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CHARACTERIZATION OF TJ-MONOPIX2

A DEPLETED MONOLITHIC ACTIVE PIXEL SENSOR WITH COLUMN DRAIN READOUT ARCHITECTURE

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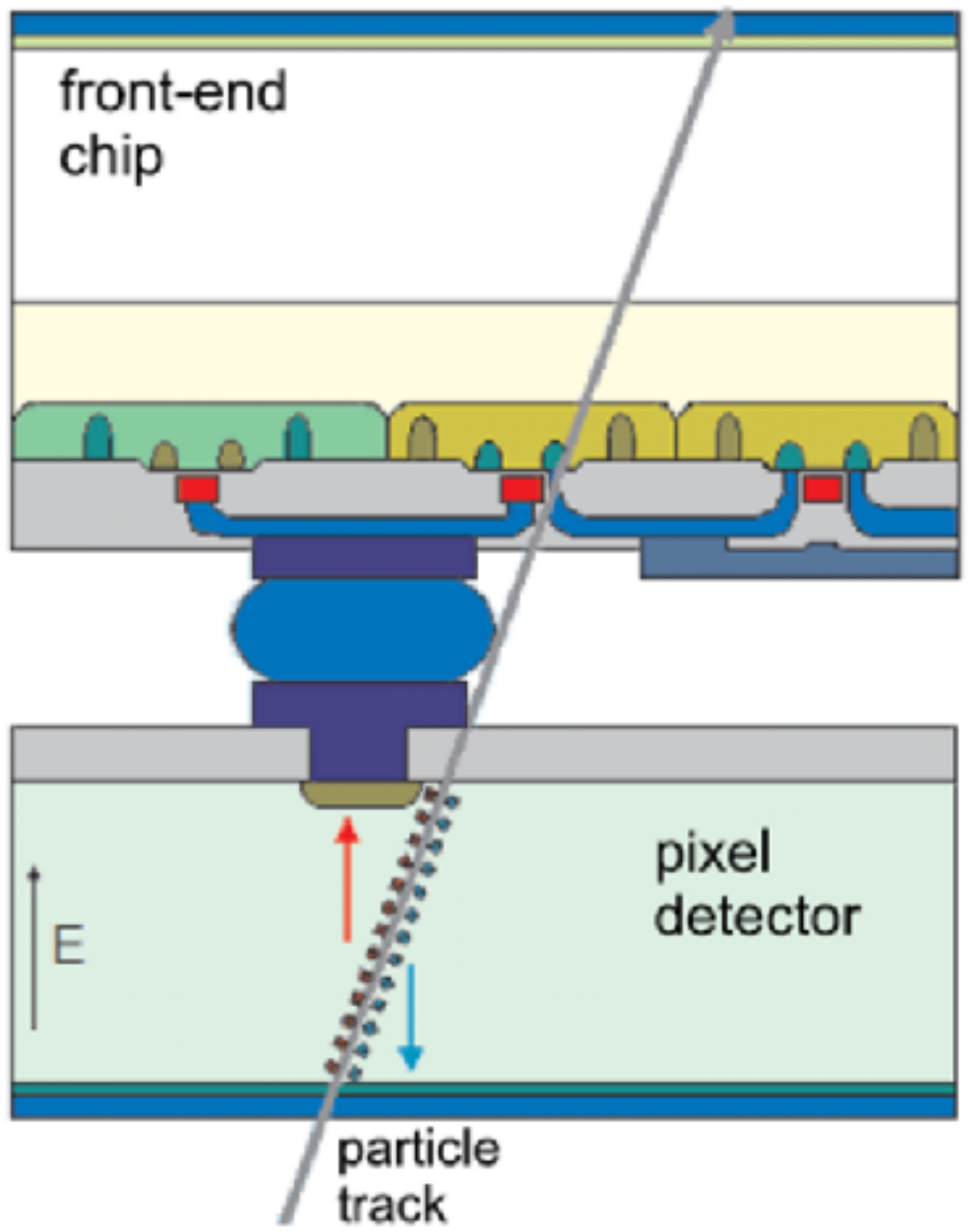
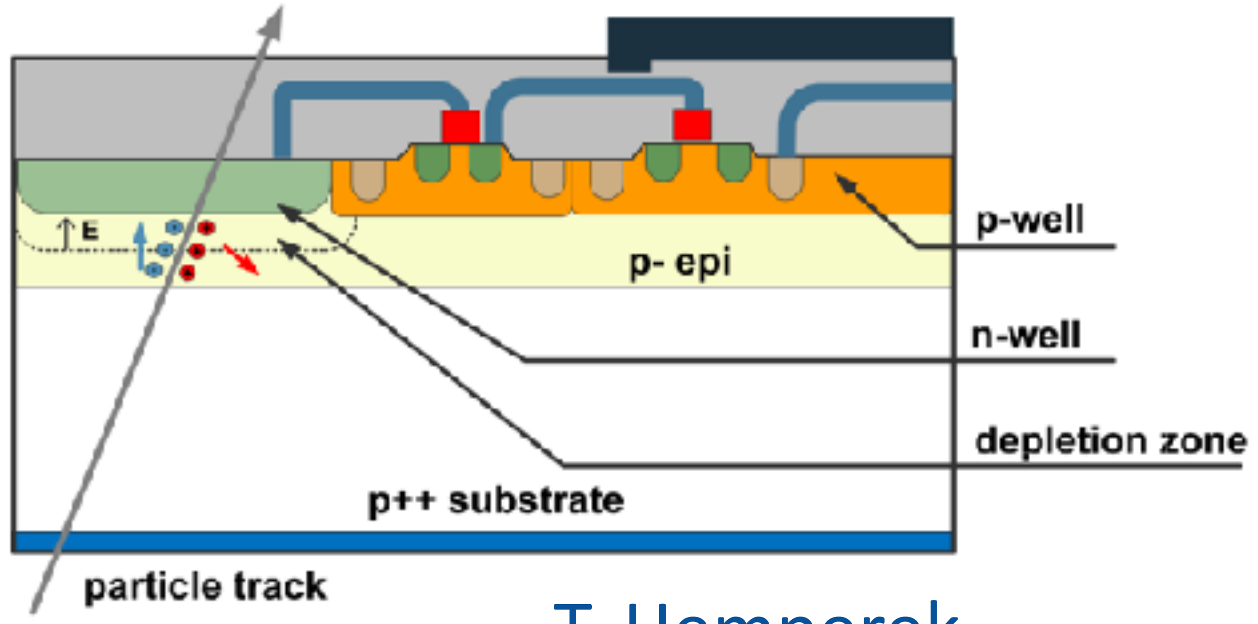
MONOLITHIC ACTIVE PIXEL DETECTORS

- 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)
- Low material budget for tracking detectors
- But: can we achieve significant levels of radiation hardness with good performance and fast readout for high-rate environments?

Hybrid pixel detector



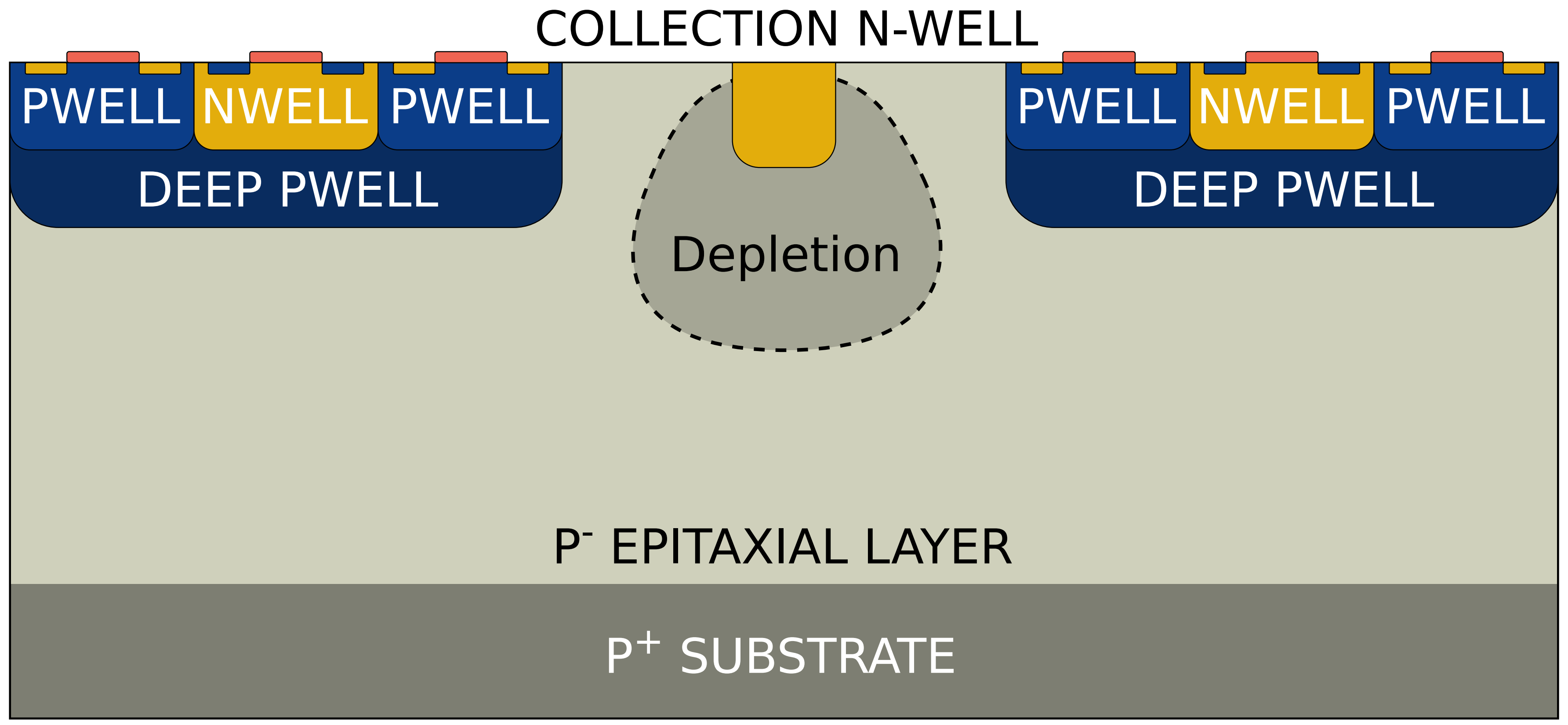
MAPS



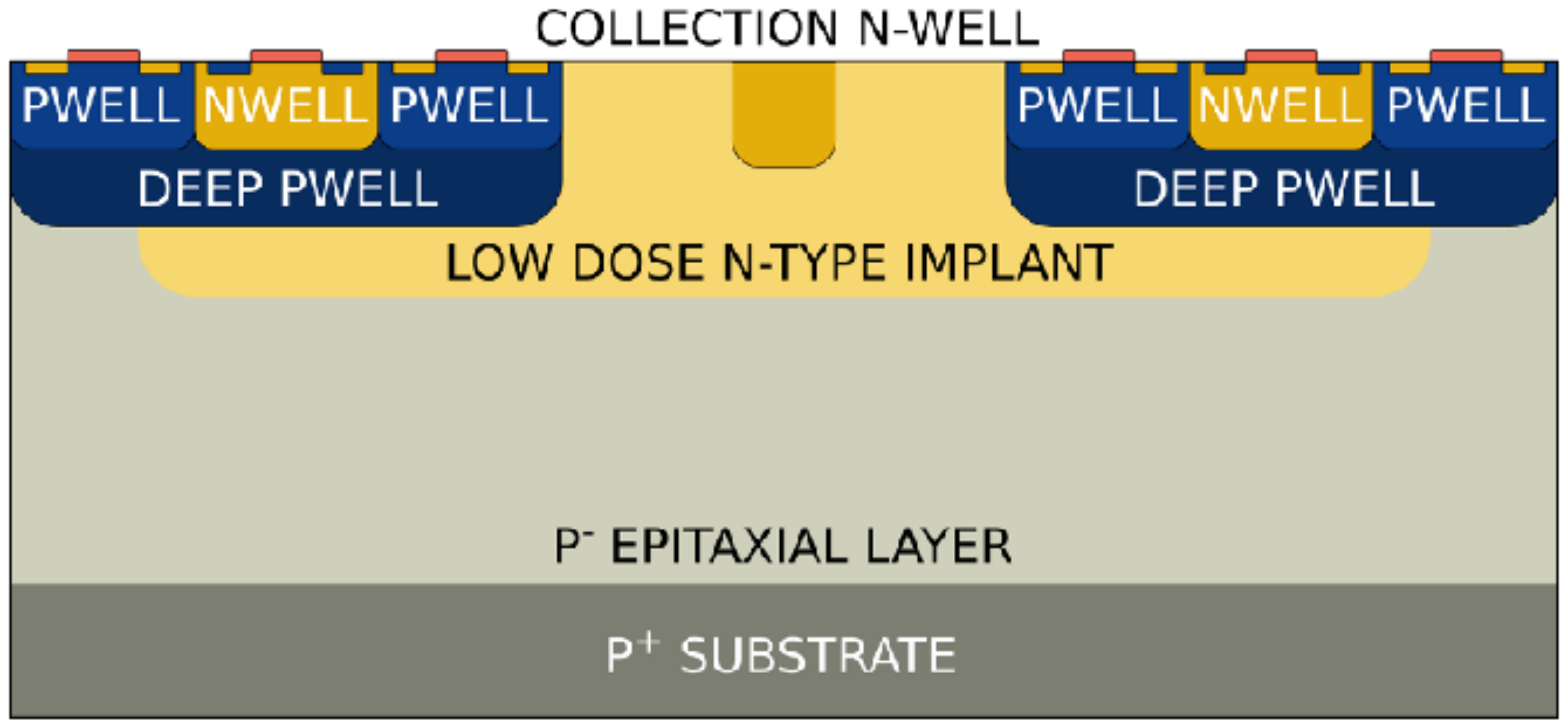
T. Hemperek

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



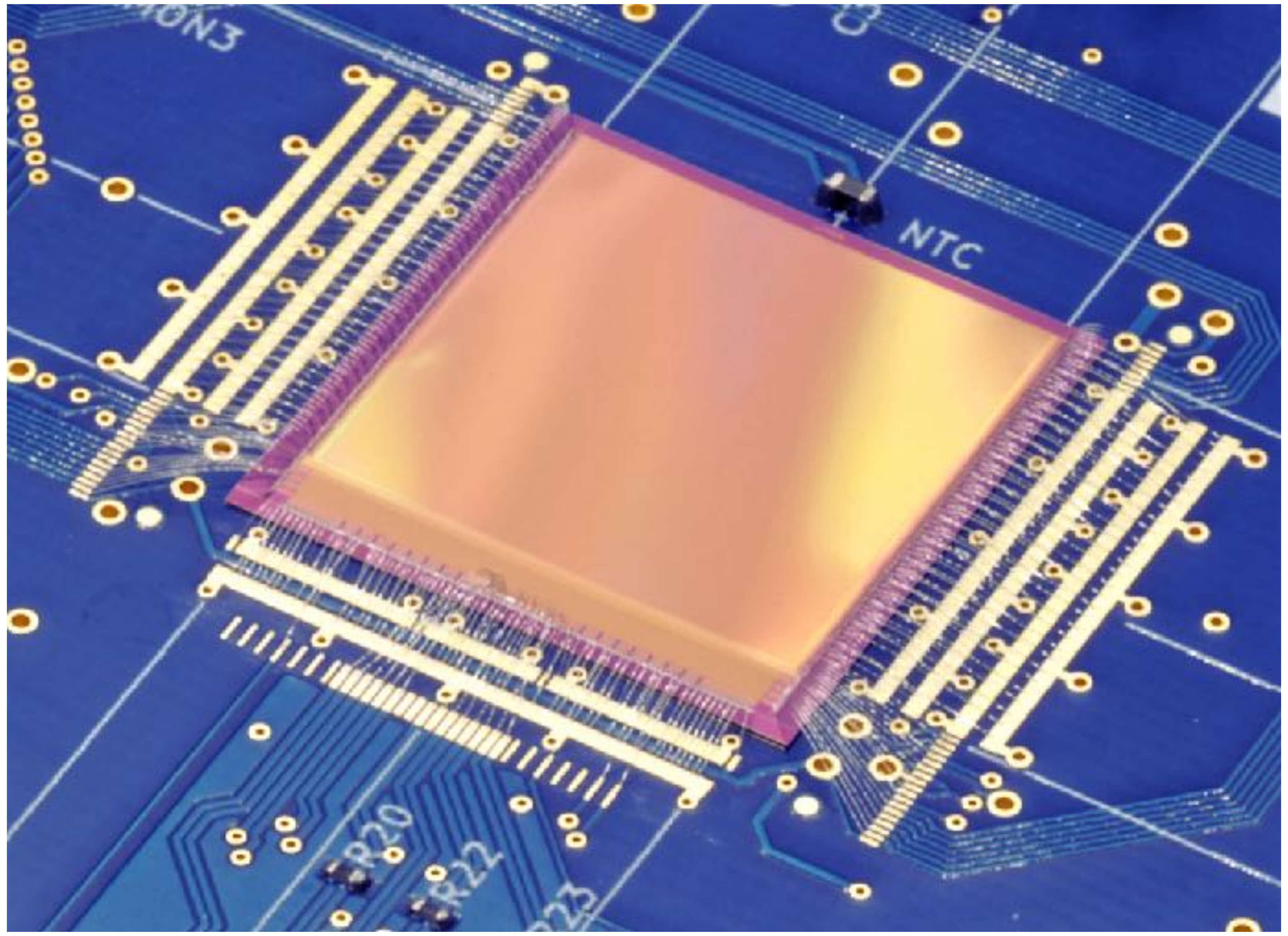
Standard MAPS cell



Modified process for full depletion (see later for variants)

TJ-MONOPIX DESIGN

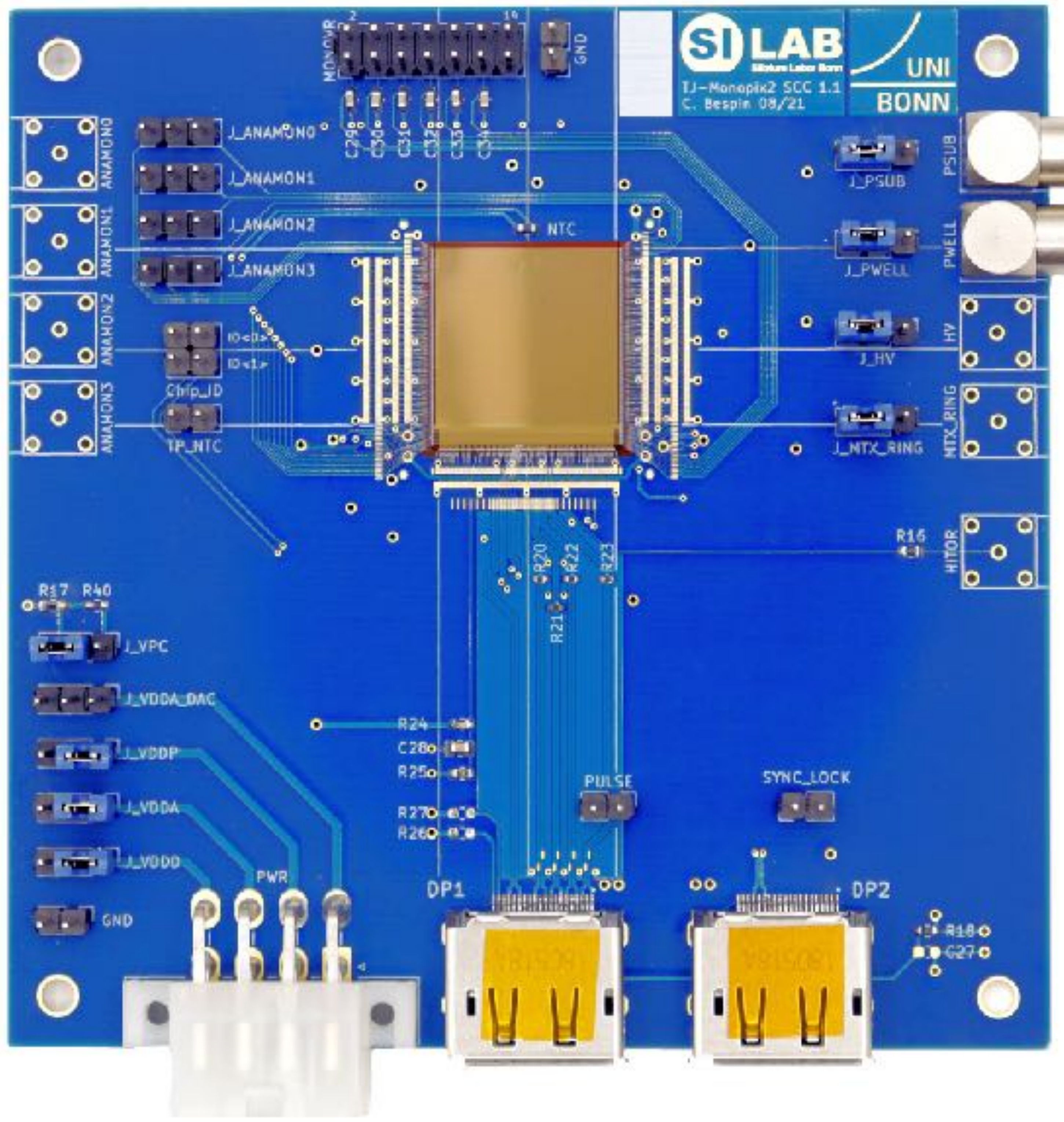
- Designed for ATLAS ITk outer layer specs with column-drain readout like in FE-I3 in a 2 cm column
  - Pixel readout capable of dealing with hit rate > 100 MHz / cm^2
  - Goal: 10^{15} 1 MeV $^{neq}/_{cm2}$ NIEL tolerance and 100 MRad TID
- Latest iteration TJ-Monopix2: 33.04 µm pixel pitch in 512 x 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)



TJ-MONOPIX2 DAQ SYSTEM

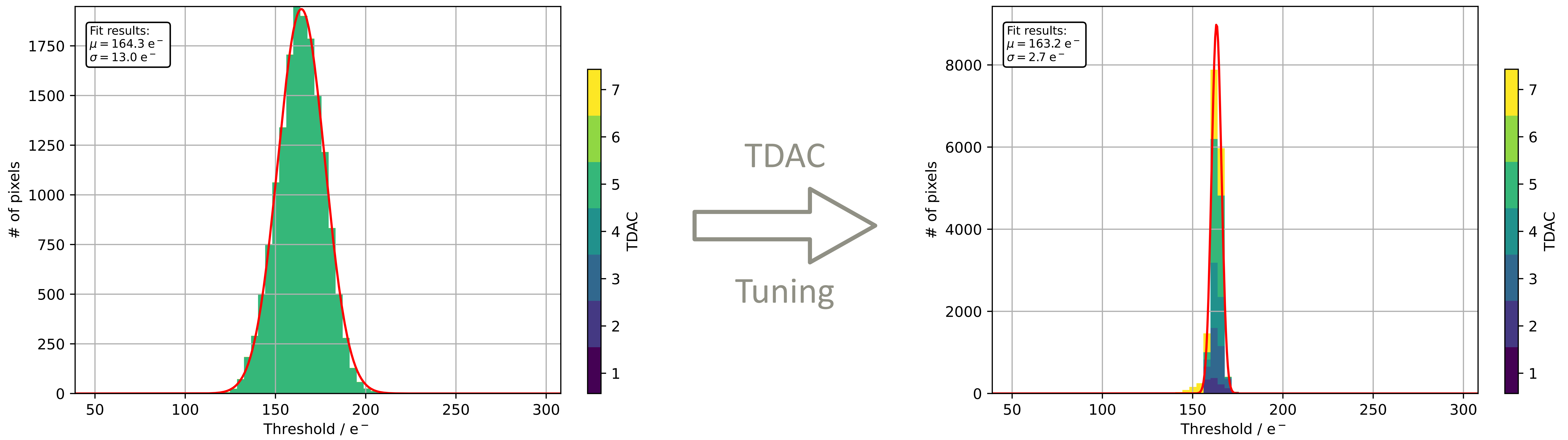
- DAQ System based on RD53A/B readout board bdaq53
- Standalone carrier PCB with power and DisplayPort connector
- Readout board with 1 Gbit/s connection to DAQ computer (10 Gbit/s possible)
- Small and portable setup for irradiations, beam tests etc.

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



TJ-MONOPIX2 LAB TESTS

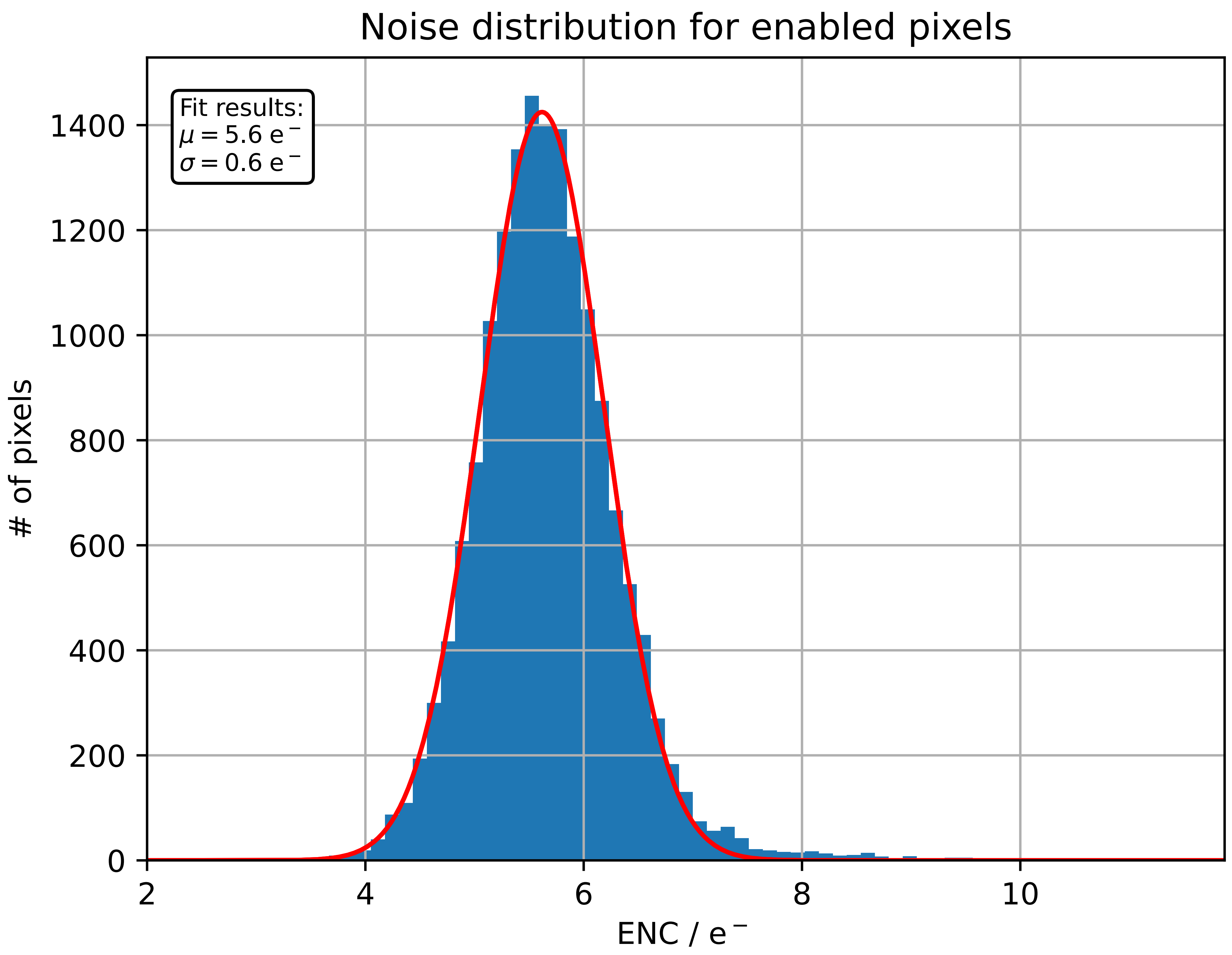
- Lab tests conducted for threshold and noise measurements
- Design goals: operational threshold ≈ 100 e^-, threshold dispersion < 10 e^-, ENC ≈ 5 e^-
- In-pixel threshold trimming (3 bit) significantly reduces threshold dispersion to less than design value
- Operational threshold higher than anticipated,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



TJ-MONOPIX2 LAB TESTS

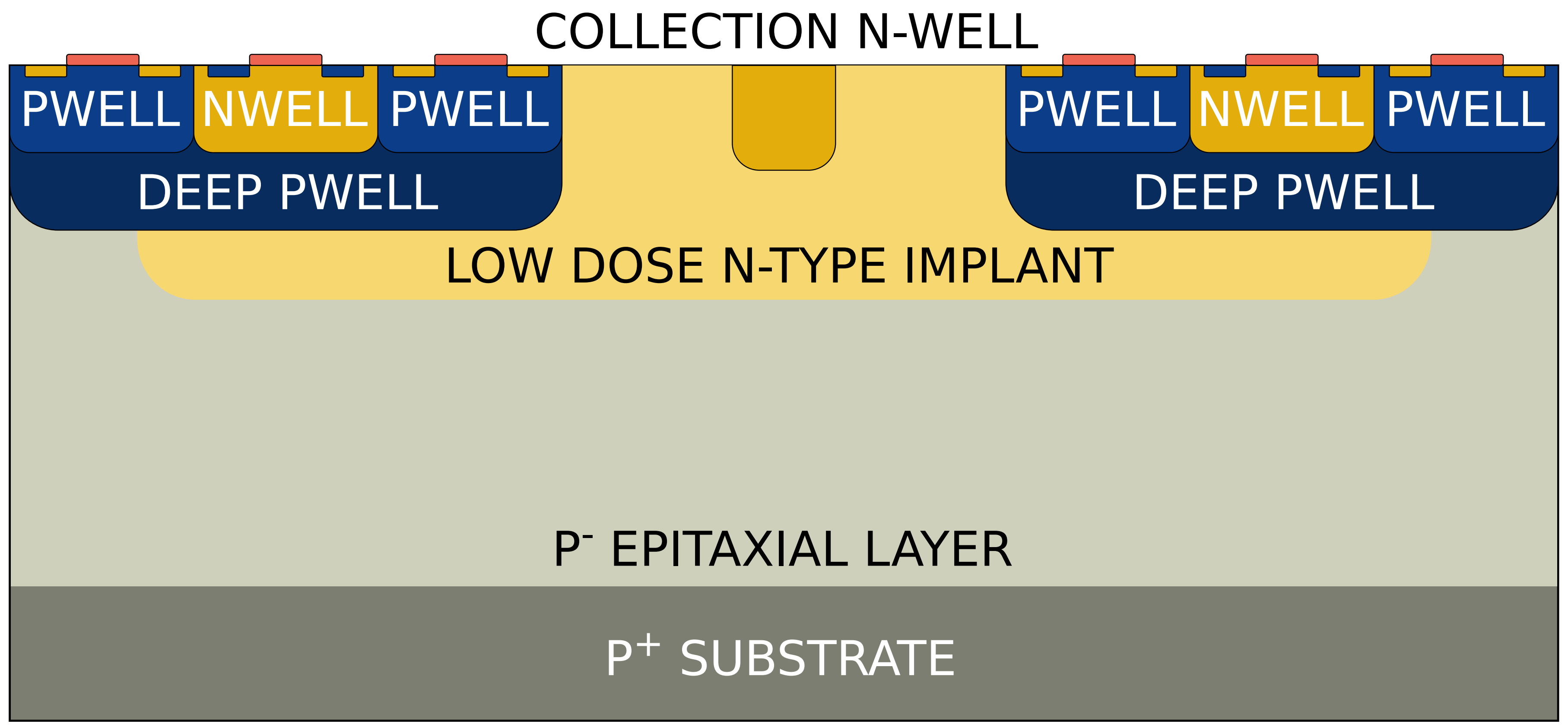
- Noise (ENC) measured from steepness of S-curve when injecting varying charges
- Mean noise 5.6 e^- in accordance with design goal
- No RTS noise tail observed as in TJ-Monopix1
- Allows operation at low thresholds thanks to large S/N ratio

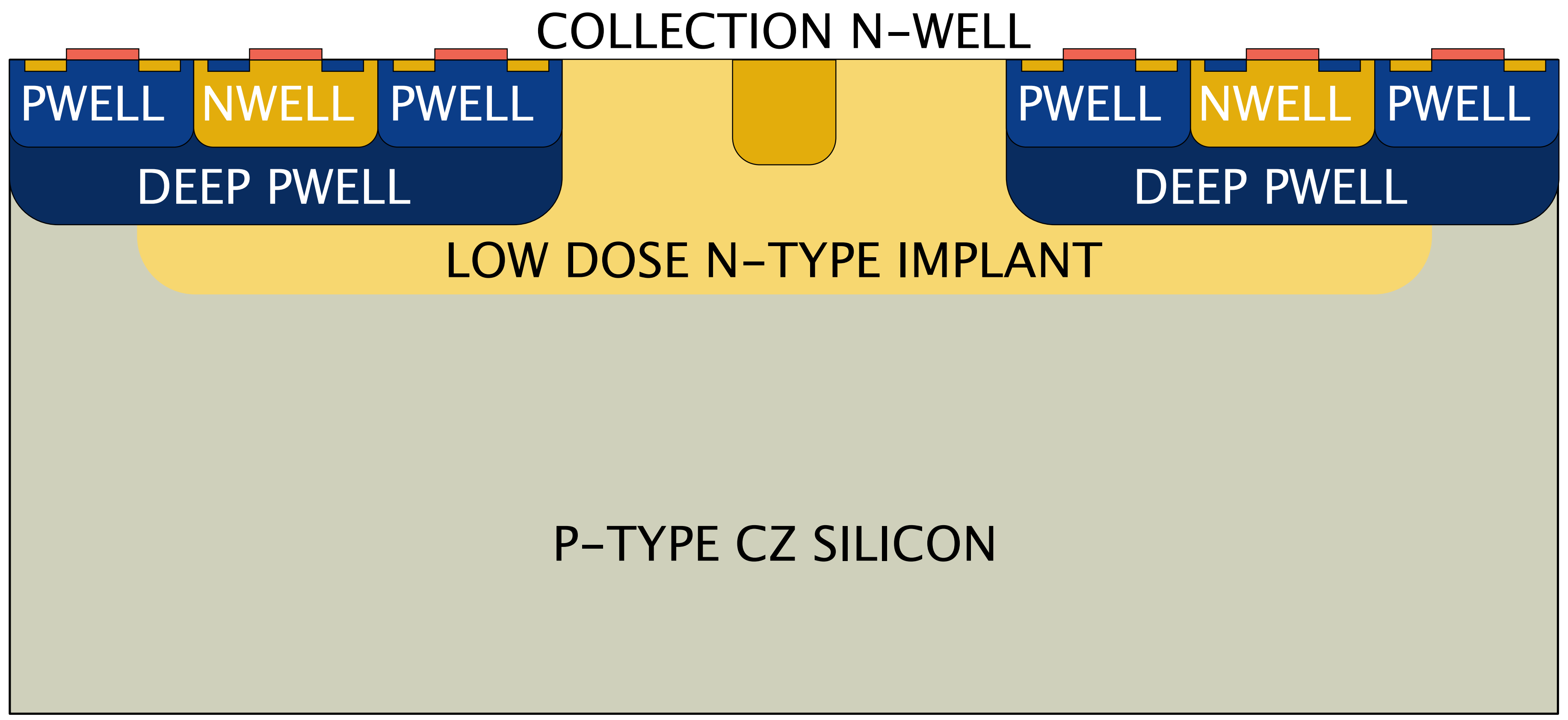
- Reminder: in TJ-Monopix1, operational threshold was O(400 e^-) which lead to efficiency losses in pixel corners, especially after irradiation



TJ-MONOPIX2 BEAM TESTS

- Beam tests performed at DESY in November 2022 (5 GeV electron beam, Mimosa26 telescope)
- Investigated samples (unirradiated):
  - epitaxial silicon (30 µm thickness) with gap in n-layer
  - 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^-

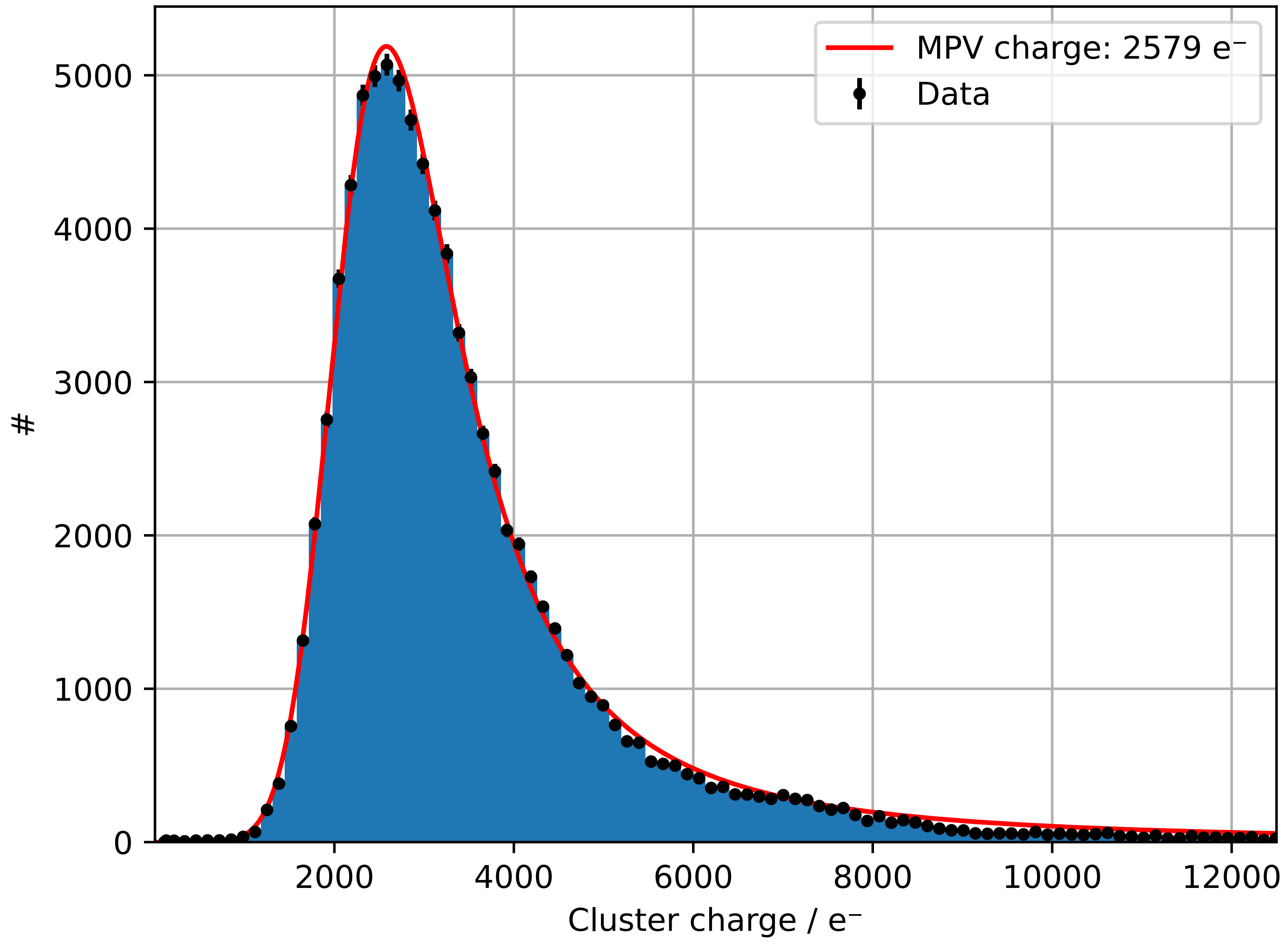




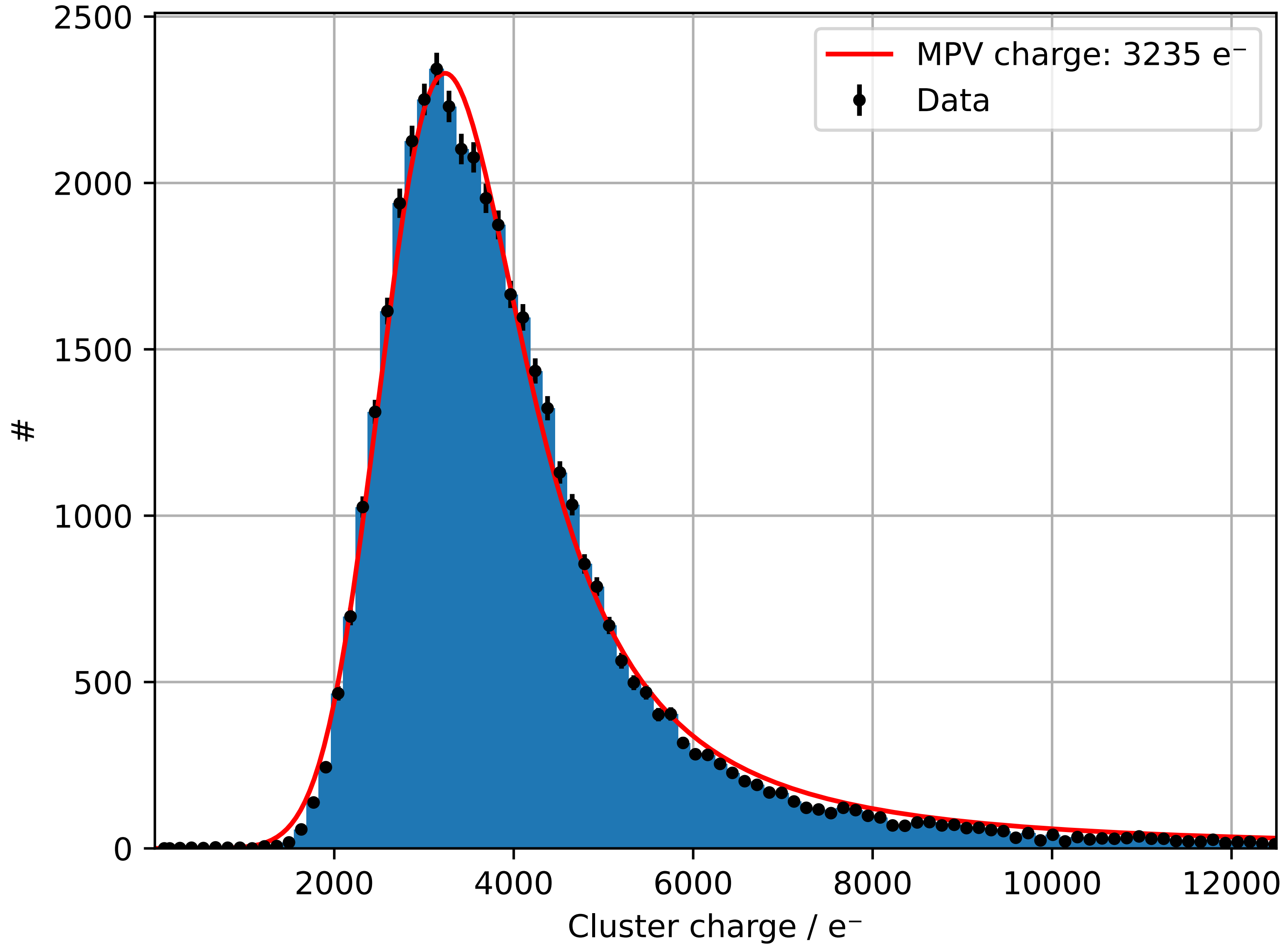
TJ-MONOPIX2 CLUSTER CHARGE

- 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 gap in n-layer (30 µm): 2579 e⁻



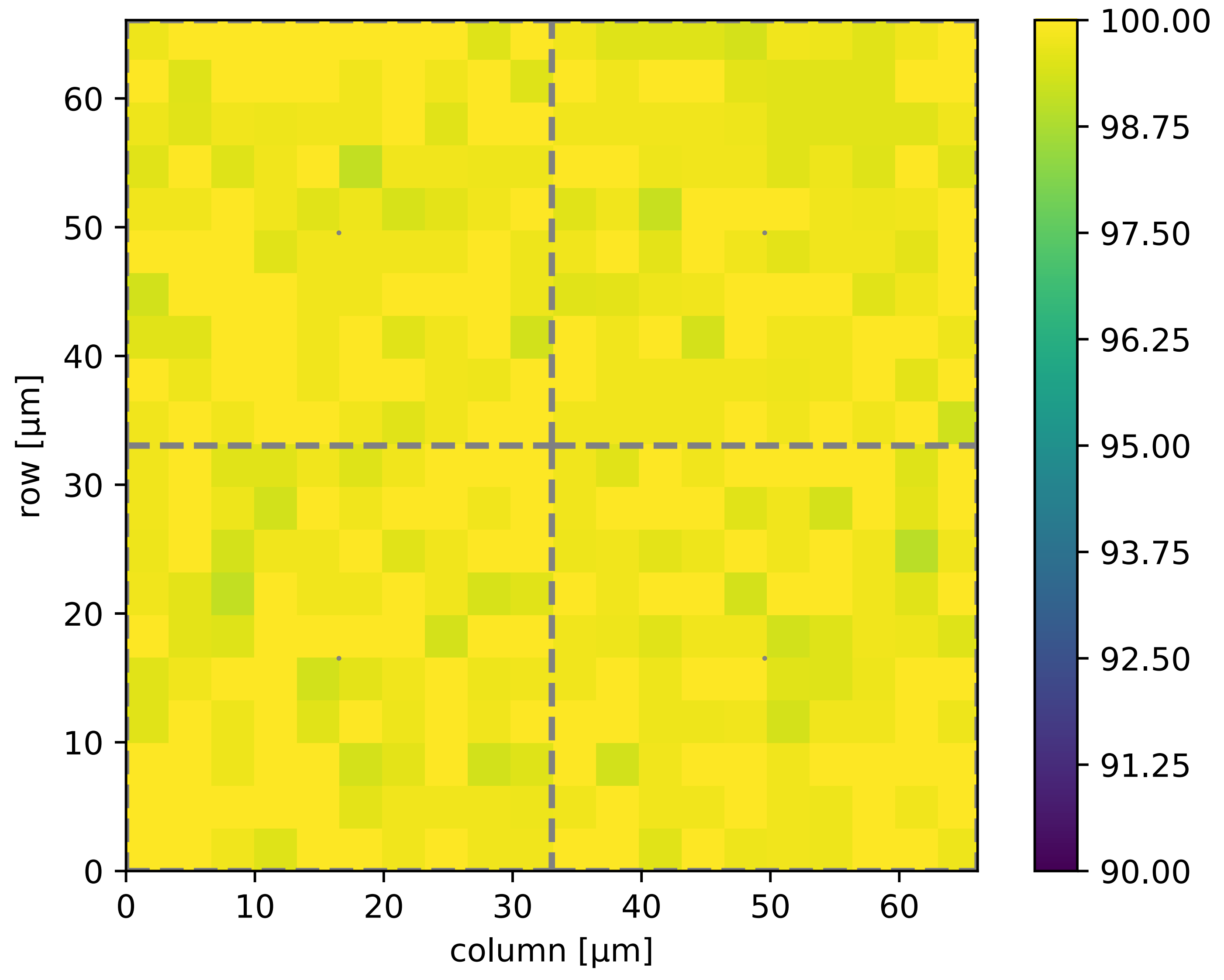
Cz gap in n-layer (100 µm): 3235 e⁻



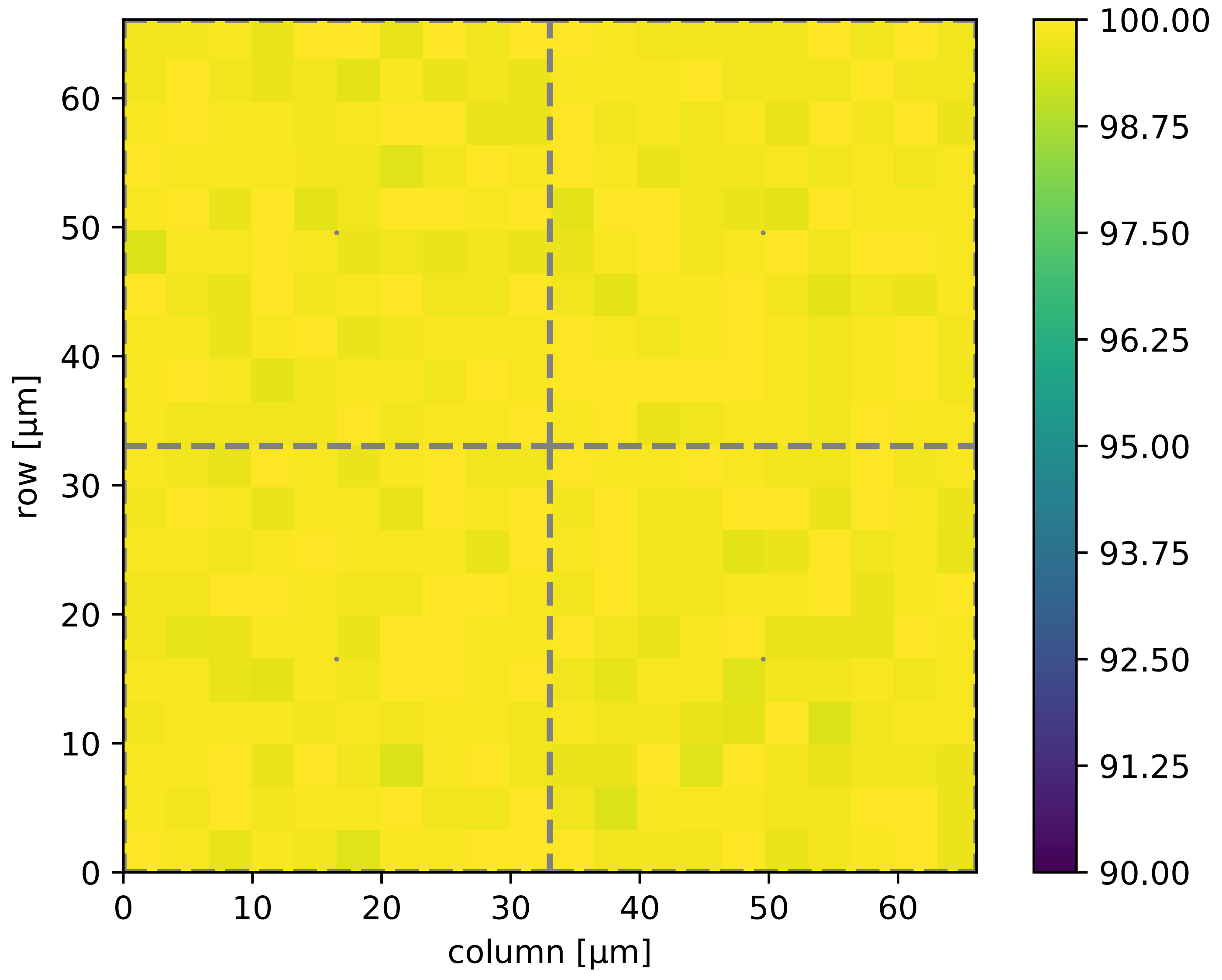
TJ-MONOPIX2 EFFICIENCY

- 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 gap in n-layer (30 µm): 99.80 %



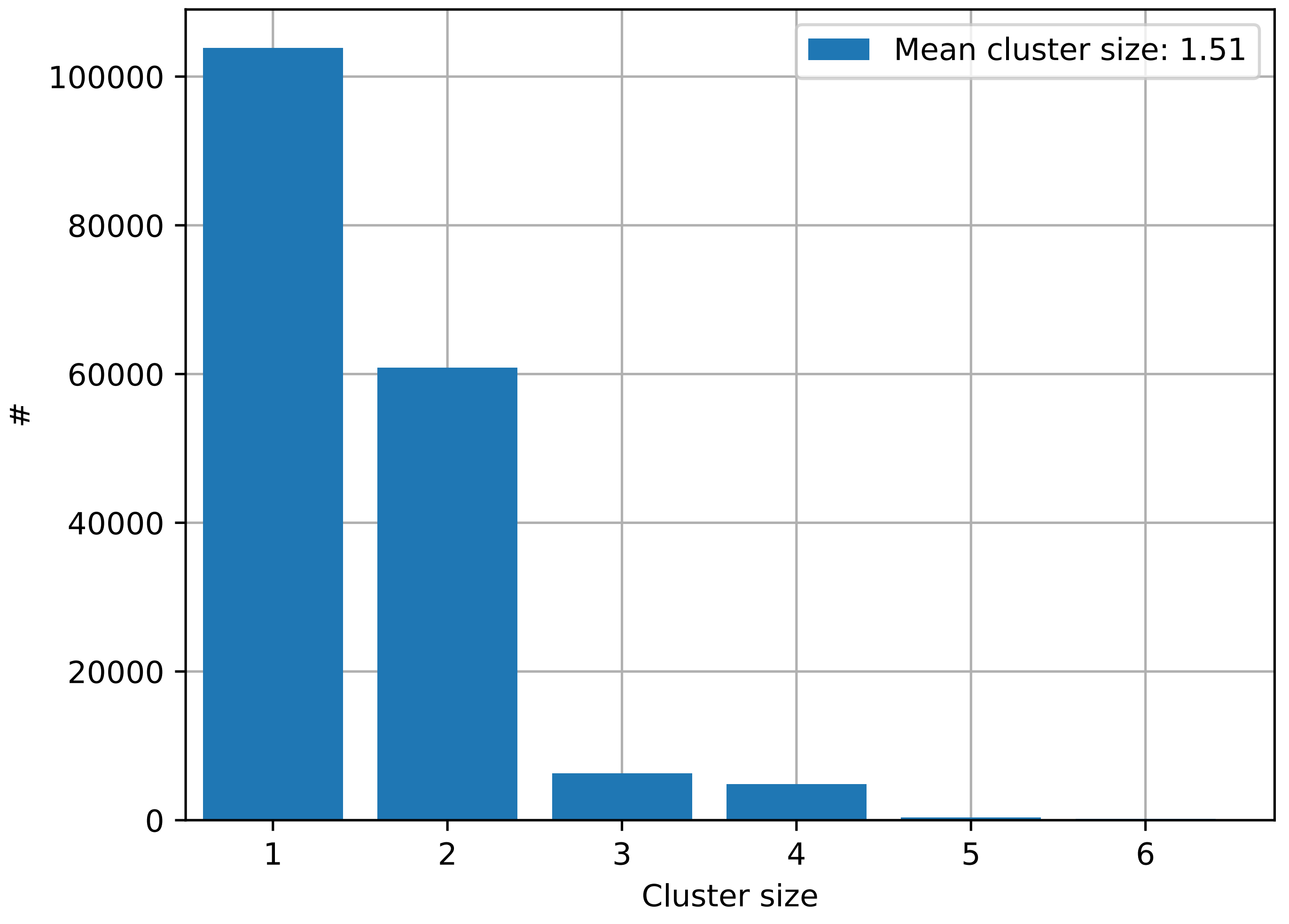
Cz gap in n-layer (100 µm): 99.79 %



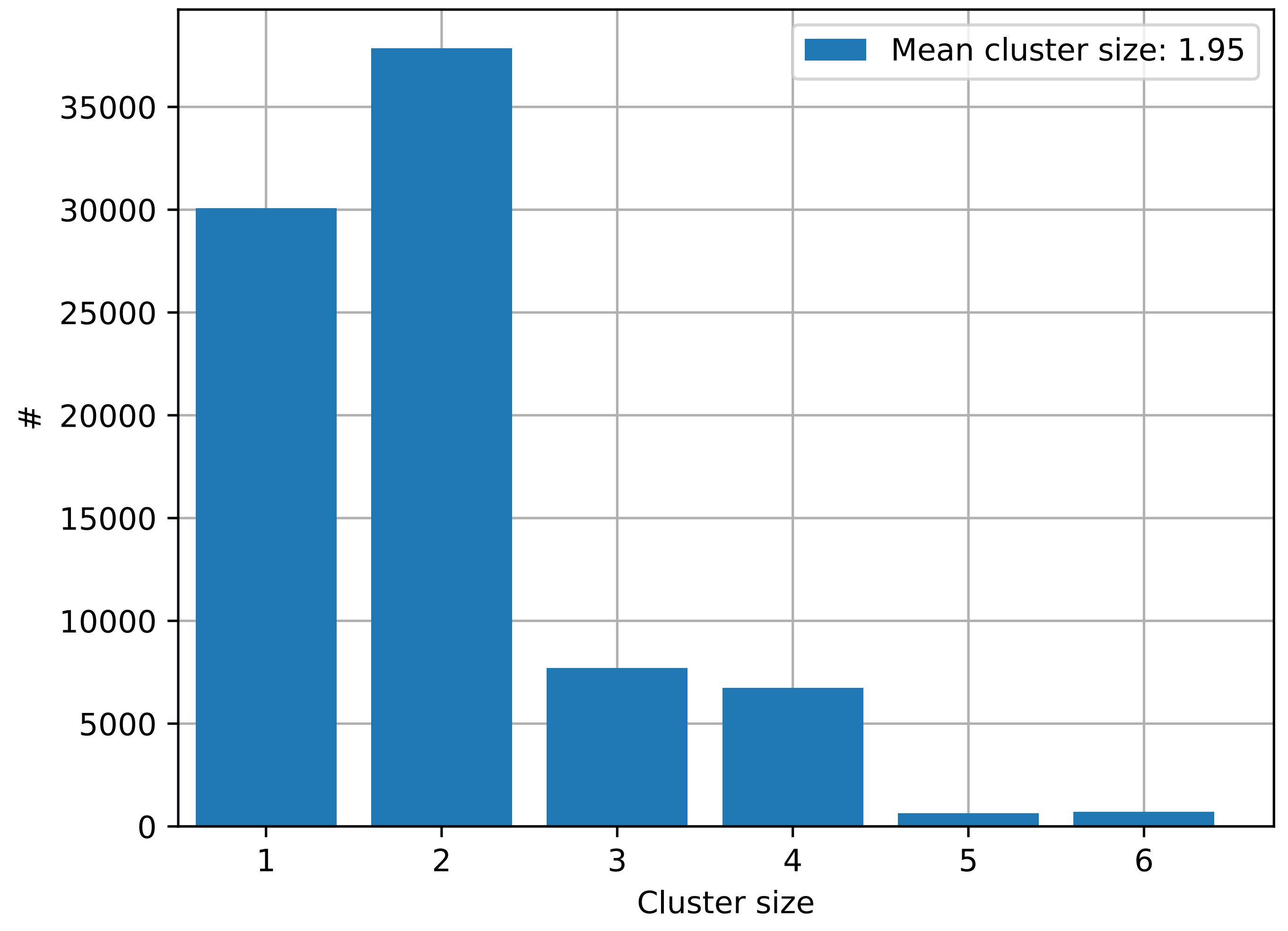
TJ-MONOPIX2 CLUSTER CHARGE

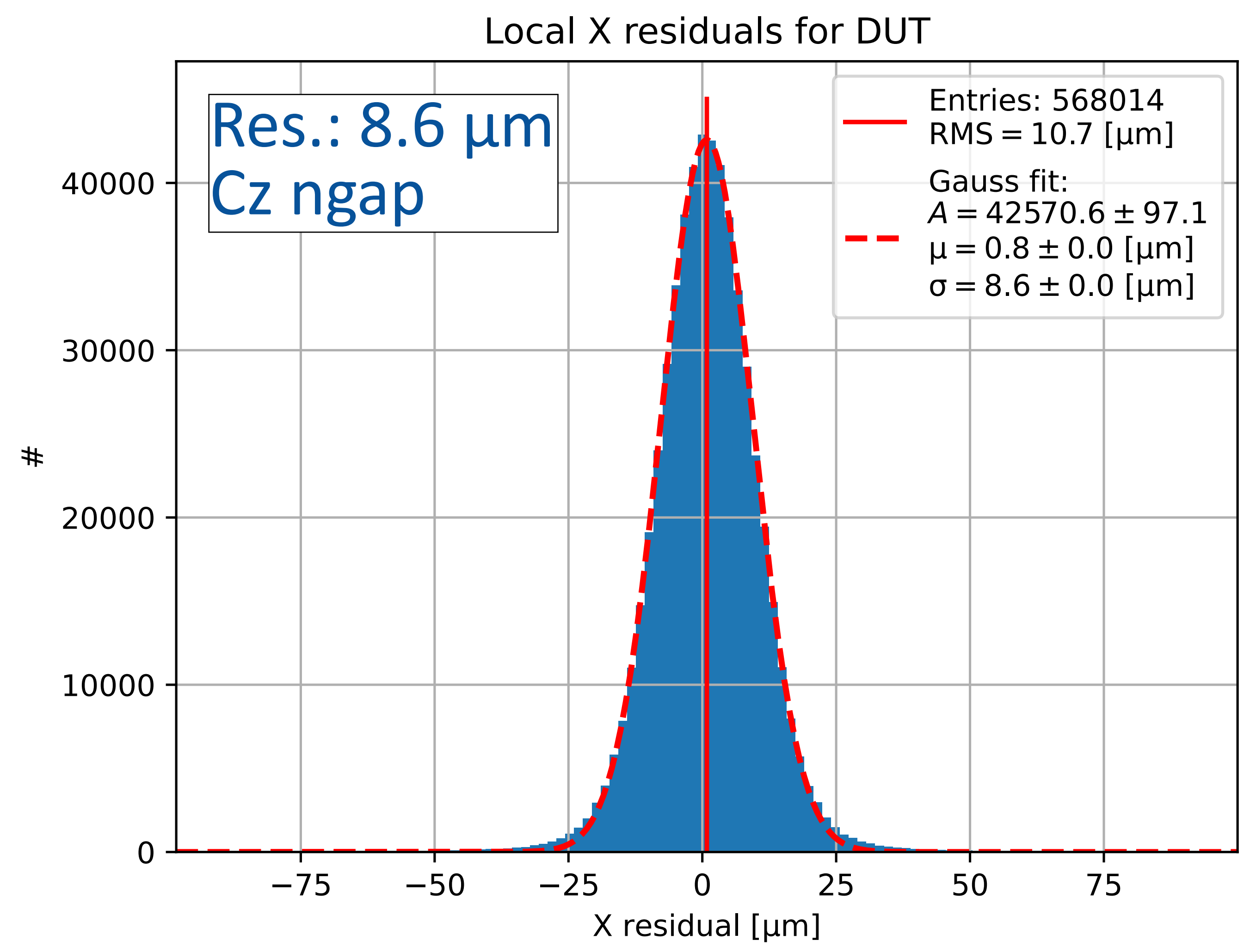
- Compare different sensor materials (epi 30 µm / Cz 100 µm) regarding cluster size
- As expected from accumulated charge and higher depletion than 30 µm cluster size is significantly larger in 100 µm silicon (not fully depleted)
- High (average) cluster size allows for high spatial resolution; better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

Epi gap in n-layer: 1.51



Cz gap in n-layer: 1.95

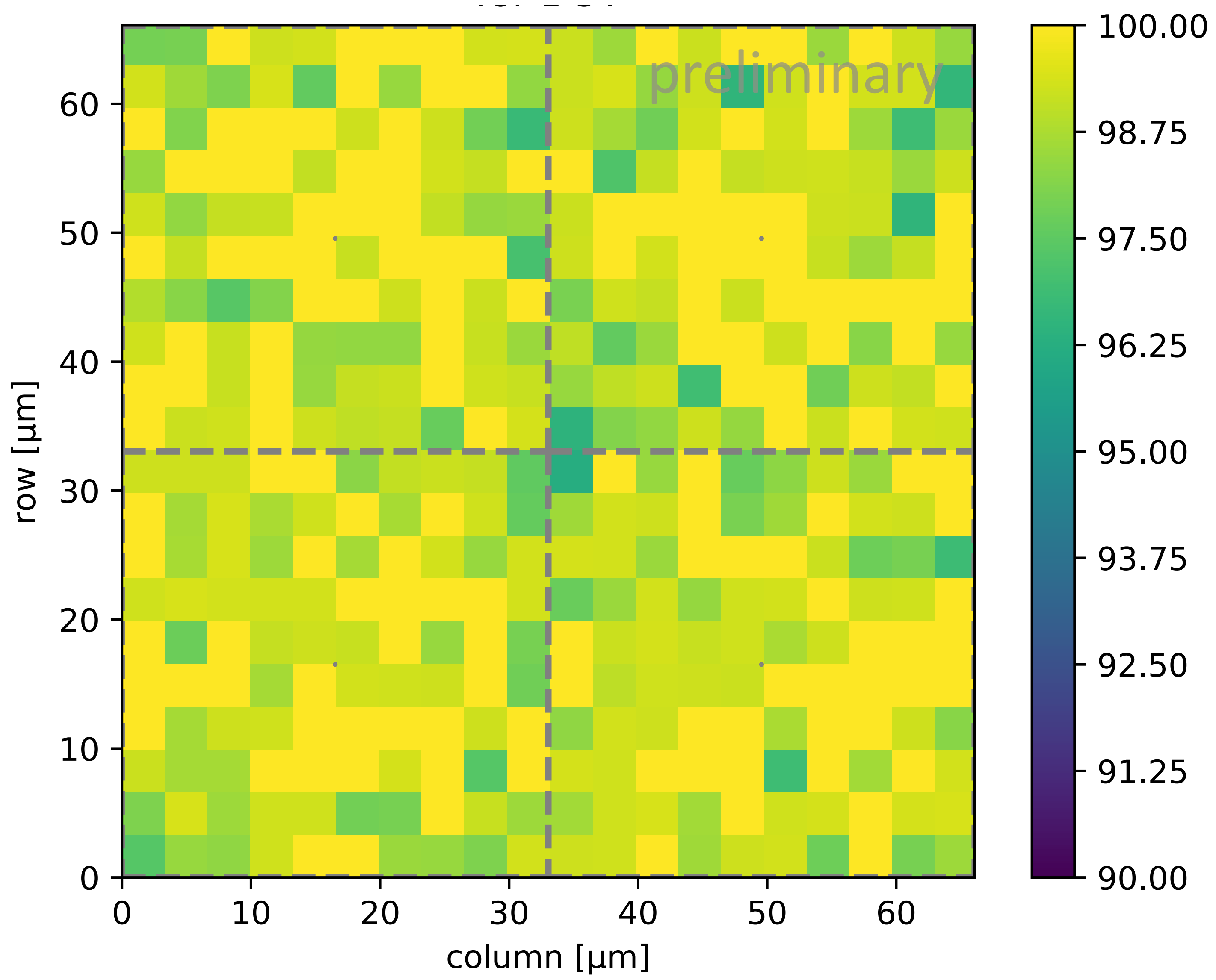




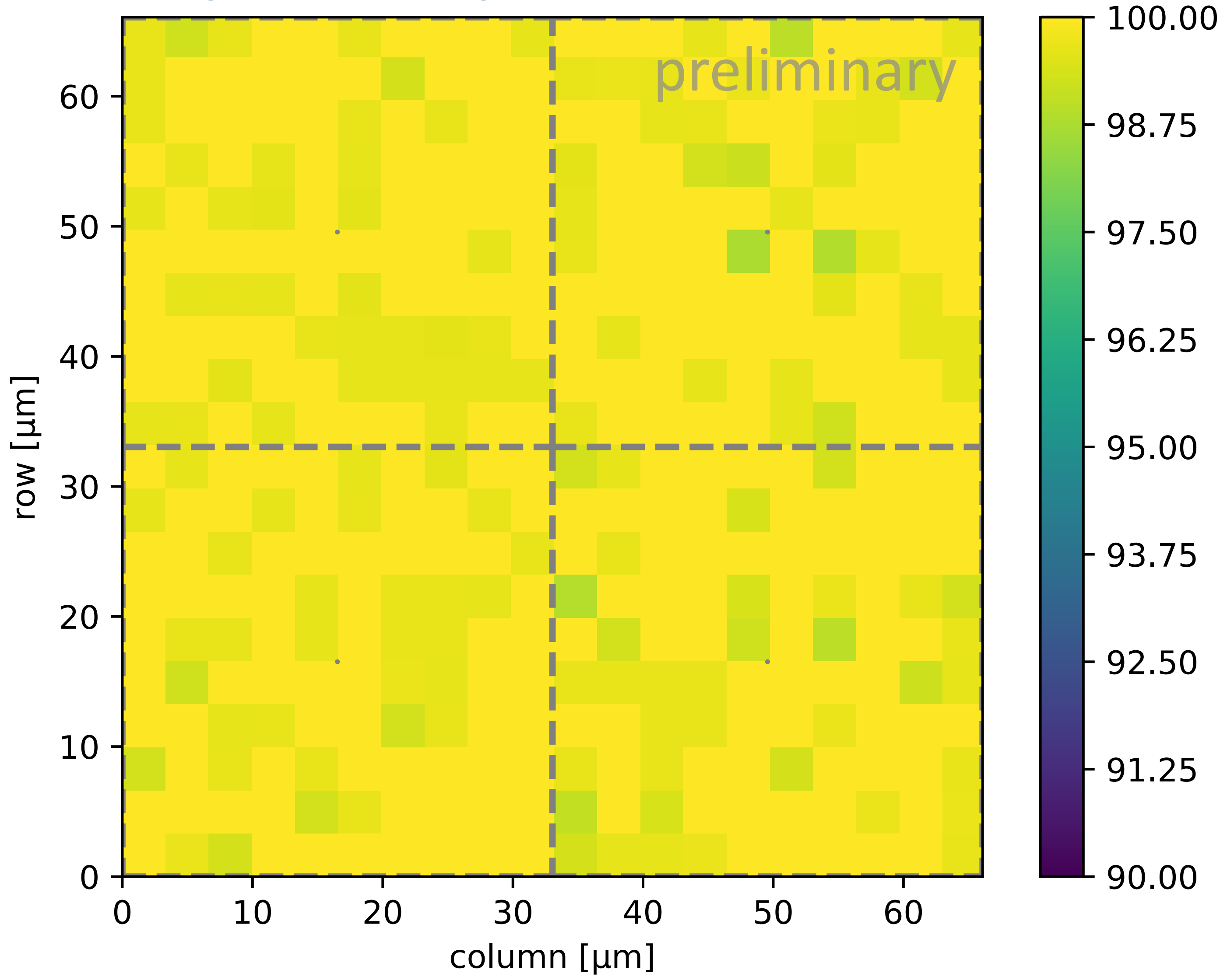
TJ-MONOPIX2 EFFICIENCY (HV)

- 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)

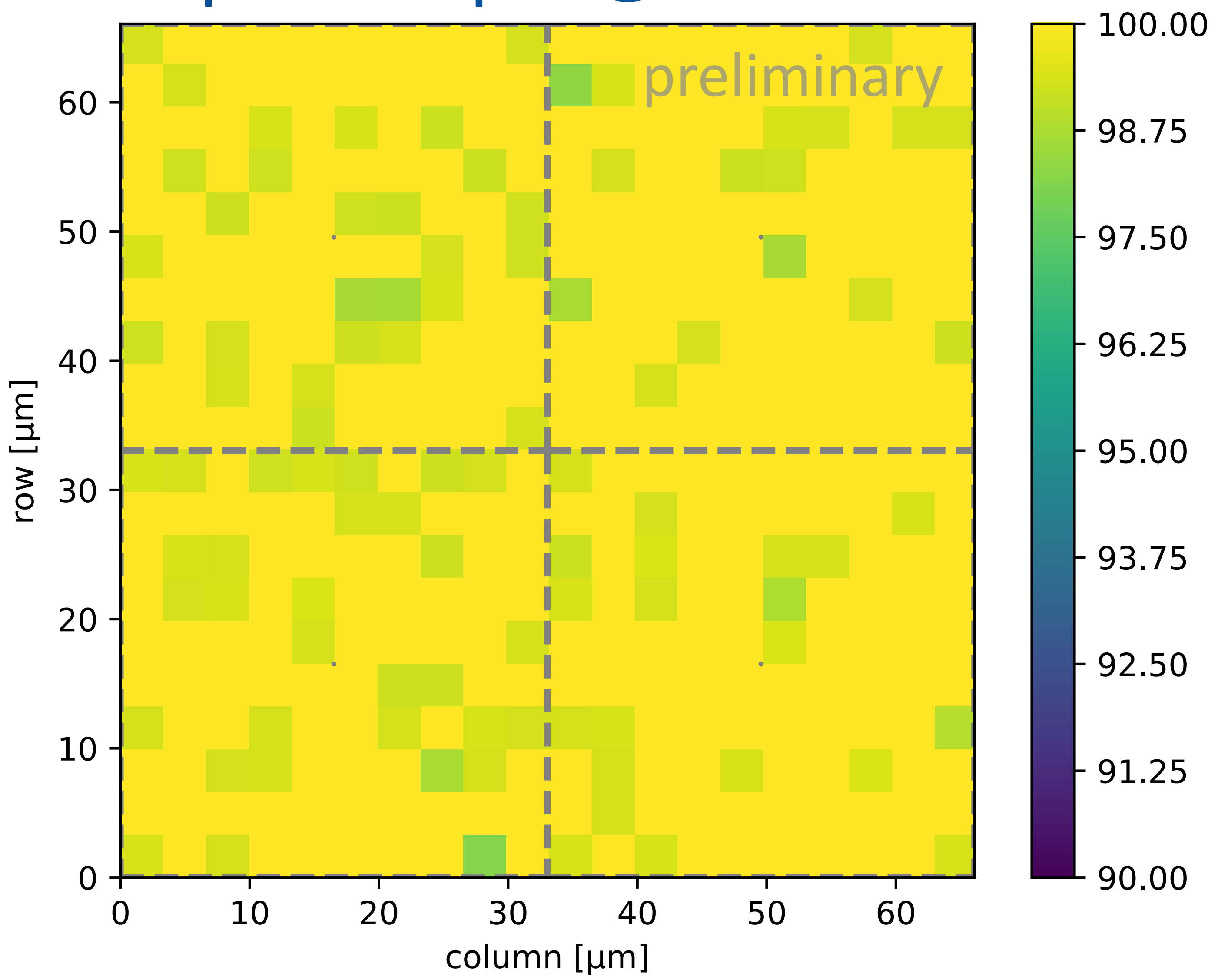
100 µm sample @ 5 V: 99.21 %



100 µm sample @ 25 V: 99.85 %



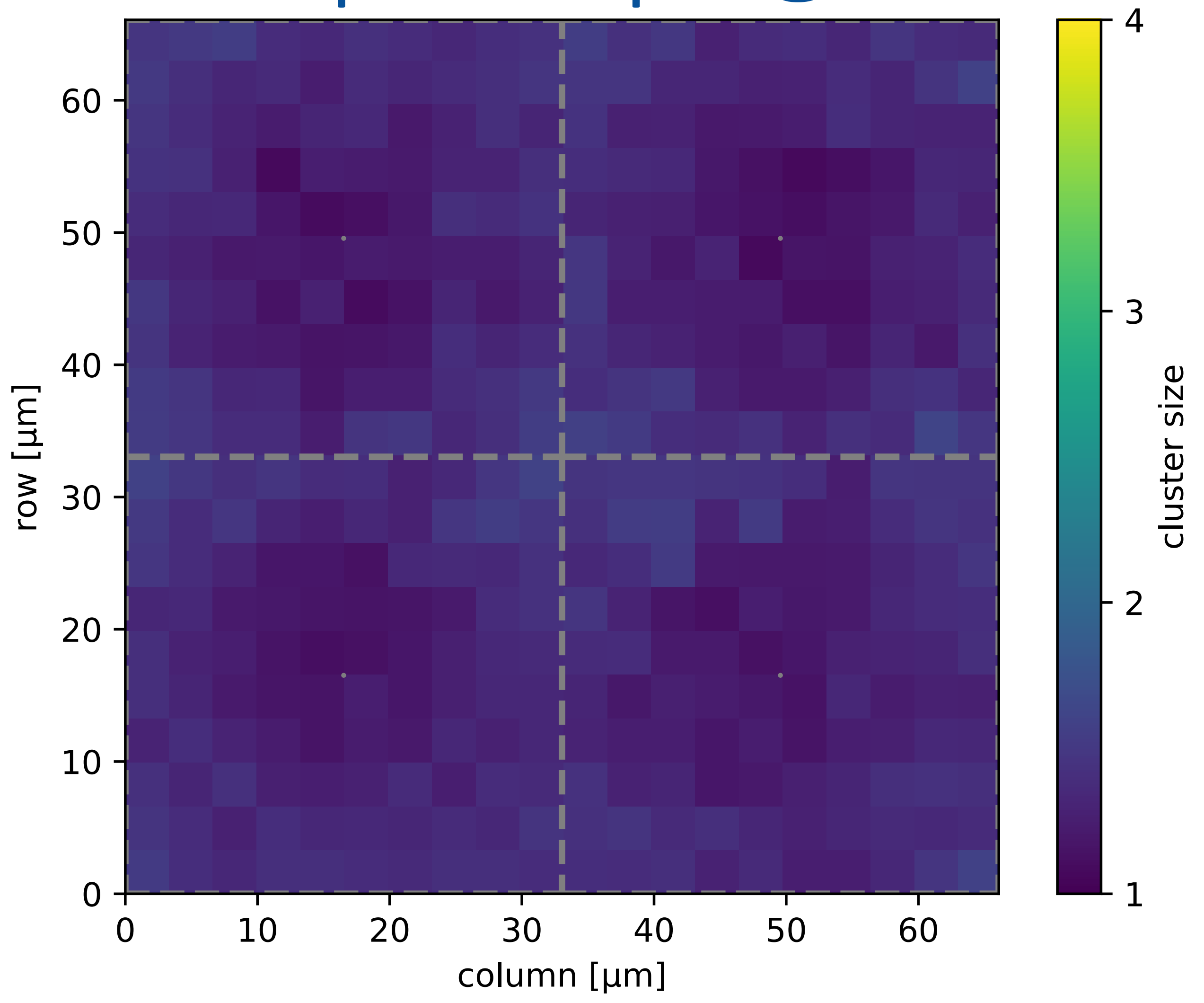
100 µm sample @ 50 V: 99.82 %



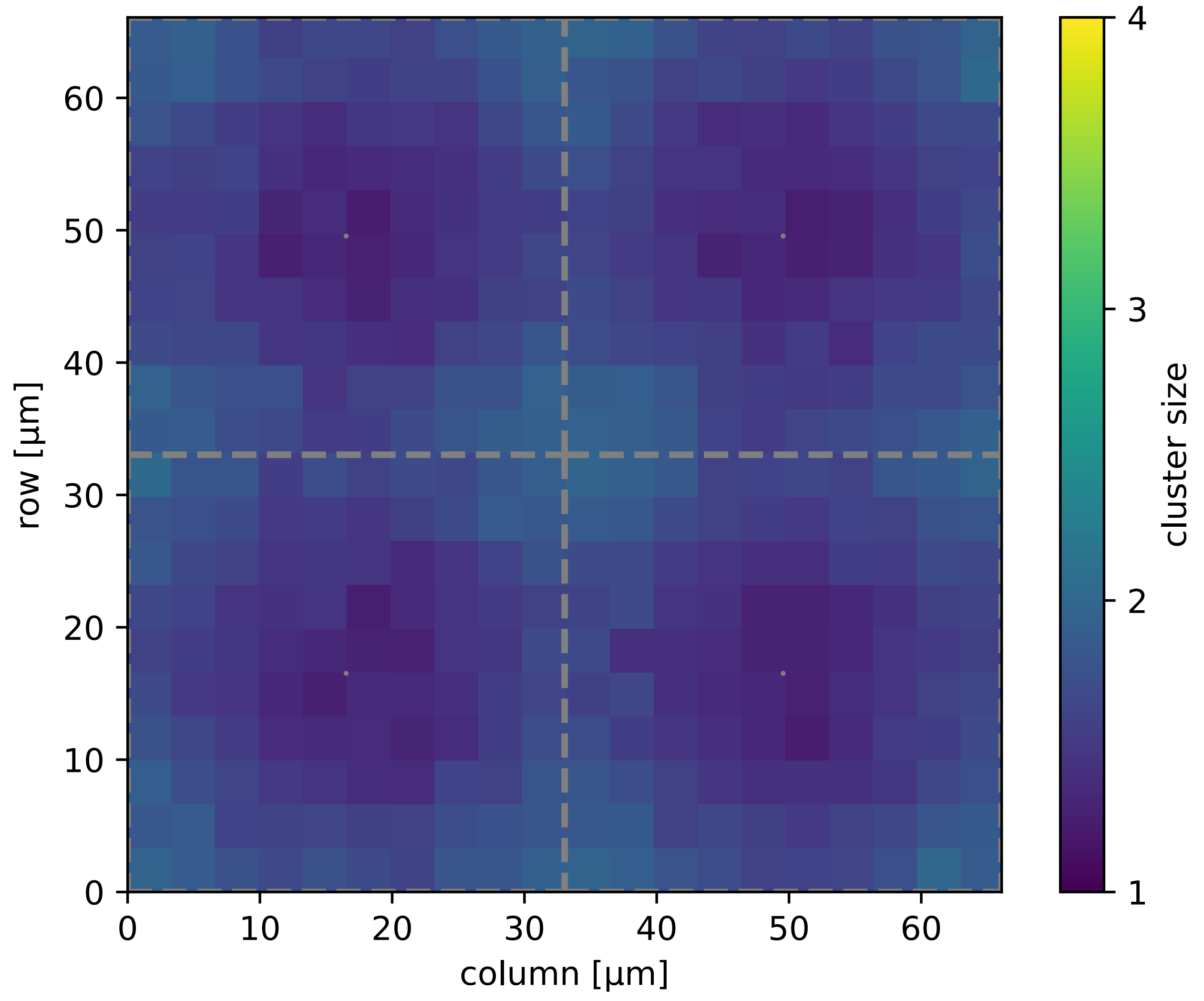
TJ-MONOPIX2 CLUSTER SIZE (HV)

- 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)

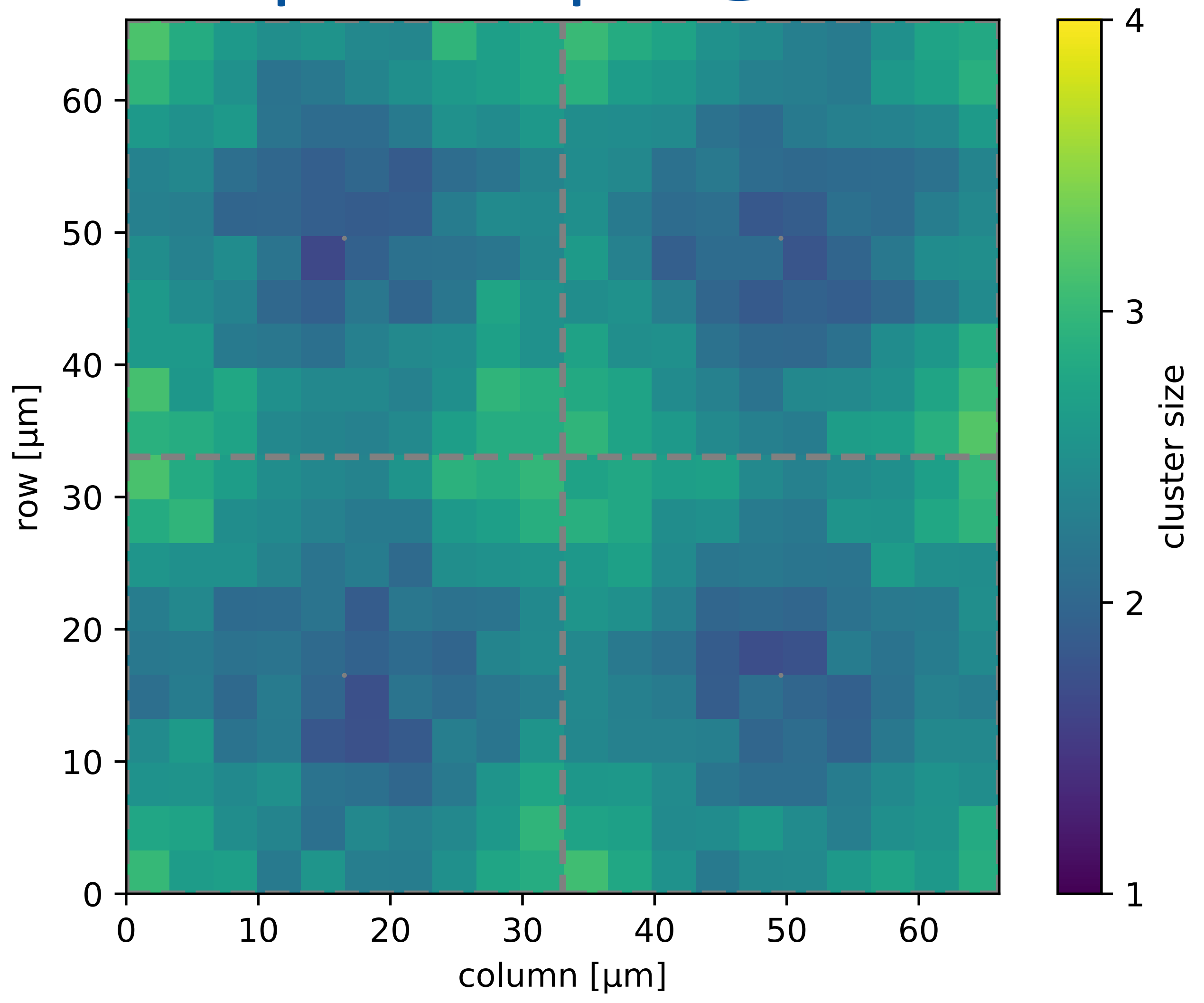
100 µm sample @ 5 V



100 µm sample @ 25 V

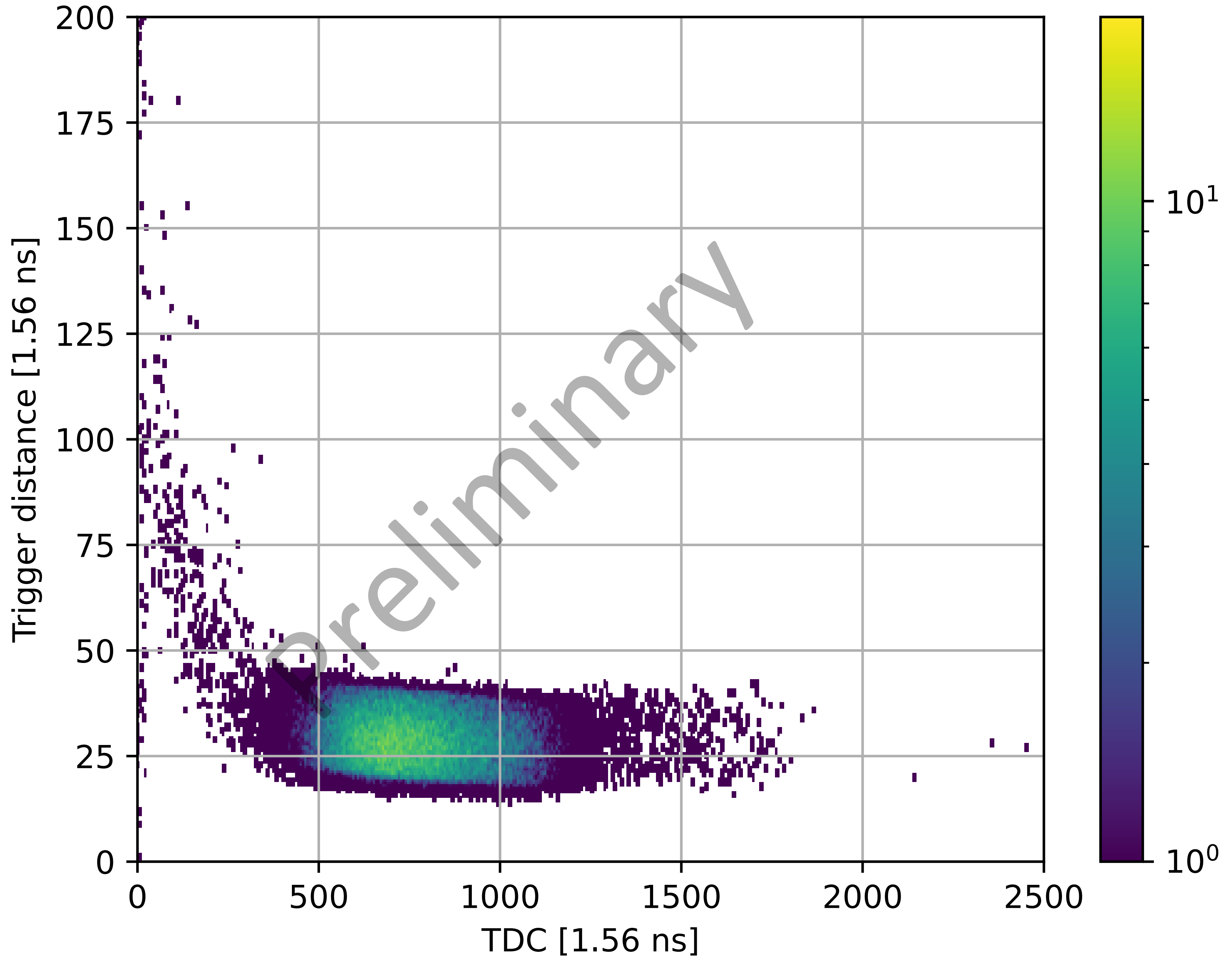


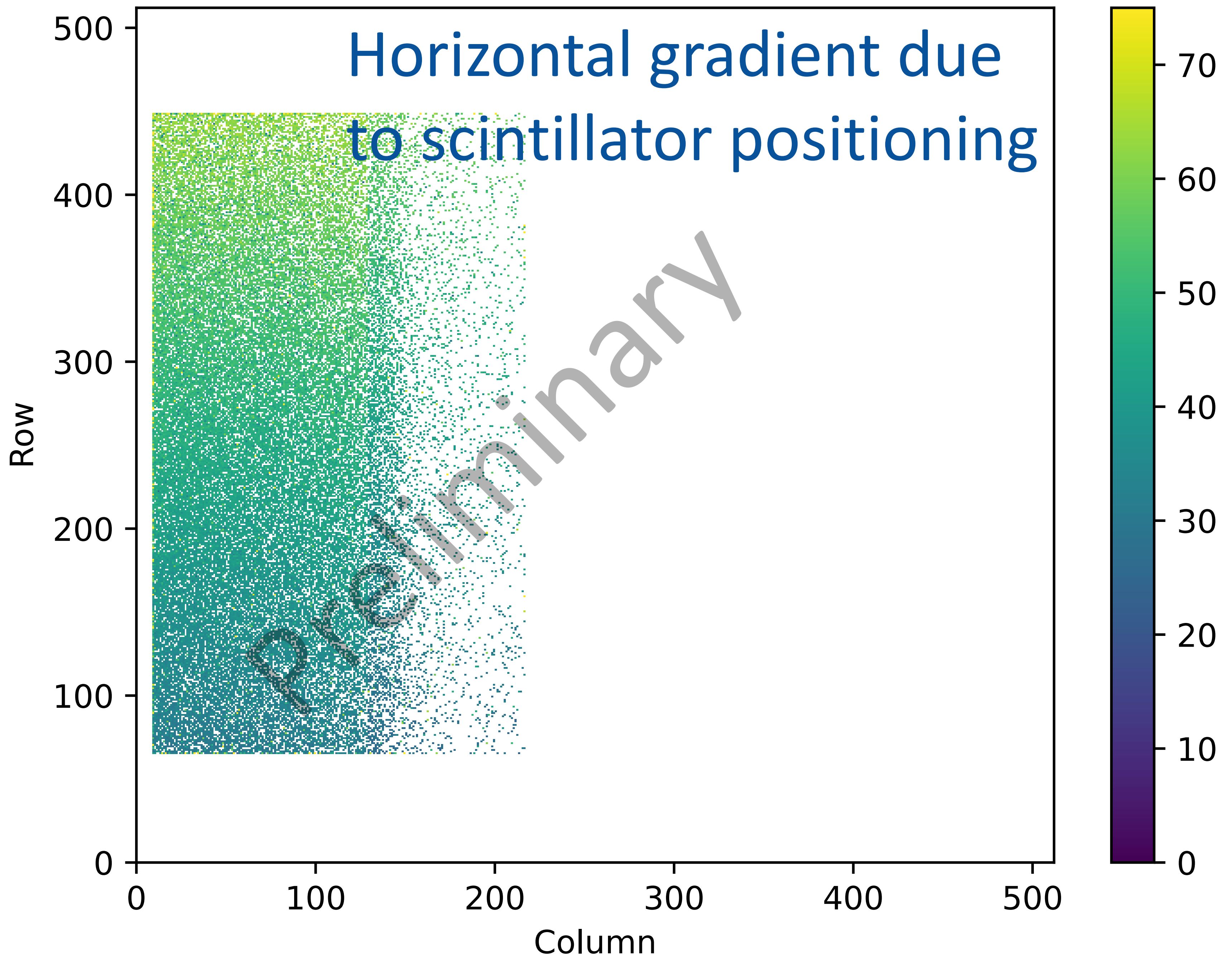
100 µm sample @ 50 V



PRELIMINARY TIMING STUDIES

- Recent beam test at DESY (03/2023)
- Measure time between scintillator hit and HITOR word from in-pixel discriminator
- Time distribution surprisingly wide, but large delay along column observed -> under investigation





SUMMARY / OUTLOOK

- Fully working DMAPS with column-drain readout in 2 cm long columns
- 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
- Detailed C_{inj} calibration ongoing
- Analysis of latest beam test data for bias voltage dependency and timing ongoing
- Chips sent for neutron irradiation, test in beam planned for later this year

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).

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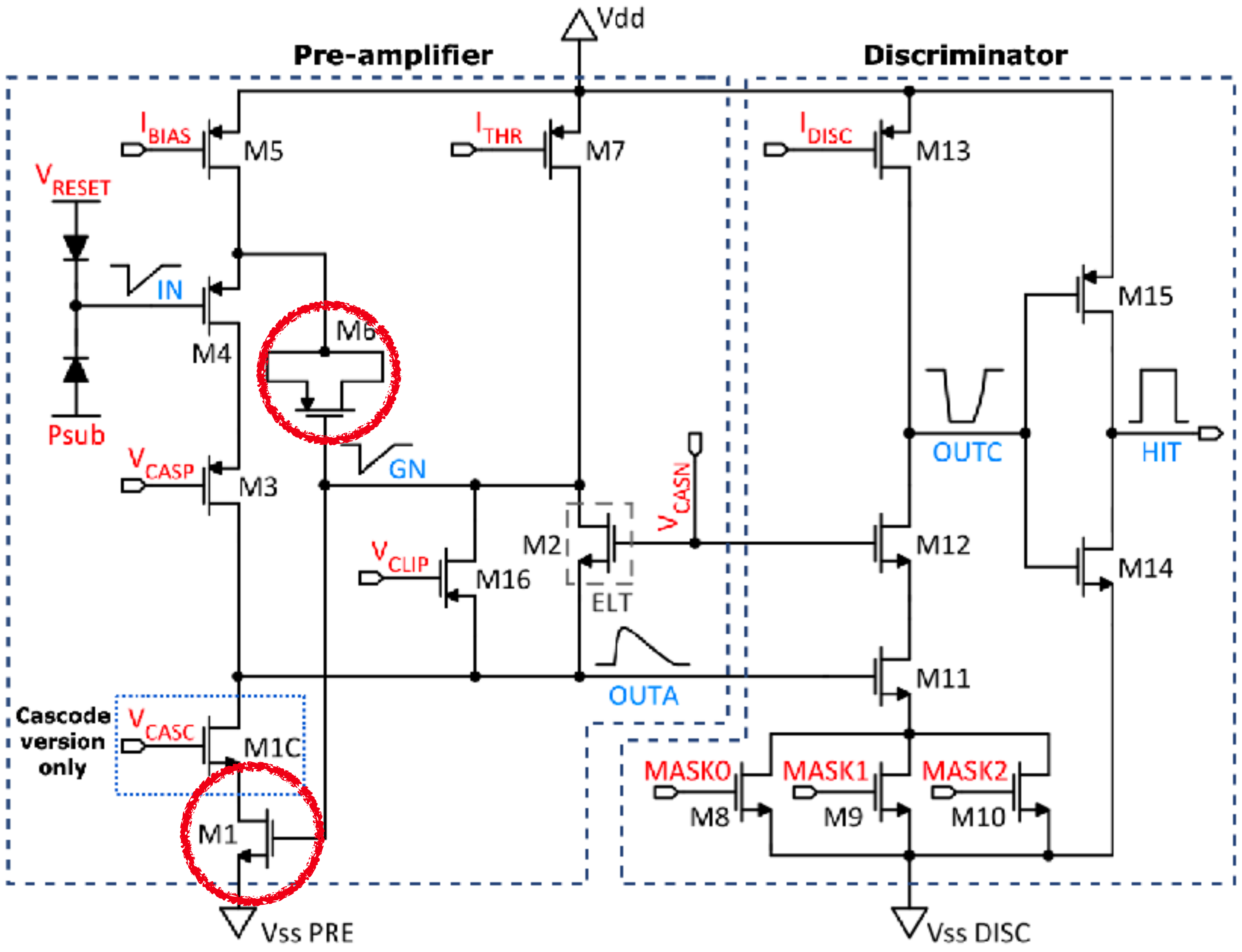
BACKUP

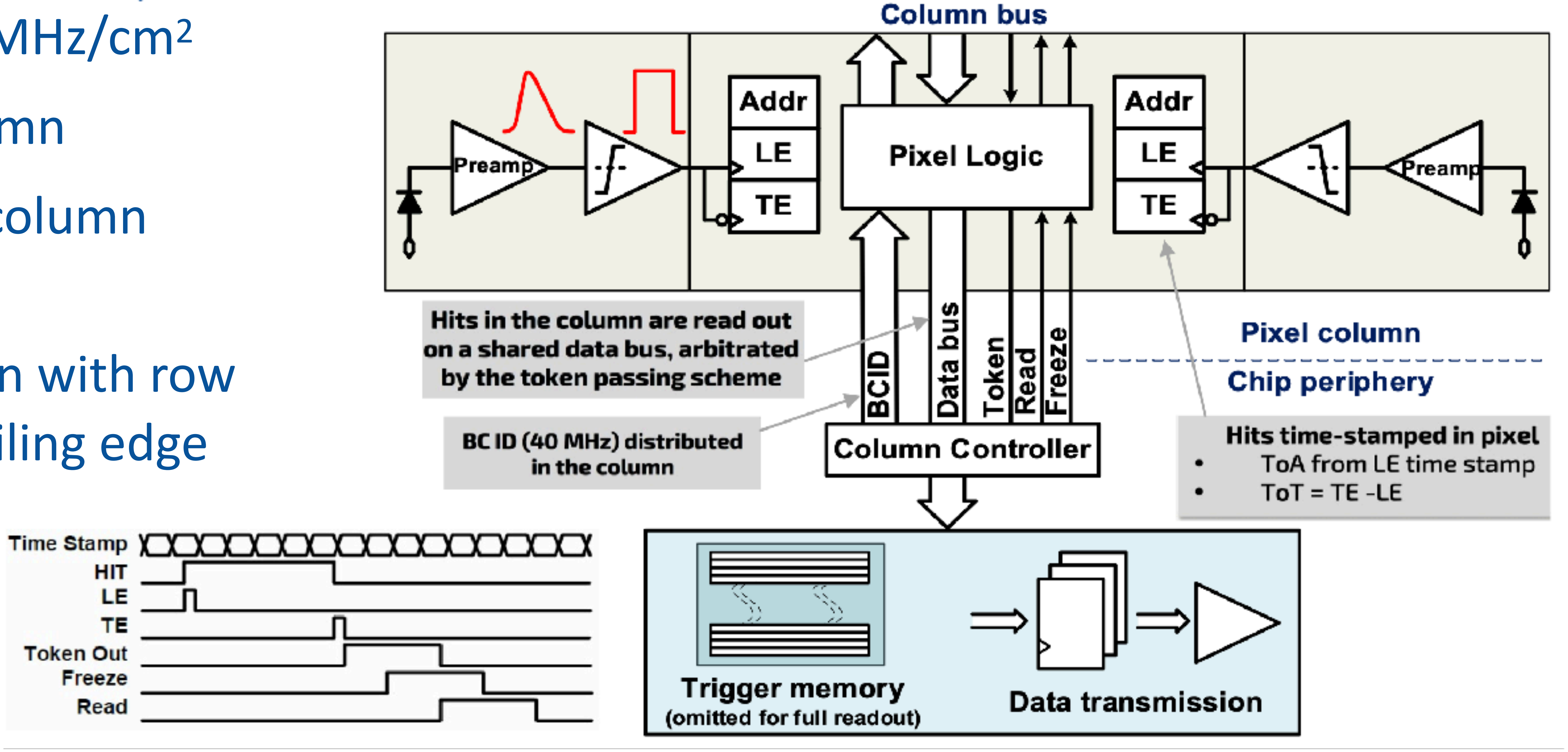
TJ-MONOPIX2 FRONT-END

- Increased size of M1 (and also M6) increases the gain and effectively decreases ENC which in turn allows for lower thresholds
- M6 is coupling capacitor, area increased by factor 7.5 for better coupling to GN node (gain stage input)
- Impedance matching M1 (output) to M2 (input)
- ENC reduced by factor 2 (by simulation)
- Gain at threshold increased by factor 3 (again sim)



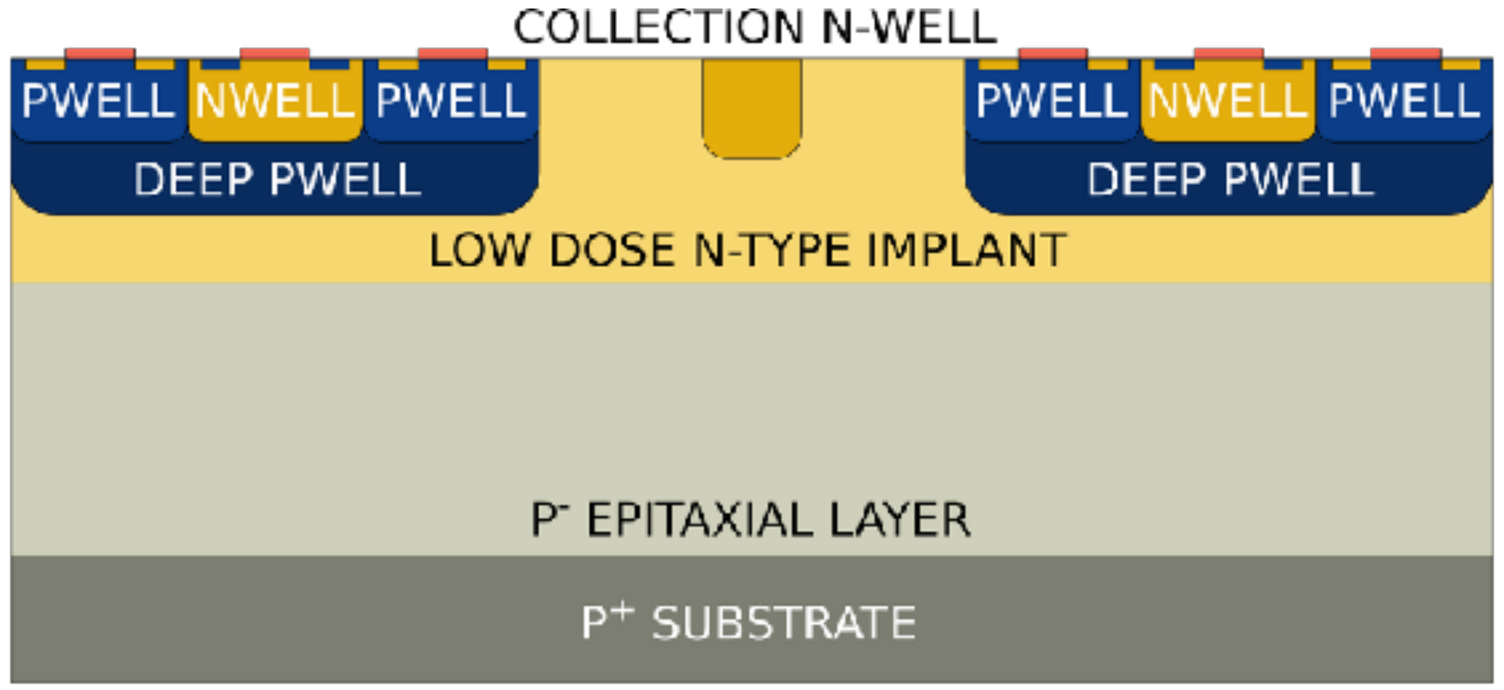
COLUMN DRAIN READOUT

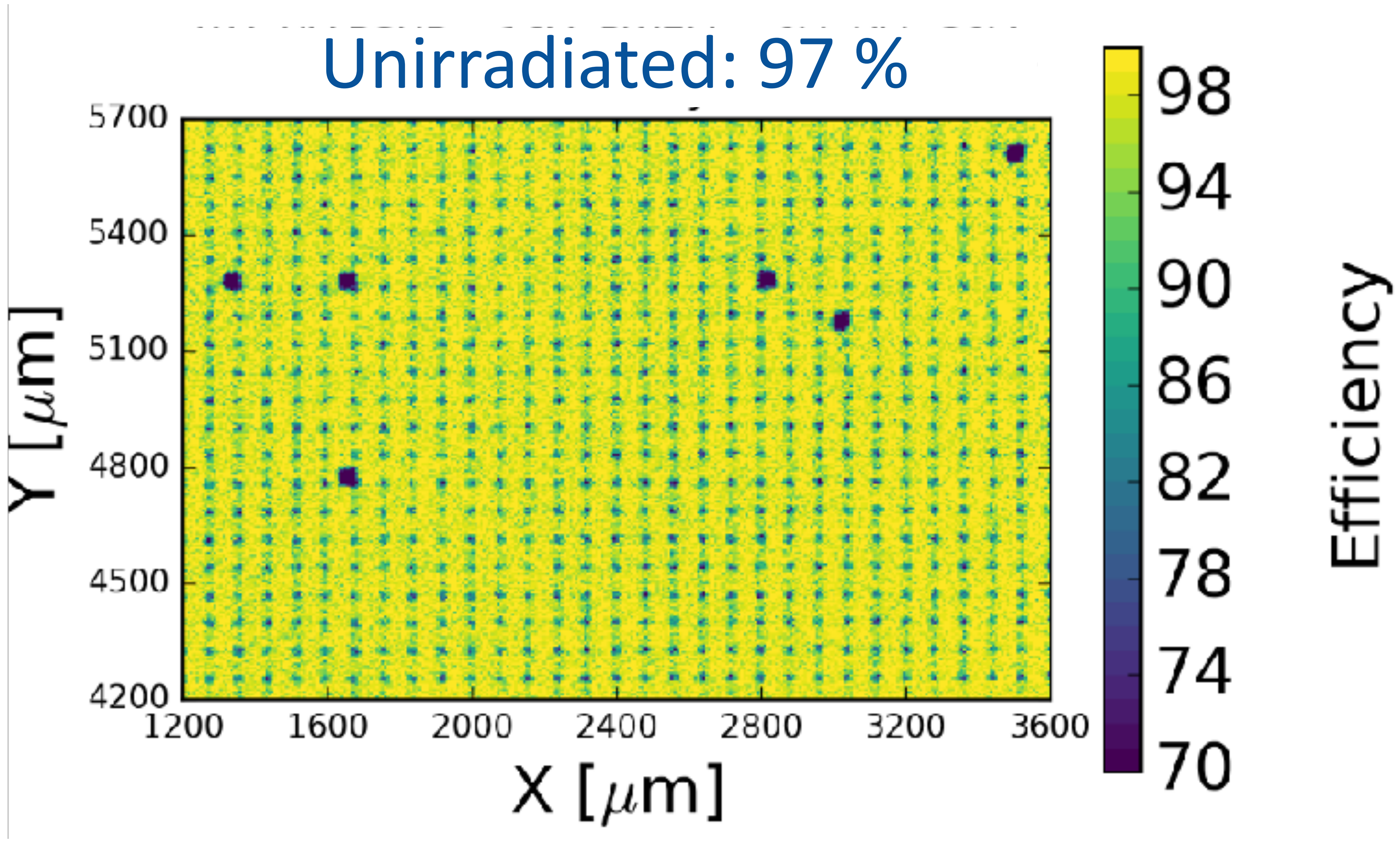
- Derived from ATLAS FE-I3 readout chip
- Rate capabilities around 100 MHz/cm^2
- Token propagation along column
- Readout controller at end of column (READ, FREEZE to pixels)
- Data propagated along column with row address, leading edge and trailing edge
- Periphery merges data from one TOKEN signal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

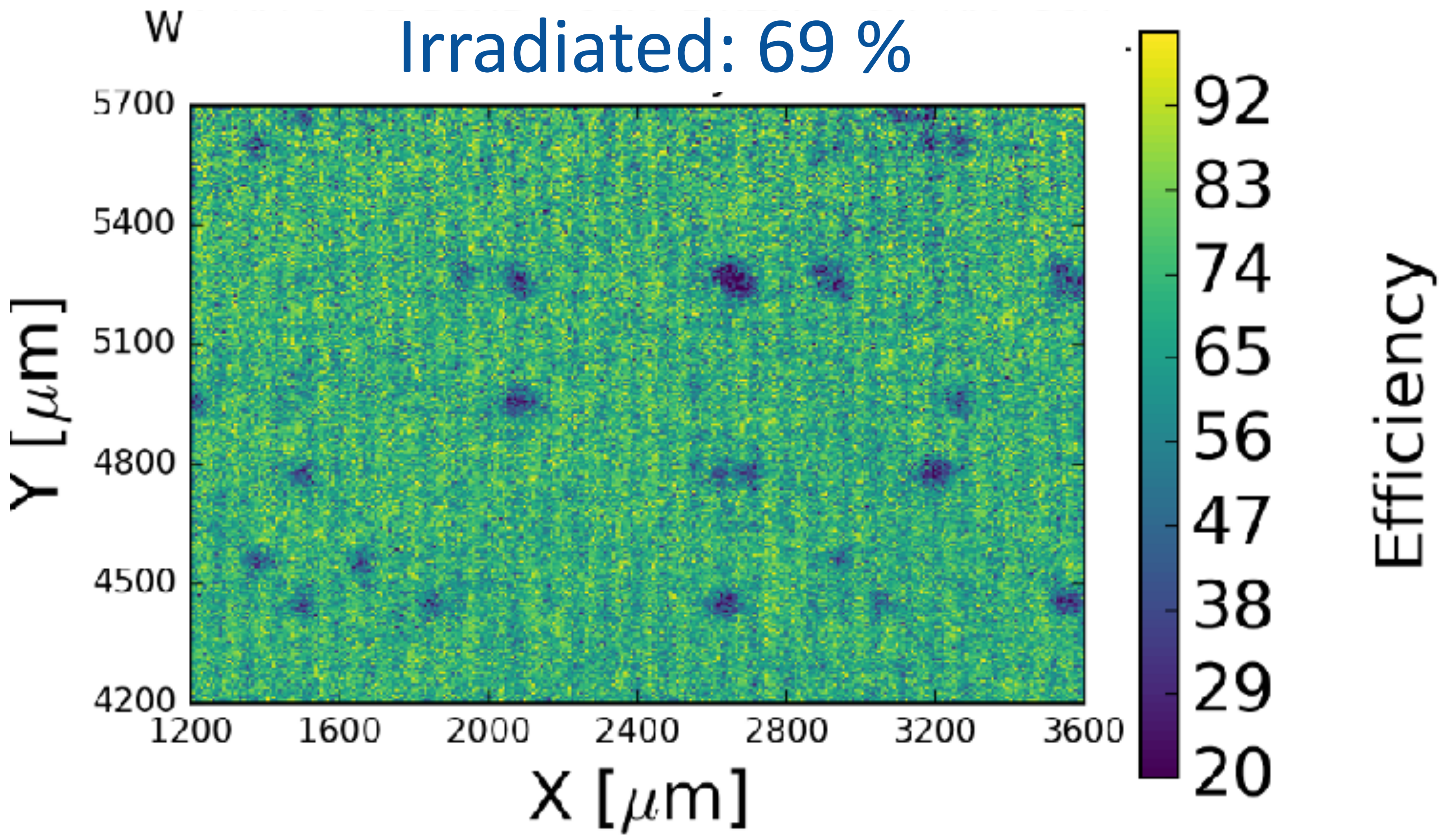


TJ-MONOPIX1 EFFICIENCY

- Significant efficiency loss after irradiation to < 70 % (at $10^{15}\,\mathrm{neq\,cm^{-2}}$)
- Charge is lost due to E-field shaping under deep pwell -> need another modification besides low dose n-type



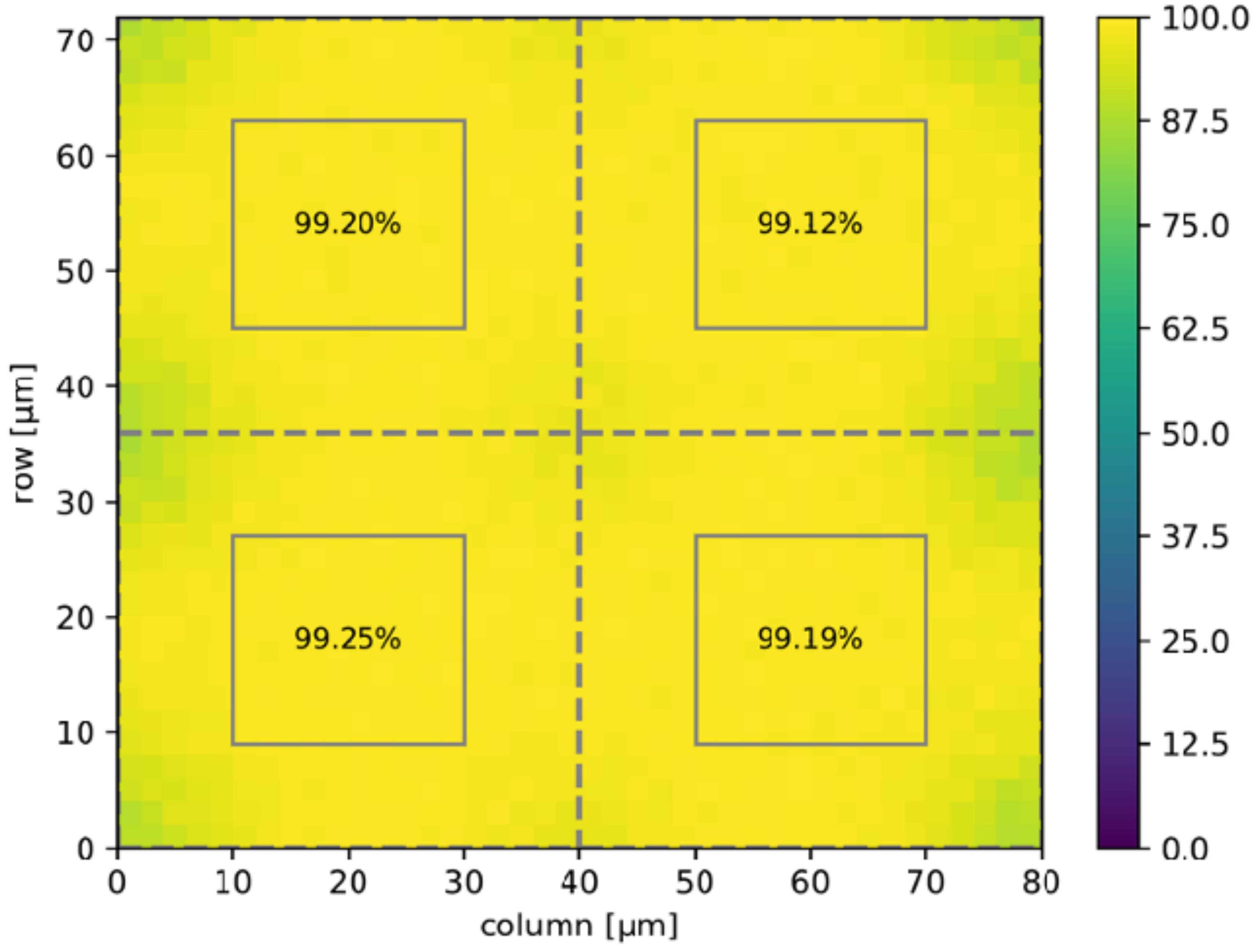




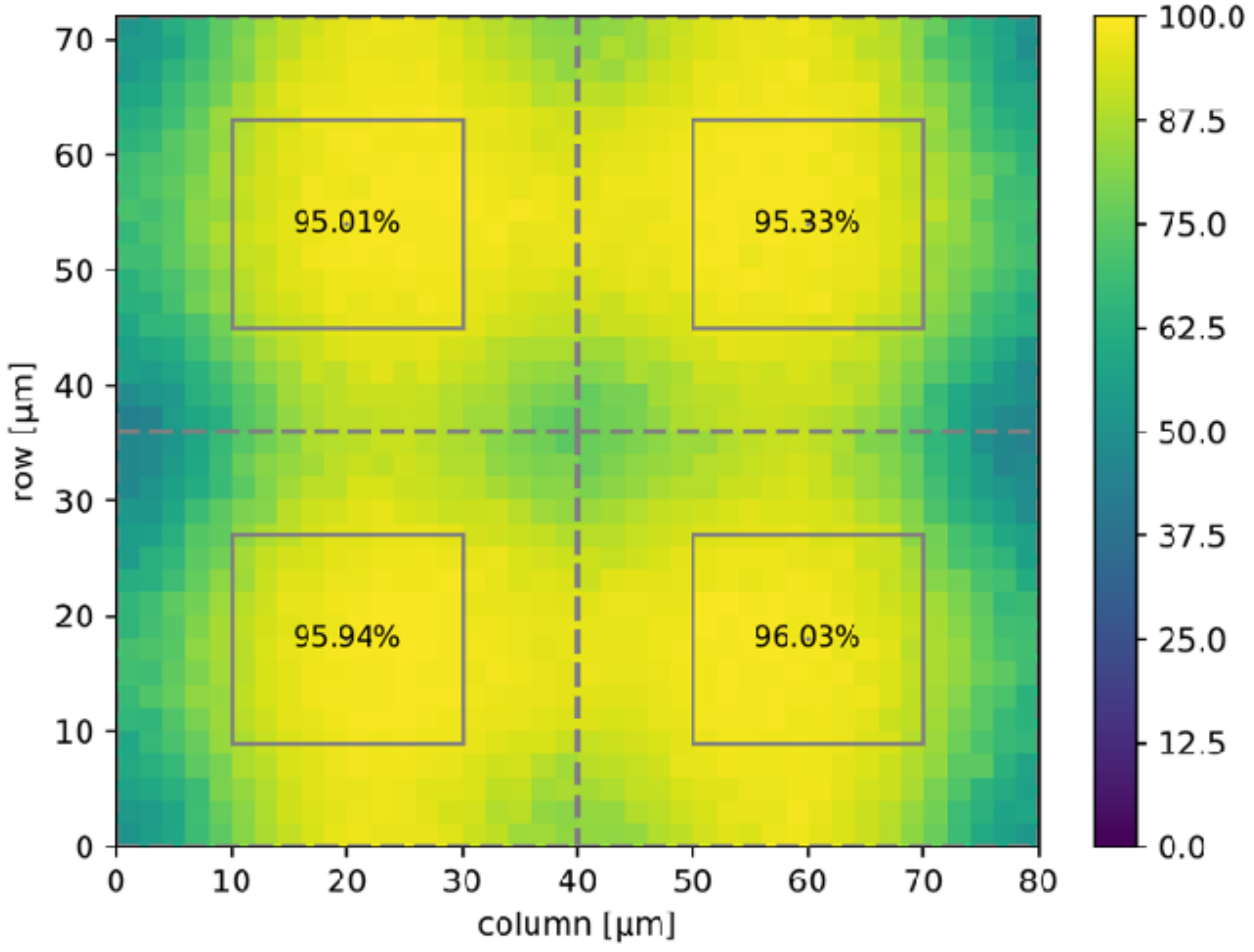
TJ-MONOPIX1 SENSOR MODS

- Measured $10^{15}\,\mathrm{neq\,cm^{-2}}$ irradiated chips in 5 GeV electron beam at DESY
- Efficiency improvement in epi chip from 69 % to 87 % due to sensor modifications
- More sensitive volume and more charge in Cz leads to full efficiency after irradiation

300 µm Cz: 98.6 % @ 490 e-

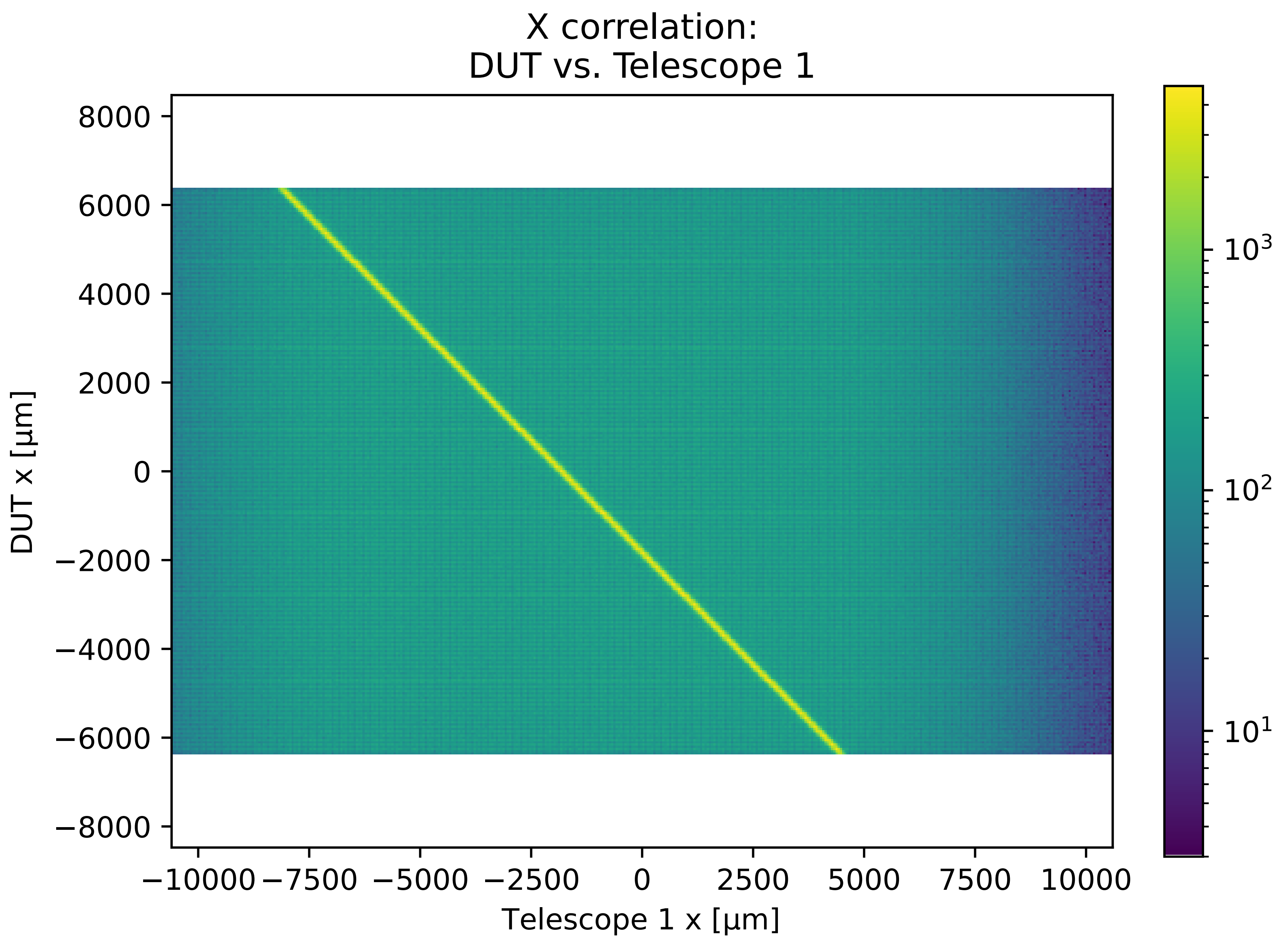


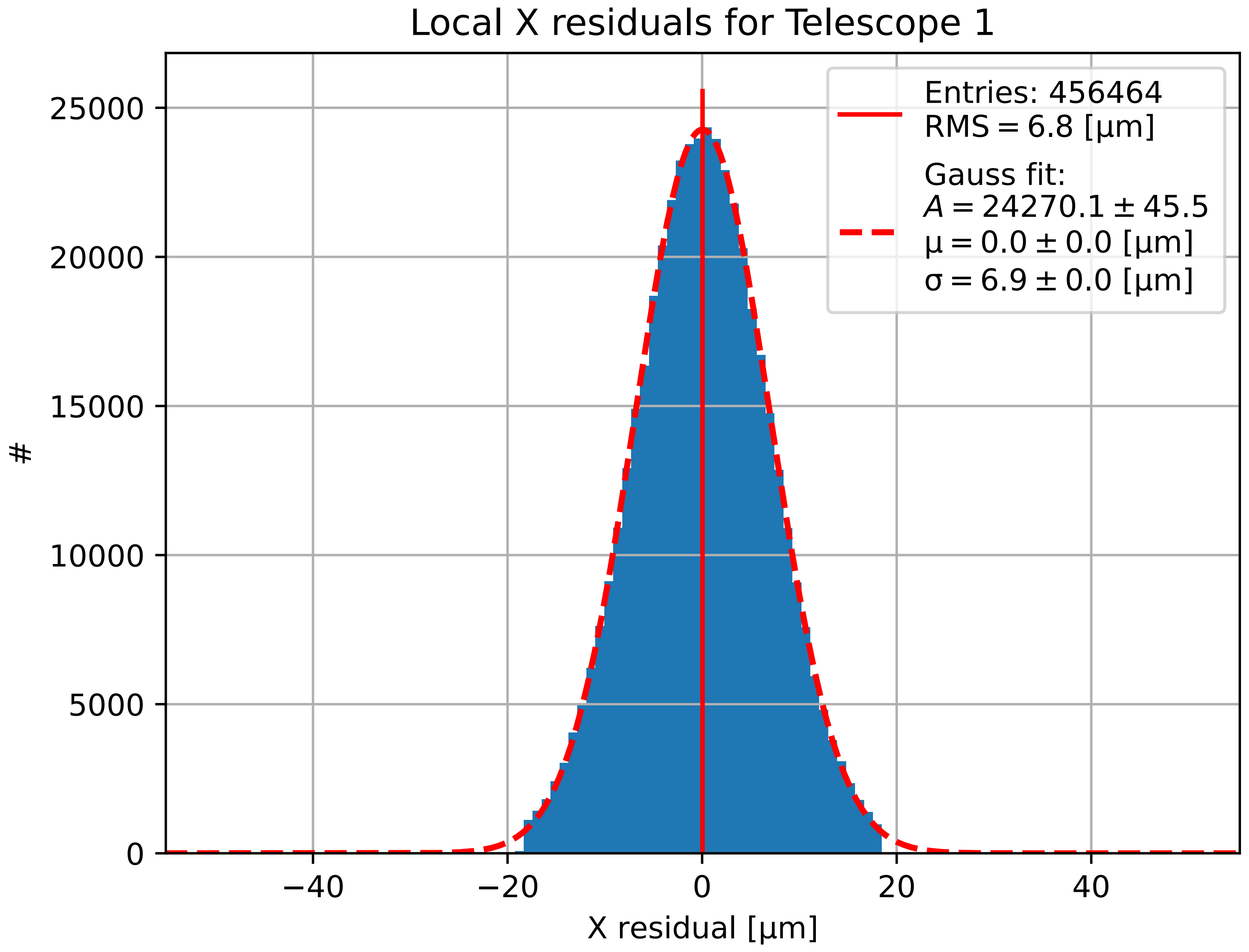
30 µm Epi: 87.1 % @ 500 e-

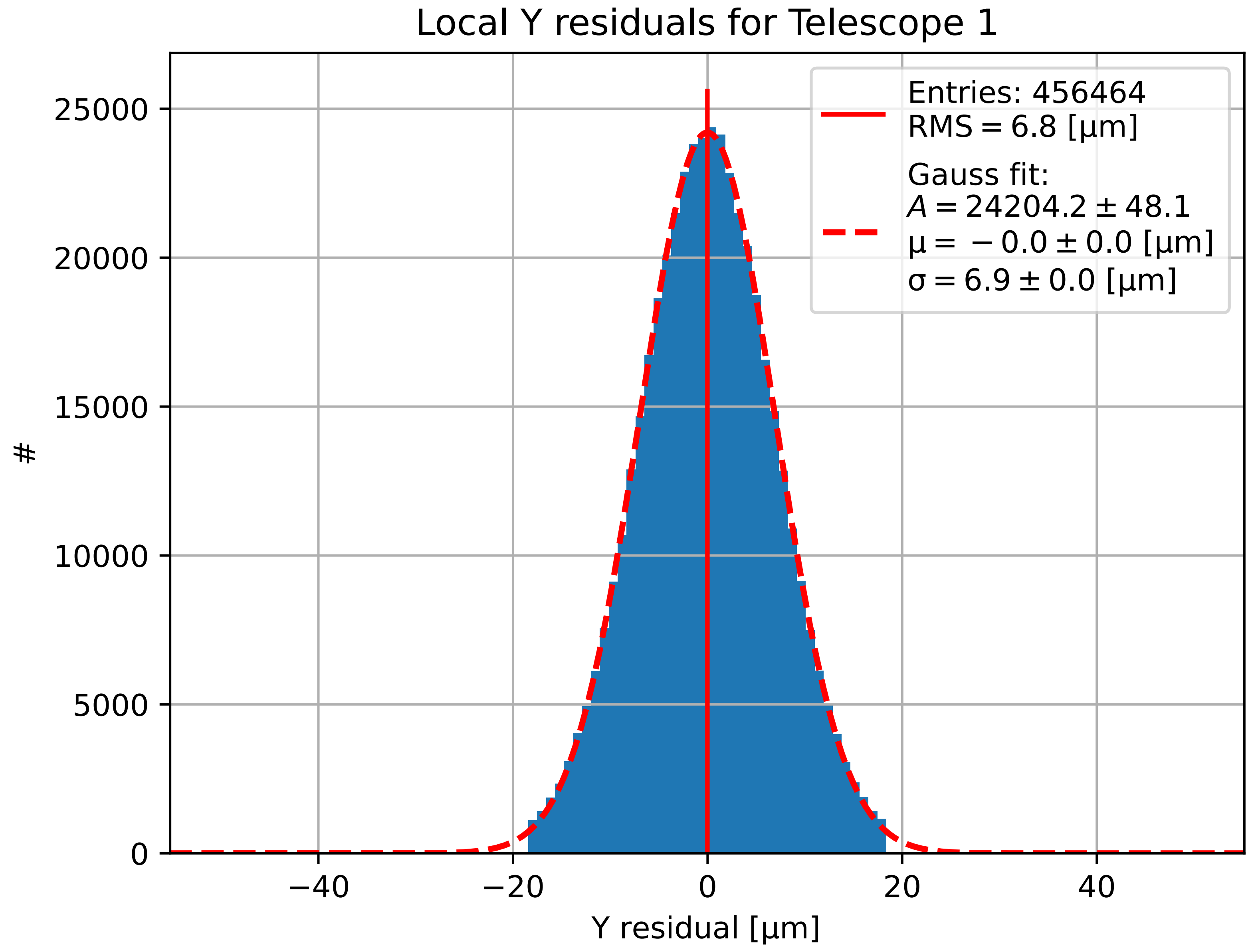


TJ-MONOPIX2 BEAM TESTS

- 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-MONOPIX DESIGN SPECS

	ALICE LHC	ATLAS HL-LHC		Belle II SuperKEKB
		Outer	Inner	
Time resolution [ns]	20 000	25	25	(100)
Particle rate [kHz / mm^2]	10	1000	10 000	1500
Fluence [neq cm^{-2}]	> 10^{13}	10^{15}	2 x 10^{16}	10^{14}
Ion. Dose [MRad]	0.7	50	> 1000	100

Design specification for rad-hard DMAPS

DMAPS potential candidate