4D tracking at FCC-ee

An overview of the present activities aimed at developing trackers with excellent spatial and temporal resolutions

(this short summary covers sensors with internal gain, other possibilities in other talks)

UFSD group

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

Extensive collaborations with other groups and within the RD50 CERN collaboration

erc UFSD

PRIN 4DInSiDe

AIDA Innova

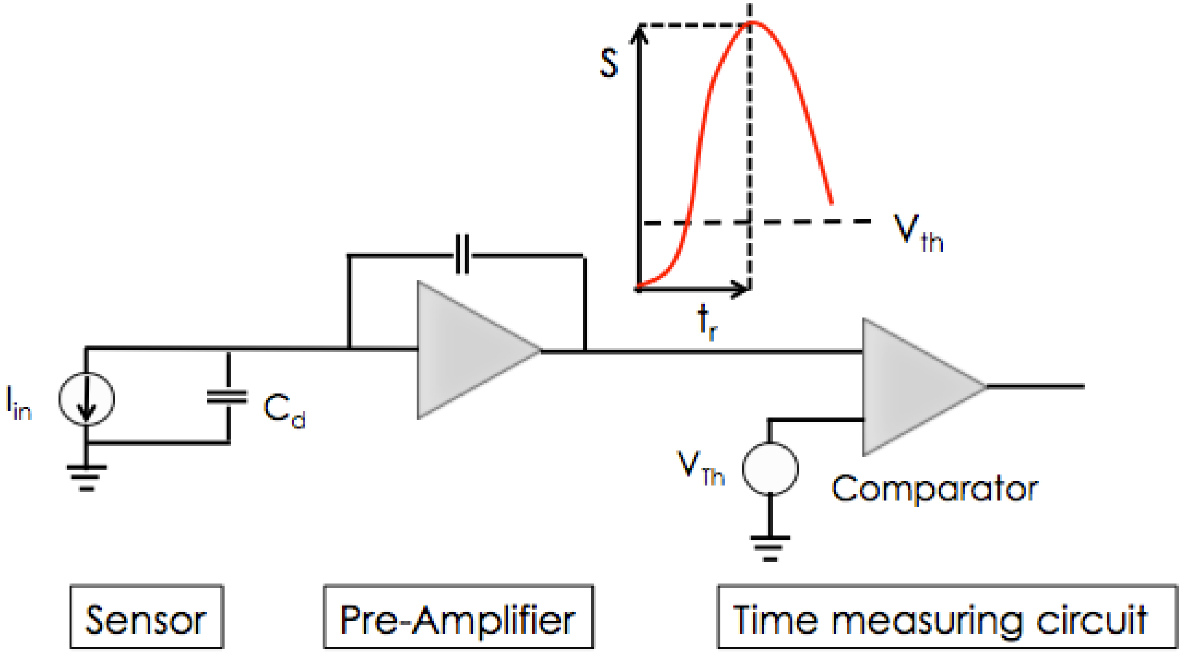
Setting the stage

The first step is to define the phase space of the required performances (table from the ECFA document presentlyin preparation)

	Vertex	Tracker	ToT
Position precision (um)	< 3	~ 6	
material X/Xo	0.05	1	
Power (mW/cm^2)	20	<100	
Rates (GHz/cm^2)	0.05		
Timing precision (ns)	25	< 0.1	~ 0.01

Silicon time-tagging detector

(a simplified view)



Time is set when the signal crosses the comparator threshold

The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning.

Strong interplay between sensor and electronics

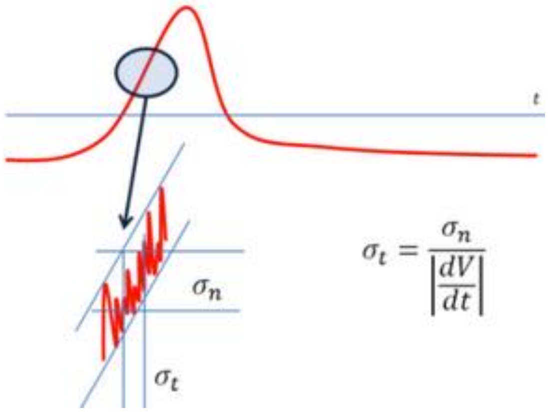
Temporal resolution: electronics and sensors

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

Minimized by electronics

Usual **"Jitter"** term

Here enters everything that is "Noise" and the steepness of the signal



Need large dV/dt

➔ Need internal gain

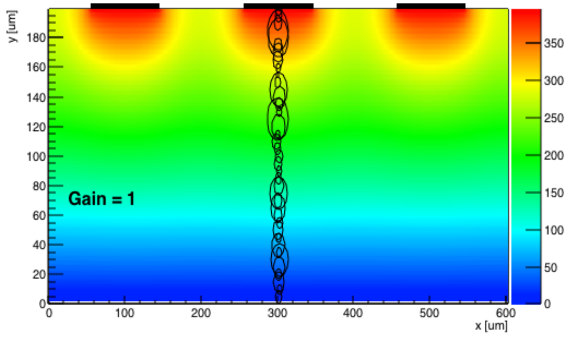
Minimized by good sensor design

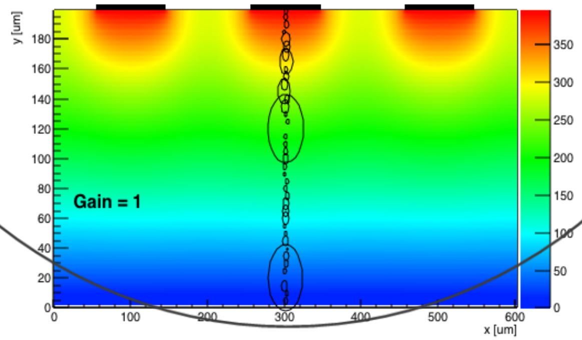
Amplitude variation:

variation in the total charge

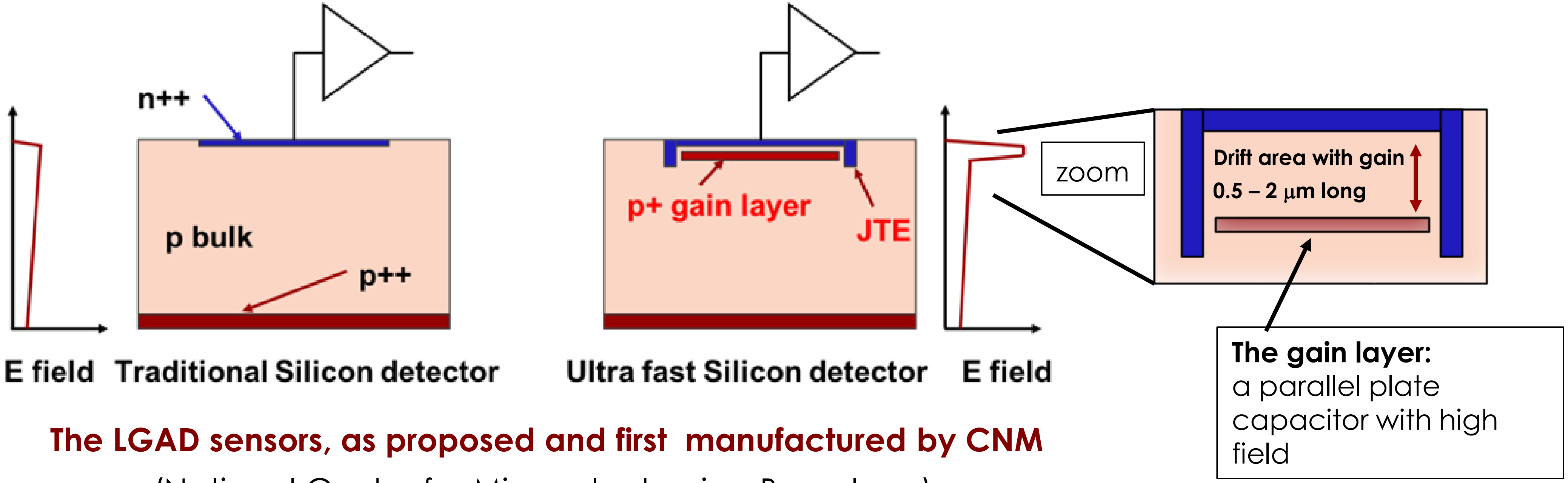
Shape distortion:

non homogeneous energy deposition





First design innovation: low gain avalanche diode (LGAD)



The LGAD sensors, as proposed and first manufactured by CNM

(National Center for Micro-electronics, Barcelona):

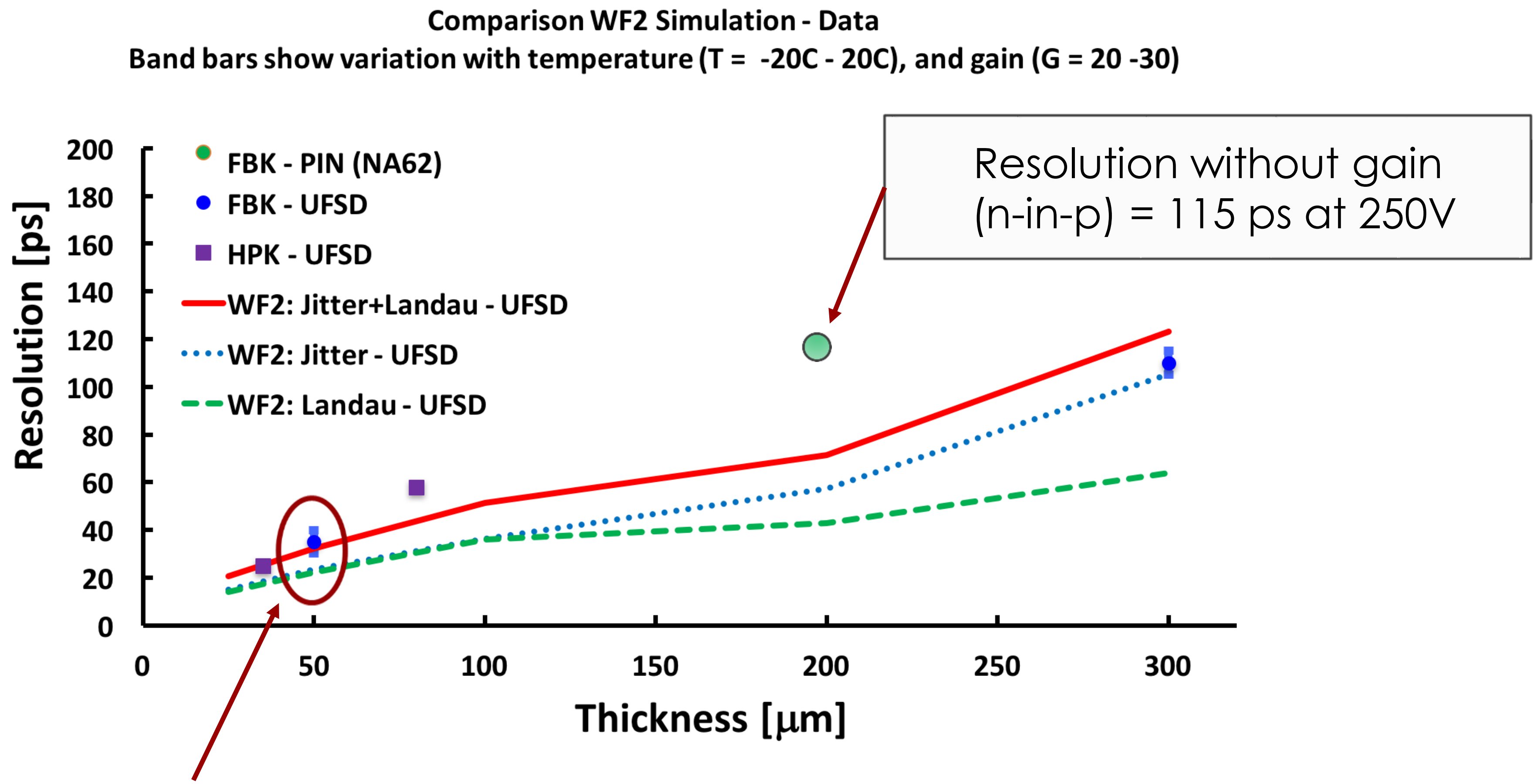
High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage

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

Low gain is the key ingredient to good temporal resolution

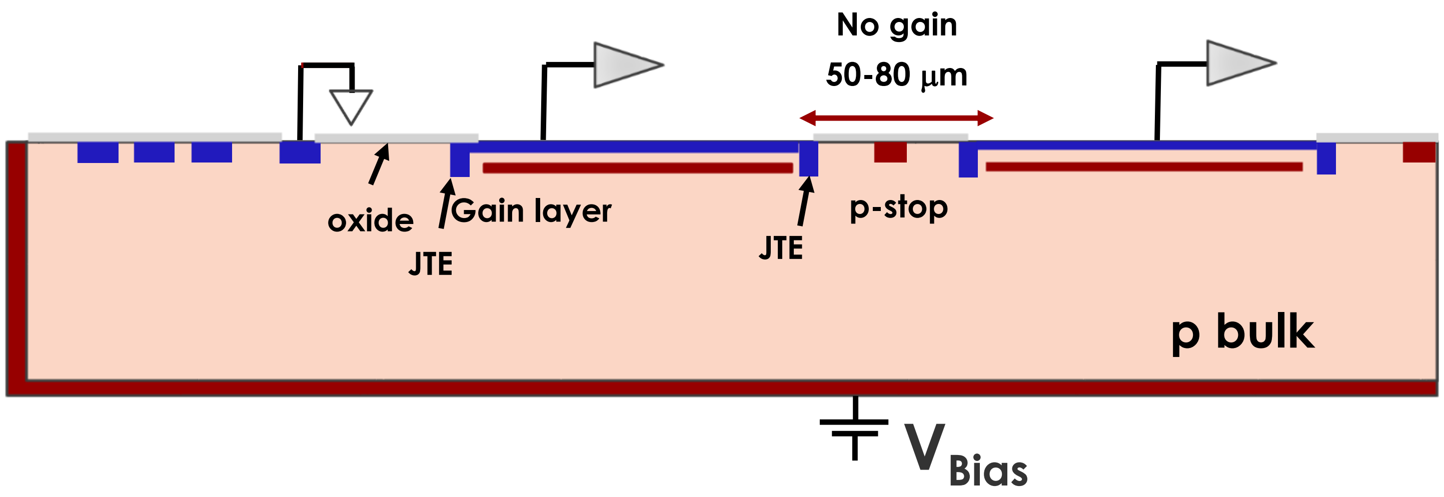
Summary of UFSD temporal resolution

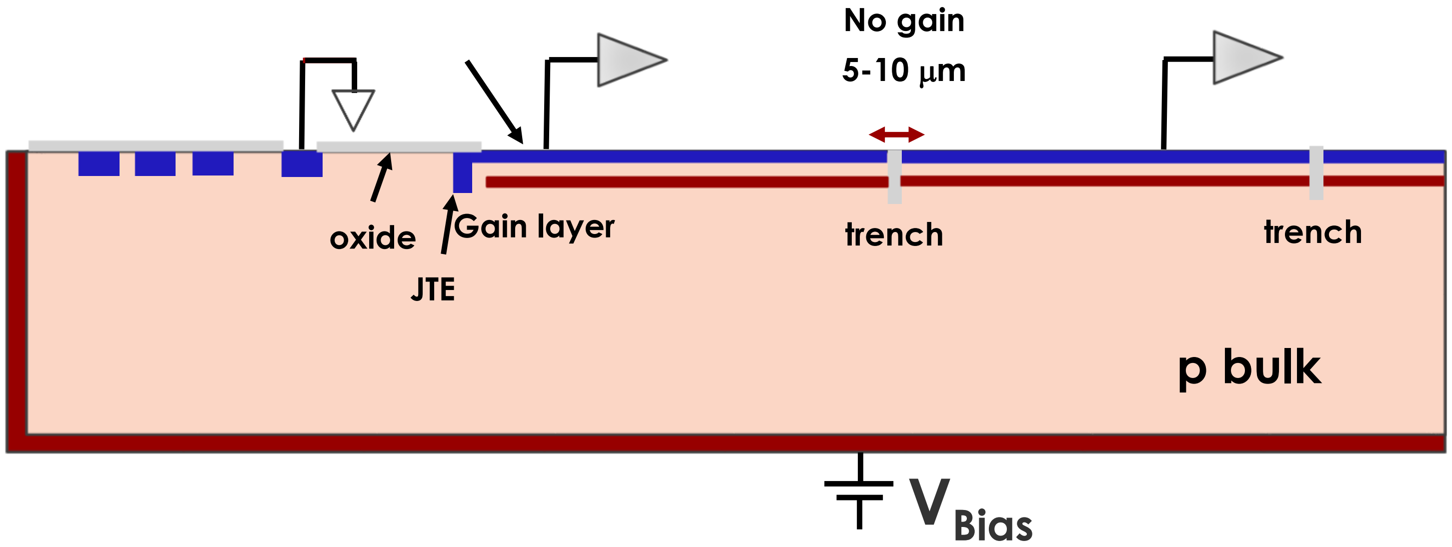


There are now hundreds of measurements on 45-55 µm-thick UFSDs

➔ Current sensor choice for the ATLAS and CMS timing layers

Towards 100% fill factor: Trench Isolated LGAD





No-gain region ~ 50-80 μm

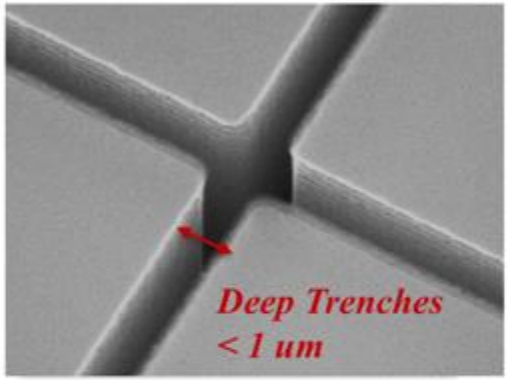
➔ cannot use UFSDs for small pixels

Solution: use trenches for pad isolation

➔ No-gain region ~ 5 – 10 μm

RD50-TI production

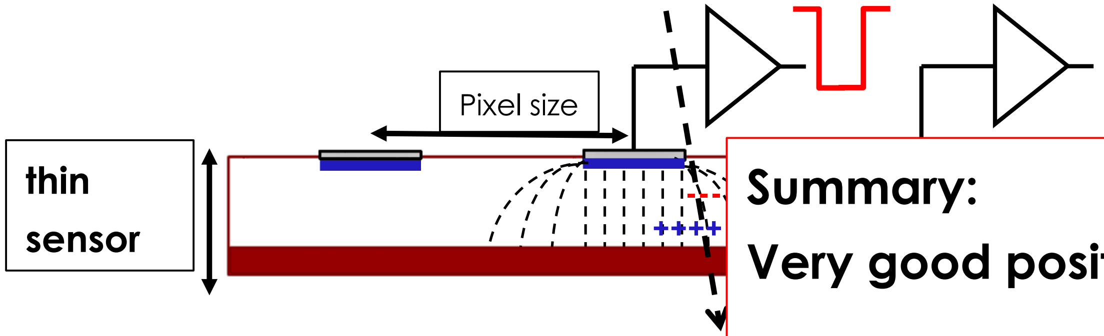
Interpad design	Interpad distance [μm]
V1_1TR	2.7 ± 0.2
V2_1TR	6.5 ± 0.2
V3_1TR	7.9 ± 0.1
V4_1TR	10.6 ± 0.2
V2_2TR	8.9 ± 0.2
V3_2TR	10.3 ± 0.1

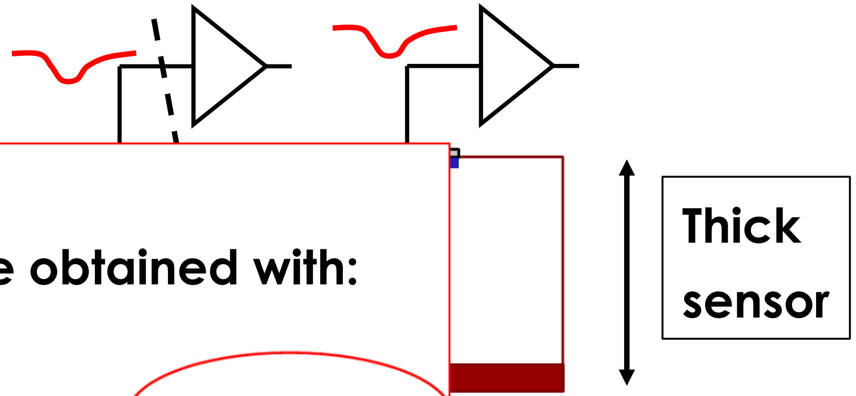


The R&D to achieve small pixels is clear (AIDAInnova is part of this)

Position precision σ_x, readout, and material budget

Binary readout	**Analog readout**
where the only information is hit/miss (0,1)	where the amplitude of the signal is recorded





Summary:

Very good position precision can be obtained with:

(1) Digital readout && very small pixels && thin sensors

(2) Analog readout && large pixels && thick sensors

$\sigma_x = k \frac{pitch}{\sqrt{12}}, k$ ...

Can we have the best of both options?

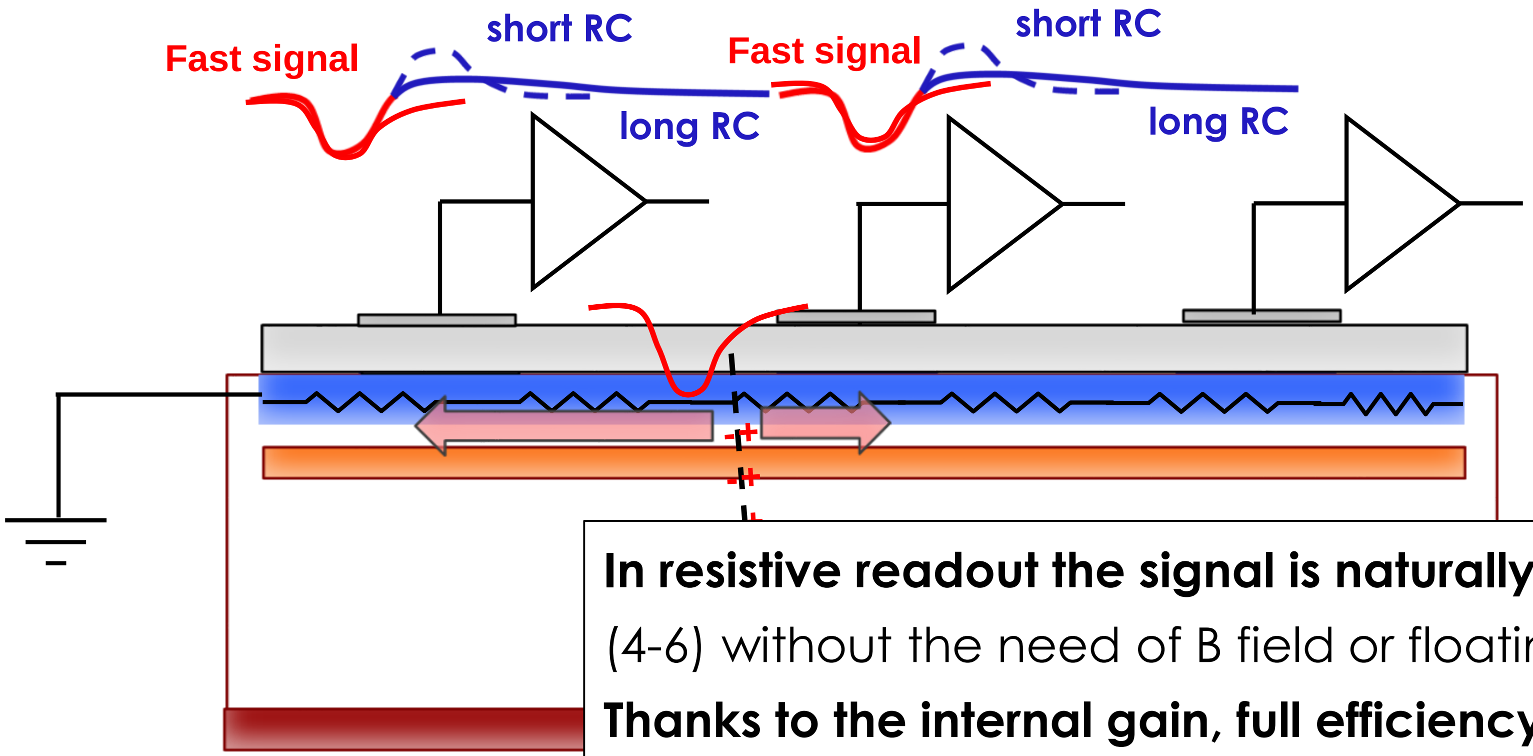
Very good precision with

Large pixels && low material budget?

- σ_x depend on the pixe...
  pixel = 100 μm ➔ ...
  ...ain efficiency
- σ_{MS} small : sensors might be thin
  ...)

Second design innovation: resistive read-out

- 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

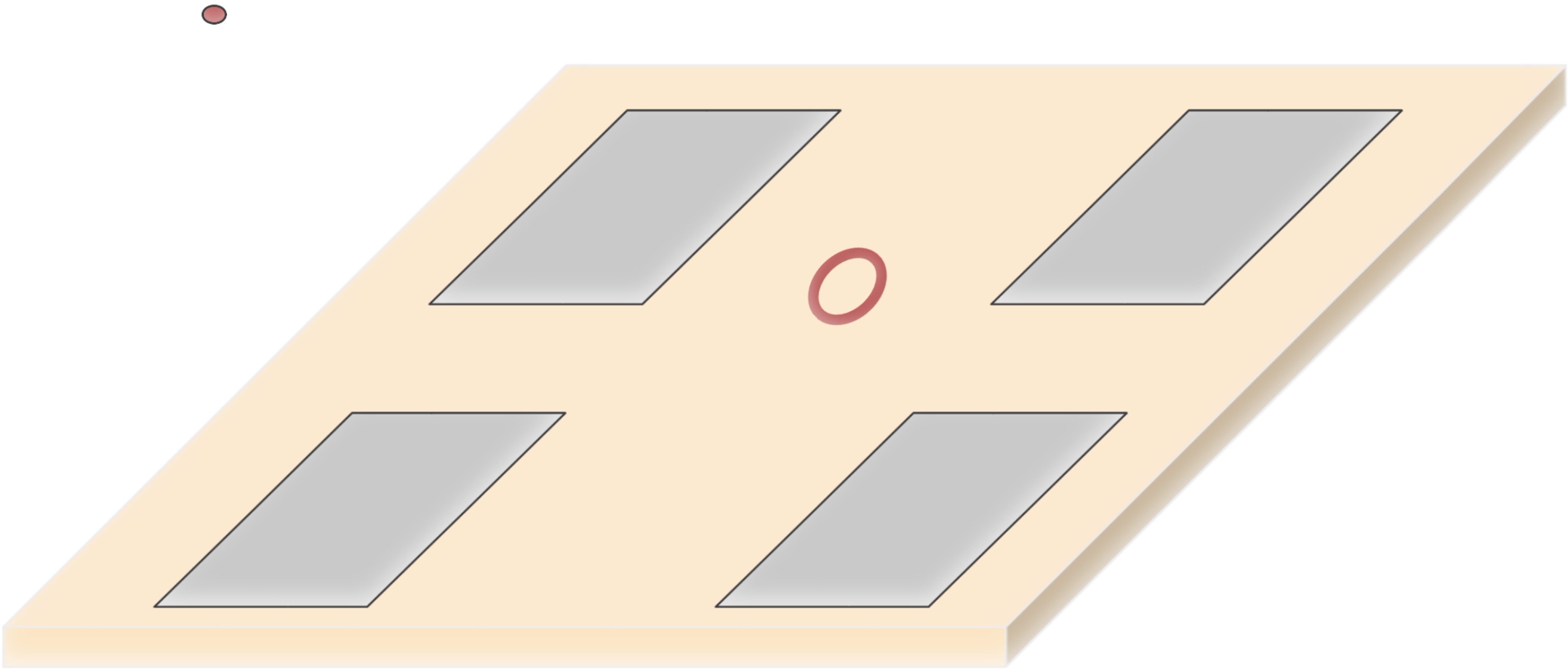


In resistive readout the signal is naturally shared among pads (4-6) without the need of B field or floating pads

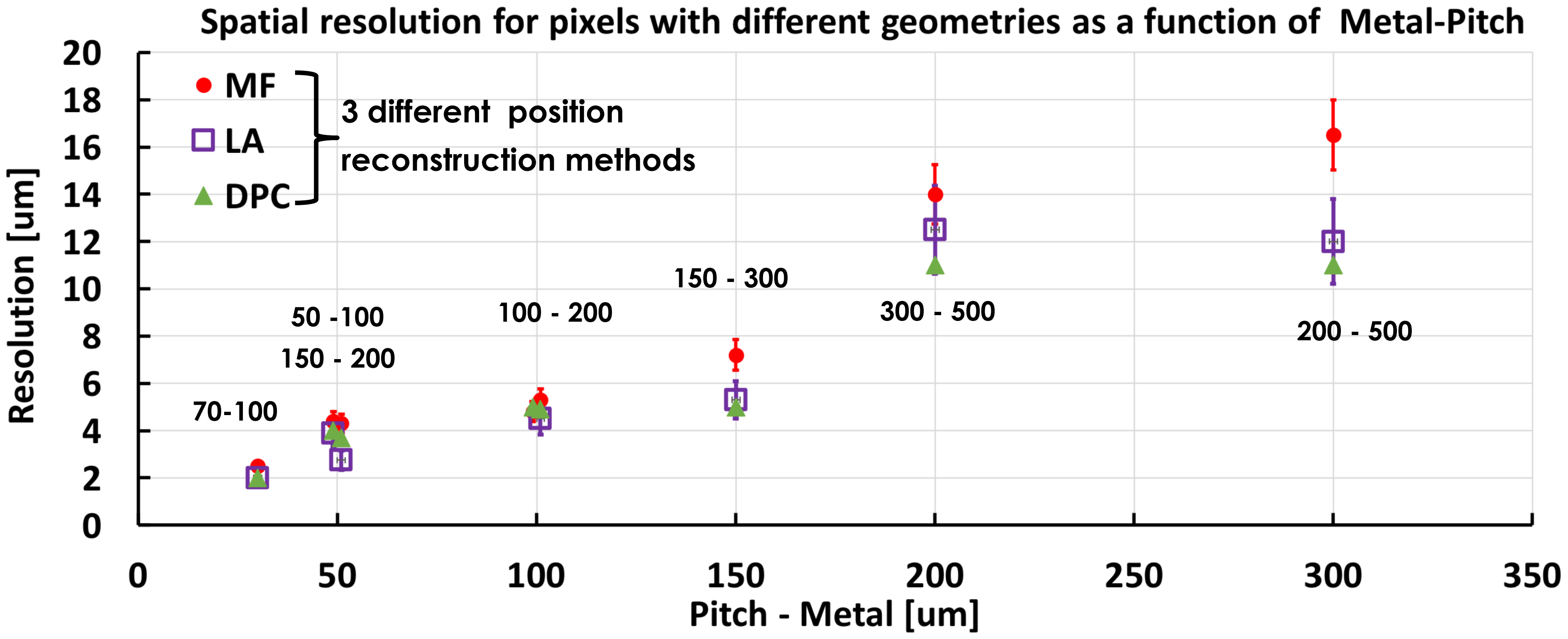
Thanks to the internal gain, full efficiency even with sharing

Results presented here are from the FBK RSD1 production

RSD main formula in motion



Laser study: position resolution as a function of pixel geometry



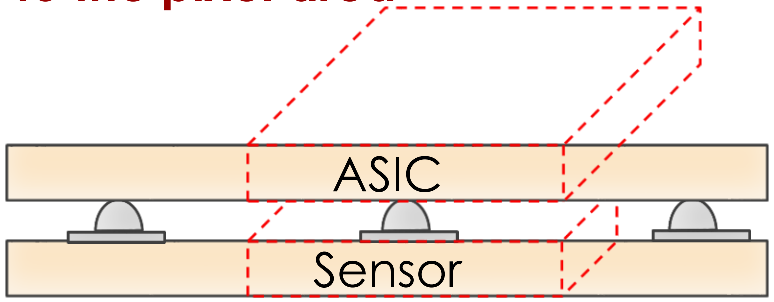
RSDs reach a spatial resolution that is about 5% of the inter-pad distance

➔ ~ 5 μm resolution with 150 μm pitch

RSDs have the “usual” UFSD temporal resolution of 30-40 ps

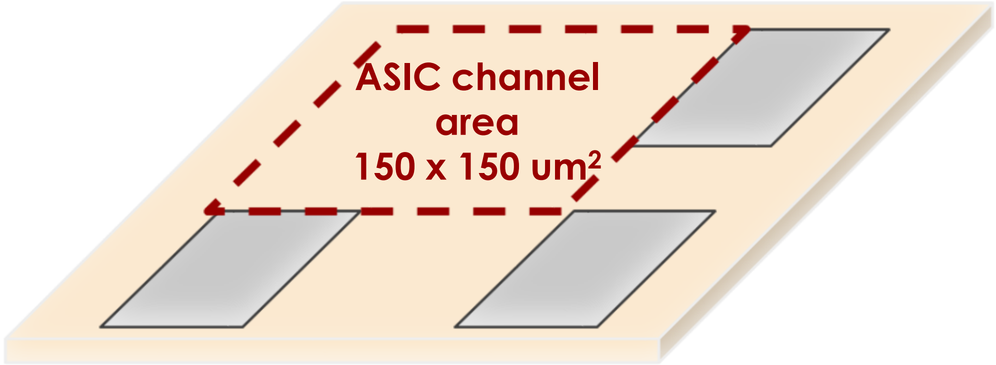
ASIC for RSD

Very important point: in hybrid technology (sensor bump-bonded to the ASIC),
the area available for each read-out channel is identical to the pixel area

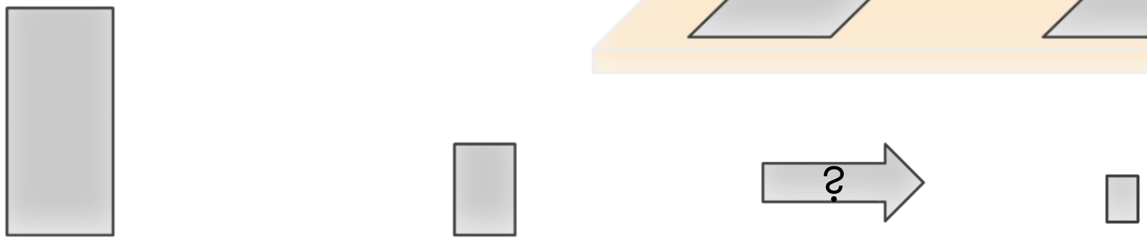


Assuming a goal of ~ 5 mm spatial resolution,
the RSD pitch can be 150-200 μm

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



Example:
TDC evolution

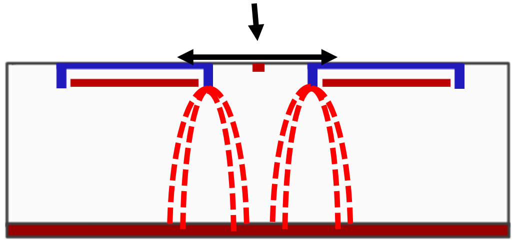


130 nm:
70 x 150 micron

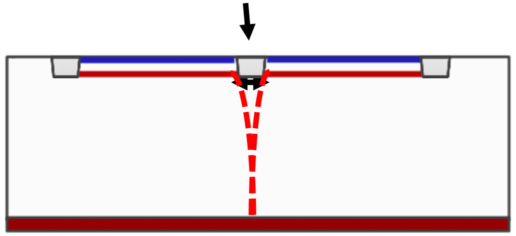
65 nm:
40 x 60 micron

28 nm:
~20 x 30 micron

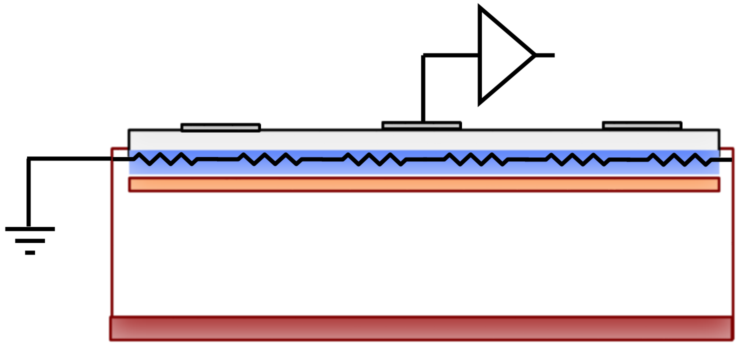
UFSD Summary: more gaining and more sharing



JTE + p-stop design



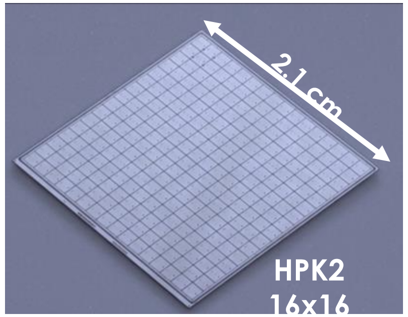
Trench-isolated design



RSD -- AC-LGAD

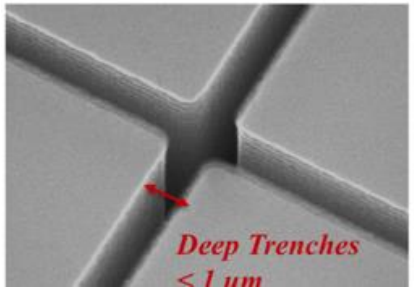
JTE/p-stop UFSD

- 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



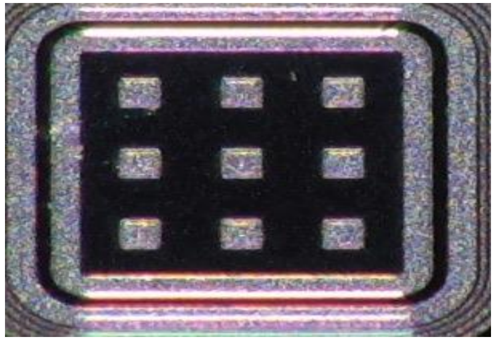
UFSD evolution: use trenches

- 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



Outlook

Silicon detectors, thanks to internal gain and resistive readout, are offering unprecendented combinations of

temporal resolution && spatial resolution && low mass && large pixels

Personal point of view: in this moment, sensors are ahead of readout.
The design of the ASICs to read-out the sensors is complex (~ 5 years)

The R&D path is very open, a strong project can define the future evolution of silicon detectors.

The R&D offers a unique combination of sensors' development and ASIC designs in the very new 4D tracking field (not yet charted).

It takes a village

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

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

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