1st MONOLITH Workshop on silicon sensors for timing and their applications
Genève, 5-6 Sept. 2022

FBK LGAD Technology for fast timing

FBK LGAD group: A. Bisht, G. Borghi, M. Boscardin, M. Centis Vignali, F. Ficorella, O. Hammad Ali, G. Paternoster

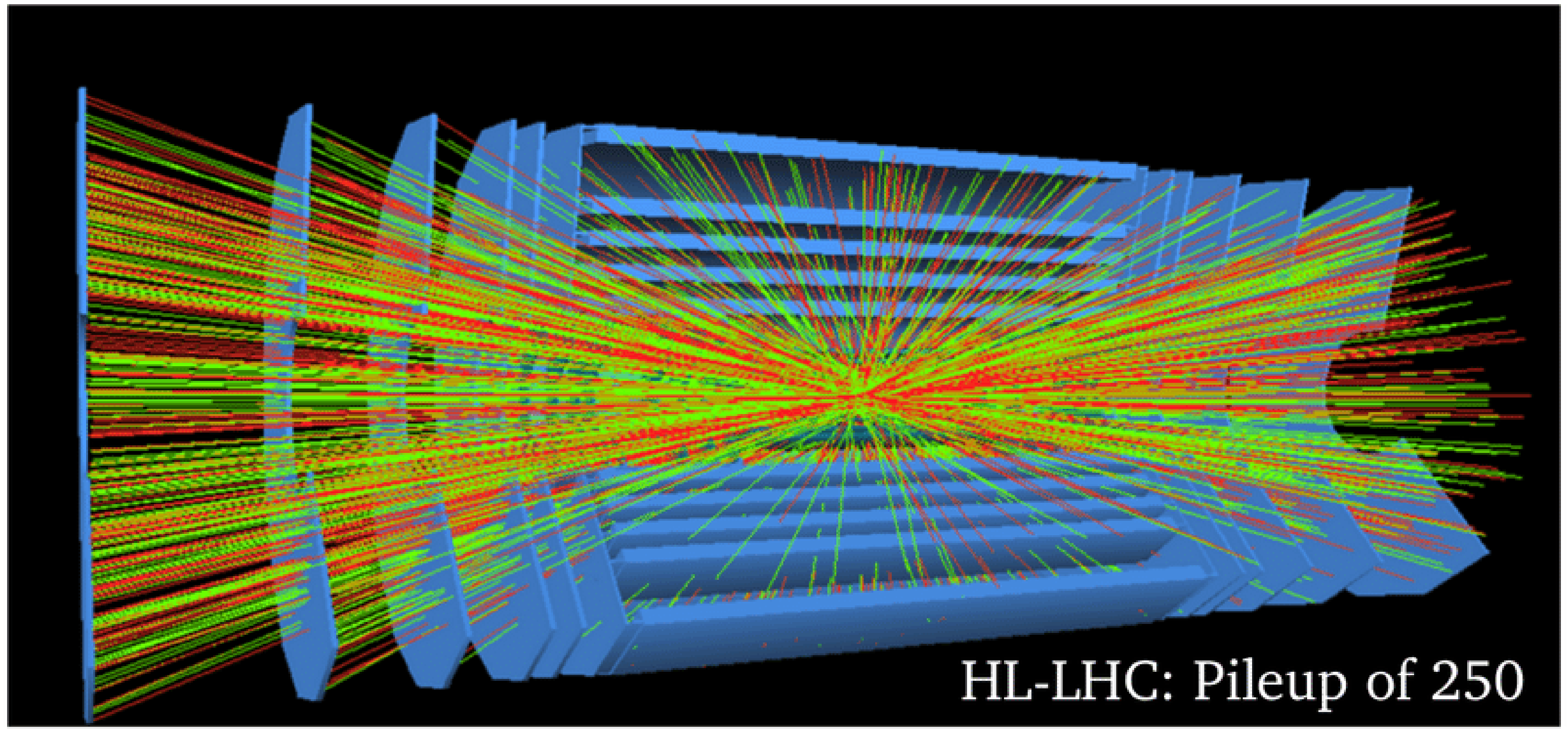
UFSD group
INFN Torino, Univ. of Turin, Univ. of Piemonte Orient, Univ. of Trento, FBK Trento, Univ. of California at Santa Cruz.

paternoster@fbk.eu

Introduction and Motivation

- ➢ LGAD Technology developed at FBK since 2015
- ➢ Developed together with INFN Turin and University Trento for 4d-tracking
- ➢ More than 15 batches produced since 2015

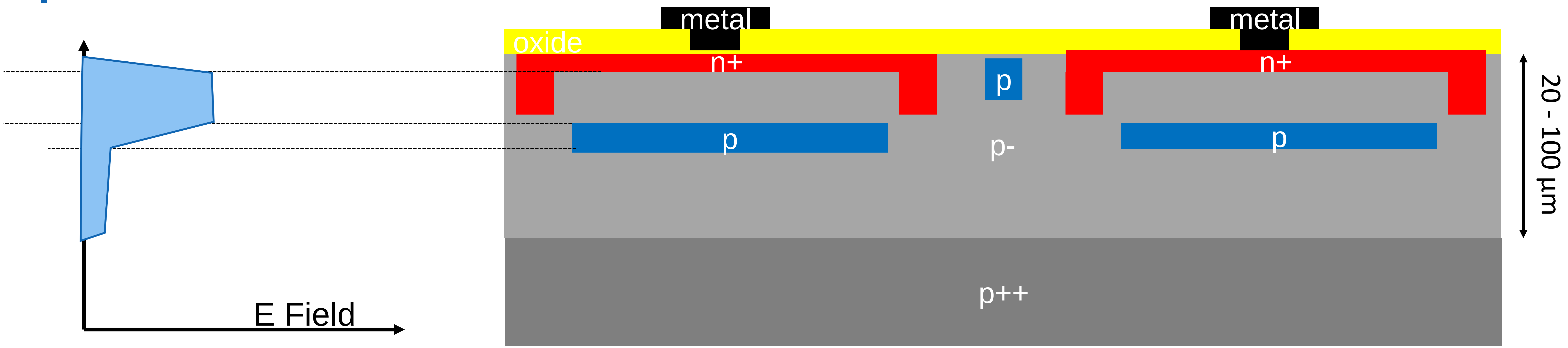
Motivation



- High Luminosity LHC (HL-LHC, operational in 2026):
  - 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: $> 1 \cdot 10^{15}\ n_{eq} \cdot cm^{-2}$

LGAD Technology



Technological features

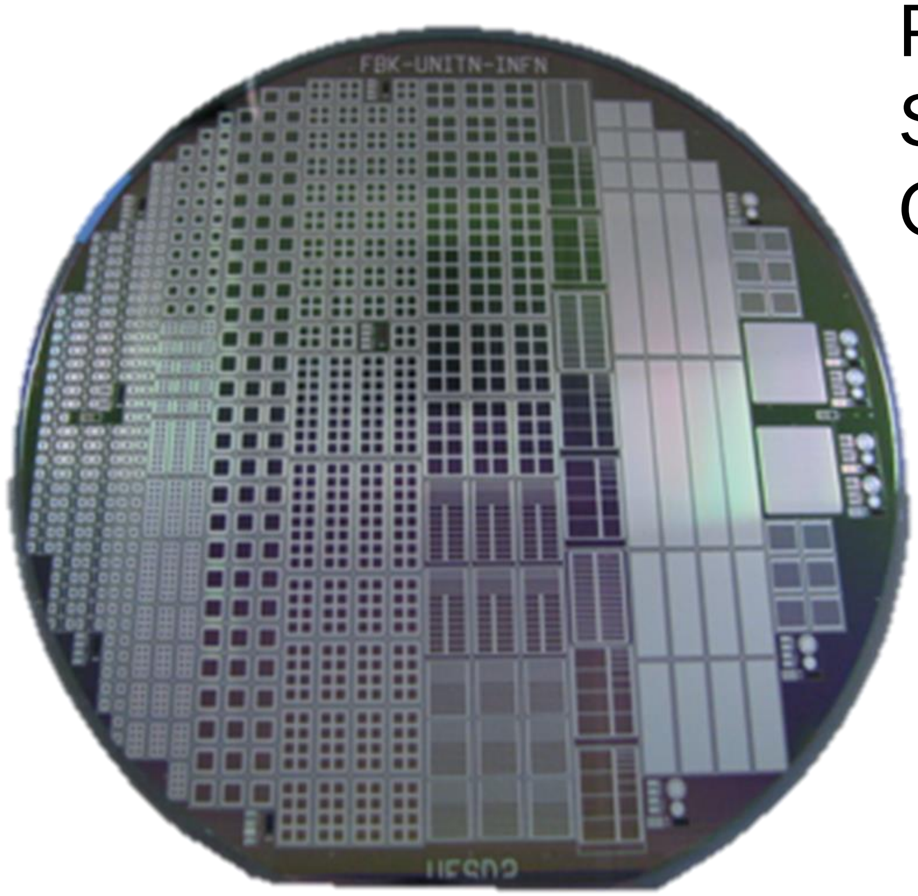
- Silicon detectors with internal charge multiplication
- Gain: 10-20
- Gain layer provides high-field region
- Depleted thickness: 20 - 100 µm (epi or Si-Si wafers)

Main functionalities

- Time resolution 30 ps with thin 50 µm sensor
- Improve SNR of the system (when the sensor shot noise is not dominating)
- Low Noise and power consumption

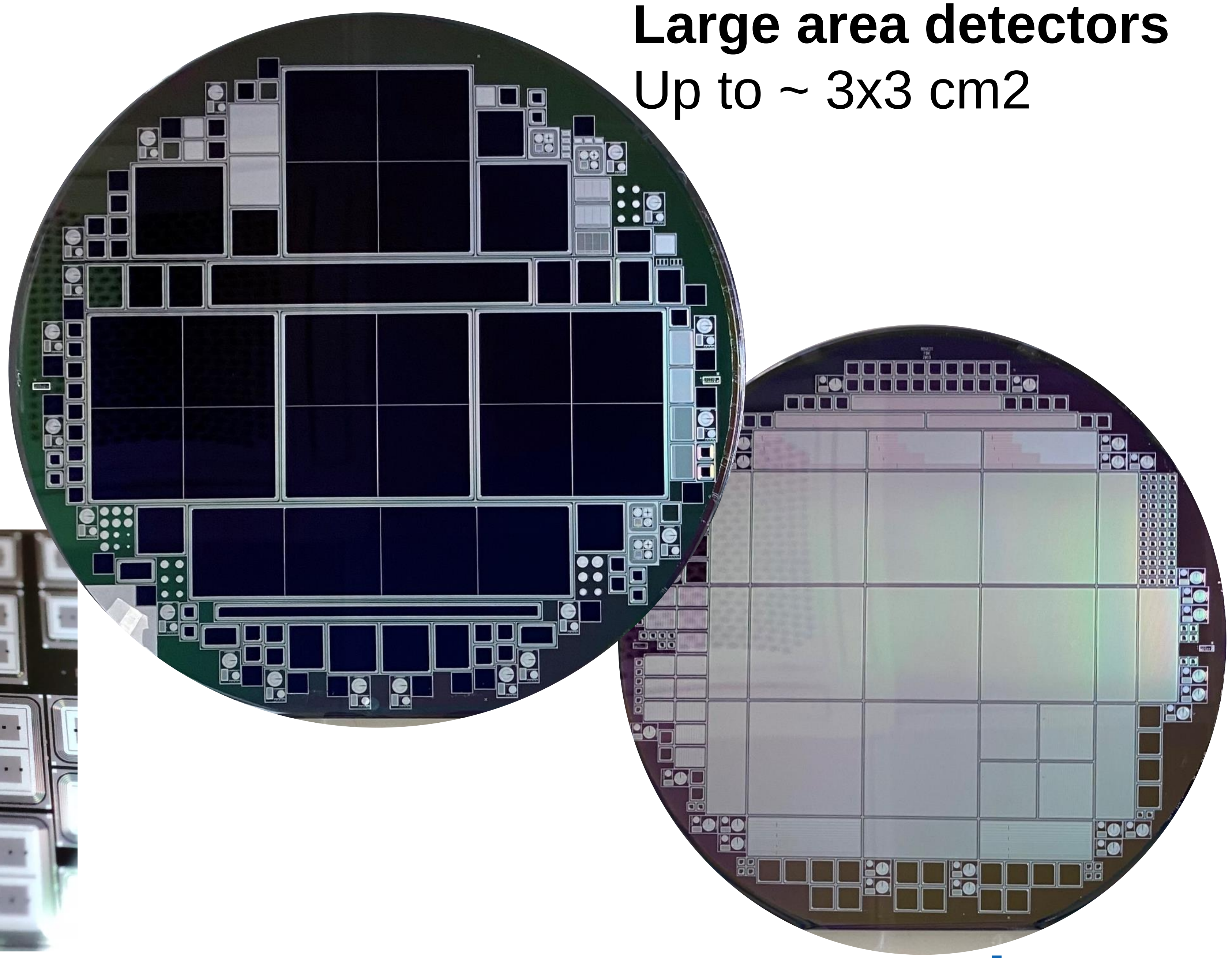
LGAD Fabrication Technology

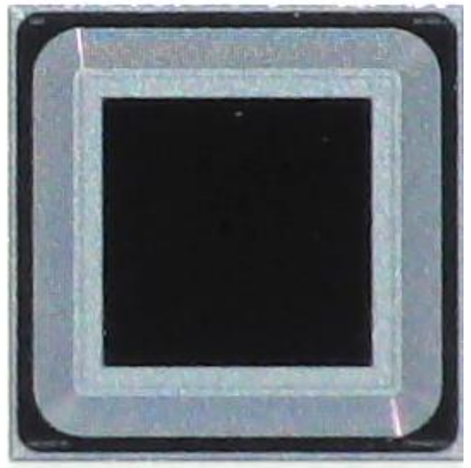
- Fabricated on 6 inches Wafers
- Custom CMOS-like Technology
- Fabricated in the FBK internal facility (ISO 9001:2015 certified)

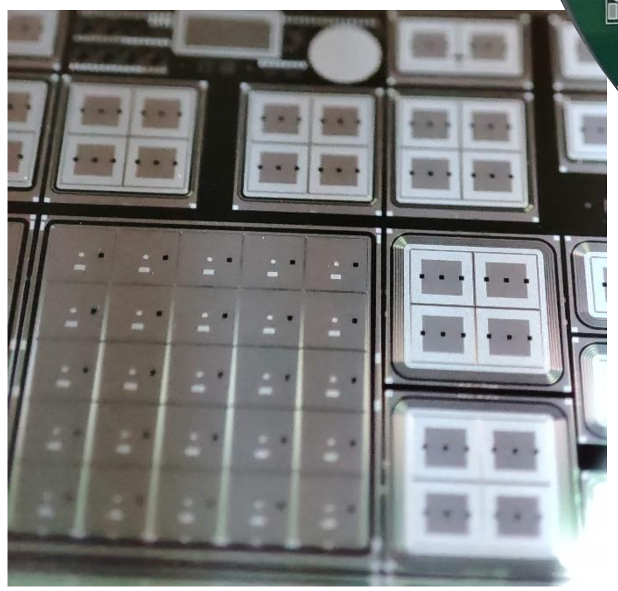


Single pads,
Pad arrays;
Strips;
Other pixelated detectors….

Large area detectors
Up to ~ 3x3 cm2







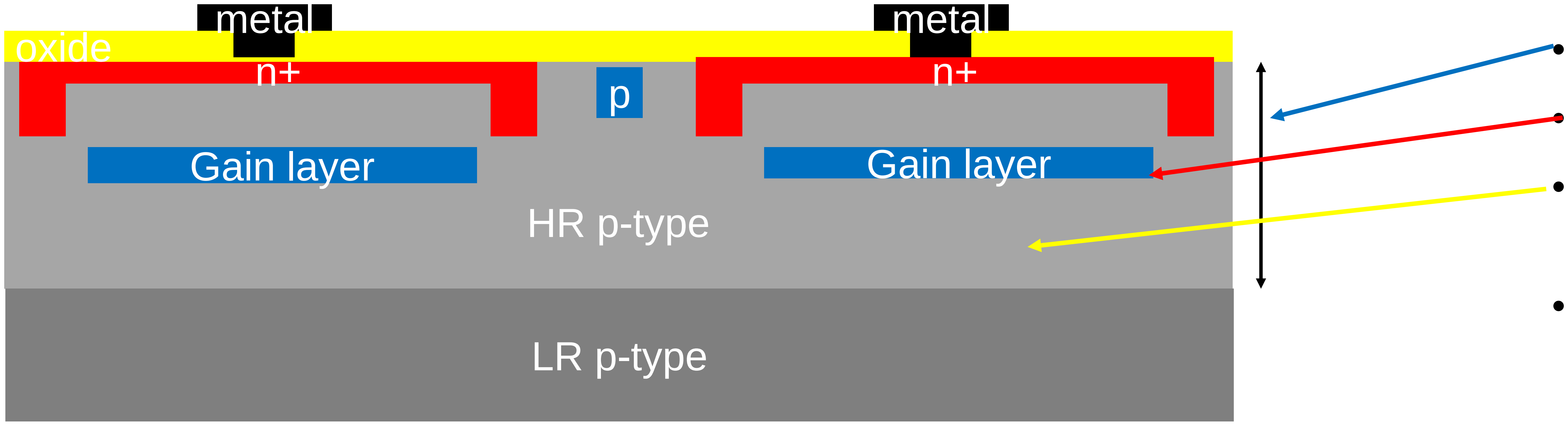
FBK LGAD Technology Roadmap

Different designs, optimized for different applications

UFSD	Fast timing and radiation resistance	4D-tracking at HL-LHC
iLGAD (double-sided)	Fine-segmentation, Thin-Entrance window	Soft x-ray detection
TI-LGAD (trench-isolated)	Fine segmentation, fast-timing, radiation resistance	4D-tracking, soft x-ray
RSD (Resistive Silicon Detectors)	New red-out paradigm: high temporal- and space-resolution with reduced # of channels	4D-tracking

UFSD: Recipe for fast timing

Key factors governing time resolution of LGADs.
Both design & technology



- Thickness
- Gain
- Drift velocity of e^- in the bulk
- Pad geometry (weighing field)

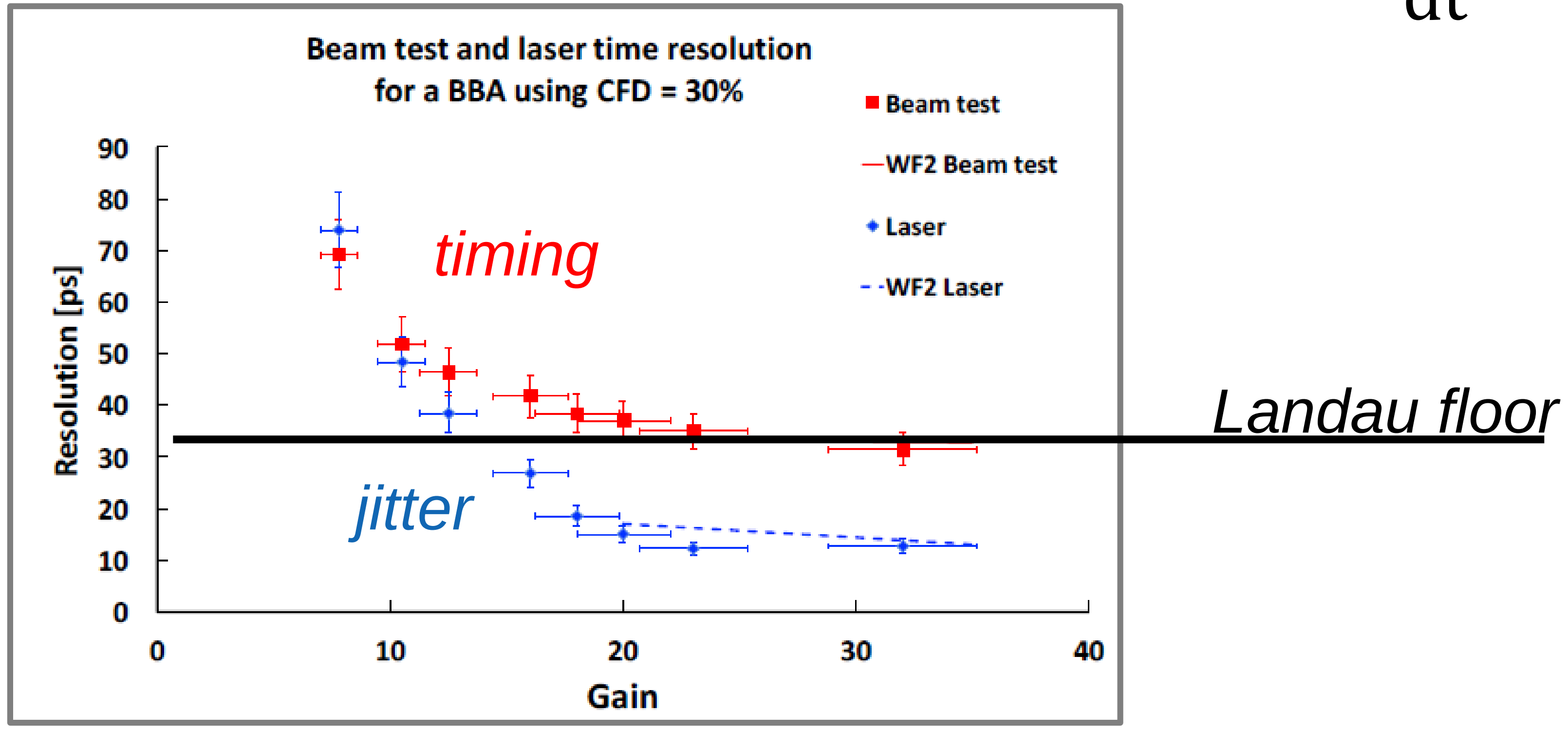
Recipe for fast timing

slew rate $\frac{dV}{dt} \propto \frac{G}{d}$

Gain

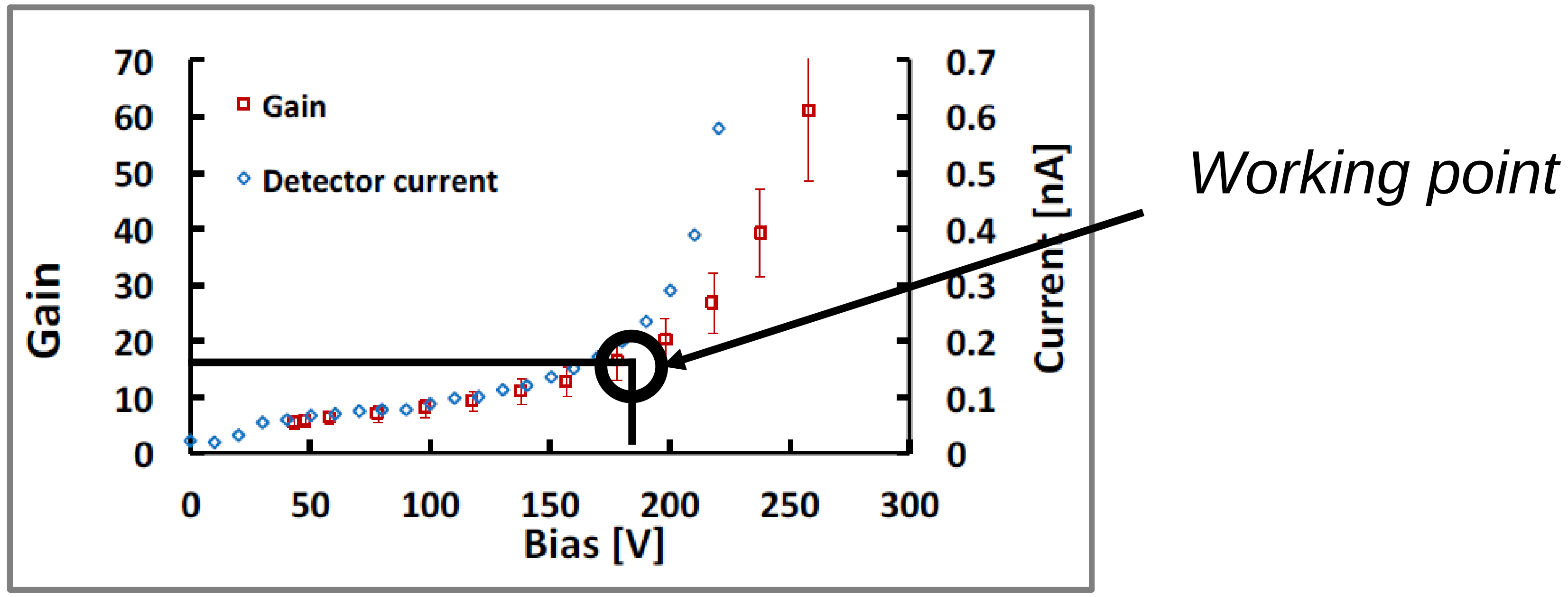
- Gain depends on GL dose and Bias Voltage
- High Gain reduces the jitter
- At too high gain the time resolution is dominated by Landau noise

Rule: use the minimum gain that allows reaching the minimum value in time resolution



Bulk E_{field}

- Target gain should be reached at a Bias where the e- velocity in the bulk is saturated (E > 3e4 V/cm)
- For 50 µm the target is **G~10 at V > 200 Volts**

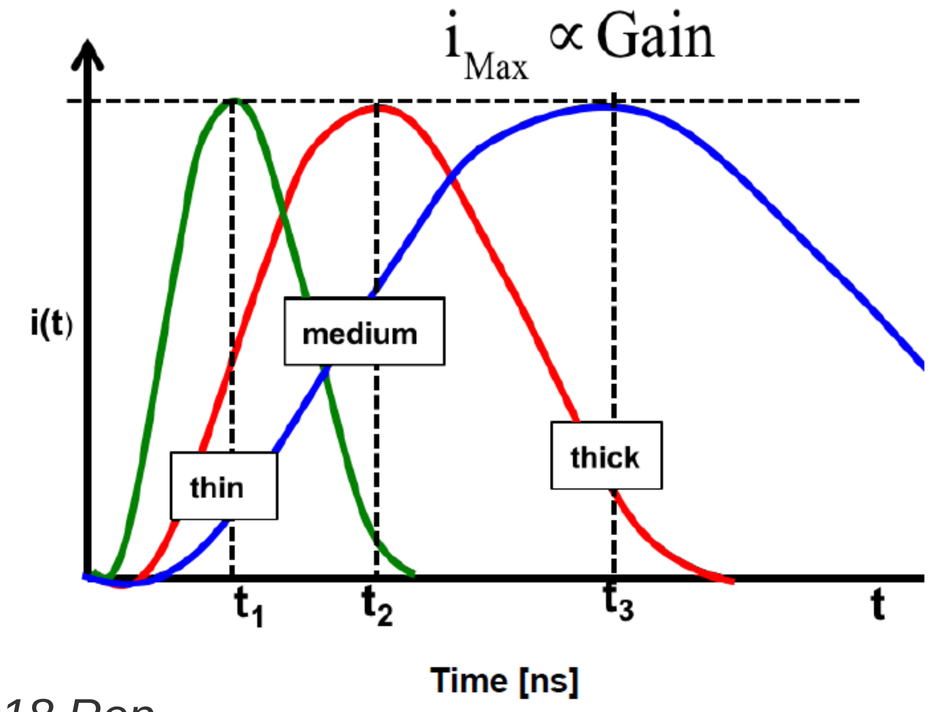


Sadrozinski et al 2018 Rep. Prog. Phys. **81** 026101

Recipe for fast timing

Thickness

$$\text{slew rate } \frac{dV}{dt} \propto \frac{G}{d}$$

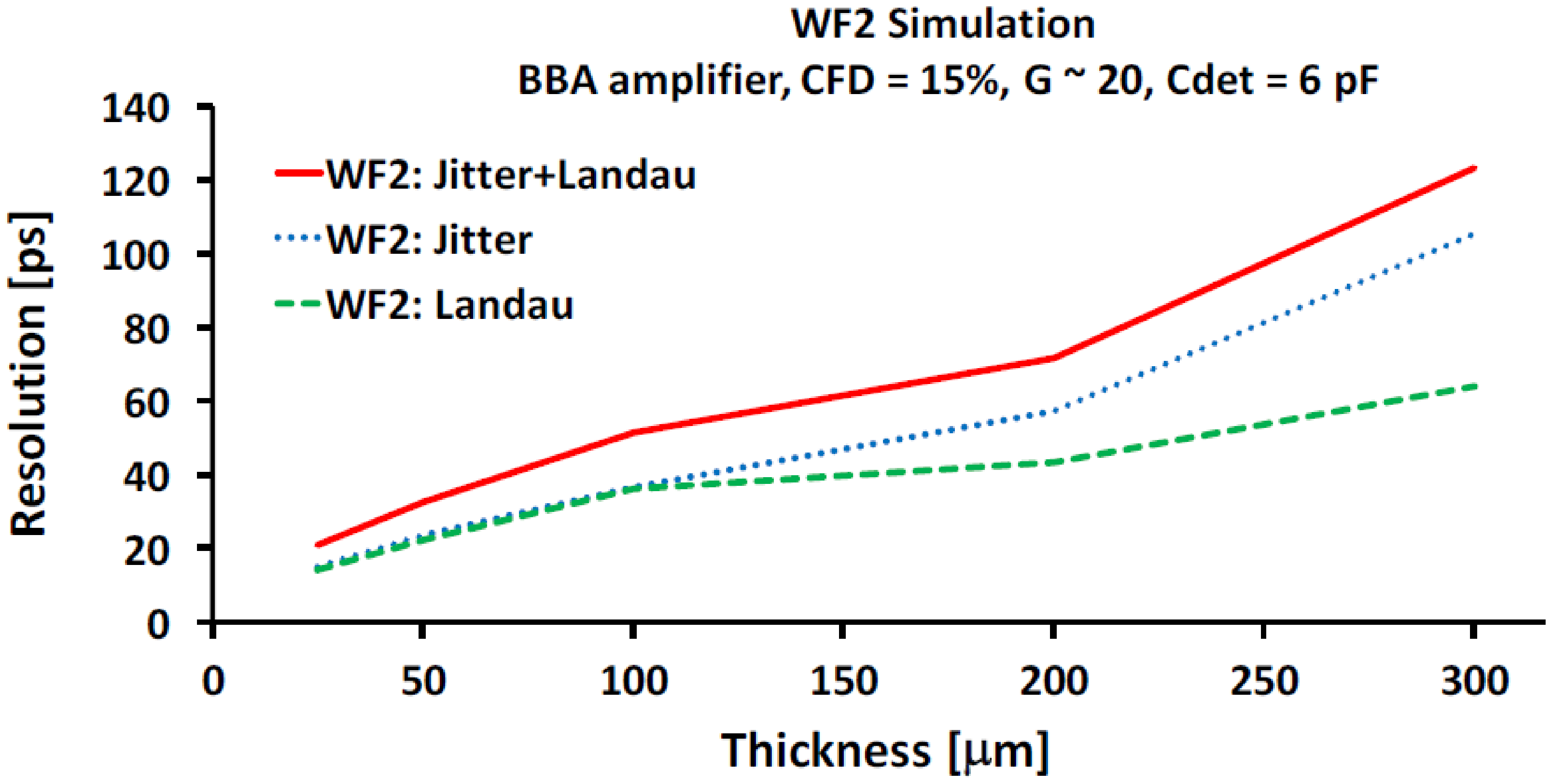


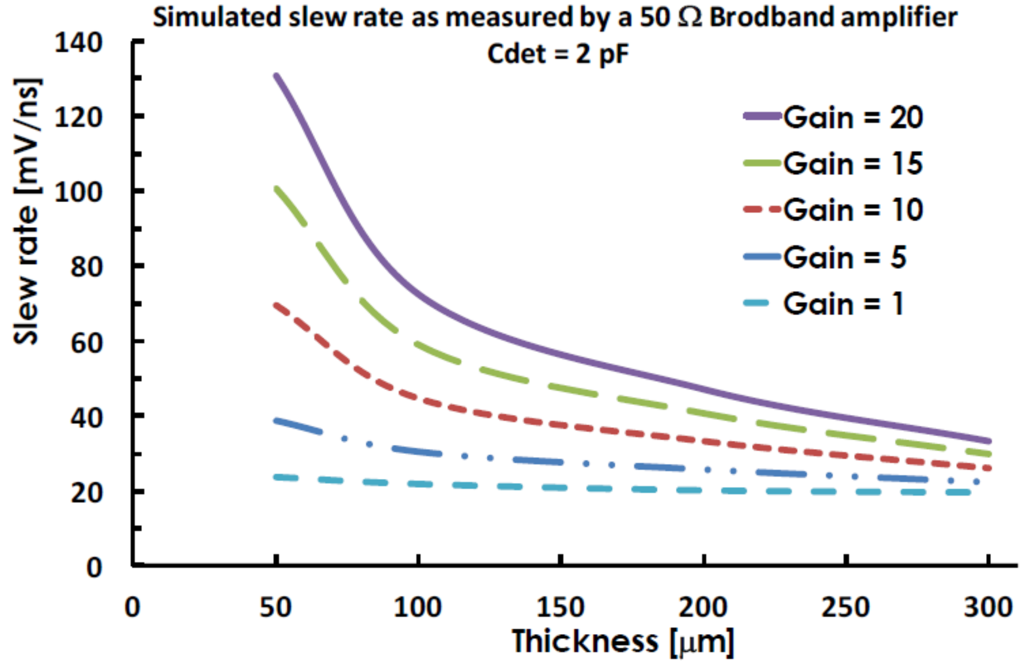
Sadrozinski et al 2018 Rep. Prog. Phys. ***81*** *026101*

Reducing Thickness ->

Higher slew-rate
Lower Landau and Time-walk
High capacitance
Less radiation resistance (SEB)

Trade off ~ 50 um





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Recipe for fast timing

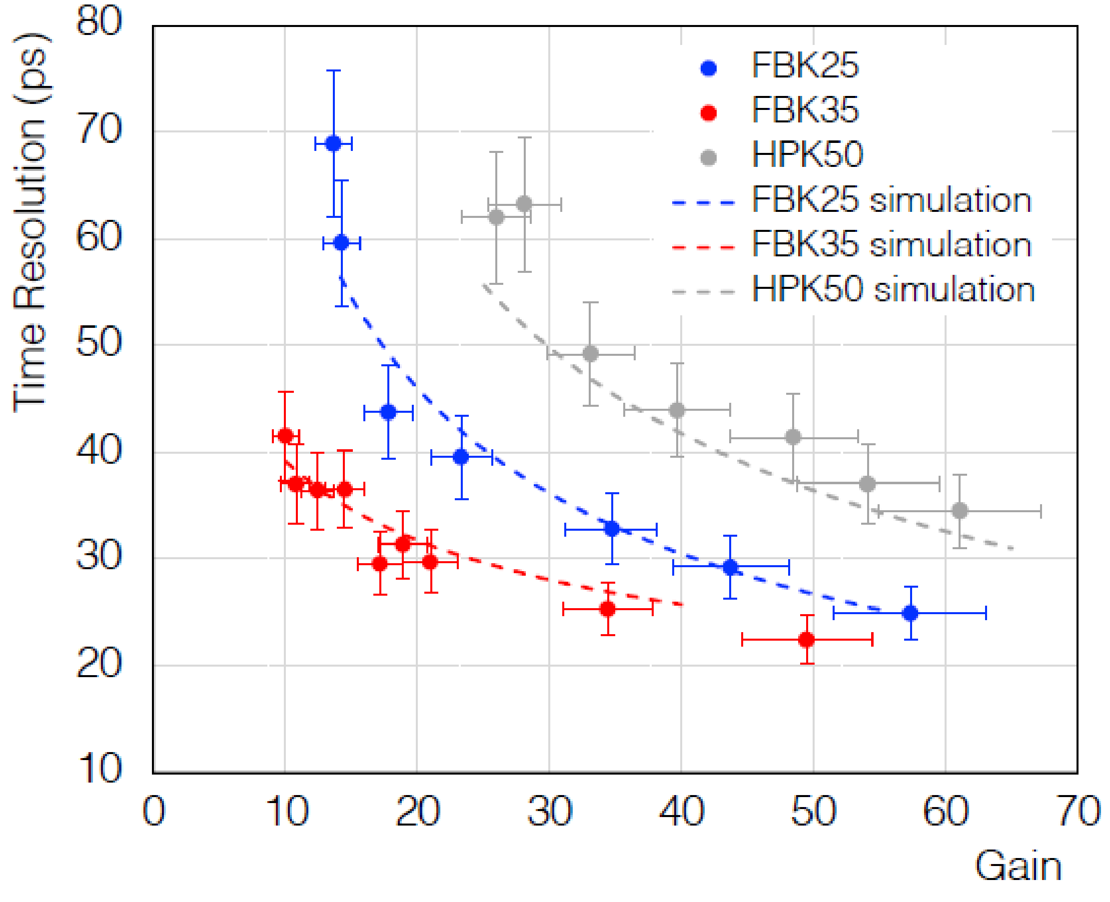
Thickness

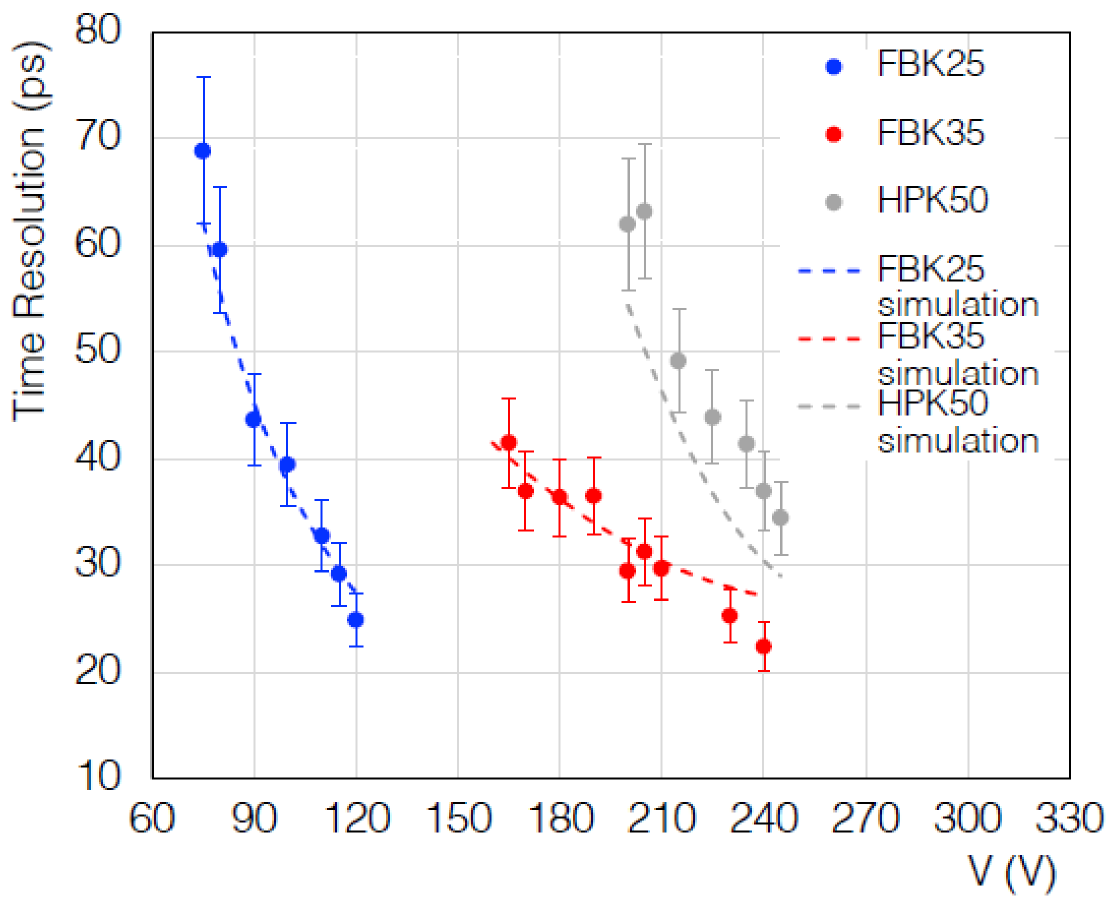
Latest test with ultra-thin LGADs
35 μm and 25 μm

Wafers from eXFlu0 production

- Ultra-thin sensors produced at FBK (EXFLU project)
- Characterized at INFN Bologna, INFN Turin and CERN

F. Carnesecchi, arXiv:2208.05717





- 35μm thick LGADs approach 20ps time resolution (mainly thanks to Landau noise reduction)
- No further improvement moving to 25 μm. Possible causes:
  - higher substrate doping (not saturated electrons velocity in the bulk)
  - Higher noise of the sample

SENSORS AND DEVICES
FONDAZIONE BRUNO KESSLER

Radiation Hardening

Initial Acceptor removal

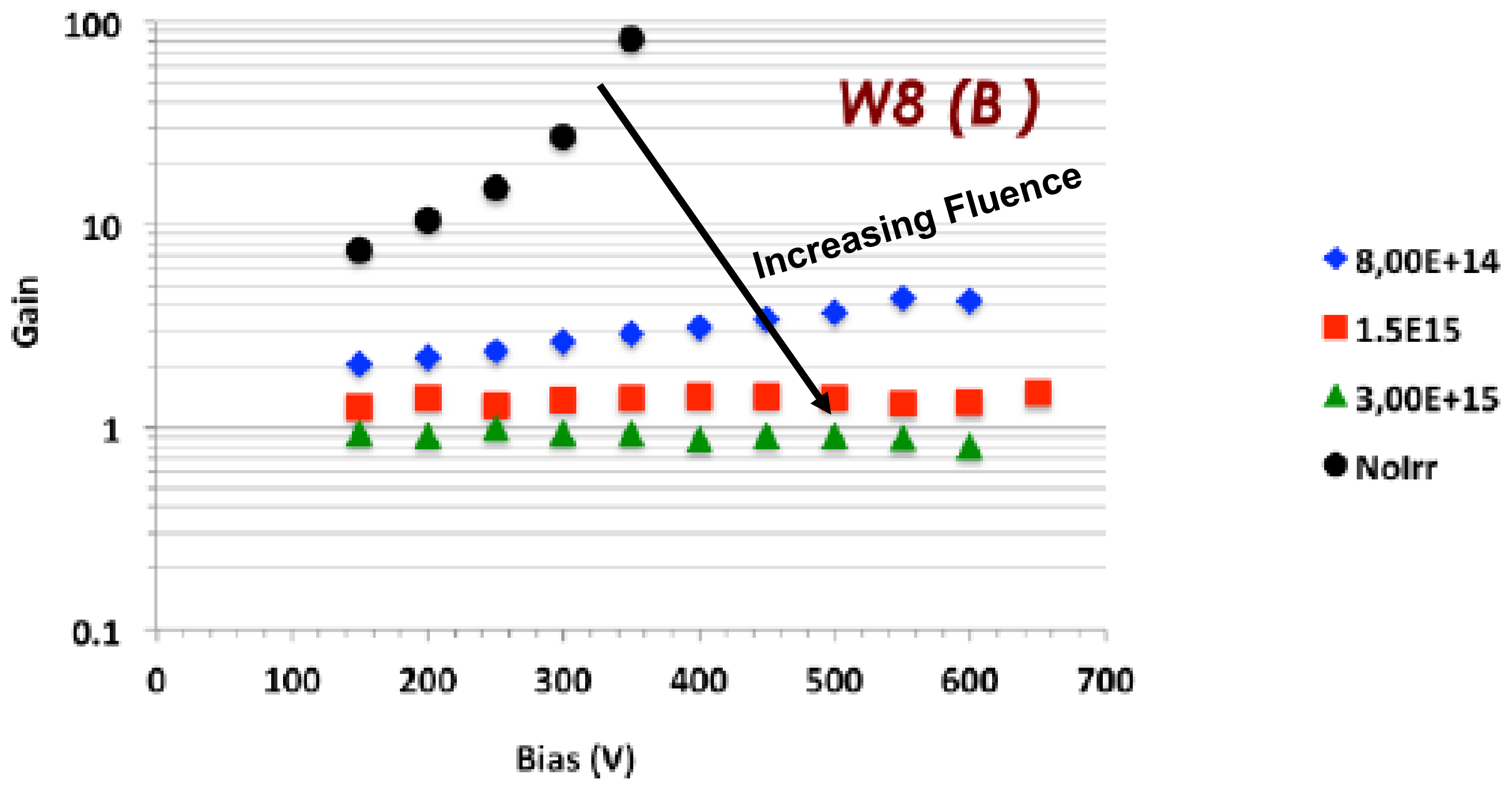
- During irradiation the Gain of LGADs is reduced
- The mechanism can be explained with a reduction of the acceptor concentration in the Gain Layer

$$N_A(\emptyset) = N_A(0)\, e^{-c\emptyset}$$

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

[R. Arcidiacono TREDI2018]

Gain = Q(LGAD) / Q(PiN)



Possible microscopic mechanism:
Boron de-activation due to Si interstitial

$$Si_i + B_s \rightarrow B_i$$
$$B_i + O_i \rightarrow B_iO_i\ (donor\text{-}like)$$

SENSORS AND DEVICES
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Radiation Hardening

Carbon Co-implantation for acceptor removal mitigation

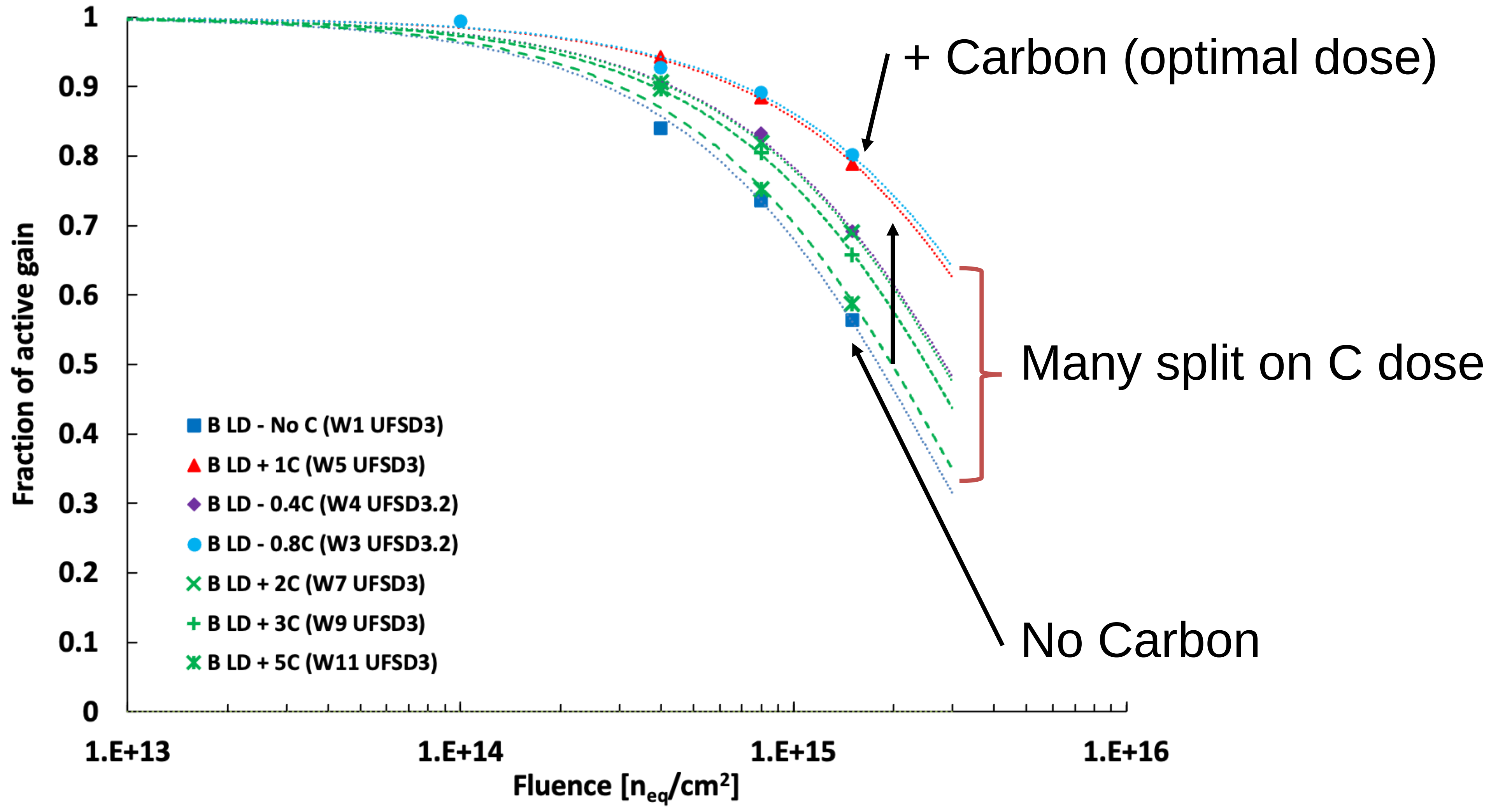
Boron removal

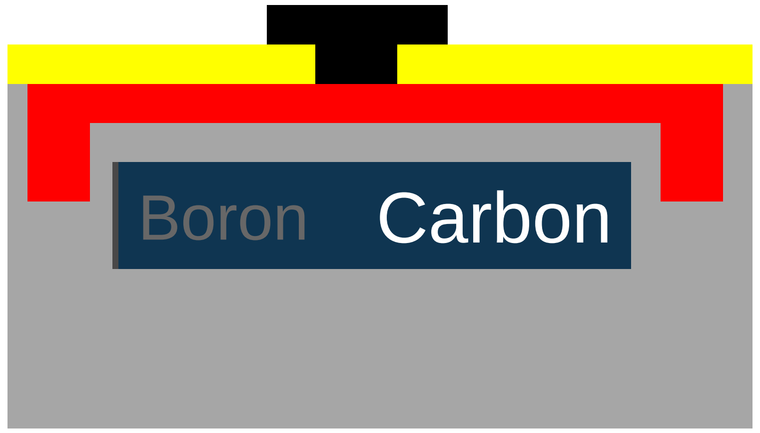
$$Si_i + B_s \rightarrow B_i$$
$$B_i + O_i \rightarrow B_iO_i \text{ (donor-like)}$$

Carbon co-implantation

Carbon Enables competing mechanism

$$Si_i + C_s \rightarrow C_i$$
$$C_i + O_i \rightarrow C_iO_i \text{ (neutral)}$$





Carbon implanted only in the Gain Layer at the same depth (overlapping to Boron)

Carbon co-implantation Optimization

- Carbon Dose
- Carbon implantation depth
- Thermal load Boron/Carbon for activation and diffusion

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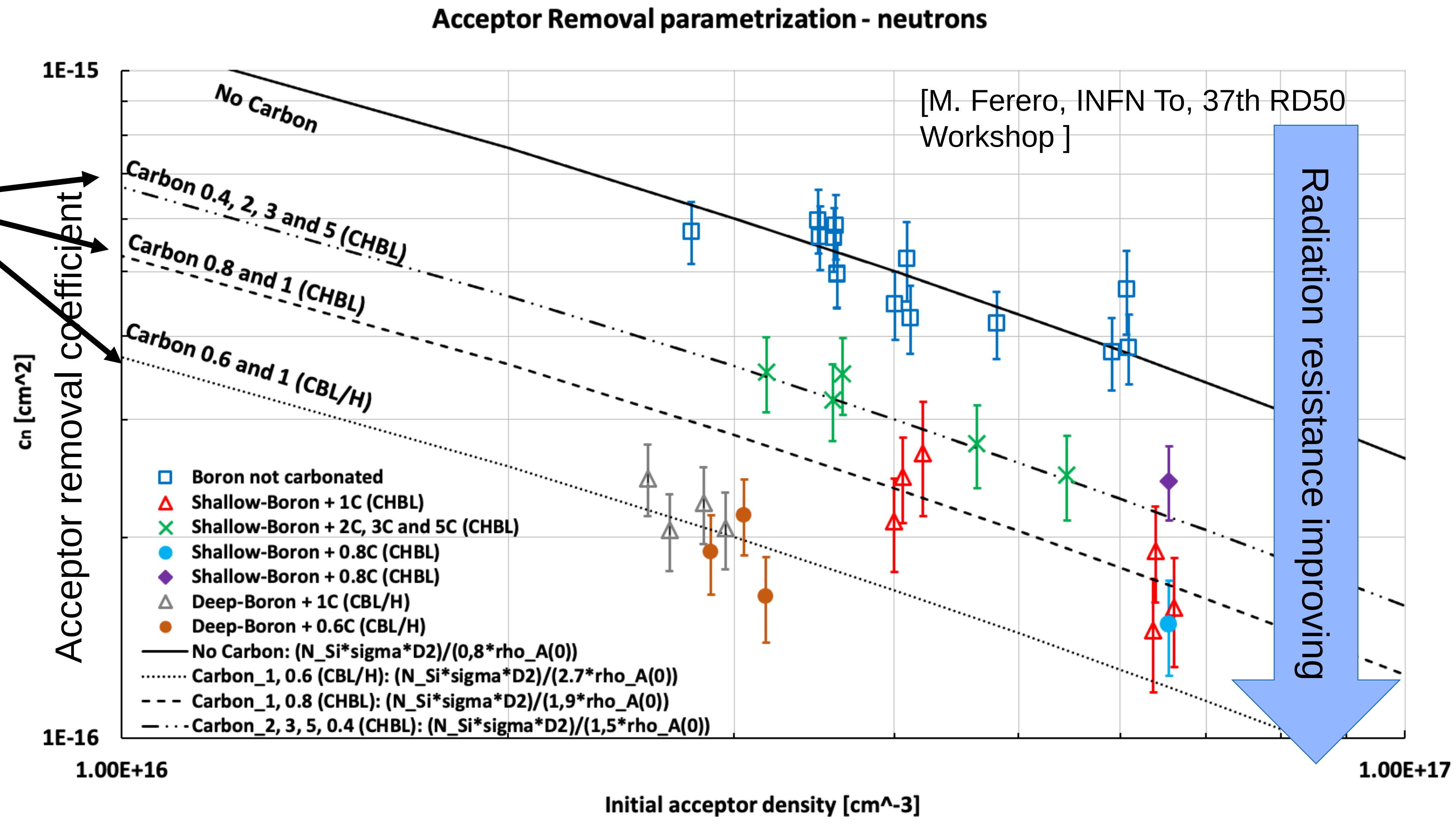
Radiation Hardening

Carbon co-implantation for acceptor removal mitigation

$$N_A(\emptyset) = N_A(0)\, e^{-c\emptyset} \qquad c = c(N_A(0))$$

Different carbon doses and Thermal Load



Higher initial boron Density

Recipe for high radiation resistance

1. Using optimized Carbon dose
2. Increase boron density (w/o increasing the gain too much)

Radiation Hardening

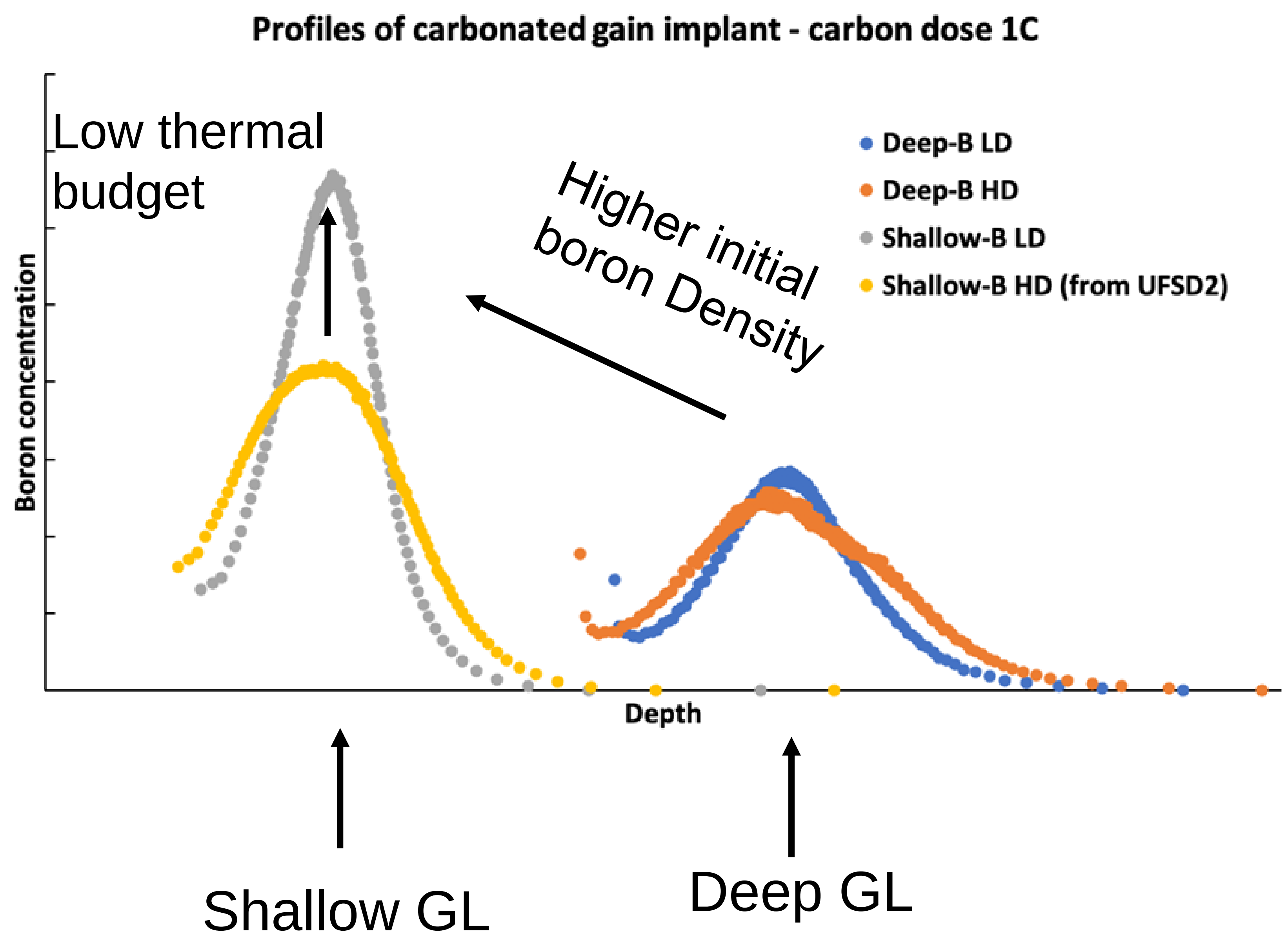
Gain layer optimization

Boron depth: Shallow (~1um) or Deep
Thermal diffusion (low or high)

Higher Boron concentration -> lower c factor

- Shallow B implant
  (more dose for the same gain)
- Narrower (low diffused) B profiles

Disadvantages of a Shallow gain layer:
• Worst gain recovery than deep-gain implant, using external bias

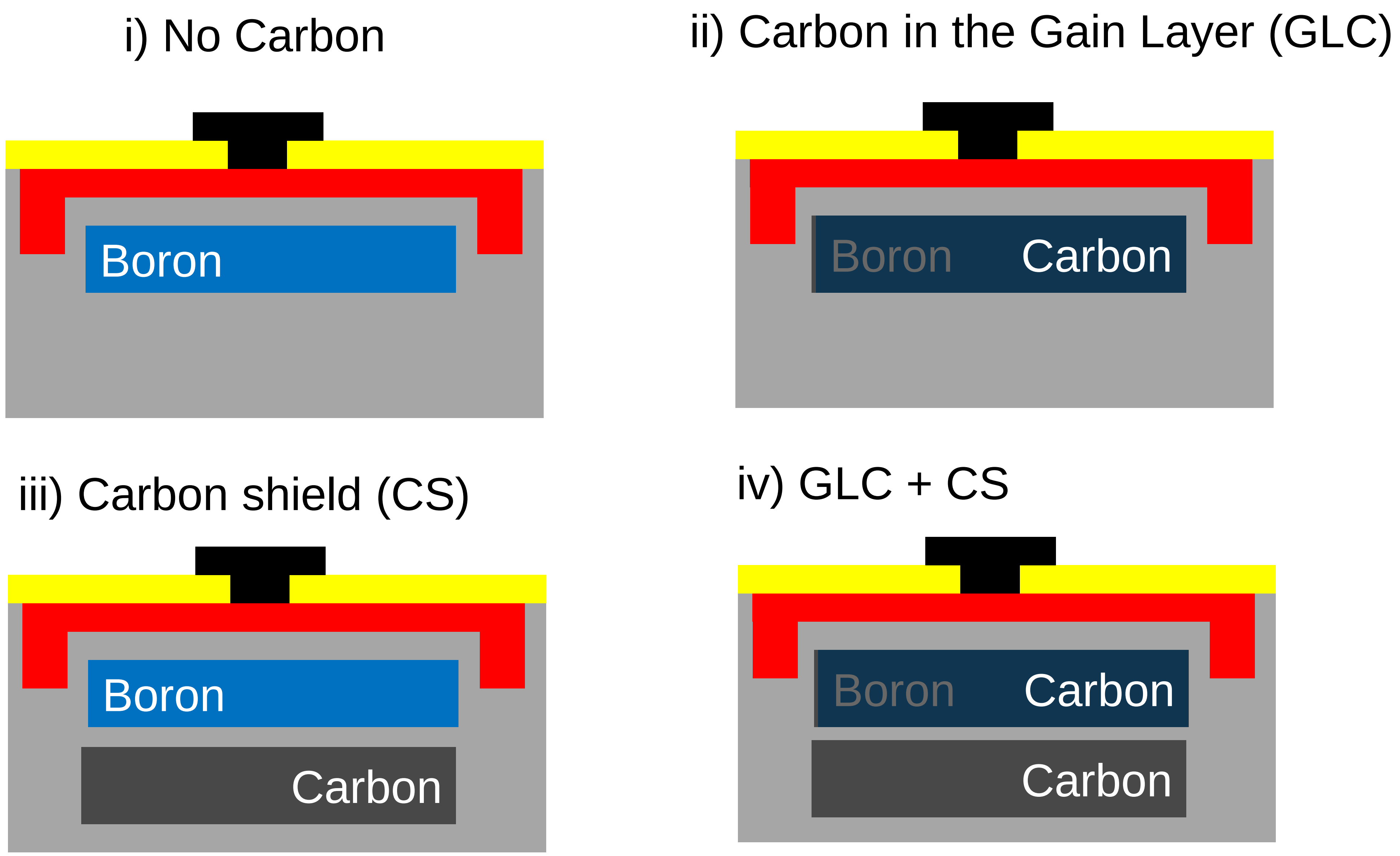


Radiation Hardening

Carbon Co-implantation for acceptor removal mitigation

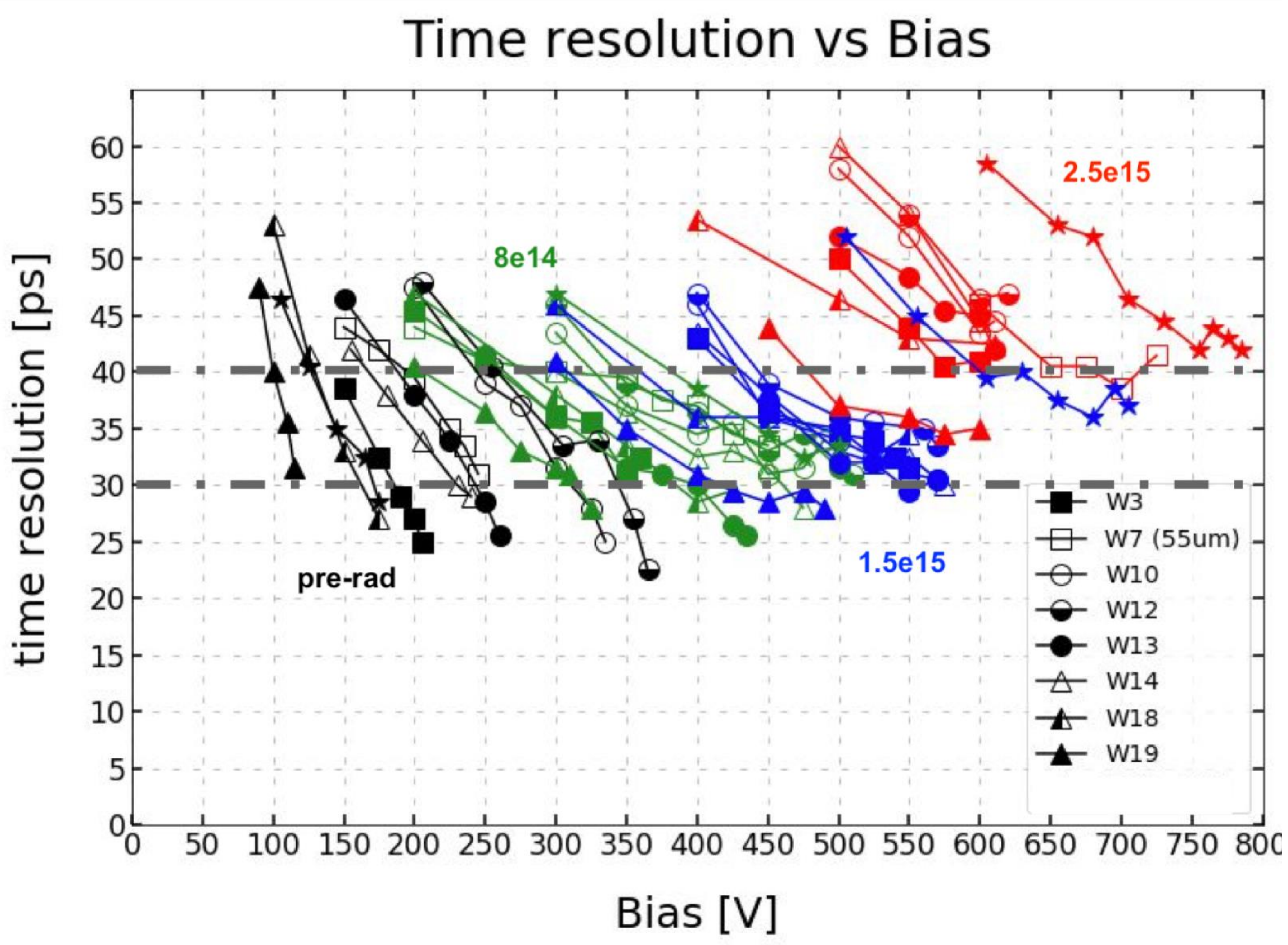
- Shifting (or adding) an additional Carbon implant deeper than the Gain Layer (Carbon shield)
- More tests are ongoing…

First tests on GLC + CS show a further decreasing of the c factor of ~ 20%.



(the right place to add Carbon has still to be understood…)

Recipe for fast timing



Time resolution

< 30 ps up to 1e15 neq/cm^2

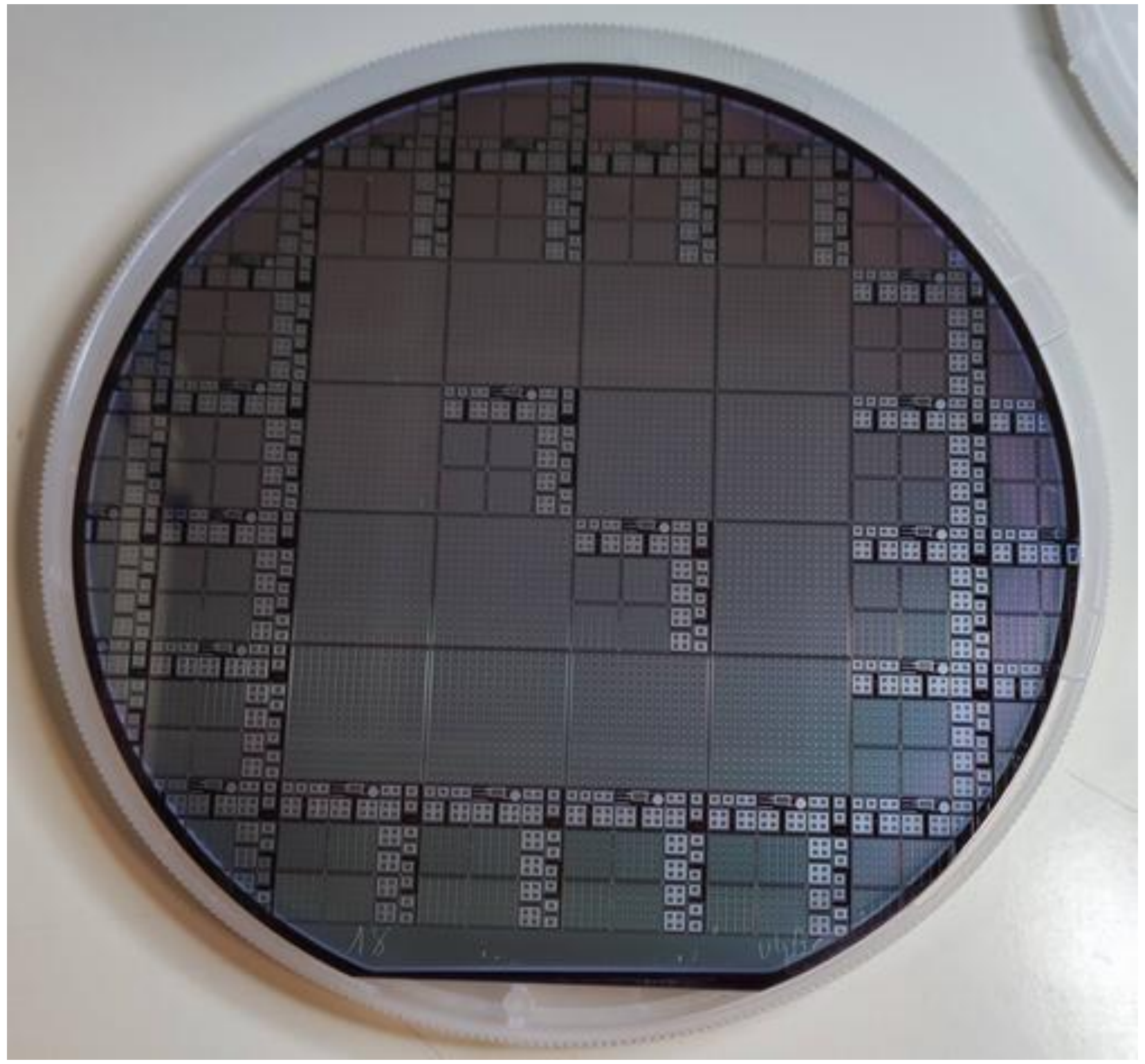
< 40 ps up to 2.5e15 neq/cm^2

Demonstrated radiation resistance and time resolution for HL-LHC

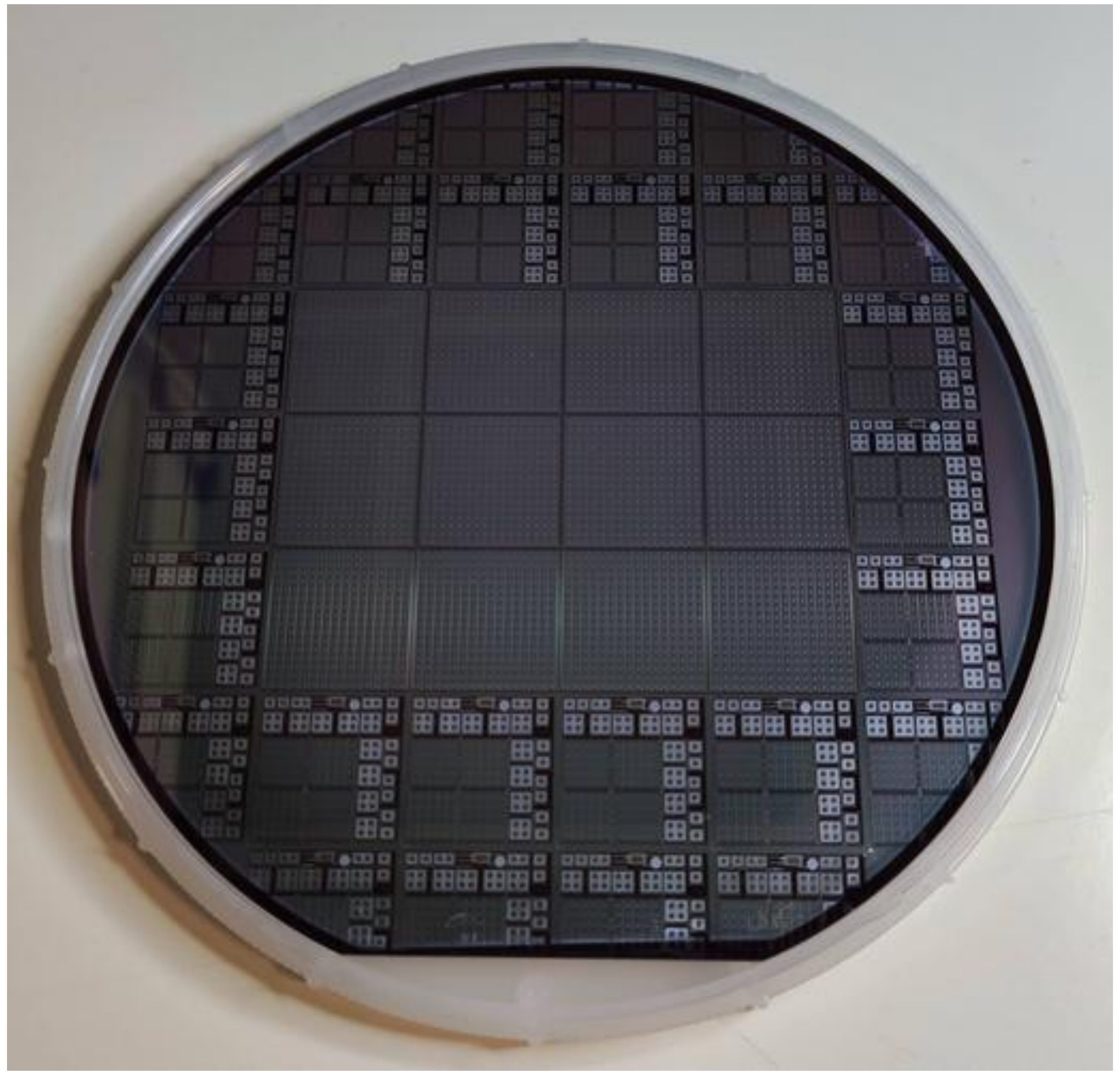
Recipe for fast timing

Production qualification

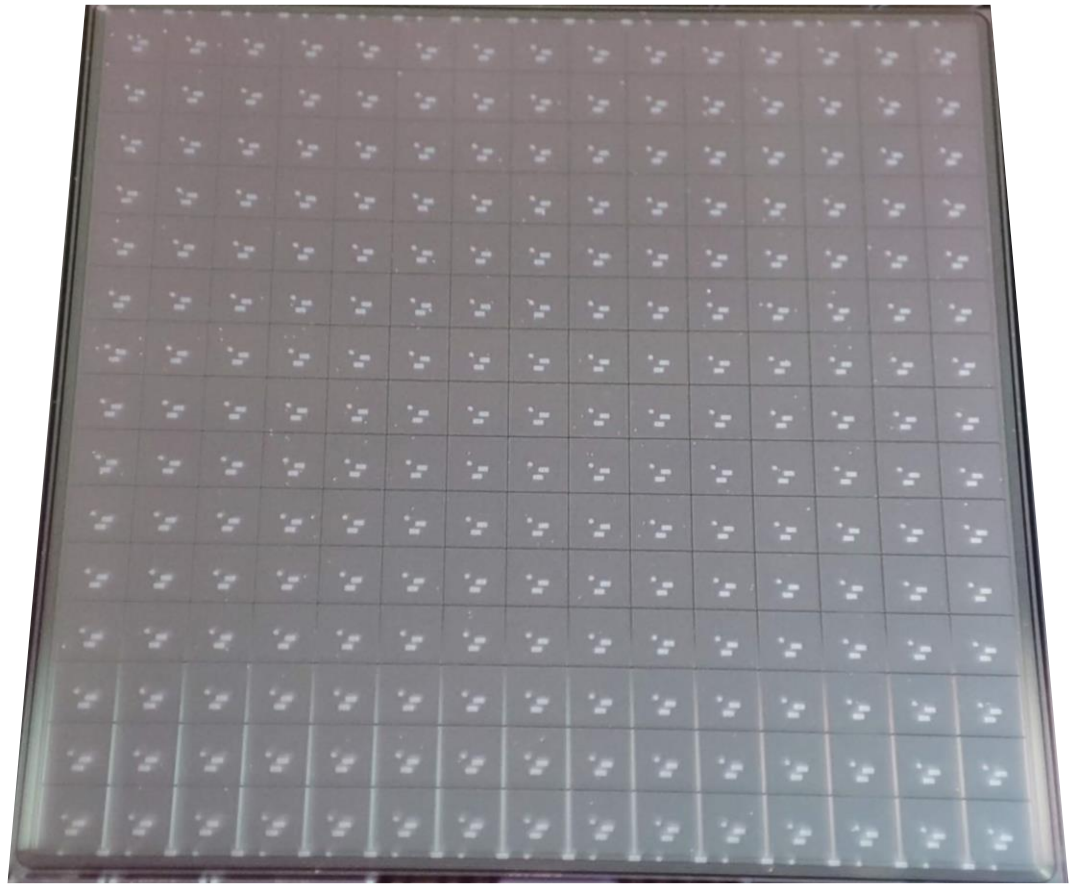
ATLAS - HGTD



CMS - ETL



- Full sensors ~ 2 x 2 cm^2
- 15 x 15 and 16 x 16 arrays
- 1.3 mm^2 pads

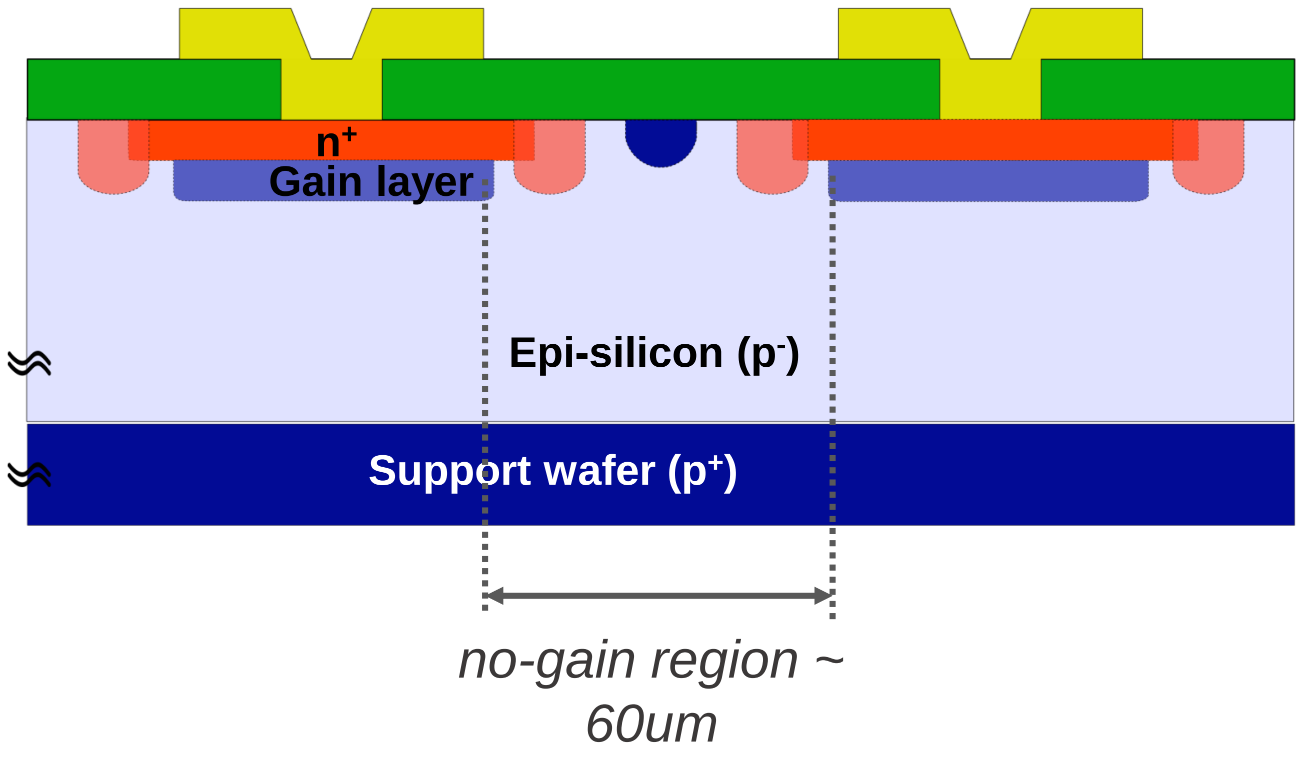


UFSD 4 batch for final sensor qualification

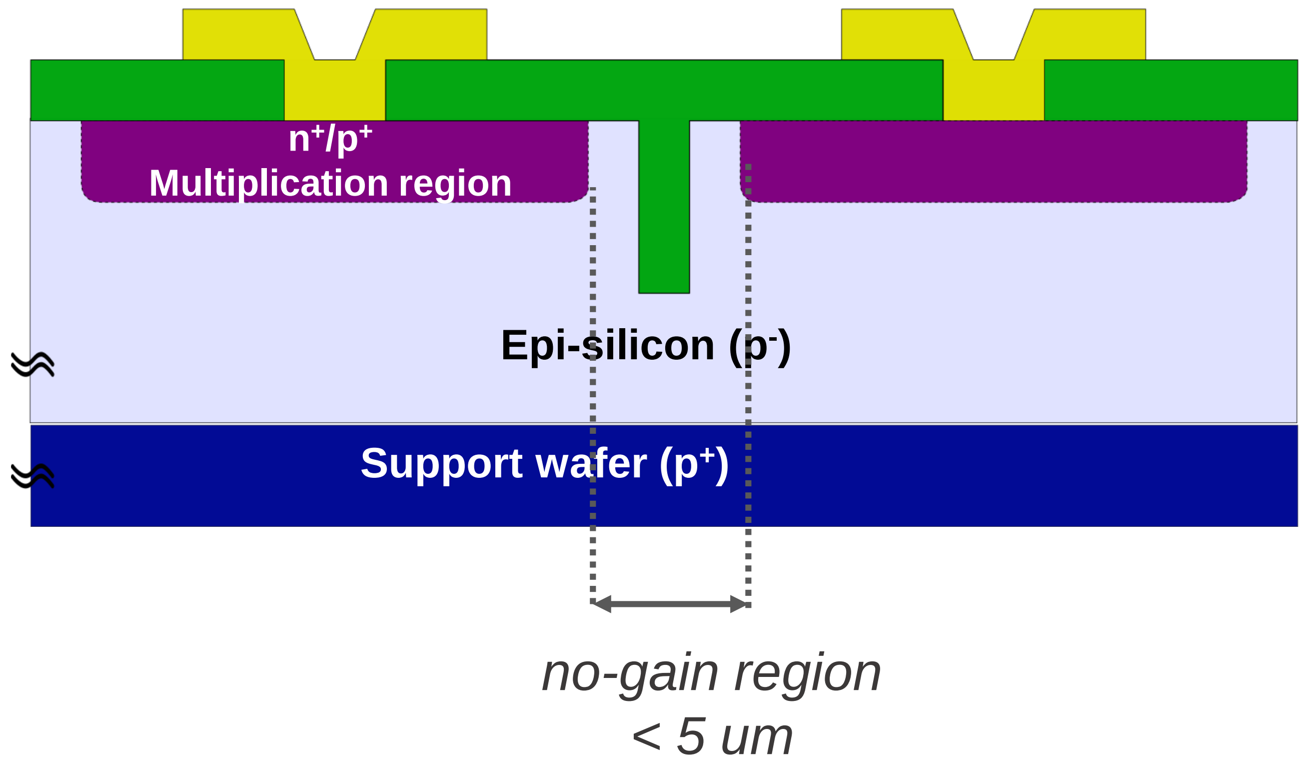
Novel LGAD schemes for fine-segmentation

Trench Isolated - LGAD Technology

Segmented Standard LGAD



Trench-Isolated LGAD



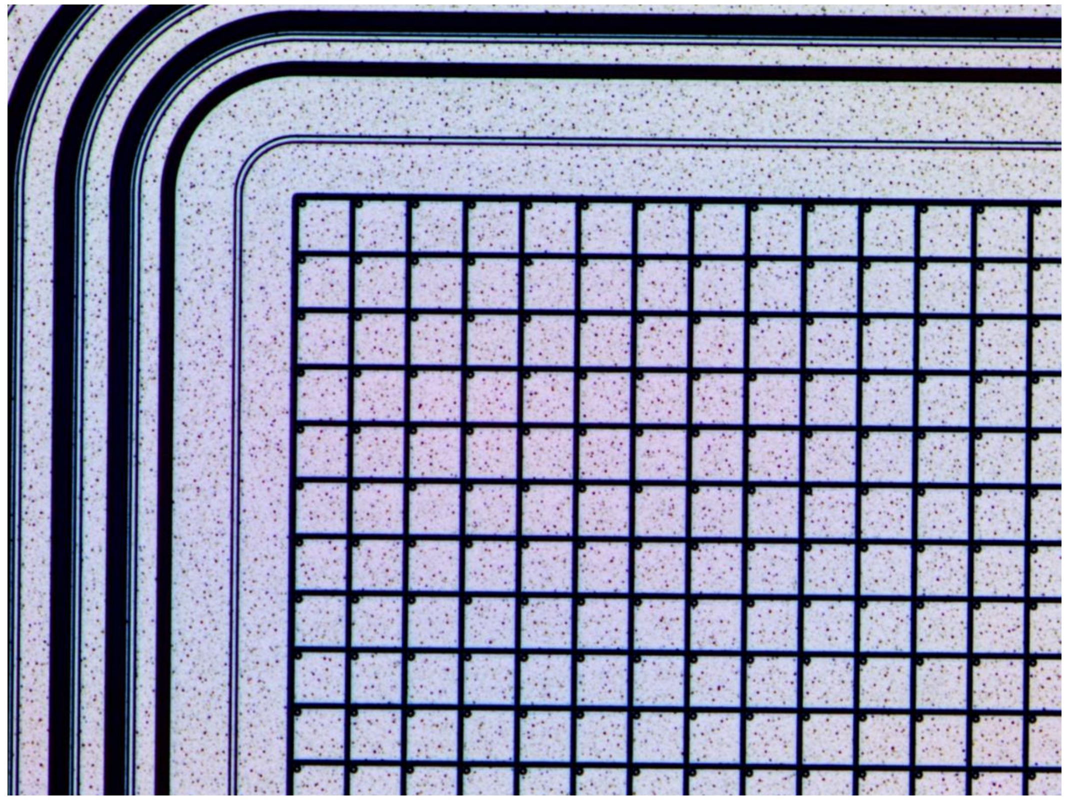
- No-gain region at the pixel border due to isolation and termination structures: JTE and p-stop
- Dead distance for charge multiplication ~ 40 - 80 µm

- **JTE and p-stop are replaced by a single trench (< 1 um wide)**
- Trenches act as a drift/diffusion barrier for electrons and isolate the pixels.

Novel LGAD schemes for fine-segmentation

Trench Isolated - LGAD Technology

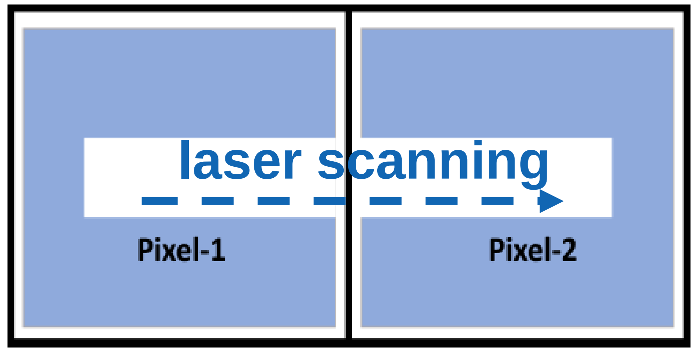
Pixels
55 × 55 μm² (Medipix/Timepix)
FF > 80%

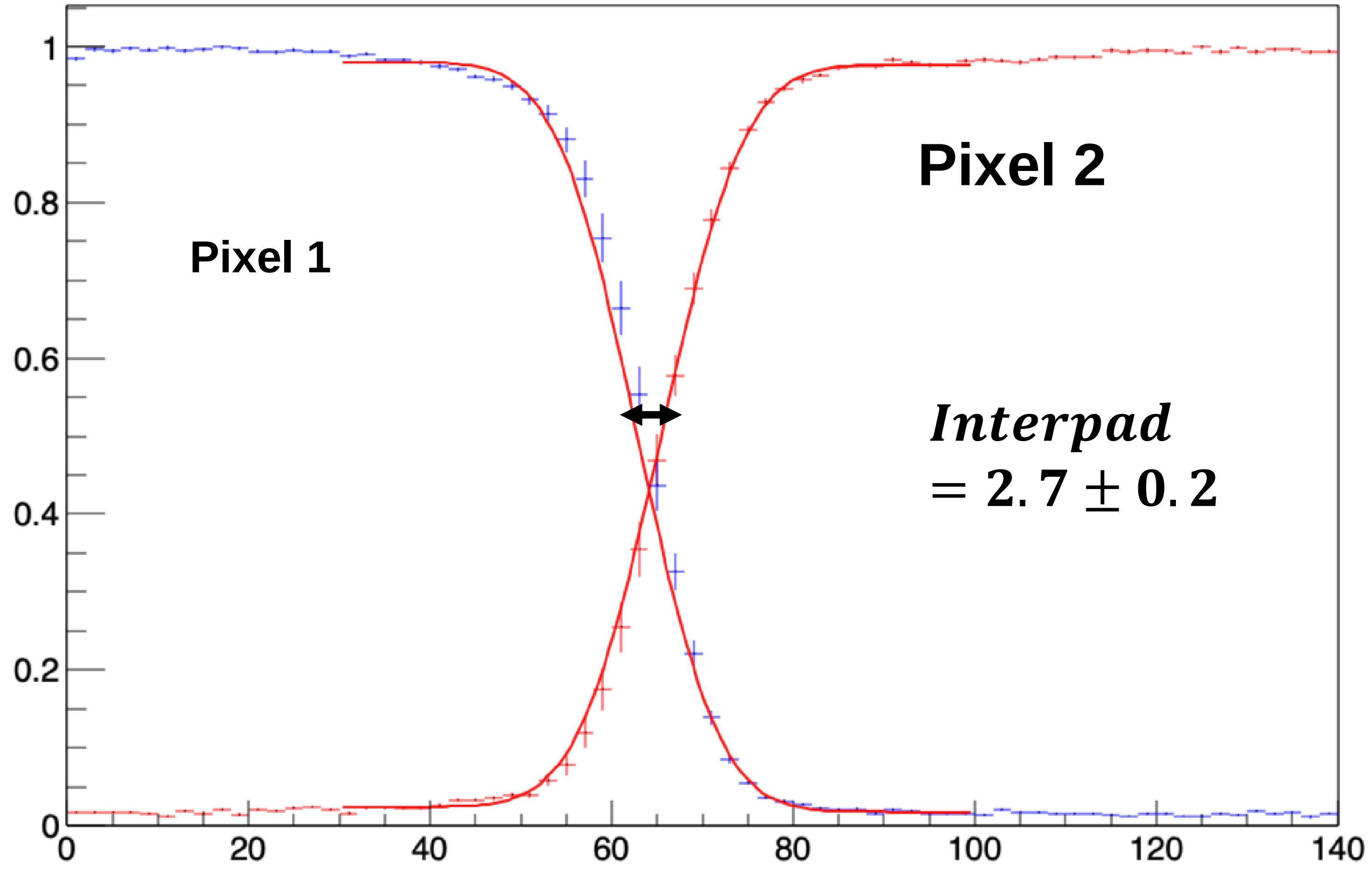


Inter-pad distance
Measured with TCT setup (red laser)

Measured at INFN TO (courtesy of M. Ferrero)

Interpixel distance in the range 2-10 um (depending on the layout split)





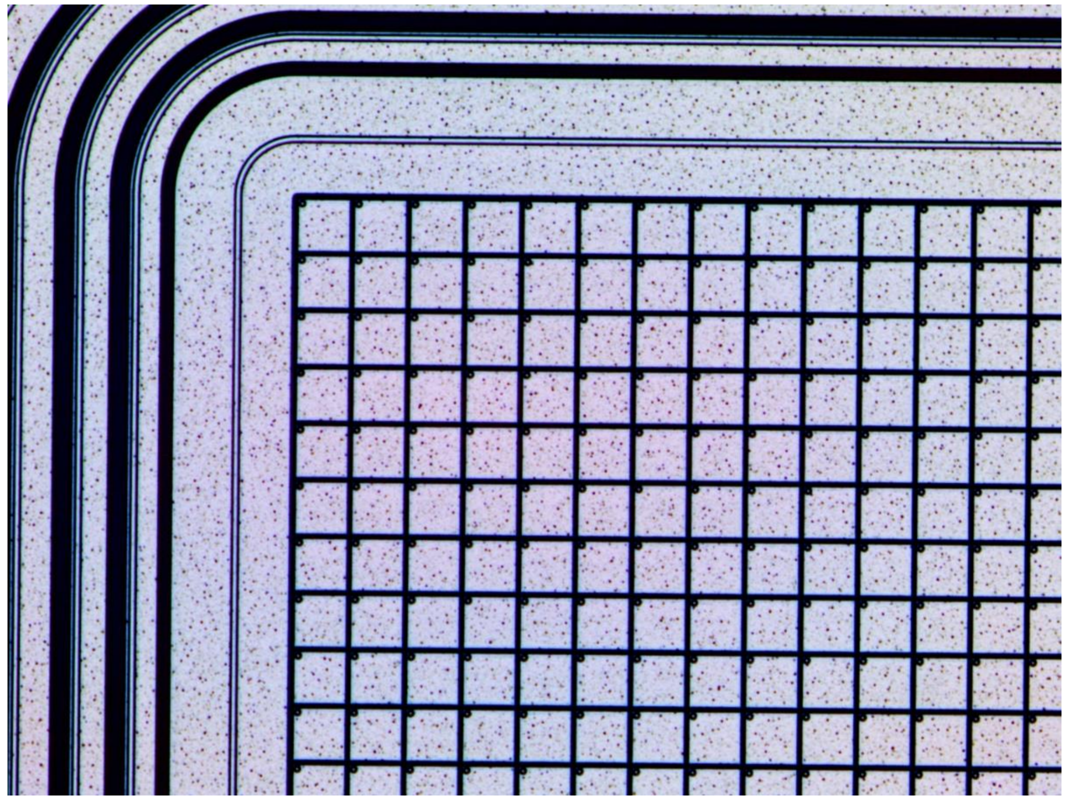
Novel LGAD schemes for fine-segmentation

Trench Isolated - LGAD Technology

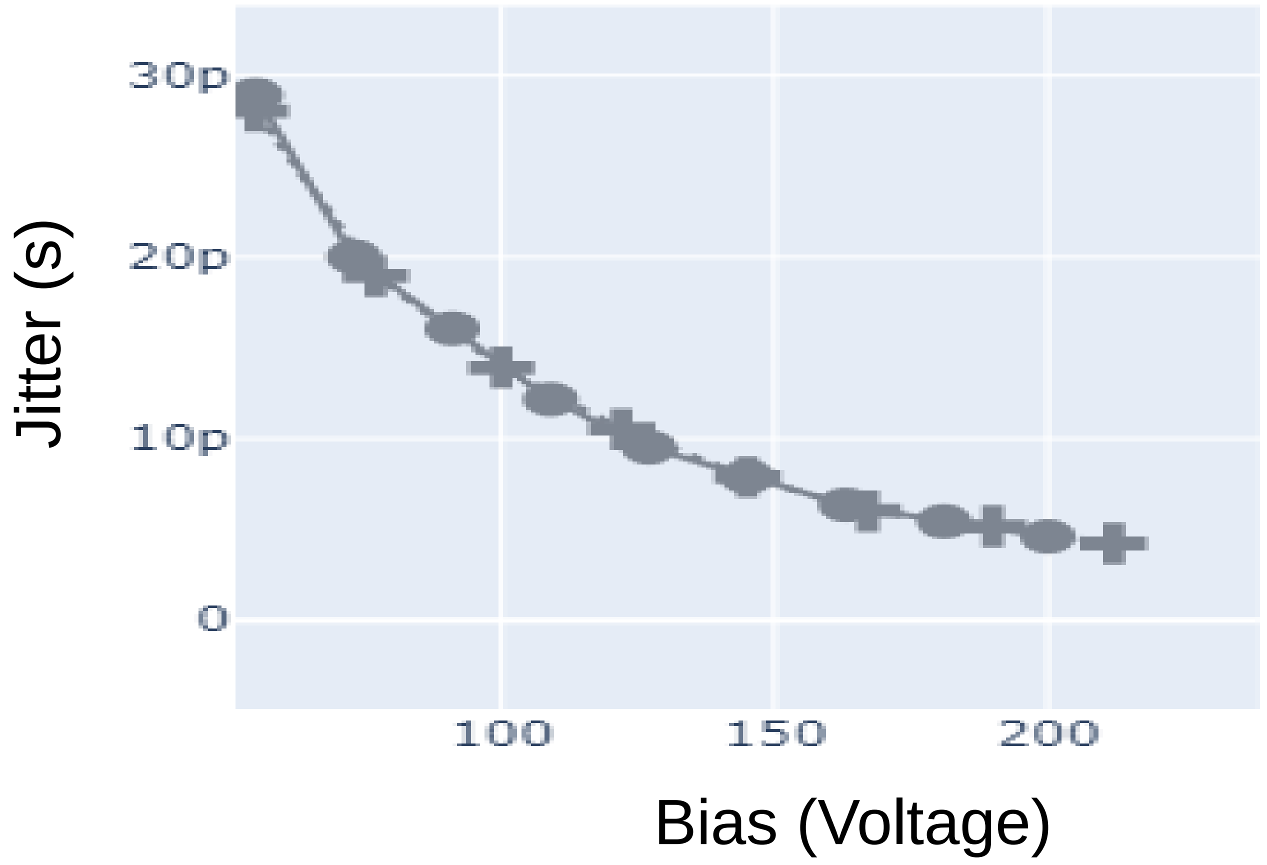
Pixels
55 × 55 µm^2 (Medipix/Timepix)
FF > 80%

Time Resolution (jitter)
Measured with TCT setup (red laser)

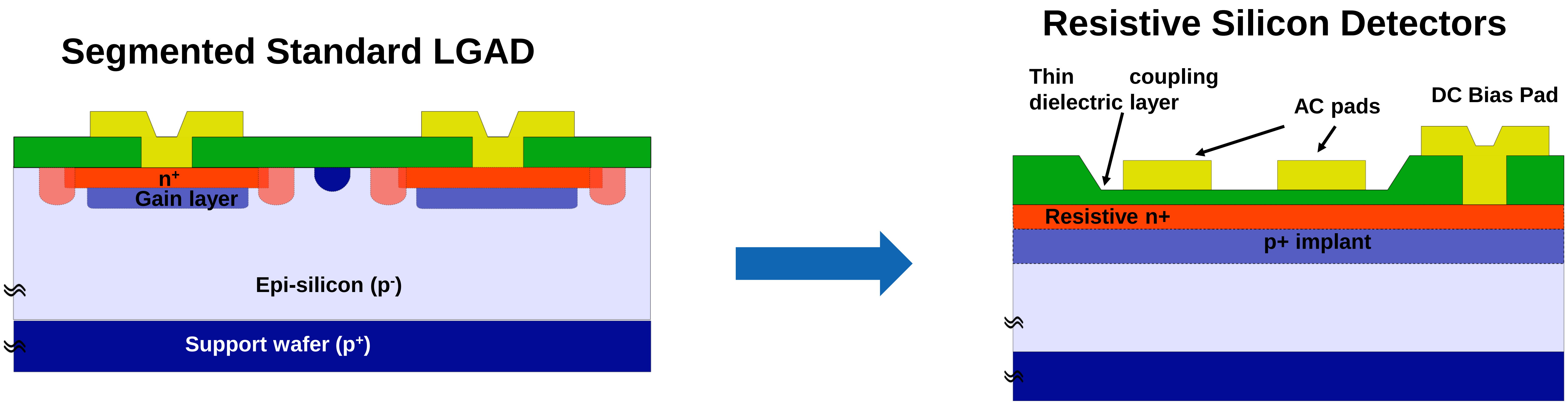
M. Senger – VCI 2022



- Not-degradated time resolution wrt standard LGADs
- Time resolution (laser setup) < 10 ps



RSD – Resistive Silicon Detectors (aka AC-LGADs)



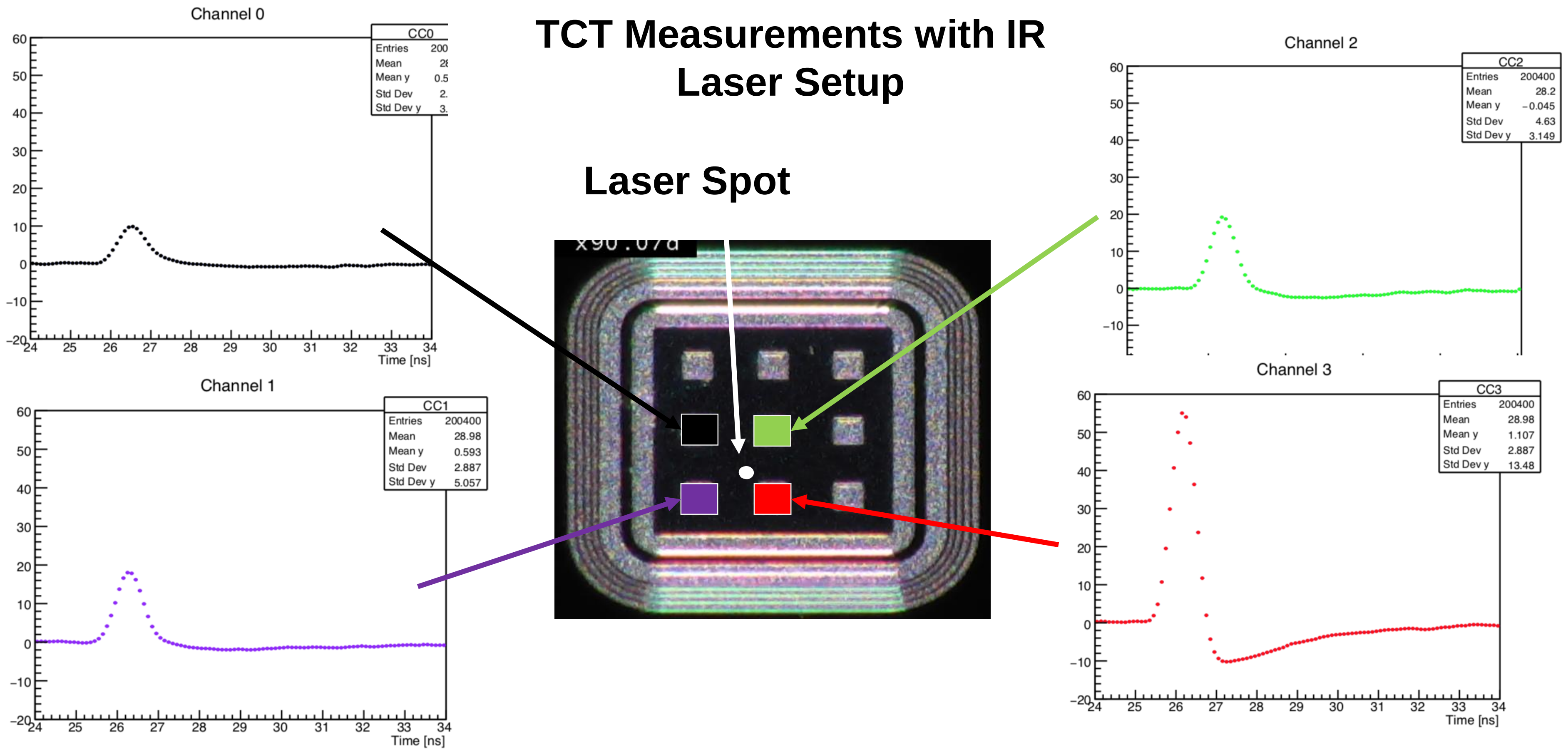
Main Technological Features

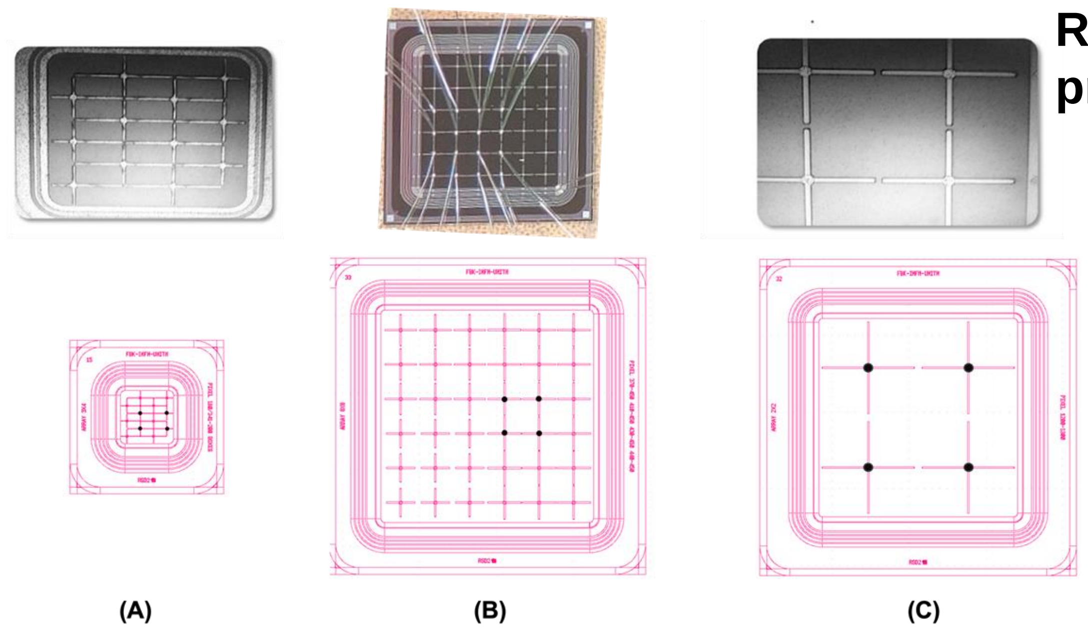
- Not-segmented p-gain implant
- Resistive n+ implant
- AC Metal pads

RSD is not just an LGAD with AC-pads.
It is a different way to read-out the signal and to segment the sensor

RSD – Resistive Silicon Detectors (aka AC-LGADs)

How does it works

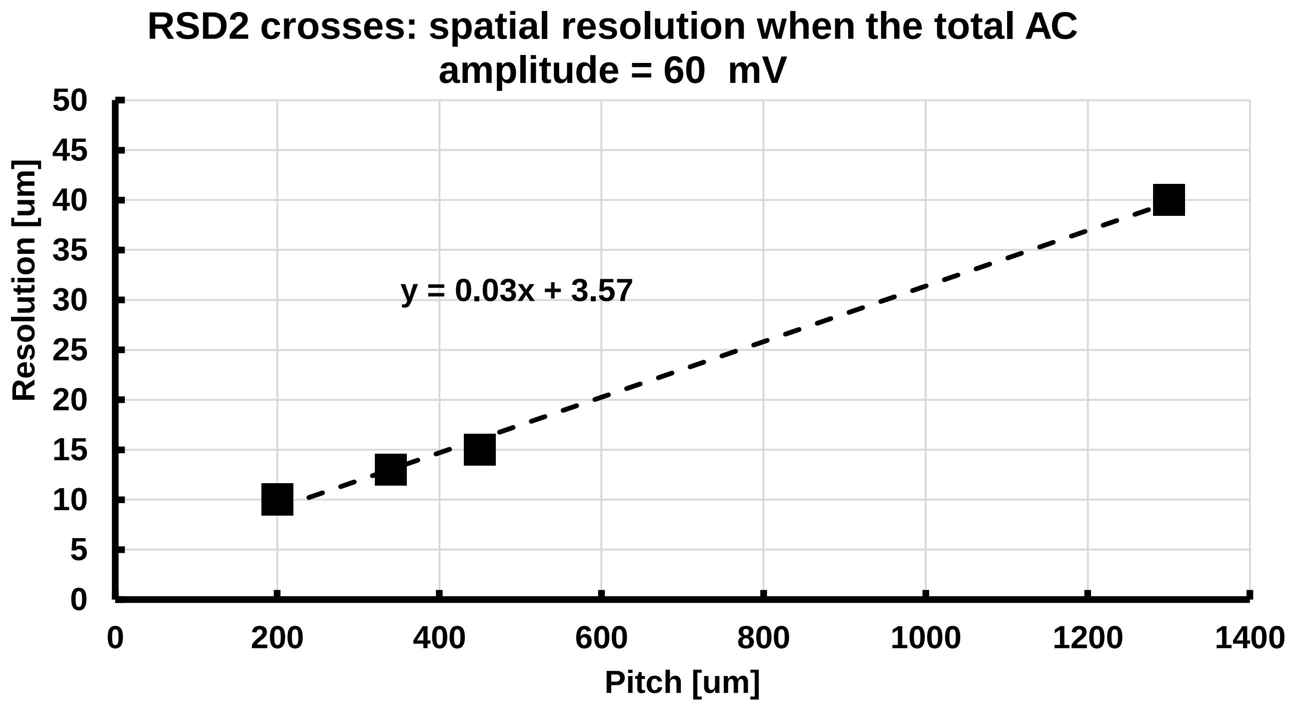




RSD2 production

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

N. Cartiglia



the resolution is 3% of the pixel size

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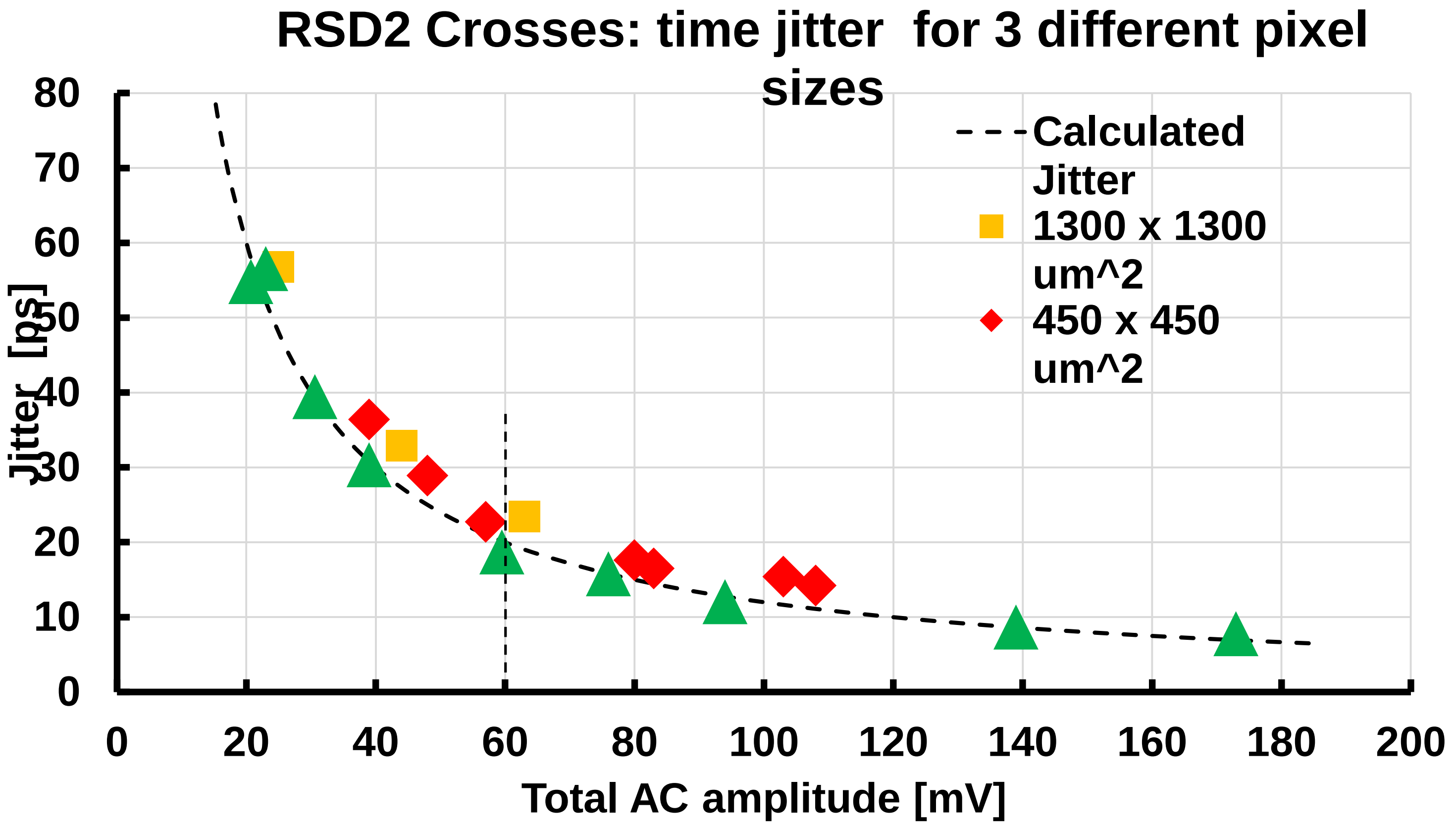
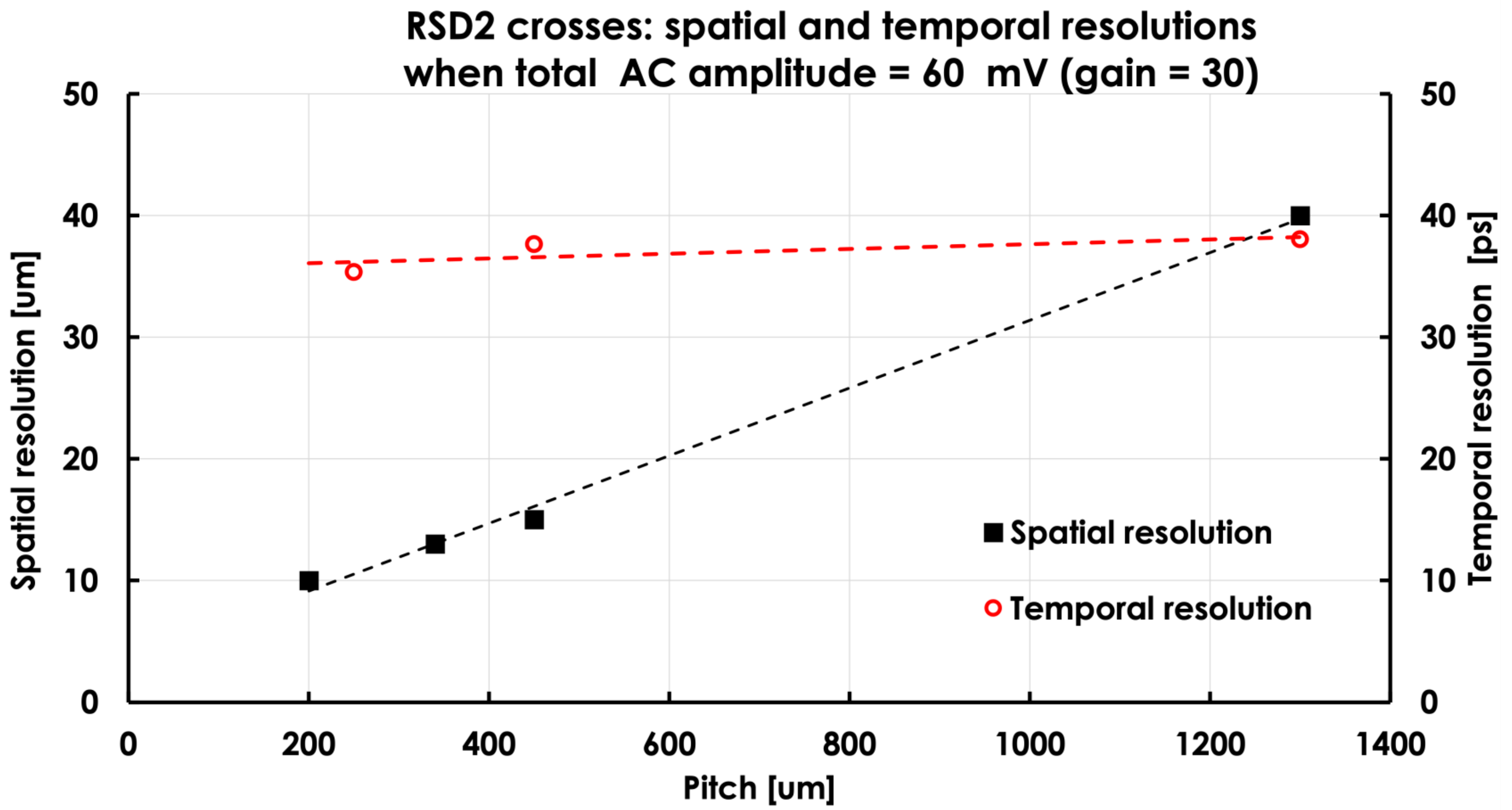
RSD – Resistive Silicon Detectors (aka AC-LGADs)

N. Cartiglia

Time resolution



The temporal resolution does not depend on the pize size, only on the total amplitude.
(total amplitude = sum of the amplitudes of the 4 read-out electrodes at the pixel corner)



RSD2 crosse overall result:

- Spatial resolution ~ 3% pitch size
- Temporal resolution ~ 35 ps, regardless of pitch size

SENSORS AND DEVICES
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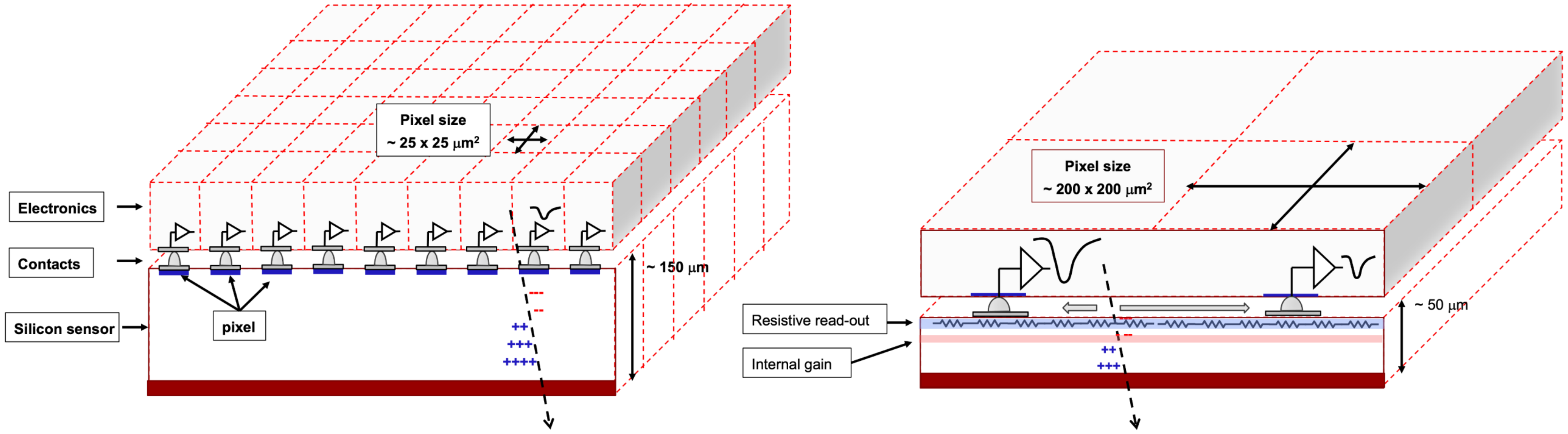
RSD – Resistive Silicon Detectors (aka AC-LGADs)

Final GOAL



Standard tracker **RSD-based tracker**

The design of a tracker based on RSD:

It delivers ~ 30 ps temporal resolution and excellent spatial resolution with large pixels

- For the same spatial resolution, RSD trackers use 50-100 fewer pixels
- The electronic circuitry can be easily accommodated
- The power consumption is much lower;

Conclusions

- In the last years FBK developed LGADs technology for 4D-tracking
- 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
- The radiation resistance can be further increased by optimizing Carbon co-implantation or dopant co-implantation
- The new TI-LGAD technology preserves the time resolution of LGADs scaling down the pixel size to few tens of microns.
- RSD technology can combine the 30ps time resolution, few microns space resolution and radiation hardness with a reduced number of read-out channels.

Thank you for your attention

Acknowledgements

- Part of the work has been performed in the framework of RD50
- Some batches have been produced in the framework of convenzione INFN/FBK
- Horizon 2020, grant UFSD669529
- Progetto PRIN2017, MIUR, 4DInSide, Prin2017
- Progetto FARE, MIUR, R165xr8frt_fare
- Dipartimenti di Eccellenza, Torino Physics Dep. (ex L. 232/2016, art. 1, cc. 314, 337)

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

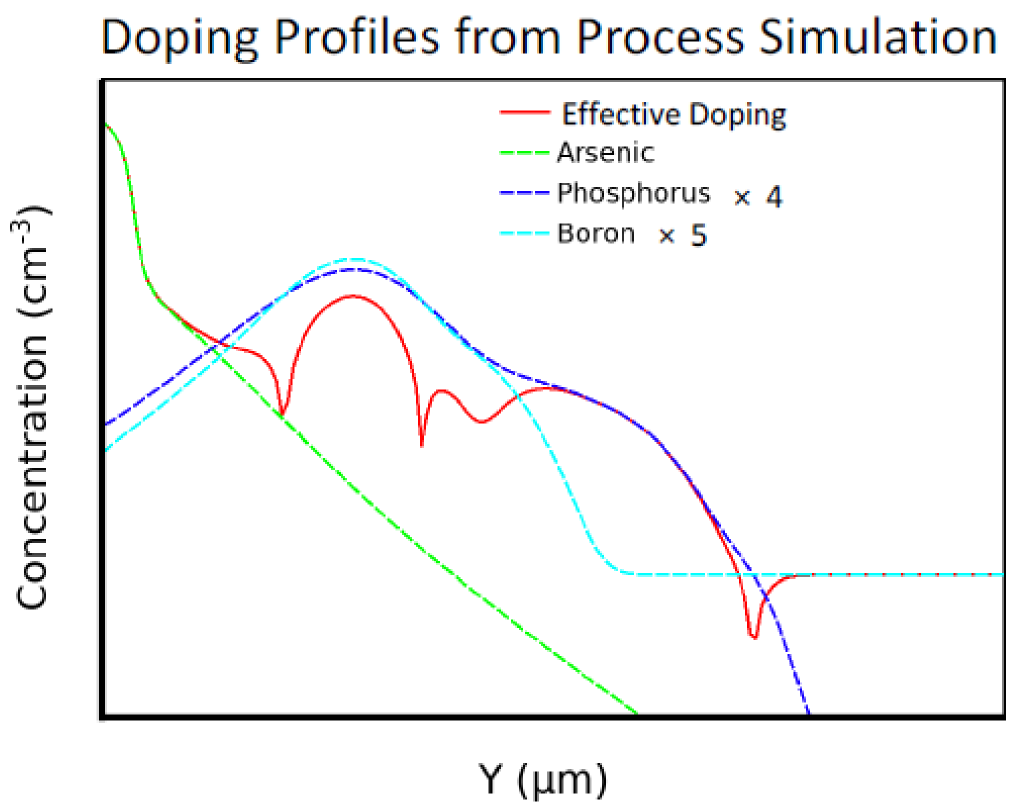
paternoster@fbk.eu

Radiation Hardening at extreme fluences

Psphorous/Boron co-doping

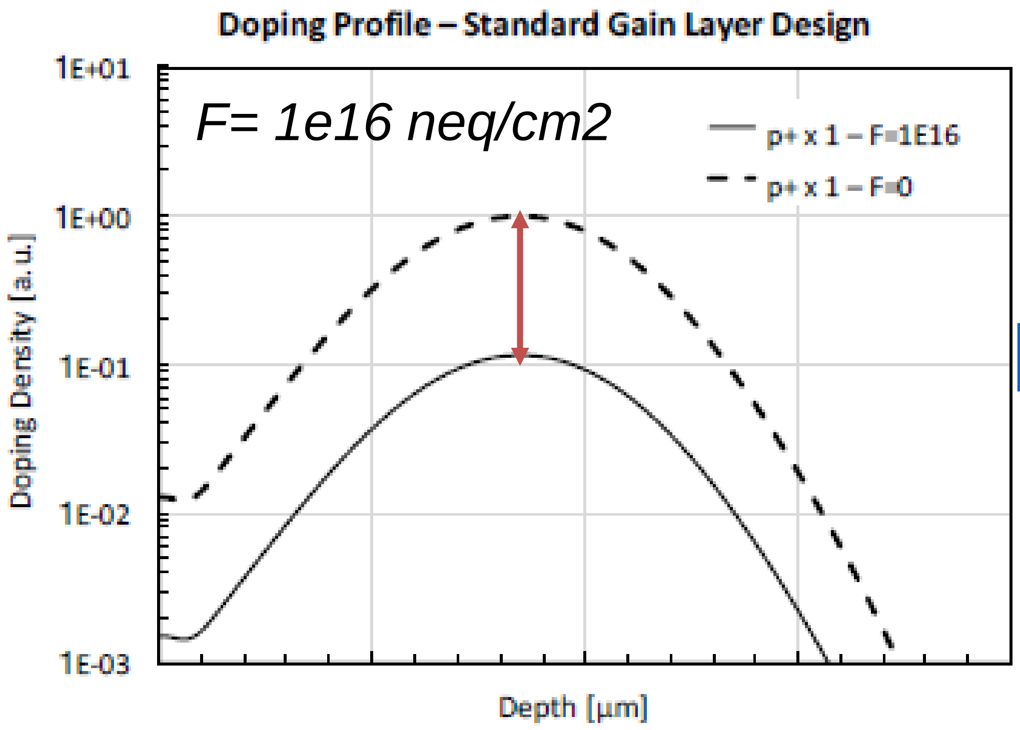
eXFlu project (V. Sola, INFN To)

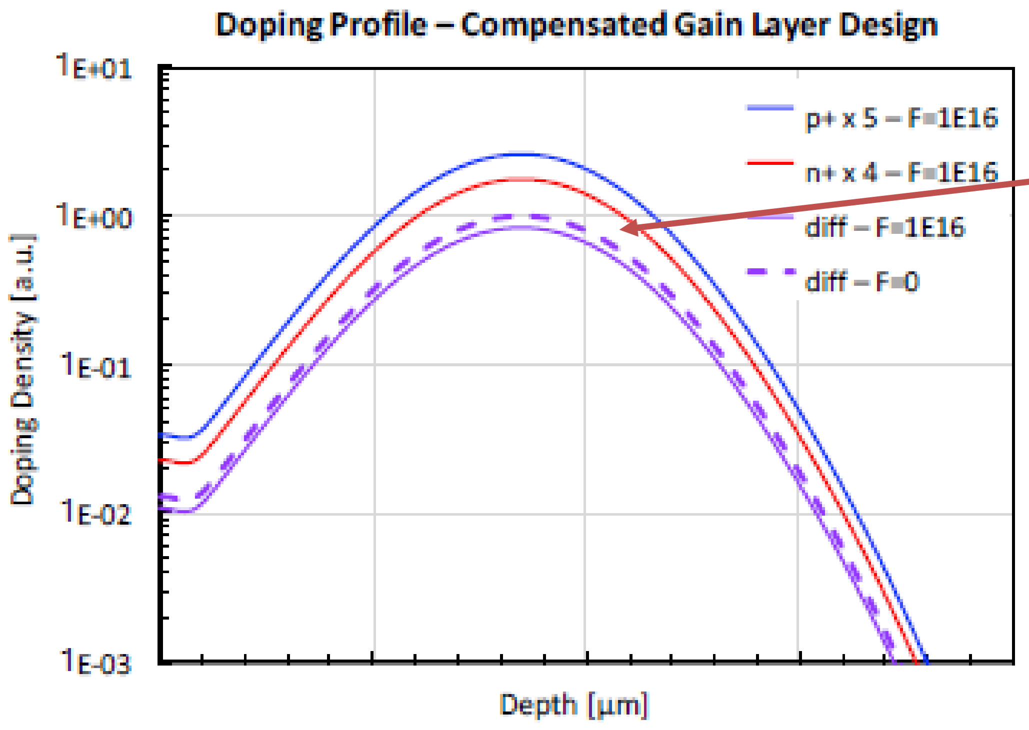
GOAL: operate LGADs at fluence > 10^{16} neq/cm



Gain layer is obtained by co-implanting Boron and Phosphorous

1*B -> 5*B + 4*Ph





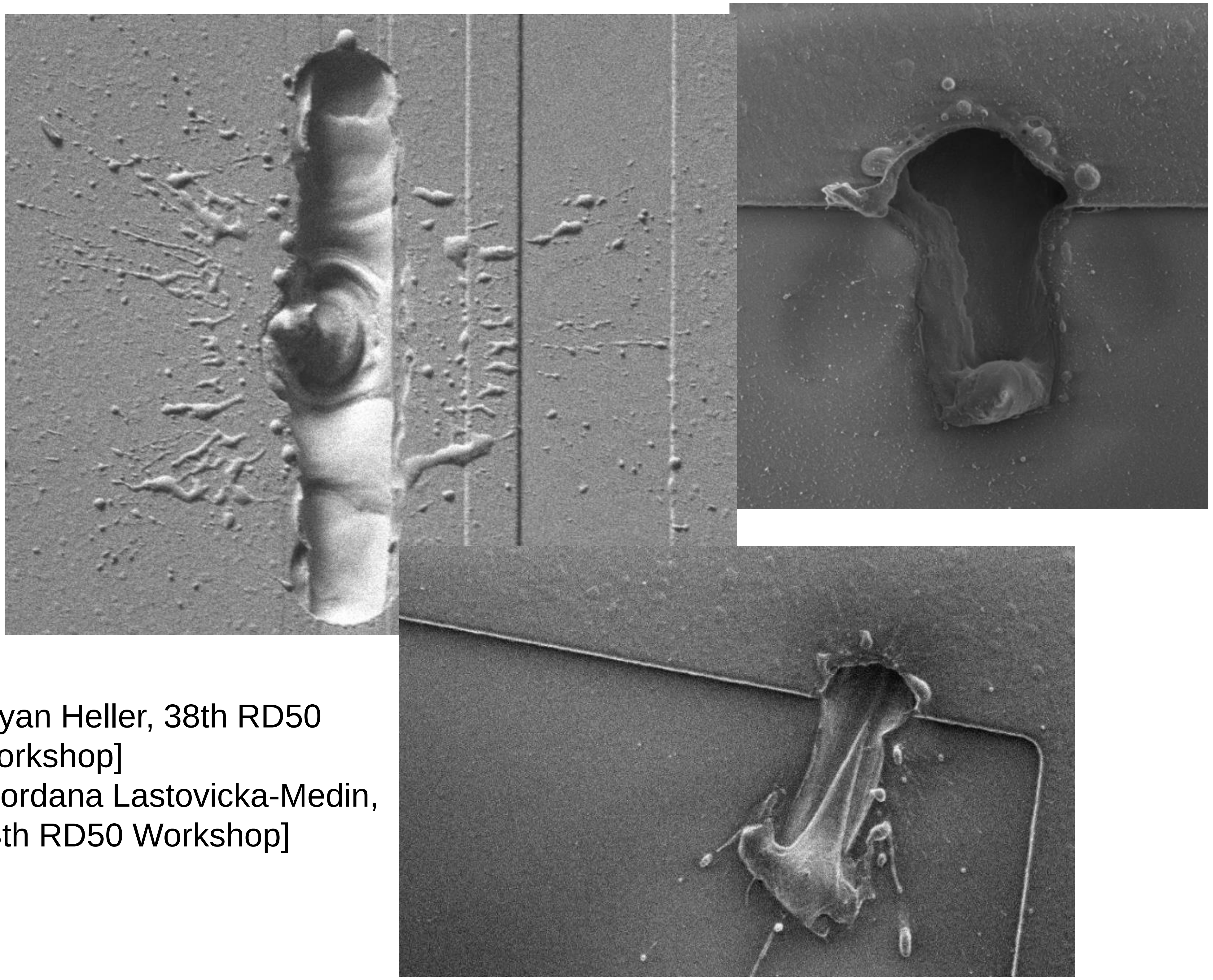
- No acceptor removal after F= 1e16 neq/cm2
- It works under the assumption ($c_A \approx c_B$)
- Production to be completed in October 2022

LGAD – Radiation hardness

Thickness

SEB = Single Event Burnout

- 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
- Fatal Voltage becomes lower for thinner sensors

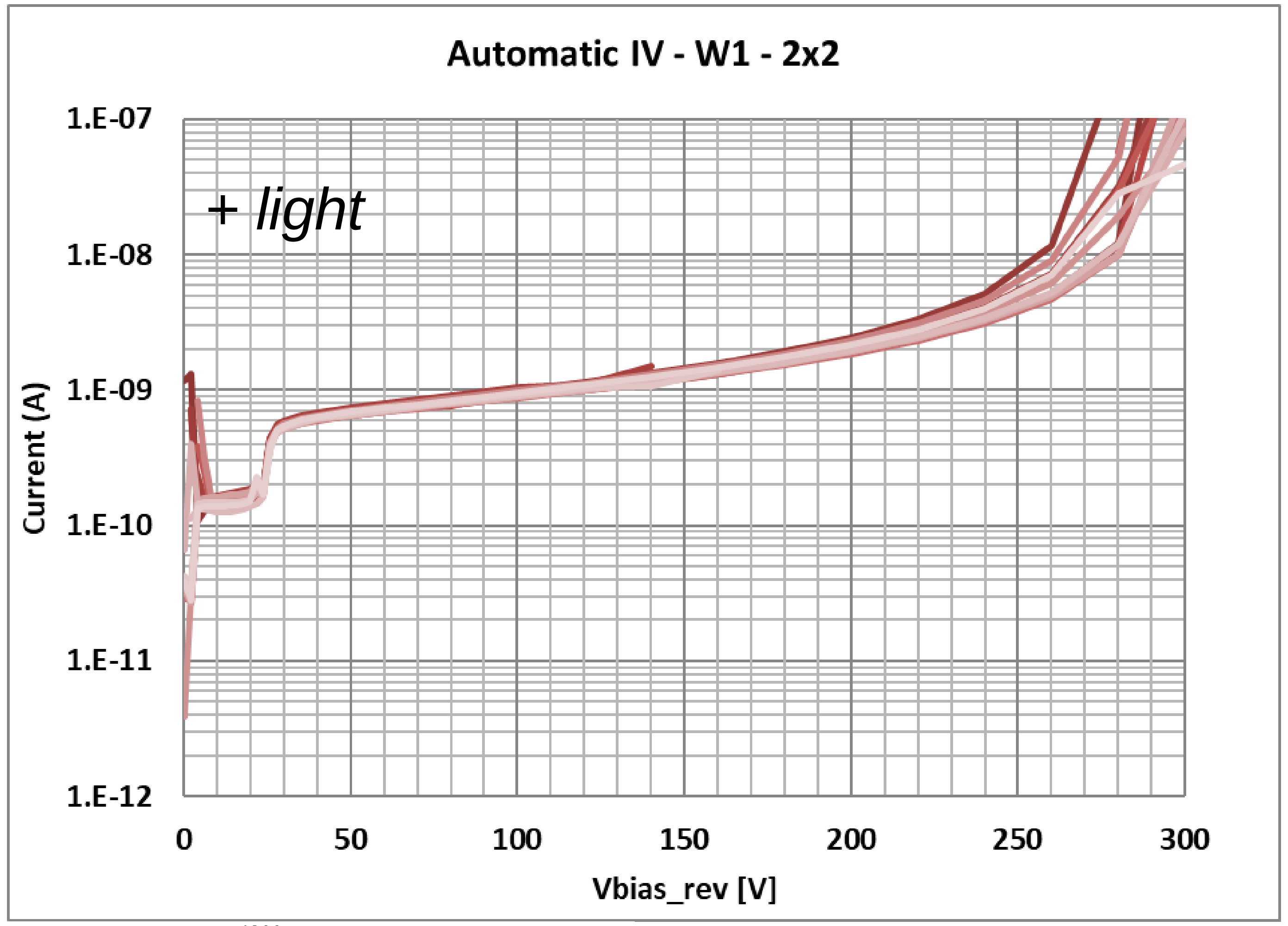


[Ryan Heller, 38th RD50 Workshop]
[Gordana Lastovicka-Medin, 38th RD50 Workshop]

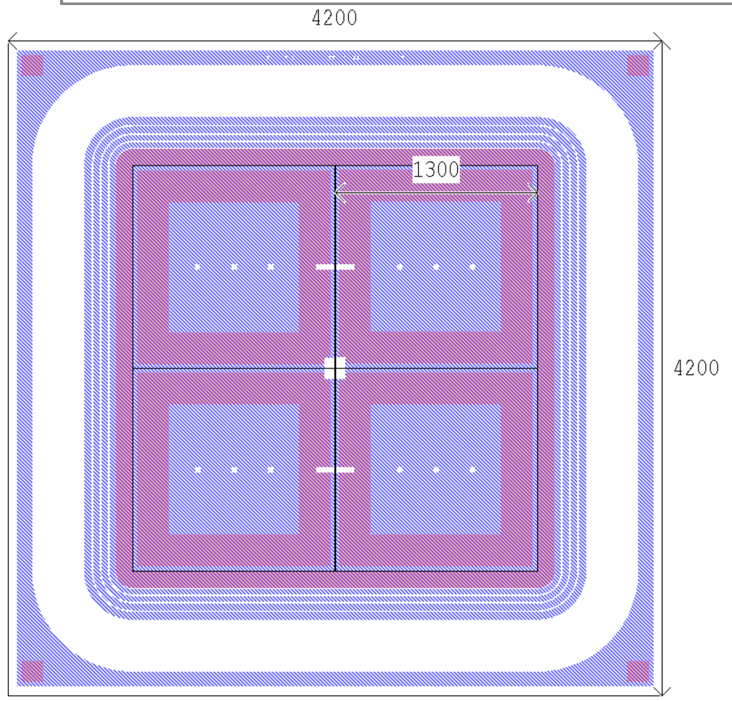
FONDAZIONE BRUNO KESSLER — SENSORS AND DEVICES

TI-LGAD Production Batch: Electrical characterization

Automatic IV characterization

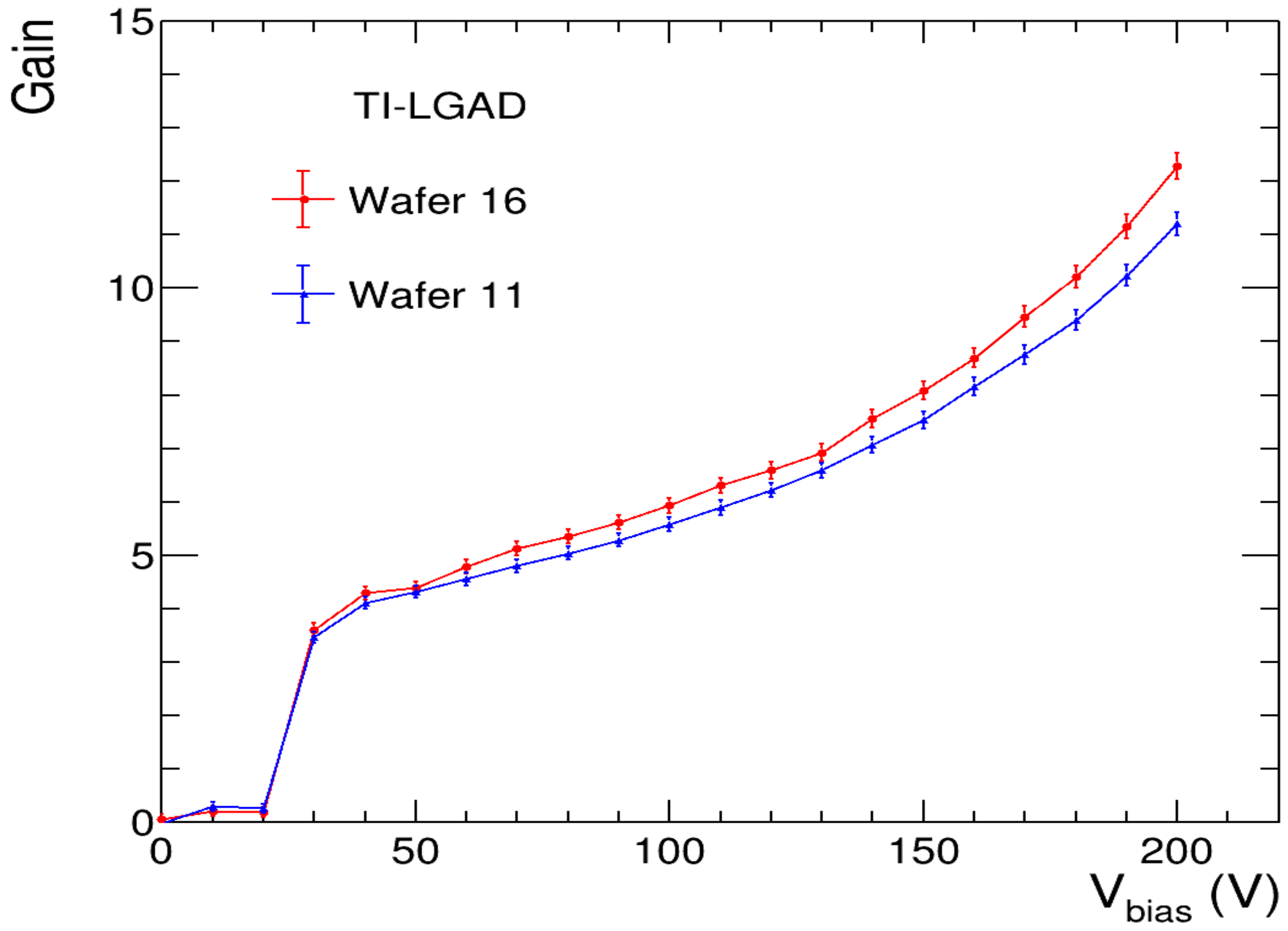


Dark current ~ 10 pA/mm²



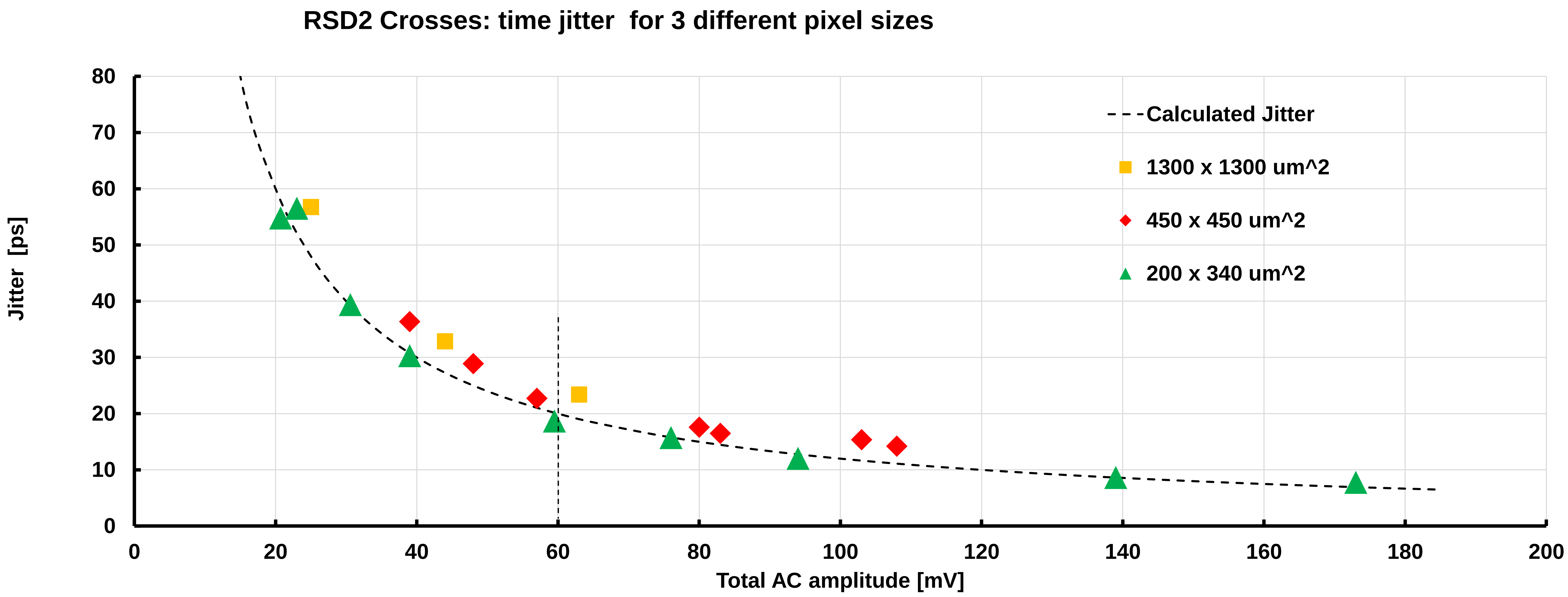
2x2 pixels
1.3 mm² pixels
ATLAS/CMS Timing Layer

GAIN



- TCT Setup with IR Laser
- 200V and RT
- $$Gain = \frac{Q_{LGAD}}{Q_{PiN}}$$

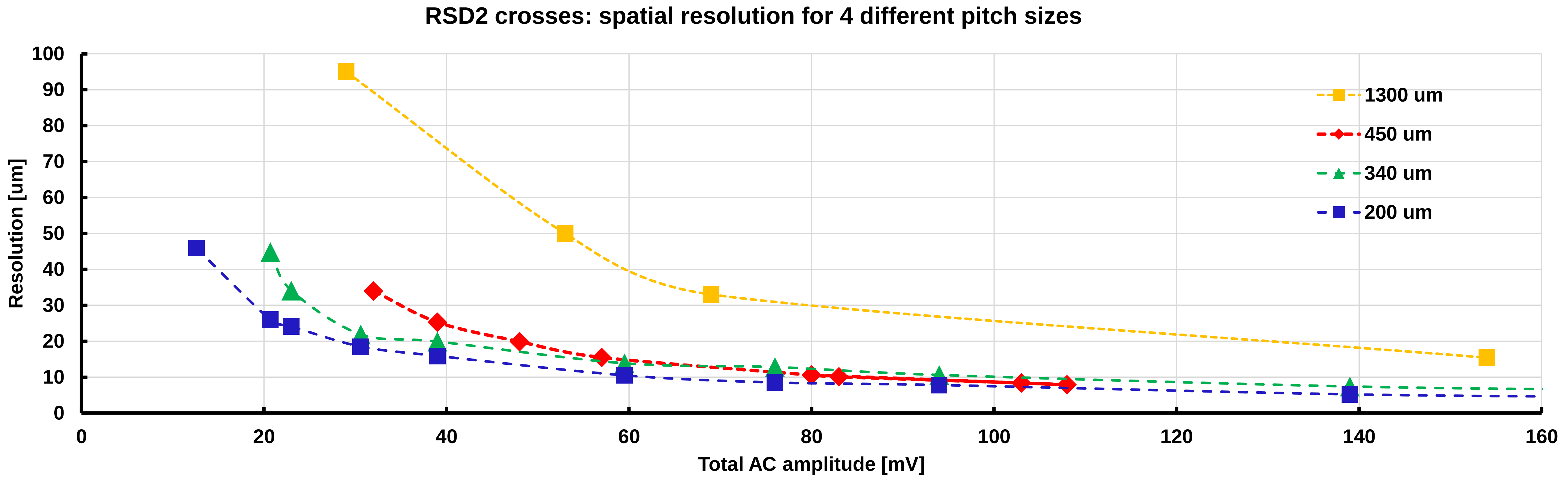
Temporal resolution

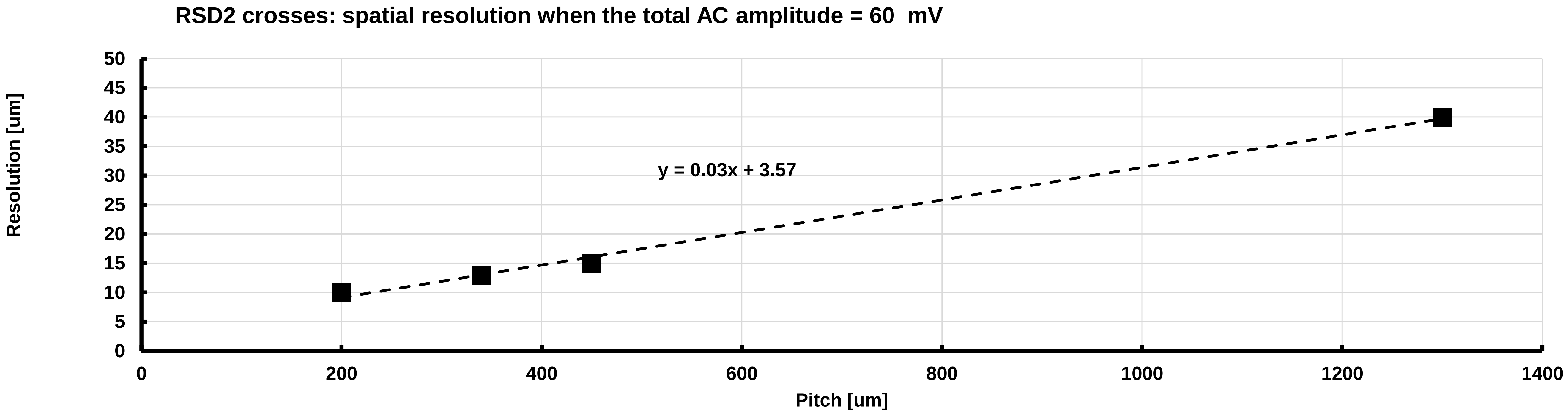


The temporal resolution does not depend on the pize size, only on the total amplitude.

(total amplitude = sum of the amplitudes of the 4 read-out electrodes at the pixel corner)

Spatial resolution as a function of the signal amplitude for 4 pitch sizes



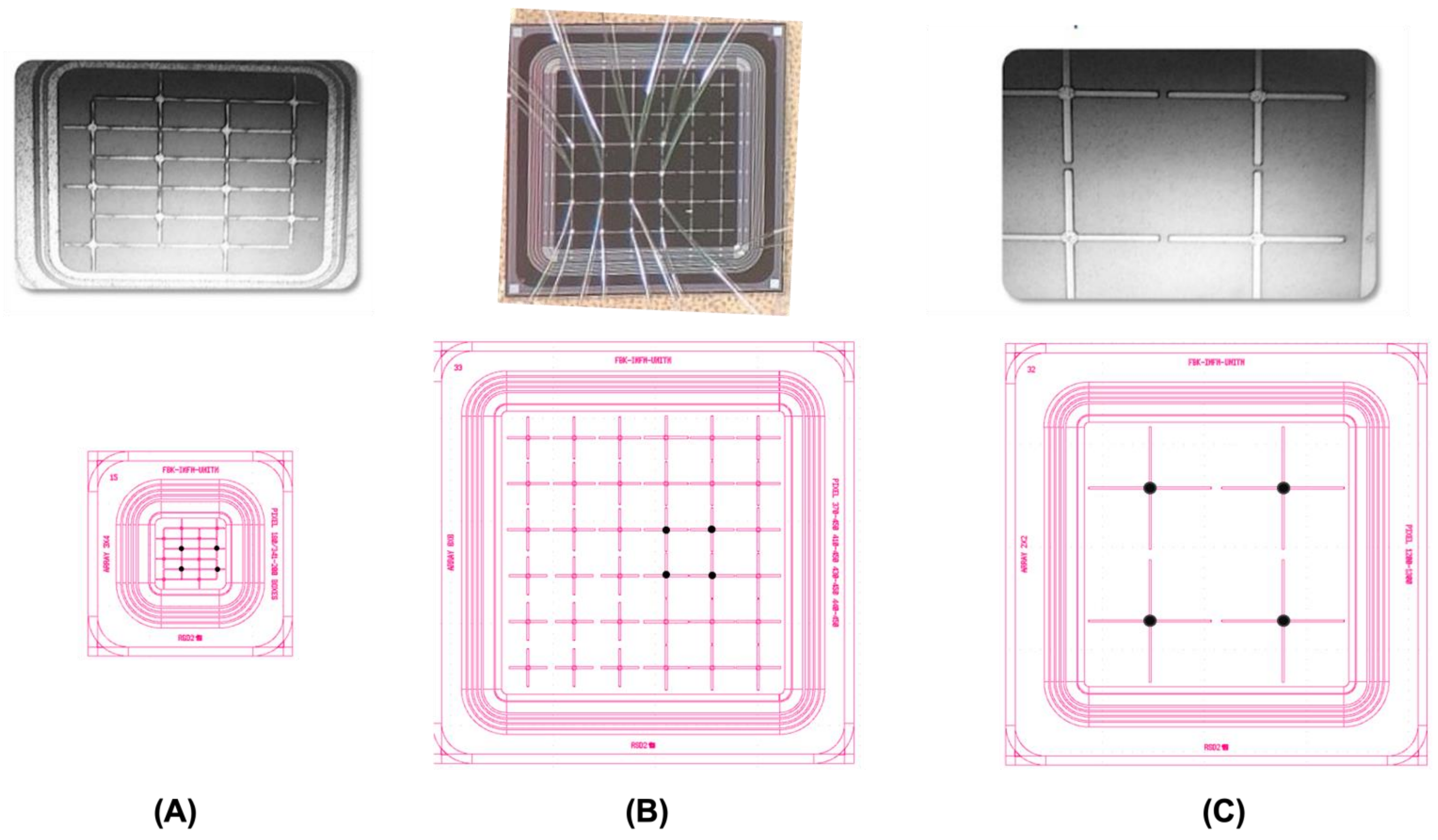


Executive summary: the resolution is 3% of the pixel size

(total amplitude = sum of the amplitudes of the 4 read-out electrodes at the pixel corner)

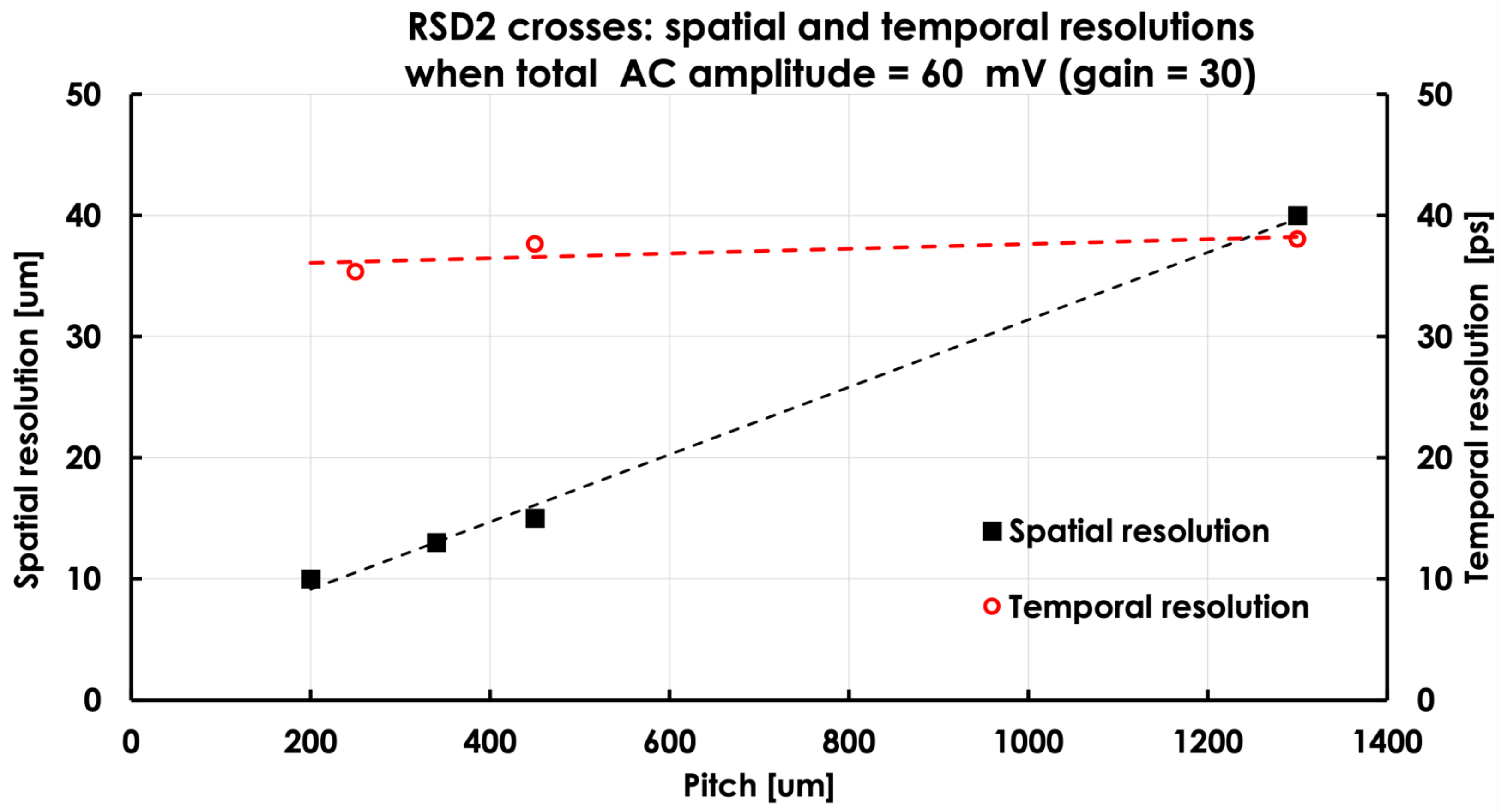
Latest FBK RSD production RSD2

The key feature of RSD2 is to design the electrodes to have as little metal as possible and to maximize sharing among the read-out pads at the corner of the pixel



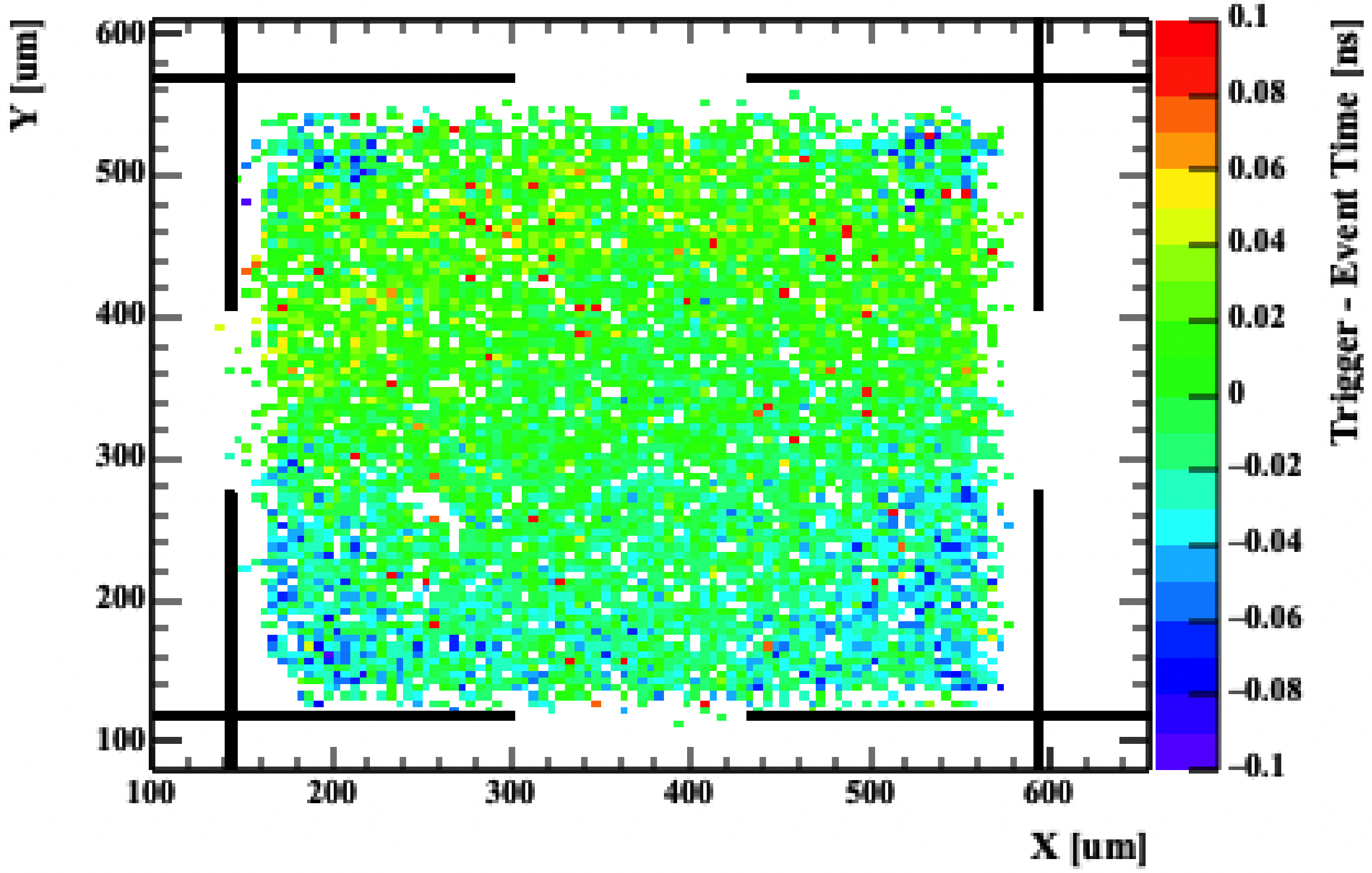
RSD2 crosse overall result:

- Spatial resolution ~ 3% pitch size
- Temporal resolution ~ 35 ps, regardless of pitch size

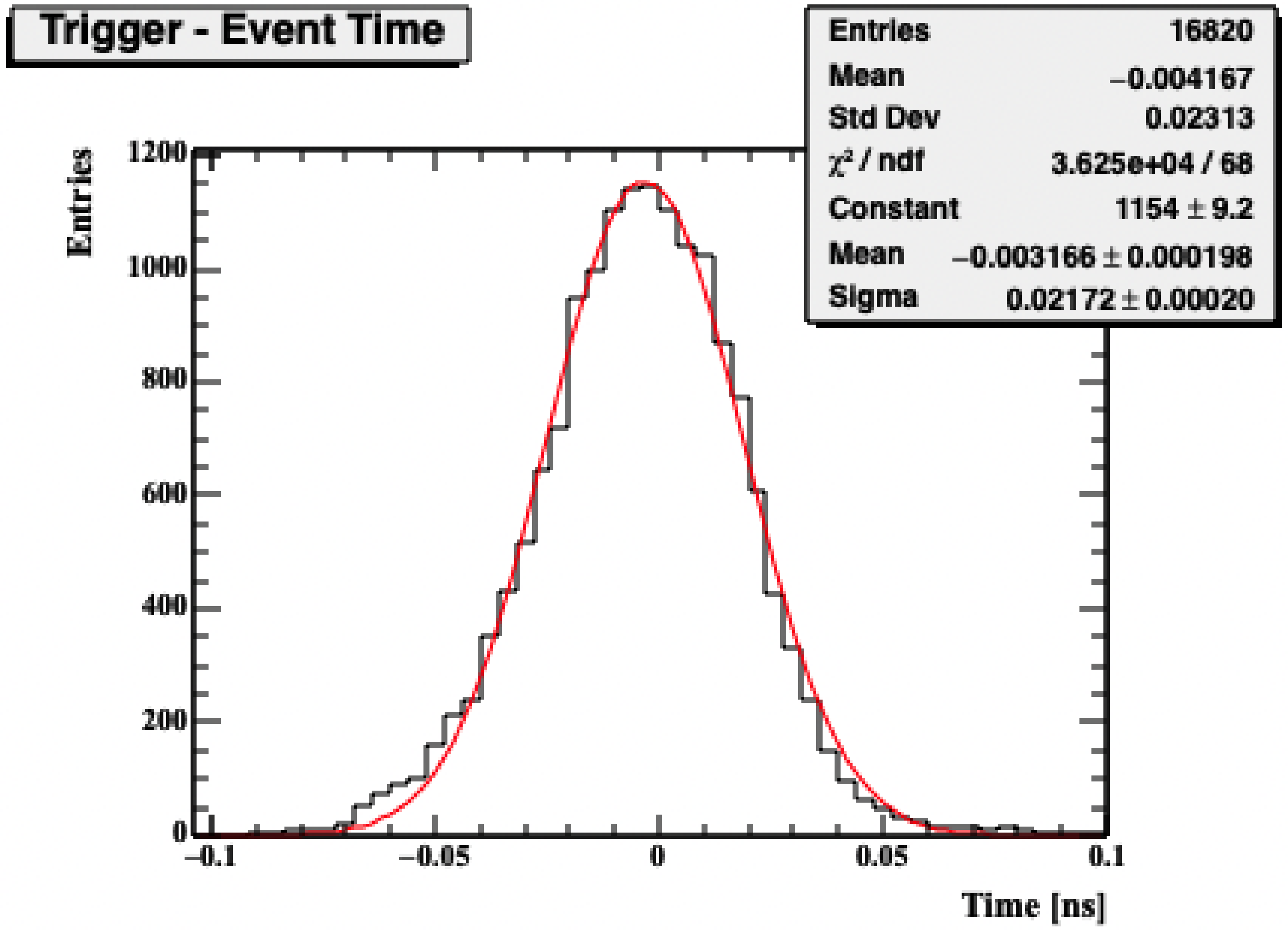


for Gio'

Example of uniformity in the time resolution over the whole pa



(A)



(B)

Plot obtained by shooting laser shots (TCT system) over the whole pixel surface and comparing the