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PERFORMANCE OF TJ-MONOPIX

A DEPLETED MONOLITHIC ACTIVE PIXEL SENSOR WITH COLUMN DRAIN READOUT ARCHITECTURE

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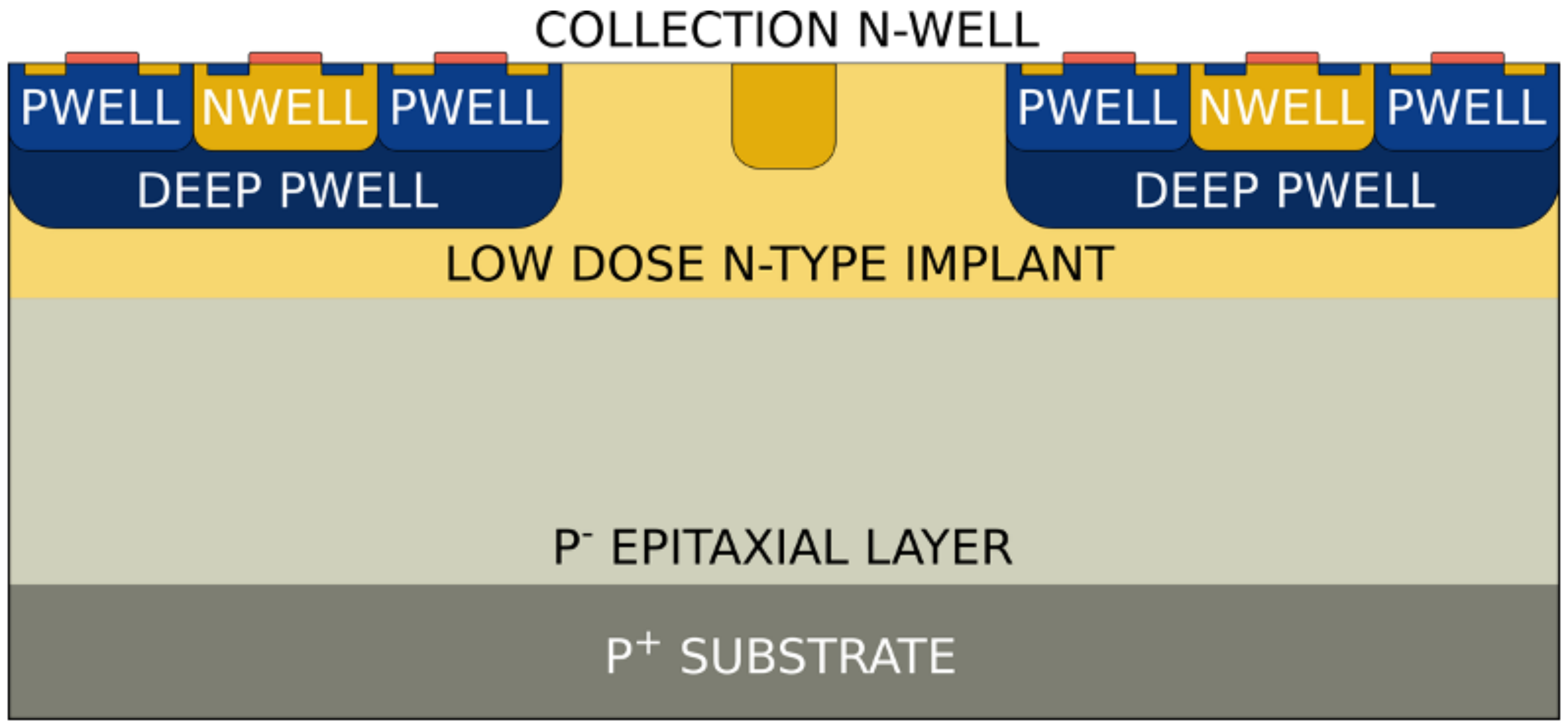
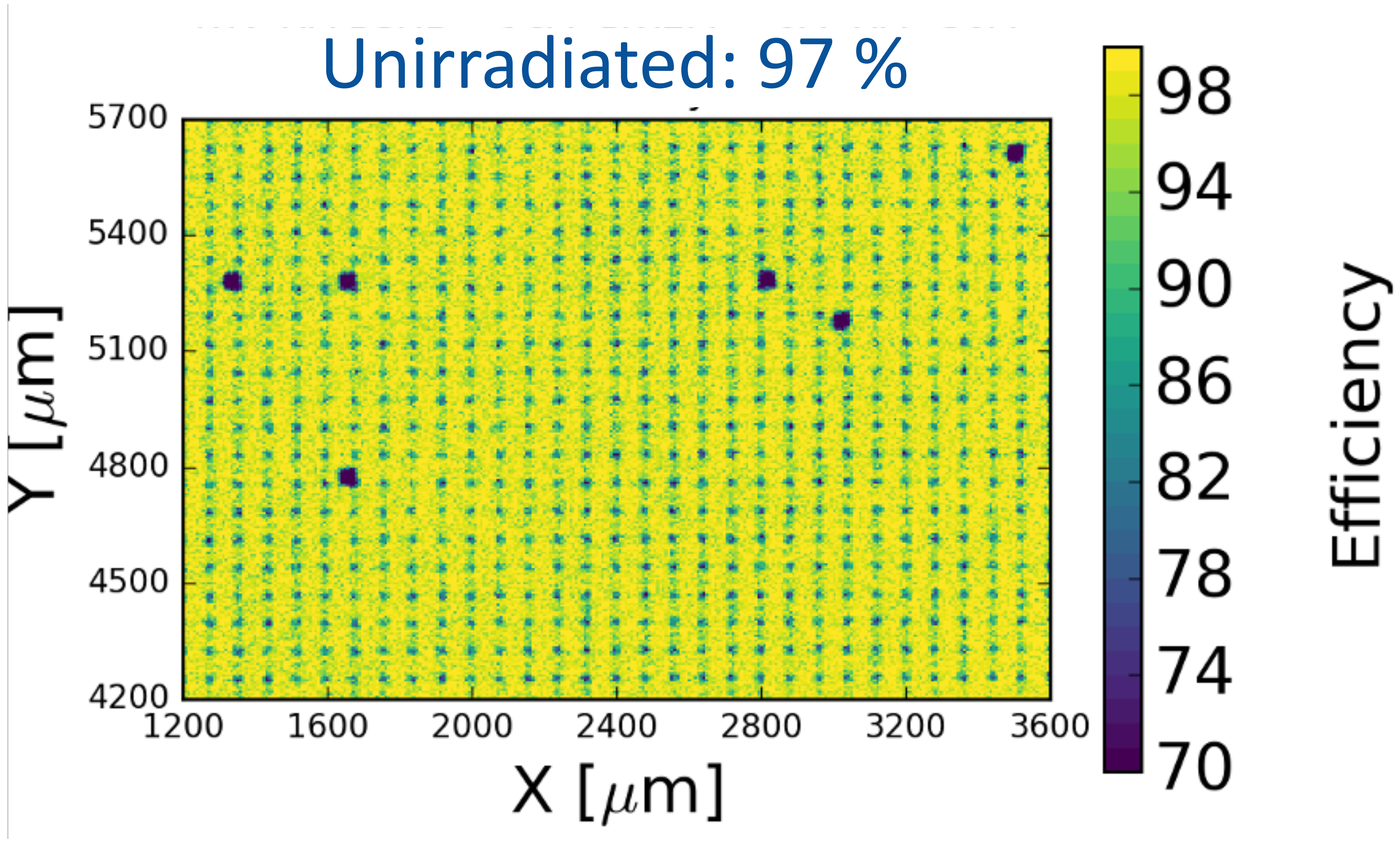
TJ-MONOPIX1 DESIGN

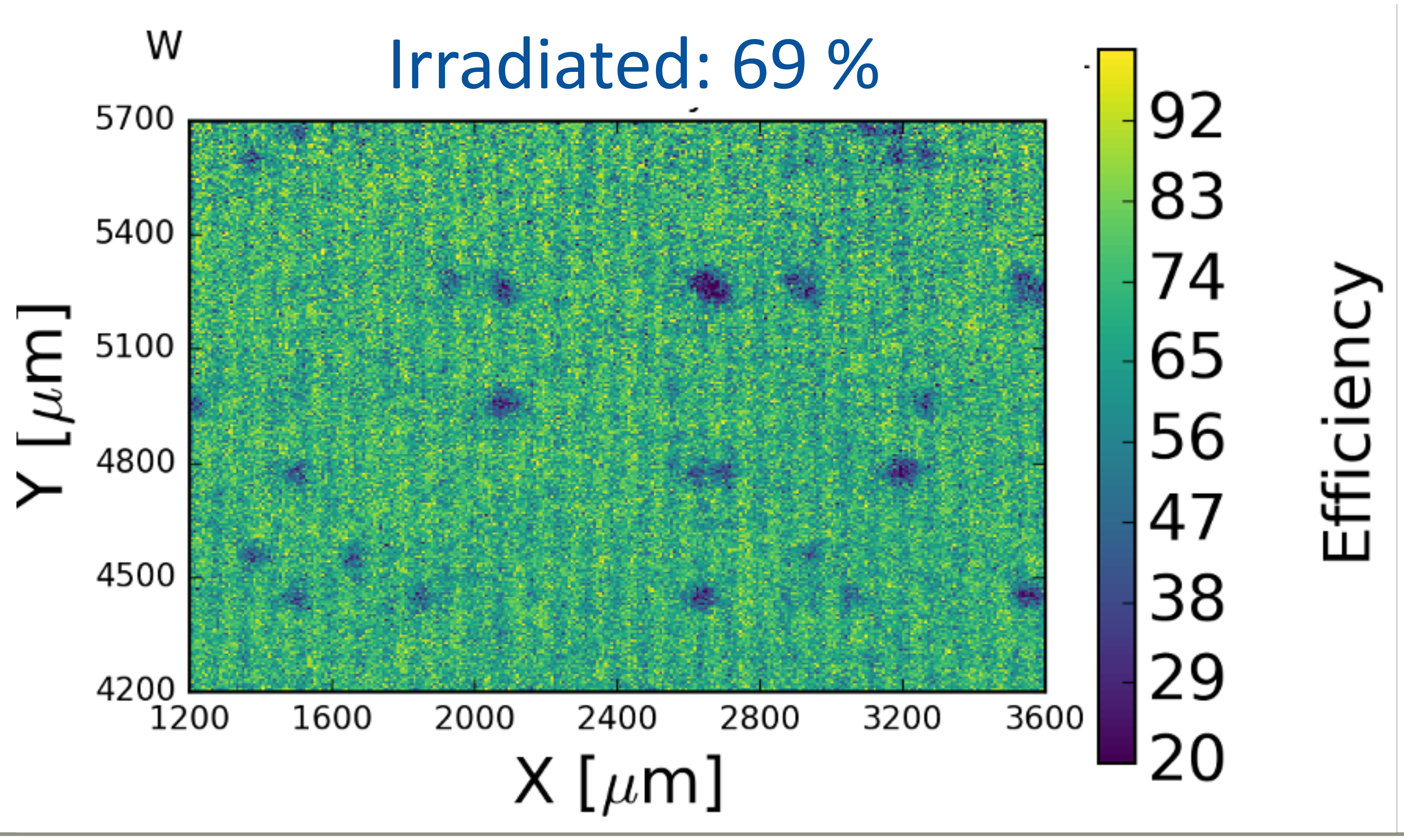
- TJ-Monopix is line of DMAPS designed in a 180 nm Tower CMOS process based on ALPIDE sensor for ALICE ITS upgrade
- Small collection electrode for operations with low power and low noise
- Designed for ATLAS ITk outer layer specs with column-drain readout like in FE-I3 in a 2 cm column
  - Pixel readout capable of dealing with hit rate > 100 MHz / cm^2
  - Goal: 10^{15} 1 MeV $^{neq}/_{cm2}$ NIEL tolerance and 100 MRad TID
- Low dose n-type implant for homogeneous depletion of sensor volume (initial design)
- Radiation hardness not straight-forward in small collection electrode design



RADIATION HARDNESS TJ-MONOPIX1

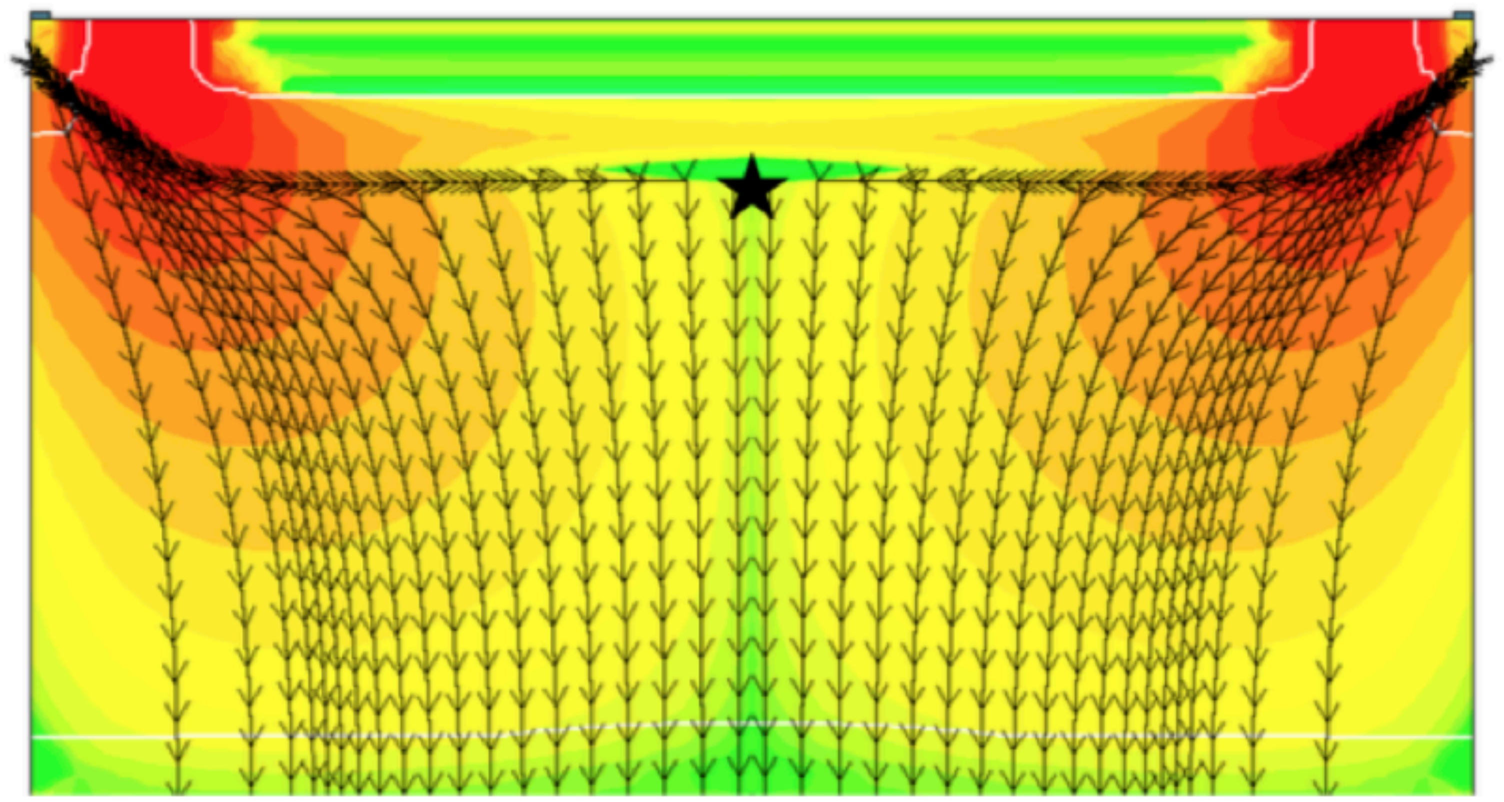
- Extensive tests performed in 2018 at ELSA beam line (2.5 GeV electrons) in Bonn
- Significant efficiency loss after irradiation to < 70 % (at $10^{15}\,\mathrm{neq\,cm^{-2}}$)
- Charge is lost due to E-field shaping under deep pwell -> need another modification besides low dose n-type

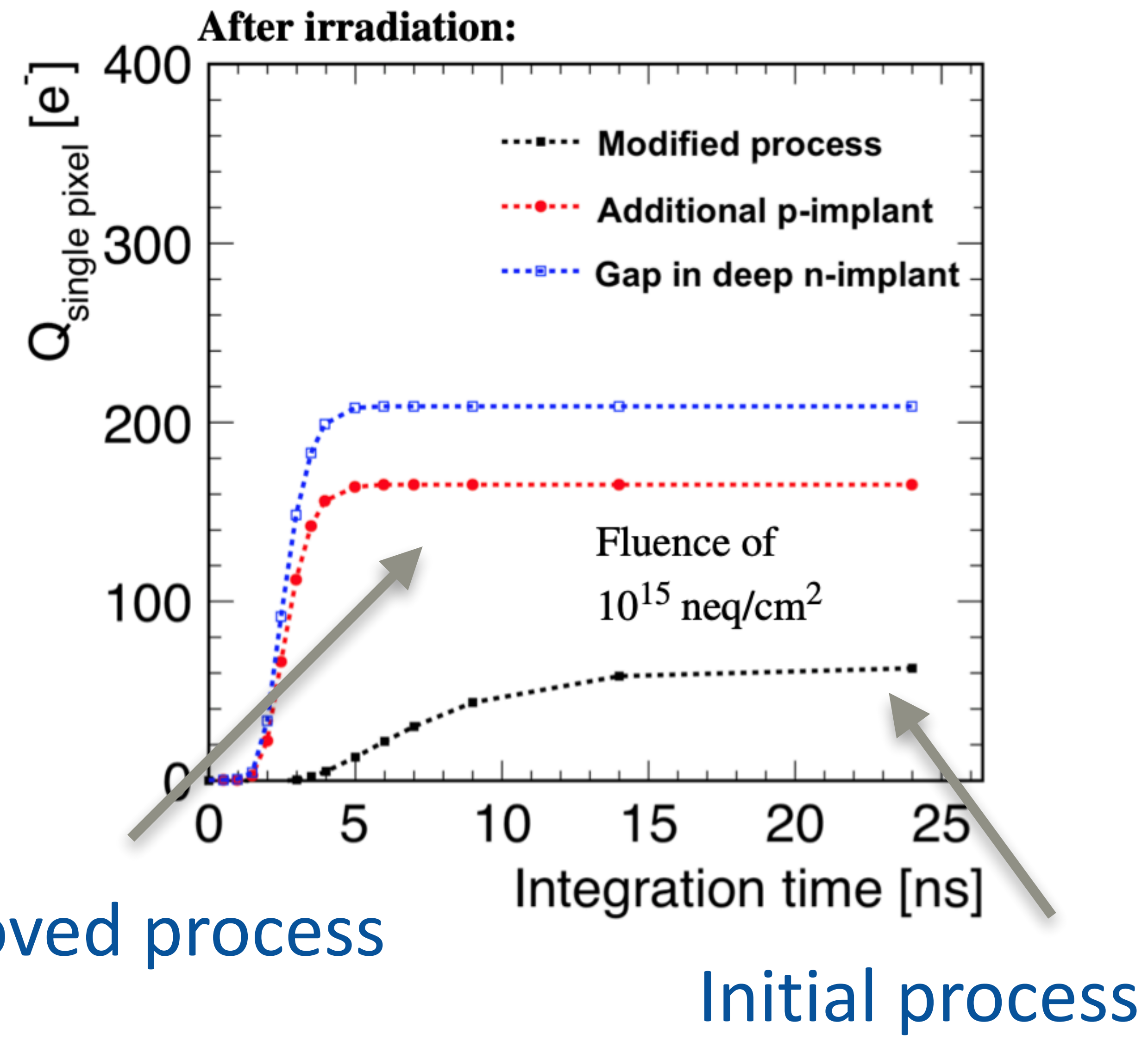




IMPROVED SENSOR DESIGN

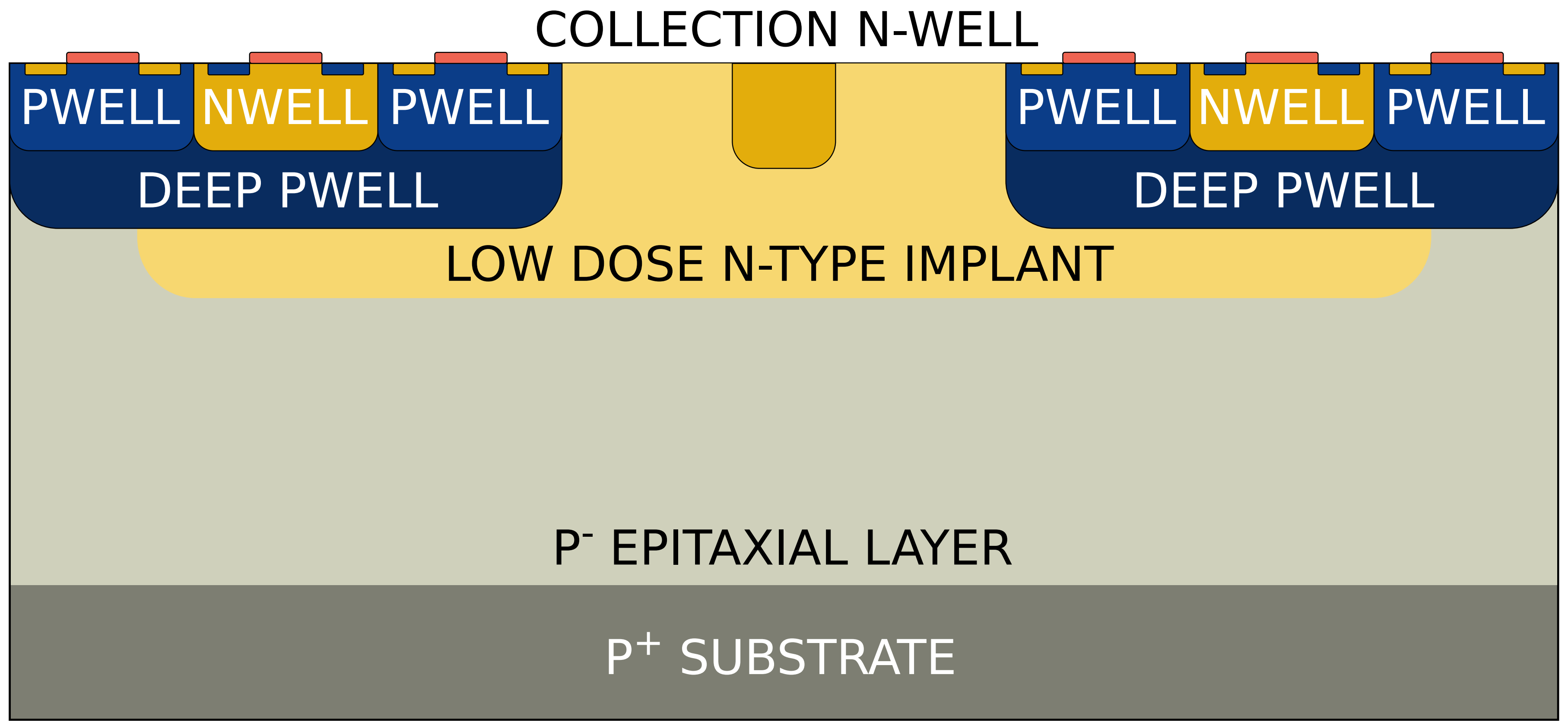
- Low electric field below deep p-well in between pixels (minimum indicated by star)
- Gap in n-type implant (or additional p-type well) below readout electronics to shape electrical field towards collection node

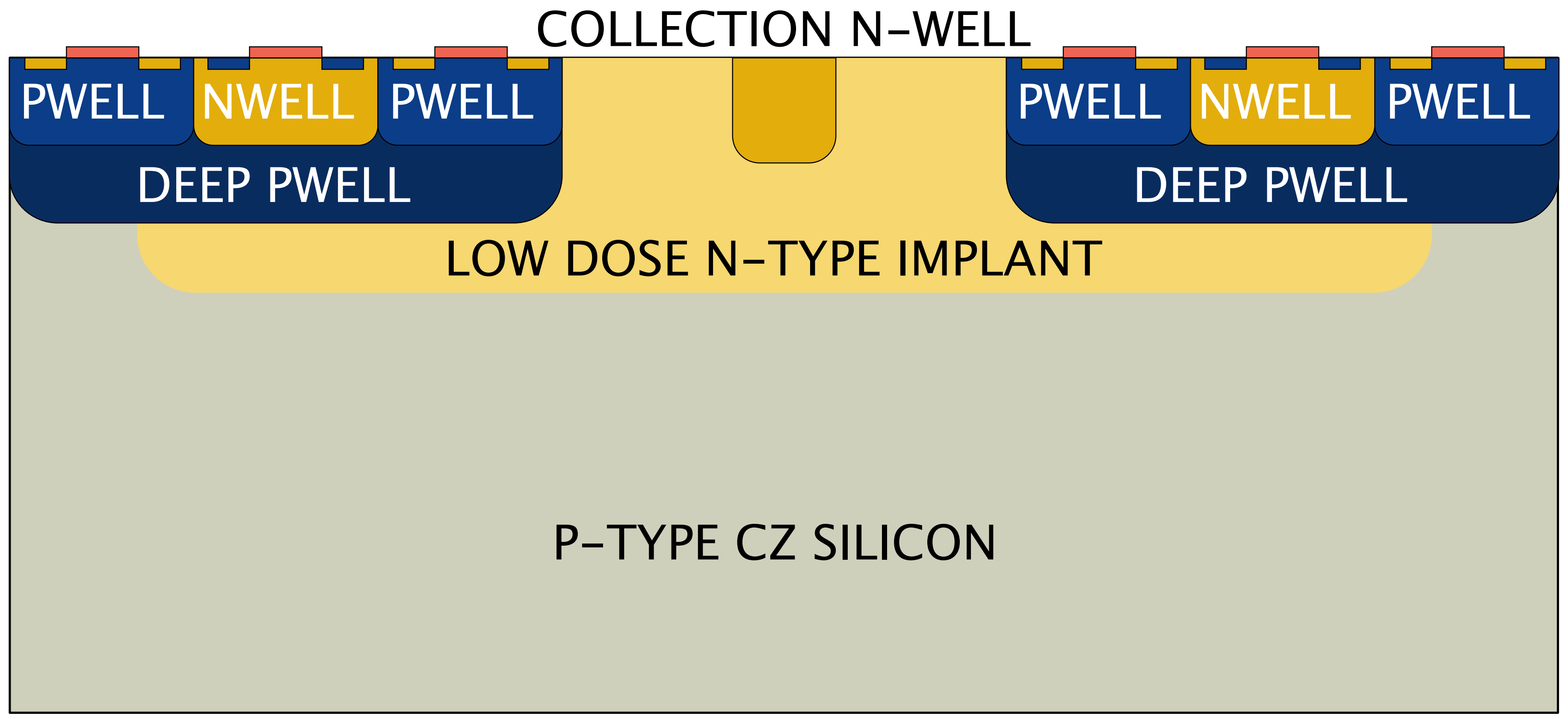




Both: doi.org/10.1088/1748-0221/14/05/C05013

- Additionally produced on Cz substrate with possibly larger volume

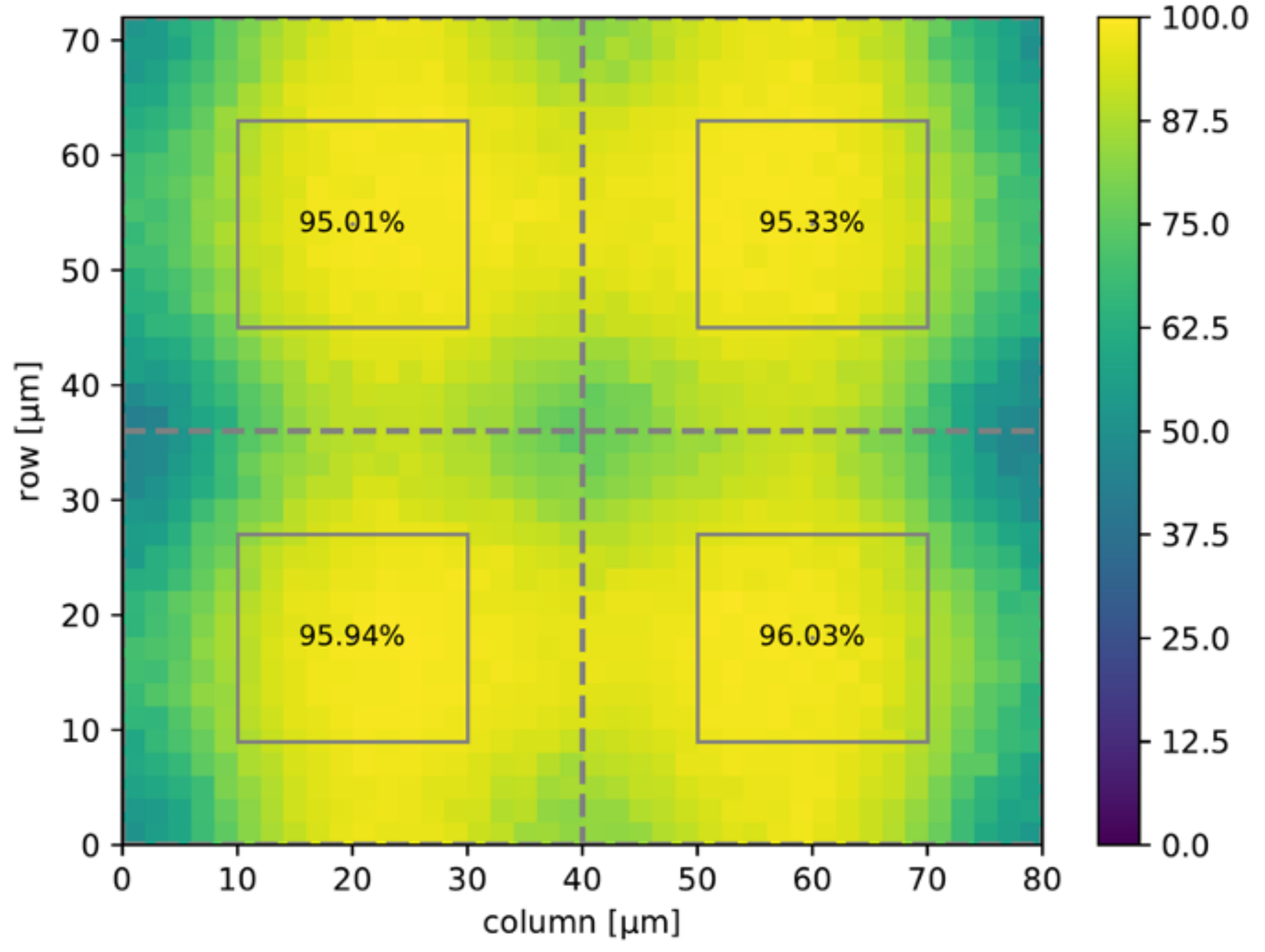




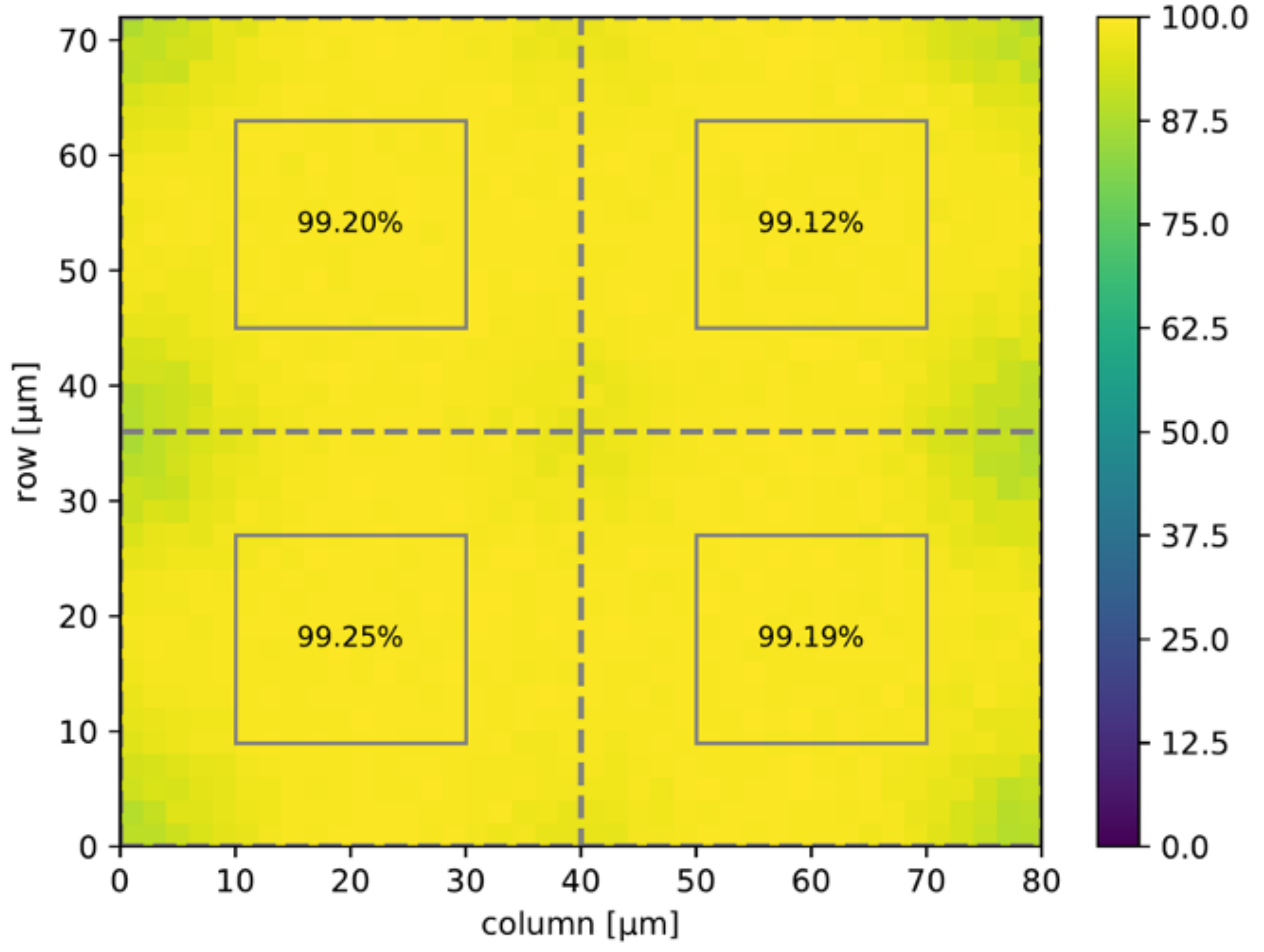
RADIATION HARDNESS NEW DESIGN

- 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

30 µm Epi: 87.1 % @ 500 e-



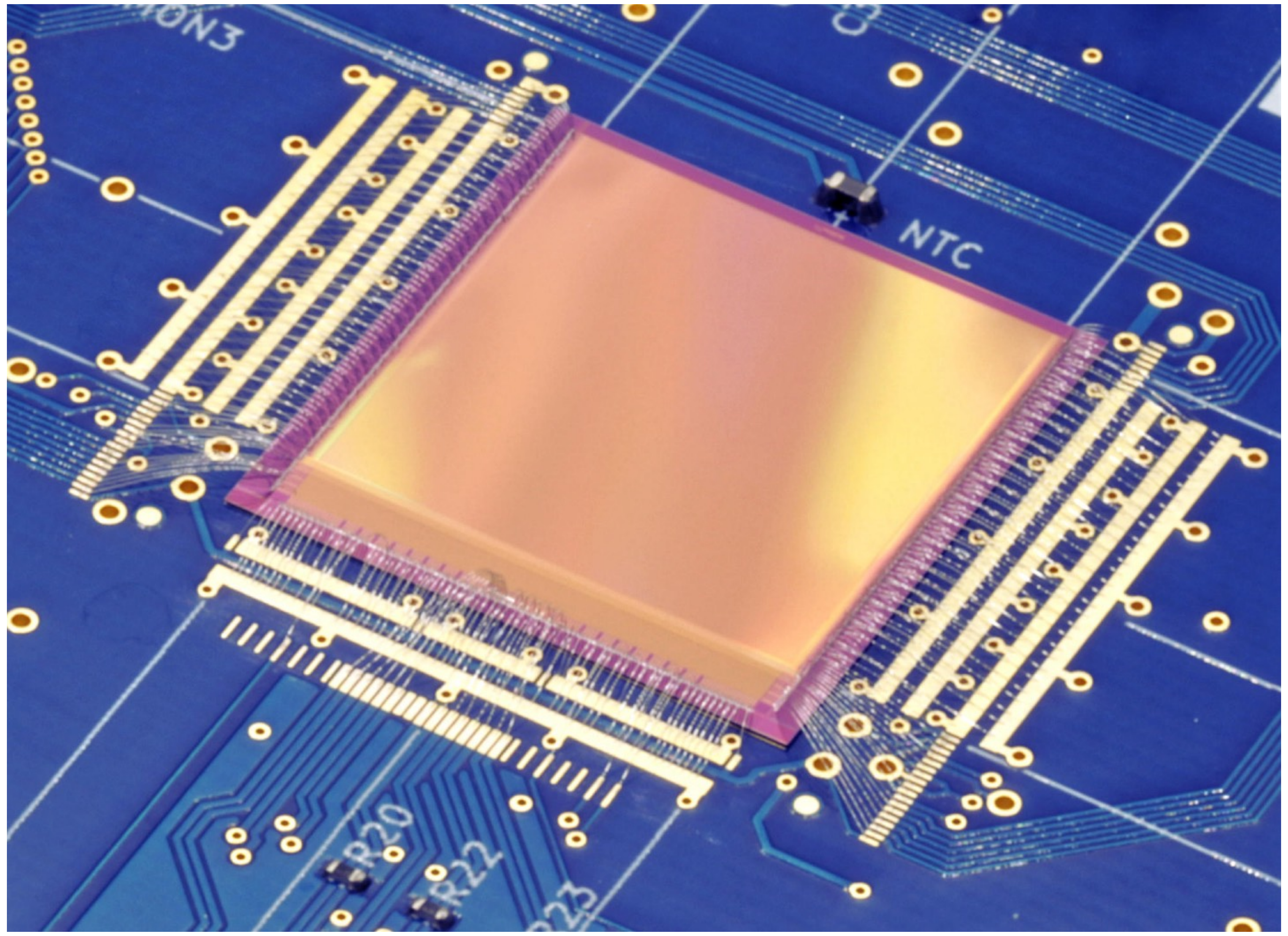
300 µm Cz: 98.6 % @ 490 e-



TJ-MONOPIX DESIGN

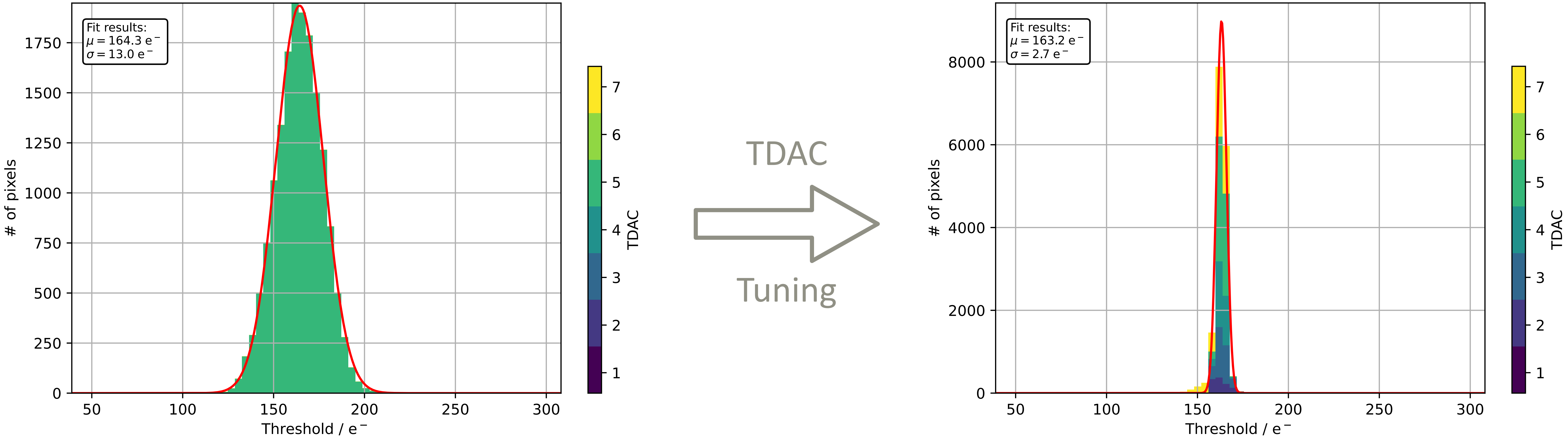
- Latest iteration TJ-Monopix2: 33.04 µm pixel pitch in 512 x 512 pixel matrix (2 x 2 cm^2)
- 7 bit TOT resolution (40 MHz BCID clock - 25 ns timing)
- 3 bit in-pixel threshold tuning
- Communication via four differential lines
  - Command-based slow control (taken from RD53B)
  - 160 MHz data output rate (frame-based 8b10b encoding)

- bdaq53 readout board (from RD53A/B testing)
- Possible multi-chip readout not implemented yet



TJ-MONOPIX2 LAB TESTS

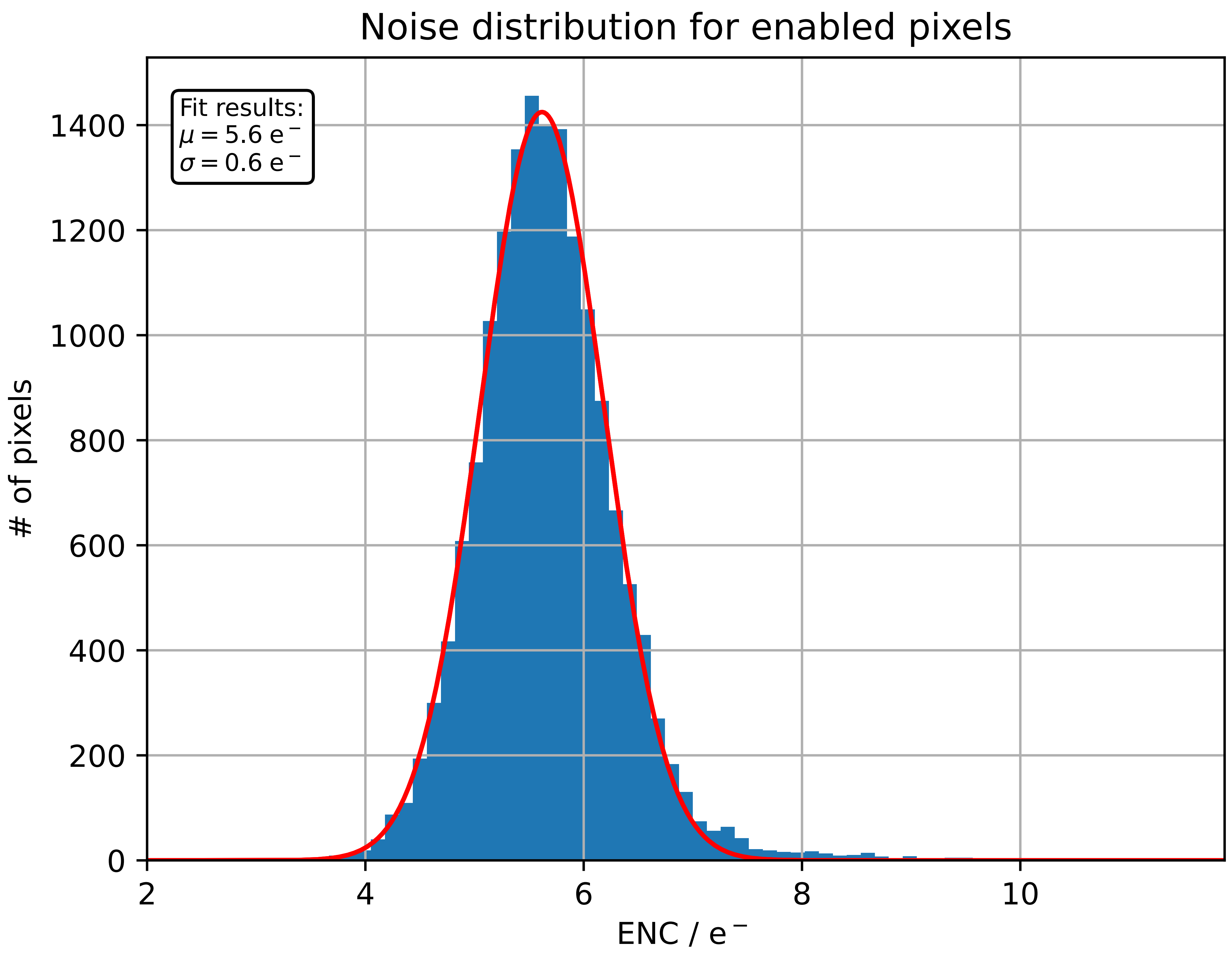
- Lab tests conducted for threshold and noise measurements
- Design goals: operational threshold ≈ 100 e^-, threshold dispersion < 10 e^-, ENC ≈ 5 e^-
- In-pixel threshold trimming (3 bit) significantly reduces threshold dispersion to less than design value
- Operational threshold higher than anticipated,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



TJ-MONOPIX2 LAB TESTS

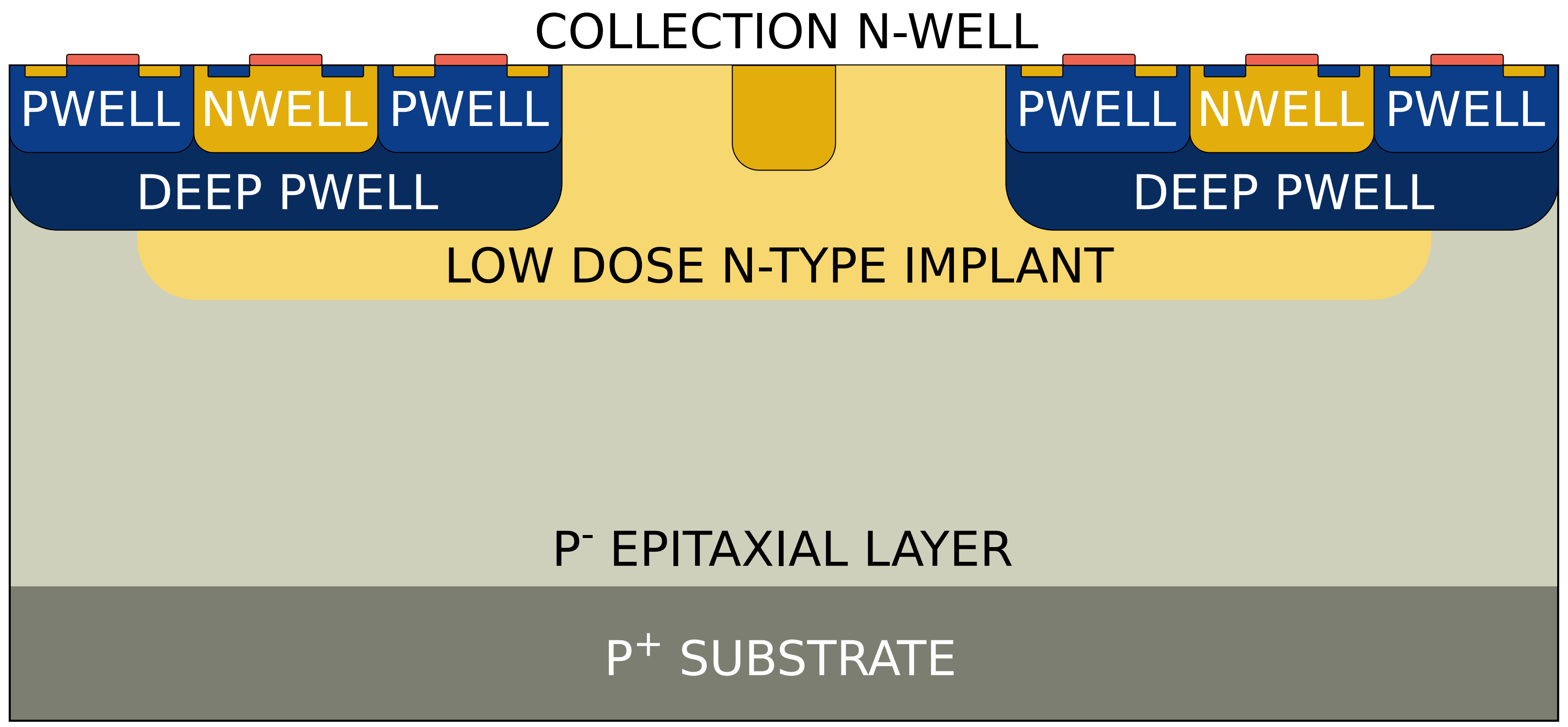
- Noise (ENC) measured from steepness of S-curve when injecting varying charges
- Mean noise 5.6 e^- in accordance with design goal
- No RTS noise tail observed as in TJ-Monopix1
- Allows operation at low thresholds thanks to large S/N ratio

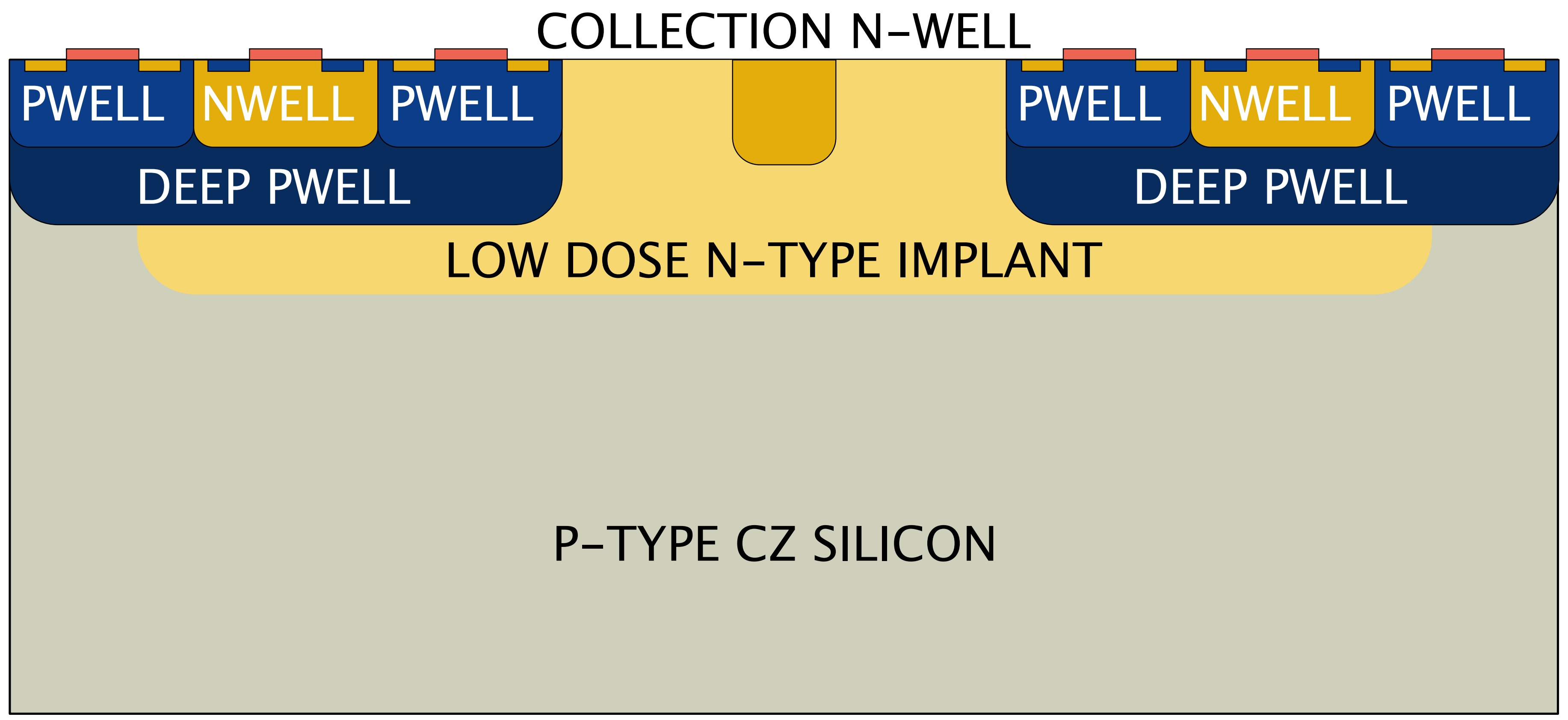
- Reminder: in TJ-Monopix1, operational threshold was O(400 e^-) which lead to efficiency losses in pixel corners, especially after irradiation



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^-

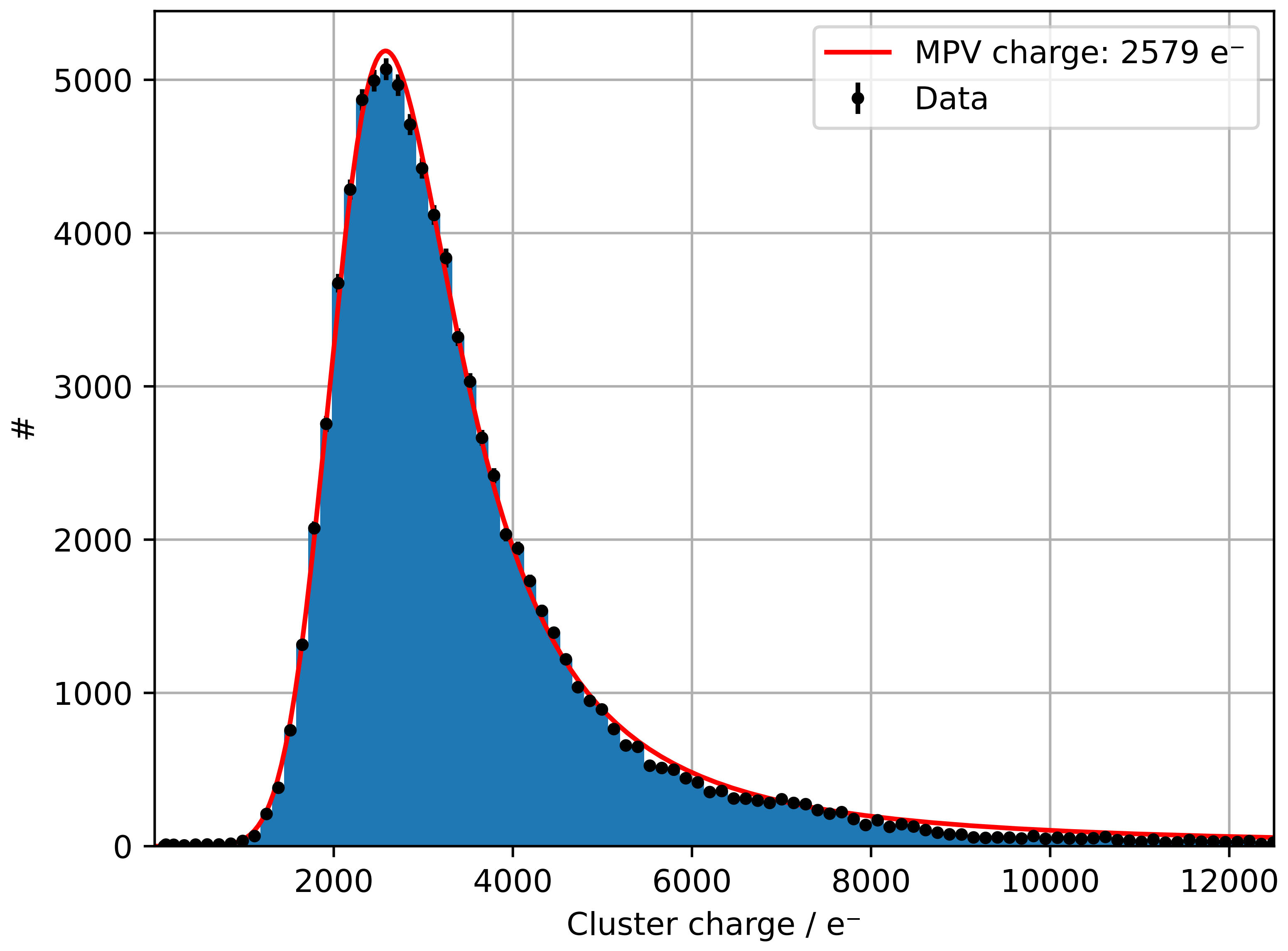




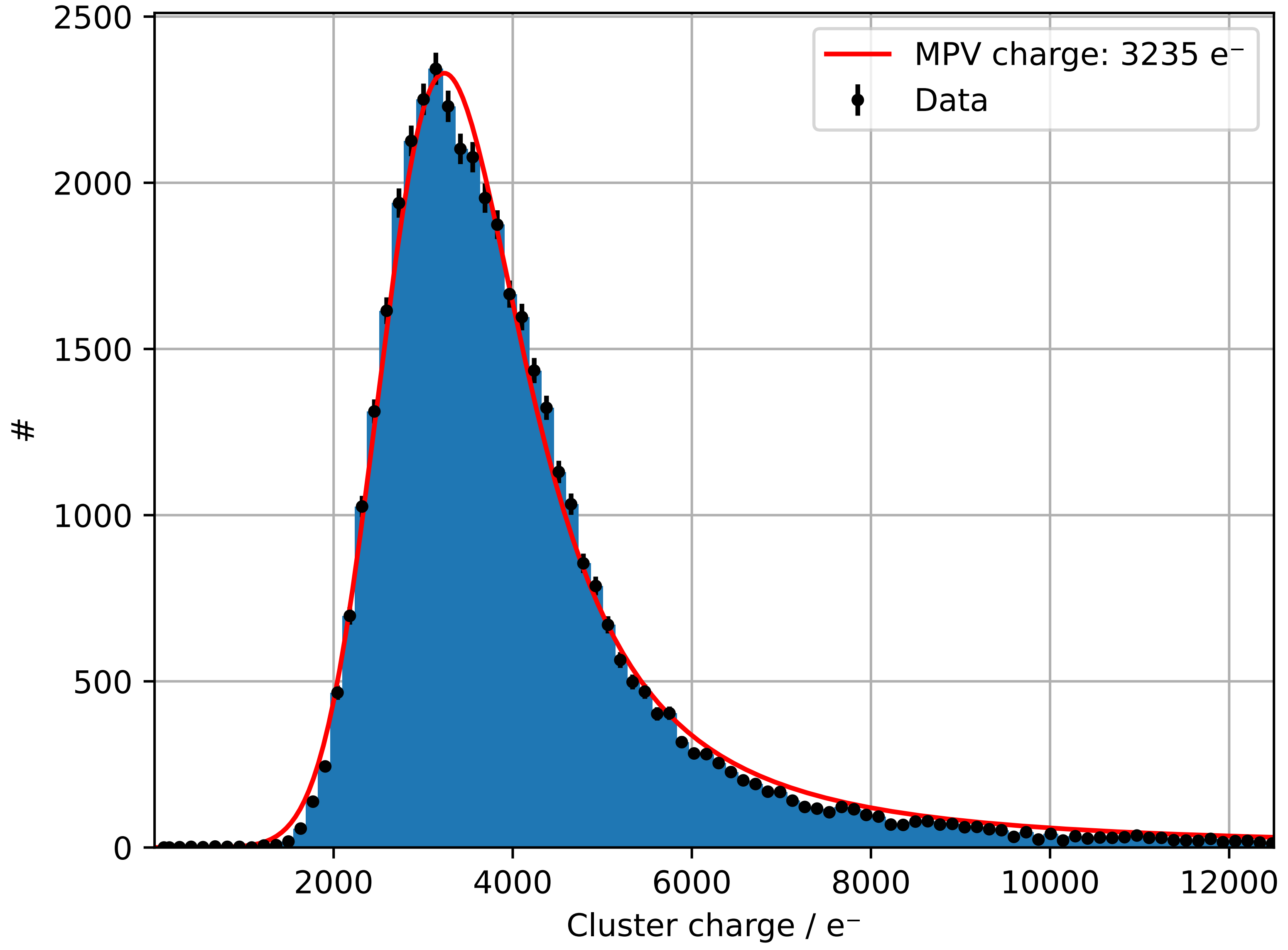
TJ-MONOPIX2 CLUSTER CHARGE

- 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⁻



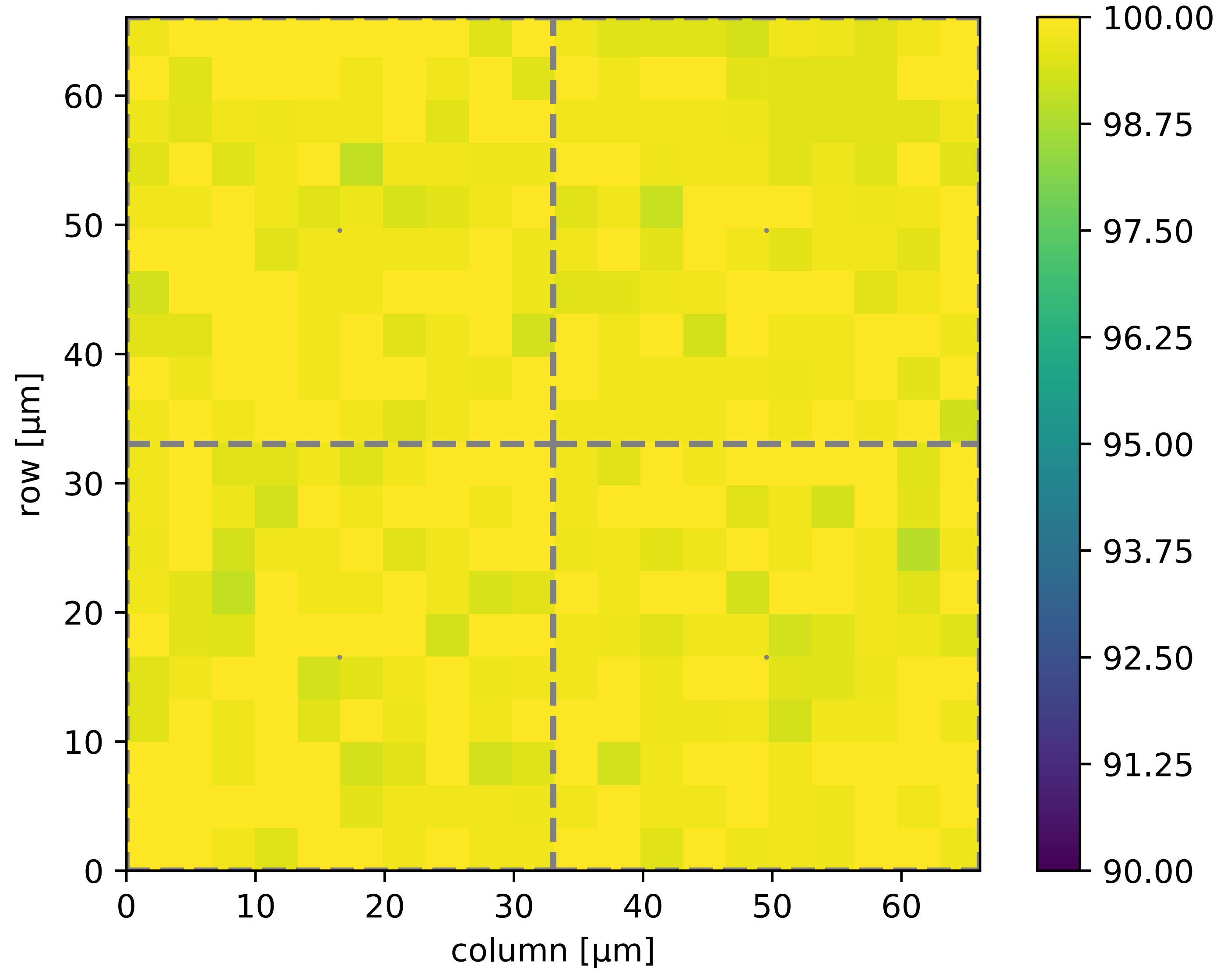
Cz gap in n-layer (100 µm): 3235 e⁻



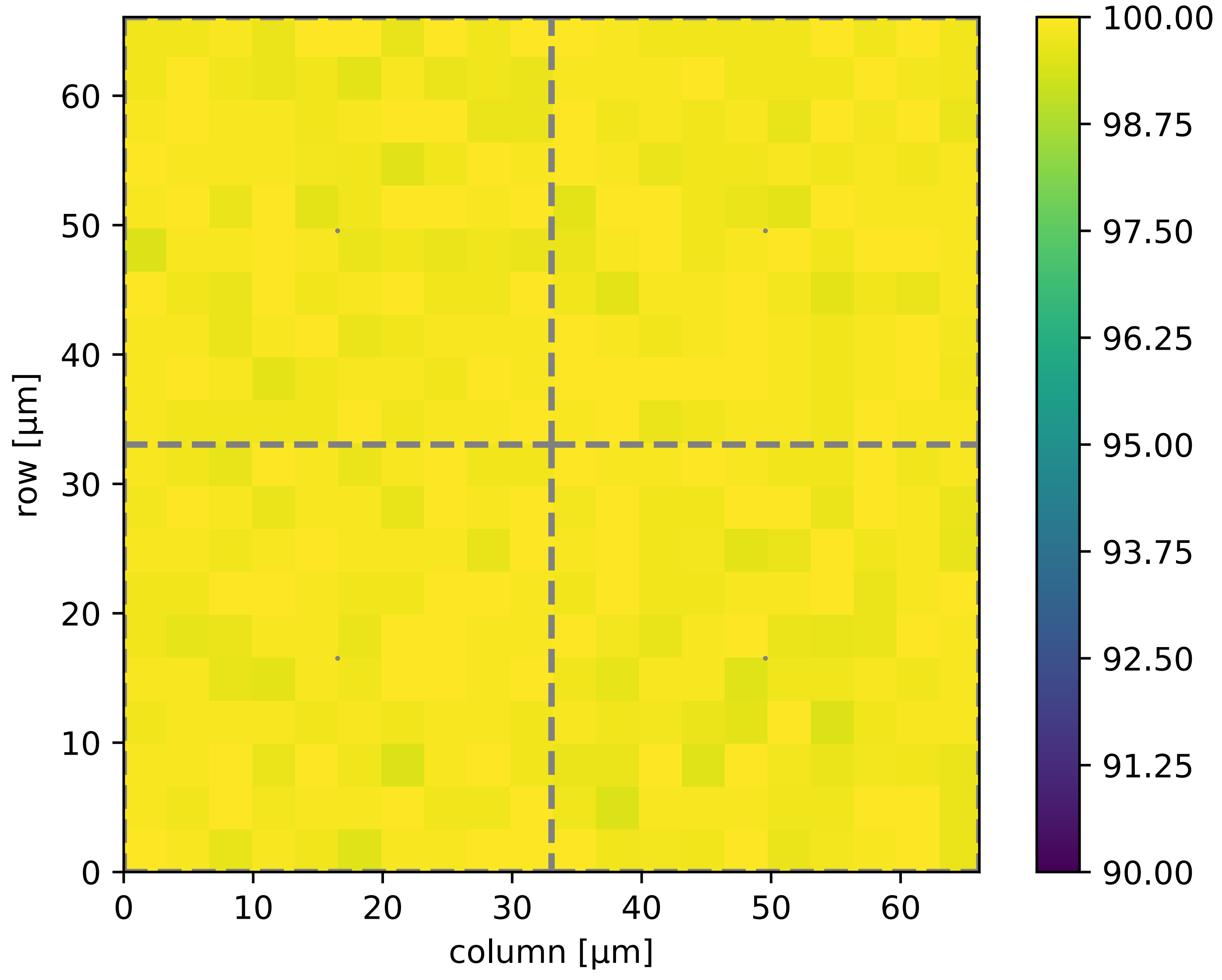
TJ-MONOPIX2 EFFICIENCY

- 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 %



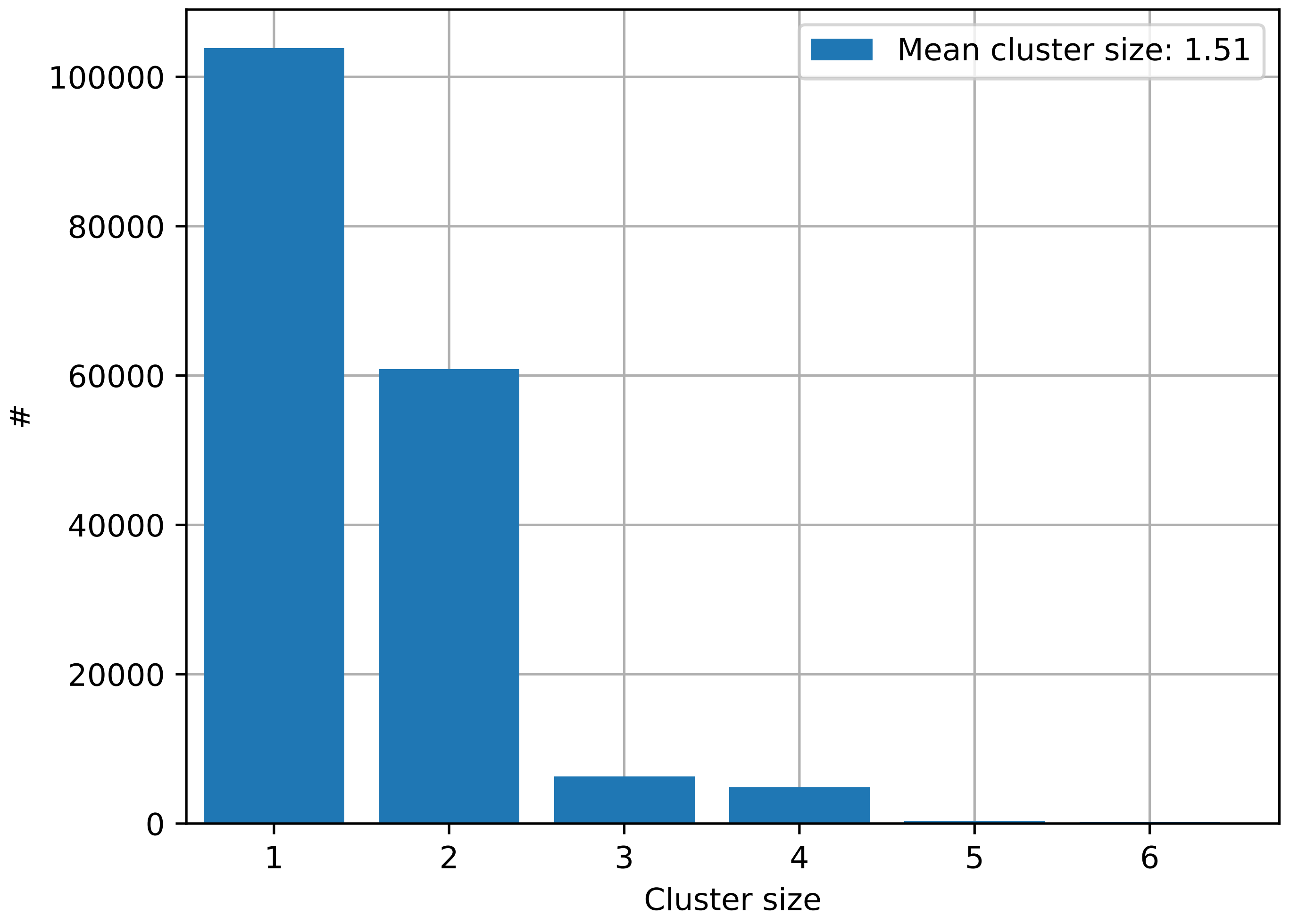
Cz gap in n-layer (100 µm): 99.79 %



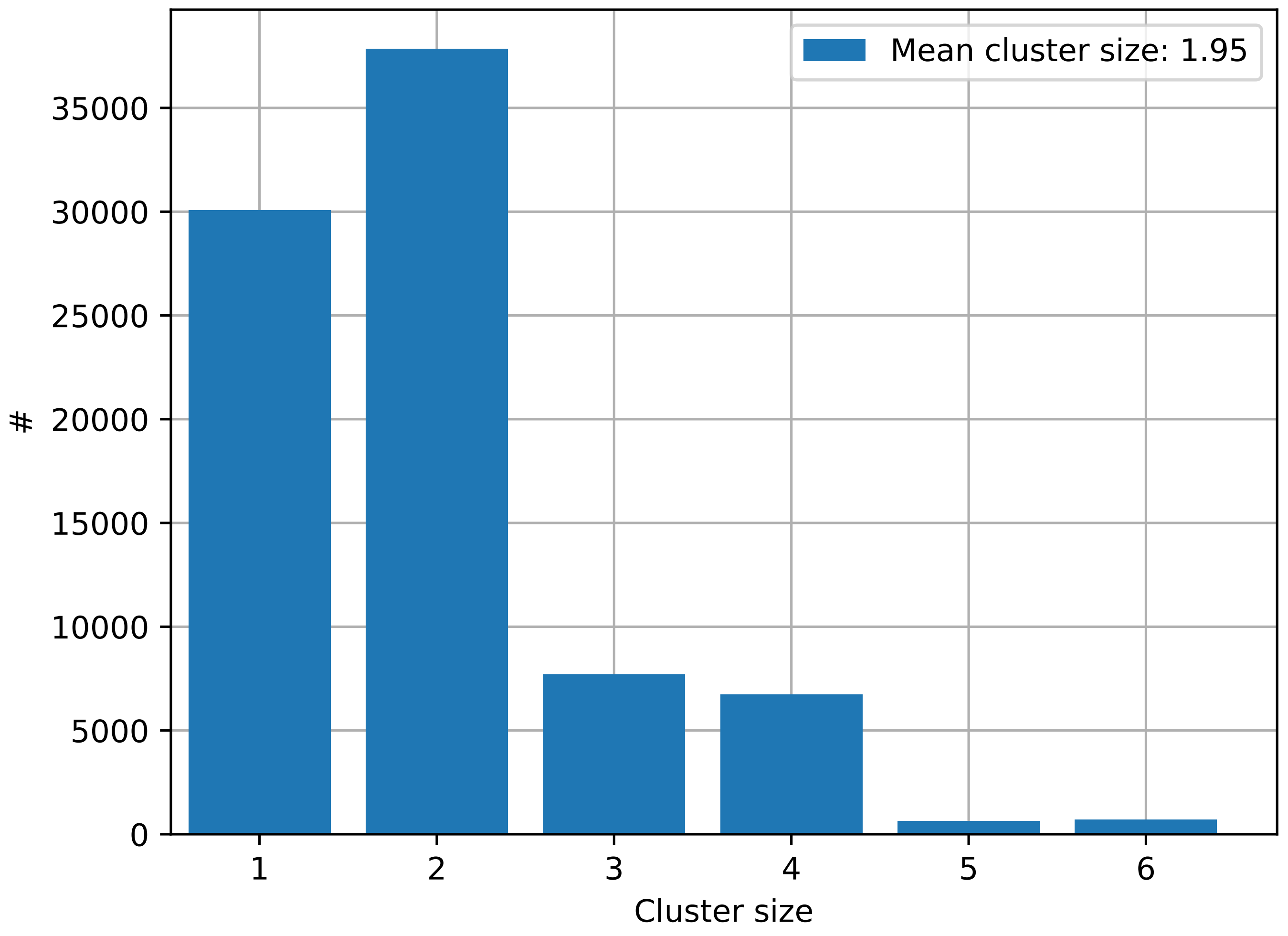
TJ-MONOPIX2 CLUSTER CHARGE

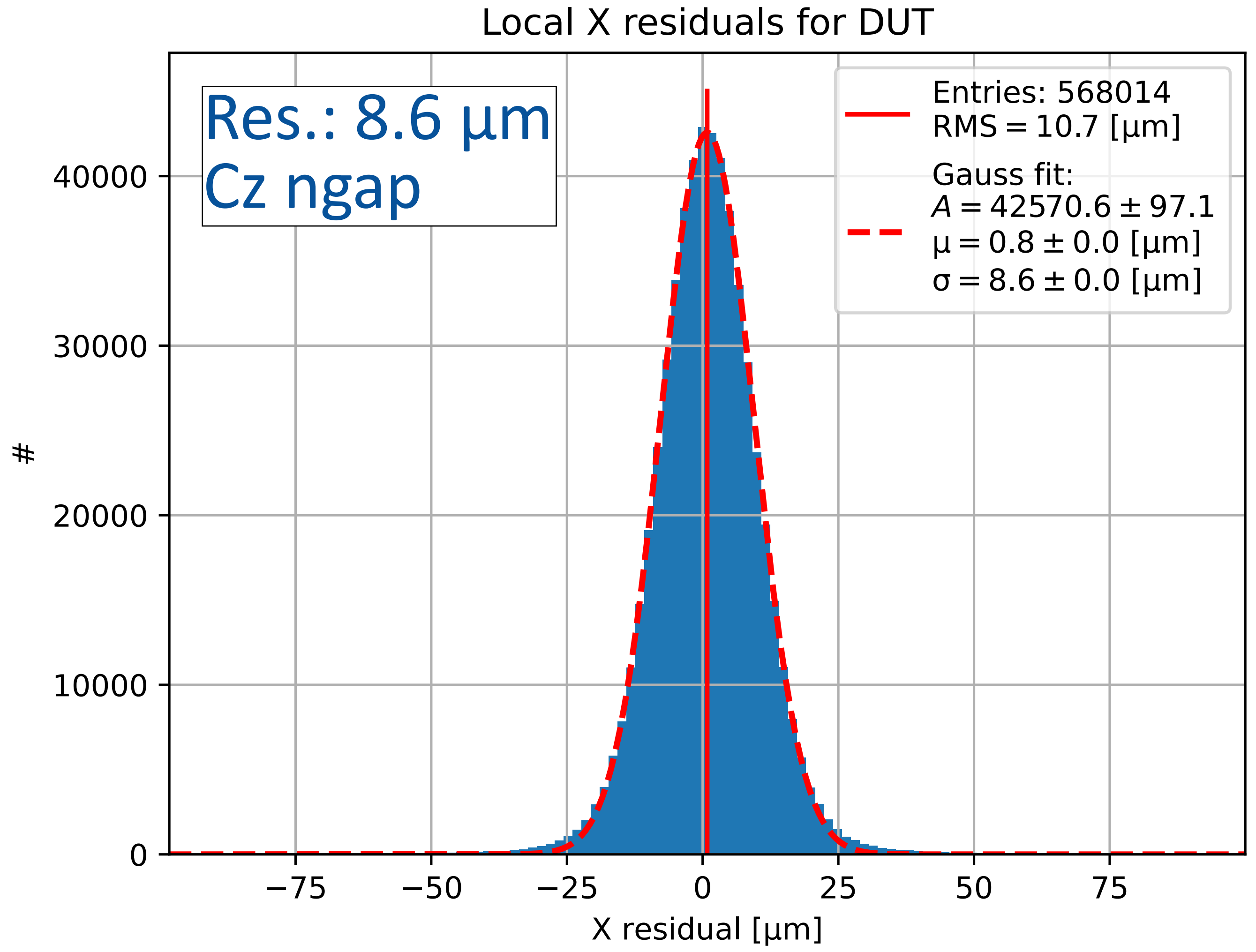
- Compare different sensor materials (epi 30 µm / Cz 100 µm) regarding cluster size
- As expected from accumulated charge and higher depletion than 30 µm cluster size is significantly larger in 100 µm silicon (not fully depleted)
- High (average) cluster size allows for high spatial resolution; better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

Epi gap in n-layer: 1.51



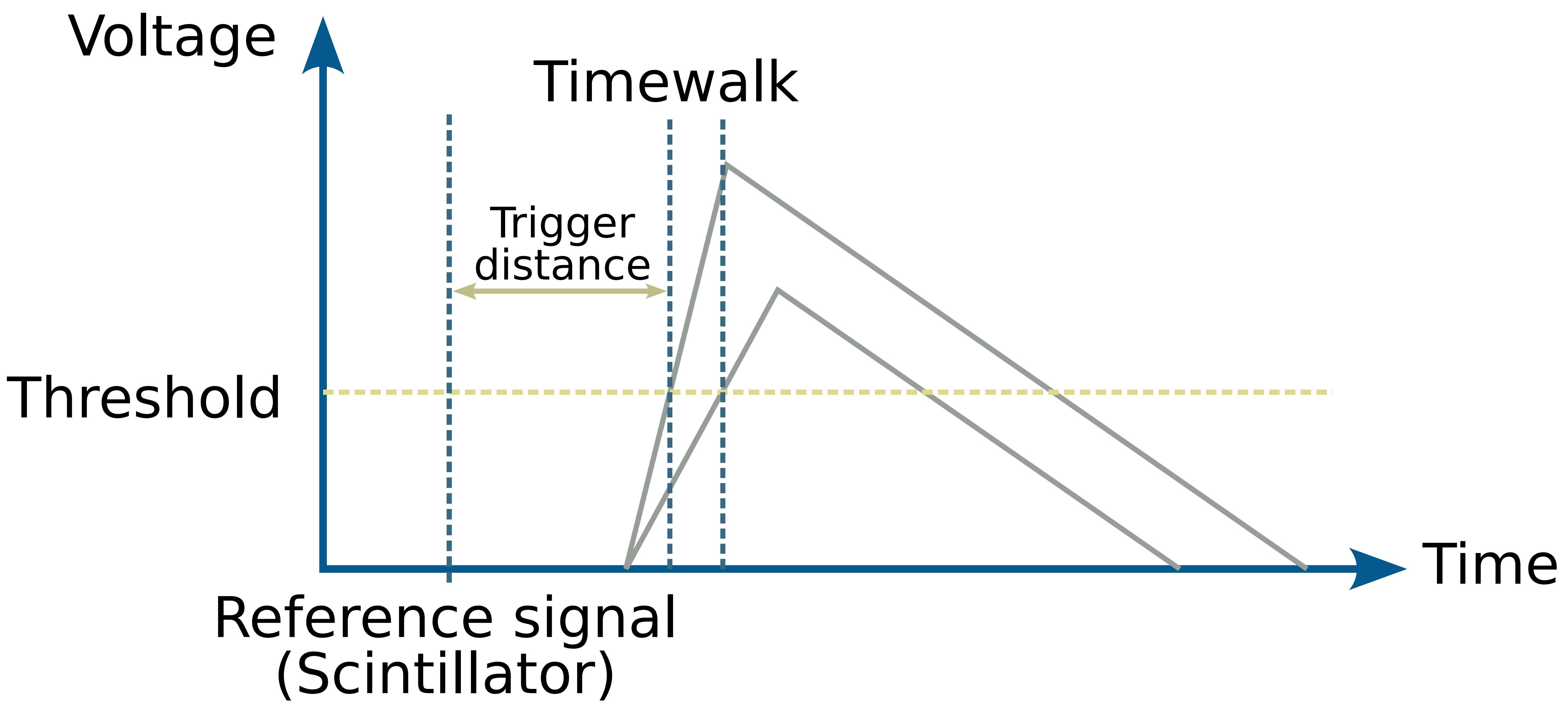
Cz gap in n-layer: 1.95

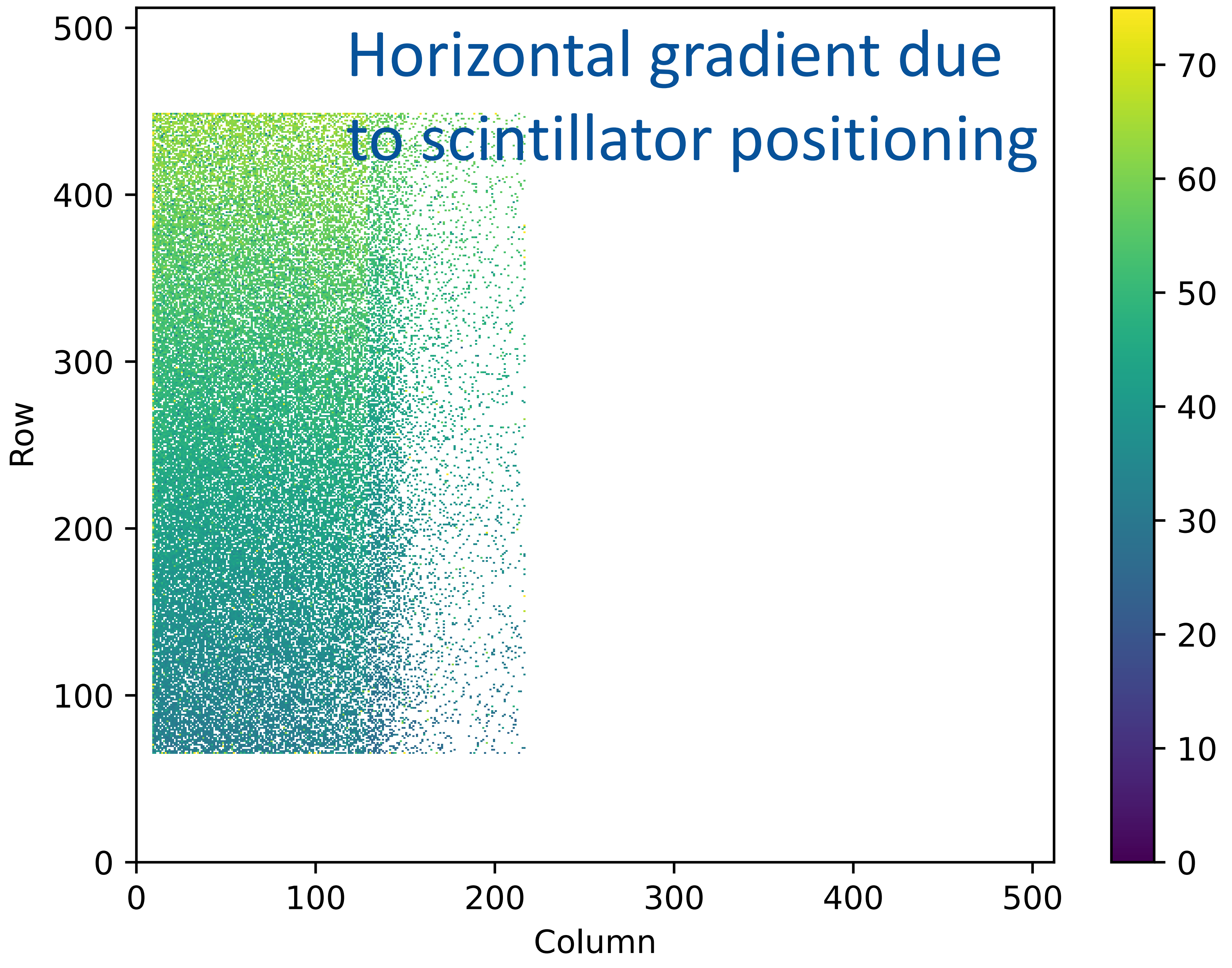




TIMING IN BEAM

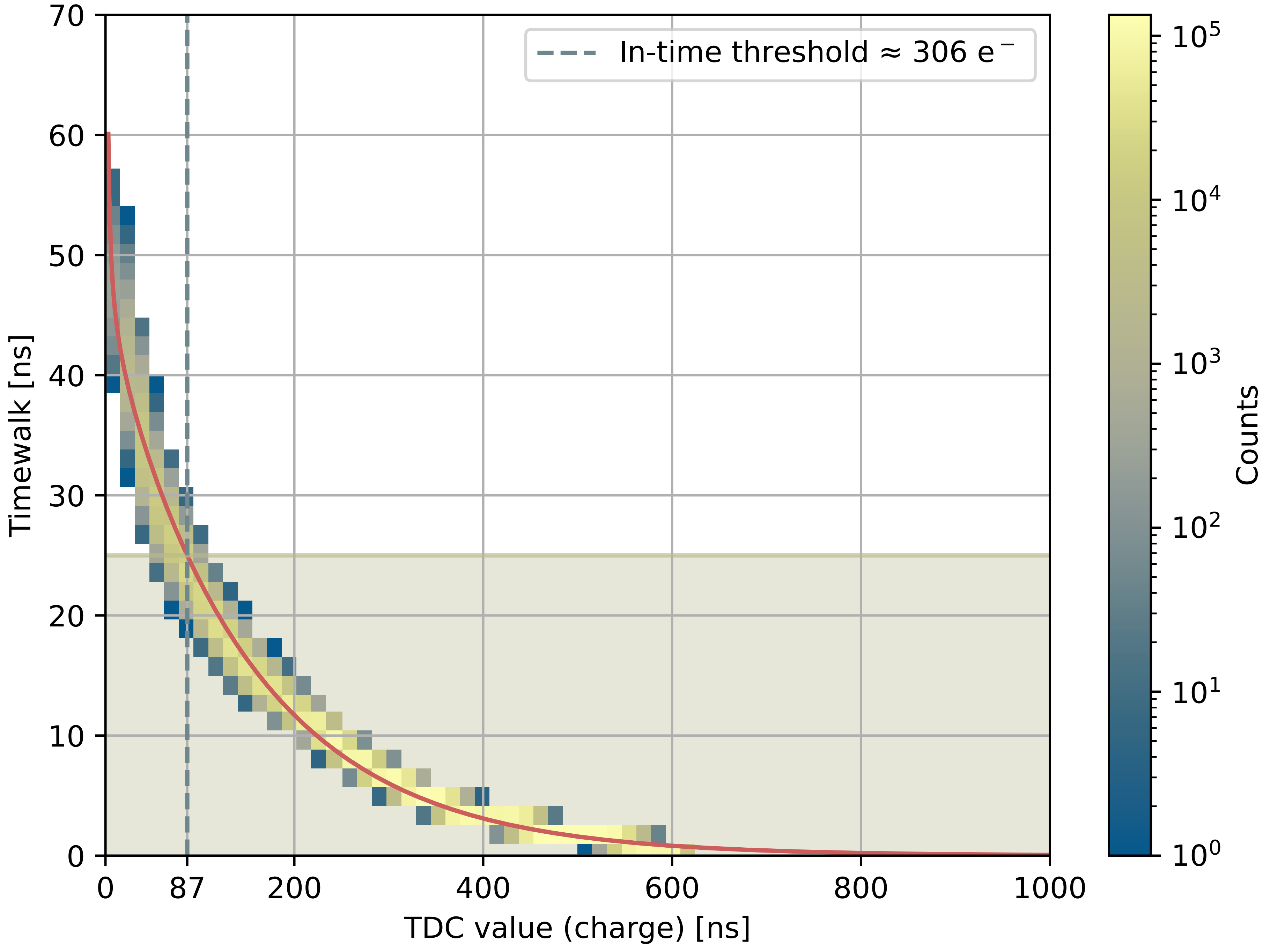
- Beam tests performed at DESY (03/2023)
- Measure time between scintillator hit and HITOR word from in-pixel discriminator
- Delay gradient along column due to signal propagation –> investigate for possible correction





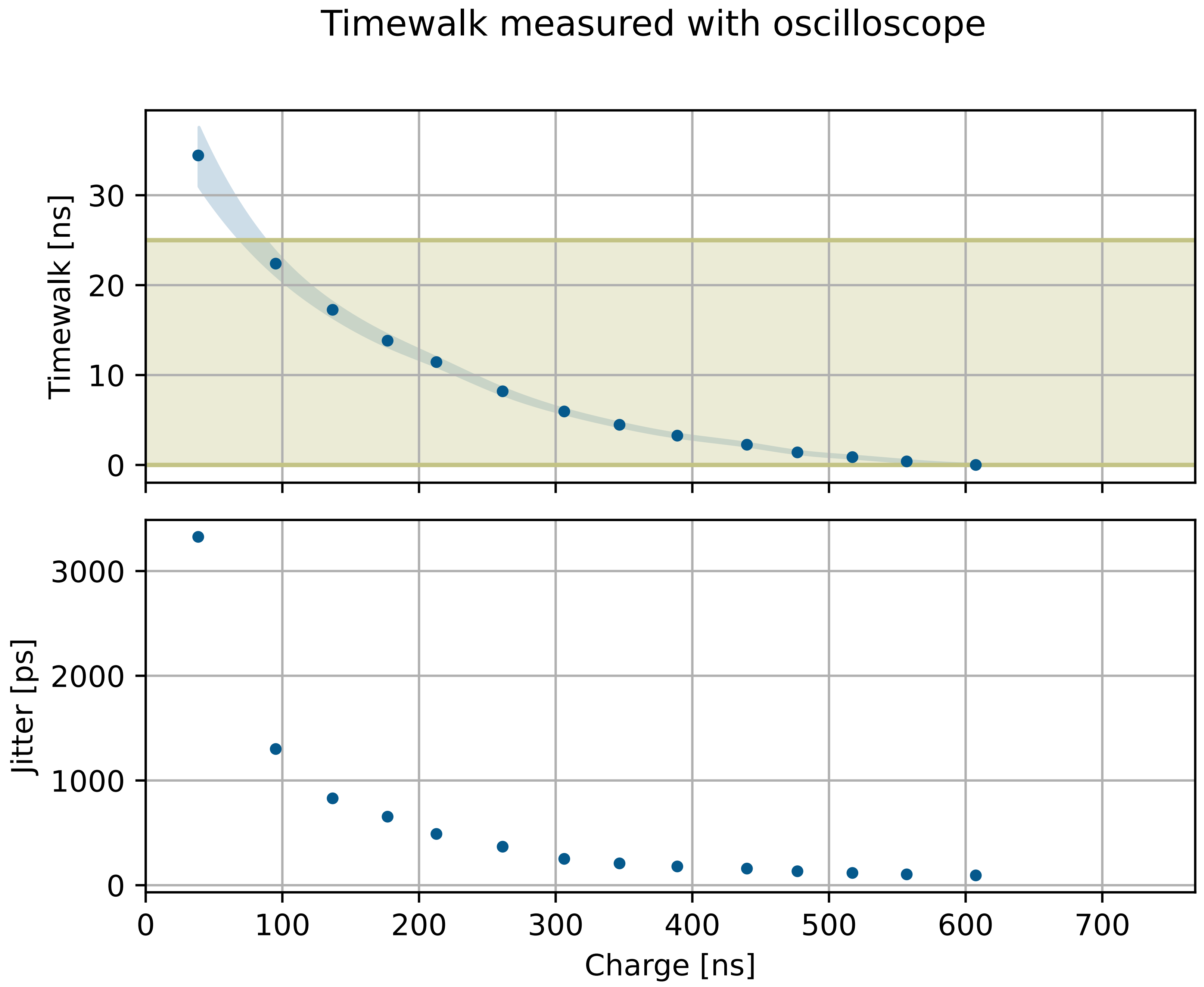
SINGLE PIXEL

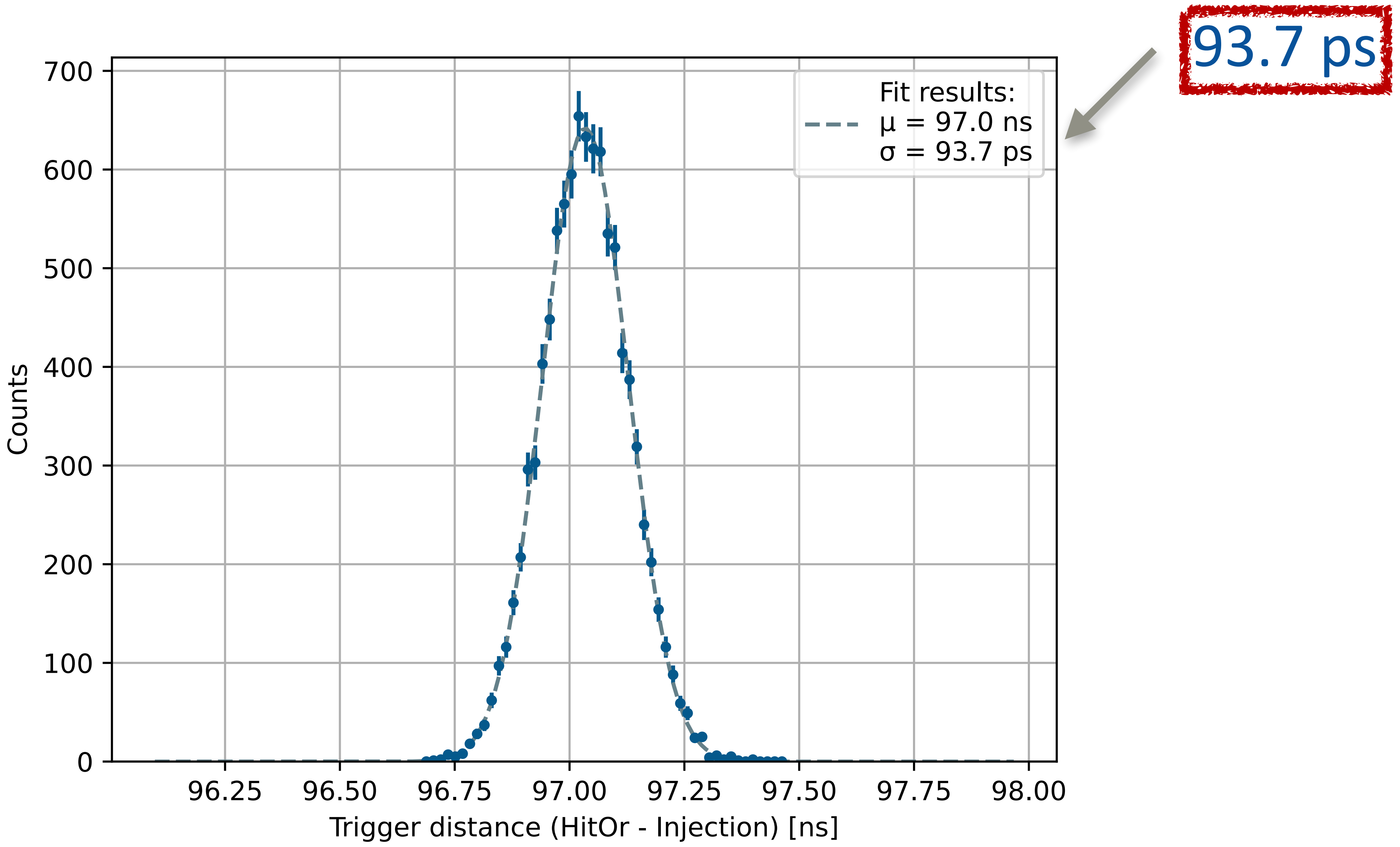
- Test single pixels with injection and HitOr
- Performed detailed study of time walk and more
- Charge injection circuit limits measurement range, extrapolate to plateau region which defines 25 ns window
- In-time threshold for these front-end settings:
  - 306e, with threshold tuned to 240e (lowest achievable at these front-end settings in test beam)



SINGLE PIXEL JITTER

- Also checked jitter, but: measurement with FPGA TDC running on 640 MHz clock is too slow for low jitter as expected in TJ-Monopix2
- Fall back to analog output on oscilloscope (one specific pixel only, different from digitally measured one)





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
- In-time threshold (not minimal one) at 300 e^- for given threshold of 240 e^-
- Neutron irradiated sensors available very recently, beam time in Q4 planned

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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