Development of LGADs and 3D detectors at FBK

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Detectors for 4D Tracking in High-Energy Physics

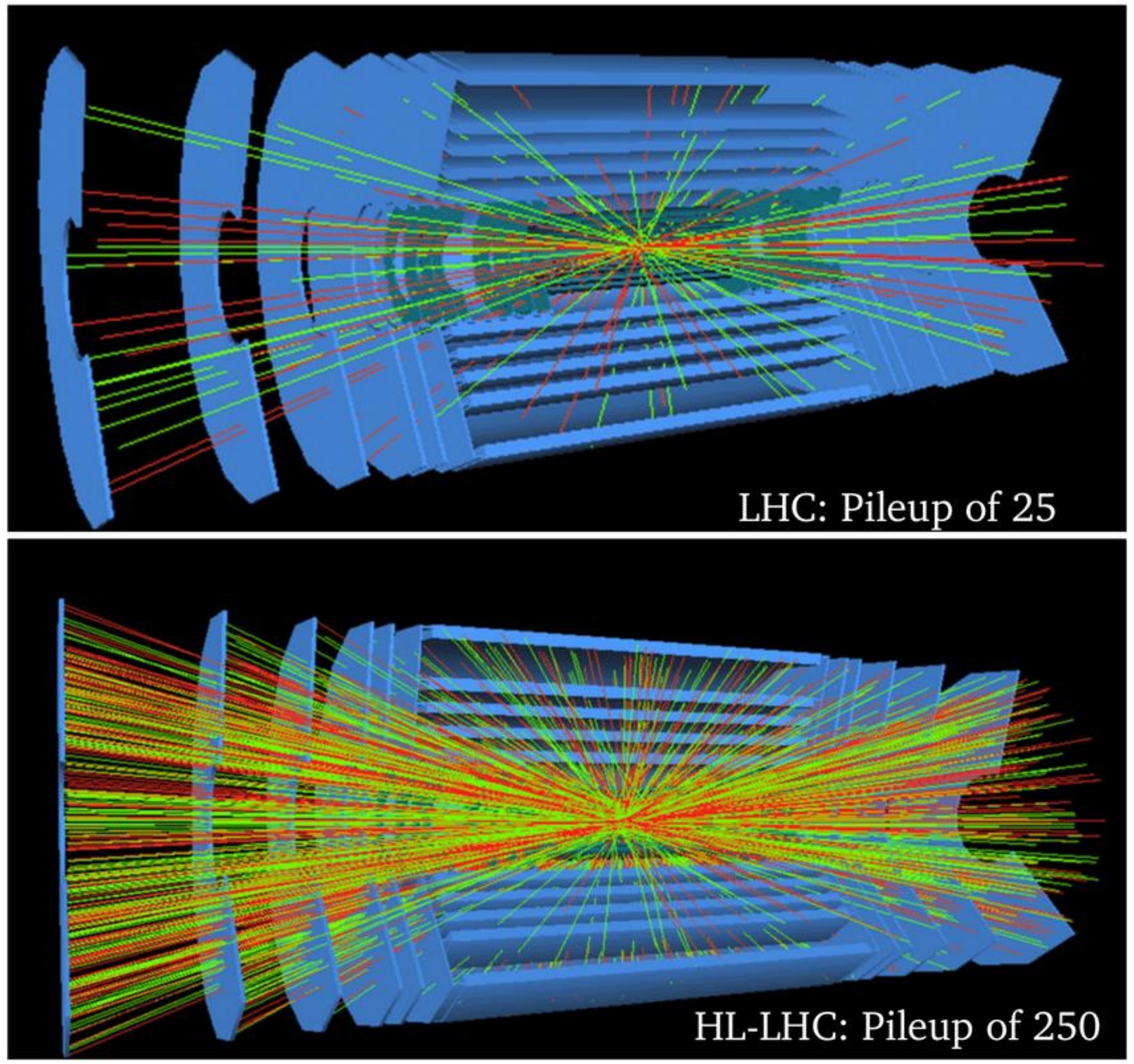


Image from: “Development and evaluation of novel, large area, radiation hard silicon microstrip sensors for the ATLAS ITK experiment at the HL-LHC” Hunter, R.F.H.. (2017)

Particle tracking in HEP experiments

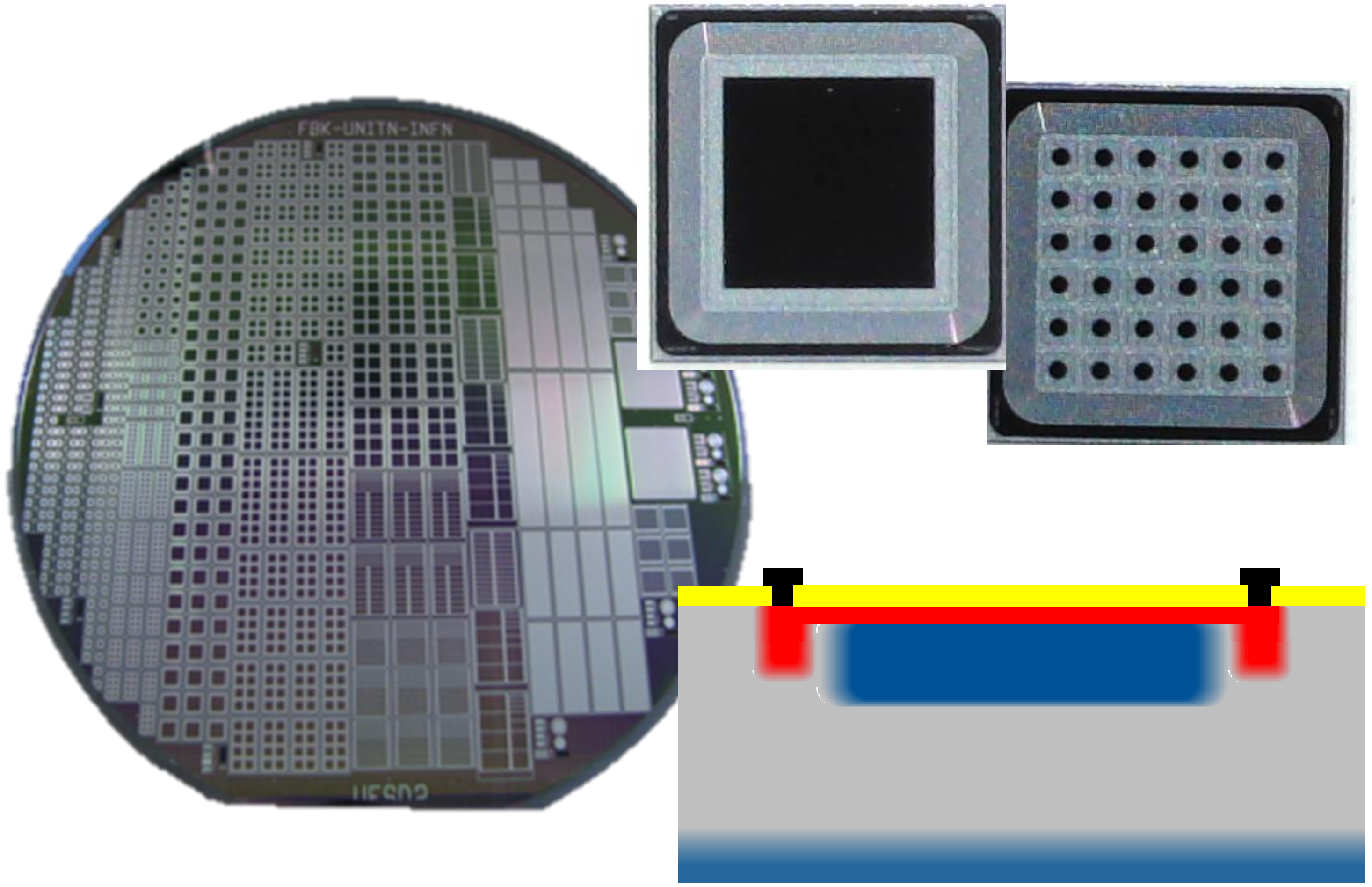
- High Luminosity LHC (HL-LHC, operational in 2025) [1,2]:
  - Luminosity: ×5 compared to LHC → 150-200 events per bunch crossing
  - Timing and spatial resolution of standard silicon tracking sensors not sufficient: *10-15% of vertexes composed of 2 events*

- Requirements for silicon timing detectors in HL-LHC:
  - Timing resolution: *30 ps (rms)*
  - Low spatial granularity: ~1 mm (timing information assigned to the track)
  - High radiation hardness: $> 1 \cdot 10^{15}\ n_{eq} \cdot cm^{-2}$

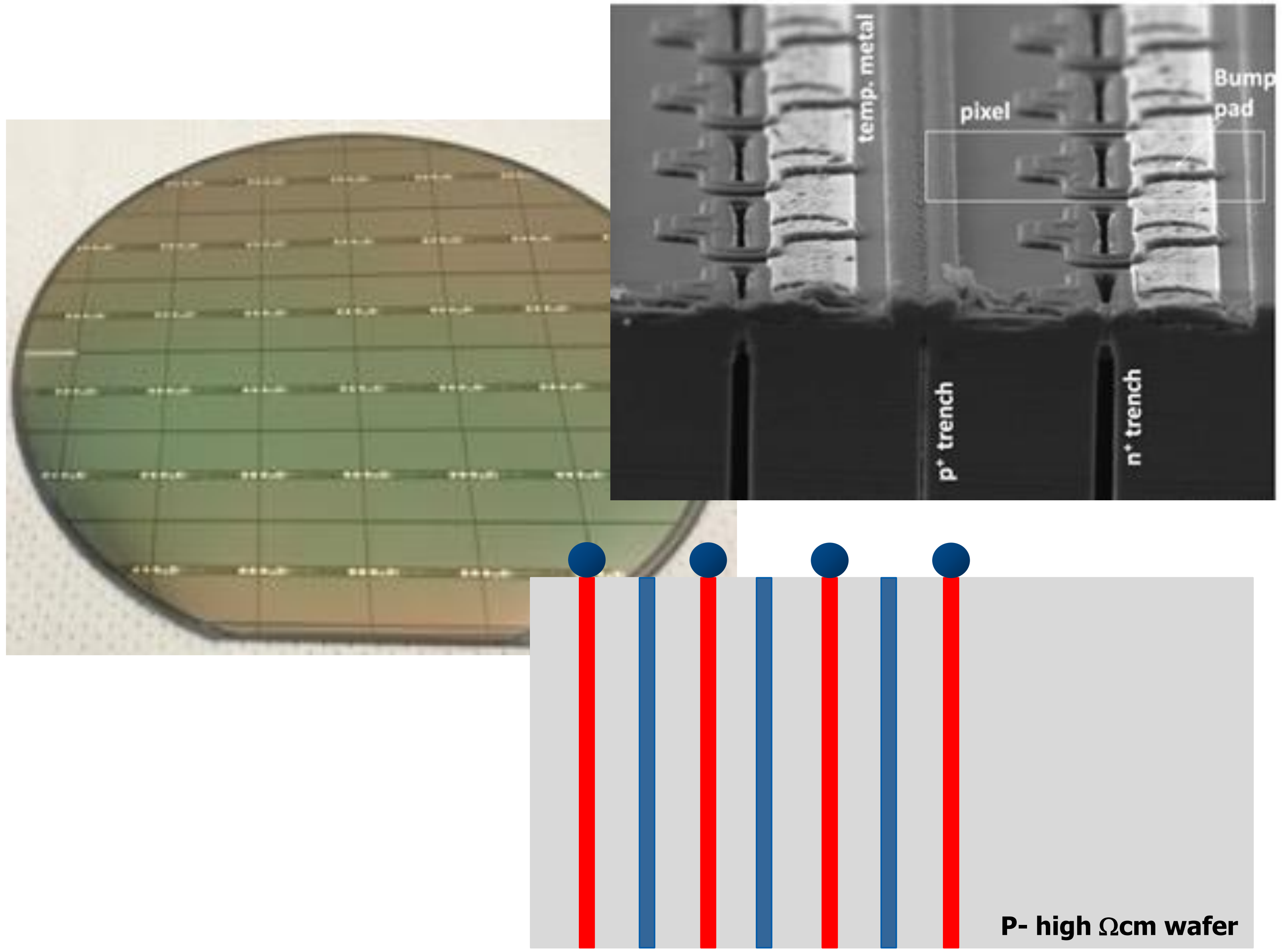
- Real 4D tracking detectors required for future colliders (CLIC, FCC, etc.) [3]:
  - Timing resolution: ~10 ps (rms)
  - High spatial granularity: ~10 µm
  - High radiation hardness: $> 1 \cdot 10^{16/17}\ n_{eq} \cdot cm^{-2}$

Detectors for 4D Tracking in High-Energy Physics

Low Gain Avalanche Diode

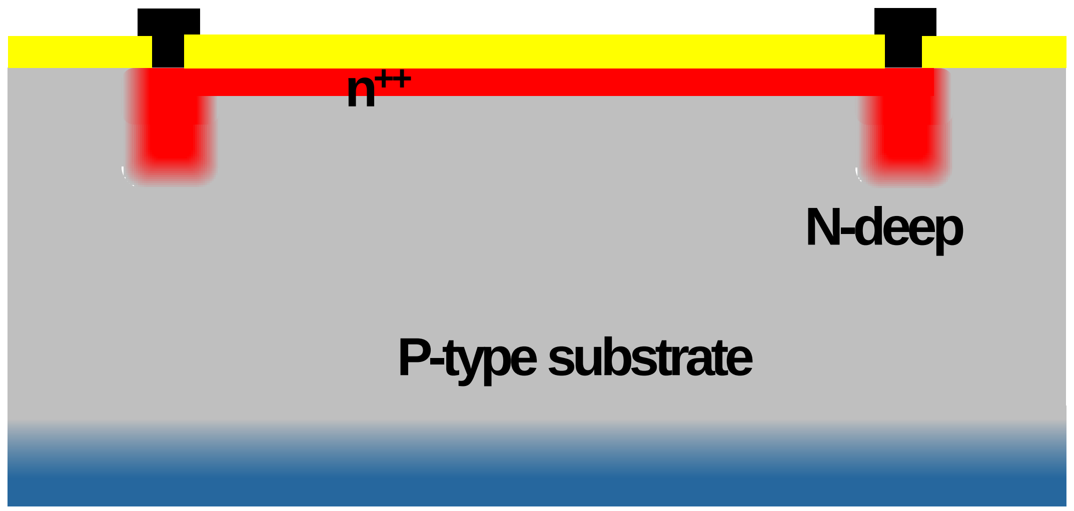


3D Detectors



LGAD Technology

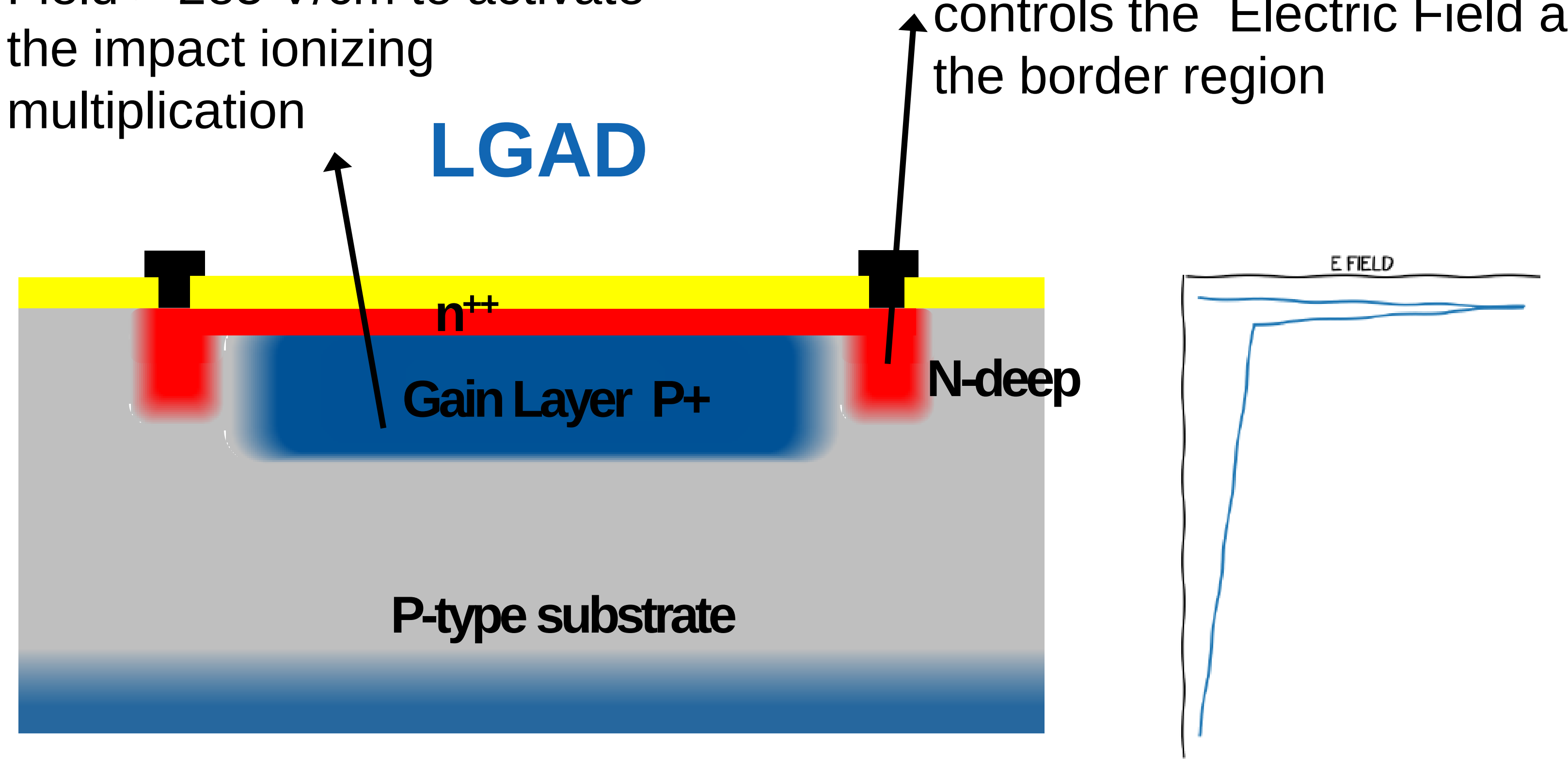
PIN



High-Field region: Electric Field > 2e5 V/cm to activate the impact ionizing multiplication

LGAD

Junction Termination Edge: controls the Electric Field at the border region

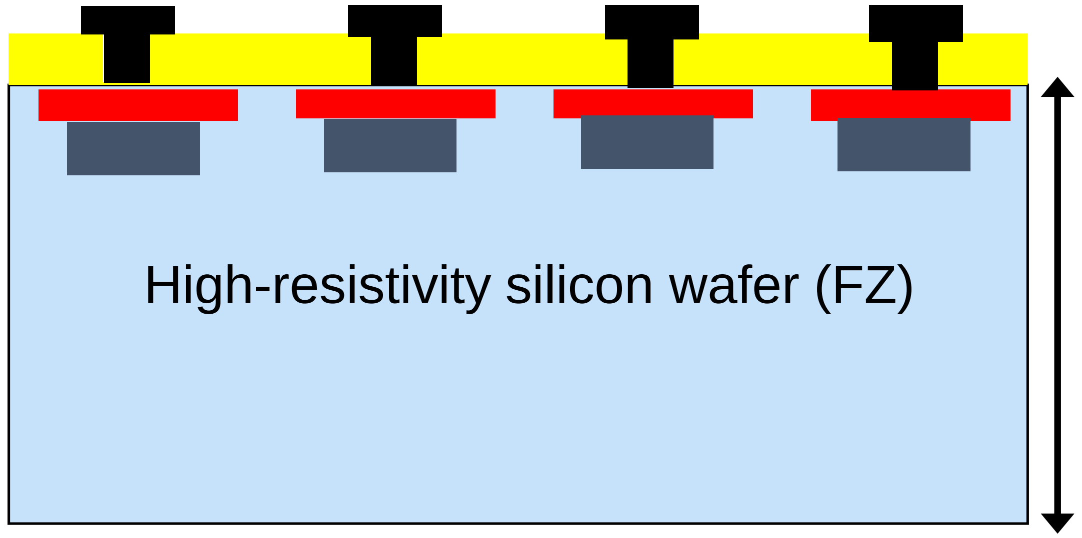


- **Traditional silicon sensors cannot fulfill some of the requirements:**
  - Standard PiN diode sensors (pixels/microstrips): limited timing resolution (~200 ps)
  - APDs: excessive shot noise

- **LGAD detectors:**
  - n^{++}/p junction + a p^{+} enrichment region
  - Low gain (~10) → Reduced excess noise factor
  - Uniform weighting field (large pad area) → homogeneous time response

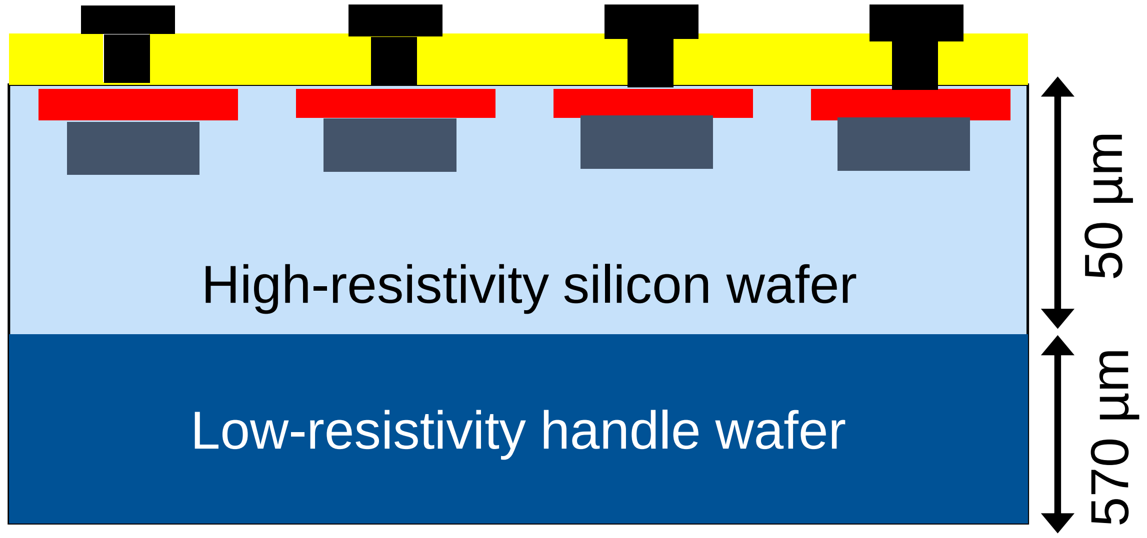
LGAD for Timing

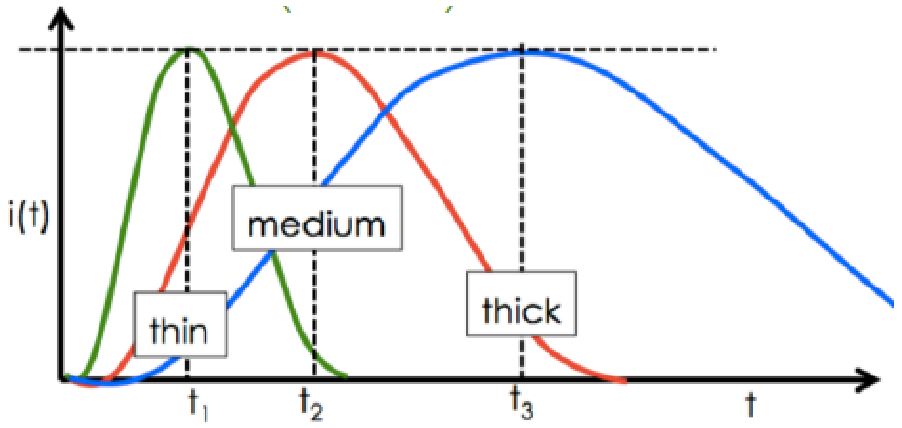
Thick LGAD (2015/2016)



go thin

Thin LGAD (>2016)





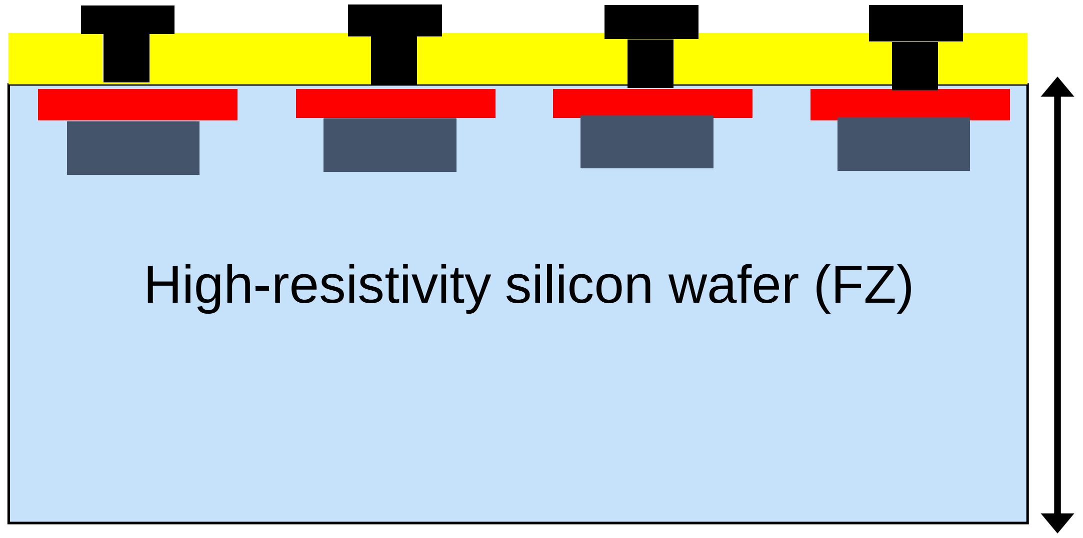
N. Cartiglia

dV/dt ~ $\frac{di_{gain}}{dt} \propto \boxed{\frac{G}{d}}$

- Reduced thickness (50 µm) → Increase slew rate of the signal
- Uniform weighting field (large pad area) → homogeneous time response
- Saturated drift velocity (Efield > 30 kV·cm-1) → Reduce jitter

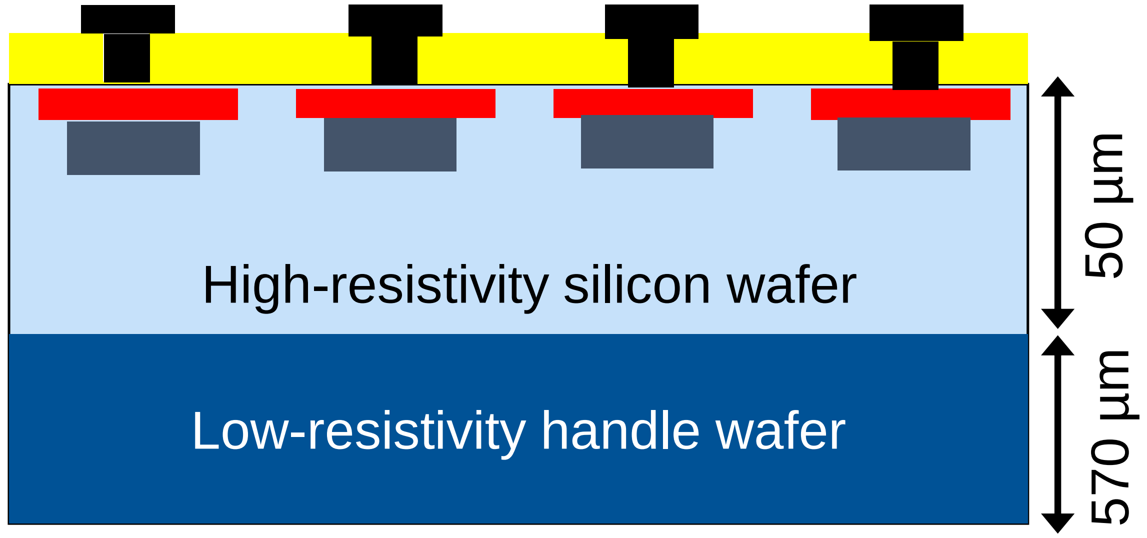
LGAD for Timing

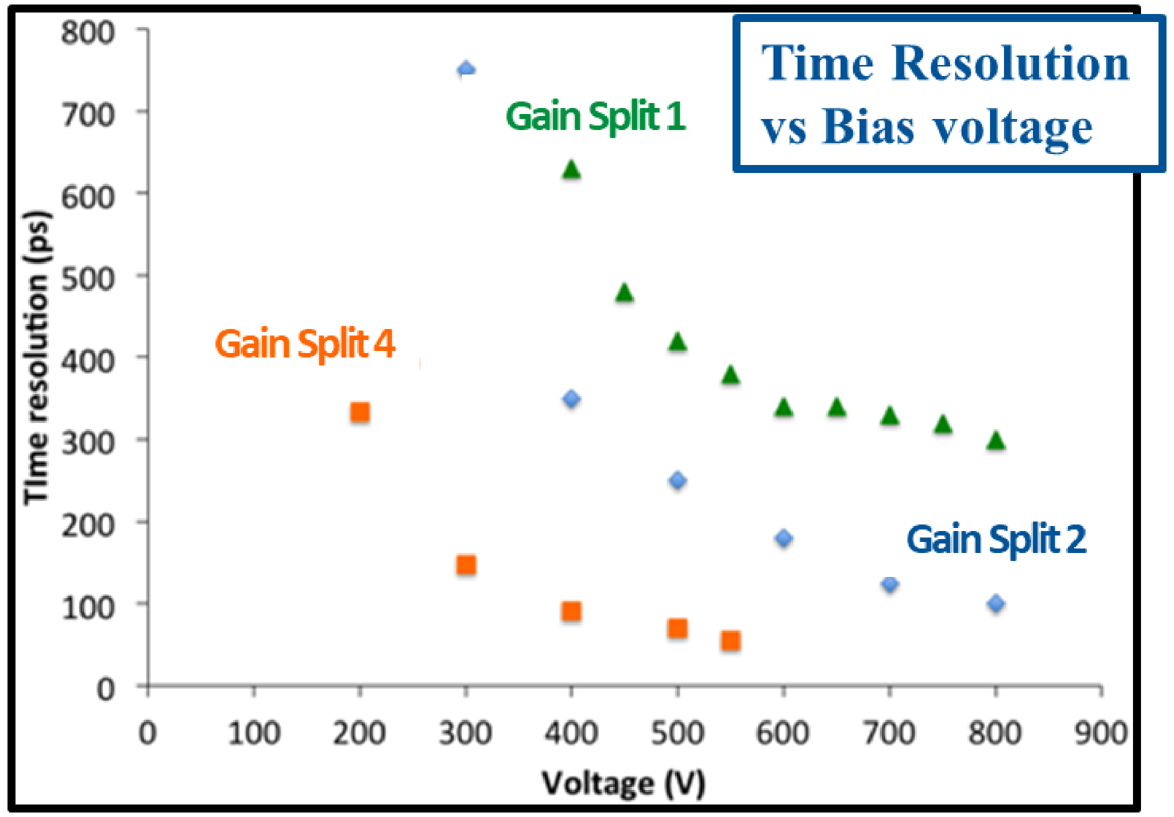
Thick LGAD (2015/2016)



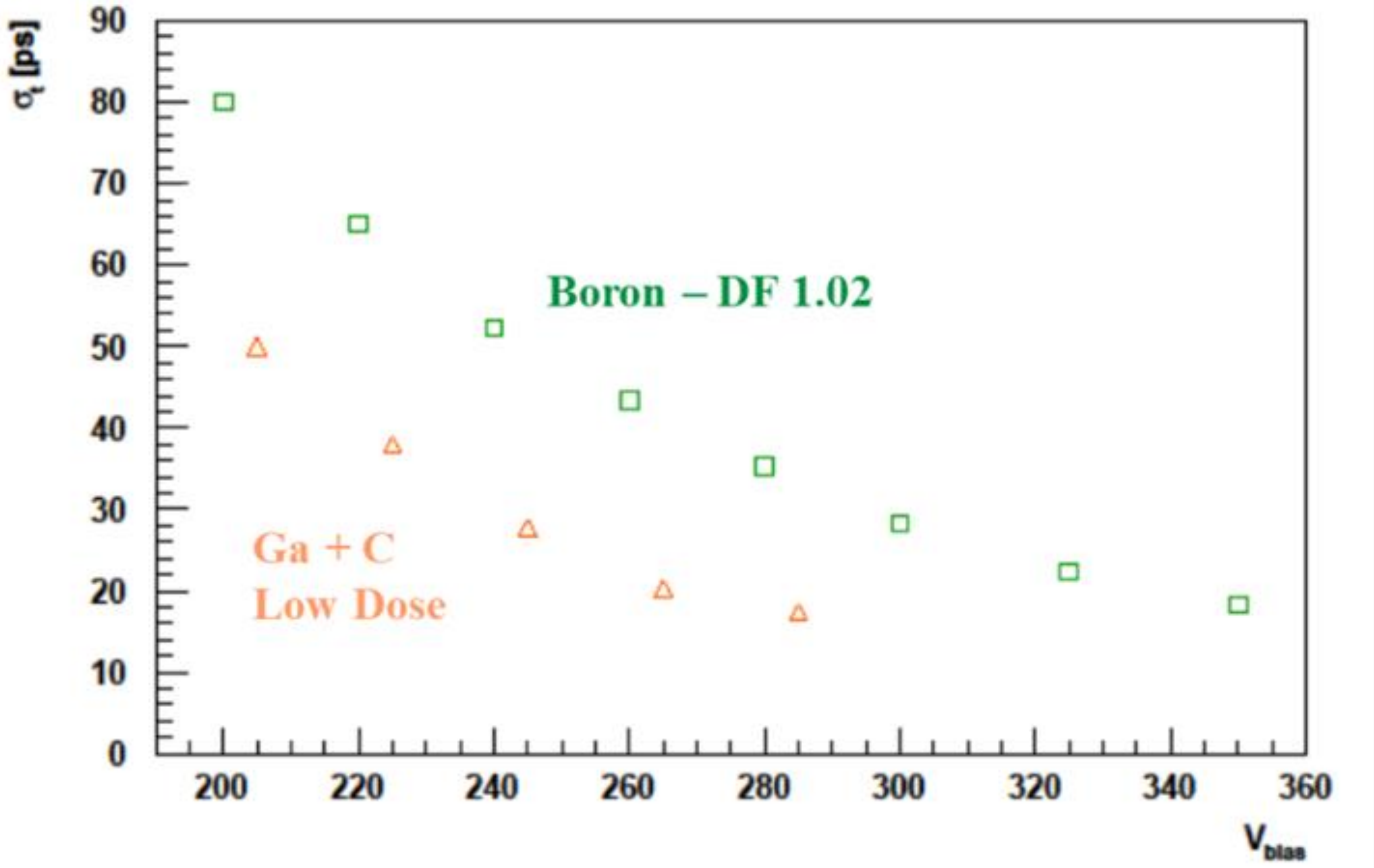
go thin

Thin LGAD (>2016)



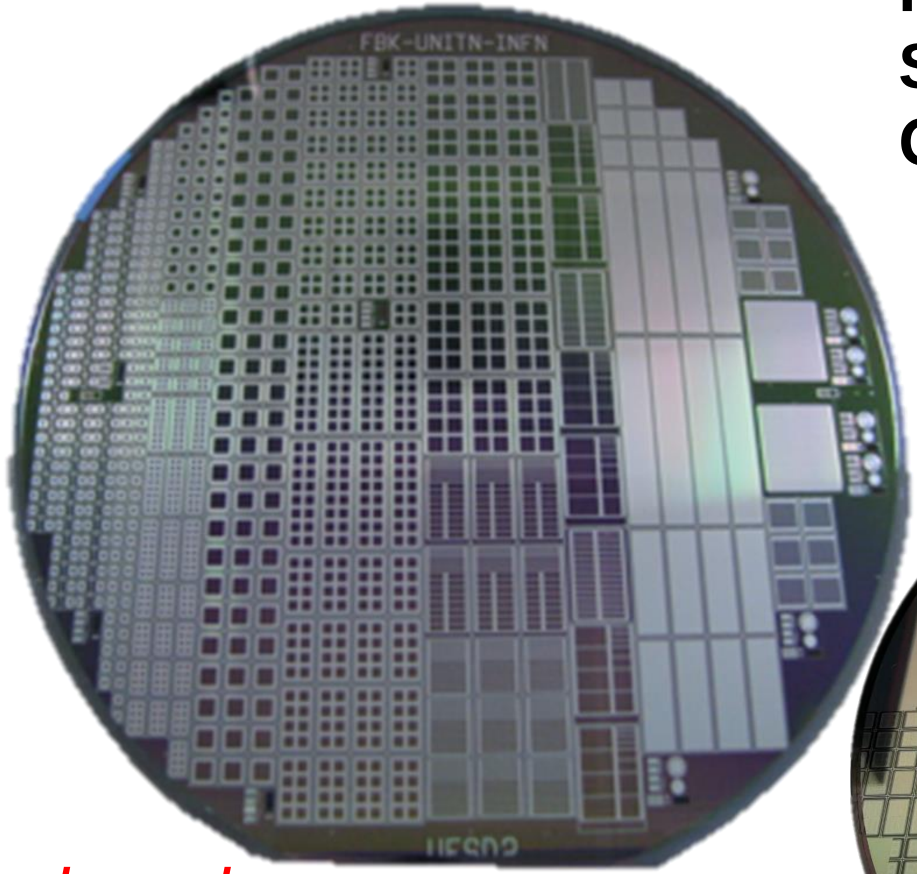


Time jitter
(not-irradiated)



LGAD Fabrication Technology

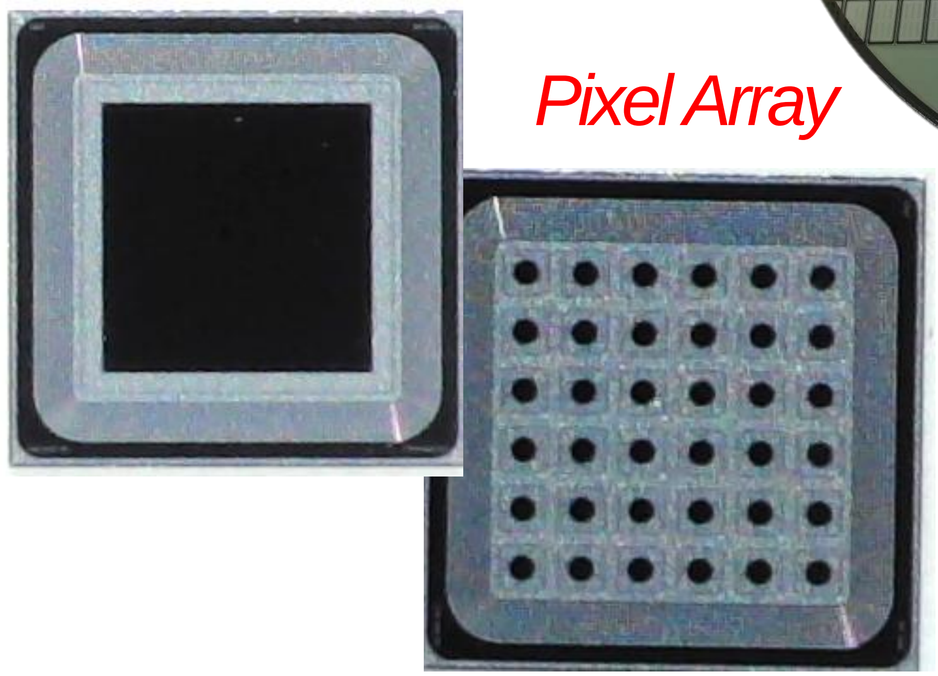
- Fabricated on 6 inches Wafers
- Custom CMOS-like Technology
- Fabricated in the FBK internal facility (ISO 9001:2015 certified)

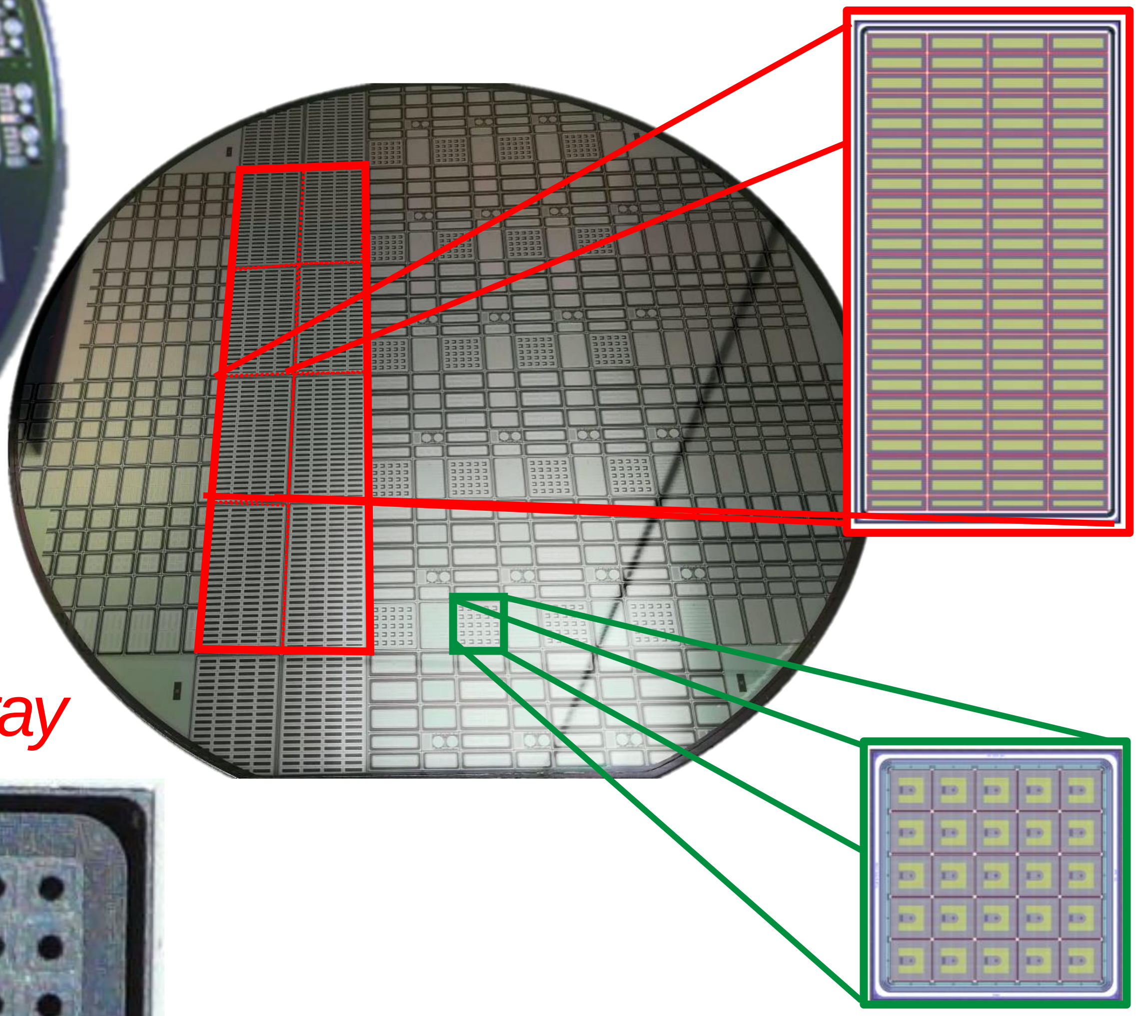


Single pads,
Pad arrays;
Strips;
Other pixelated detectors….

Single pad

Pixel Array





CMS ROC

Pad: 3 x 1 mm^2
Array 4 x 24 pads
Array Size: 13.2x25.0 mm^2

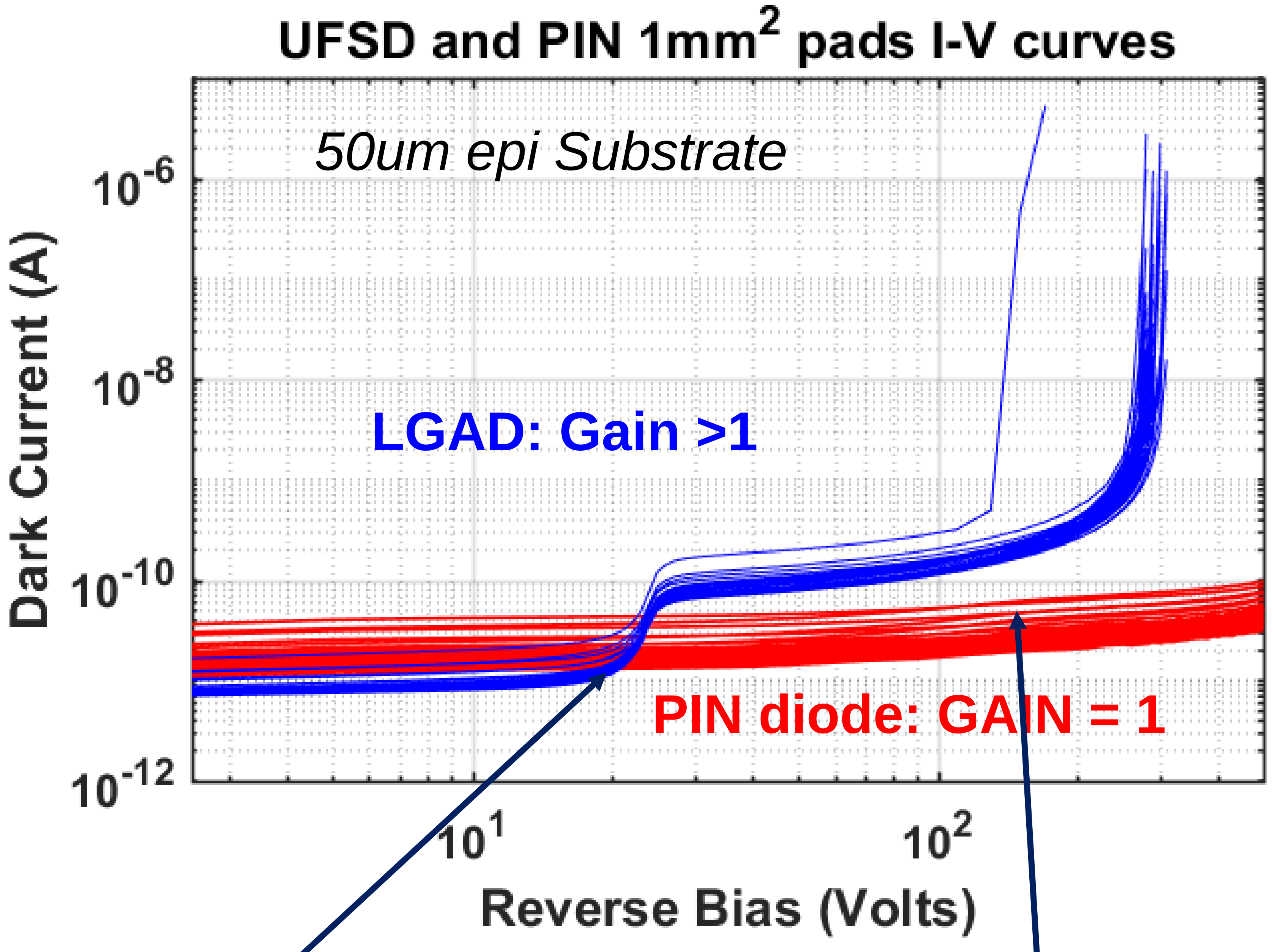
8 full arrays per Wafer

ATLAS ALTIROC

Pad: 1.3 x 1.3 mm^2
Array 5 x 5 pads
Array Size: 8.0x8.0 mm^2

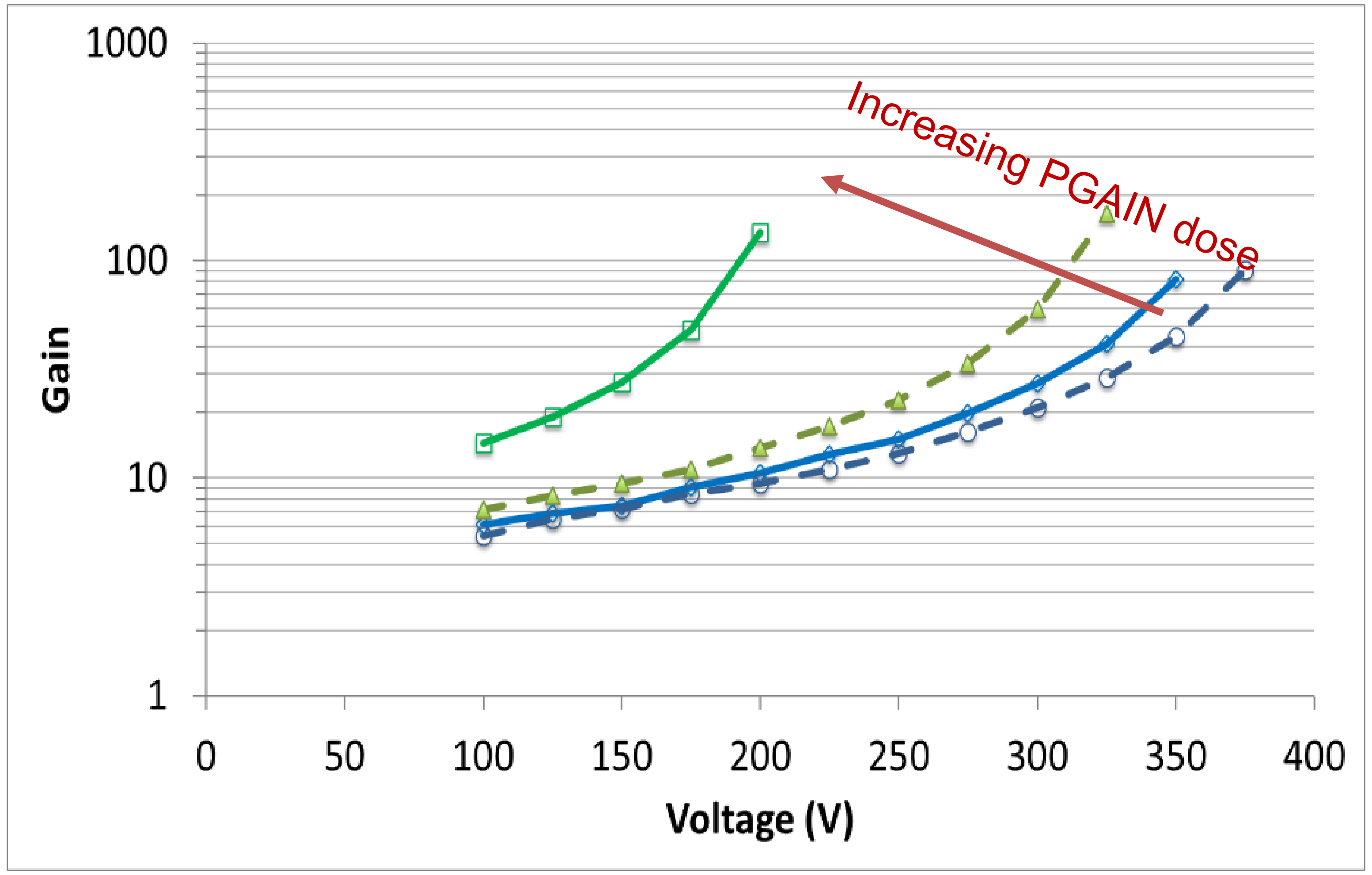
20 full arrays per Wafer

LGAD Fabrication Technology



gain layer
depletion Voltage

The Gain increases with the
Voltage up to the Breakdown



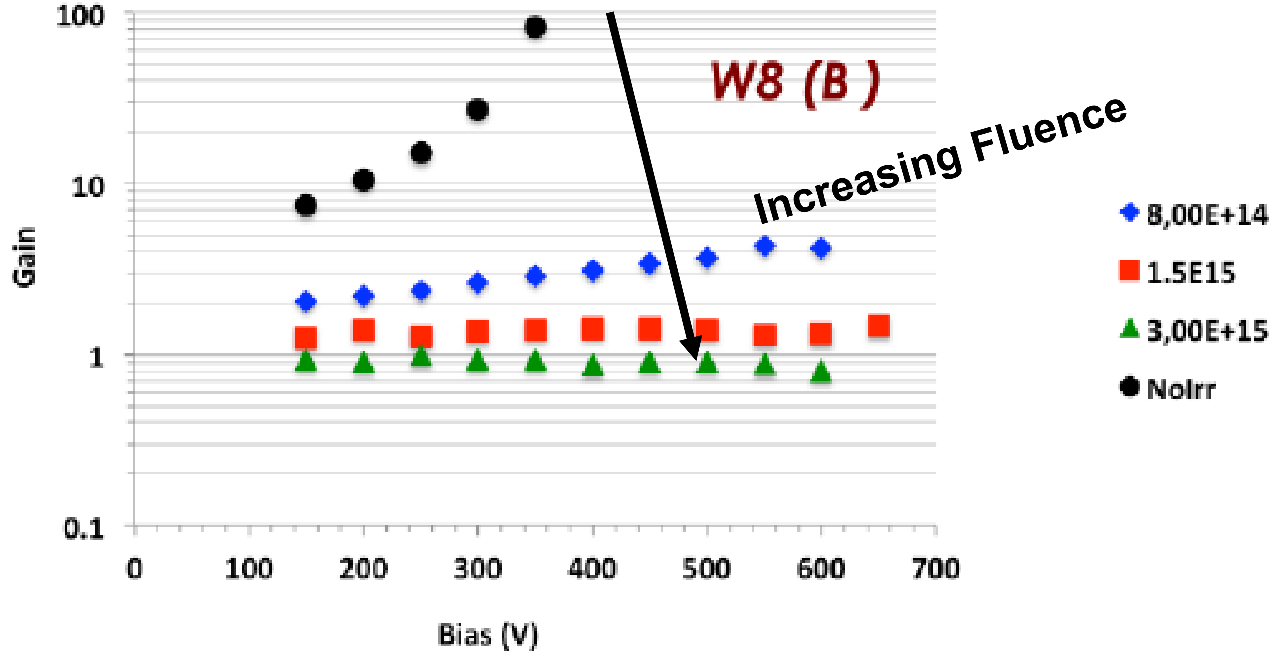
- The Detector Gain depends on:
  - implantation dose of the Gain layer
  - Bias Voltage
- Samples with higher dose have higher gain at lower Voltage

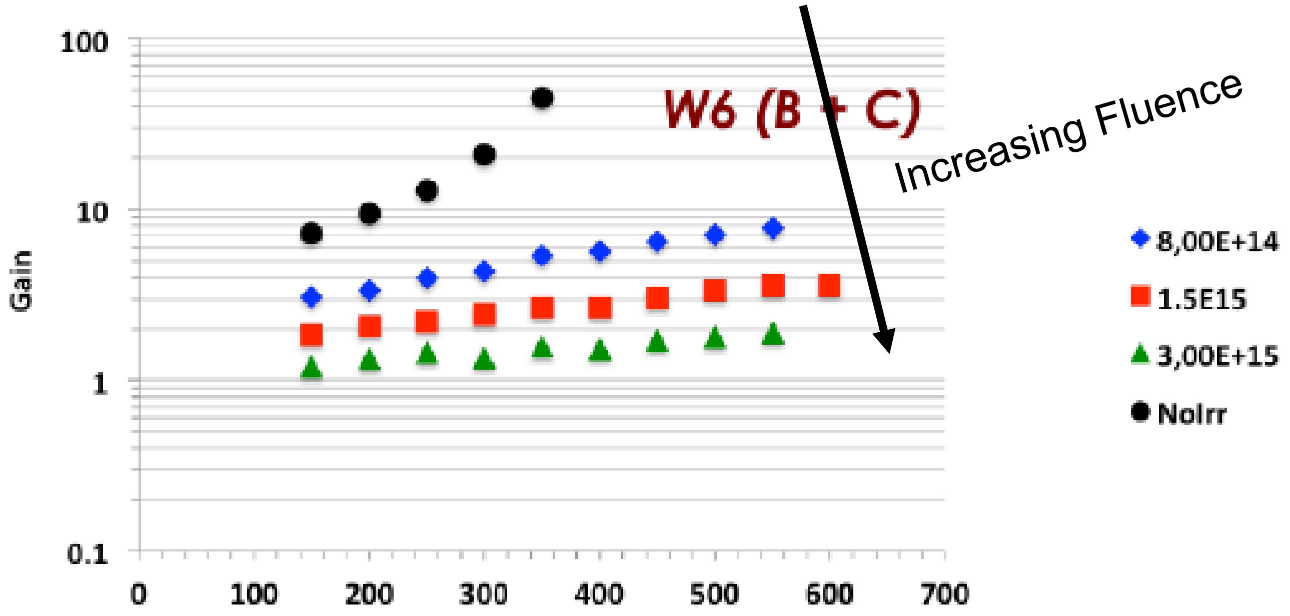
LGAD – Radiation hardness

Problem: Radiation level de-activate the dopant of the gain layer, reducing the effective gain after irradiation **(Initial Acceptor Removal Effect)** [M. Moll, Vertex 2019]

[R. Arcidiacono TREDI2018]

Gain = Q(LGAD) / Q(PiN)





- After irradiation the Gain of LGADs id reduced
- Gain is completely lost after 1e15 neq/cm^2
- It is possible to partially compensate the gain-loss by increasing the bias voltage

- We demonstrated that the inclusion of some chemical impurities (like Carbon) in the silicon lattice is effective in mitigating this effect

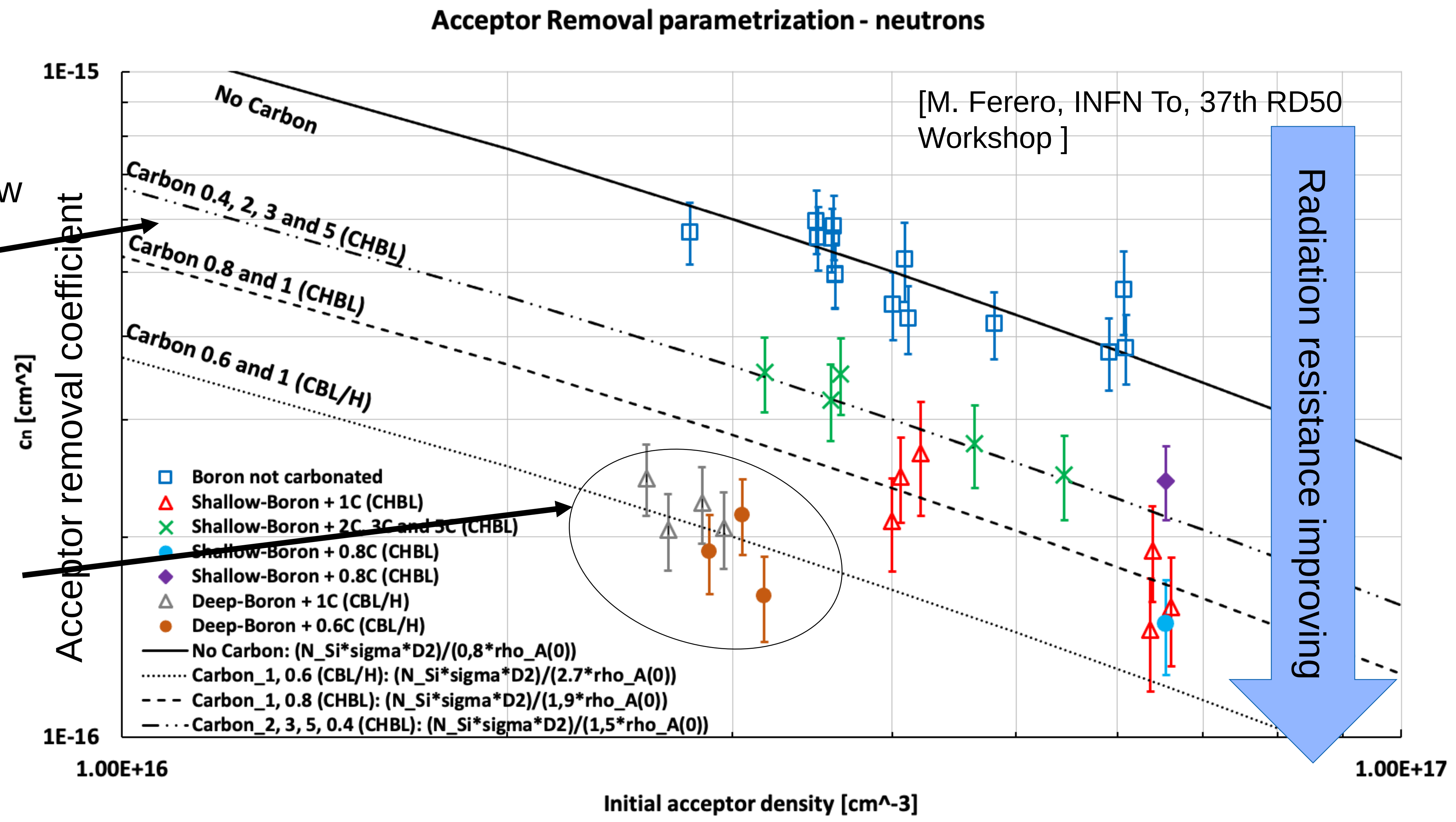
LGAD – Radiation hardness

Acceptor removal parametrization (M. Ferrero and N. Cartiglia)

$$\frac{N_B(\emptyset)}{N_B(0)} = e^{-c\emptyset} \qquad c(N_B) = \frac{N_{Si} * \sigma_{Si} * D_2}{k_{param.} * N_B(0)}$$

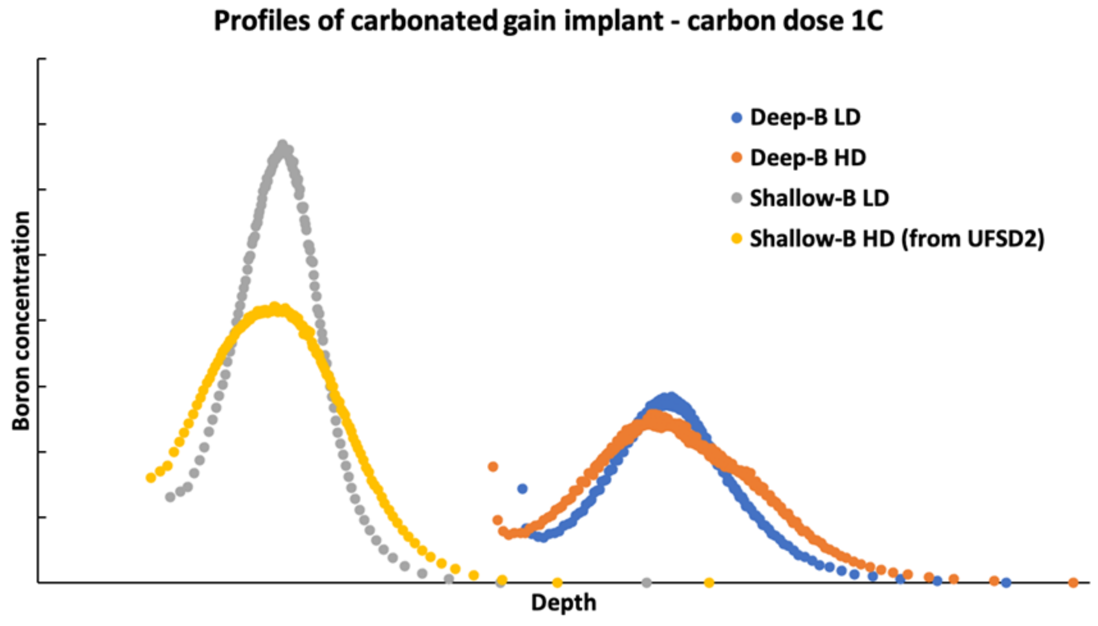
Too high or too low Carbon dose

Optimal carbon dose with low thermal diffusion

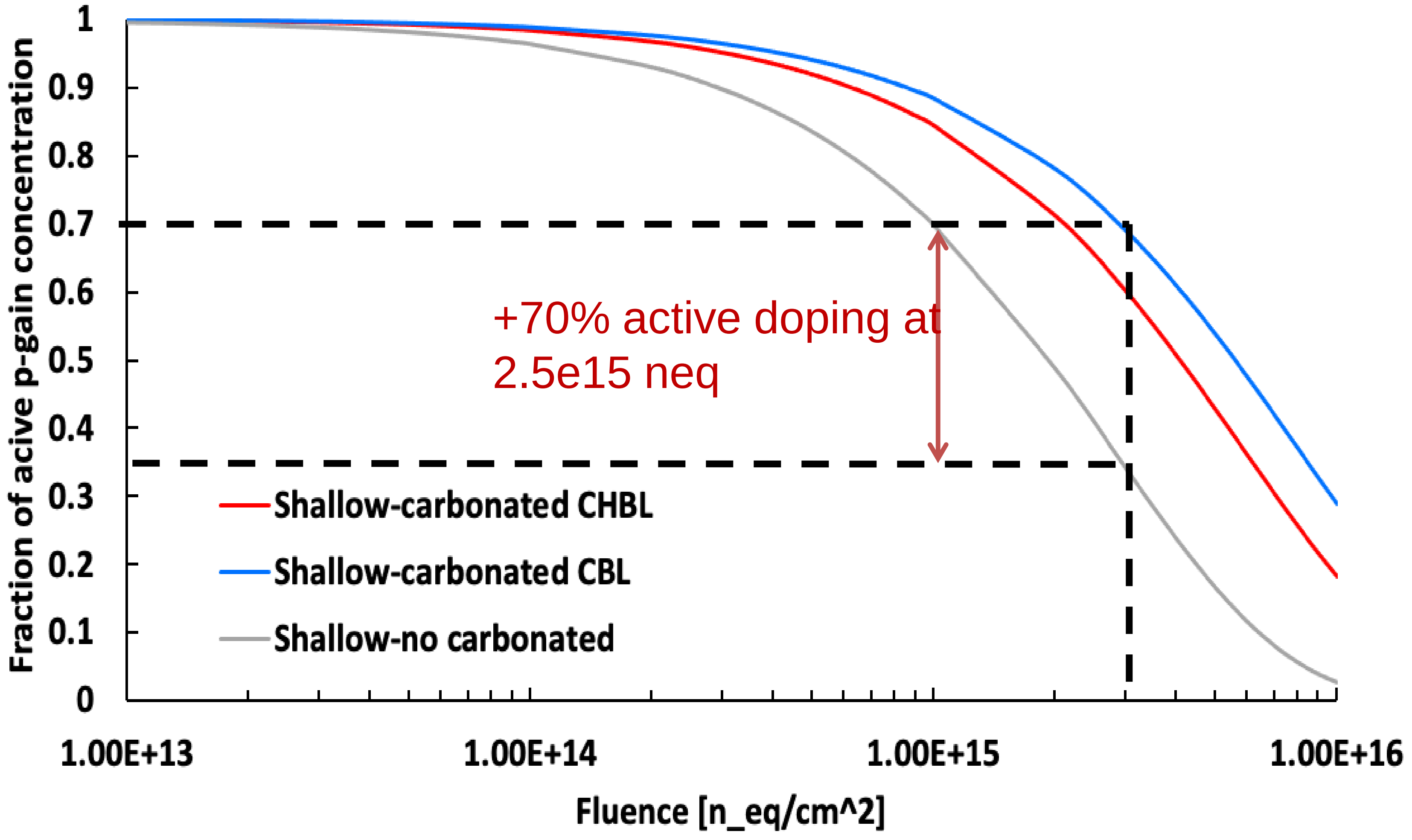


Carbon co-implantation Optimization

- Carbon Dose
- Boron Implantation (PGAIN) Depth
- Boron/Carbon Activation and Diffusion
- Boron Profile and peak concentration

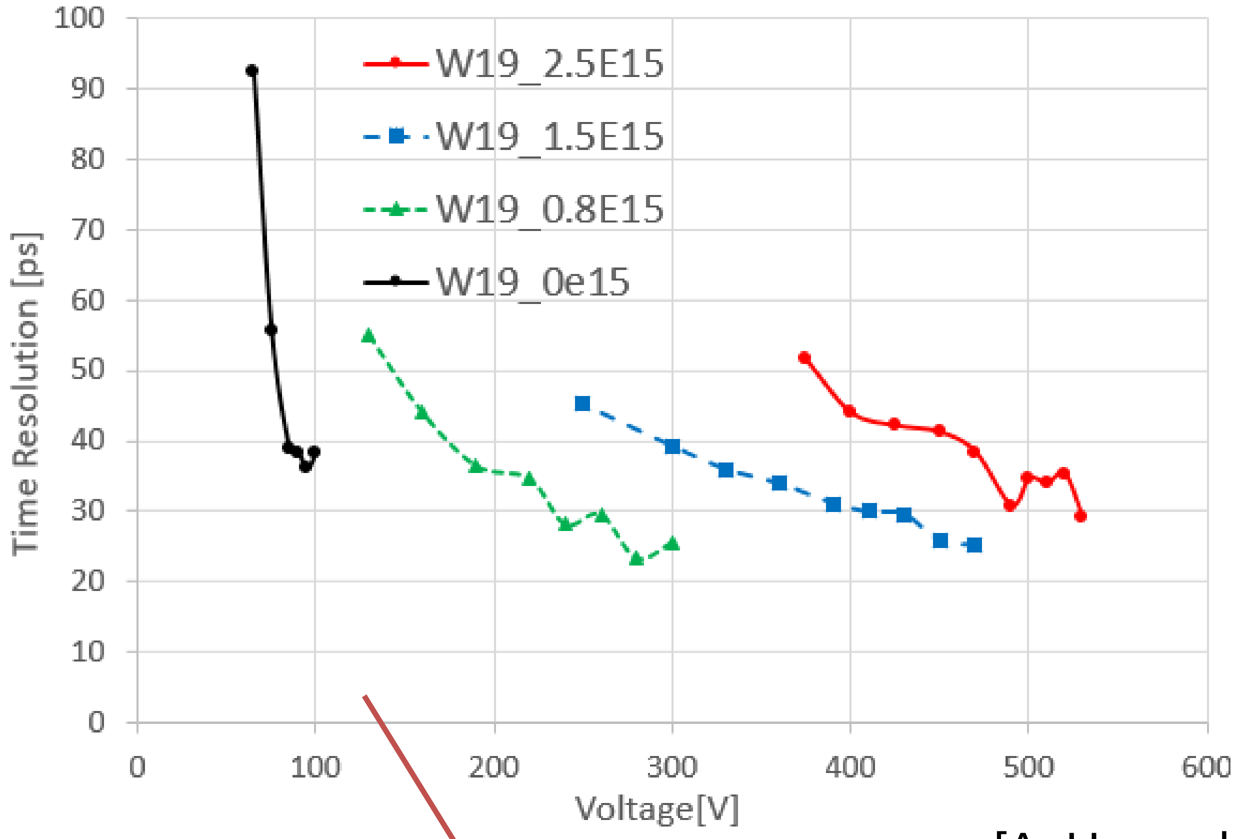


LGAD – Radiation hardness

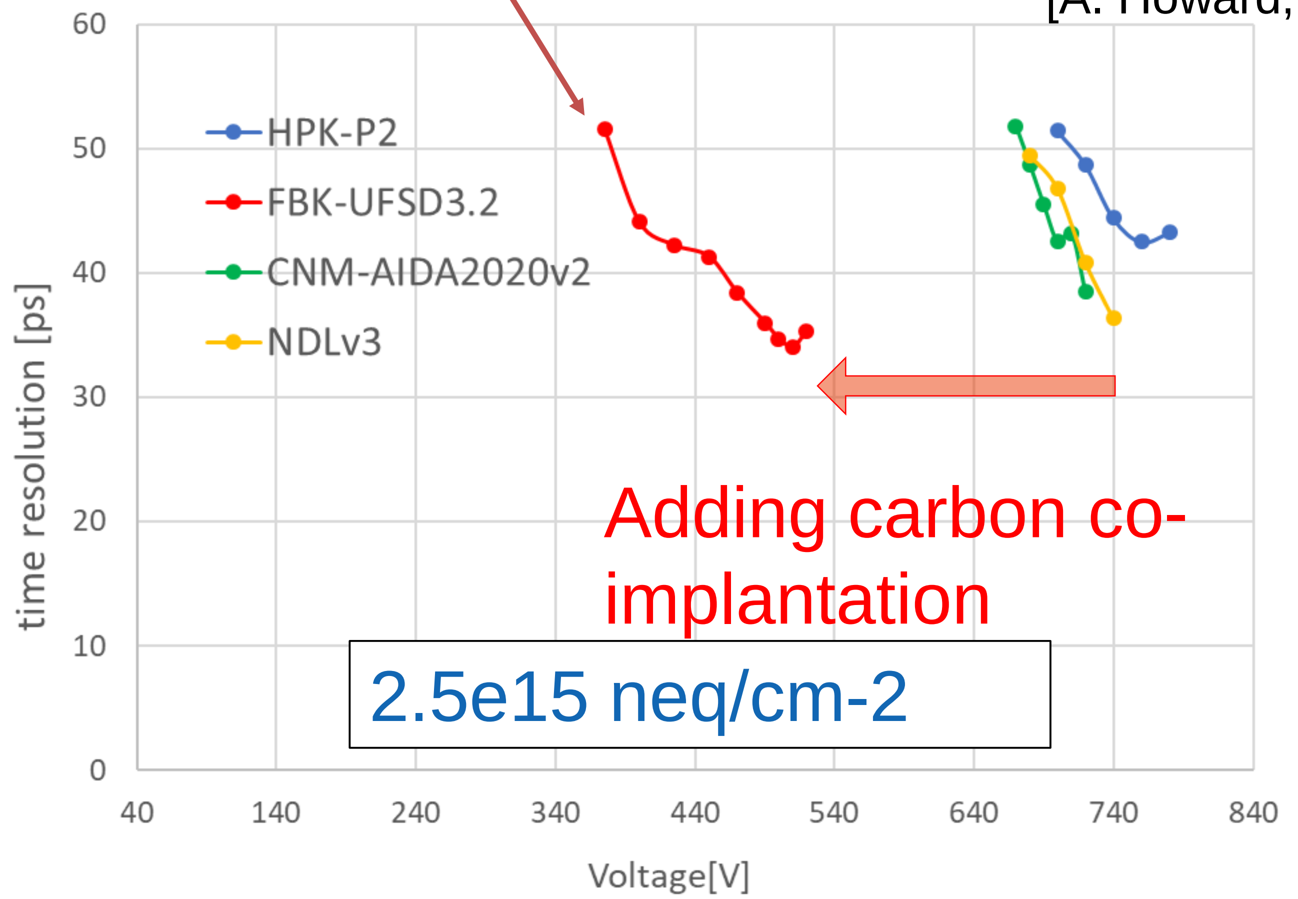


+70% active doping at 2.5e15 neq

- Carbon co-implantation allows to reach an exceptional time resolution (~ 30 ps) after irradiation (2.5e15 cm-2 neq) using about 300 Volts less wrt not carbonated samples.



[A. Howard, 37th RD50 Workshop]



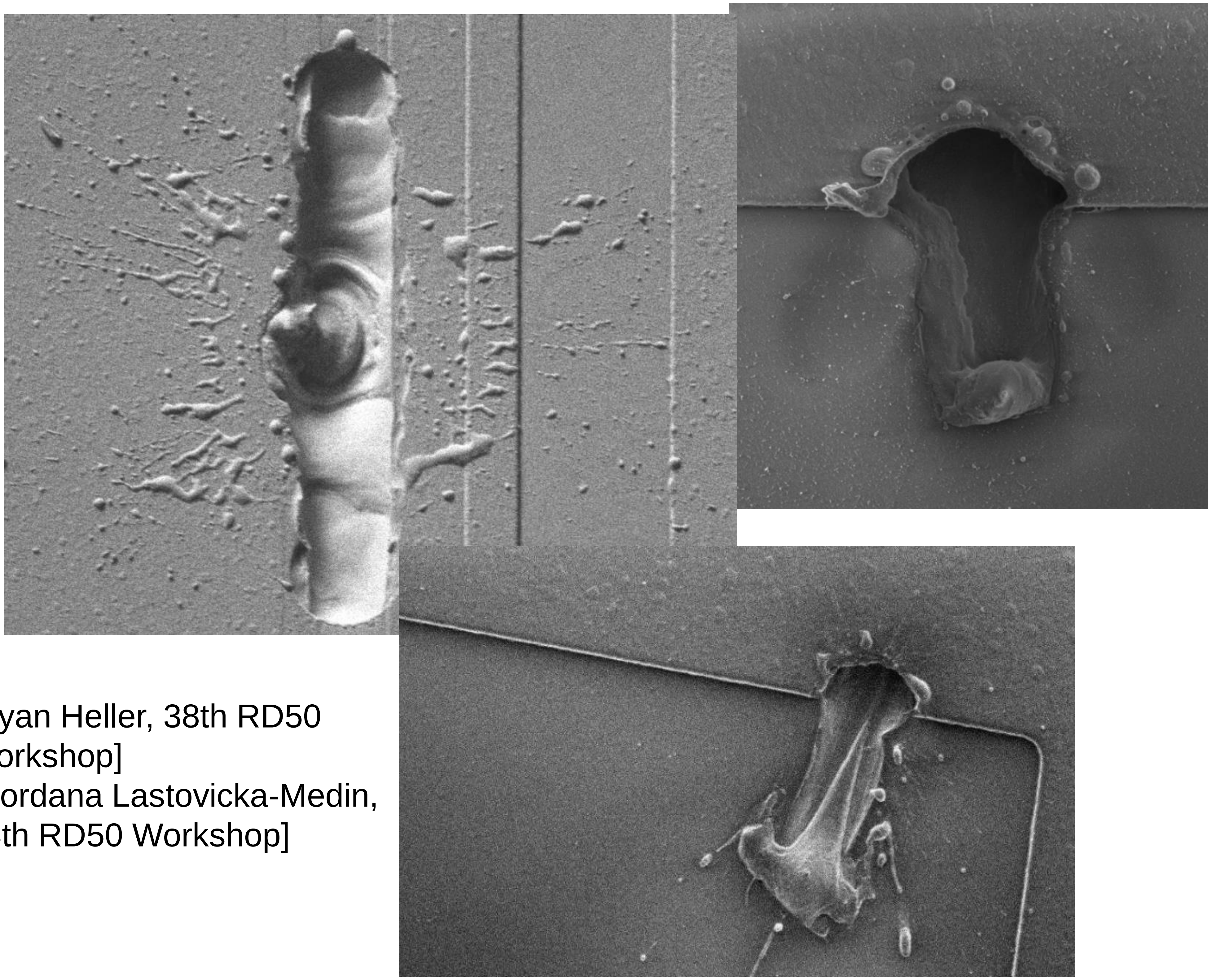
Adding carbon co-implantation

2.5e15 neq/cm-2

LGAD – Radiation hardness

LGAD Mortality during Test Beam

- There is an evidence for death of highly irradiated LGADs at test beam
- Probably due to a rare, large ionization events producing large current in narrow path
- Mortality is function of sensor thickness and voltage only (Gain is not necessary for death mechanism)
- Fatal voltage: > 600V for 50 um Sensors
- Carbon co-implantation (lower operative bias) or using thicker substrates reduce the sensor mortality

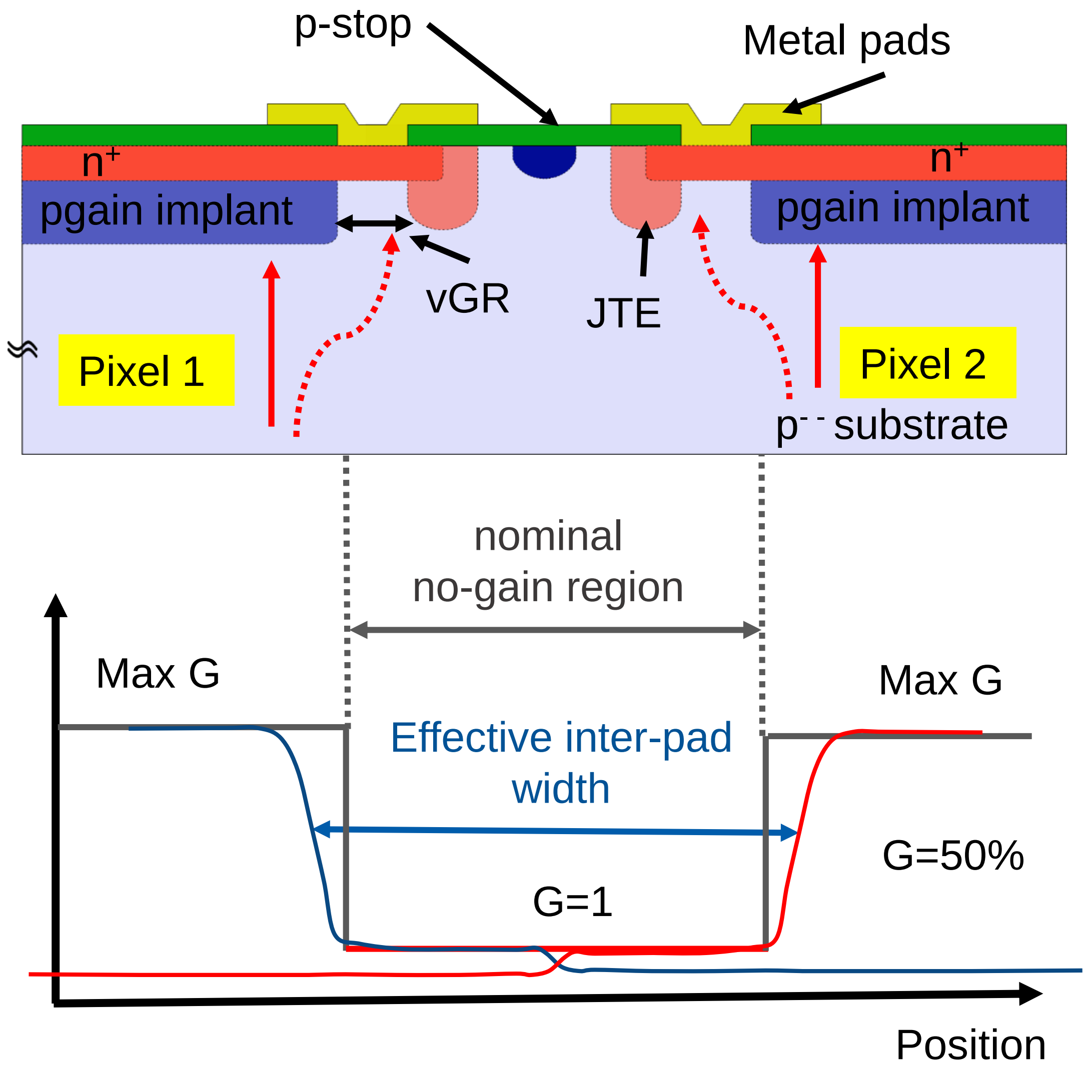


[Ryan Heller, 38th RD50 Workshop]
[Gordana Lastovicka-Medin, 38th RD50 Workshop]

FONDAZIONE BRUNO KESSLER SENSORS AND DEVICES

LGAD – Fine segmentation (TI-LGAD)

Segmented Standard LGAD

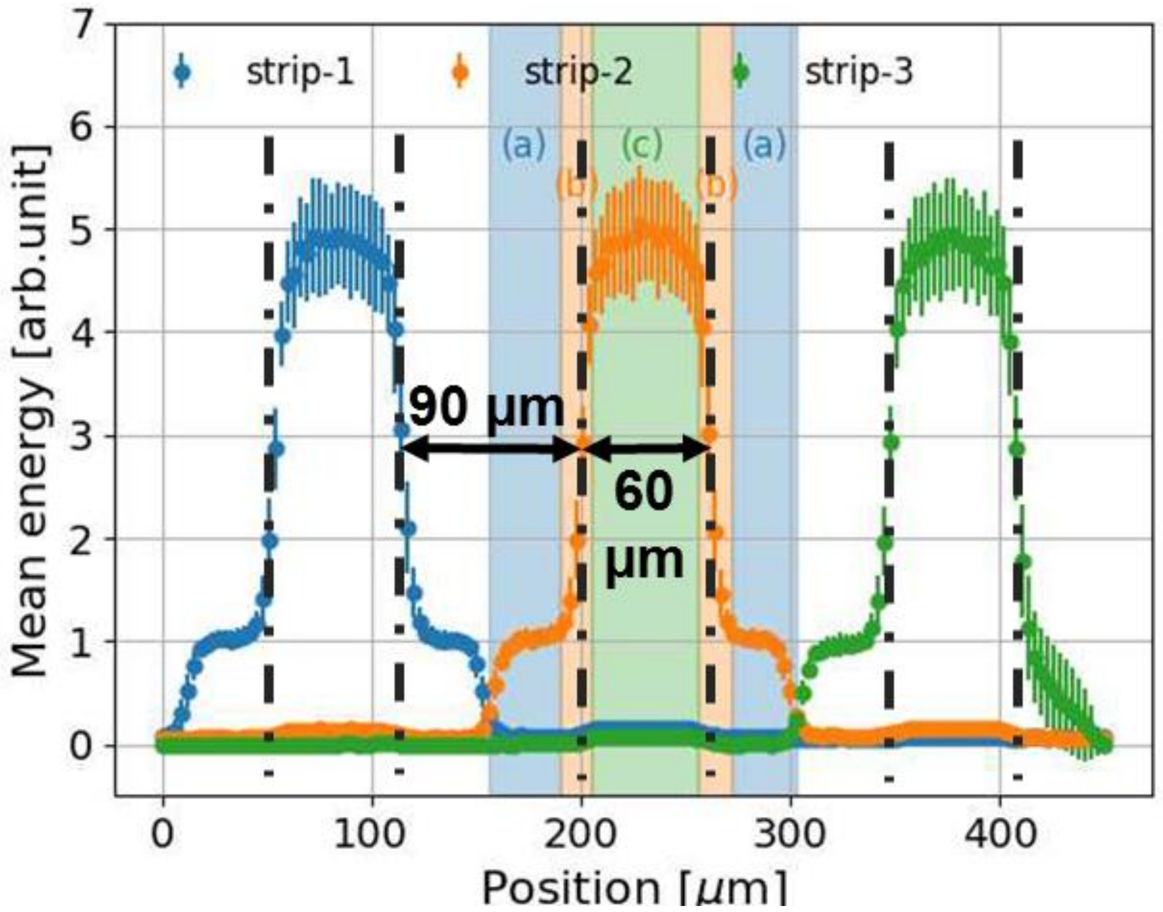


LGADs pixels have limited Fill Factor

- No-gain region at the pixel border due to isolation and termination structures:
  - Dimensions defined by technological and physical constraint
  - Dead distance for charge multiplication ~ 40- 80 µm

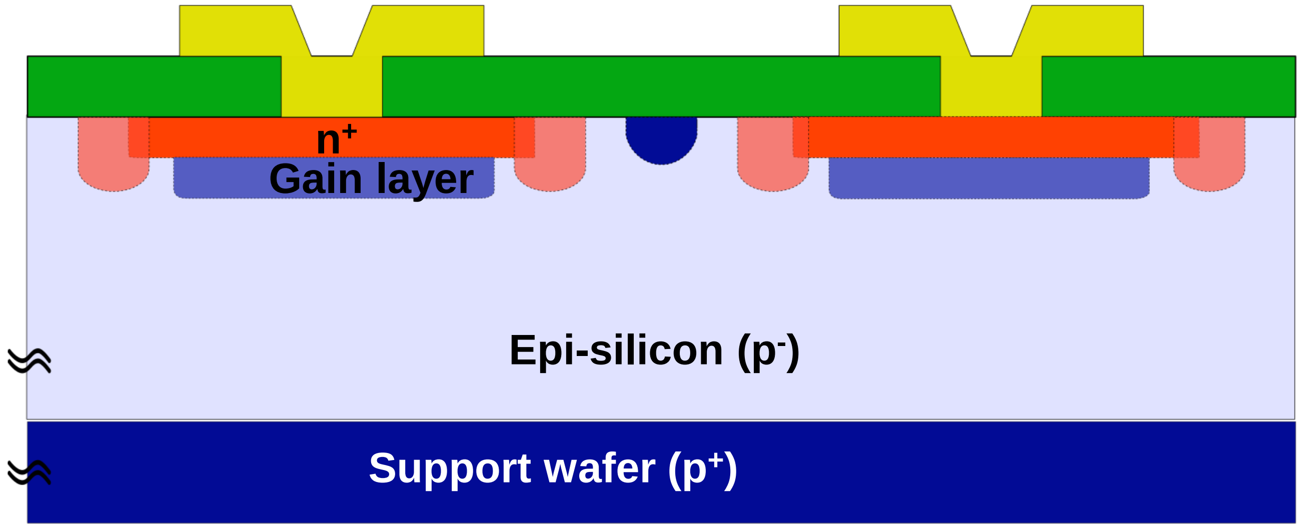
Experimental measurement of LGAD fill-factor using a micro-focused x-ray beam (3 µm, 20 keV) at Swiss Light Source at PSI [5]:

- LGAD micro-strip (146 µm pitch, older UFSD technology)
- Spectrum mean energy as a function of beam position crossing 3 strips
- Nominal FF: 80 µm (55%)
- Measured FF: ~60 µm (40%)

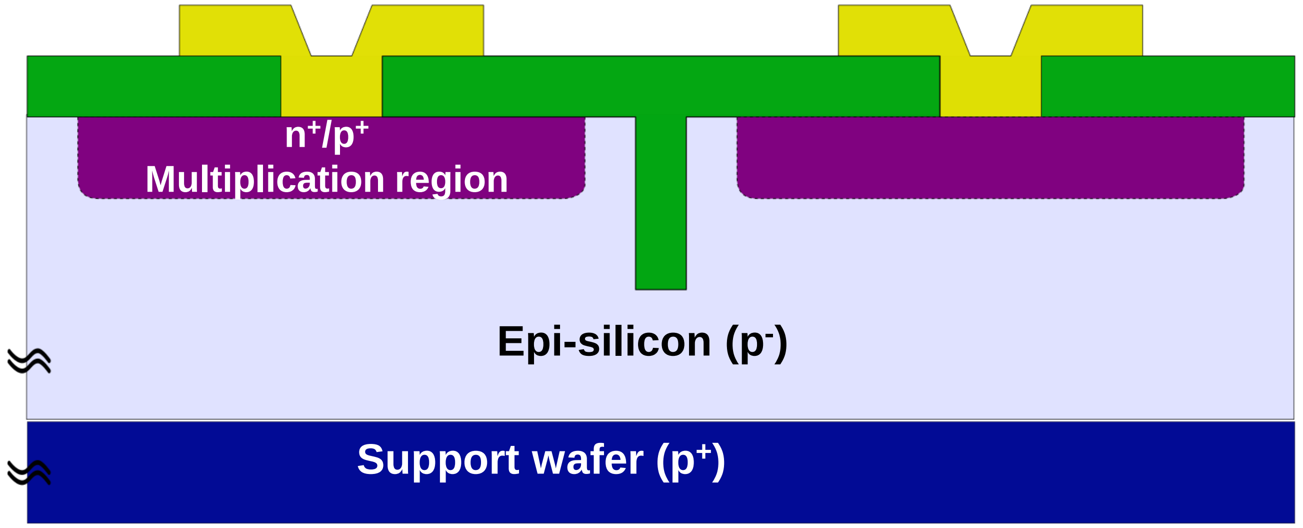


LGAD – Fine segmentation (TI-LGAD)

Segmented Standard LGAD

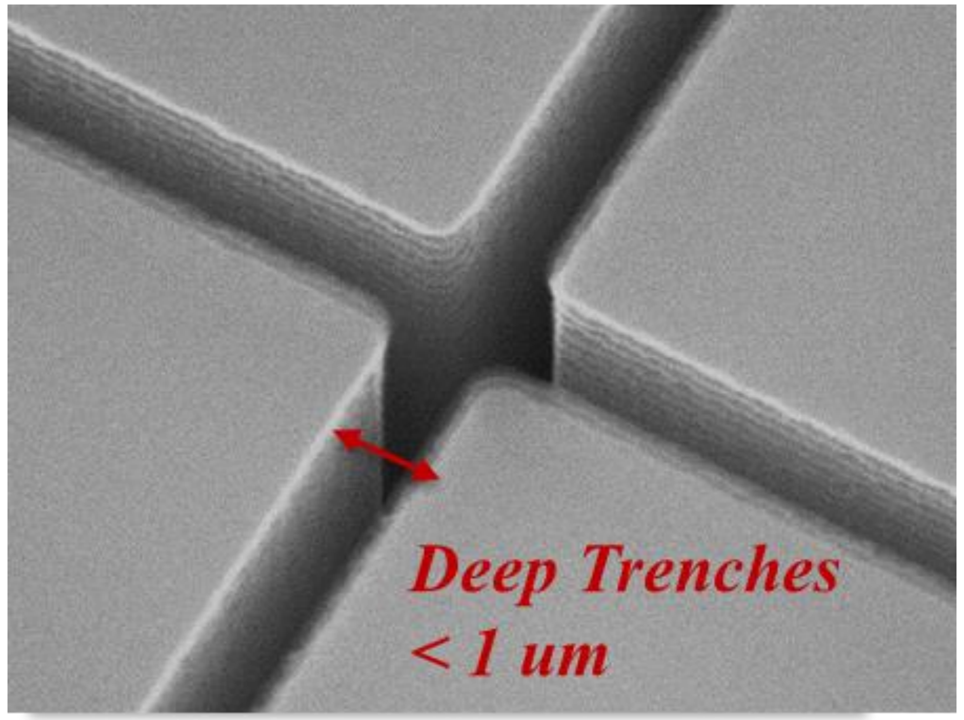


Trench-Isolated LGAD



New **TI-LGAD** technology proposed by FBK:

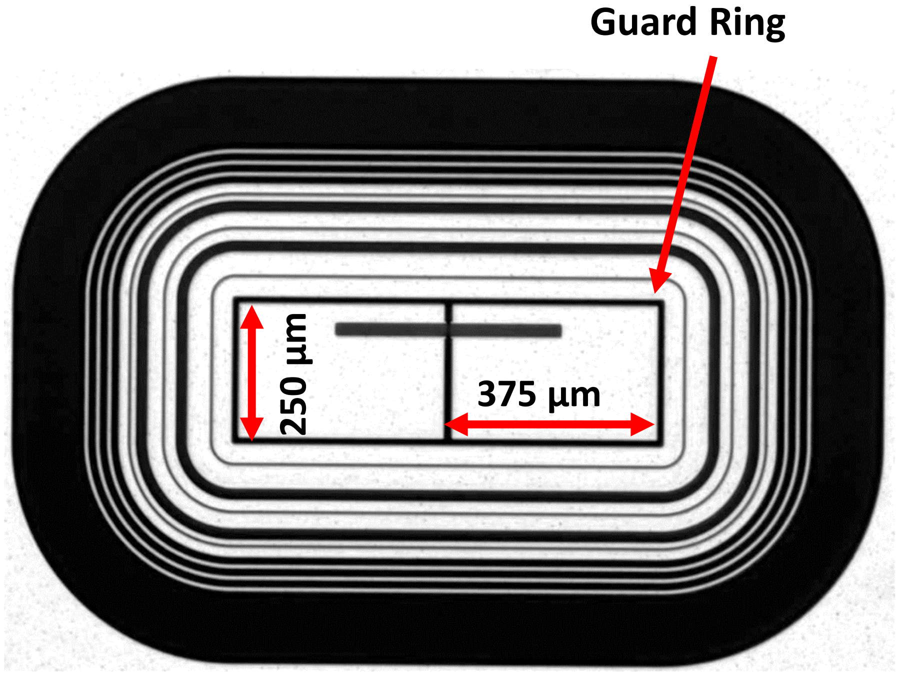
- **JTE and p-stop are replaced by a single trench.**
- Trenches act as a drift/diffusion barrier for electrons and isolate the pixels.



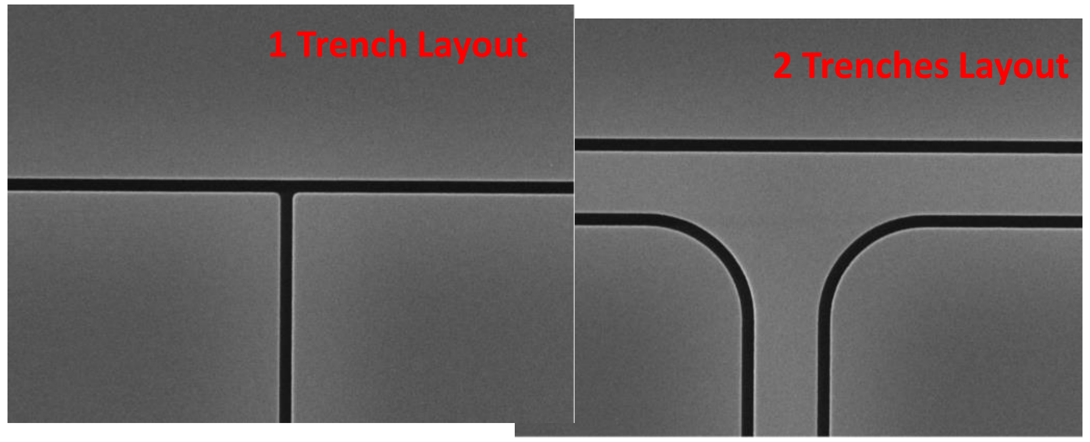
- The trenches are a few microns deep and < 1um wide.
- Filled with Silicon Oxide
- The fabrication process of trenches is compatible with the standard LGAD process flow.

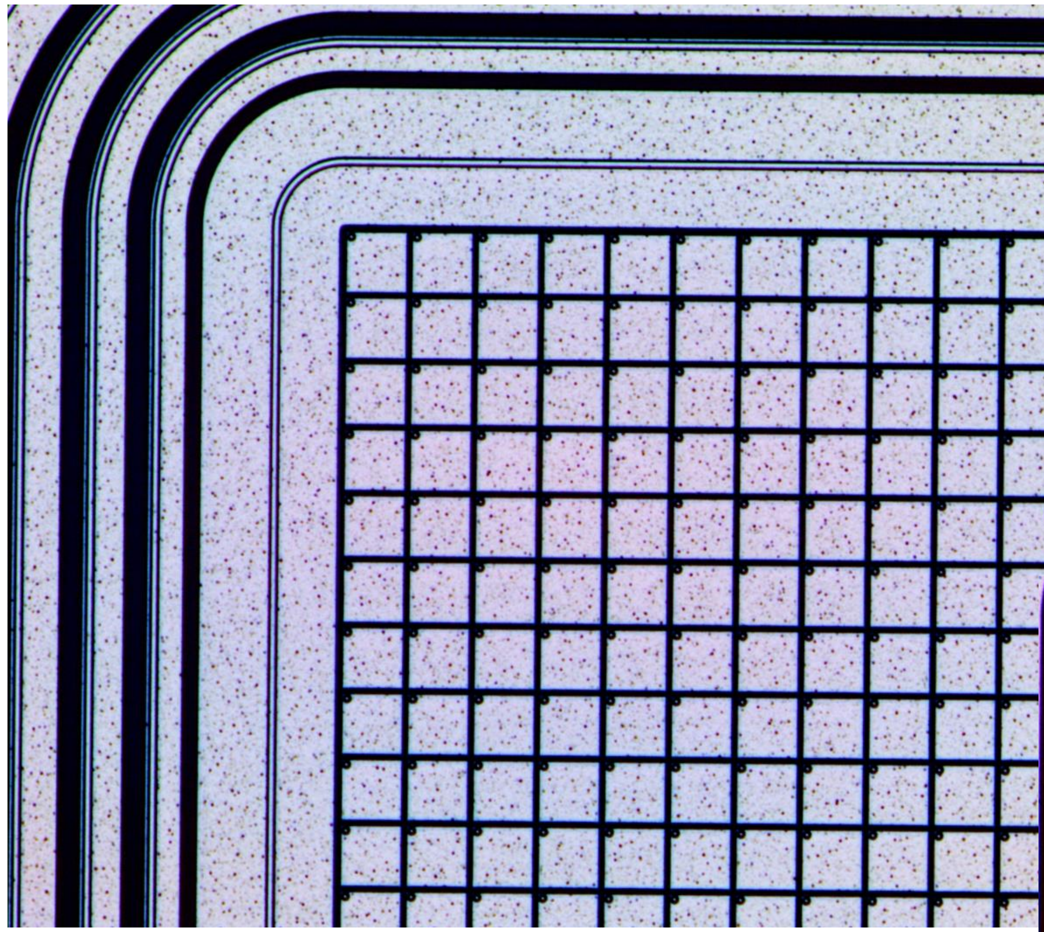
LGAD – Fine segmentation (TI-LGAD)

New RD50 Batch



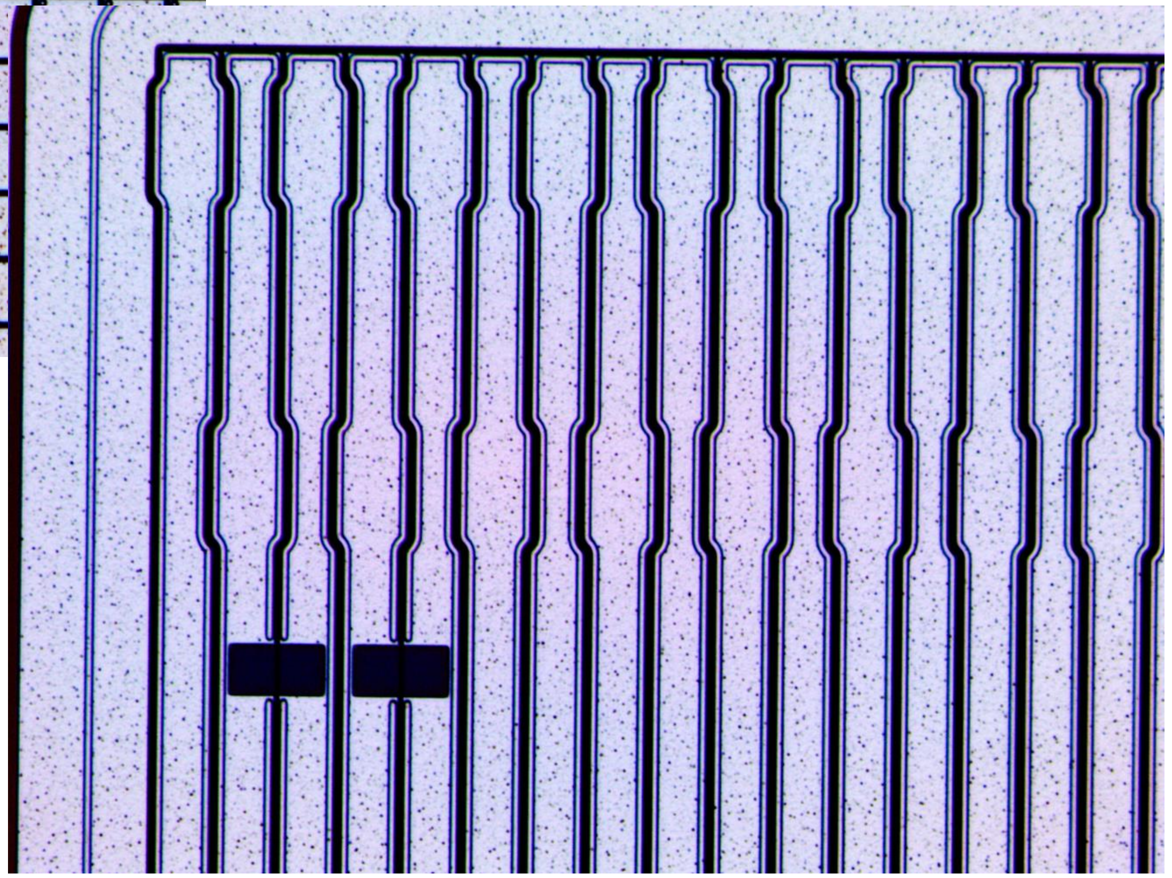
SEM images after trench etching





55um Pixels

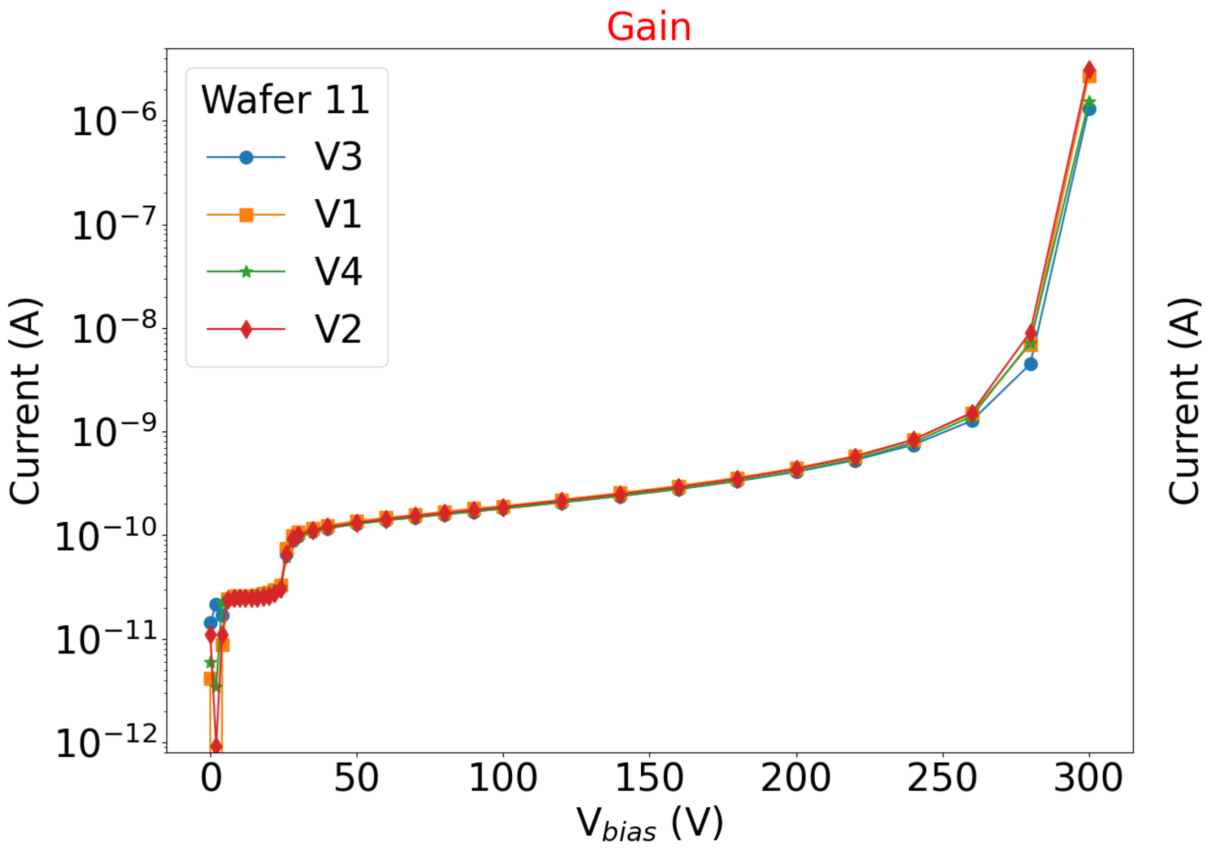
50-100 um strips

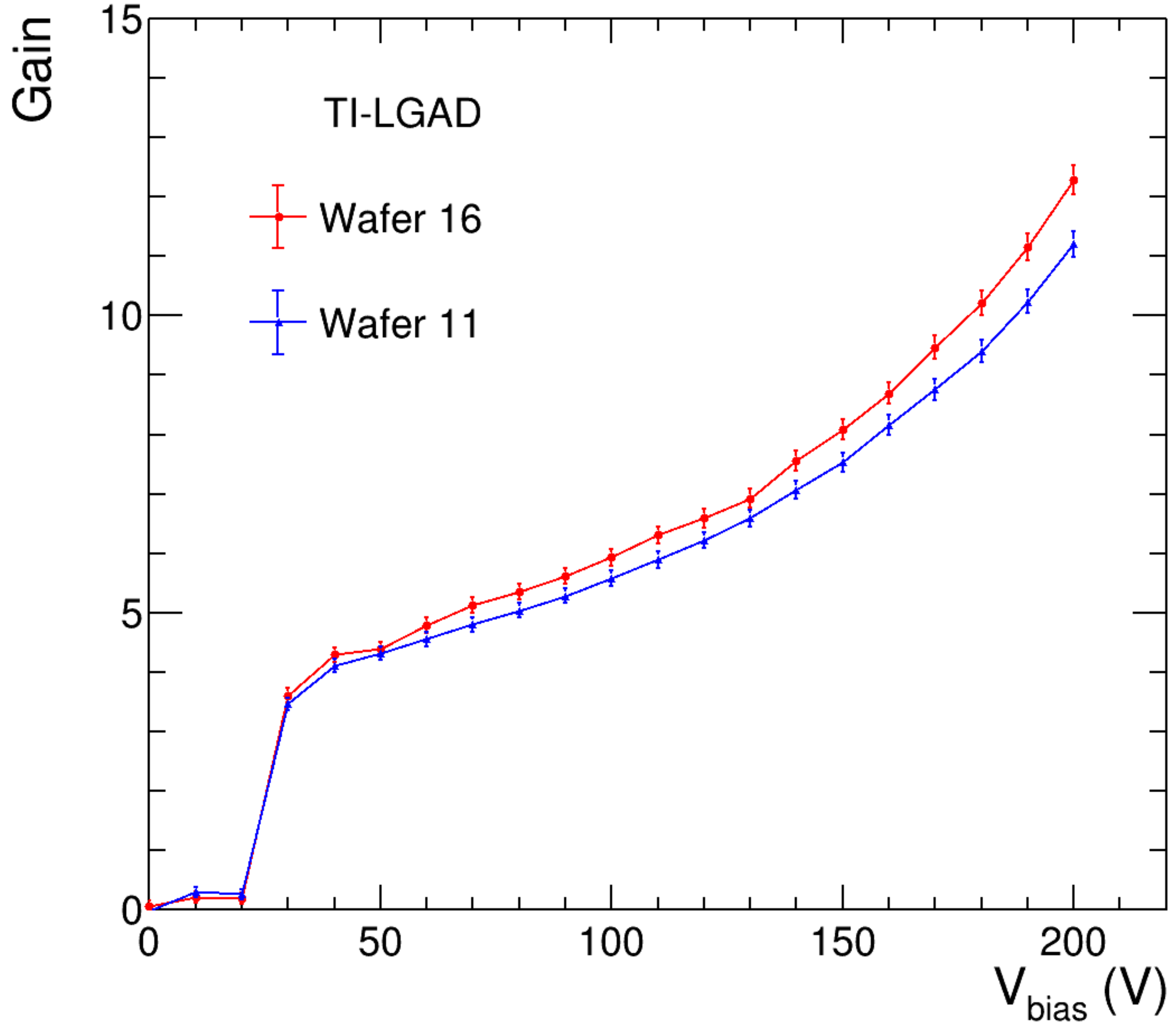


Nominal FF > 80%

LGAD – Fine segmentation (TI-LGAD)

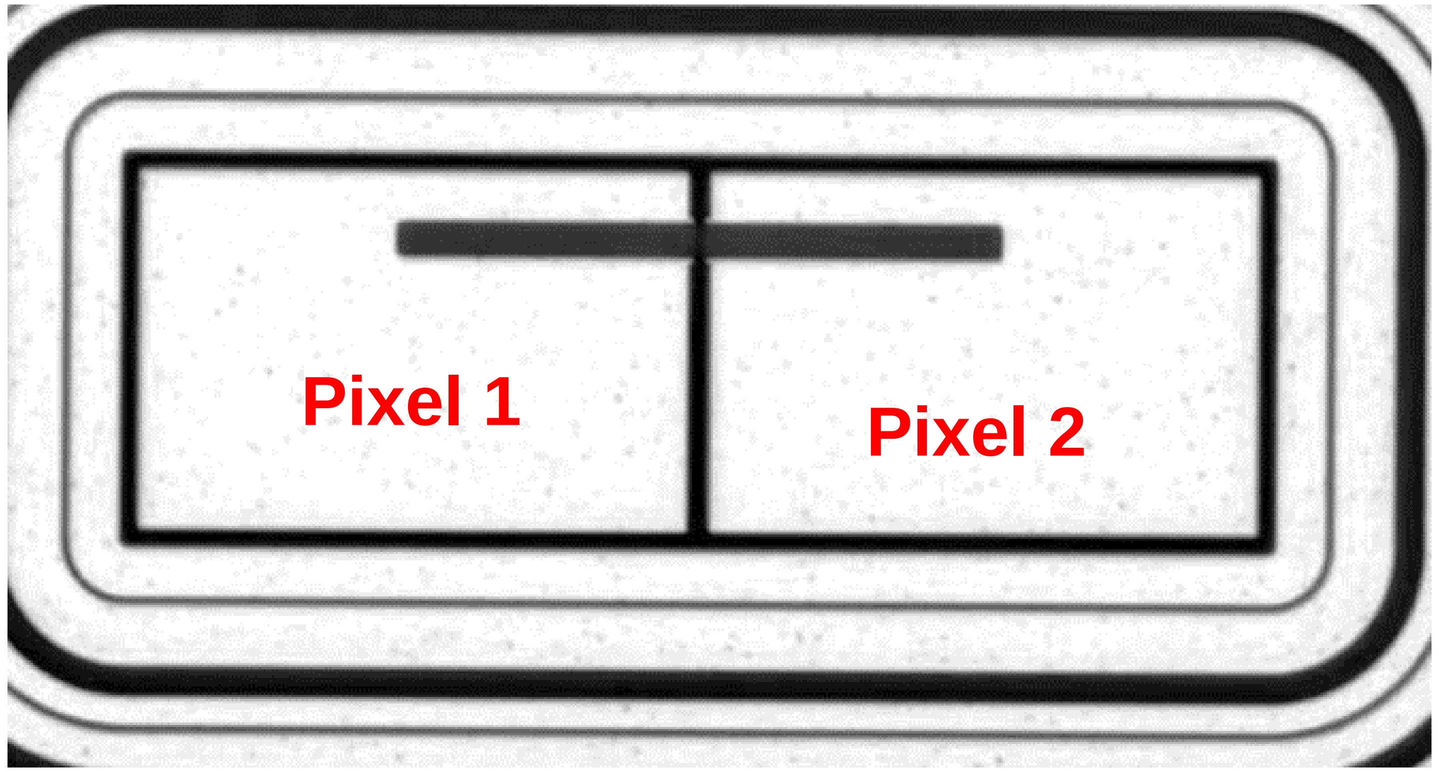
- IV curves show expected behaviour of TI-LGADs
- and PiN diodes.
- TI-LGADs: Gain\knee" 25 V / Breakdown > 250
- ! LGAD breakdown is due to gain layer

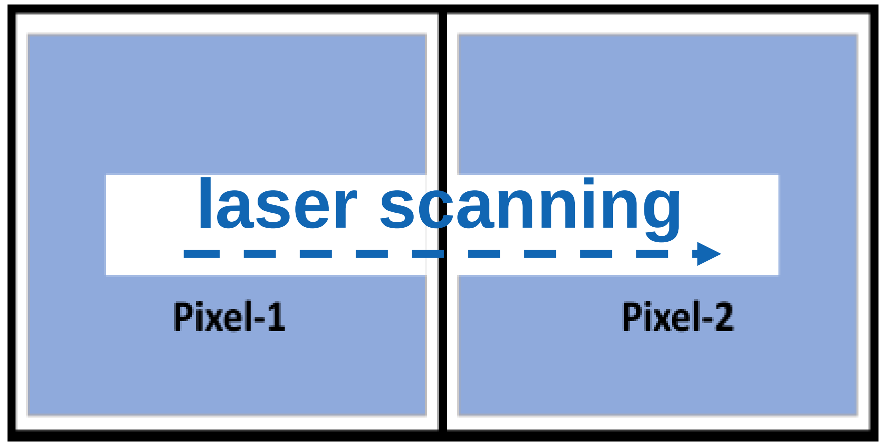


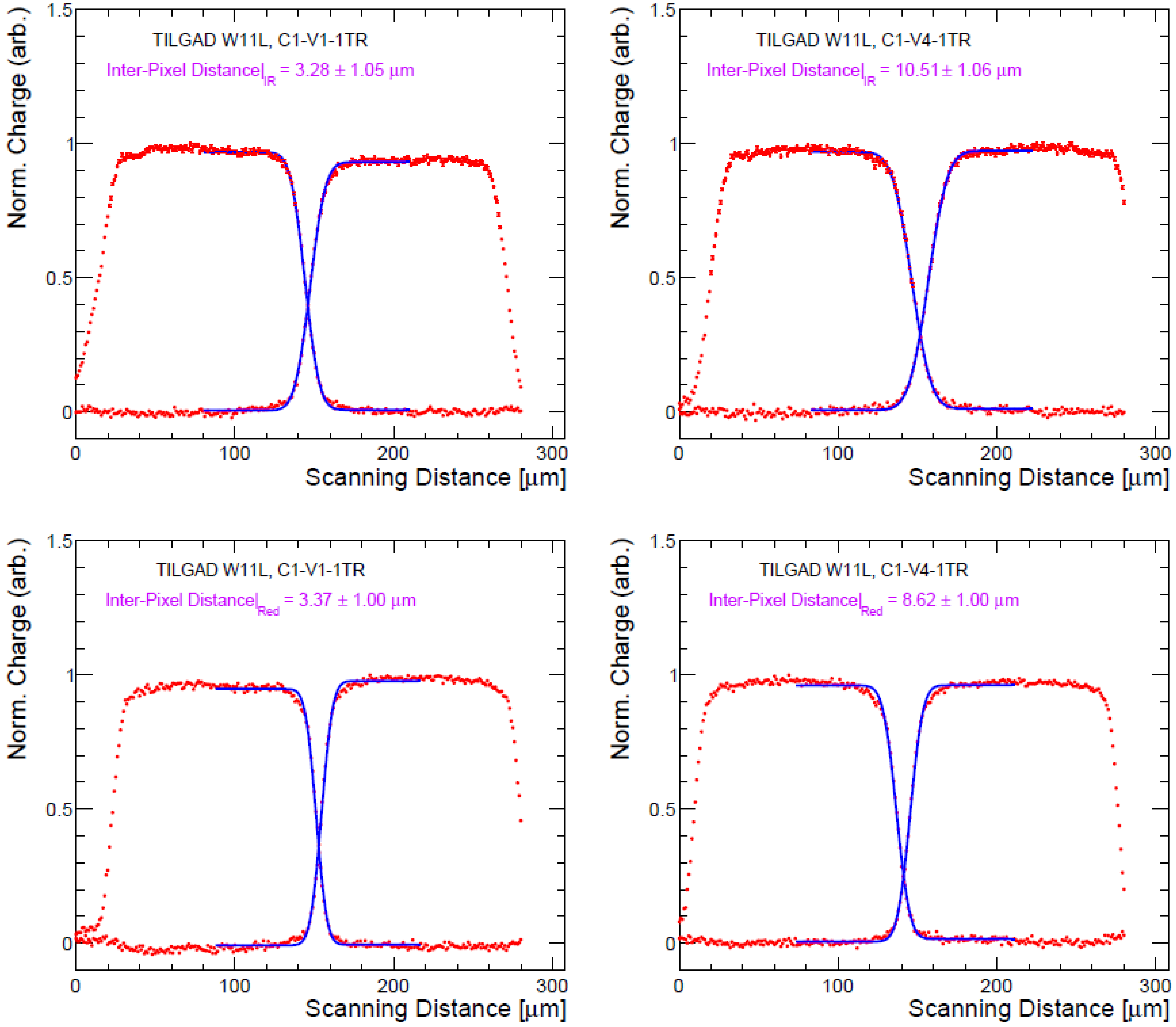


LGAD – Fine segmentation (TI-LGAD)

Inter-pad characterization





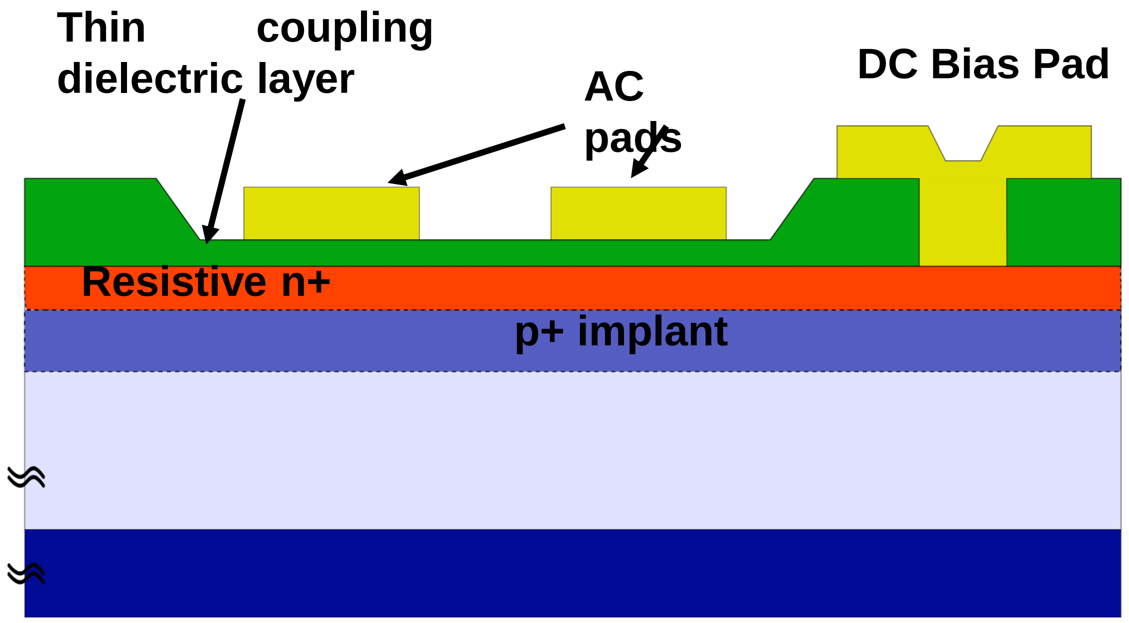


Interpixel distance in the range 3-10 um (depending on the layout split)

x10 times lower wrt standard LGAD

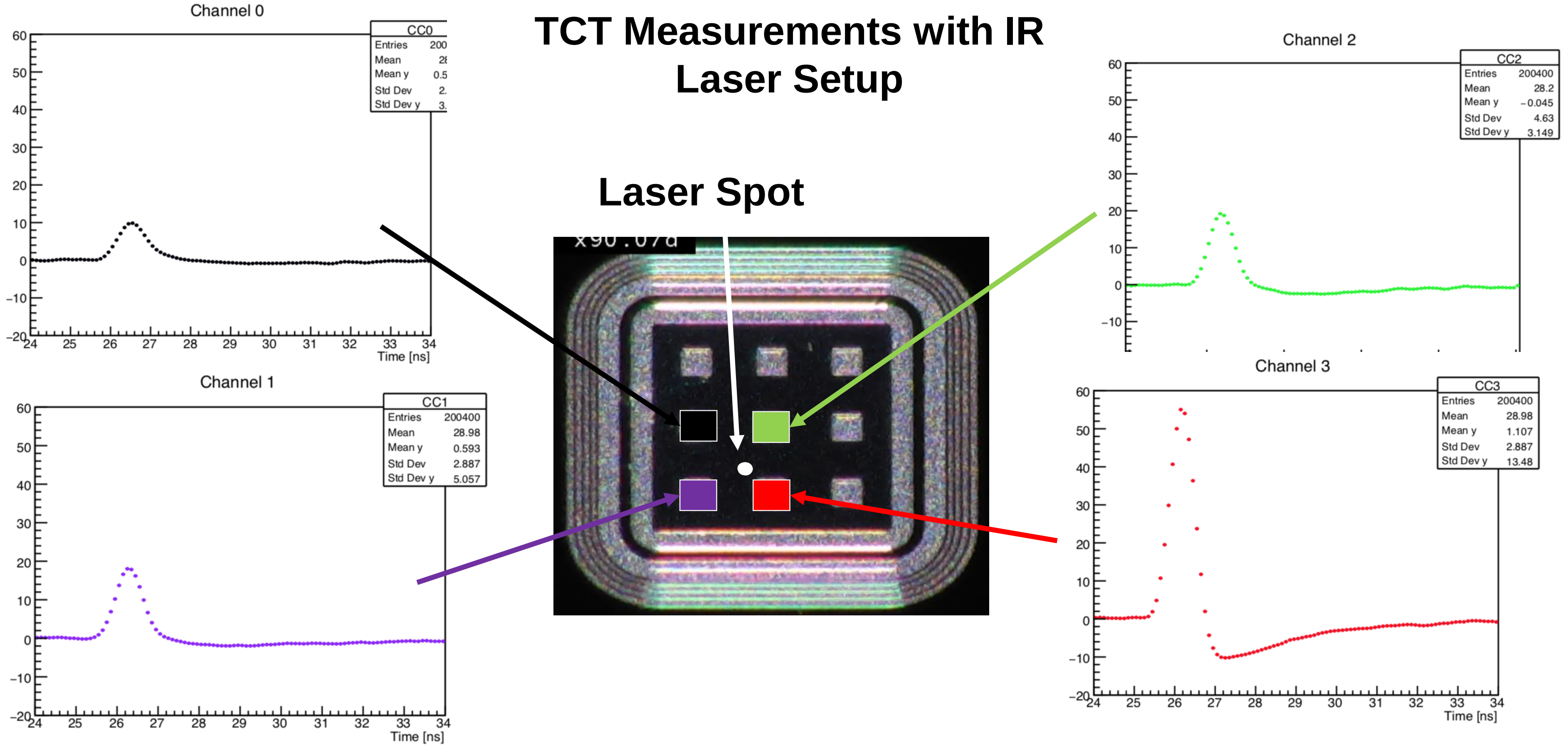
LGAD – Fine segmentation (RSD)

N. Cartiglia



Main Technological Features

- Not-segmented p-gain implant
- Resistive n+ implant
- AC Metal pads
- Segmentation of the AC pads defines the pitch
- Thin coupling dielectric layer under yhe AC pads



The signal spreads on several pads, with **amplitude inversely proportional to the hit distance**

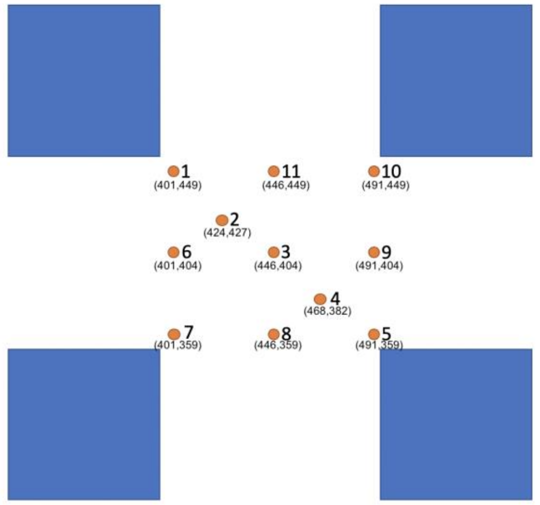
Note: the amplitudes on far away pads is much larger than what is predicted by direct induction

LGAD – Fine segmentation (RSD)

Space Resolution

The position of the hit is obtained as:
(amplitude>10 mV)

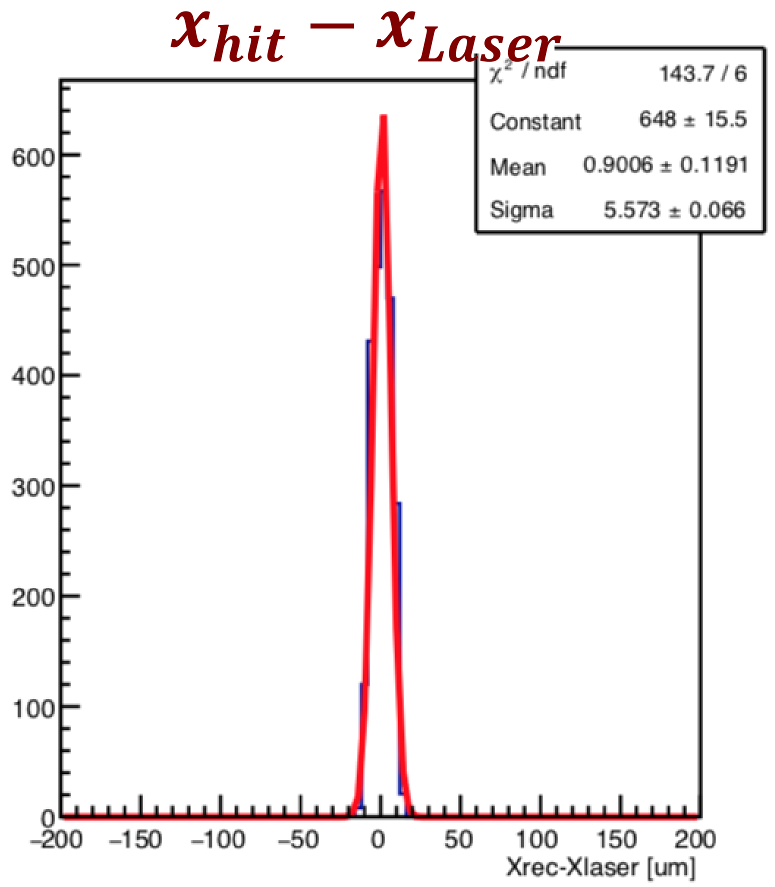
$$x_{hit} = \frac{\sum_{i=1}^{i=4} x_{pad}(i) * Amp(i)^{Cor}}{\sum_{i=1}^{i=4} Amp(i)^{Cor}}$$



100um pitch Array:

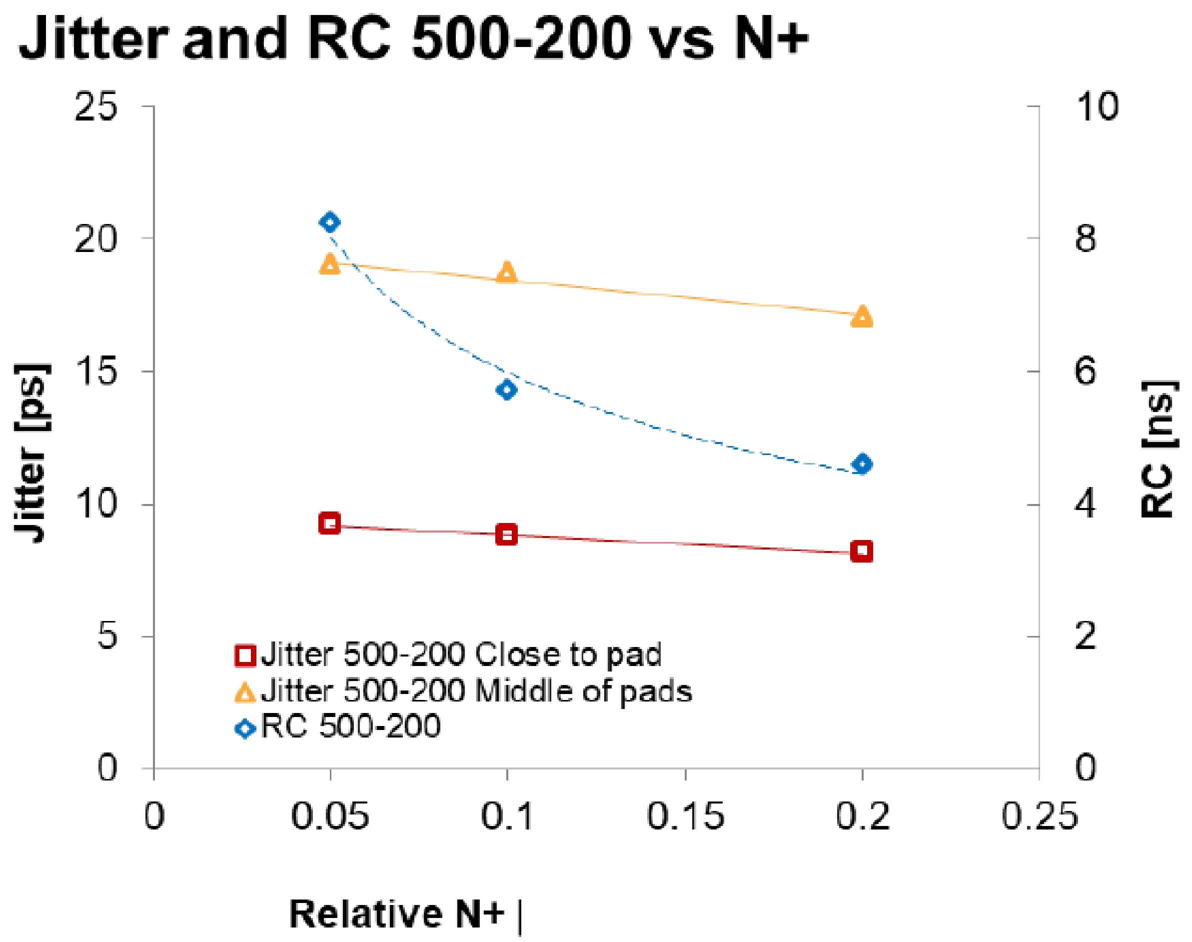
x resolution: 6 um, with an offset of 1 um

N. Cartiglia



PITCH	x resolution [um]	Y resolution [um]
100 um	4-6	4-6
200 um	6	6
500 um	19	18

Time Resolution

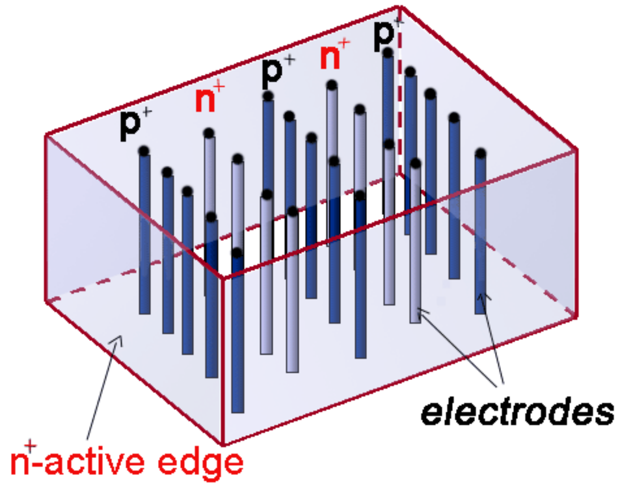

Jitter and RC 500-200 vs N+

A. Sadrozinski

3D Detectors

3D Detectors

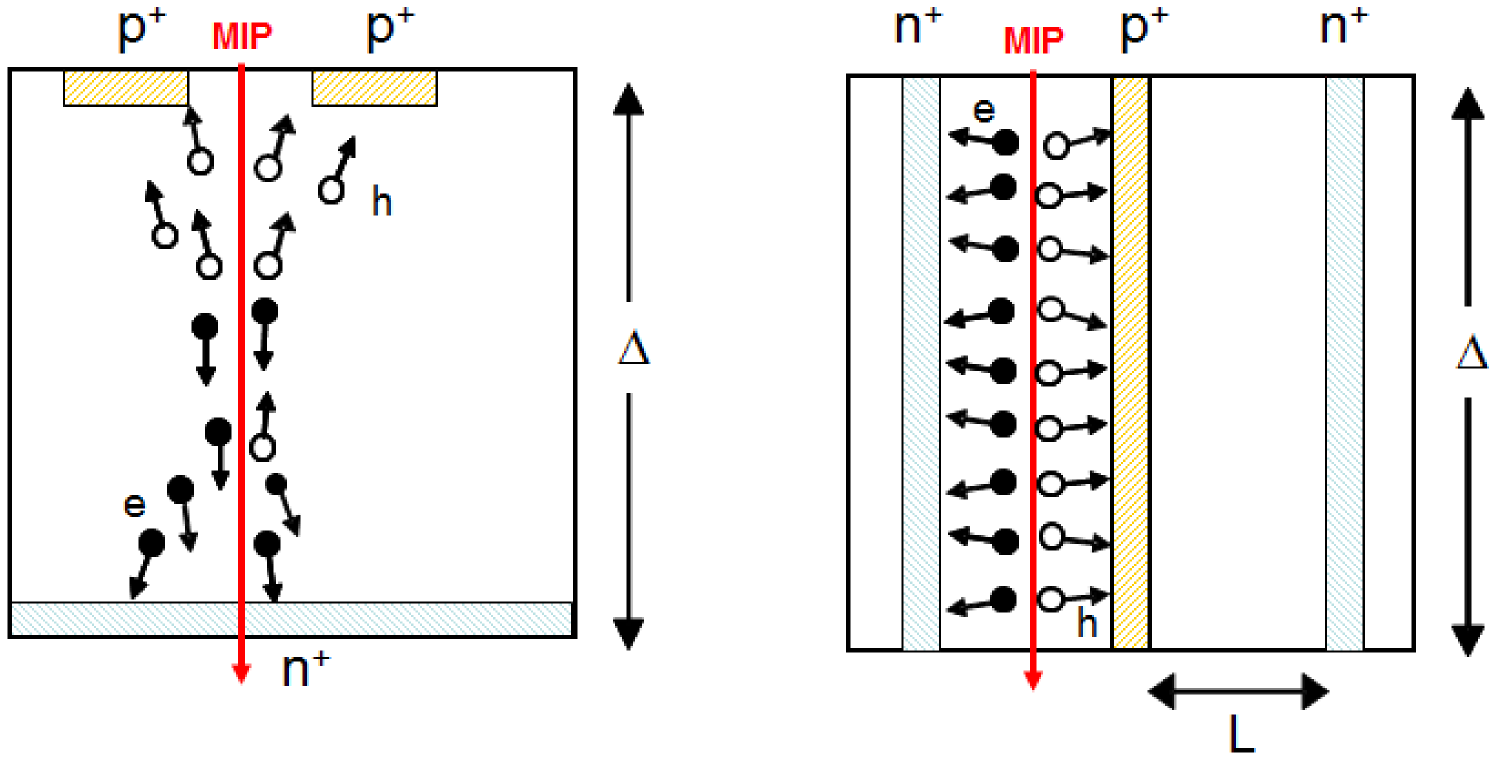
S. Parker et. al. NIMA 395 (1997) 328



ADVANTAGES:

- Low depletion voltage (low power diss.)
- Short charge collection distance:
  - Fast response rise
  - Less trapping probability after irr. -> **high radiation hardness**
- Lateral drift → cell "shielding" effect:
  - Lower charge sharing

Drift distance (L) and active substrate thickness (D) are decoupled → L<<D by layout

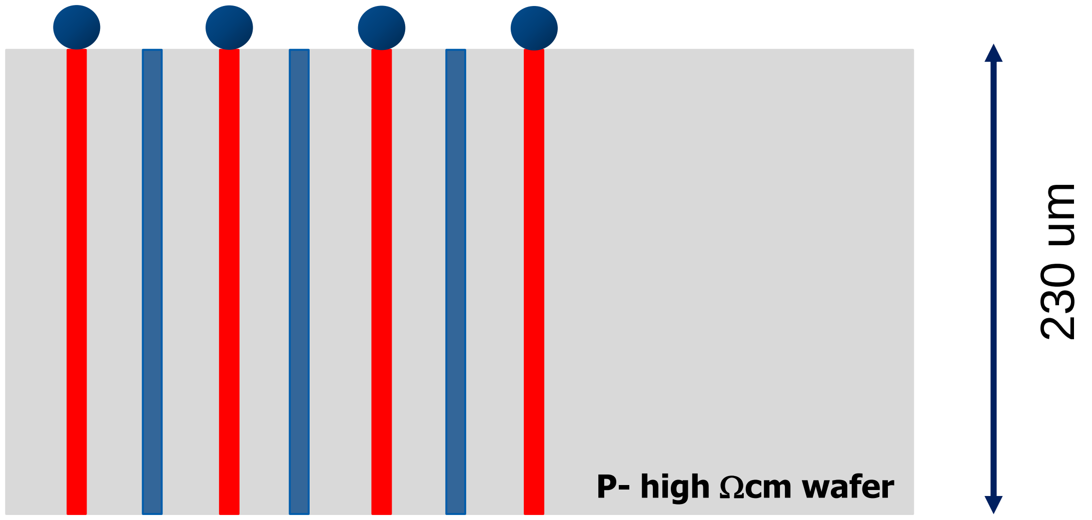


DISADVANTAGES:

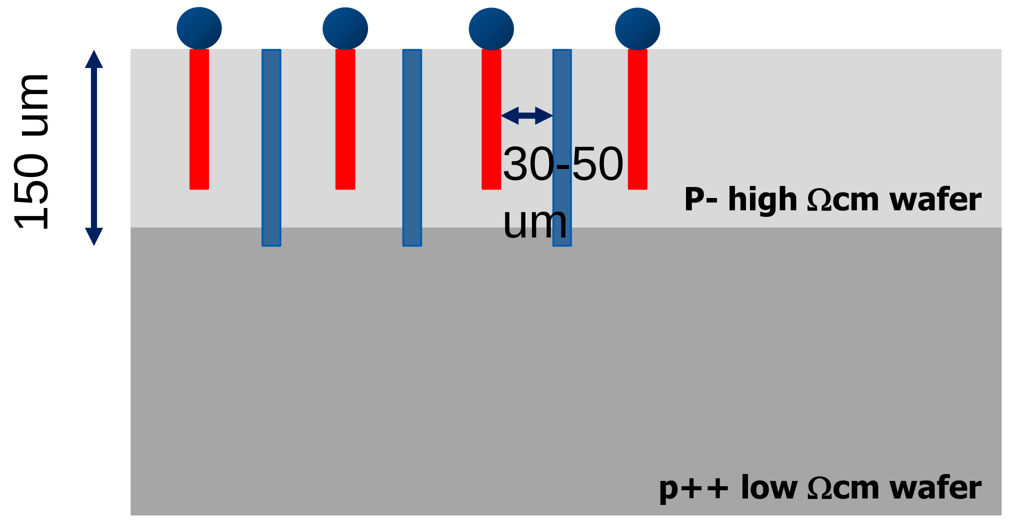
- Non uniform spatial response (electrodes and low field regions)
- Higher capacitance with respect to planar (~3-5x for ~ 200 mm thickness)
- Complicated technology (cost, yield)

3D Detectors Technology

Double-side 3D, produced by FBK for IBL



New single-side 3D technology/design for HL-LHC

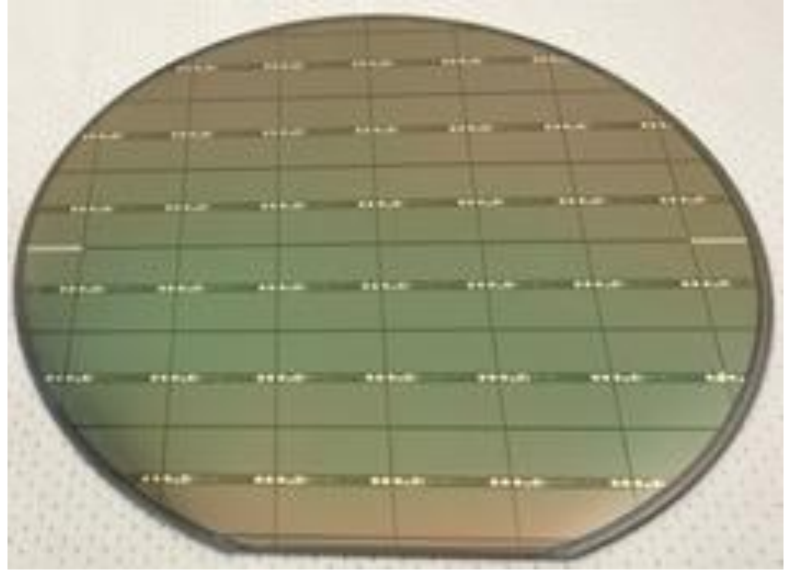


- D =230 um, L~ u7 mm, column diam. ~12 um
- Excellent performance up to $5x10^{15}$ n_{eq} cm^{-2} also pushed to ~$1.4x10^{16}$ n_{eq} cm^{-2} in AFP tests

- Thinner sensors (100-150 µm),
- Narrower electrodes 5 µm
- reduced inter-electrode spacing (~30 µm)

FBK will be one of the lab involved in the realization of 3D Si for HL LHC ATLAS ITK *[Lapertosa @ TREDI2021]*

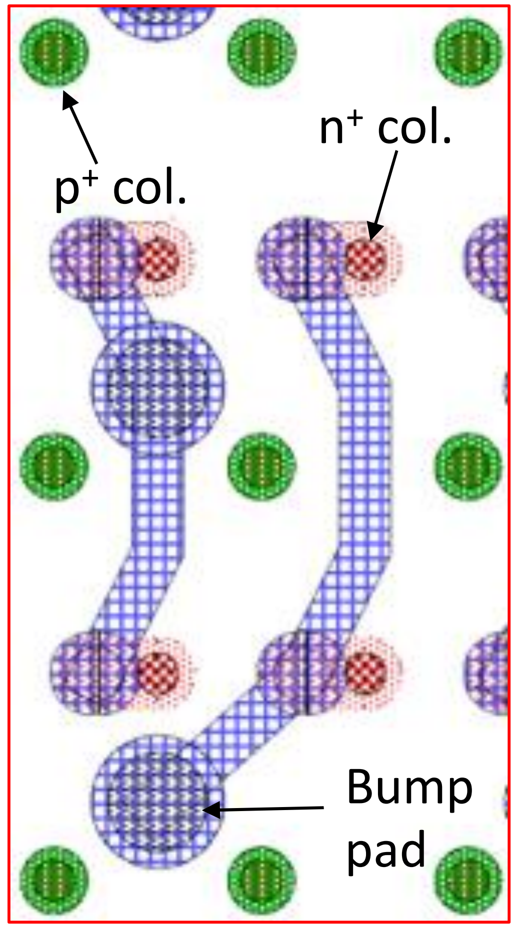
3D Detectors Technology



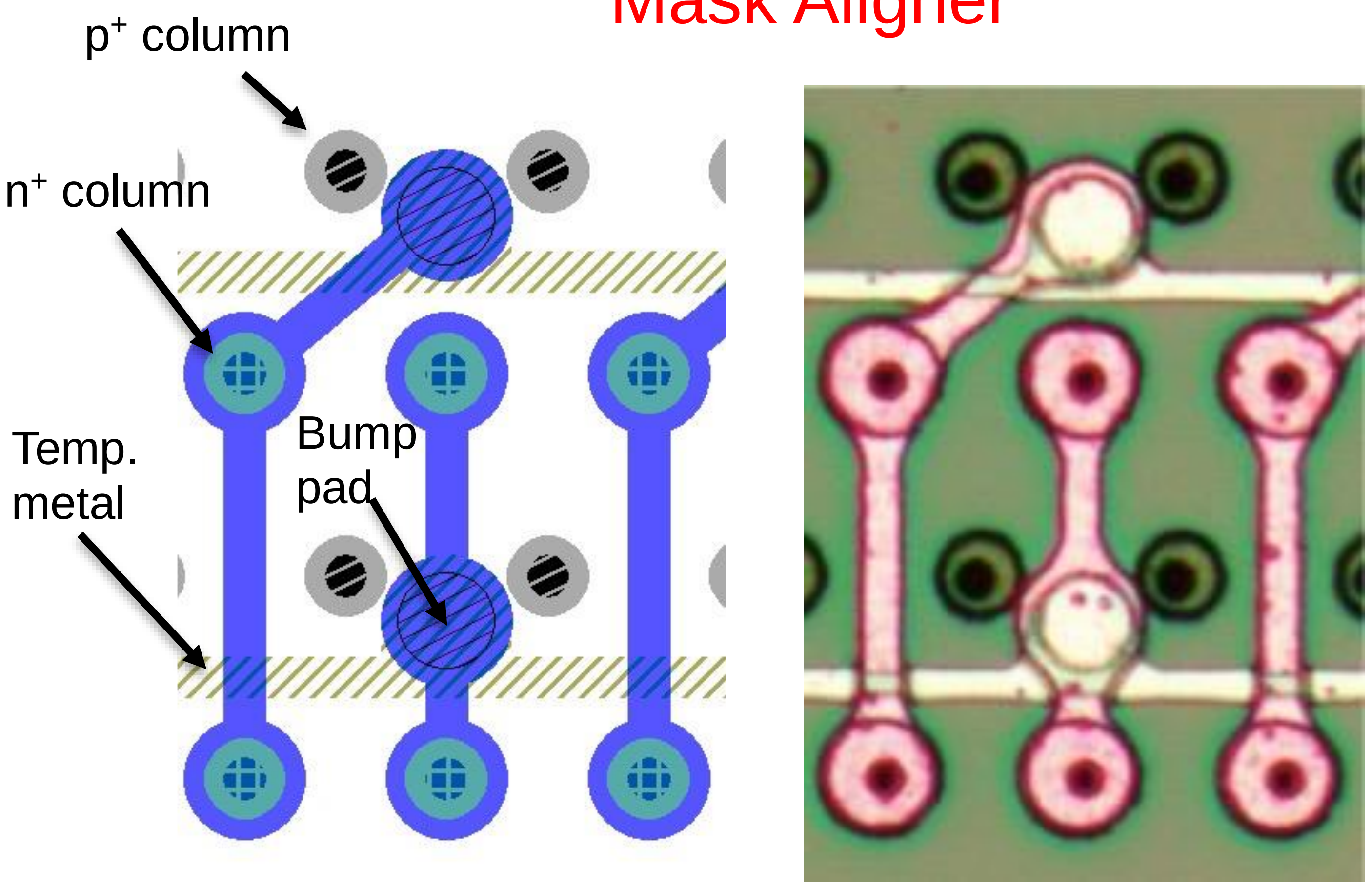
New single-side 3D technology/design for HL-LHC

- Mask aligner is not accurate enough for the «25 x 100 – 2E» layout
- Stepper allows for more aggressive layout rules and preserves critical details

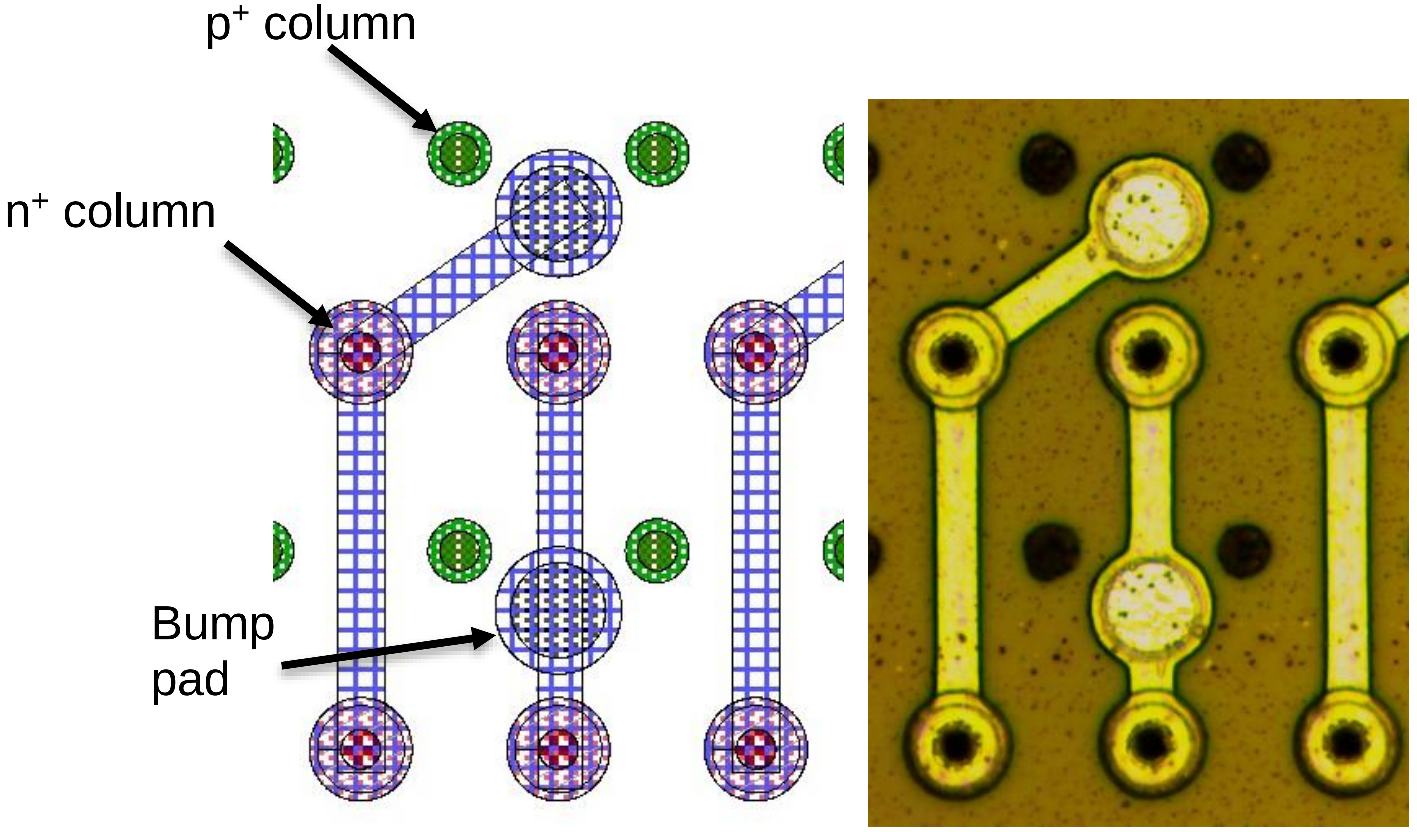
e) 25 x 100 – 2E (H-ear)



Mask Aligner



Stepper



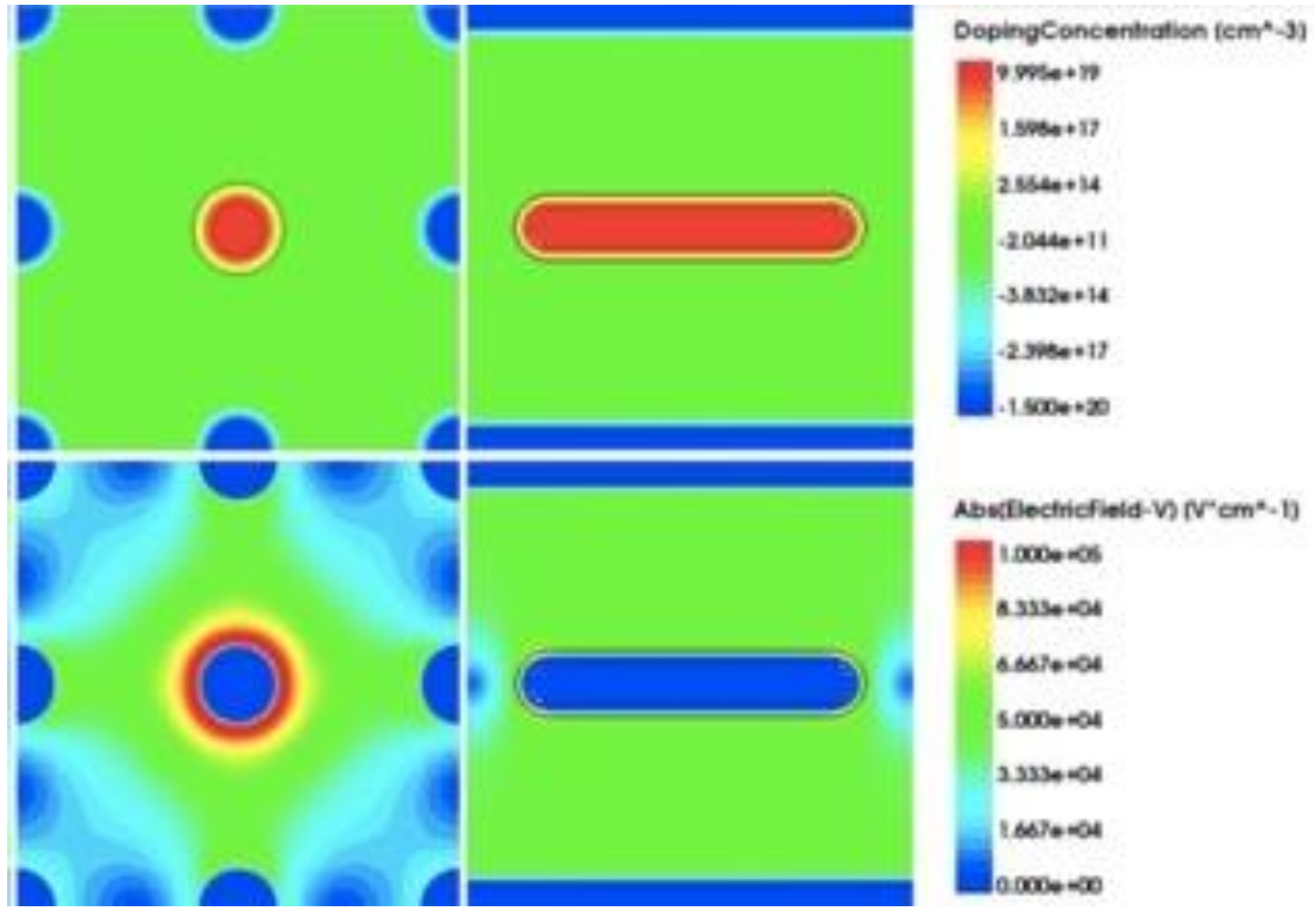
Batch	Yield on full RD53A sensors (%)		
	50×50-1E	25×100-1E	25×100-2E
Mask Aligner	64±23	60±31	19±14
Stepper	58±15	63±18	38±20

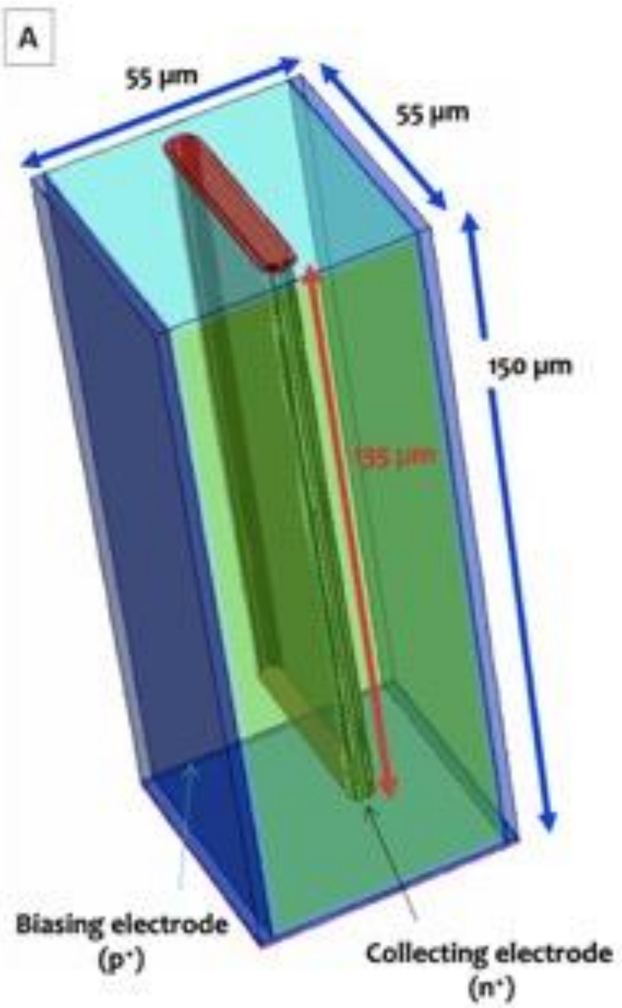
3D Detectors for timing

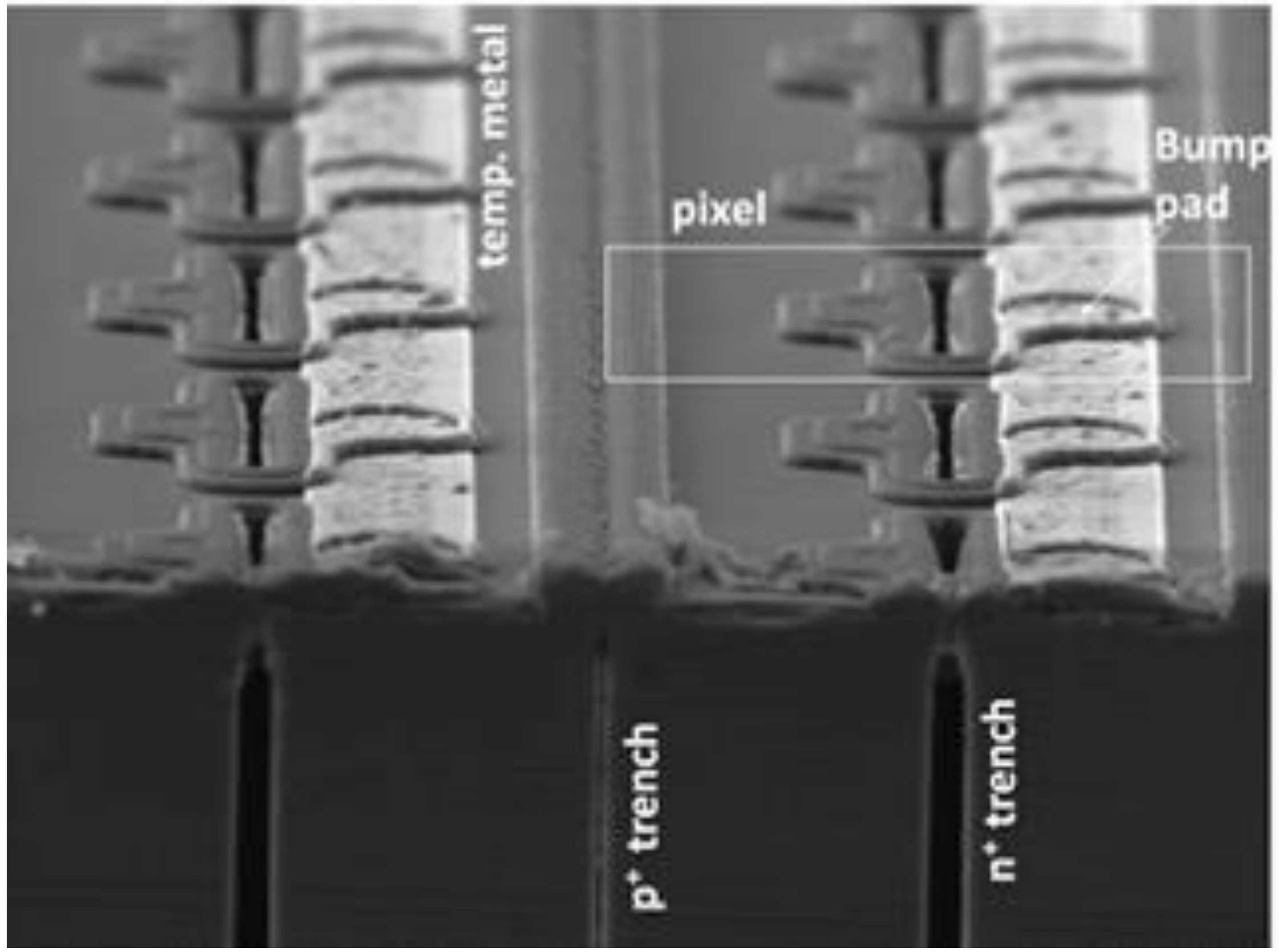
- 3D sensors are also expected to be fast …
- But layouts with columnar electrodes have non uniform electric and weighting field distributions → go for trenches

TimeSPOT

See A. Lai talk







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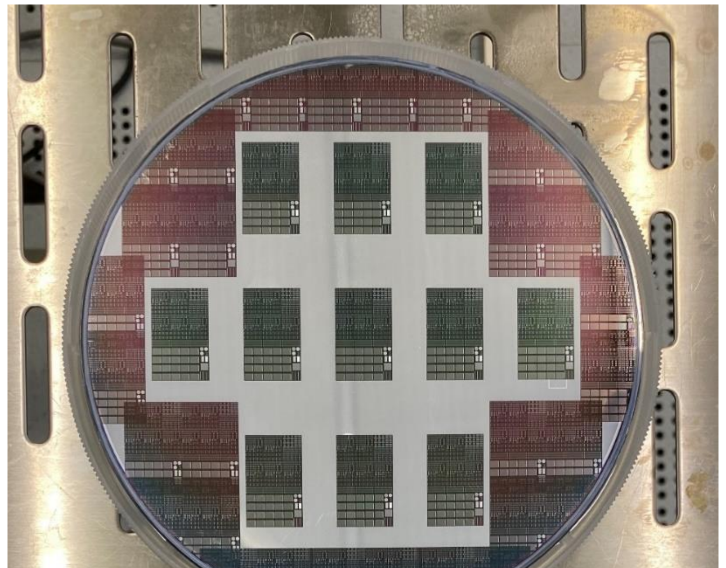
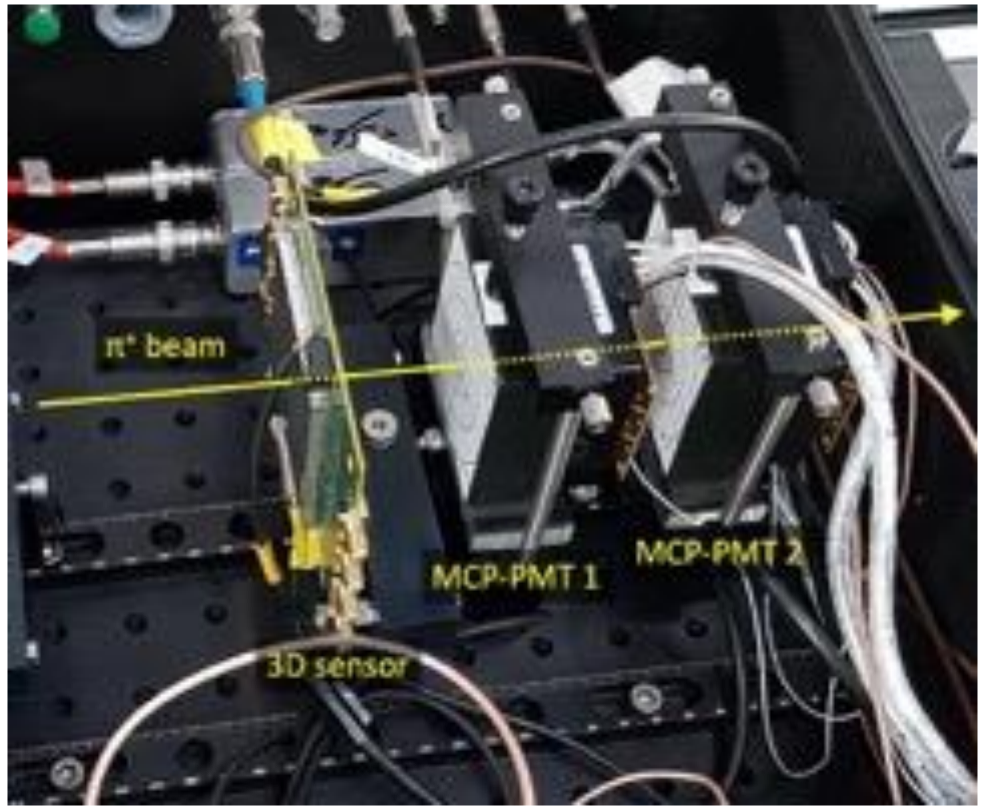
3D Detectors for timing

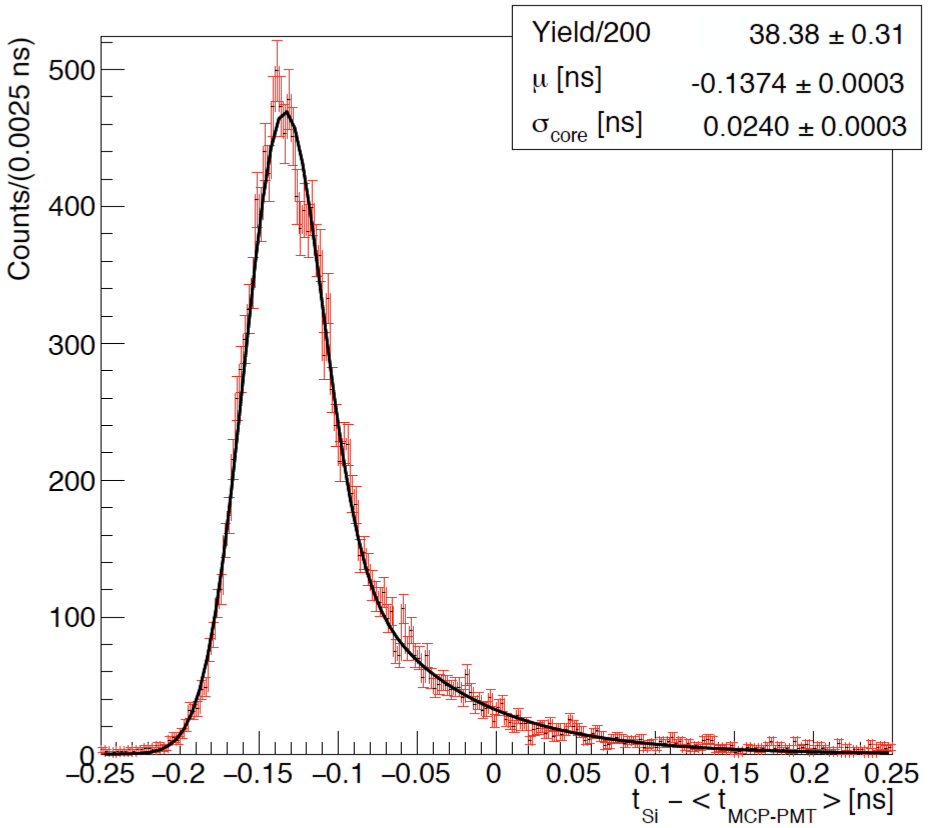
Time resolution of 3D-trench silicon pixels with MIPs (test-beam & lab) at room temperature

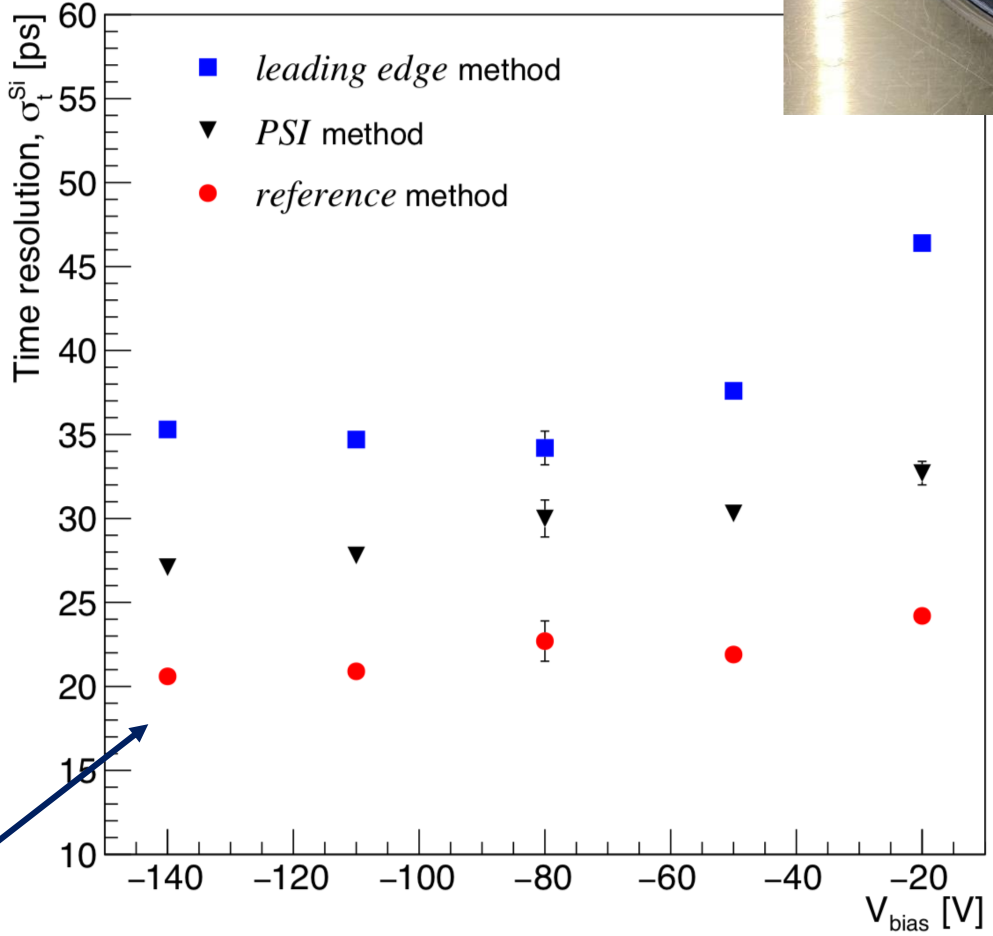
(*Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection*, 2020 JINST 15 P09029)





Beam test @ PSI (10/2019)





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s_t ≈ 20 ps

(after correction for MCP contribution) confirmed in corresponding laboratory measurements (with ^{90}Sr source)

Conclusions

- In the last years FBK developed two technologies of silicon detectors for 4D-tracking with concurrent time and spatial resolution: LGAD and 3D

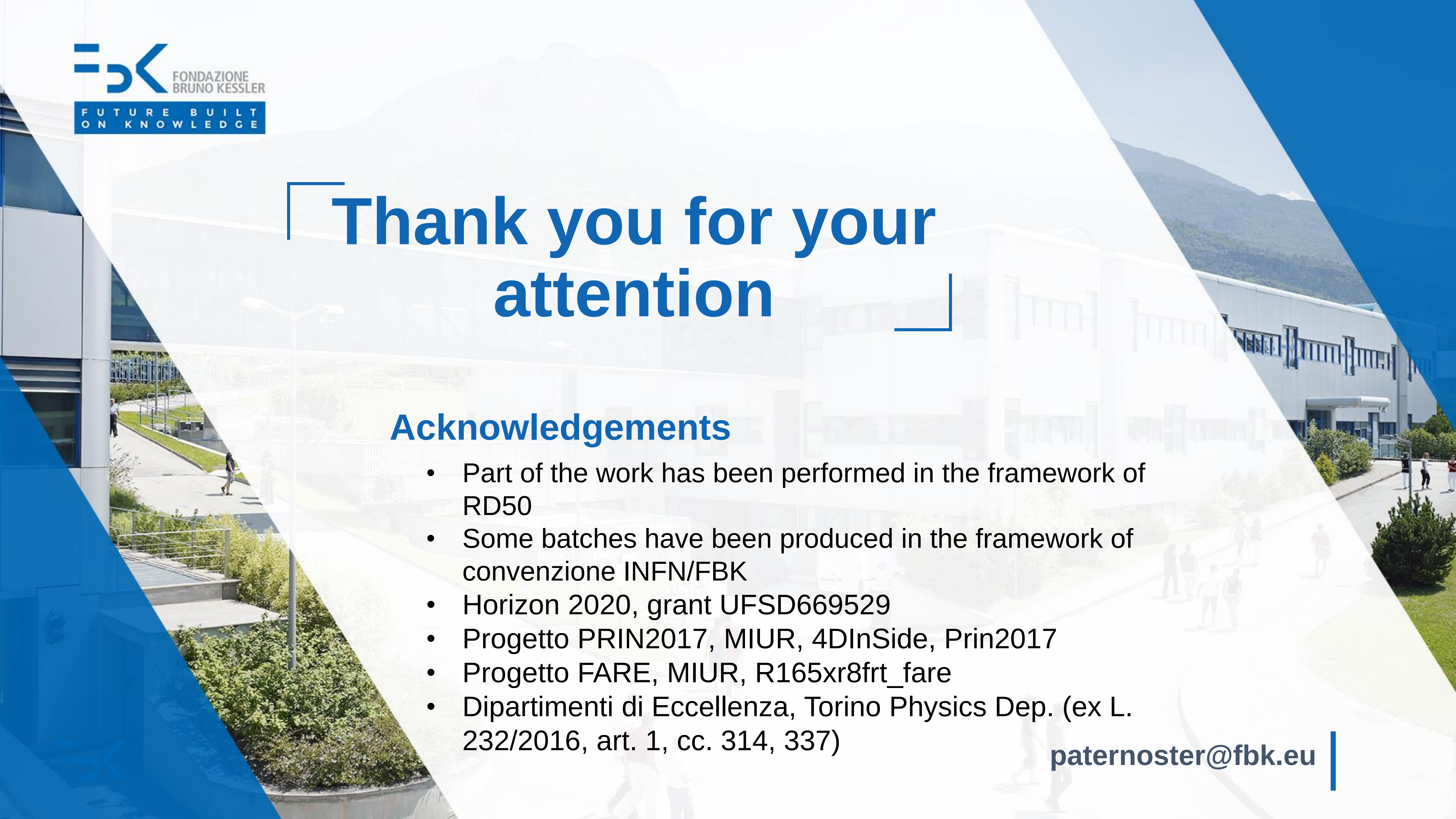
- Last developments in LGAD lead to time resolution ~30ps up to fluences of 2.5e15 neq, mainly thanks to the using of thin substrates and initial acceptor removal mitigation

- New developments for fine-segmented LGADs are ongoing: RSD and TI-LGADs providing high FF and high spatial resolution

- Latest developments on 3D detectors allowed to improve the technology (minimum CD & yield)

- 3D detectors shown an intrinsic high radiation resistance up to 1e16 neq

- 3D detectors for timing have been developed in TimeSpot project, time resolution down to 20ps has been demonstrated



Thank you for your attention

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