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CHARACTERIZATION OF TJ-MONOPIX2

A DEPLETED MONOLITHIC ACTIVE PIXEL SENSOR WITH COLUMN DRAIN READOUT ARCHITECTURE

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MONOLITHIC ACTIVE PIXEL DETECTORS

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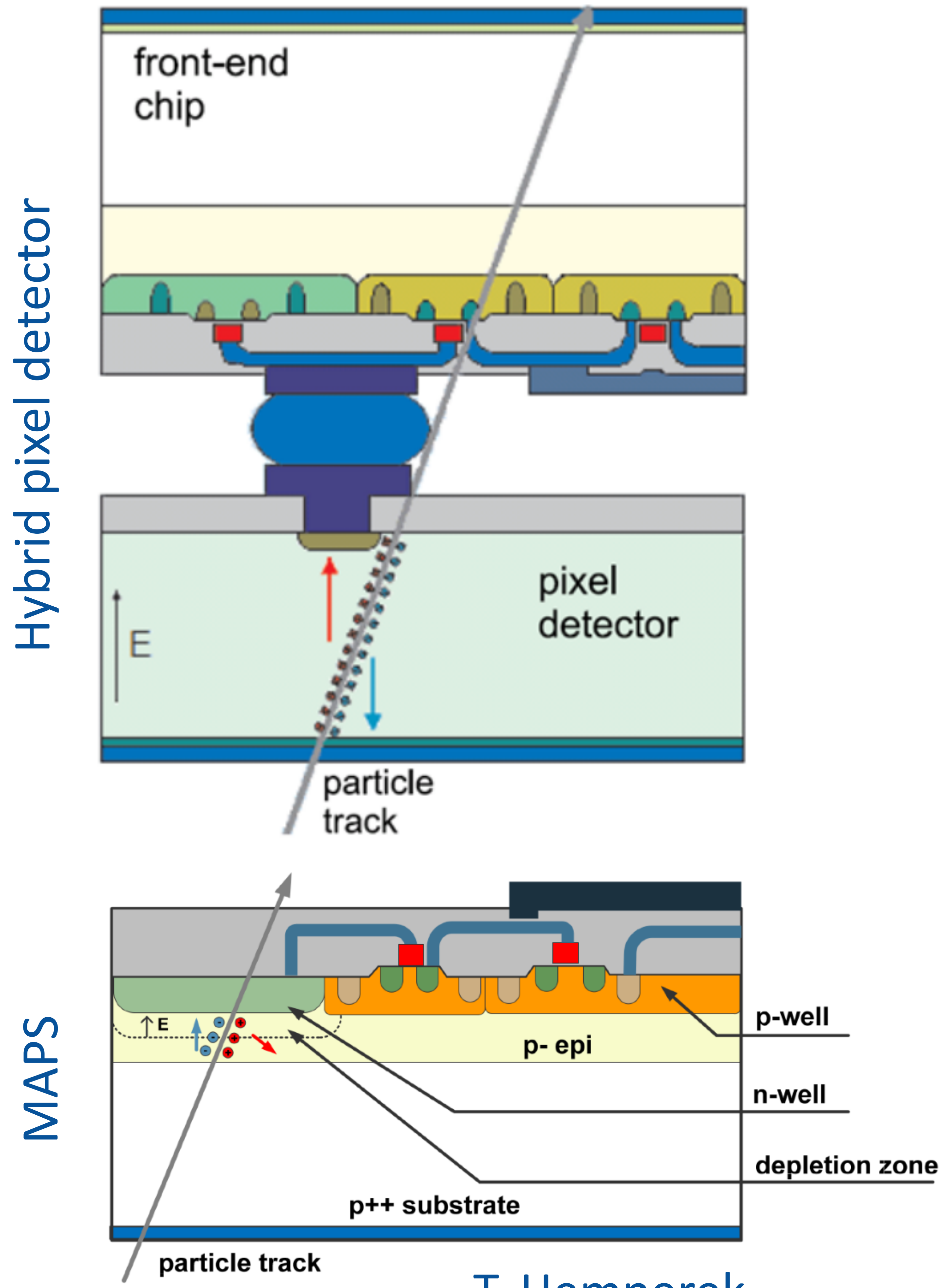
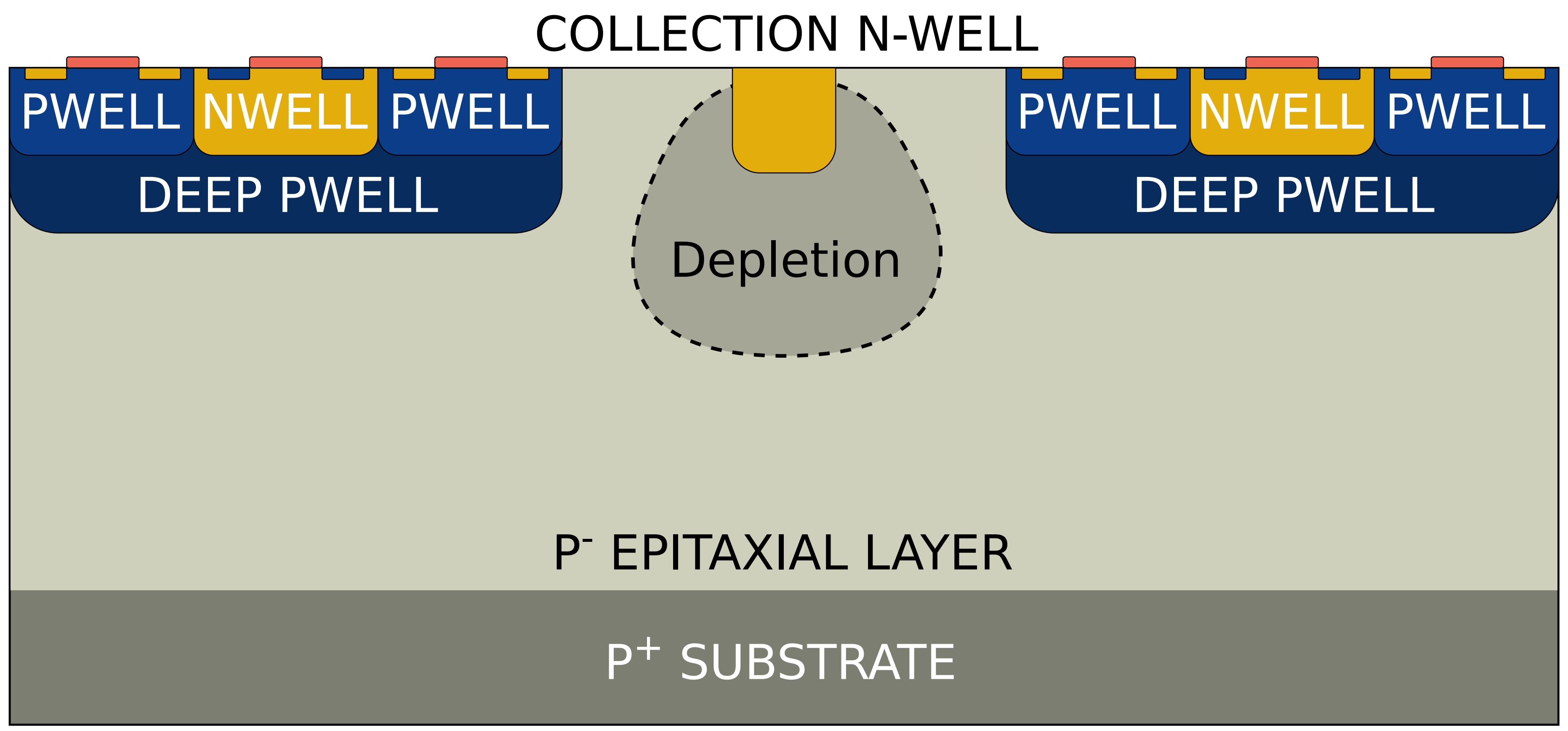
- Monolithic active pixel sensors (MAPS) combine sensor material and active readout electronics on the same wafer
- Usually low-ohmic substrates and low-voltage capabilities
- Need depletion for high-radiation environments
  - Achievable through high substrate resistivity and/or high voltage
  - Availability of these features in commercial CMOS processes fueled R&D of *depleted* monolithic active pixel sensors (DMAPS)



T. Hemperek

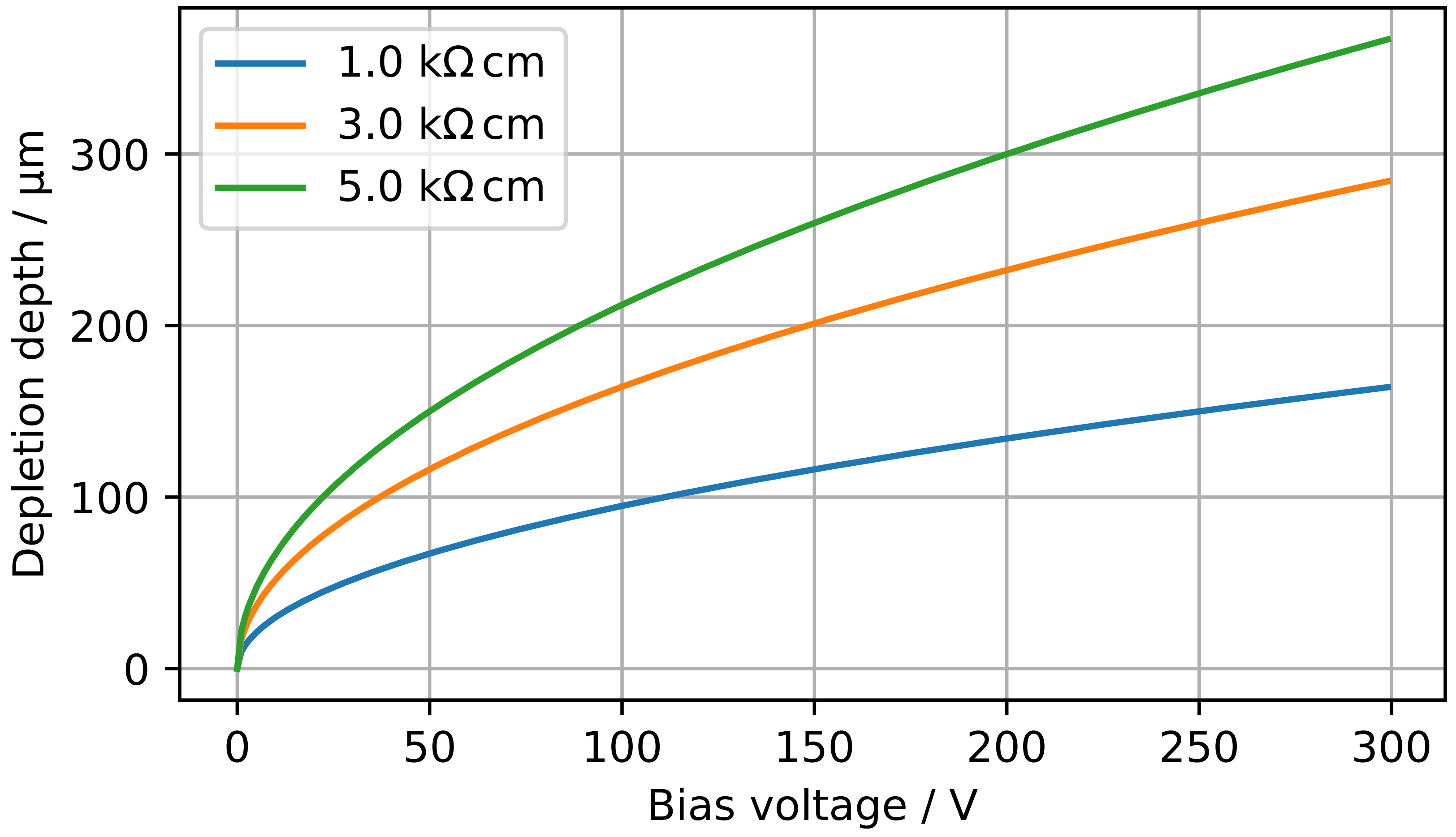
DEPLETED MAPS

- Offer relatively cheap, fast and high volume production using commercial CMOS processes
- Low material budget for tracking detectors
- Question is: can we achieve significant levels of radiation hardness with good performance and fast readout for high-rate environments?



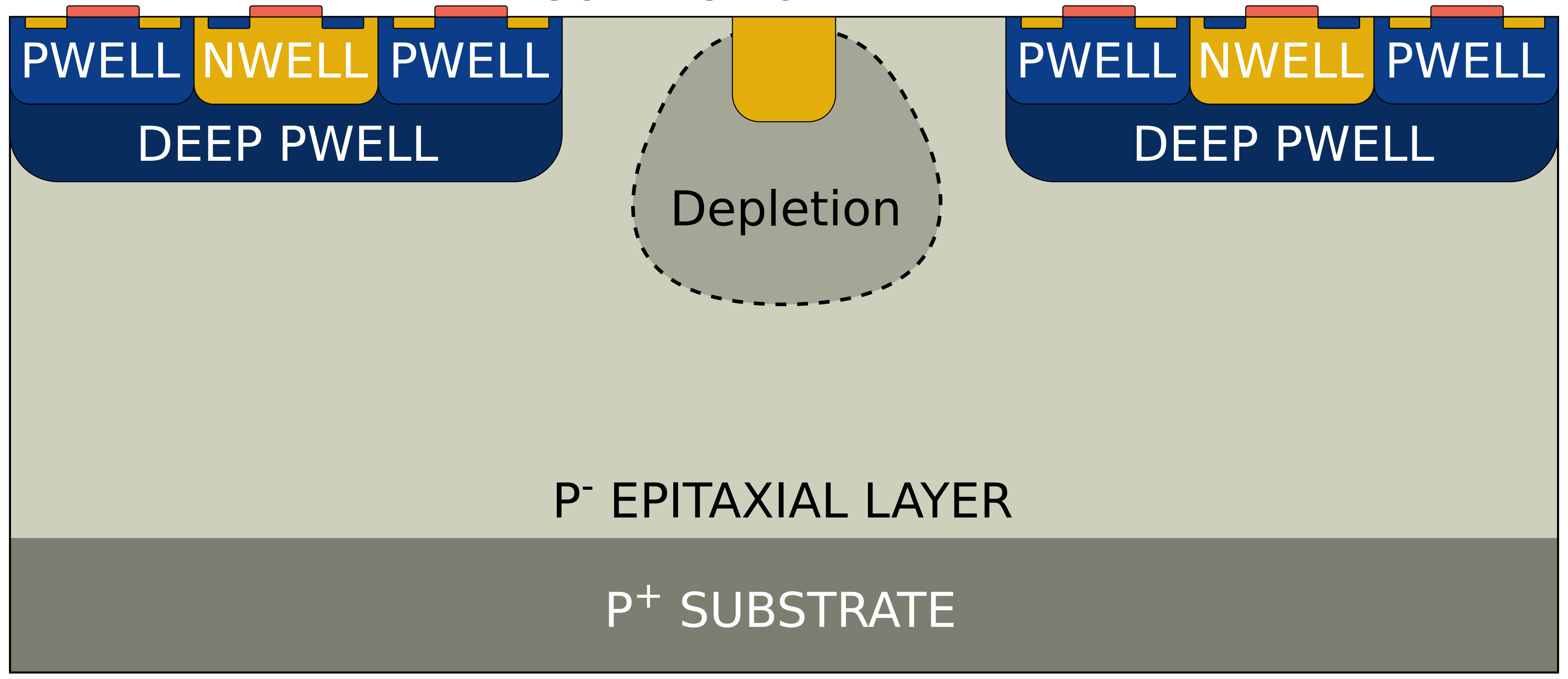
Standard MAPS cell

+

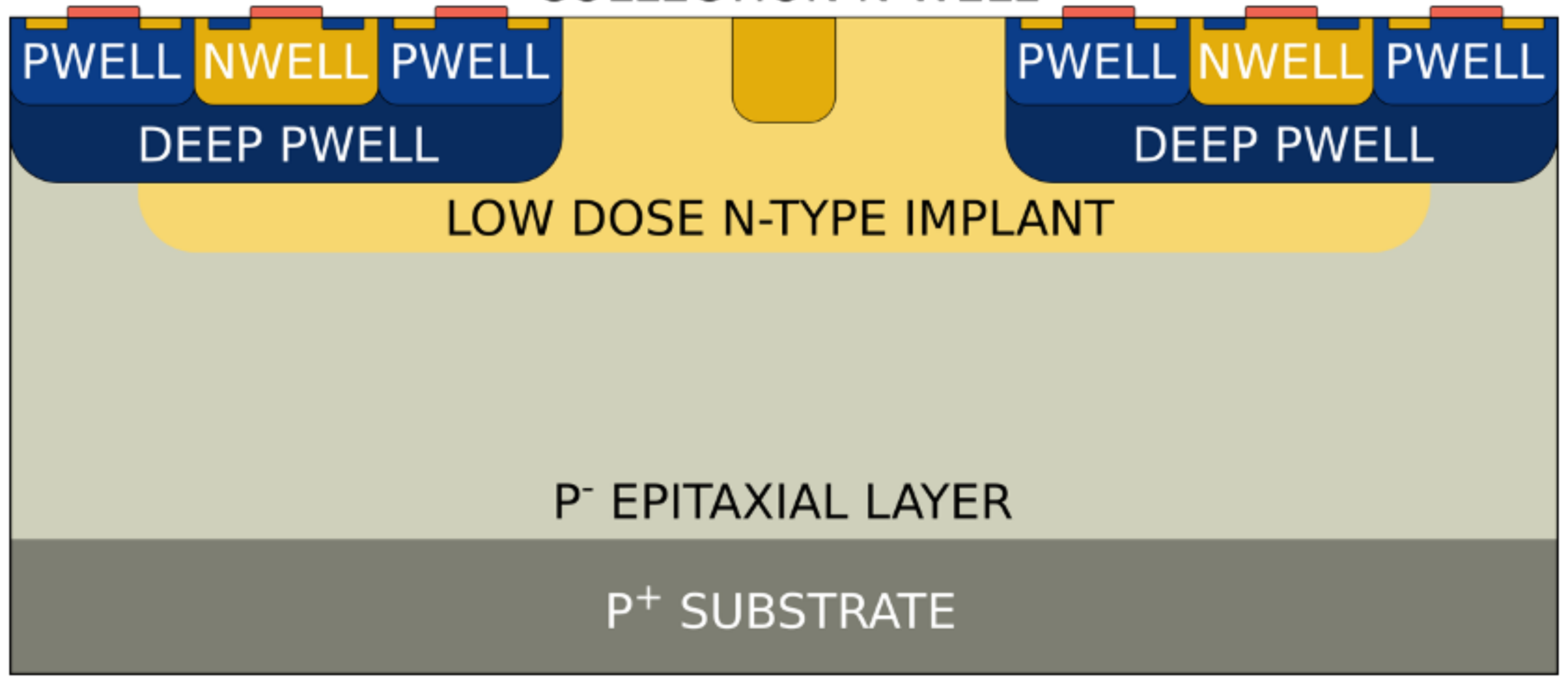


TJ-MONOPIX DESIGN

- TJ-Monopix is line of DMAPS designed in a 180 nm Tower CMOS process based on ALPIDE sensor for ALICE ITS upgrade
- Small collection electrode for operations with low power and low noise
- Depletion grows from collection electrode, for uniform depletion add lateral n-type implant for homogeneous electrical field across sensor volume (1 - 3 kΩcm substrate resistivity)
- Gap in n-type implant (or additional p-type well) below readout electronics to shape electrical field towards collection node



Standard MAPS cell



Modified process for full depletion (see later for variants)

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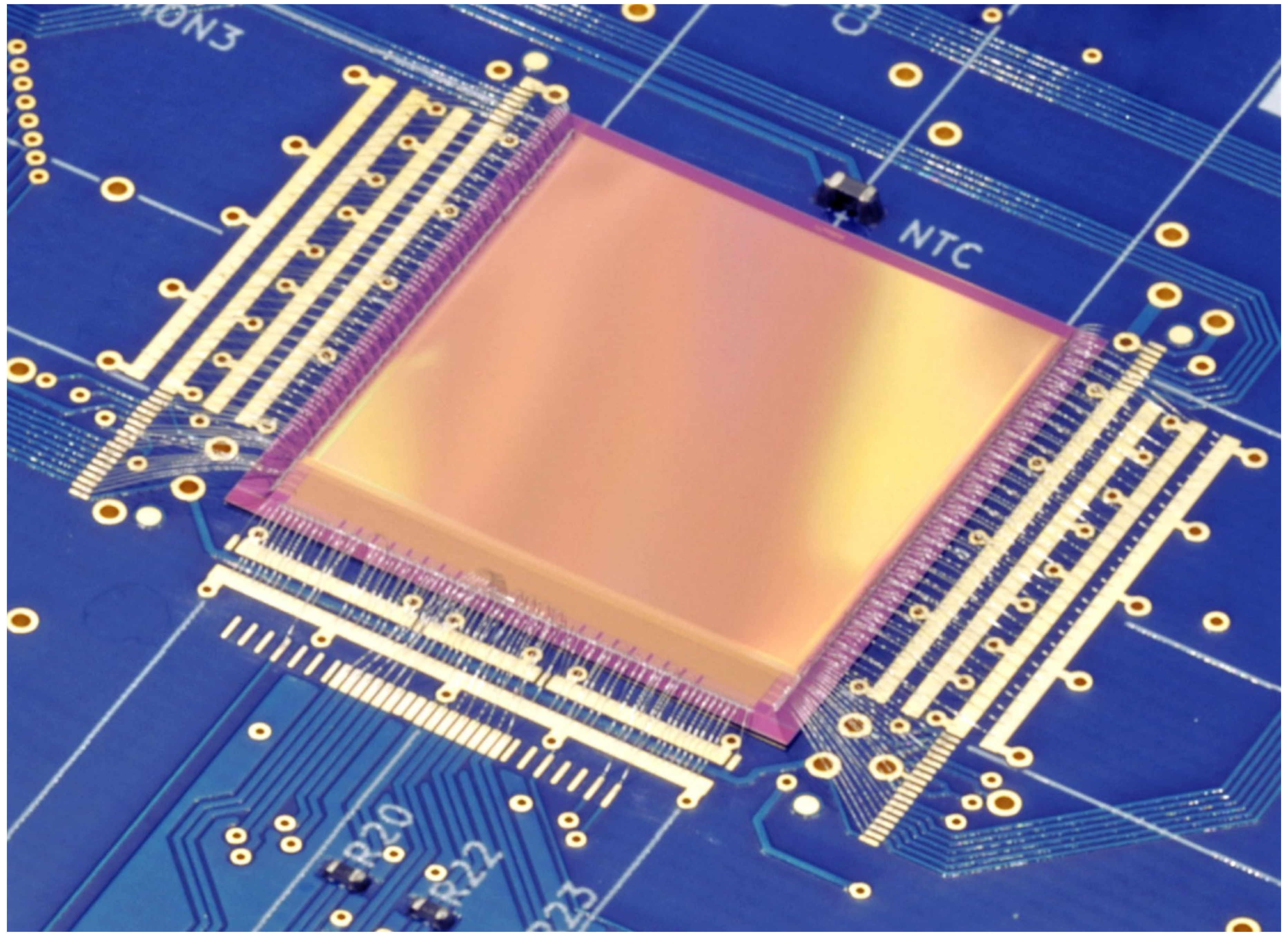
TJ-MONOPIX DESIGN

- Designed for ATLAS ITk outer layer specs with column-drain readout like in FE-I3 in a 2 cm column
  - Pixel readout capable of dealing with hit rate > 100 MHz / cm^2
  - Goal: 10^{15} 1 MeV $^{neq}/_{cm2}$ NIEL tolerance and 100 MRad TID
- Latest iteration TJ-Monopix2: 33.04 µm pixel pitch in 512 x 512 pixel matrix (2 x 2 cm^2)
- 7 bit TOT resolution (40 MHz BCID clock - 25 ns timing)
- 3 bit in-pixel threshold tuning
- Communication via four differential lines
  - Command-based slow control (taken from RD53B)
  - 160 MHz data output rate (frame-based 8b10b encoding)



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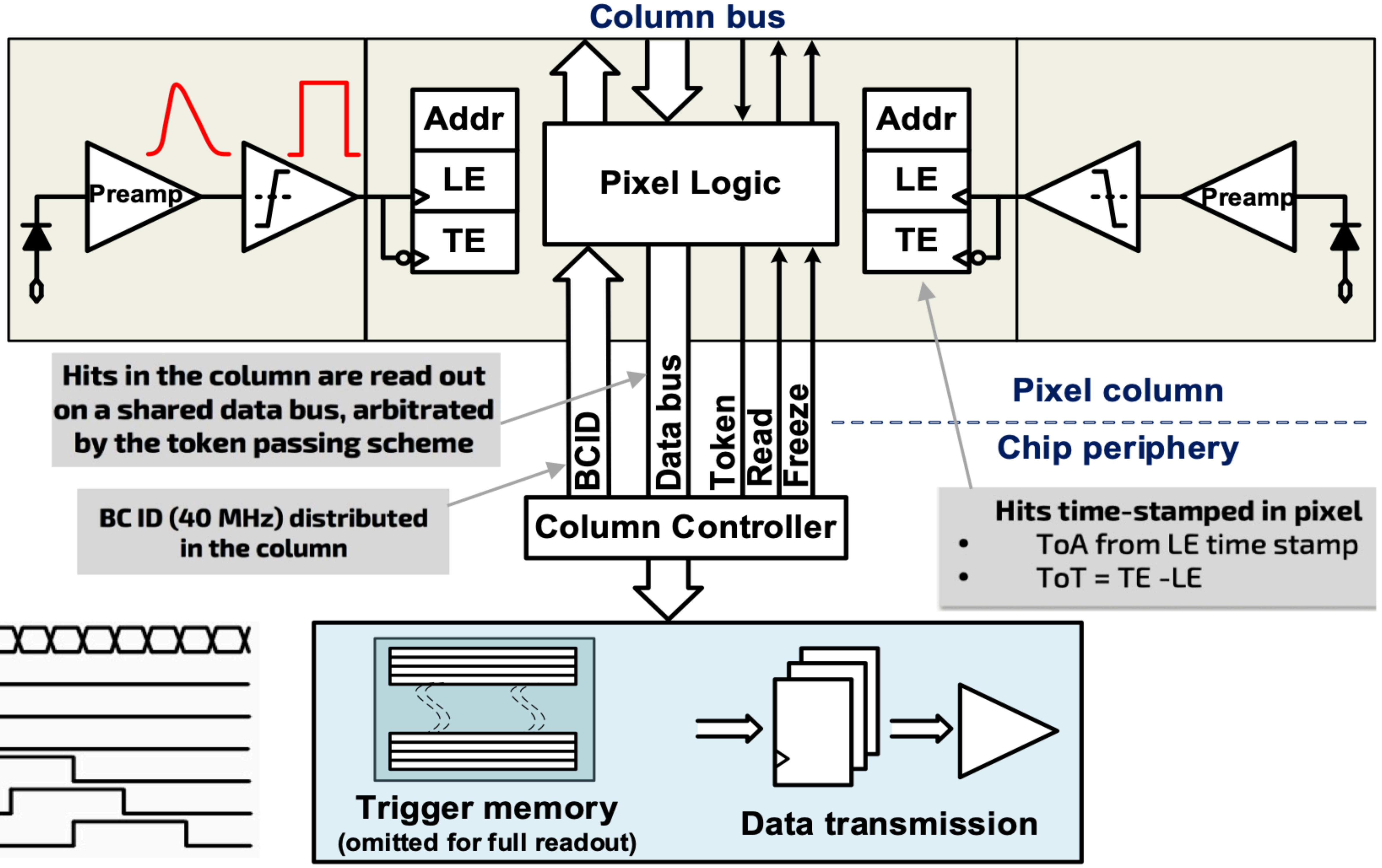
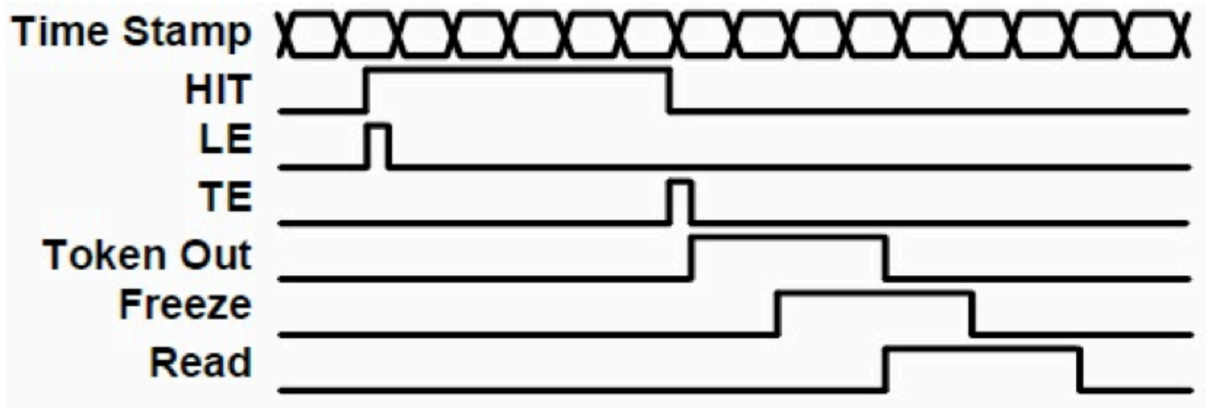
COLUMN DRAIN READOUT

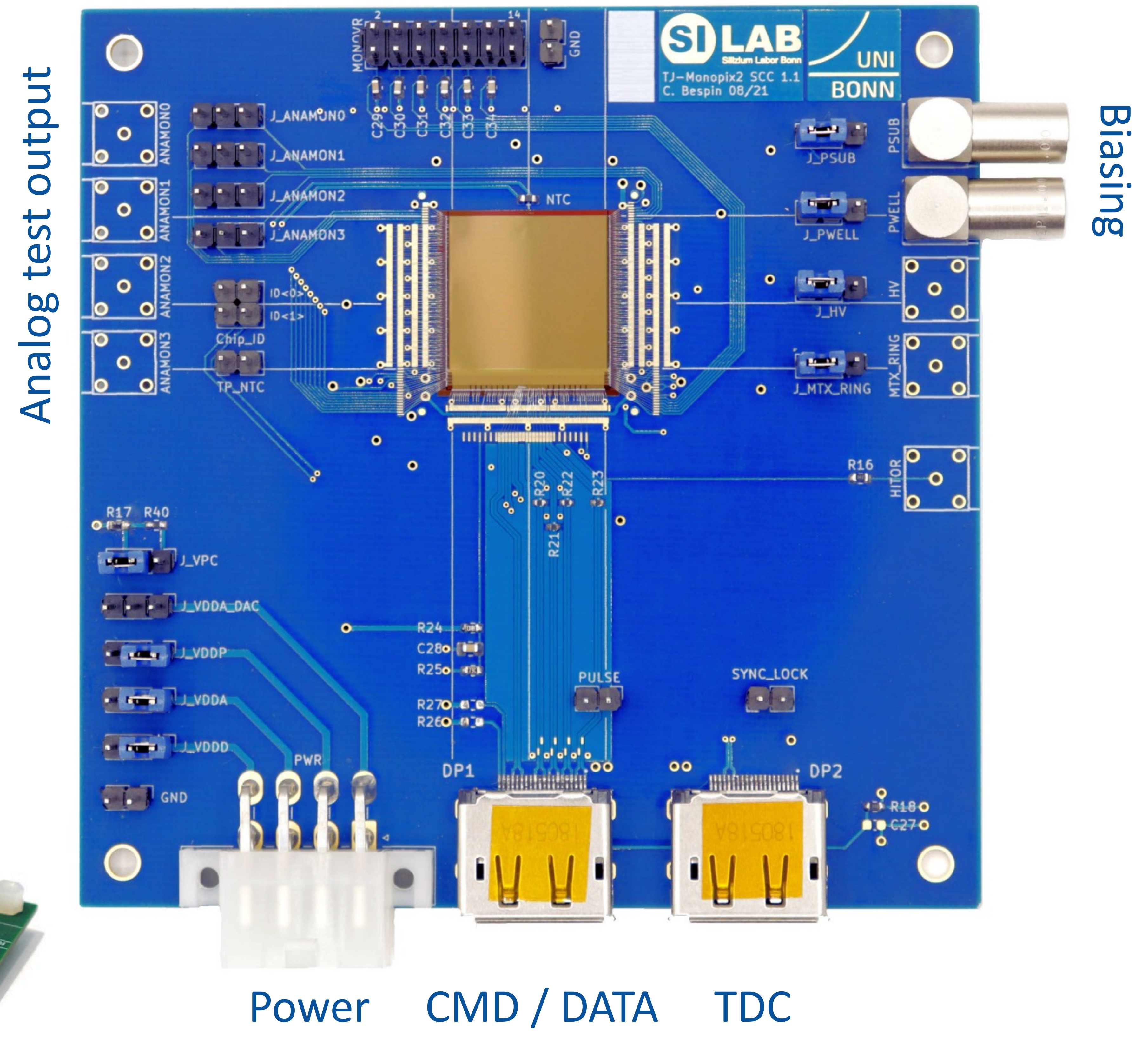
- Derived from ATLAS FE-I3 readout chip
- Rate capabilities around 100 MHz/cm^2
- Token propagation along column
- Readout controller at end of column (READ, FREEZE to pixels)
- Data propagated along column with row address, leading edge and trailing edge
- Periphery merges data from one TOKEN signal into frames that are transmitted 8b10b encoded to readout board



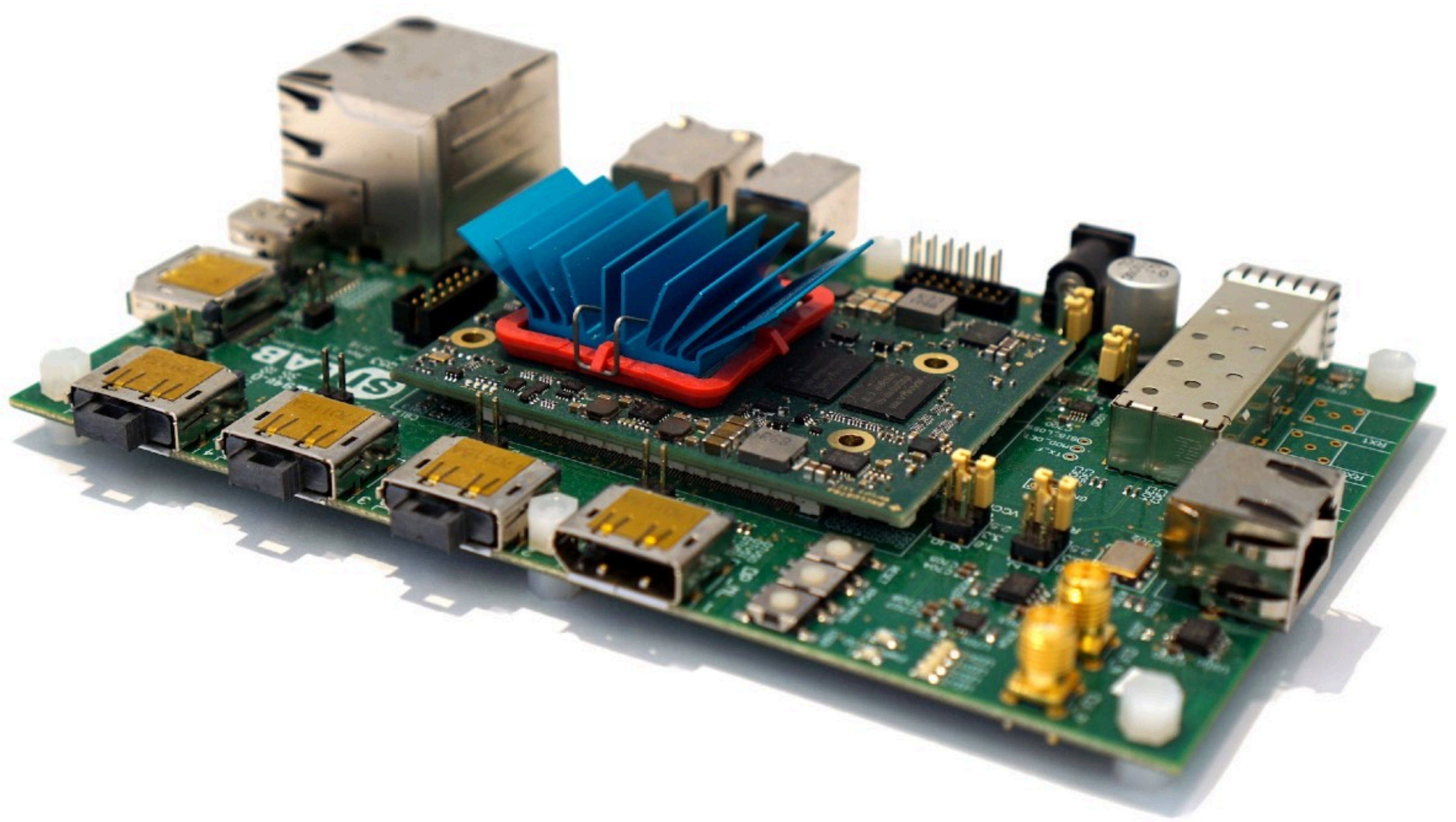


TJ-MONOPIX2 DAQ SYSTEM

- DAQ System based on RD53A/B readout board bdaq53
- Standalone carrier PCB with power and DisplayPort connector
- Readout board with 1 Gbit/s connection to DAQ computer (10 Gbit/s possible)
- Small and portable setup for irradiations, beam tests etc.

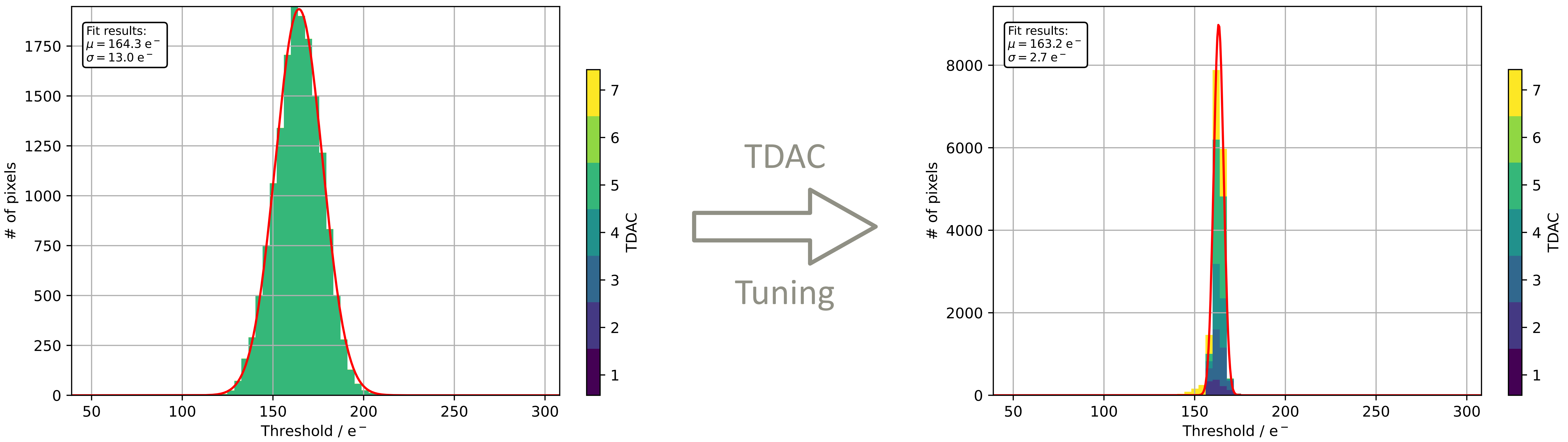


- Chip supports addressing by chip ID (jumper on pin header)
  - Multi-chip readout should be possible with bdaq53



TJ-MONOPIX2 LAB TESTS

- Lab tests conducted for threshold and noise measurements
- Design goals: operational threshold ≈ 100 e^-, threshold dispersion < 10 e^-, ENC ≈ 5 e^-
- In-pixel threshold trimming (3 bit) significantly reduces threshold dispersion to less than design value
- Operational threshold higher than anticipated, but we will see later that it should not be a problem



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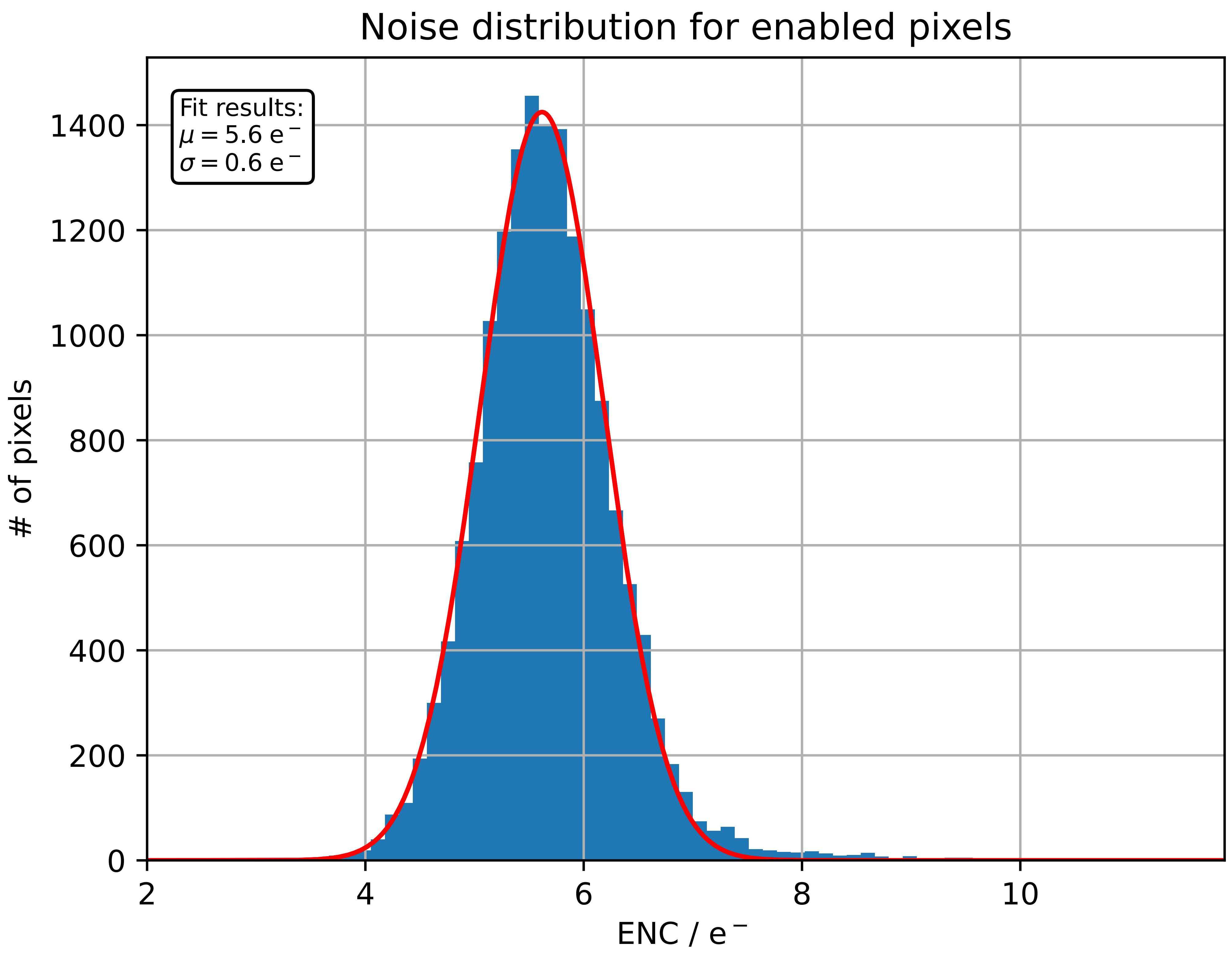
TJ-MONOPIX2 LAB TESTS

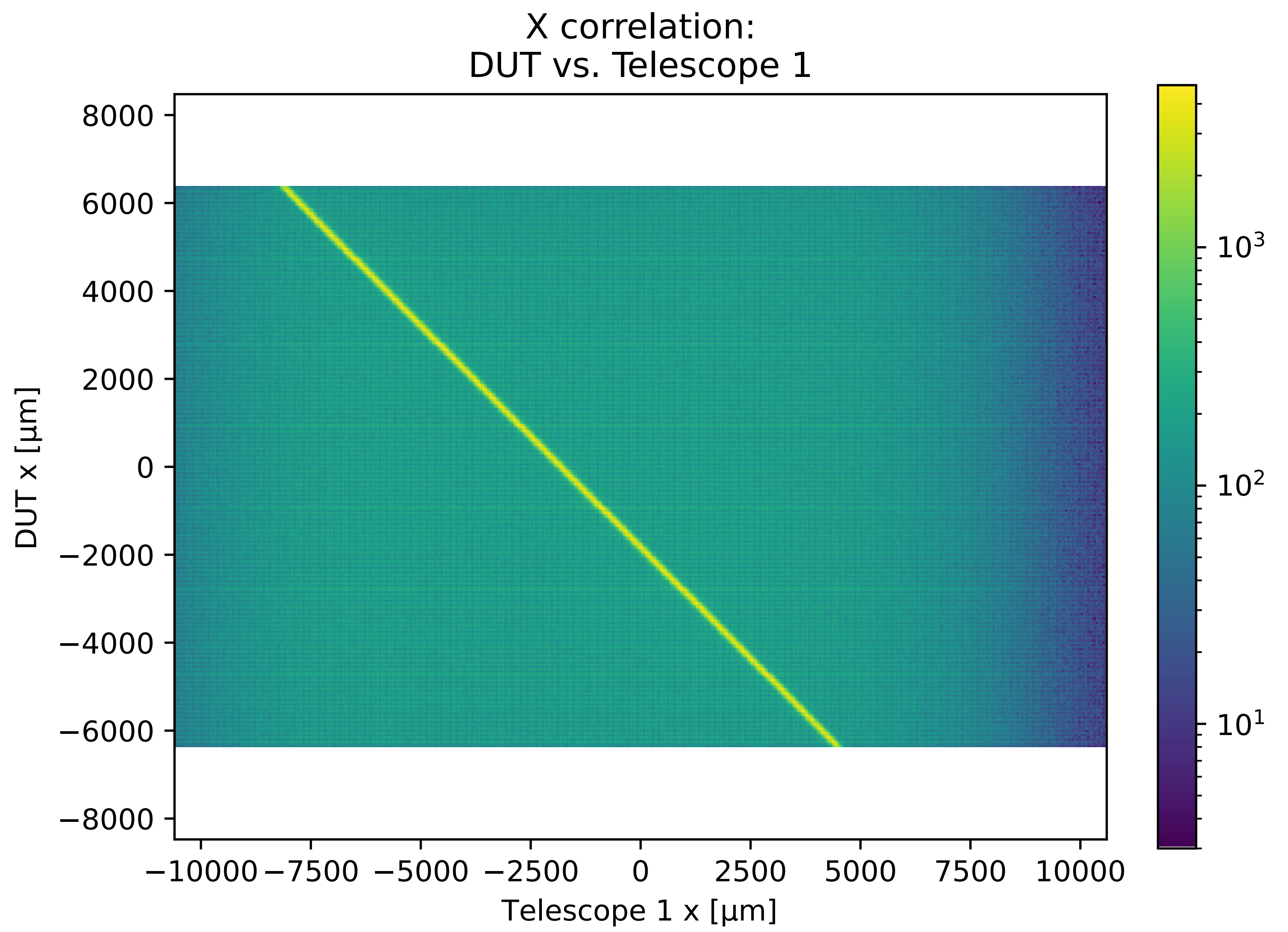
- Noise (ENC) measured from steepness of S-curve when injecting varying charges
- Mean noise 5.6 e$^-$ in accordance with design goal
- No RTS noise tail observed as in TJ-Monopix1
- Allows operation at low thresholds thanks to large S/N ratio

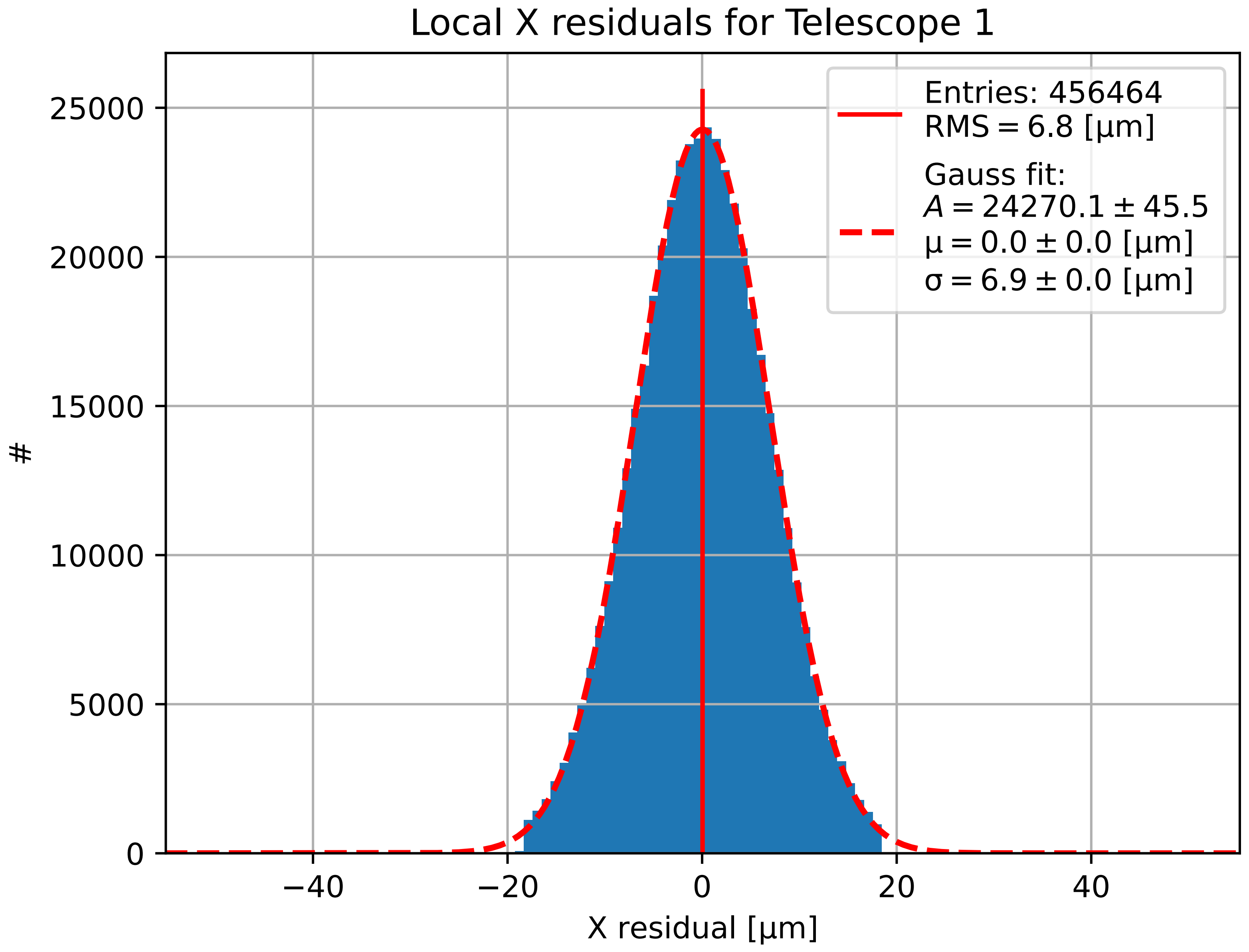
- Reminder: in TJ-Monopix1, operational threshold was O(400 e$^-$) which lead to efficiency losses in pixel corners, especially after irradiation

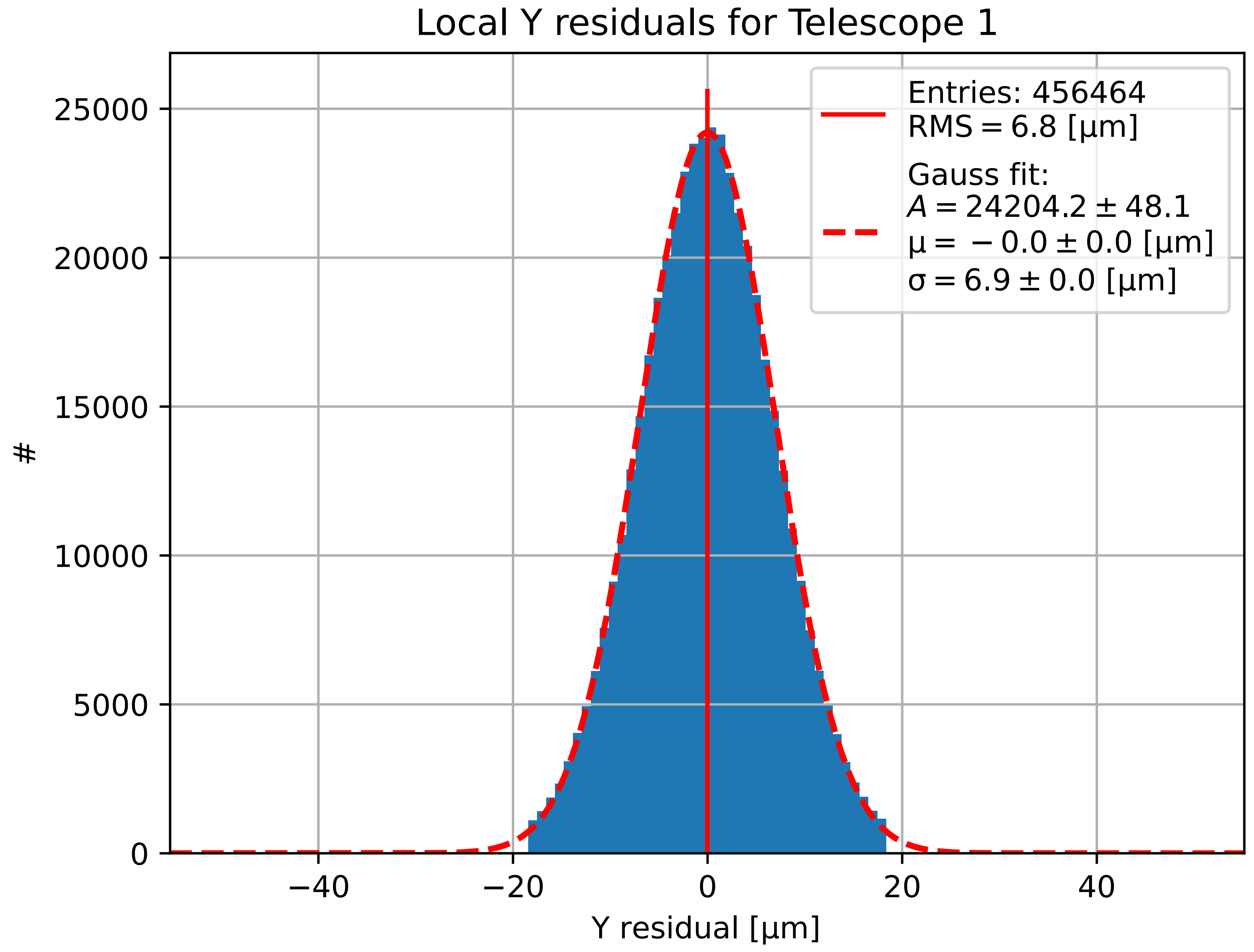


TJ-MONOPIX2 BEAM TESTS

- Beam tests performed at DESY in November 2022 (results fresh off the press, still preliminary)
- 5 GeV electron beam with Mimosa26 telescope and FE-I4 time reference
- Good correlation between TJ-Monopix2 DUT and telescope planes

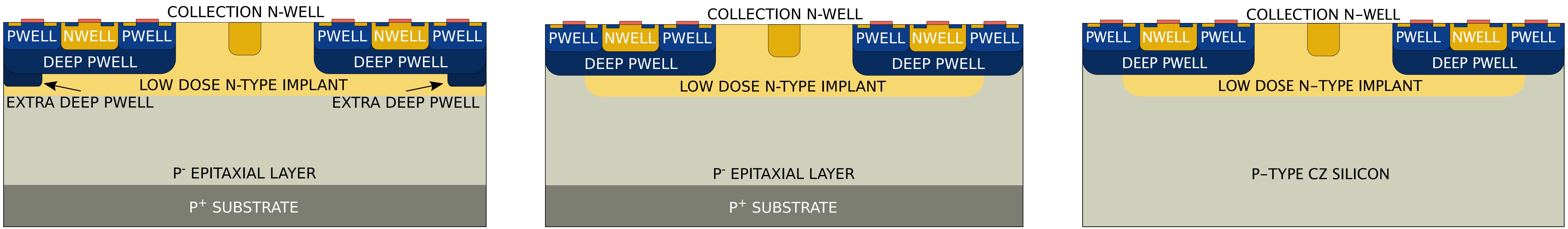






TJ-MONOPIX2 BEAM TESTS

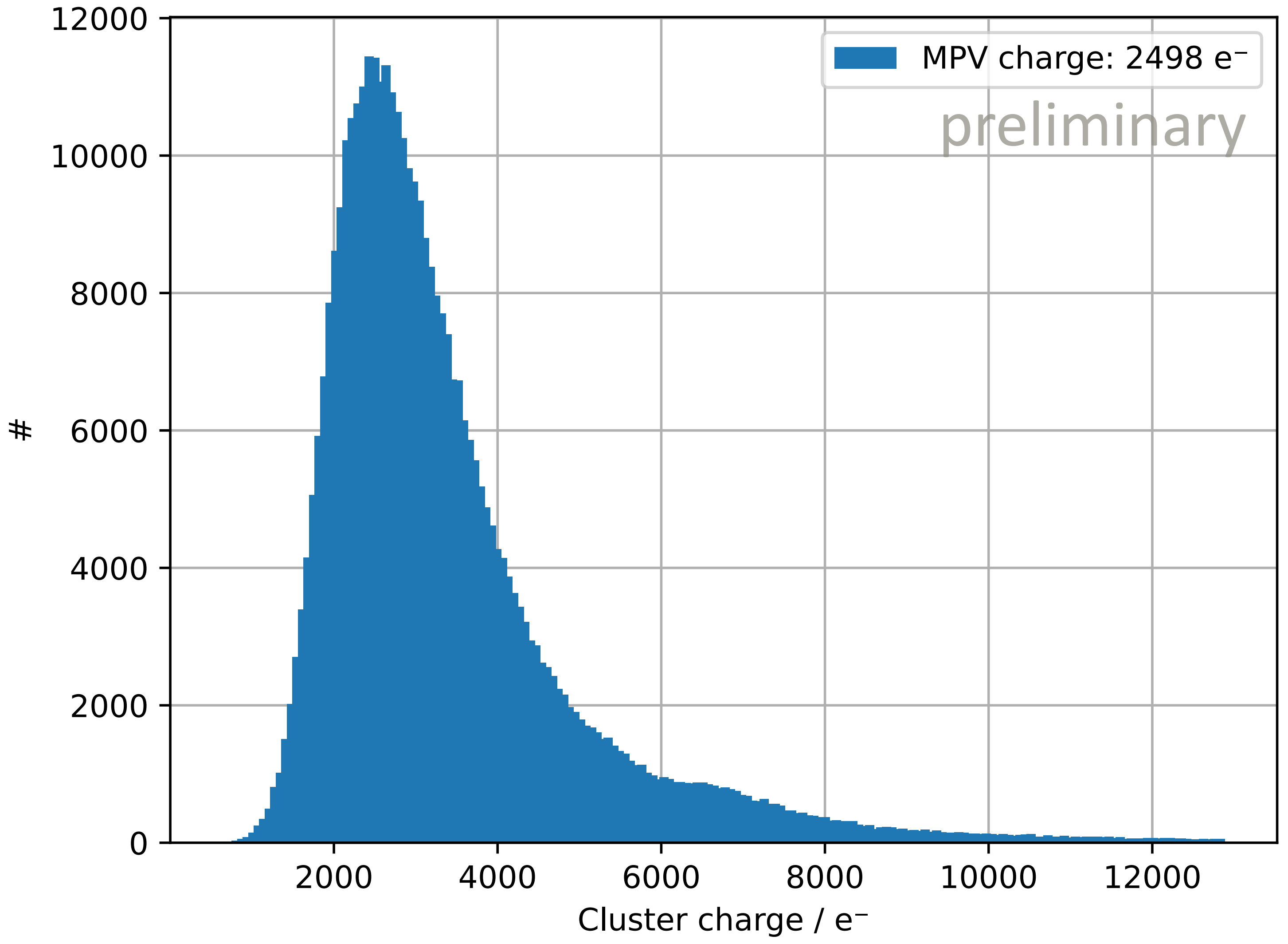
- Investigated samples (unirradiated):
  - epitaxial silicon (30 µm thickness) with gap in n-layer and with additional p-well
  - Czochralski silicon (100 µm thickness) with gap in n-layer
  - Type of silicon growth (epi vs Cz) not part of investigation, but thickness of sensitive volume
- All samples operating at a threshold of ~200 e^-



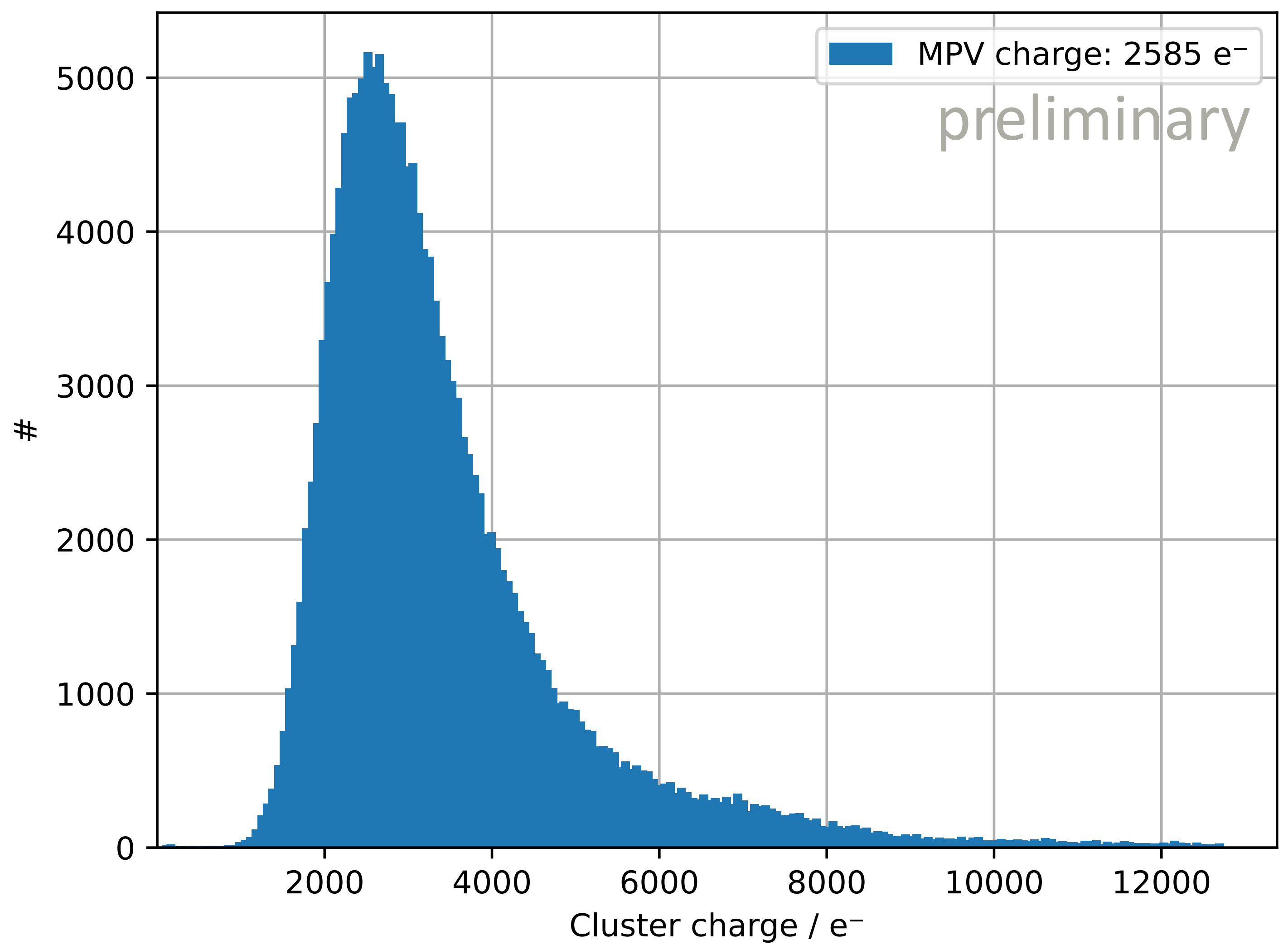
TJ-MONOPIX2 CLUSTER CHARGE

- Cluster charge (MPV) for standard pixel flavor
- Cz sample has higher MPV since depletion is not limited by thickness of epi layer (30 µm)
- Still not fully depleted because of -6 V bias voltage on substrate and p-wells on top of chip

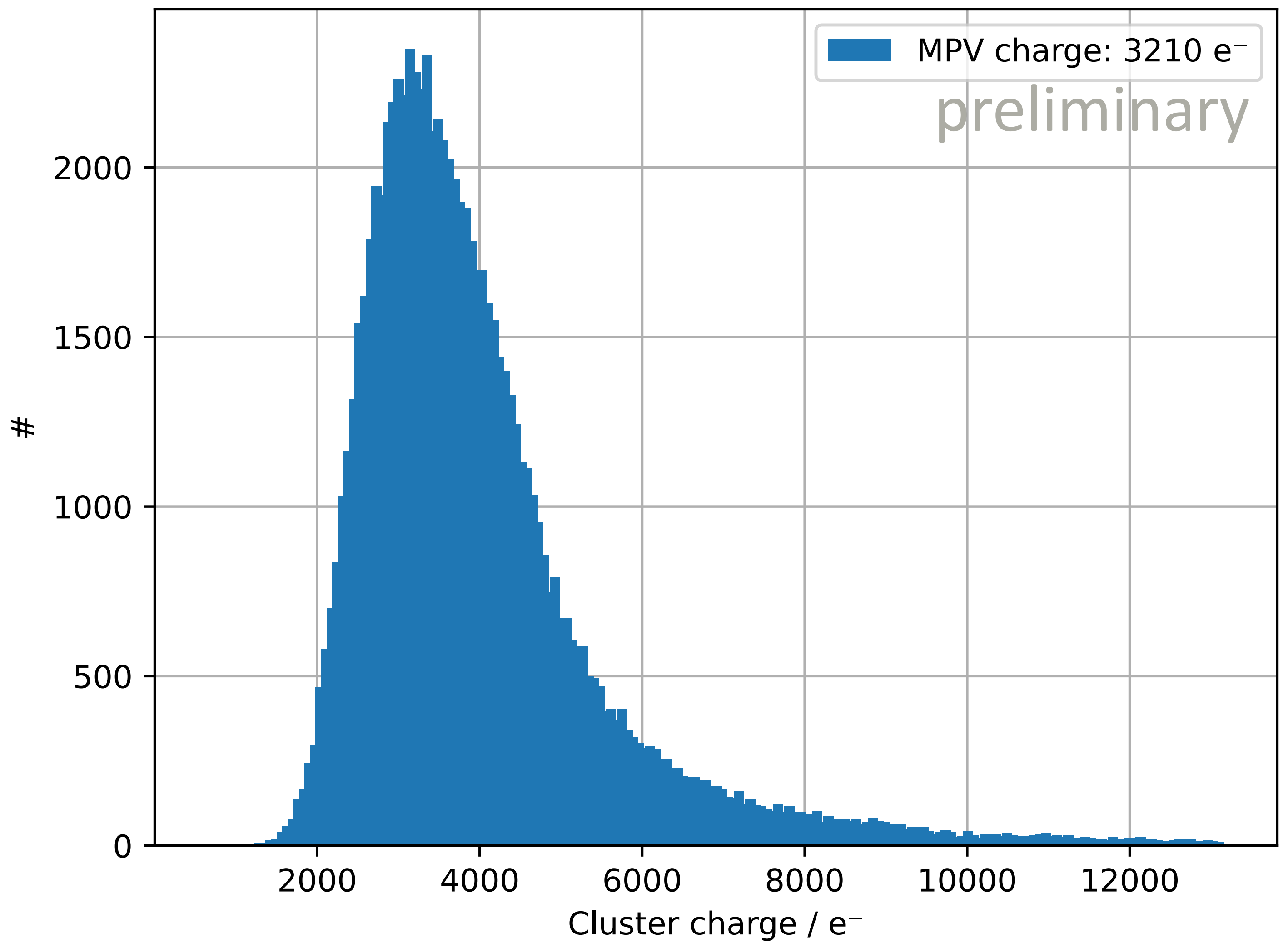
Epi add. p-well: 2498 e$^-$ MPV



Epi gap in n-layer: 2585 e$^-$ MPV



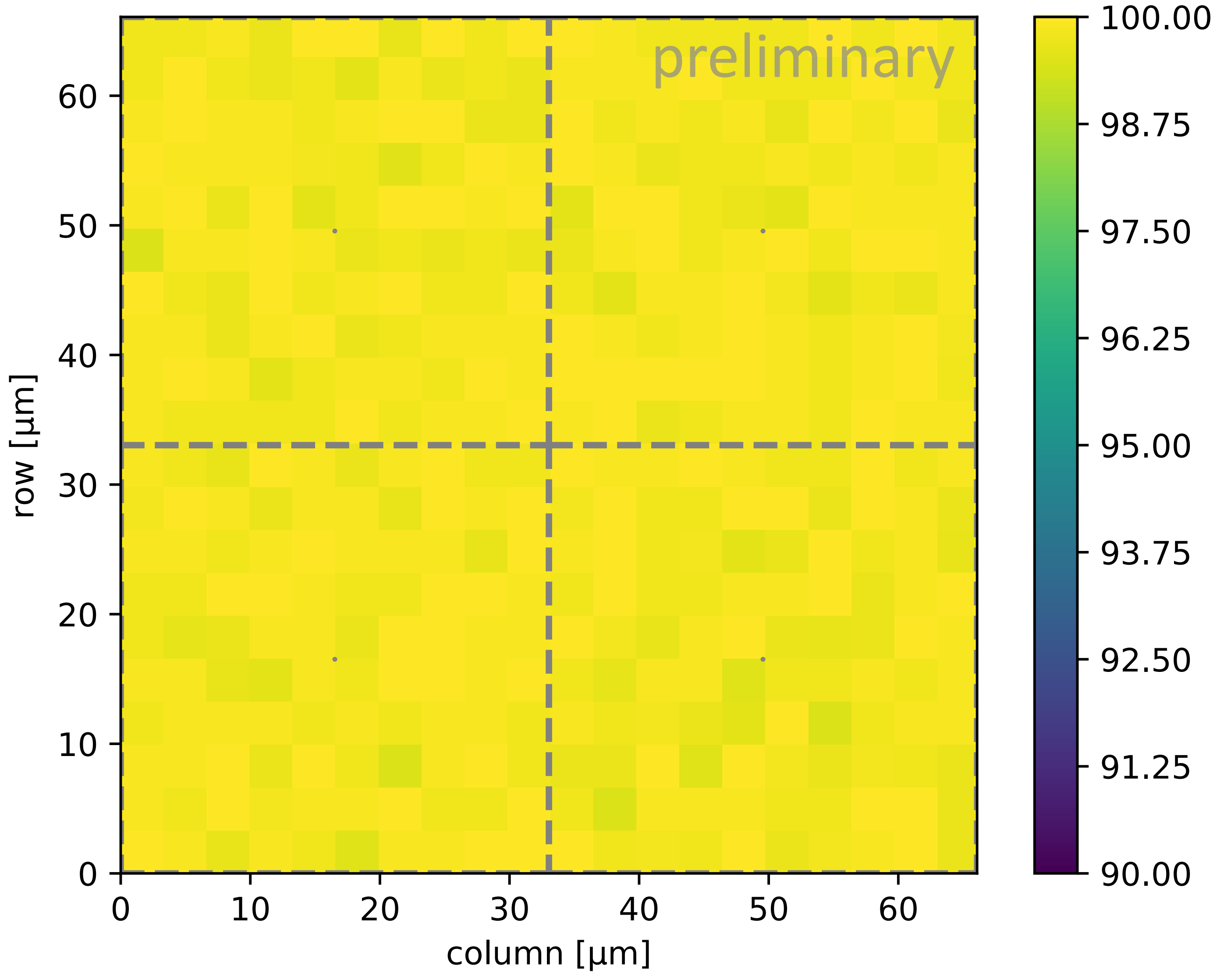
Cz gap in n-layer: 3210 e$^-$ MPV



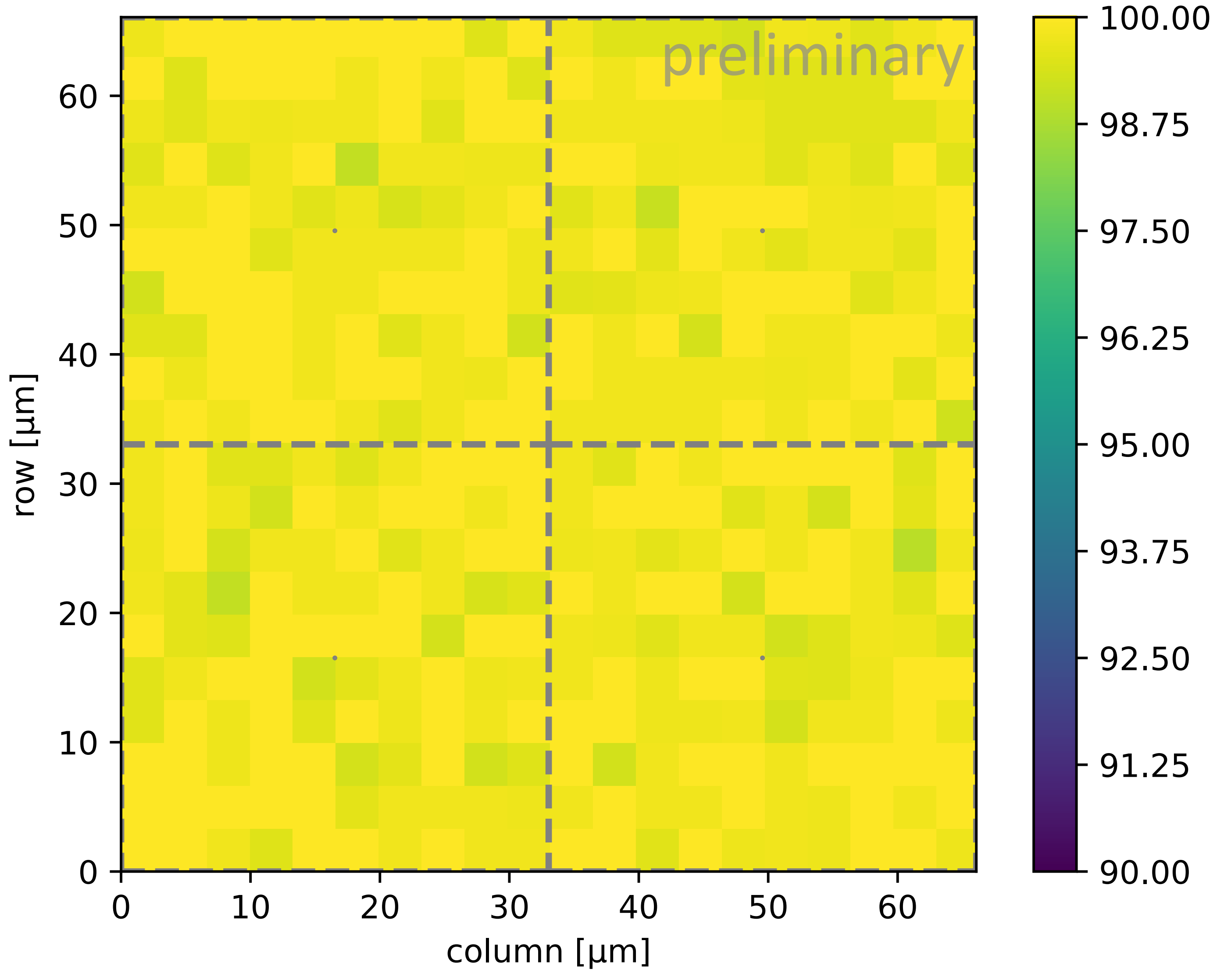
TJ-MONOPIX2 EFFICIENCY

- In-pixel efficiency for standard pixel flavor
- Homogeneous efficiency > 99 % with no losses in the corners, higher than TJ-Monopix1 already
- With ~200 e^- threshold no difference between samples expected for the observed cluster charge, deviation within error (estimated around 0.1 %)

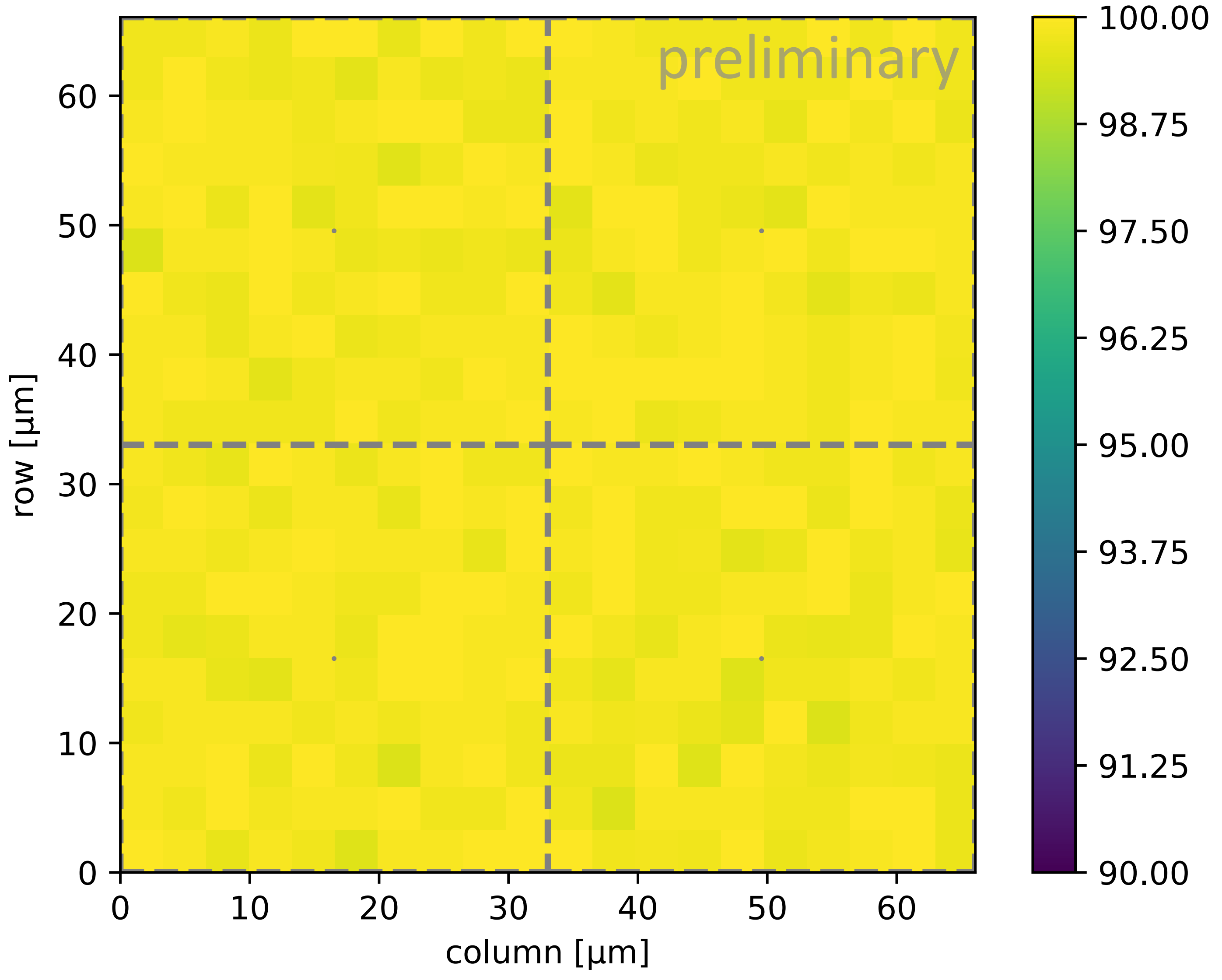
Epi add. p-well: 99.85 %



Epi gap in n-layer: 99.80 %



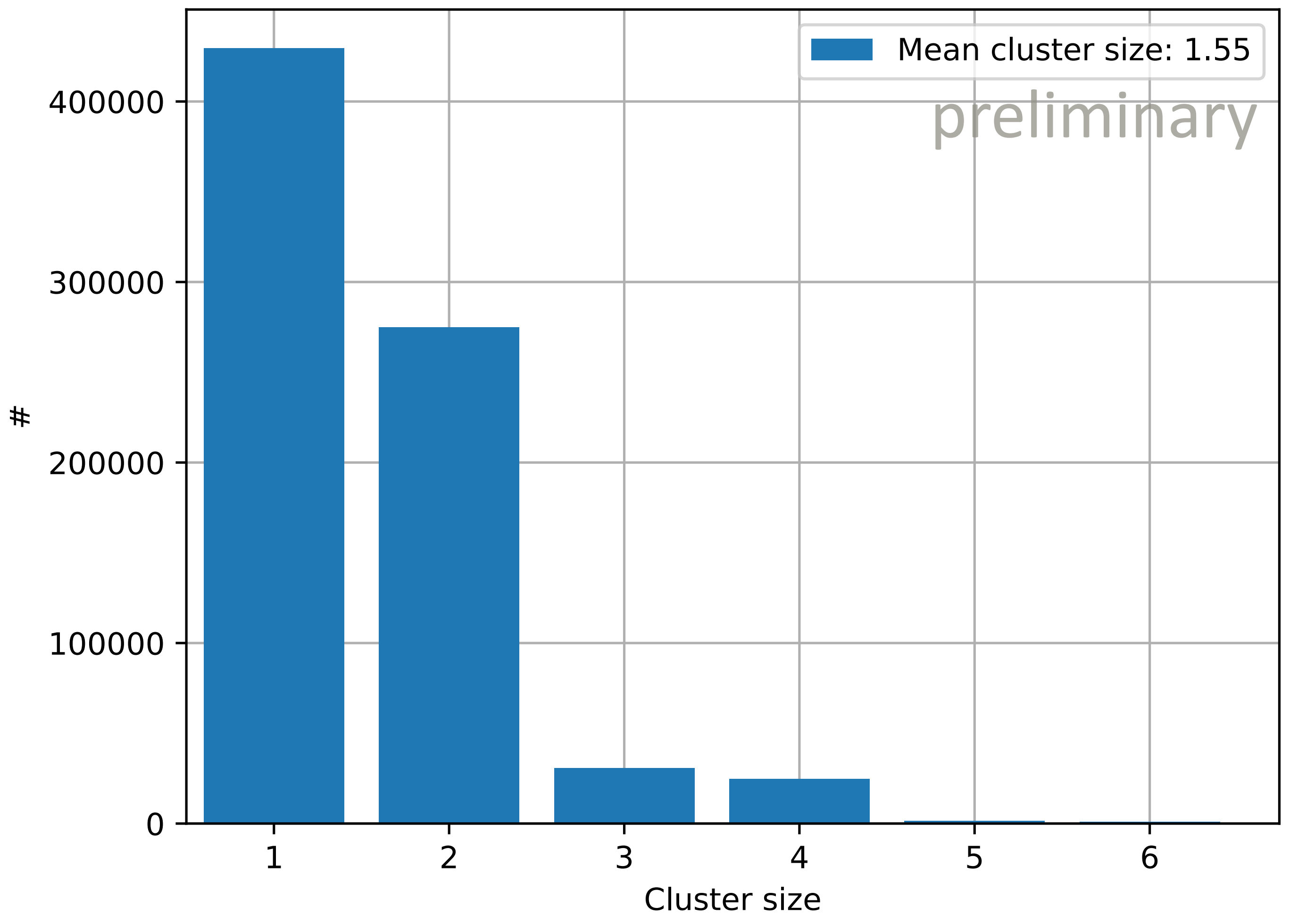
Cz gap in n-layer: 99.79 %



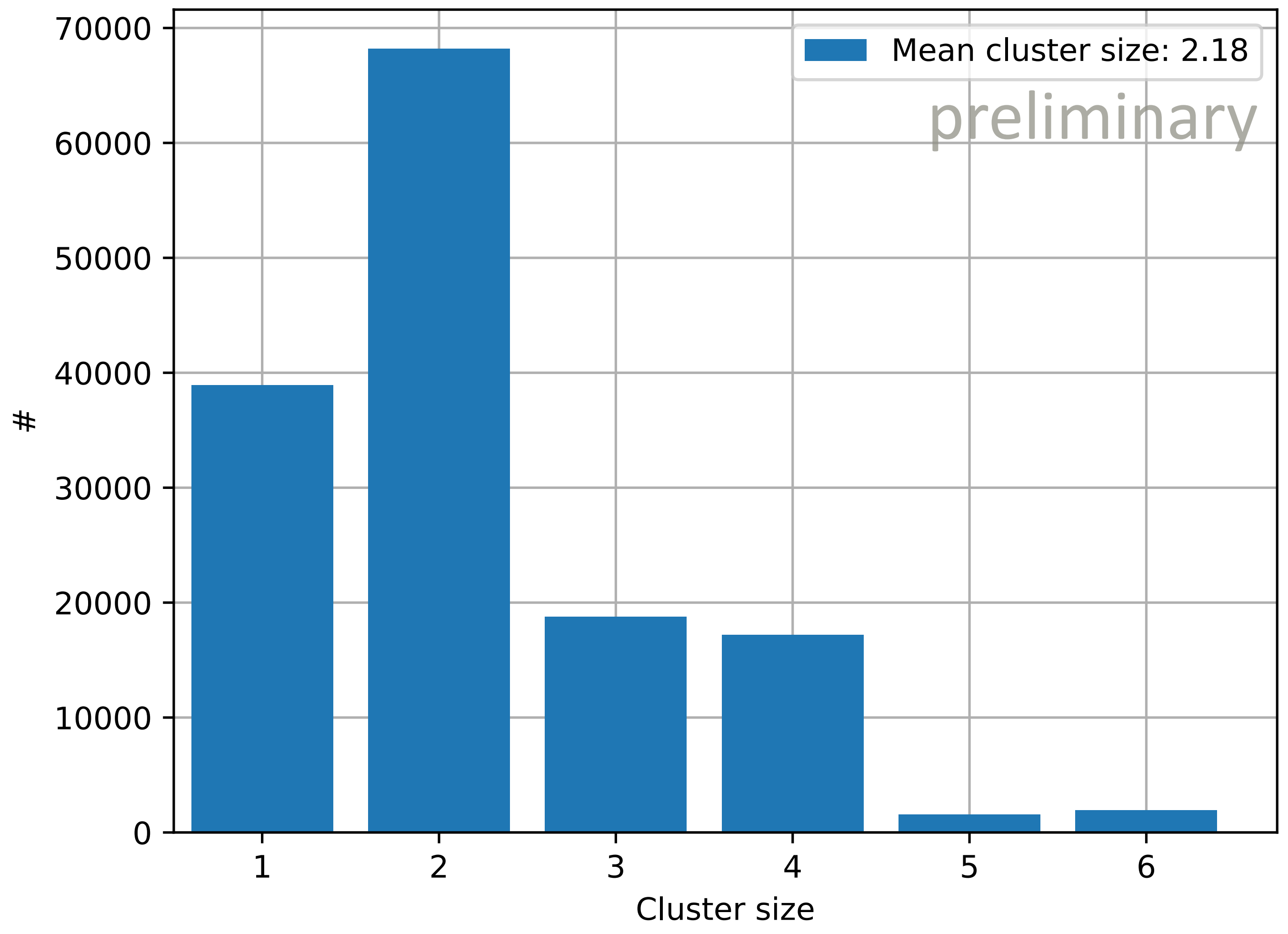
TJ-MONOPIX2 CLUSTER CHARGE

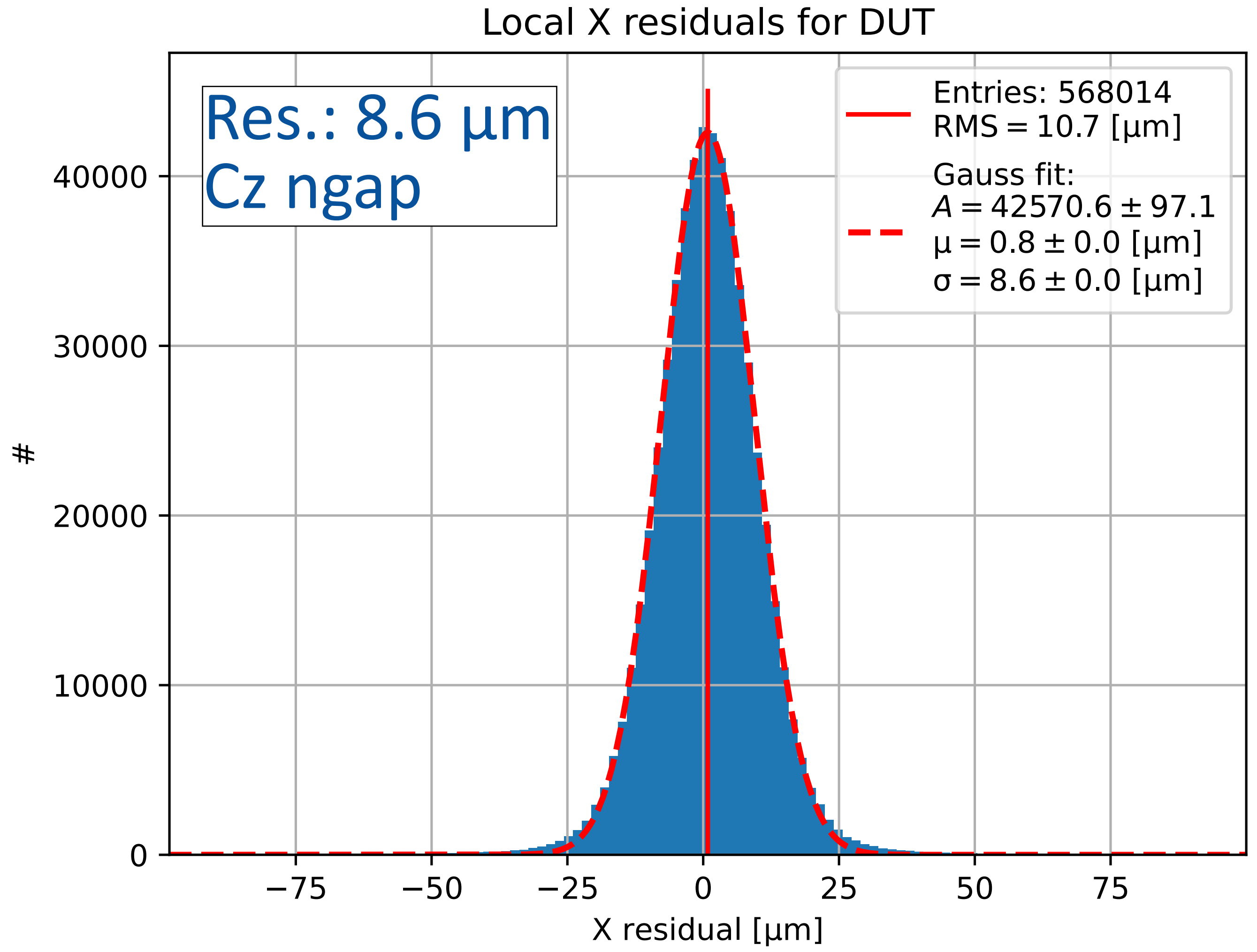
- Compare different sensor materials (epi 30 µm / Cz 100 µm) regarding cluster size
- As expected from accumulated charge and higher depletion than 30 µm cluster size is significantly larger in 100 µm silicon (not fully depleted)
- High (average) cluster size allows for high spatial resolution; better than $\frac{d}{\sqrt{12}}$ in Cz chip

Epi gap in n-layer: 1.55



Cz gap in n-layer: 2.18

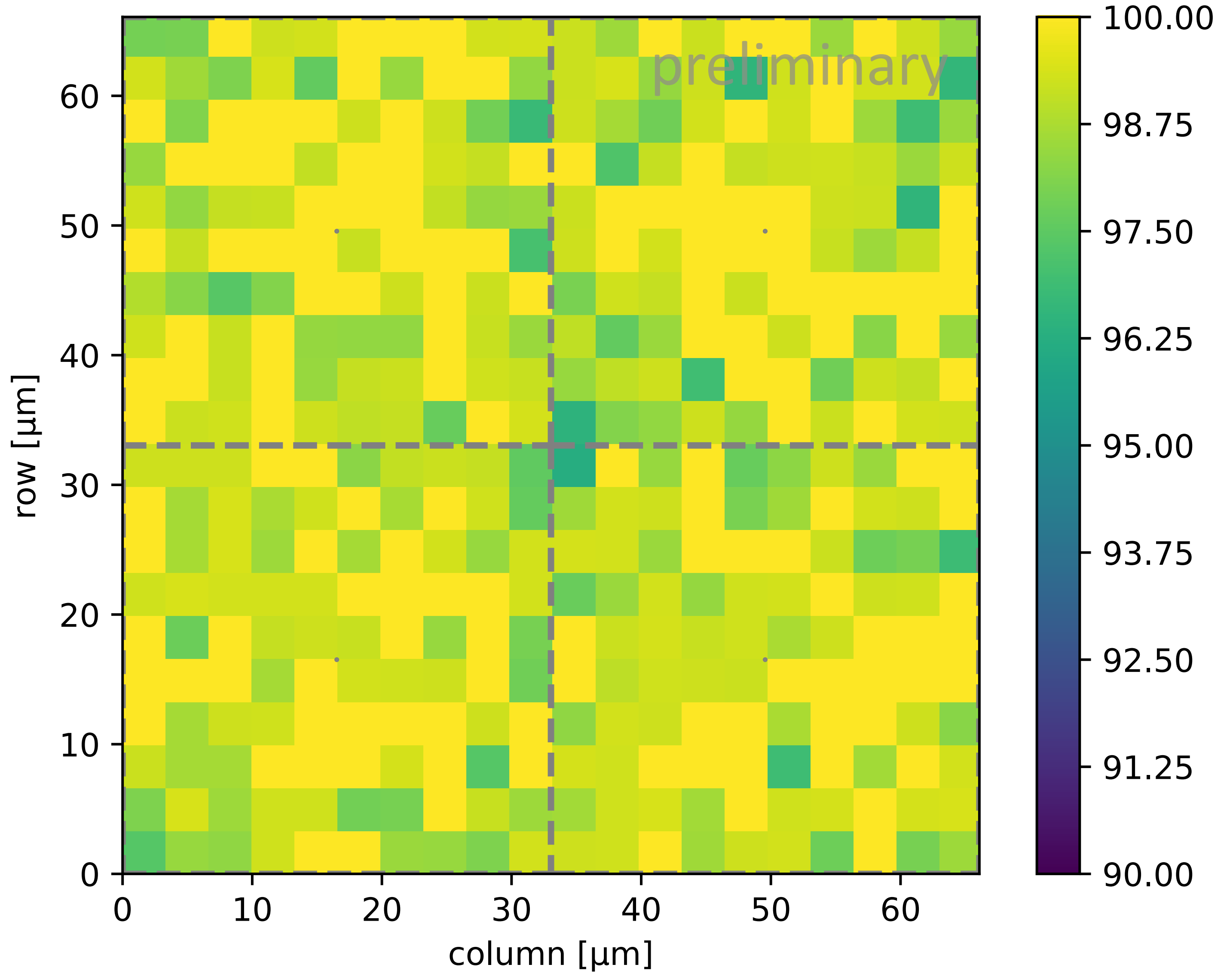




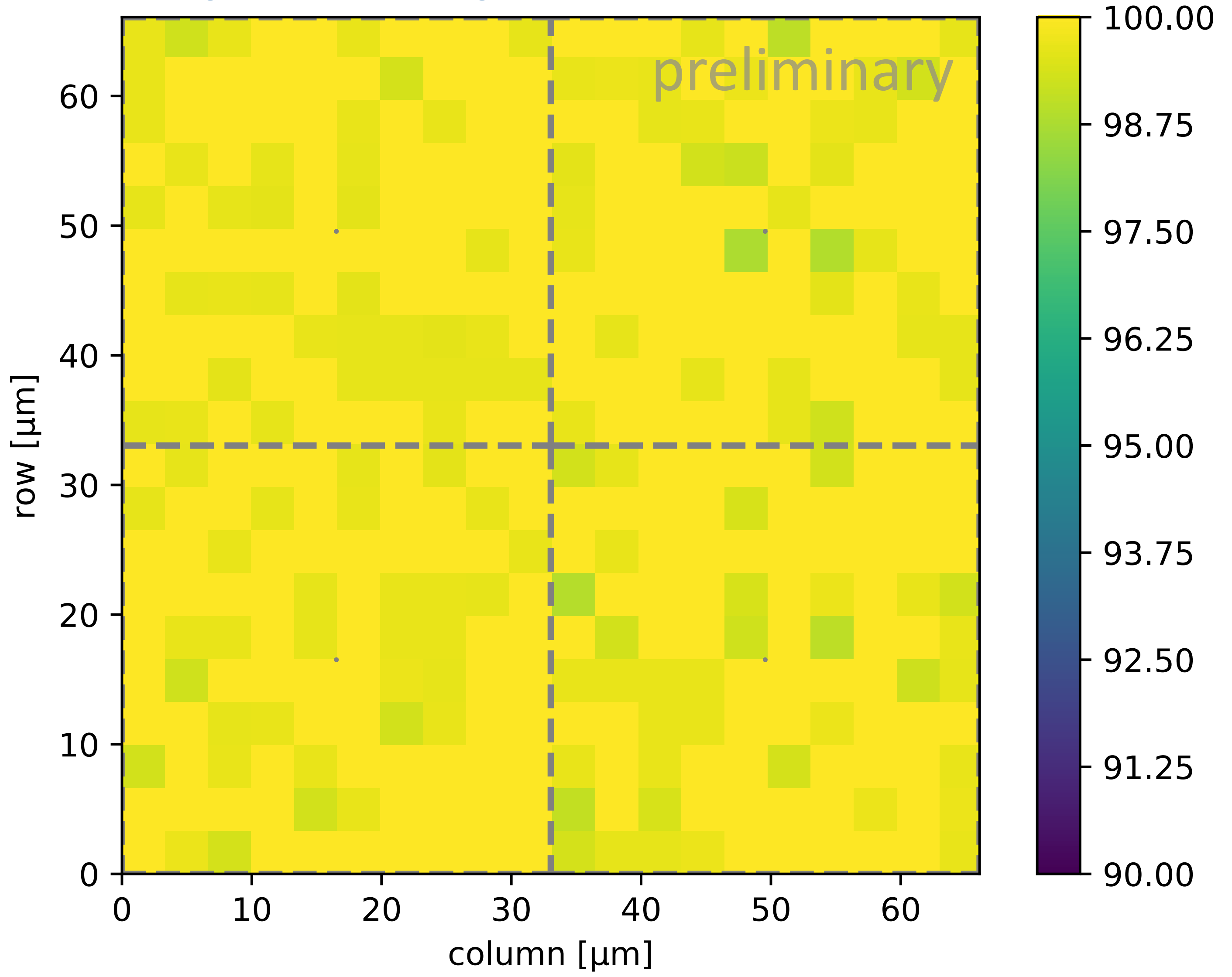
TJ-MONOPIX2 EFFICIENCY (HV)

- More „experimental“ front-end (called „HV“) with biasing from collection n-well (AC coupled with possibility of up to 50 V bias voltage)
- Studied efficiency for different bias voltages, analysis still ongoing, but even at 5 V bias > 99 % efficiency (plots suffer from low statistics due to few columns in flavor)

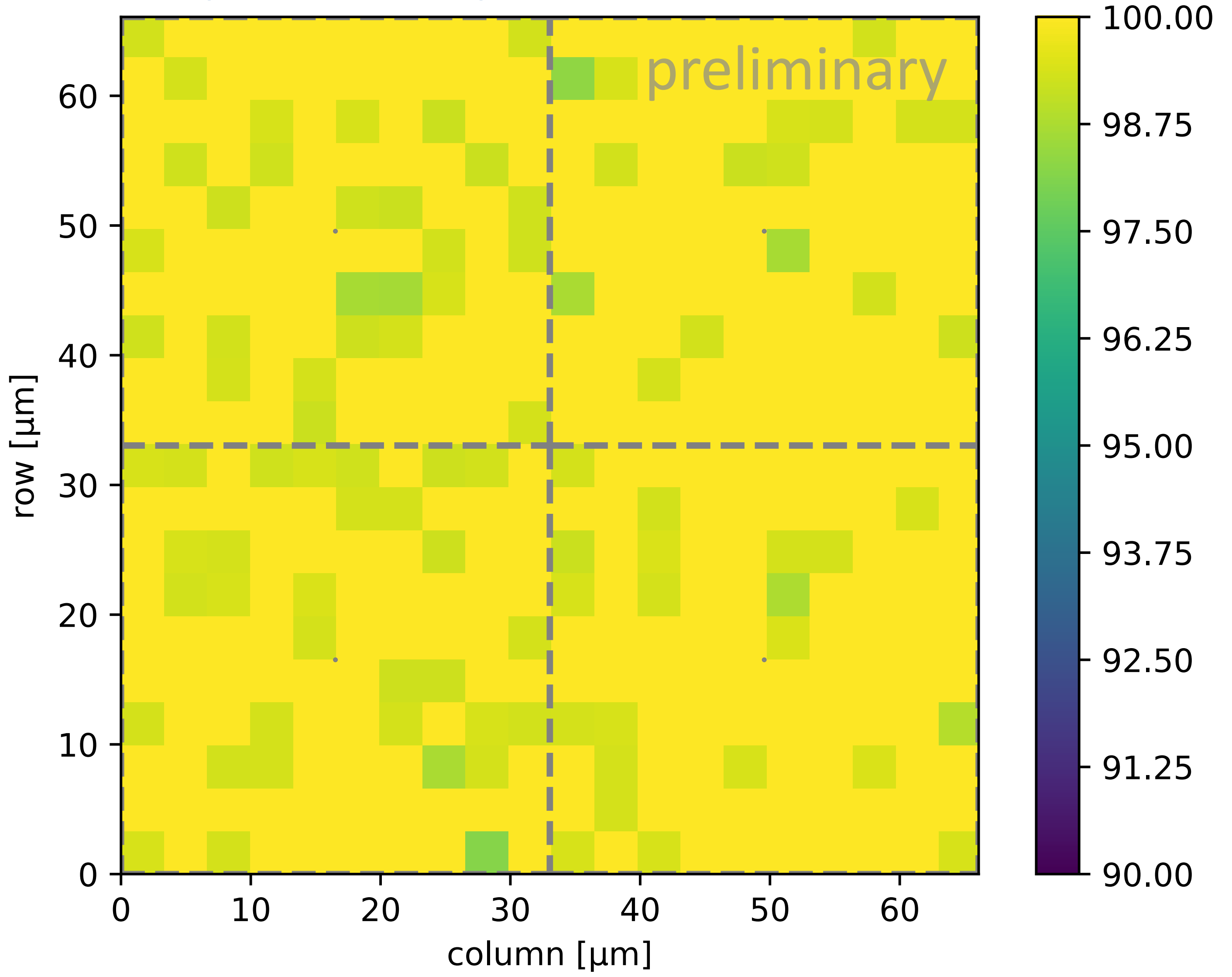
100 µm sample @ 5 V: 99.21 %



100 µm sample @ 25 V: 99.85 %

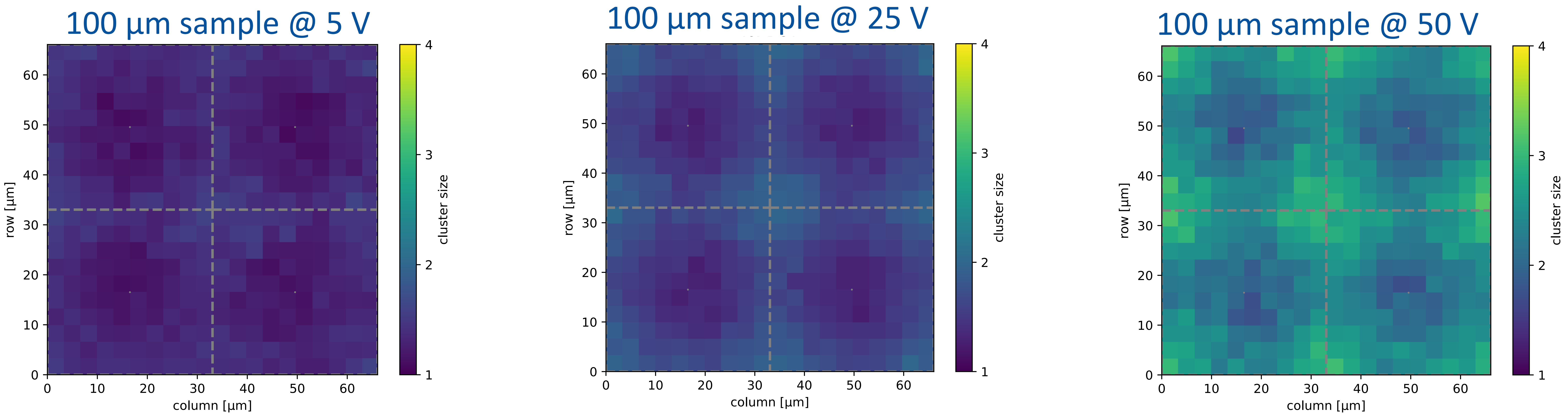


100 µm sample @ 50 V: 99.82 %



TJ-MONOPIX2 CLUSTER SIZE (HV)

- In-pixel cluster size for different bias voltages in HV flavor
- Qualitative increase in cluster size observed
- As expected, cluster size in center of pixel smaller than in corners
- Important to keep threshold low to collect shared charges, especially after irradiation (losses observed in TJ-Monopix1)



OUTLOOK

- Most of the results still preliminary, run and cross-check analysis of all testbeam datasets
- Improve front-end parameters for lower operational thresholds
- Analysis of pixel flavors that were not presented here (slightly modified front-end)
- Detailed charge calibration to be done shortly
- Irradiations with protons and neutrons planned for next months to fluences of 10^{15} 1 MeV $^{neq}/_{cm2}$
- Testbeam campaigns already planned for first half of 2023 for irradiated sensors, threshold studies, …

- Ongoing activity from VTX Collaboration with DMAPS proposal for Belle II PXD upgrade based on TJ-Monopix design

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CONCLUSIONS

- Fully working DMAPS with column-drain readout in 2 cm long columns
- All pixel-related electronics including digitization integrated in pixel
- Operational values mainly match design values, except threshold
- Collected charge > 2000 e^- for MIPs with efficiency > 99 % for unirradiated chips across front-end and substrate variants

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

This project has received funding from the Deutsche Forschungsgemeinschaft DFG (grant WE 976/4-1), the German Federal Ministry of Education and Research BMBF (grant 05H15PDCA9), and the European Union's Horizon 2020 research and innovation program under grant agreements no. 675587 (Maria Sklodowska-Curie ITN STREAM), 654168 (AIDA-2020), and 101004761 (AIDAinnova).