Development of Segmented 4H-SiC LGADs

Peter Švihra

on behalf of FZU, CAPADS & onsemi teams

[1] MSCA-cofund fellow, FZU CAS

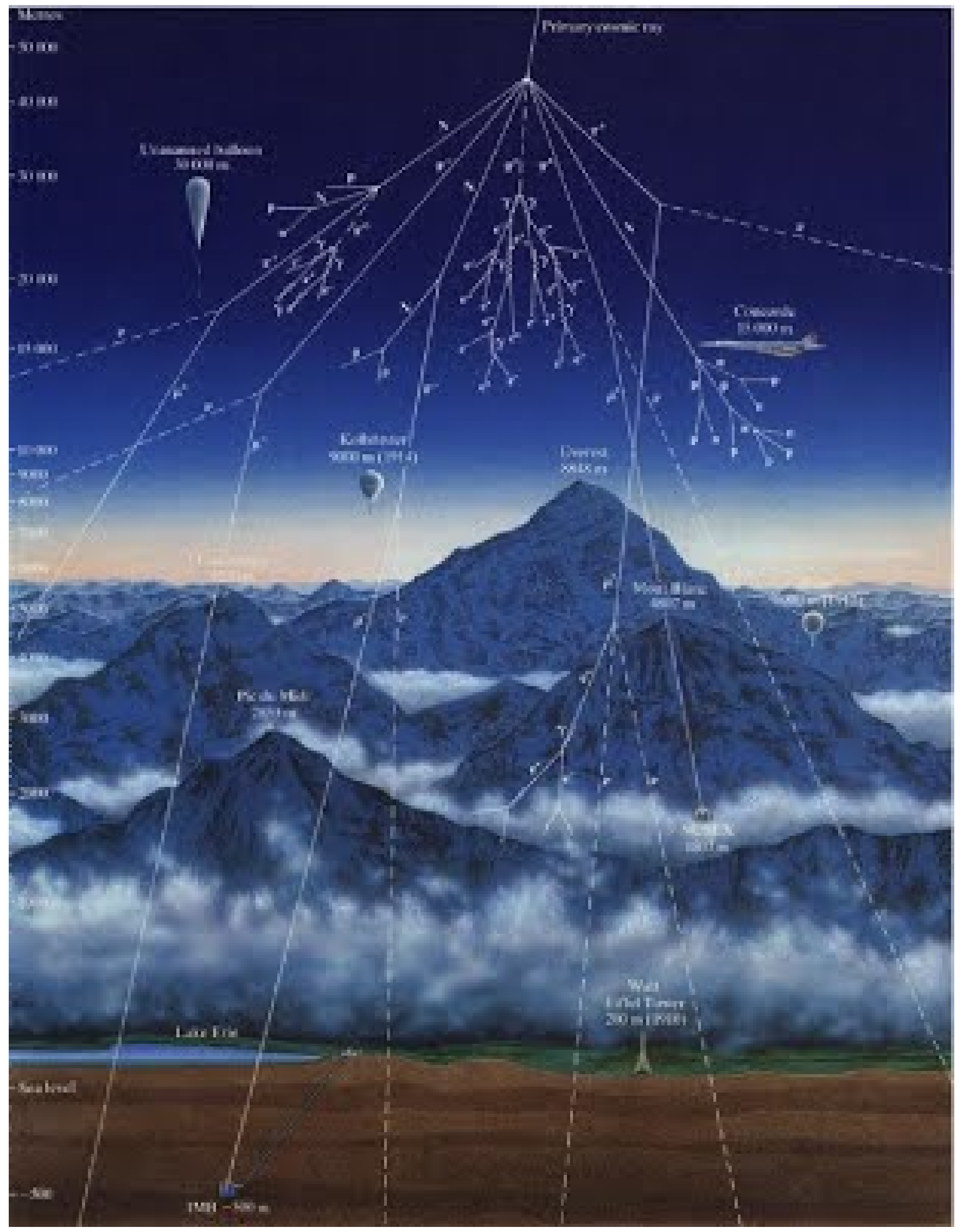
FZU Institute of Physics of the Czech Academy of Sciences

PHYSICS FOR FUTURE

Co-funded by the European Union

Division of Elementary Particle Physics

Ionising radiation around us

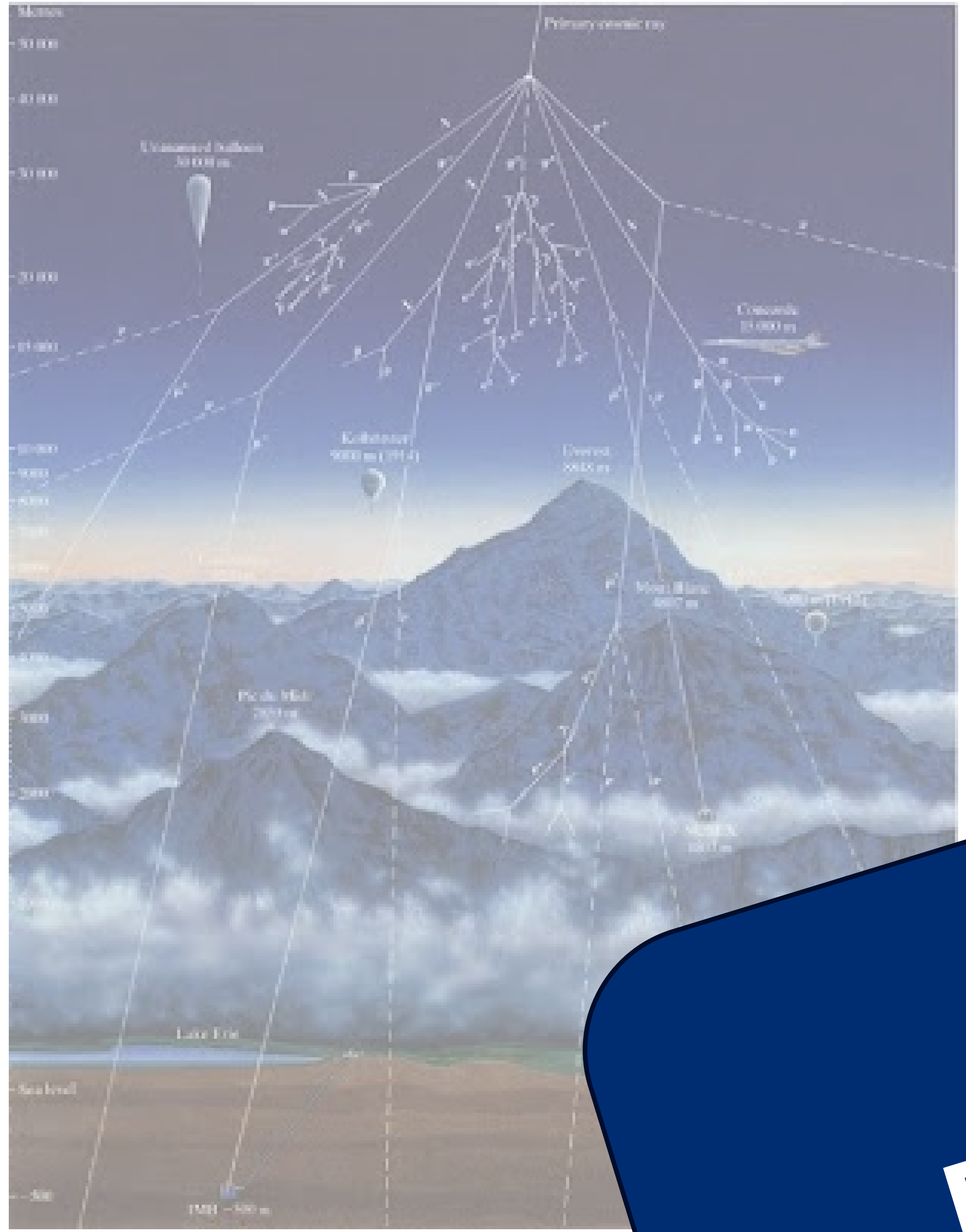


From outer space …

… through research centres deep underground …

… all the way to saving lives!

Ionising radiation around us



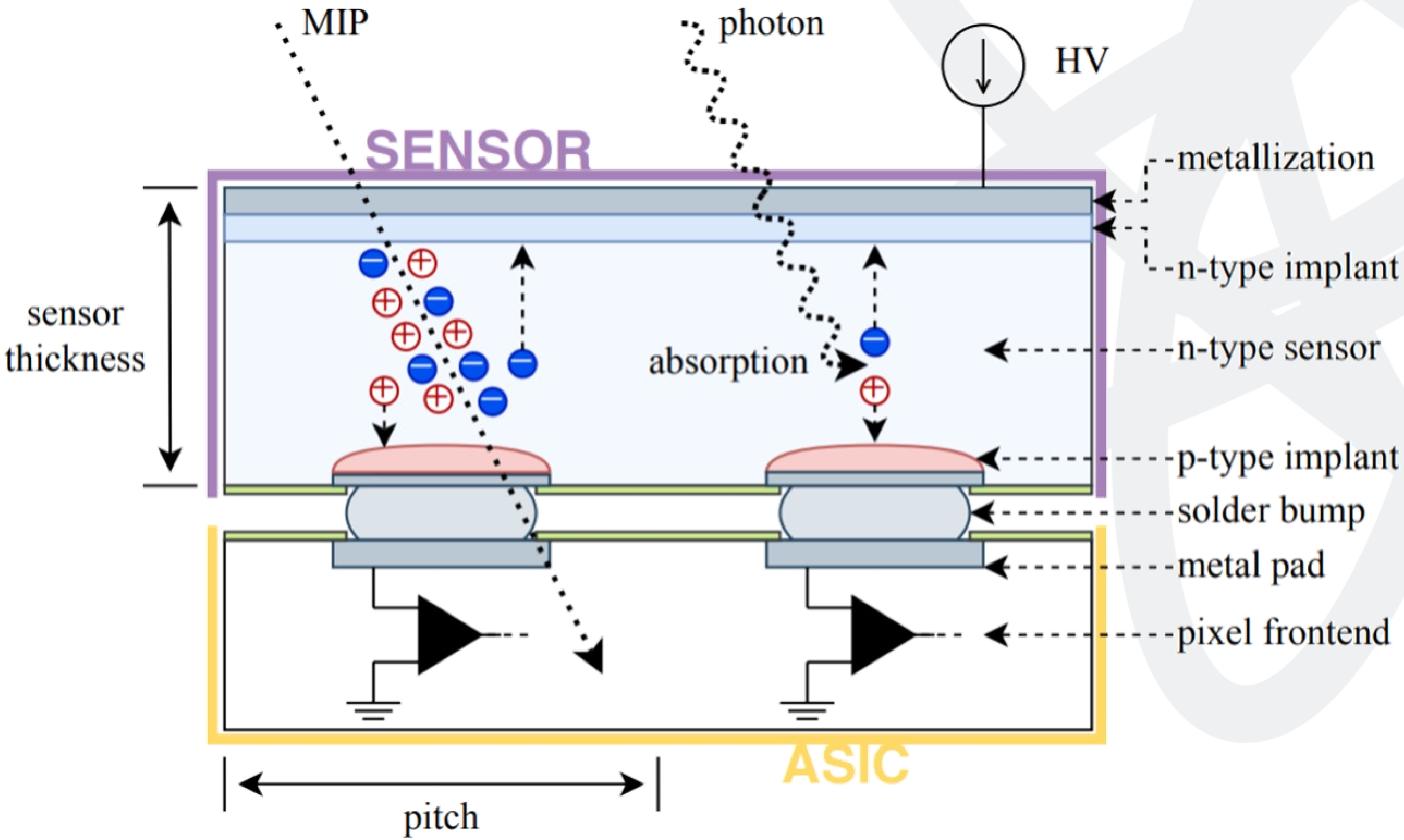
From outer spa

ugh research centres deep underground …

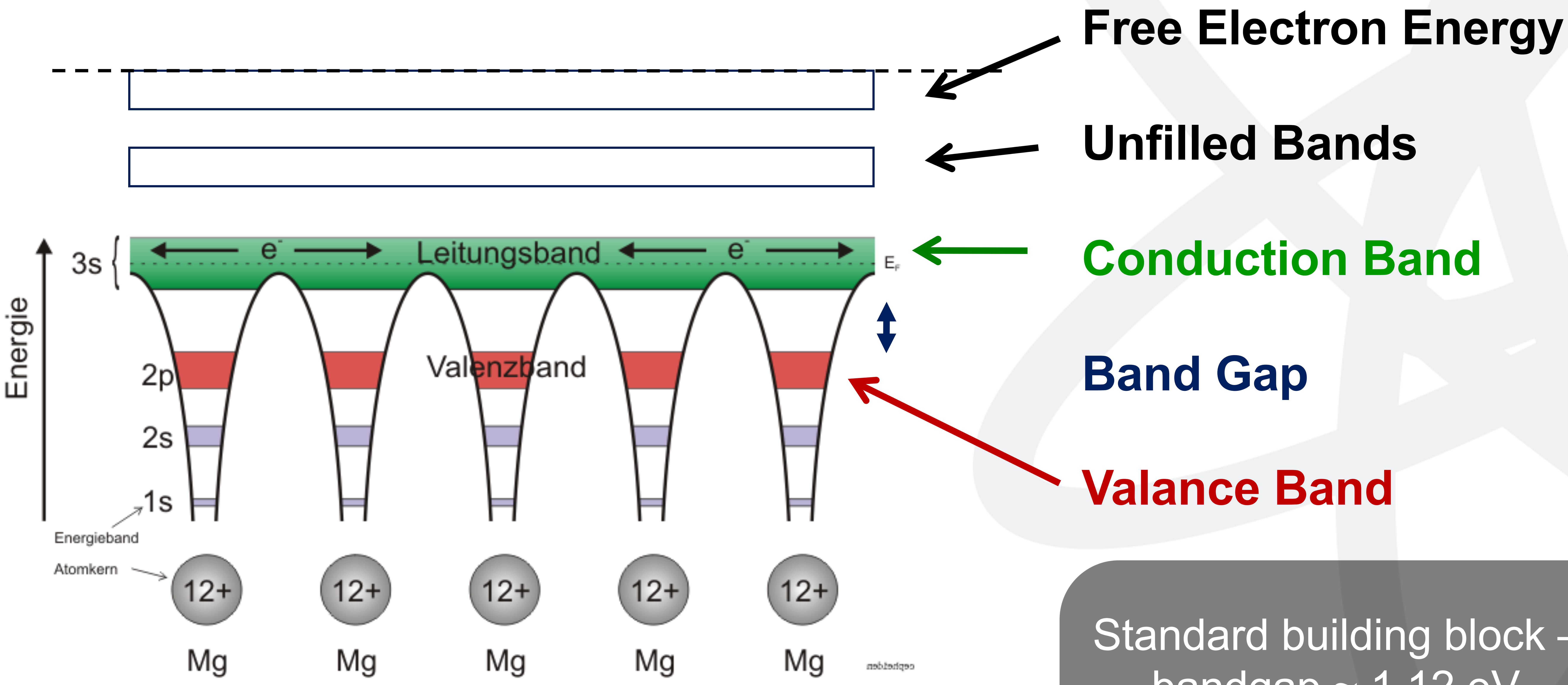
… all the way to saving lives!

But how to record or detect it?

Using semiconductor detectors!



What is a semiconductor?



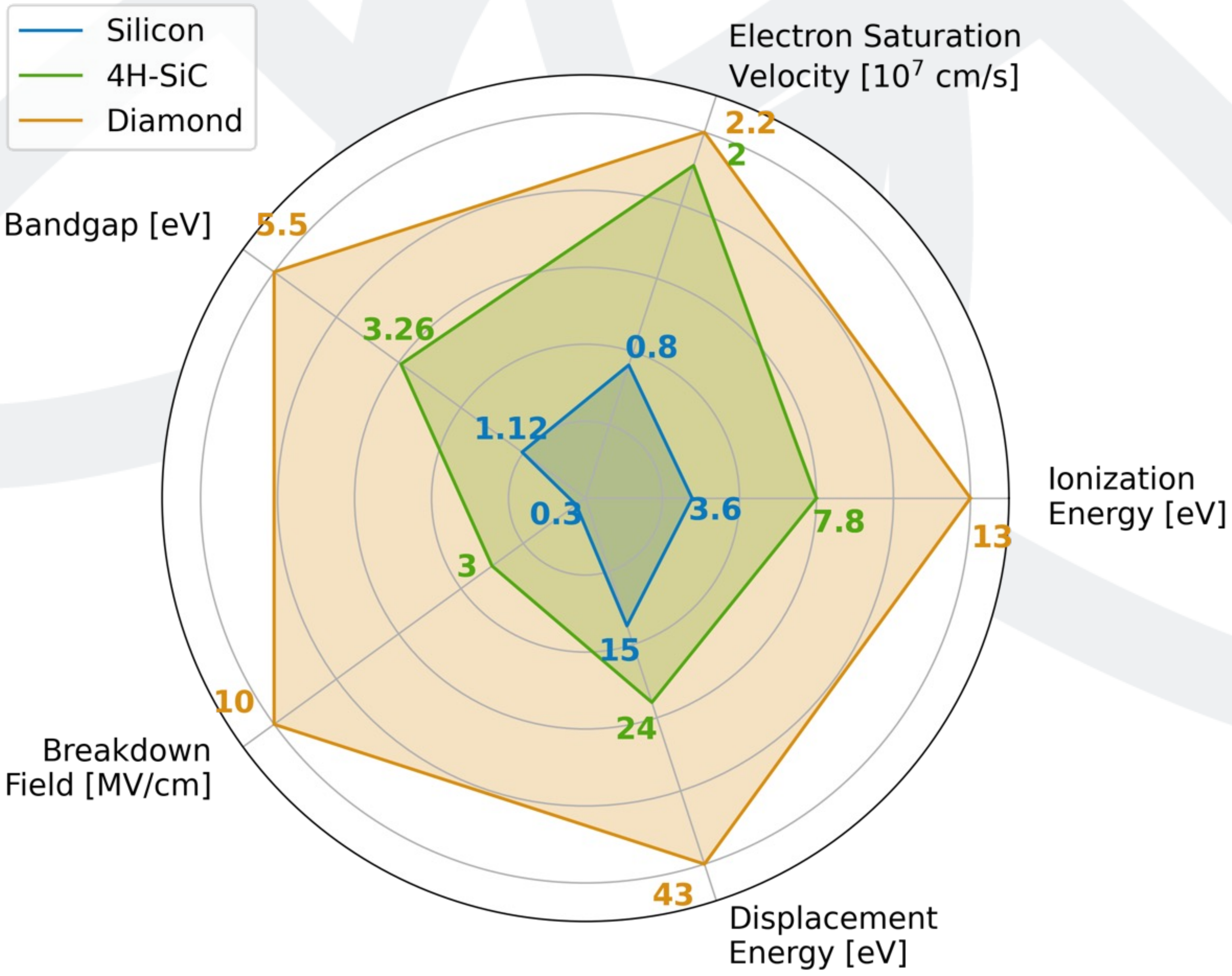
Standard building block – **silicon**

- bandgap ~ 1.12 eV
- used for detection and logic
- very good manufacturing
- abundant material

Wide-bandgap in a nutshell

- **Wider bandgap of 2.4 < Eg < 3.3 eV**
- **Lower signal per charge, lower leakage, better thermal cond., operation at higher temperature (100 °C)**
- **Higher (x10) electric field before breakdown, faster (x2) charge collection**

	Si	4H-SiC	GaN	β-Ga2O3	Diamond
Bandgap (eV)	1.12	**3.26**	3.39	4.8	5.47
Electron mobility ($cm^2 \cdot V^{-1} \cdot s^{-1}$)	1500	**900**	1400	300	2200
Critical electric field ($MV \cdot cm^{-1}$)	0.3	**2.8**	3.3	8	10
Thermal conductivity ($W \cdot cm^{-1} \cdot K^{-1}$)	1.5	**3.7**	2	4.8	20
Baliga's figure of merit	1	**340**	650	3400	27000
Current production status	Mass prod.	**Mass prod.**	Production	R&D	R&D



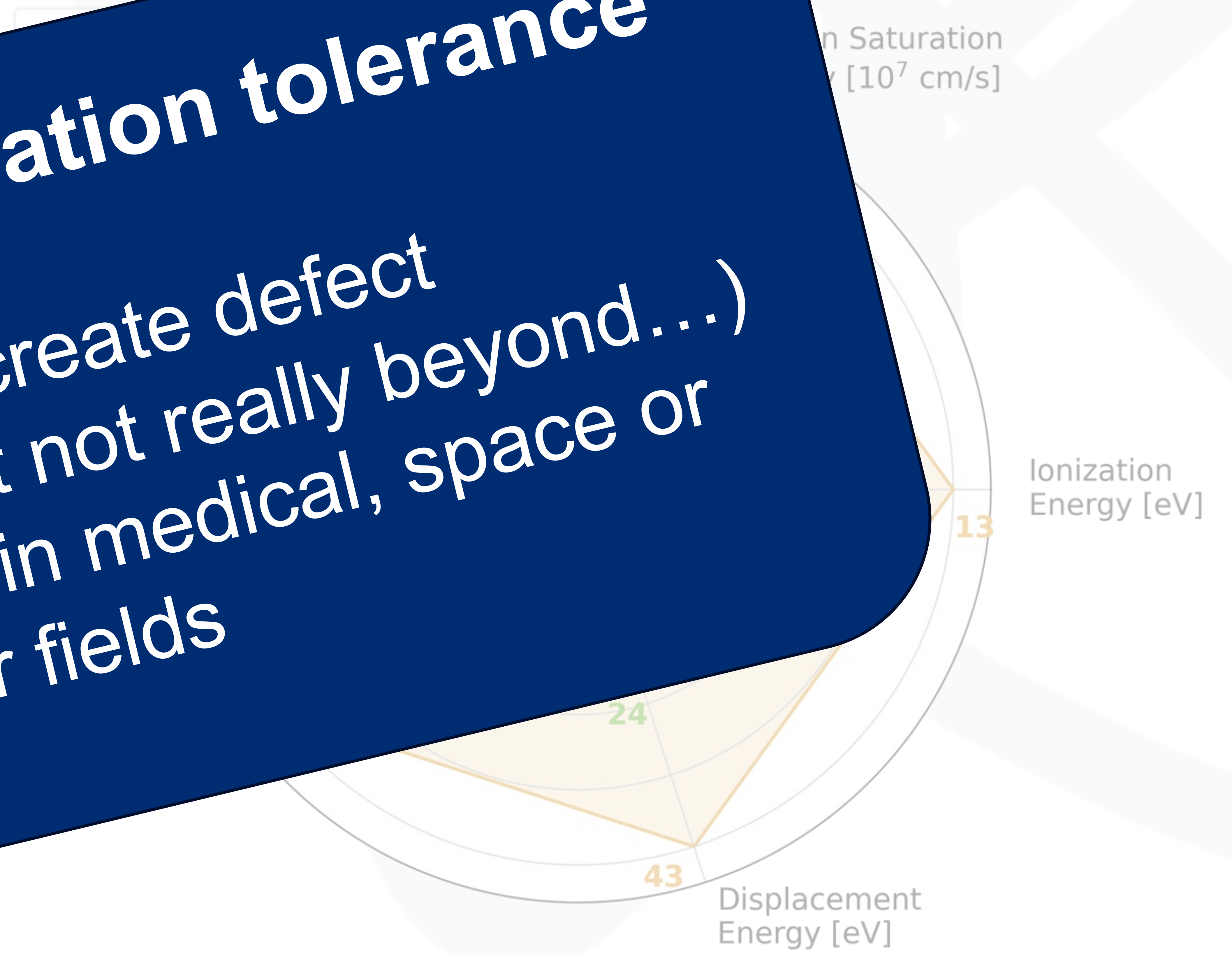
Wide-bandgap in a nutshell

- Wider bandgap of 2.4 < Eg < 3.3 eV
- Lower signal per charge, lower le… better thermal cond… temperatur…
- Higher (x… breakdow…

Promise of higher radiation tolerance

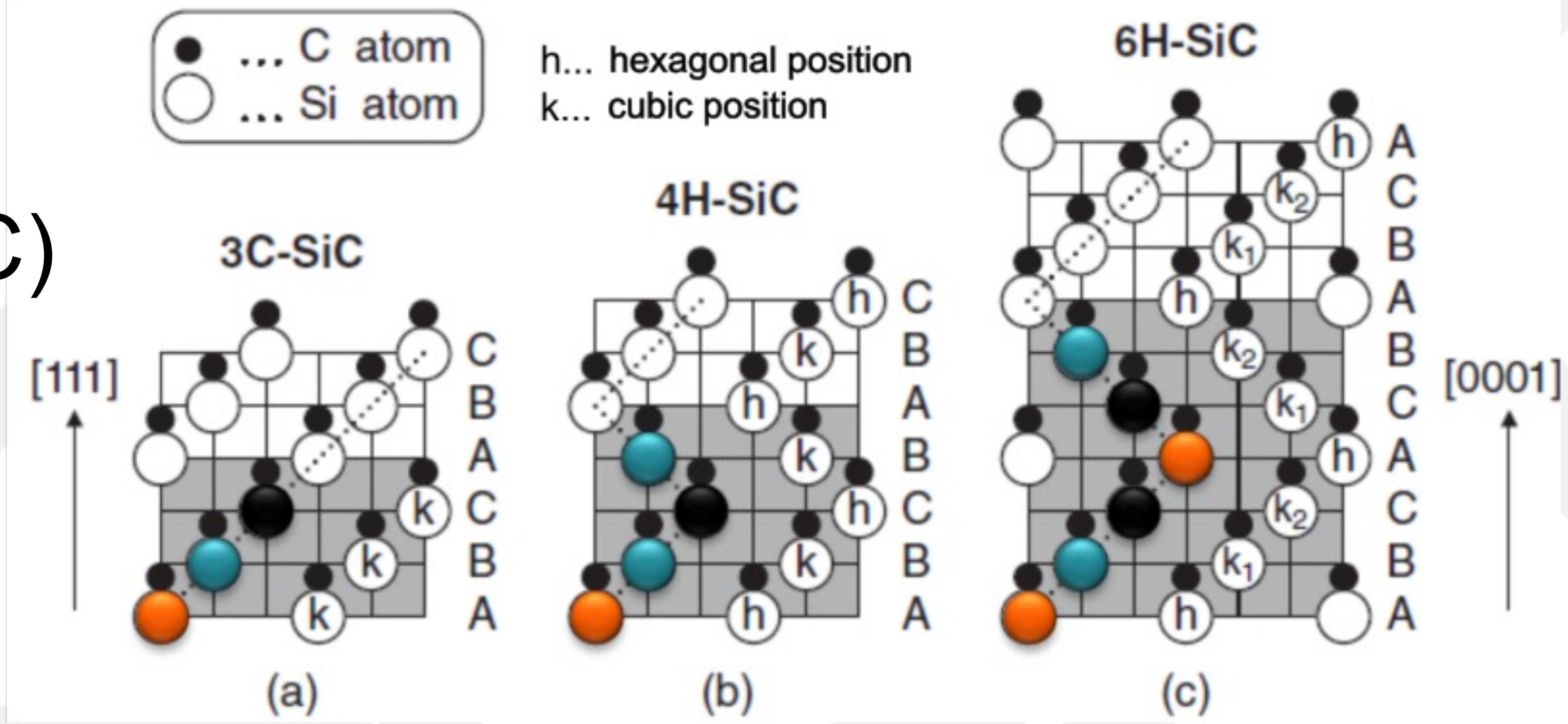
- More energy to create defect
- Needed for HL-LHC (but not really beyond…)
- Potential applications in medical, space or nuclear fields

Bandgap (eV)					
Electron mobility (cm^2·V^{-1}·s^{-1})					
Critical electric field (MV·cm^{-1})					
Thermal conductivity (W·cm^{-1}·K^{-1})					20
Baliga's figure of merit			650	3400	27000
Current production status	Mass prod.	Mass prod.	Production	R&D	R&D



”Re-discovery” of Silicon-Carbide

- **Advantages**
  - Lower dark current
  - Excellent temperature stability (up to 300 °C)
  - High radiation tolerance (*supposed*)
  - Material hardness (resistant)
- **Disadvantages**
  - Material hardness (hard to dice, easier to shatter)
  - Difficult to manufacture
  - Lower signal



	3C-SiC	6H-SiC	4H-SiC	Si
Bandgap (eV)	2.36	3.02	**3.26**	1.12
Electron mobility ($cm^2 \cdot V^{-1} \cdot s^{-1}$)	1000	450	**900**	1500
Critical electric field ($MV \cdot cm^{-1}$)	1.40	3.00	**2.80**	0.30
Saturated e^- drift velocity (1E7 $cm \cdot s^{-1}$)	2.00	1.90	**2.20**	1.0

”Re-discovery” of Silicon-Carbide

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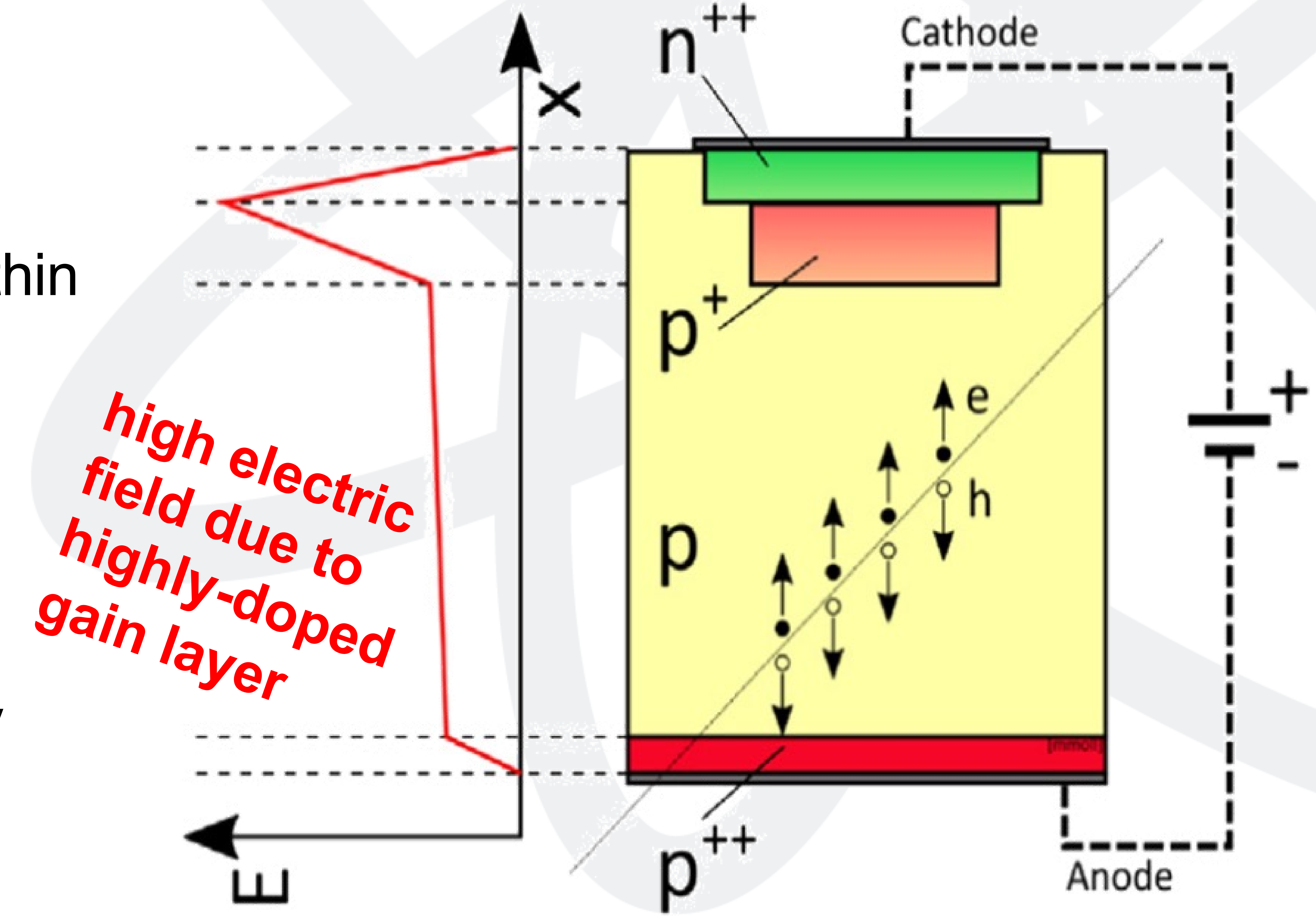
How to benefit from its advantages and keep disadvantages in check?

- improved processing thanks to industry and SiC use in power electronics
- design sensor with internal amplification

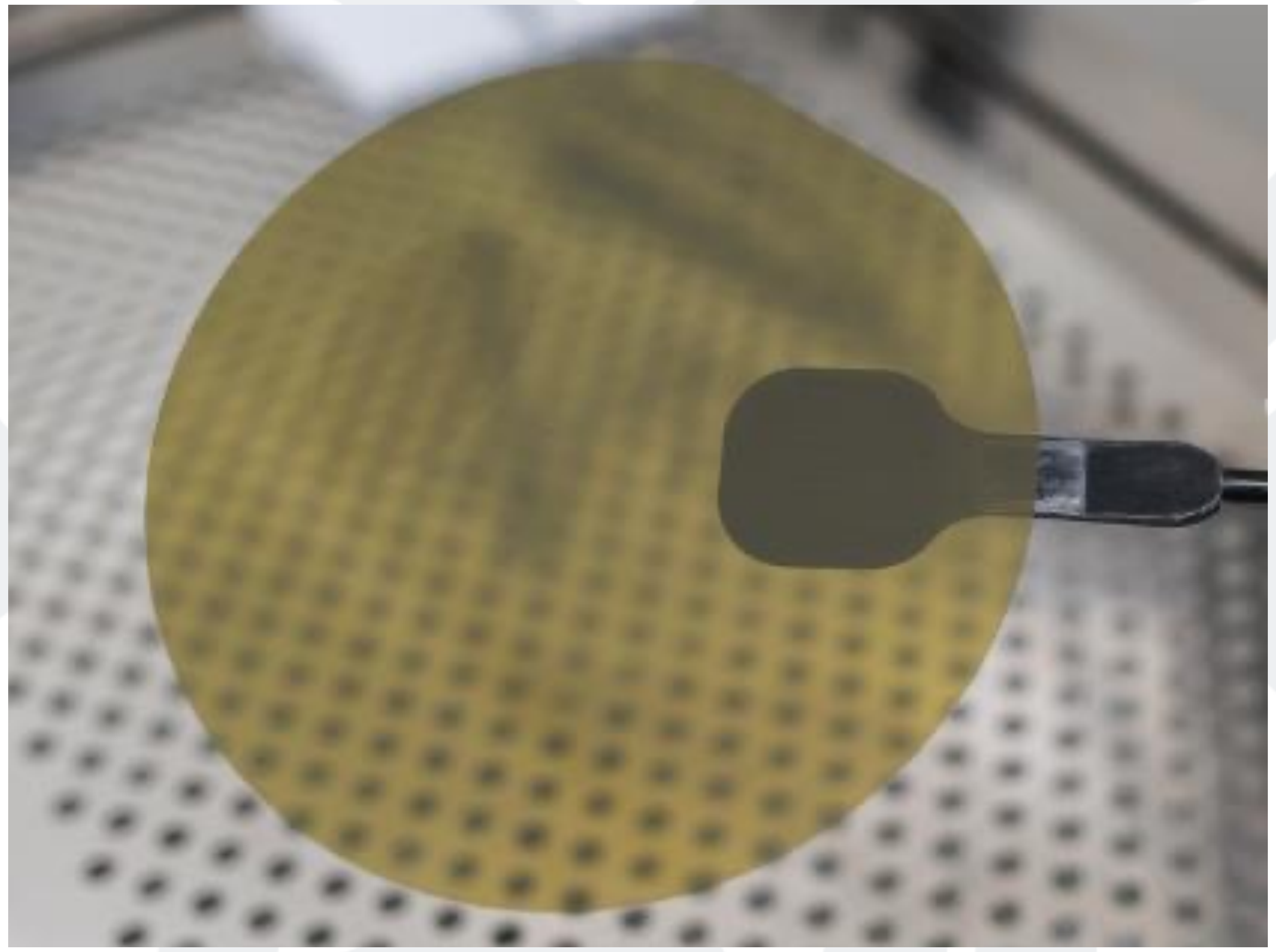
Low Gain Avalanche Detectors (LGADs)

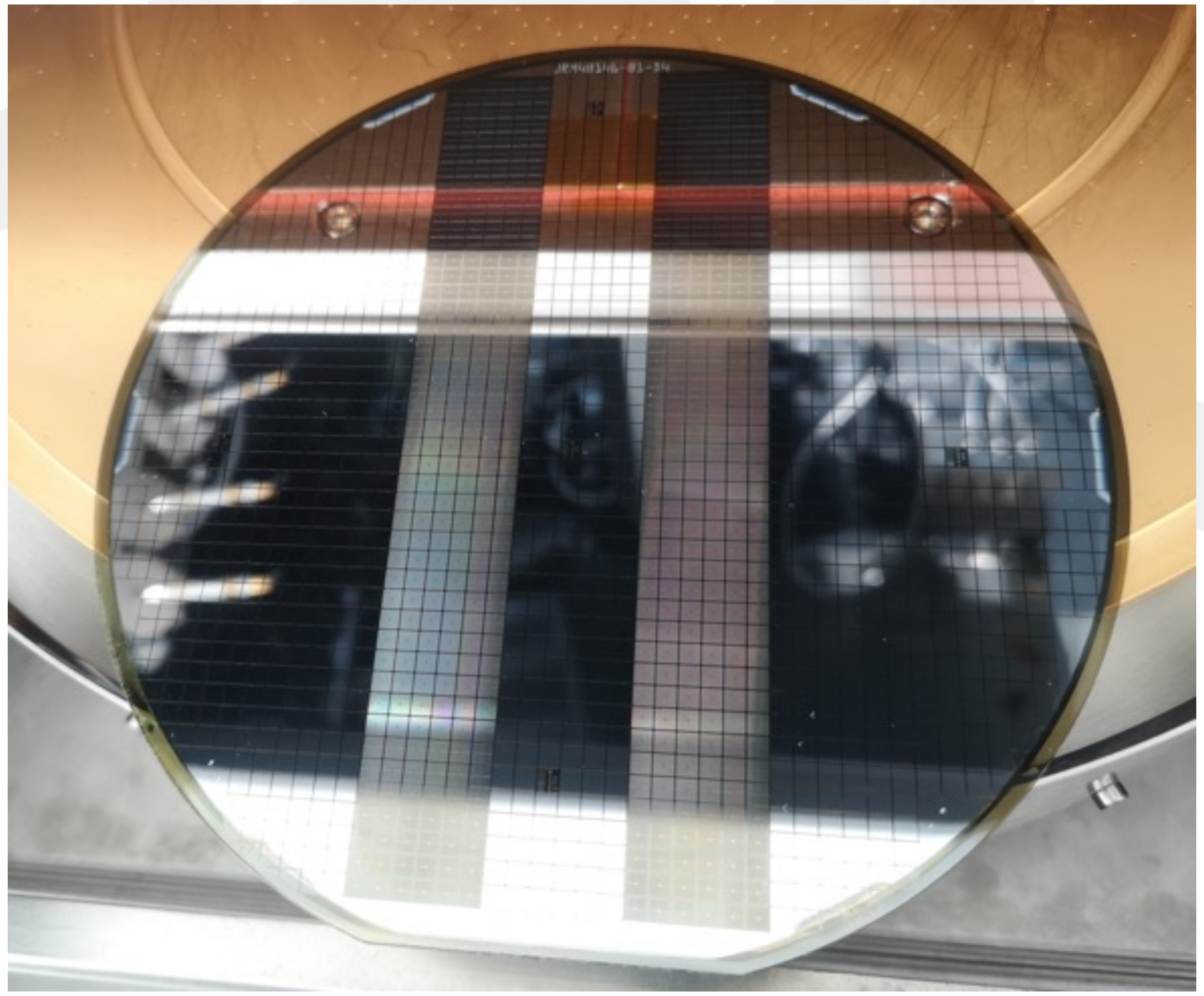
- **Benefits of intrinsic charge multiplication**
  - Improved Signal-to-Noise Ratio
  - Excellent timing capabilities (~ 40 ps) for thin LGADs (~ 50 μm)
  - Low energy X-rays detection (< 5 keV)
- 🔻**Performance degradation with radiation damage**
- **Challenging performance uniformity with small pixels**



LGADs on SiC – design

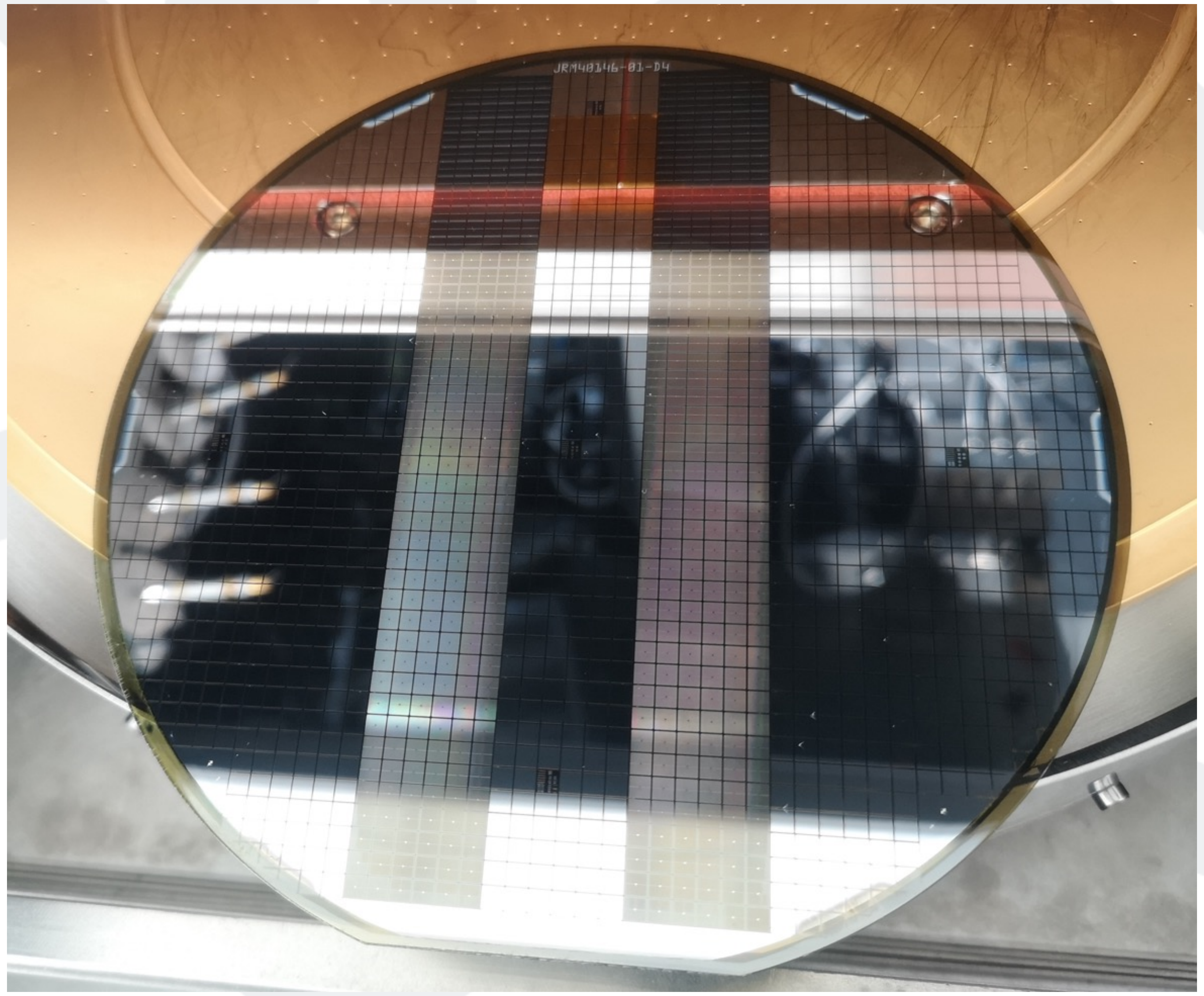
- Diode 3 x 3 mm^2 used for R&D
- Comparison no-gain and LGAD
- 30-100 µm EPI grown on 4H-SiC substrate
- n-type bulk





Produced runs

- **Always both PN and LGAD designs on the same wafer**
- **Around nine 6” wafers per lot:**
- **Lot1 (2022/2023)**
  - Initial tests, feasibility of production, not diced
- **Lot2 (2024)**
  - First dicing, IV/CV test, β-source, TCT, irradiation
- **Lot3 (2024/2025)**
  - Large irradiation campaign (pending results)
- **Lot4 (2025/2026)**
  - **Segmentation**, plan for improved gain stability



Producing and testing Lot4

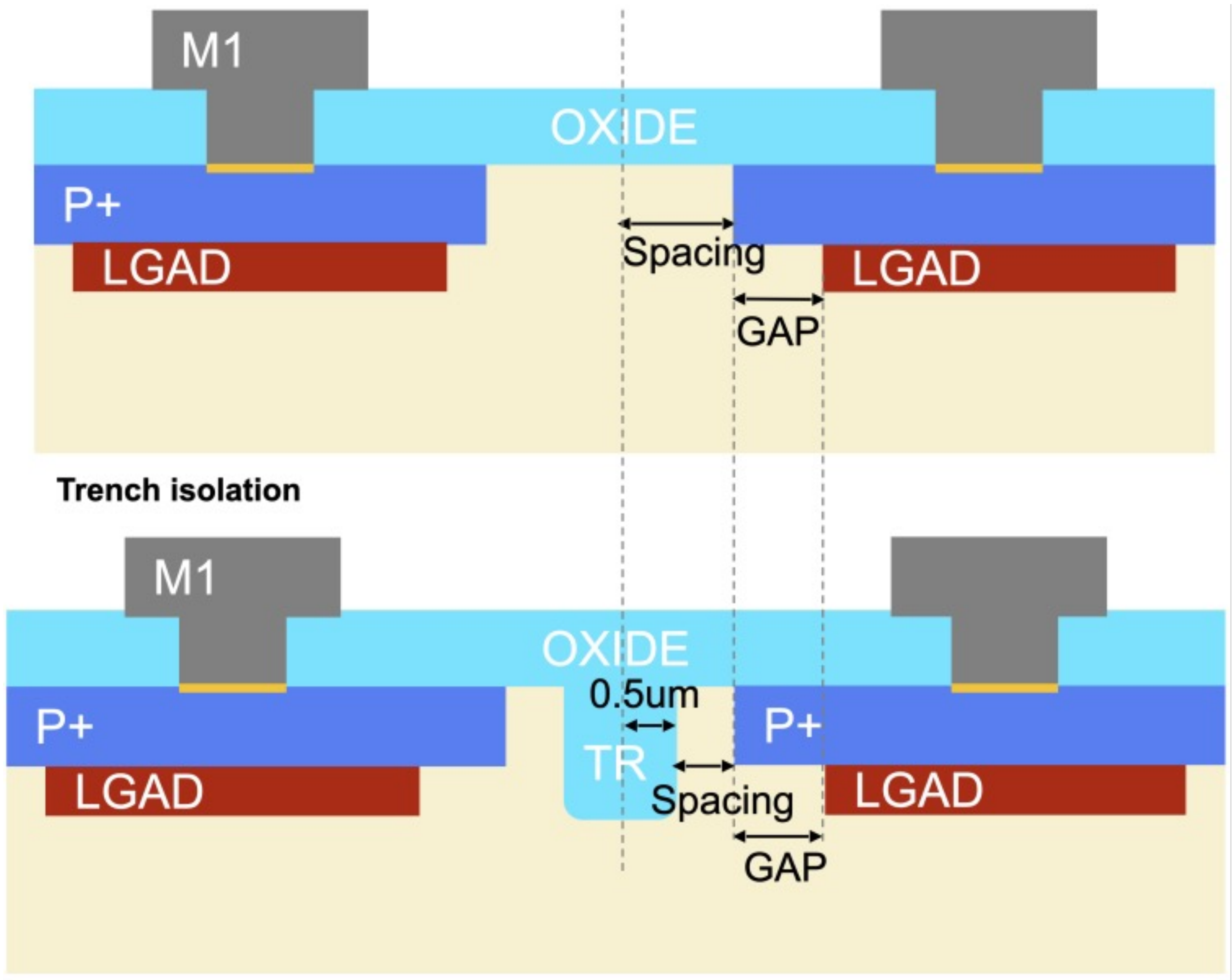
- **Designed gain (factor 5-10)**
- **First pixel/strip segmented 4H-SiC LGADs!**

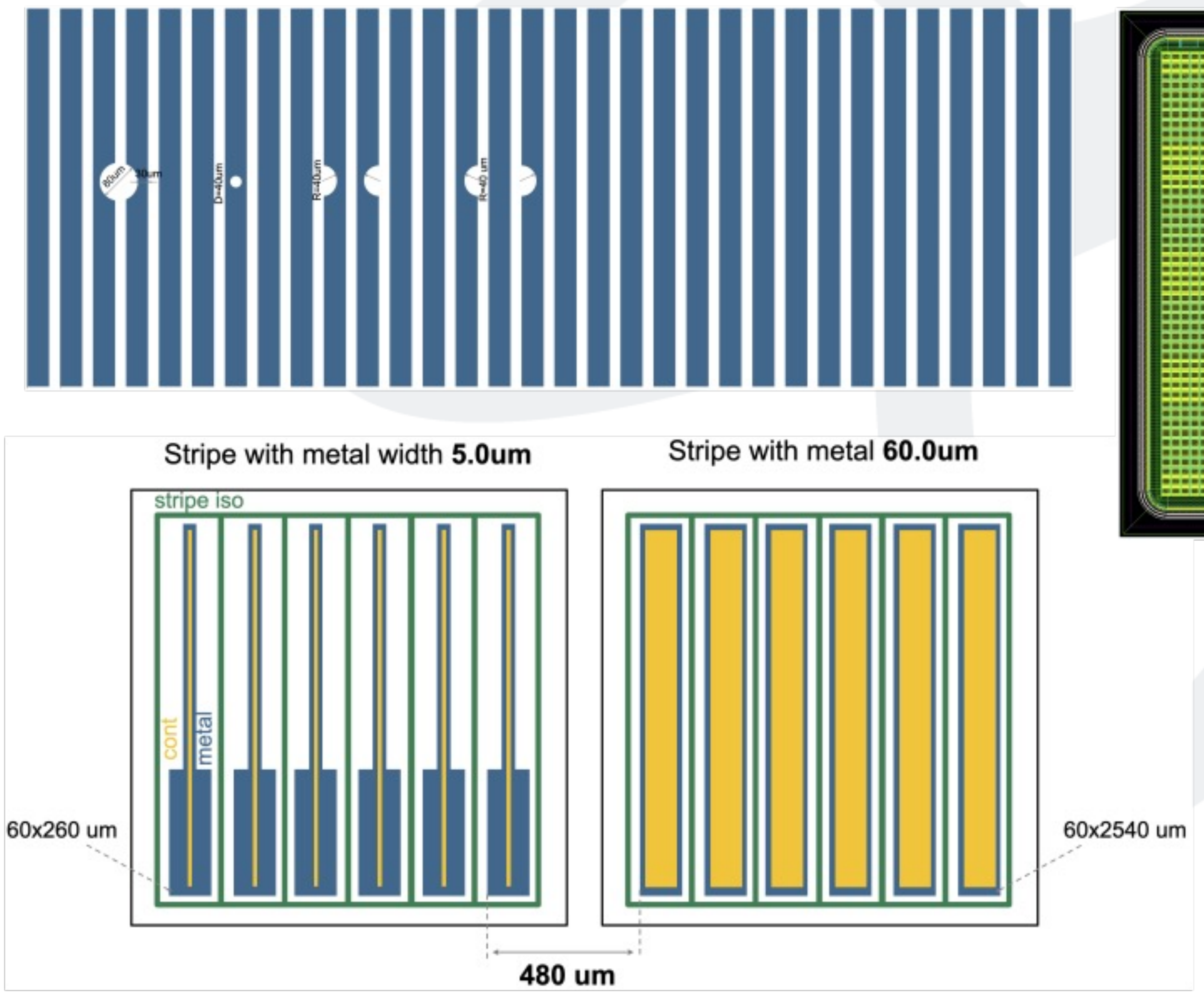
- **Identified issue with gain stability between productions**
  - 6 additional wafers produced to evaluate impact of implantation

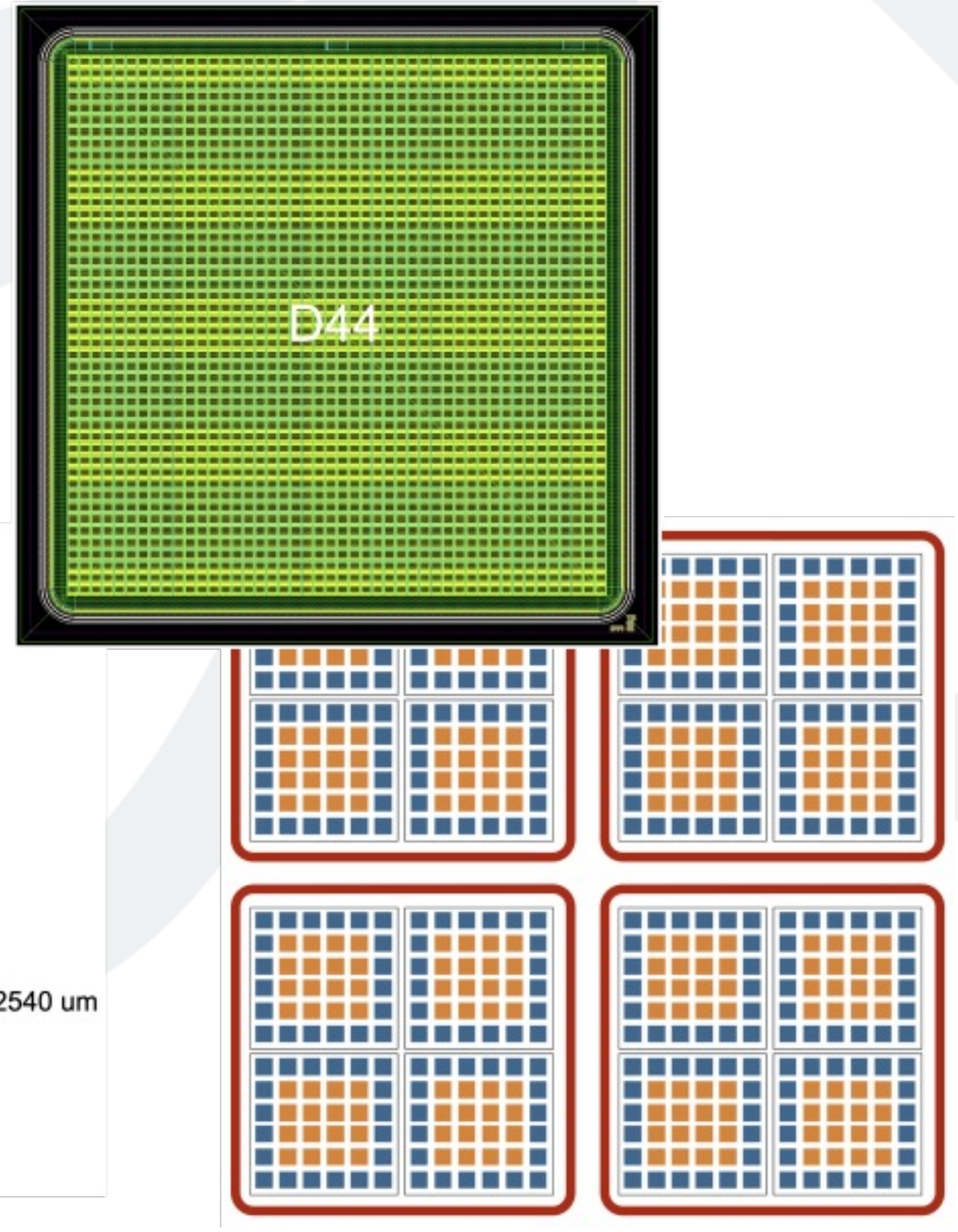
- **CERN SPS testbeam (*alongside Lot3*)**
  - w. help of Nikhef team – K. Akiba, G. Cheng, F. Fassin
- **TCT campaign at ELI ERIC (*alongside Lot3*)**
  - w. help of MBI team – T. Bergauer, S. Gundacker, S. Onder, D. Radmanovac

Segmentation strategies – Lot4

- Same story as with silicon, but different …
- Trenches difficult to make … but is JTE needed between channels?

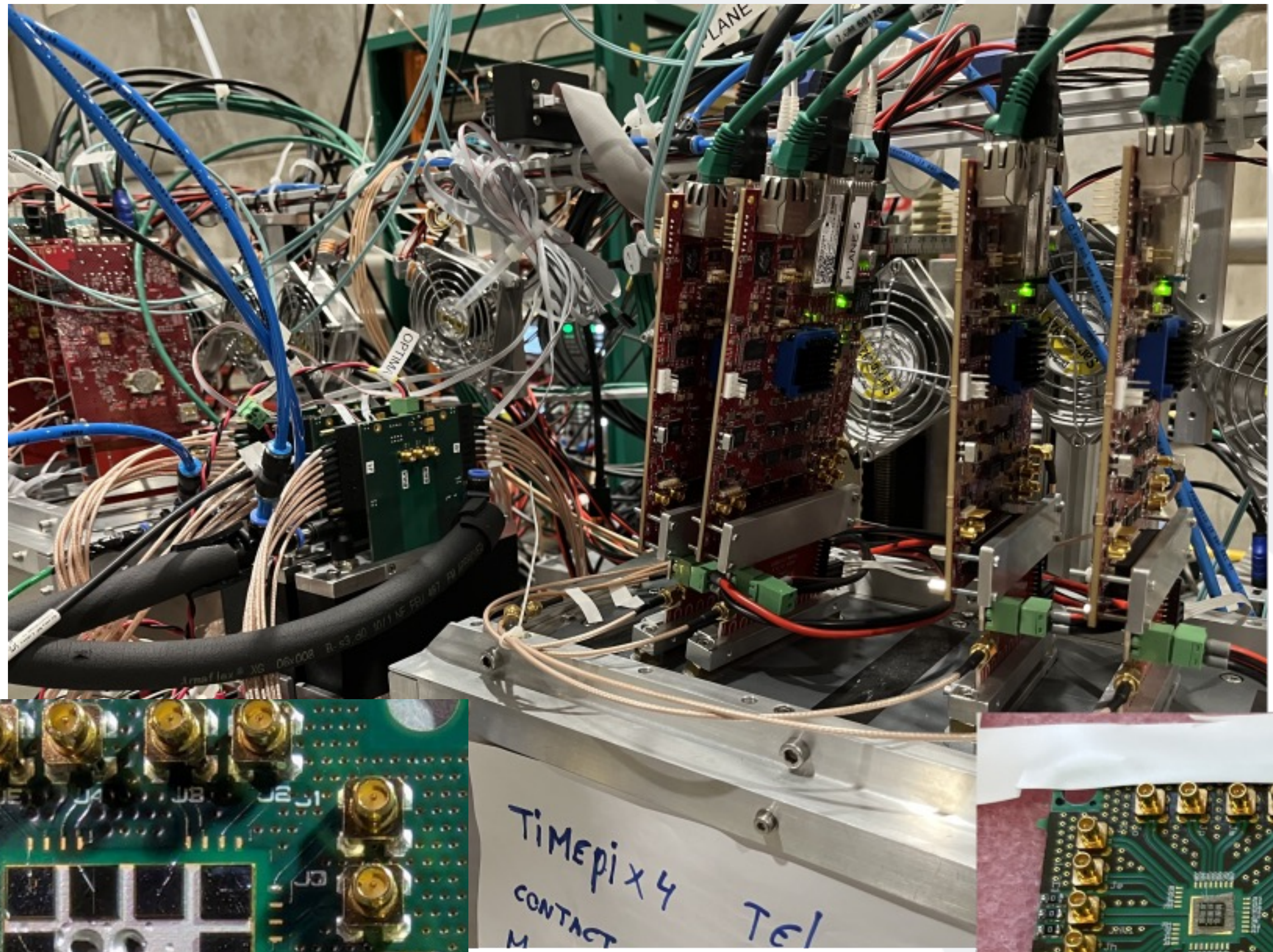


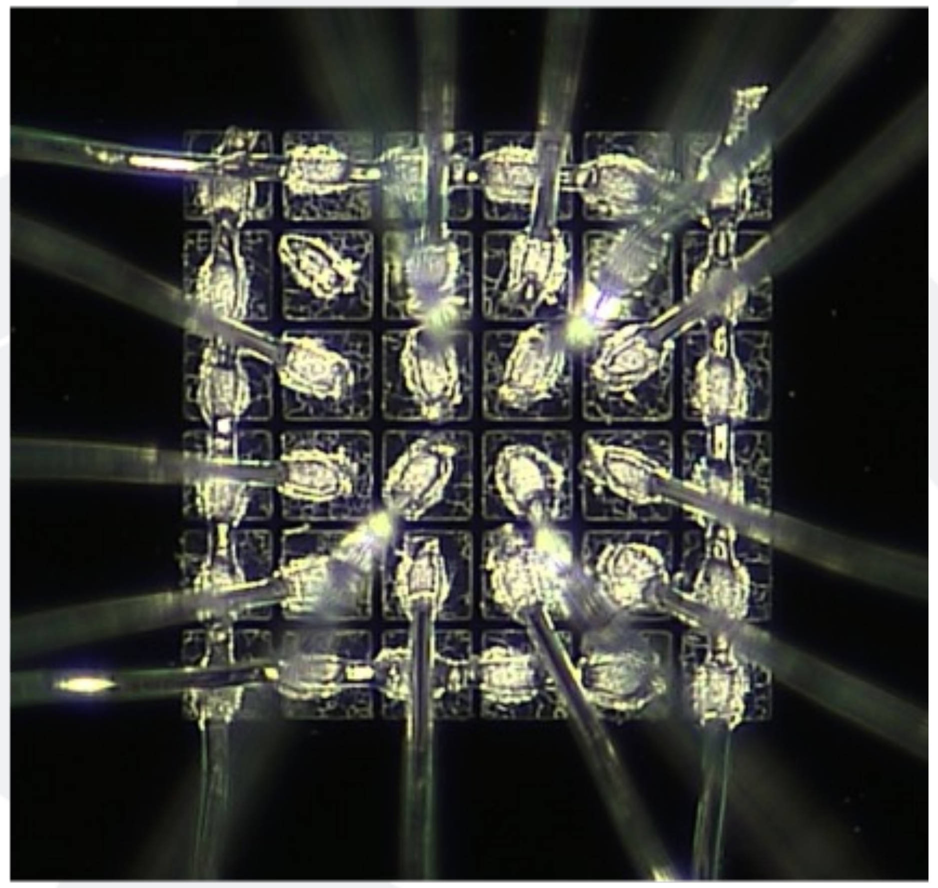


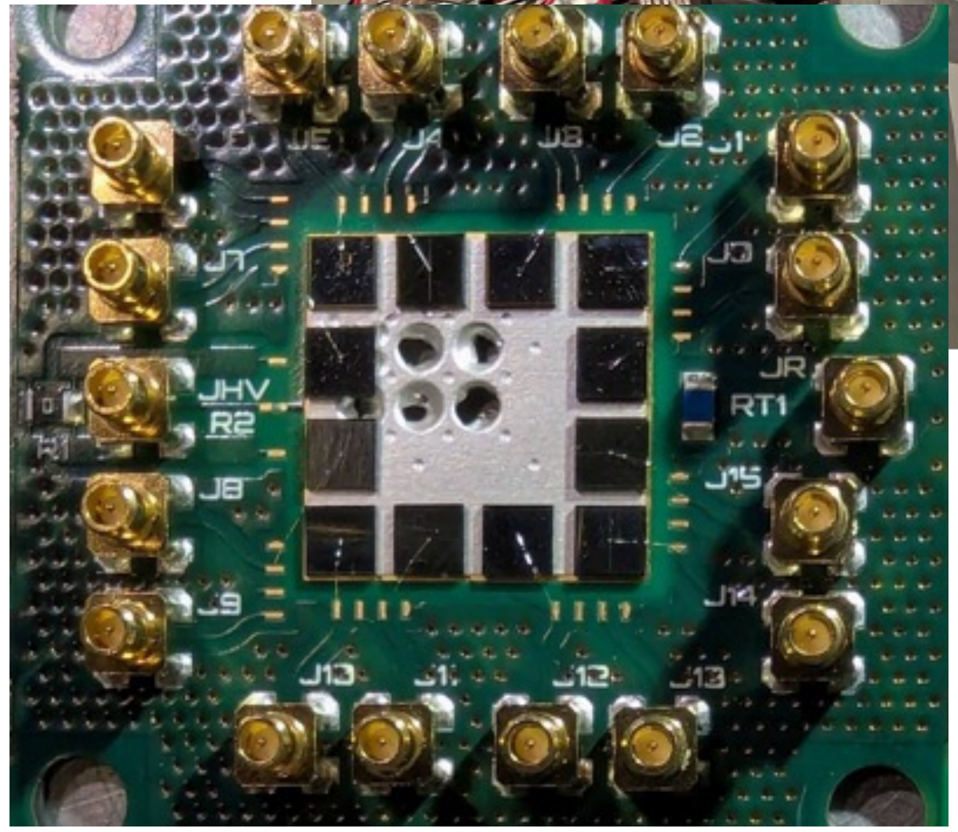


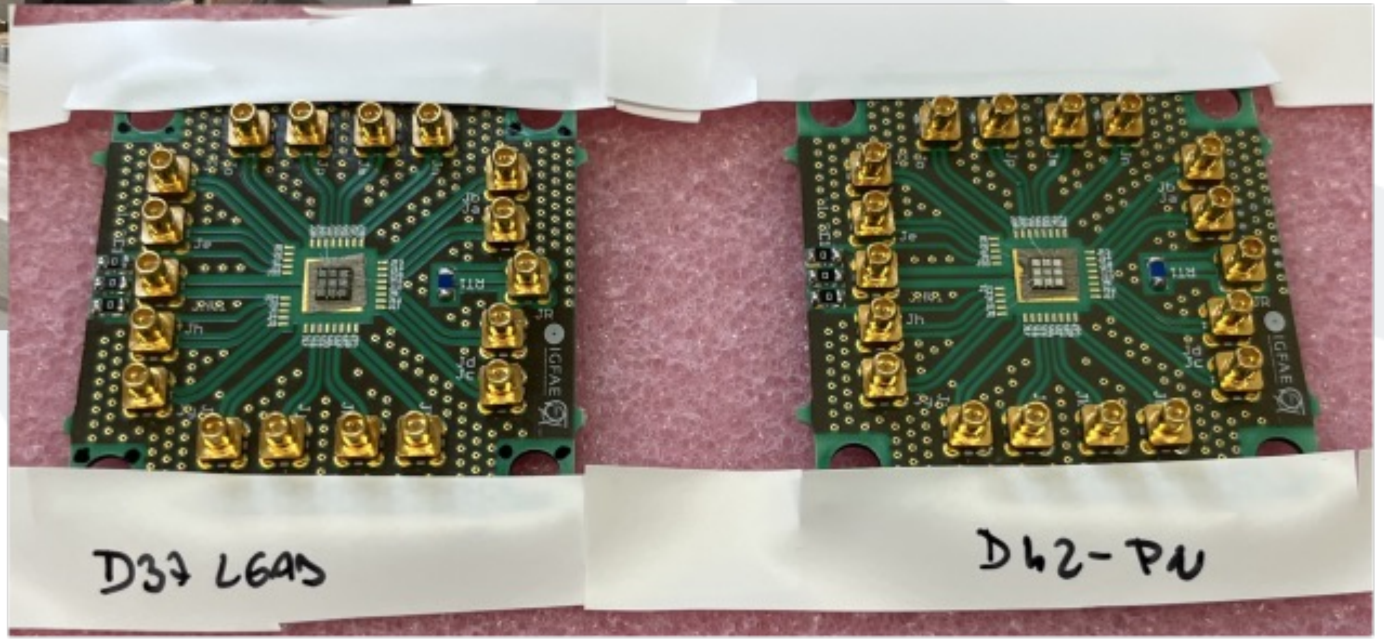
Beam test – Lot4

- Part of Timepix4-LHCb testbeam campaign in 10/2025 with Nikhef team
- CERN SPS H8 beamline in, ~120 GeV/c pions
- 50 μm EPI thickness
  3x3 mm^2 diodes (Lot3)
  110x110 μm^2 pixels





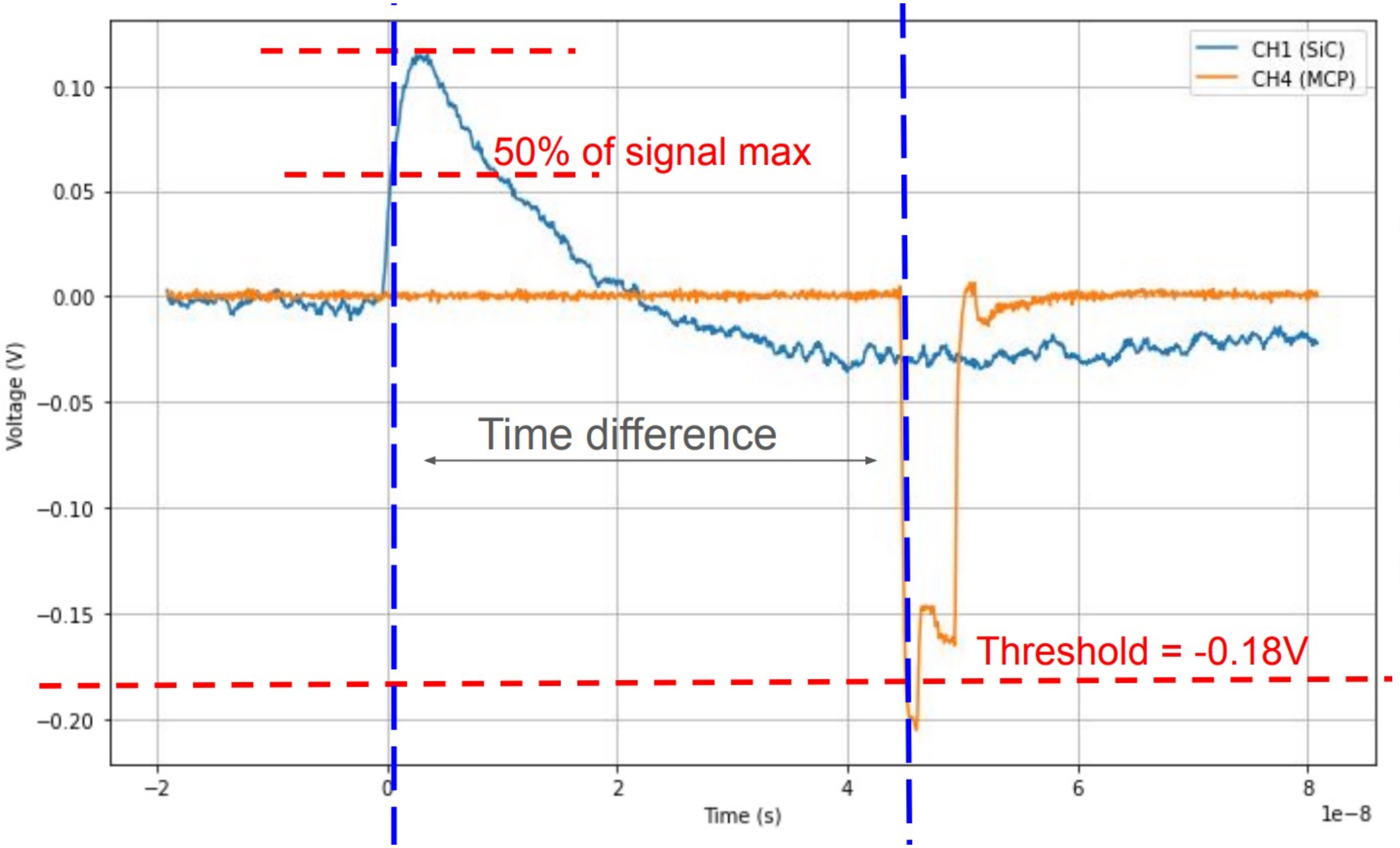


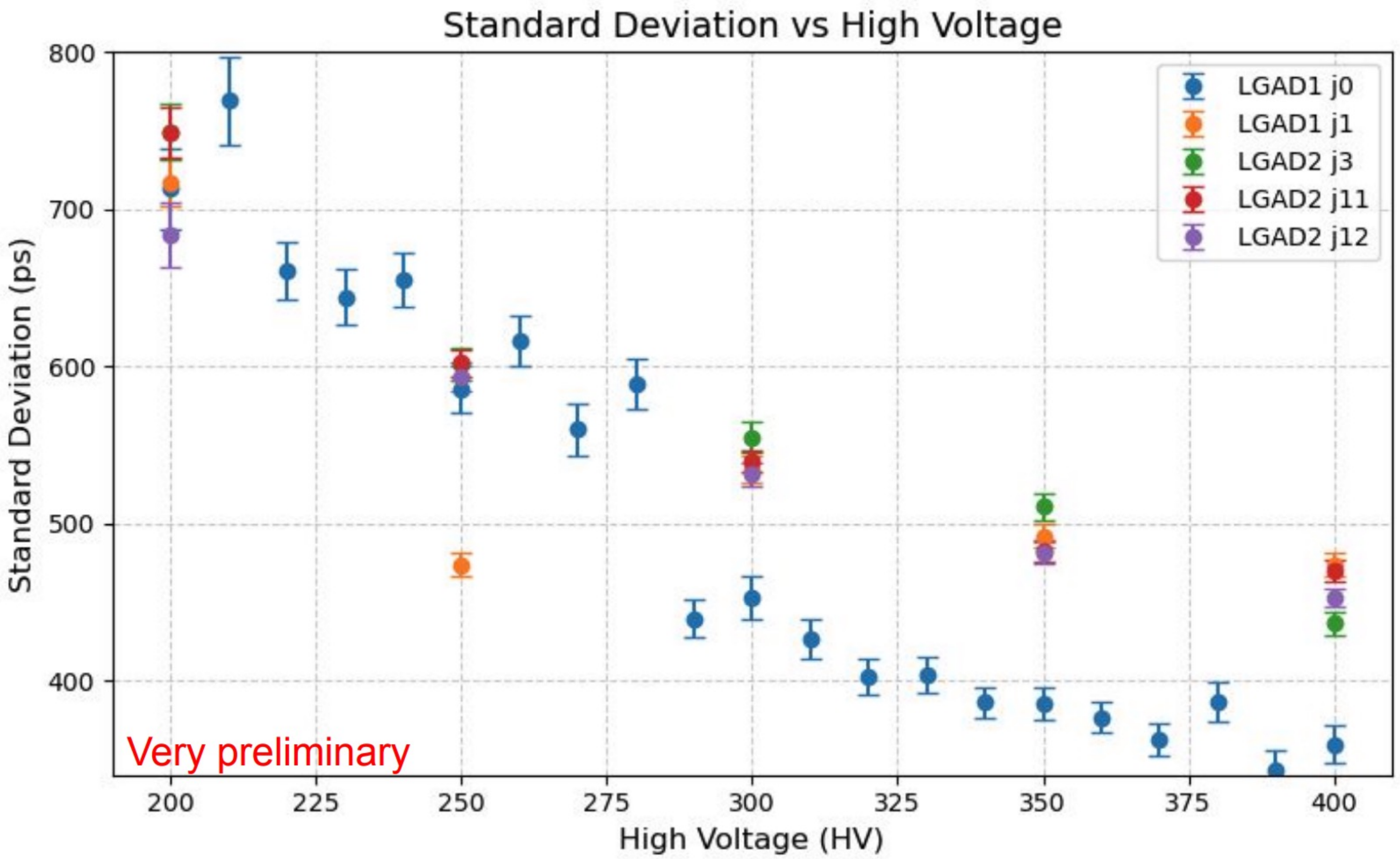


First results from beam – Lot3

by F.Fassin

- MCP reference, SiC LGAD: 3x3 mm^2, ~15pF, gain 5 → 400 ps timing





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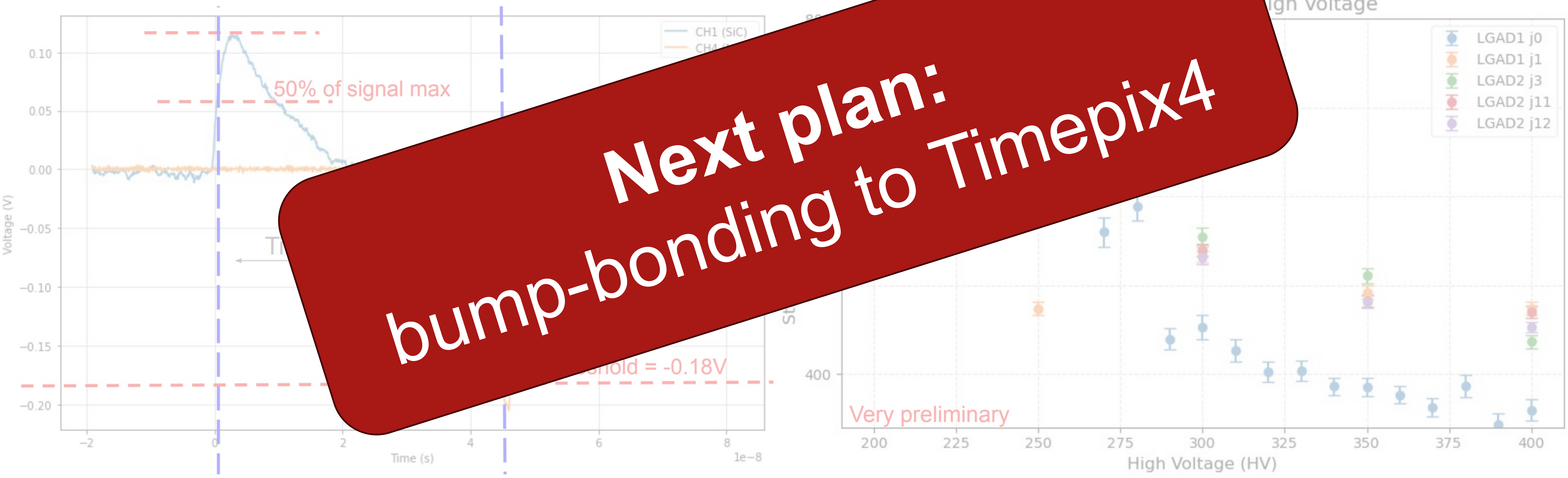
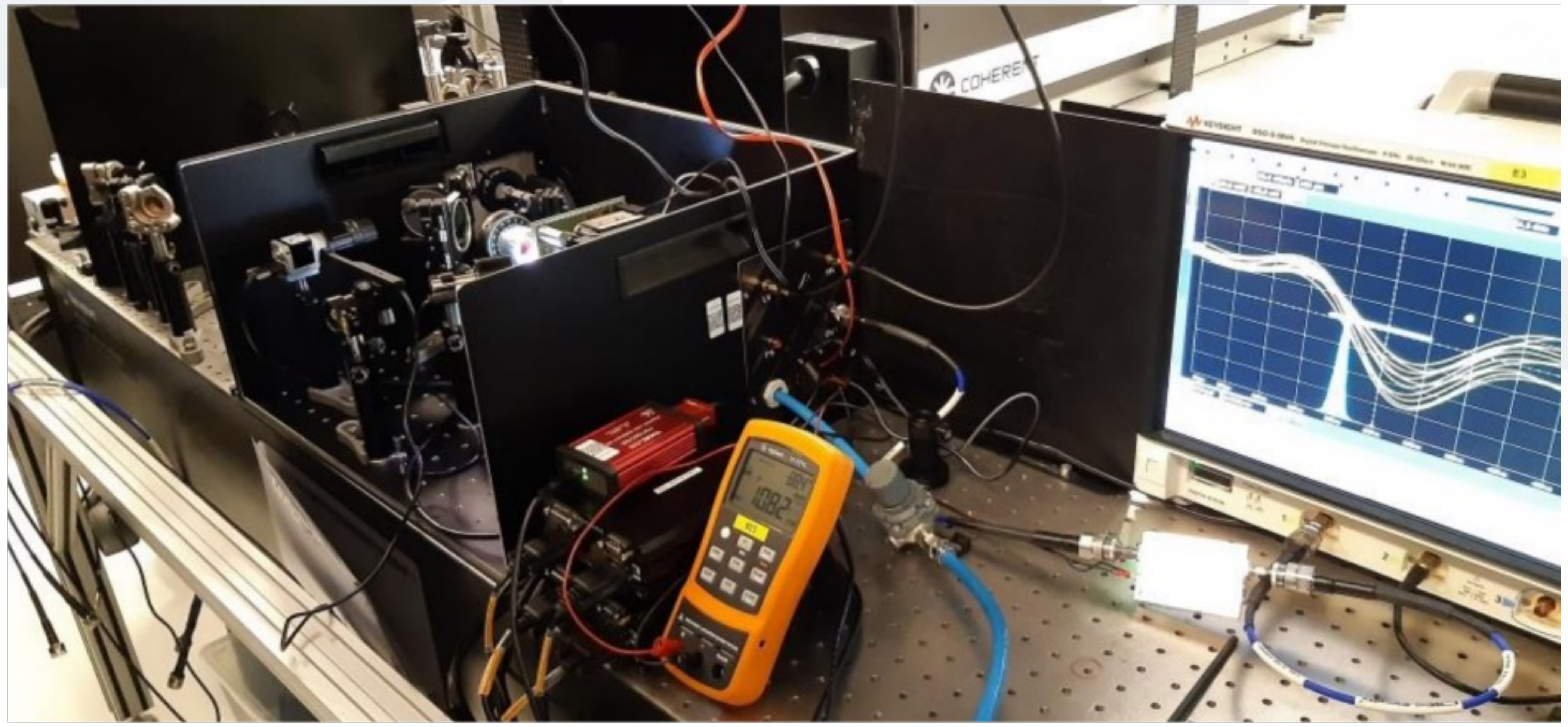


Next plan: bump-bonding to Timepix4

First results from TCT – Lot4

- **Campaign at ELI ERIC @ Prague**
  - 12/2025, comparison of segmentations, intial tests
  - 03/2026, verification of new implantation profiles
- **Highly tunable laser system**
  - Beam spot ~ 2 μm
  - Pulse duration ~ 50 fs
- **400 nm TPA-TCT**
  - Overnight bias-depth-position scans

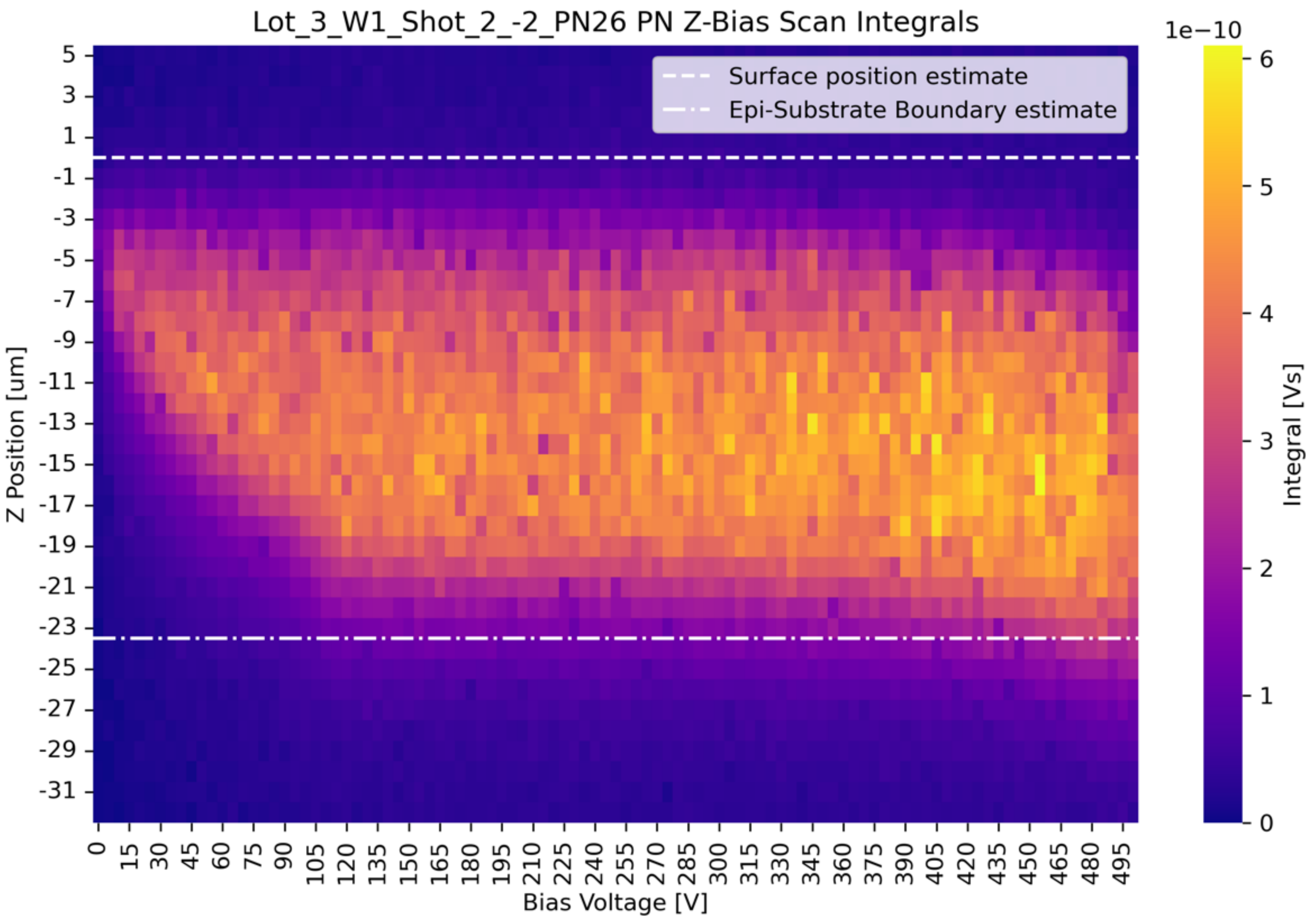


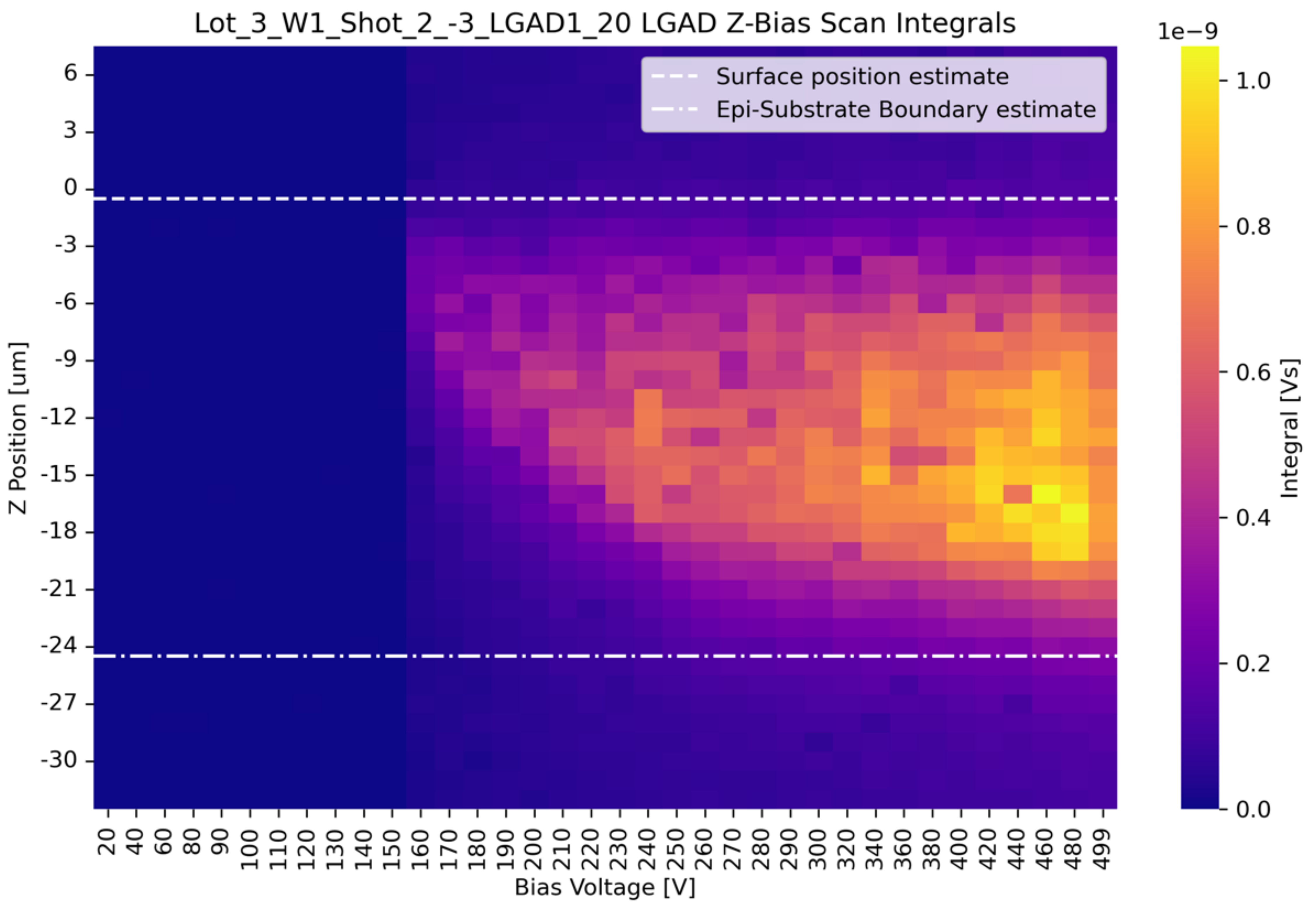
lot of help with testing and analysis by MBI team

MBI Marietta-Blau-Institut für Teilchenphysik by V. Kracmar

TPA-TCT diodes – Lot4

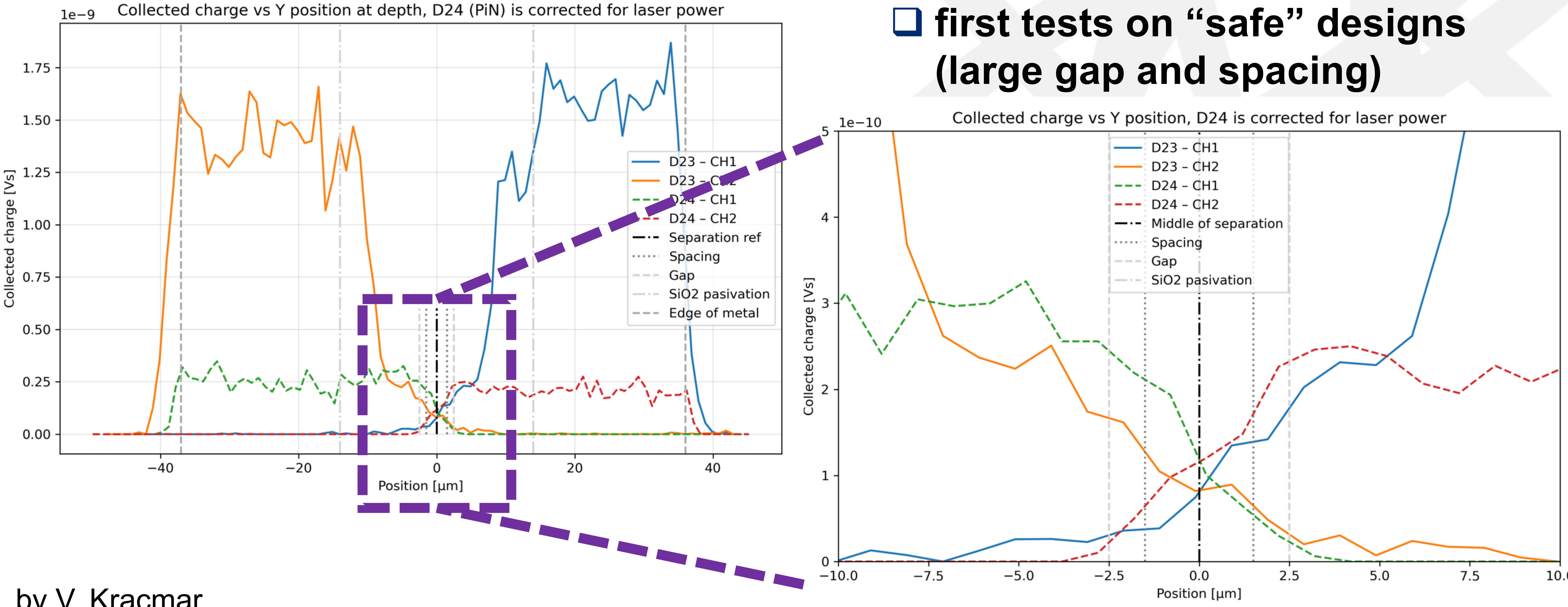
- **Verified on simple diodes without and with gain**





TPA-TCT strips – Lot4

- confirmed gain ~5 @ 300V
- wider no-gain region than estimated (15 µm vs 5 µm)
- first tests on "safe" designs (large gap and spacing)



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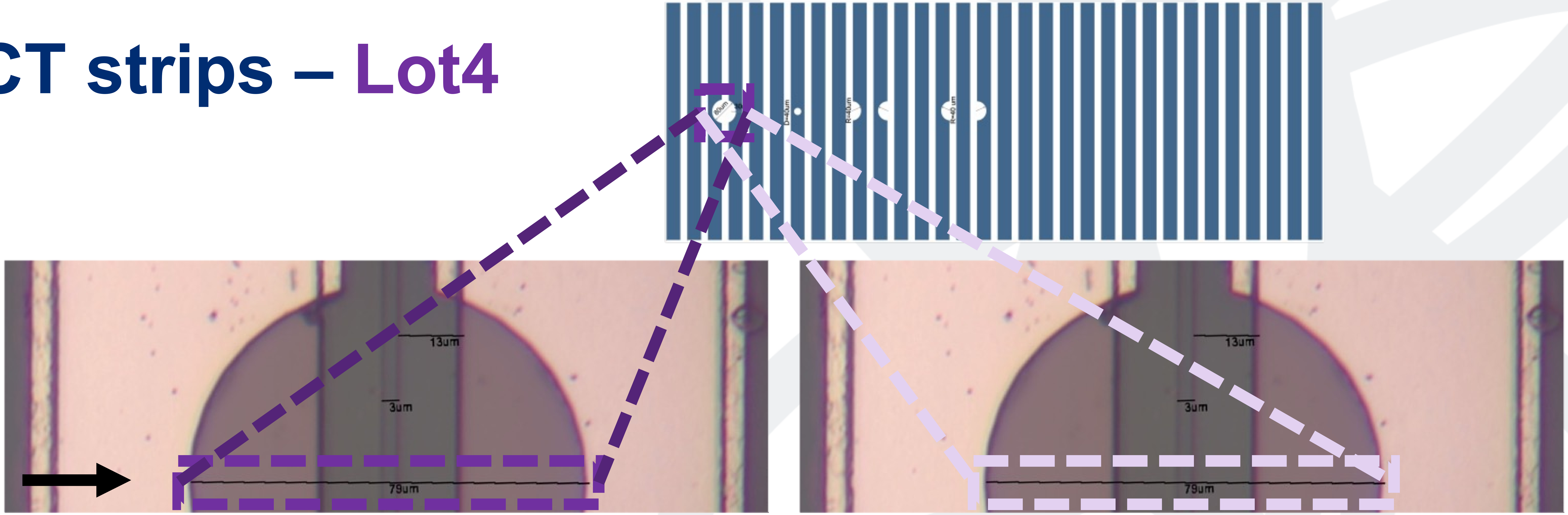
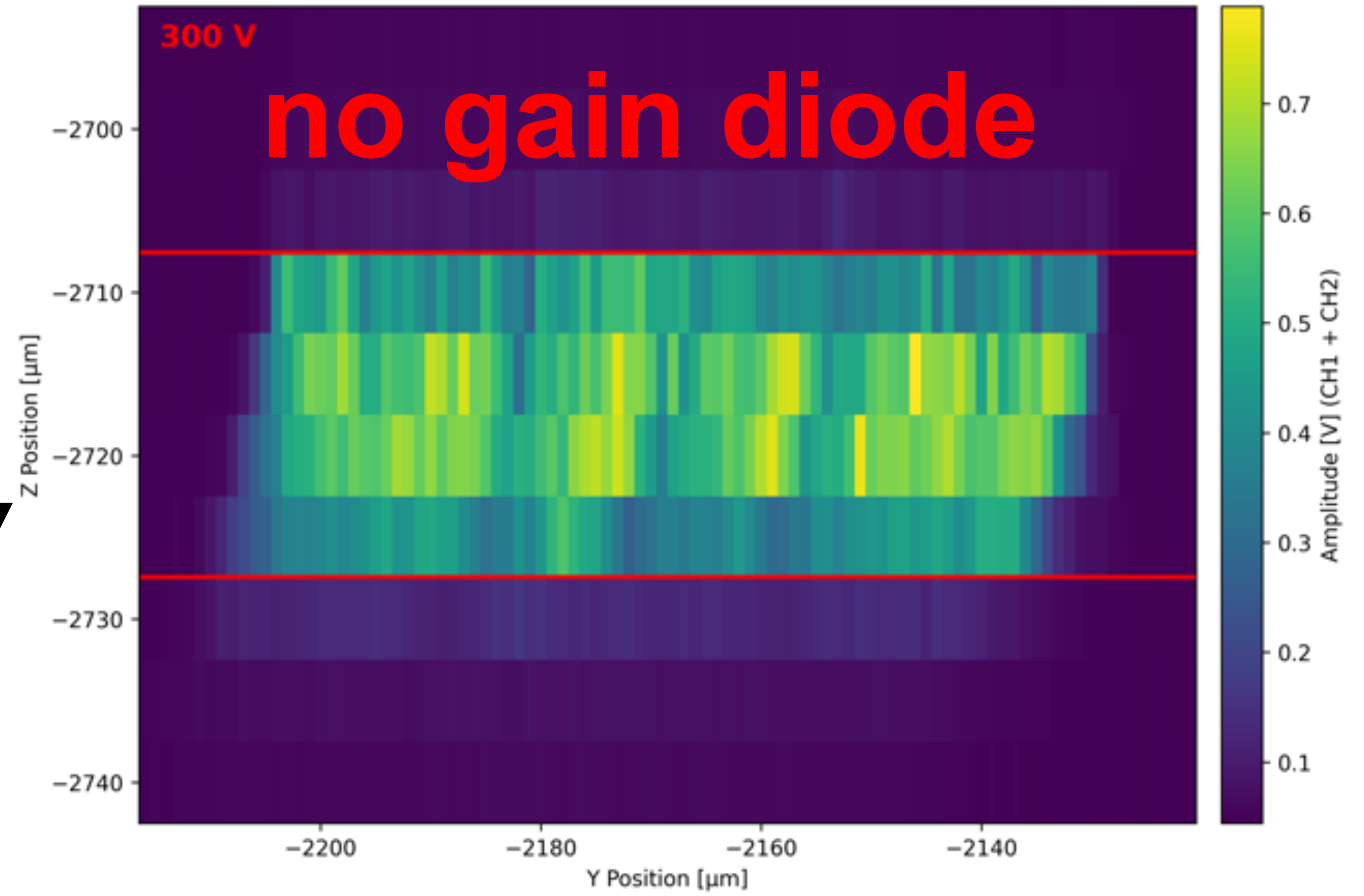
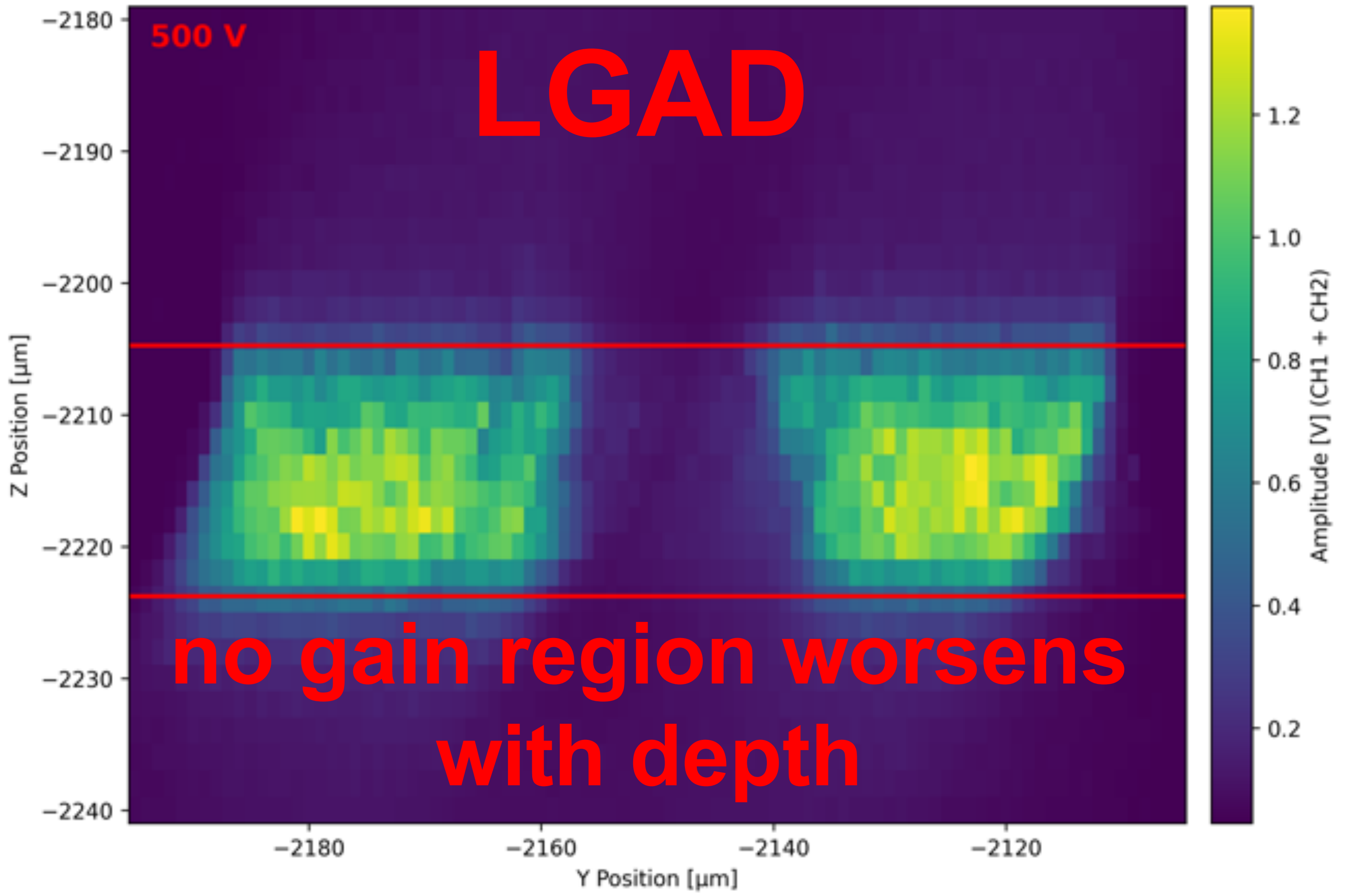
TPA-TCT strips – Lot4



line scan →

+ depth scan ↓





Summary

- SiC becoming more available
- Radiation hard(er)? – being investigated
- Newly produced segmented designs being verified

- On a path to reach the same level of performance
  - … R&D still necessary but promising!

url: FORTE

url: P4F

url: OnSemi

url: FZU

url: CAPADS

Thank you!

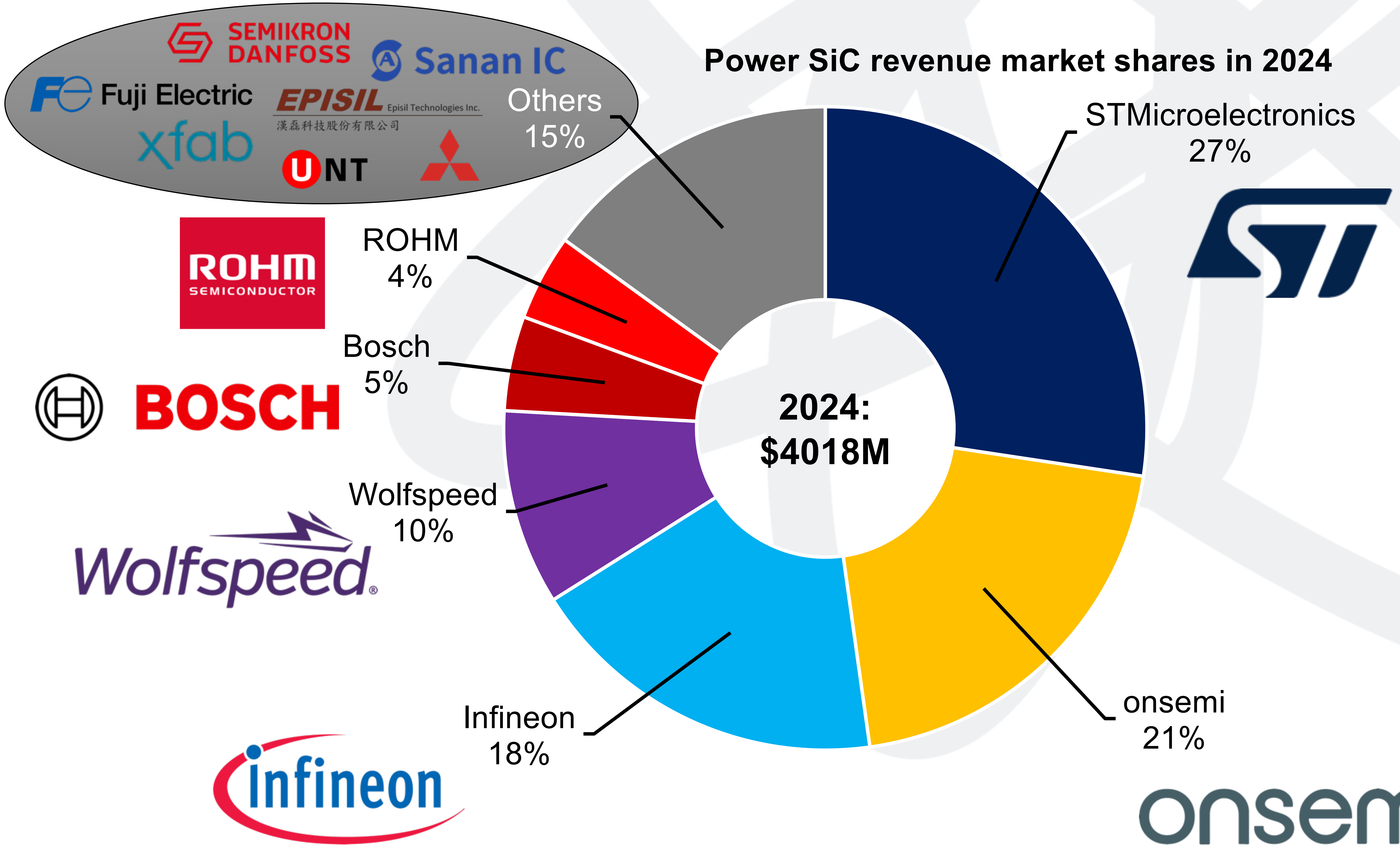
Peter Švihra

- Department of Detector Development and Data Processing (33)
- svihra@fzu.cz

Backup

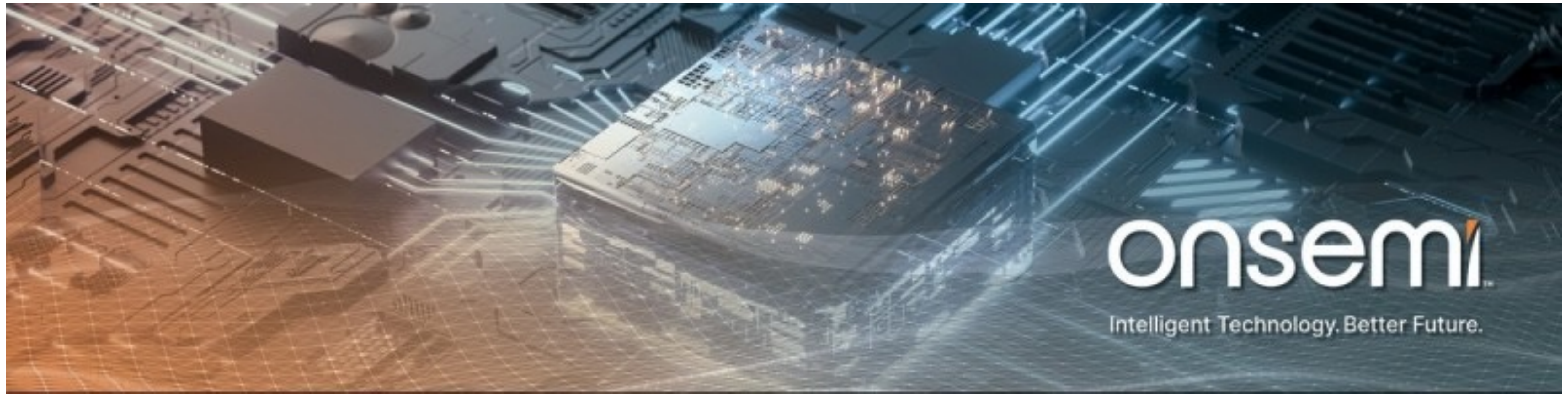
Our availability thanks to onsemi

- International SiC device manufacturers maintain the largest market share.
- Few Chinese players gained significant growth in revenue in 2024, e.g., UNT and Sanan.



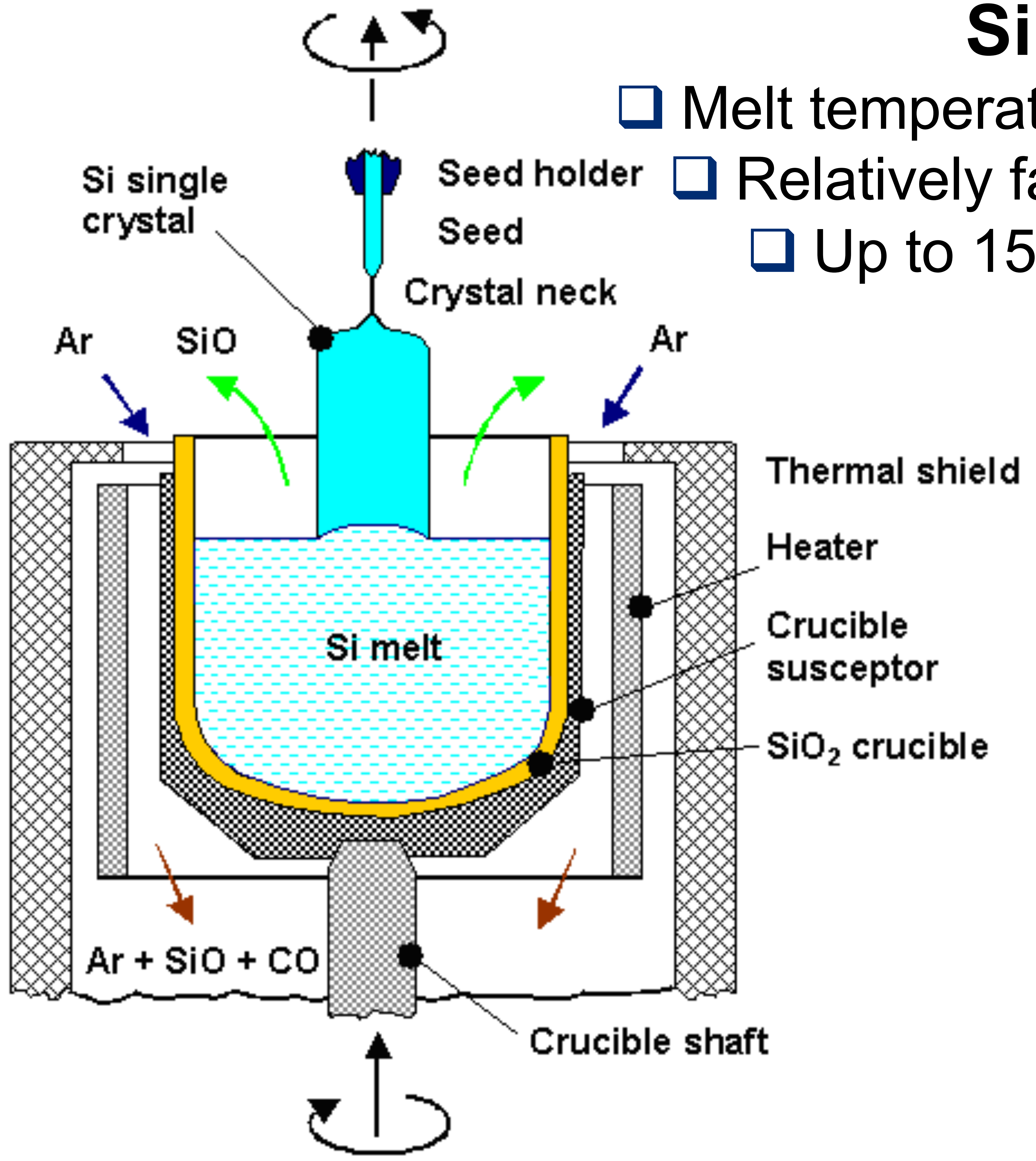
Our availability thanks to onsemi

- ❑ **Silicon sensor manufacturing for ATLAS detector**
- ❑ **New SiC design center in CZ**
- ❑ **Multiple common project developing SiC detectors segmented SiC LGAD**
  - ❑ Czech Technology Agency (TAČR)
  - ❑ Czech Ministry of Industry and Trade (MPO)



Onsemi invests 2bn $ in SiC fab in Roznov, CZ

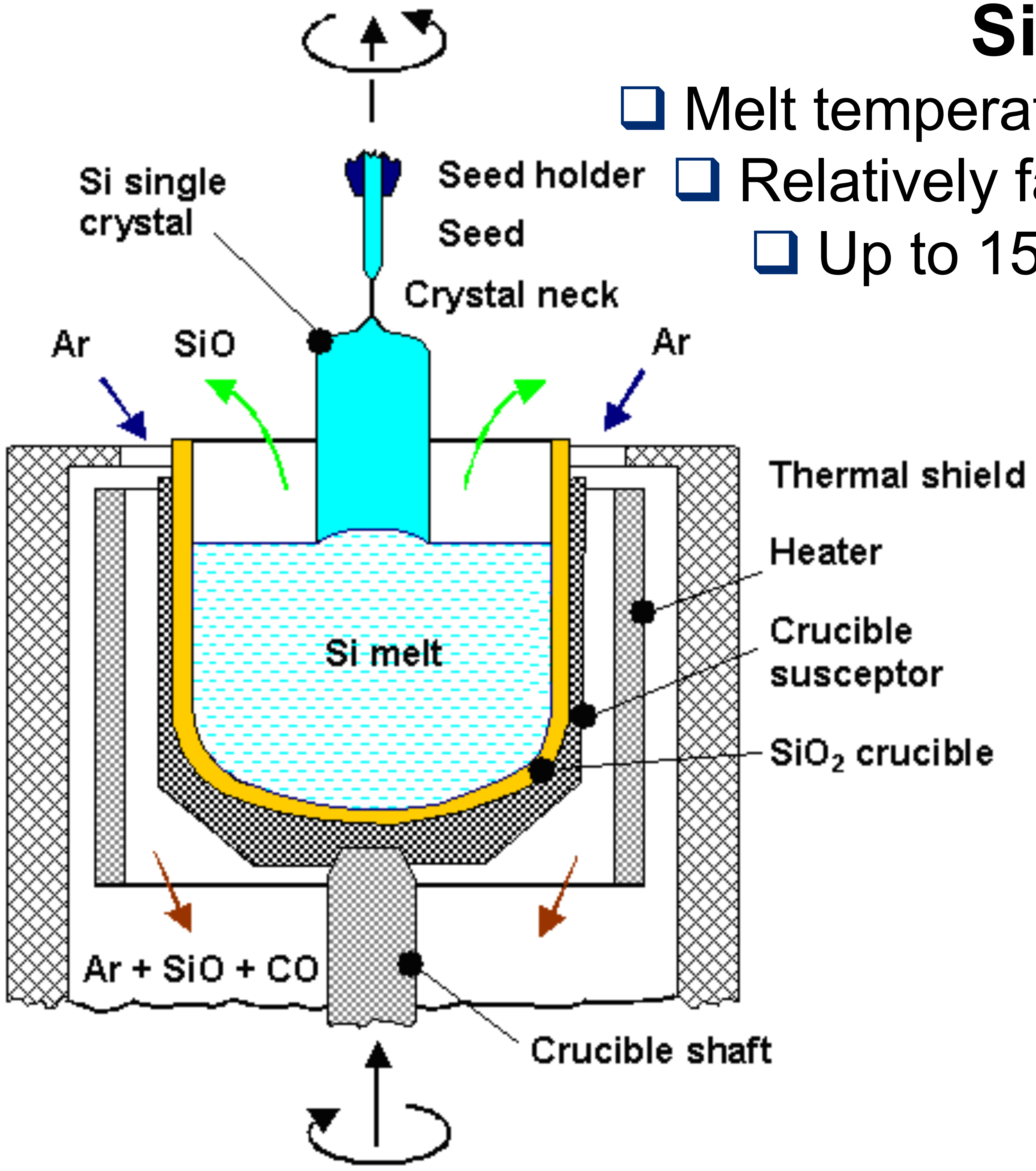
Si and SiC manufacturing



Si

- ❑ Melt temperature (1417°C)
- ❑ Relatively fast process
- ❑ Up to 15'' wafers

Si and SiC manufacturing

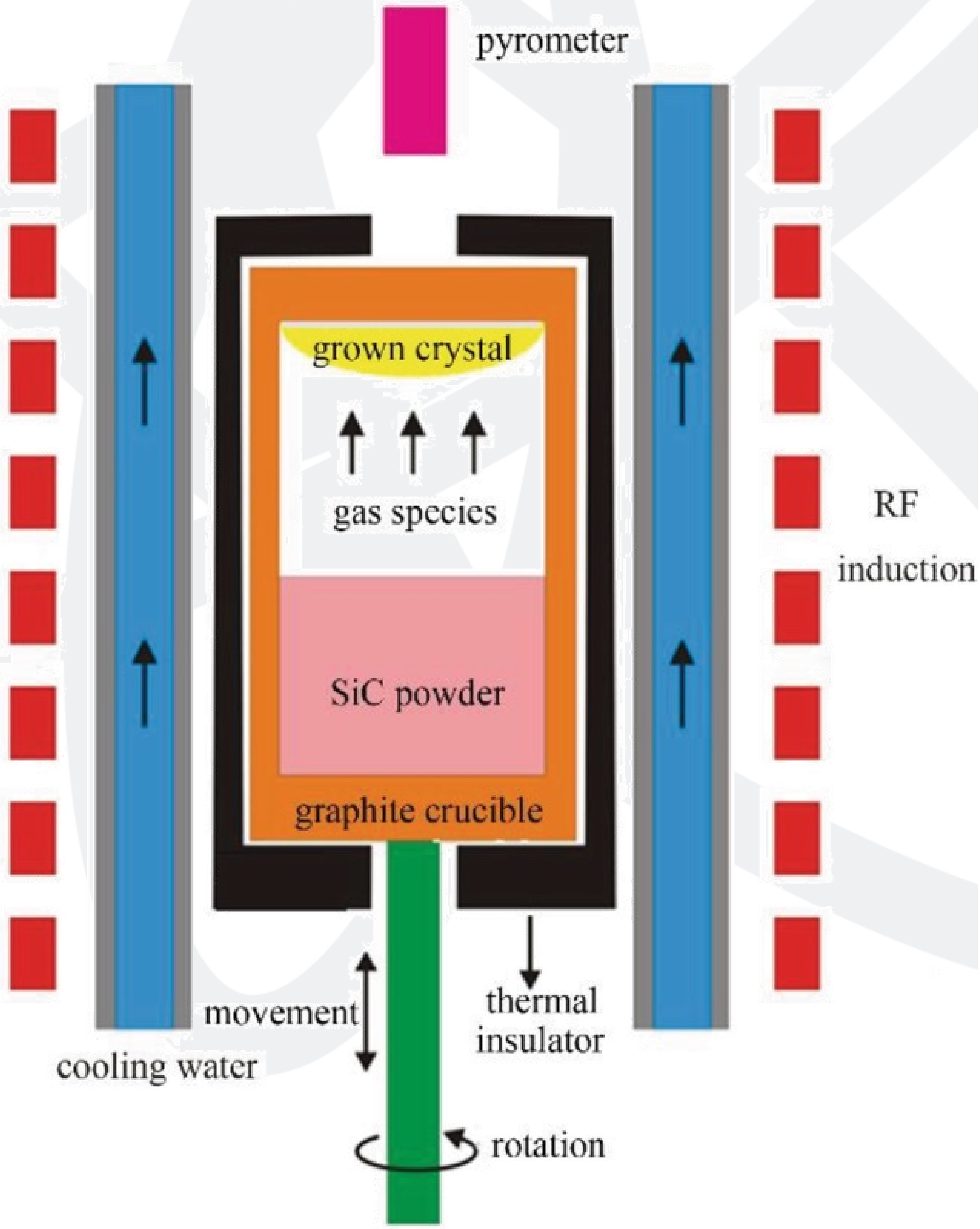


Si

- Melt temperature (1417°C)
- Relatively fast process
- Up to 15" wafers

SiC

- Growth at high temperature (**2300°C**)
- Slow process
- **Very expensive**
- 6" - 8" wafers



SiC manufacturing

- **SiC produced from SiO_2 and C by Acheson process (inv. 1897)**
- **Melt would require 3200 ◦C and pressure of 105 atmospheres**
  - sublimation in ~2300 ◦C, low pressure, Ar atmosphere with N_2

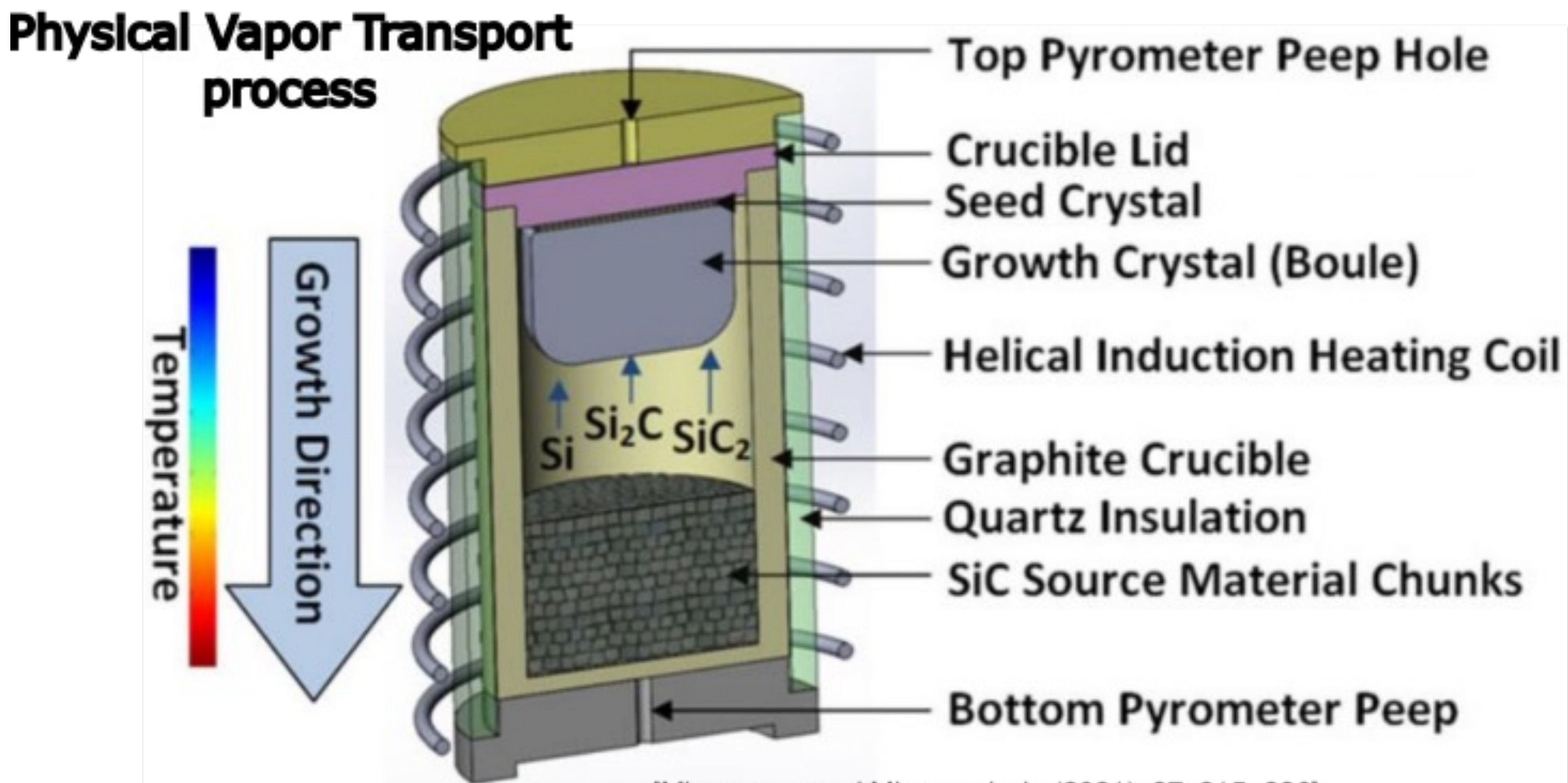
$$SiO_2(s) + 3C(s) + 625.1\ \text{kJ} \rightarrow \alpha\text{-}SiC(s) + 2CO(g)$$

$$SiO_2(s) + C(s) \longrightarrow SiO(g) + CO(g)$$

$$SiO_2(s) + CO(g) \longrightarrow SiO(g) + CO_2(g)$$

$$C(s) + CO_2(g) \longrightarrow 2CO(g)$$

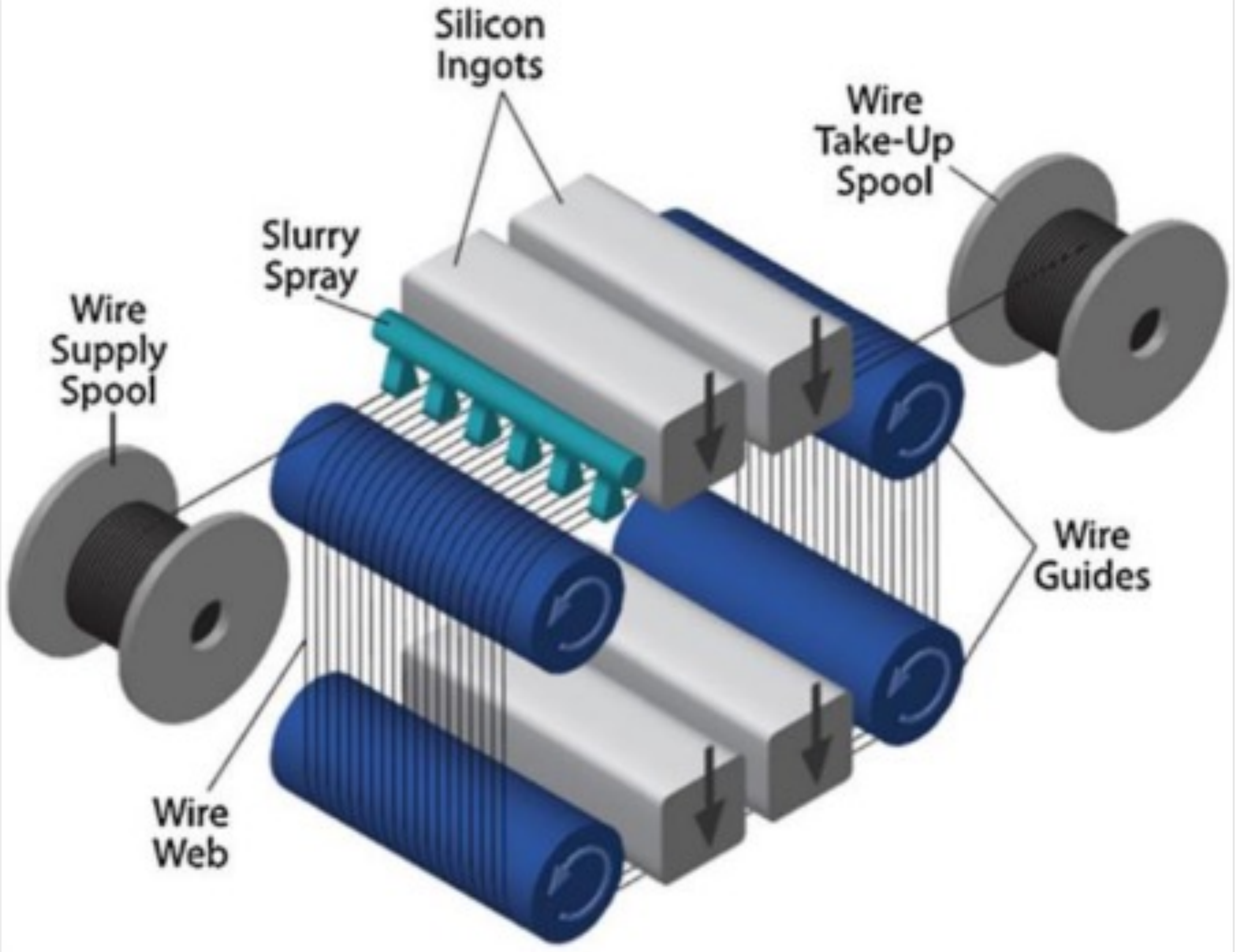
$$2C(s) + SiO(g) \longrightarrow SiC(s) + CO(g)$$



[Microscopy and Microanalysis (2021), 27, 215–226]

Si and SiC – wafer dicing

- ❑ **Common approach by wire sawing technology**



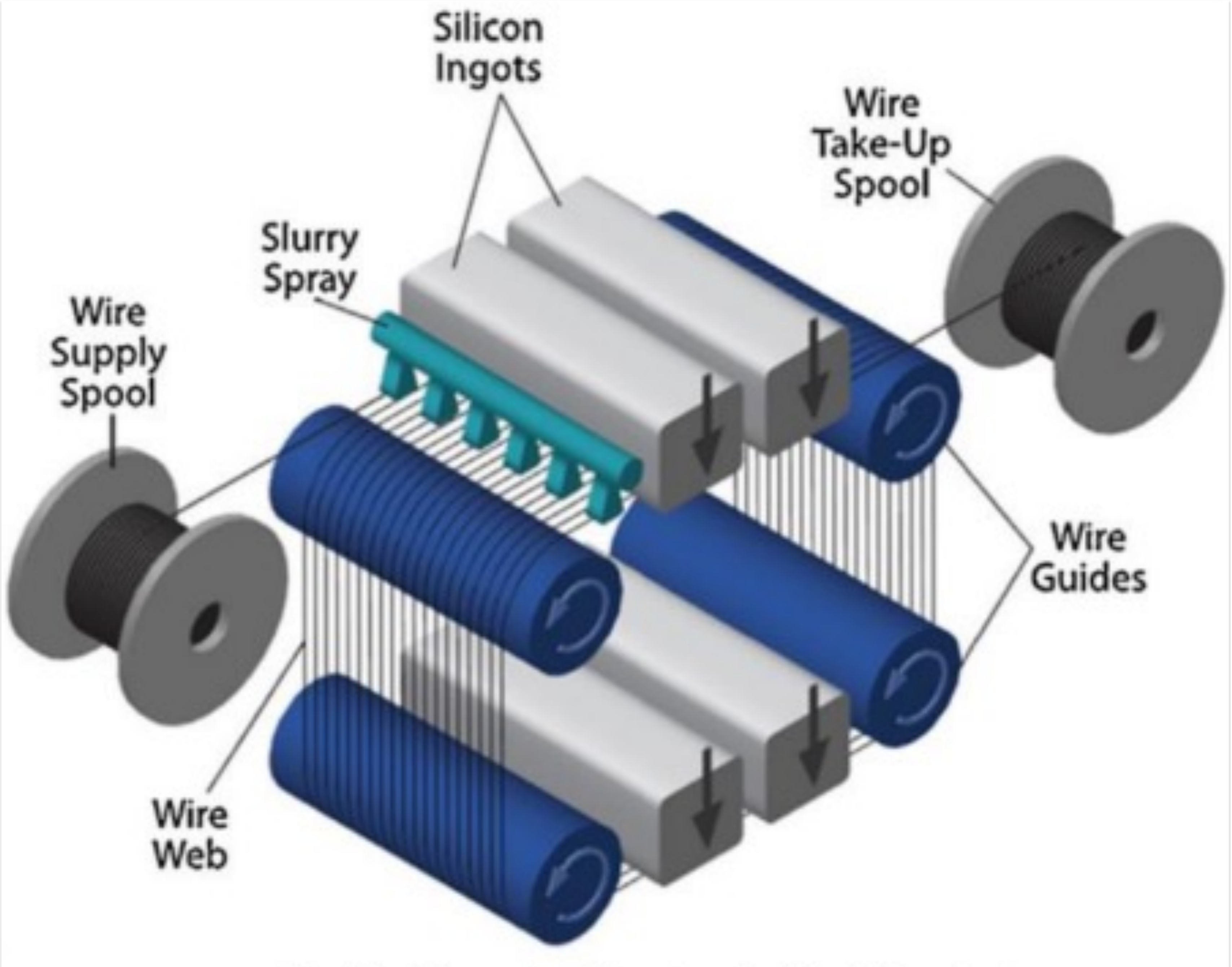
[Hao Wu, Wire sawing technology: A state-of-the-art review, Precision Engineering, Volume 43, 2016, 1-9.]

Impossible for SiC!

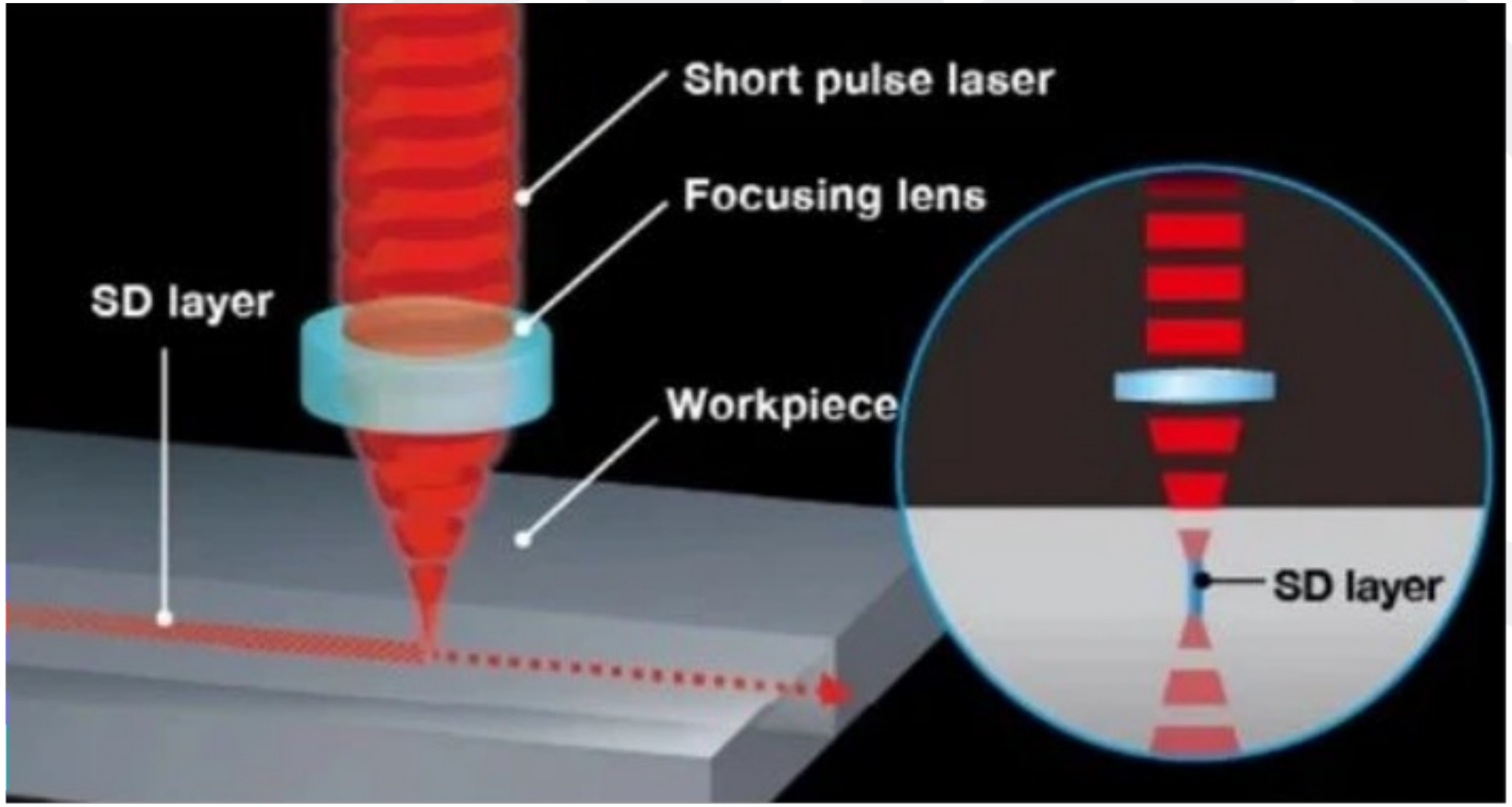
- Loss of material due to wire thickness
- Thin pucks (few centimeters)
- Takes too long since material is very stiff

Si and SiC – wafer dicing

- ❑ **Common approach by wire sawing technology**
- ❑ **KABRA (3-photon absorption of 1064 nm Nd:YAG laser)**

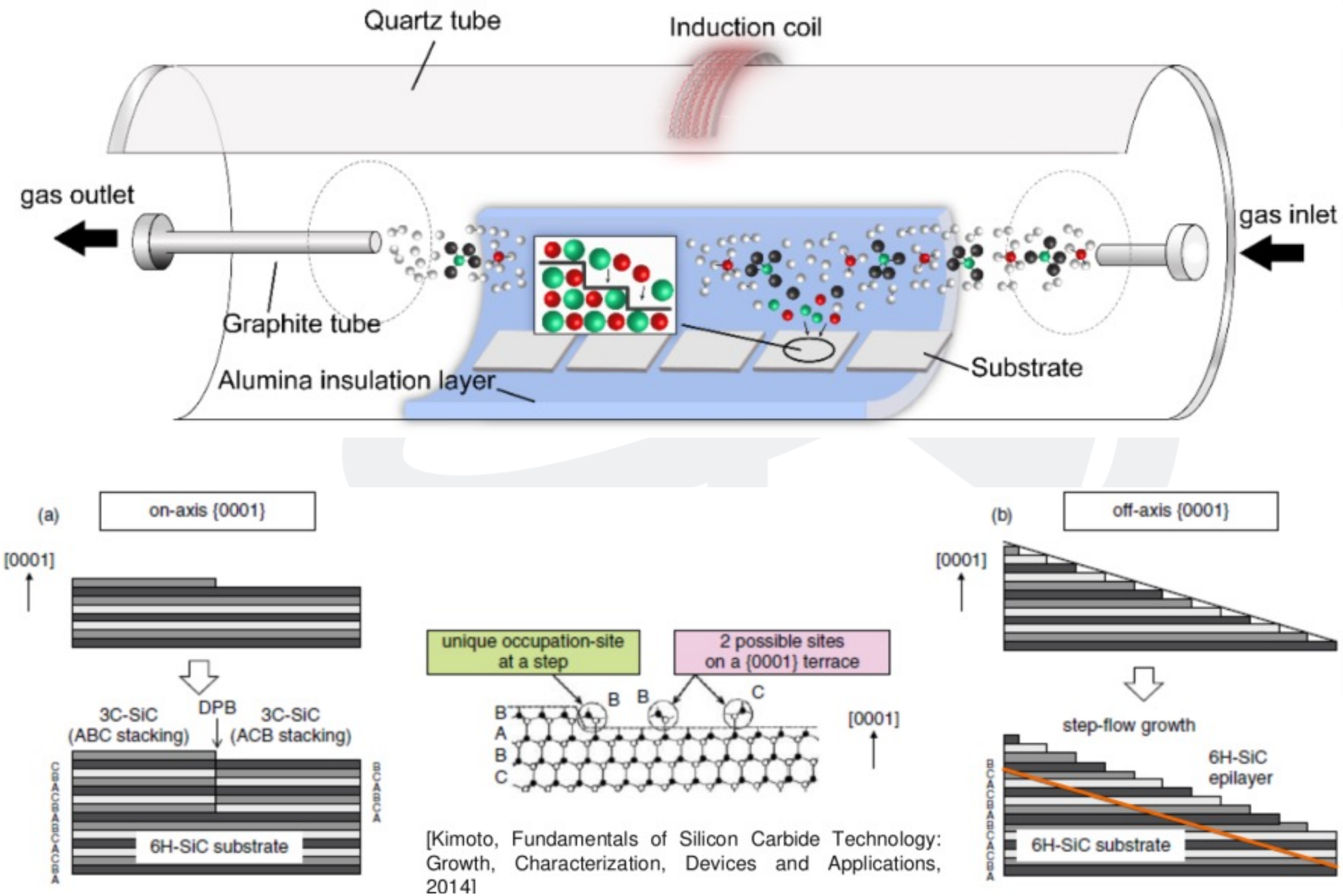


[Hao Wu, Wire sawing technology: A state-of-the-art review, Precision Engineering, Volume 43, 2016, 1-9.]



Epitaxial growth

- **Commercially available 6“ and 8“ nitrogen doped substrate ≈ 1E19 cm^{-3}**
  - **Need higher resistivity** for viable detector operation
- **Vapour deposition method to produce epitaxial (EPI) layer**

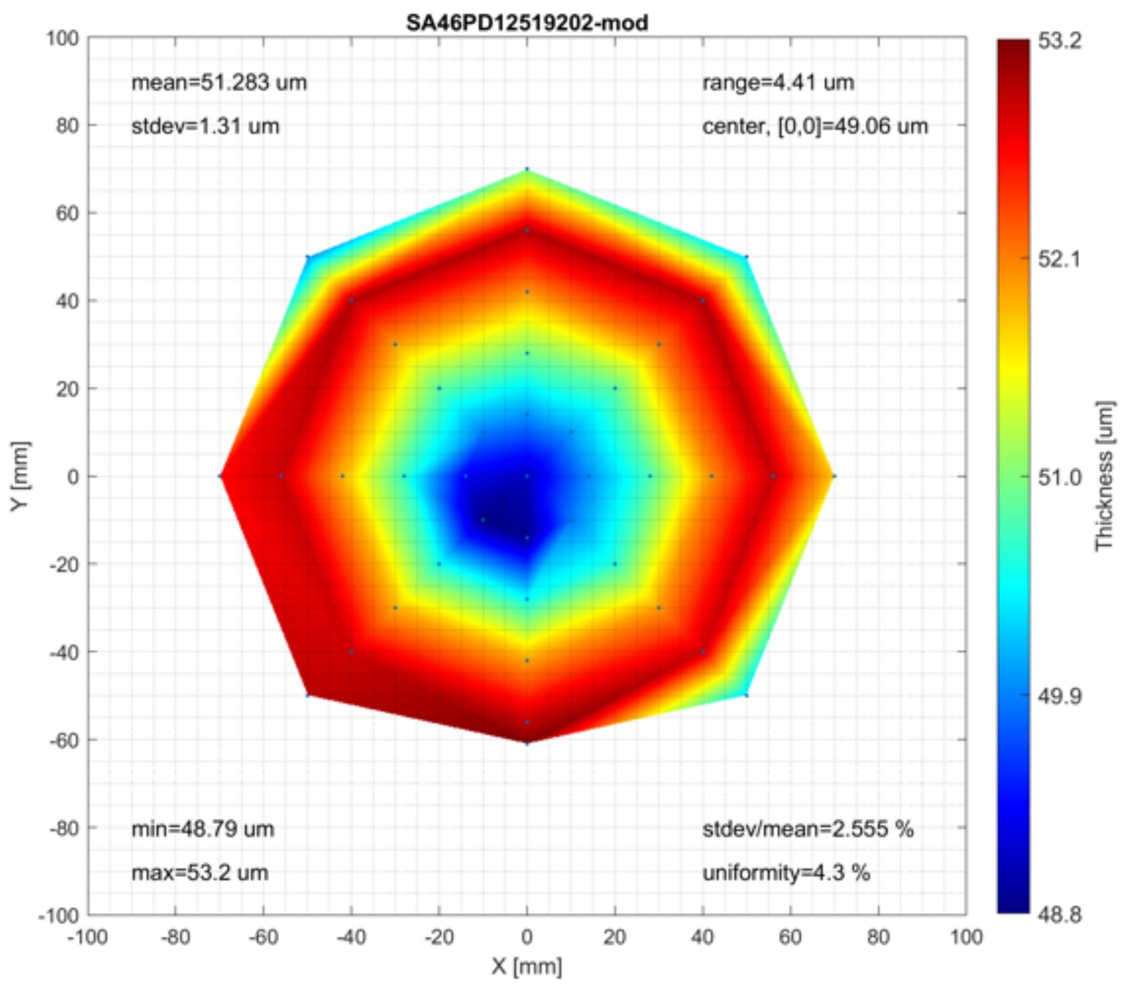


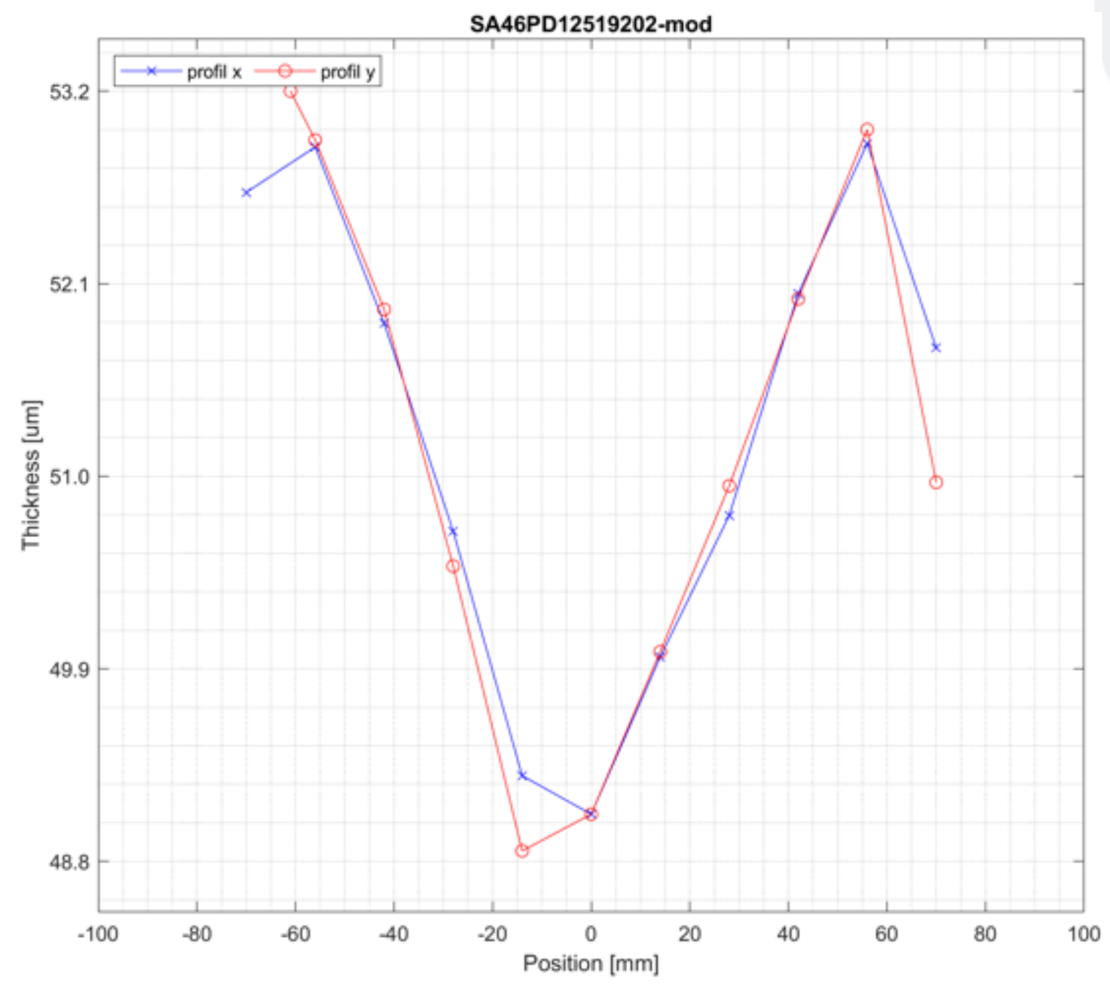
[Kimoto, Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices and Applications, 2014]

4H-SiC EPI layer

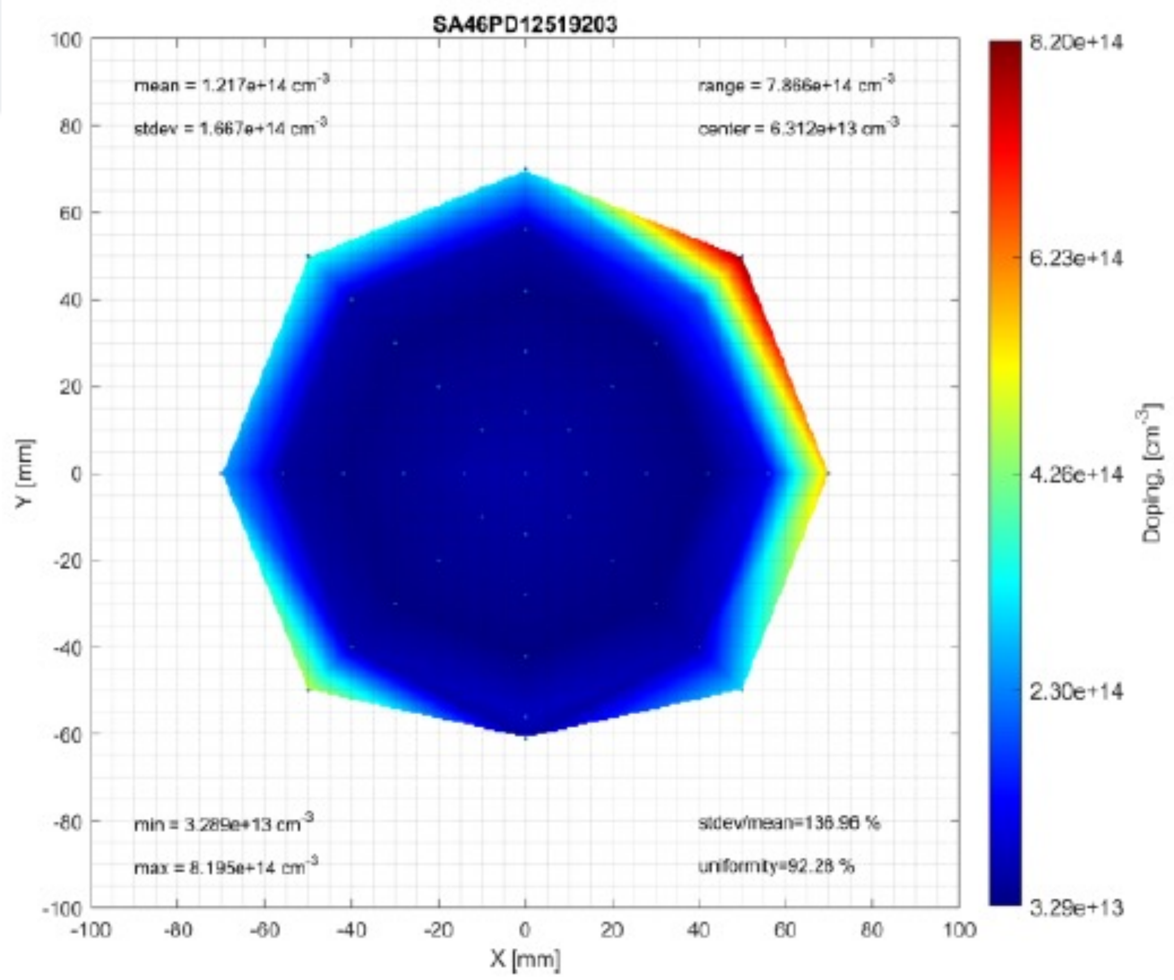
- Thickness tens of µm, doping below 1E14 cm^{-3} is difficult in SiC epitaxy
- Layers in range 30-100 µm, down to ≅5E13 cm^{-3} successfully prepared!!

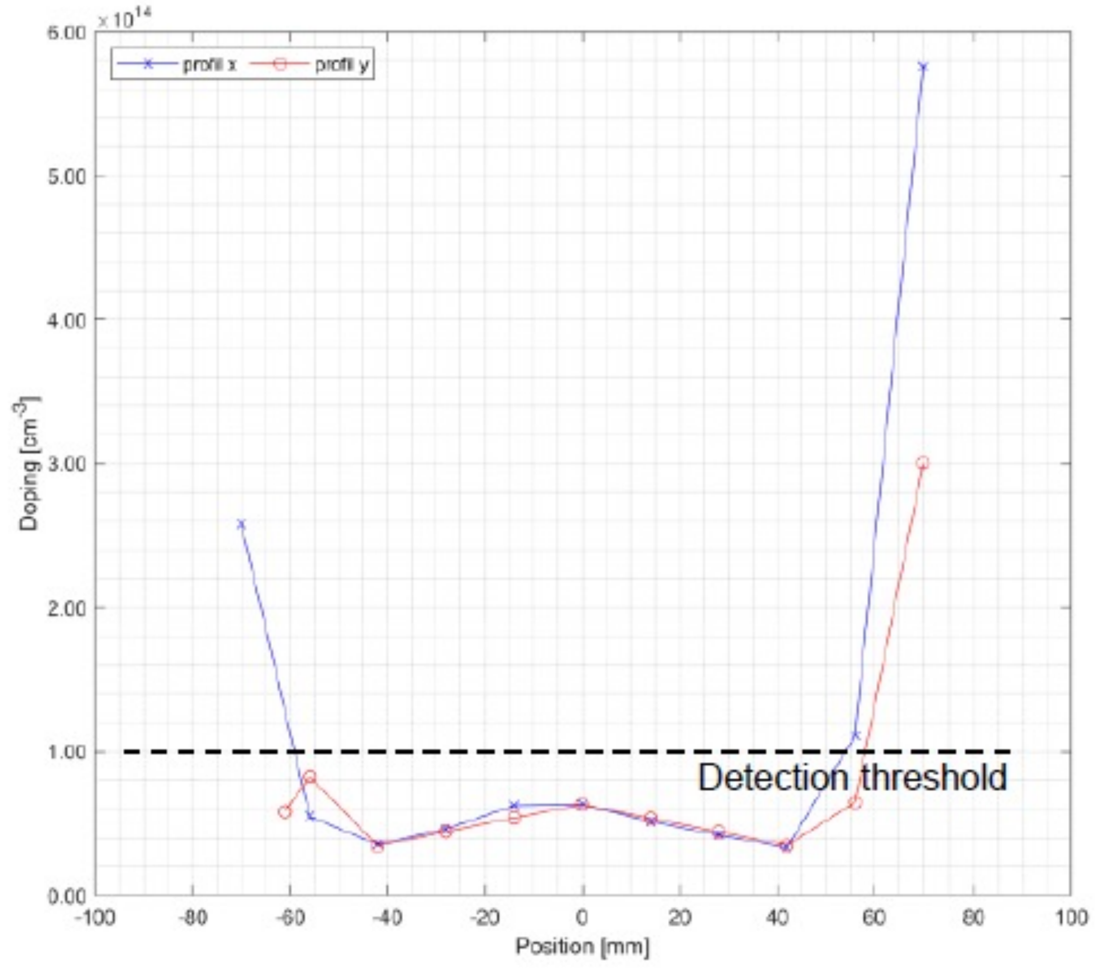
Epi thickness map (FTIR)





Epi resistivity map (Mercury CV)
– limit of method is ≈1E14 cm-3



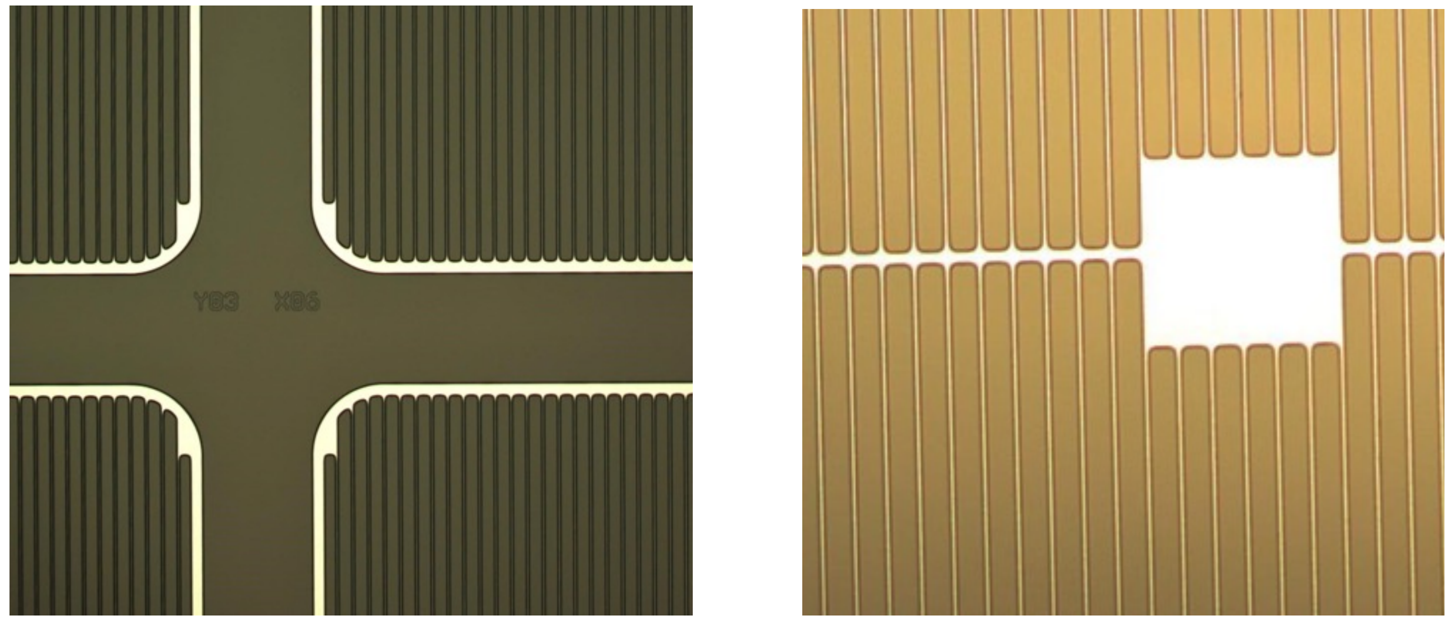


4H-SiC LGAD diode process flow

onsemi

- P+ and LGAD layers were evaluated using DOE splits of implant energy/dose
  - P+ - chain implant with energies 30 -> 200 keV, doses 1 -> 8 E14 cm^{-2}
  - LGAD – single implant 950 –> 1250 keV, 1.5 –> 1.8 E13 cm-2

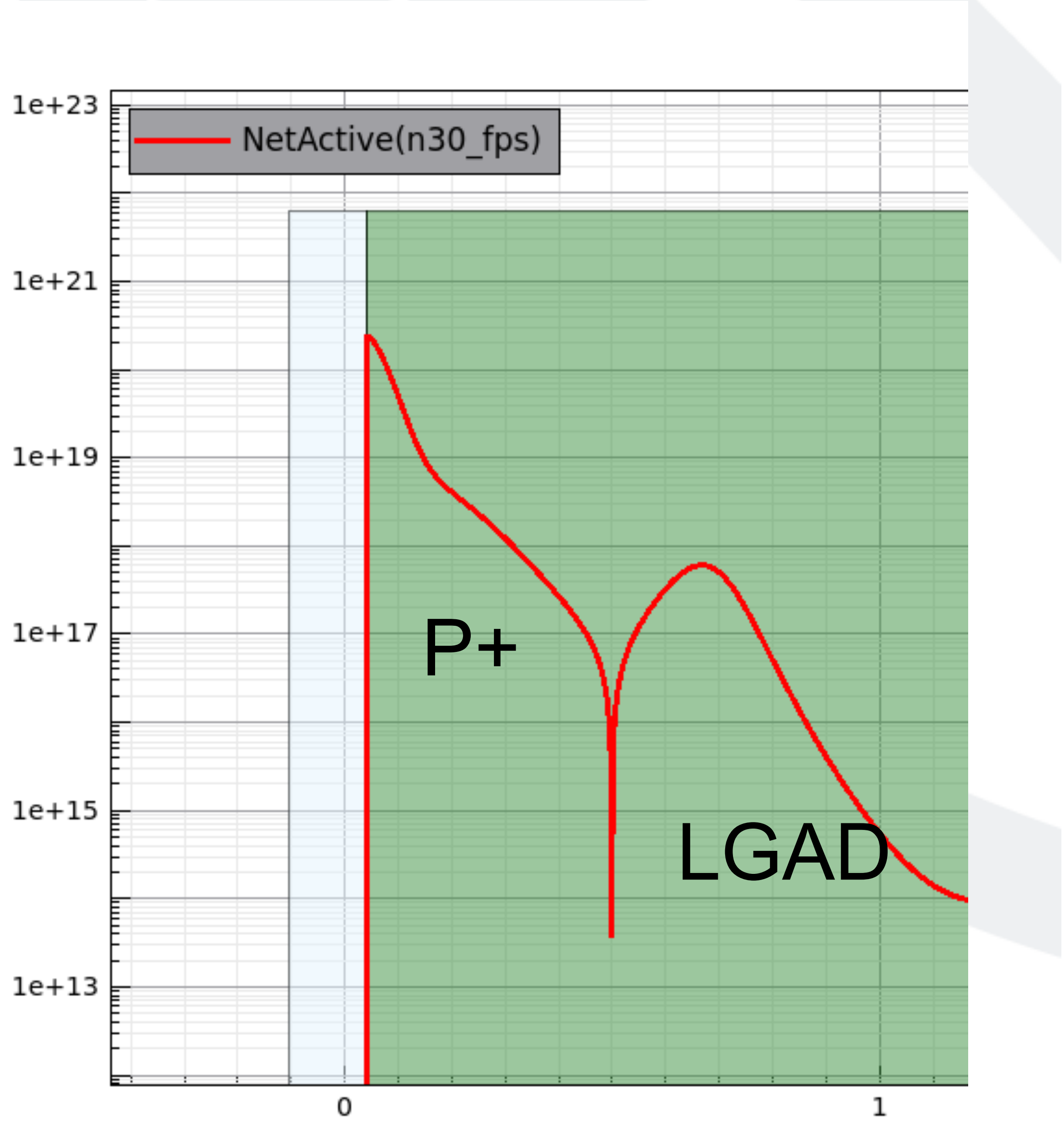
Metal stripe pattern – optical microscopy image of finished diode



Simplified process flow

Photo JTE implantation
Implant JTE (Aluminium)
Photo JTE2 implantation
Implant JTE (Aluminium)
Photo P+
Implant P+ (Aluminium)
Photo LGAD
Implant LGAD (nitrogen)
High Temperature Annealing (>1600°C)
Metal deposition
Photo metal
Metal etch
Passivation deposition
Photo passivation
Passivation etch
Back side metal

Exampla of simulated profiles of active structure in LGAD diode



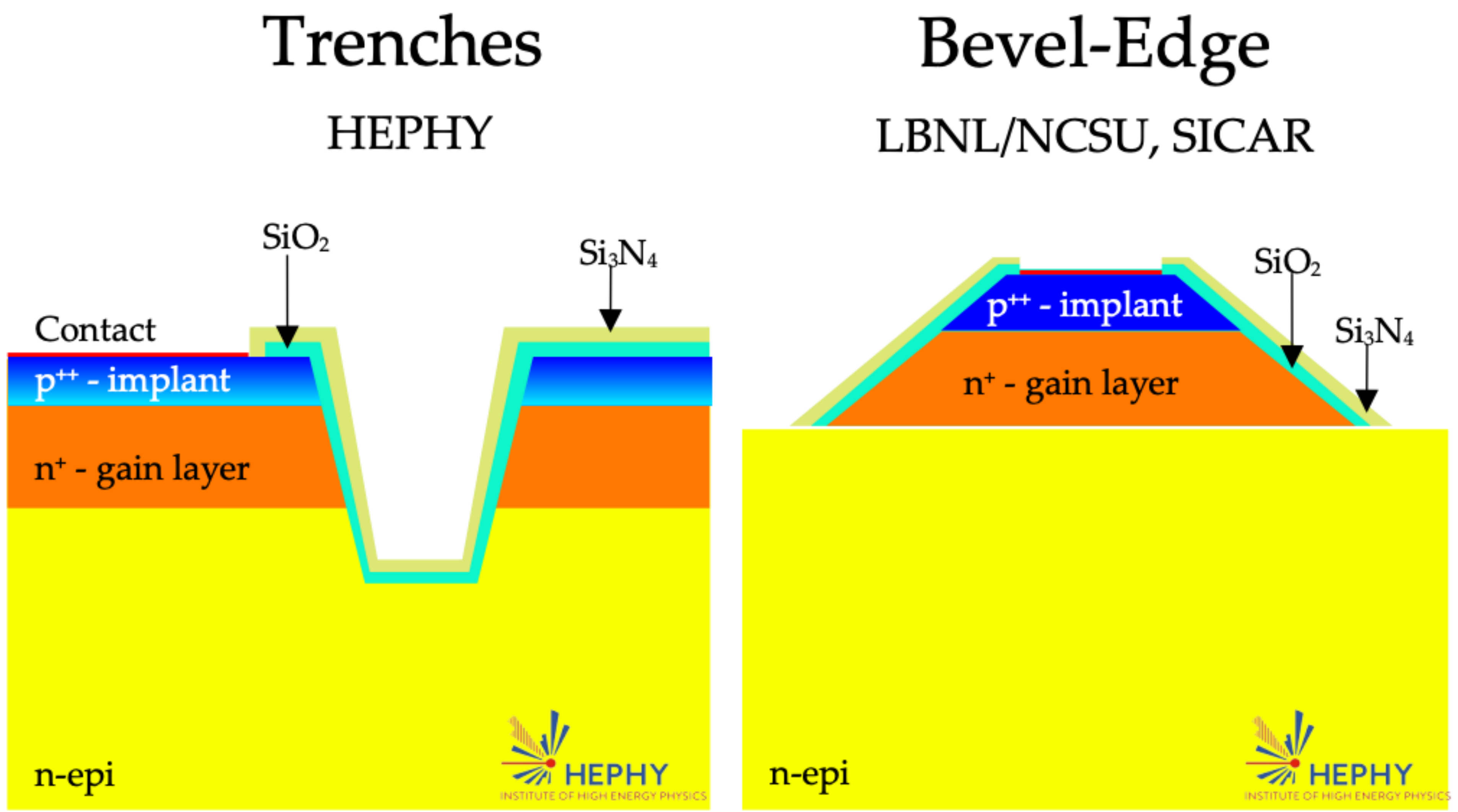
Previous (or ongoing) projects

Lot of effort within DRD3 WG6

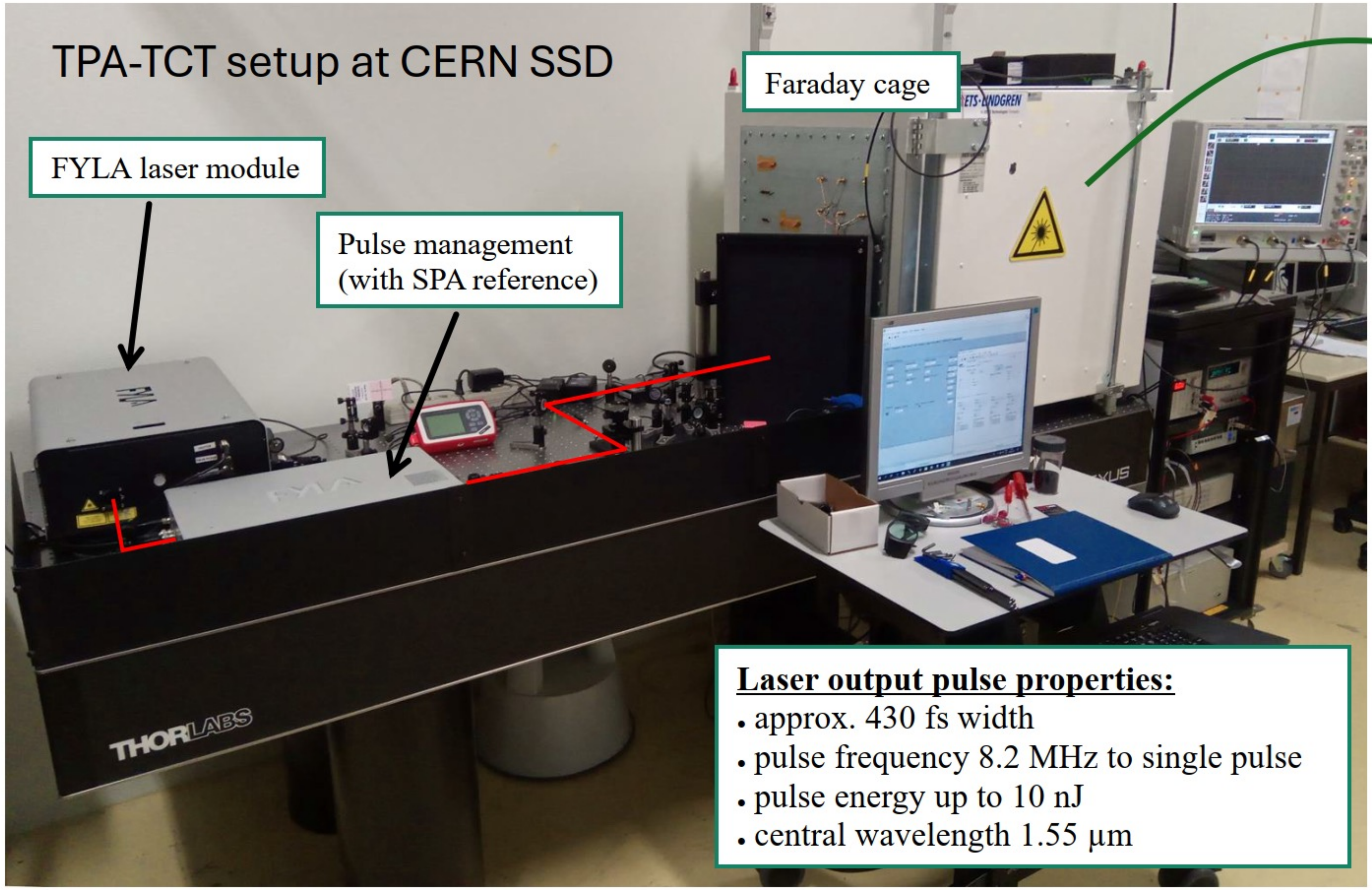
- **RD50 common project**
  - Run1 in 2024, Run2 in 2025
  - 5 wafers in total
  - Production in CNM
- **SICAR**
  - Runs in 2023/2024 and beyond
  - IHEP CAS
  - “mesa” like structures

- **All layers epitaxially grown**
- **All groups (mostly) aiming for LGADs**

Title of project: *SiC-LGAD*
Contact person: *Thomas Bergauer (HEPHY Vienna)*
Nikolsdorfer Gasse 18, 1050 Wien, Vienna, Austria
Thomas.Bergauer@oeaw.ac.at
RD50 Institutes:
1. *OEAW-HEPHY, Thomas Bergauer, Thomas.Bergauer@oeaw.ac.at*
2. *CSIC-IMB-CNM, Giulio Pellegrini, giulio.pellegrini@csic.es*
3. *CERN, Susanne Kühn, susanne.kuehn@cern.ch*
4. *INFN Perugia, Francesco Moscatelli, moscatelli@iom.cnr.it*
5. *IFCA Santander, Ivan Vila ivan.vila@csic.es*
6. *NIKHEF, Kazu Akiba kazu.akiba@nikhef.nl*

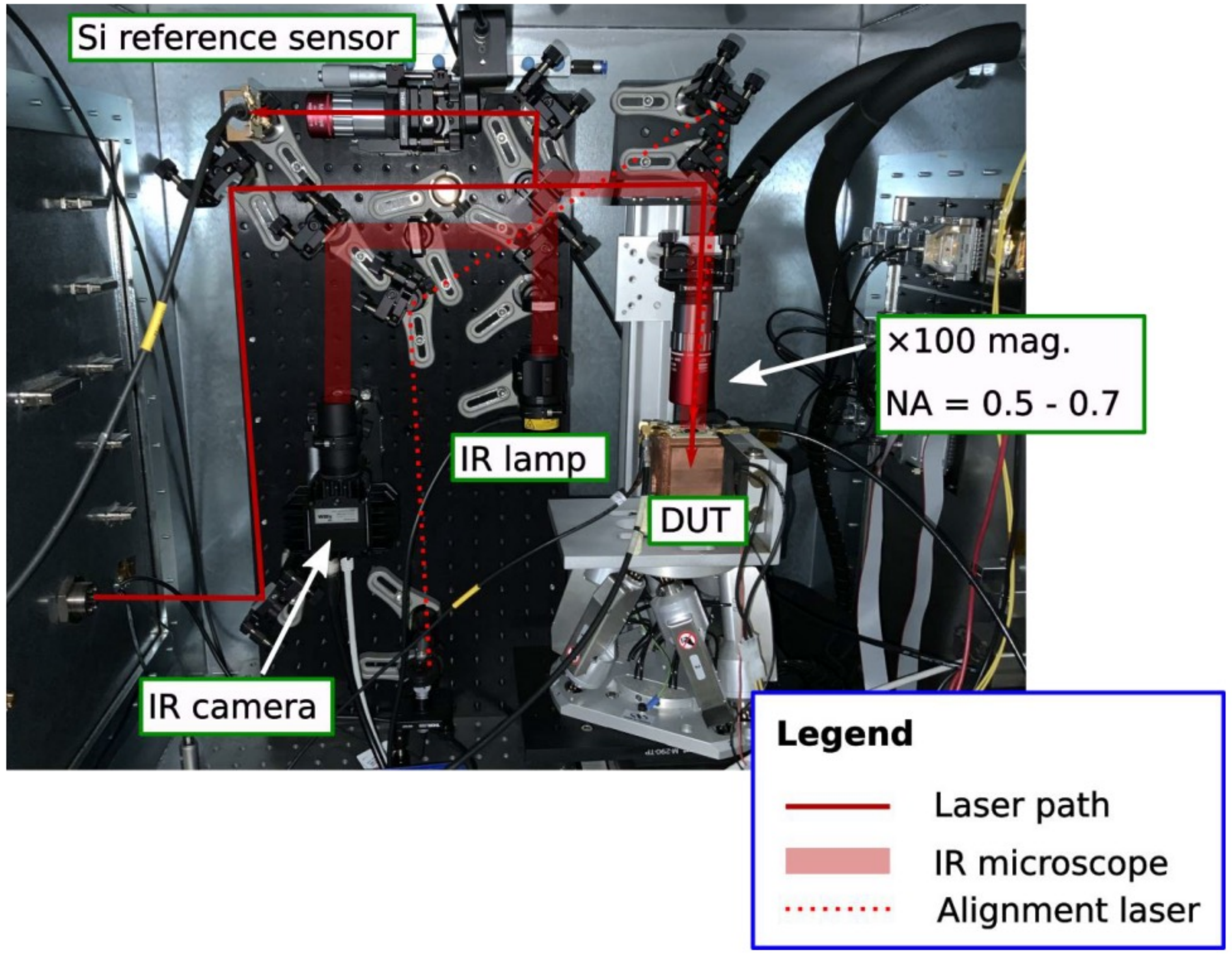


Transient Current Technique (TCT)



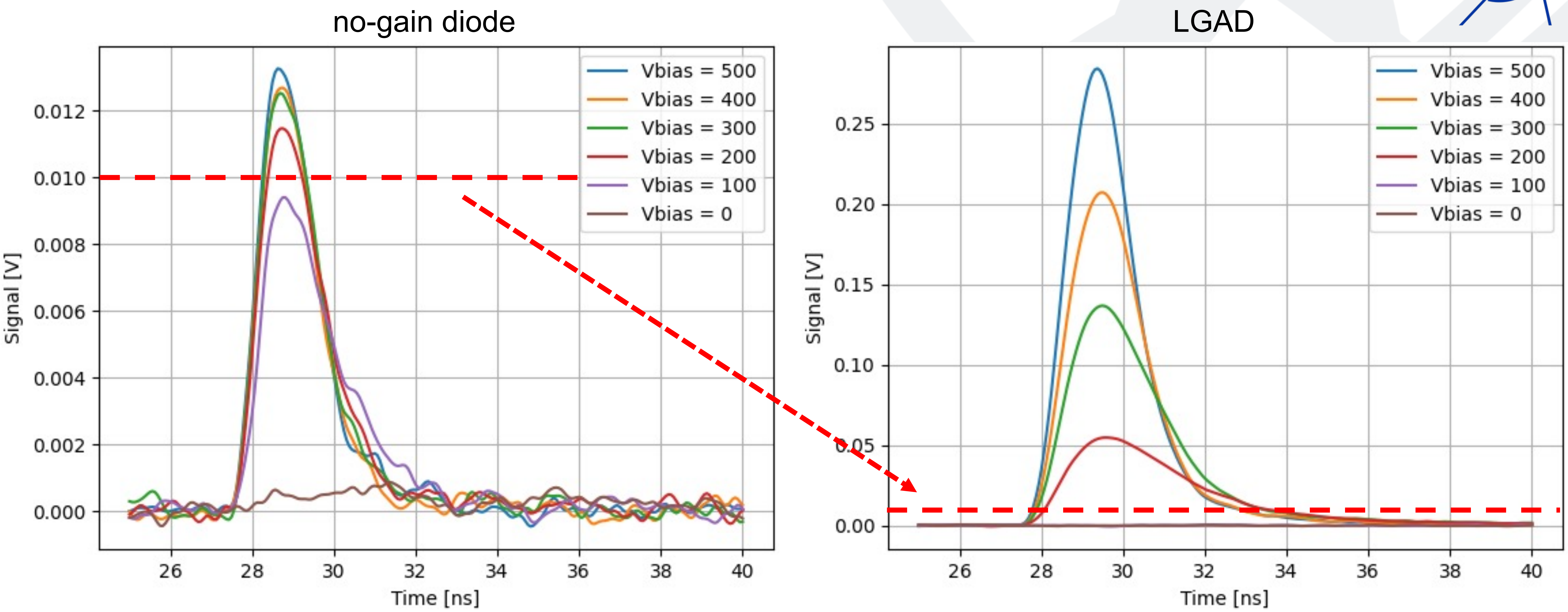
Laser output pulse properties:
- approx. 430 fs width
- pulse frequency 8.2 MHz to single pulse
- pulse energy up to 10 nJ
- central wavelength 1.55 µm

Inside the Faraday cage



TCT – results Lot2

Help of M. Wiehe

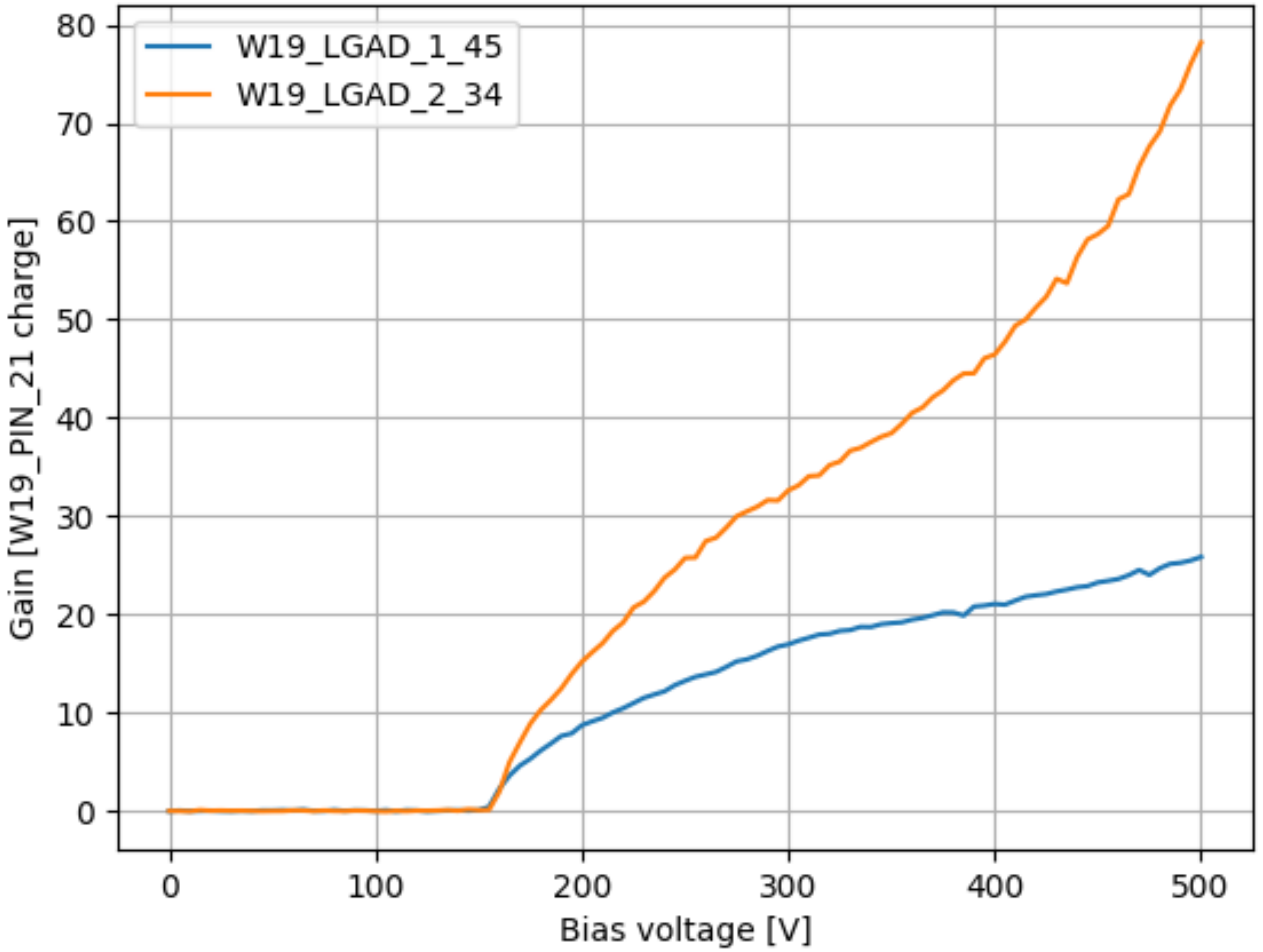


- ❑ **Clear difference of gain on signal response**

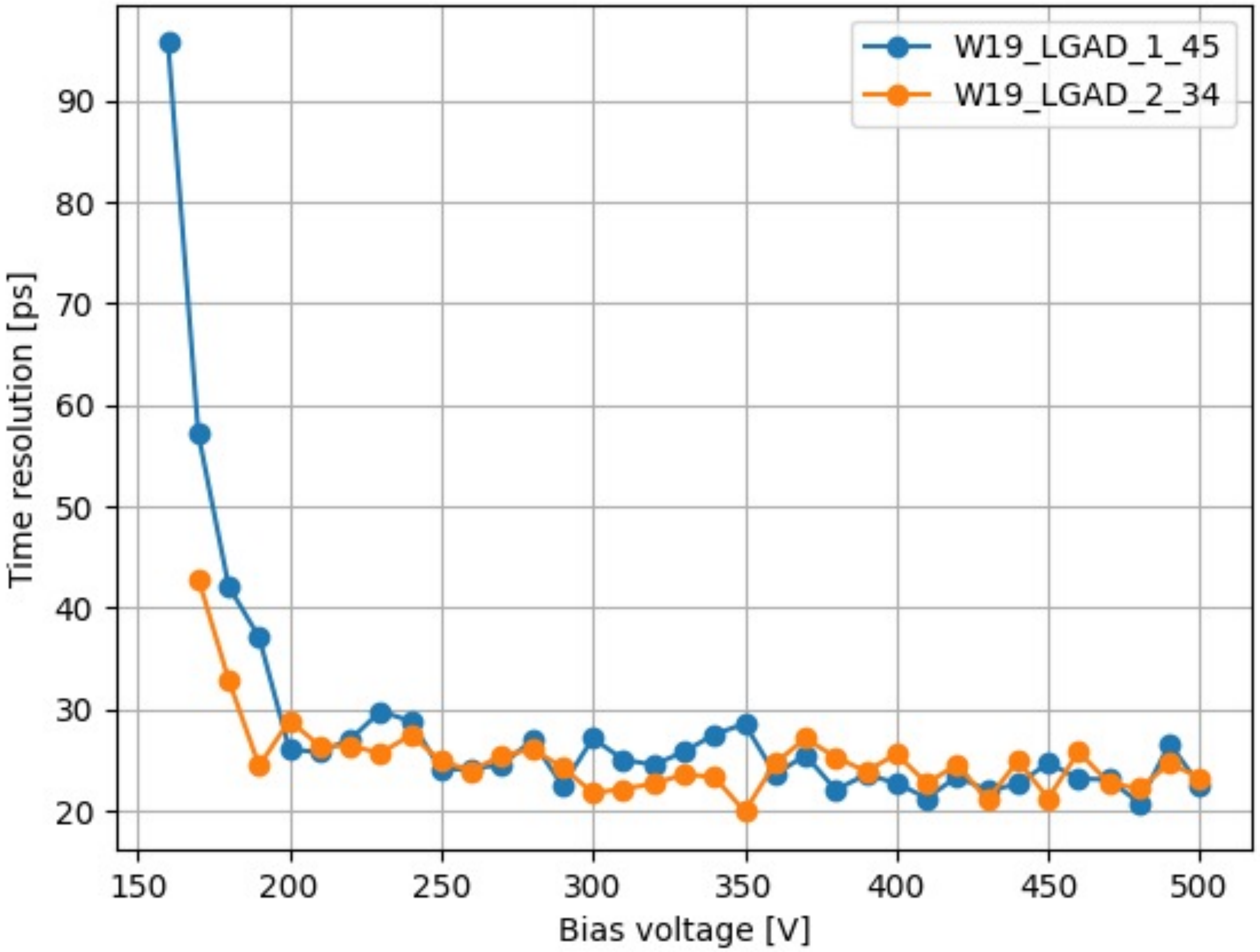
Transient Current Technique – results Lot2

Help of M. Wiehe

Gain comparison



Timing-to-trigger



- **Gain in range of 10-80, non-calibrated signal response down to 20ps**

FZU Institute of Physics of the Czech Academy of Sciences

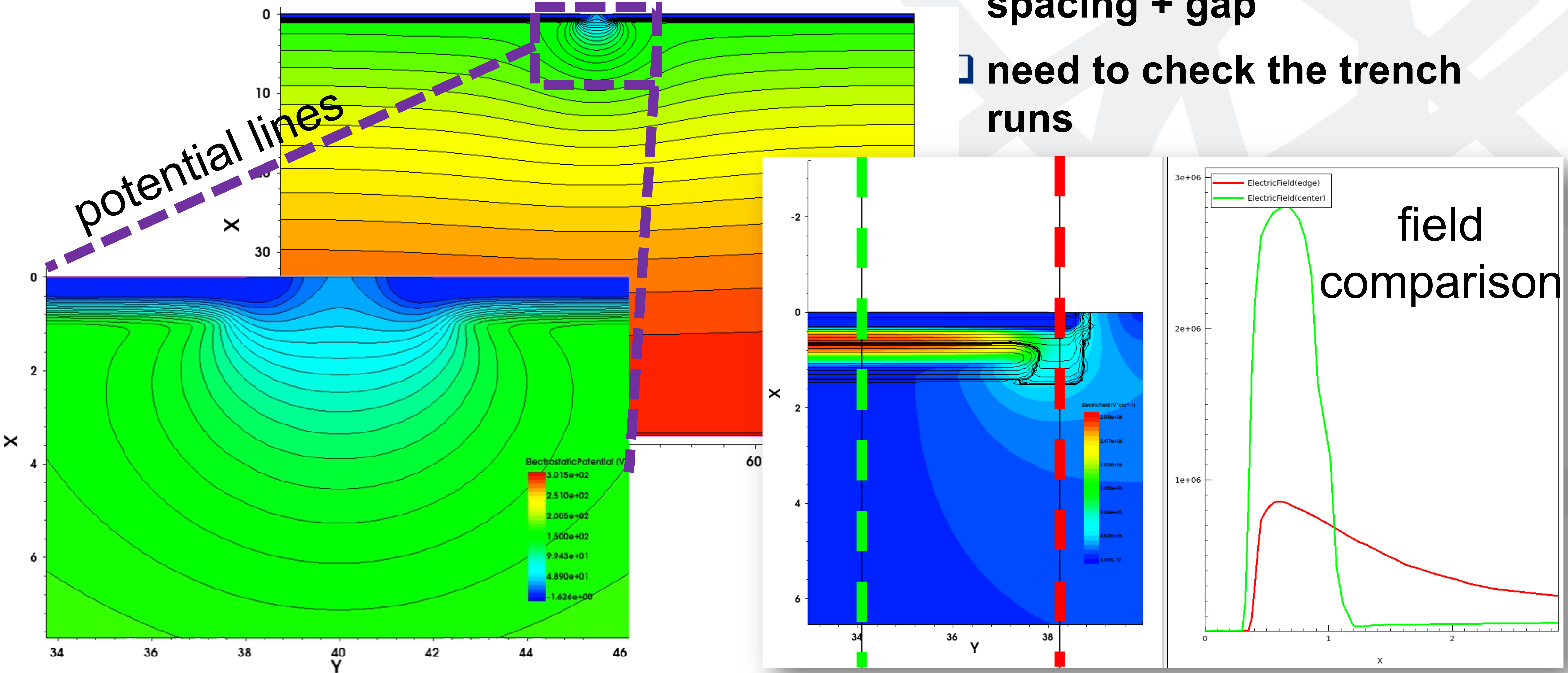
PHYSICS FOR FUTURE

Co-funded by the European Union

TCAD verification

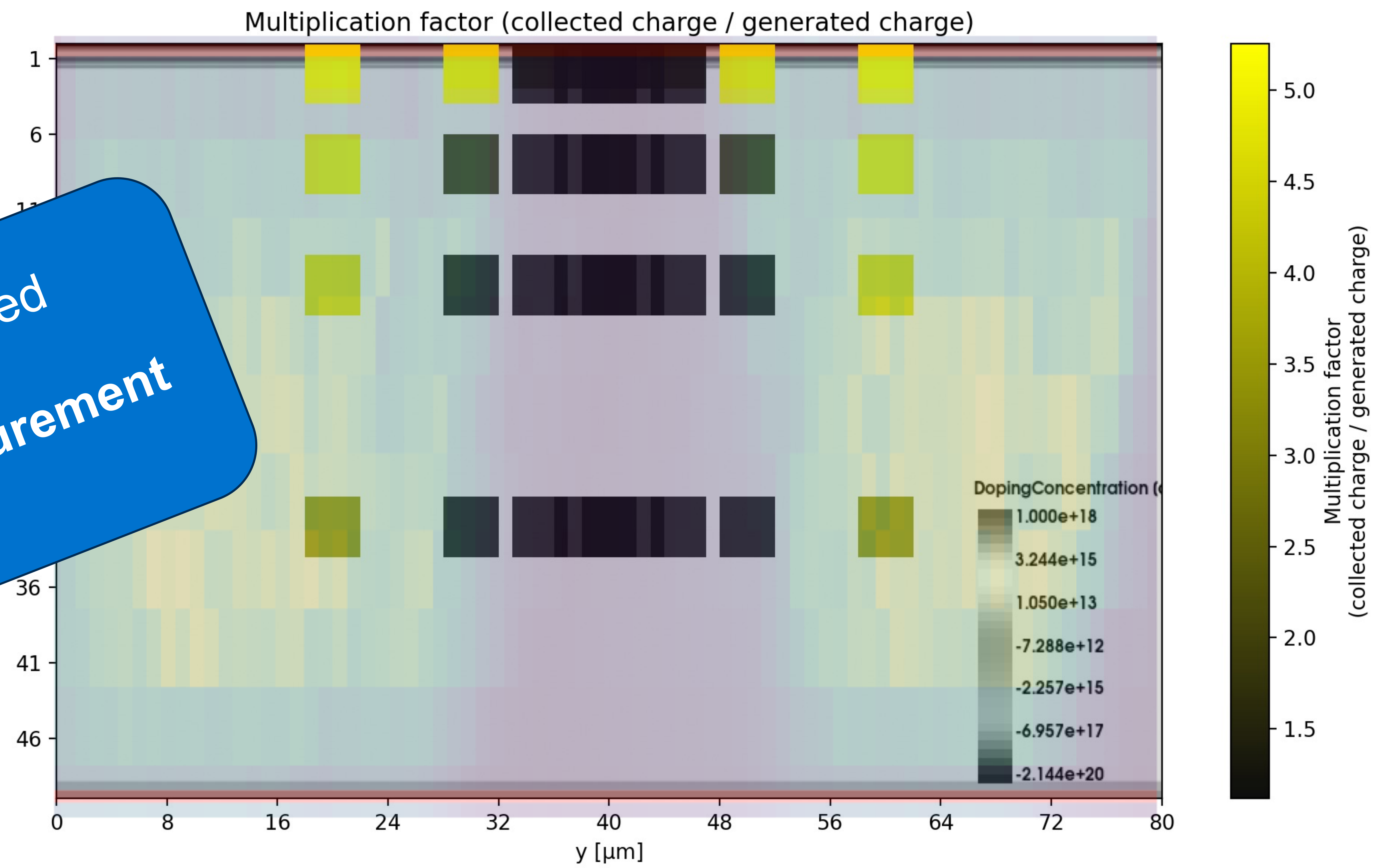
by T. Vasiljev

- verifying other designs of spacing + gap
- need to check the trench runs



by T. Vasiljev

TCAD verification



simulated gain (coloured squares) **matches with measurement** (shaded overlay)