Performance Study of Neutron Irradiated HV-MAPS

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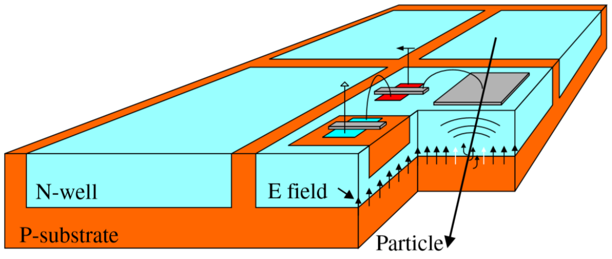
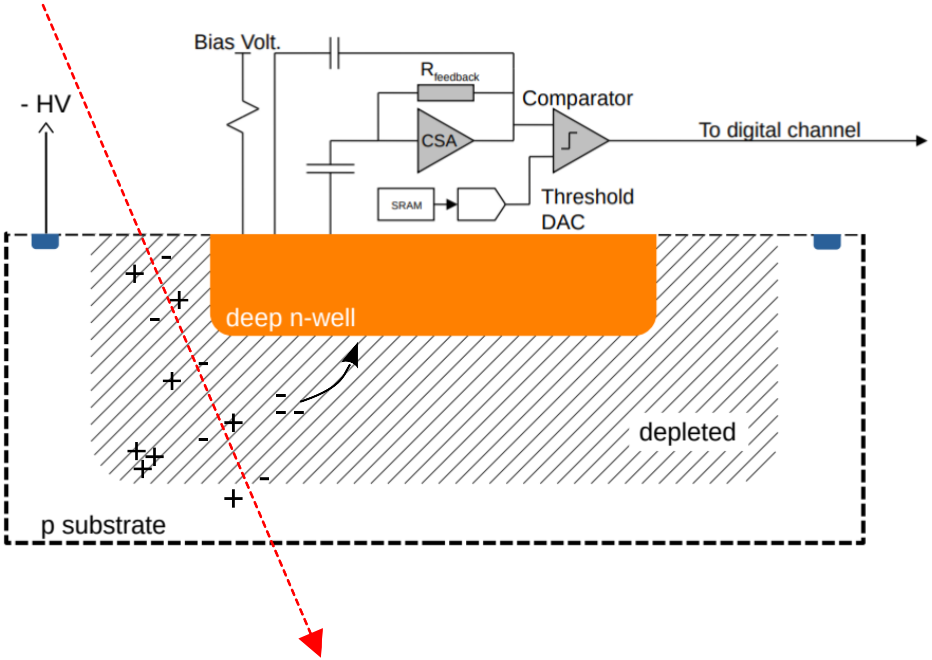
High-Voltage Monolithic Active Pixel Sensors



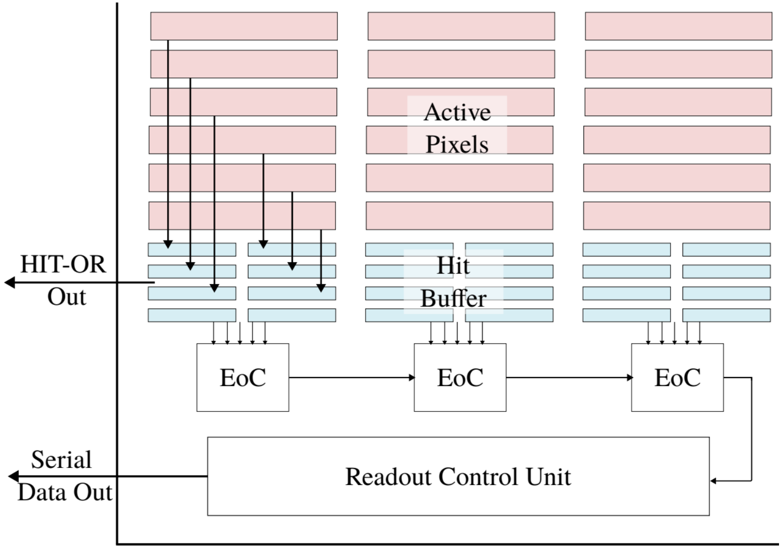
[I Peric, NIM A 582 (2007) 876]

- Commerical HV-CMOS processes
- Large fill factor deep n-well diodes
- Reverse high voltage bias from top side
- Charge collection via drift
- Sensor thickness can be thinned down to 50 µm

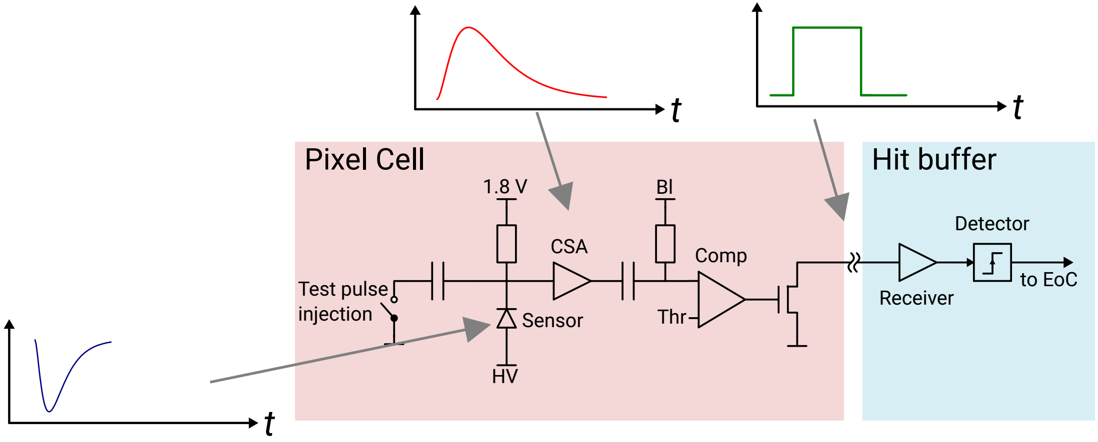


High-Voltage Monolithic Active Pixel Sensors

- In pixel electronics
  - Charge sensitive amplifier
  - Tuneable comparator
- Digitisation in hit buffers in periphery
- Column drain readout architecture

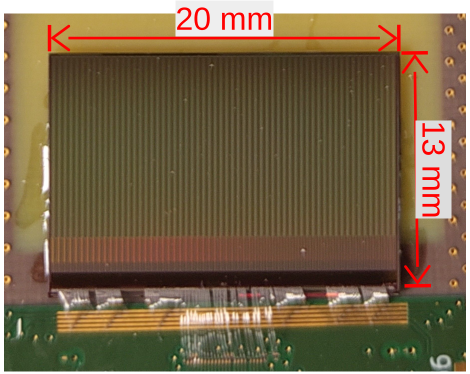


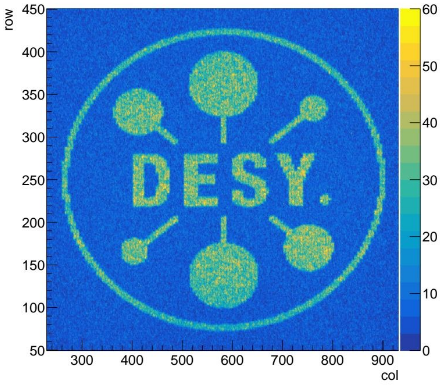
Not to scale



TelePix2

- TSI 180 nm HV-CMOS process
- 200 – 400 Ωcm Cz p-substrate
- Reverse HV-bias up to ~140 V → ≈ 70 µm depletion zone
- 120 × 400 pixels with size 165 × 25 µm²
- Designed as a fast timing and triggering plane for beam telescopes:
  - Configurable trigger output (analogue Hit-OR)
  - 4 ns Time-of-Arrival sampling
  - 8 ns Time-over-Threshold sampling
  - Hit driven readout at 1.25 Gbit/s
- In operation as user infrastructure at DESY test beam





Hits triggered by TelePix2's Hit-OR

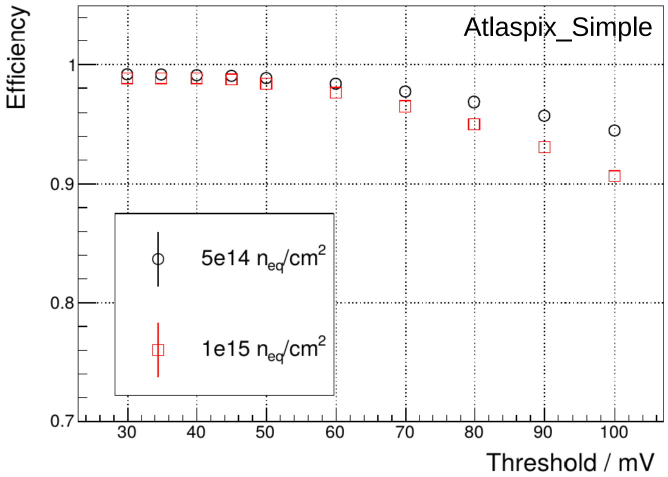
Irradiation Effects

[1] CERN-LHCC-2021-012
[2] 10.11588/heidok.00027893

- Radiation tolerance of HV-MAPS last evaluated in context of a possible usage in the ATLAS upgrade
- HV-MAPS technology is the baseline design choice for LHCb's Upgrade 2 Mighty Tracker[1]

→ Requirements on HV-MAPS technology

  - 99 % detection efficiency within 25 ns (bunch crossing)
  - Radiation tolerance up to 3×10^{14} n_{eq}/cm^2
  - Noise rate < 400 kHz/cm²



[A. Herkert, PhD Thesis 2020 Heidelberg[2]]

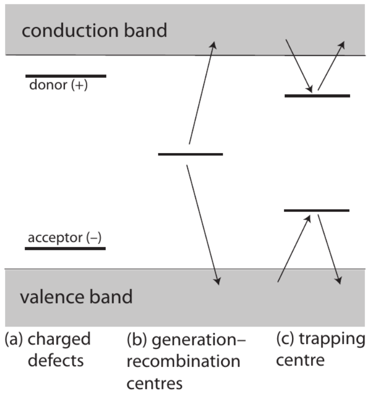
Expected Radiation Effects

- Increase in leakage due to defect energy levels

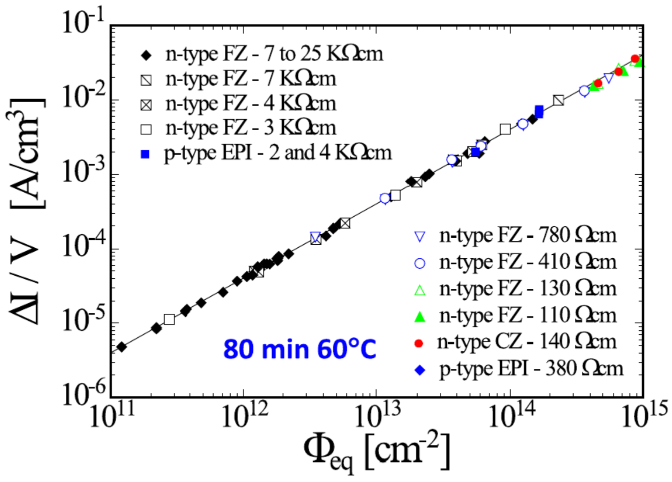
  → Higher noise level

- Change in substrate resistivity ρ due to acceptor removal

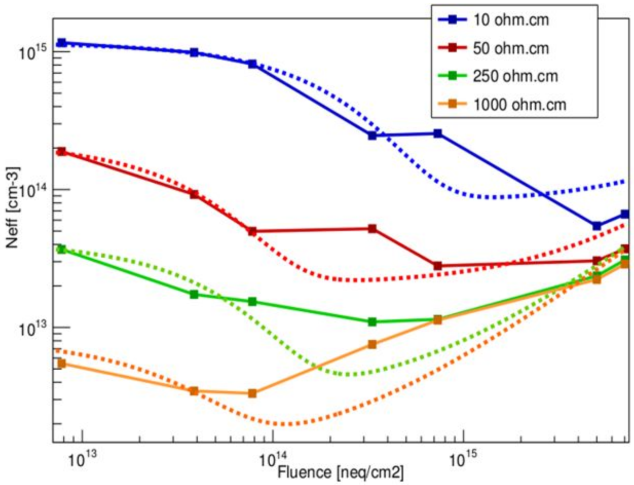
  → Depletion zone changes $d \sim \sqrt{\rho_{material} V_{bias}}$



[Kolanoski & Wermes, Particle Detectors 2022]



[M. Moll, IEEE Trans. Nucl. Sci. 65 (2018) 1561]

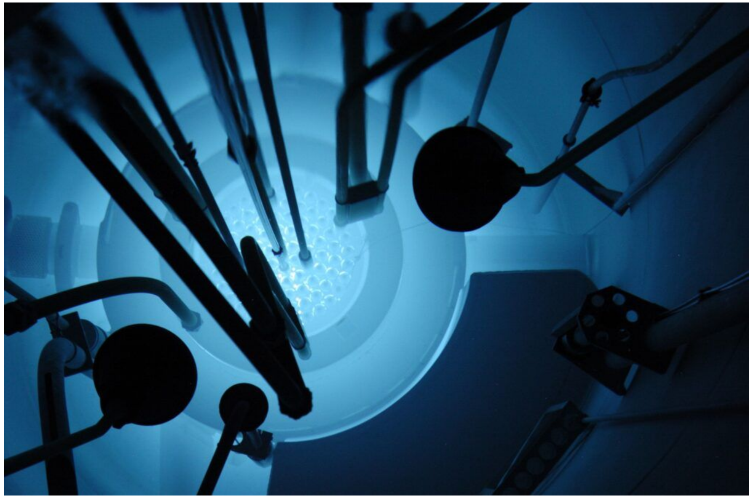


[M. Moll, PoS (Vertex2019) 027]

Irradiation Study

[3] Radiochim. Acta 107 (7) (2019) 535
[4] Ann. Nucl. Energy 14 (2025) 111122

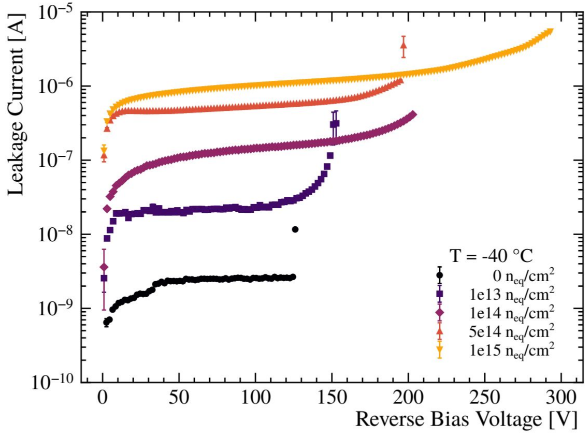
- TelePix2 irradiation in the TRIGA reactors at JGU Mainz[3] and JSI Ljubljana[4]
- Annealing after irradiation at 60°C for 120 mins

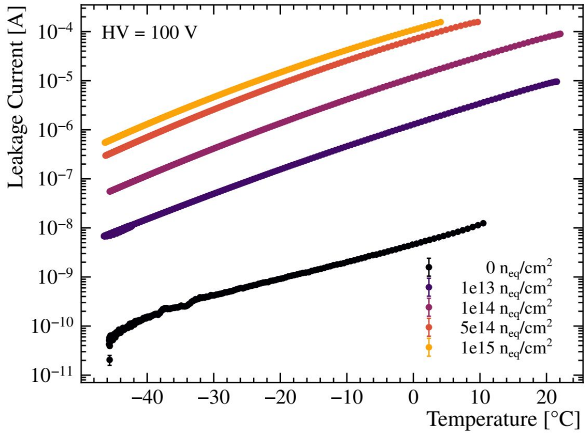


[Triga JGU Mainz]

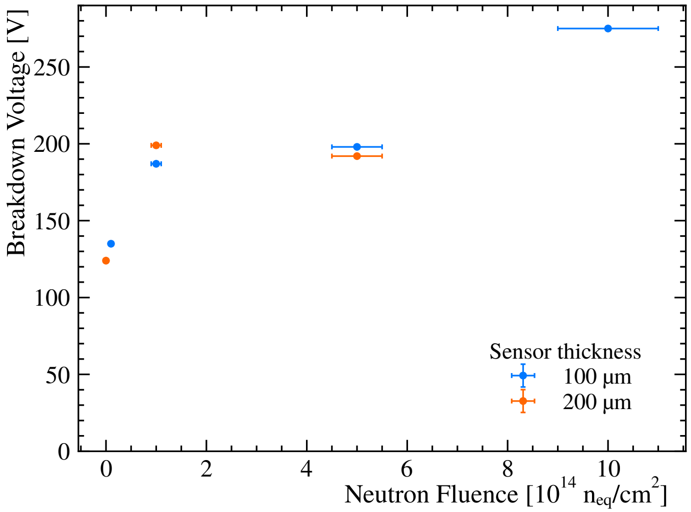
NIEL [n_{eq}/cm^2]	Irradiation Facility	Sensor Thickness [µm]
0	-	200
1e13	JSI Ljubljana	100
1e14	JSI Ljubljana	100
1e14	JGU Mainz	200
5e14	JSI Ljubljana	100
5e14	JGU Mainz	200
1e15	JSI Ljubljana	100

IV - Characteristics



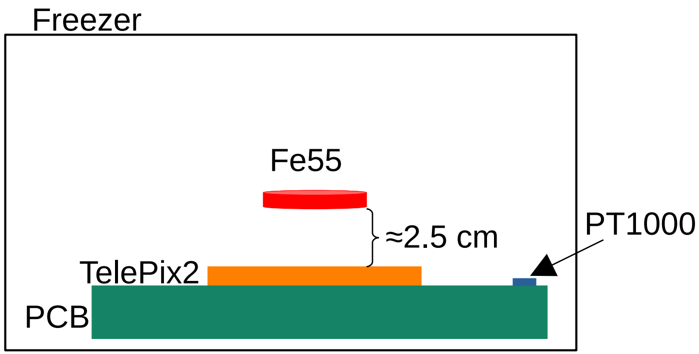


- Leakage increases with radiation damage due to defects
- Cooling needed to keep noise from leakage manageable
- Observe increasing breakdown voltage
  → Change in effective doping affects biasing structure

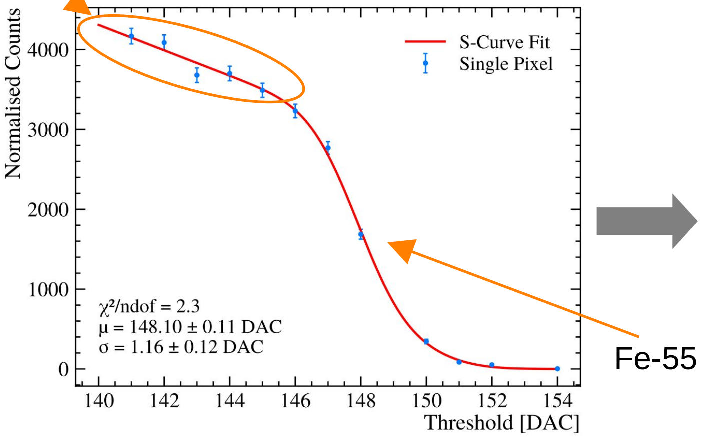


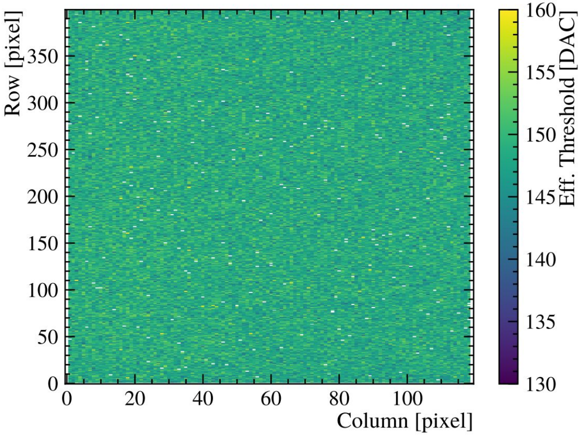
Signal Response after Irradiation

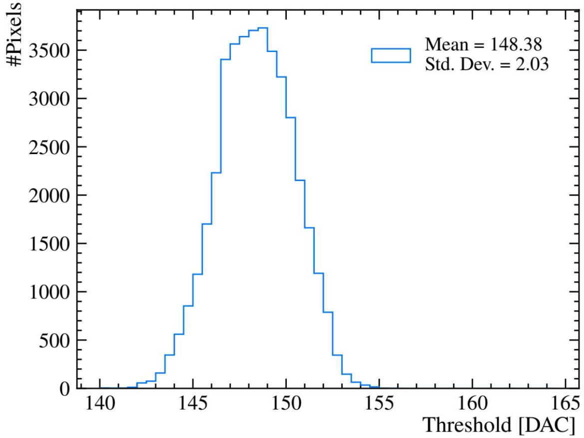
- Using x-ray from Fe-55 (5.9 keV) to gauge signal response after irradiation
- PCB cooled to -35°C
- Reverse bias of 130 V
- S-curve measurement for **every** pixel
- Extract effective **threshold *μ*** and **noise *σ***



Charge sharing

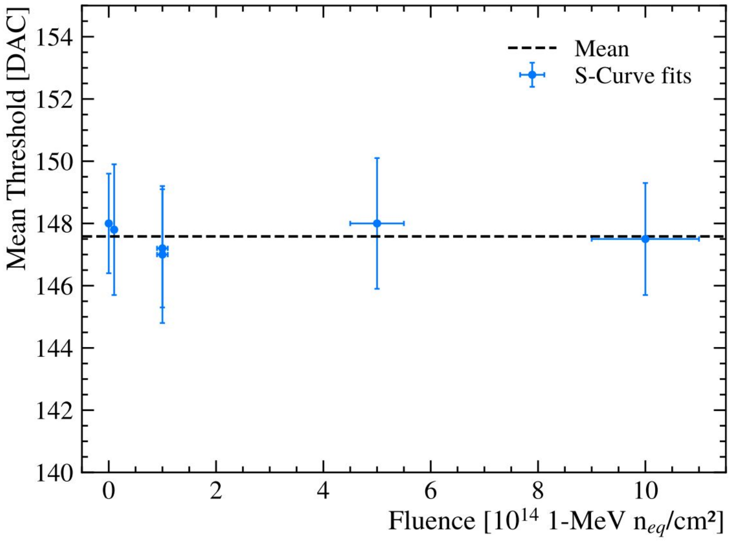


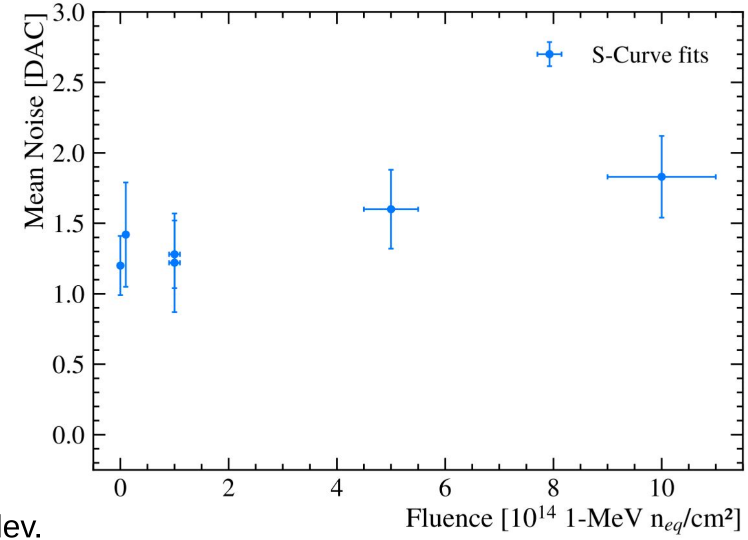




Signal Response after Irradiation

- Effective threshold μ not affected by neutron irradiation
- Mean across all samples: 148 DAC ≈ 1600 e
- No threshold calibration due to non-linearity of CSA
- Noise σ increases with radiation damage



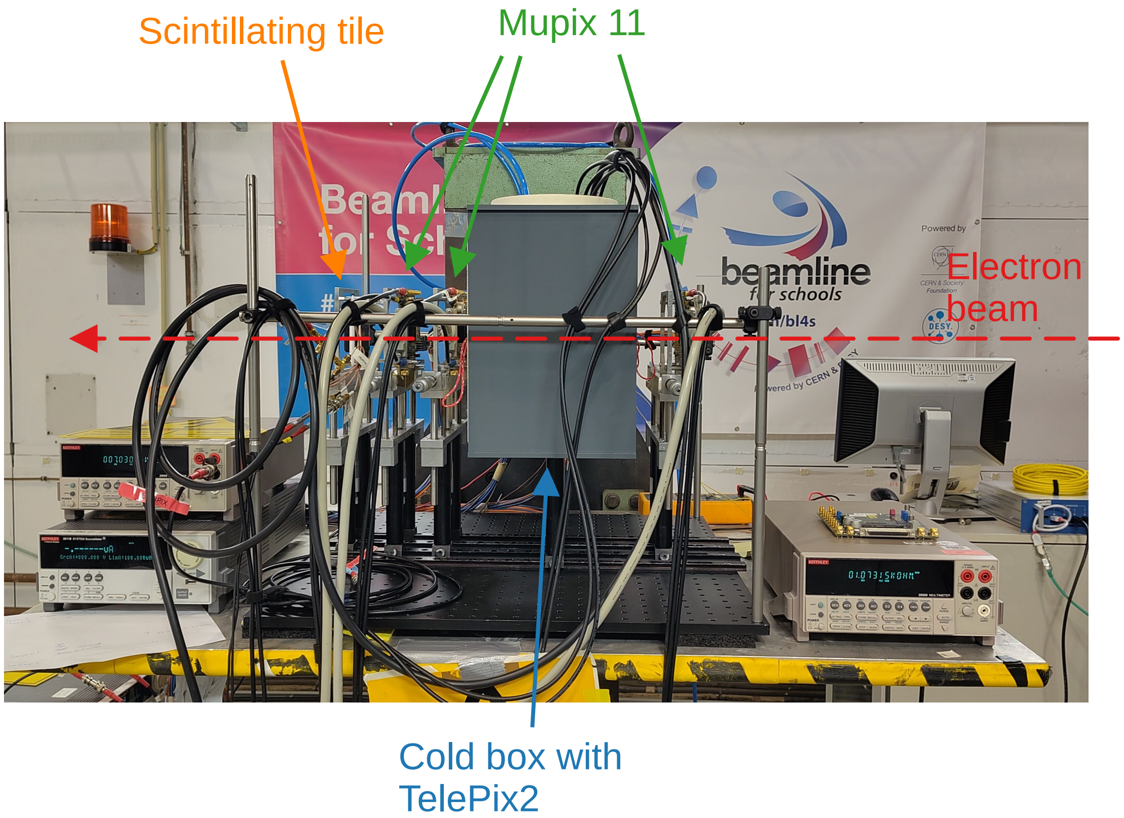


Error bars denote std.dev.

Test Beam Evaluation

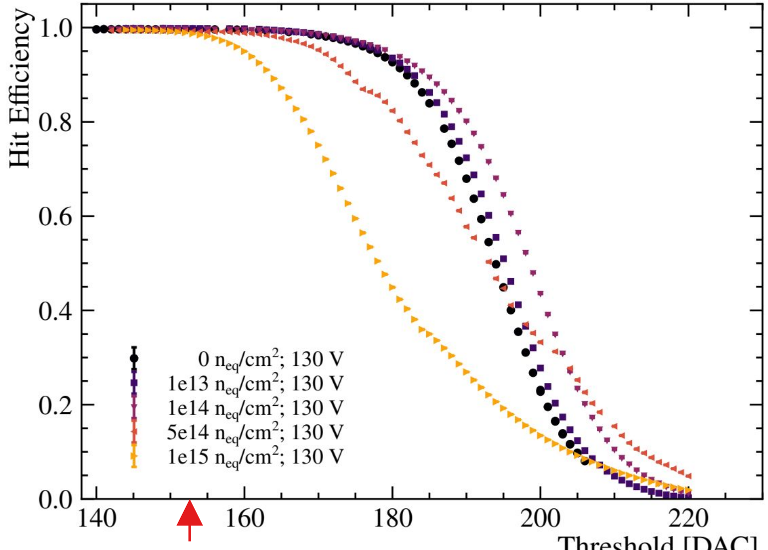
5 NIM A 922 (2019) 265
6 J. Instr. 16 (2021) P03008

- Test beam evaluation @ DESY[5]
  - **4 GeV electrons**
  - Goal: hit efficiency & time resolution
- Reference system
  - Track reconstruction:
    3 layers of **Mupix11** ($\sigma_x \approx 23$ µm)
  - Timing: **Scintillating tile** ($\sigma_t < 1$ ns)
- **TelePix2 in cold box** with dry ice and fans
  - Monitoring with PT1000 on chip carrier PCB
  - PCB temp. between -10°C and -45°C
- Data analysed with Corryvreckan[6]

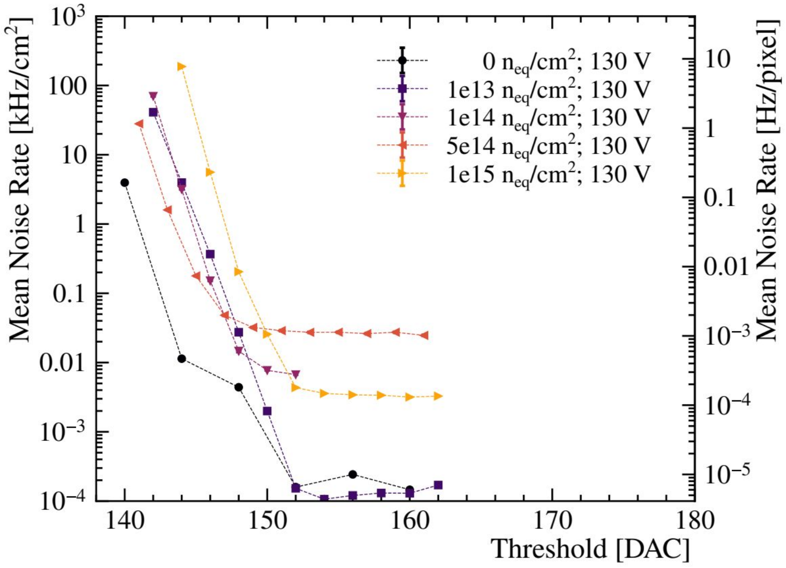


Hit Efficiency at Nominal Bias

- **99% hit efficiency** at noise ≈ 0.01 Hz/pixel for **all** irradiated samples
- Noise rate measured with beam off @ < 1 % masked pixels
- Larger ε > 99% plateau for 1×10^{13} and 1×10^{14} n_{eq}/cm^2
  → Compatible with a change of substrate resistivity



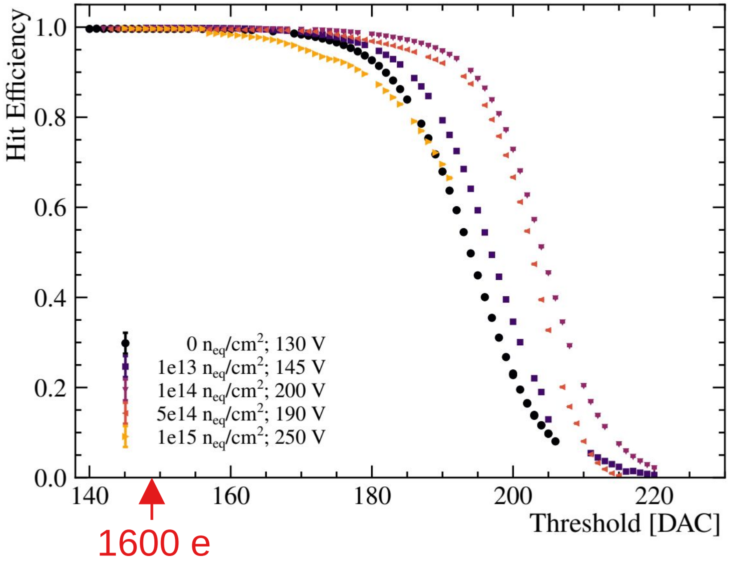
1600 e

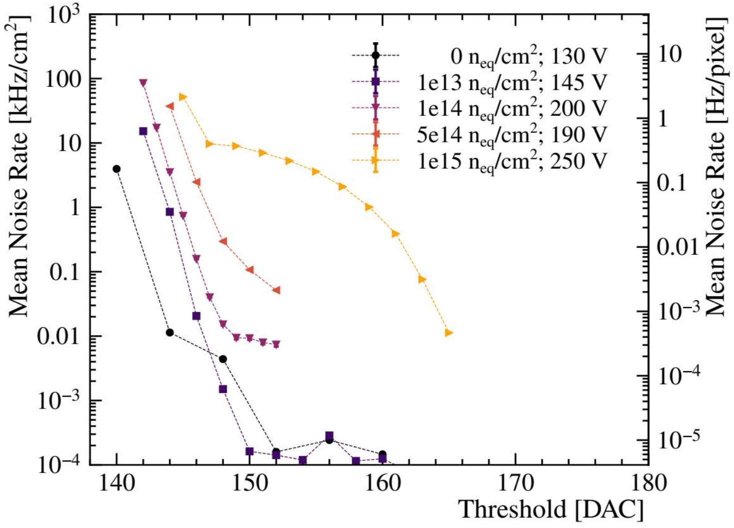


- Temperatures between -25°C and -35°C (PCB)
- Masked pixel are included in hit efficiency

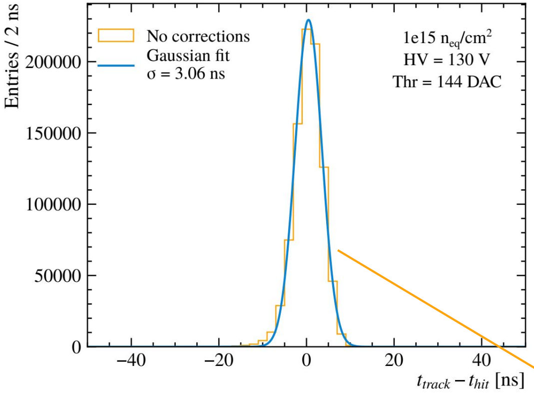
Hit Efficiency at Maximum Bias

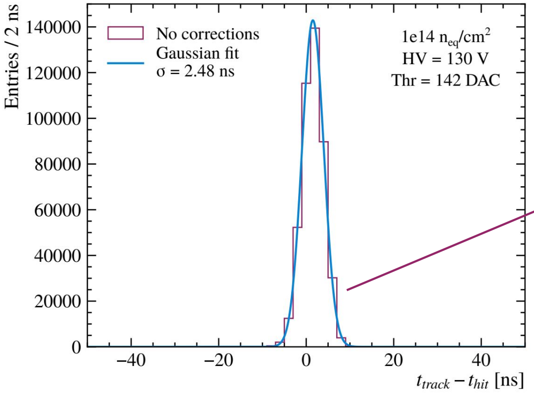
- Higher breakdown voltage for higher neutron fluence
  → Allows to recover performance for the higher irradiated samples
- **99 % hit efficiency** at a noise rate ≈ 0.5 Hz/pixel
- Observe increased noise rate for higher reverse bias voltage
  → Need more cooling: -10°C @ 1×10^{13} n_{eq}/cm^2 to -45°C @ 1×10^{15} n_{eq}/cm^2



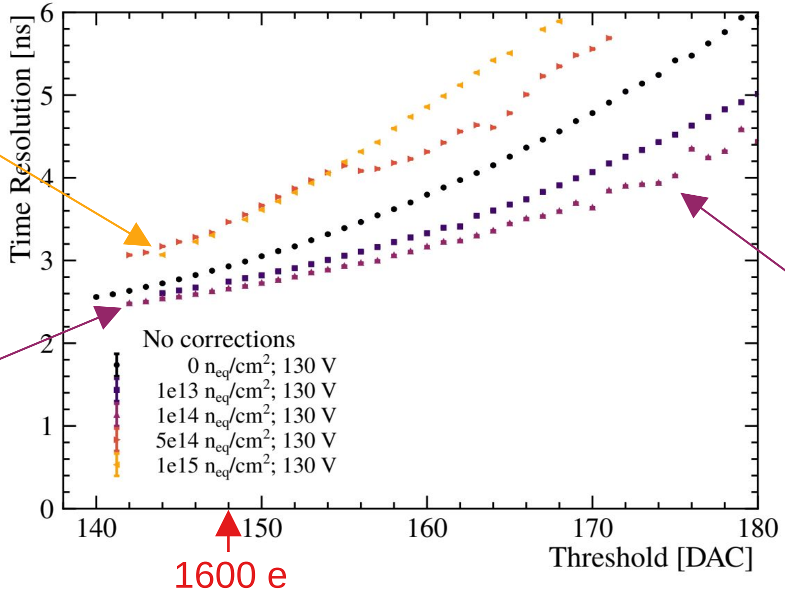


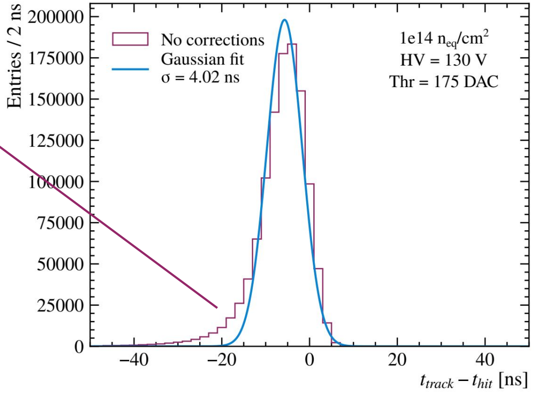
Time Resolution at Nominal Bias





- Irradiation affects time resolution similarly
  → Resolution likely dominated by collected charge
- No timewalk visible at low thresholds → No timewalk correction here
- Time resolution **≲ 3 ns** for all samples (not corrected for reference resolution)



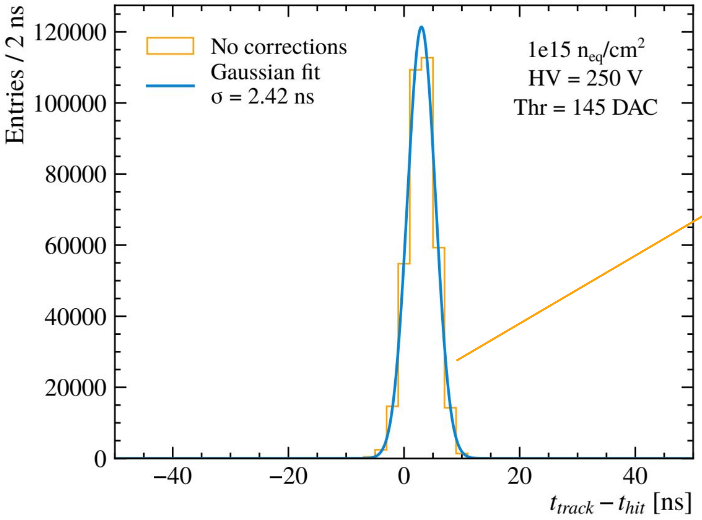


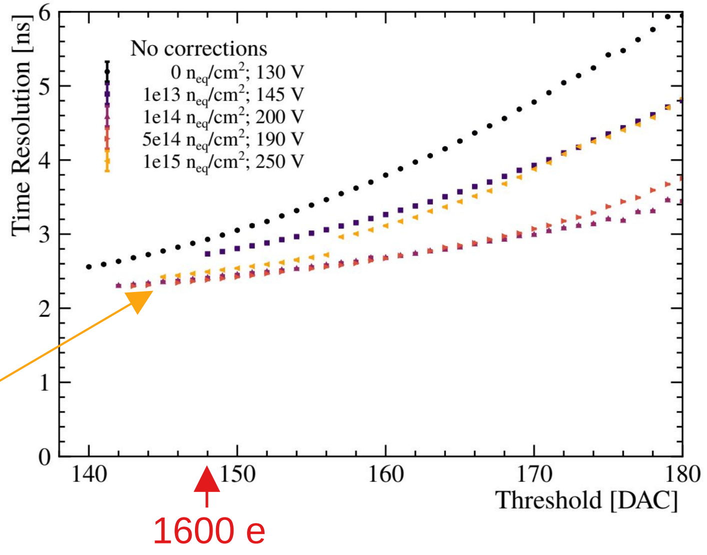
Time Resolution at Maximum Bias

- Increasing bias voltage improves time resolution

  → All irradiated samples achieve **better** time resolution than reference sample

- After 1×10^{15} n_{eq}/cm^2: $\boldsymbol{\sigma_t < 2.42}$ **ns**
  (not corrected for reference resolution)

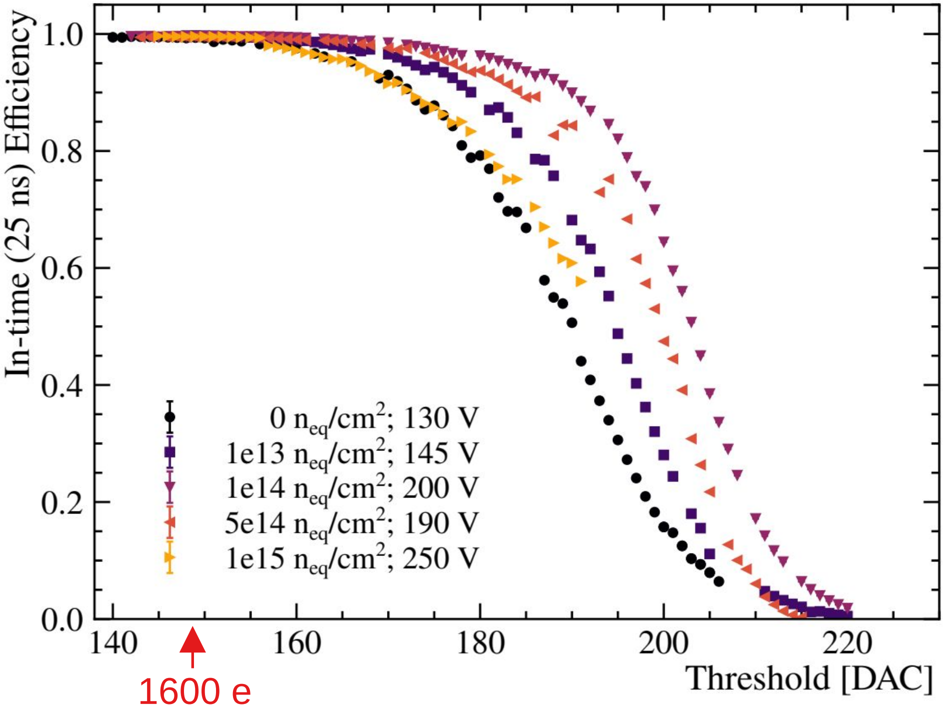




In-25ns Efficiency

LHCb Mighty Tracker:
- NIEL = 3×10^{14} n_{eq}/cm^2
- In-25ns efficiency > 99 %
- Noise rate < 400 kHz/cm²

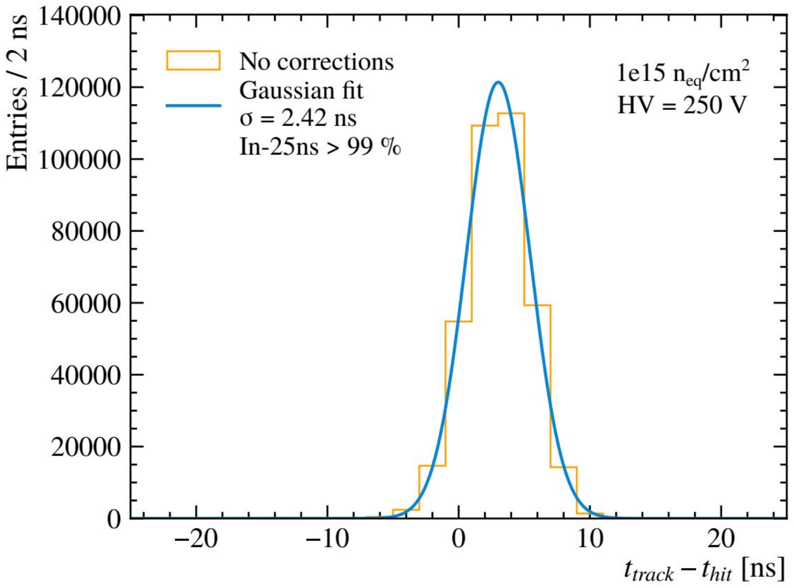
- In-25 ns efficiency is the important quantity for LHCb
- 99 % in-25ns efficiency up to 1×10^{15} n_{eq}/cm^2
- Noise rate below 100 kHz/cm² for all samples
- Radiation tolerance of HV-MAPS technology is **sufficient** to be employed in the LHCb Upgrade 2 Mighty Tracker



$$\text{In-25ns efficiency} = \frac{\text{Detected tracks within 25 ns}}{\text{All tracks}}$$

Summary

- Effective threshold not affect by neutron radiation damage
- TelePix2 is radiation tolerant up to 1×10^{15} n_{eq}/cm^2
  - Hit efficiency > 99 %
  - Time resolution < 2.4 ns
- HV-MAPS technology is sufficiently tolerant to neutron radiation for use cases such as LHCb Upgrade 2



We thank the TRIGA reactor teams of JSI Ljubljana and JGU Mainz for their support irradiating the samples.
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).

Back-up

Test Beam Temperatures

Fluence	Temperature @ HV = 130 V	Temperature @ max. HV
0	-25 °C	-
1×10^{13} n_{eq}/cm^2	-25 °C	-10 °C
1×10^{14} n_{eq}/cm^2	-30 °C	-30 °C
5×10^{14} n_{eq}/cm^2	-30 °C	-40 °C
1×10^{15} n_{eq}/cm^2	-35 °C	-45 °C

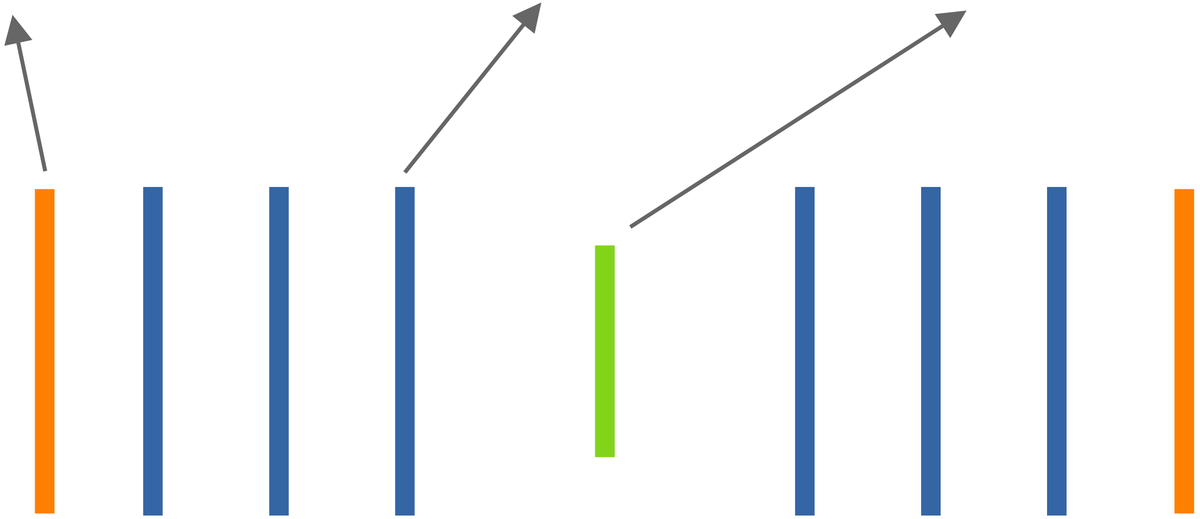
PCB temperature

A Test Beam Telescope

Scintillators:
- Produce trigger
- Good time resolution
- No spatial information

Monolithic pixel sensors:
- Triggered readout
- No time information
- High spatial resolution

Device under test:
- Different size
- Different readout frame
- ...

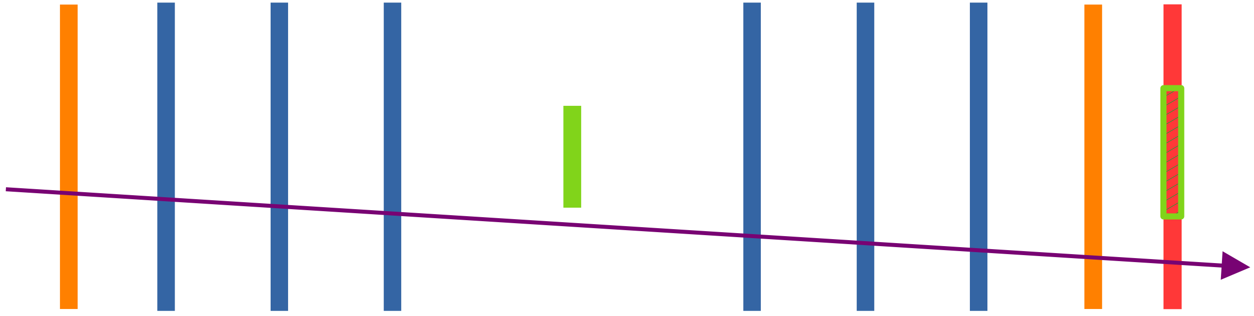


Case 1: Small DUT

Scintillators:
- Produce trigger
- Good time resolution
- No spatial information

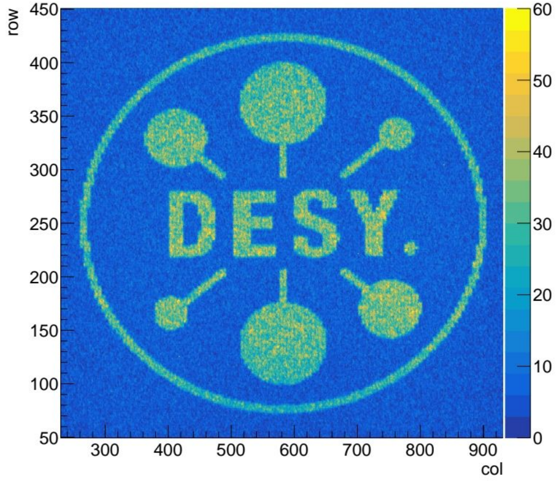
Monolithic Pixel Sensors:
- Triggered readout
- No time information
- High spatial resolution

Device Under Test:
- Different size
- Different readout frame
- ...



TelePix2:
- User configurable trigger output

→ Efficient data taking



[arXiv:2503.08177]

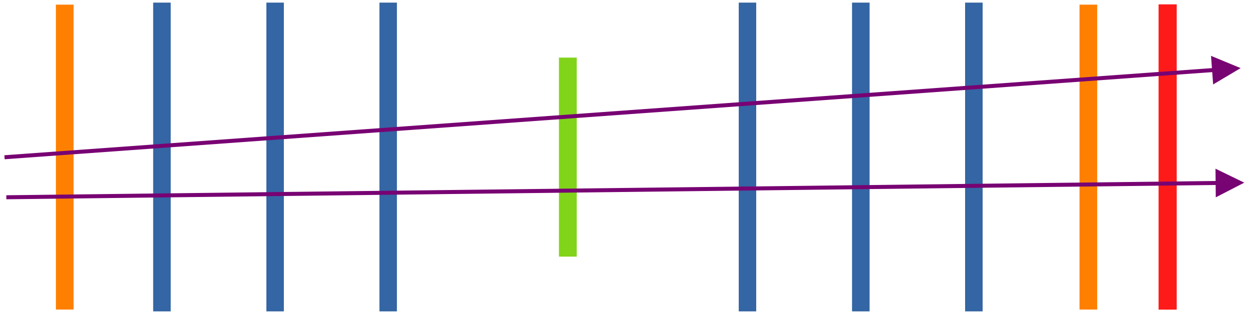
Hits in telescope layer triggered by TelePix2

Case 2: Multiple Particles

Scintillators:
- Produce trigger
- Good time resolution
- No spatial information

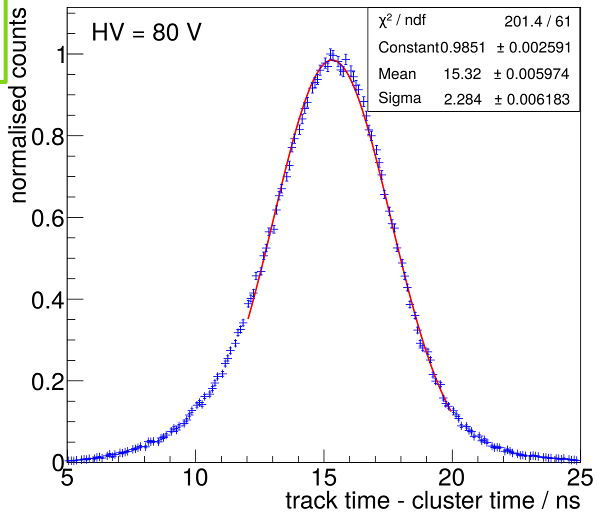
Monolithic Pixel Sensors:
- Triggered readout
- No time information
- High spatial resolution

Device Under Test:
- Different size
- Different readout frame
- ...



TelePix2:
- O(10 µm) spatial resolution
- O(ns) time resolution

→ Solves ambiguities

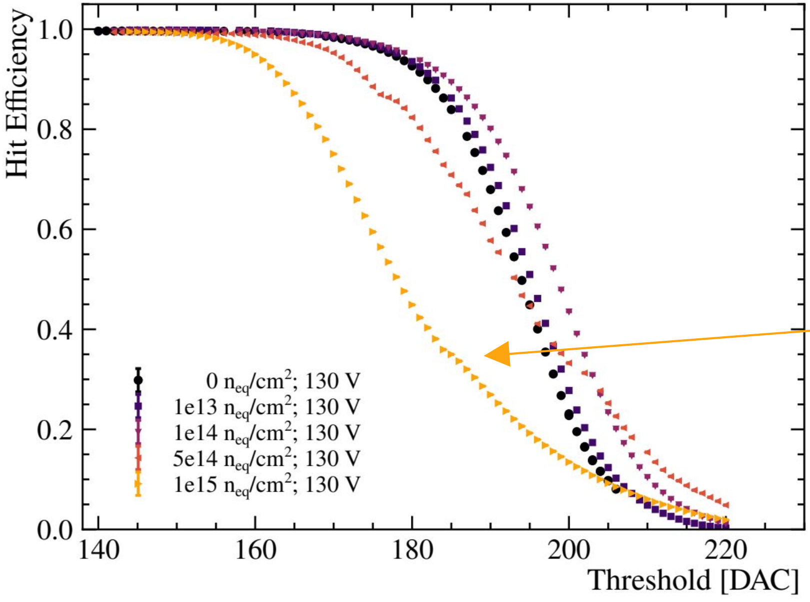


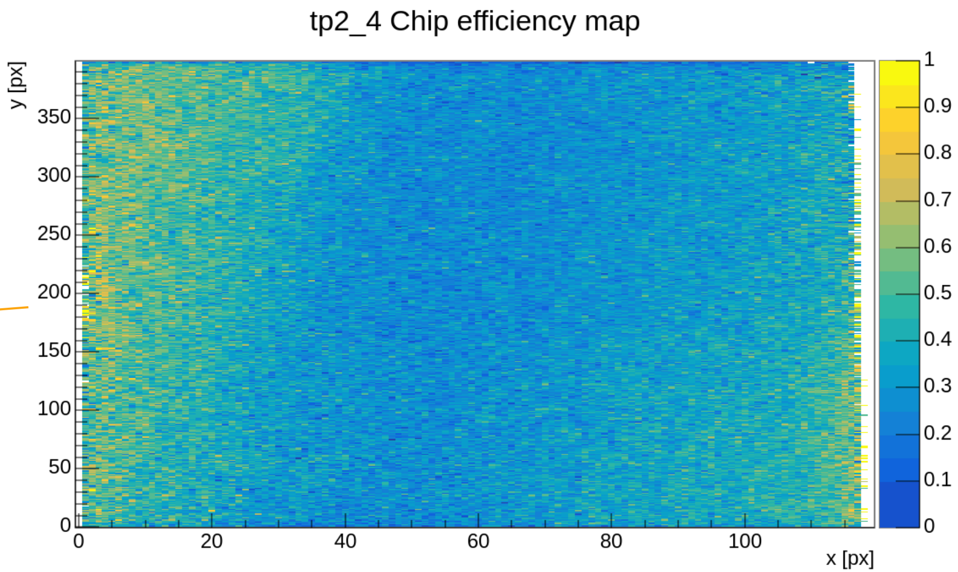
[arXiv:2503.08177]

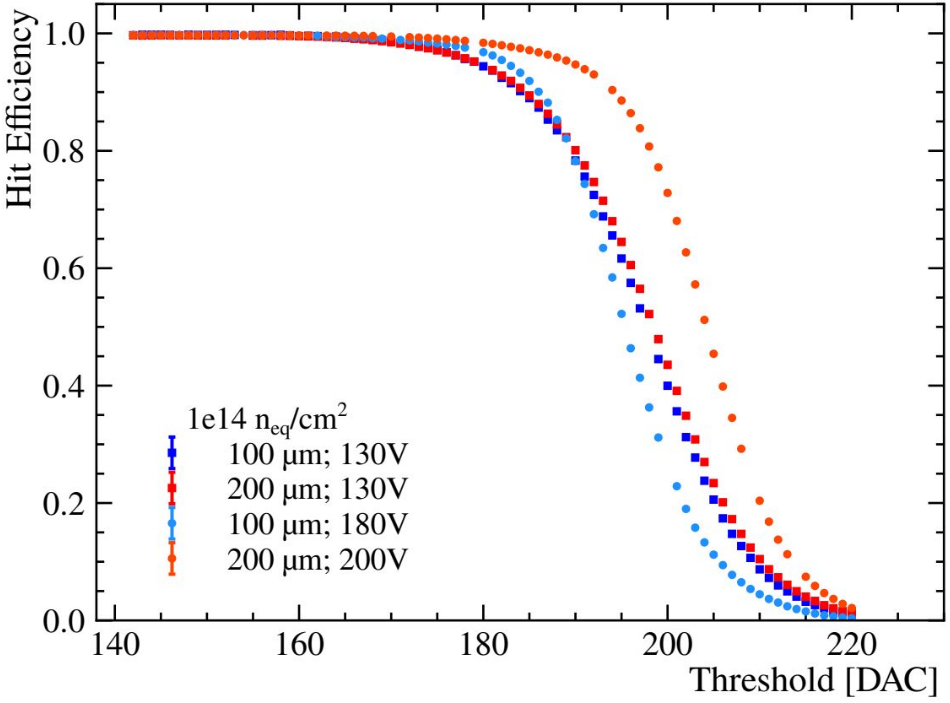
Time resolution of TelePix2's trigger output

$\sigma = 2.284$ ns

Hit Efficiency at 130 V

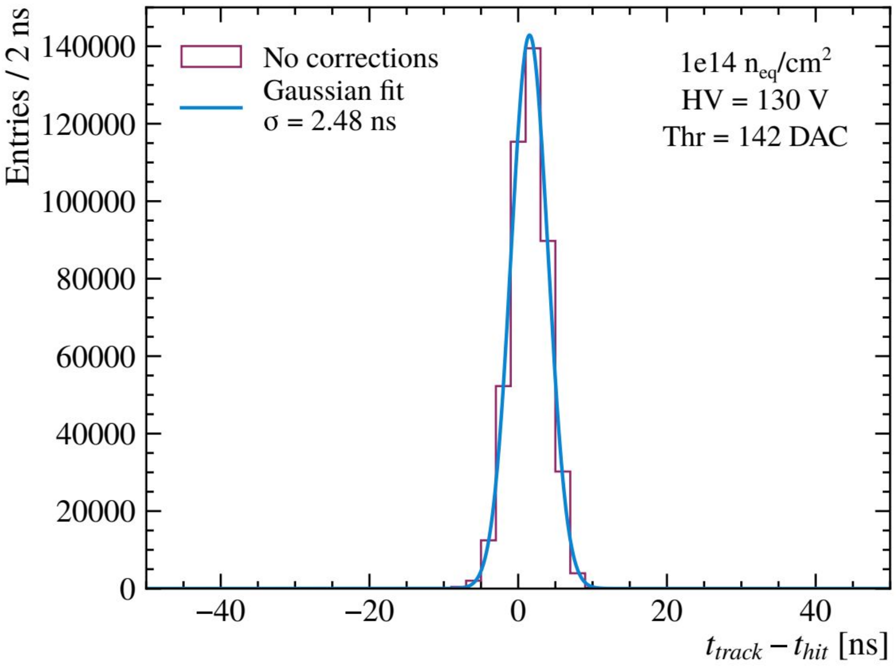




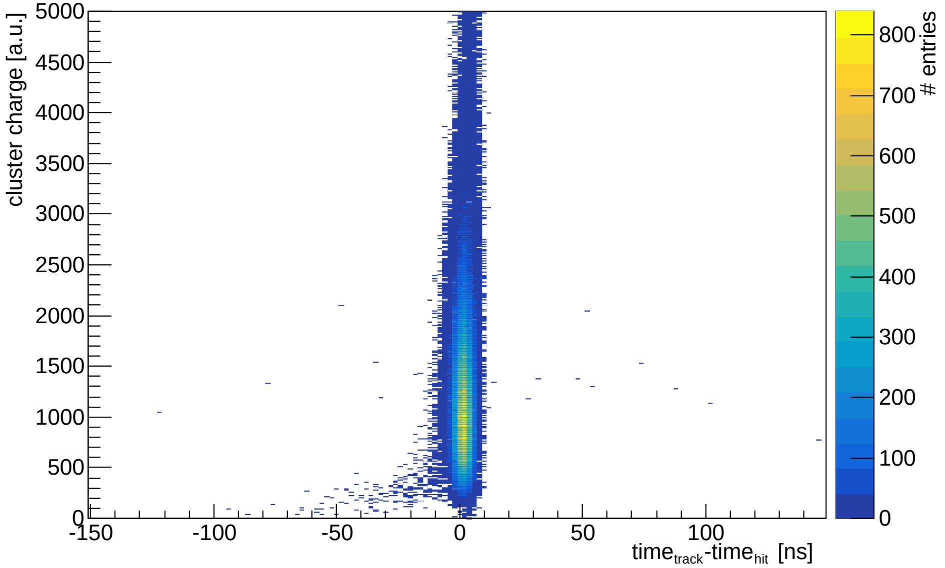


Hit Efficiency
1.0
0.8
0.6
0.4
0.2
0.0
140
160
180
200
220
Threshold [DAC]
1e14 n_{eq}/cm^2
100 µm; 130V
200 µm; 130V
100 µm; 180V
200 µm; 200V

Timewalk

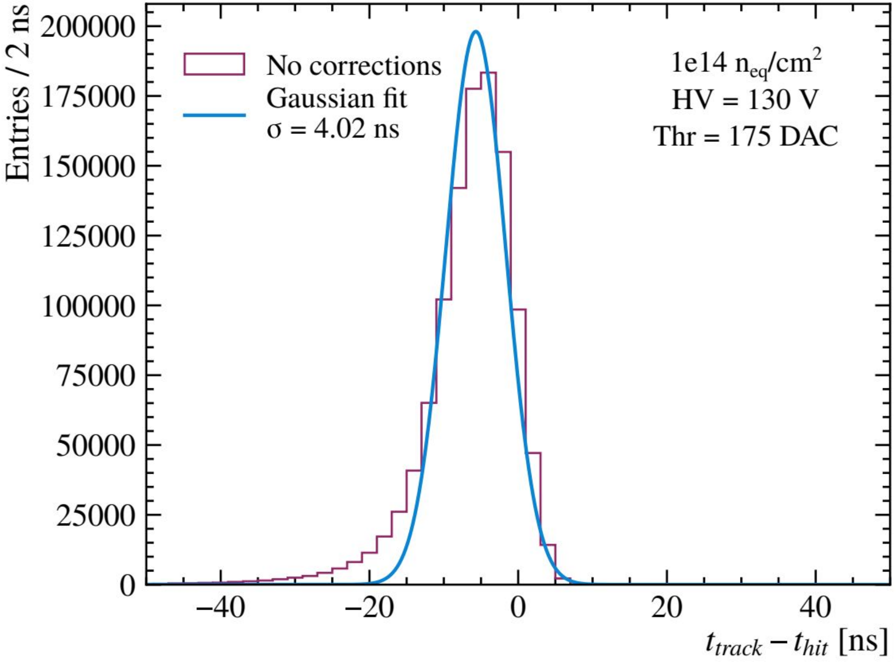


No corrections
Gaussian fit
σ = 2.48 ns
1e14 n_{eq}/cm^2
HV = 130 V
Thr = 142 DAC
Entries / 2 ns
140000
120000
100000
80000
60000
40000
20000
0
−40
−20
0
20
40
$t_{track} - t_{hit}$ [ns]

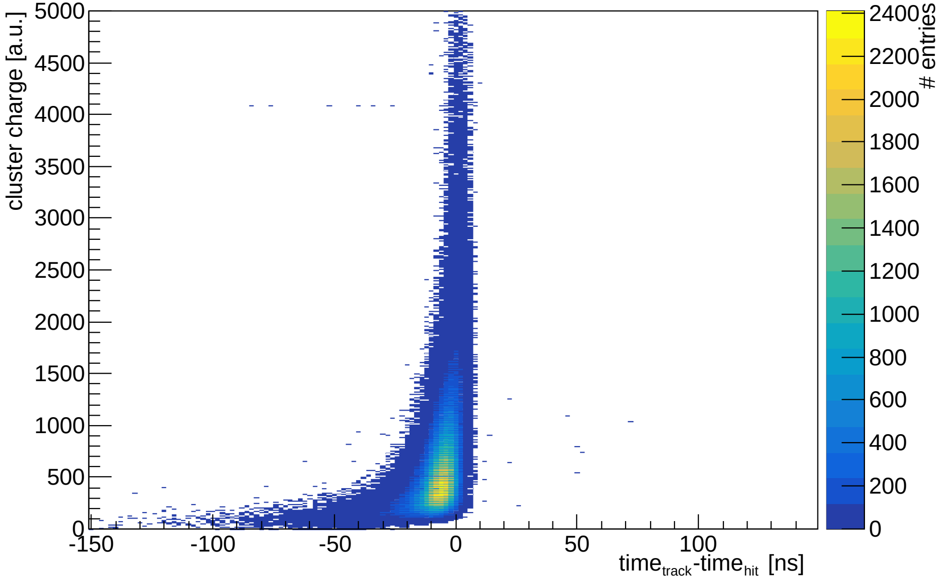


cluster charge [a.u.]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-150
-100
-50
0
50
100
$time_{track}$-$time_{hit}$ [ns]
entries
800
700
600
500
400
300
200
100
0

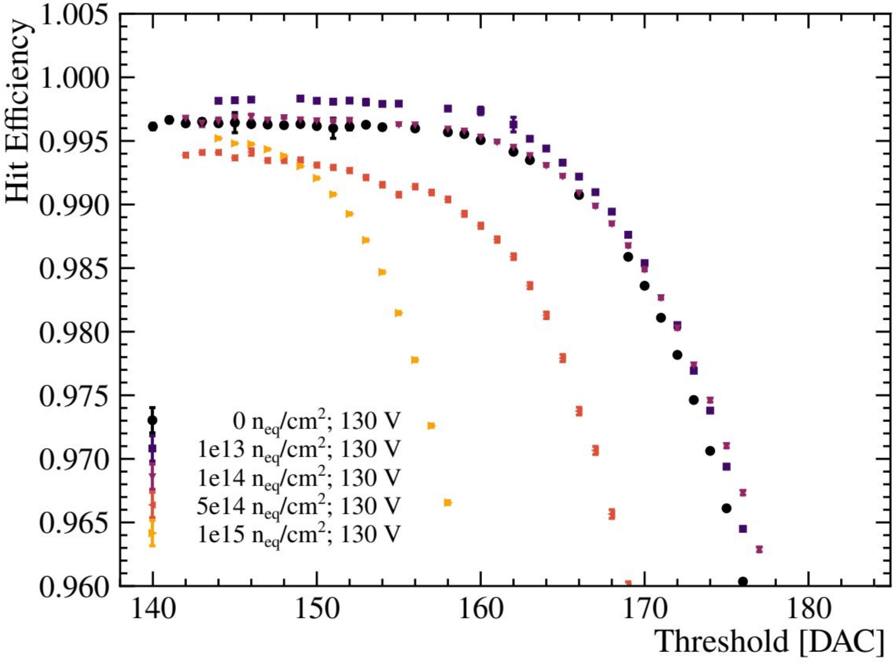
Timewalk

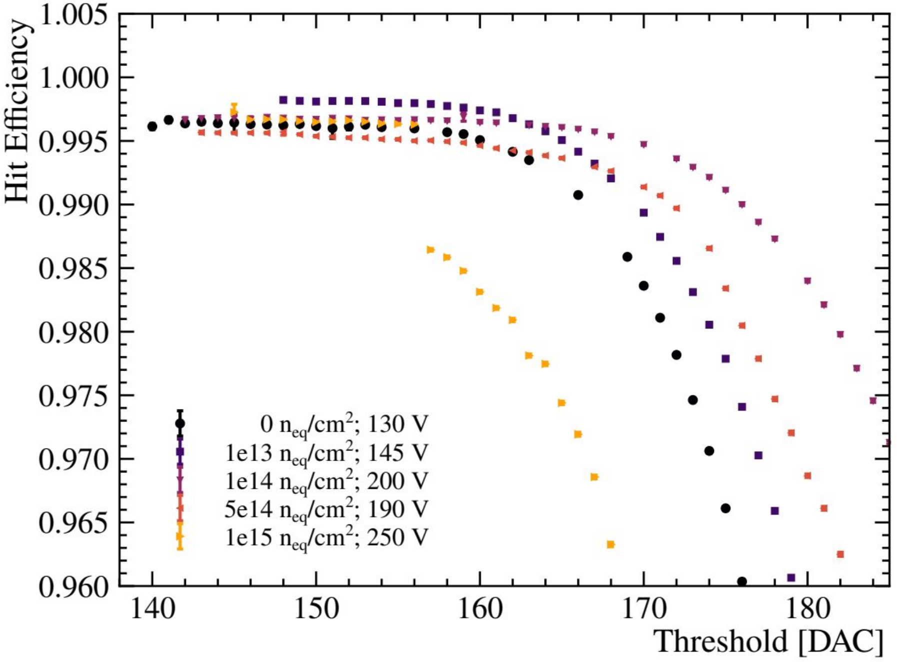


Entries / 2 ns
200000
175000
150000
125000
100000
75000
50000
25000
0
No corrections
Gaussian fit
σ = 4.02 ns
1e14 n_{eq}/cm^2
HV = 130 V
Thr = 175 DAC
−40
−20
0
20
40
$t_{track} - t_{hit}$ [ns]

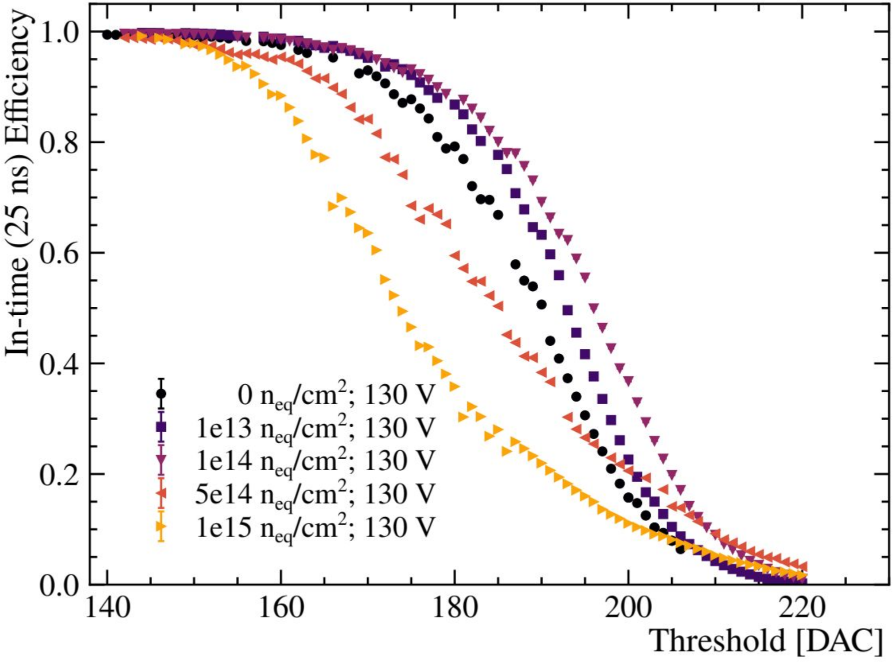


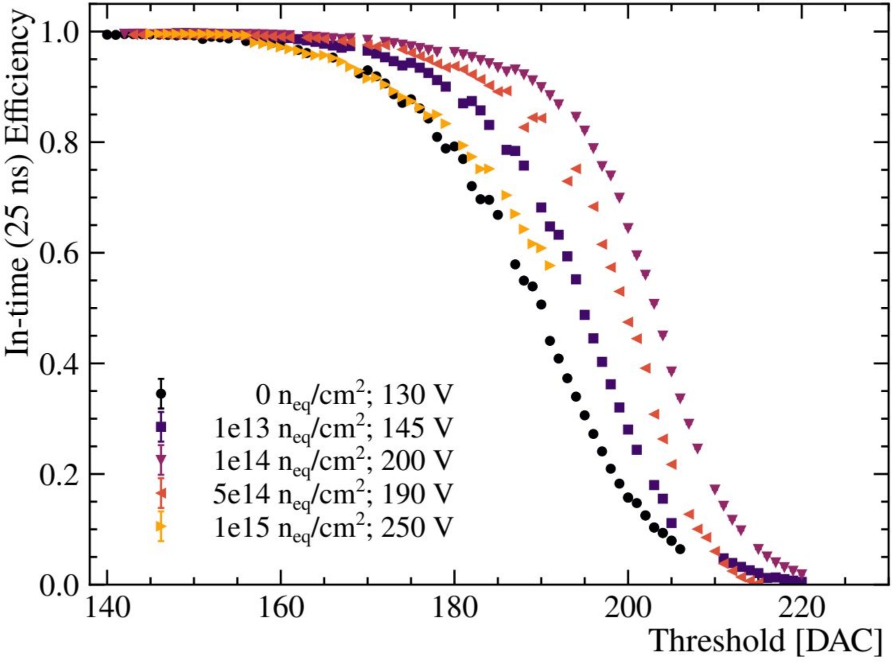
cluster charge [a.u.]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-150
-100
-50
0
50
100
$time_{track}$-$time_{hit}$ [ns]
entries
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0


Hit Efficiency
Threshold [DAC]
0 n_{eq}/cm^2; 130 V
1e13 n_{eq}/cm^2; 130 V
1e14 n_{eq}/cm^2; 130 V
5e14 n_{eq}/cm^2; 130 V
1e15 n_{eq}/cm^2; 130 V


Hit Efficiency
Threshold [DAC]
0 n_{eq}/cm^2; 130 V
1e13 n_{eq}/cm^2; 145 V
1e14 n_{eq}/cm^2; 200 V
5e14 n_{eq}/cm^2; 190 V
1e15 n_{eq}/cm^2; 250 V

In-25ns Efficiency





Reactor Validation