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STATUS AND PROGRESS TJ-MONOPIX2

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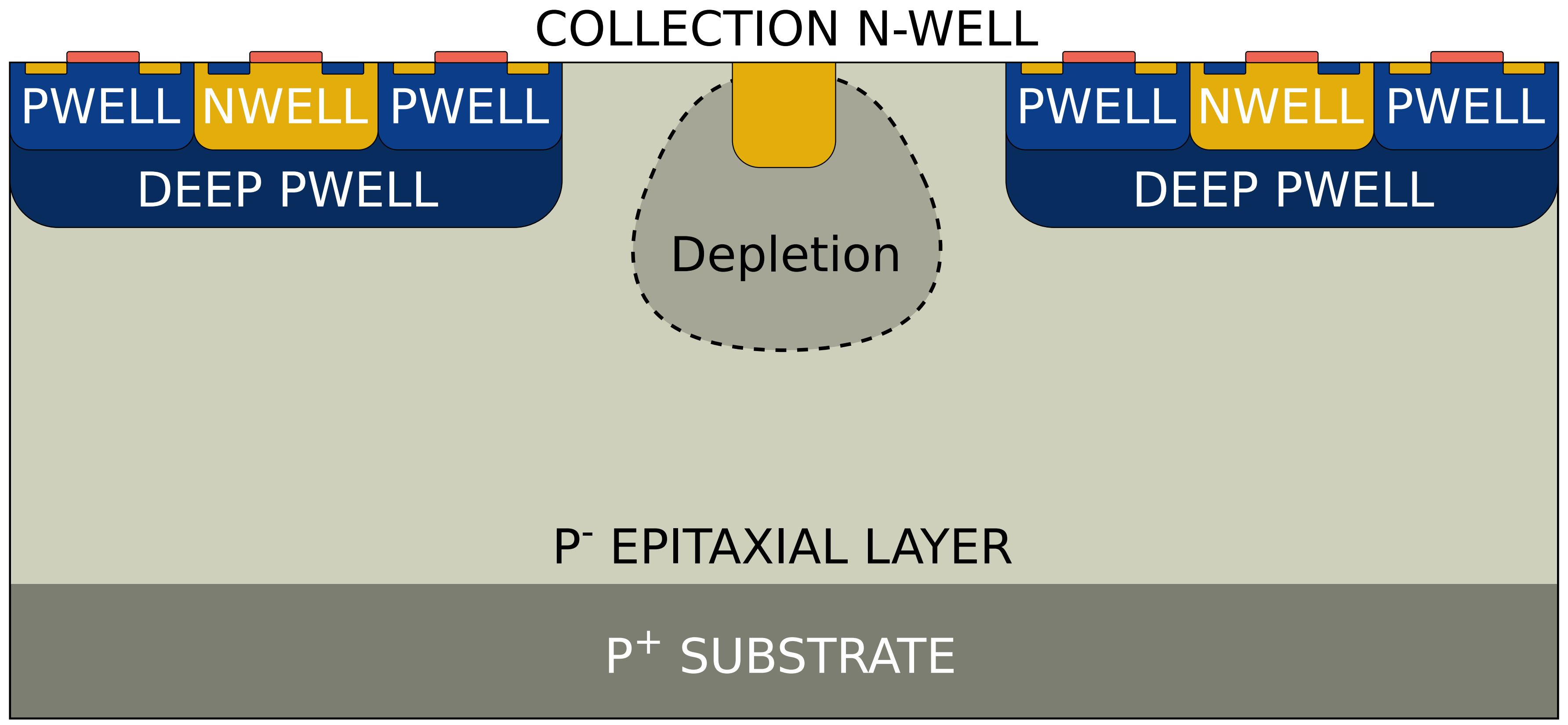
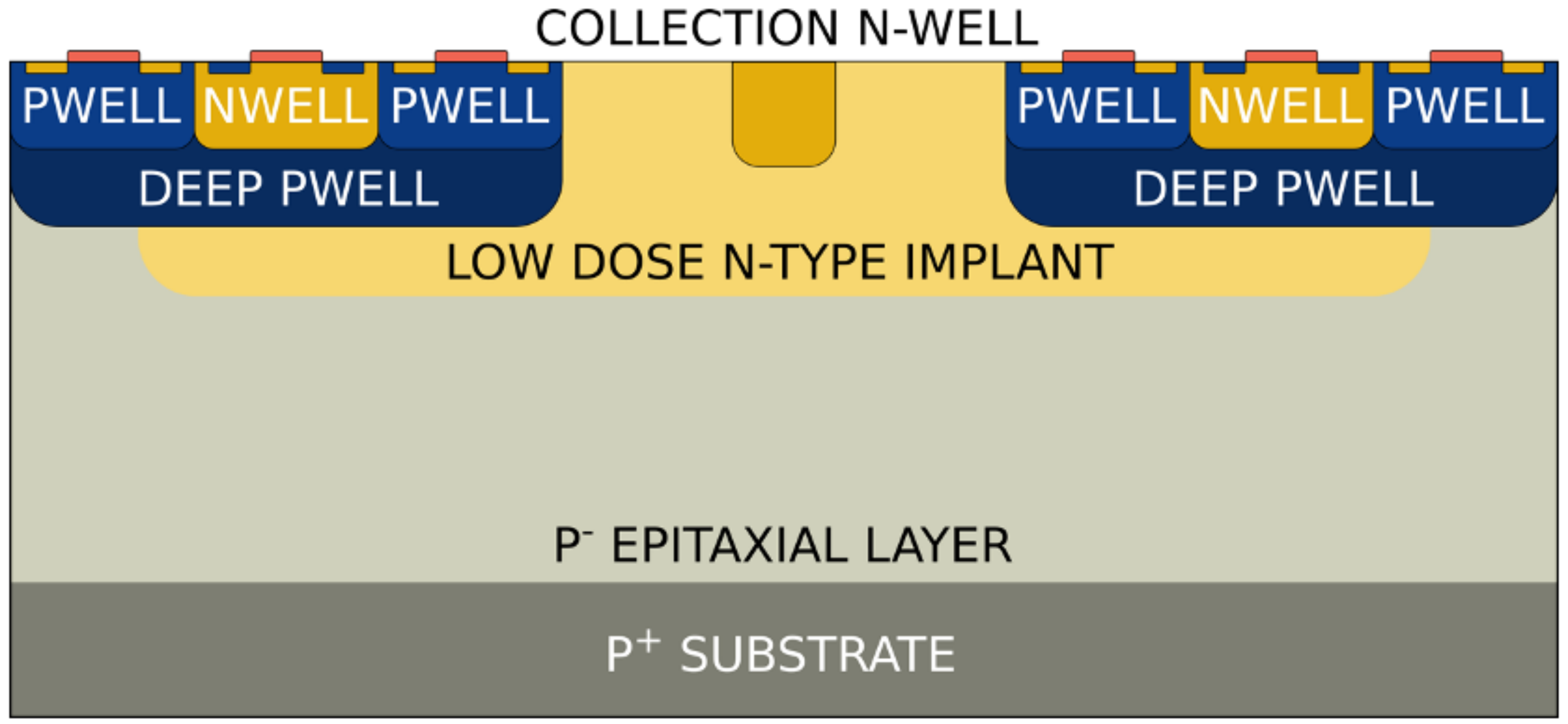
TJ-MONOPIX DESIGN

- 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



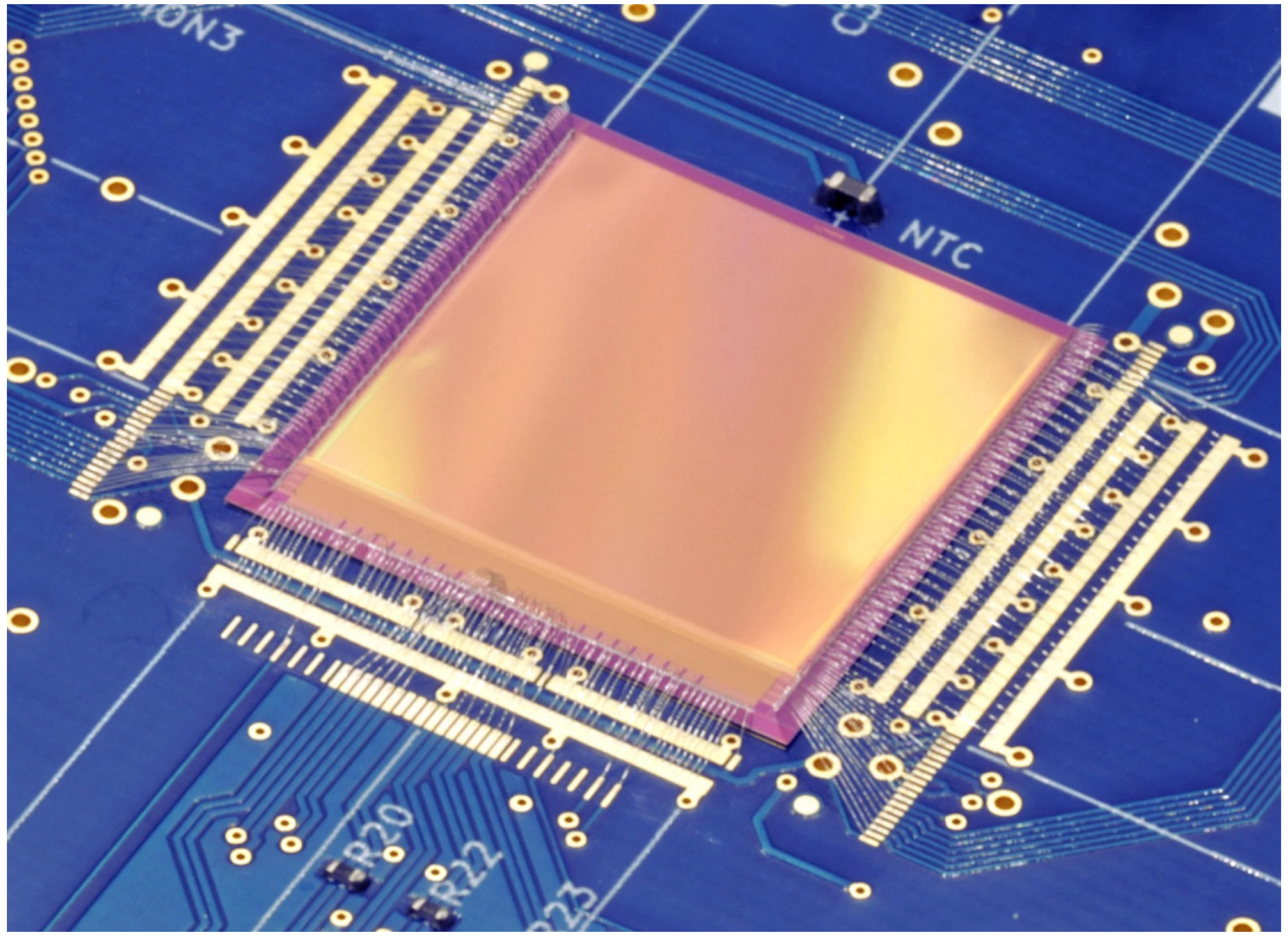
Standard MAPS cell



Modified process for full depletion (see later for variants)

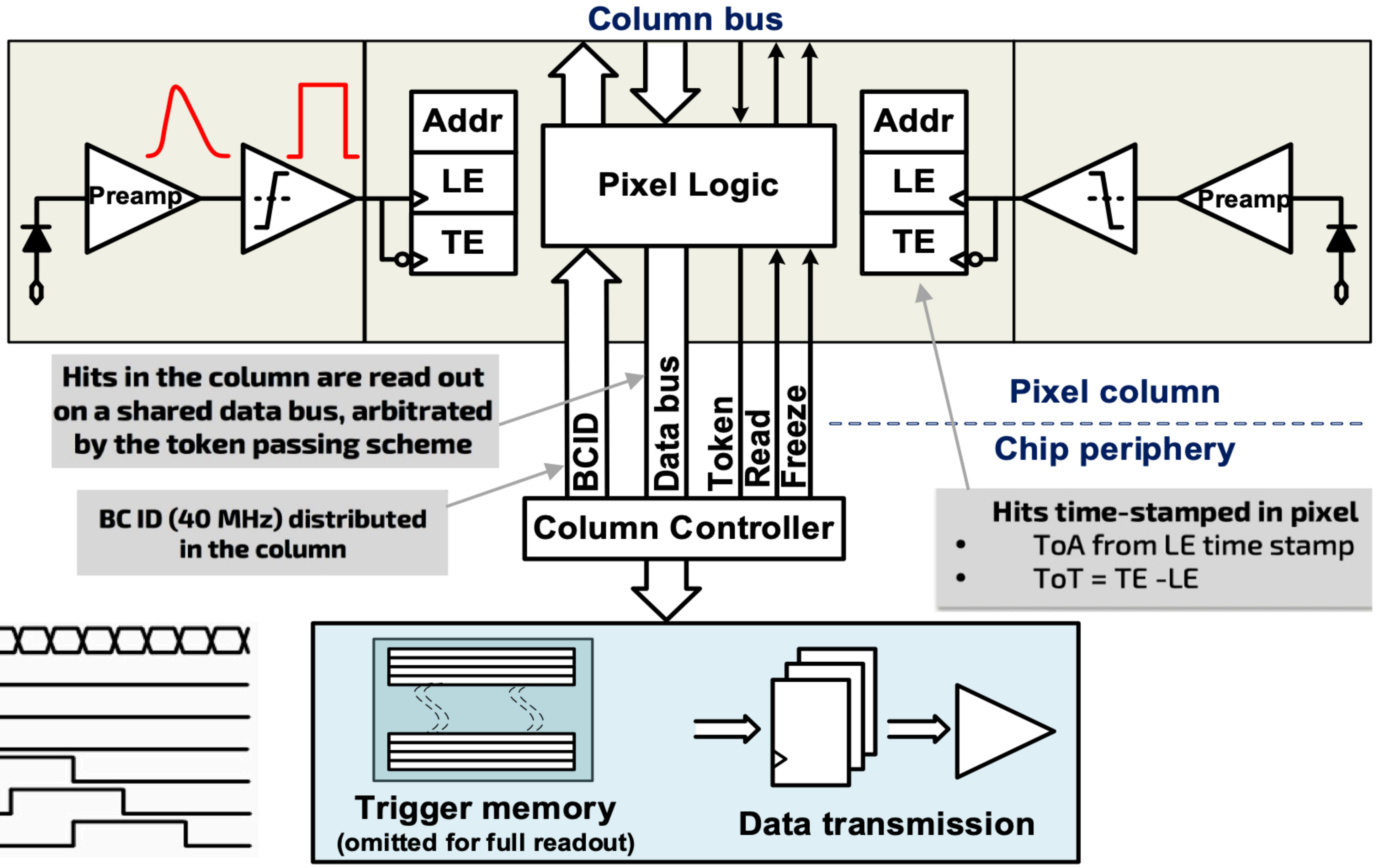
TJ-MONOPIX DESIGN

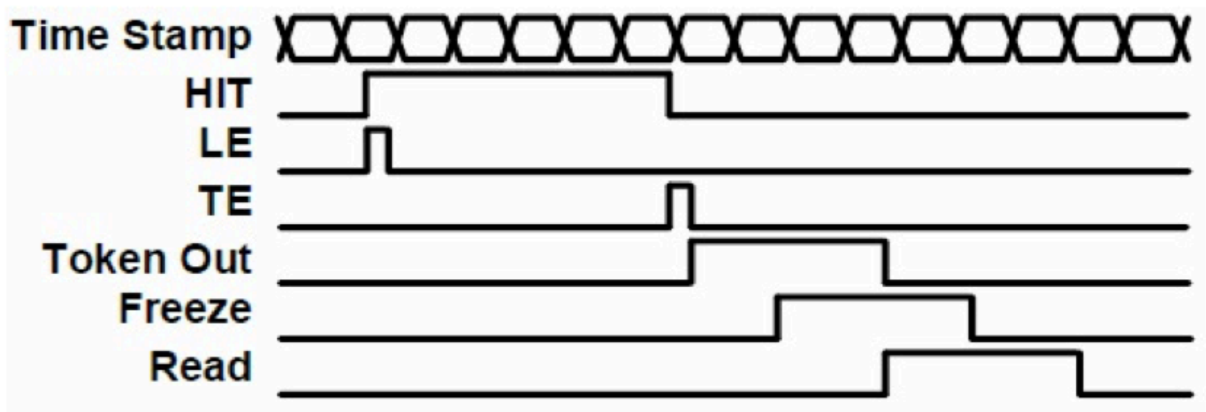
- Designed for ATLAS ITk outer layer specs with column-drain readout like in FE-I3 in a 2 cm column
  - Pixel readout capable of dealing with hit rate > 100 MHz / cm^2
  - Goal: 10^{15} 1 MeV $^{neq}/_{cm2}$ NIEL tolerance and 100 MRad TID
- Latest iteration TJ-Monopix2: 33.04 µm pixel pitch in 512 x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



COLUMN DRAIN READOUT

- Derived from ATLAS FE-I3 readout chip
- Rate capabilities around 100 MHz/cm²
- 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

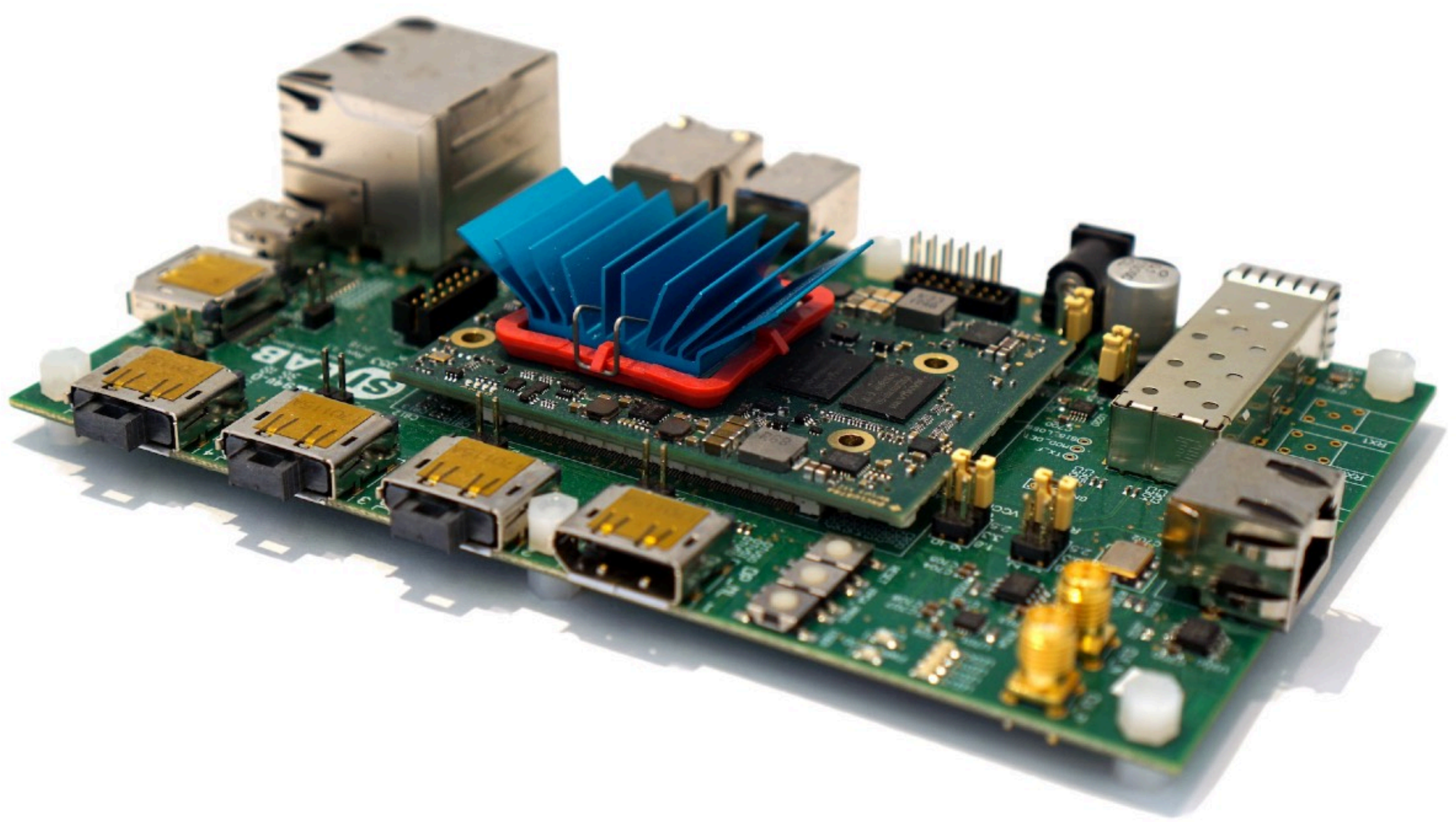


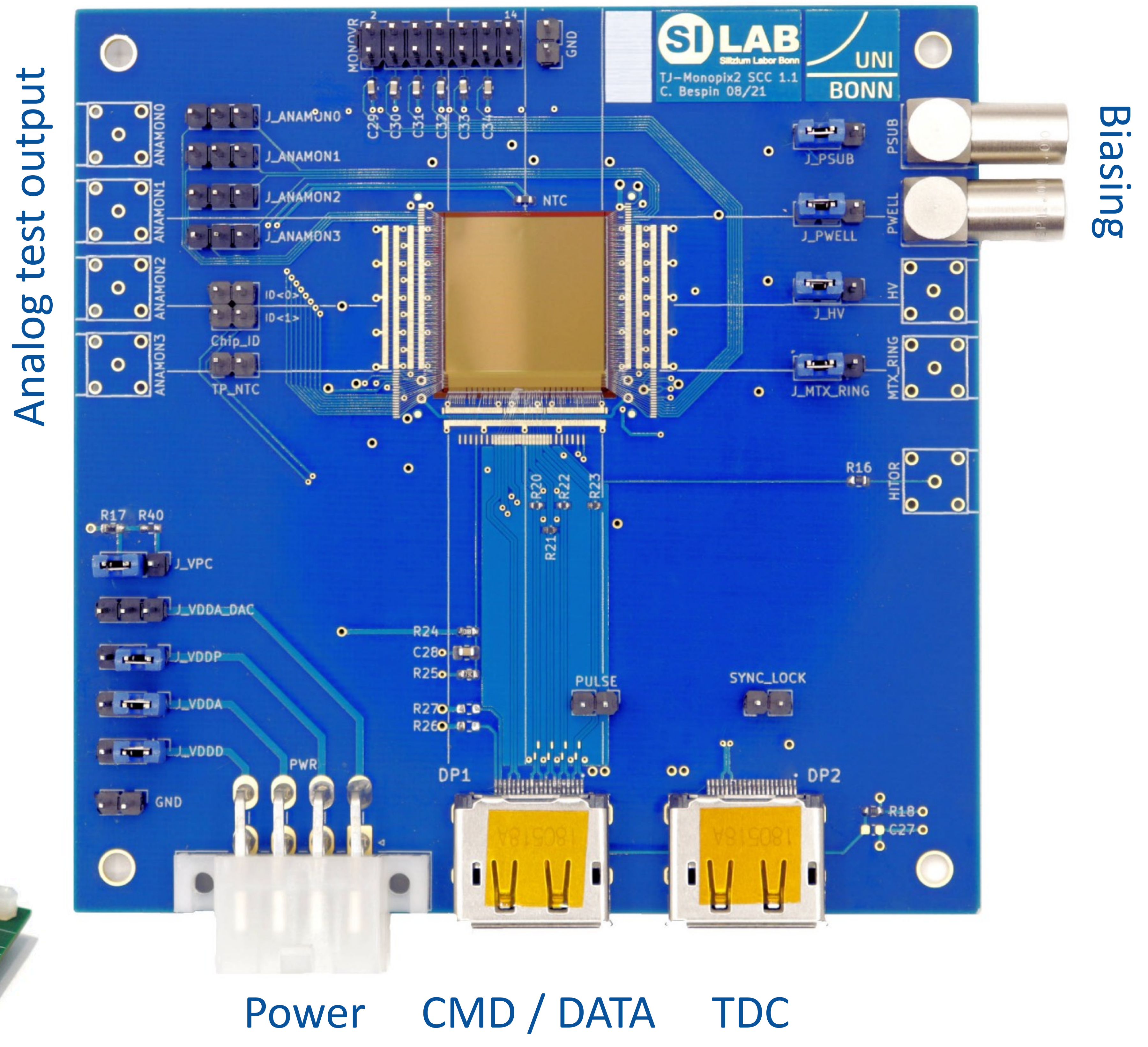


TJ-MONOPIX2 DAQ SYSTEM

- 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.

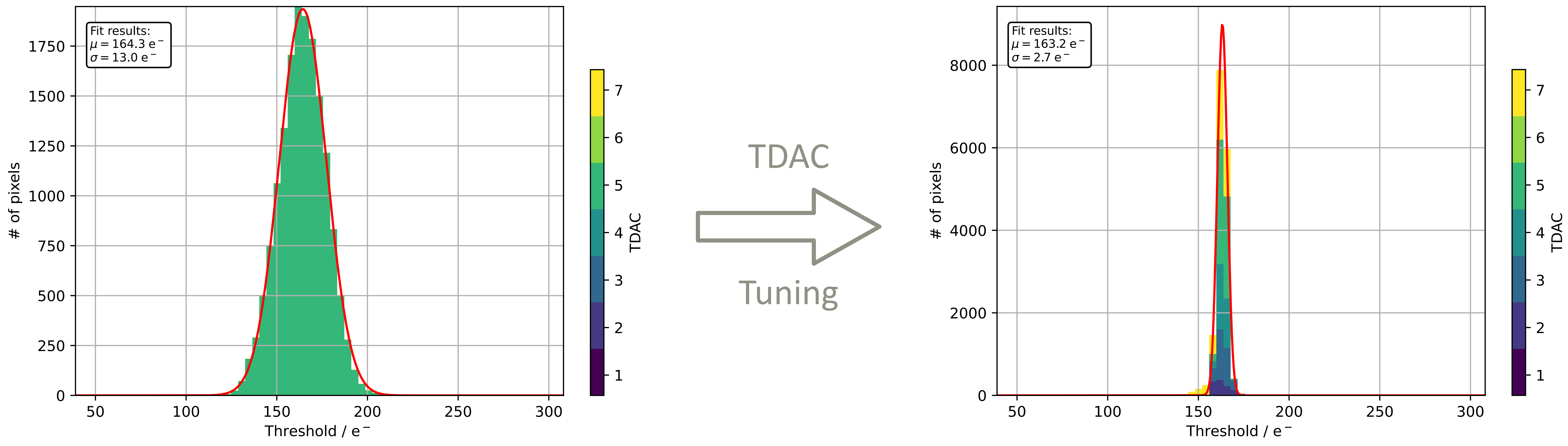
- Chip supports addressing by chip ID (jumper on pin header)
  - Multi-chip readout should be possible with bdaq53





TJ-MONOPIX2 LAB TESTS

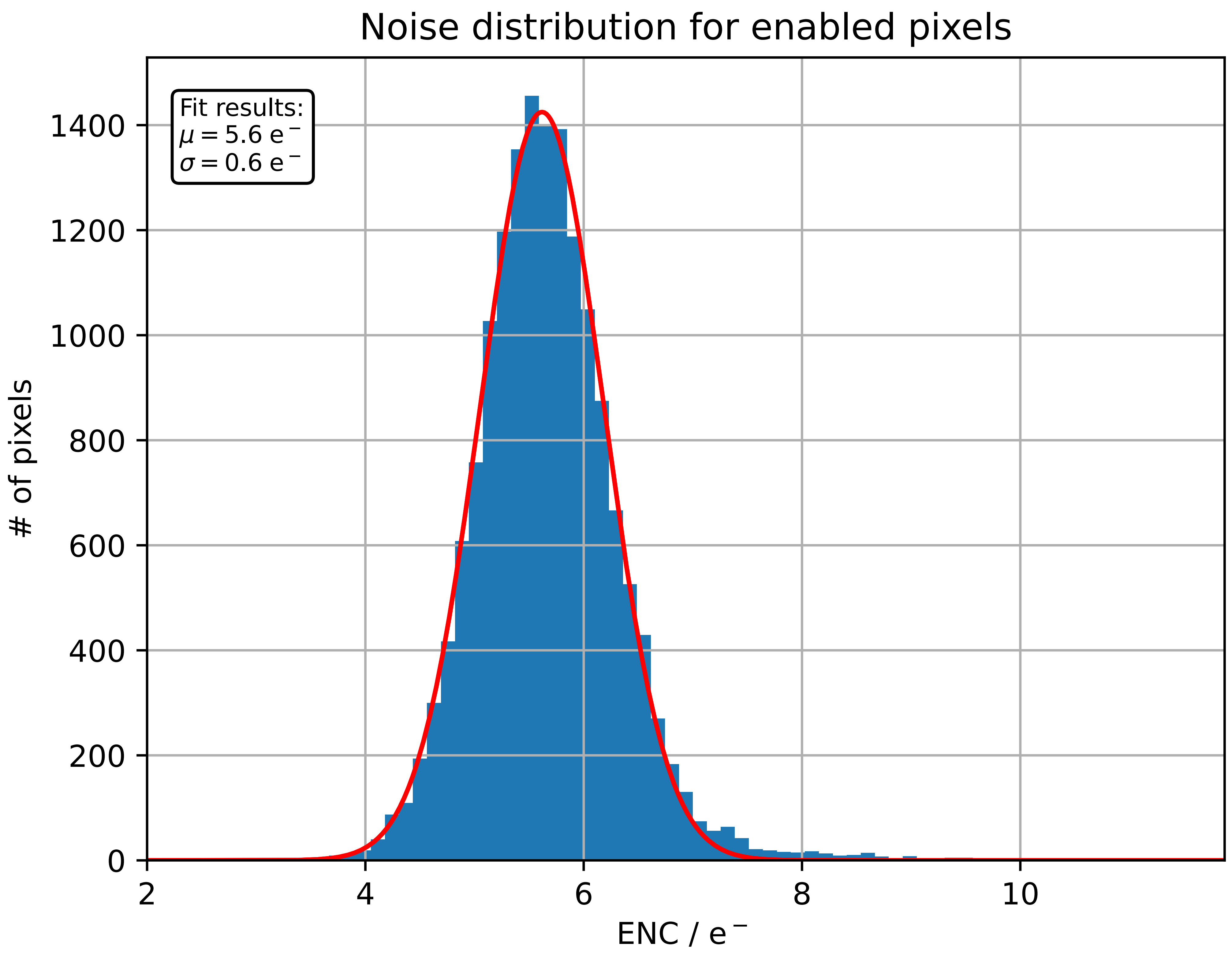
- Lab tests conducted for threshold and noise measurements
- Design goals: operational threshold ≈ 100 e$^-$, threshold dispersion < 10 e$^-$, ENC ≈ 5 e$^-$
- In-pixel threshold trimming (3 bit) significantly reduces threshold dispersion to less than design value
- Operational threshold higher than anticipated,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



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



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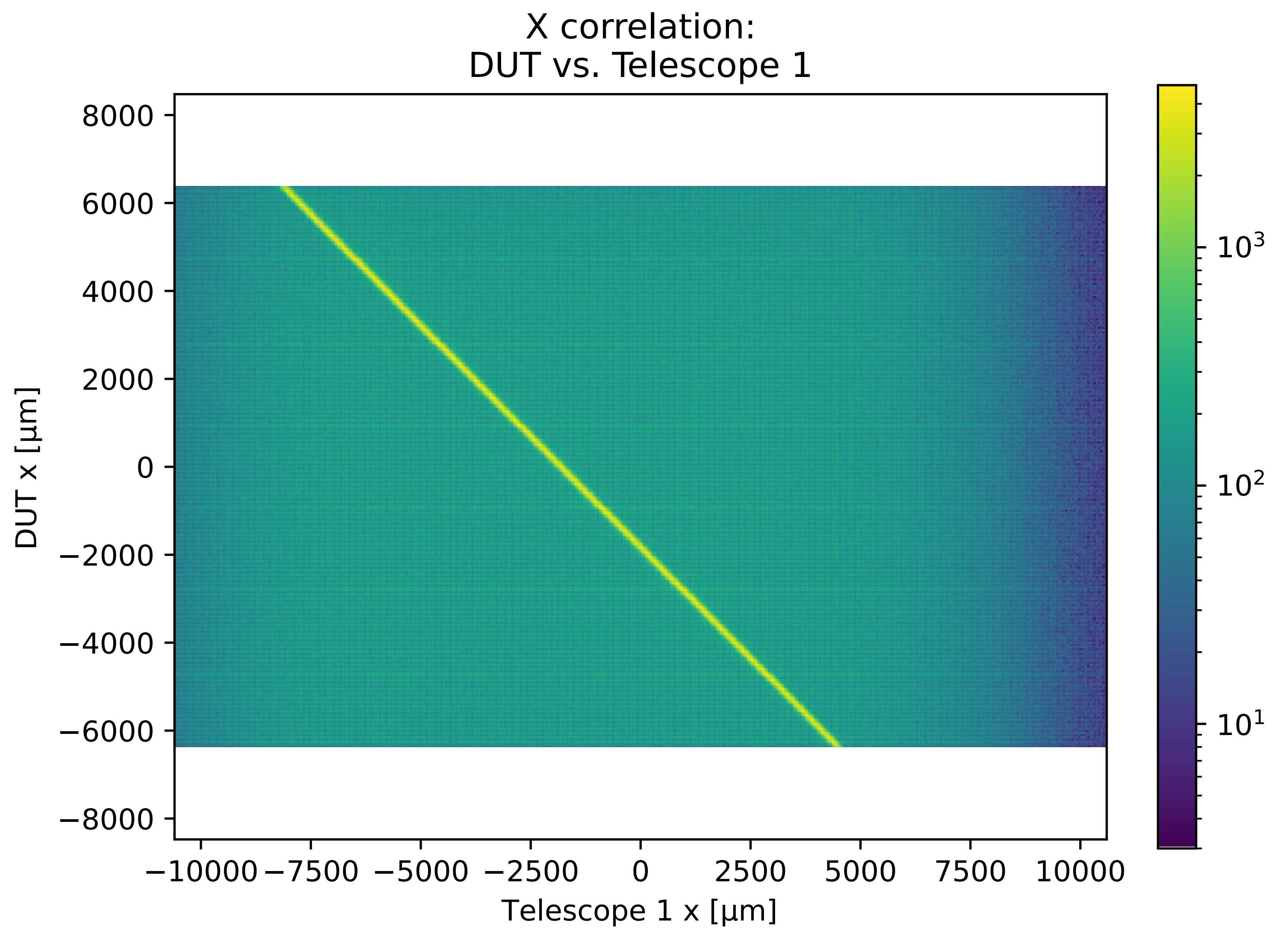
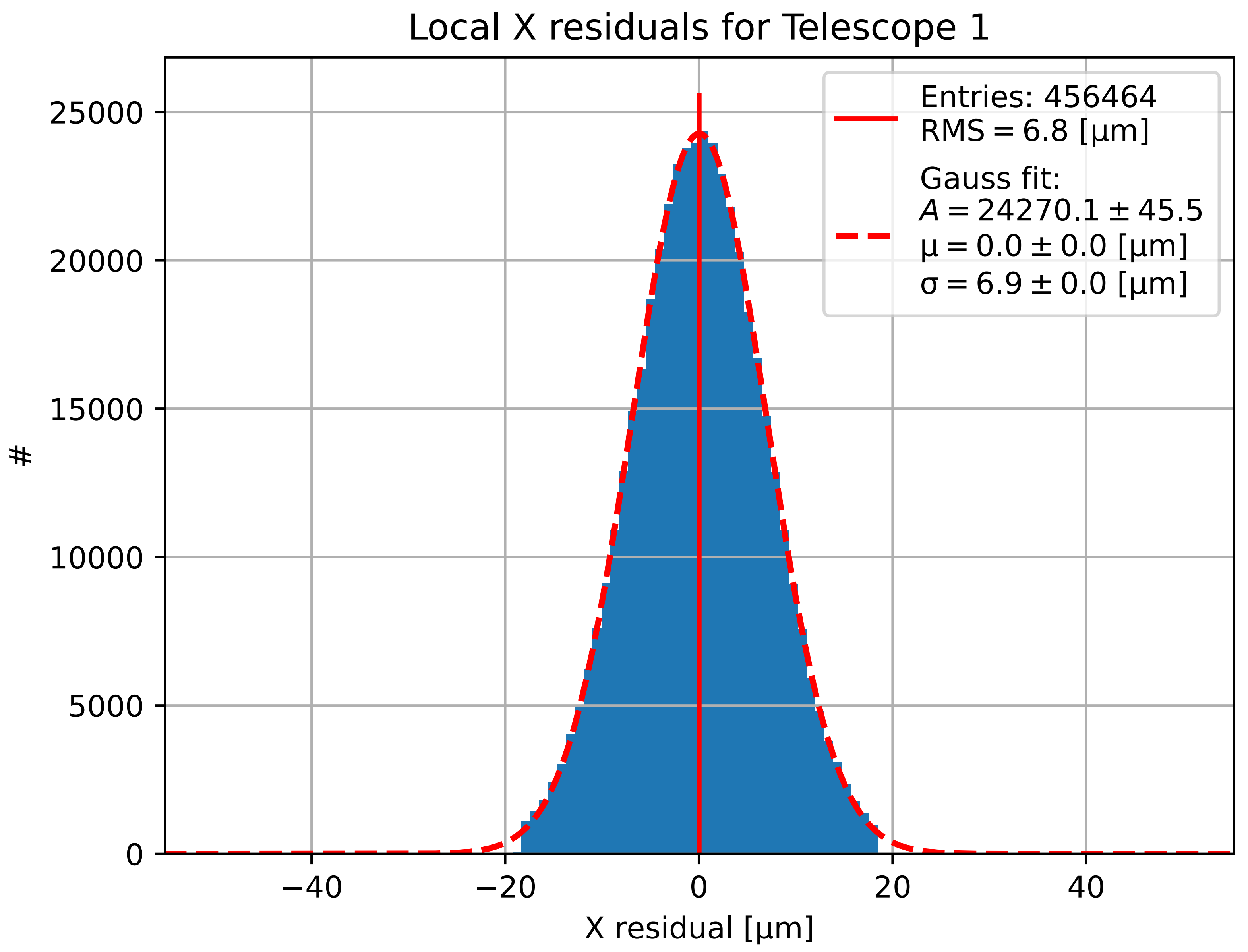
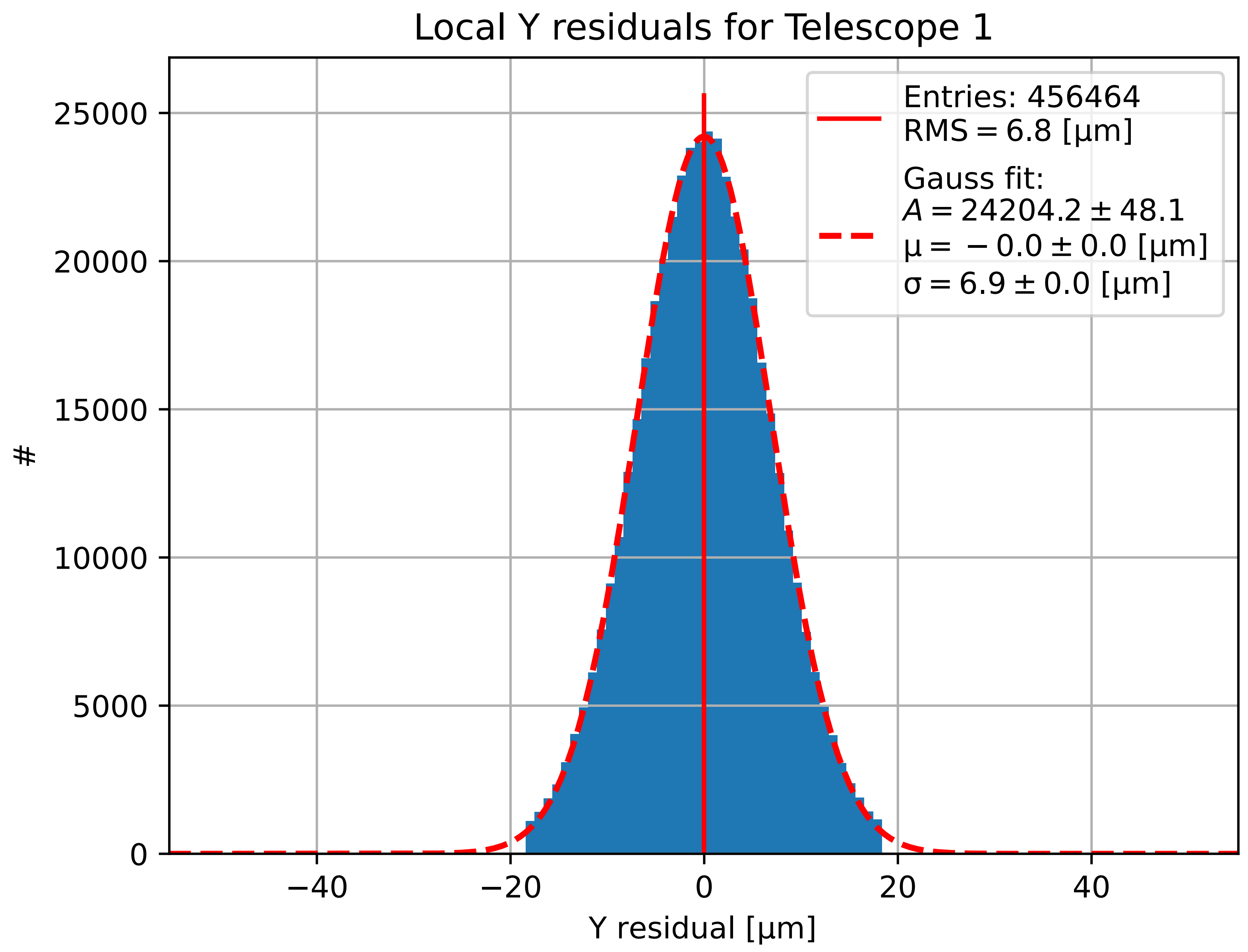
TJ-MONOPIX2 BEAM TESTS

- 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

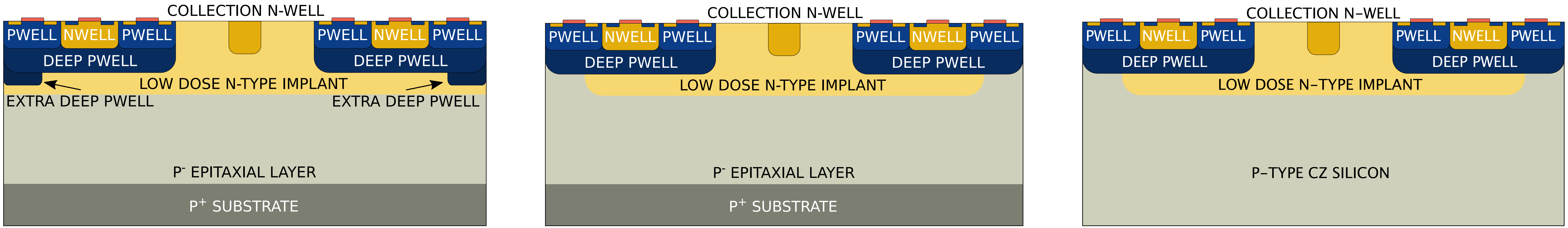






TJ-MONOPIX2 BEAM TESTS

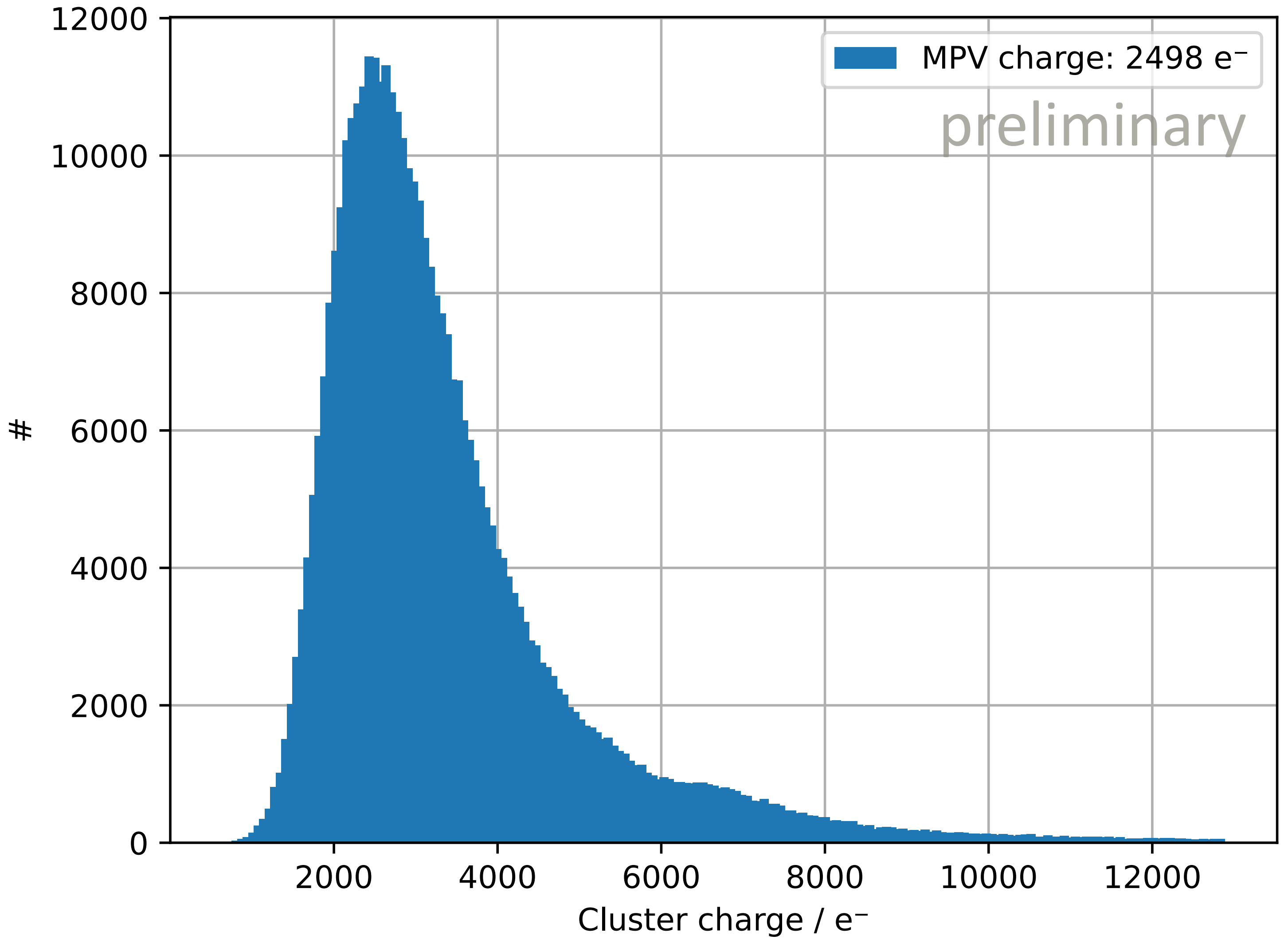
- Investigated samples (unirradiated):
  - epitaxial silicon (30 µm thickness) with gap in n-layer and with additional p-well
  - Czochralski silicon (100 µm thickness) with gap in n-layer
  - Type of silicon growth (epi vs Cz) not part of investigation, but thickness of sensitive volume
- All samples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



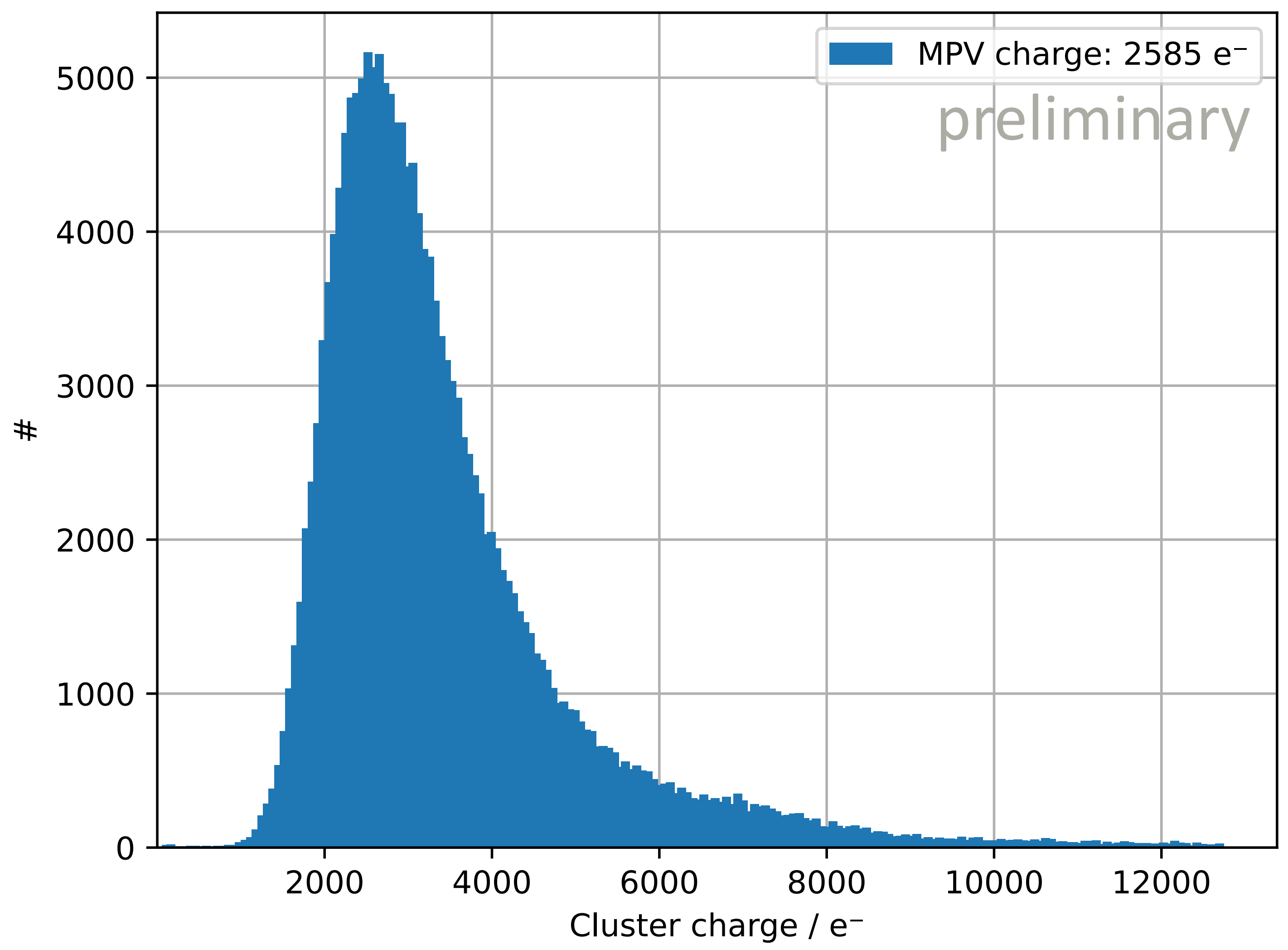
TJ-MONOPIX2 CLUSTER CHARGE

- 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

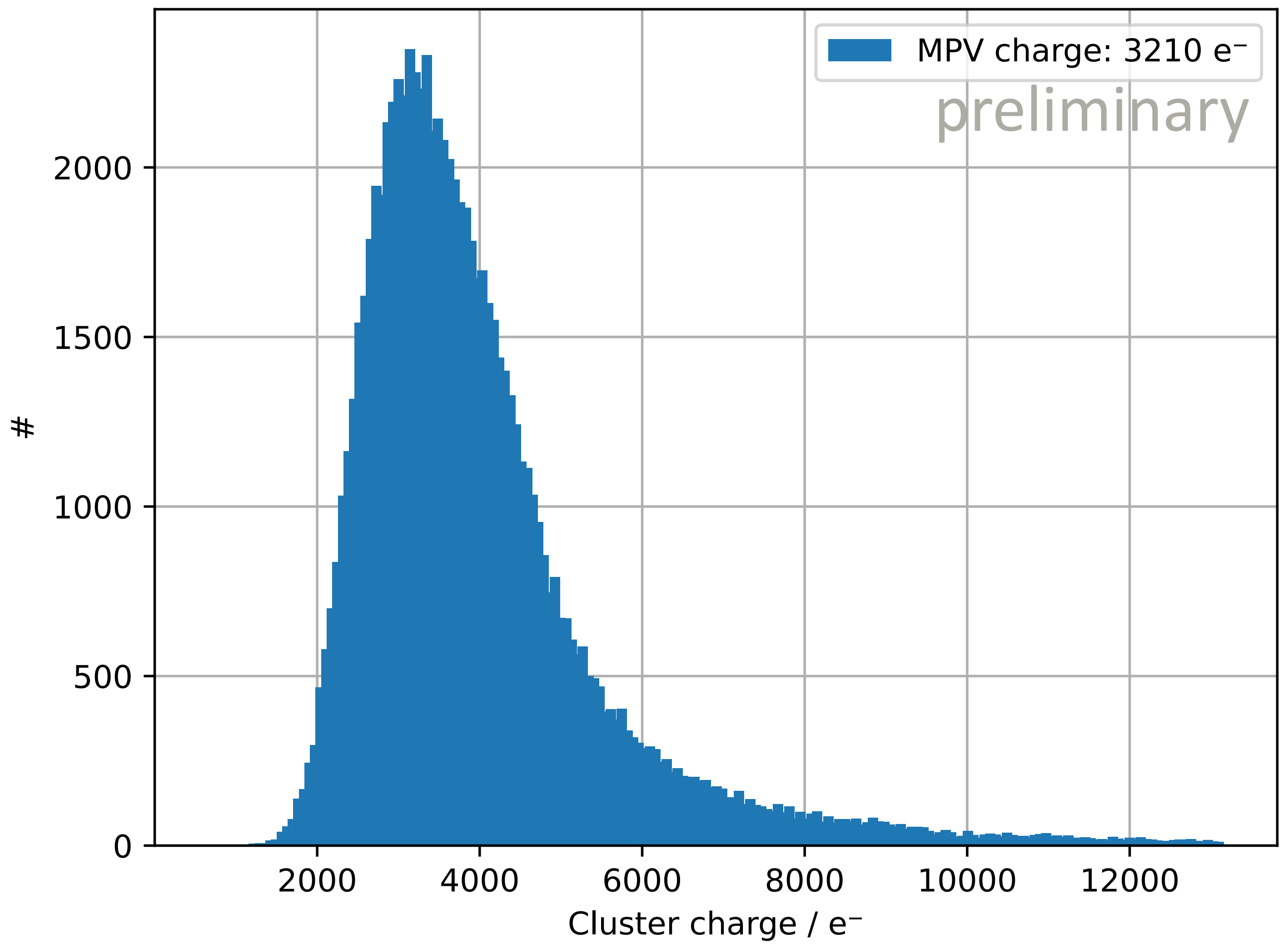
Epi add. p-well: 2498 e$^-$ MPV



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



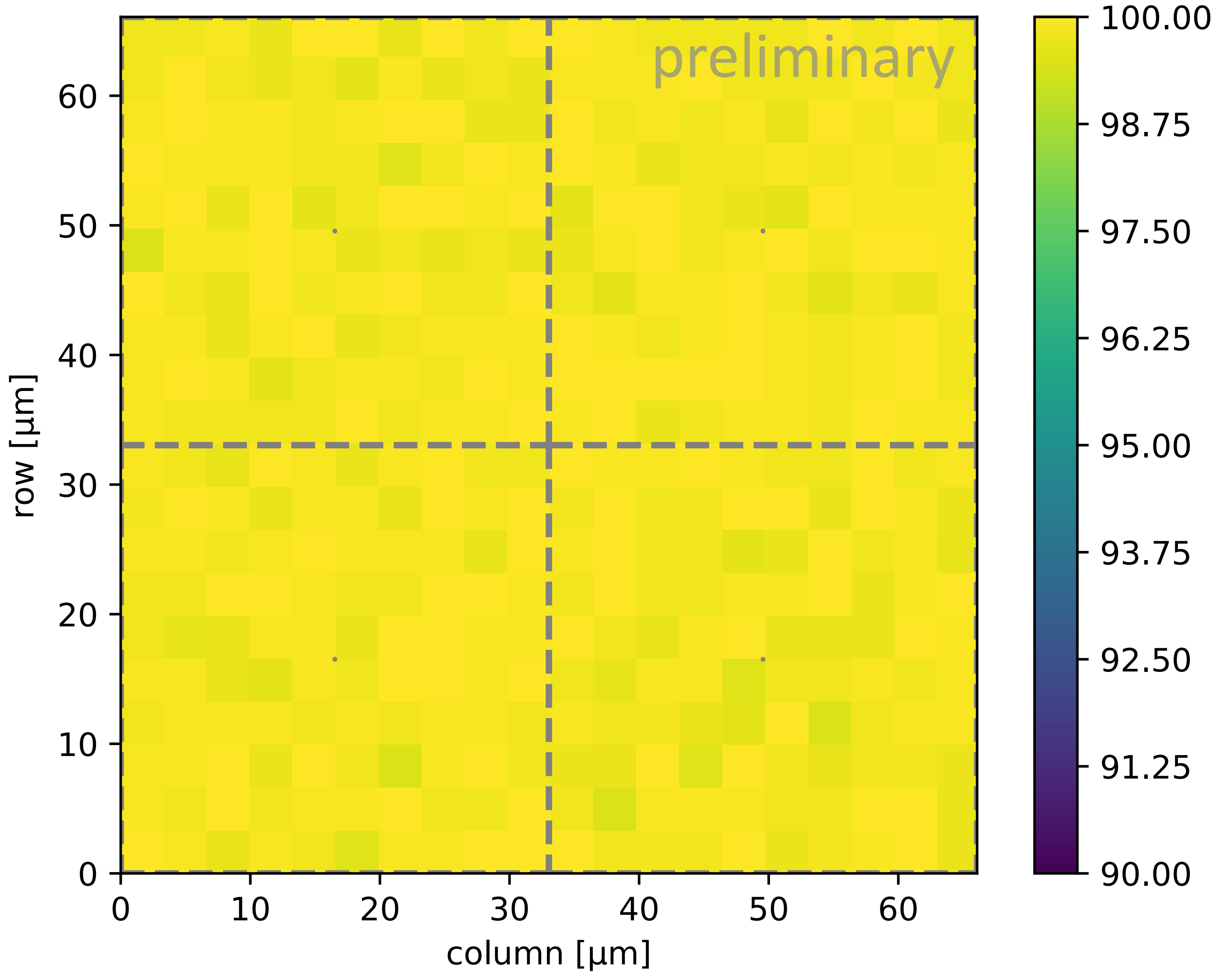
Cz gap in n-layer: 3210 e$^-$ MPV



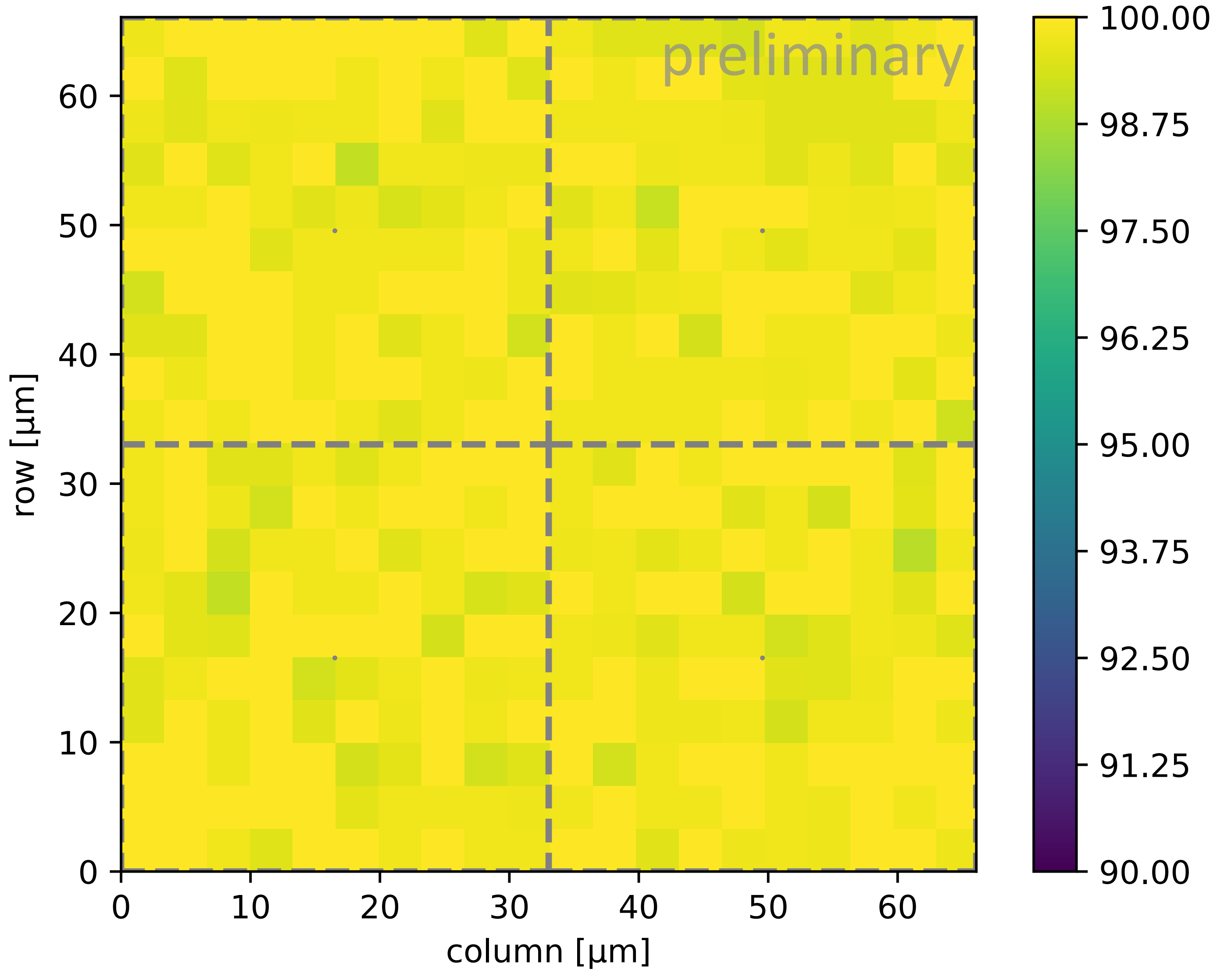
TJ-MONOPIX2 EFFICIENCY

- 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 %)

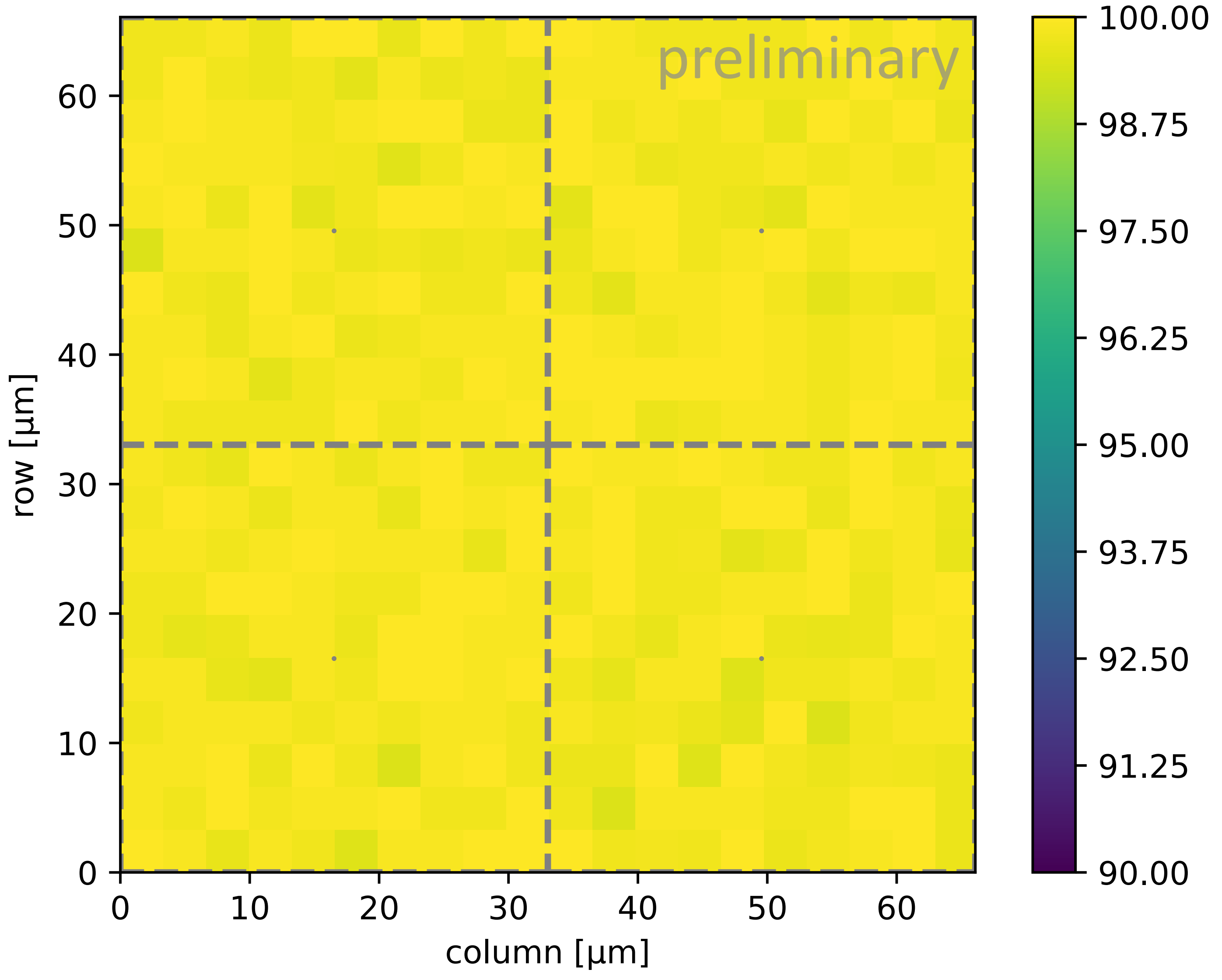
Epi add. p-well: 99.85 %



Epi gap in n-layer: 99.80 %



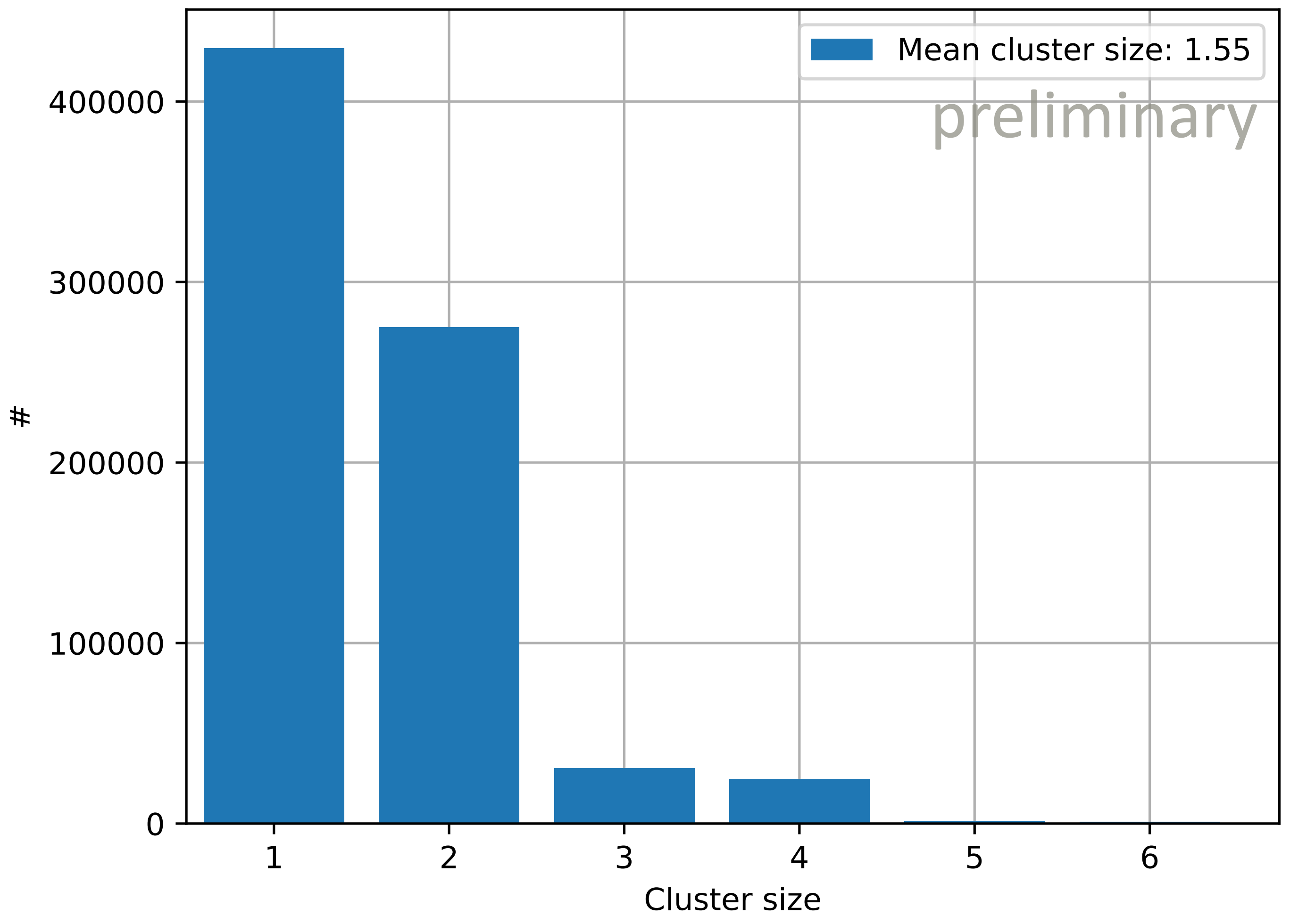
Cz gap in n-layer: 99.79 %



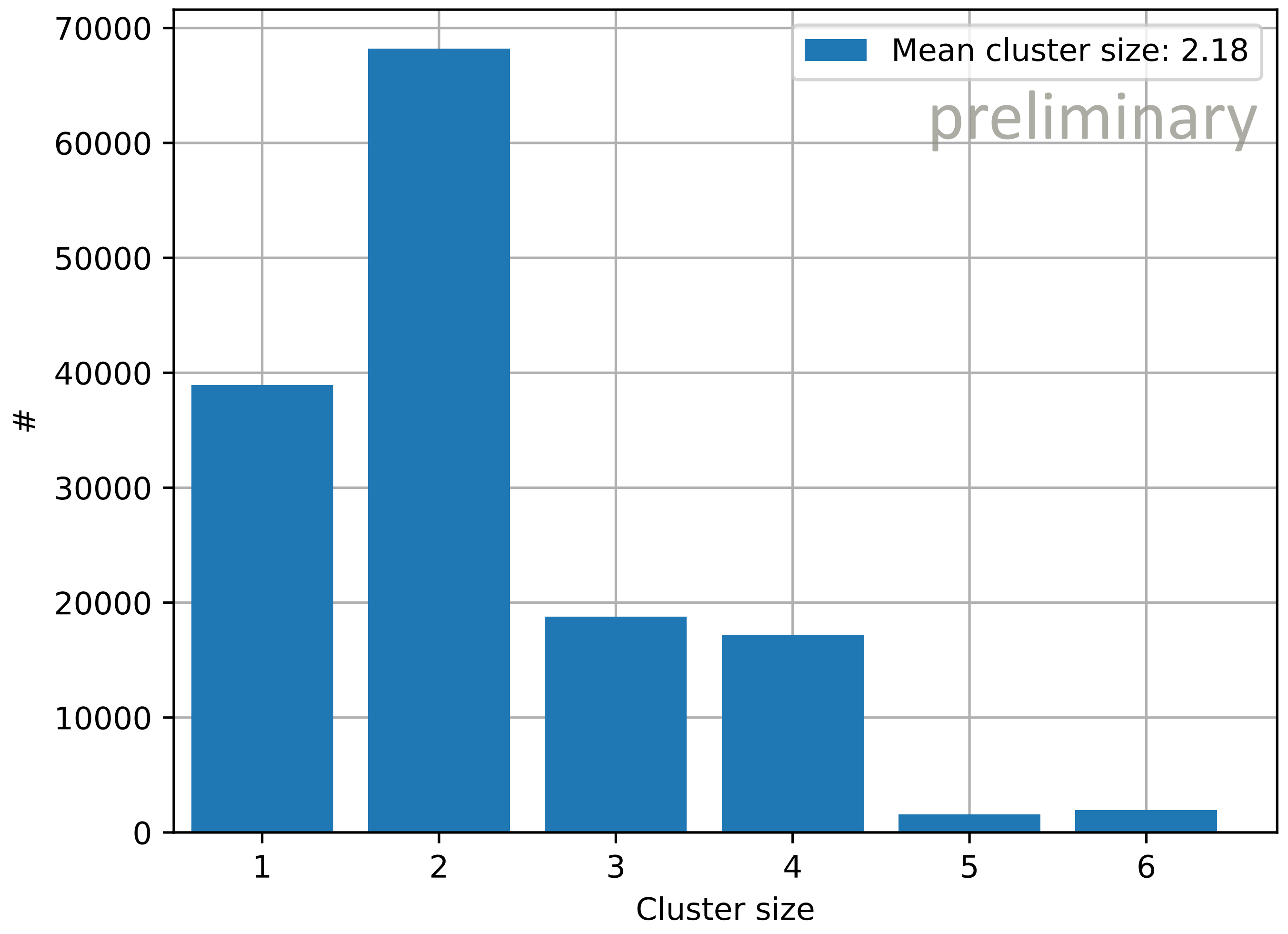
TJ-MONOPIX2 CLUSTER CHARGE

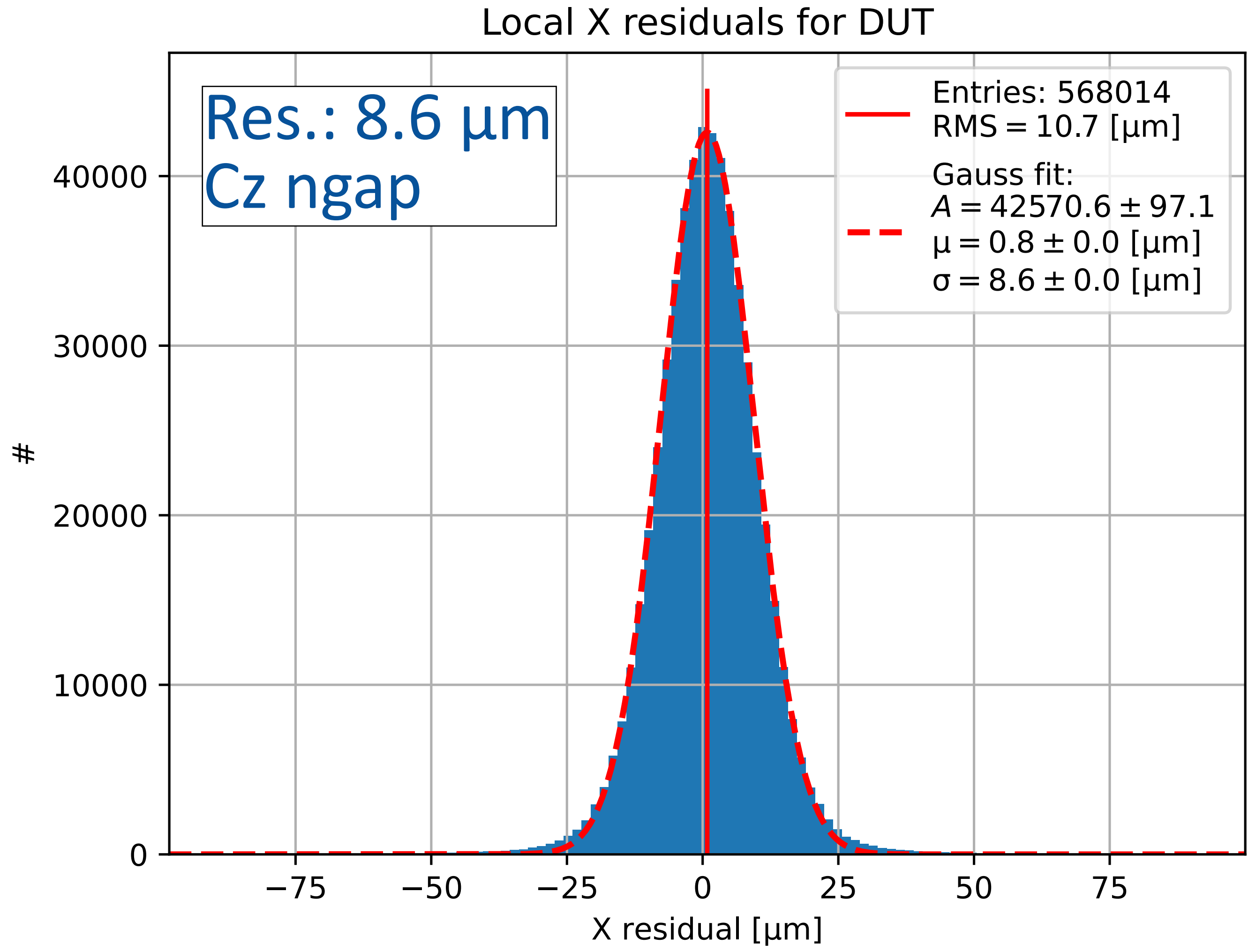
- Compare different sensor materials (epi 30 µm / Cz 100 µm) regarding cluster size
- As expected from accumulated charge and higher depletion than 30 µm cluster size is significantly larger in 100 µm silicon (not fully depleted)
- High (average) cluster size allows for high spatial resolution; better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

Epi gap in n-layer: 1.55



Cz gap in n-layer: 2.18





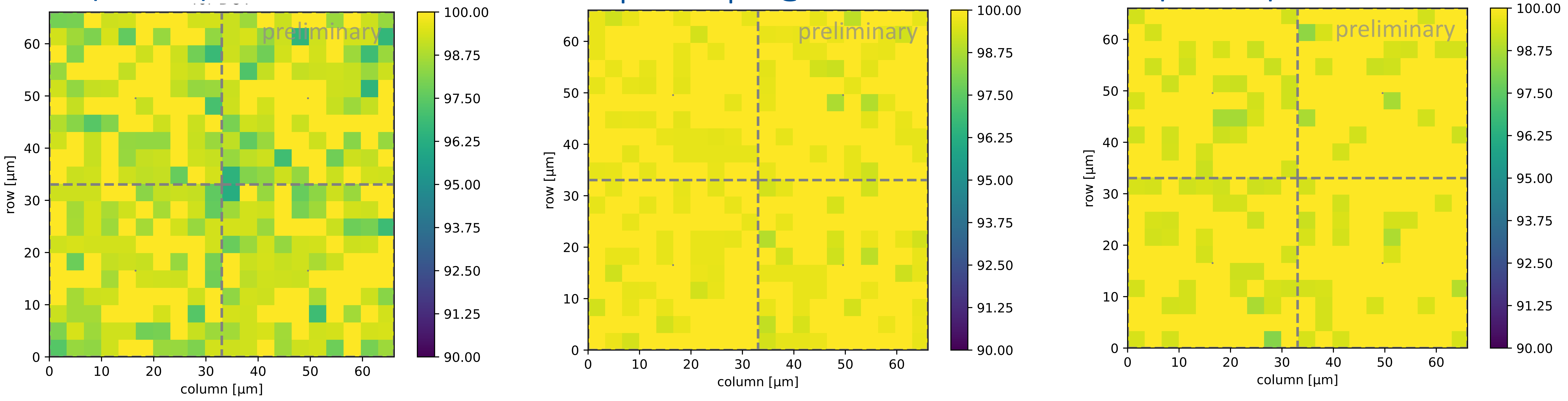
TJ-MONOPIX2 EFFICIENCY (HV)

- 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 %

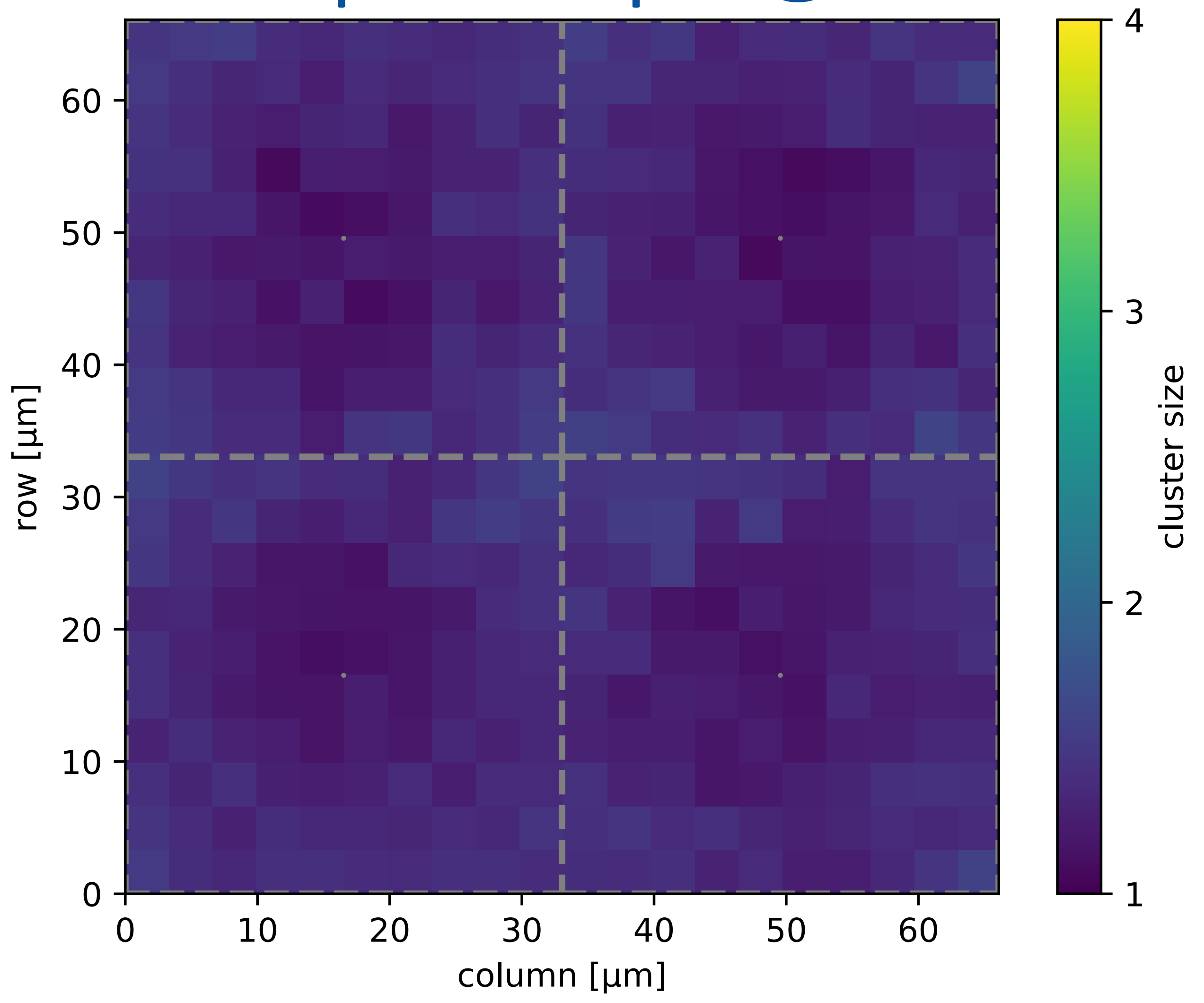
100 µm sample @ 50 V: 99.82 %



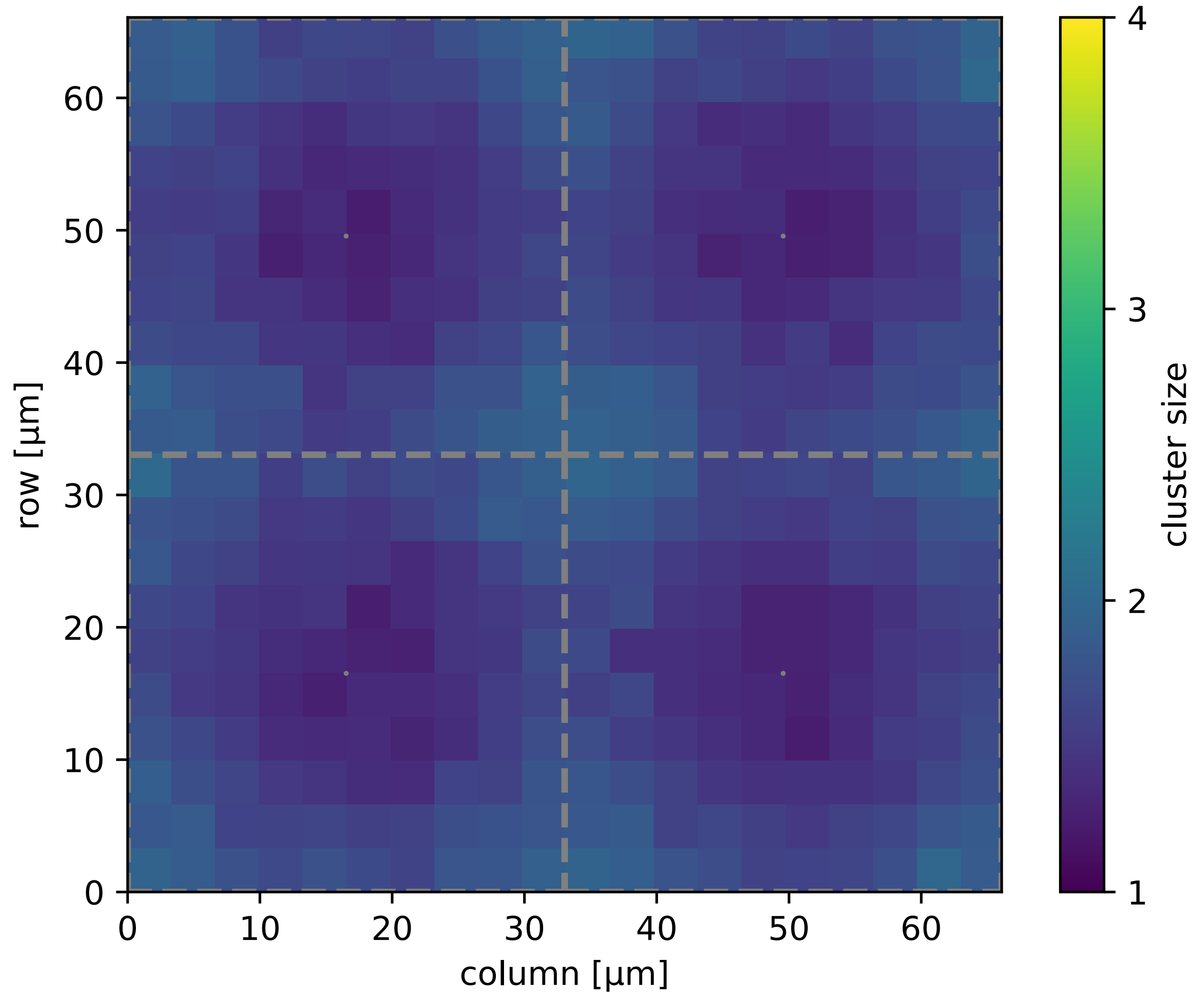
TJ-MONOPIX2 CLUSTER SIZE (HV)

- 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)

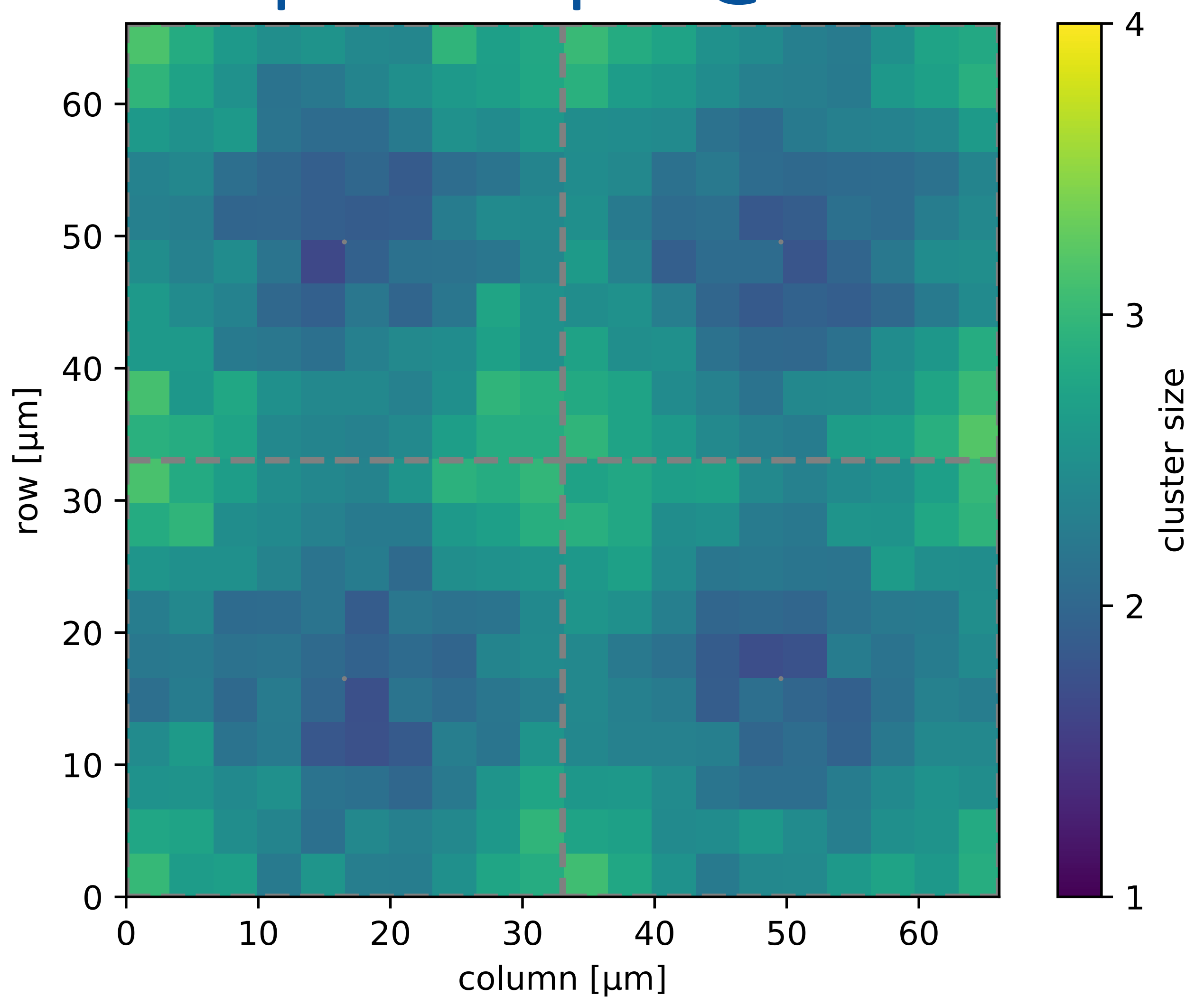
100 µm sample @ 5 V



100 µm sample @ 25 V



100 µm sample @ 50 V



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SUMMARY / OUTLOOK

- Check front-end parameters for possibly lower operational thresholds
- 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
- Testbeam campaigns already planned for first half of 2023 for irradiated sensors, threshold studies, …

- PIXEL2022 proceeding: submitted / arXiv:2301.13638
- VERTEX proceeding (I.Caicedo): submitted

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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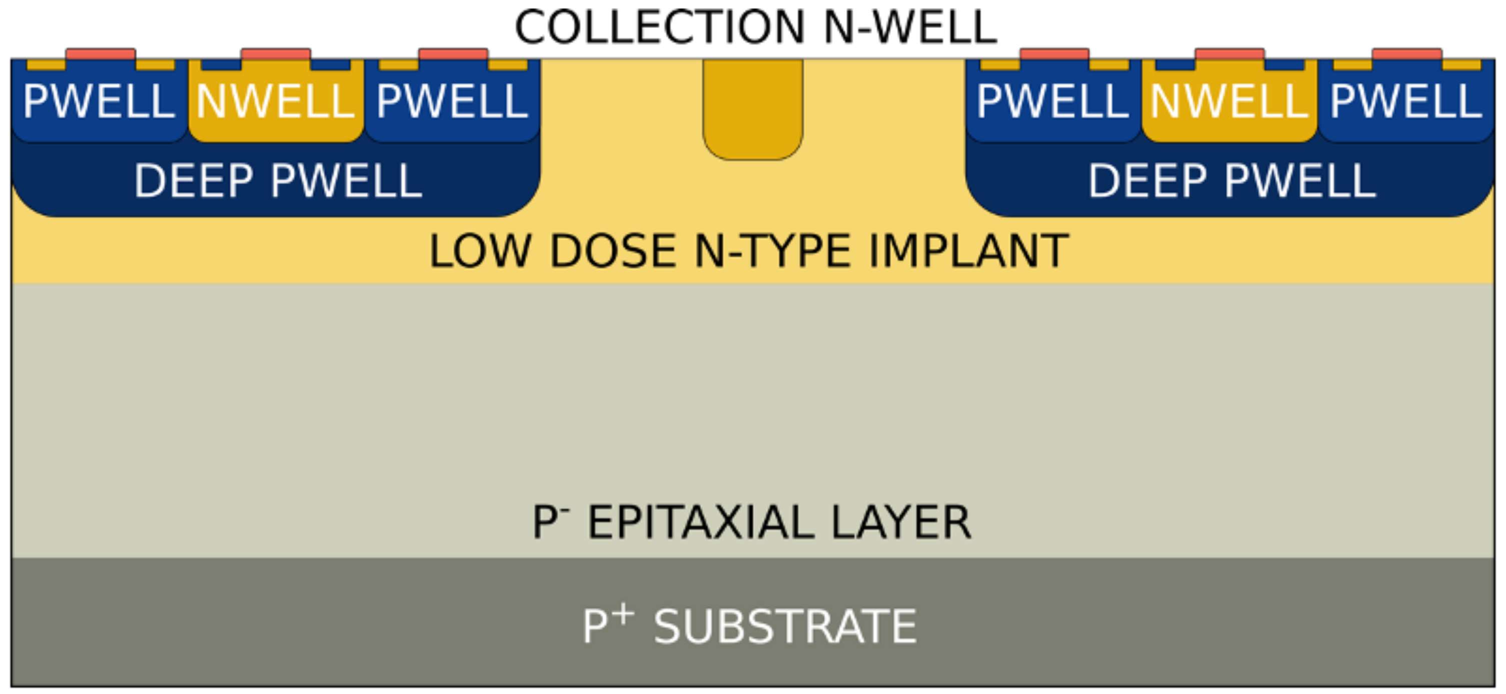
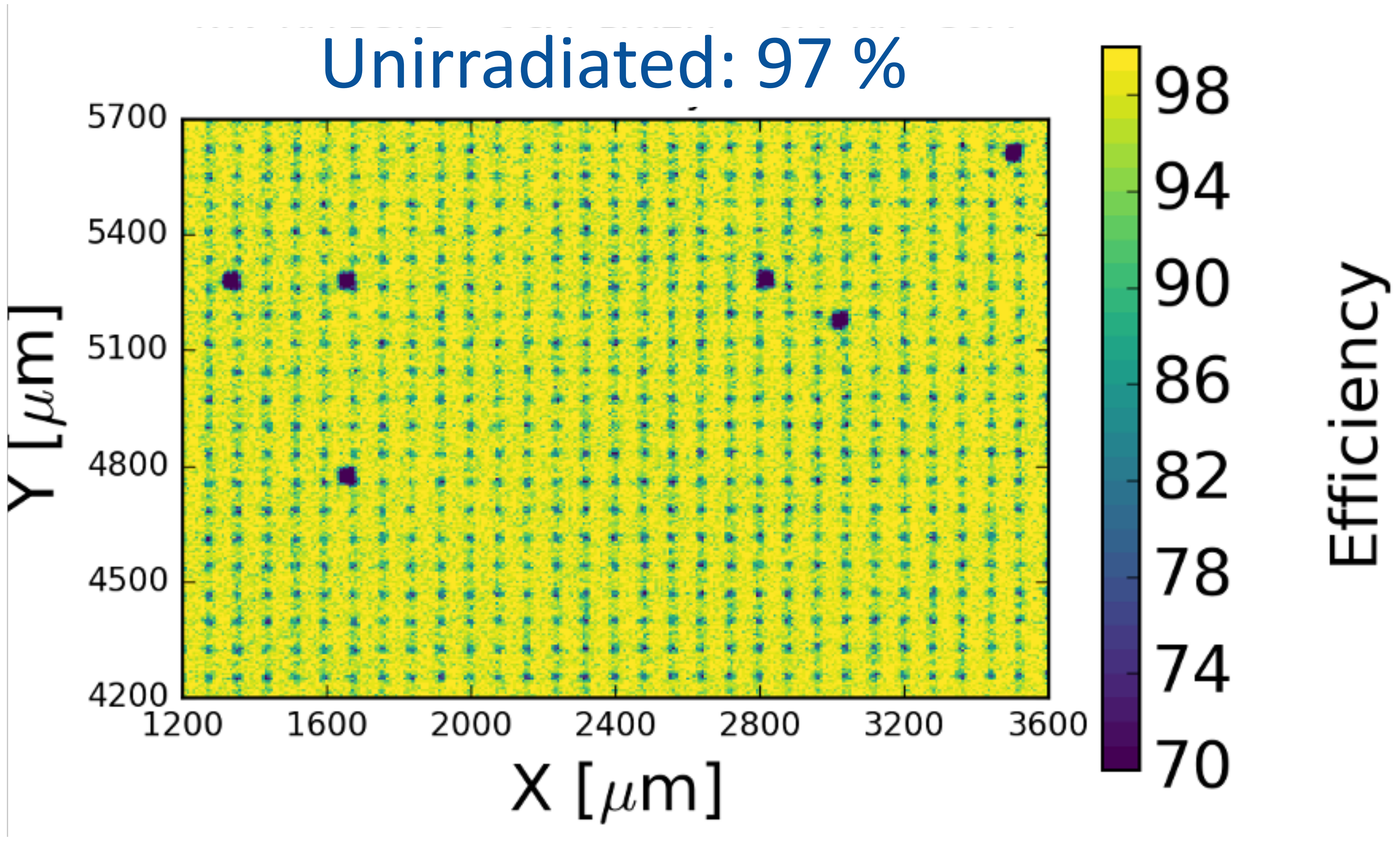
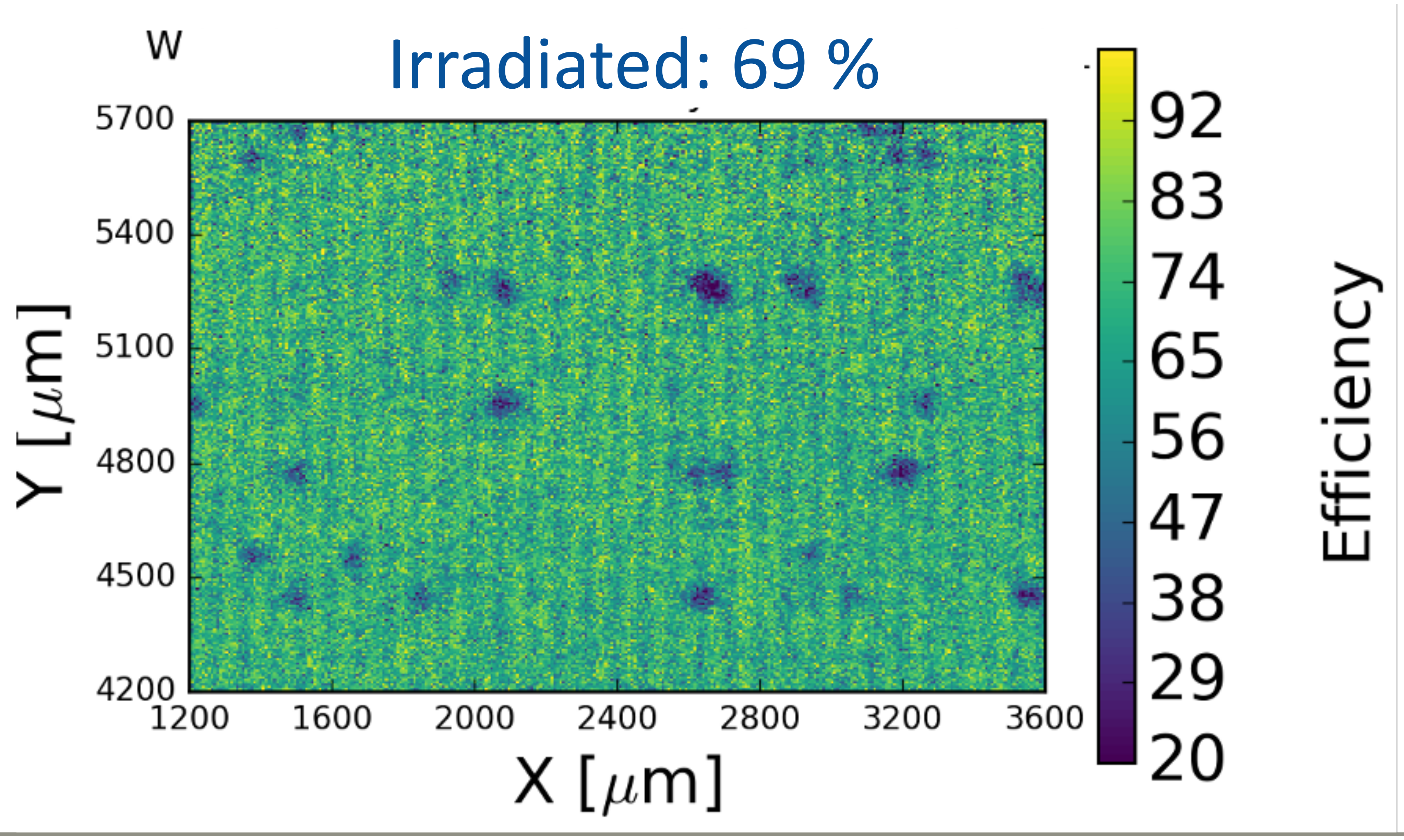
BACKUP

TJ-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



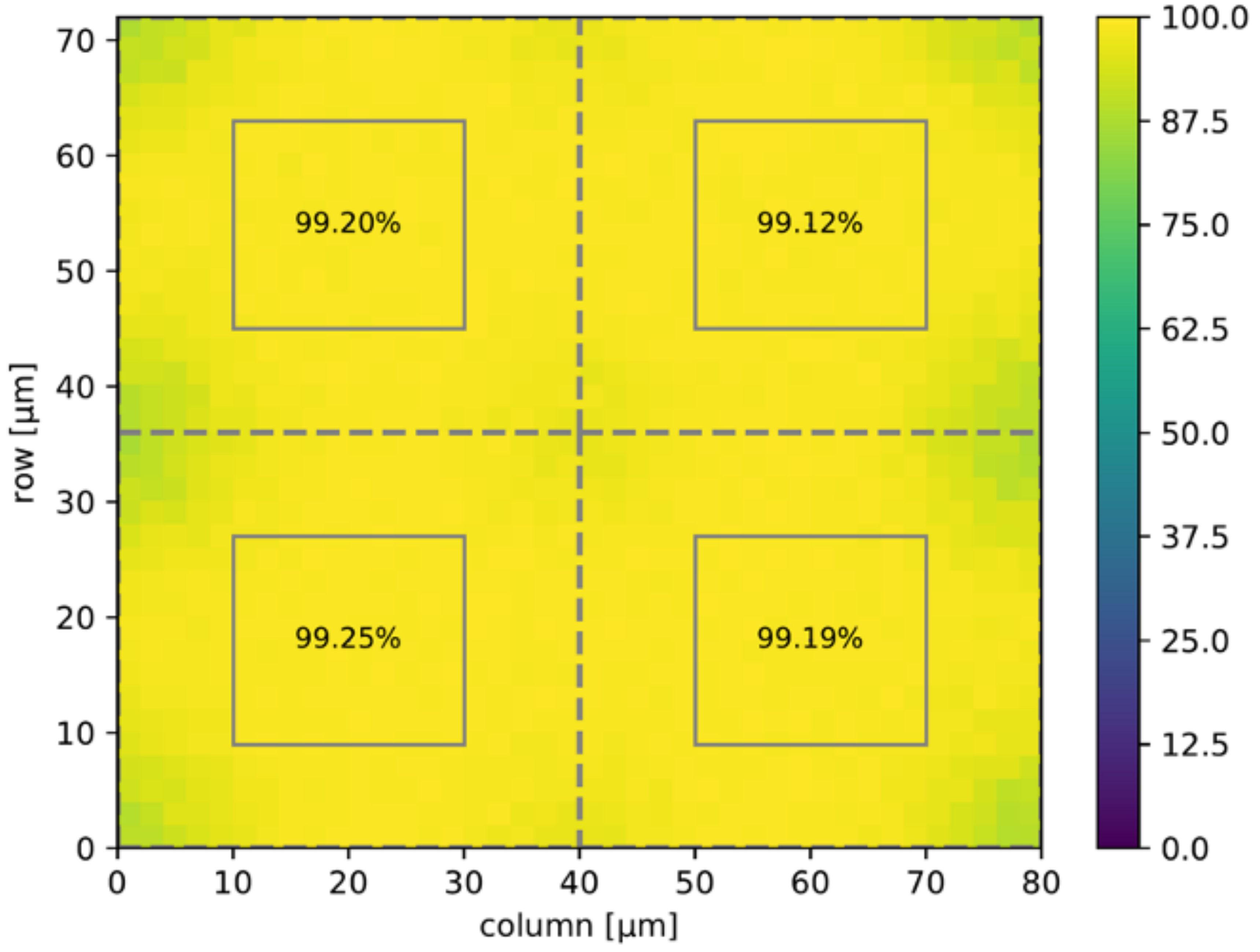




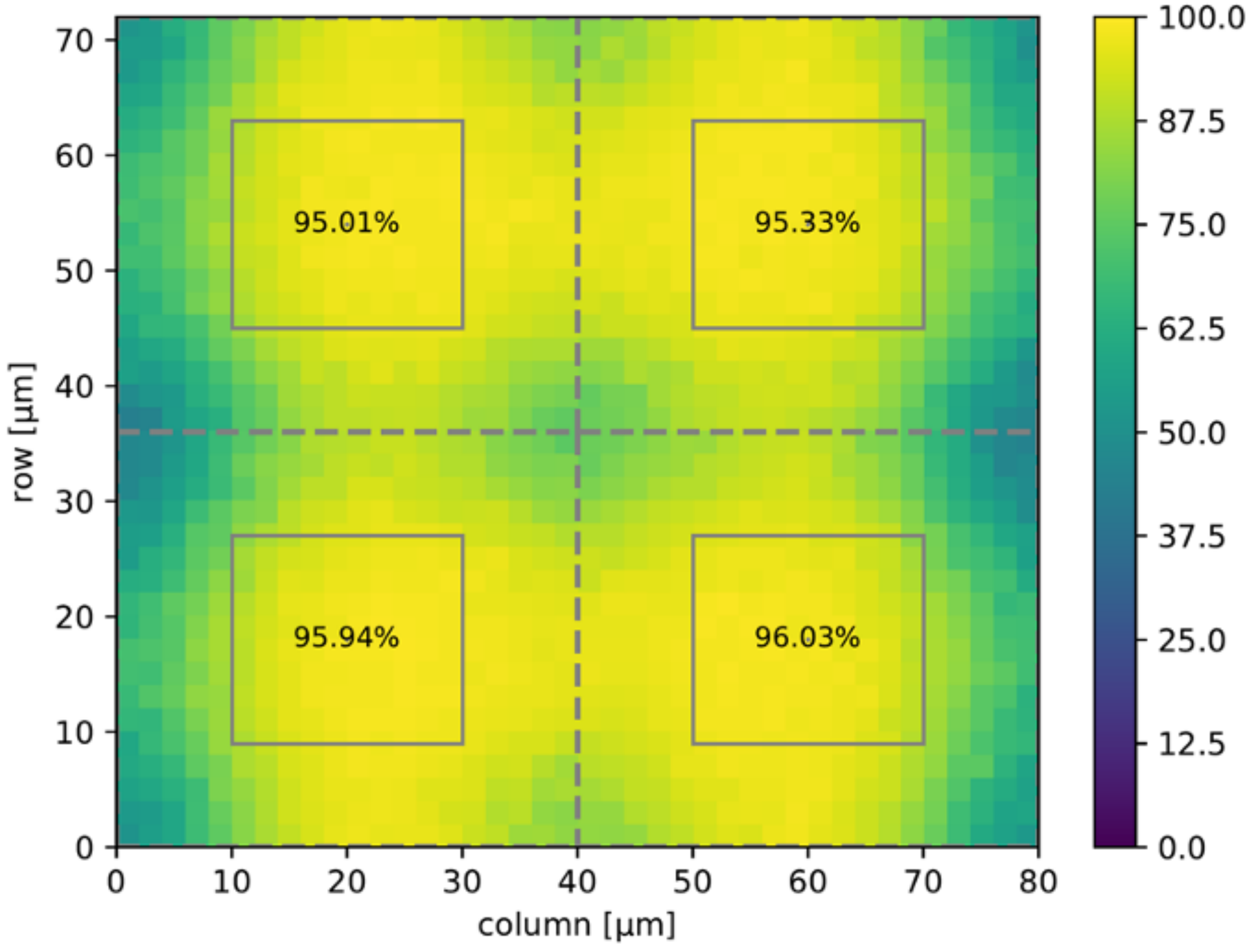
TJ-MONOPIX1 SENSOR MODS

- 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-



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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

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)