The ARCADIA Fully Depleted MAPS: laboratory characterization and particle tracking performance

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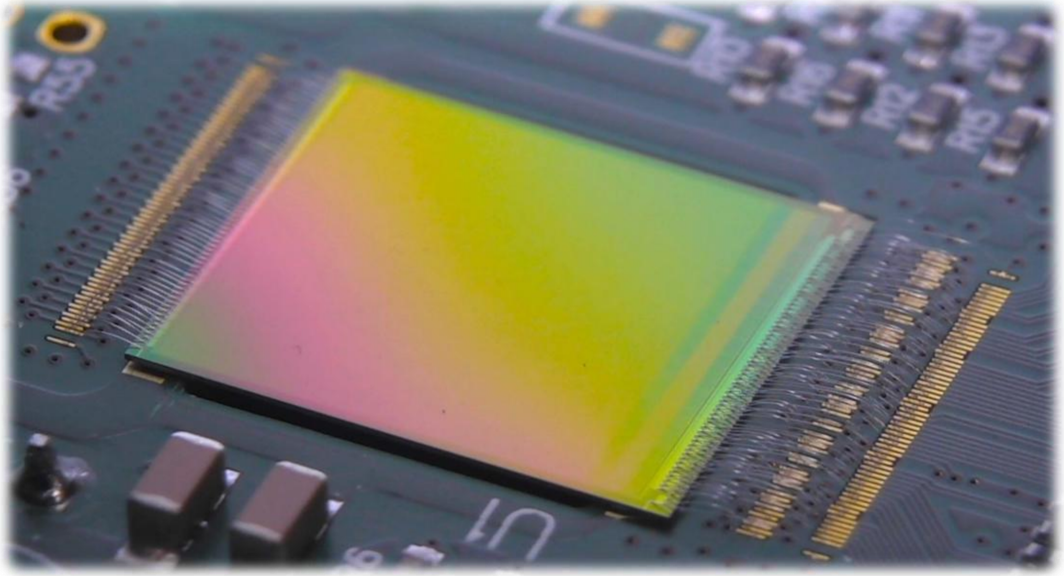
ARCADIA

FUTURE CIRCULAR COLLIDER



ARCADIA Fully Depleted MAPS

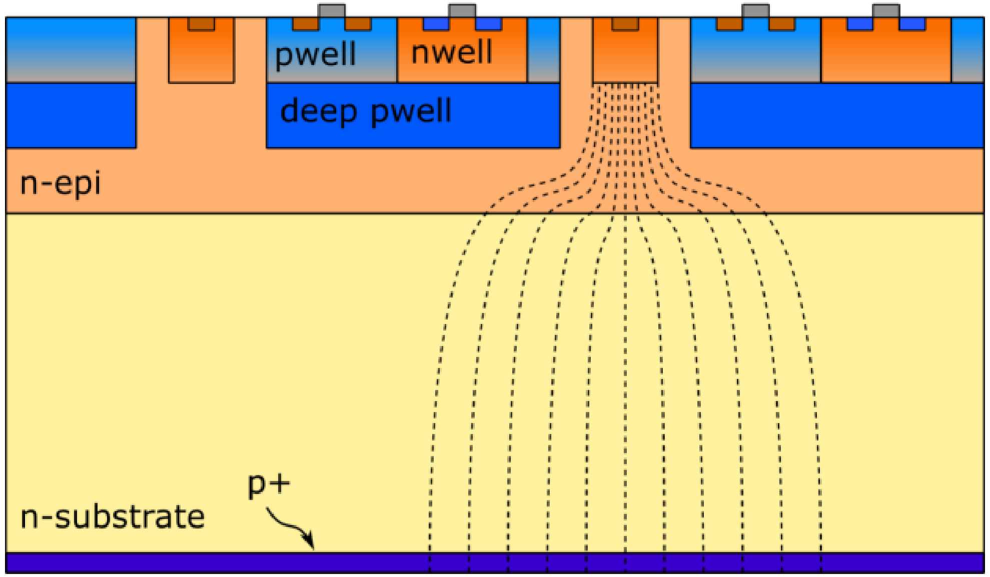
Advanced **R**eadout **C**MOS **A**rchitectures with **D**epleted **I**ntegrated sensor **A**rrays

R&D project, funded by INFN CSN5, on the **development of thick FD-MAPS** in a customized **LFoundry 110 nm CIS** process in view of the next generation of HEP experiments, e.g. FCC-ee, space experiments and X-ray detection

Sensor

- n-type high resistivity active region (up to 500 μm)
- n-epi layer to control the potential below the deep pwell
- sensing electrodes can be biased at low voltage (< 1V)
- backside p^+ implantation: depletion from back to top

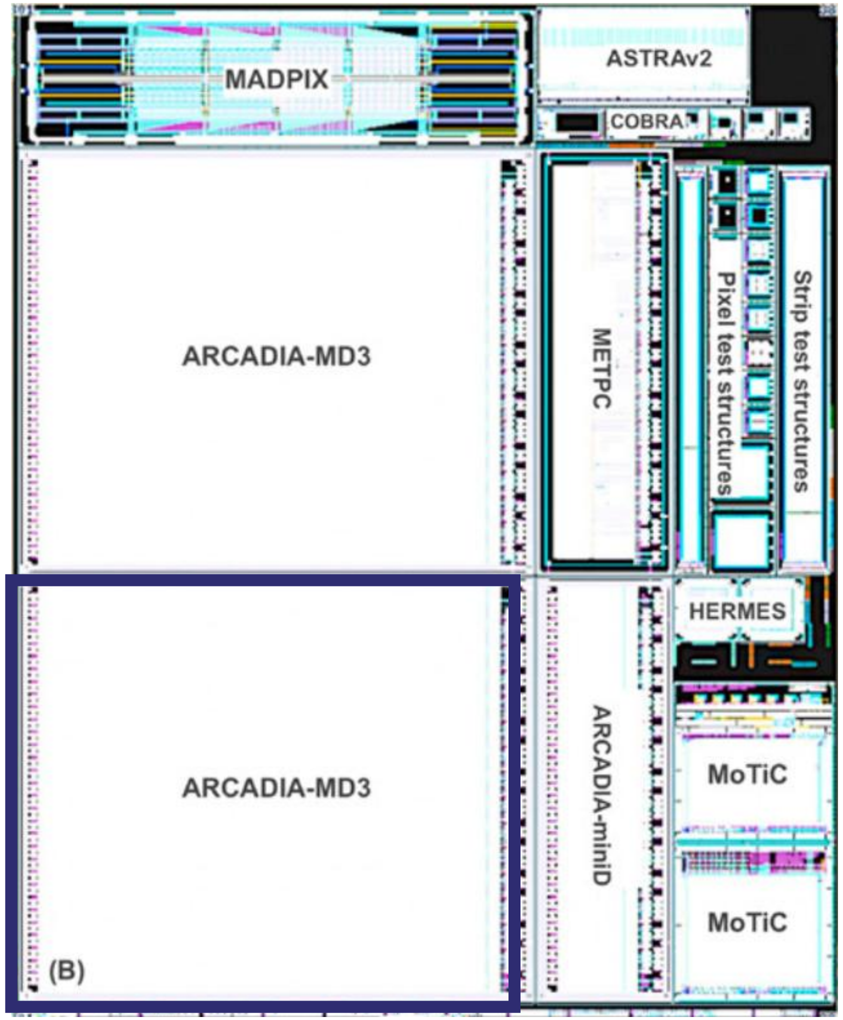
Scalable readout architecture with ultra-low power capability O(10 mW/cm^2)



M. Rolo, VERTEX2023, https://agenda.infn.it/event/35597/contributions/211639/
L. Pancheri et al, 2019 JINST 14 C06016, DOI: 10.1088/1748-0221/14/06/C06016

See M. Rolo «Status and plans of the ARCADIA project and LFoundry 110 nm»

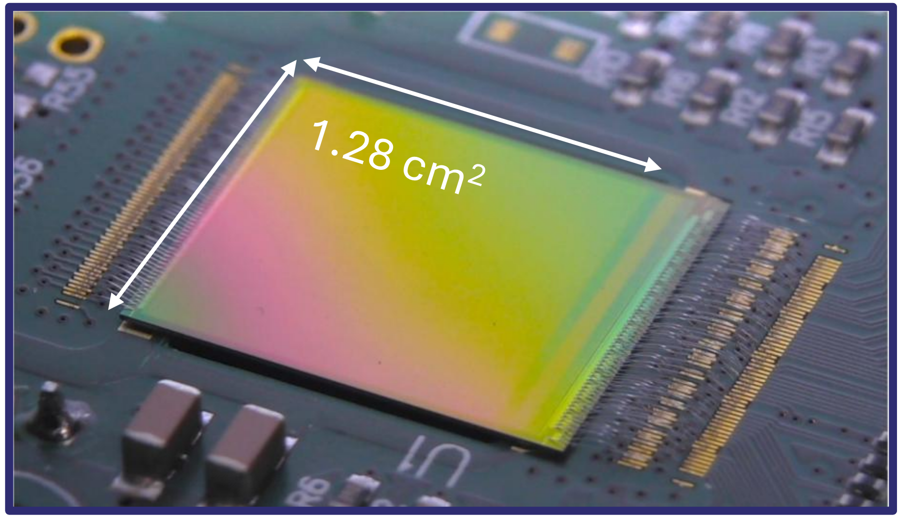
ARCADIA MD3



More details in: M. Rolo et al., ARCADIA fully depleted CMOS MAPS development with LFoundry 110 nm,
DOI:10.3389/fsens.2025.1603755ISSN=2673-5067

Full chip demonstrator MD3

Pixel array	512 × 512 pixels
Pixel pitch	25 µm
Readout	Data-driven binary
Power consumption	< 30 mW/cm² (down to 10 mW/cm² in low rate mode)
Active thickness	50, 100, **200 µm**
Rate capability	100 MHz /cm²
Applications	Particle tracking – Space - Medical

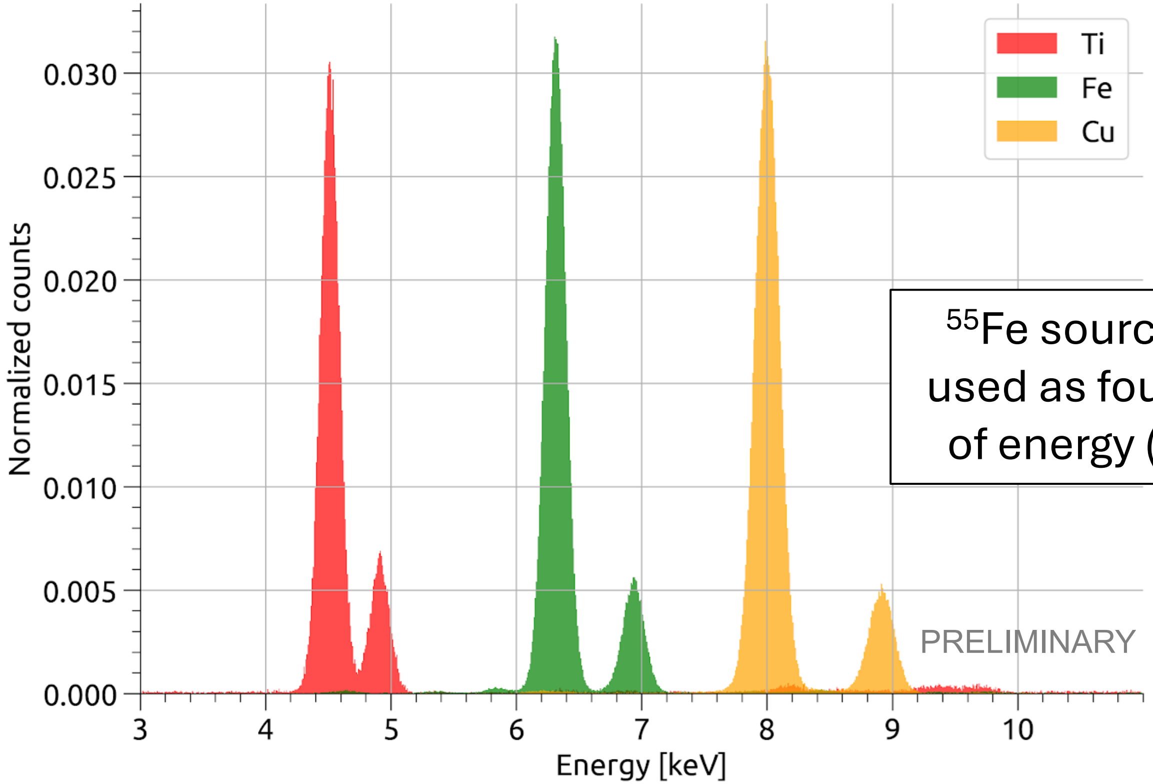


FUTURE CIRCULAR COLLIDER

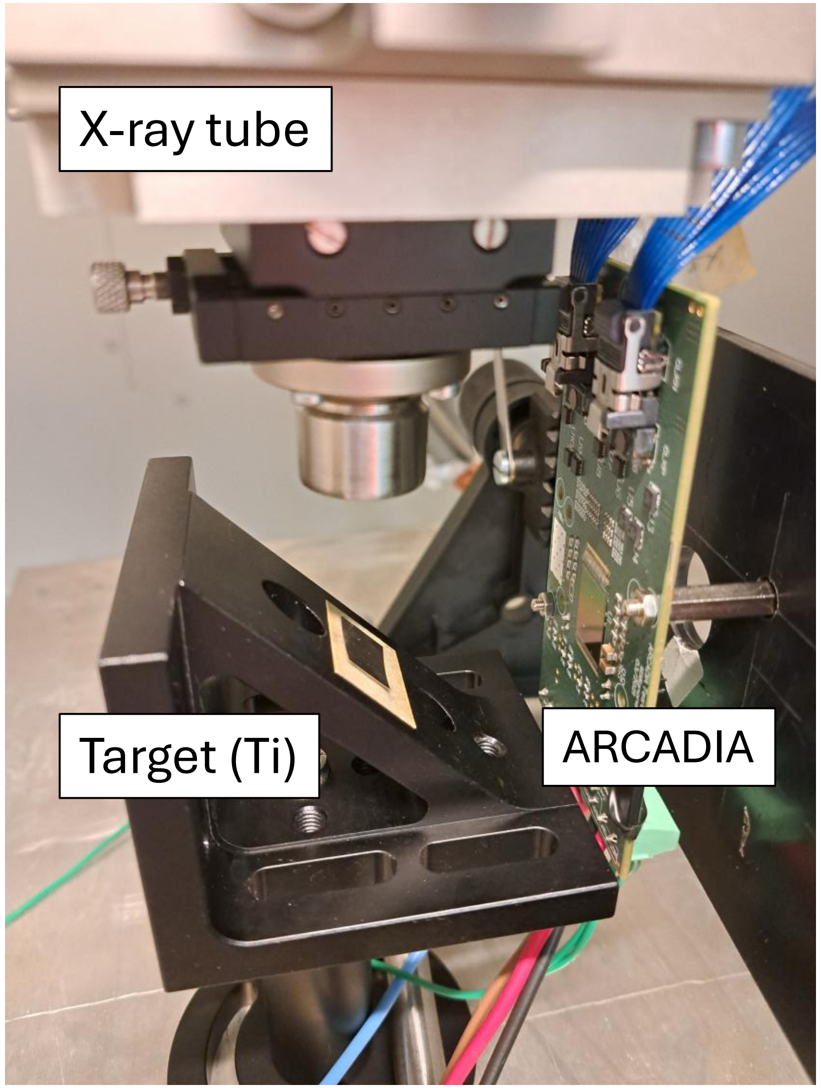
MD3 characterization: fluorescence

Fluorescence is a source of very monochromatic X-ray.
It can be exploited to calibrate the sensor.

Setup:
- X-ray tube with Tungsten anode used at 40kV and 50 mA
- Target of different materials at 45°
- 16×16 pixel array tested



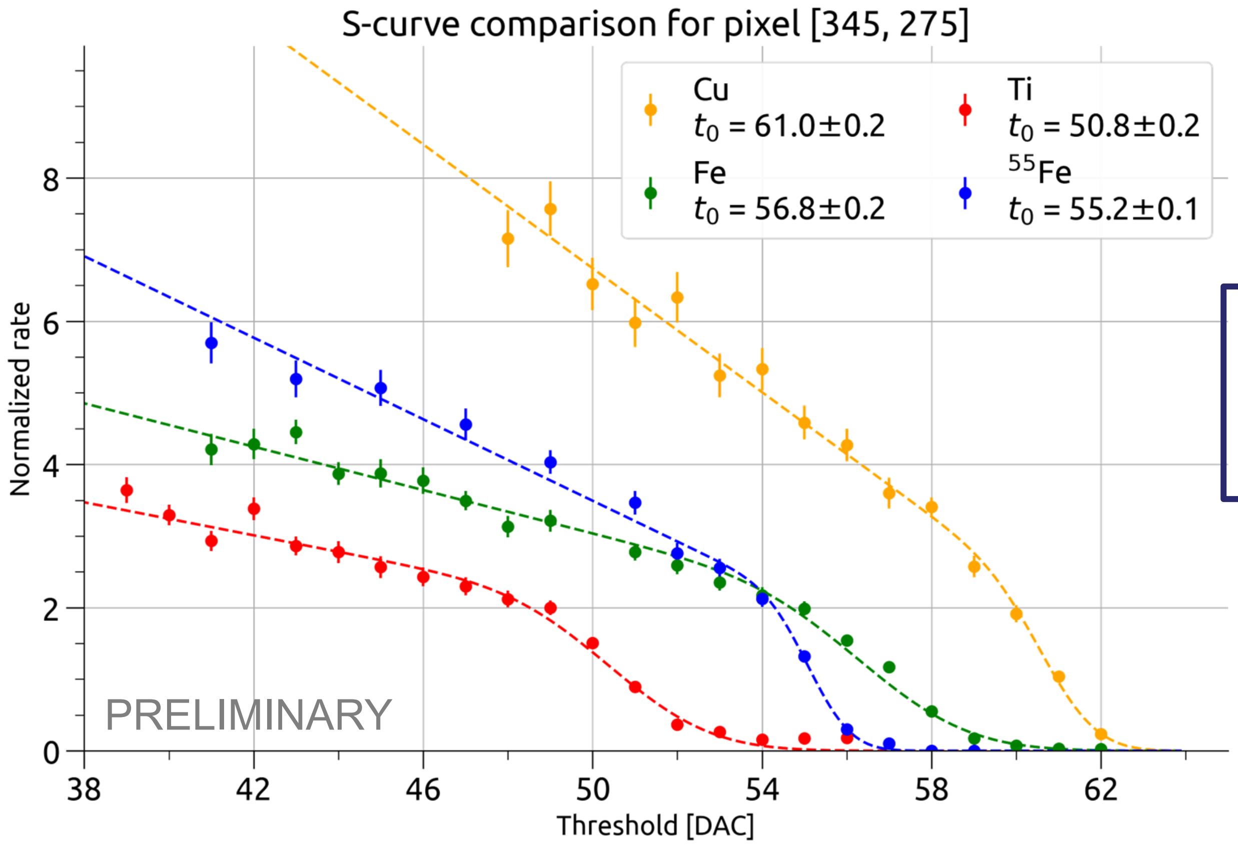
^{55}Fe source is also used as fourth value of energy (5.9 keV)

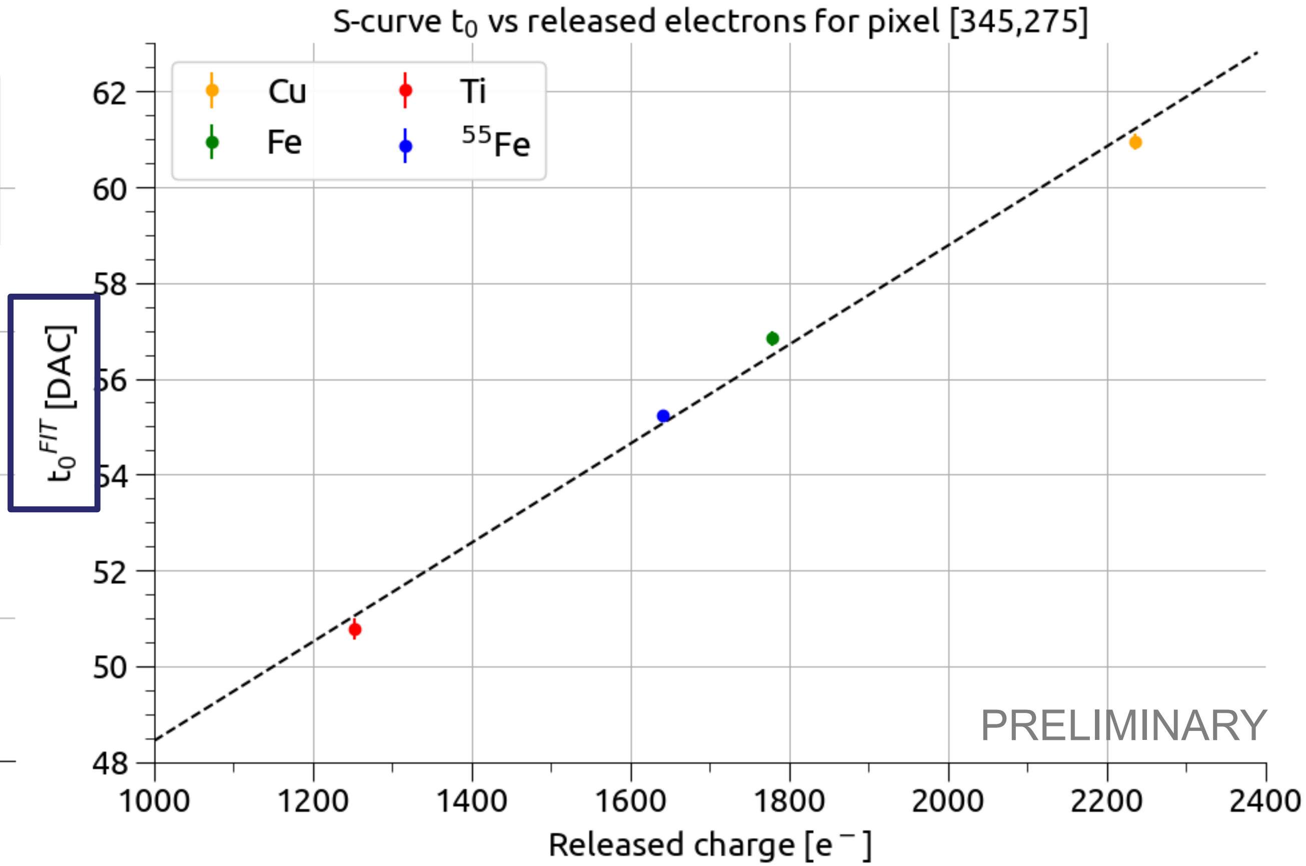


Spectra acquired with Amptek XR-100CR detector

MD3 characterization: calibration

Comparison of s-curve for all targets from fluorescence and from ^{55}Fe source.
The rate is normalized to have the s-curve middle point (t_0) at rate equals to 1.





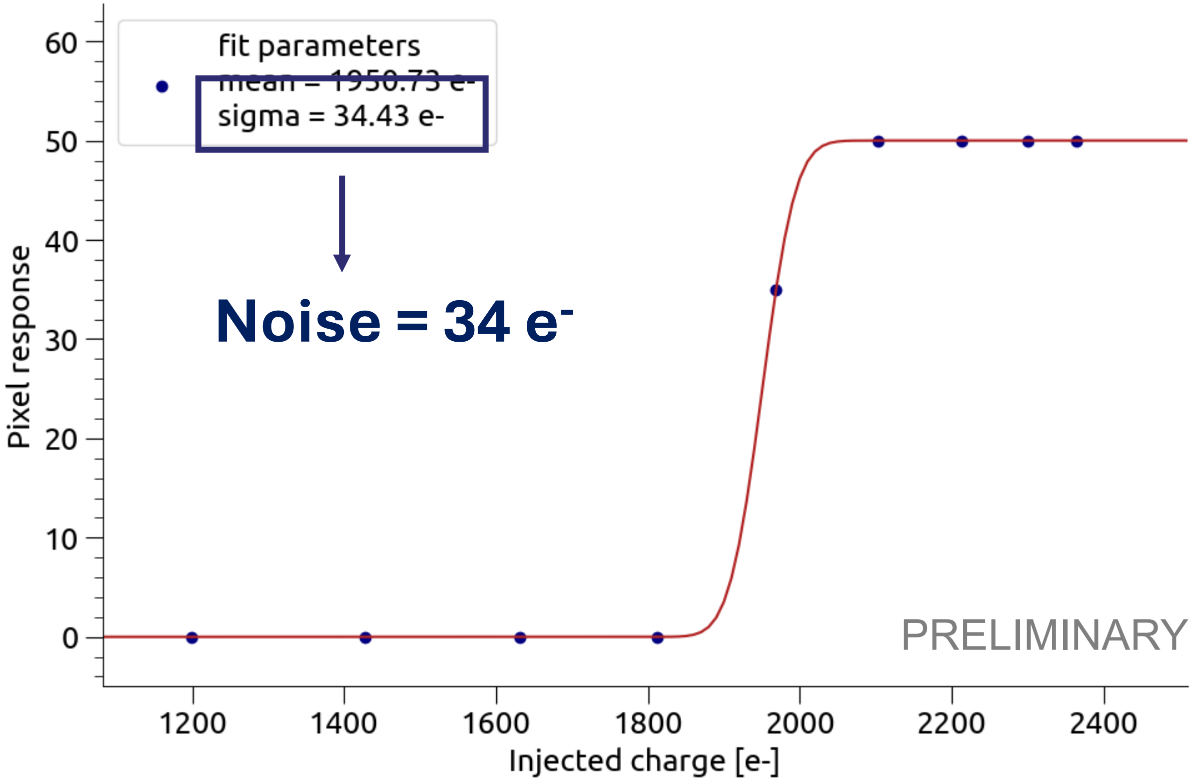
$$N(t) = N_0 \left[1 + \frac{C_s}{\sigma}(t_0 - t)\right]\left[1 + \mathrm{erf}\left(\frac{\boxed{t_0} - t}{\sqrt{2}\sigma}\right)\right]$$

Kraft, P., et al. "Performance of single-photon-counting PILATUS detector modules." *Synchrotron Radiation* 16.3 (2009): 368-375.
https://doi.org/10.1107/S0909049509009911

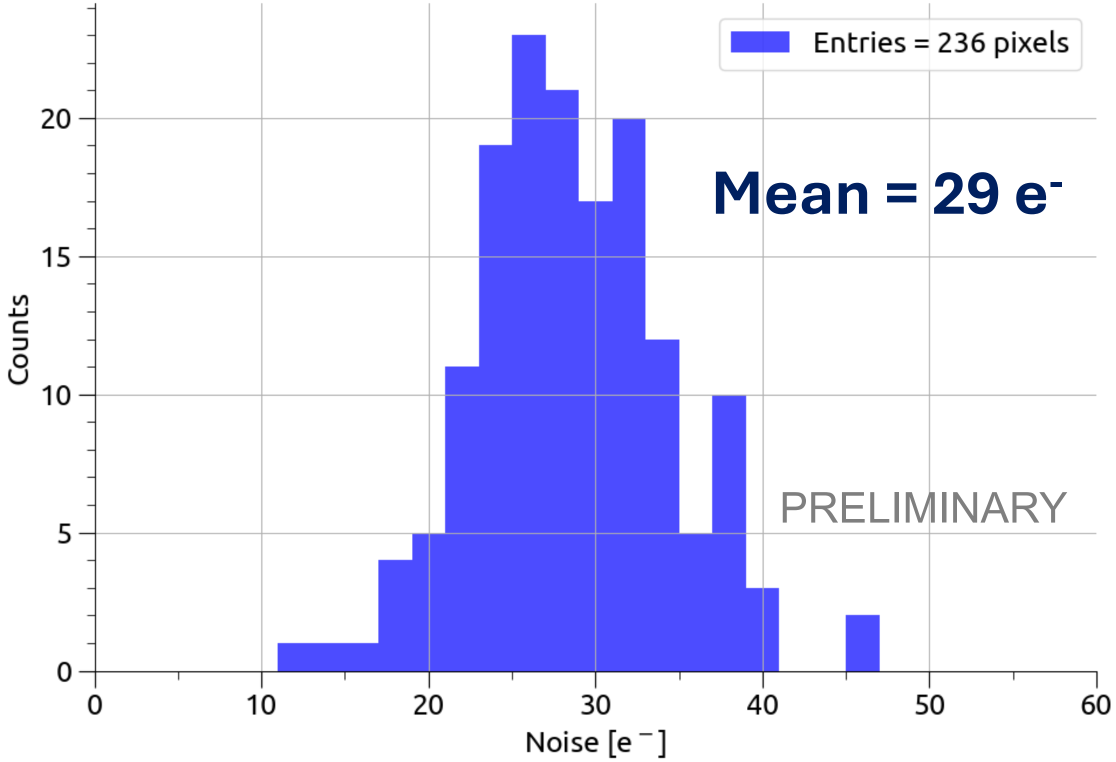
MD3 characterization: noise

Thanks to fluorescence results it is possible to calibrate the charge injected with test pulses pixel by pixel.
Noise from single pixel is obtained as the sigma of the s-curve

s-curve for single pixel @ thr = 58 [DAC]



Noise distribution for the 16 × 16 sub-array



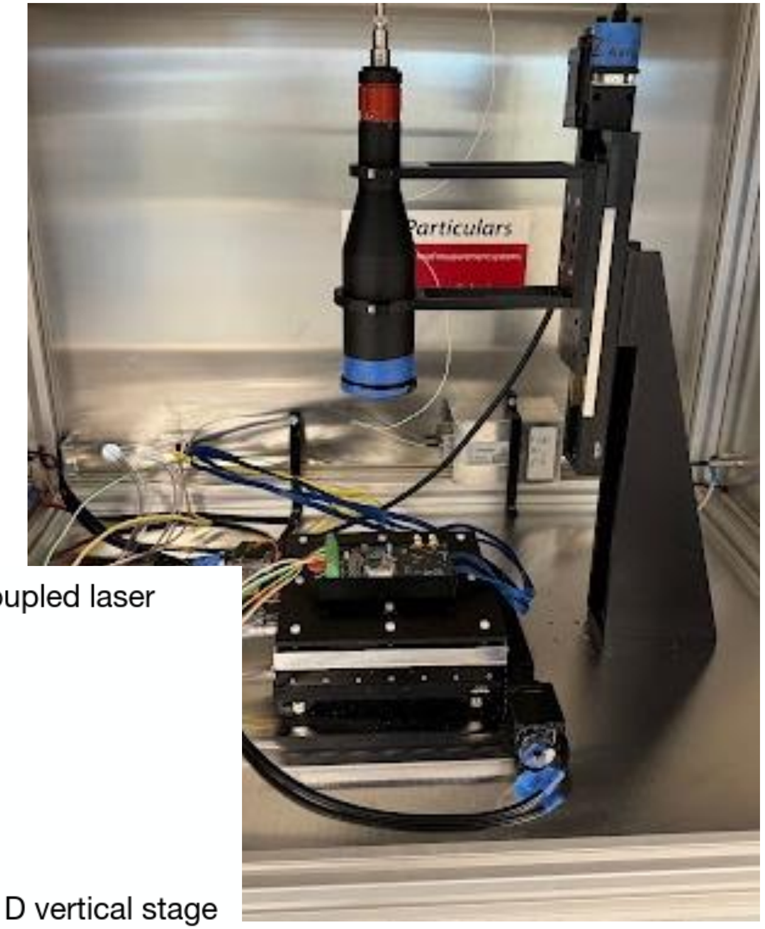
MD3 characterization: laser

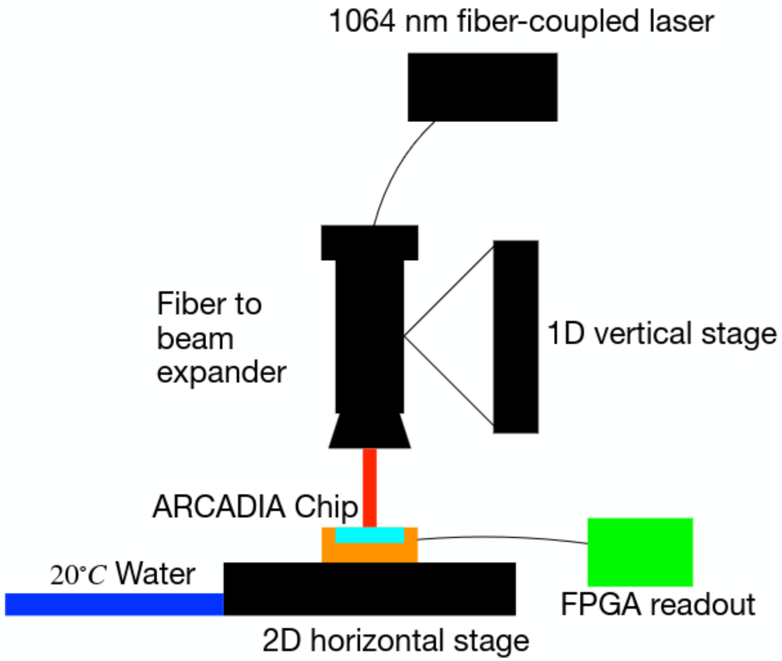
Results by Fermilab team :
T. Zenger, A. Apresyan, N. Bacchetta,
L. Bolla, A. Hayrapetyan, N. Salvador, I. Zoi

Goal:
- In-pixel efficiency map
- Efficiency uniformity over a 10 x 6 pixel array

Setup:
- 1kHz micro-focused IR laser (1064 nm)
- 2D horizontal stage: 5x5 in-pixel steps (5 μm)
- Temperature controlled environment

Measurements:
- In-pixel efficiency map at fixed threshold
- Threshold scan to reconstruct s-curve





MD3 characterization: laser

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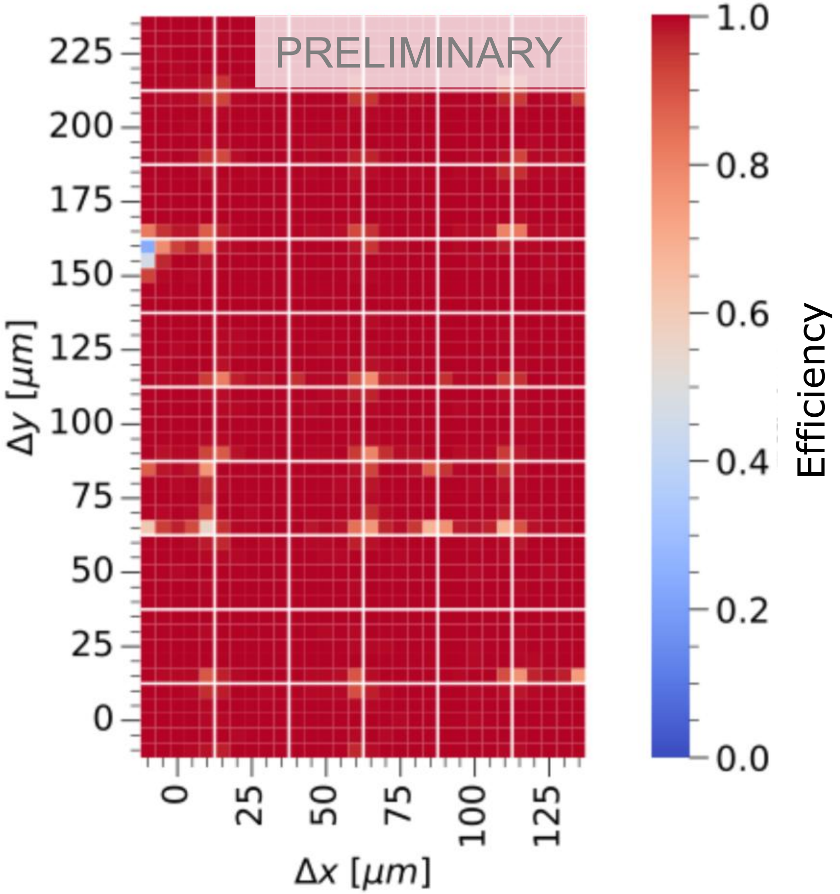
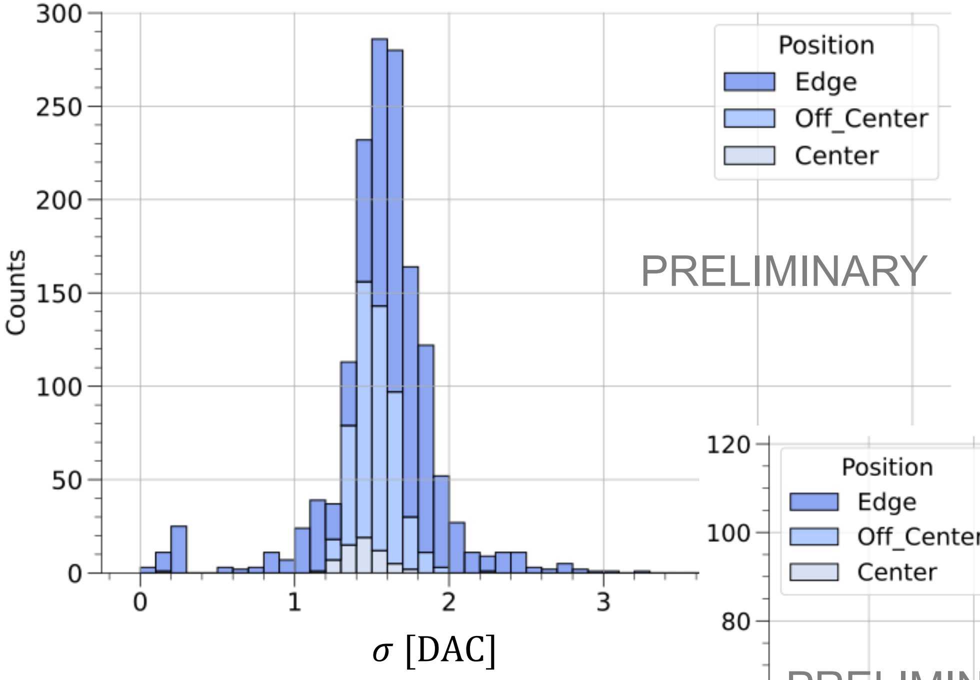
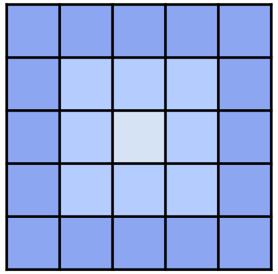
Efficiency
thr = 52 DAC



s-curve σ

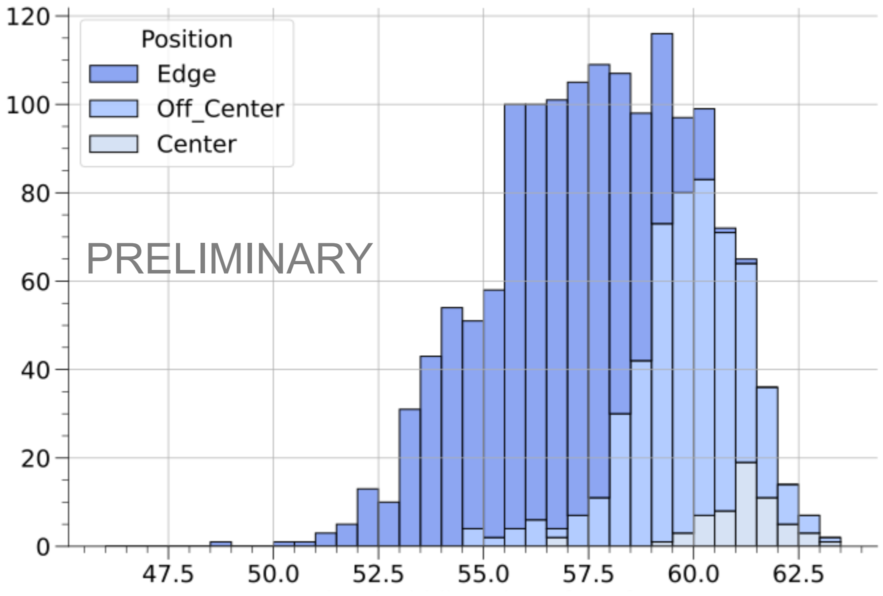




5x5 in-pixel steps

σ: width of s-curve

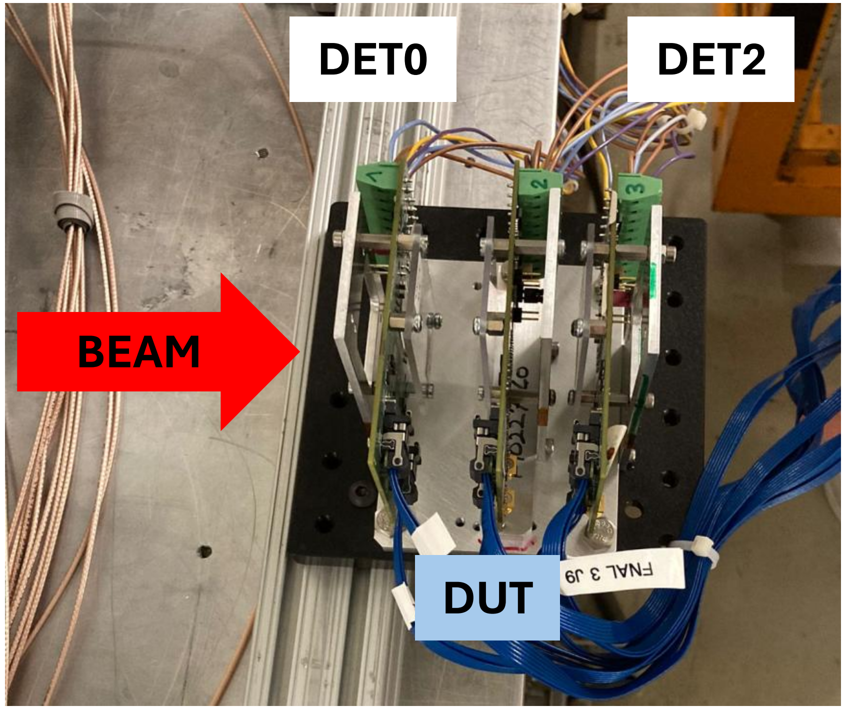
s-curve t_0



Middle point t_0: threshold value corresponding to 50% efficiency

MD3 test beam: overview

Test beam measurements done at **Fermilab Test Beam Facility** (**FNAL FTBF**) in Summer 2024 with a **120 GeV proton beam.**



Measurements performed:

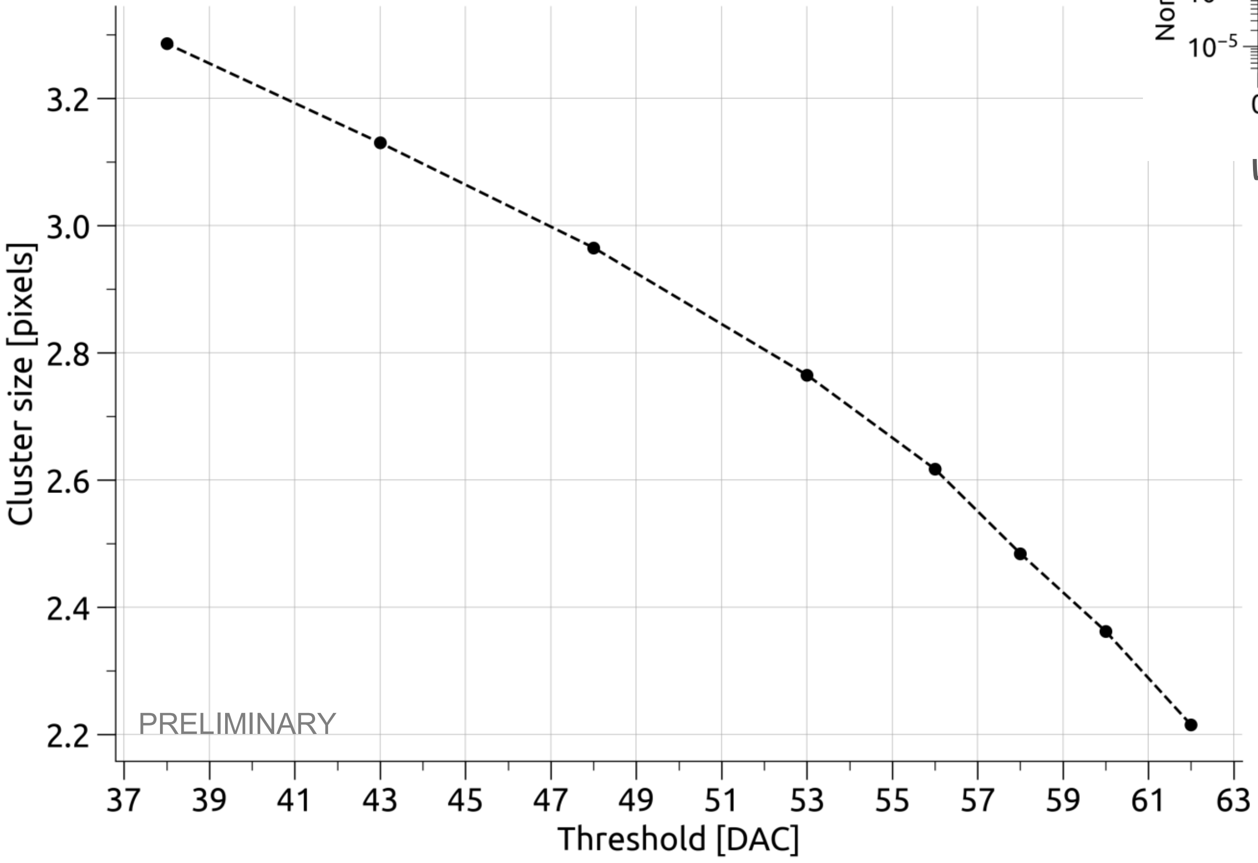
- Threshold scan
- Scan on FE parameters
- Depletion voltage scan
- Threshold scan with tilted DUT

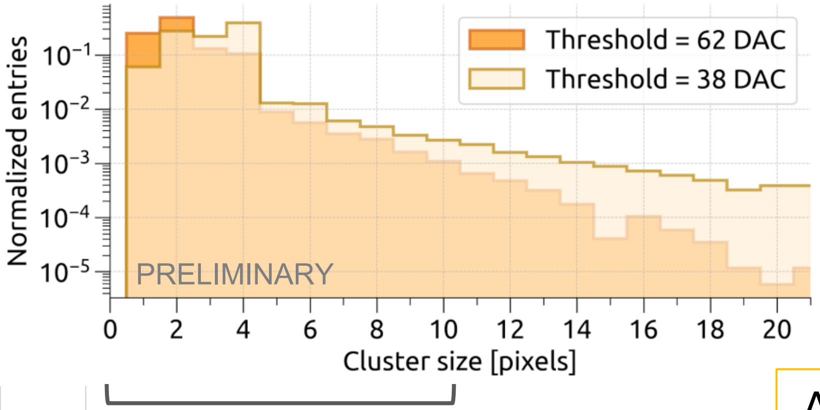
Experimental setup:

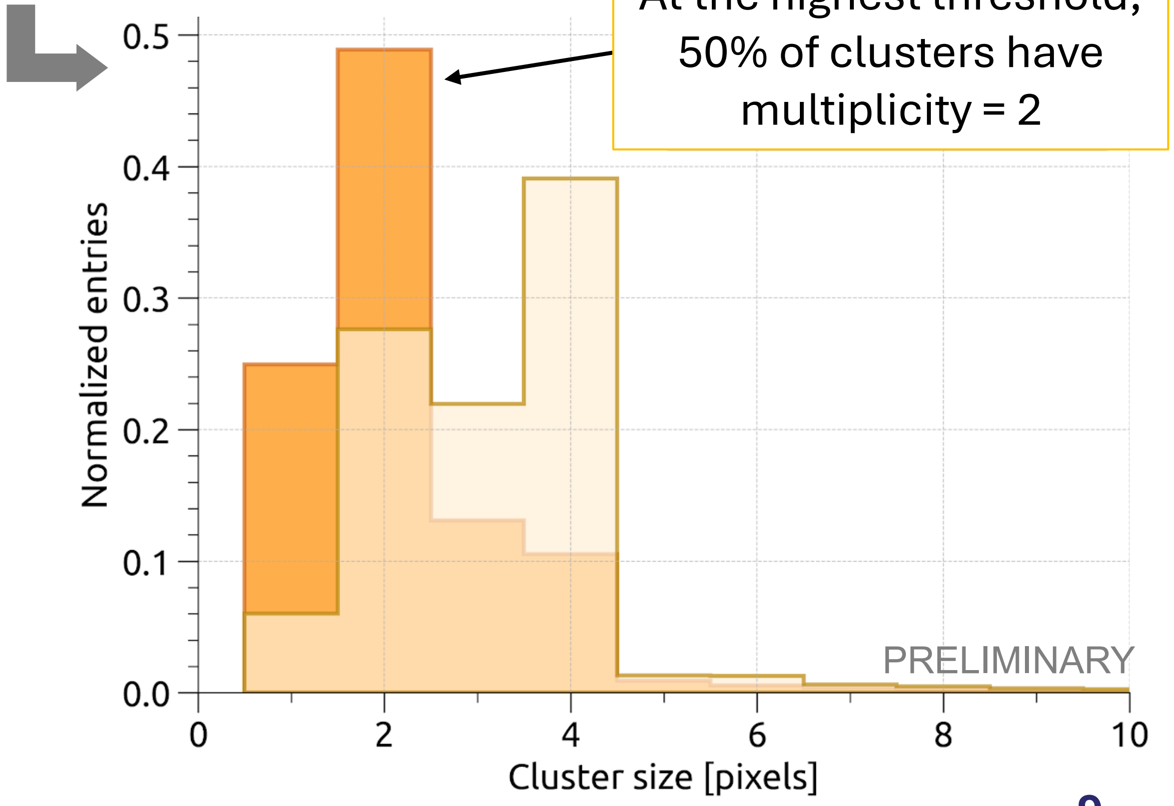
- Two ARCADIA MD3 (200 µm thick) as tracking planes
- One ARCADIA MD3 (200 µm thick) as Device Under Test
- DAQ: Triggerless acquisition with timestamp synchronization

MD3 test beam: cluster size

DUT clusters associated to tracks

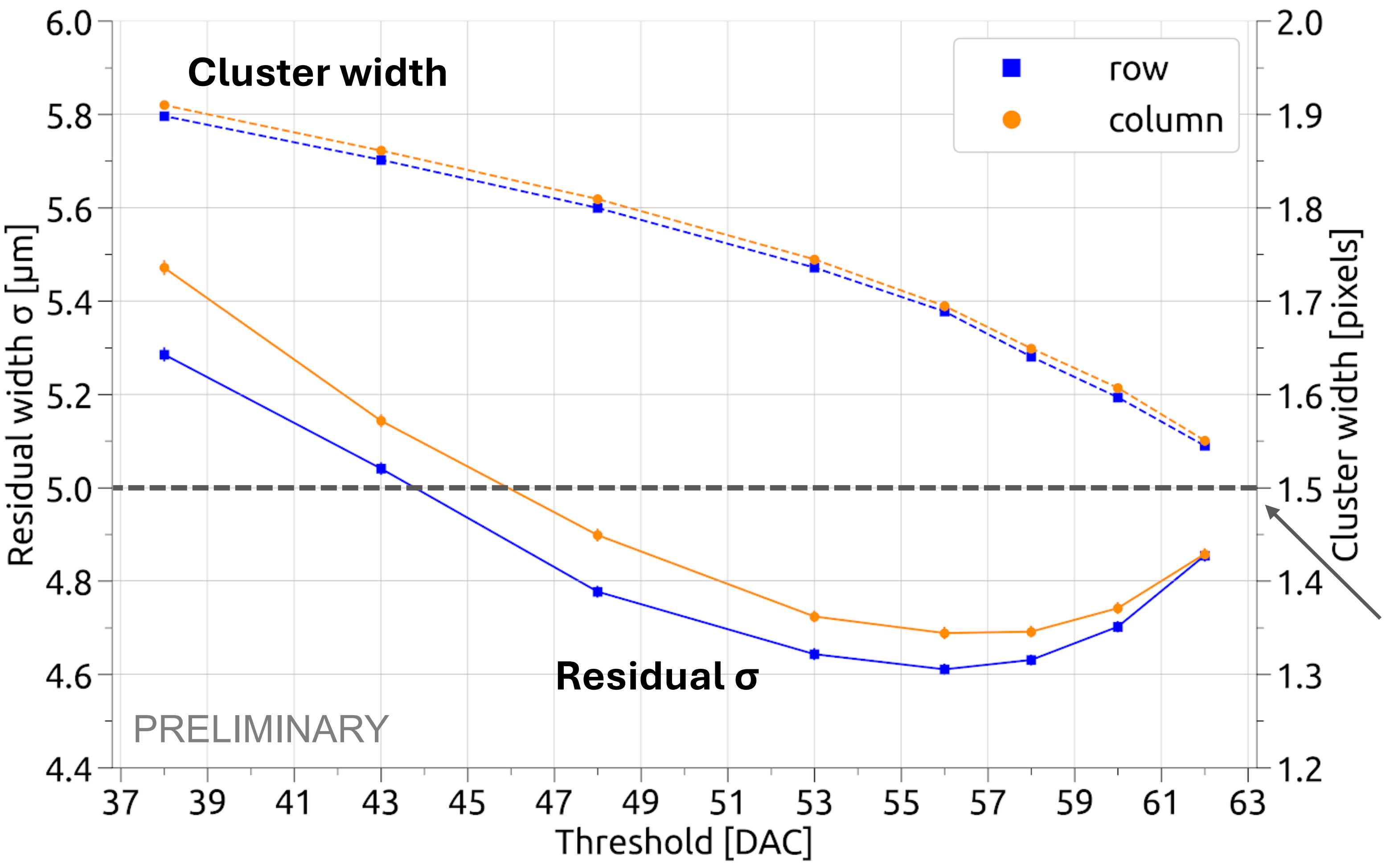






At the highest threshold, 50% of clusters have multiplicity = 2

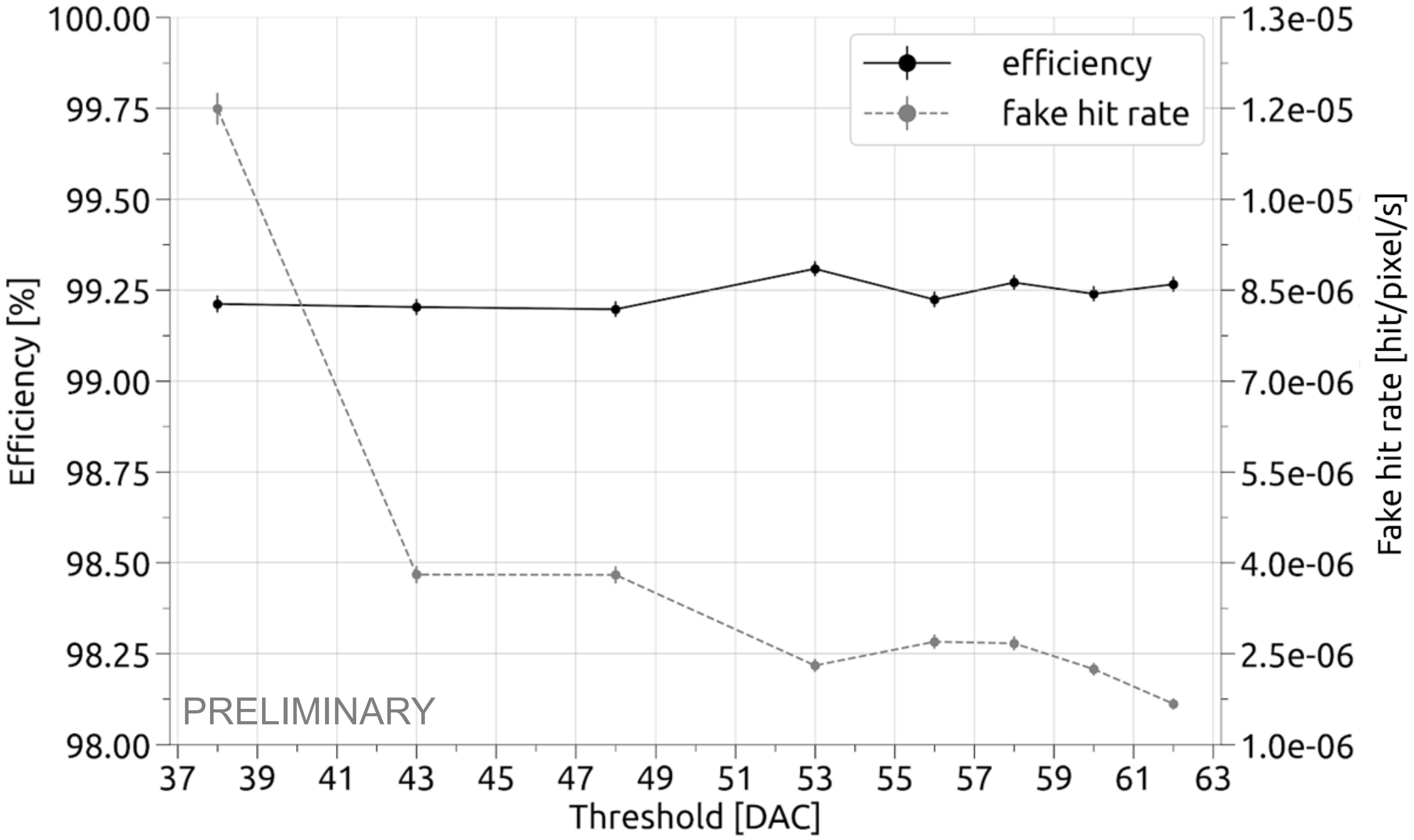
MD3 test beam: resolution



Cluster width always greater than 1.5 pixels

Residual width always below the **binary resolution (7.2 μm)**

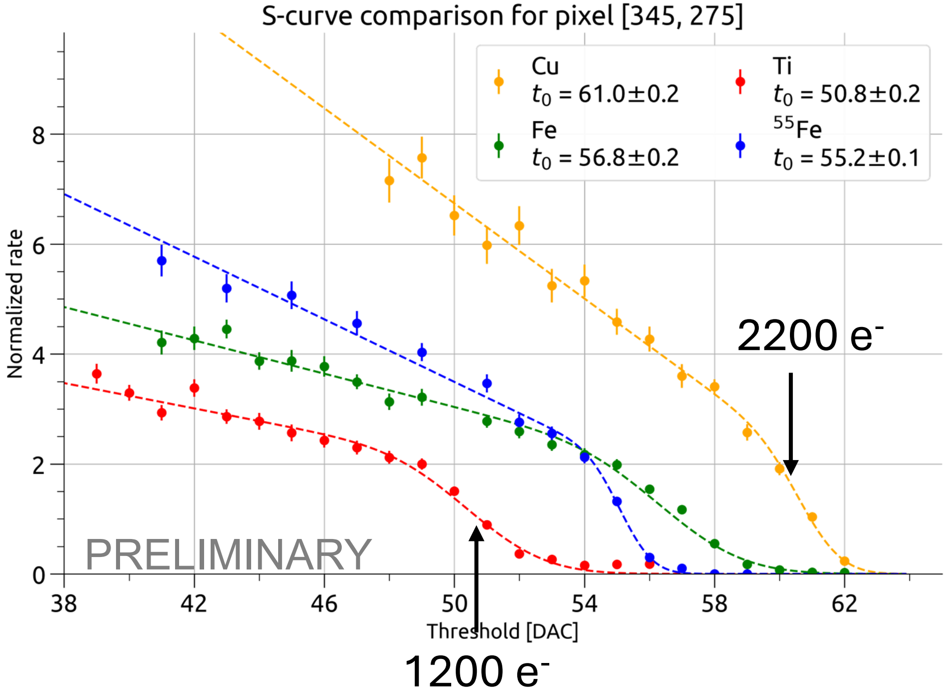
MD3 test beam: efficiency and fake hit rate

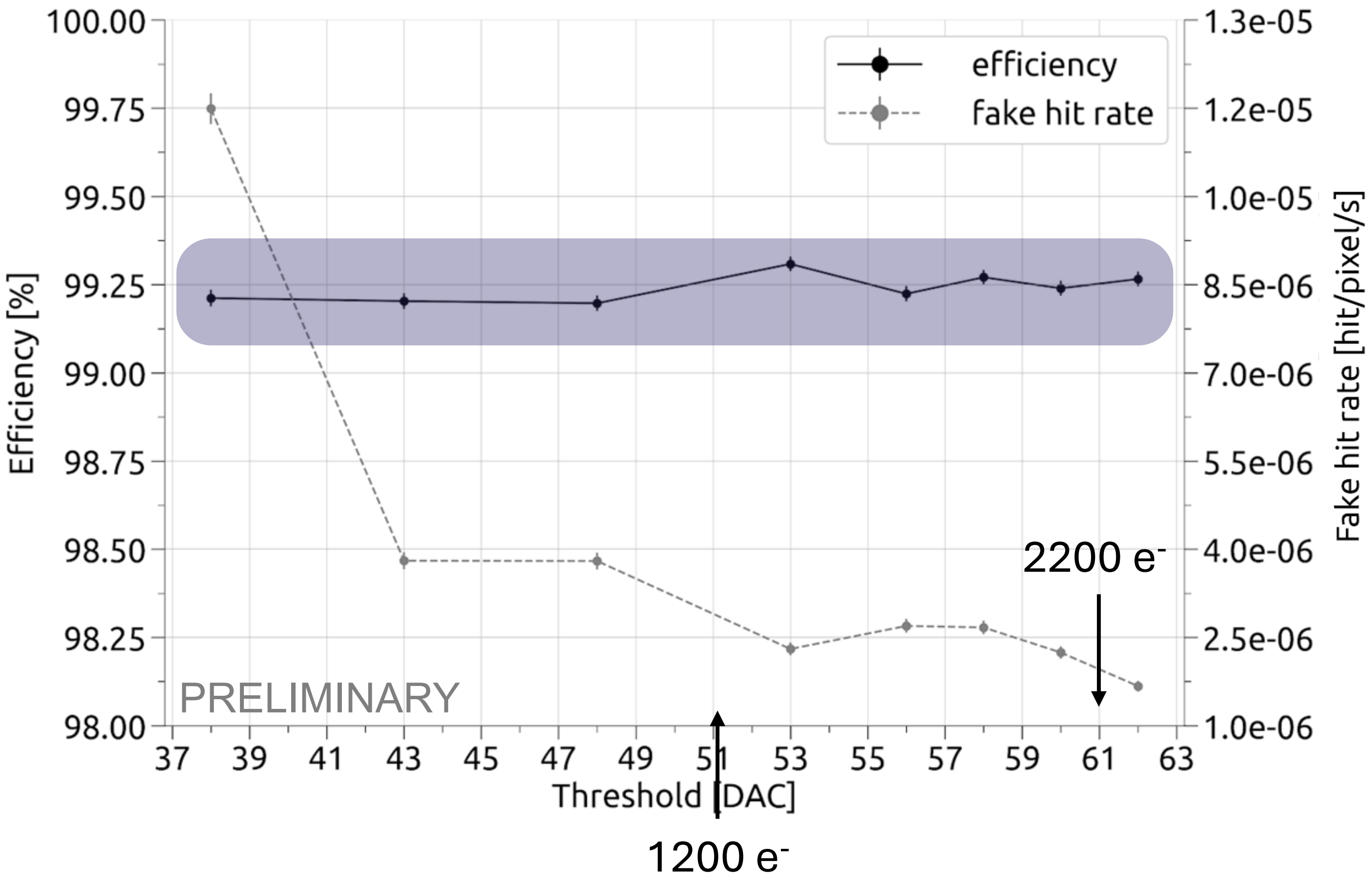


Fake hit rate measured during no-beam time

12 masked pixels on the DUT

MD3 test beam: efficiency and fake hit rate





Maximum threshold value corresponds roughly to **2200 electrons** (calibrated via fluorescence measurements).
In 200-µm thickness, a MIP releases ~ 16000 e$^-$ → the highest available threshold corresponds to a much lower charge released.

Summary and outlook

- **Lab characterization** of ARCADIA: **threshold calibration** and **efficiency uniformity** studies
- **First in-beam characterization** of the ARCADIA chip
- Thick active region and low threshold range → **strong effect of charge sharing**
- **Spatial resolution:** the minimum width of the residual distribution of **4.6 μm** with a 1D average cluster width of about 1.6 pixels
- **Efficiency** always **above 99%**

Future developments:

- **Characterization paper** ready for submission and **test beam paper coming** next
- **Additional test beam campaign** with an **extended telescope** to improve track reconstruction and validate these first results
- Comparison of performances for DUTs with **different active thicknesses**
- Measurements with **low-energy electron beam**
- Specific measurements on **power consumption for space** application

Summary and outlook

- **Lab characterization** ... **uniformity** studies
- **First in-beam charac**...
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Future developments:

- **Characterization pa** ... **ng** next
- **Additional test bean** ... track reconstruction and validate these first re...
- Comparison of perfo...
- Measurements with **L**...
- Specific measurements on **power consumption for space** application

Padova team

Thank you for your attention

Backup

ARCADIA wafer

Timing application

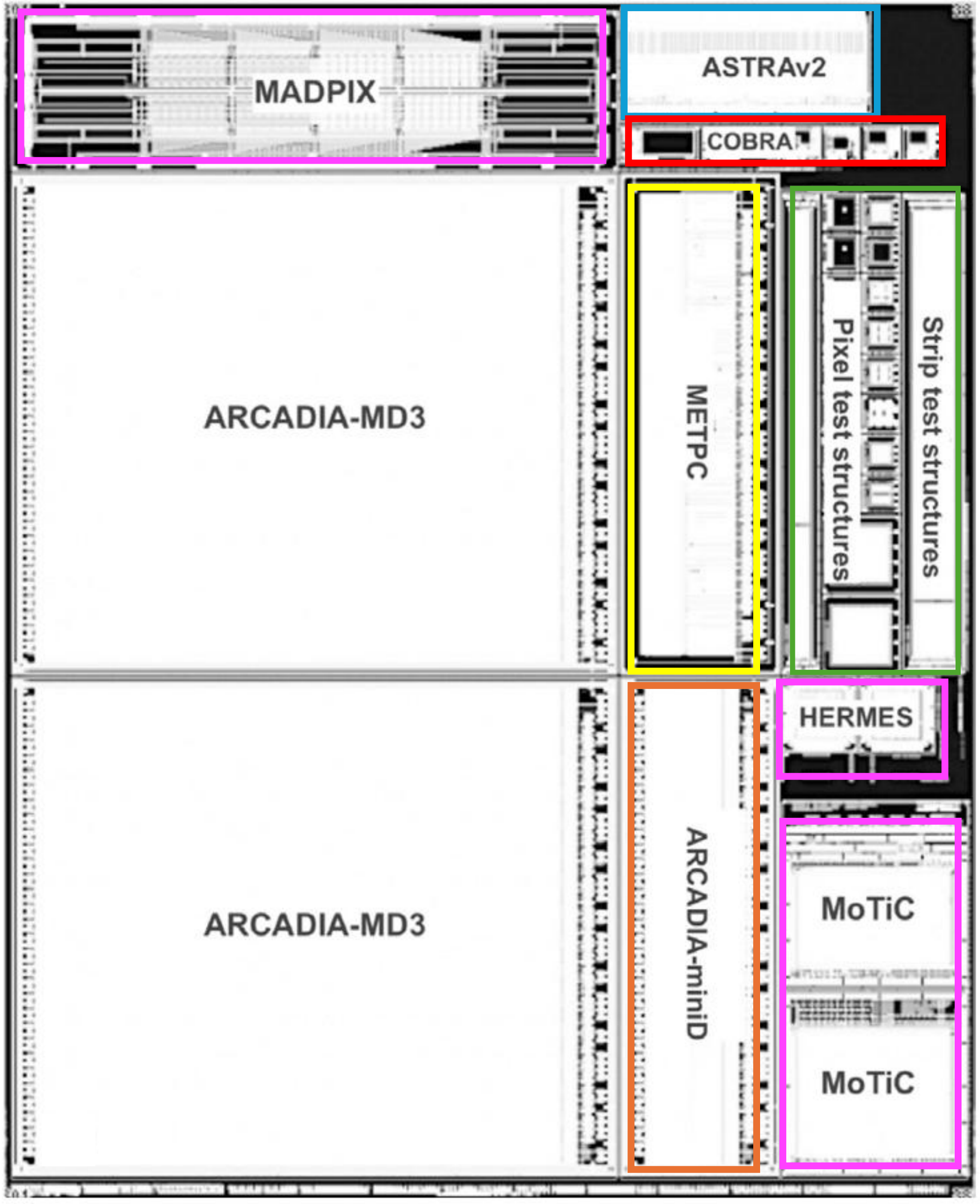
Passive structures for electrical characterization

X-ray application (multi photon counter)

Debugging implemented power management IPs

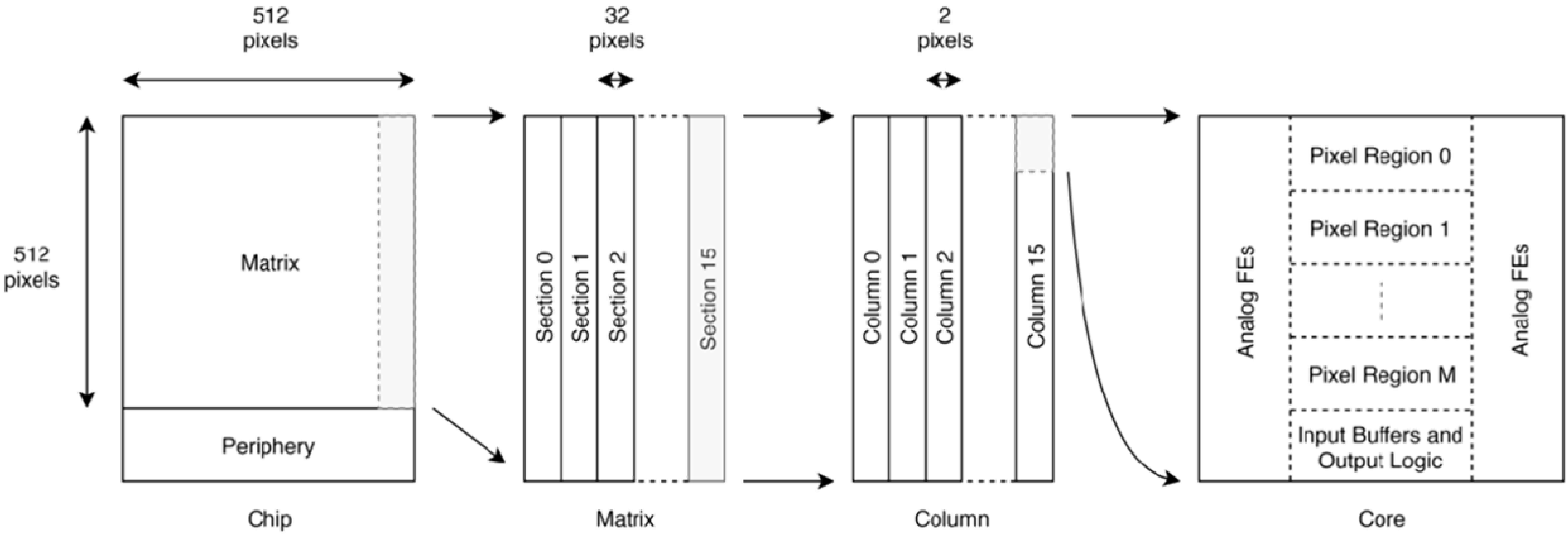
Space-borne applications

Tracking and dosimetry



More details in: M. Rolo et al., ARCADIA fully depleted CMOS MAPS development with LFoundry 110 nm, DOI:10.3389/fsens.2025.1603755ISSN=2673-5067

MD3 architecture

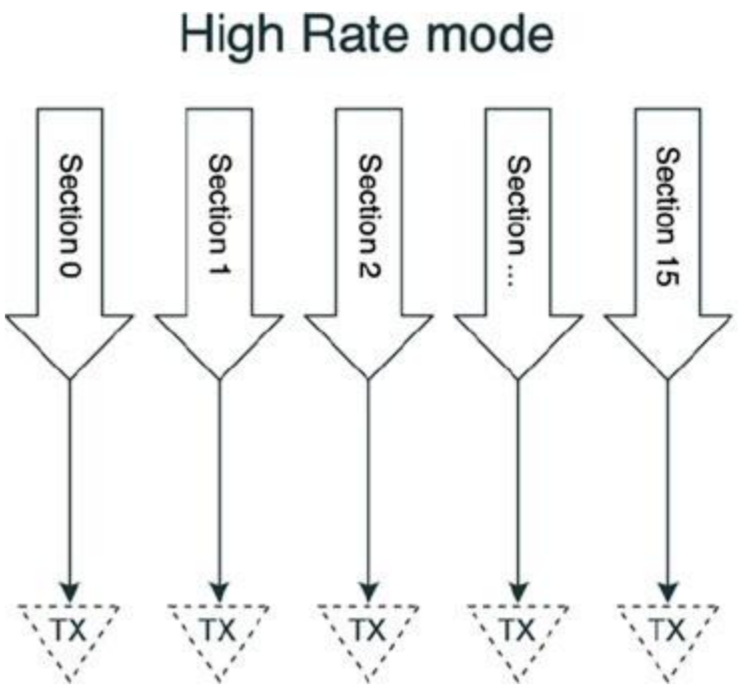


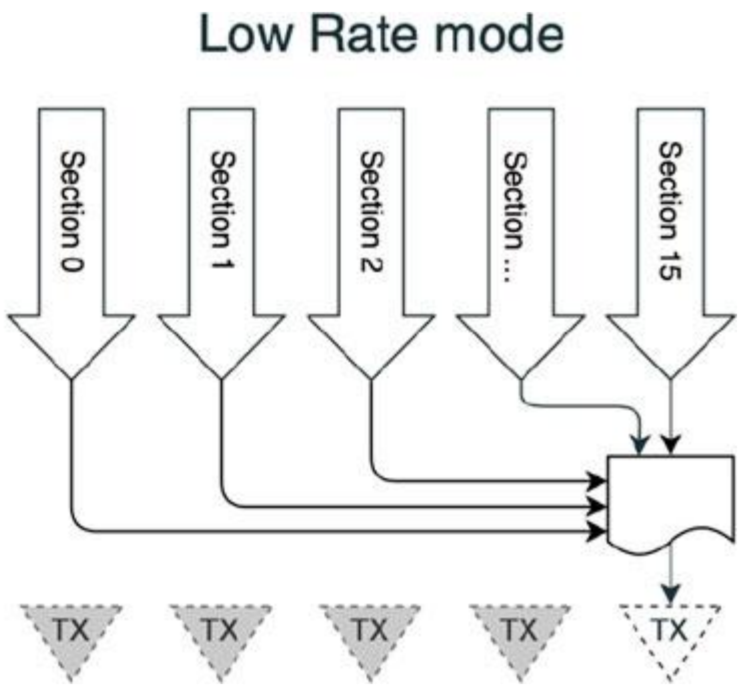
16 independent
Sections

32 x 2 pixel core minimum
synthesizable units

More details in: M. Rolo et al., ARCADIA fully depleted CMOS MAPS development with LFoundry 110 nm, DOI:10.3389/fsens.2025.1603755ISSN=2673-5067

Low rate configuration





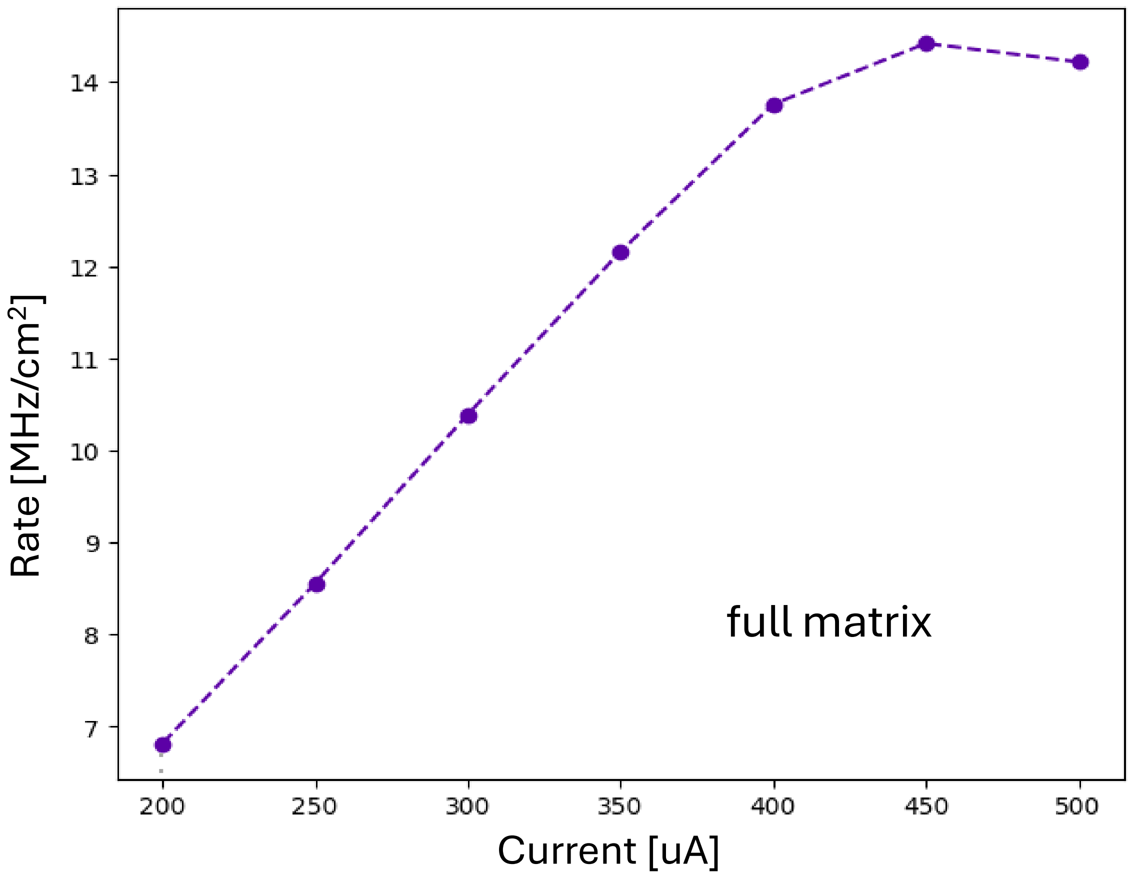
Designed to sustain particle rate of 100 MHz/cm^2

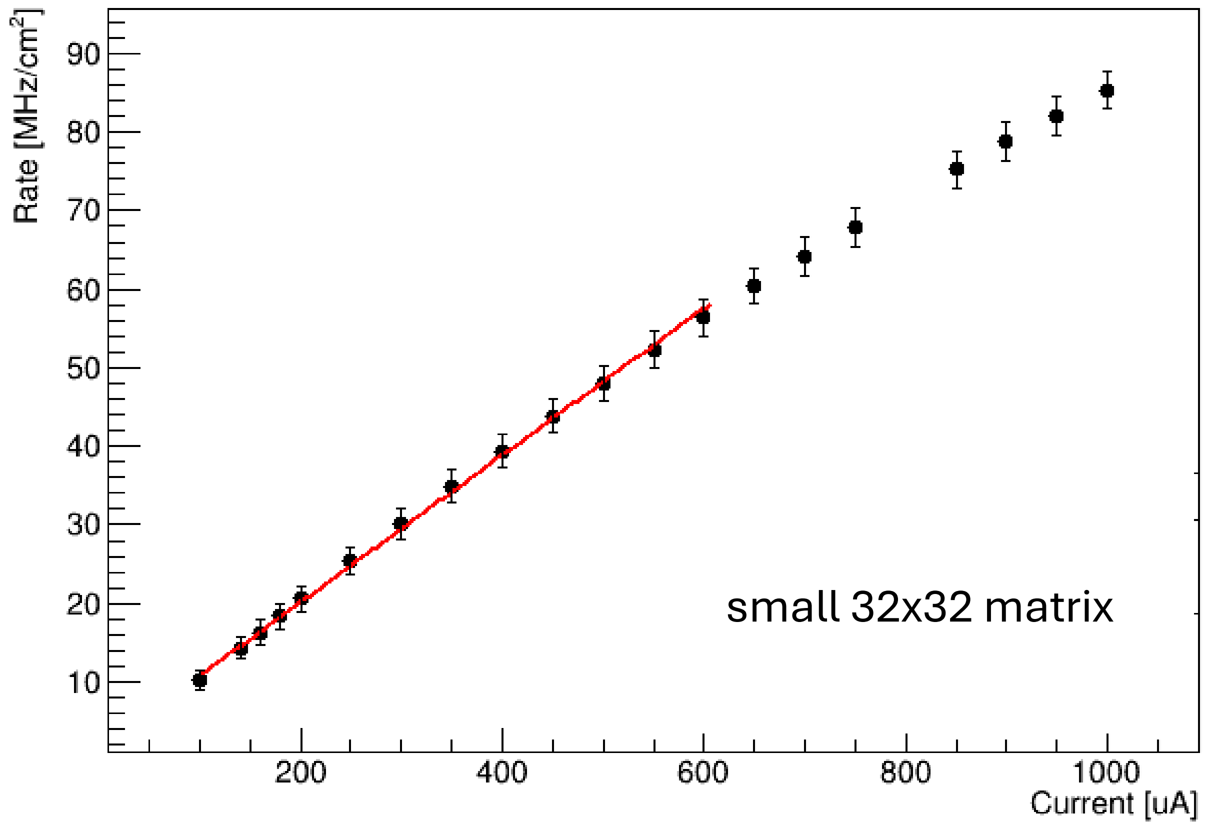
For low-rate applications:
Data from all section readout units are buffered into a central FIFO and only one transceiver is enabled.

Power consumption: o(10 mW/cm^2)

MD3 characterization: rate evaluation

Rate response is evaluated as function of the current of the X-ray tube.
Results for cluster rate @80kV X-ray tube voltage.

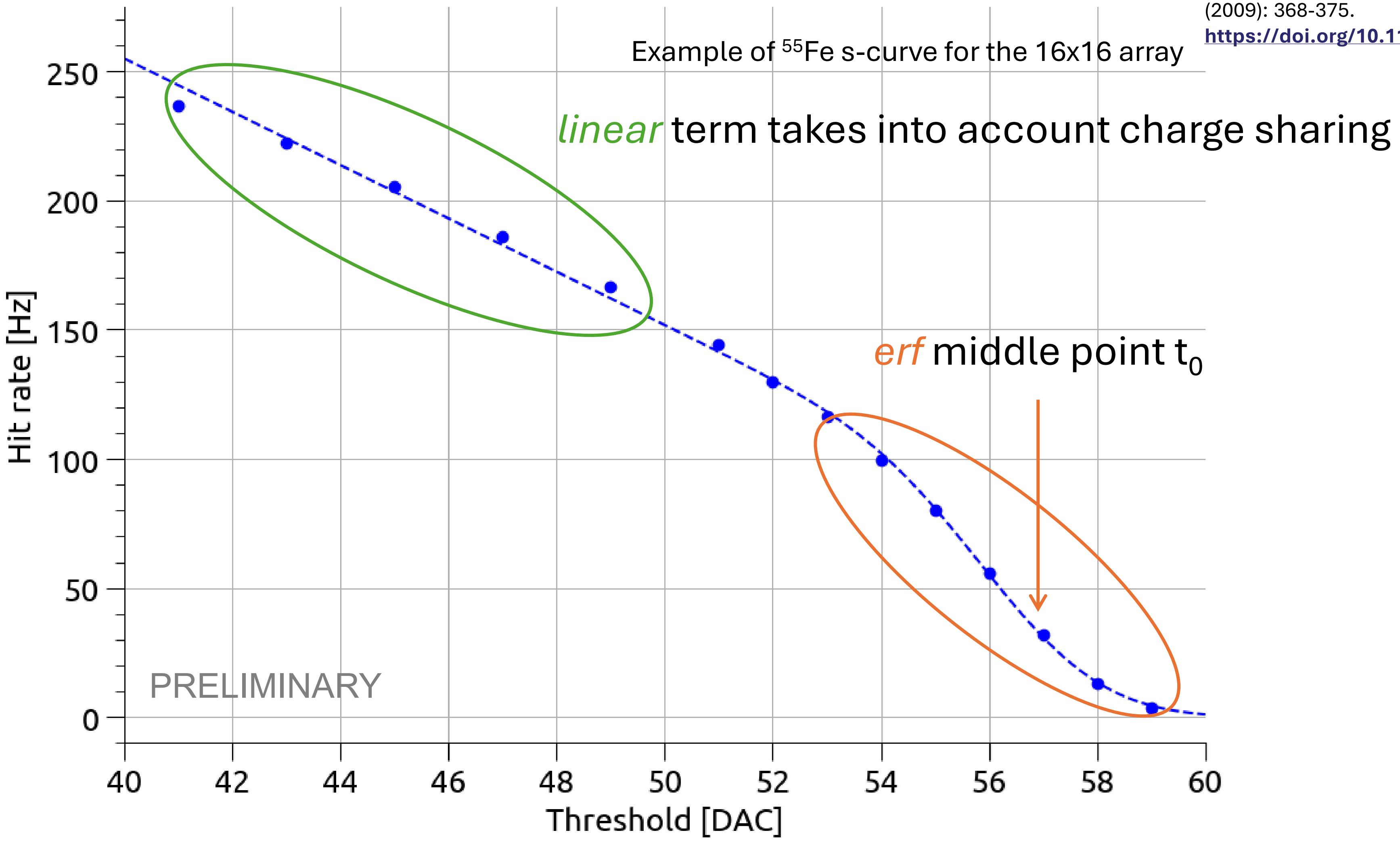




MD3 characterization: fluorescence

Hit rate vs threshold: the electronic cloud released by X-ray diffuses in silicon leading to charge sharing, therefore the fit model is modified with respect to test pulse s-curve.

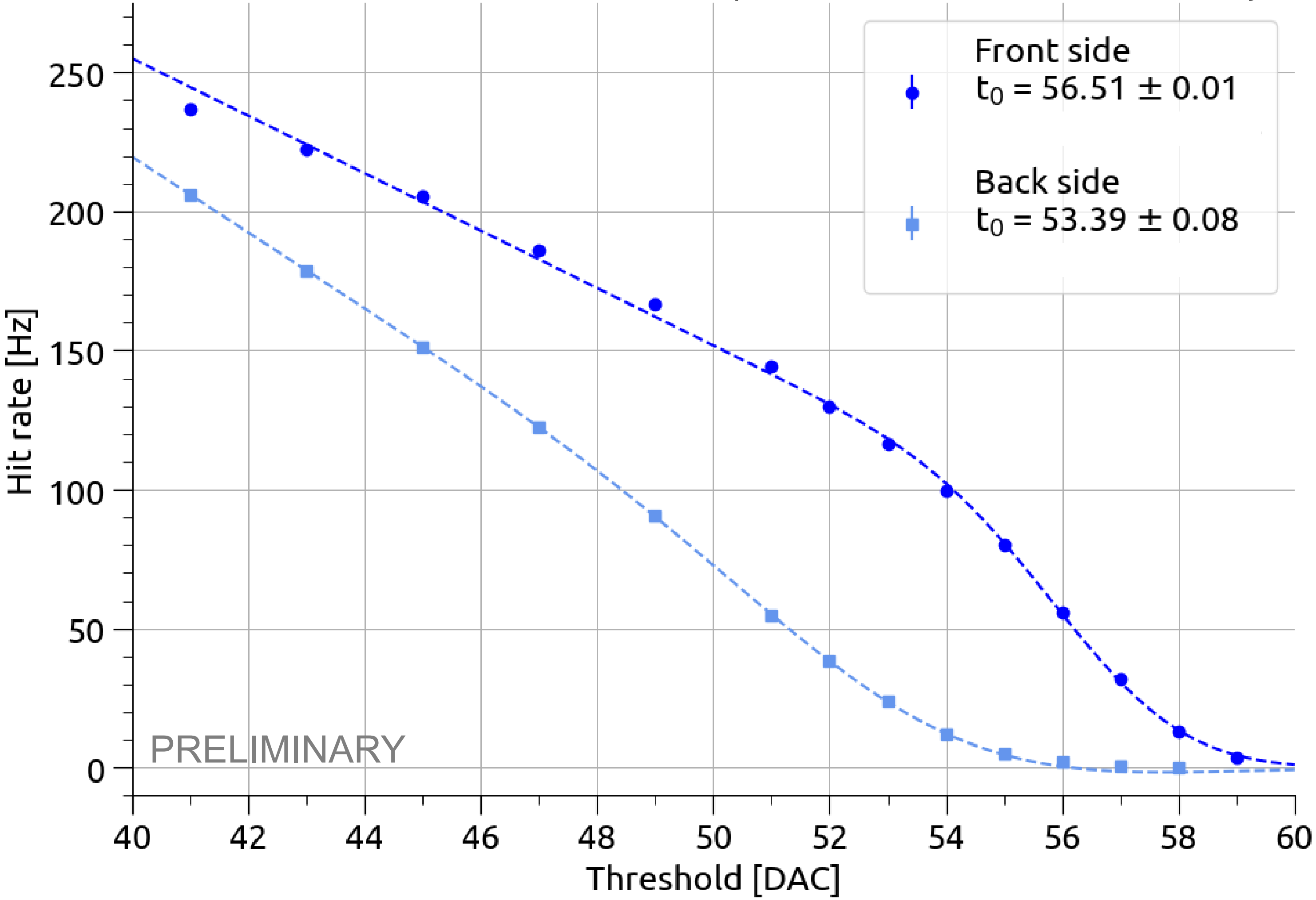
Kraft, P., et al. "Performance of single-photon-counting PILATUS detector modules." *Synchrotron Radiation* 16.3 (2009): 368-375.
https://doi.org/10.1107/S0909049509009911



MD3 characterization: front-back measurements

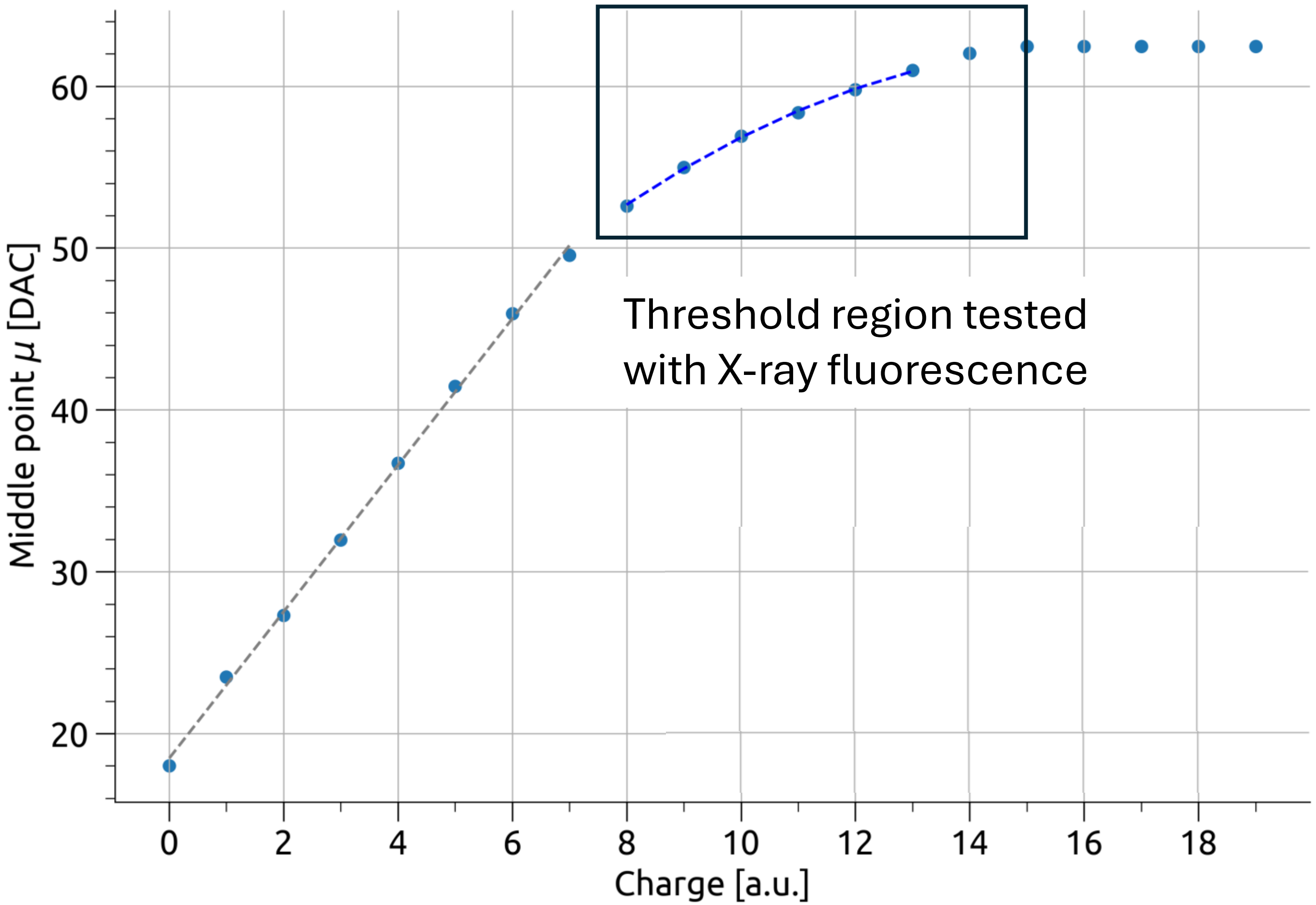
The electronic cloud released by X-ray diffuses in silicon leading to charge sharing.
More charge sharing when illuminating from the back side

Example of ^{55}Fe s-curve for the 16x16 array



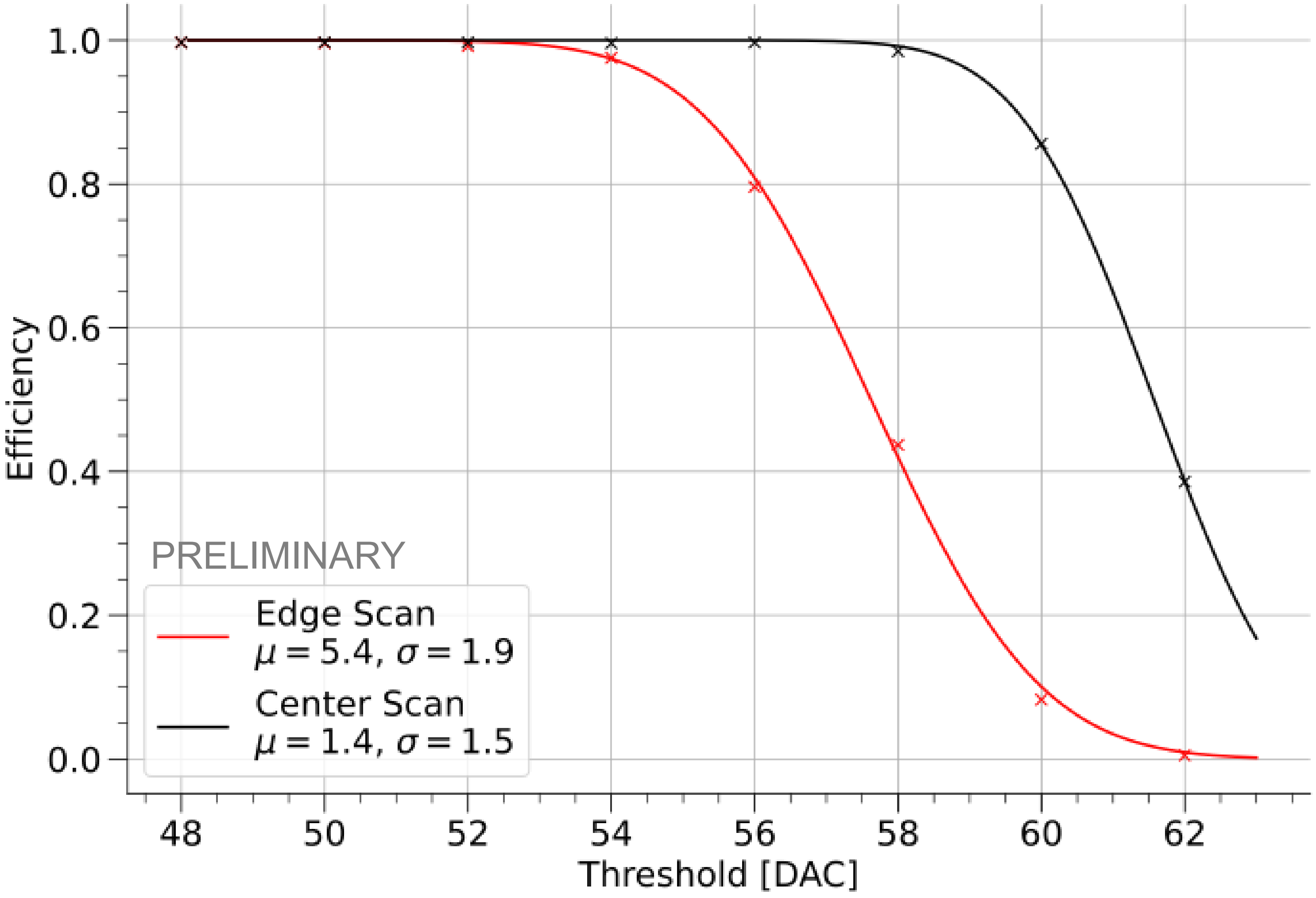
MD3 characterization: injection charge calibration

Middle point of the s-curve as a function of the injected charge in arbitrary units for a single pixel.
There are clearly two regimes, at some point the linearity is lost



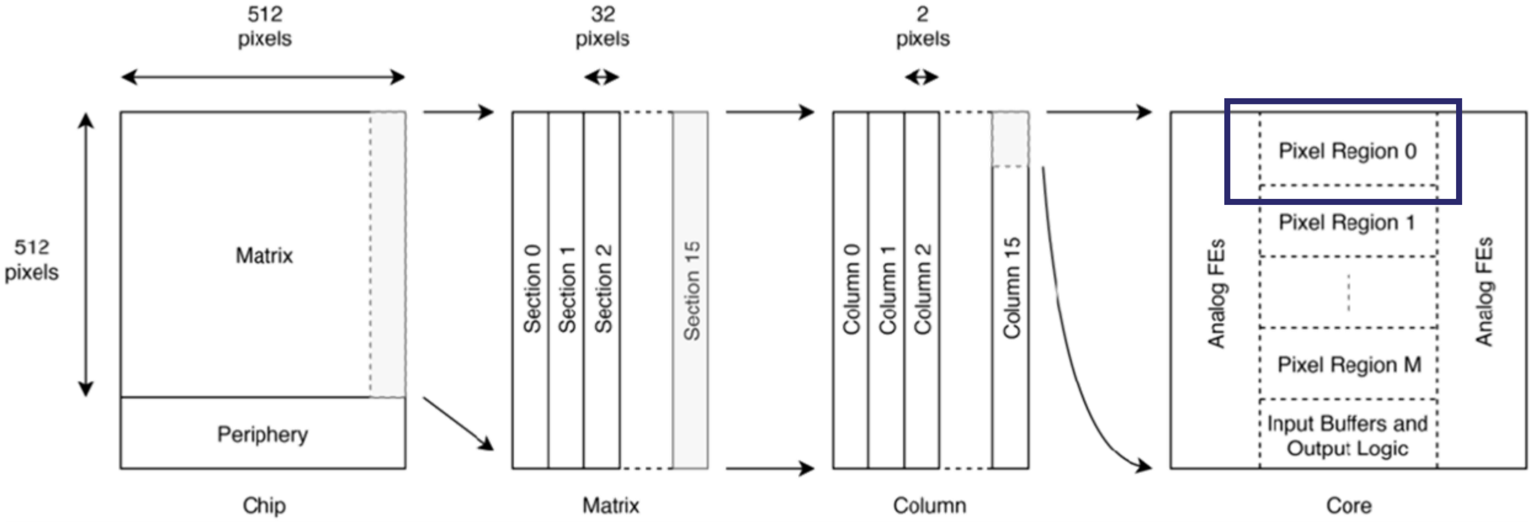
MD3 characterization: laser

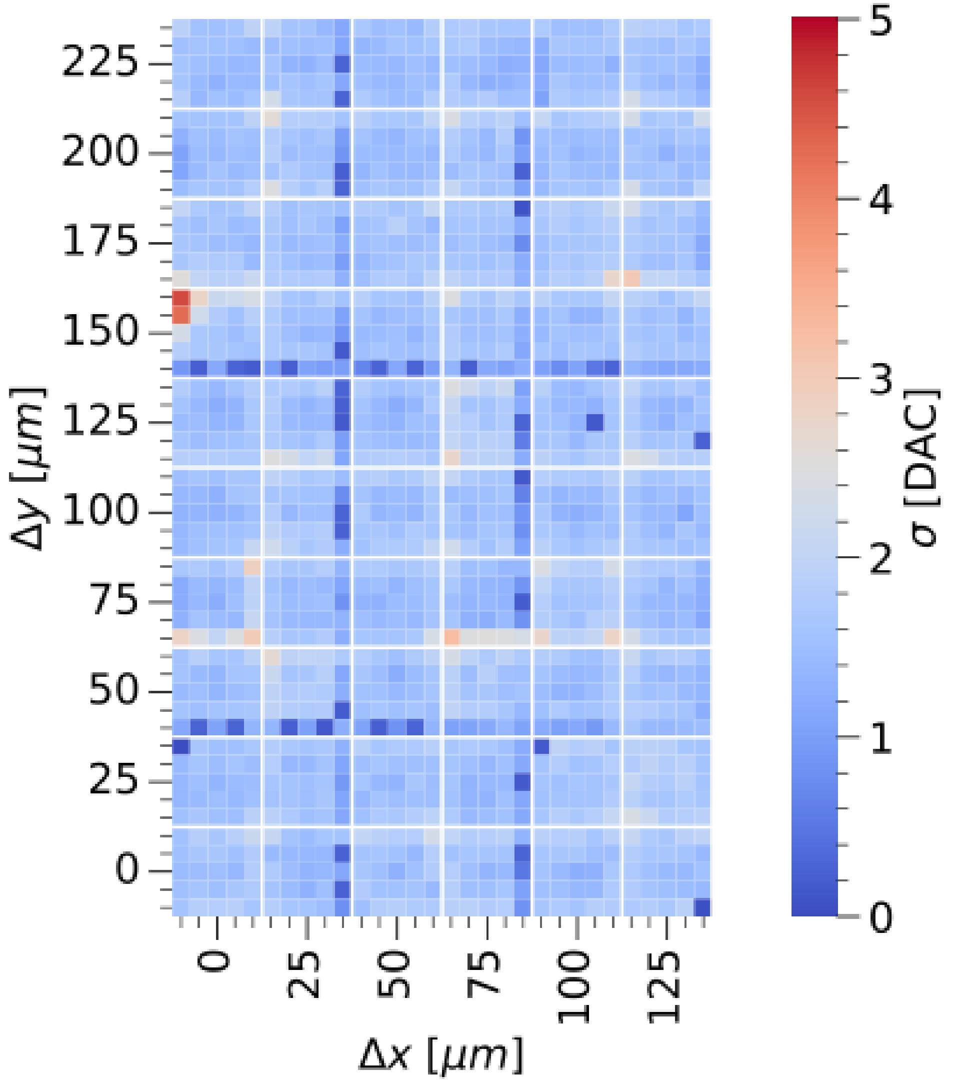
Example of in-pixel efficiency s-curve with IR laser illumination



MD3 characterization: laser

Very low values of σ correspond to the edges of the 4x2 pixel region.





MD3 test beam: measurements and analysis

Data are analysed spill-by-spill using the **Corryvreckan** software.

Analysis steps:

- **Clusterization**
- **Prealignment** of the three planes from correlation plots
- **Alignment** of the DUT with DUT residual distribution
- **Tracking** with the two external planes and **DUT association**
- Analysis of the **residual** distribution and **efficiency**
  - Association window: 5 μs and 500 μm
  - Edge cut: 30 pixels on both row and column axis

D. Dannheim, et Al., “Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data,” *Journal of Instrumentation*, vol. 16, no. 03, p. P03008, Mar. 2021. doi:10.1088/1748-0221/16/03/P03008