H2M: Porting a hybrid readout architecture into a monolithic 65 nm CIS

Rafael Ballabriga, Eric Buschmann, Michael Campbell, Raimon Casanova Mohr, Dominik Dannheim, Ana Dorda, Finn King, Ono Feyens, Philipp Gadow, Ingrid-Maria Gregor, Karsten Hansen, Yajun He, Lennart Huth, Iraklis Kremastiotis, Corentin Lemoine, Stefano Maffessanti, Larissa Mendes, Younes Otarid, Christian Reckleben, Sebastien Rettie, Manuel Alejandro del Rio Viera, **Sara Ruiz Daza**, Judith Schlaadt, Adriana Simancas, Walter Snoeys, Simon Spannagel, Peter Svihra, Tomas Vanat, Anastasiia Velyka, Gianpiero Vignola, Håkan Wennlöf

PIXEL (Strasbourg, France)

21 November 2024

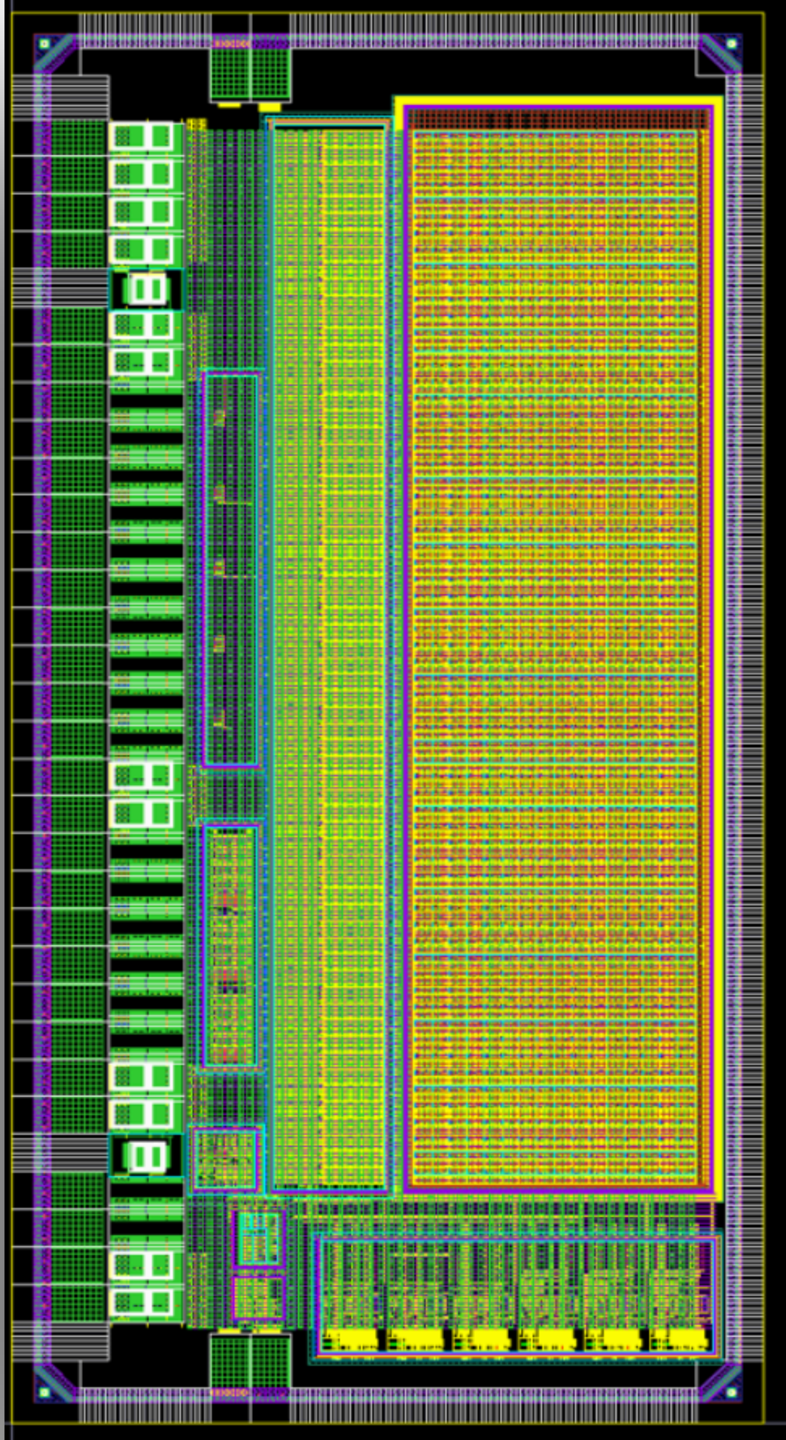
EP R&D

Institut de Física d'Altes Energies

HELMHOLTZ

UNIVERSITÄT BONN

DESY.

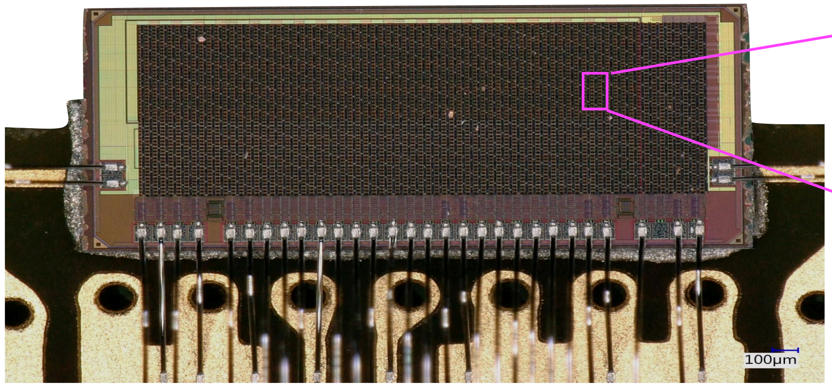


H2M (Hybrid-to-Monolithic)

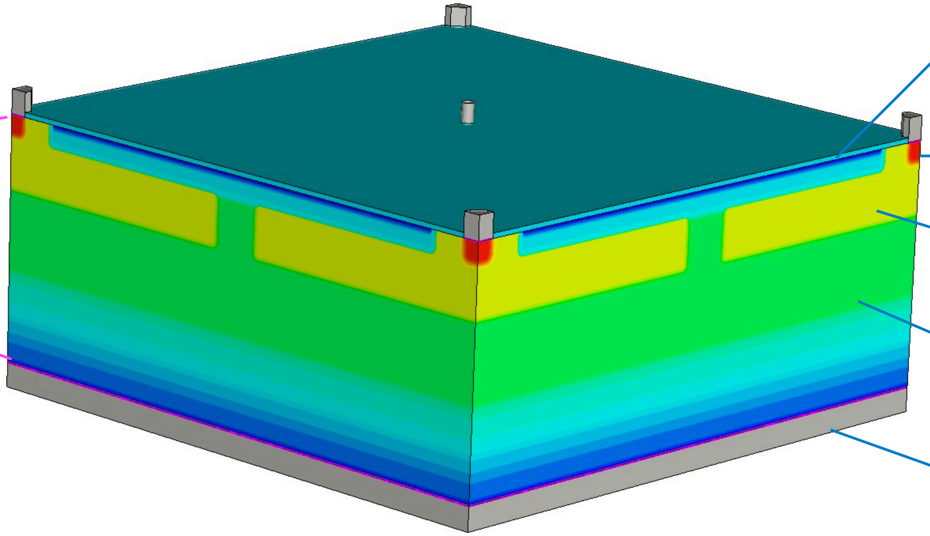
Vertex detector requirements:

- ➢ Sensor thickness: ⩽ 50 μm
- ➢ Spatial resolution: ⩽ 3 μm
- ➢ Time resolution: ~ ns

- Developed within the framework of **R&D for future lepton colliders and test beam telescopes**.
- Ports a **hybrid pixel detector architecture into a monolithic chip**.
- **Digital-on-top** design workflow.
- Manufactured in a modified TPSCo **65 nm CMOS imaging process**.

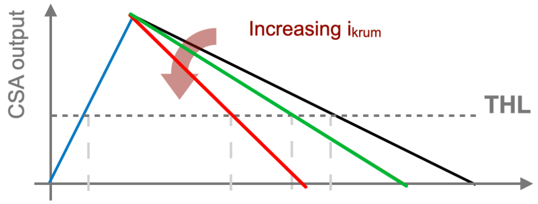


Active area outside of the chipboard to reduce material budget

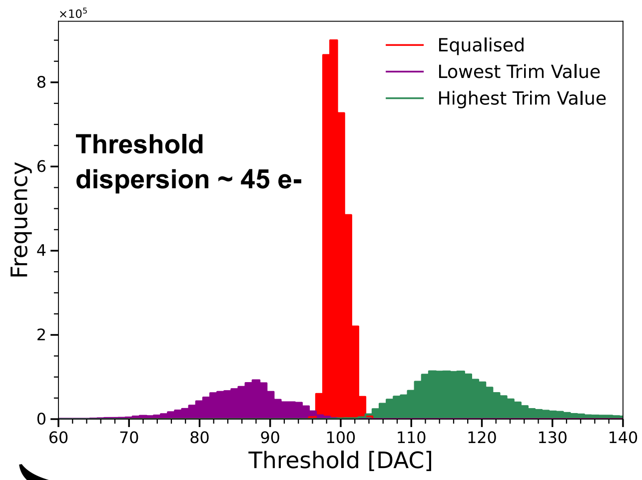


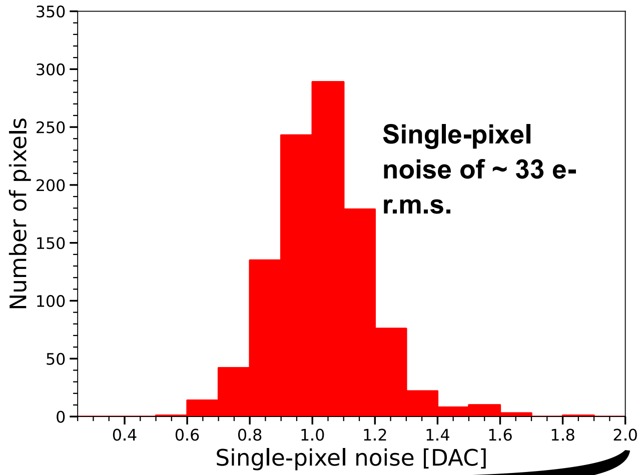
- **35 μm pixel pitch in 64x16 pixel matrix** (total sensitive area: 2.24 × 0.56 mm²). Total thickness ~ 50 μm (p-epi ~ 10 μm).
- **Analog and digital front-end per pixel**.

Analog front-end design



Constant slope of falling edge tuned with Krummenacher feedback current (**ikrum**).





Charge sensitive amplifier with Krummenacher feedback

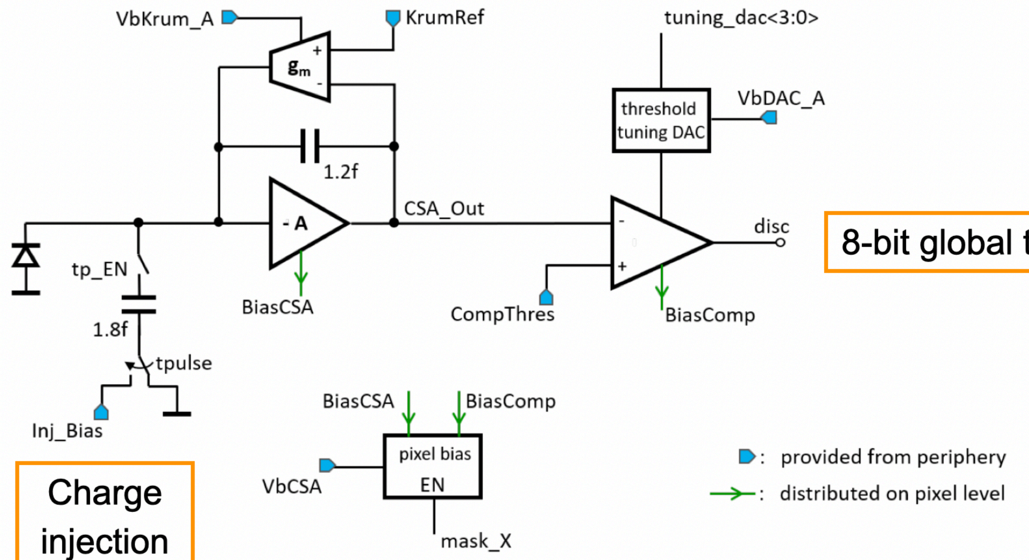
4-bit in-pixel trimming DAC → threshold mismatch compensation

Sensor diode

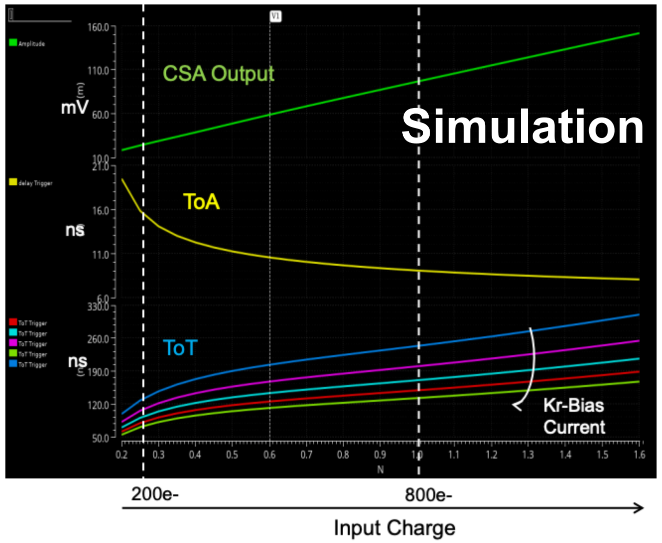
8-bit global threshold DAC

Charge injection

Pixel enable/ disable



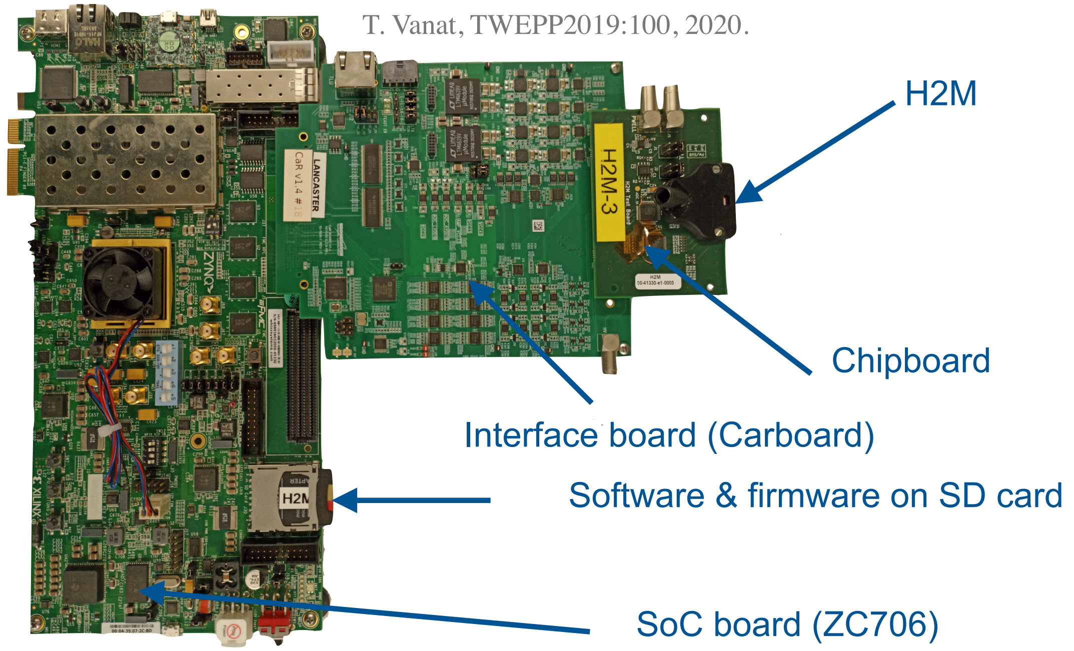
ToA/ToT as function of input charge



https://h2m-chip.docs.cern.ch/

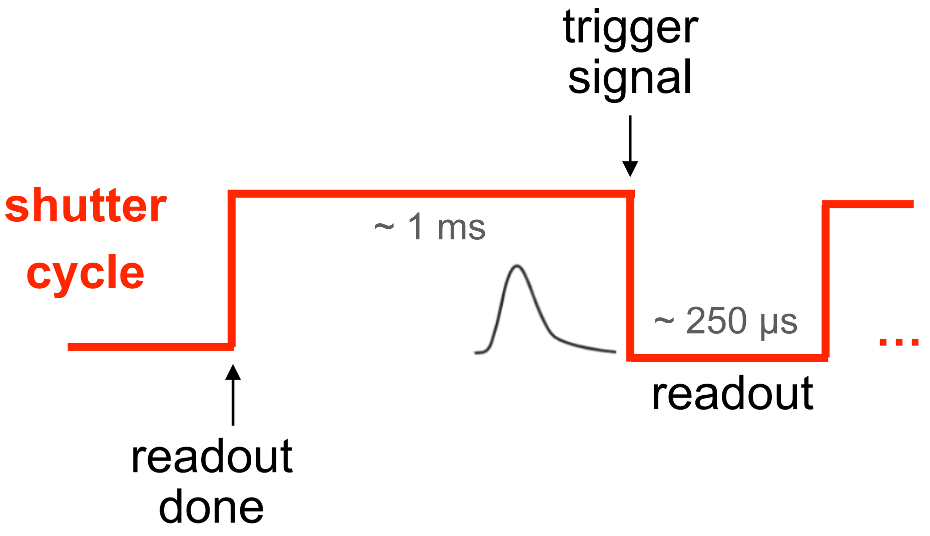
- **Time walk below 10 ns** for input charges larger than 400 electrons expected from **analog FE simulations**.

Data acquisition



T. Vanat, TWEPP2019:100, 2020.

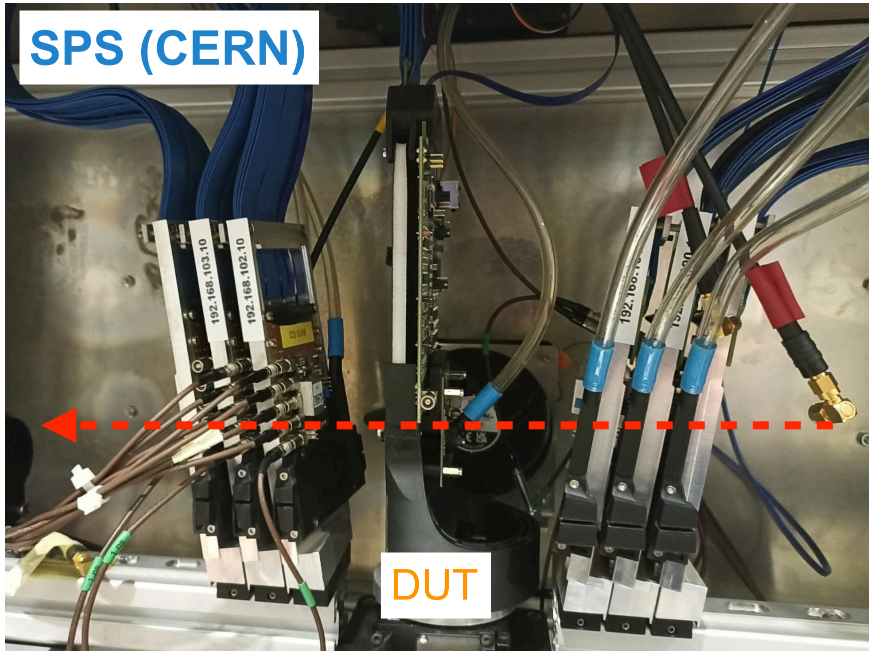
- **Non-simultaneous 4 acquisition modes**:
  - 8 bit ToT,
  - 8 bit ToA (100 MHz clock - 10 ns binning),
  - photon counting (number of hits above threshold),
  - triggered.



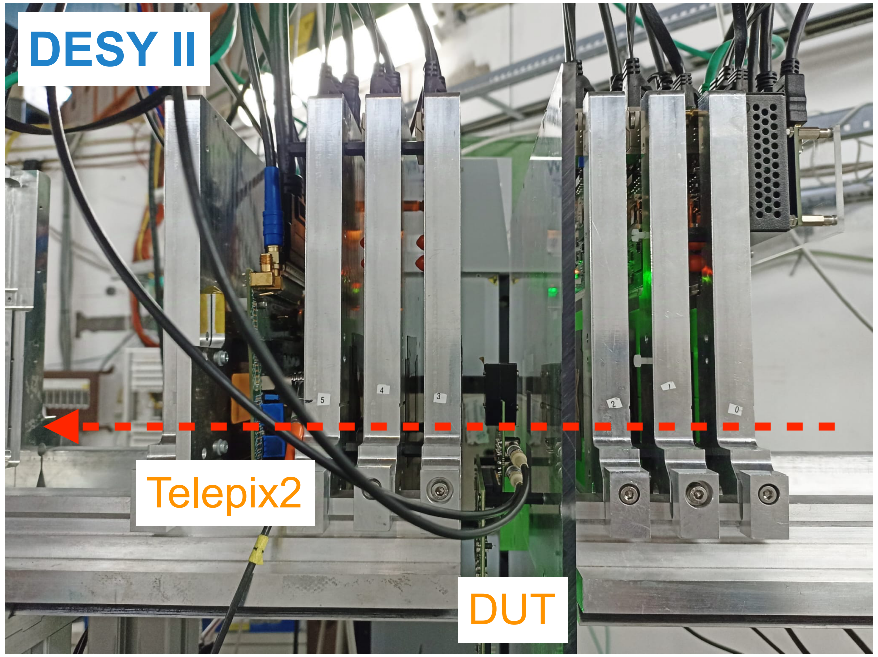
- **Readout**: 40 MHz clock, frame-based without zero-suppression.
- Integrated into the **Caribou DAQ system**.

↪See poster by Younes Otarid

Test beam campaings



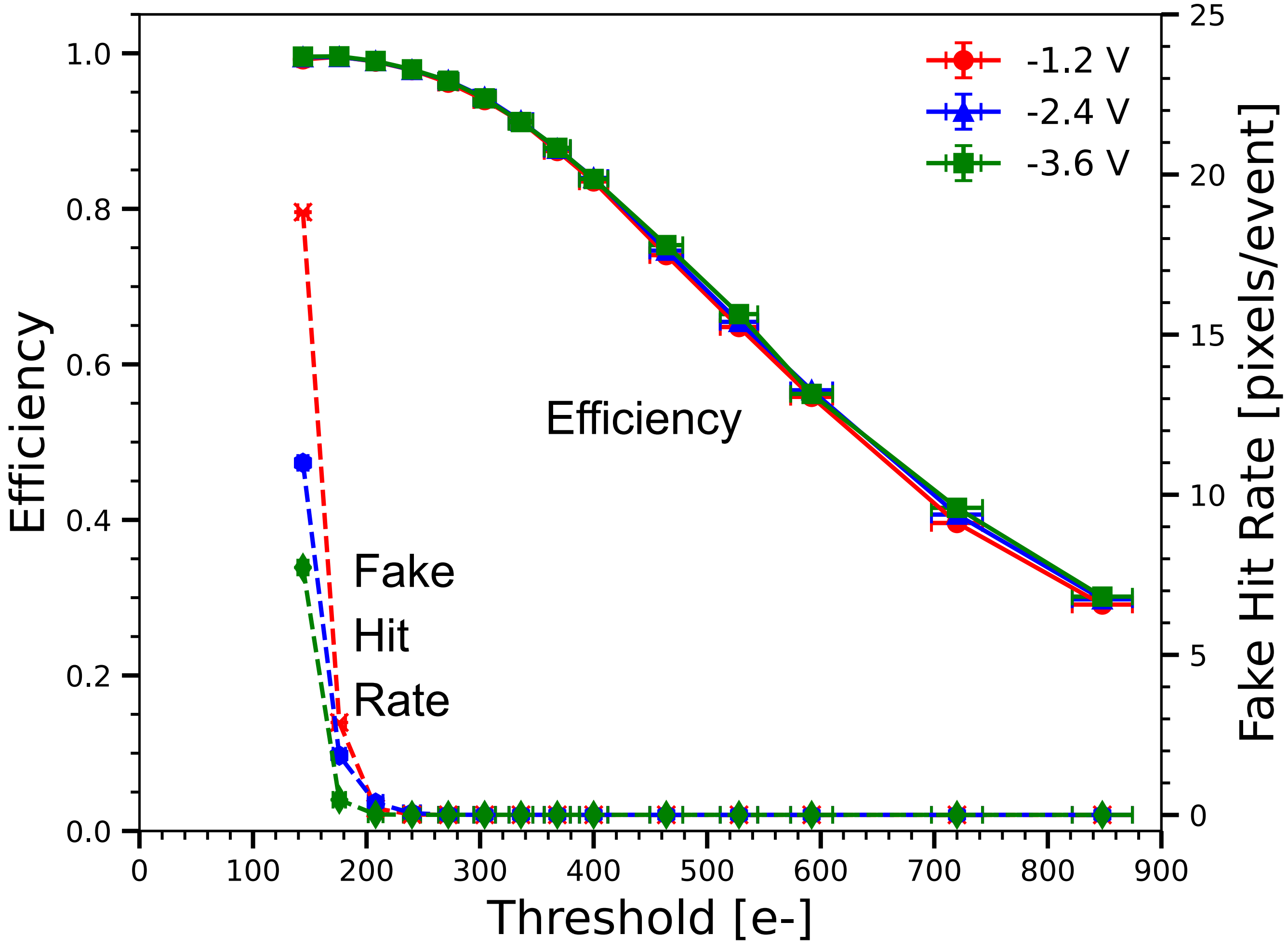
- H6 beam line, 120 GeV charged pions.
- **Timepix3 reference telescope.**
  - Pointing resolution ~ 1.5 µm
- Continuous DUT readout with 150 us (2.56 us) shutter duration for ToT (ToA) mode.



- Beamline 22, electron beam ~4.8 GeV.
- **ALPIDE reference telescope.**
  - Pointing resolution ~ 4 µm
- Telepix2 used as ROI trigger and timing layer (<4 ns time resolution).

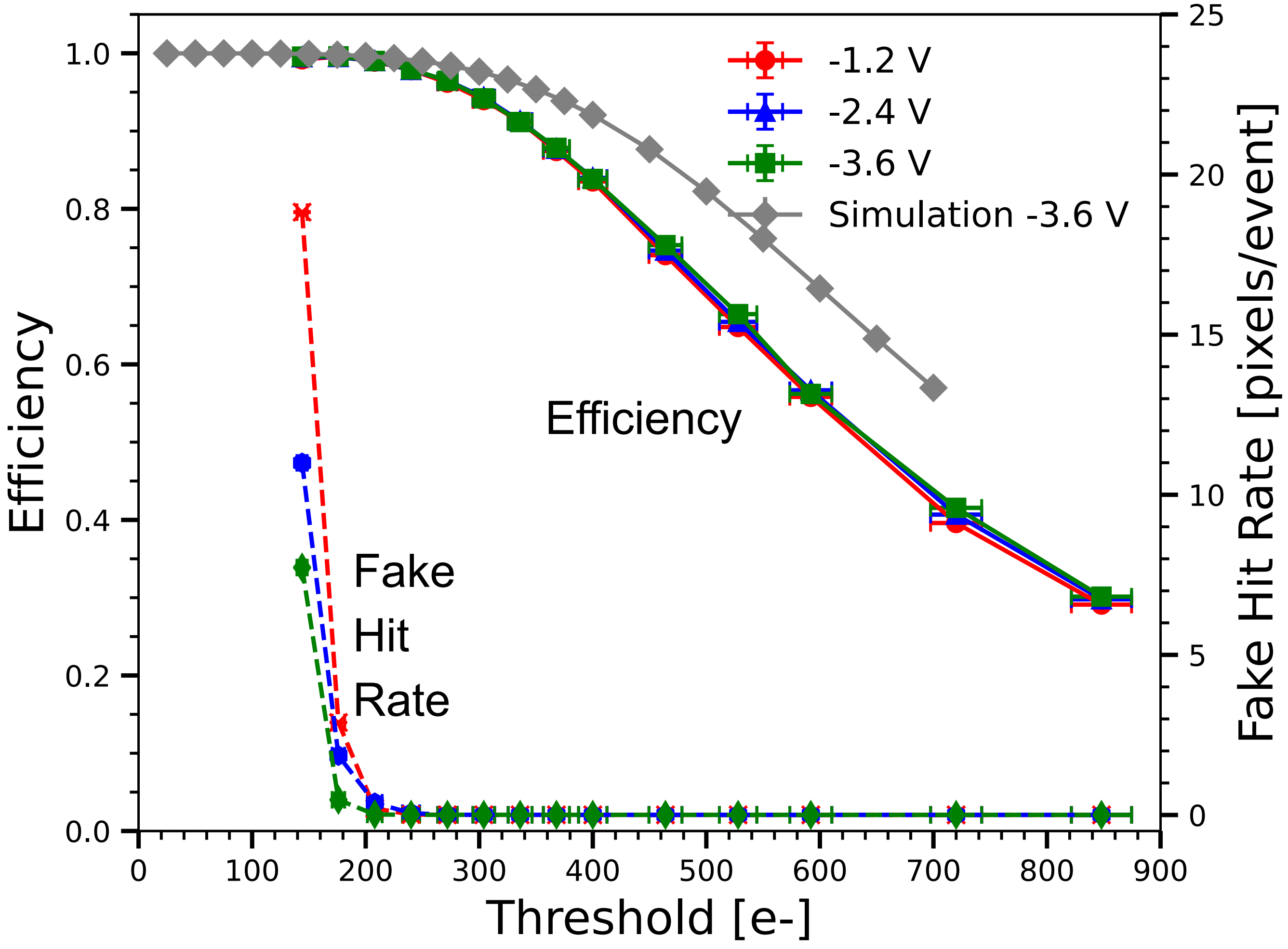
↪ *See talk of Arianna Wintle on Tuesday*

Efficiency and fake hit rate (triggered mode)



- No significant differences between bias voltages.
- For a fake hit rate < 10 pixels/event, **efficiency of 99.6%** at a threshold of 144 e- (~5σ_{noise}) and -3.6 V.

Efficiency and fake hit rate (triggered mode)



- No significant differences between bias voltages.
- For a fake hit rate < 10 pixels/event, **efficiency of 99.6%** at a threshold of 144 e- (~$5\sigma_{noise}$) and -3.6 V.
- However, **lower efficiency was measured than expected from simulations** (using generic methods without proprietary information, and simulating the deep p-wells as flat profiles/nothing within the deep p-wells https://arxiv.org/abs/2408.00027).

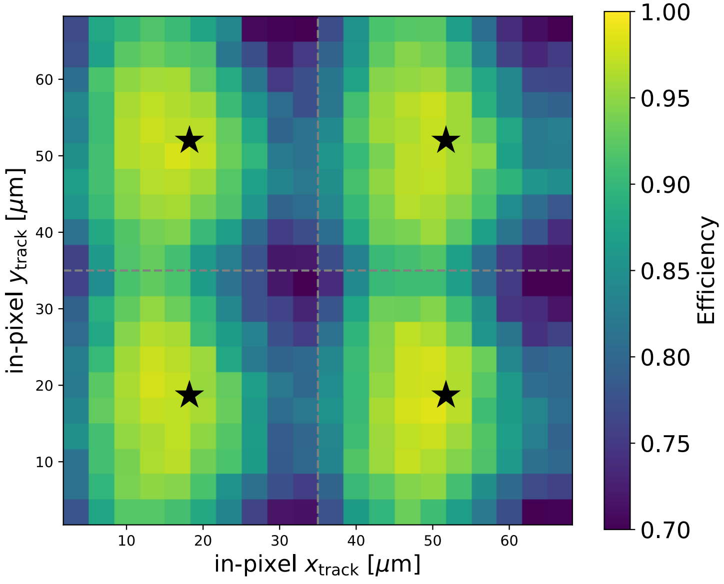
Non-uniformity in-pixel response

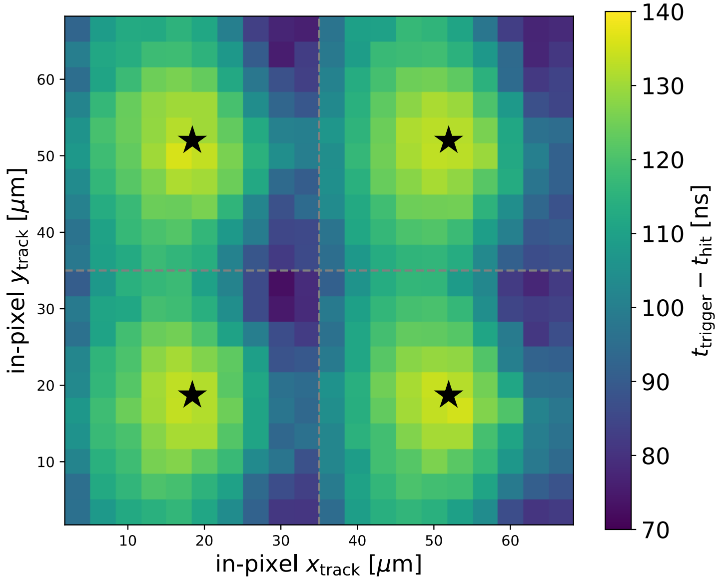
★ Collection electrode

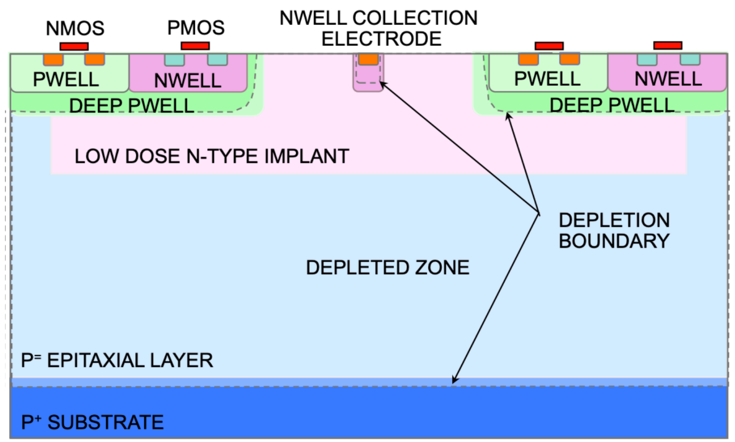
Efficiency

V_{bias} = - 1.2 V, ikrum = 21, THL = 332 e-

ToA



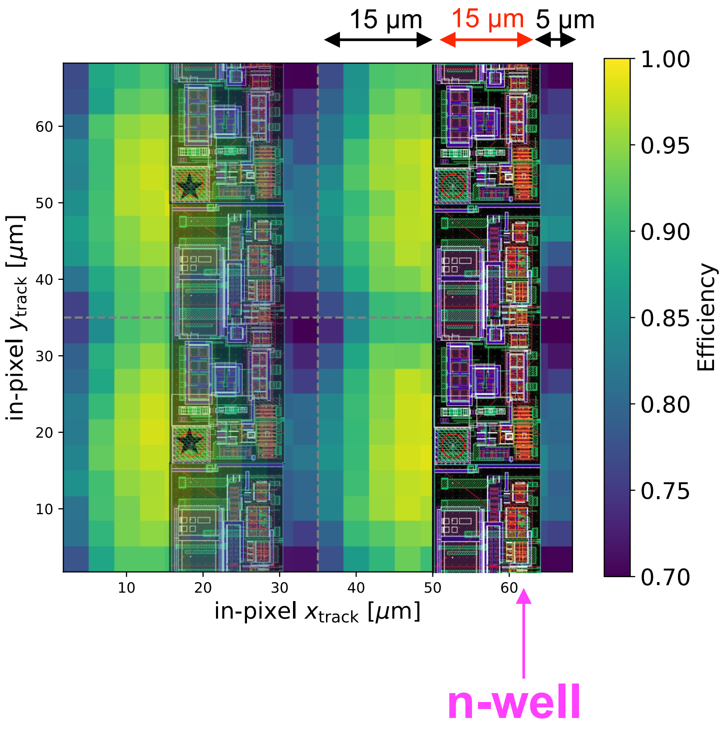


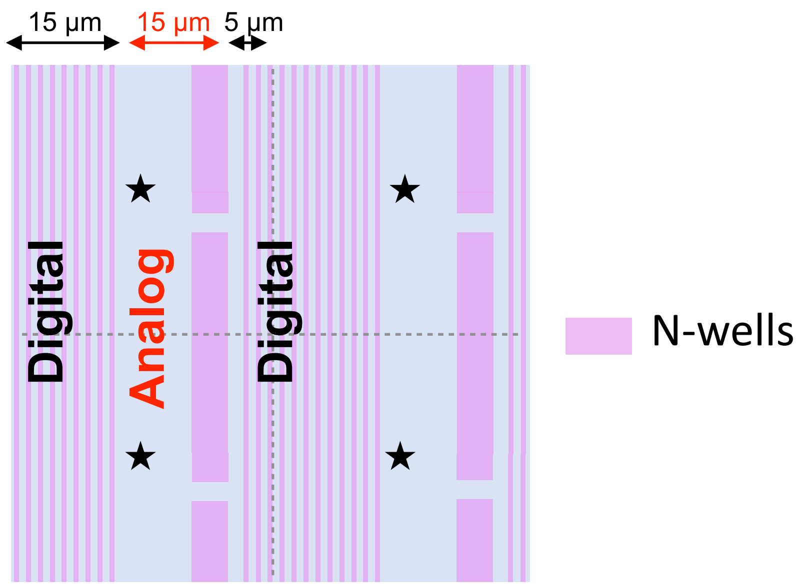


W. Snoeys, DOI:10.1016/j.nima.2017.07.046

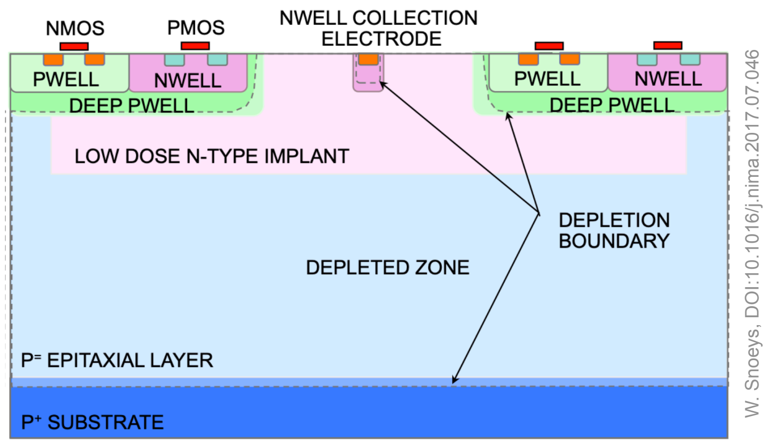
Non-uniformity in-pixel response

★ Collection electrode





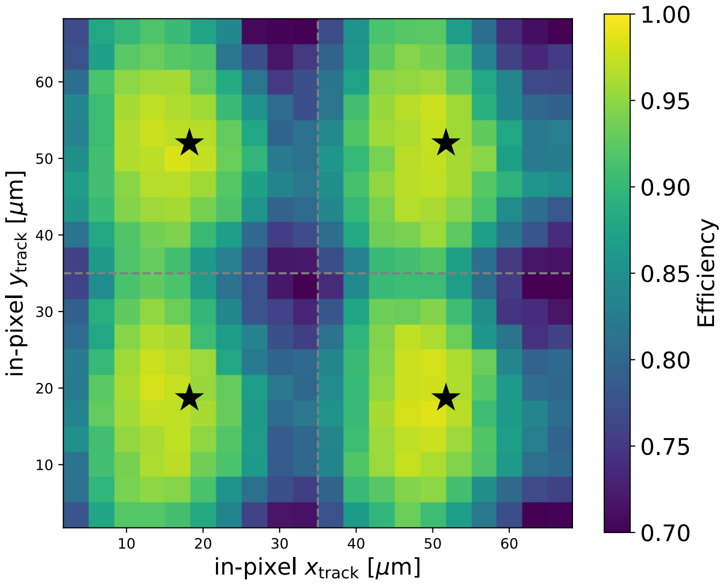
- Related to the **size and location of the n-wells** of the analog circuitry.



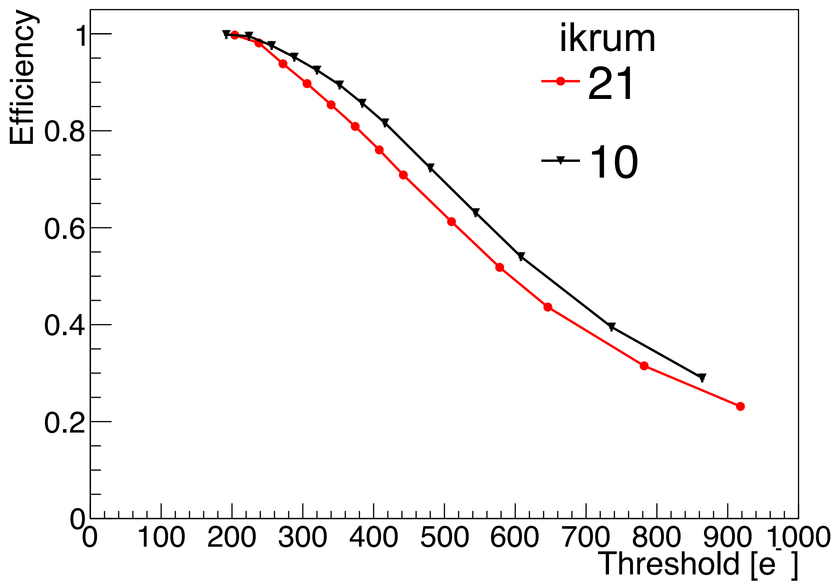
Non-uniformity in-pixel response

★ Collection electrode

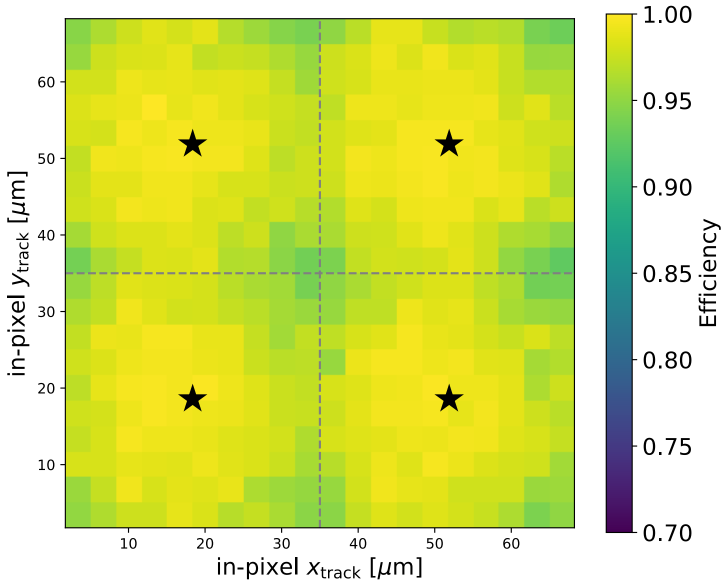
V_{bias} = - 1.2 V, ikrum = 21, THL = 332 e⁻



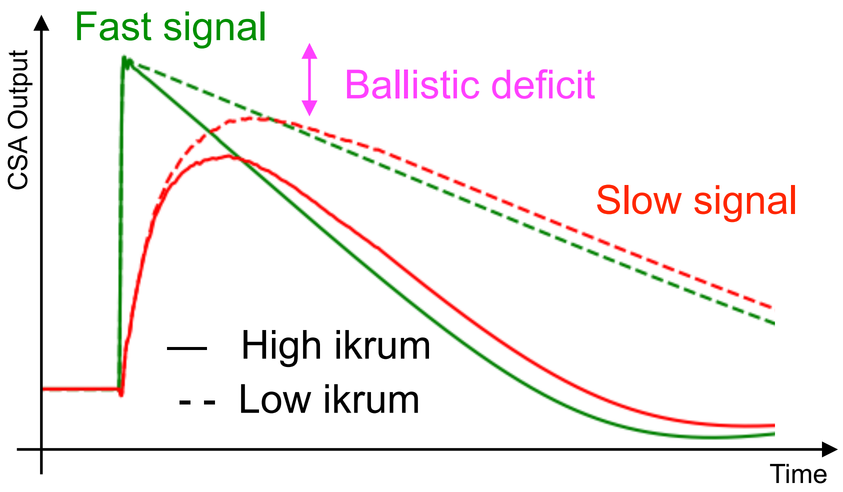
V_{bias} = - 1.2 V



V_{bias} = - 3.6 V, ikrum = 10, THL = 240 e⁻

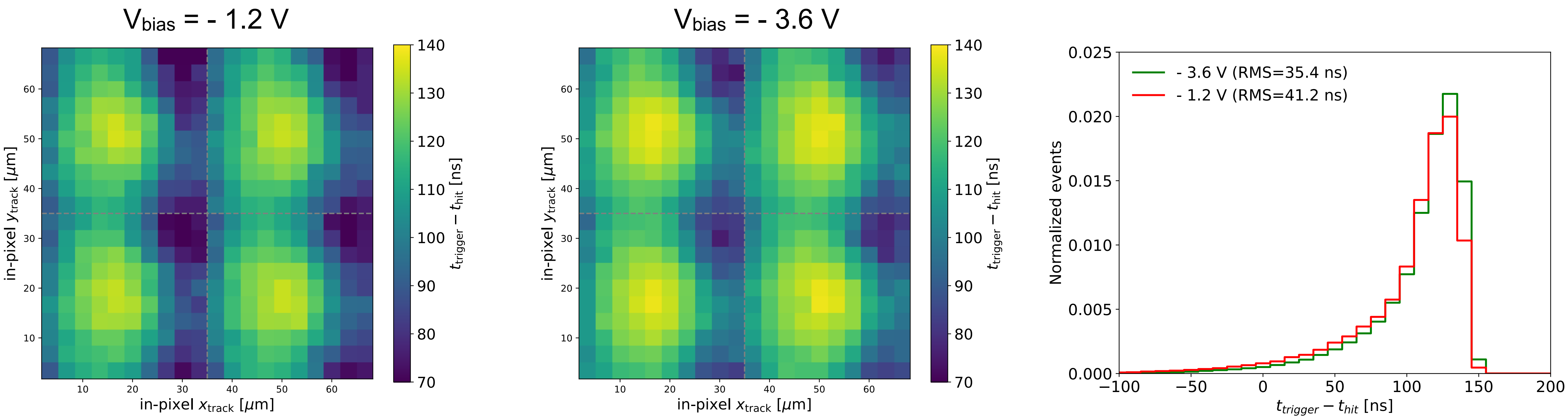


- Related to the size and location of the n-wells of the analog circuitry.
- Mitigated at **lower ikrum**, **higher bias voltages**, and **lower threshold**.
  - Collection speed influences the amplitude due to ballistic deficit.
- Additionally, effects of fast front-end and large pixel size.
- Qualitatively confirmed by **simulations with real profiles** (see next talk by Corentin Lemoine).



Time resolution (ToA)

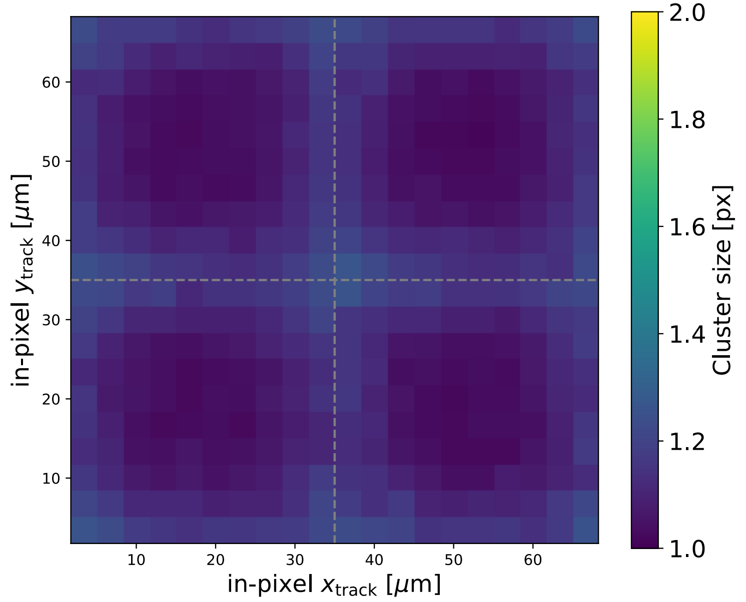
ikrum = 10, THL = 304 e⁻

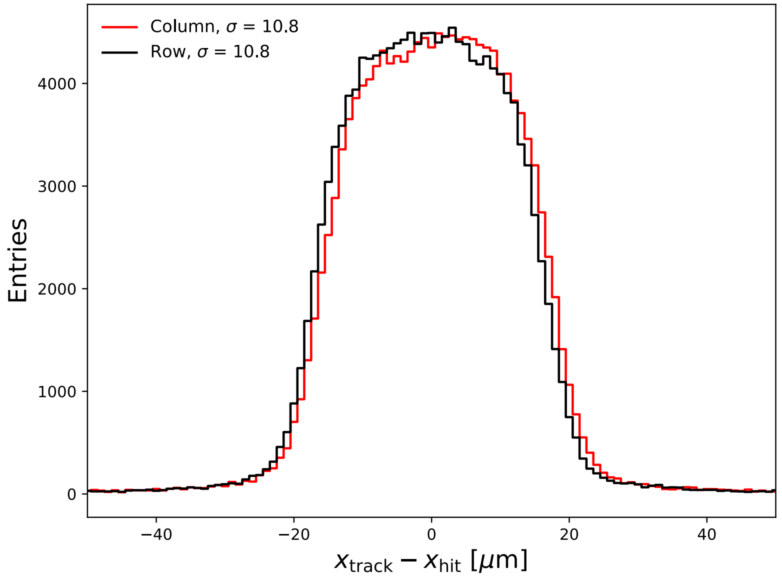


- Strong dependency of arrival time on track impact position→**timing limited by non-uniformity of charge collection.**
- **Better timing resolution for -3.6 V than -1.2 V** due to more uniform charge-collection time across the pixel.
- **No possibility of time-walk correction** since charge information is not available simultaneously.

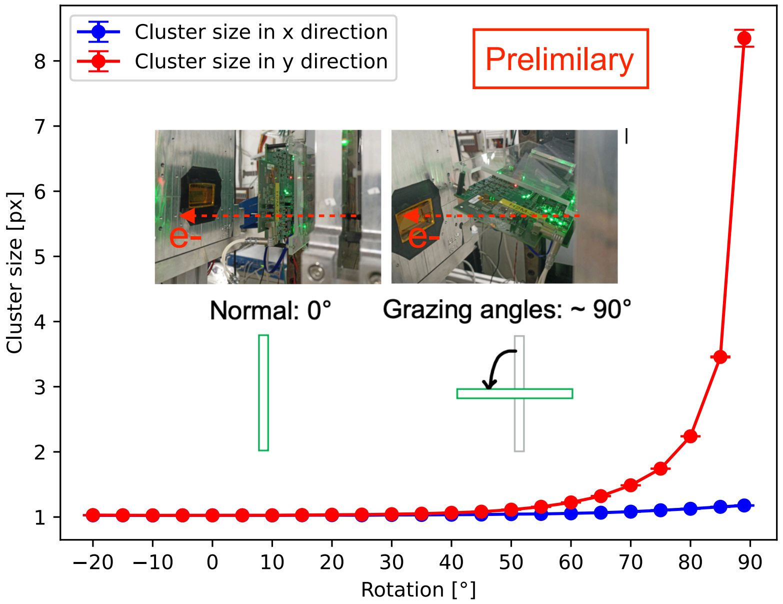
Cluster size and spatial resolution (ToT)

V_{bias} = - 3.6 V, ikrum = 10, THL = 240 e^-



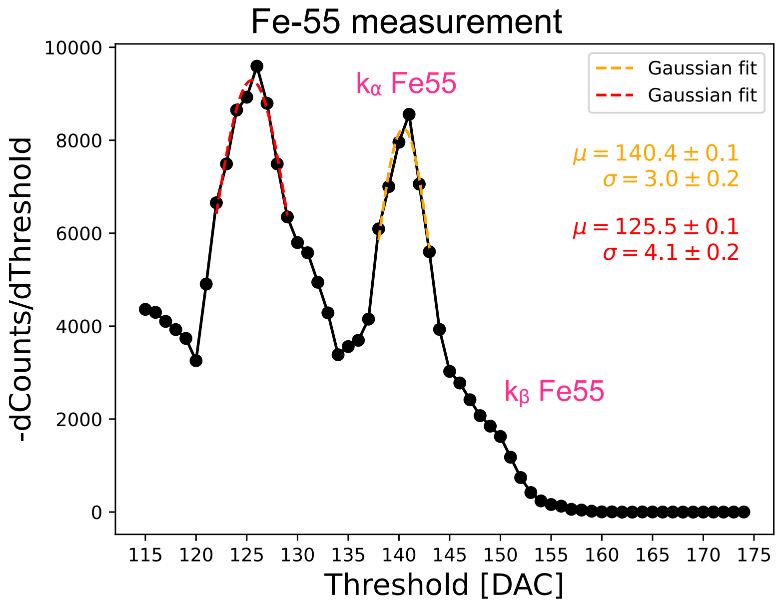


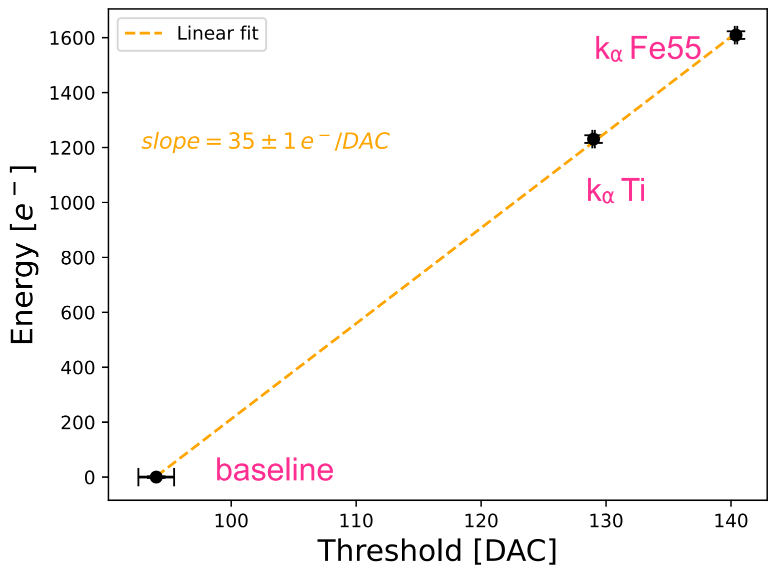
Rotation analysis



- **Spatial resolution in X** (same in Y) $\sqrt{10.8^2 - 3.8^2} = 10.1$ μm (~ $35/\sqrt{12}$ μm) and **cluster size** ~ 1.
  - Dominated by the large pitch of 35 μm, even at low threshold.
  - Asymmetric residuals in the row direction due to the low-efficiency part.
- Analysis of rotation data ongoing (grazing-angle study) → **extract active thickness**.

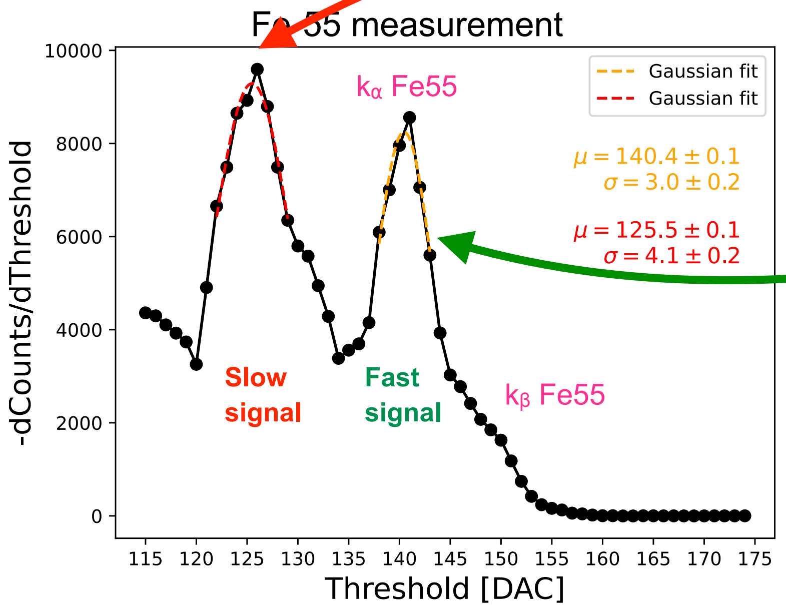
Threshold and ToT calibration

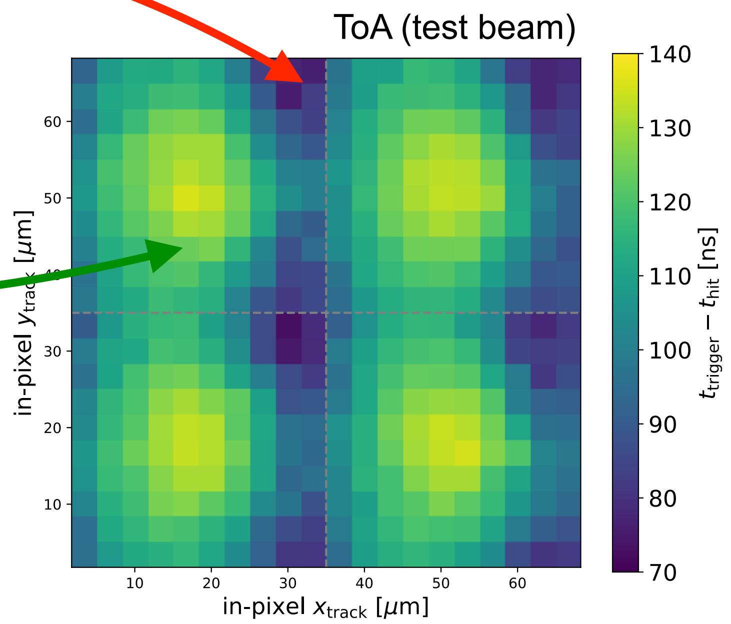


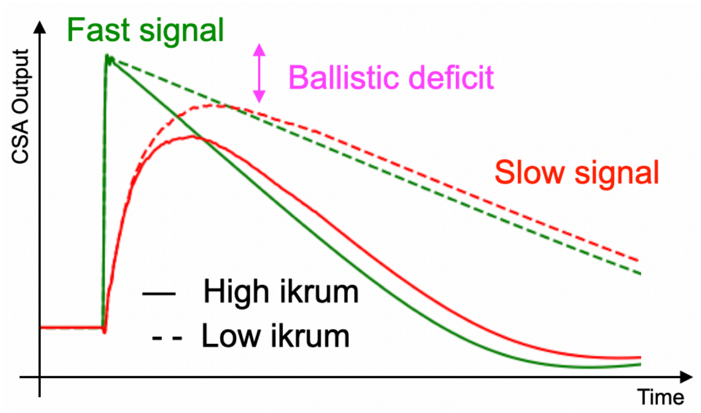


- **Threshold calibration** to find the relation between threshold-DAC and electrons for comparison with simulations.
  - Source measurements (Fe-55, Ti).

Threshold and ToT calibration



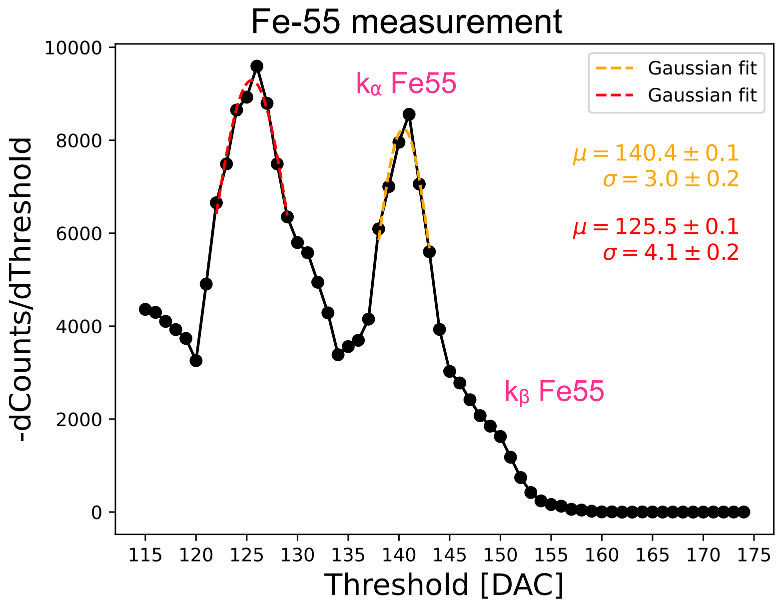


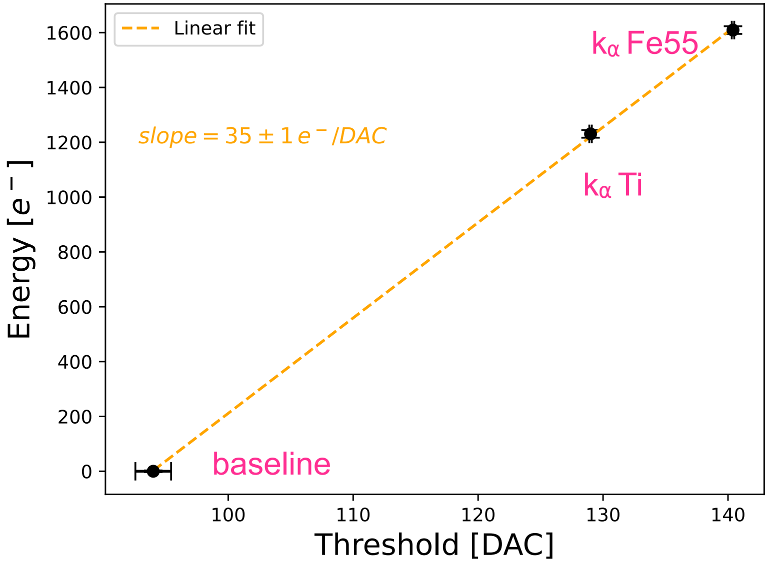


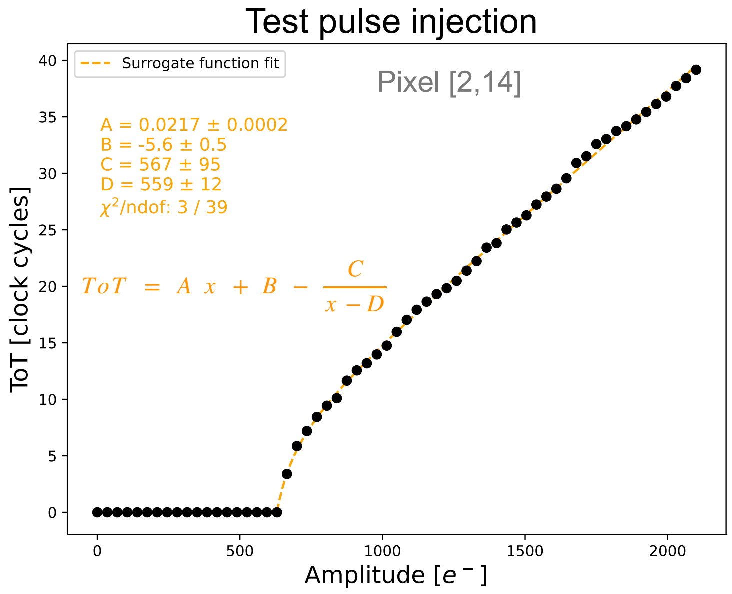
- **Threshold calibration** to find the relation between threshold-DAC and electrons for comparison with simulations.
  - Source measurements (Fe-55, Ti).

  → Two peak structure originates from fast/slow charge-collection regions inside the pixel. Fast signal used to obtain the calibration factor.

Threshold and ToT calibration



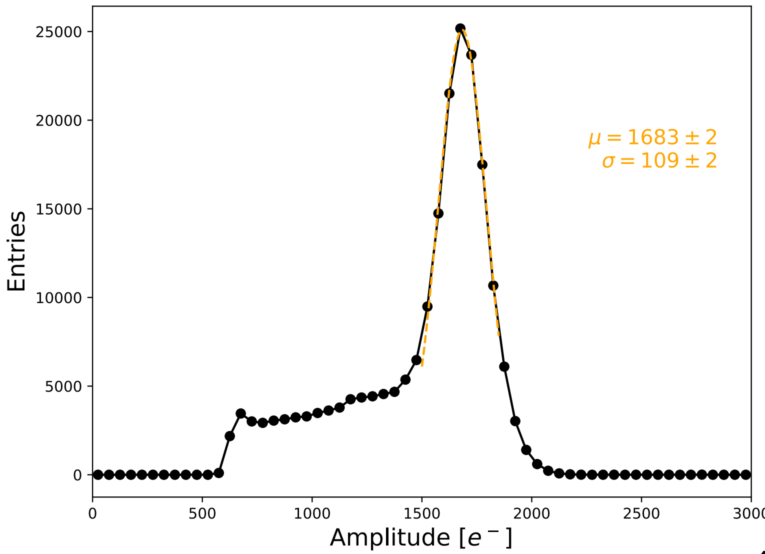




- **Threshold calibration** to find the relation between threshold-DAC and electrons for comparison with simulations.
  - Source measurements (Fe-55, Ti)

  → Two peak structure originates from fast/slow charge-collection regions inside the pixel. Fast signal used to obtain the calibration factor.
- **Test pulse calibration** to find the relation between ToT and signal height per pixel.

  → **Resolved Fe-55 K_α amplitude with 5% accuracy.**

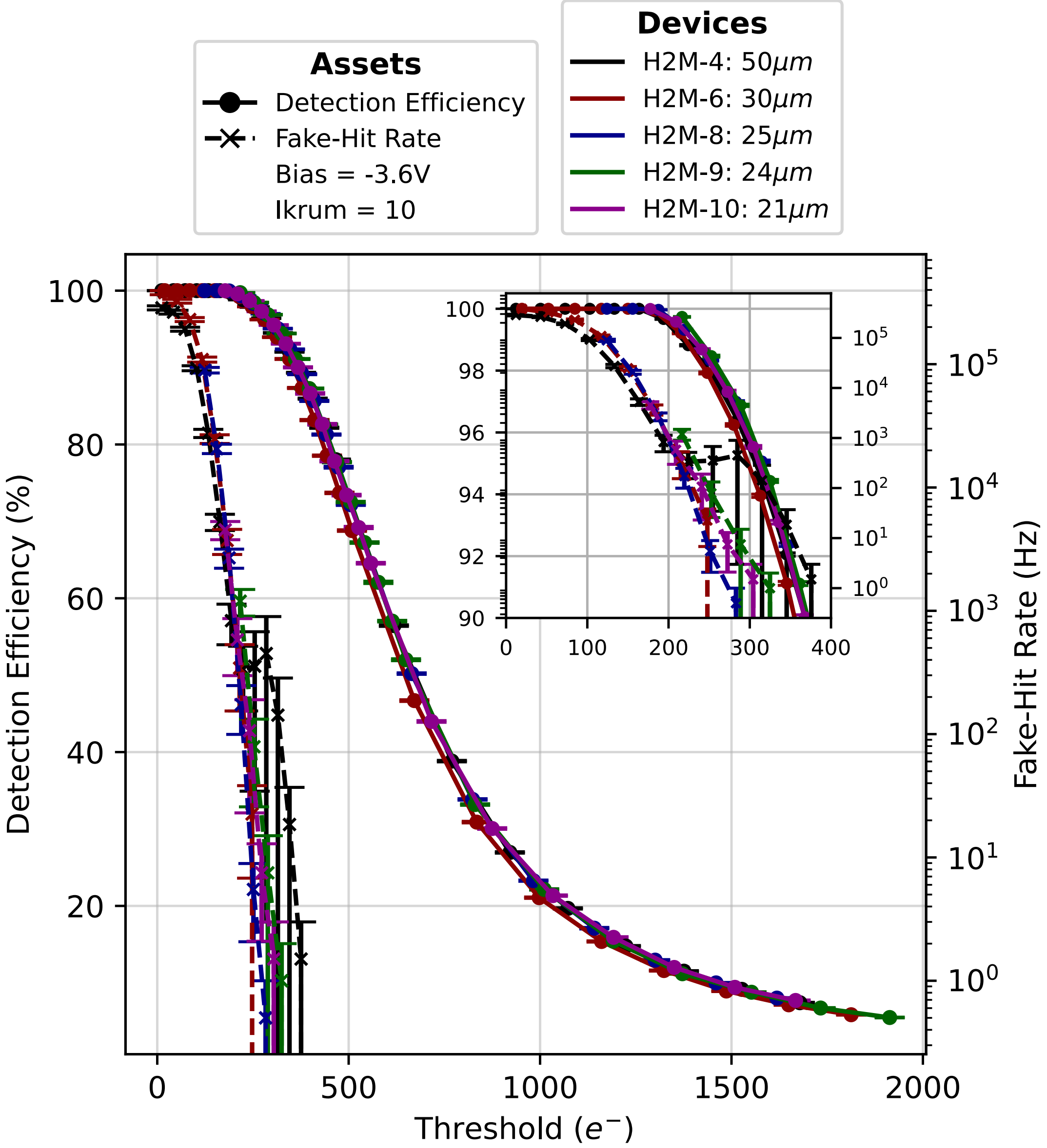


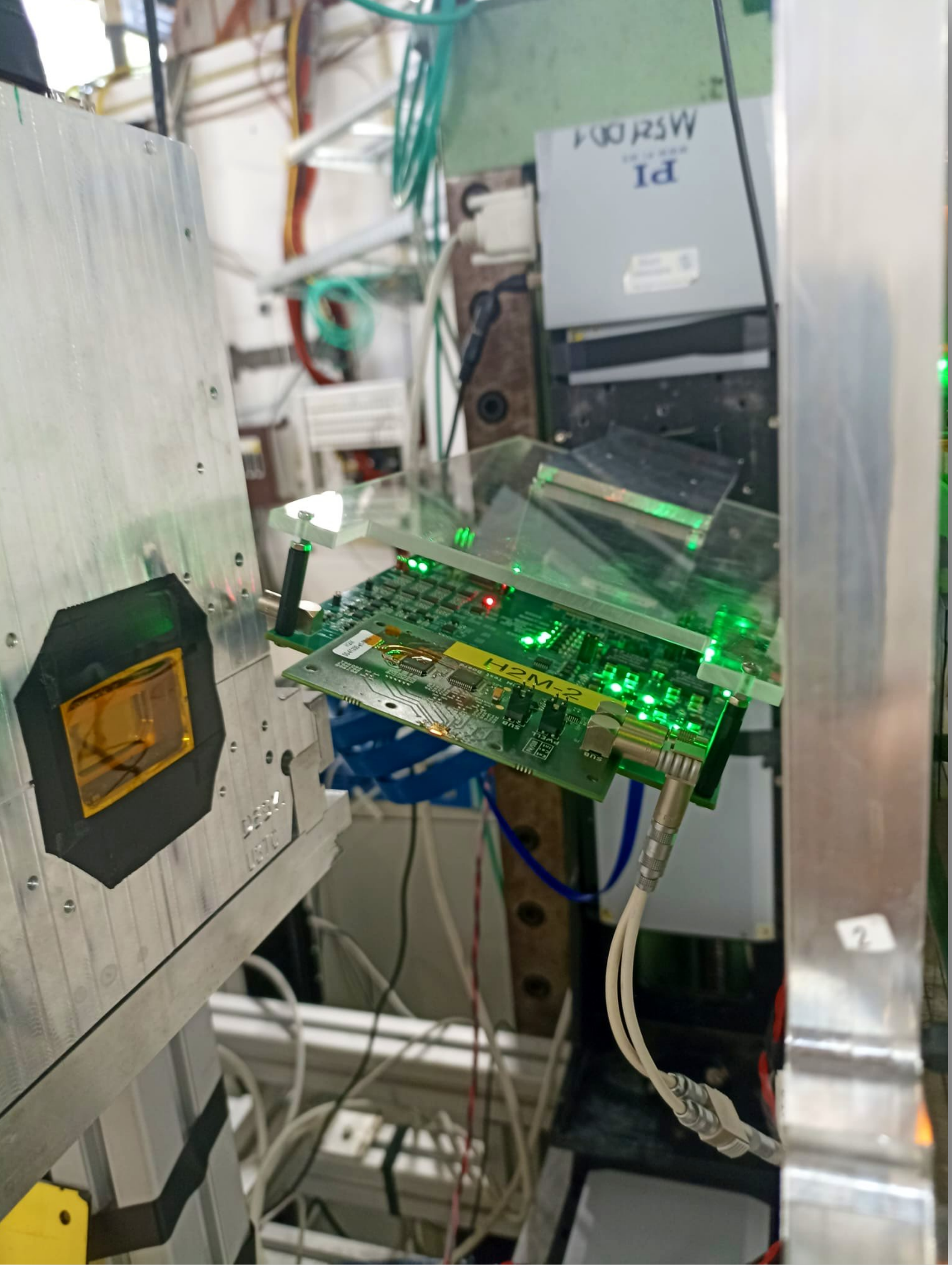
Thin samples (ToT mode)

- **Single-die backside thinning** of H2M samples, performed by OPTIM WS
  → 30, 25, 24, 21 µm physical thickness
- Includes ~5 µm circuitry + ~10 µm epitaxial layer

- Efficiency >99% for ~200 e- threshold.
  → **No performance degradation from thinning.**

- Studying the possibility of thinning down to below 20 microns.





Summary

- **Fully functional digital-on-top monolithic sensor in a 65 nm CIS.**
- **Calibration and characterisation** of performance with **laboratory** and **test beam** measurements
  - <35 e- noise, 99.6% efficiency at a threshold of 144 e- (~$5\sigma_{noise}$).
  - Spatial resolution 10.1 µm (~ pitch/$\sqrt{12}$).
  - Thining down to 21 µm without performance loss.
- **Impact of n-wells on charge-collection** → efficiency and timing limitation.
  - More details in the **next talk by Corentin Lemoine**.

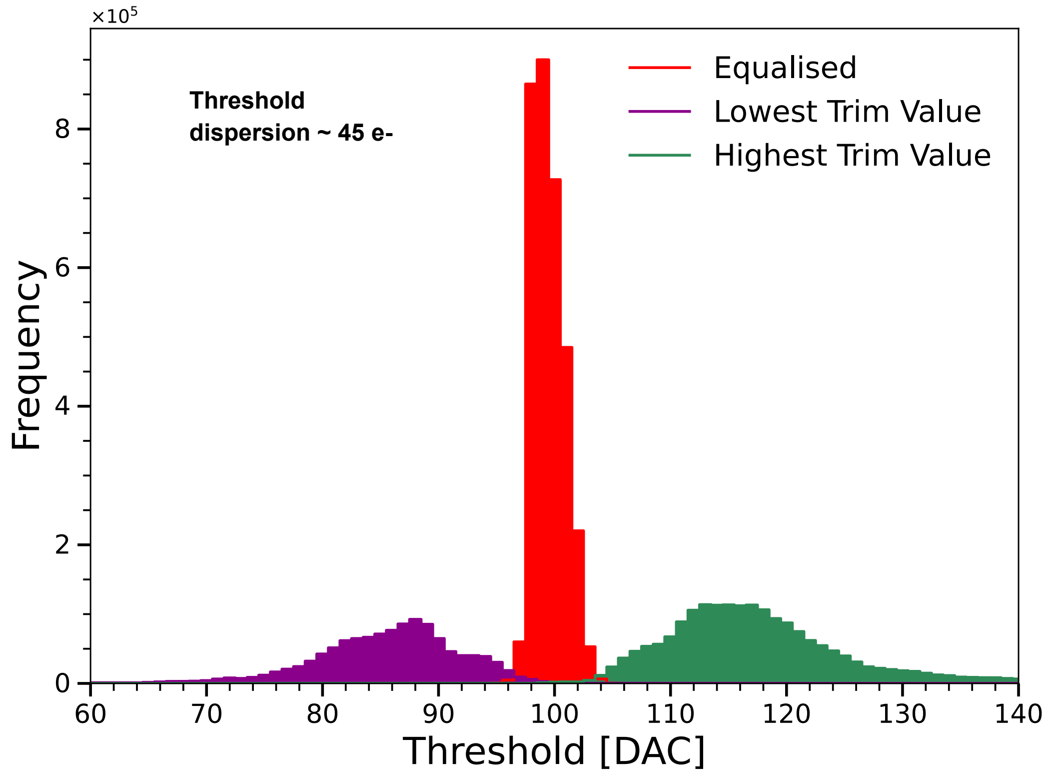
Outlook

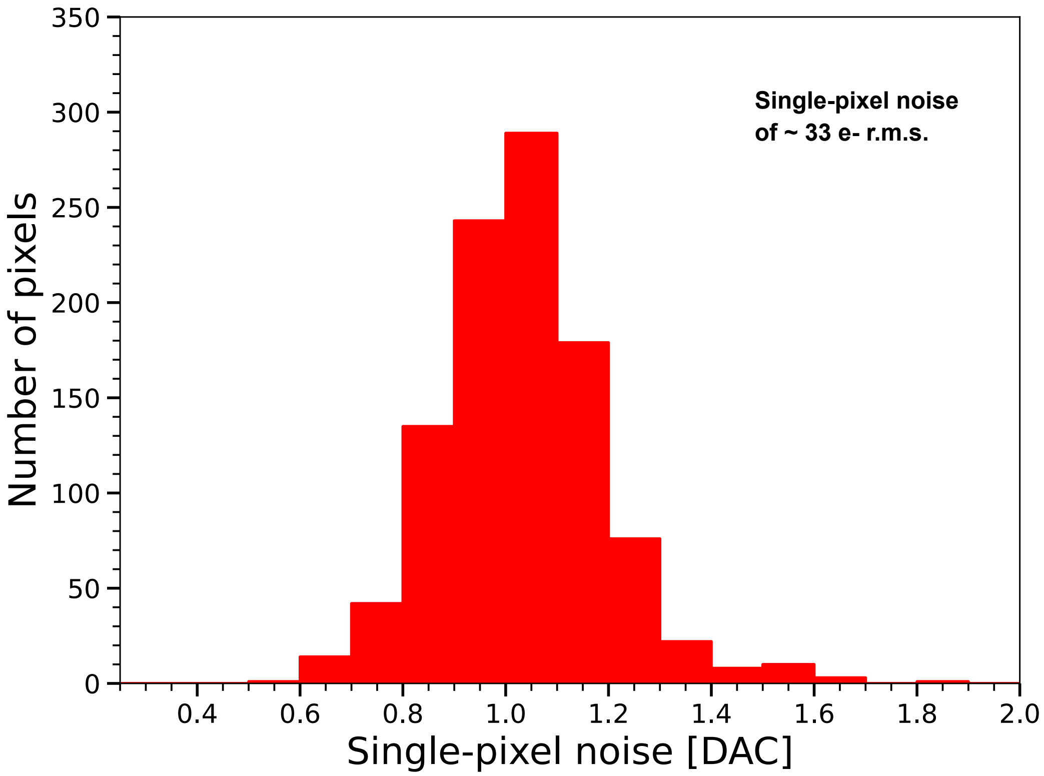
- Analysis of rotation data (**grazing-angle study**)
- Investigating the possibility of **thinning** the chips down to a total thickness **below 20 micros**.

Thank you!

"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)".

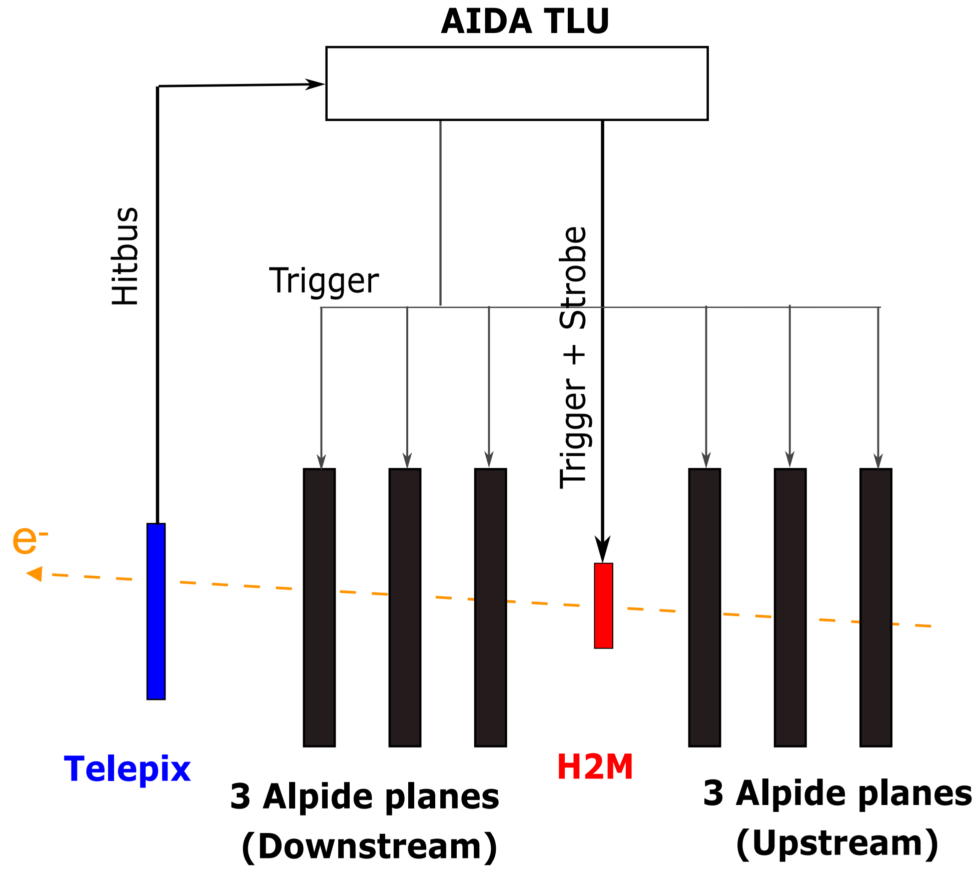
Threshold equalisation and single-pixel noise

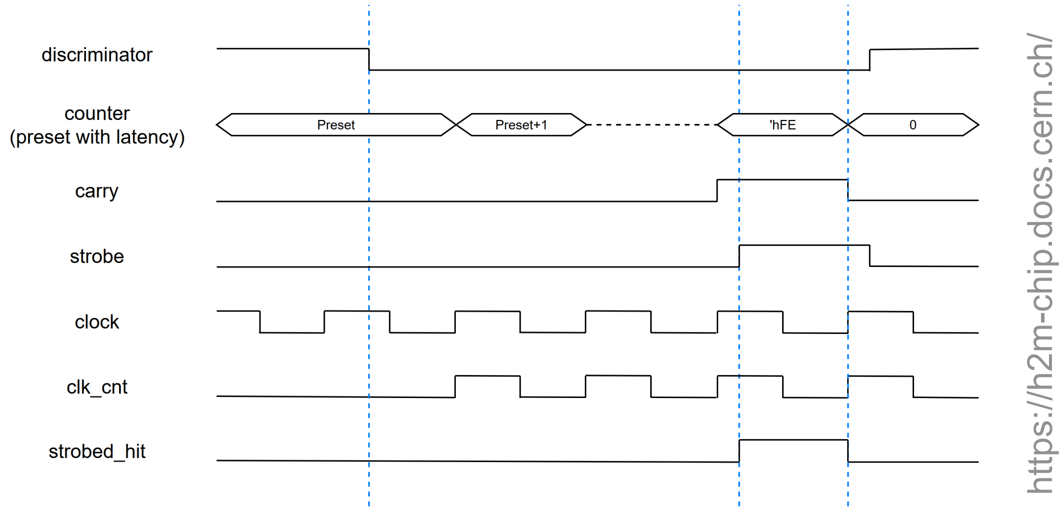




- **Equalisation** of the hit detection threshold:
  1) Threshold scan in counting mode for the 16 trimming values.
  2) Determine the baseline for each pixel for each trimming value.
  3) For each pixel, the trimming DAC is adjusted to the one that makes the closest to a fixed trimming target.
- **Single pixel-noise** obtained from width of threshold turn-on curves.

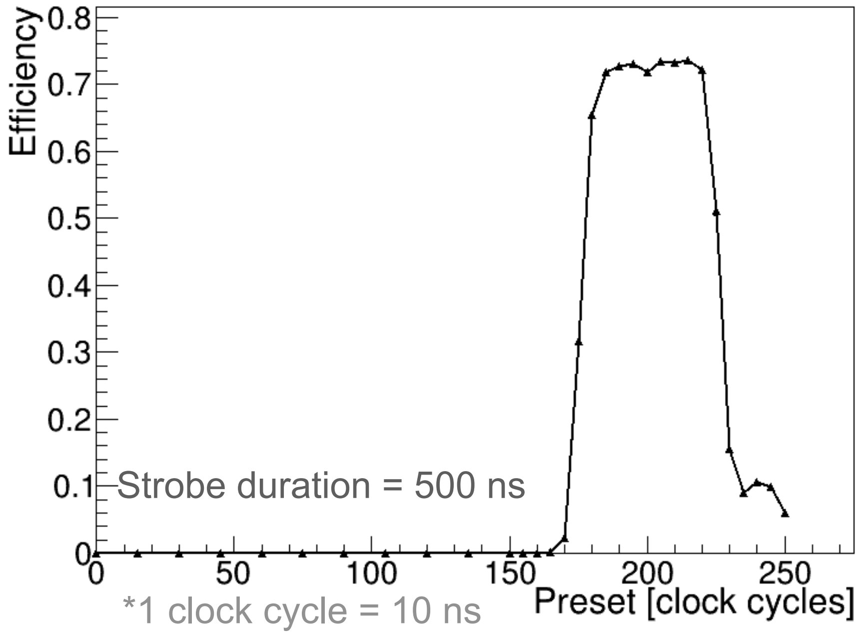
Triggered mode





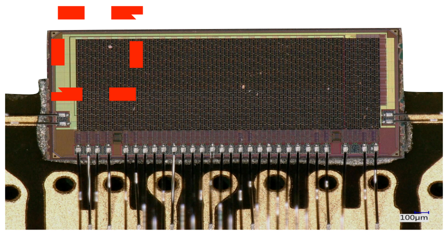
- **Strobe window duration** accounts for time walk (~ 100 ns).
- **Preset** value accounts for the trigger latency.

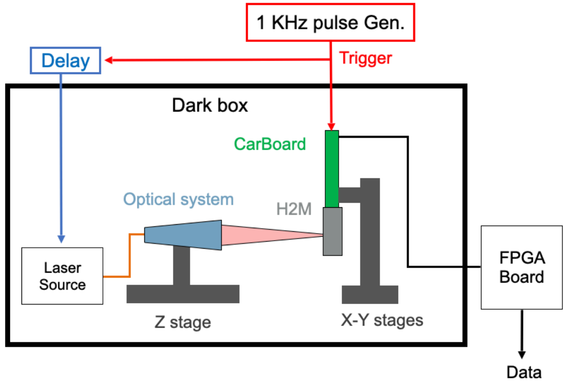
Shutter (strobe signal) open for 500 ns vs O(ms) in ToT/ToA.
→ Efficiency compatible with the other acquisition modes, fake rate reduced by a factor of about 100, and minimum threshold achievable ~ 144 electrons.



*1 clock cycle = 10 ns

Measurements with a laser setup

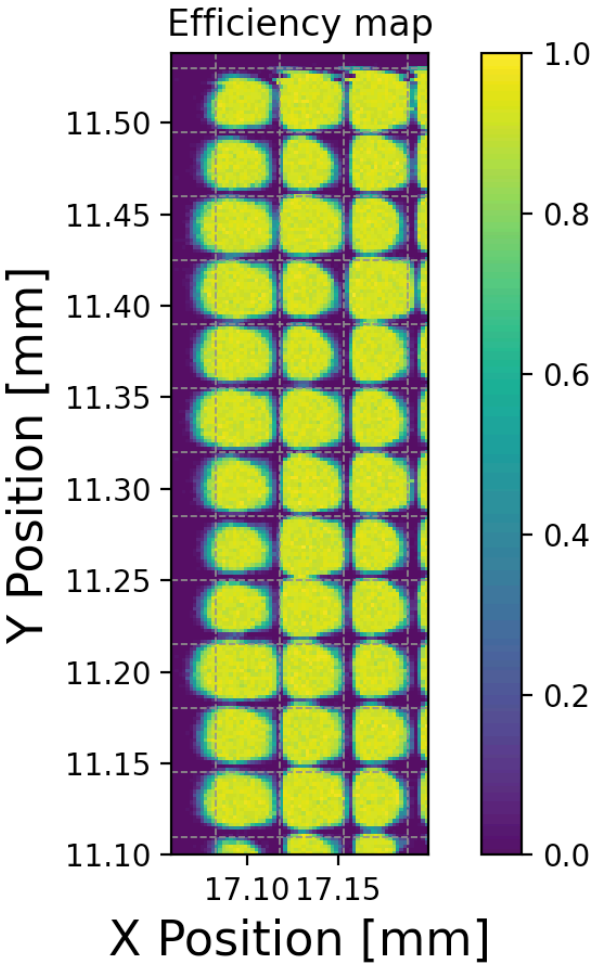


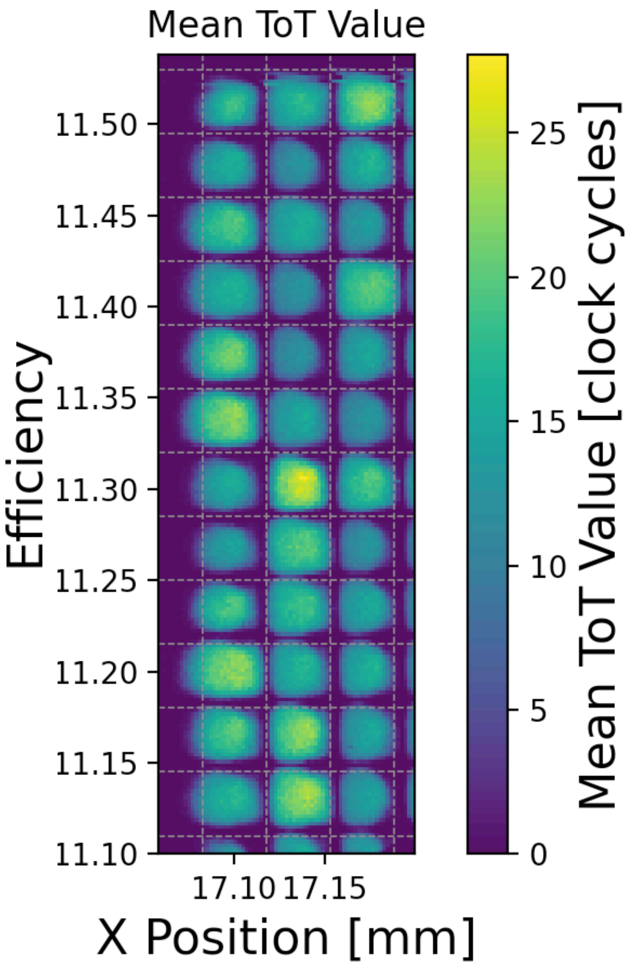


- Backside incidence with an **infrared pulsed laser**. Light intensity tuned to correspond to the ToT MPV signal of 1 MIP.

- Confirmation of the **in-pixel efficiency pattern** observed in the test beam measurements and its orientation.

- **Pixel-to-pixel differences** attributed to different returns to baseline due to differences in the circuit's Krummenacher current and feedback capacitance.



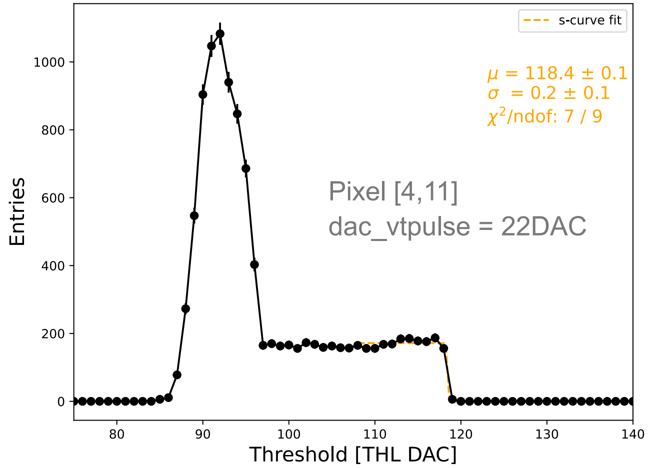


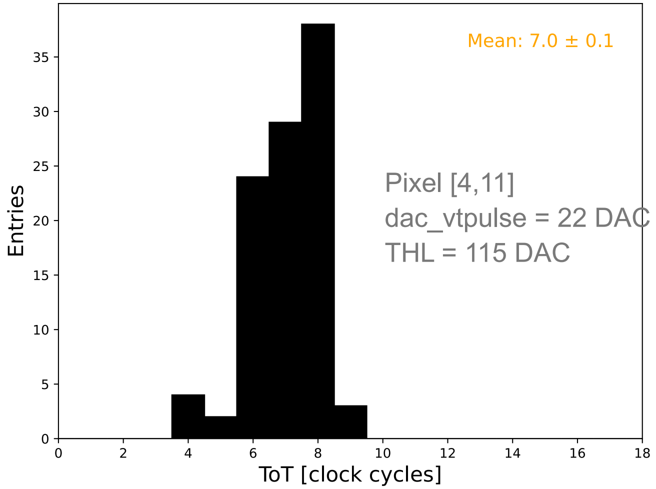
*1 clock cycle = 10 ns

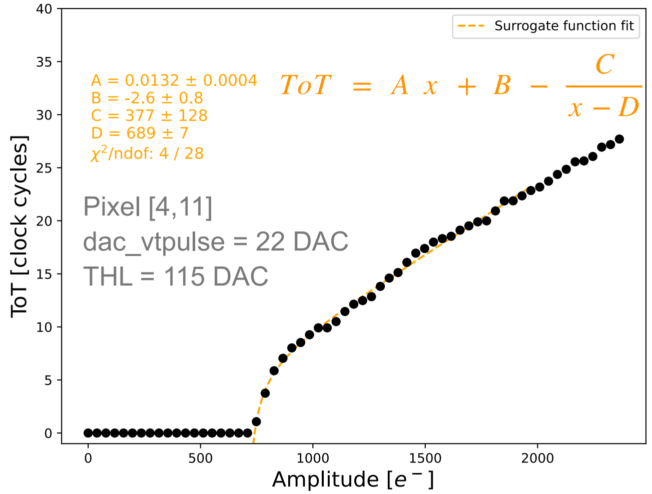
ToT calibration

1. Amplitude vs dac_vtpulse + 2. ToT vs dac_vtpulse ⇒ 3. ToT vs amplitude

One pixel







All pixels