to ~ 5E15 – 1E16 n_{eq}/cm^2

Acceptor removal

Unfortunate fact: irradiation de-activate p-doping removing Boron from the reticle

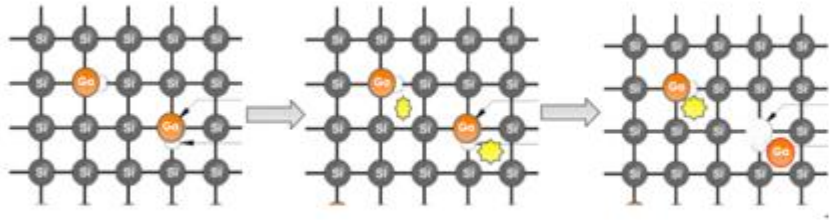
$$N(\emptyset) = N(0) * e^{-c\emptyset}$$



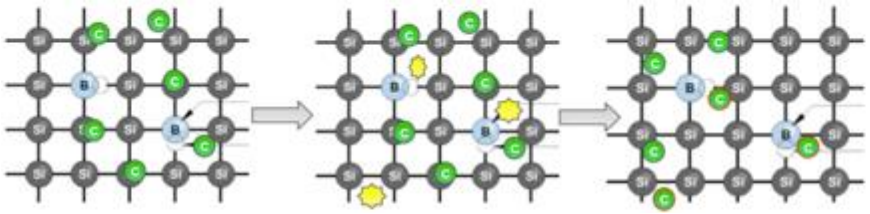


Boron
Radiation creates interstitial defects that inactivate the Boron: Si_i + B_s → Si_s + B_i

Two possible solutions: 1) use Gallium, 2) Add Carbon



Gallium
From literature, Gallium has a lower possibility to become interstitial

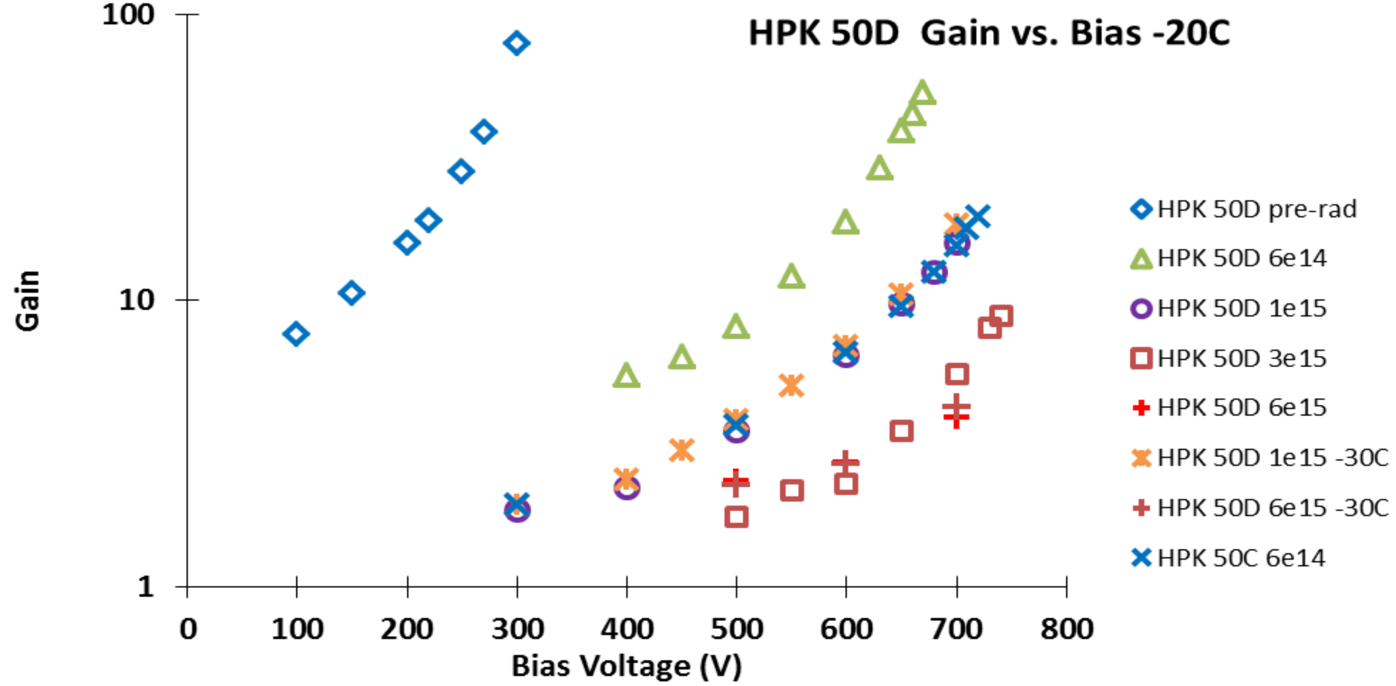


Carbon
Interstitial defects filled with Carbon instead of with Boron and Gallium

Effect of acceptor removal

$$N(\emptyset) = N(0) * e^{-c\emptyset}$$

Acceptor removal,
Gain layer deactivation



To some extent, the gain layer disappearance might be compensated by increasing the bias voltage

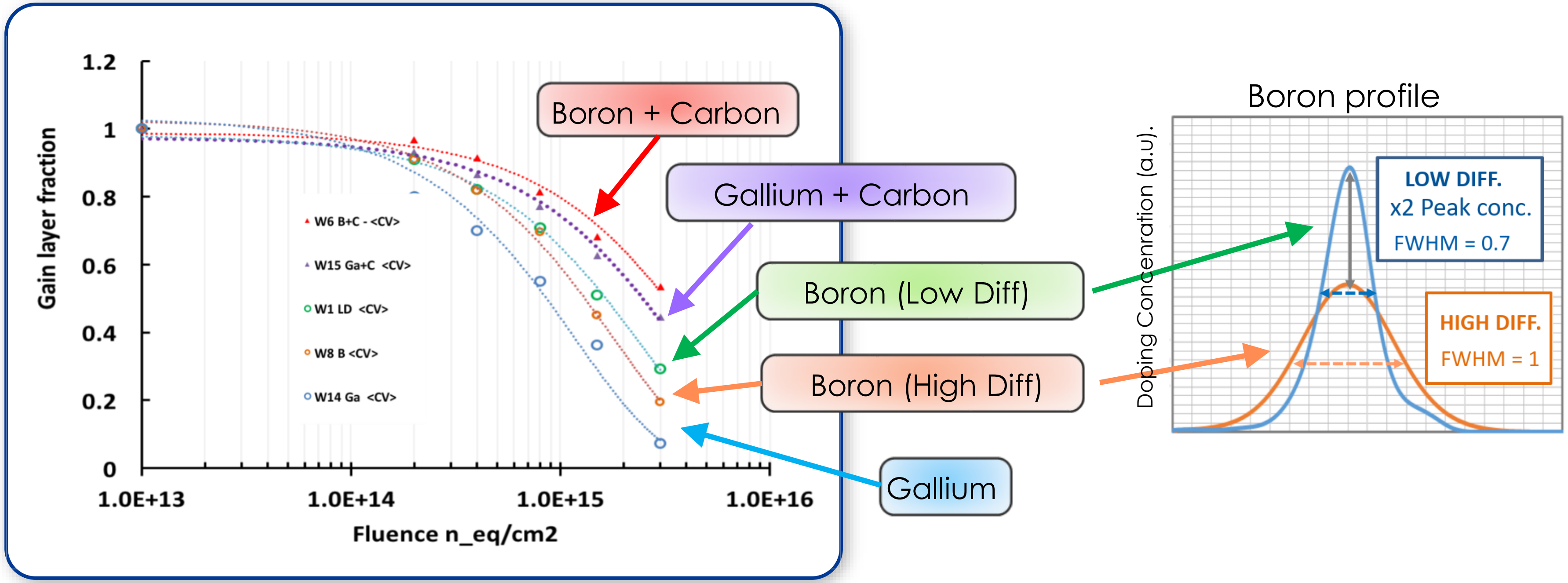
LGAD radiation hardness improvement

Defect Engineering of the gain implant

- **Carbon** co-implantation mitigates the gain loss after irradiation
- Replacing Boron by **Gallium** did not improve the radiation hardness

Modification of the gain implant profile

- Narrower **Boron doping profiles** with high concentration peak (Low Thermal Diffusion) are less prone to be inactivated



Summary so far…

- Low gain was introduced to compensate charge trapping
- Low gain is a key technological innovation to reach good temporal resolution with silicon detectors
- Low gain in thin silicon sensors allows reaching a temporal precision of about 30 ps (50 micron thick sensors)
- The radiation resistance of LGAD is achieved by designing a gain implant that is less sensitive to acceptor removal.
- Silicon detectors with good timing capability have been widely adopted in future experiments.
- 4D tracking is possible ONLY if sensors and electronics are designed together.

Summary so far…

- Low gain was introduced to compensate charge trapping
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- Silicon detectors with good timing capability have been widely adopted in future experiments.
- 4D tracking is possible ONLY if sensors and electronics are designed together.

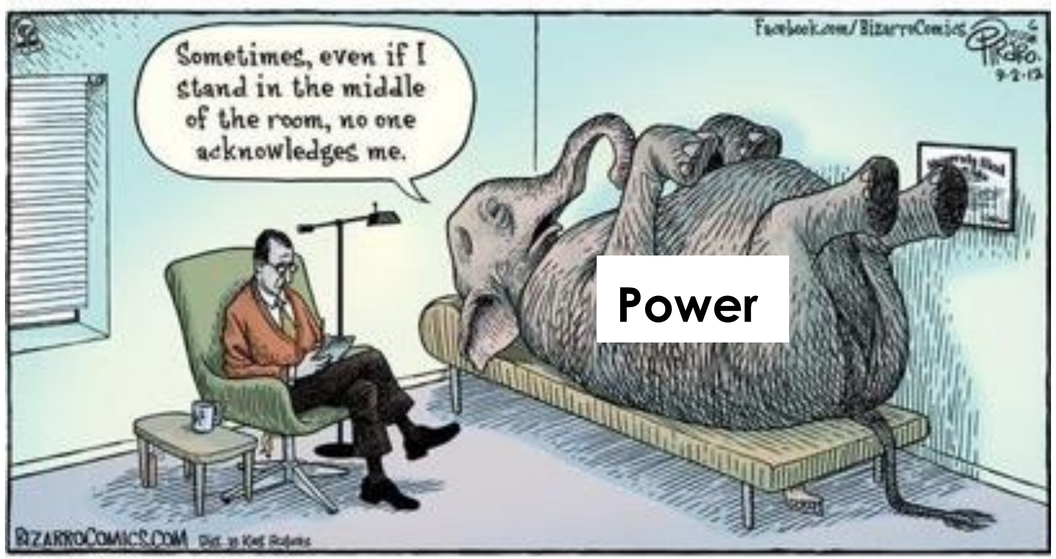
Can we achived 4D tracking, i.e. 4D information in each layer of the tracker?

Interplay of power, pixel size, and electronics

- The LGAD mechanism provides large signals, a fundamental component for achieving high temporal resolution.
- However: when using small pixels, the power requirement/cm^2 is too high

Power will determine:

- The architecture of 4D tracking detectors
    - how many layers will be 4D and how many will be 3D
- The pixel size and the temporal precisions.



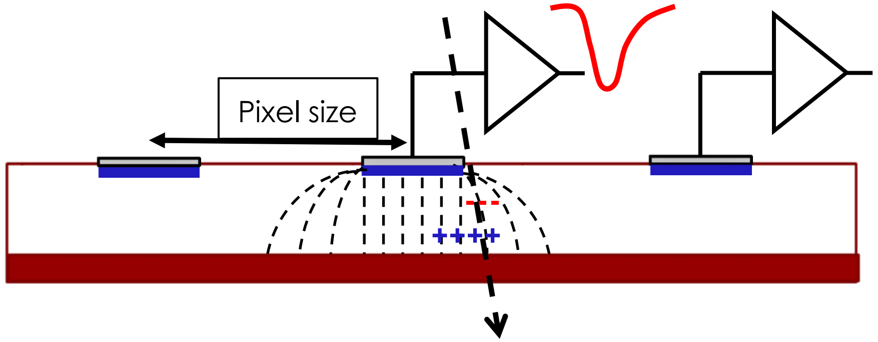
Spatial resolution: single and multi pixels read-out

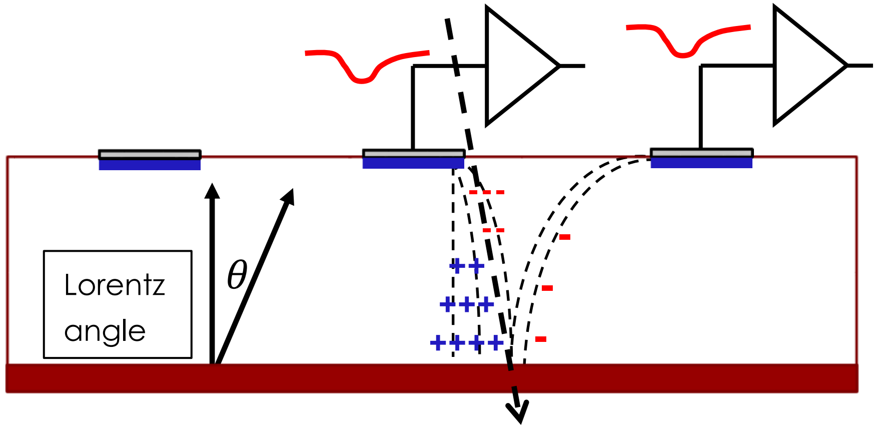
Single pixel

where the charge is collected in one pixel

Multi pixels

where the charge is collected in a few pixels





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

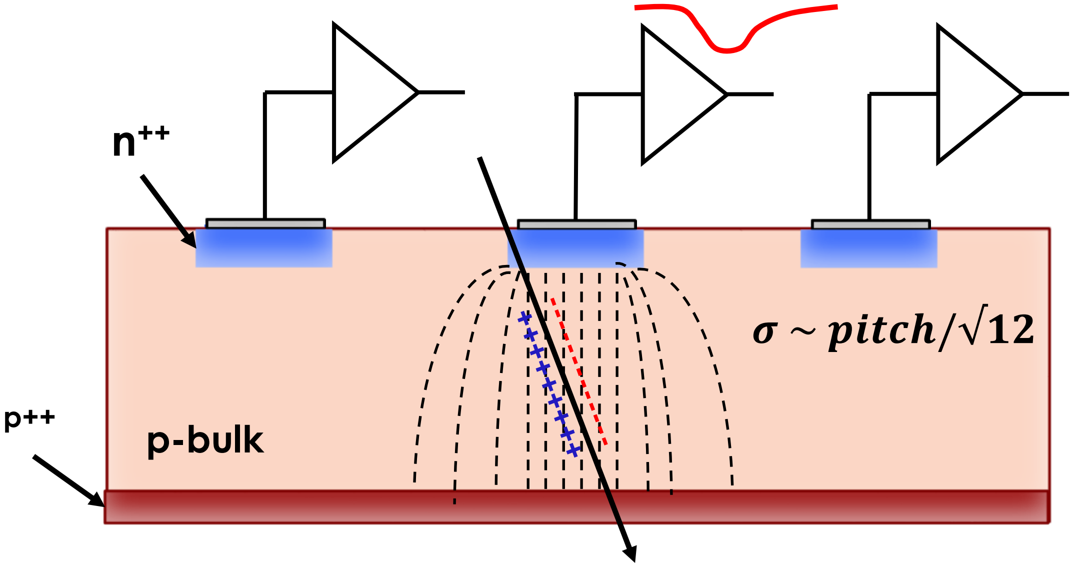
$$x_i = \frac{A_i x_i}{\sum_1^2 A_l x_l}$$

- **σ_x depend on the pixel size**

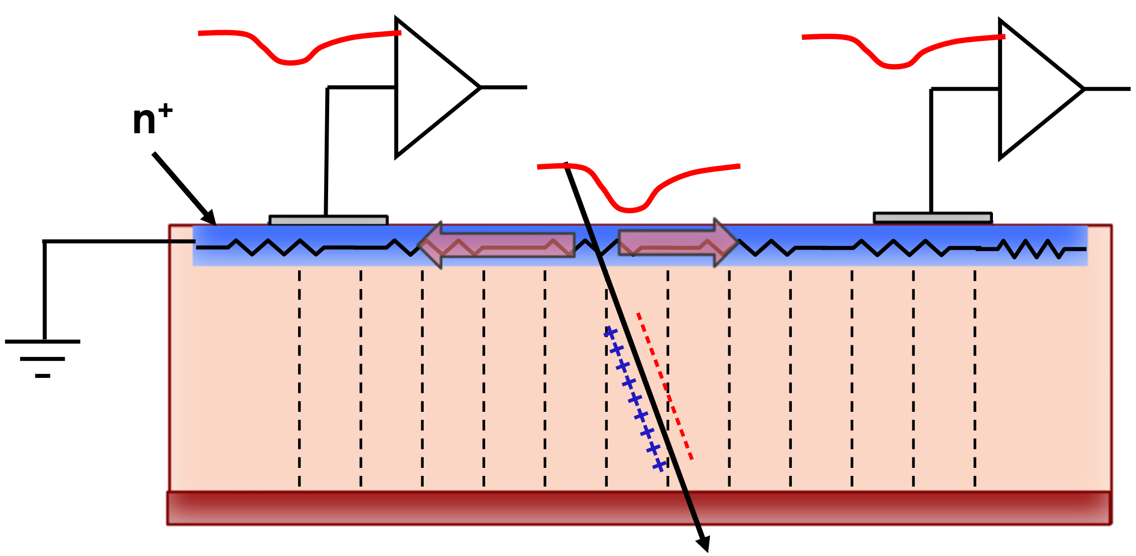
  pixel = 100 μm ➔ $\sigma_x = 20\ \mu m$

- **σ_x << pixel size**
- Sensors have to be thick to maintain efficiency
- Need B field (or floating electrodes) to spread the signal

Second design innovation: resistive read-out



Silicon detector with standard read-out

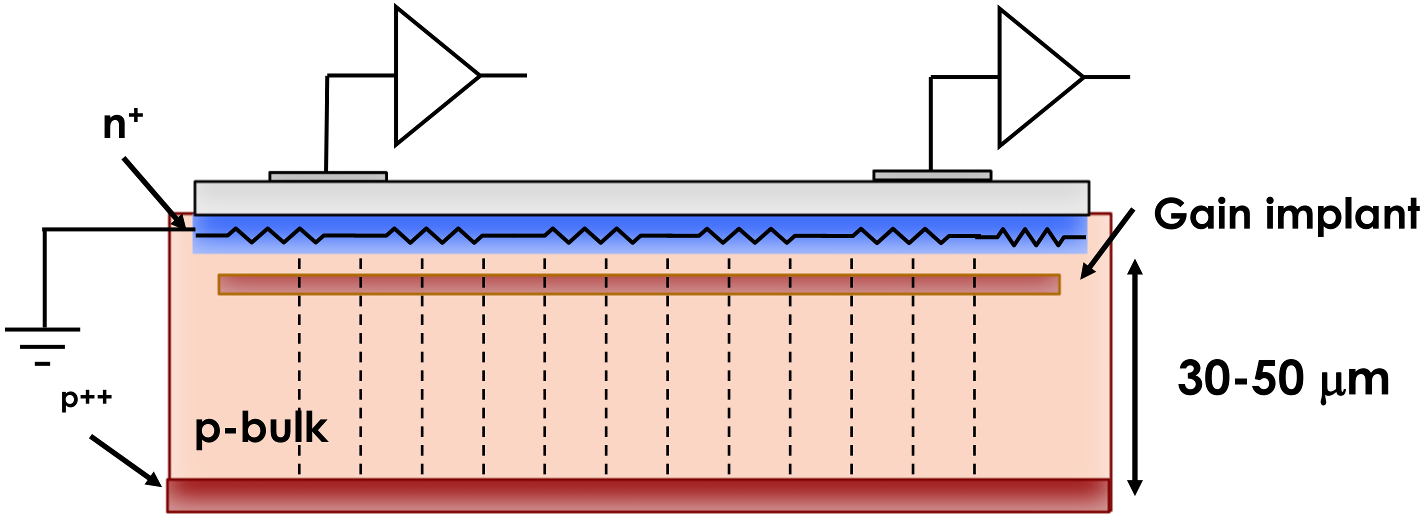


Silicon detector with resistive read-out

- In resistive read-out, instead of many p-n diodes, there is a single diode.
- The n-doped implant is resistive and acts as a signal divider
- Very uniform Electric and Weighing fields

Signal sharing is the key ingredient to excellent spatial resolution

Resistive Silicon Detector (RSD)

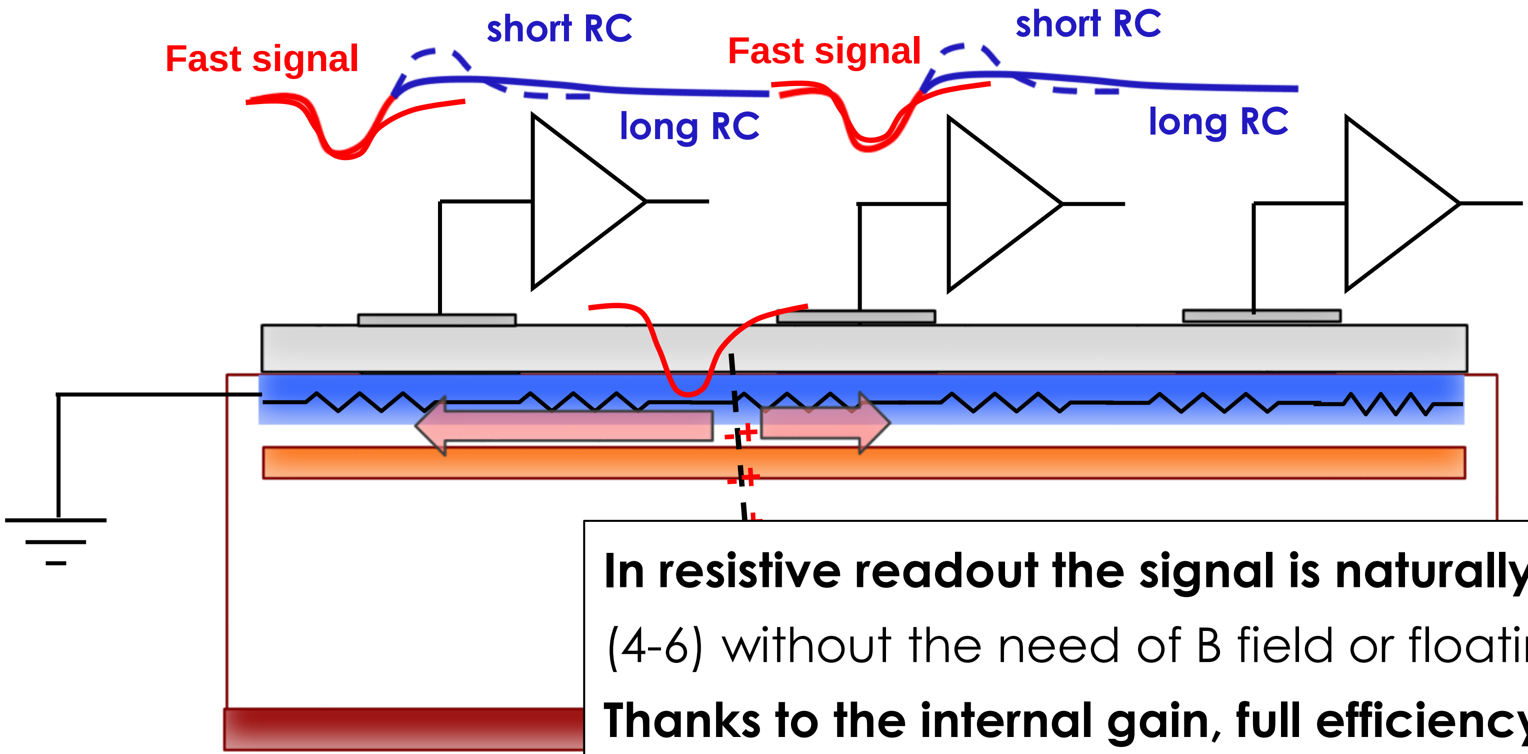


Resistive Silicon Detectors

combine low-gain and resistive read-out

Signal formation and sharing in RSD

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



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

Thanks to the internal gain, full efficiency even with sharing

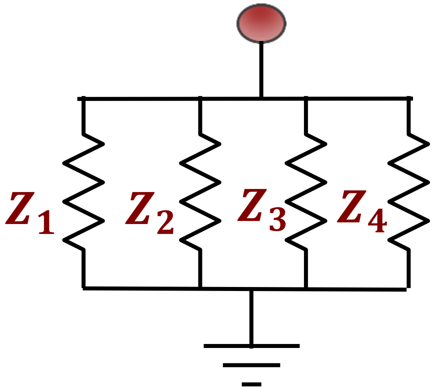
Results presented here are from the FBK RSD1 production

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

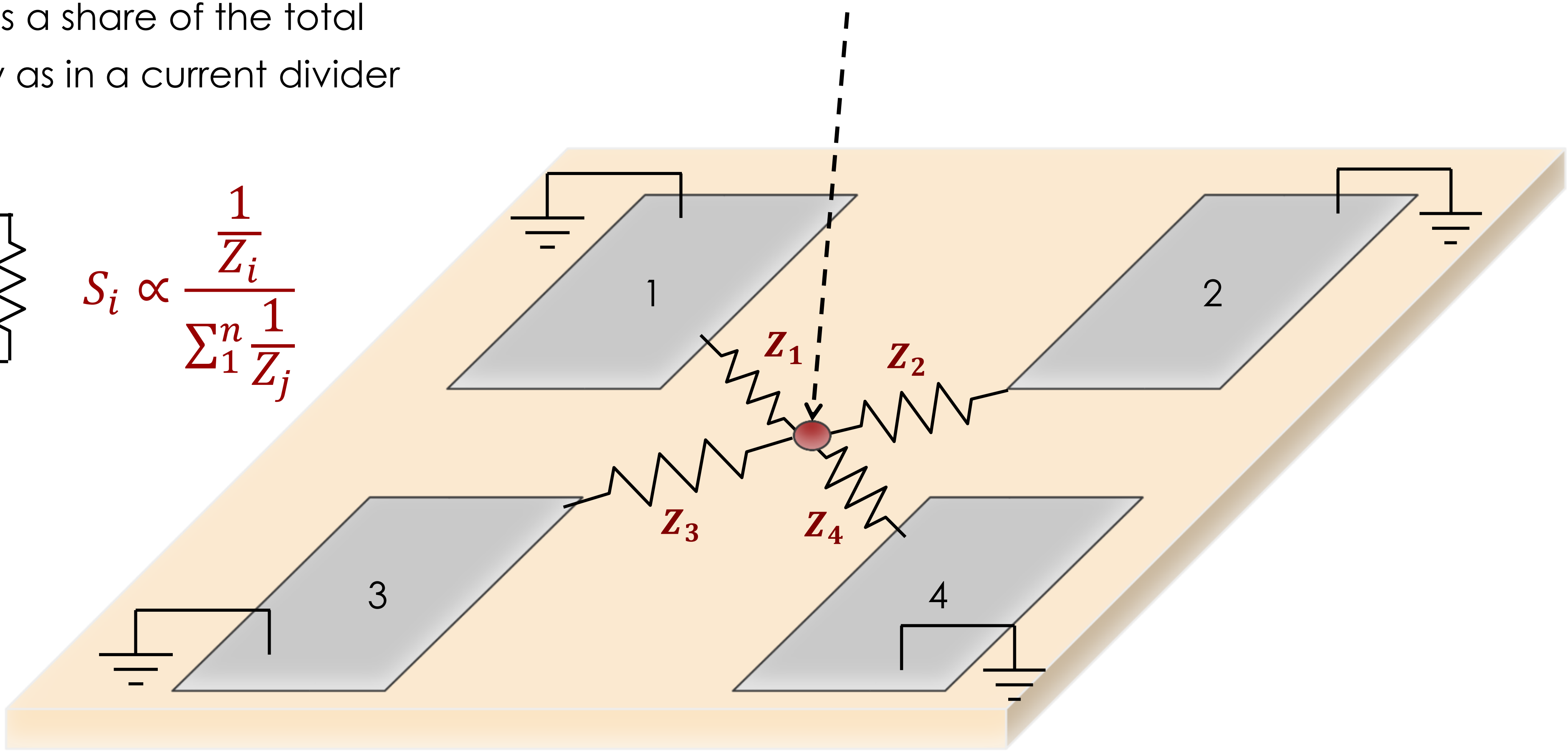
Charge sharing in RSD

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

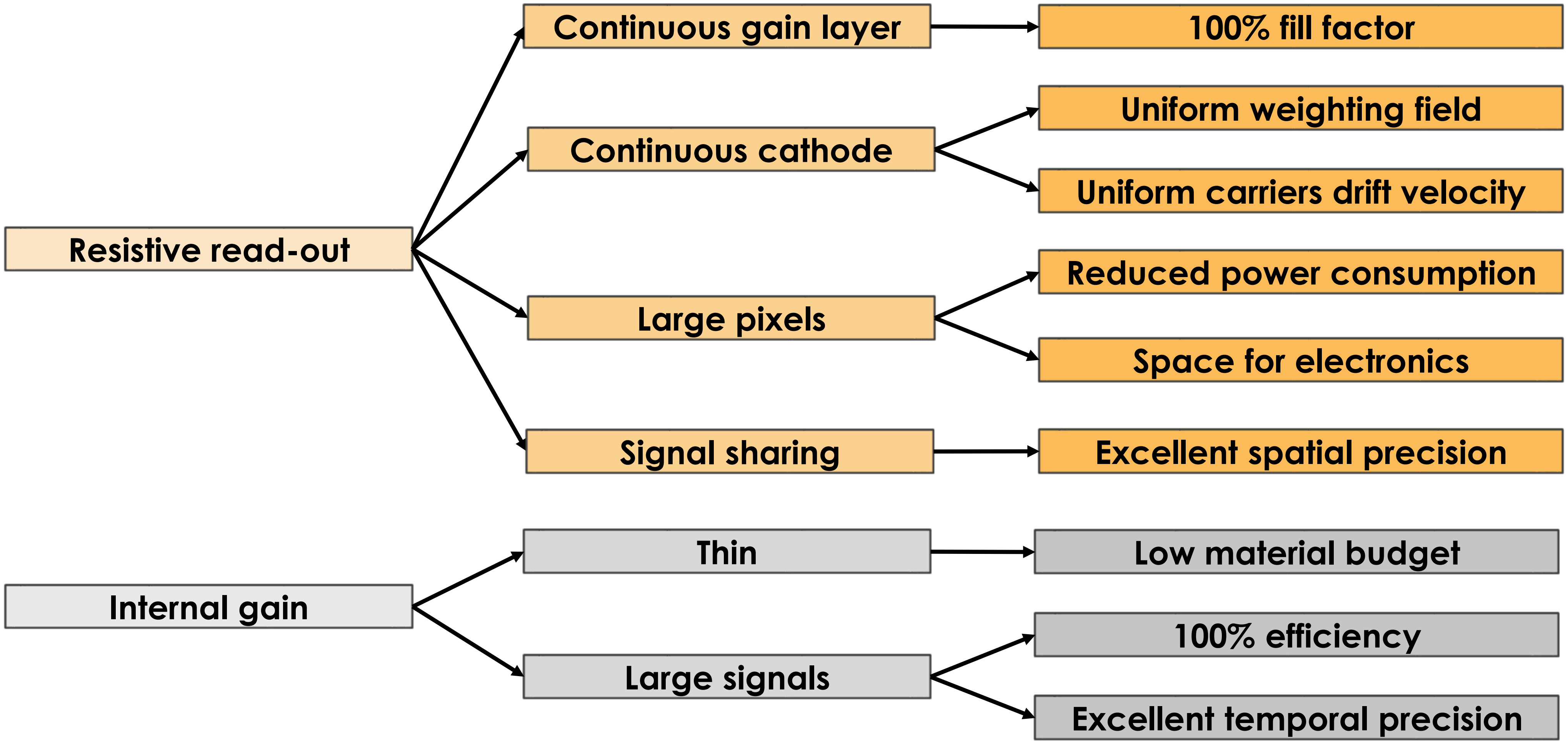


$$S_i \propto \frac{\frac{1}{Z_i}}{\sum_1^n \frac{1}{Z_j}}$$



N. Cartiglia, INFN, Torino, 7th INFIERI School, 30/09/23

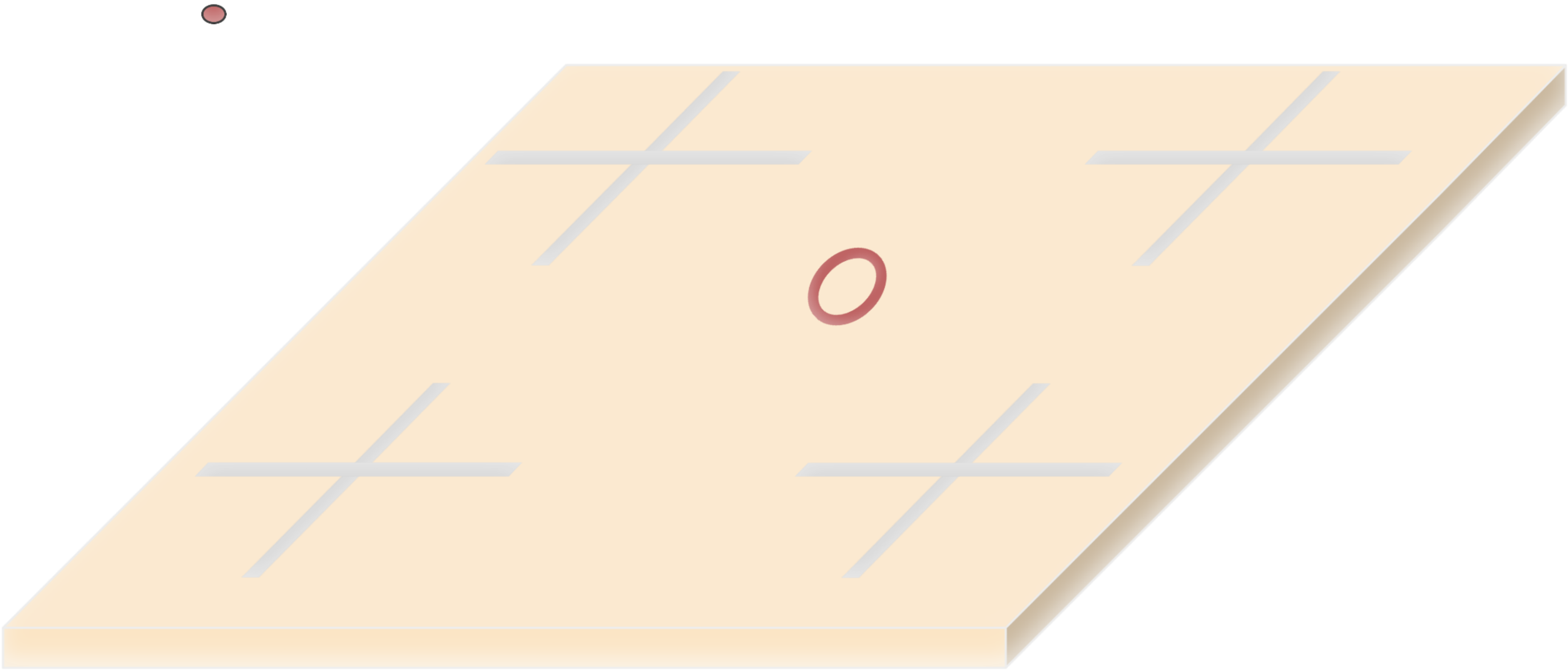
Why are RSDs well-suited for 4D tracking?



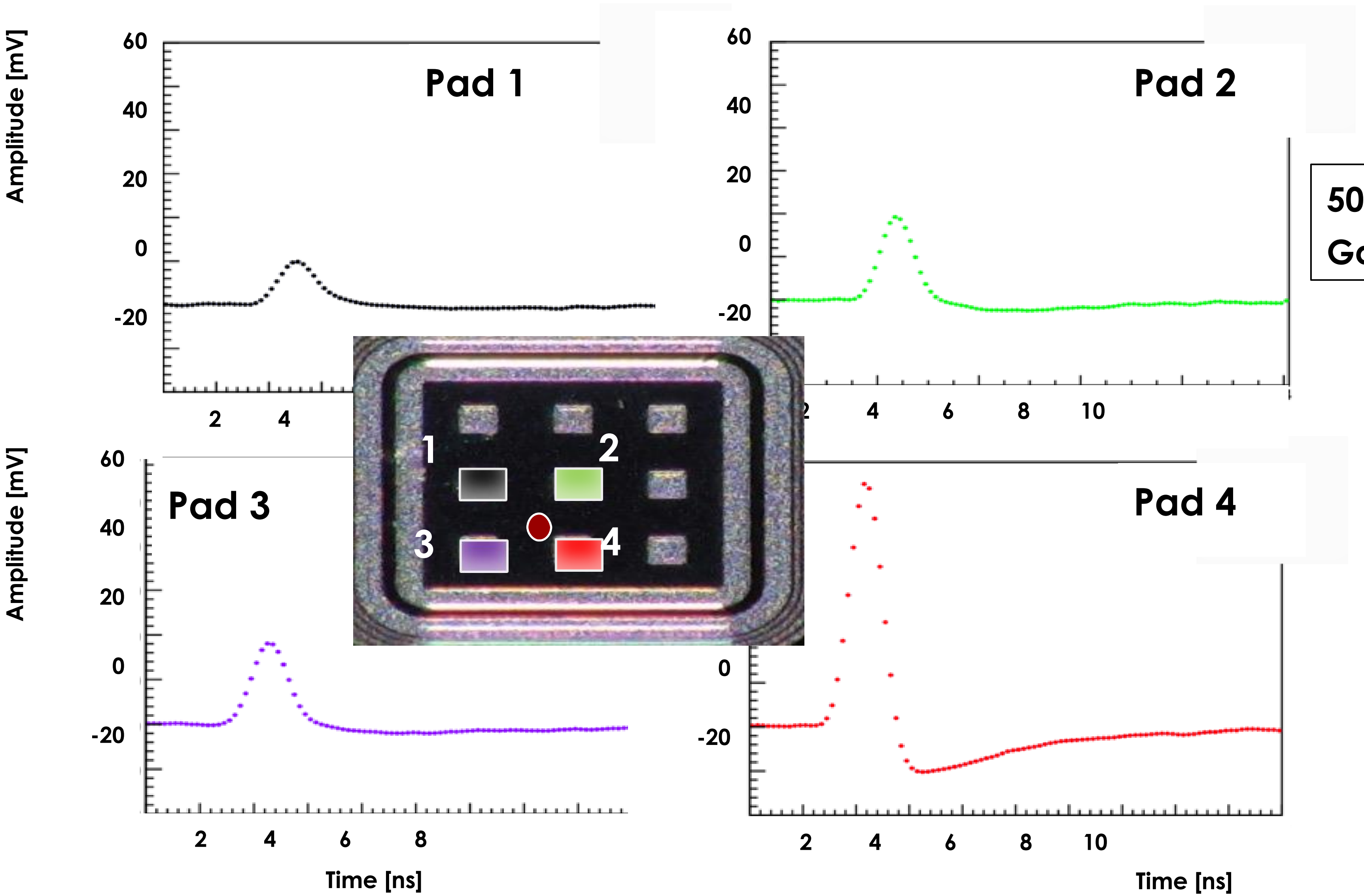
Innovation | **Sensor property** | **Experimental feature**

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

RSD principle of operation in motion



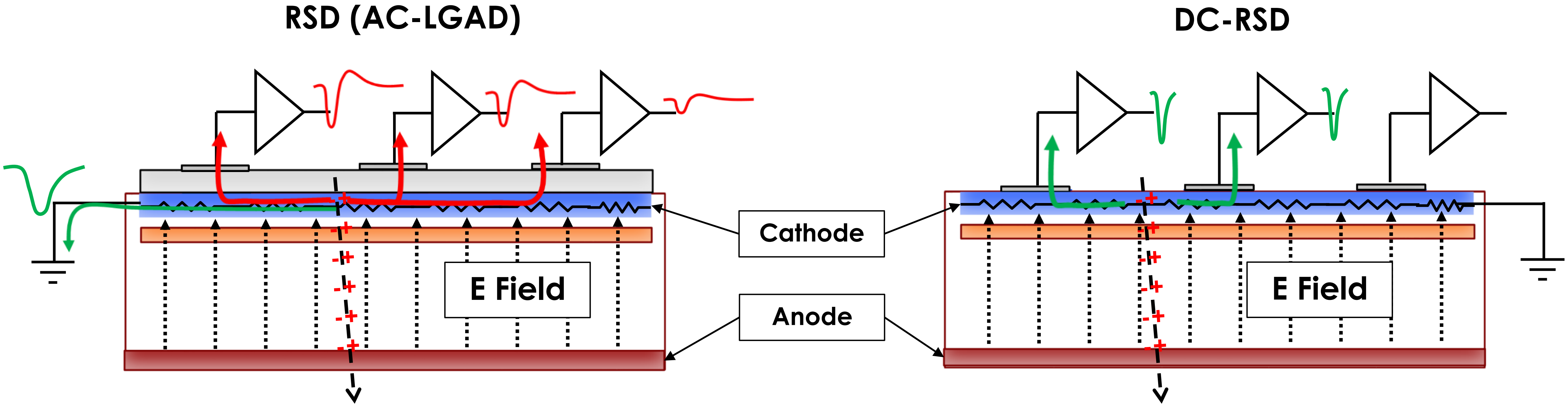
Example of signal sharing



50-mm thick RSD,
Gain ~ 20

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

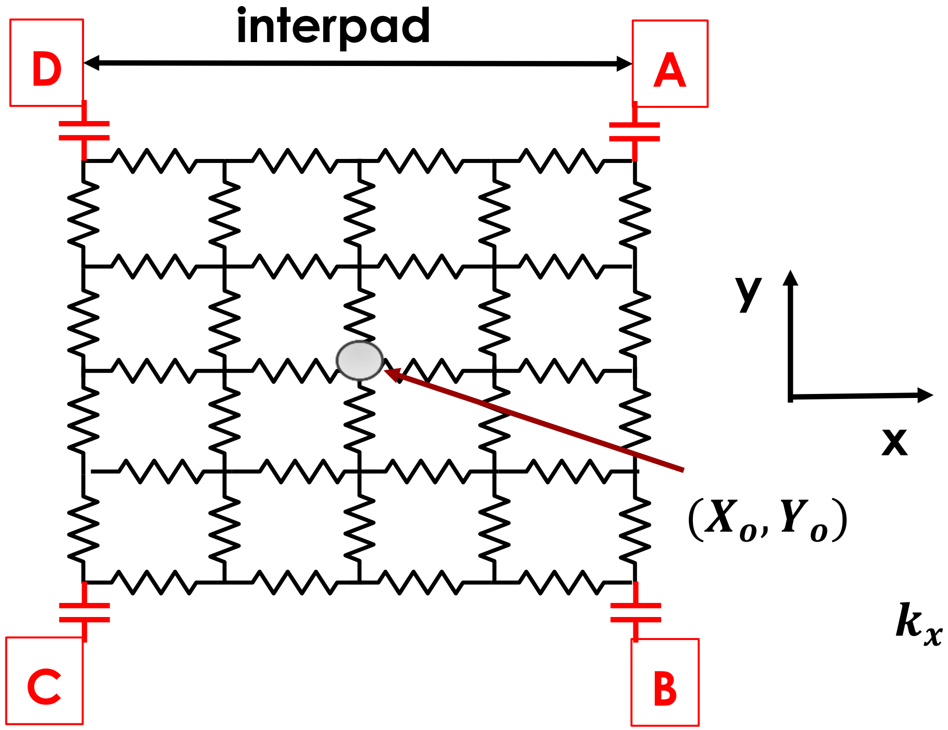
Present RSD research paths



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

This design is presently under development by FBK
The main advantage of the DC-RSD design is the ability to control the signal spread

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

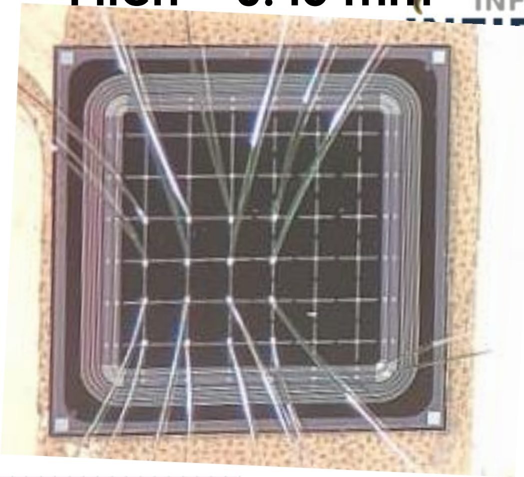
➔ no need for a analytical sharing law.

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

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

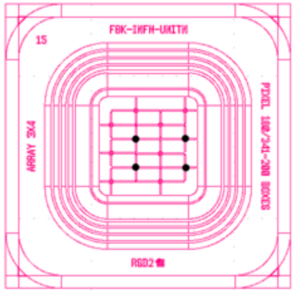
RSD2 sensors with cross-shaped electrodes

Pitch = 0.45 mm

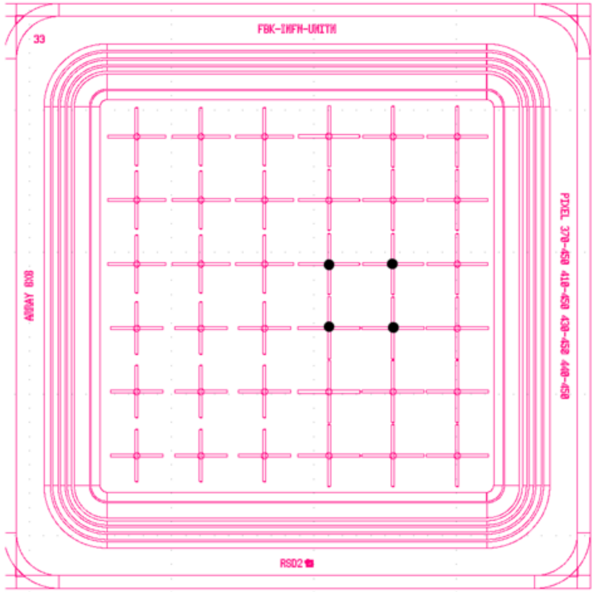


Sensor production at Fondazione Bruno Kessler

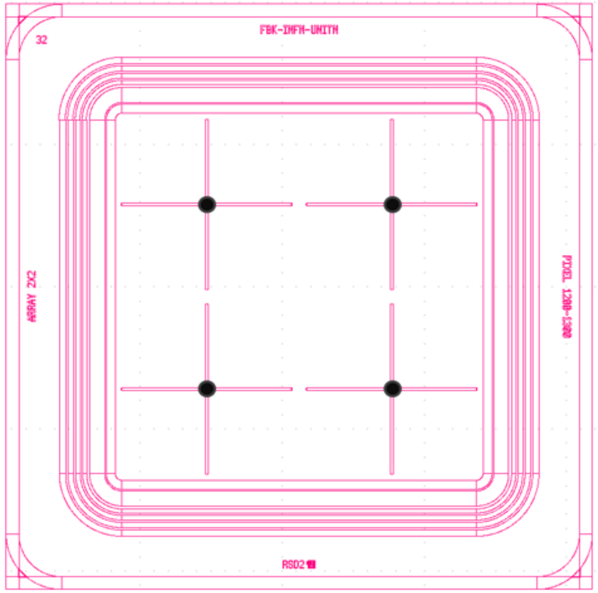
Several geometries are exploded in RSD2, for example cross with different pitch and arm length: 200, 340, 450, and 1300 μm



(A)
200 x 340 μm^2

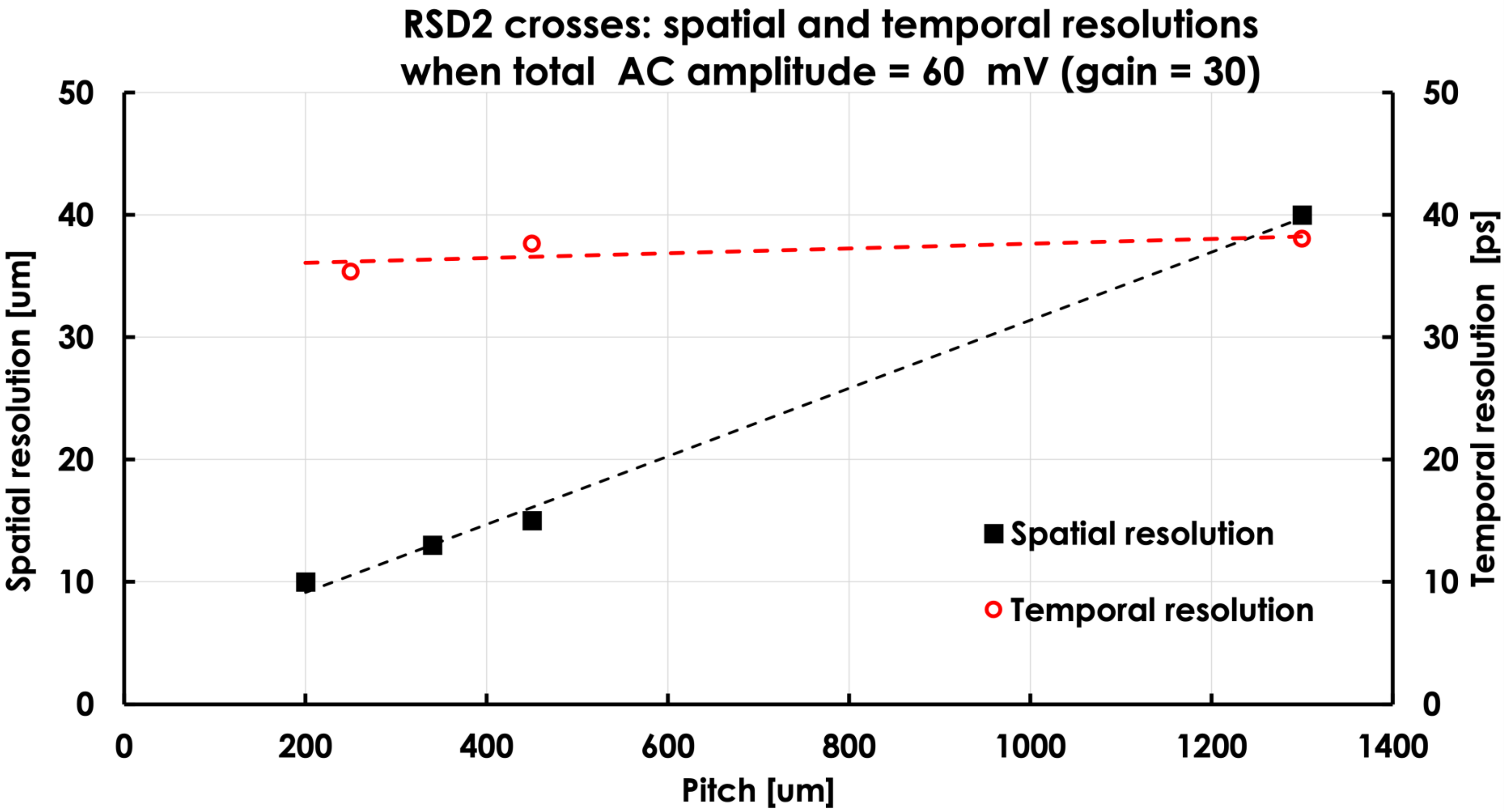


(B)
Pitch = 450 μm



(C)
Pitch = 1300 μm

FBK-RSD2 performance summary



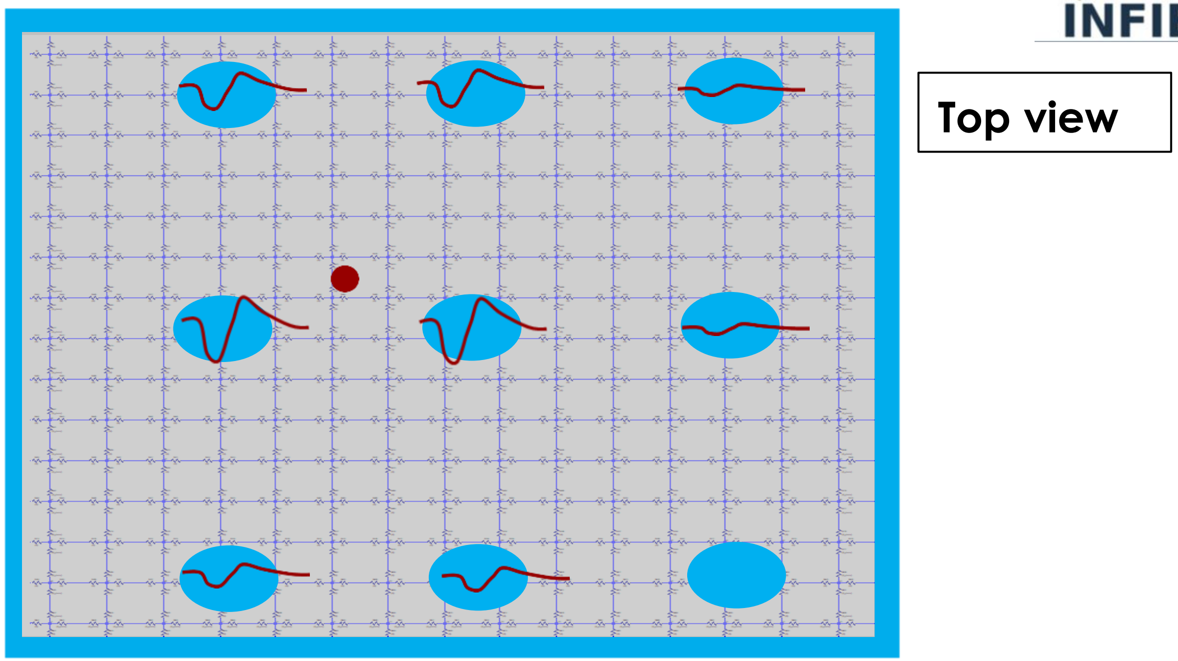
Limiting the signal spread to a single cell

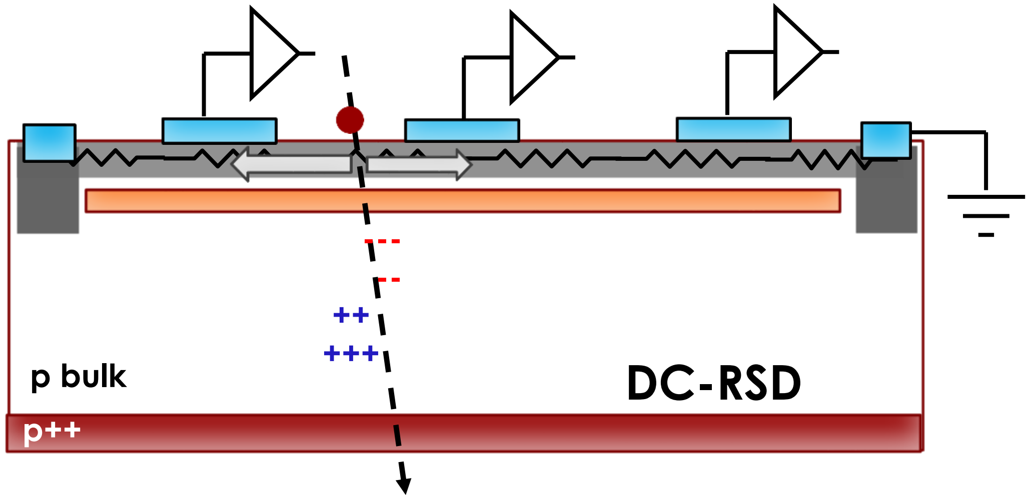
Problem:

we have been too successfull in charge sharing.

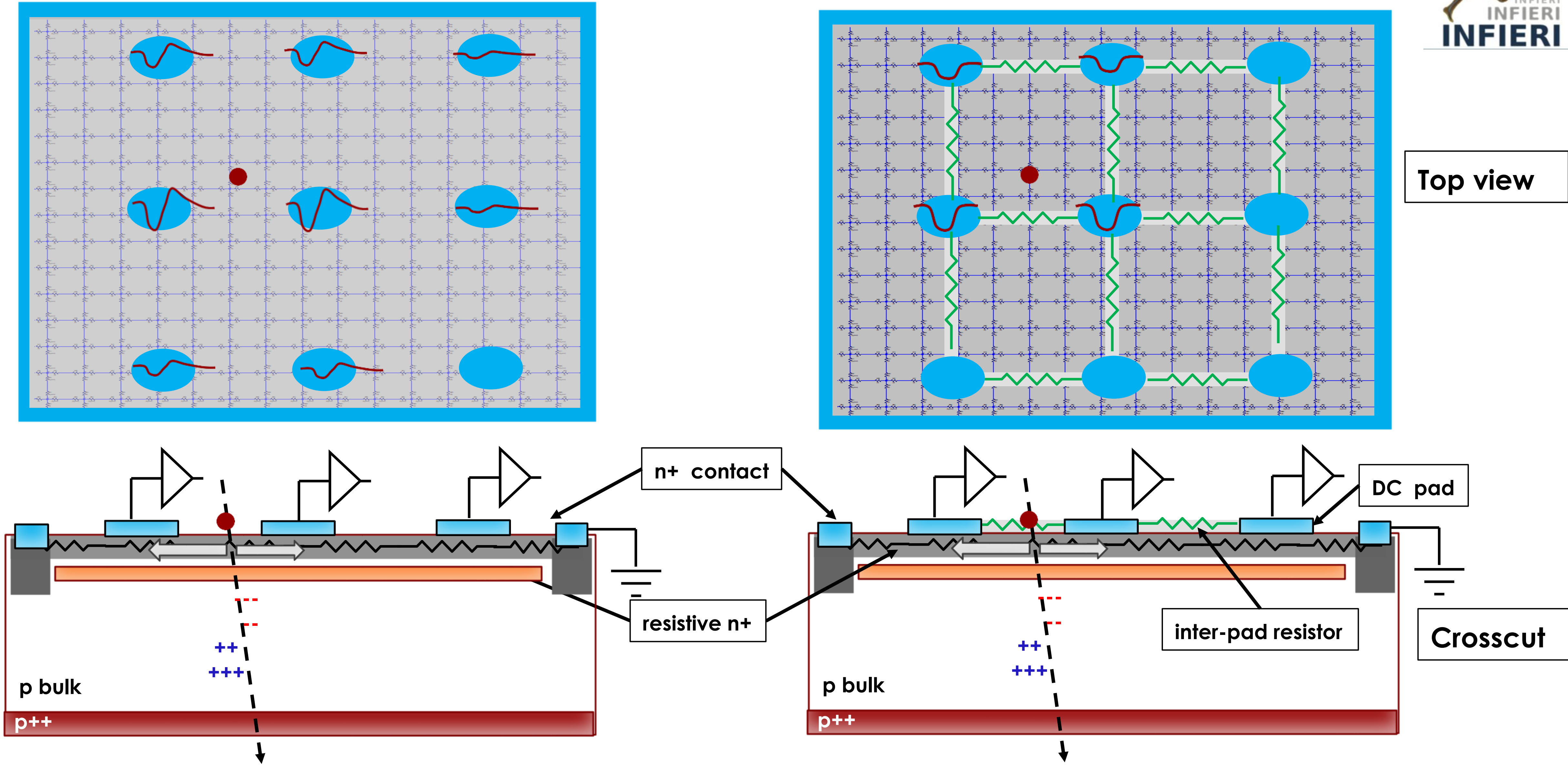
In our measurements, the signal is shared on too many electrodes.

If the signal is shared on too many electrodes, the signal-to-noise ratio is degraded





Adding resistors in between electrodes



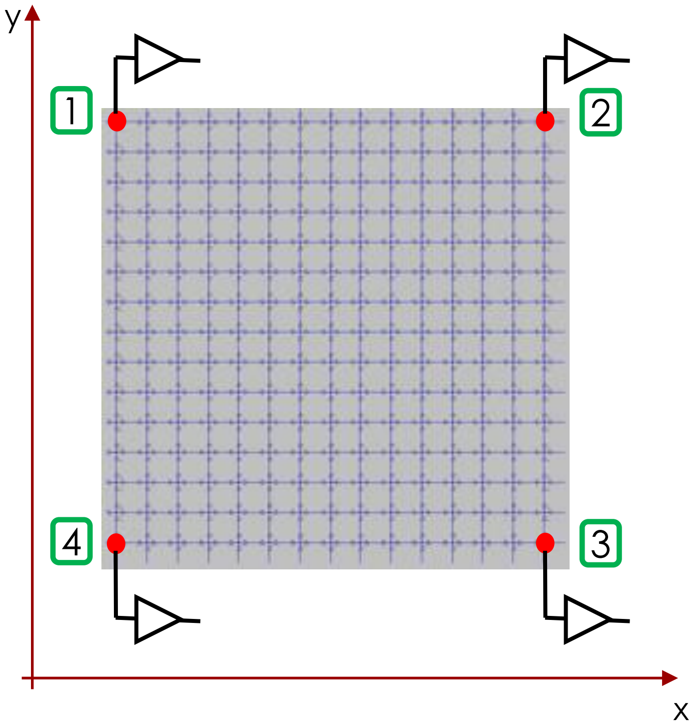
DC-RSD **DC-RSD**

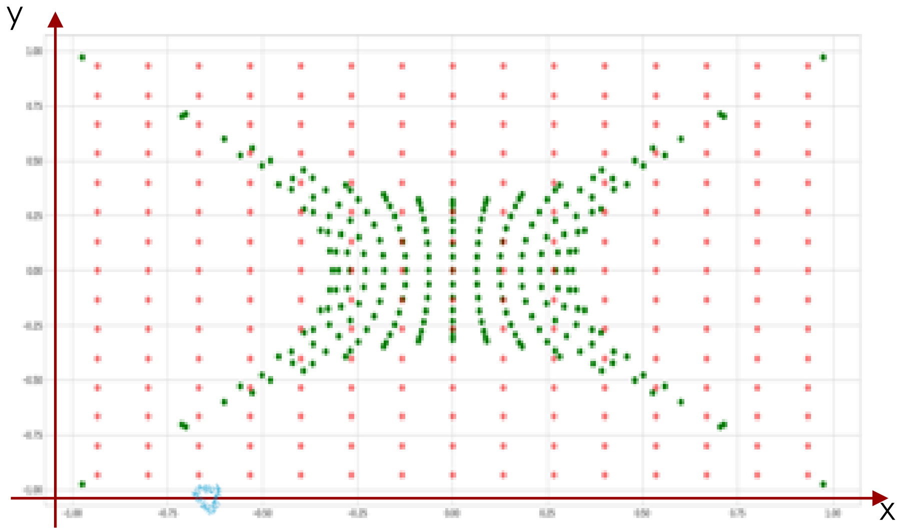
Position Reconstruction: DC-RSD

Position distortion is typical of resistive devices and well documented in the literature.

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

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





Red
original points

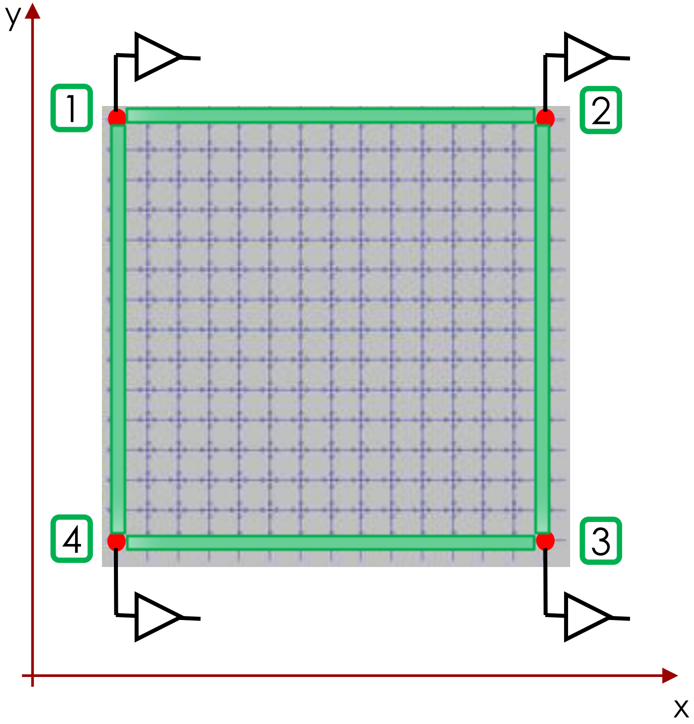
Green
reconstructed points

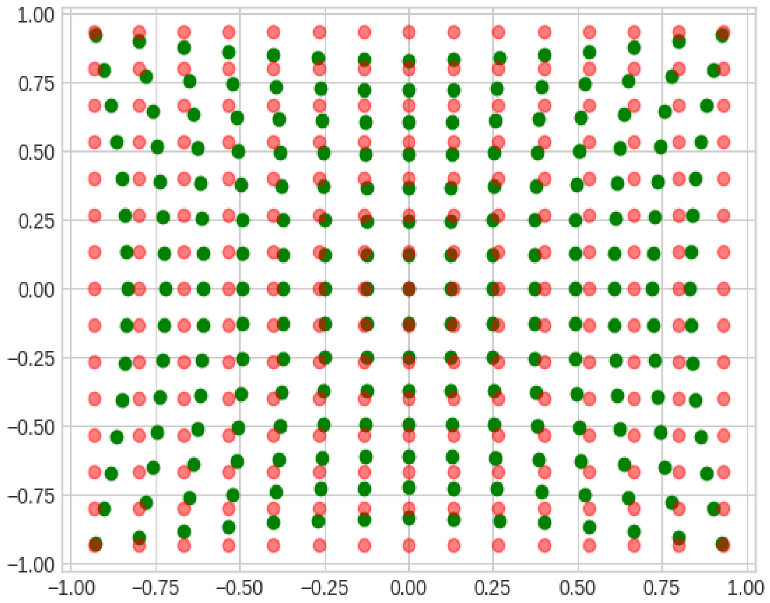
This is an extreme case, chosen to illustrate the problem

Position Reconstruction: DC-RSD with resistive strip

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

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





Red
original points

Green
reconstructed points

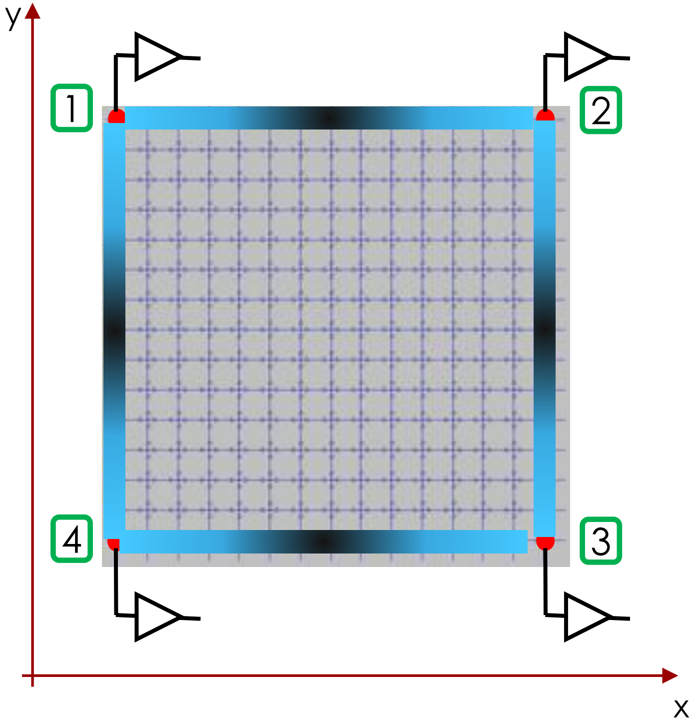
The distortion in the reconstruction can be strongly reduced by adding resistive strips connecting the electrodes.

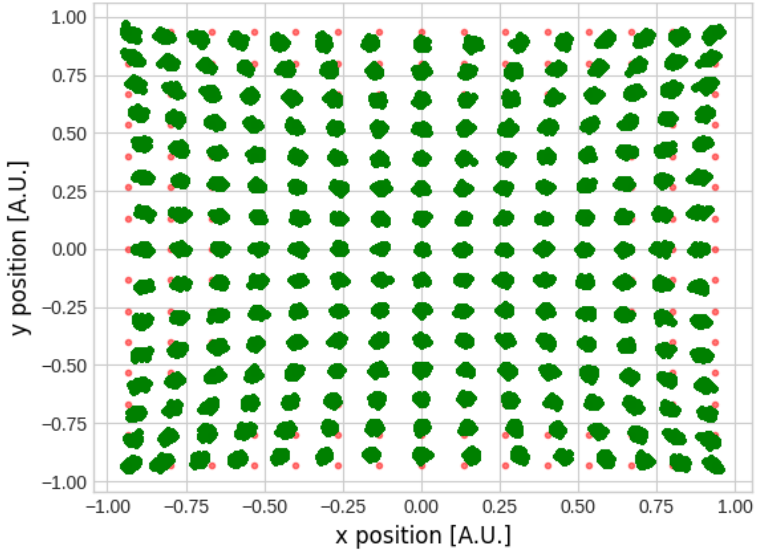
Proposed in: *On the dynamic two-dimensional charge diffusion of the interpolating readout structure employed in the MicroCAT detector,* Wagner et al., NIM A, (2002).

Position Reconstruction: DC-RSD with variable resistive strip

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

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





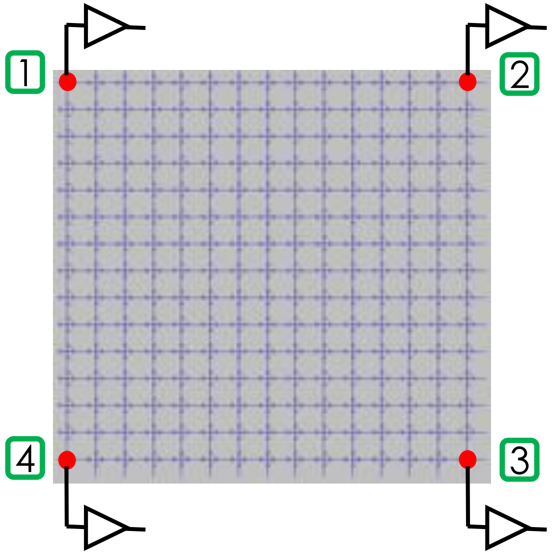
Red
original points

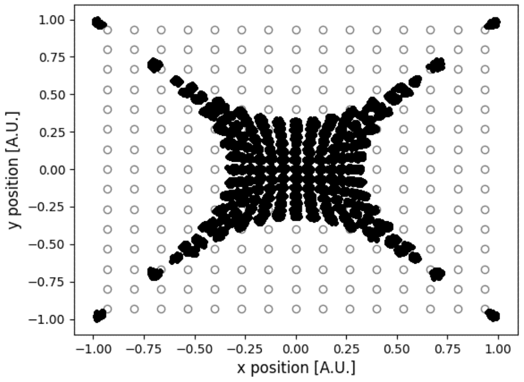
Green
reconstructed
points

Variable resistive strips have the potential to almost totally eliminate the distortion in the position reconstruction

DC-RSD research paths

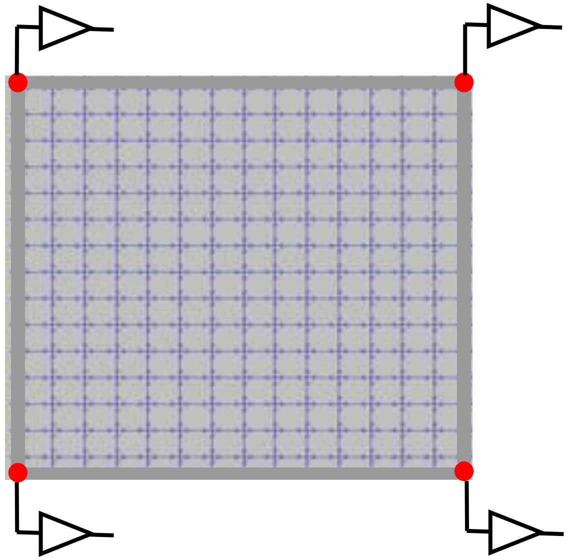
DC-RSD

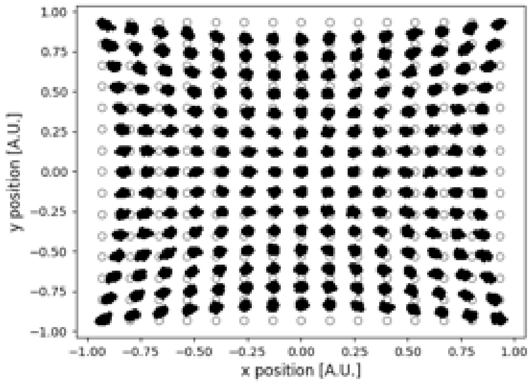




DC-RSD

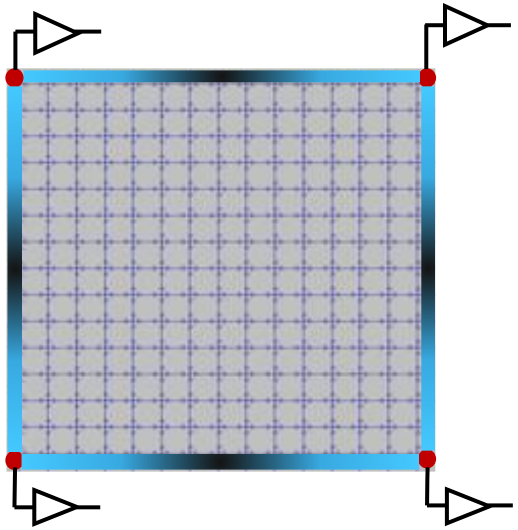
with resistive strips

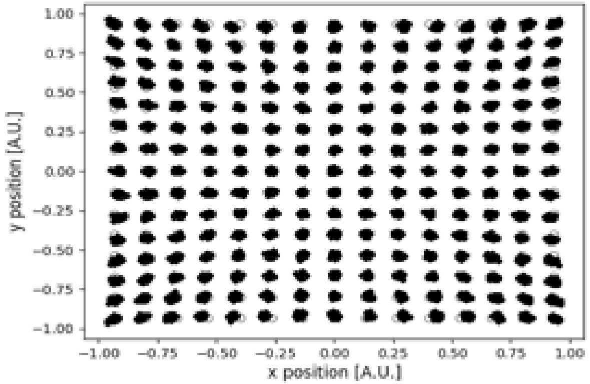




DC-RSD

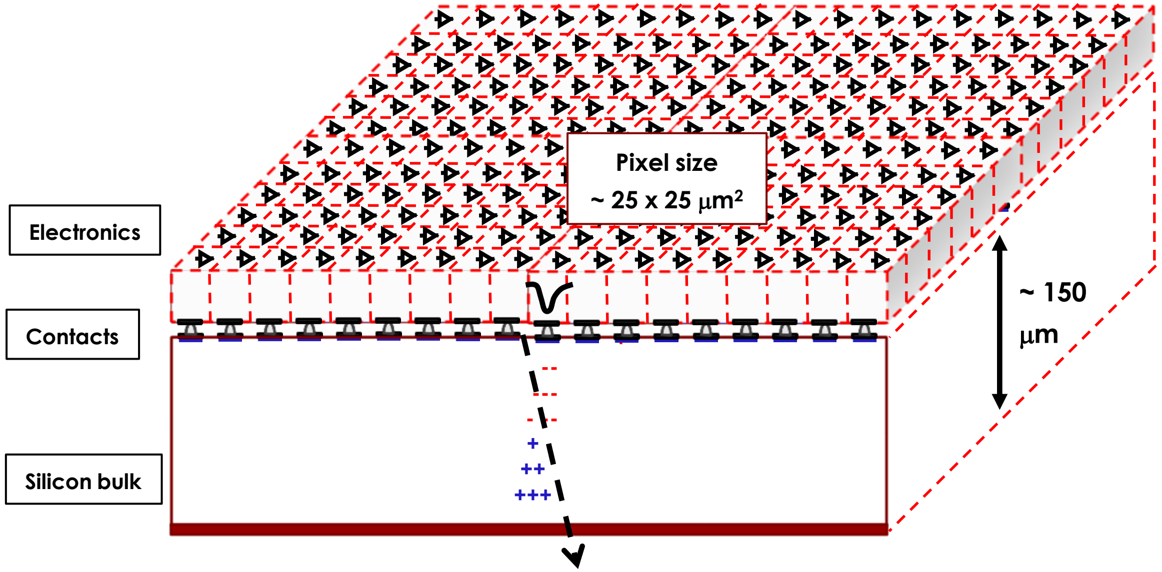
with variable resistive strips



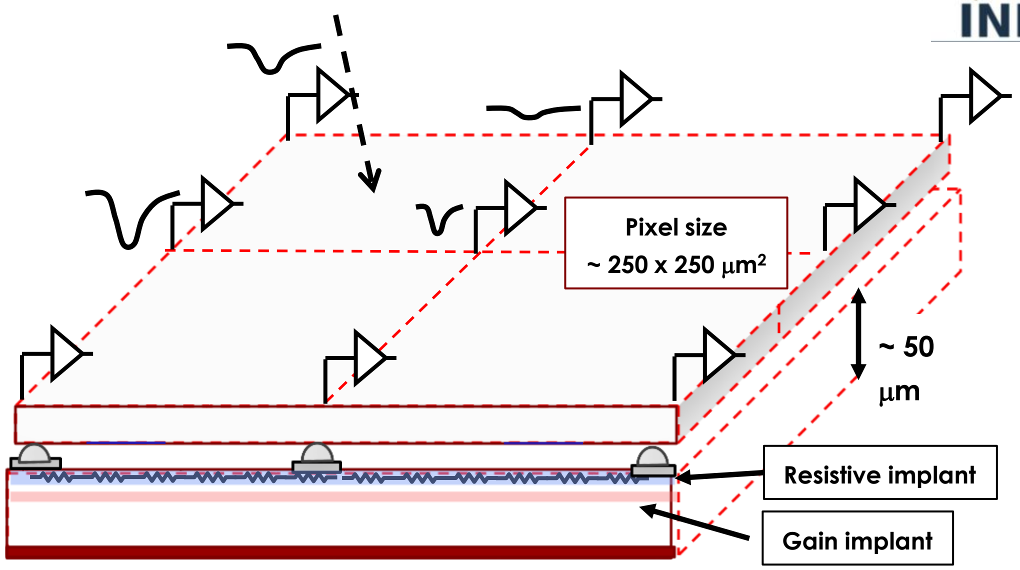


Empty circles: original points
Filled Circles: reconstructed points

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



Standard Tracker



RSD-based tracker

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

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

RSD Read-out scheme

Signal characteristics:

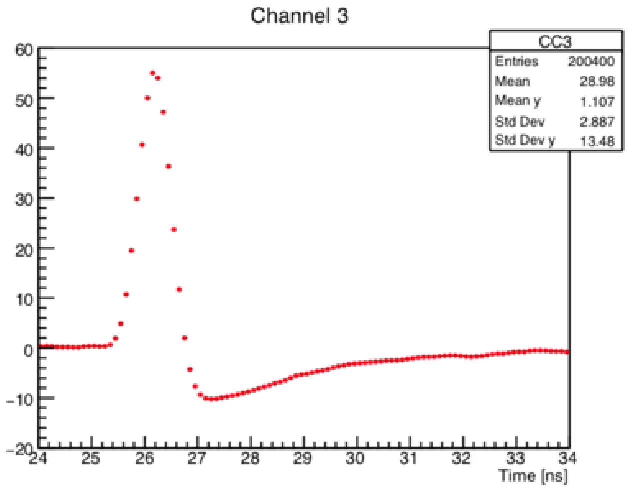
- Short and fast, very similar to standard UFSD

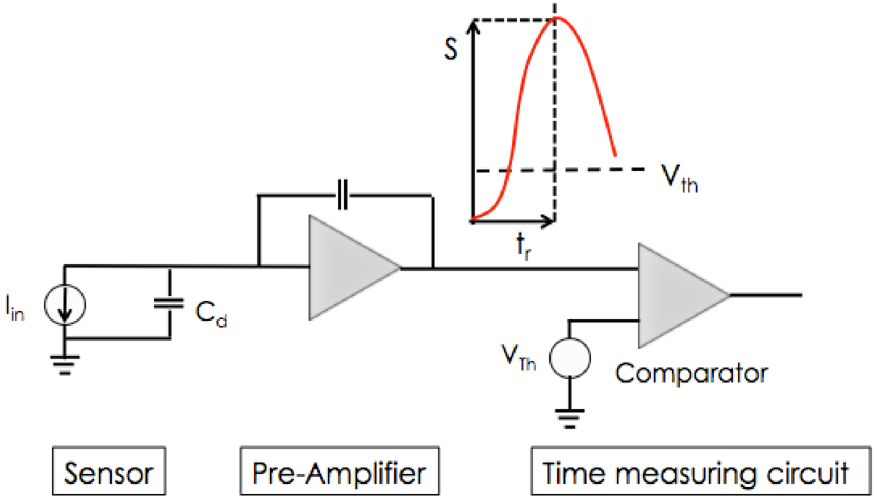
Read-out characteristics:

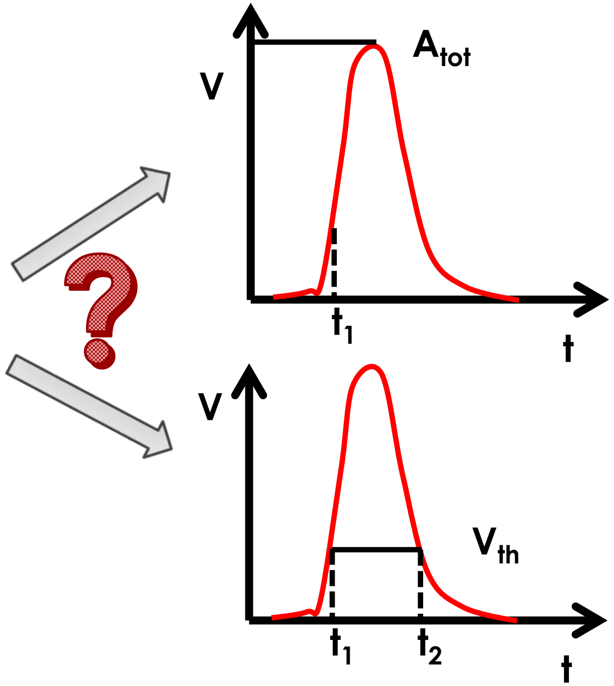
- Record signal amplitude with good precision for position
- Timing capabilities: keep the jitter below the Landau floor

  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 $t_{1,}$

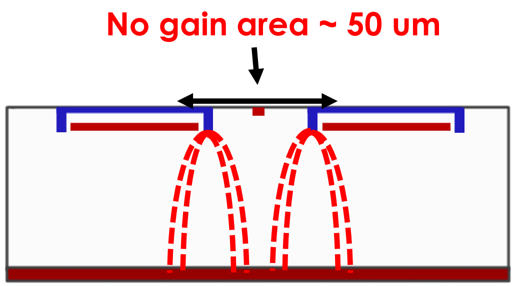
ADC for A_{tot}

Time over Threshold:

$ToT = t_2 - t_1$

Need TDC for $t_{1,} t_2$

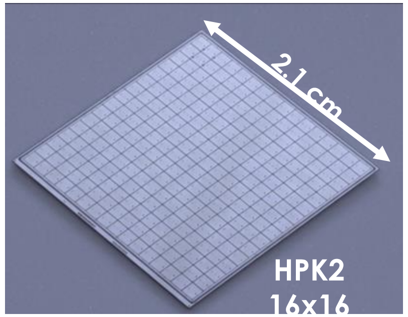
UFSD Summary: more gaining and more sharing

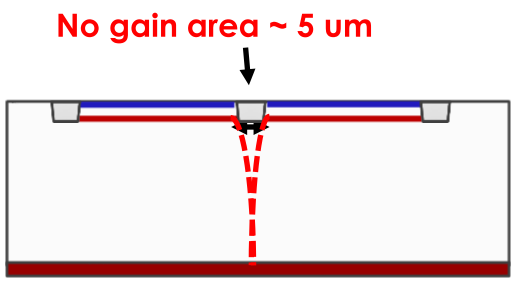


JTE + p-stop design

JTE/p-stop UFSD

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

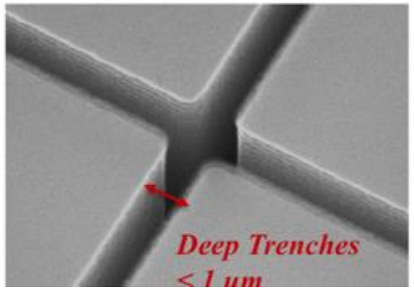


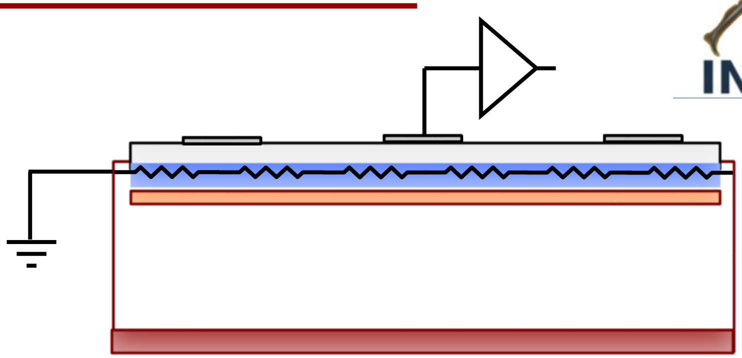


Trench-isolated design

UFSD evolution: use trenches

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

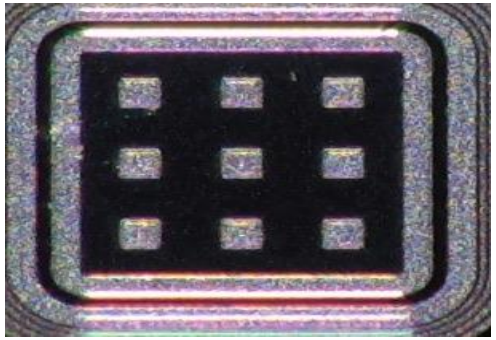




RSD -- AC-LGAD

RSD evolution: resistive readout

- Signal in many pixels
- 100% fill factor
- Excellent position resolution:
  ~ 5 μm with large pixels
- Temporal resolution (50 μm) : 35-40 ps
- Rate ~ 10-50 MHz
- Rad hardness: to be studied



Conclusions

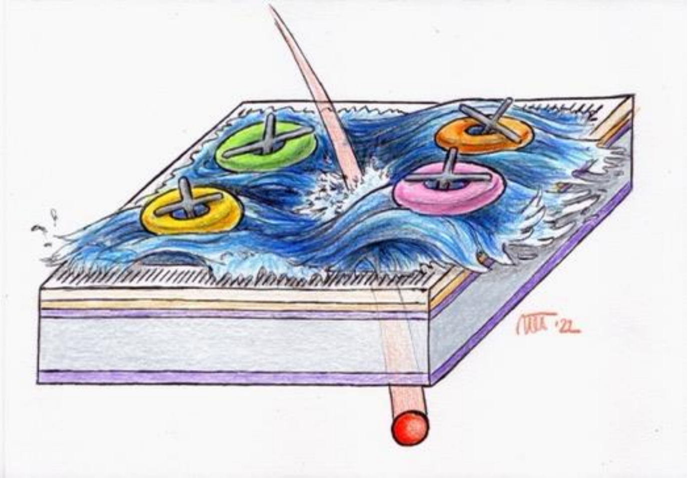
The combination of internal multiplication and built-in charge sharing leads to the design of a new type of silicon tracker.

Resistive read-out && LGAD can be used both in hybrid and monolithic sensors

The pixel size can be quite large given the very good spatial resolution. Limitations might be introduced by occupancy.

Spatial resolution depends upon ~ 1/gain, ~ 1/pitch, and ~noise

The temporal resolution is weakly dependent on the pixel size



Our laboratory measurements yield to (at gain = 30)

- **a spatial resolution of about 3% of the pixel size**
- **a temporal resolution similar (but marginally worse) than that of standard LGADs**

Backup

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:

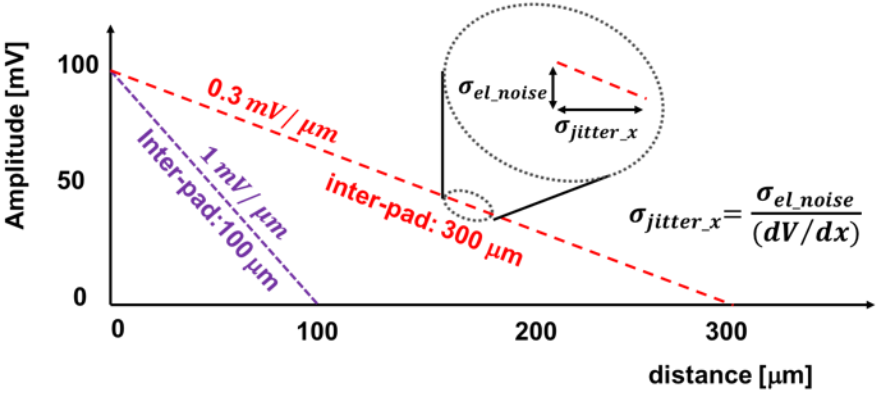
- 100 μm and 300 μm apart
- 100mV signal
- 3 mV electronic noise

100 μm: the signal changes by 1 mV/ μm

➔ σ_{Jitter} **= 3 μm**

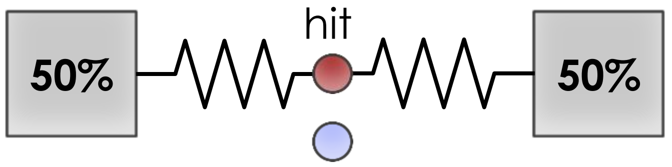
300 μm: the signal changes by 3 mV/ μm

➔ σ_{Jitter} **= 9 μm**

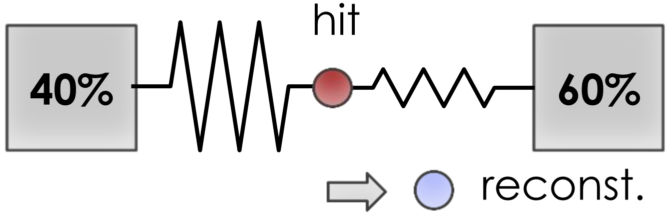


$$\sigma_{Sensor}$$

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

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

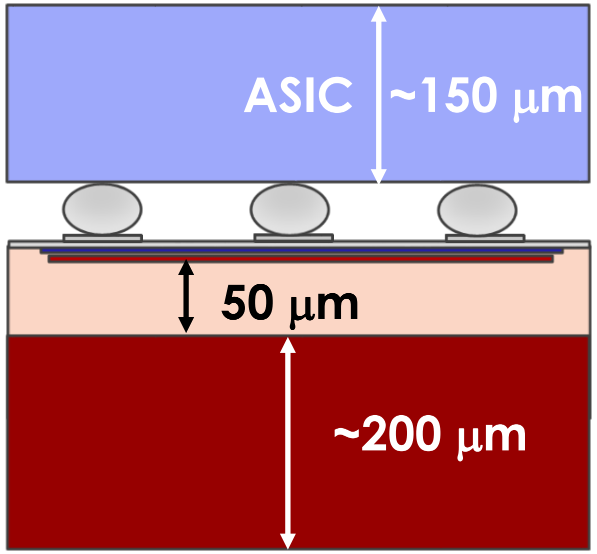
If the predicted sharing is incorrect, the reconstructed position is shifted.

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

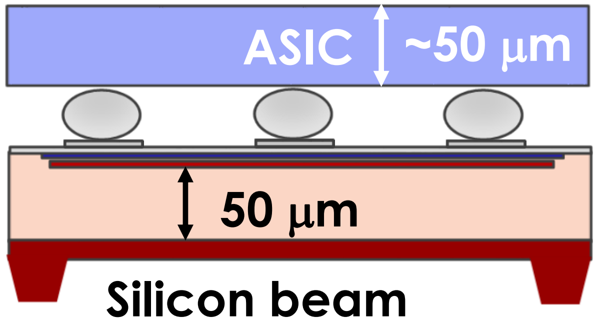
Reduced material budget

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

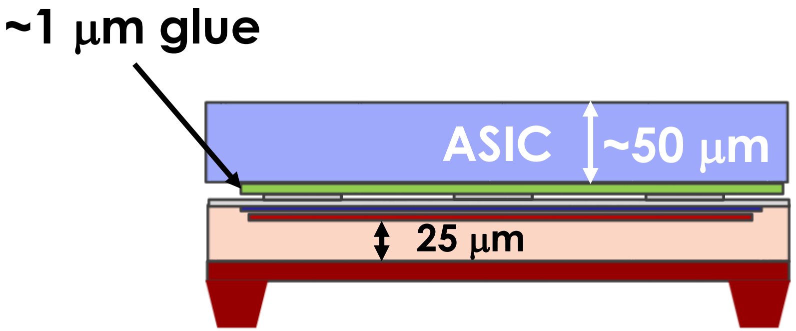
There is a clear path leading to < 100 μm material:



Present design: no material budget optimization

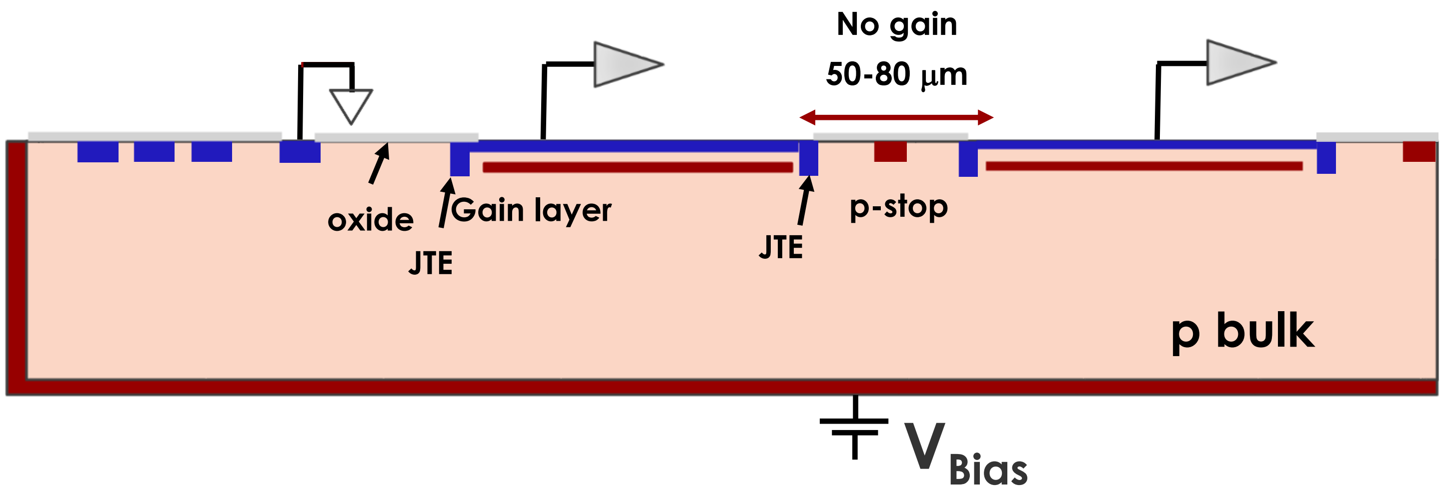


- Thinned handle wafer:
  500 um ➔ 10-20 um



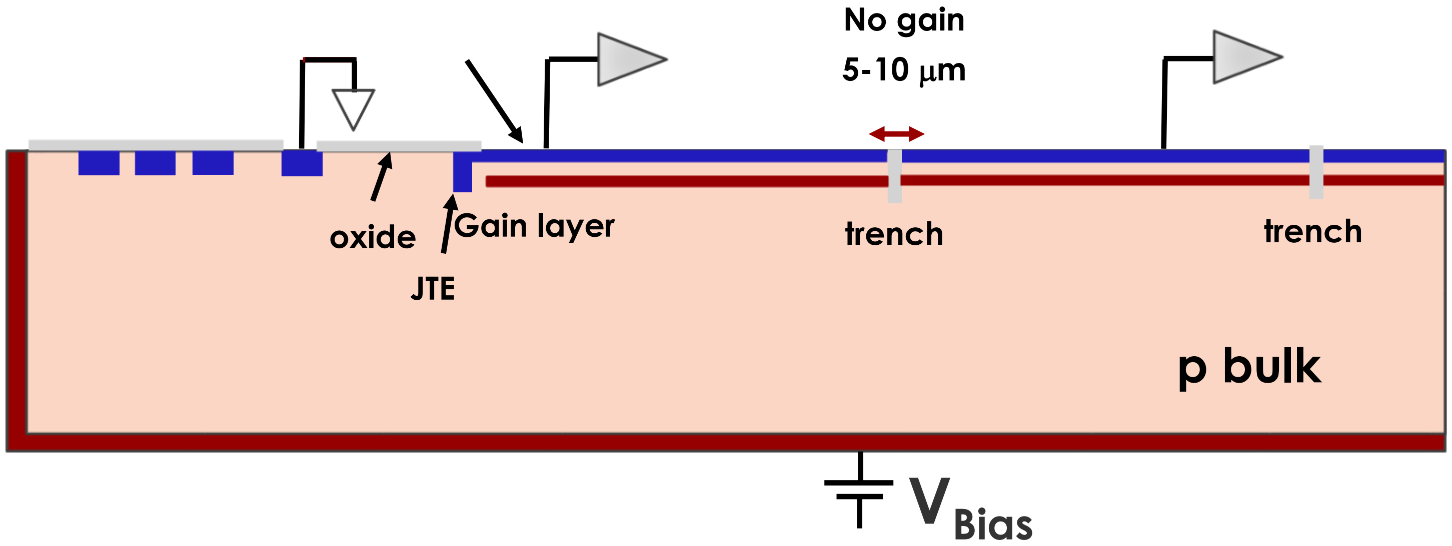
- Thinned handle wafer:
  500 um ➔ 10-20 um
- Thinned active area:
  50 um ➔ 25 um
  50 ps ➔ 25 ps

Towards 100% fill factor: Trench Isolated LGAD



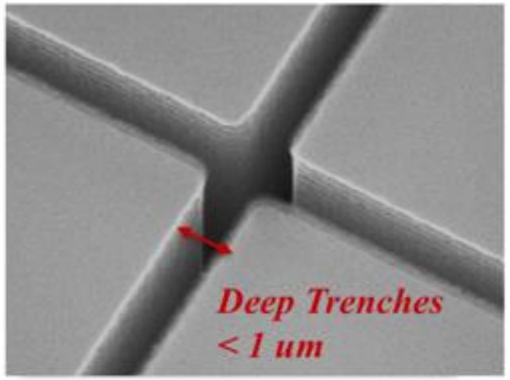
No-gain region ~ 50-80 μm

➔ cannot use UFSDs for small pixels

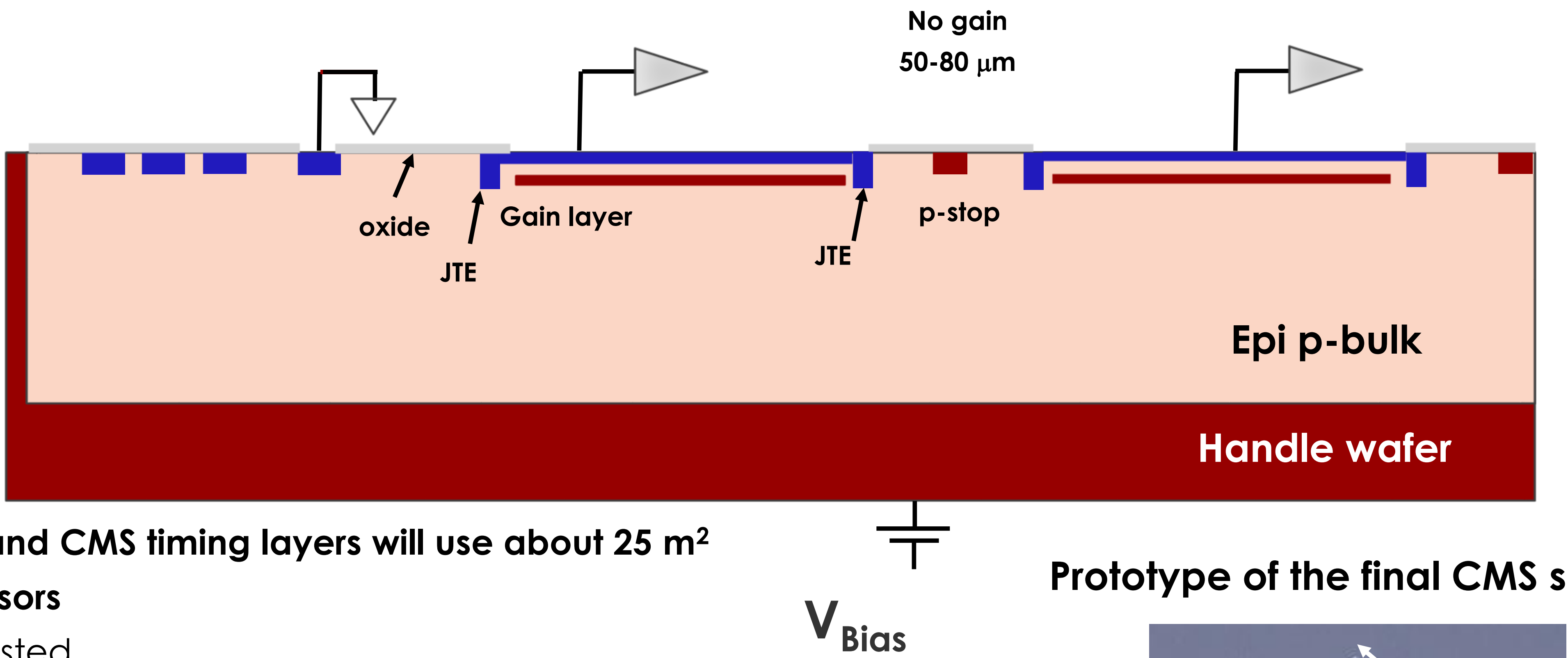


Solution: use trenches for pad isolation

➔ No-gain region ~ 5 – 10 μm

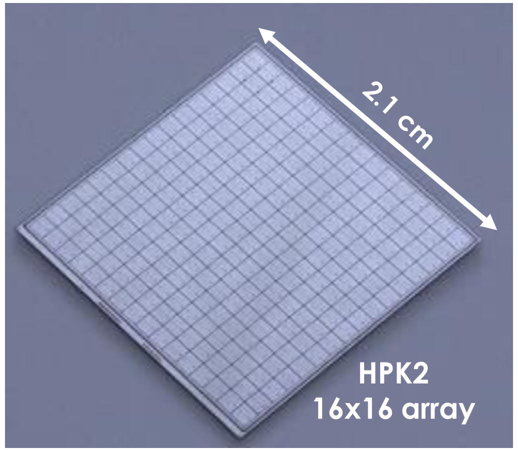


State-of-the-art: sensors for ATLAS and CMS



- **The ATLAS and CMS timing layers will use about 25 m² of UFSD sensors**
- Very well tested
- Will be used up to ~ 2 E15 n_{eq}/cm^2
- Gain ~ up to 40 when new ==> up to 20 fC
- Signal duration ~ 1 ns
- Low noise
- Rate ~ 50-100 MHz
- Excellent production uniformity

Prototype of the final CMS sensor



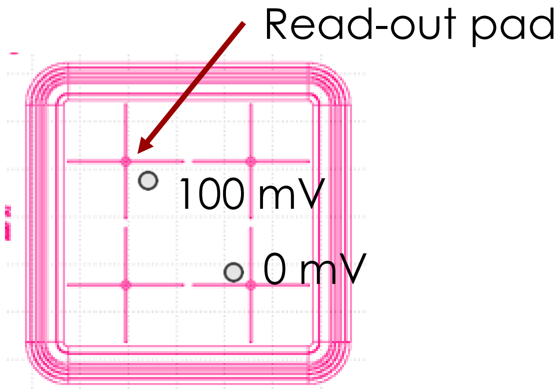
Spatial resolution: the role of jitter

The main component of the position resolution is the position jitter, defined as:

$$\sigma_{jitter} = \frac{\sigma_{el\_noise}}{\frac{dA}{dx}}$$

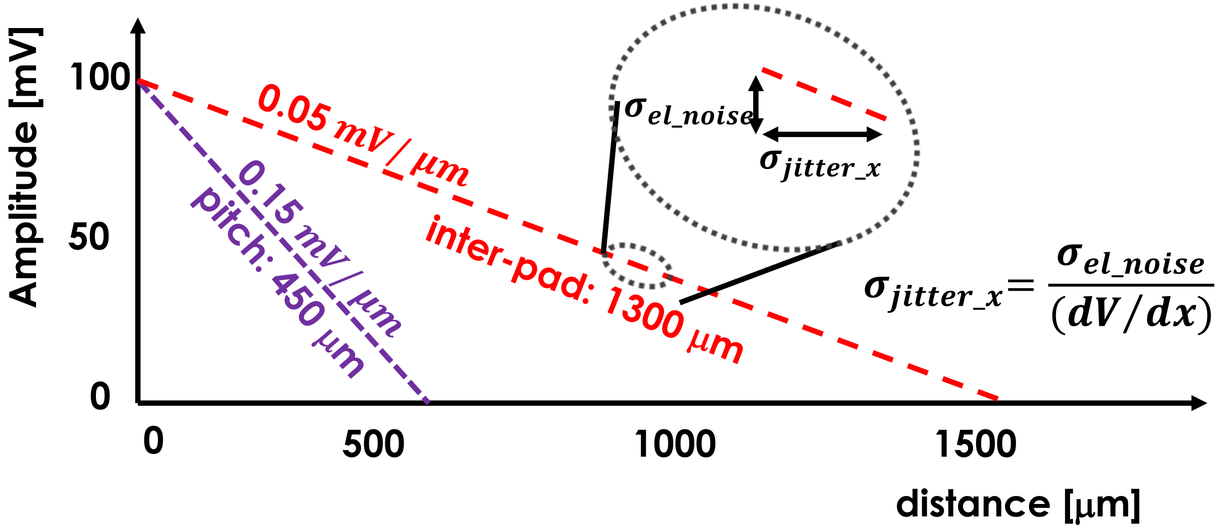
Imagine a system with a single read-out pad where a hit generates:

- A signal of 100 mV when shot near a pad
- A signal of 0 mV when shot at the opposite corner
- Noise ~1 mV (as in our lab)



In this simplified system, the signal decreases by:

- Pitch 1300 μm: 0.05 mV/μm
- Pitch 450 μm: 0.15 mV/μm



So, the jitter is:

- **Pitch 1300 μm: 1 mV/(0.05 mV/μm) = 20 μm**
- **Pitch 450 μm: 2 mV/(0.15 mV/μm) = 7 μm**

Irradiation effects

Irradiation causes 3 main effects:

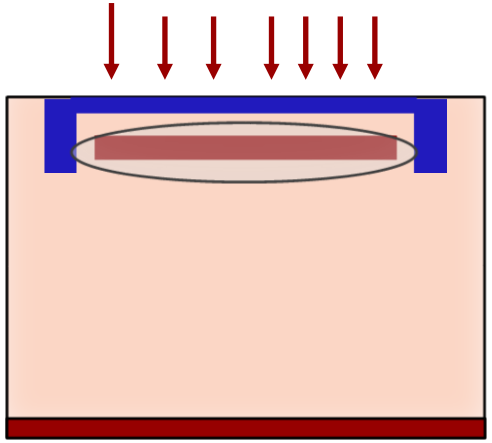
- Decrease of charge collection efficiency due to trapping
- Doping creation/removal
- Increased leakage current, shot noise

The main effect in LGAD is "acceptor removal", i.e., the reduction of the gain implant doping

The electric field due to the gain implant decreases ➔ Compensated with higher bias

Main technique to decrease acceptor removal: carbon implantation in the gain layer

carbon implantation



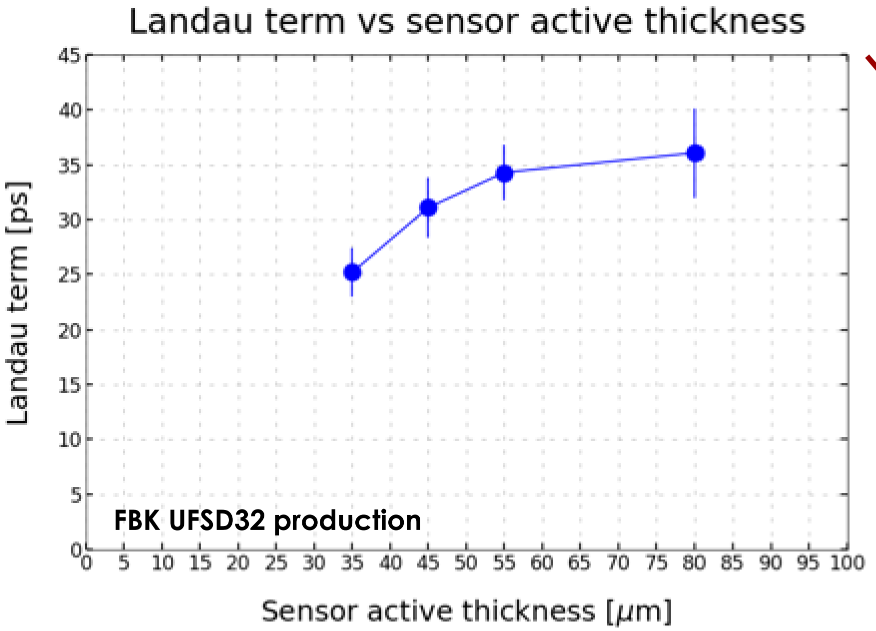
Carbon spoils the properties of silicon sensors.
However, **in the right amount and only on the gain implant, it increases the sensor rad. resistance by a factor of 3**

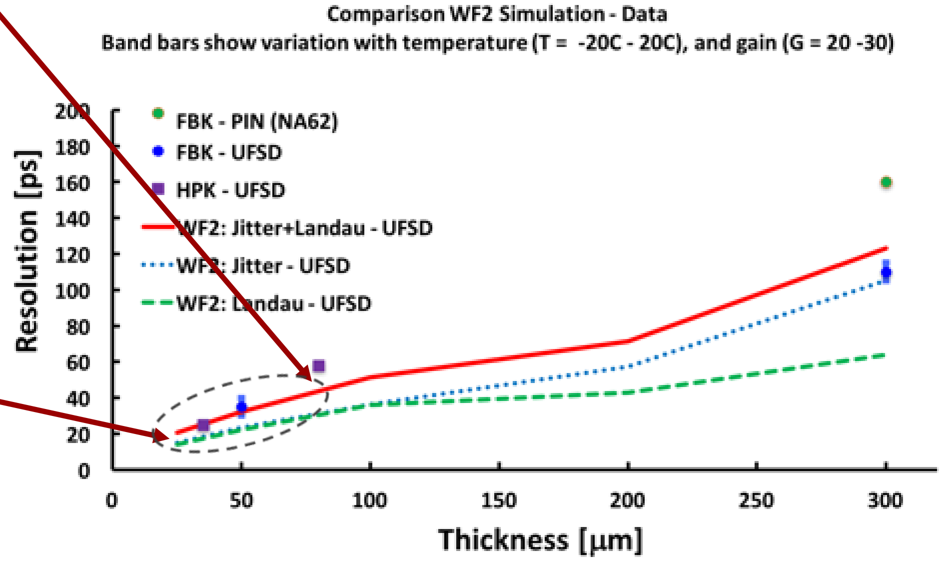
UFSD temporal resolution in thinner sensors

UFSD temporal resolution improves in thinner sensors:

==> reasonable to expect 10-20 ps for 10-20 μm thick sensors.

Be aware: very difficult to do timing with small signals… power consumption increases





Position reconstruction using charge imbalance

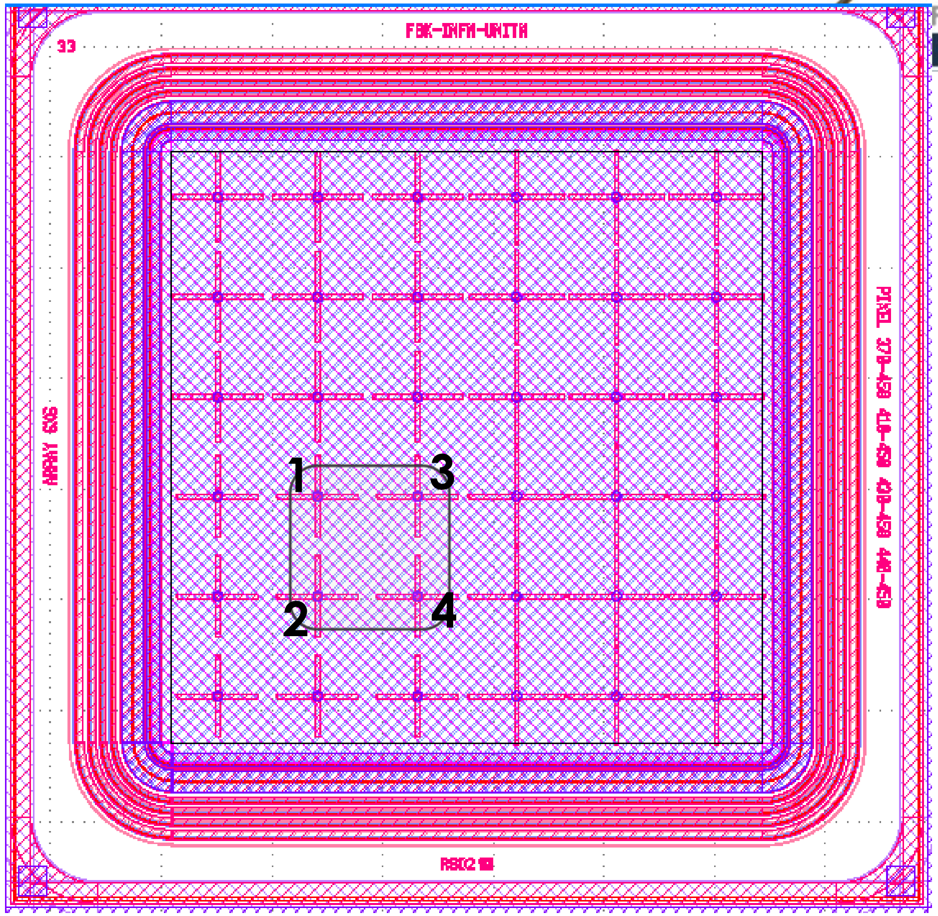
The position is reconstructed using the charge imbalance among the electrodes positioned at the 4 corners

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

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

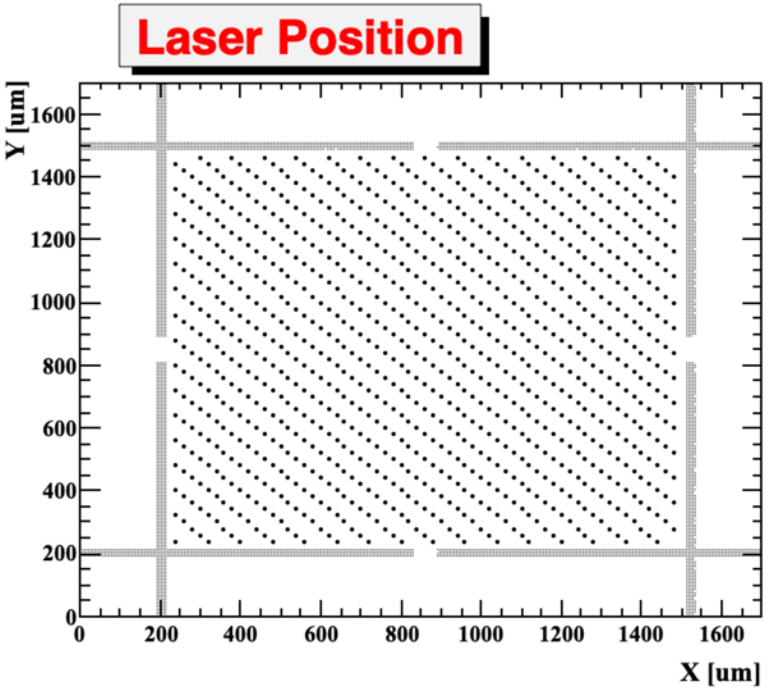
$$k_x = \frac{Q_{tot}}{Q_3 + Q_4 - (Q_1 + Q_2)} \Big|_{x@edge}$$

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

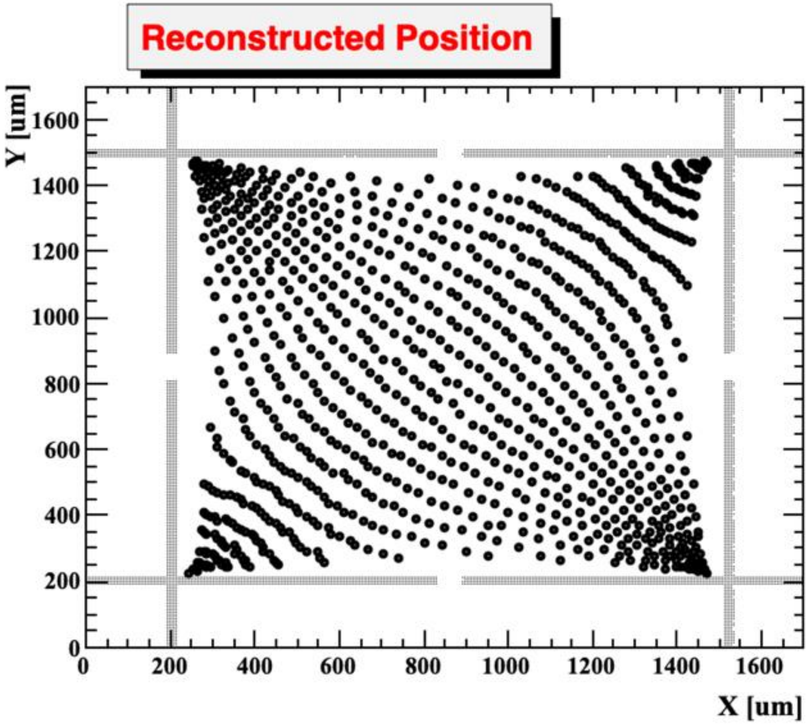


Evaluate the spatial resolution using laser TCT

Shoot the laser in a grid of points



Reconstruct the hit position with charge imbalance



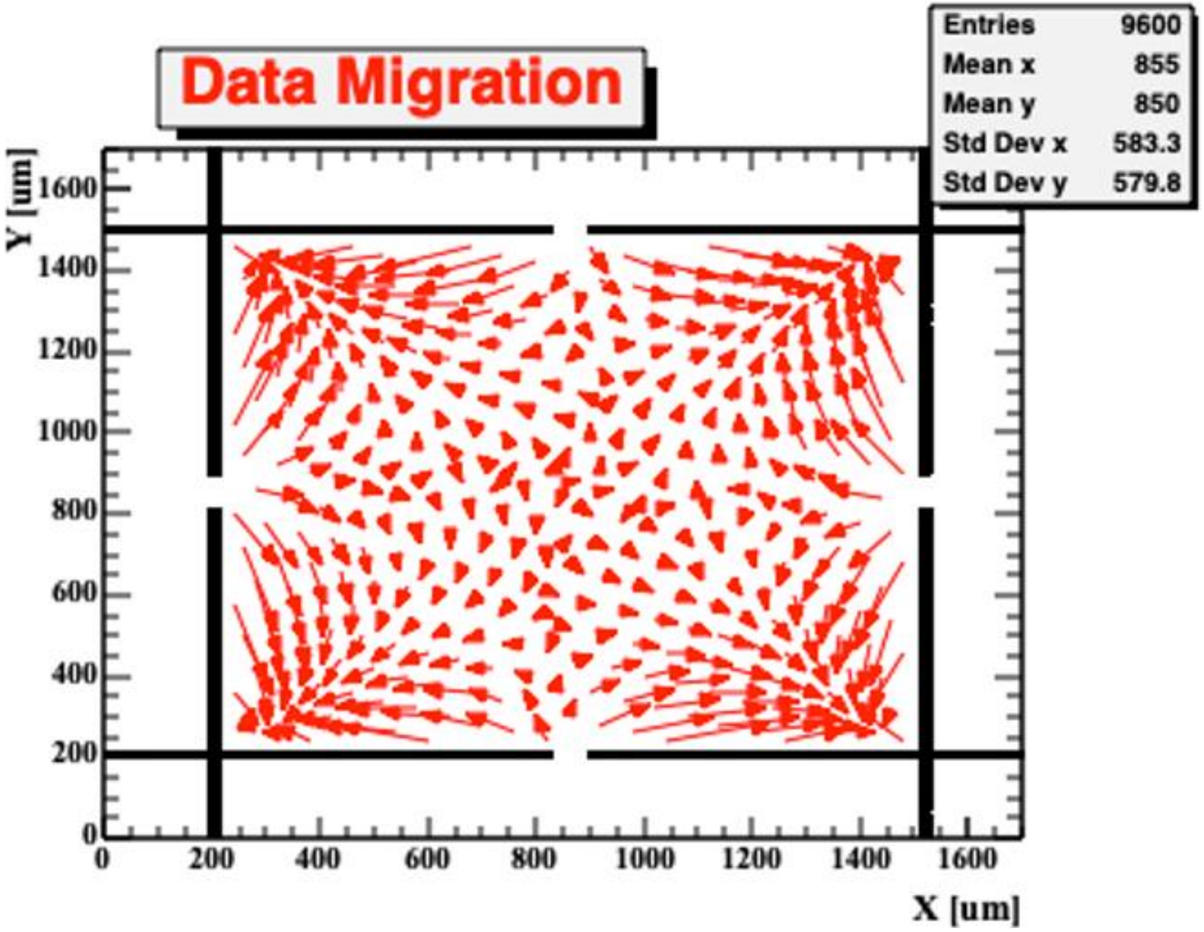
First take-home result: even without any additional correction, the cross-shaped electrodes provide a fairly accurate position reconstruction

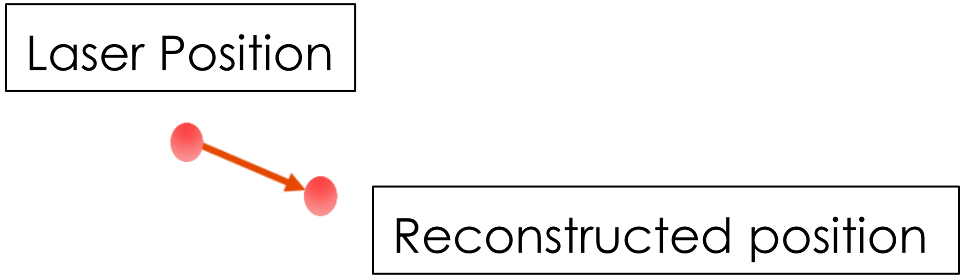
Second take-home result: near the pads, the reconstructed positions are systematically shifted with respect to true positions

Correct the reconstructed position

Compute the migration map:

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





RSD2 spatial resolution

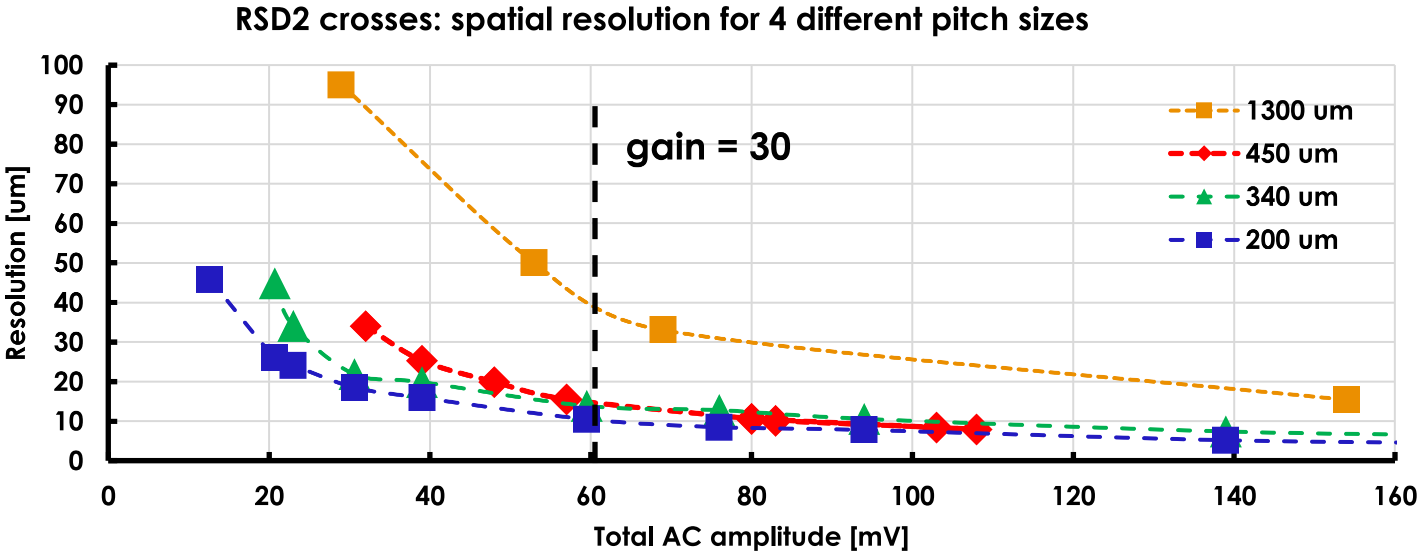
RSDs at gain = 30 achieve a spatial resolution of about 2-3% of the pitch size:

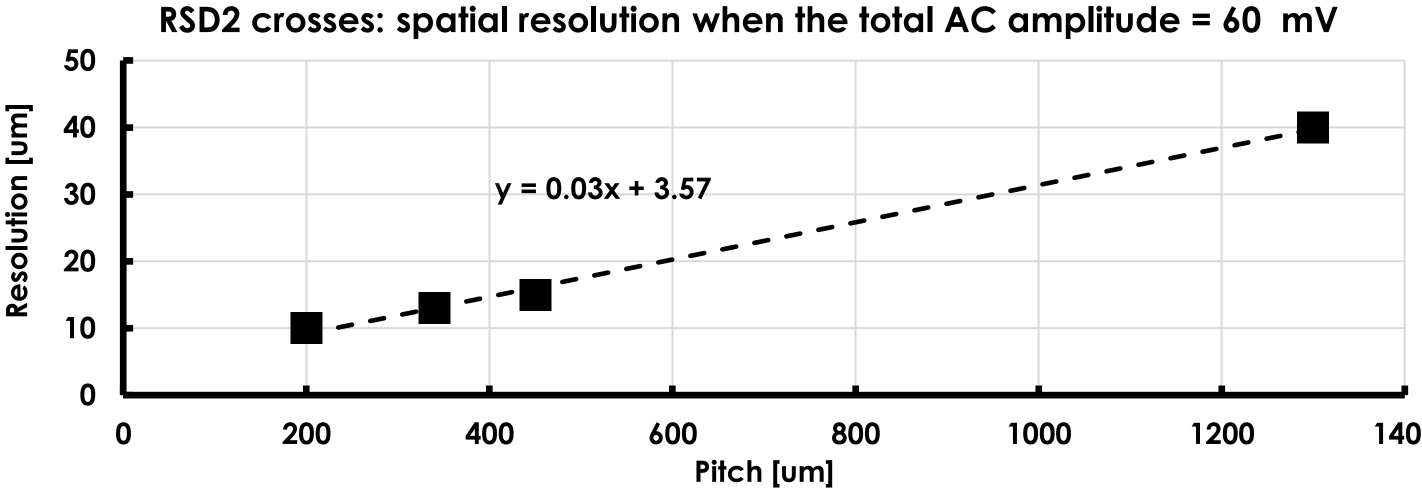
RSD:

- **1300 x 1300 mm^2: σ_x ~ 40 μm**
- **450 x 450 mm^2: σ_x ~ 15 μm**

Traditional standard pixel

- **1300 x 1300 mm^2: σ_x ~ 920 μm**
- **450 x 450 mm^2: σ_x ~ 320 μm**





N. Cartiglia, INFN, Torino, 7th INFIERI School, 30/09/23

RSD2 temporal resolution

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

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