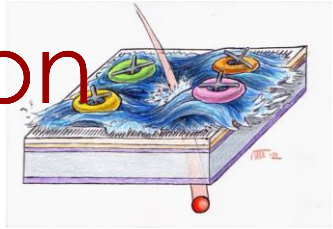
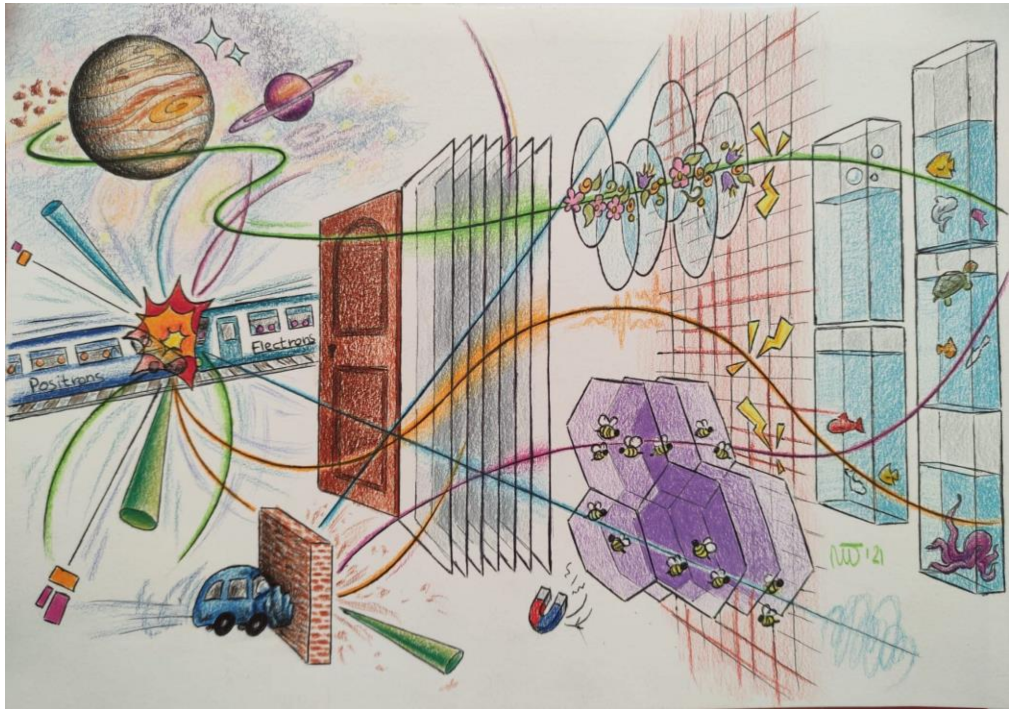
Resistive read-out and built-in amplification



New trends in silicon sensors design

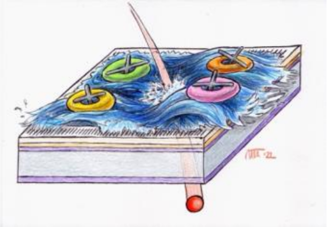


N. Cartiglia

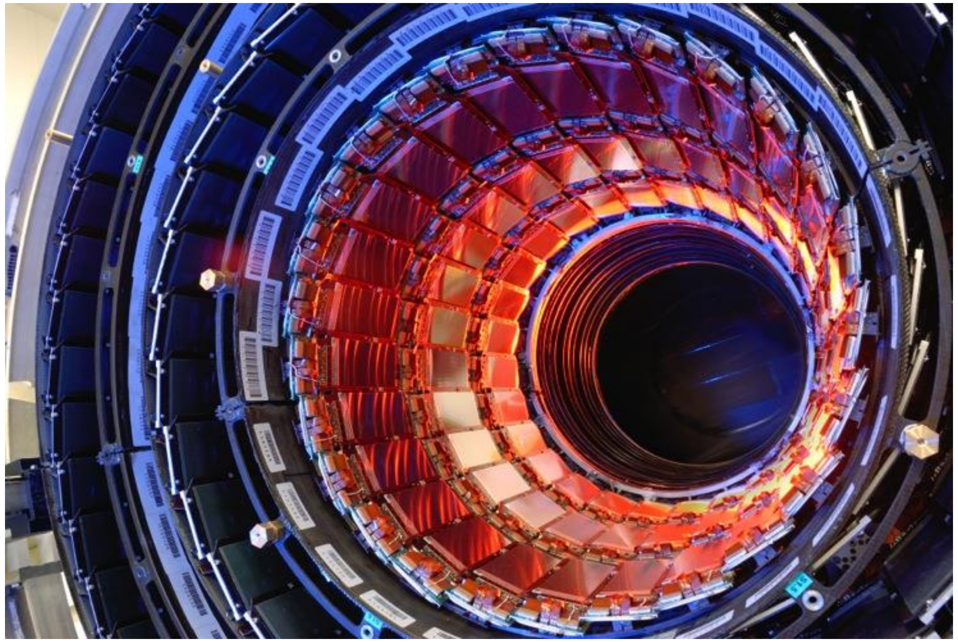
UFSD group

INFN Torino, Trento Univ., FBK, Perugia Univ., CNR Perugia

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:

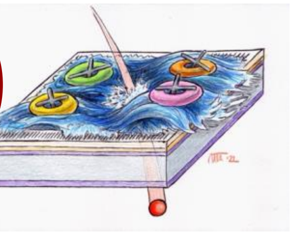
1. Silicon sensors are not suitable timing detectors
2. Silicon sensors cannot be used efficiently to detect 1-5 keV XRay

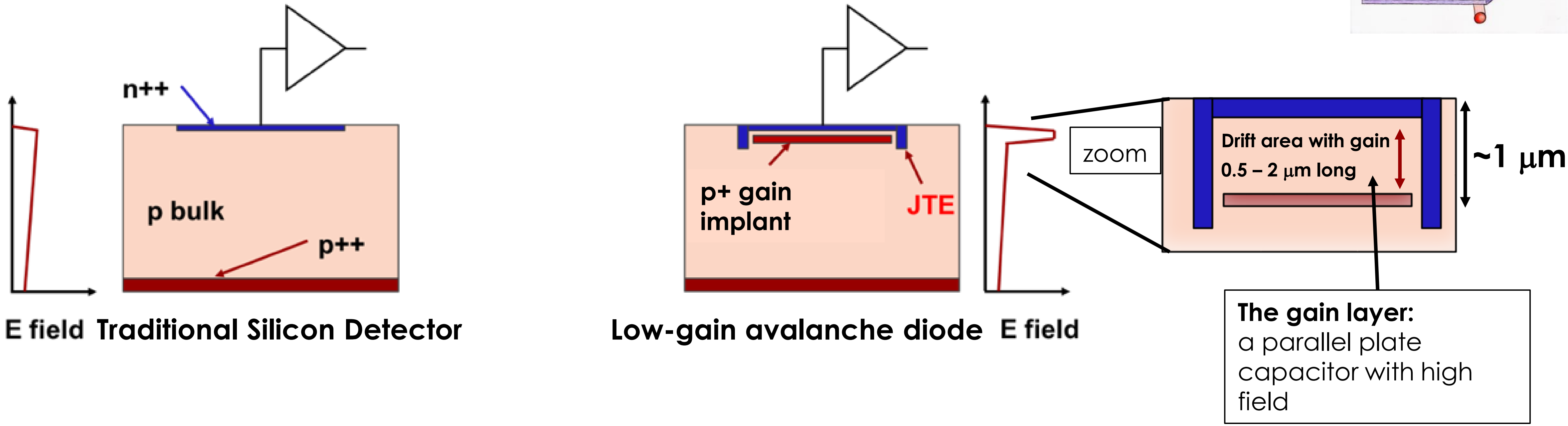
One nagging problem: radiation damage causes charge trapping, reducing the signal in heavily irradiated sensors.

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)



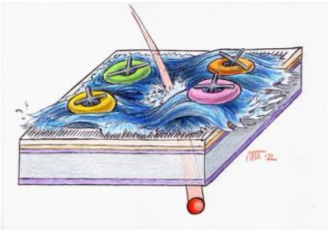


- In LGAD, a moderately p-doped implant creates a volume of high field, where charge multiplication happens.

- 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)**

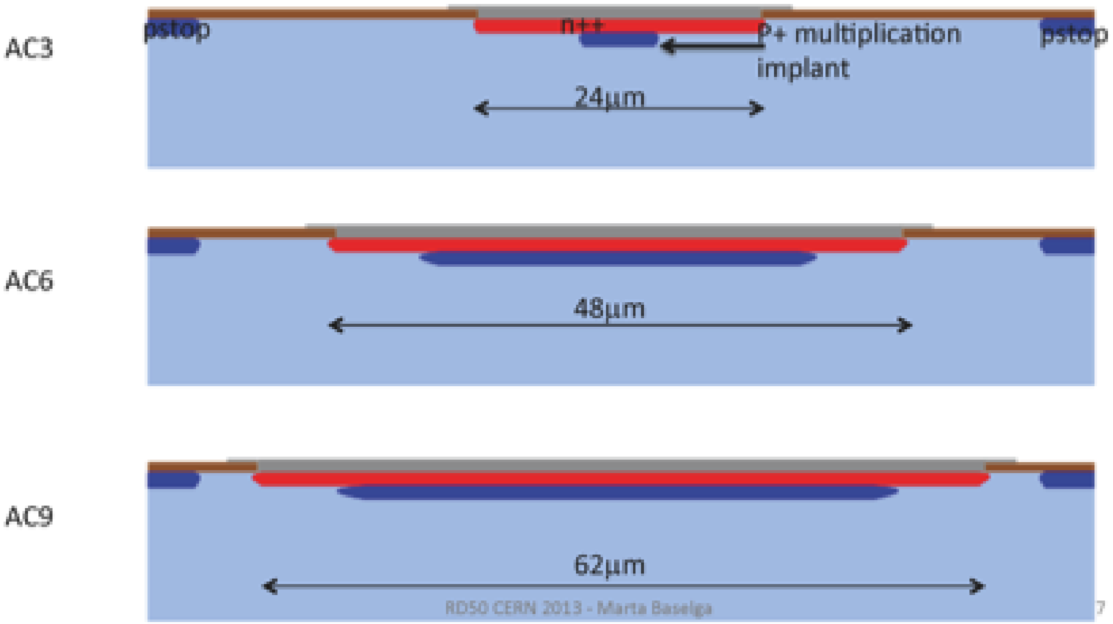
However, the LGAD design **did help solving a few other problems.**

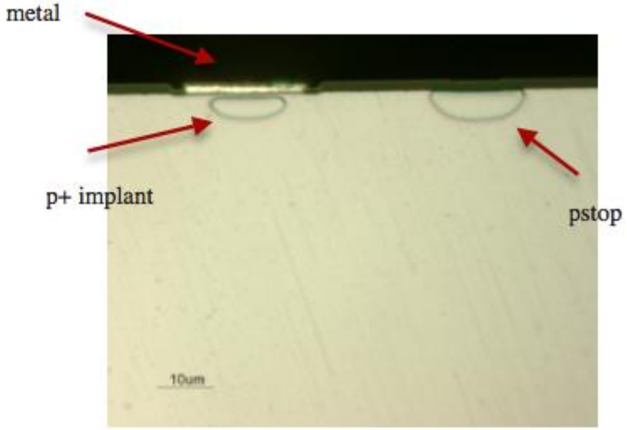
LGADs Pads, Pixels and Strips



The LGAD approach can be used in any silicon structure,

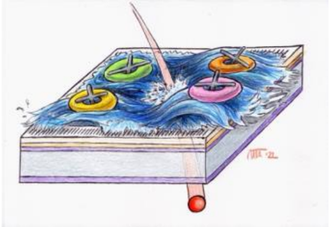
This is an example of LGAD strips



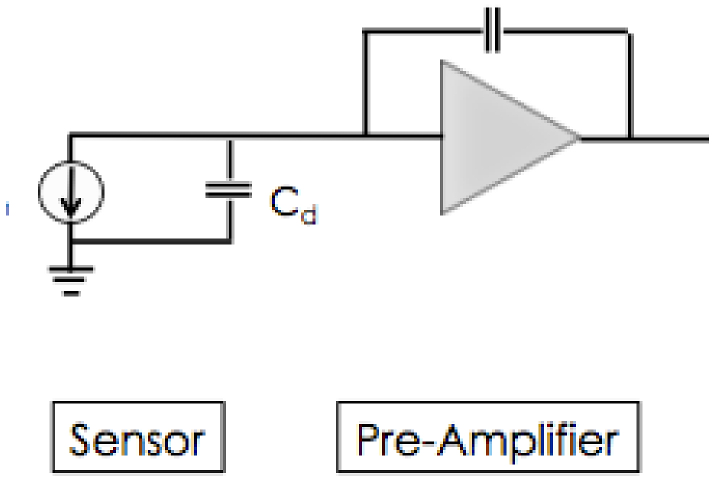


LGAD strips are considered in space application, as they allow to have longer strips while keeping constant the ratio Charge/Capacitance

What does "Low Gain" mean?



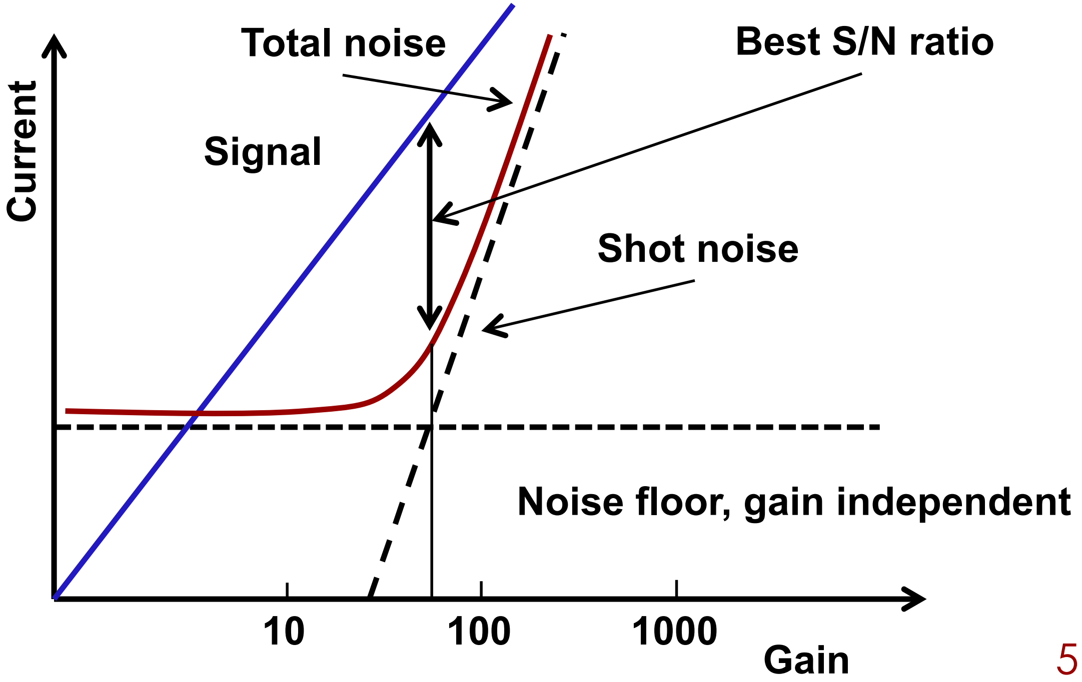
"Low gain" needs to be understood in connection with the noise of the electronics, and how silicon sensors are segmented.



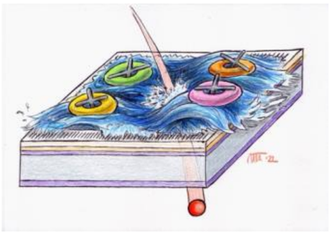
Signal multiplication decreases the sensor signal-to-noise ratio:
==> The noise increases faster than the signal

However, until the system noise is determined by the electronics, having gain improves the signal-to-noise ratio.

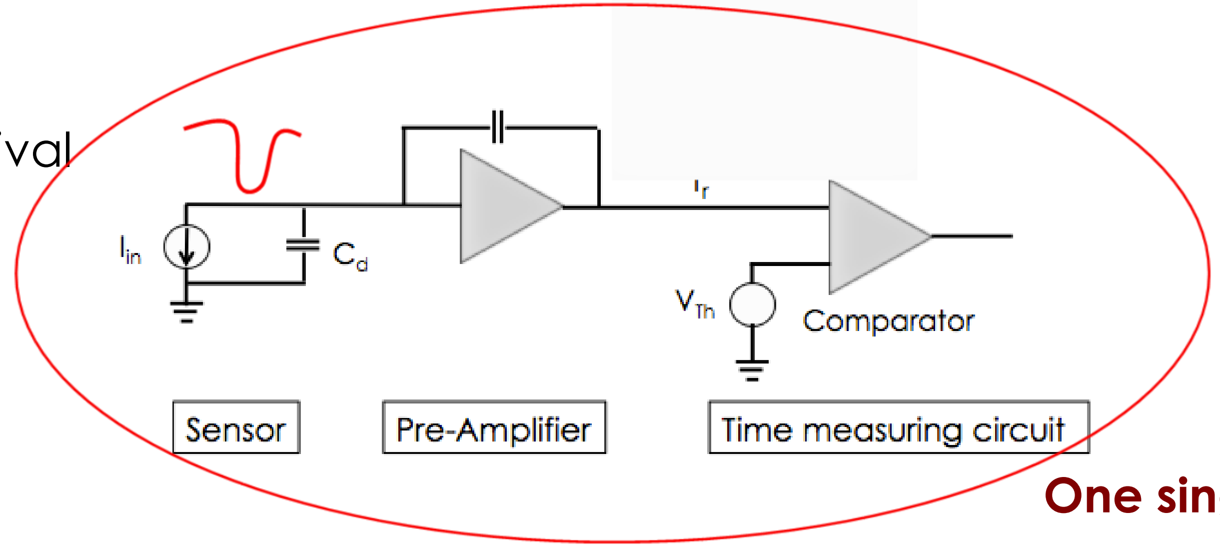
Low gain also allows segmenting the sensors.



A time-tagging detector: sensor and ASIC



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



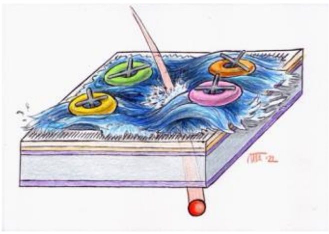
One single system

Sensors and read-out are two parts of a single object, sometimes even on the same substrate

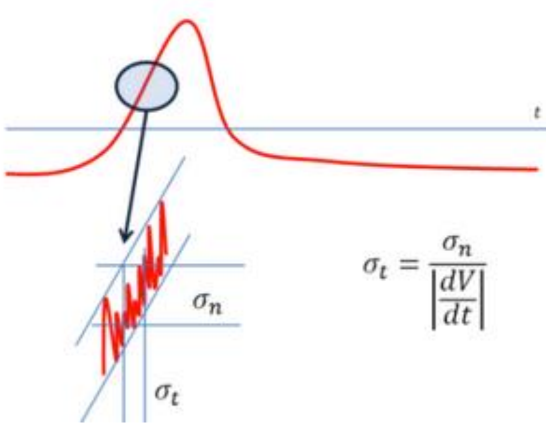
Sensors and electronics succeed (or eventually fail) together

Presently, the design of the electronics is the hardest part, the sensors have been under development for longer

Sensor and ASIC Temporal resolution



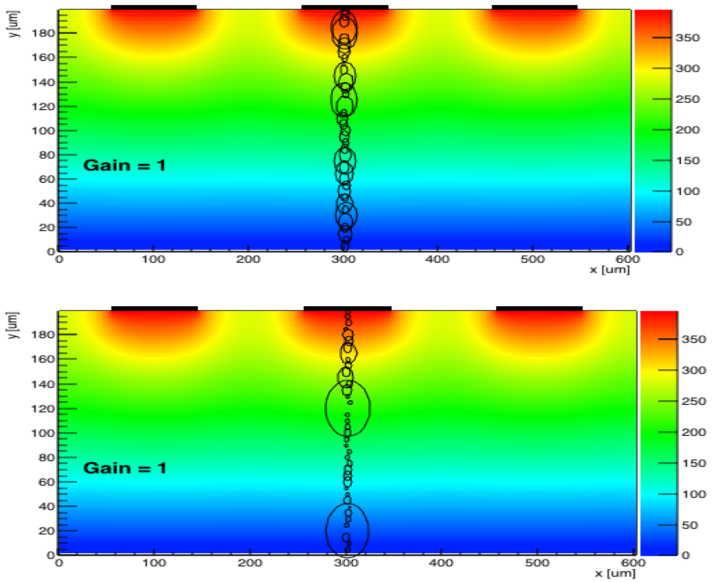
$$\sigma_t^2 = \left(\frac{Noise}{dV/dt}\right)^2 + (\Delta ionization)^2 + (\Delta shape)^2$$



"Jitter" term

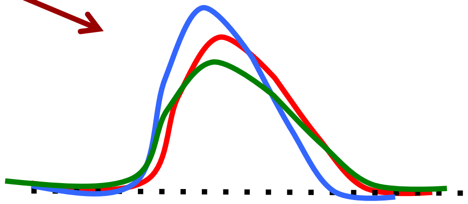
Small noise ==> choice of electronic technology

LGADs, having a larger signal, decrease the jitter component



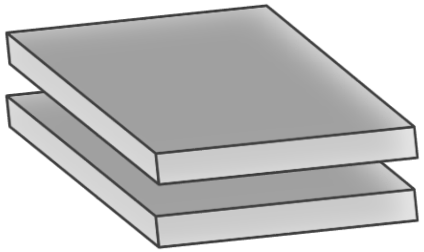
Amplitude variation ==> corrected offline (time walk)

Non-homogeneous energy deposition ==> signal change variation. Cannot be corrected, =minimized by design



Signal shape is determined by Ramo's Theorem

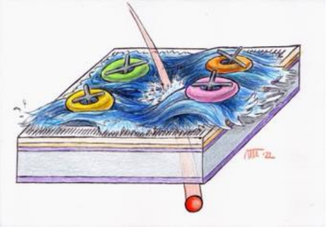
$i \mu qvE_w$



Saturated drift velocity v everywhere in the sensor volume

Well-designed LGAD sensors (sometimes called UFSD) optimize the temporal resolution

Key tool to design sensors: sensor simulation

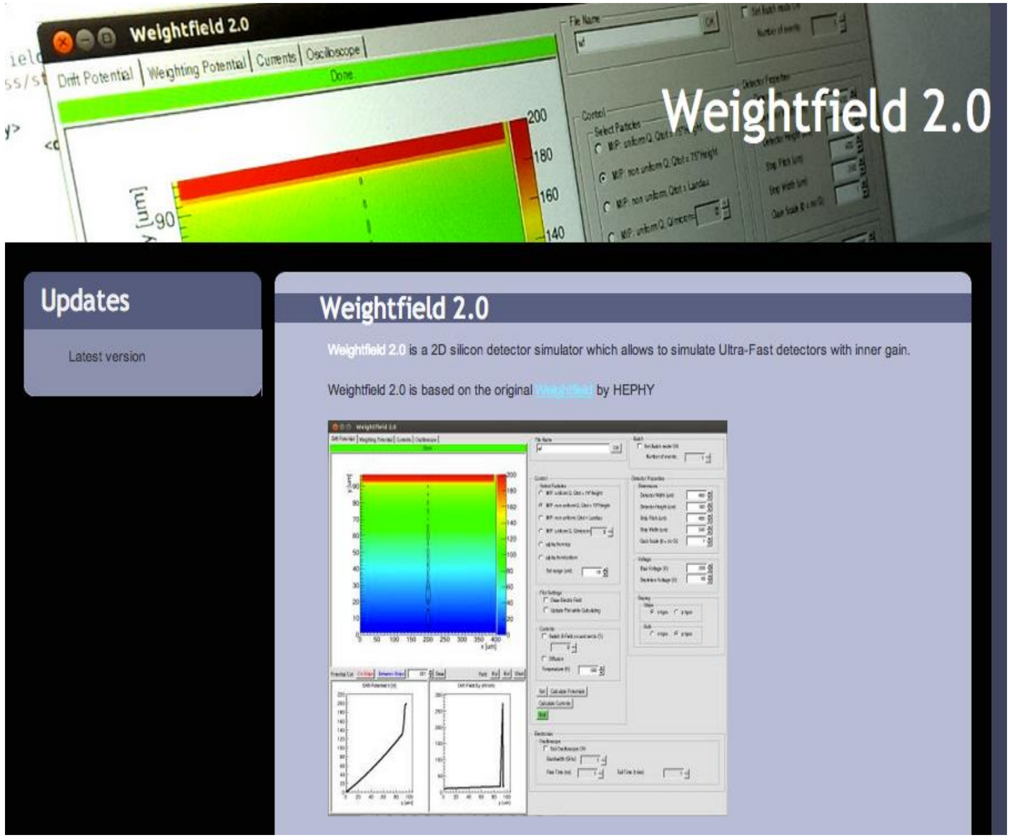


The design of innovative sensors needs a lot of simulation

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

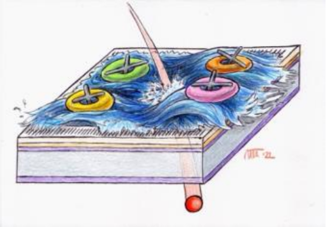
It includes:

- Charge particles and X-ray
- 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

Key tool to design sensors: sensor simulation



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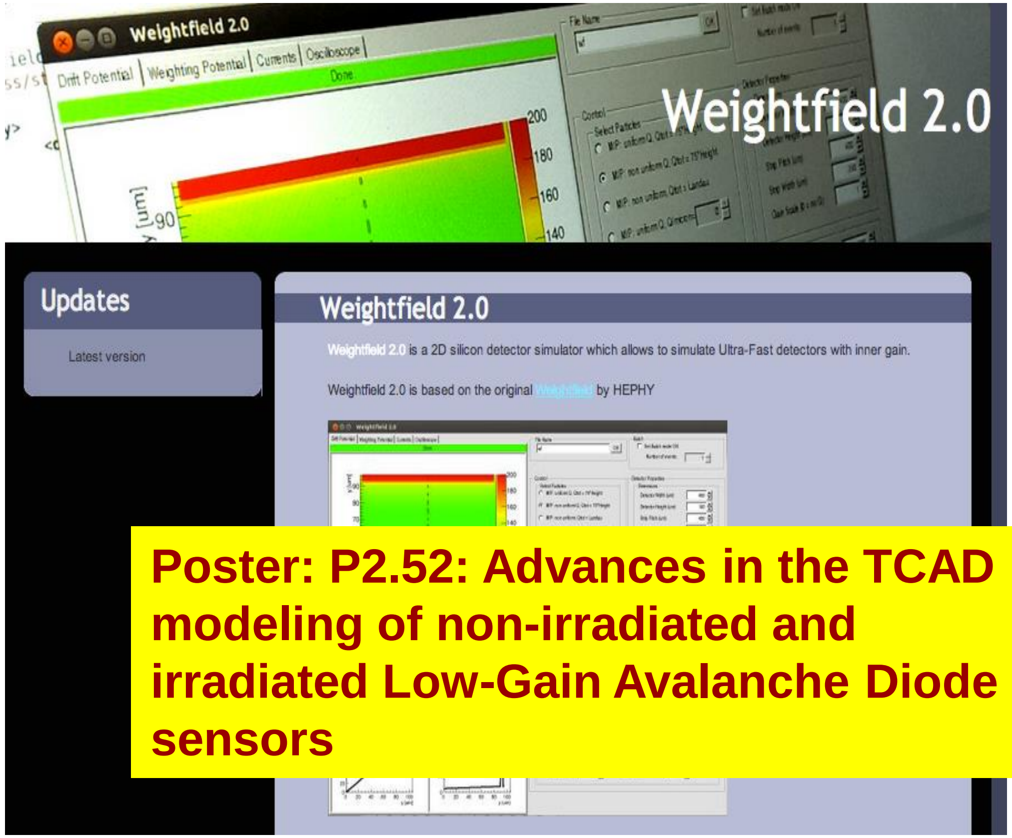
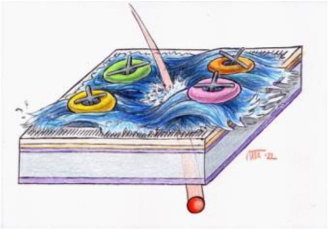
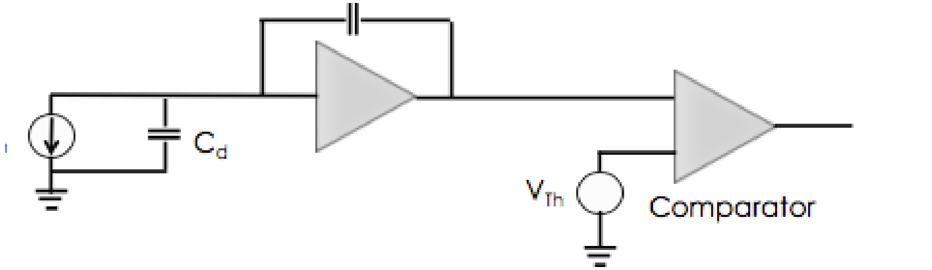


Poster: P2.52: Advances in the TCAD modeling of non-irradiated and irradiated Low-Gain Avalanche Diode sensors

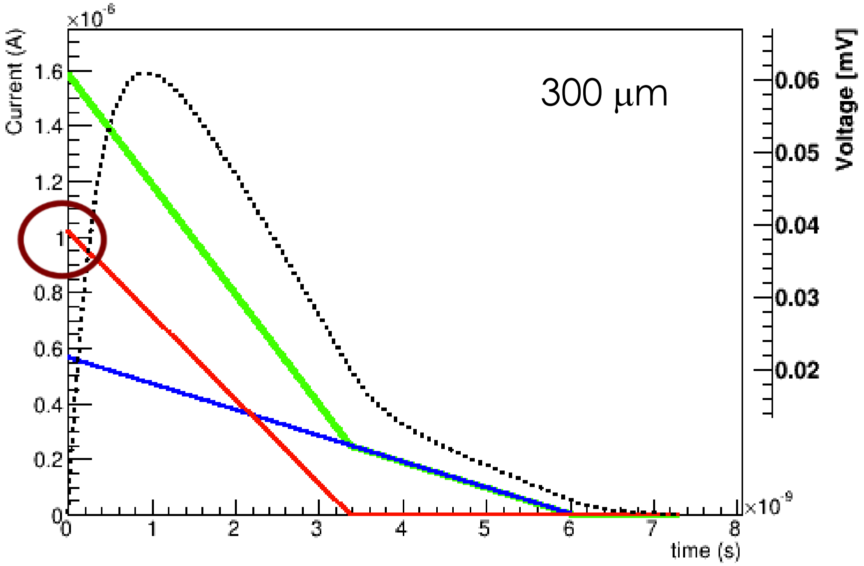
How gain shapes the signal

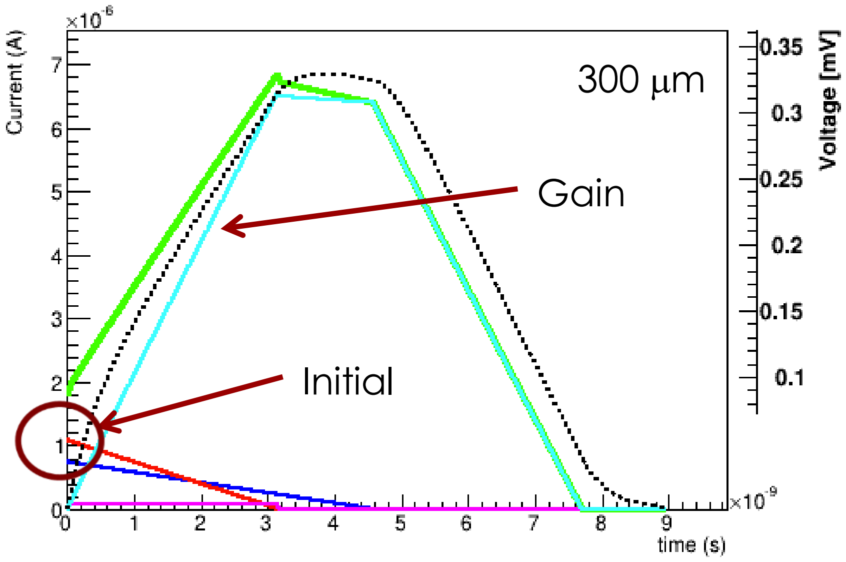


To fully exploit UFSDs, dedicated electronics needs to be designed.



The signal from UFSDs is different from that of traditional sensors





Simulated Weightfield2

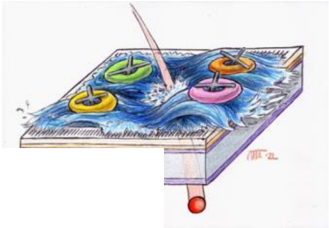
Pads with no gain

Charges generated uniquely by the incident particle

Pads with gain

Current due to gain holes creates a longer and higher signal

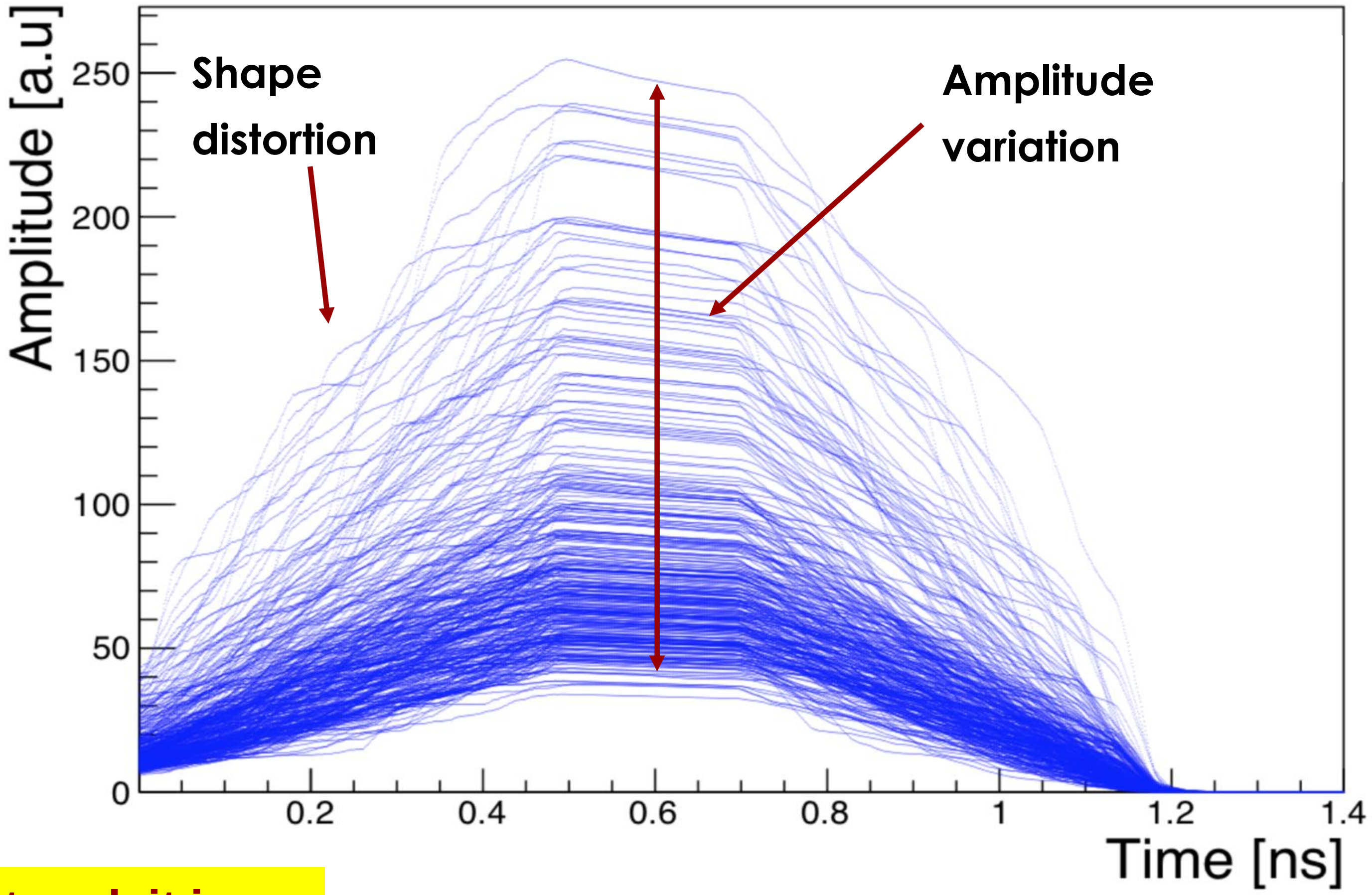
Input signals for the ASIC design



WF2 simulation shows how the current signal changes.

Two effects:

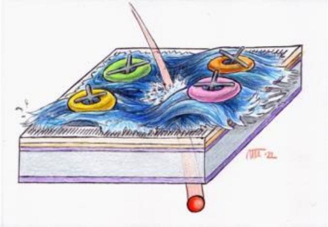
1. Amplitude variations
2. Shape distortions



To efficiently design the front-end, it is necessary to have detailed knowledge of the input signals

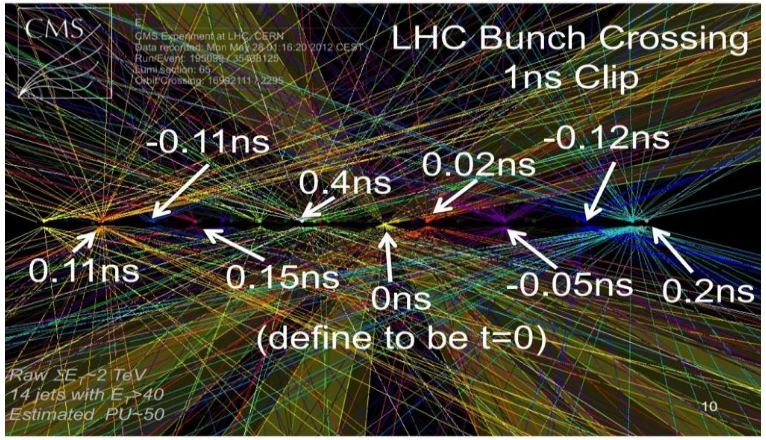
WF2 simulation of signals generated by a MIP crossing a 50 micron thick UFSD, gain ~ 20

Why is timing needed in the HL-LHC upgrade?



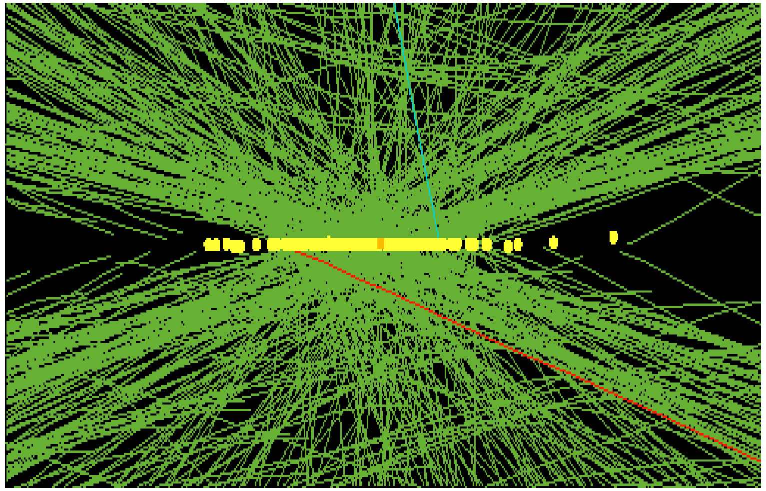
protons

protons



LHC situation:

the collisions are separated in space and time

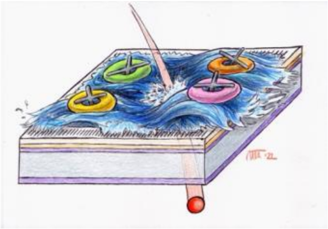


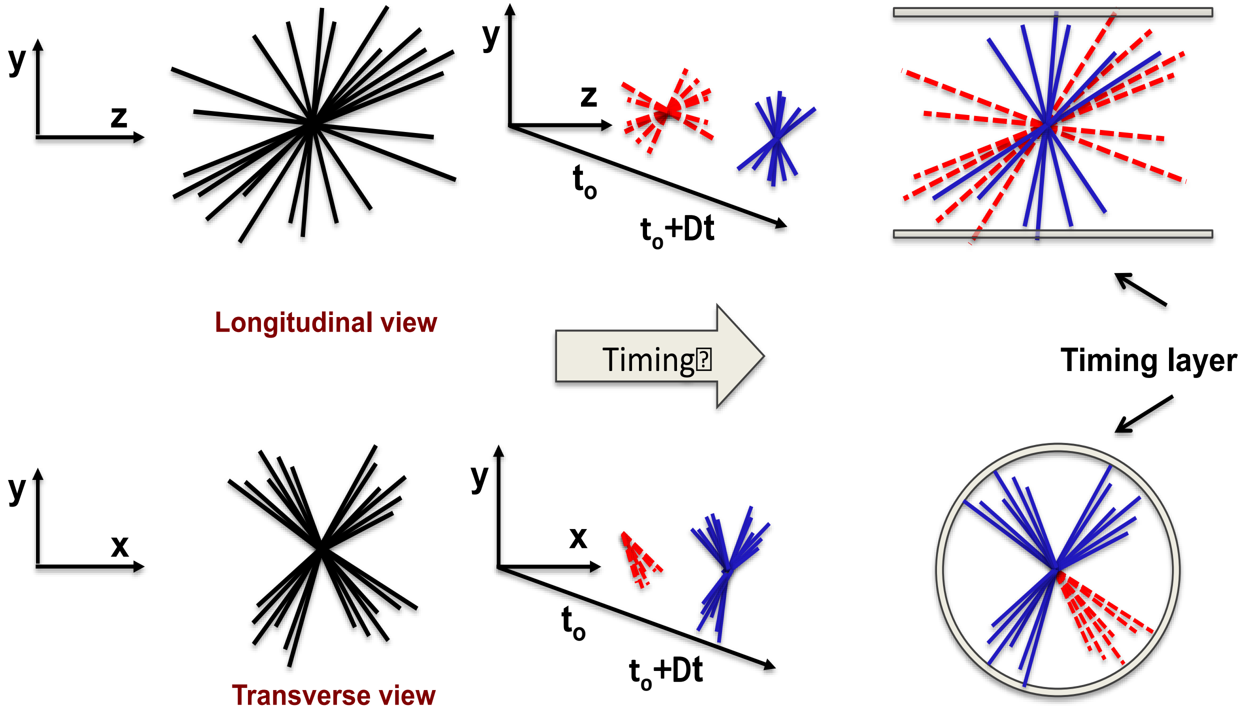
HL-LHC situation:

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

This leads to error in the reconstruction of the event

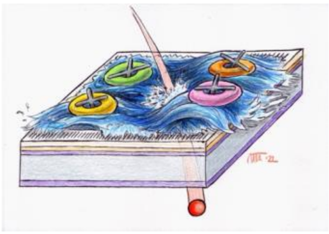
Tracking in 4Dimension





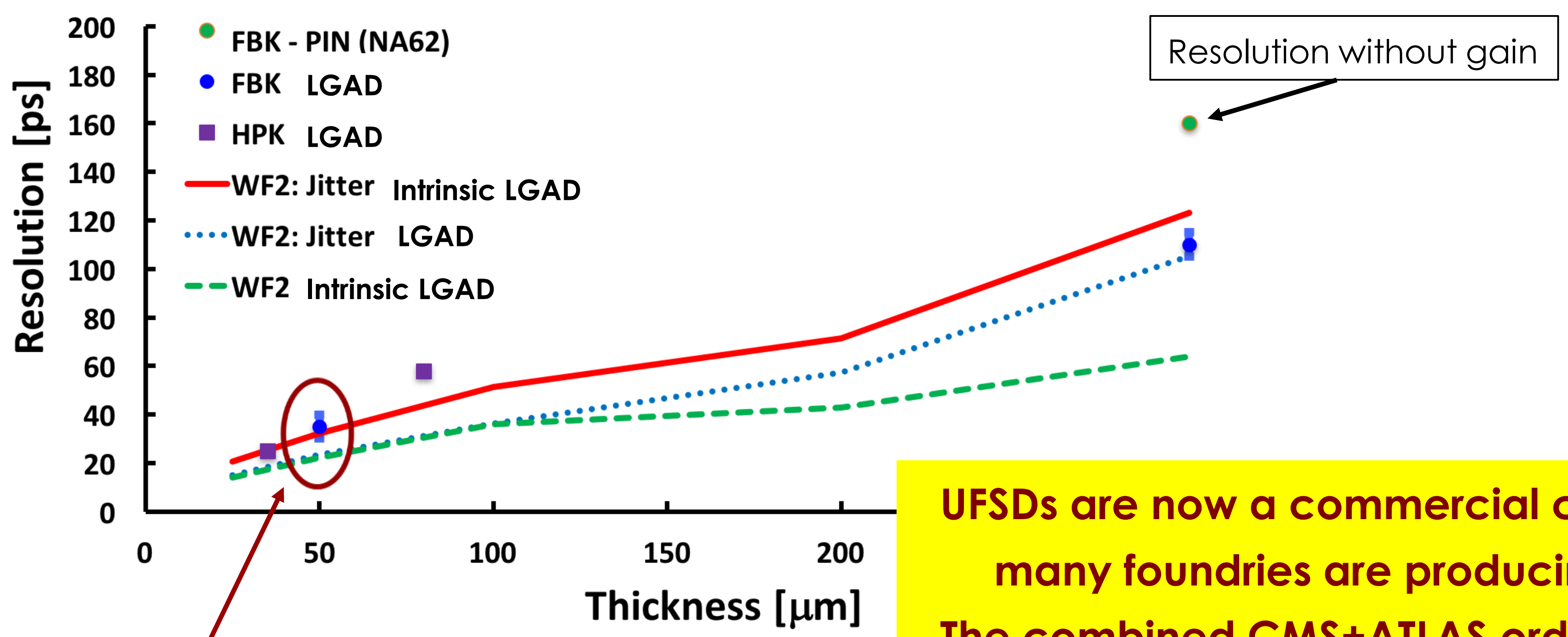
The introduction of timing allows separating collisions that happen in the same location

UFSD temporal resolution vs sensor thickness



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

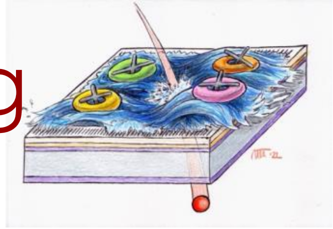
Comparison WF2 Simulation - Data
Band bars show variation with temperature (T = -20C - 20C), and gain (G = 20 -30)



UFSDs are now a commercial commodity, many foundries are producing them.
The combined CMS+ATLAS order exceeds 20 m² for a cost in excess of 5-6 million CHF

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

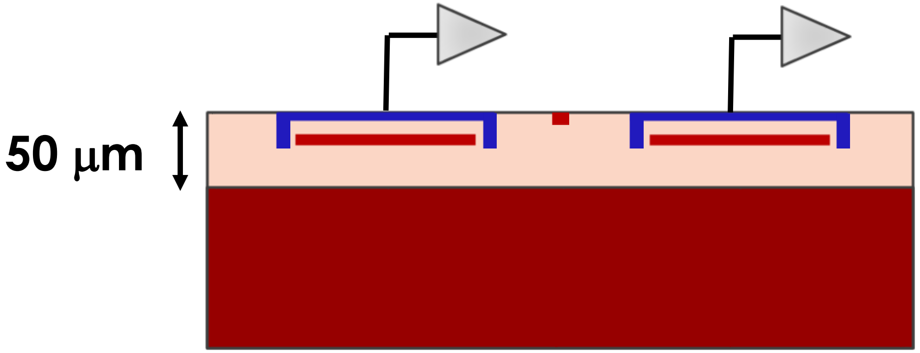
Development of low-energy X-ray detectors using LGAD sensors



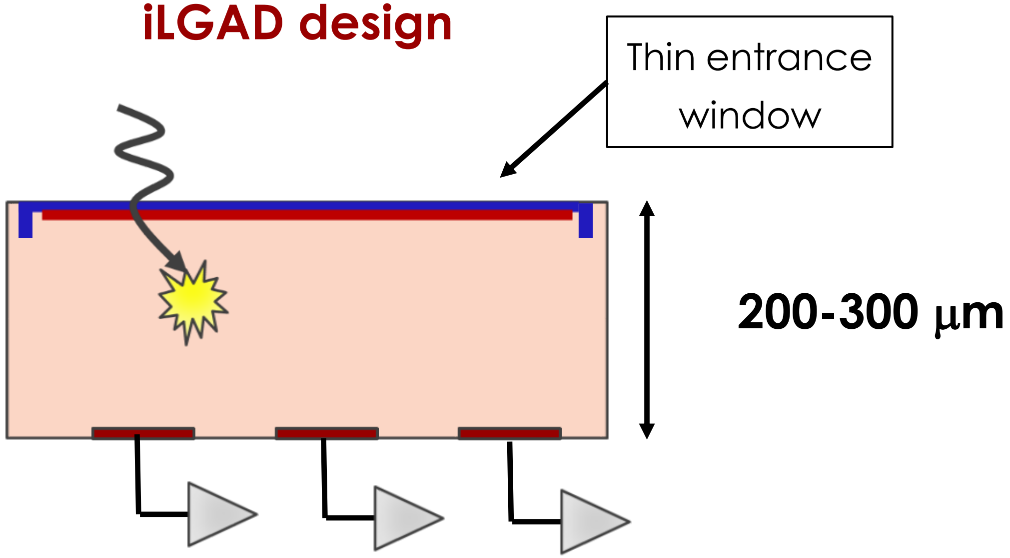
Internal gain allows boosting the sensor signal by about 10-30 times, opening up the possibility of detecting soft X-rays without changing the electronic design.

The combination of the iLGAD design with a thin entrance window lowers the minimum detectable energy to about 500 eV.

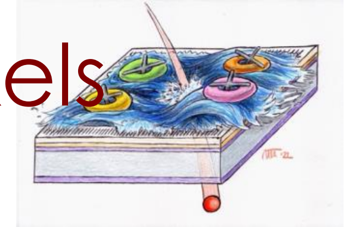
Standard LGAD design

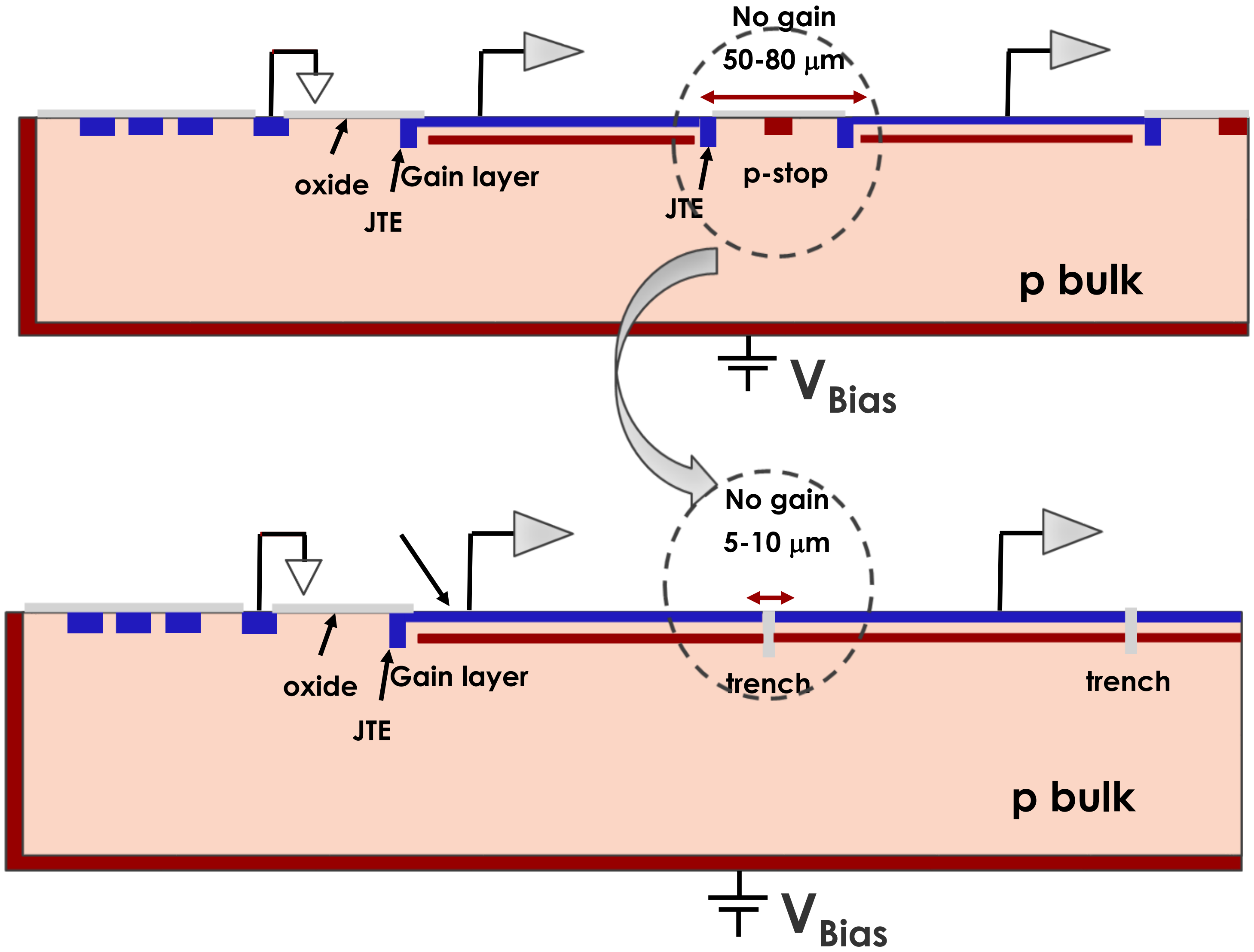


iLGAD design



LGAD Trench Isolated: enabling small UFSD pixels



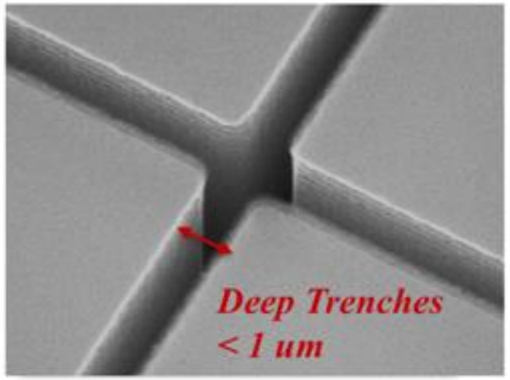


No-gain region ~ 50-80 μm

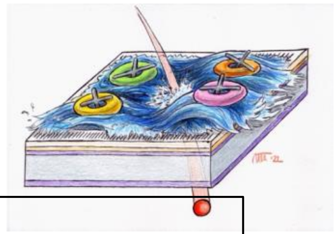
➔ cannot use for small pixels

Solution: use trenches for pad isolation

➔ No-gain region ~ 0 – 10 μm

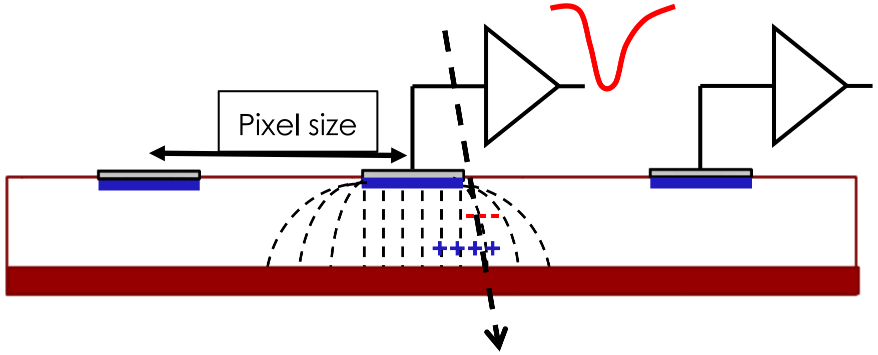


Silicon life in 2020: spatial resolution



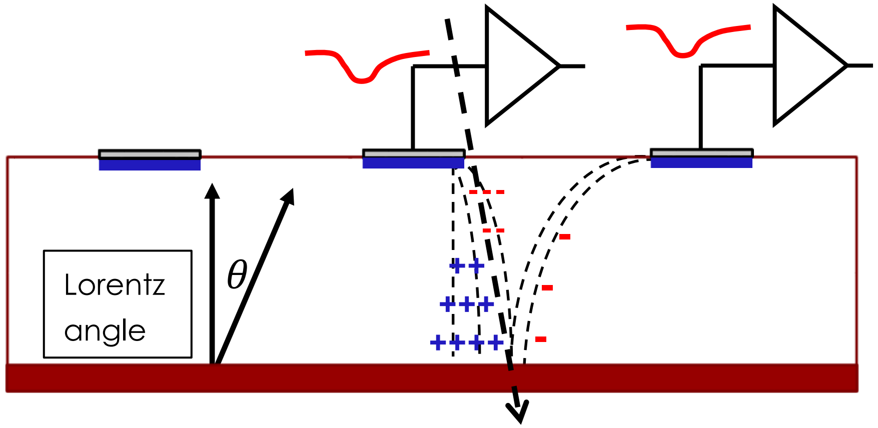
Single pixel

where the charge is collected in one pixel



Multi pixels

where the charge is collected in a few pixels



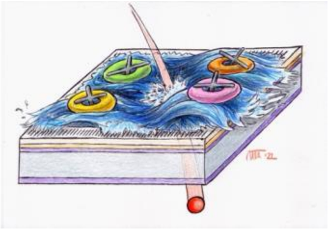
$$x_i = \frac{A_i x_i}{\sum_1^2 A_l x_l}$$

- **The need of excellent spatial resolution and low material budget forces the use of small pixels.**

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

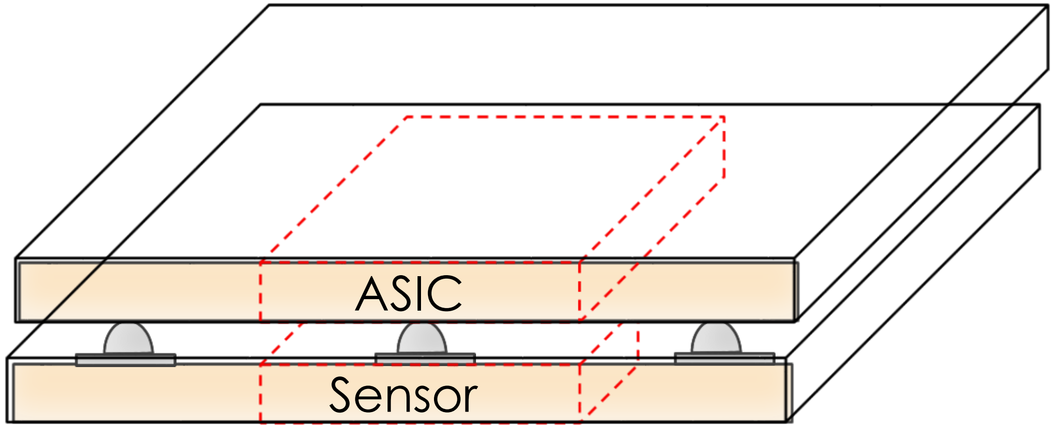
- σ_x **<< pixel size**
- Sensors have to be thick to maintain efficiency
- Need B field (or floating electrodes) to spread the signal

Spatial and temporal resolutions vs power consumption



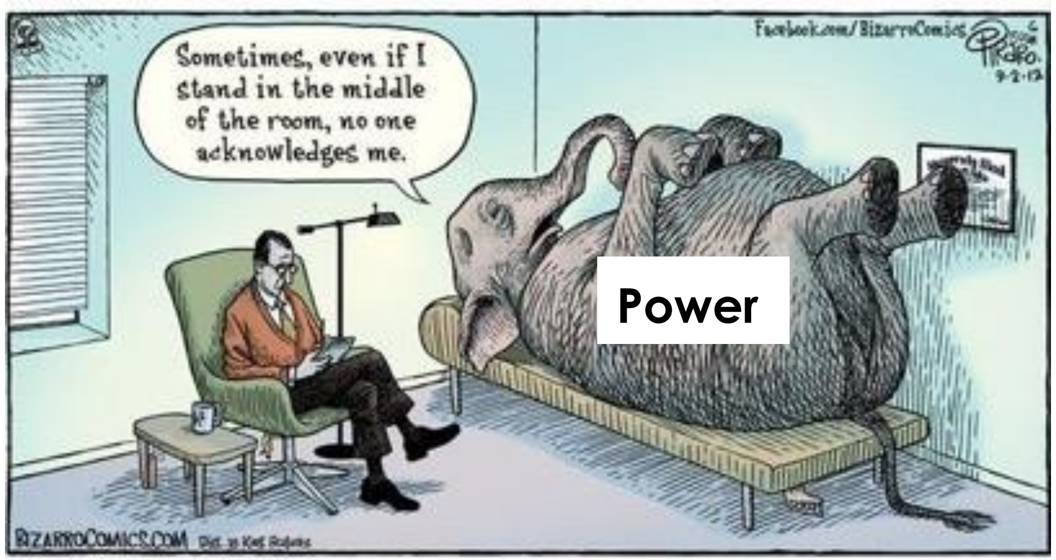
In single-pixel architecture, **the position resolution determines:**

- **The pixel size**
- **The space available for the electronics**

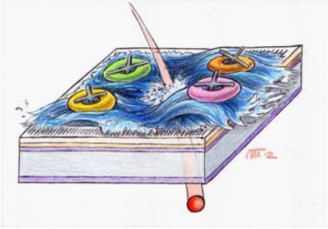


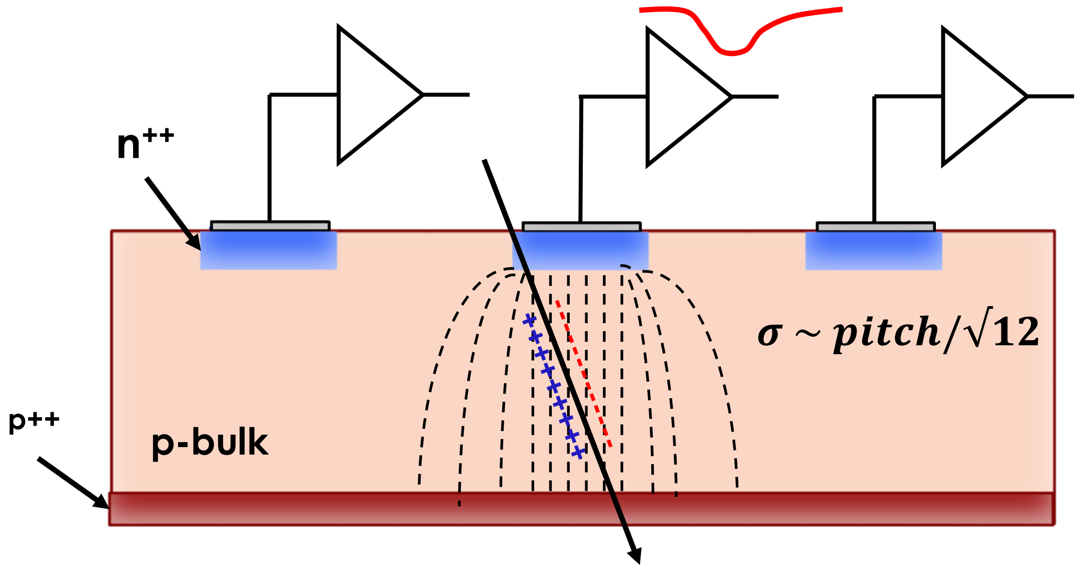
Good timing resolution requires a sizable amount of power per amplifier.

A large number of small pixels requires too much power

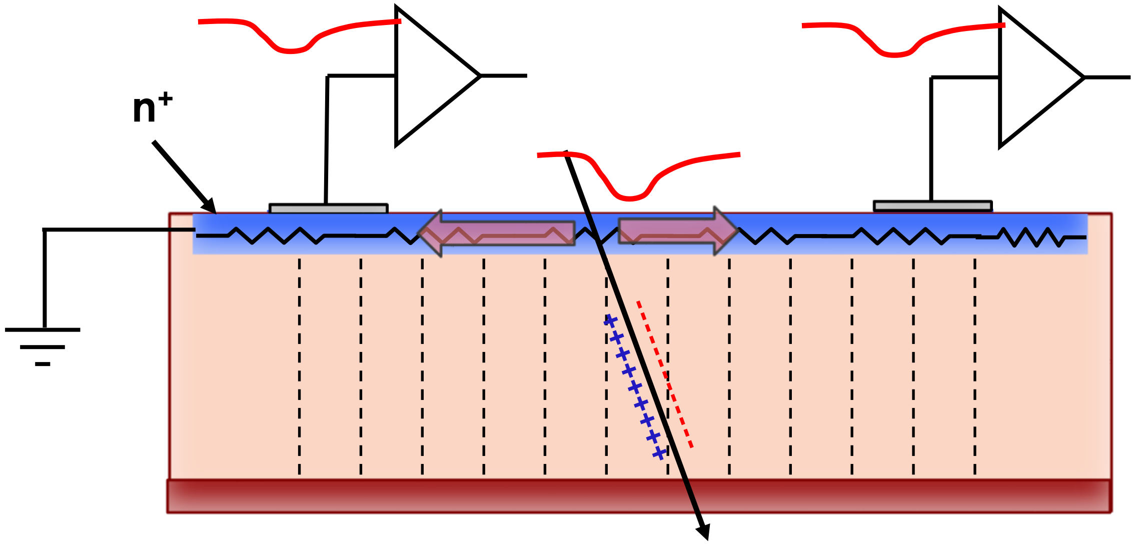


Second design innovation: resistive read-out





Silicon detector with standard read-out

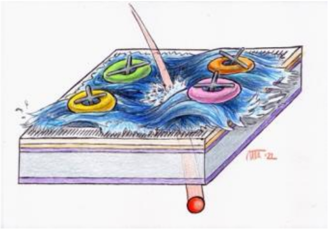


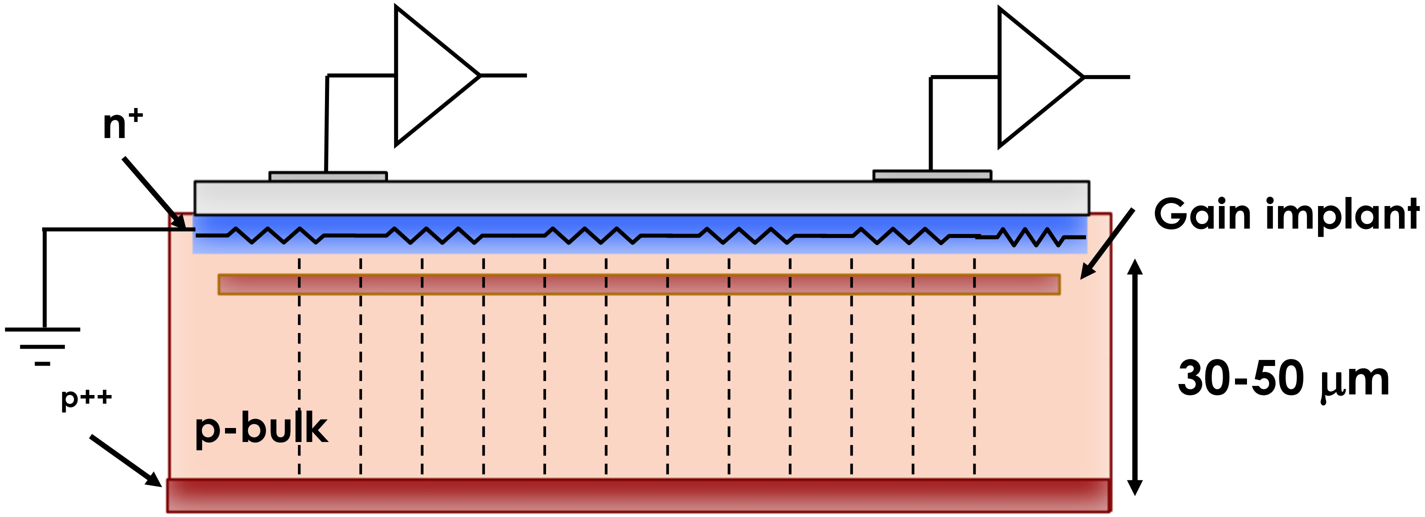
Silicon detector with resistive read-out

- 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, perfect geometry for timing

Signal sharing is the key ingredient to excellent spatial resolution using large pixels

Resistive Silicon Detector (RSD)

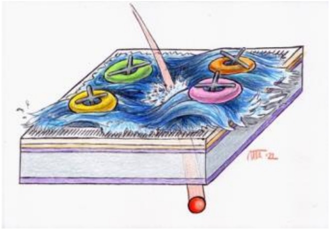




Resistive Silicon Detectors

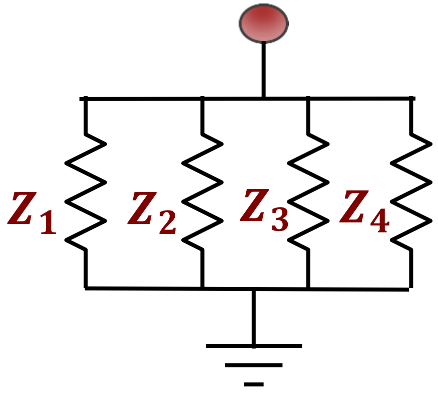
combine low-gain and resistive read-out

Charge sharing in RSD

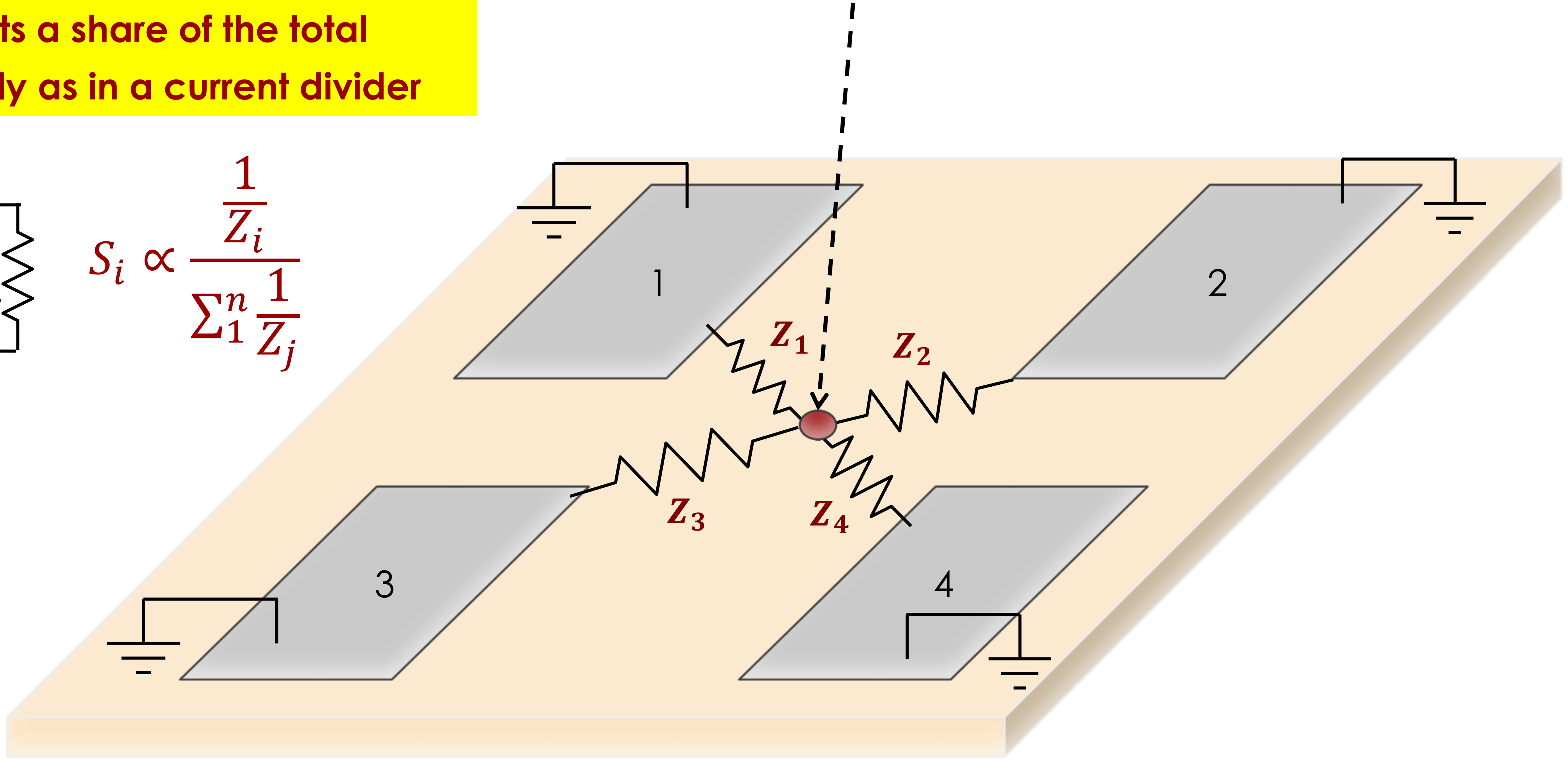


The signal sees several impedances in parallel, and it is split according to Ohm's law.

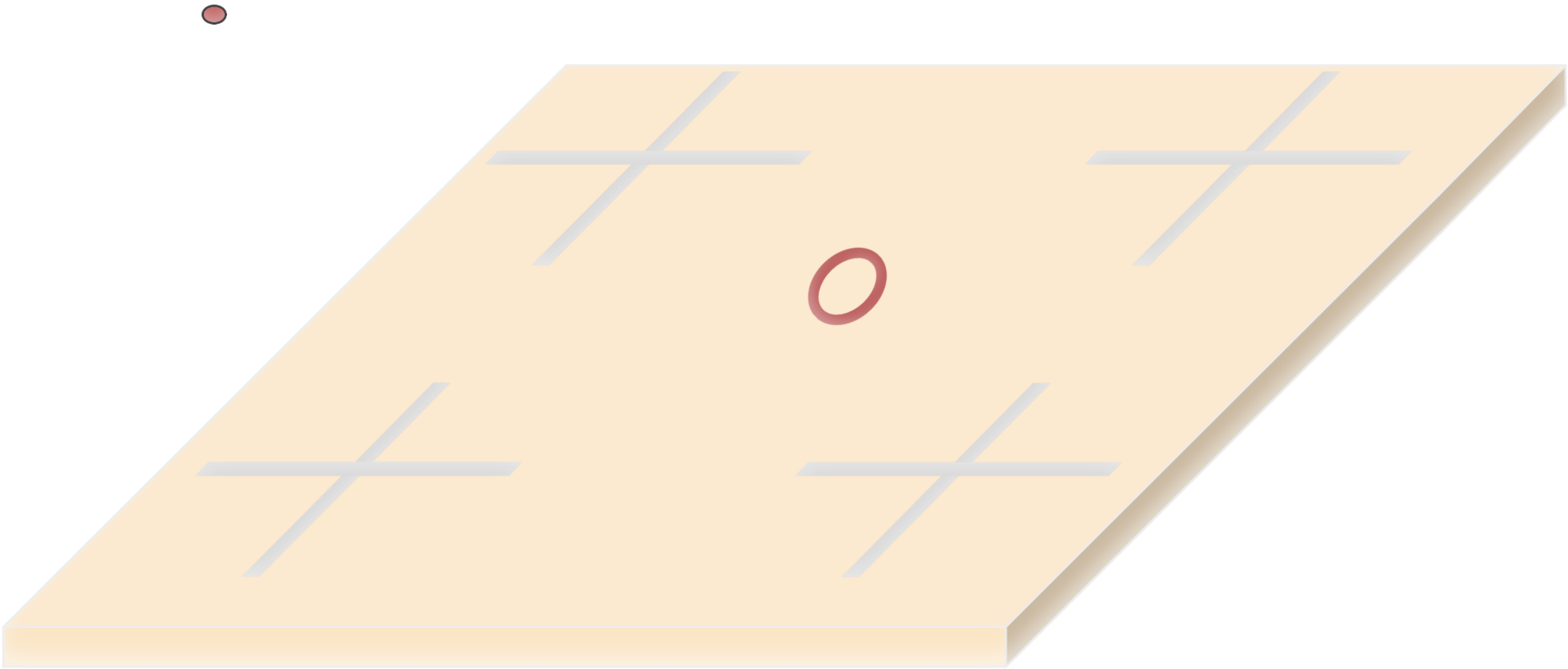
Each pad gets a share of the total signal, exactly as in a current divider

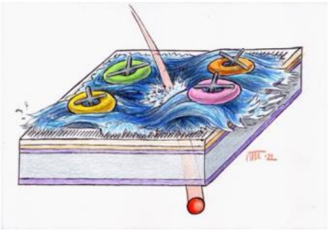


$$S_i \propto \frac{\frac{1}{Z_i}}{\sum_1^n \frac{1}{Z_j}}$$

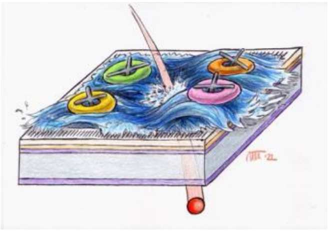


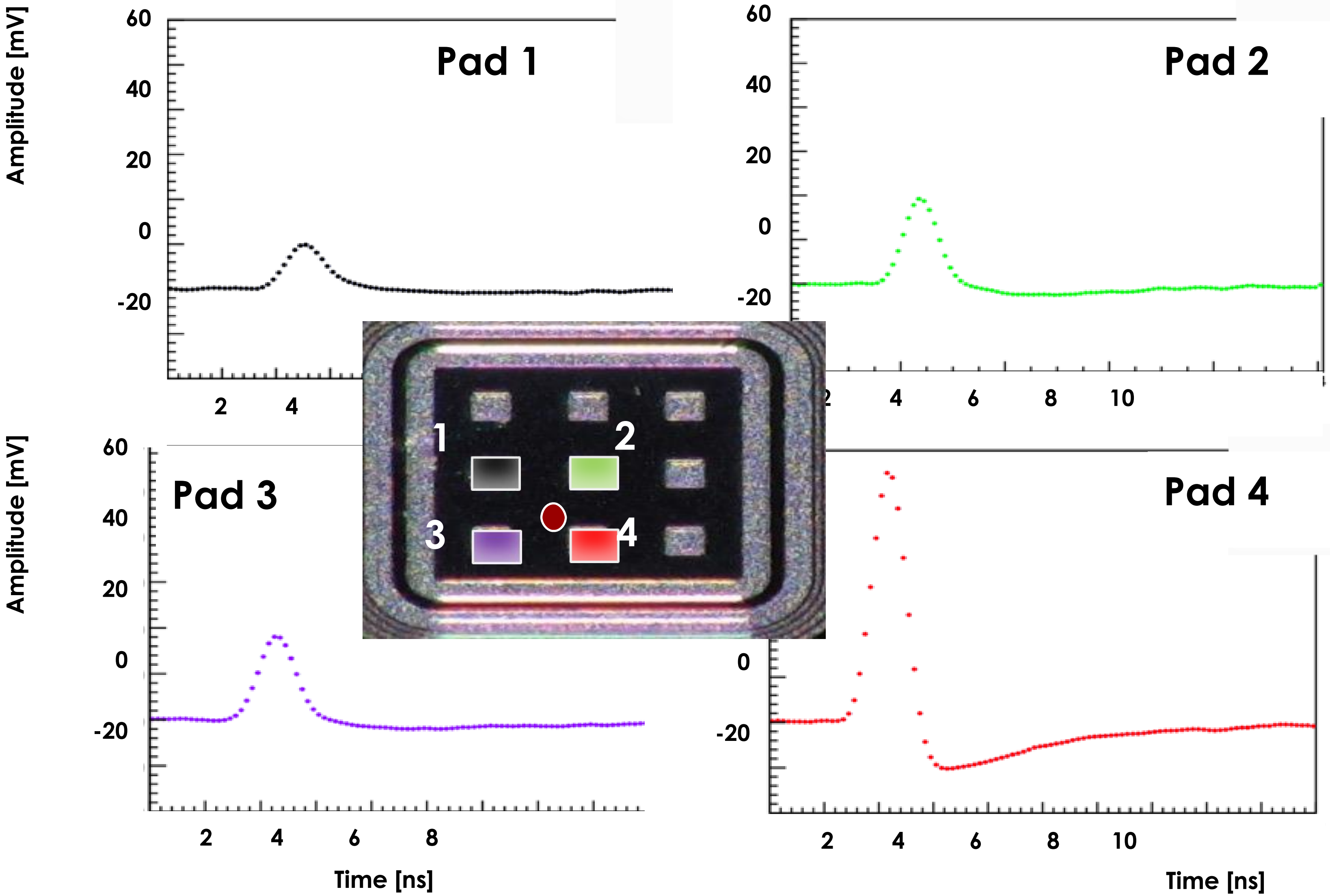
RSD principle of operation in motion





Example of signal sharing

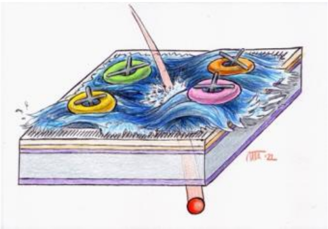


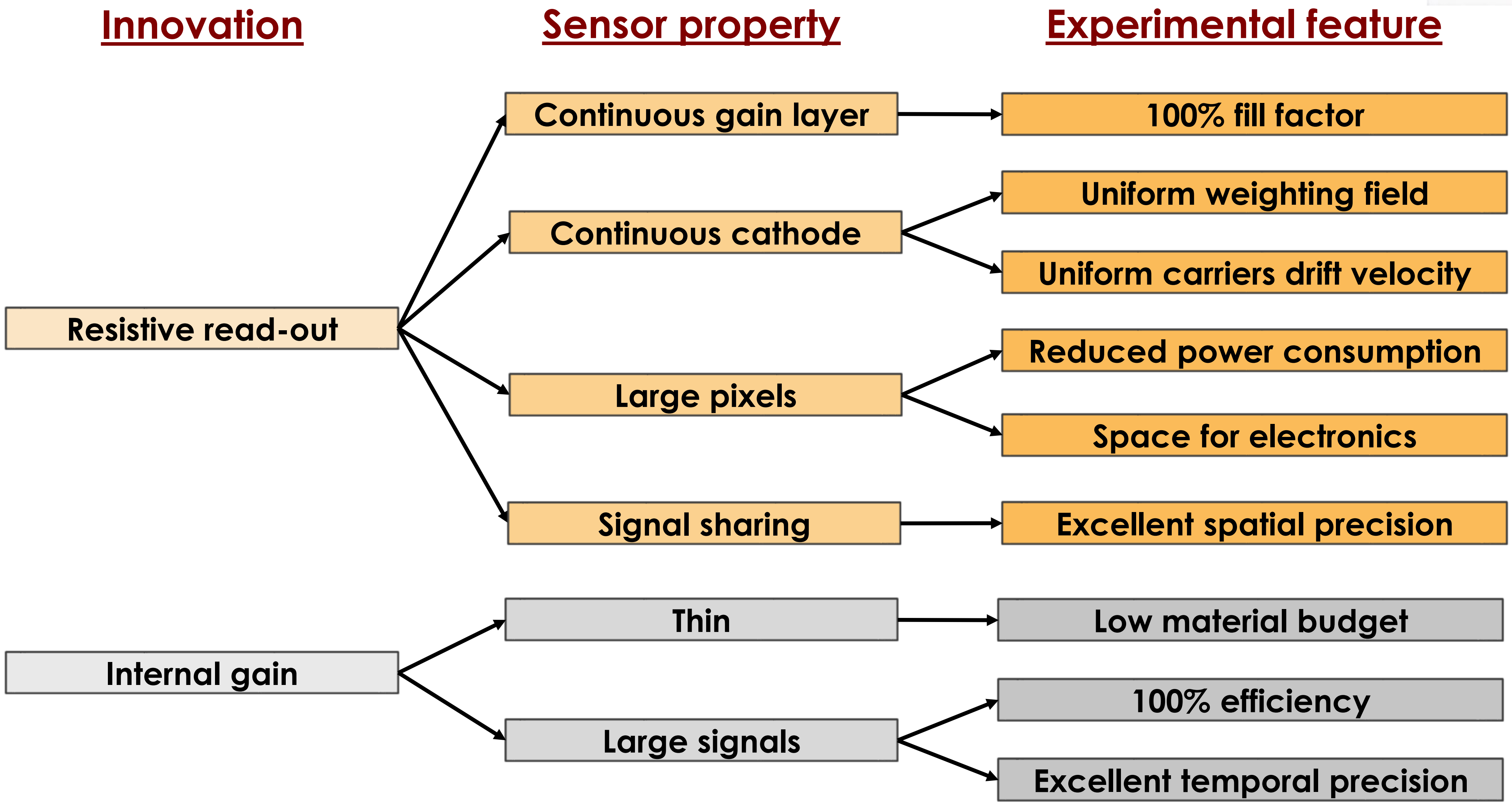


50-mm thick RSD, Gain ~ 20

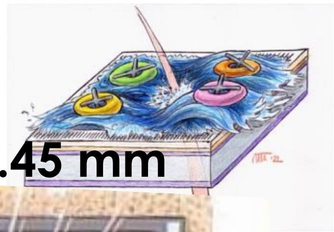
The laser is shot at the position of the red dot: the signal is seen in 4 pads

RSD: an almost “ideal” silicon sensor

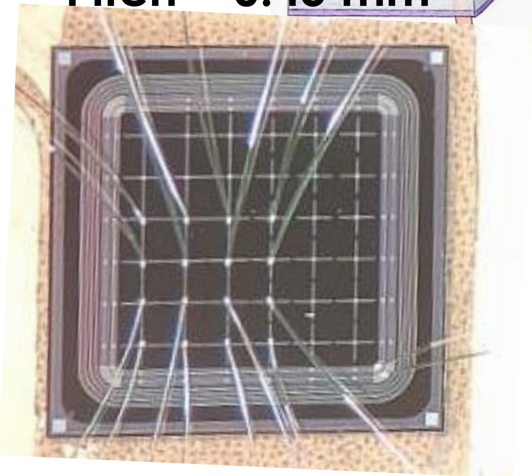




RSD2 sensors with cross-shaped electrodes

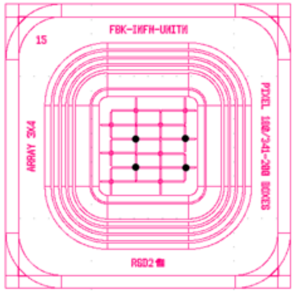


Pitch = 0.45 mm

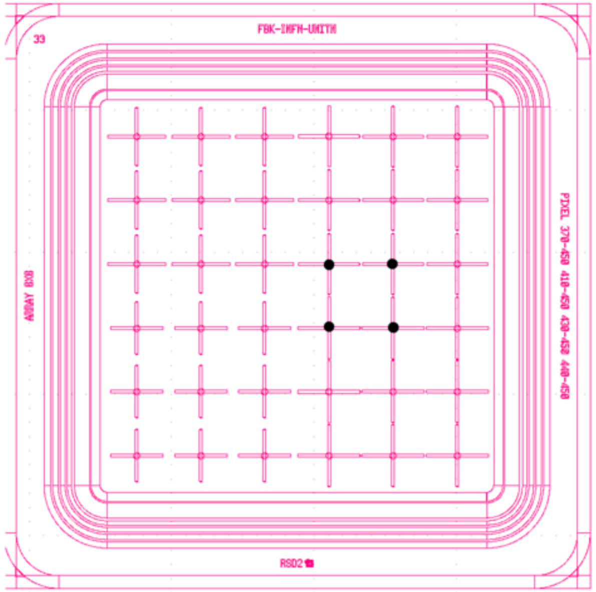


Sensor production at Fondazione Bruno Kessler

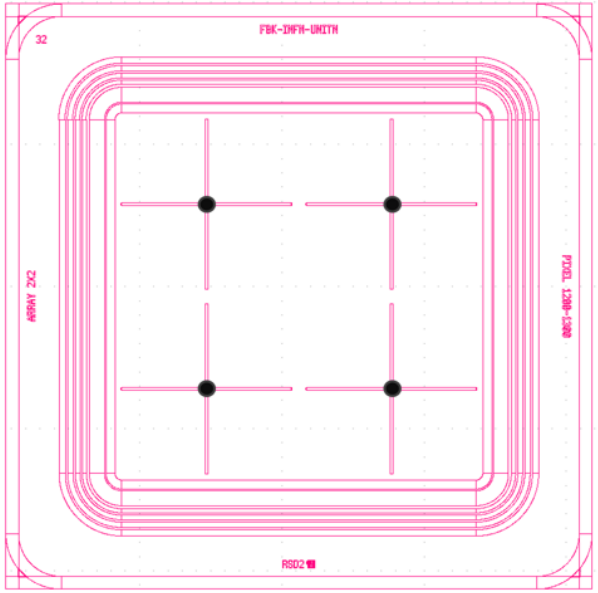
Several geometries are exploded in RSD2, for example cross with different pitch and arm length: 200, 340, 450, and 1300 μm



(A)
200 x 340 μm^2

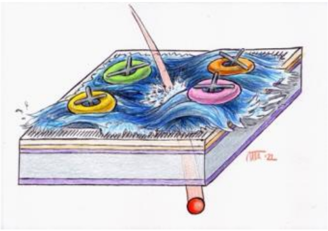


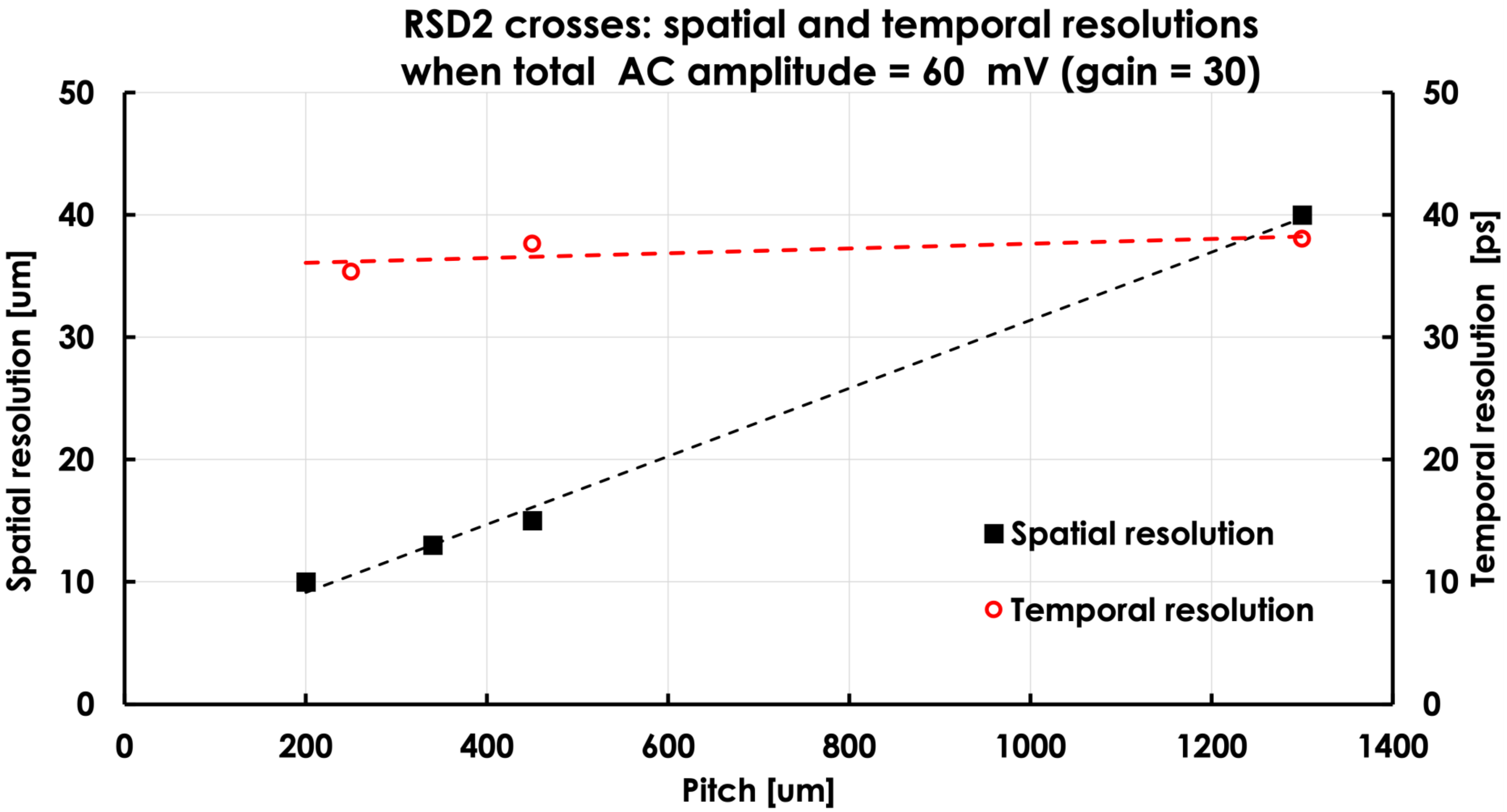
(B)
Pitch = 450 μm



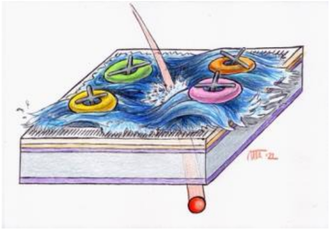
(C)
Pitch = 1300 μm

FBK-RSD2 performance summary



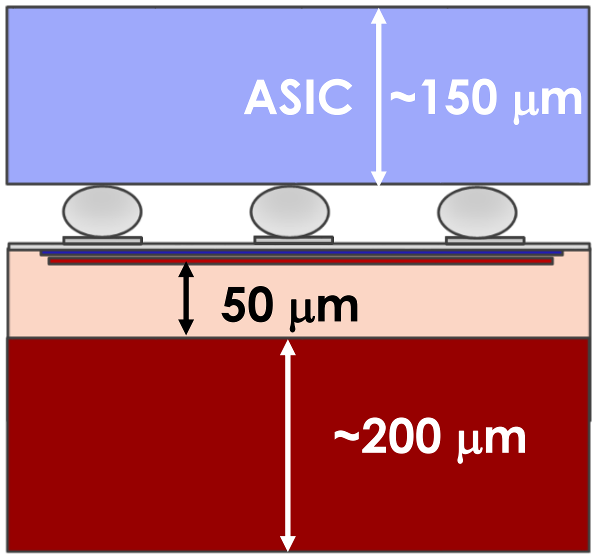


Reduced material budget

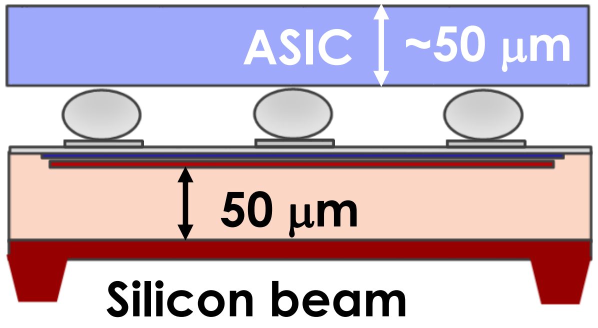


The active thickness of RSD sensor is rather small ~ 50 um.

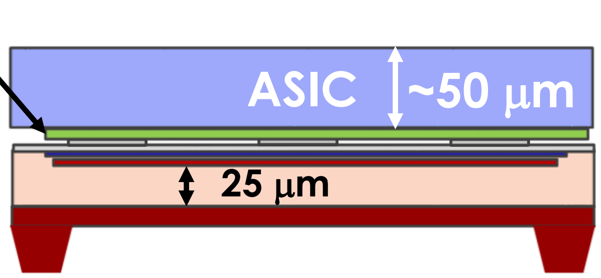
There is a clear path leading to < 100 μm material:



Present design: no material budget optimization

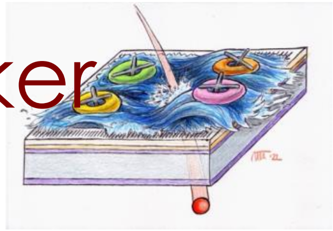


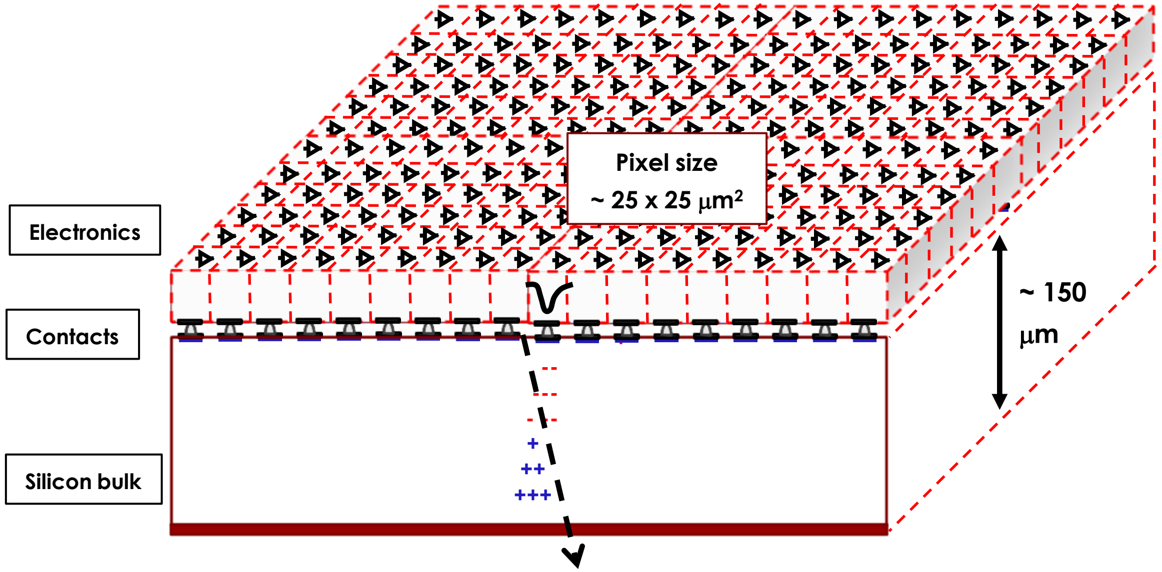
- Thinned handle wafer: 500 um ➔ 10-20 um



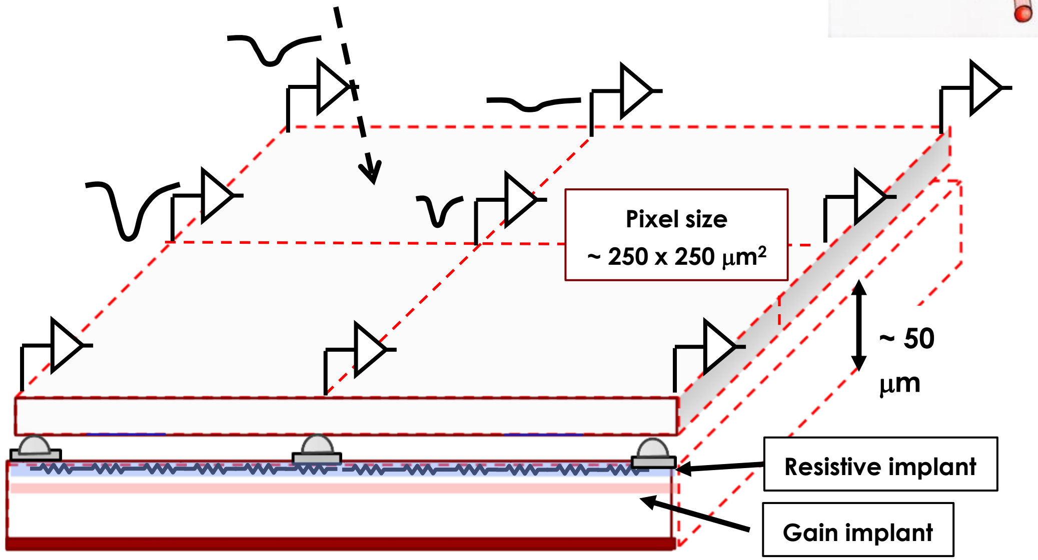
- Thinned handle wafer: 500 um ➔ 10-20 um
- Thinned active area: 50 um ➔ 25 um
  50 ps ➔ 25 ps

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





Standard Tracker

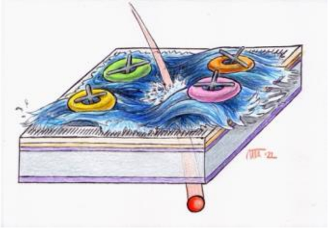


RSD-based tracker

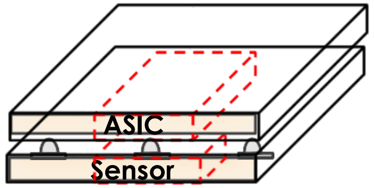
The design of a tracker based on RSD is truly innovative:

- 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

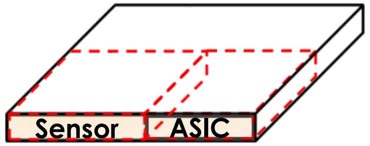
Tracking in 4-dimensions: a very rich field



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



Hybrid



Monolithic

Low-gain (LGADs)

No gain

Standard read-out

Resistive read-out

Planar

3D Si/Diamond

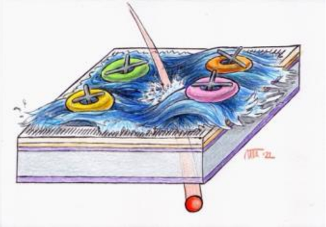
BiCMOS (SiGe)

BiCMOS (SiGe)

CMOS

In this talk, I presented a small subset, the UFSD-RSD projects
Present silicon sensors come in many different designs, optimized for specific applications.
The same will be true for 4D tracking

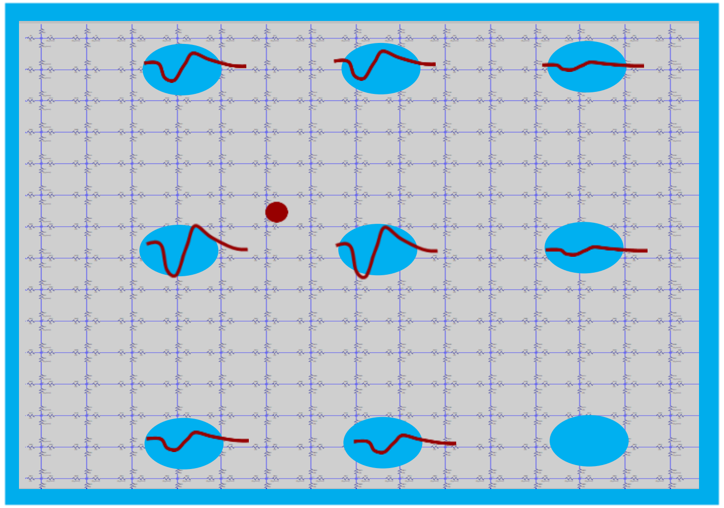
Future R&D paths in RSD

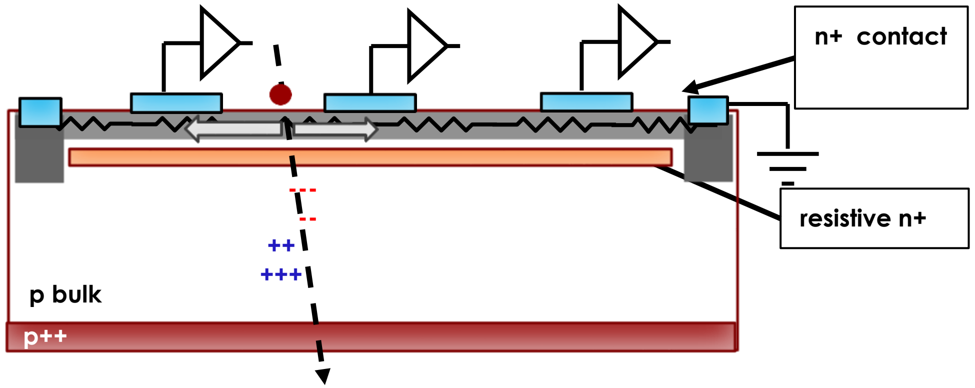


We have been too successful in signal sharing: the signal is seen on electrodes that are "far" from the hit point.

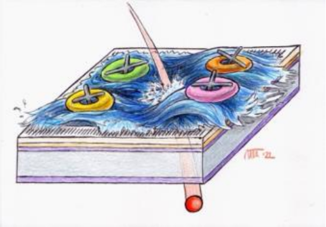
Sharing the signal on too many electrodes has several disadvantages:

- **The signal-to-noise ratio degrades**, part of the signal is wasted on electrodes that are not used.
- **The area used by a single hit becomes very large**, impacting the use of such sensors in high-occupancy environments.





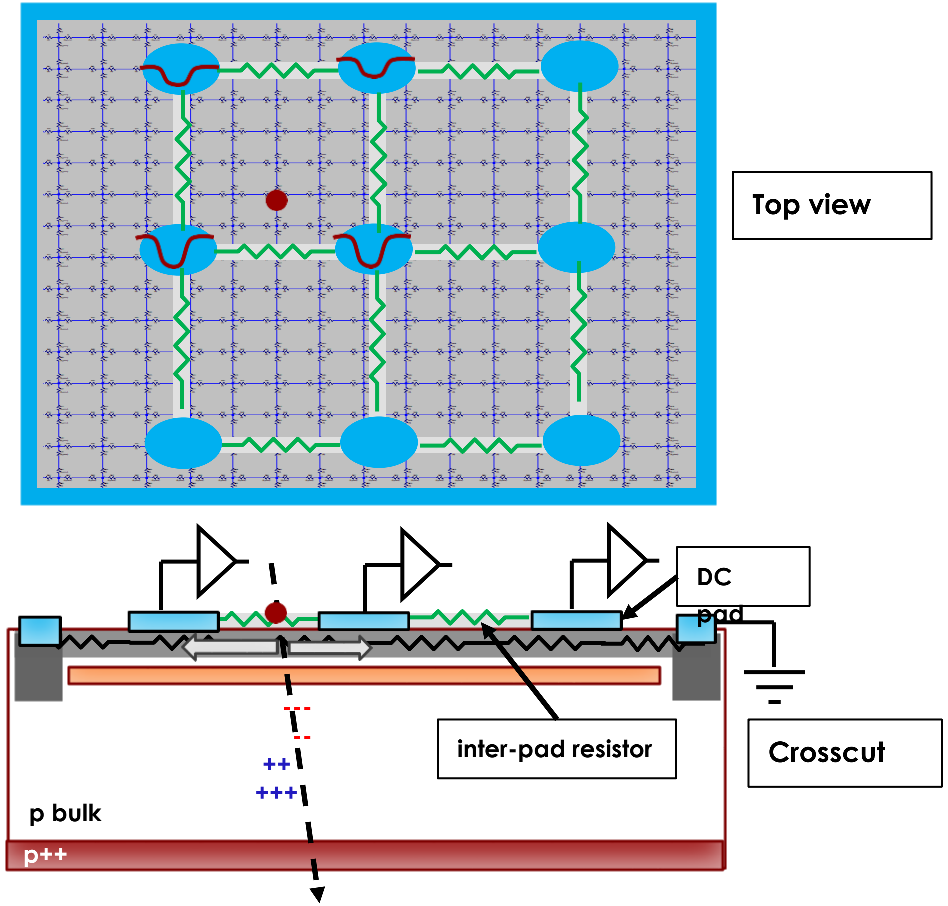
Future R&D paths in RSD: signal containment



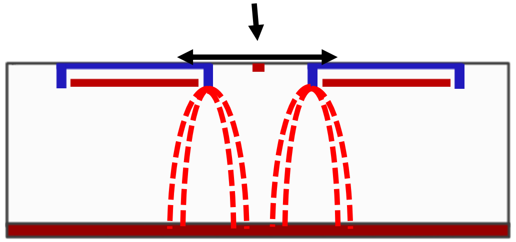
We are exploring various solutions to contain the signal only within the closest electrodes.

One interesting proposal is to **implant resistors between the electrodes.**

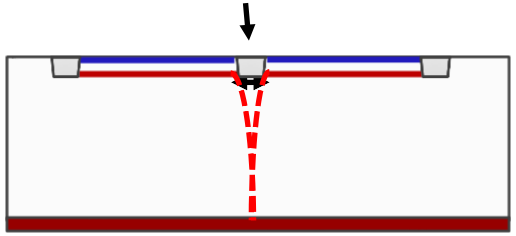
The resistors offer a lower impedance path with respect to the n++ resistive layer so that they will guide the signal to the electrodes



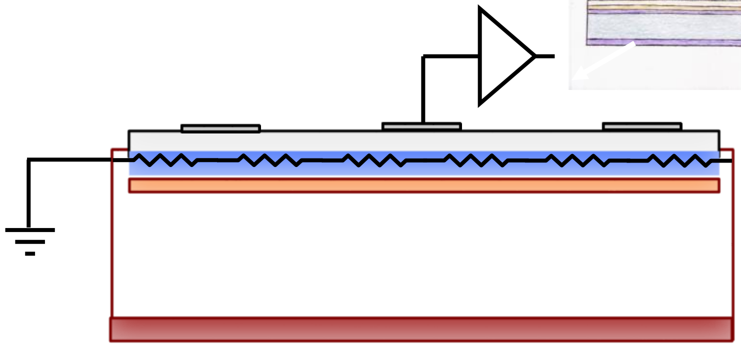
Summary: gaining and sharing

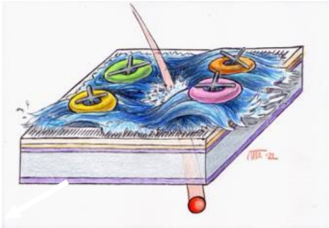


JTE + p-stop design



Trench-isolated design

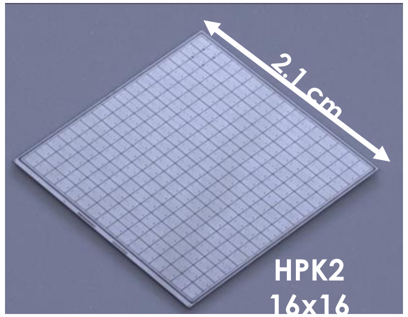




RSD -- AC-LGAD

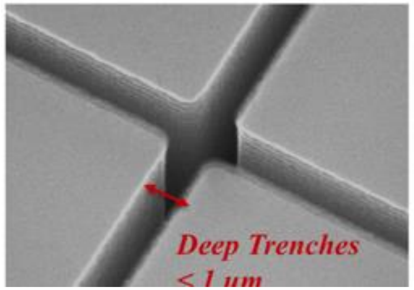
JTE/p-stop UFSD

- 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



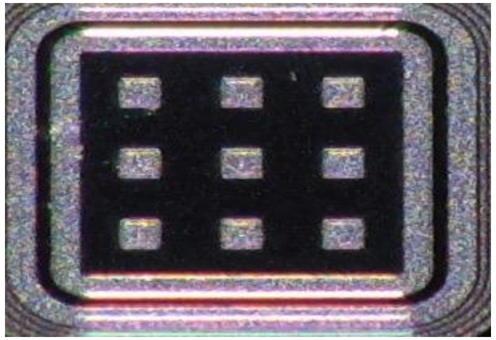
UFSD evolution: use trenches

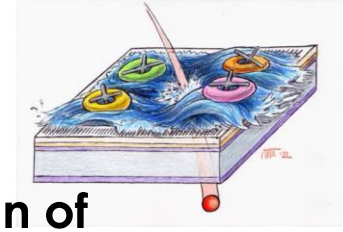
- Signal in a single pixel
- Almost 100% fill factor
- Temporal resolution (50 μm) : 35-40 ps
- High Occupancy OK
- Rate ~ 50-100 MHz
- Rad hardness: to be studied



RSD 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.

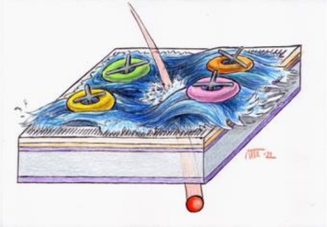
Spatial resolution depends upon ~ 1/gain, ~ 1/pitch, and ~noise

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**

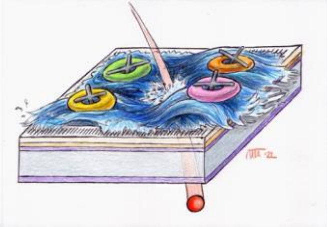
Acknowledgement



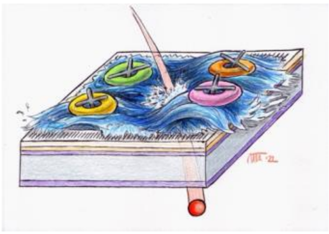
We kindly acknowledge the following funding agencies, collaborations:

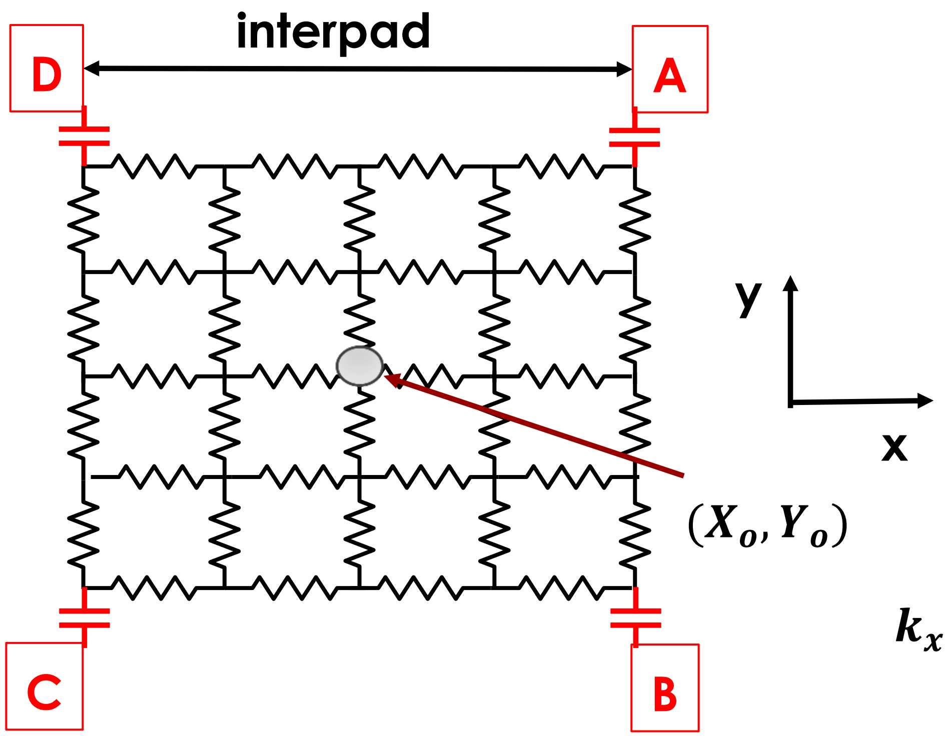
- RD50 collaboration
- INFN - Gruppo V 4DShare project
- INFN – FBK agreement on sensor production (convenzione INFN-FBK)
- Horizon 2020, grant UFSD669529

Backup



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

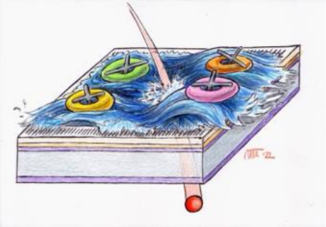
The reconstruction method uses only the signals in the 4 pads to reconstruct the hit position

➔ no need for a analytical sharing law.

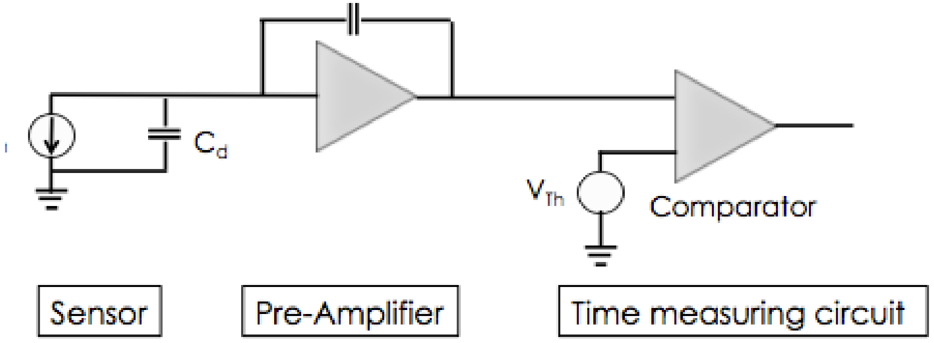
➔ $k_{x,y}$ = imbalance parameter along x or y

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

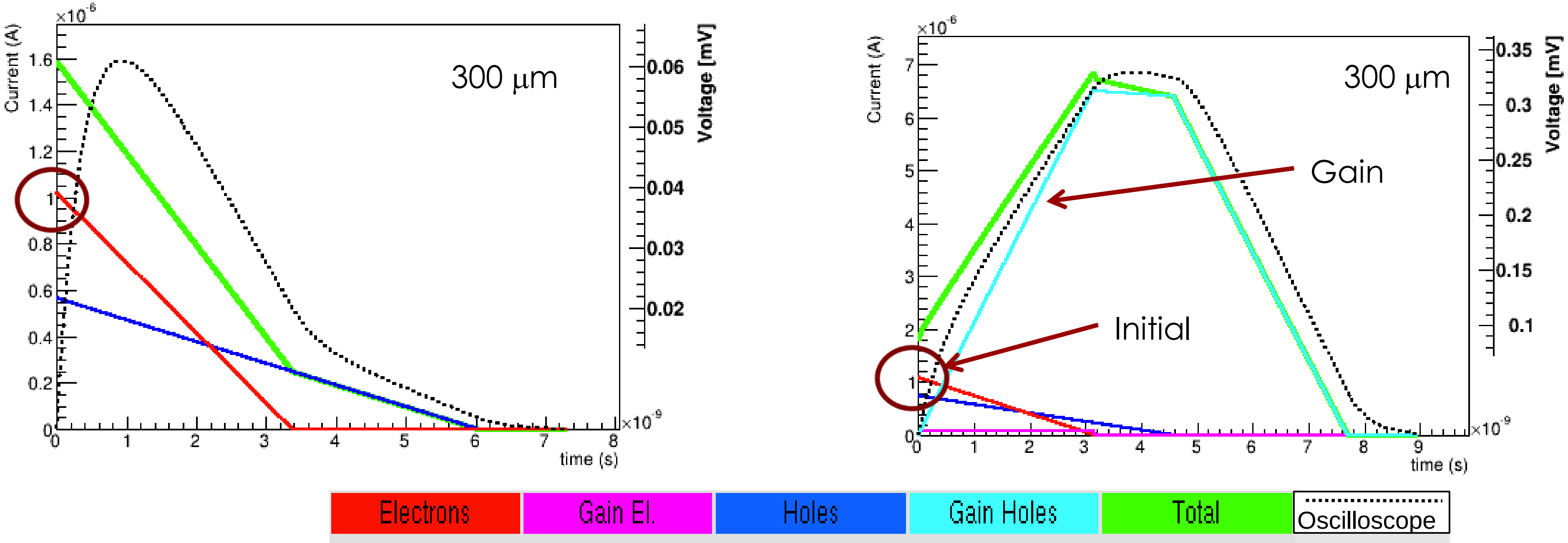
How gain shapes the signal



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



The signal from UFSDs is different from that of traditional sensors

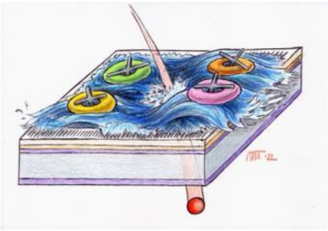


Simulated Weightfield2

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

Limiting the signal spread to a single cell

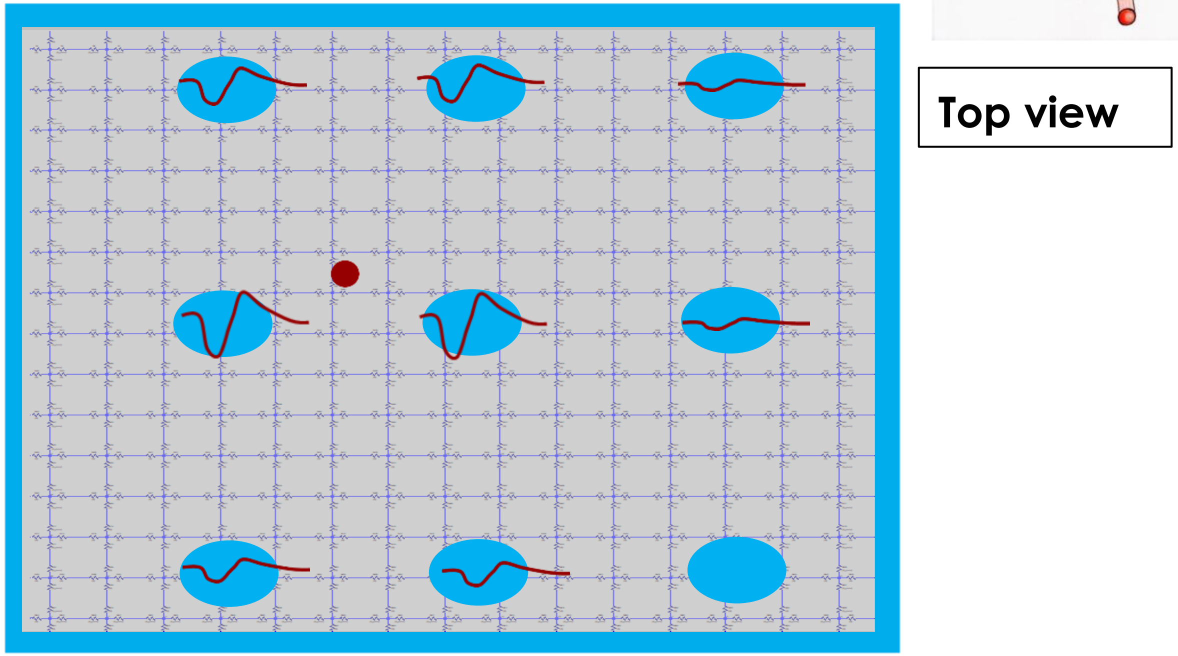


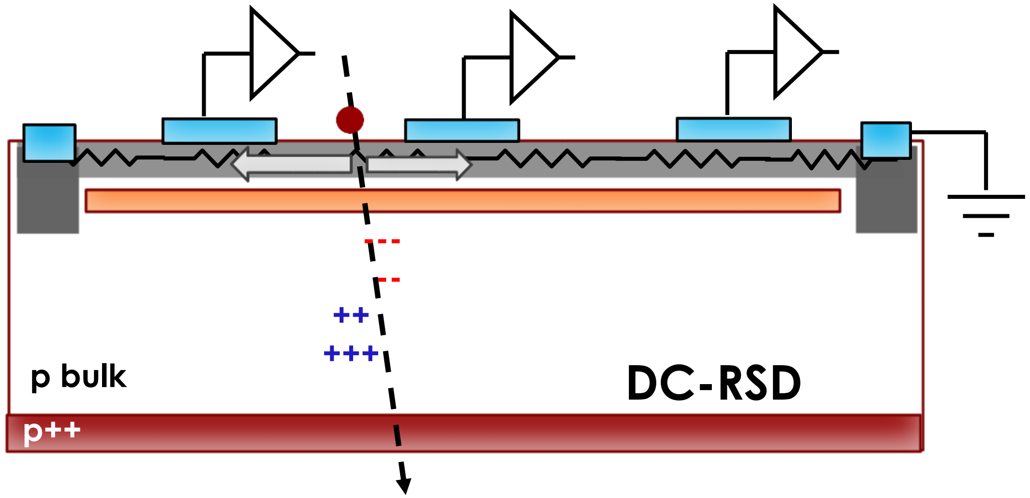
Problem:

we have been too successfull in charge sharing.

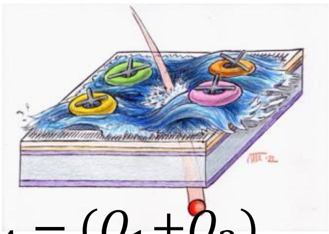
In our measurements, the signal is shared on too many electrodes.

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





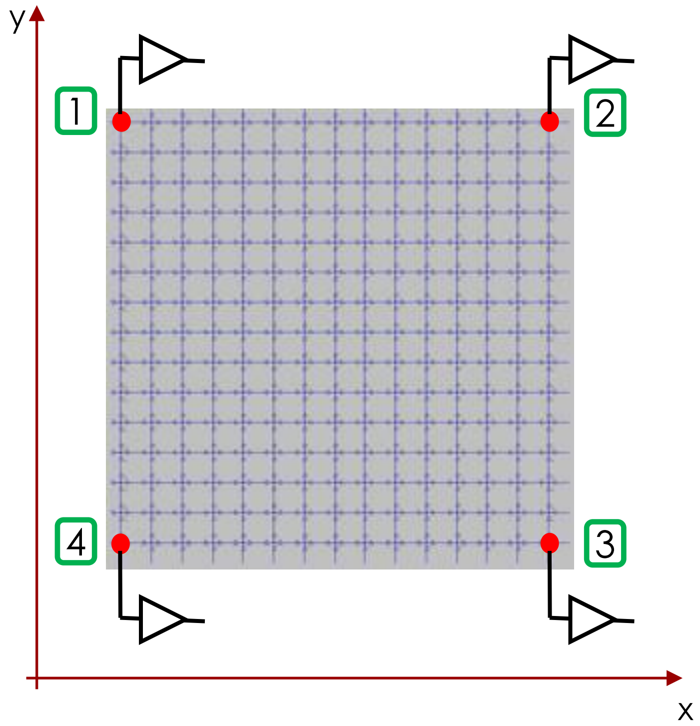
Position Reconstruction: DC-RSD

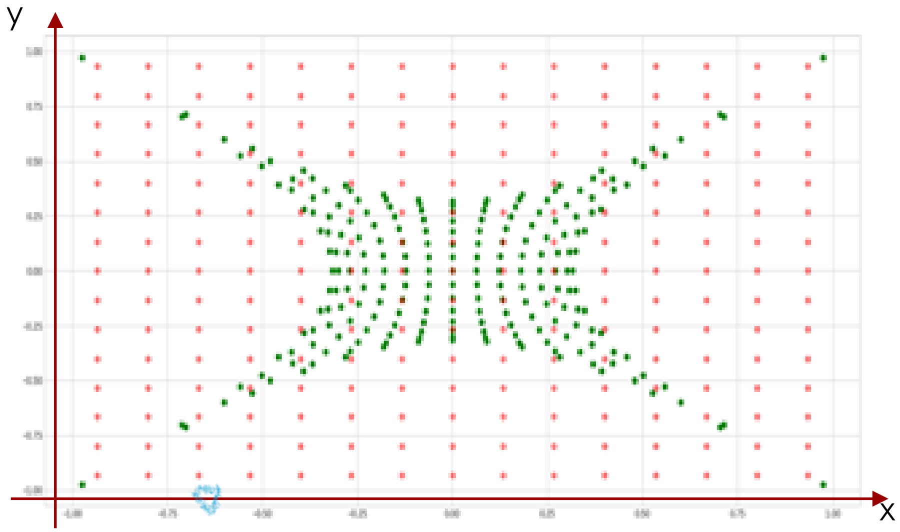


Position distortion is typical of resistive devices and well documented in the literature.

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

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



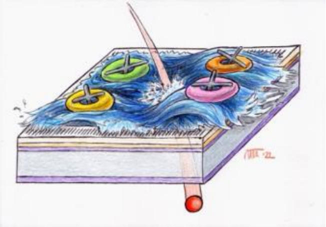


Red
original points

Green
reconstructed points

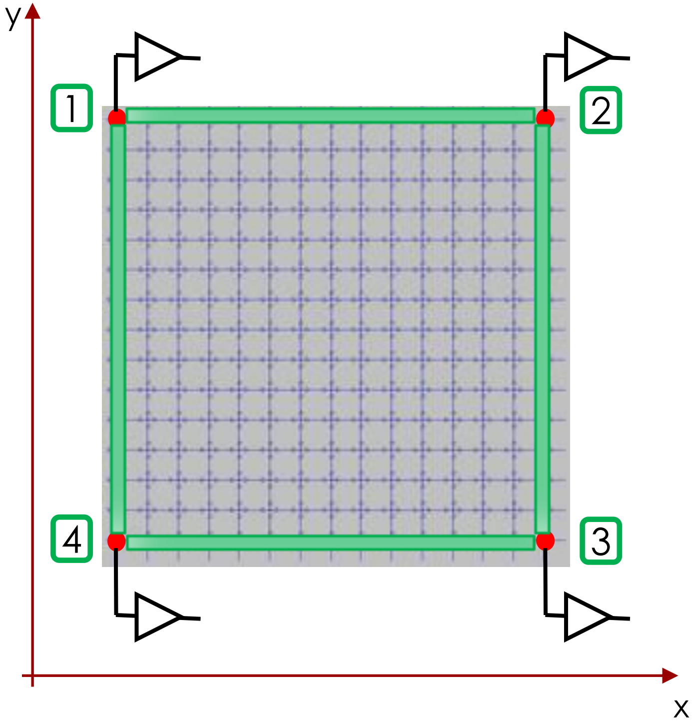
This is an extreme case, chosen to illustrate the problem

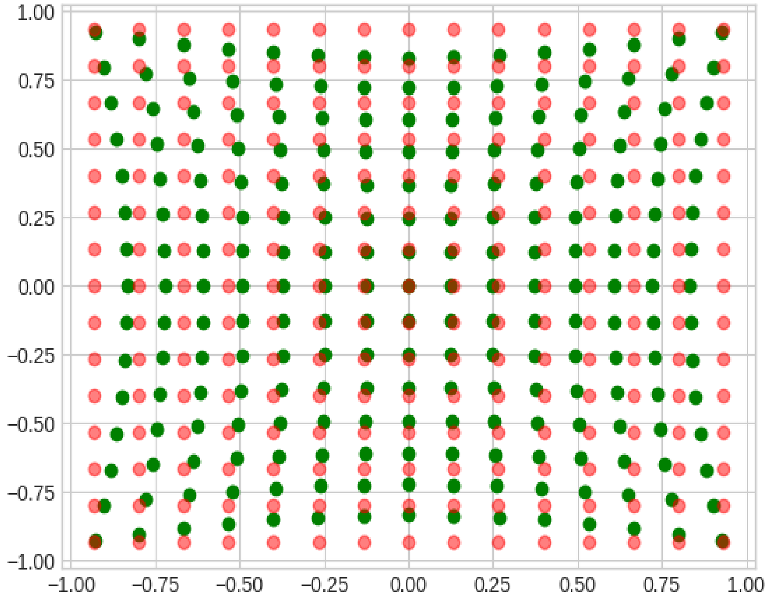
Position Reconstruction: DC-RSD with resistive strip



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

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





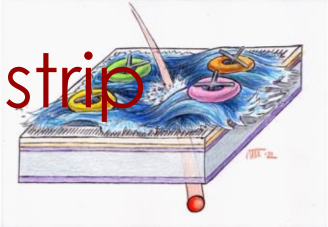
Red
original points

Green
reconstructed
points

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

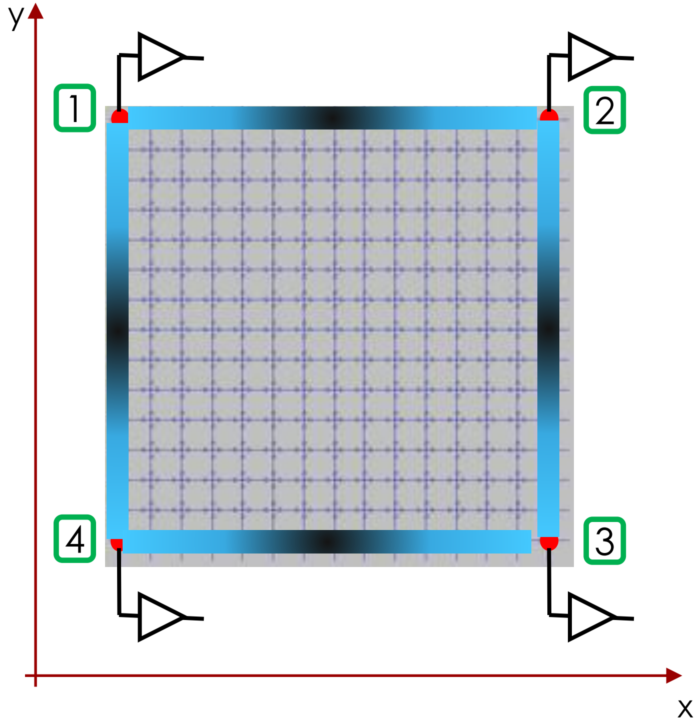
Proposed in: *On the dynamic two-dimensional charge diffusion of the interpolating readout structure employed in the MicroCAT detector,* Wagner et al., NIM A, (2002).

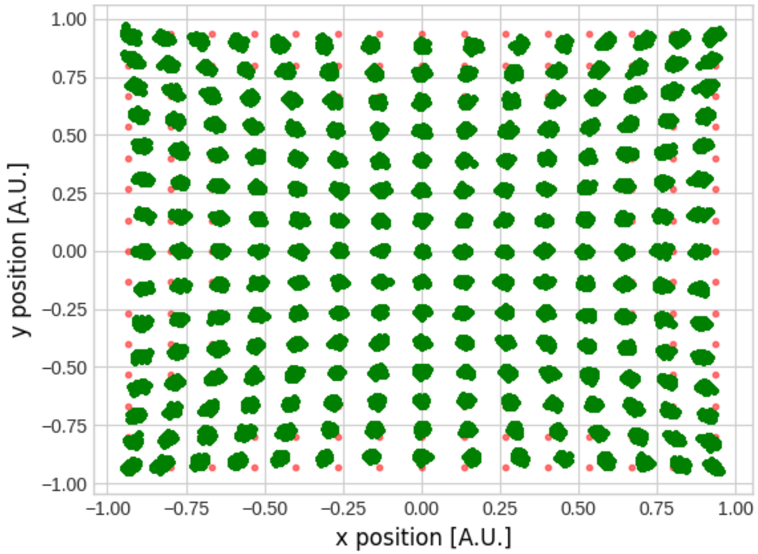
Position Reconstruction: DC-RSD with variable resistive strip



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

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



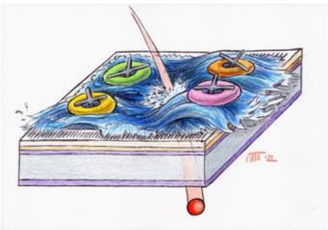


Red
original points

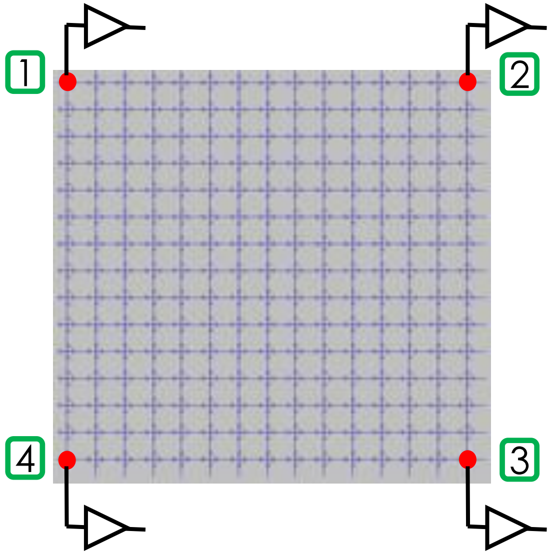
Green
reconstructed
points

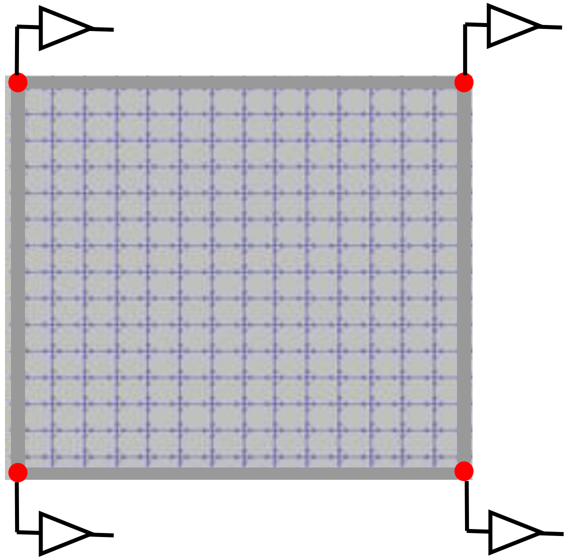
Variable resistive strips have the potential to almost totally eliminate the distortion in the position reconstruction

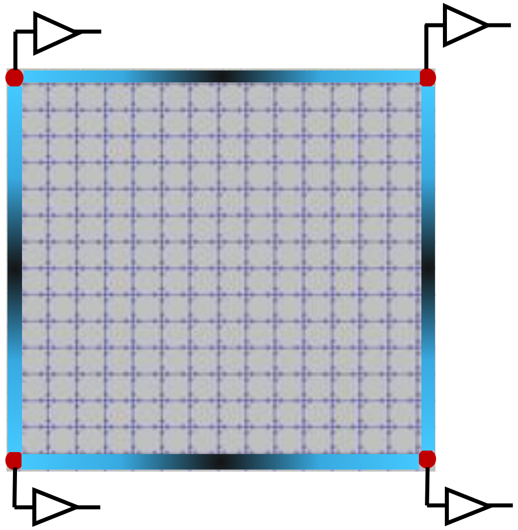
DC-RSD research paths

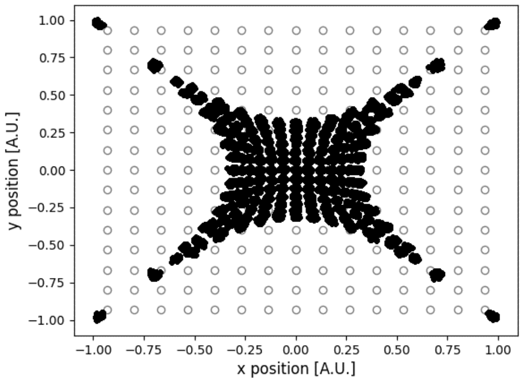


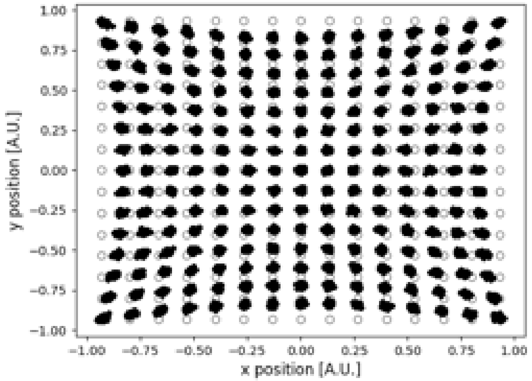
DC-RSD	DC-RSD with resistive strips	DC-RSD with variable resistive strips

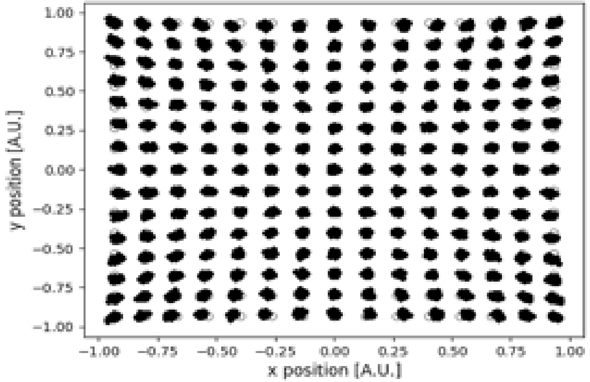






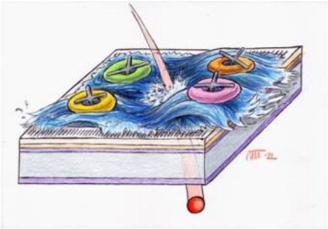






Empty circles: original points
Filled Circles: reconstructed points

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:

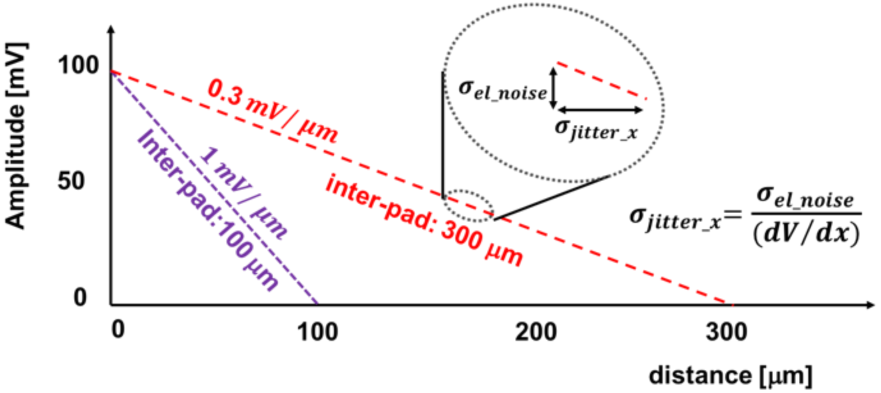
- 100 μm and 300 μm apart
- 100mV signal
- 3 mV electronic noise

100 μm: the signal changes by 1 mV/ μm

➔ σ_{Jitter} **= 3 μm**

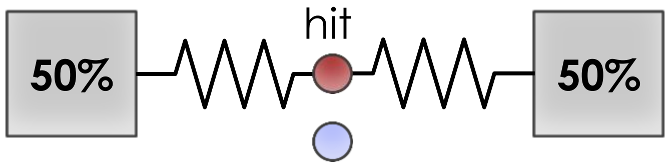
300 μm: the signal changes by 3 mV/ μm

➔ σ_{Jitter} **= 9 μm**

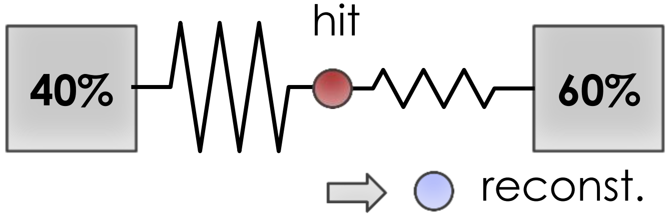


σ_{Sensor}

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

$\sigma_{Recontruction}$

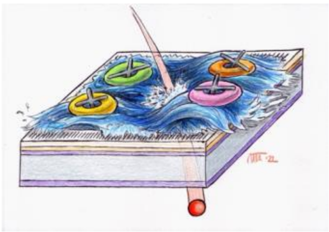
Algorithm

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

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

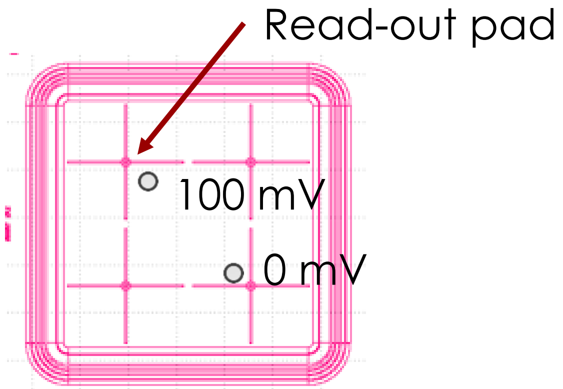
DPC: RSD might not be a perfect DPC, yielding to systematic errors.

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:

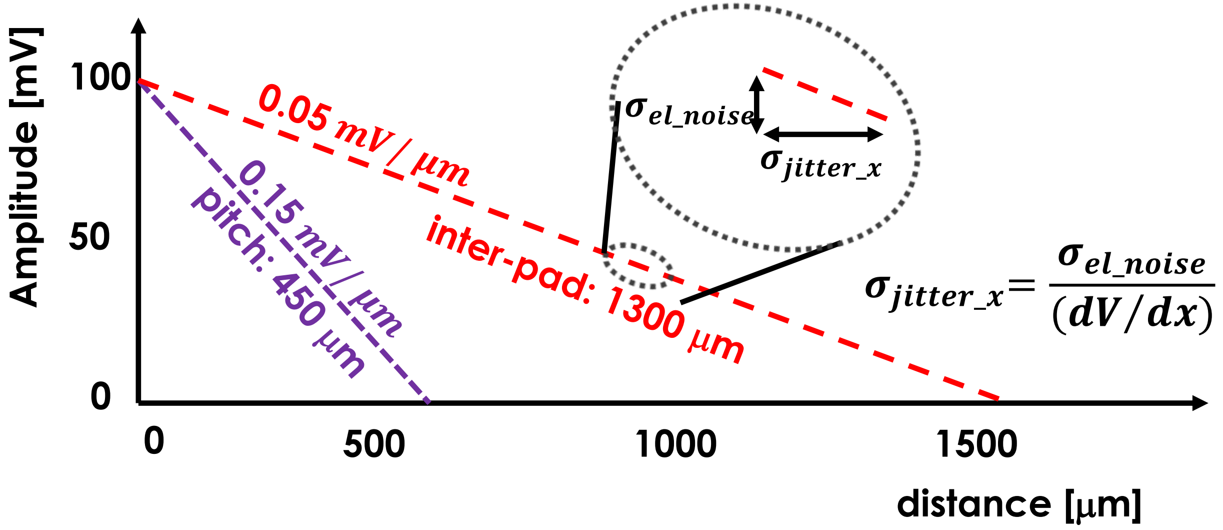
- A signal of 100 mV when shot near a pad
- A signal of 0 mV when shot at the opposite corner
- Noise ~1 mV (as in our lab)

In this simplified system, the signal decreases by:

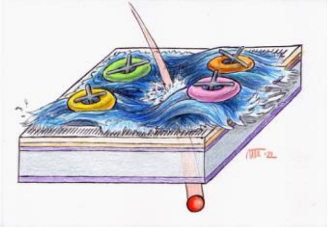
- Pitch 1300 μm: 0.05 mV/μm
- Pitch 450 μm: 0.15 mV/μm

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:

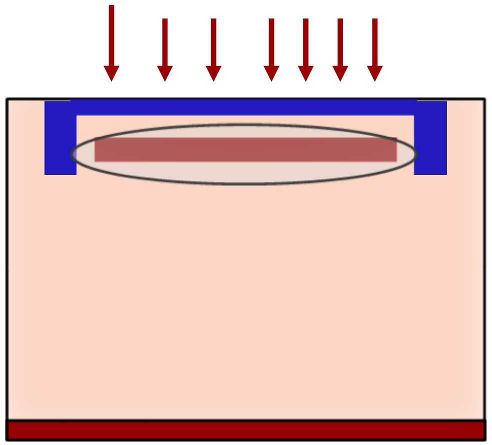
- Decrease of charge collection efficiency due to trapping
- Doping creation/removal
- Increased leakage current, shot noise

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

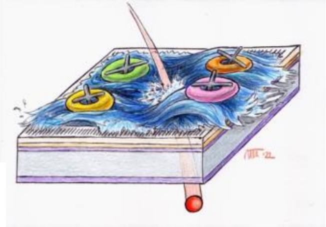
Main technique to decrease acceptor removal: carbon implantation in the gain layer

carbon implantation



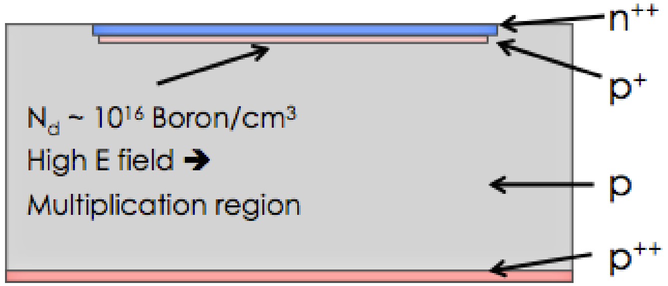
Carbon spoils the properties of silicon sensors.
However, **in the right amount and only on the gain implant, it increases the sensor rad. resistance by a factor of 3**

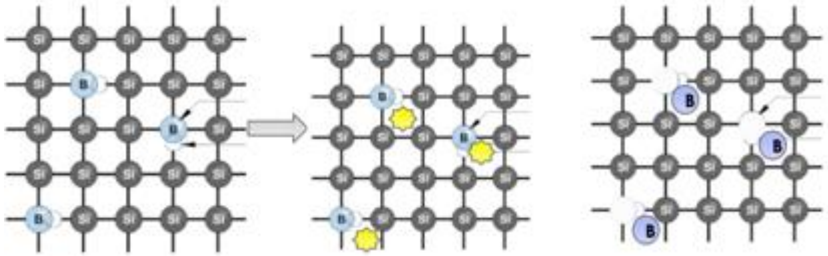
Acceptor removal



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

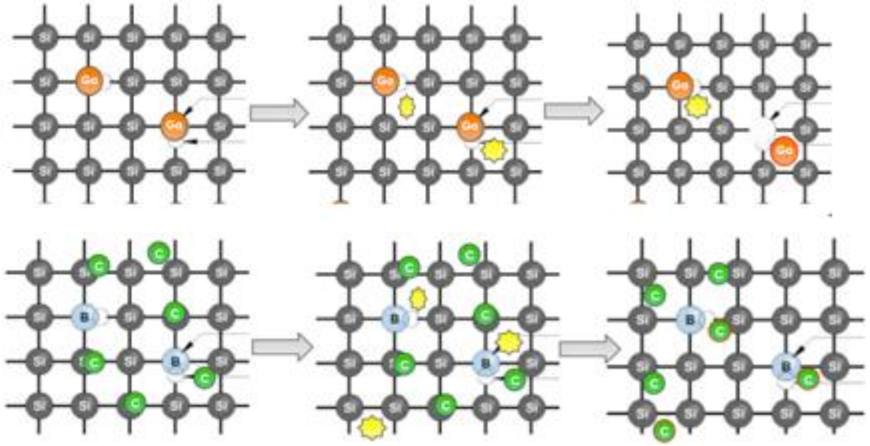
$$N(\emptyset) = N(0) * e^{-c\emptyset}$$





Boron
Radiation creates Si interstitial that inactivate the Boron:
Si_i + B_s ➔ Si_s + B_i

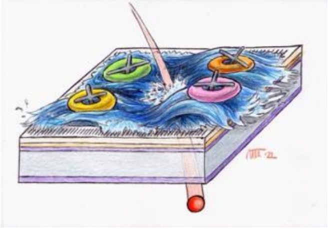
Two possible solutions: 1) use Gallium, 2) Add Carbon



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

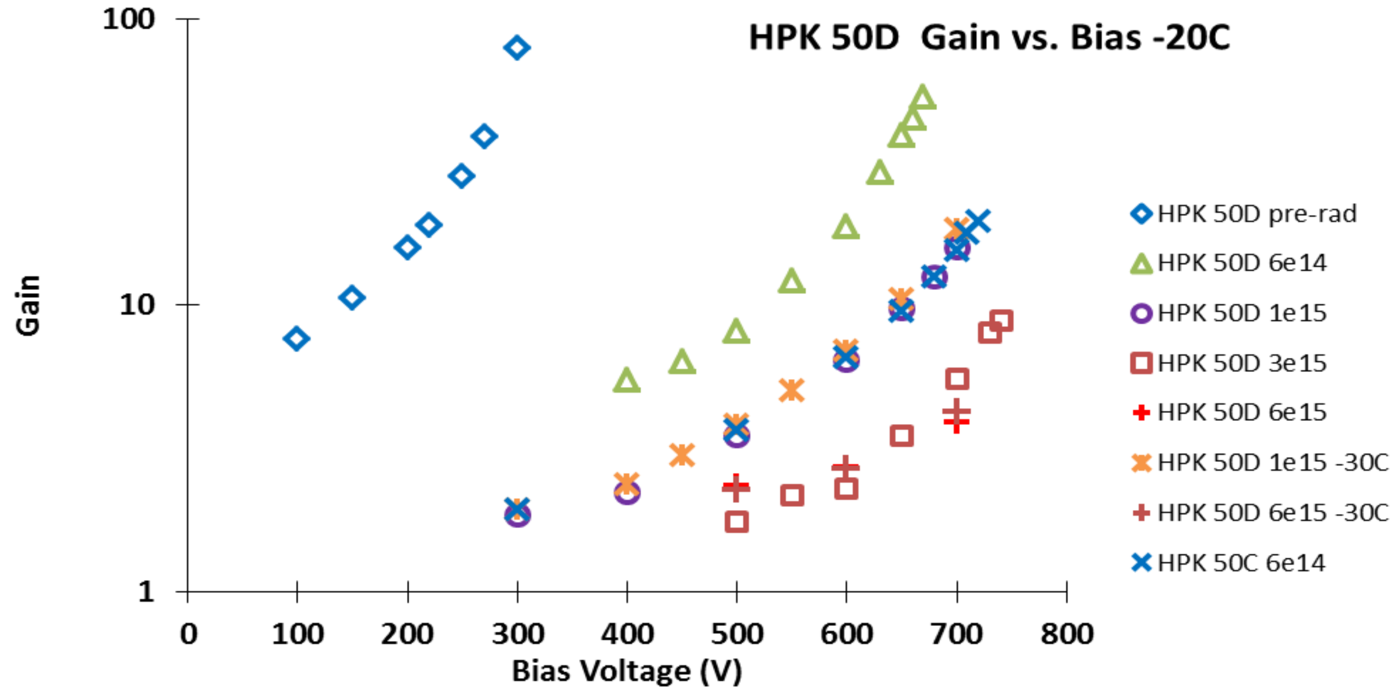
Carbon is substitutional
Interstitial Si interact with Carbon instead of with Boron and Gallium

Effect of acceptor removal



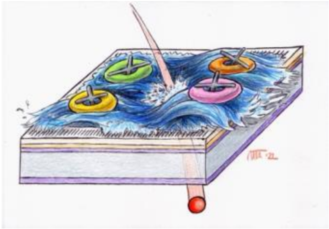
$$N_D = N_0 e^{-cf} + bf$$

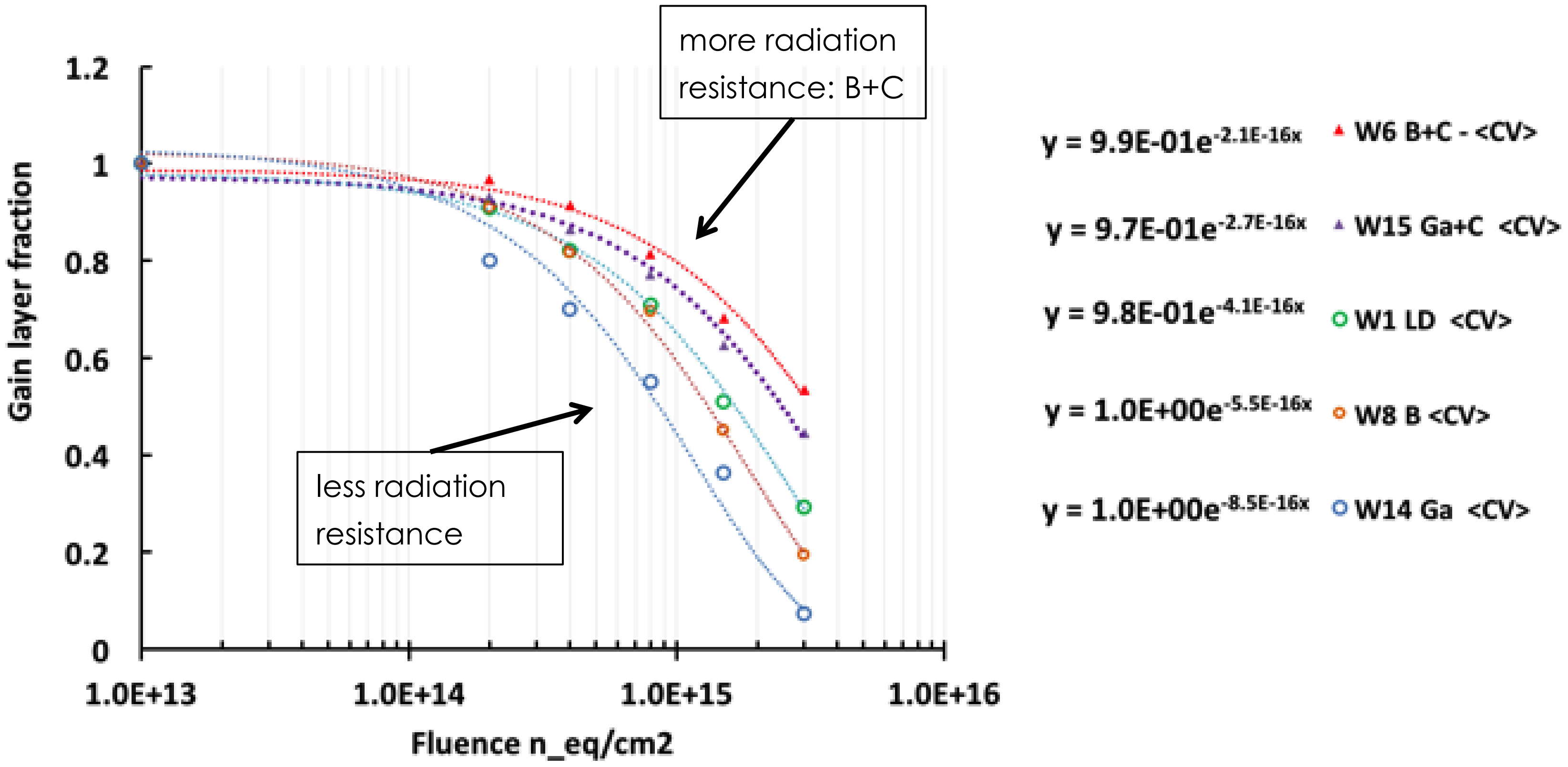
Acceptor removal,
Gain layer deactivation



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

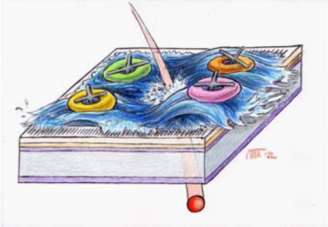
Impurity engineering of radiation resistance





1) **Carbon addition works really well, increasing by a factor of 2-3 the radiation hardness**
2) **Gallium is actually is not more rad-hard than Boron**

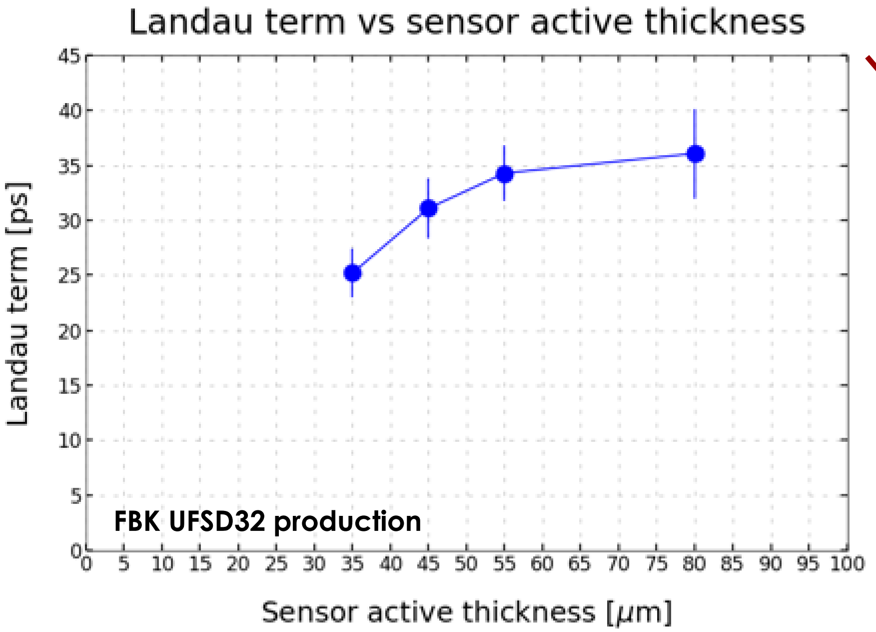
UFSD temporal resolution in thinner sensors

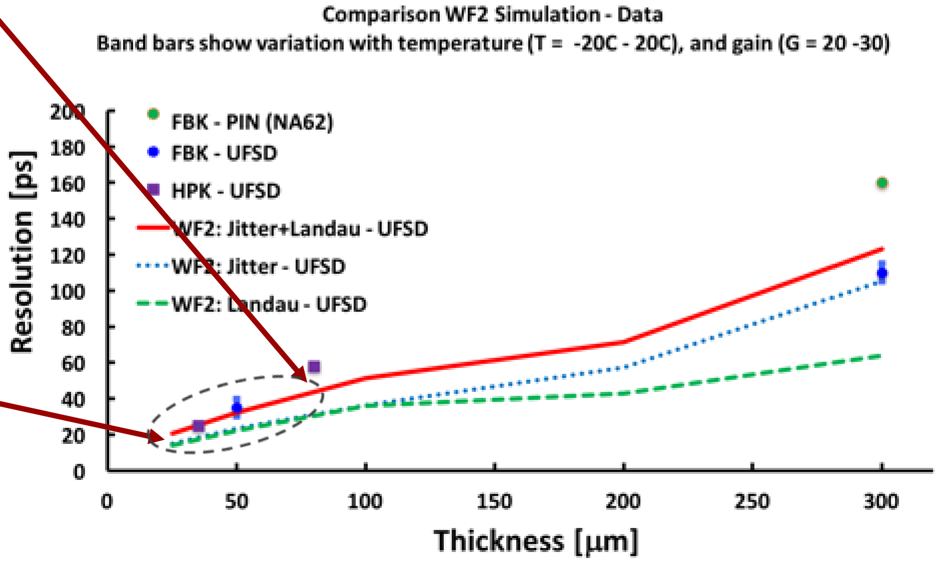


UFSD temporal resolution improves in thinner sensors:

==> 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

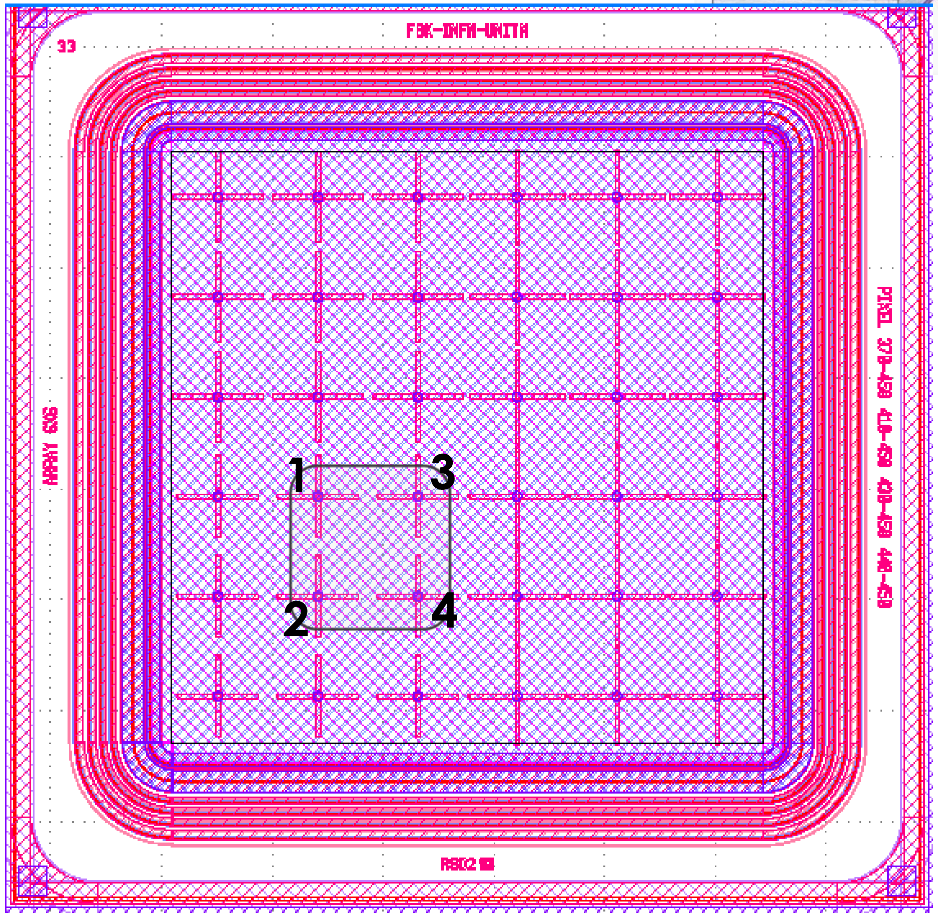
The position is reconstructed using the charge imbalance among the electrodes positioned at the 4 corners

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

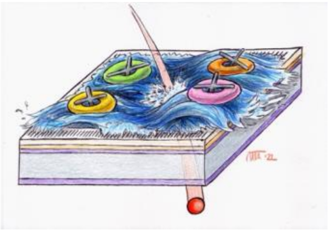
$$y_i = y_{center} + k_y \frac{pitch}{2} * \frac{Q_1 + Q_3 - (Q_2+Q_4)}{Q_{tot}}$$

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

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



RSD2 spatial resolution



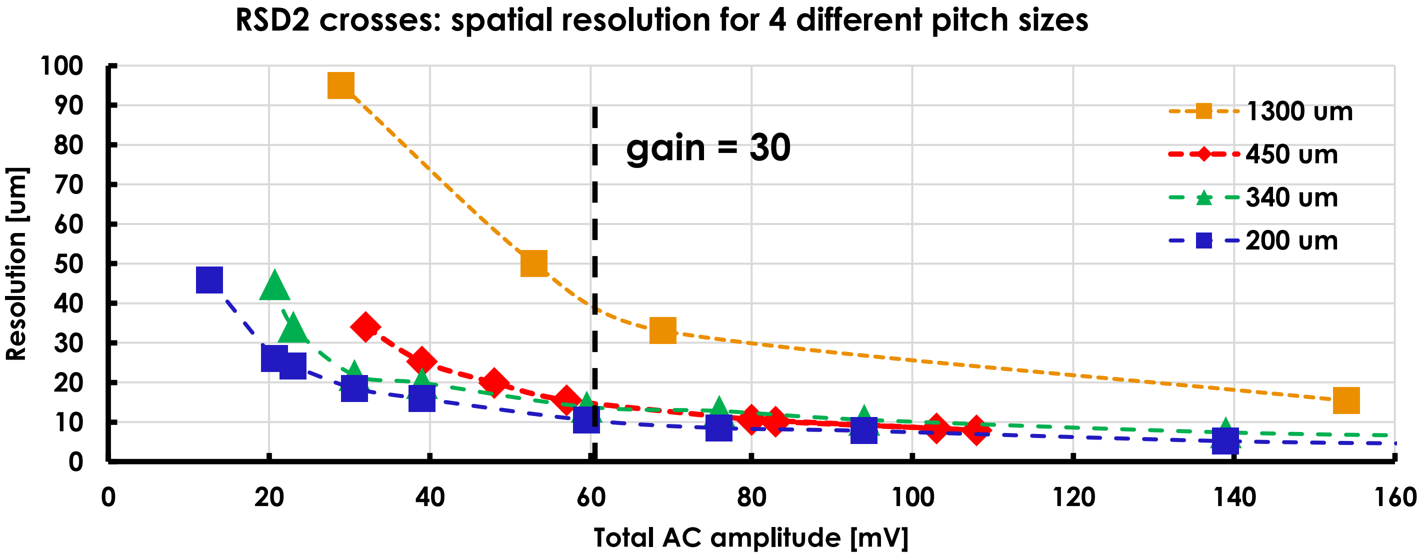
RSDs at gain = 30 achieve a spatial resolution of about 2-3% of the pitch size:

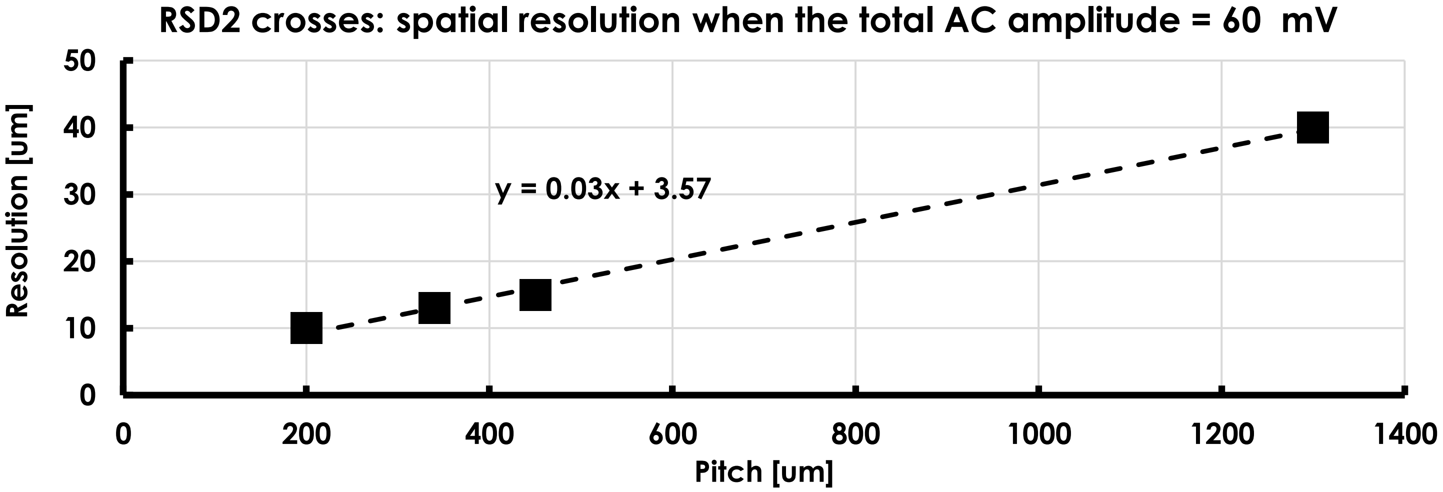
RSD:

- **1300 x 1300 mm²: σ_x ~ 40 μm**
- **450 x 450 mm²: σ_x ~ 15 μm**

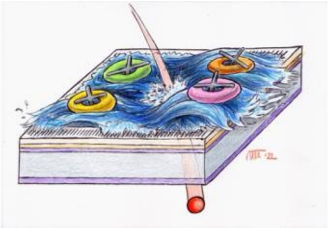
Traditional standard pixel

- **1300 x 1300 mm²: σ_x ~ 920 μm**
- **450 x 450 mm²: σ_x ~ 320 μm**



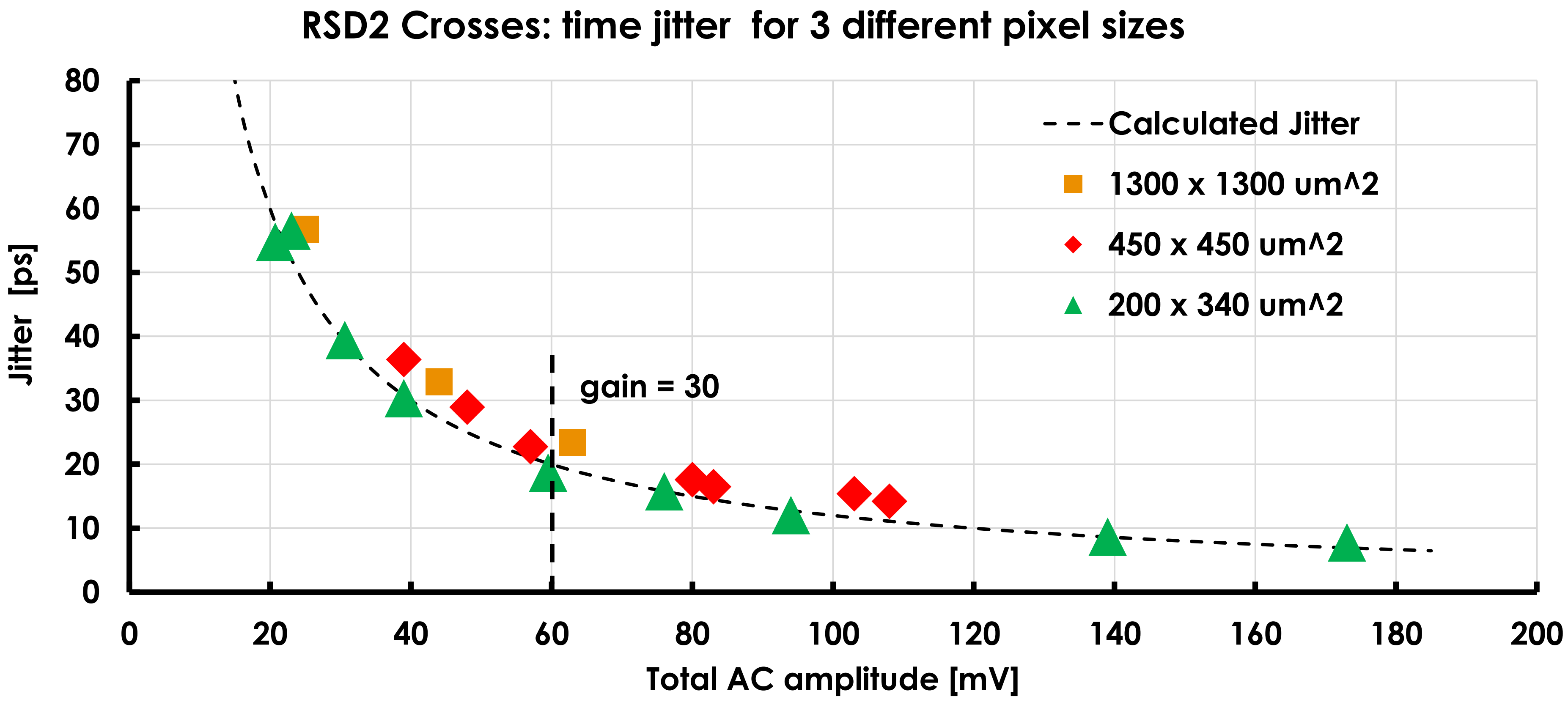


RSD2 temporal resolution

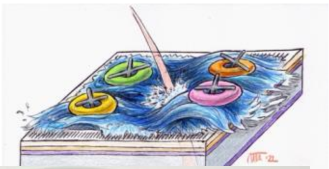


The resolution depends mostly upon the signal size and **weakly on the pixel size**

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



The UFSD project: brief history

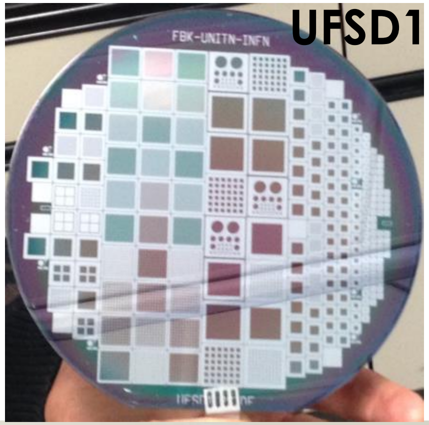


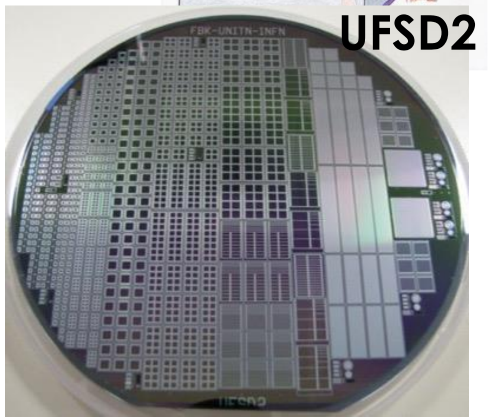
Aim: develop sensors with excellent temporal and spatial resolutions via a series of productions and design refinements

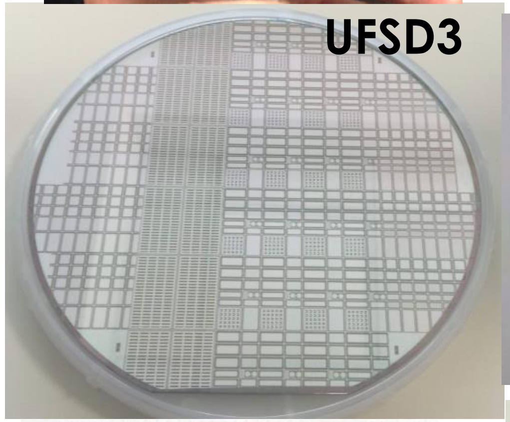
Long term R&D, Not for a specific experiments

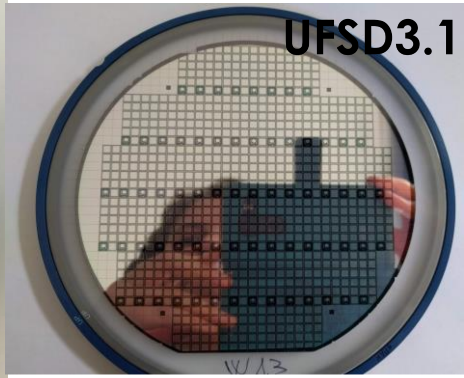
1. **2016**: UFSD1 First 300 µm thick LGAD (FBK 6” wafer)
2. **2017**: UFSD2 First 50 µm thick LGAD (FBK 6” wafer)
Gain layer doping: Boron, Gallium, Boron + Carbon,
3. **Fall 2018:** UFSD3 50 µm LGAD (FBK 6” wafer), produced with the stepper (many Carbon levels, studies of interpad design)
4. **June 2019:** UFSD3.1 50 µm LGAD (internal FBK) interpad design.
5. **June 2019** RSD1 Resistive AC-LGAD (FBK 6” wafer)
6. **June 2020:** UFSD3.2 25, 35, 45, and 55 µm LGAD, carbon studies, deep, shallow gain implant (FBK 6” wafer
7. **Q1/2021: UFSD3.3** (FBK 6” wafer)
8. **Q1/2021: Trench-Isolated** (FBK 6” wafer)
9. **Q2/2021: RSD2** (FBK 6” wafer)
10. **Q2/2021: ExFlux** -> optimized for extreme fluence

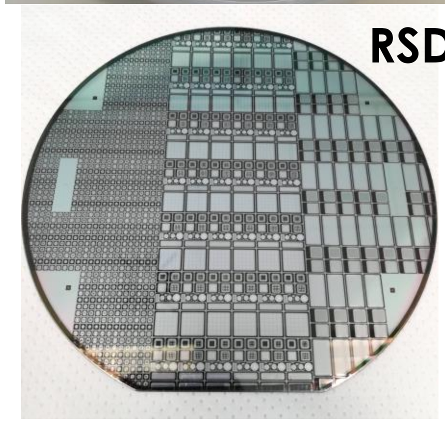
Project fully funded for 3 more years

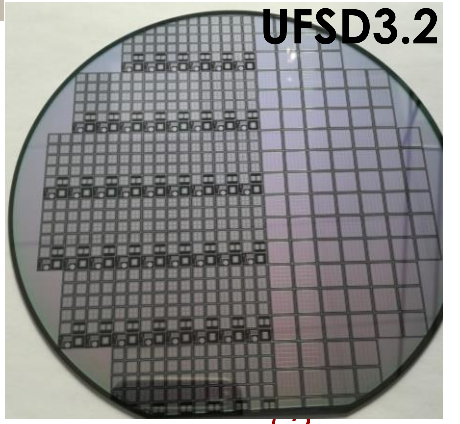




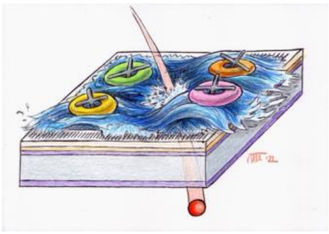


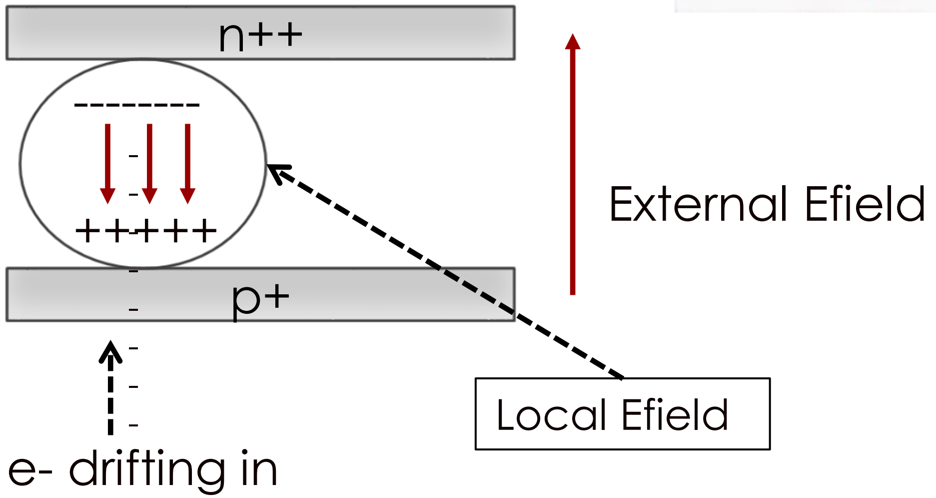






Charge screening – Gain reduction





The **External Efield** in the gain layer is due to **Bias+Doping**

When there are charges in the gain layer,on average, the electrons are one side while the holes are on the opposite side.
This imbalance creates a local Efield that is opposite to the external Efield.

$$\sigma = \frac{Q}{A}$$

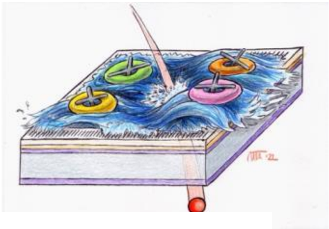
$$E_{local} = \frac{\sigma}{\varepsilon}$$

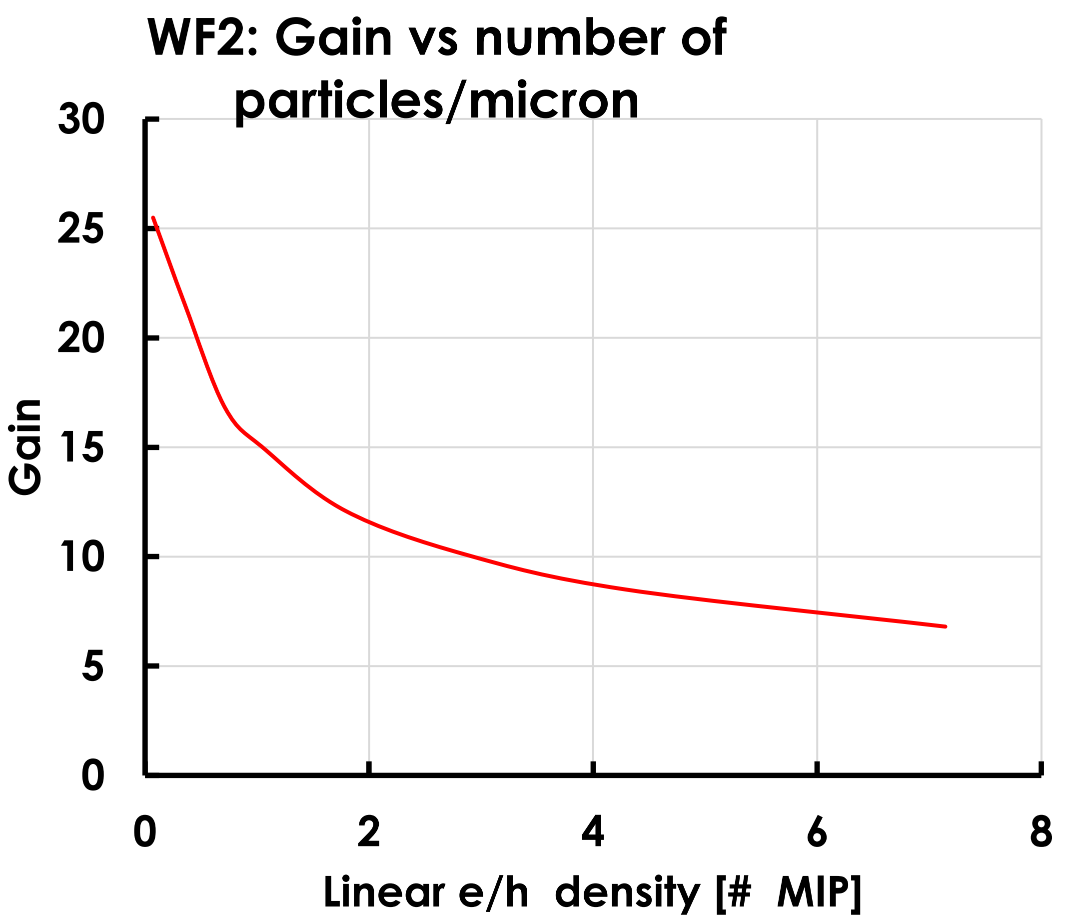
In WF2:

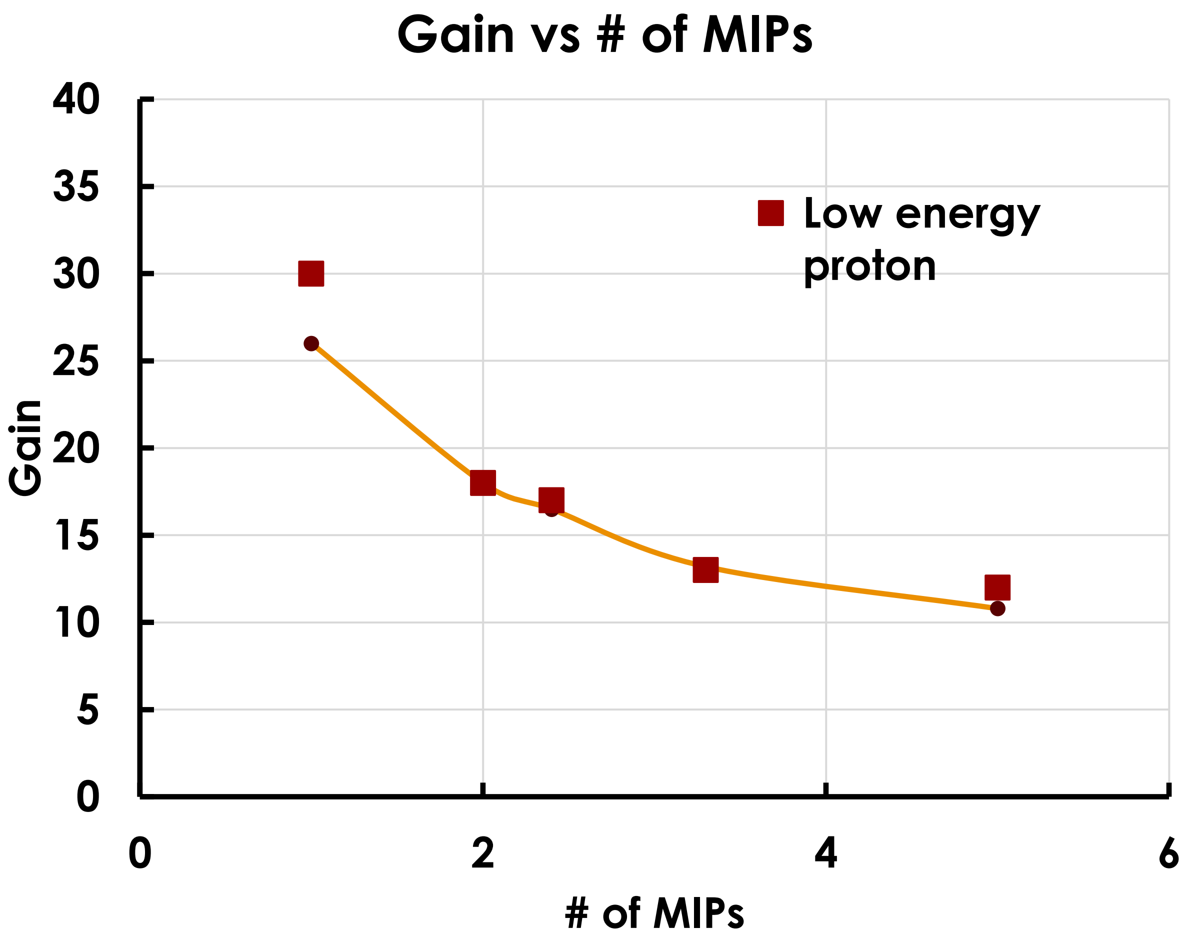
Assume charges in the gain layer form a parallel plate capacitor

- Count the charges in the gain layer
- Compute the local field ==> To do this; you need to assume the area of the capacitor
  - I assumed an area 1 x 1 um^2
- Subtract the local field from the external field

Charge screening – Gain reduction

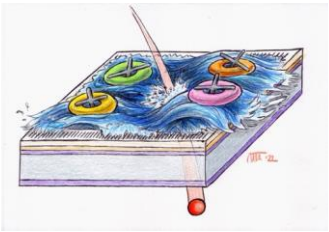


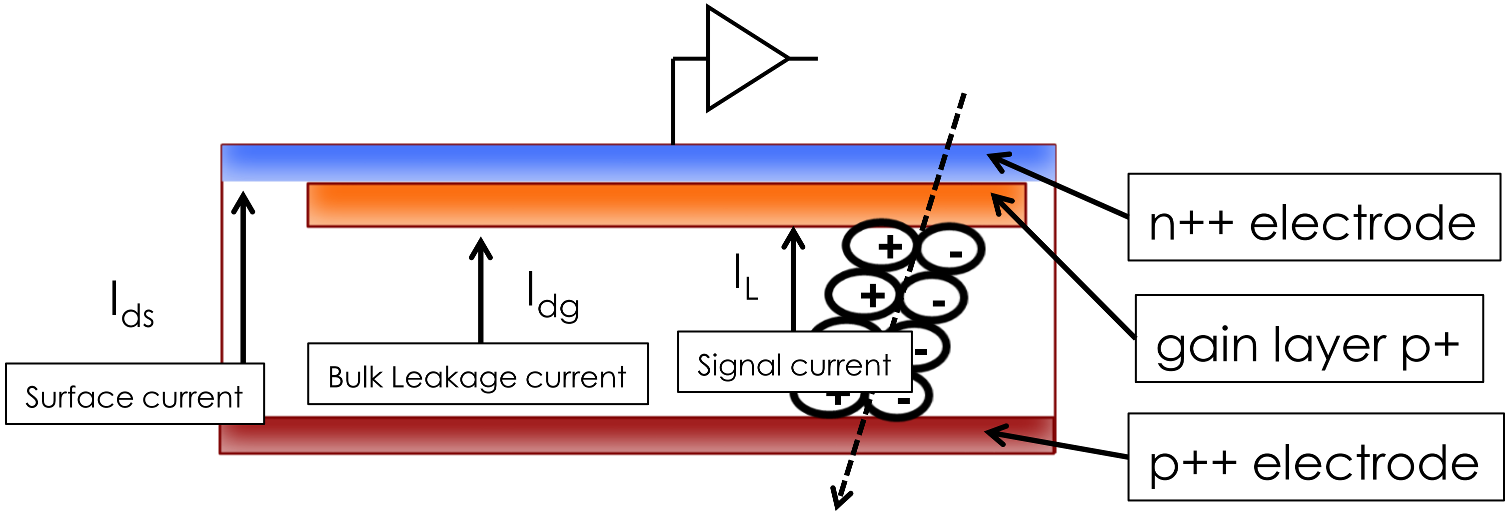




MIP = ~ 70 e/h pairs per micron

Why low gain? Shot noise in LGAD - APD





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

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

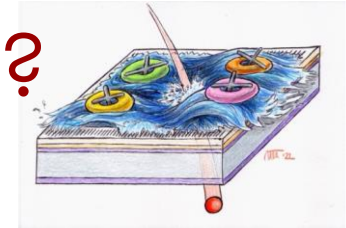
$$F = Mk + \left(2 - \frac{1}{M}\right)(1 - k)$$

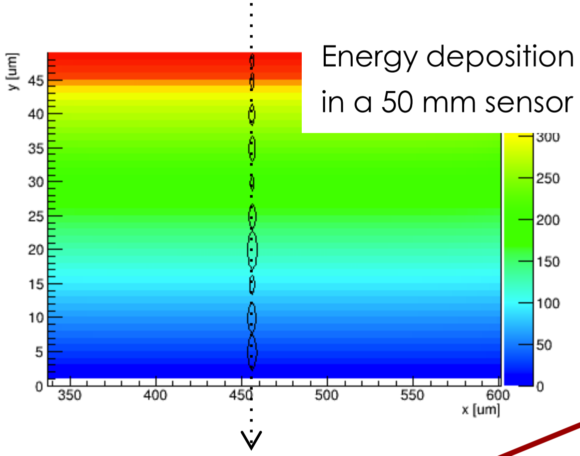
$$F \sim M^x$$

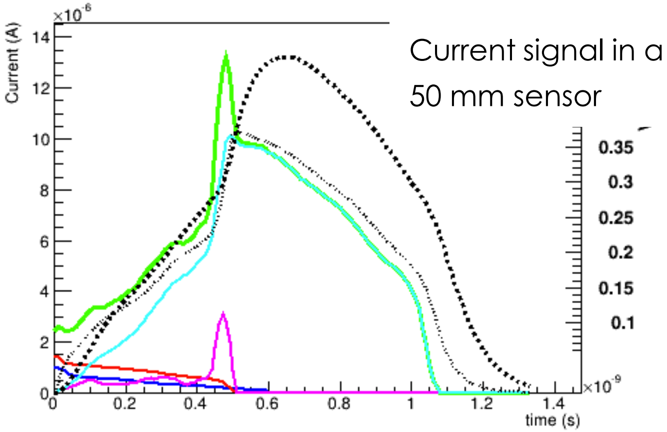
k = e/h ionization rate
x = excess noise index
M = gain

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

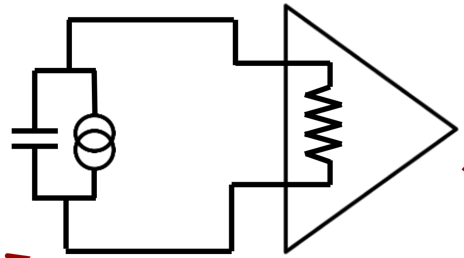
Electronics: What is the best pre-amp choice?



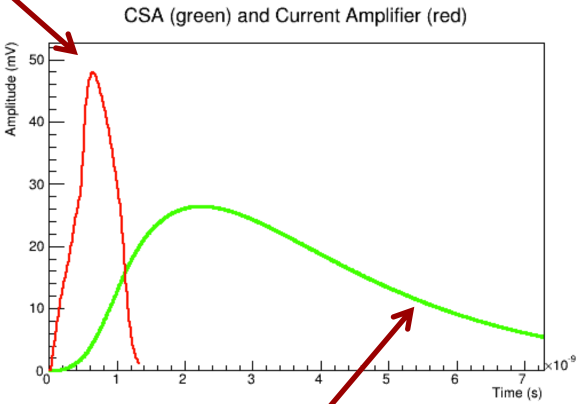




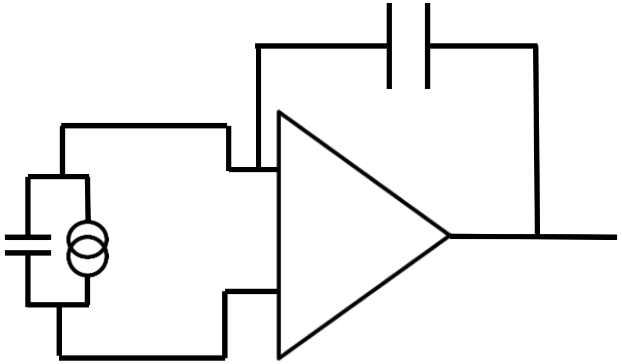
Current Amplifier



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

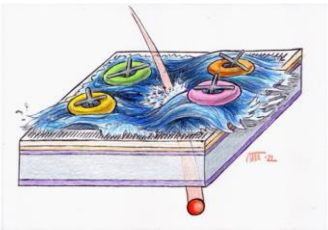


Charge Sensitive Amplifier

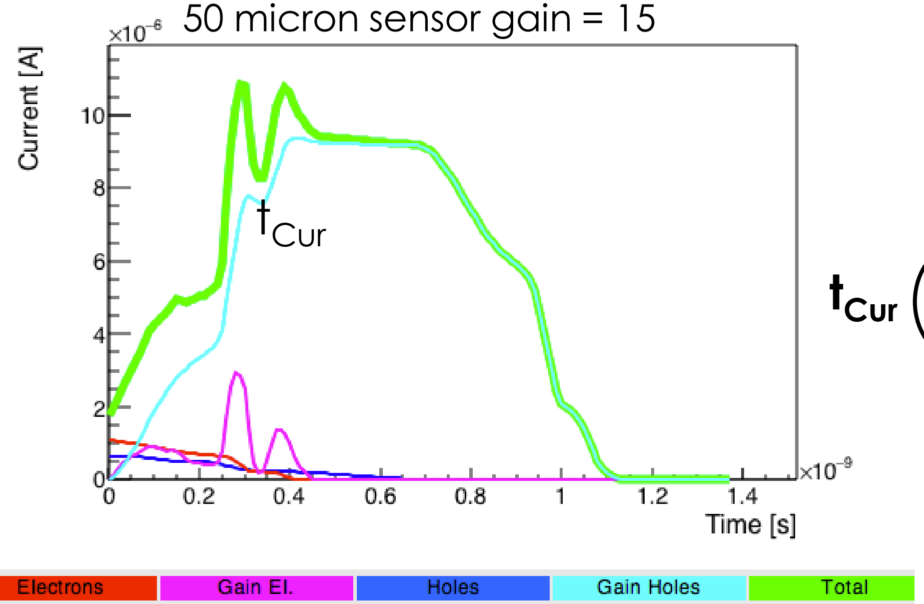


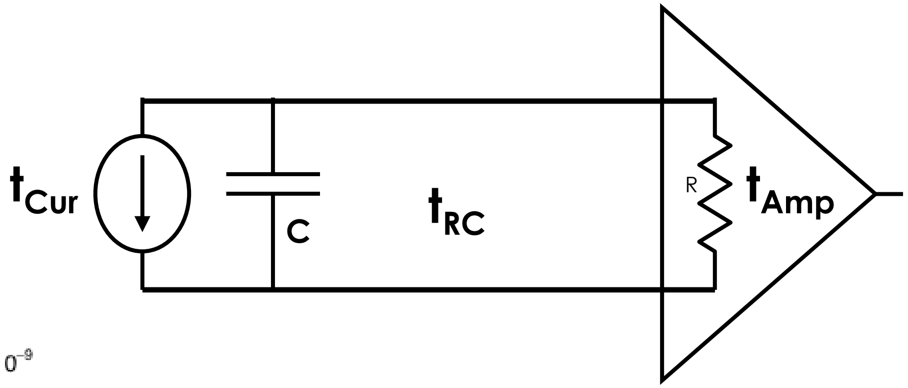
- Slower slew rate
- Quieter
- Integration helps the signal smoothing

The players: signal, noise and slope



Signal dV/dt | Landau Noise | Shot Noise | Electronic Noise



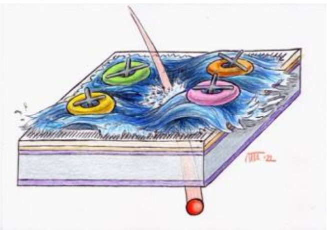


The current rise time (t_{Cur}) | The RC circuit (t_{RC}) | Amplifier rise time (t_{Amp})

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})

How to make a **good** signal

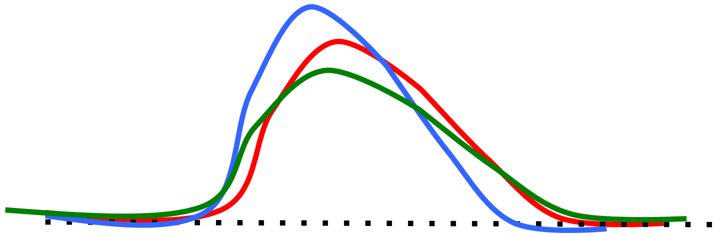


Signal shape is determined by Ramo's Theorem:

$$i \mu qvE_w$$

Drift velocity

Weighting field

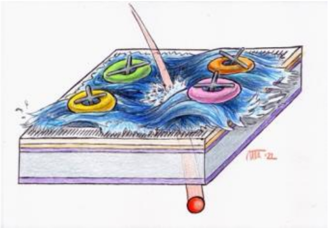


A key to good timing is the uniformity of signals:

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

N. Cartiglia, INFN, Torino, IWORID, 27/06/23

Good signals for Timing



Velocity:

$$i \propto q v E_w$$

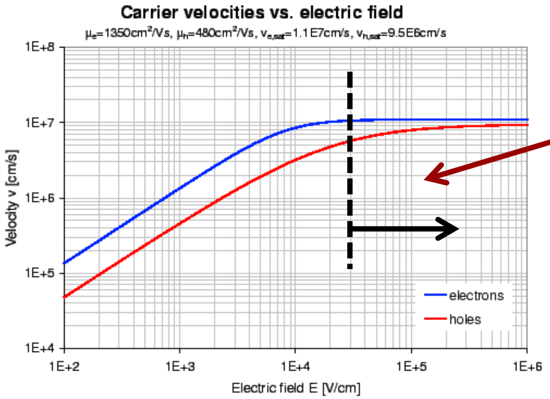
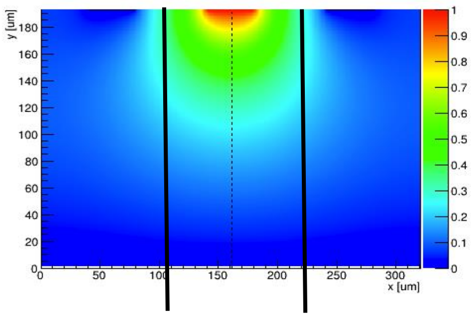


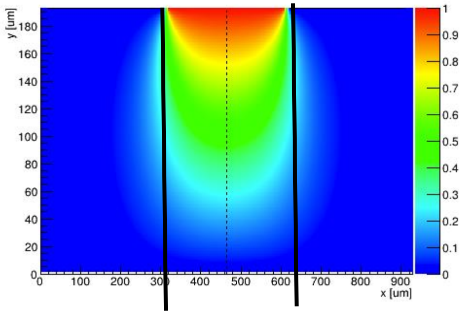
Figure: Electron and hole velocities vs. the electric field strength in silicon.

We want to operate in this regime: saturated velocity

Weighting field:

$$i \propto q v E_w$$





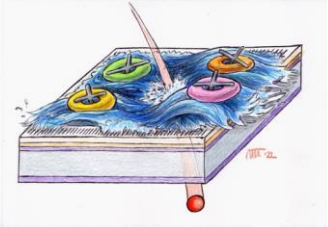
Best: uniform weighting field in a pitch

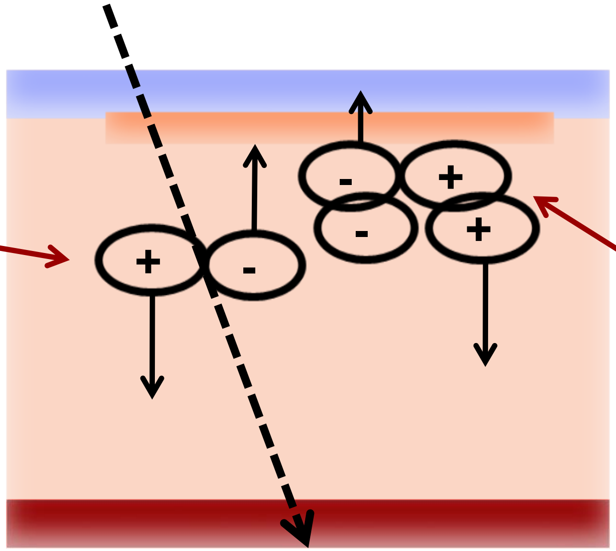
Charge:

$$i \propto q v E_w$$

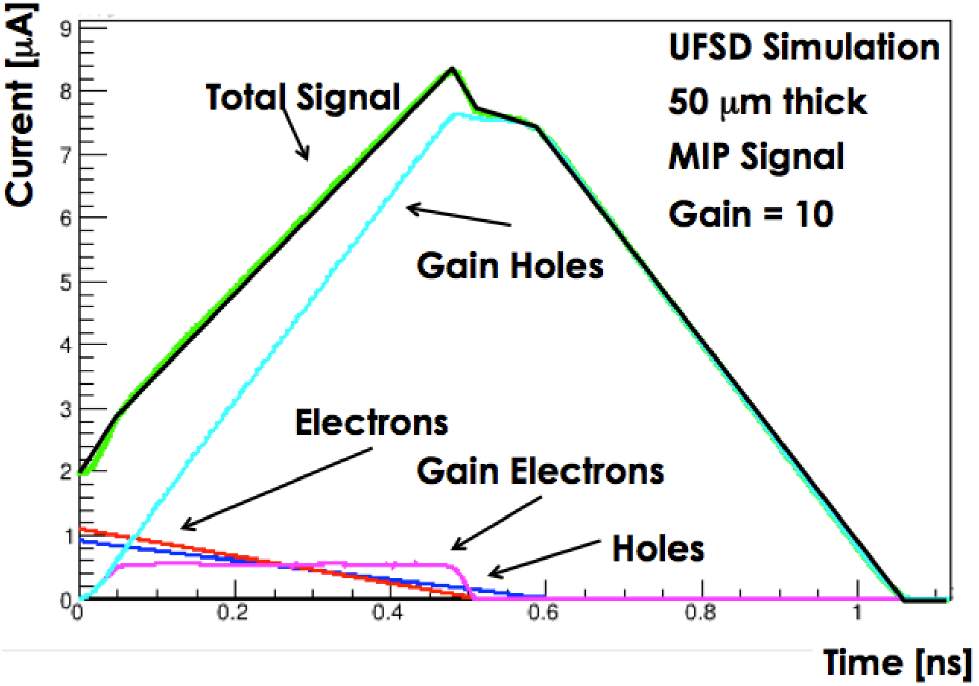
➔ Highest possible E field to saturate velocity
➔ Large pad to have uniform weighting field
➔ Lot's of charge

How gain shapes the signal





Gain electron:
absorbed immediately
Gain holes:
long drift home

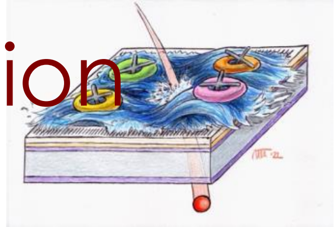


Electrons multiply and produce additional electrons and holes.

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

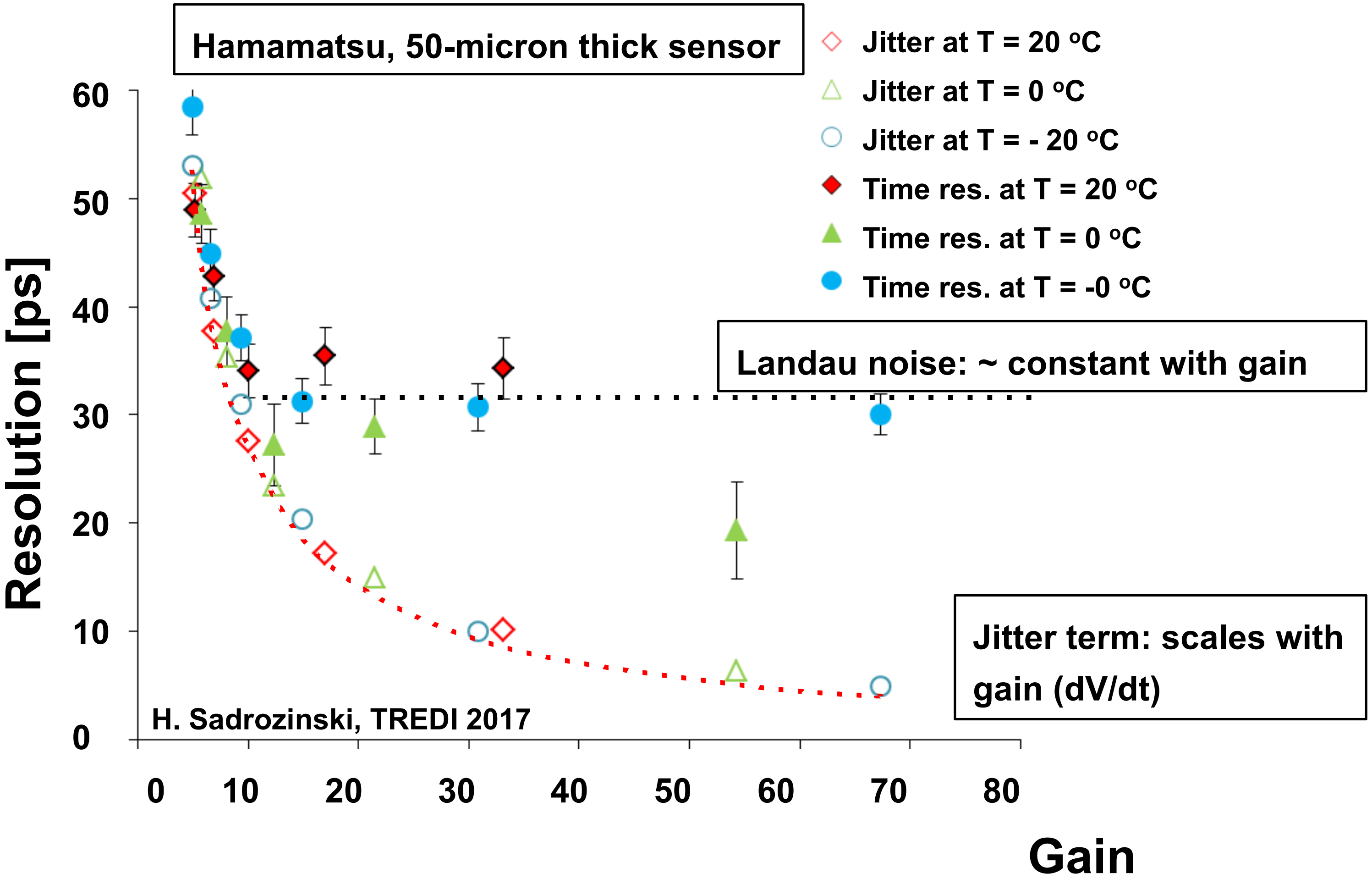
➔ **No holes multiplications**

An example ofLGAD Hamamatsu's time resolution

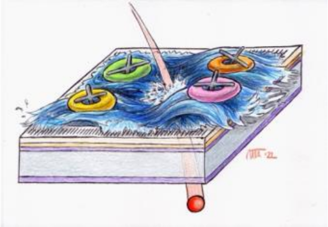


UFSD from Hamamatsu: 30 ps time resolution,

Value of gain ~ 20

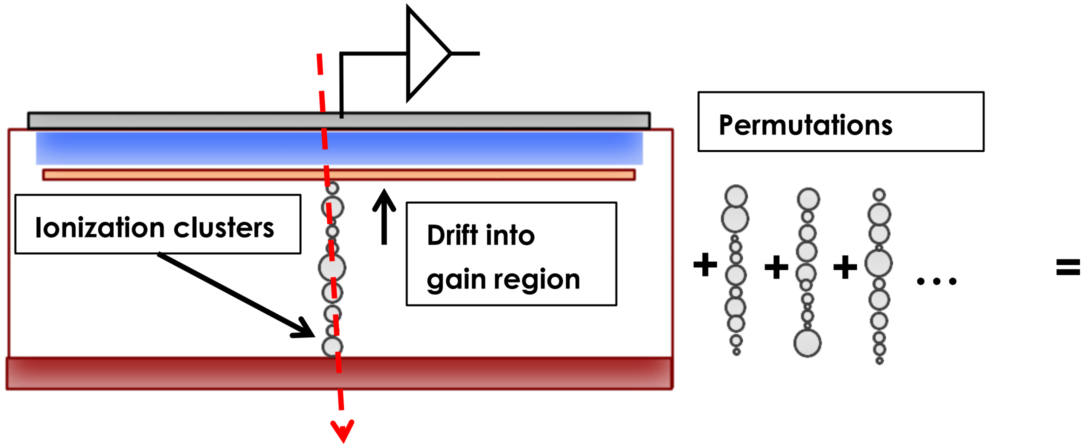


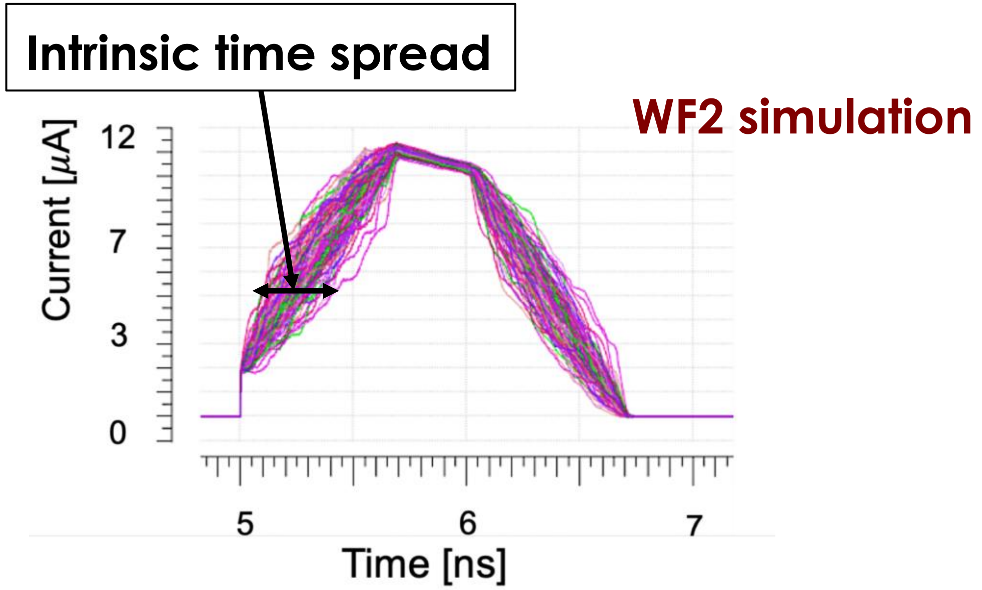
Intrinsic LGAD time resolution



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) ?



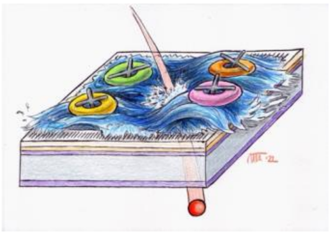


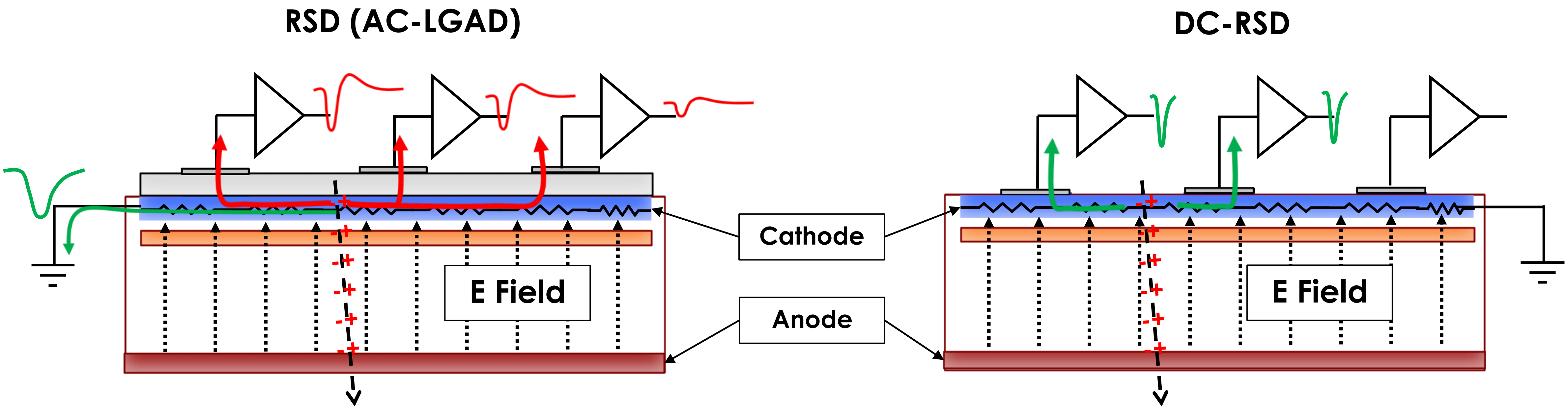
50 microns thick ==> 50! Permutations…

10 microns thick ==> 10! Permutation

The thinner the sensor, the smaller the intrinsic time resolution

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