Radiation Hardness of the HV-MAPS Technology for the Mighty-Tracker

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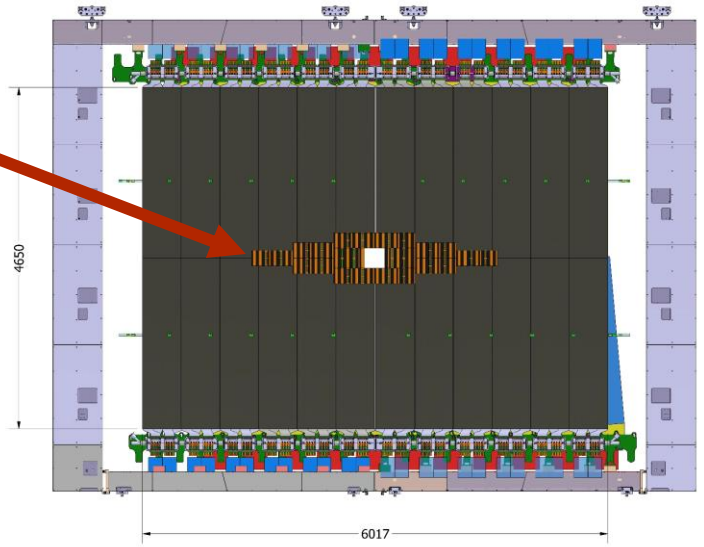
FSP LHCb

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Mighty-Pixel

Mighty-Pixel with
HV-MAPS sensors

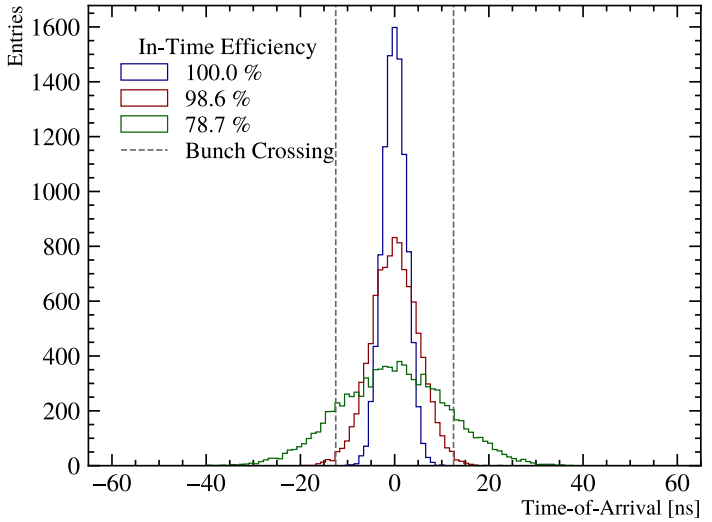
Mighty-Tracker:



Sensor Specification:

Specification	Mighty-Pixel
In-Time (25 ns) efficiency	> 99 %
Maximum noise rate	400 kHz/cm²
Maximum hit rate	37.6 MHz/cm²
Power consumption	150 mW/cm²
Radiation tolerance NIEL	$3.6 \times 10^{14}\ n_{eq}/cm^2$
Radiation tolerance TID	36 Mrad

Pixel Sensor Specifications

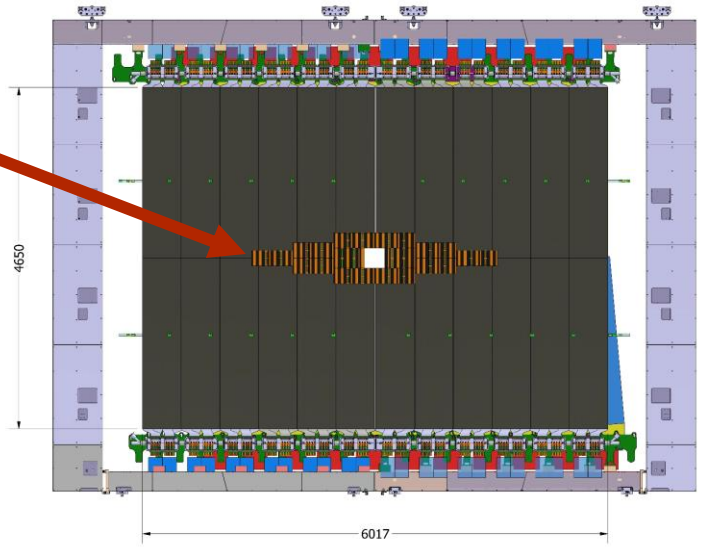


Validate sensor specification for in-time efficiency at a test beam

Mighty-Pixel

Mighty-Pixel with
HV-MAPS sensors

Mighty-Tracker:



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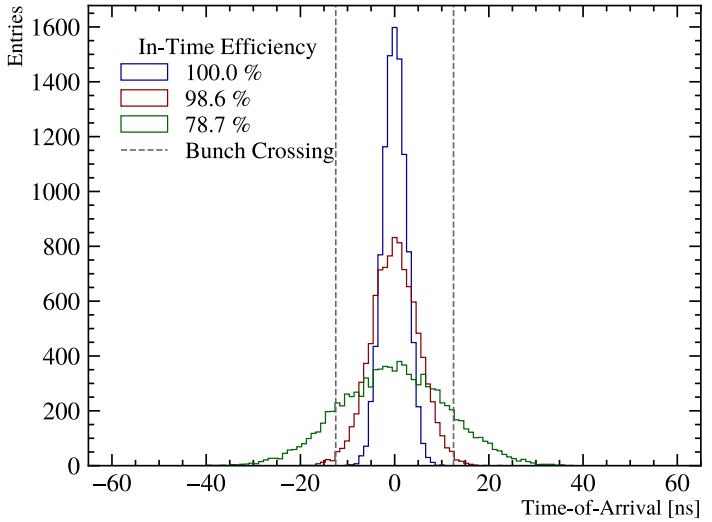
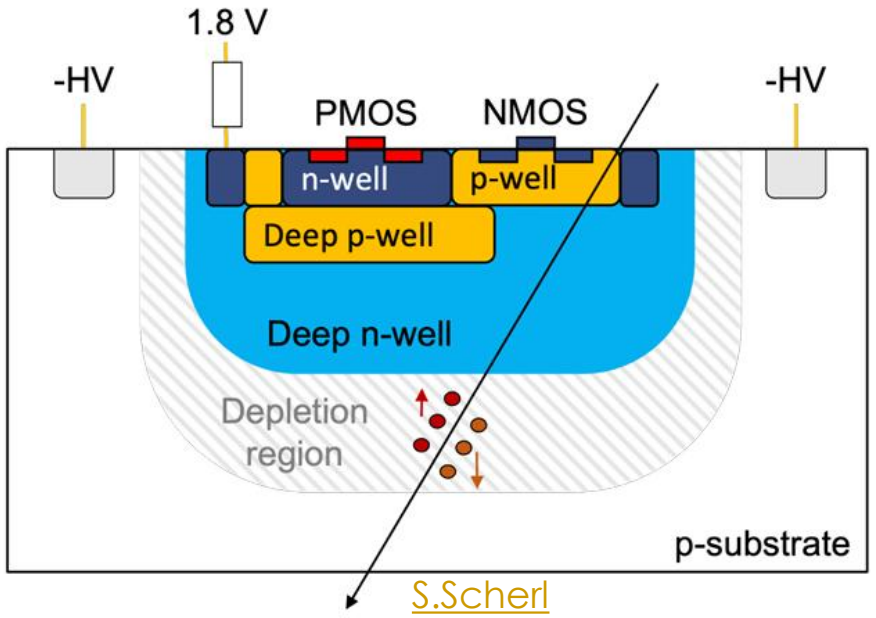


Validate sensor specification for in-time efficiency at a test beam

High-**V**oltage **M**onolithic **A**ctive **P**ixel **S**ensor (**HV-MAPS**)



S.Scherl

- Silicon pixel sensor
  - Measurement and readout element on the same sensor
- Deep n-well in p-substrate
- Reverse bias creates large depletion zone

$$d_{depl} \propto \sqrt{\rho_{substrate} \cdot V_{bias}}$$

- Fast charge collection in depletion zone via drift
- In-pixel amplifier and comparator
- Tuneable in-pixel circuit

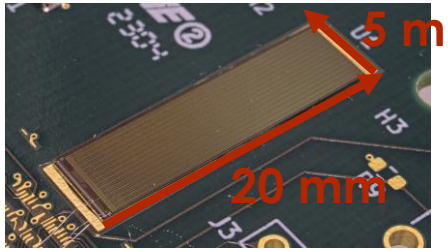
The MightyPix Sensors

HV-MAPS sensors with LHCb compatible interface

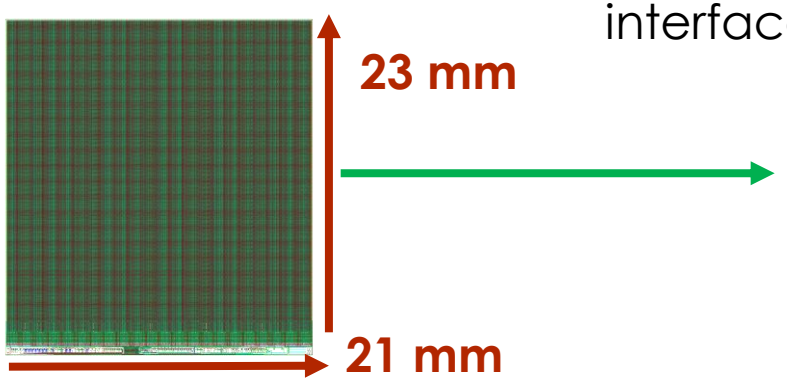
discontinued

~~**TSI 180 nm**~~

AMS 180 nm

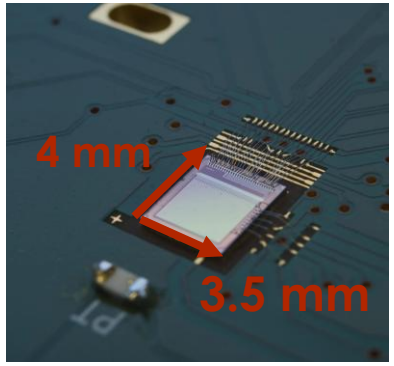


MightyPix1

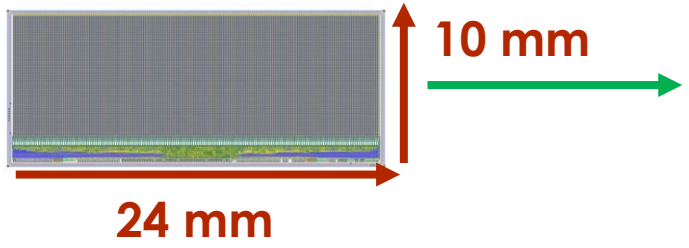


MightyPix2 (In Production)

LFoundry 150 nm



LF-MightyPix

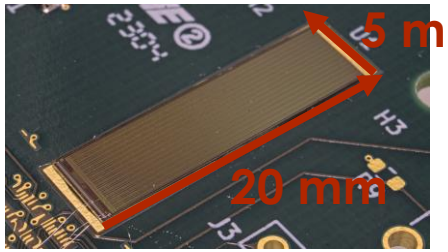


LF-MightyPix2 (In Production)

Year

2022 2024 2026 2027

The MightyPix Sensors



Parameter	MightyPix1	LF-MightyPix
CMOS technology	TSI 180 nm	LFoundry 150 nm
Pixel pitch	165 µm x 50 µm	100 µm x 100 µm
Number of pixels	29 x 320	28 x 23
Sensor thickness	100 µm – 700 µm	280 µm
Wafer resistivity	200 – 400 Ωcm	> 2 kΩcm
Time-of-arrival-(ToA) binning	≥ 12.5 ns	≥ 6.25 ns
Data link	1280/640/320 Mbit/s	1280/640/320 Mbit/s

MightyPix1:

- First (and only large size) HV-MAPS prototype for Mighty-Tracker

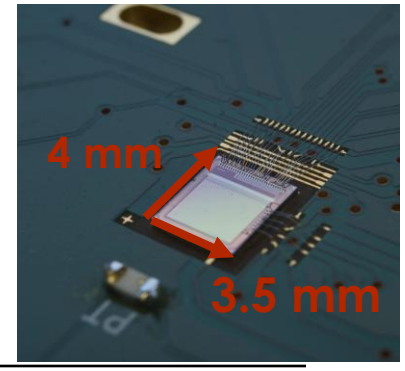
But: Design bugs:

- Unconnected shift register

→ Fix: FIB surgery → Limited availability

LF-MightyPix:

- Validate LFoundry 150 nm process
- Test features for MightyPix2



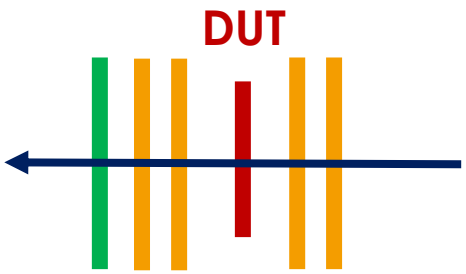
Test Beam Setup

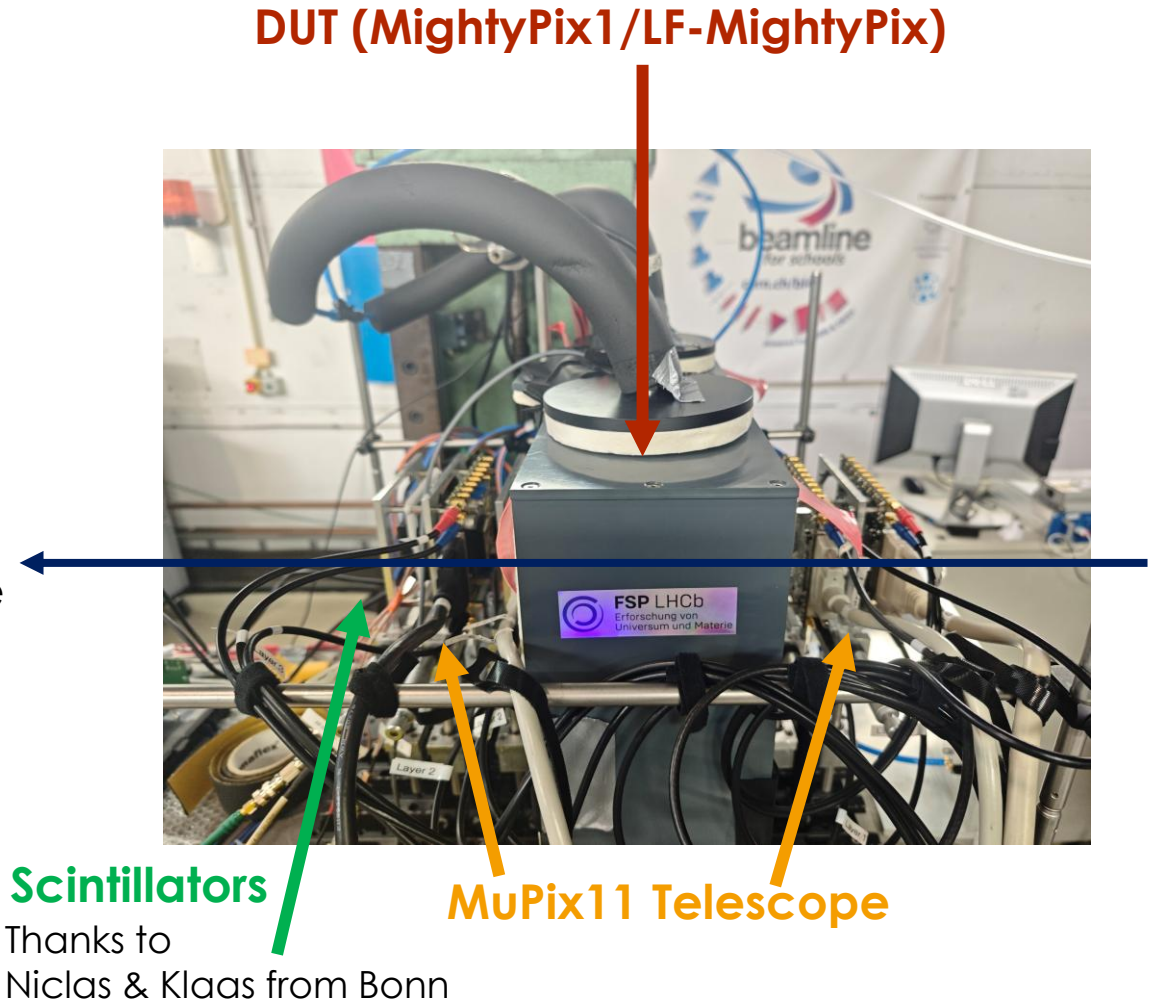
Setup:

- 4 GeV electron beam
- 4 layer MuPix11 telescope + scintillator
- Device under test (DUT) placed in a cold box

→ Dry ice + nitrogen down to ~ -45 °C air temperature

- MightyPix1/LF-MightyPix readout using Gecco DAQ
- Analysis with Corryvreckan

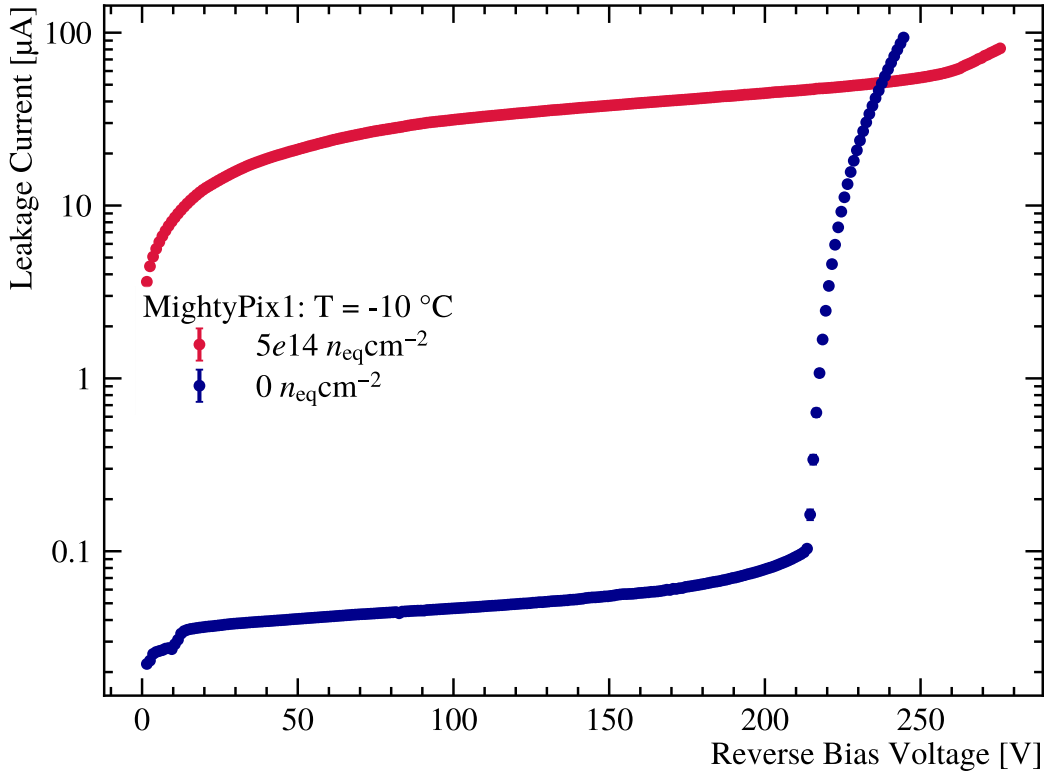




Thanks to
Niclas & Klaas from Bonn

MightyPix1: IV-Characteristics

Leakage Current:

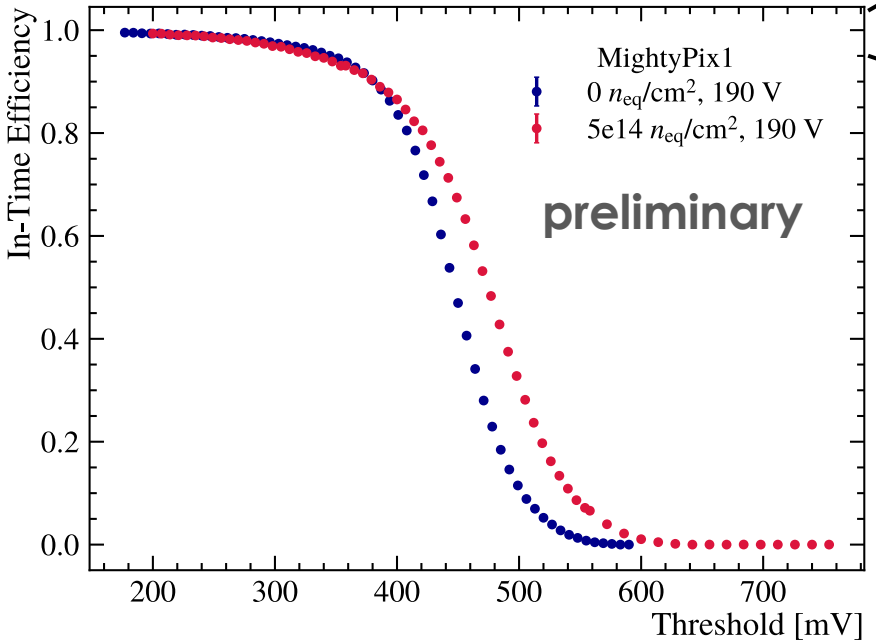


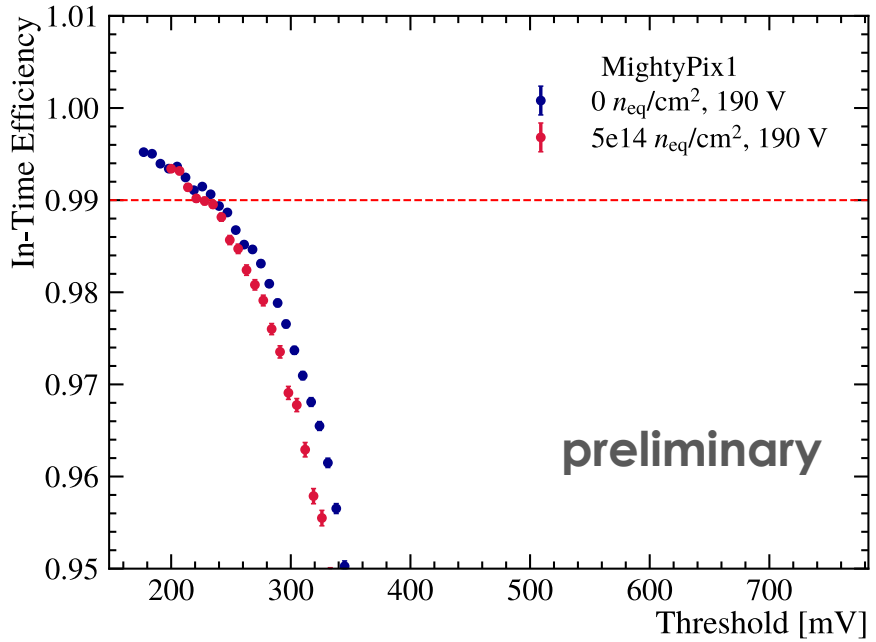
- Expected leakage current behaviour
  → Sharp increase: Diode breakdown
- Increase of breakdown voltage with irradiation
- Leakage current important quantity to study noise
- Significant increase of leakage current with irradiation

  → Expect noise increase after irradiation

MightyPix1 Performance Comparison 1.9 V LV

In-time Efficiency at 0 n_{eq}/cm^2 & 5e14 n_{eq}/cm^2

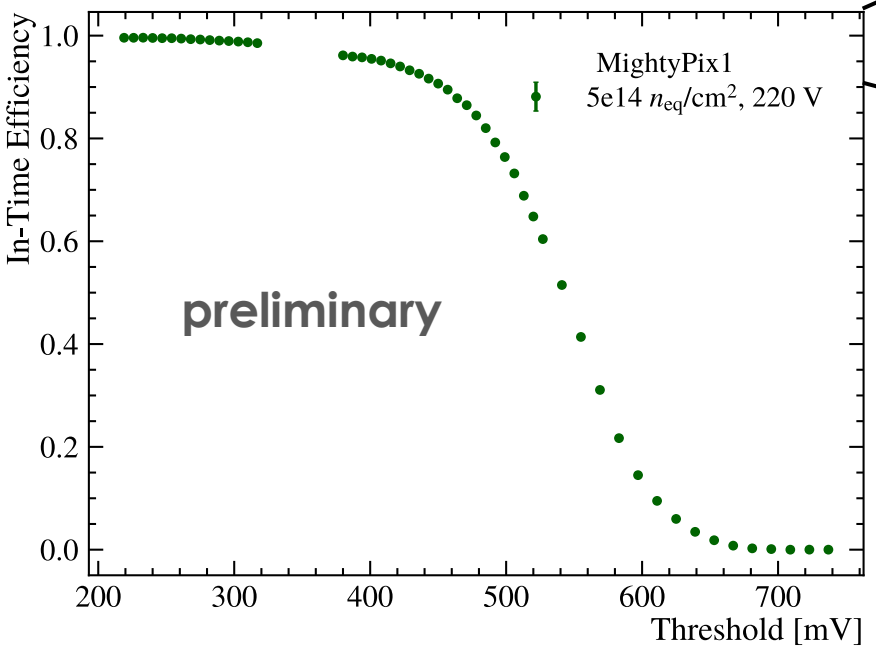


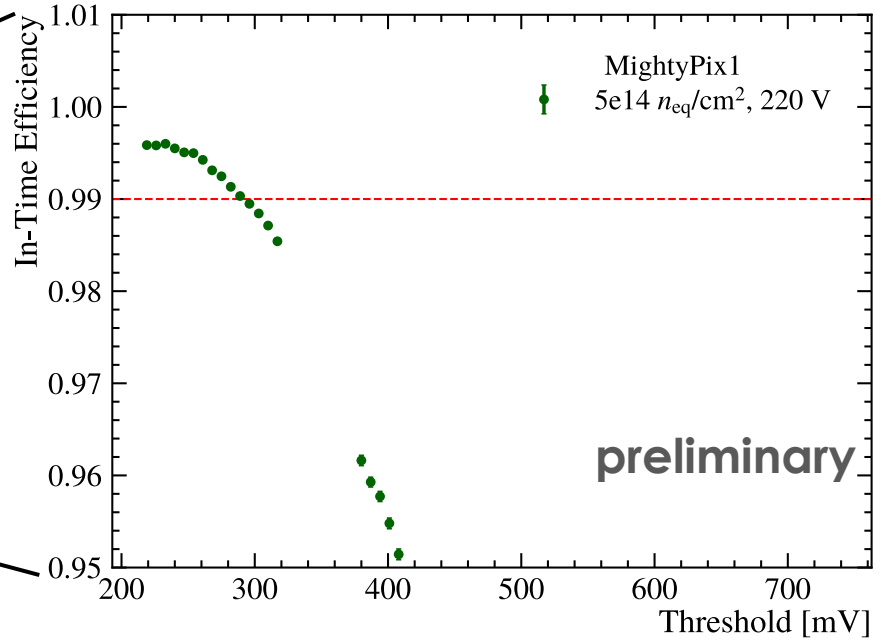


- In-time efficiency > 99 % for both non-irradiated & irradiated
- Slightly lower after irradiation
- Possible reasons:
  - Change in resistivity
  - Charge trapping due to defects

MightyPix1 Performance at 5e14 n_{eq}/cm^2 1.95 V LV

In-time Efficiency at Maximum Bias

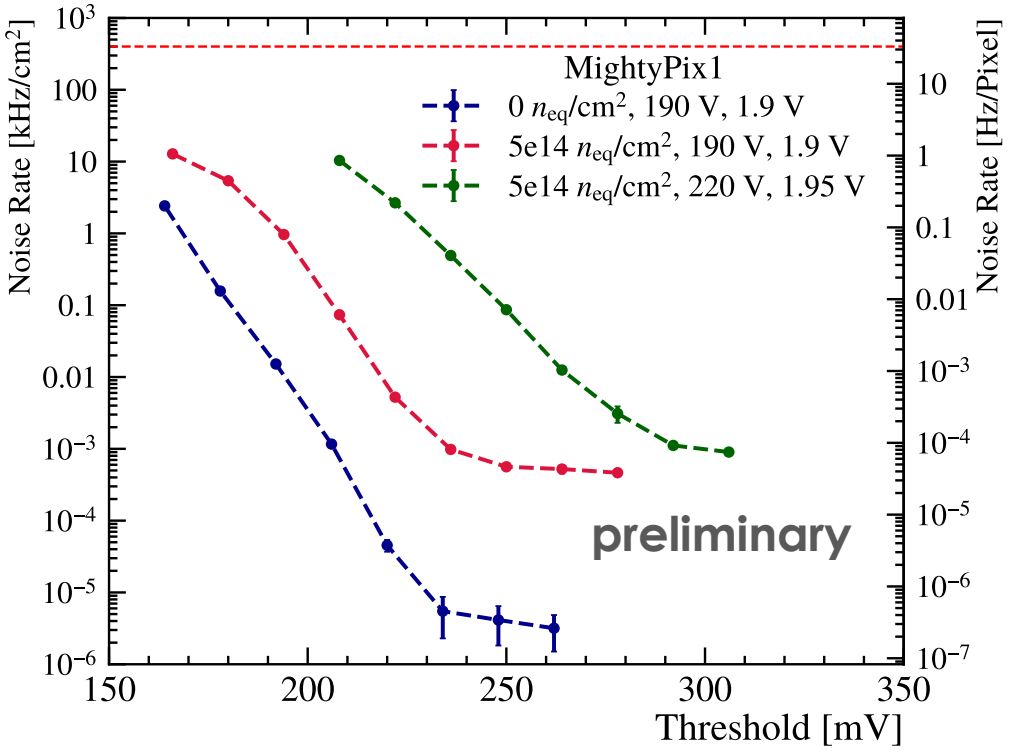




- In-time efficiency > 99 % for ~ 70 mV threshold range
- Higher bias → Performance gain
- In-time efficiency limited by large ToA binning

→ Radiation hard and fulfilling the MT specifications at 5e14 n_{eq}/cm^2 ~1.4 x MT end of life fluence

MightyPix1: Noise Rate

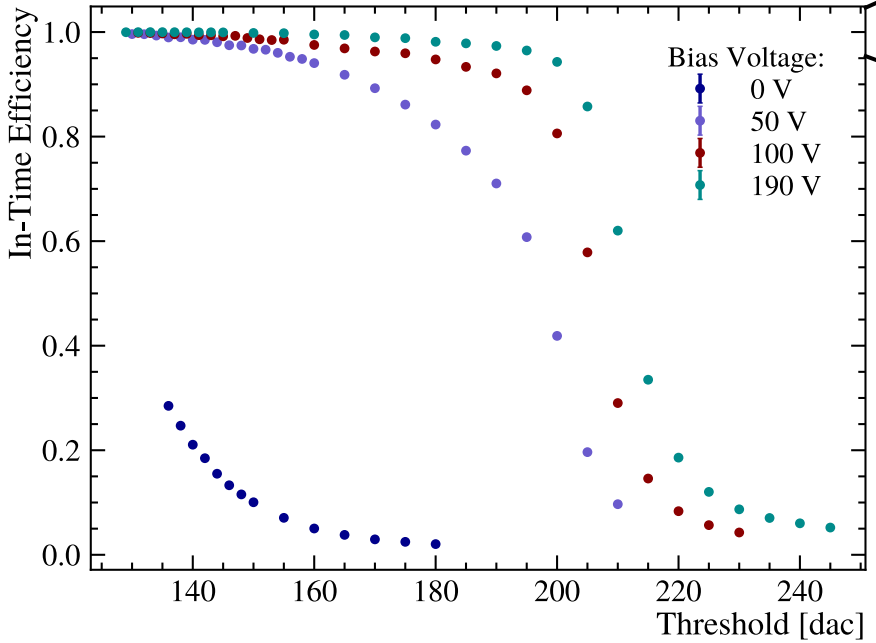


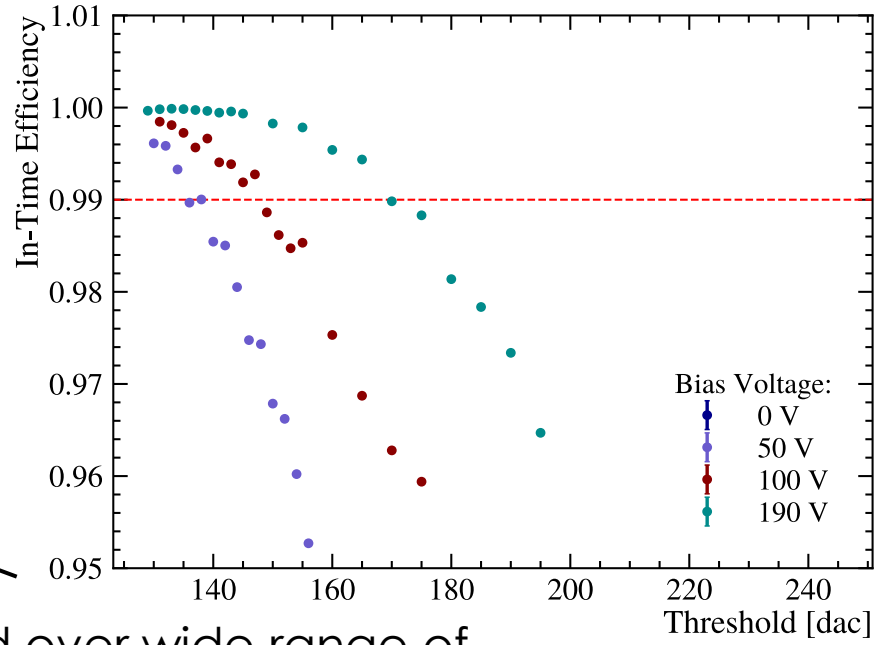
- Noise rate measured for 60 s per step in lab
- 17 Pixels masked ~ 0.2 % (5e14 n_{eq}/cm^2 sensor)

- Mean noise rate below specification limit of 400 kHz/cm² for all thresholds
- ε_{25ns} > 99 % while mean noise rate ~ 0.01kHz/cm²

LF-MightyPix: Non-Irradiated Performance

In-time efficiency for different reverse bias voltages



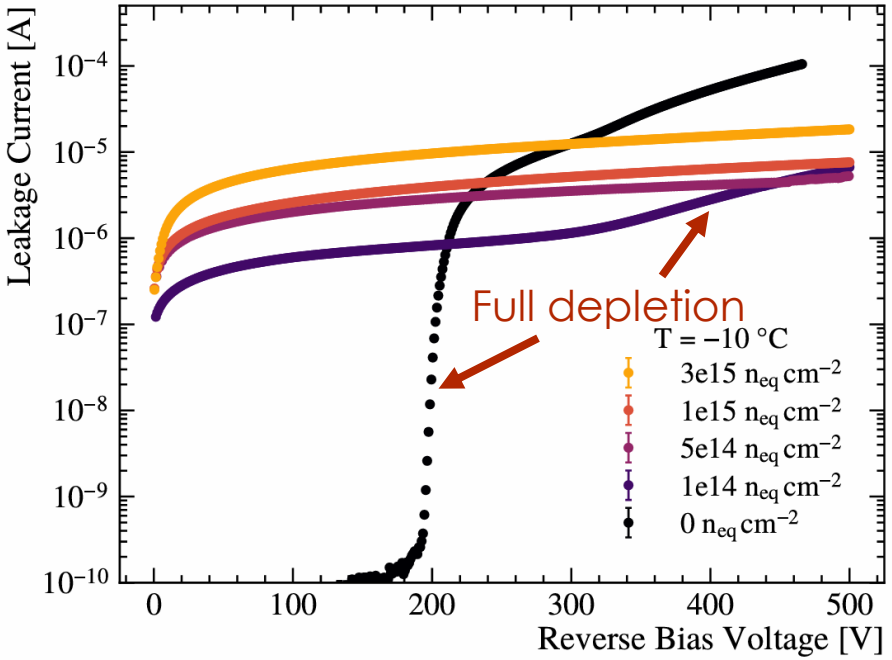


- Performance validated over wide range of measurements and reverse bias voltages
- ε_{25ns} > 99 % achieved for V_{bias} > 50 V ~ 140 µm depletion

→ No full depletion needed for excellent performance

LF-MightyPix: IV-Characteristics and Depletion

L. Dittmann

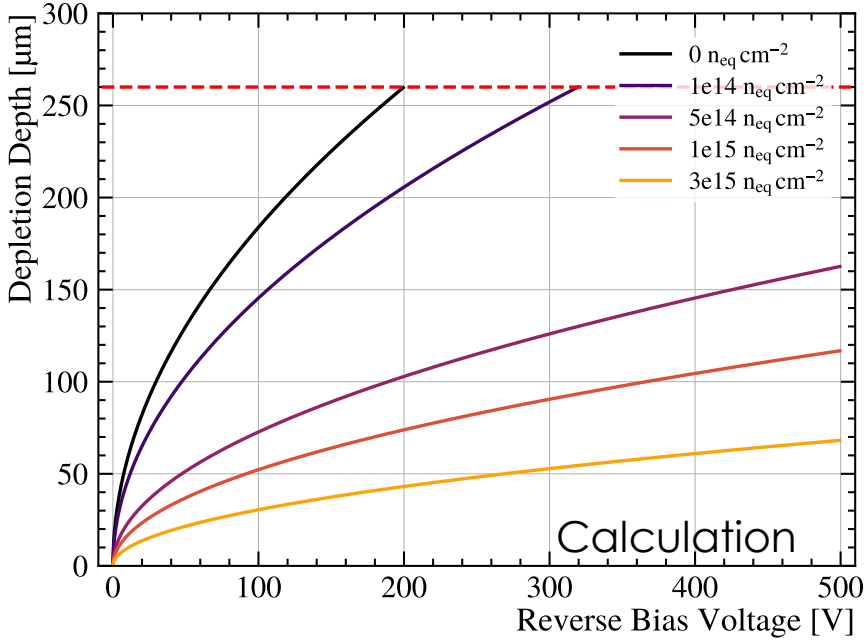


Leakage Current:

- Full depletion visible up to 1e14 $\mathrm{n_{eq}/cm^2}$
- Vanishes with irradiation

→ Change of substrate resistivity

- Increasing leakage with increasing fluence



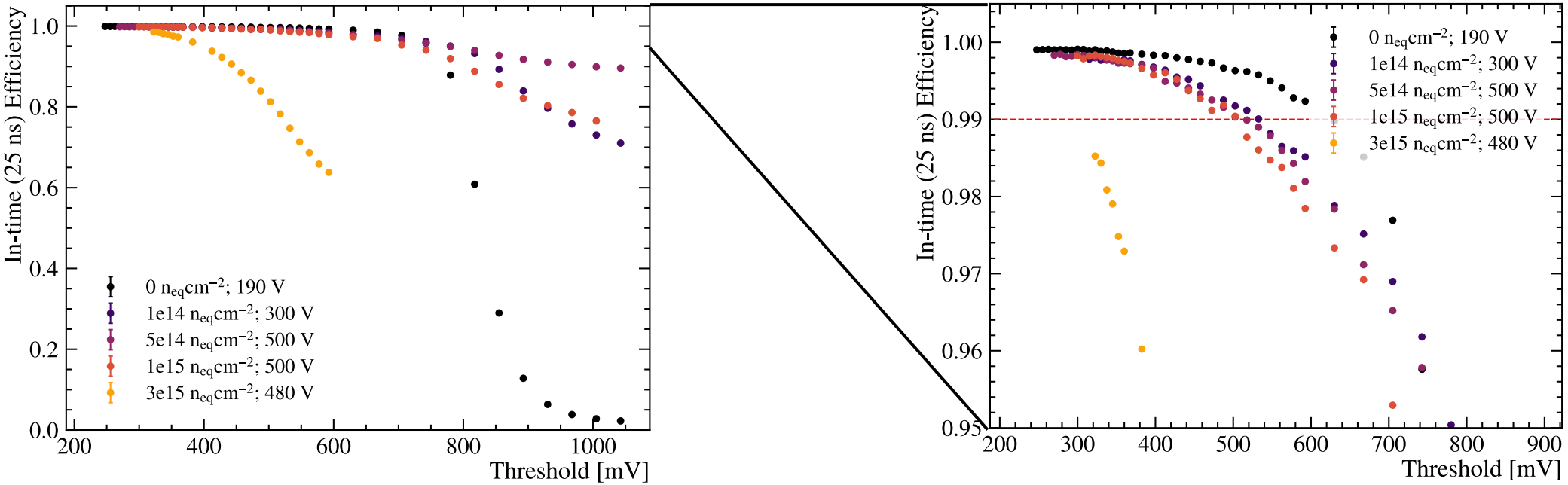
Expected depletion depth:

- Effective doping N_{eff}: substrate, foundry and fluence dependent
- Extracted from N_{eff} measurements from here
- $d \sim \sqrt{\frac{1}{N_{eff}} V_{bias}}$ → Less depletion after irradiation

LF-MightyPix: Irradiated Performance at Maximum Bias

L. Dittmann

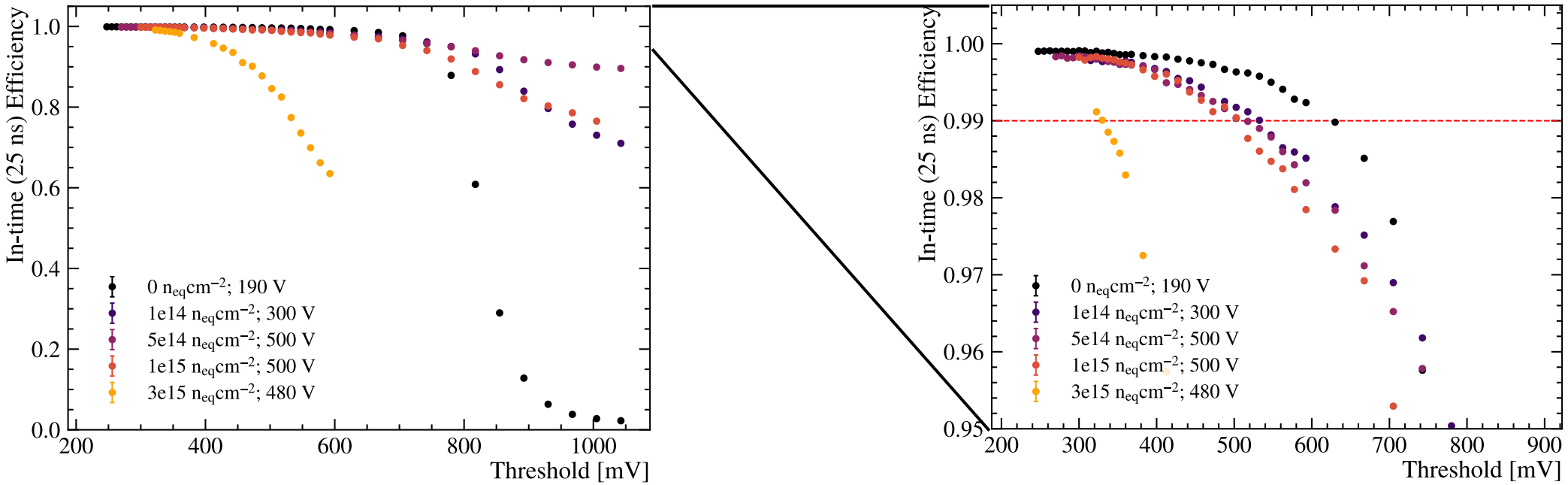
In-time efficiency



- Performance maintained for different fluences
- ε_{25ns} > 99 % up to 1e15 n_{eq}/cm^2
- ε_{25ns} > 98 % at 3e15 n_{eq}/cm^2 and ε_{hit} > 99 %

LF-MightyPix: Irradiated Performance at Maximum Bias In-time efficiency

L. Dittmann



- Applied offline correction to 3e15 n_{eq}/cm^2
- Corrected for per-pixel delay → similar effect could be achieved by initial threshold trimming or sensor setting optimisation after irradiation
- 2 Thresholds achieve ε_{25ns} > 99 %
- Mighty-Tracker specifications fulfilled up to 3e15 n_{eq}/cm^2 ~ 8.4 x MT end of life fluence

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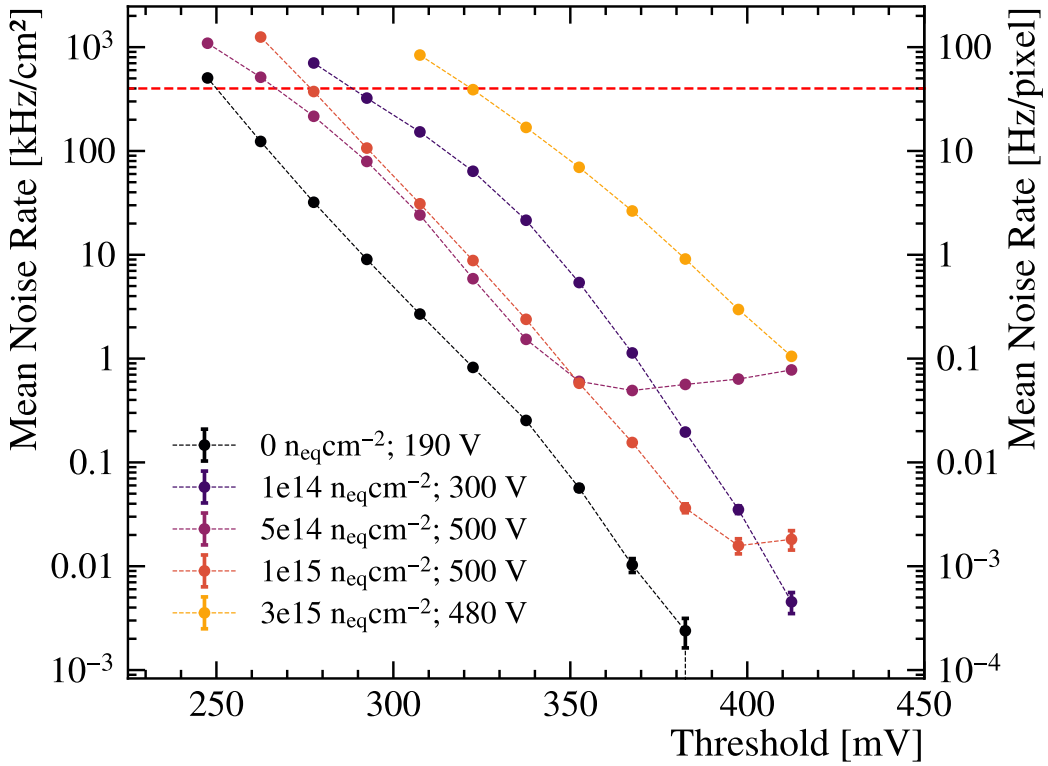
LF-MightyPix: Noise Rate at Maximum Bias



- No pixels masked during data taking (1 pixel masked offline in 5e14 $\mathbf{n_{eq}/cm^2}$)
- Mean noise rate measured for 60 s with beam turned off
- Mean noise rate increased after irradiation
- ε_{25ns} > 99 % while mean noise rate ~ 0.02 kHz/cm² up to 1e15 $\mathbf{n_{eq}/cm^2}$

"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)".

Summary

MightyPix1:

- Excellent performance before irradiation: ε_{25ns} > 99 % & noise rate << 400 kHz/cm²
- Compatible performance after irradiation at 5e14 $\mathrm{n_{eq}/cm^2}$ ~ 1.4 x MT end of life fluence

→ MightyPix1 is radiation hard & achieves Mighty-Tracker specifications

LF-MightyPix:

- Excellent performance before irradiation: ε_{25ns} > 99 % & noise rate << 400 kHz/cm²
- Compatible performance after irradiation up to 3e15 $\mathrm{n_{eq}/cm^2}$ ~ 8.4 x MT end of life fluence

→ LF-MightyPix is radiation hard & achieves Mighty-Tracker specifications

Evaluation of first generation MightyPix sensors mostly finished
→ Both technologies fulfil the Mighty-Tracker specifications after neutron irradiation
→ Optimistic expectation for similar results for the second generation

Backup

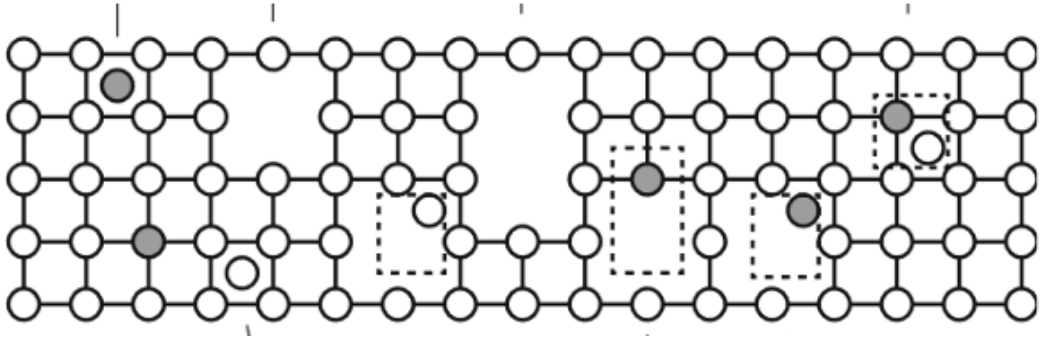
NIEL Radiation Damage in Silicon Sensors

- Created by hadrons and nuclei
- Damages silicon: Interaction displaces a lattice atom

  → Acts as an intermediate level in band gap structure
- Damage can lead to:
  - Change of substrate resistivity

    → Change of voltage needed for full depletion
  - Increased leakage current

    → Higher noise level

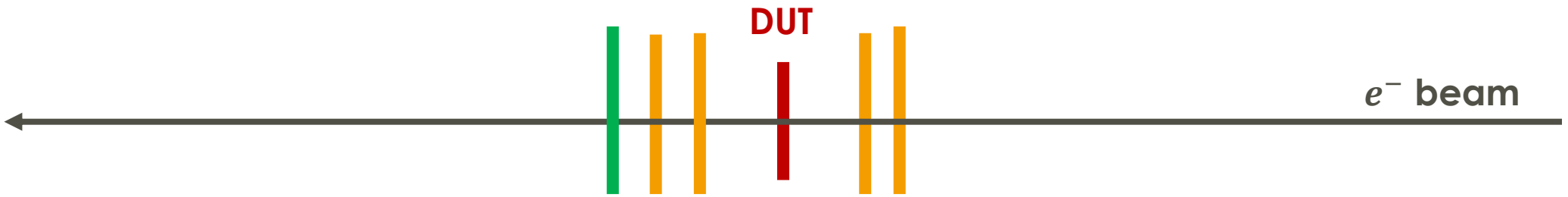


Kolanoski & Wermes

Possible change of sensor performance
Important to validate sensor performance at the expected fluence at end of life

Test Beam Principle

Time Reference: Scintillators
Reference: MuPix Telescope
DUT: MP1



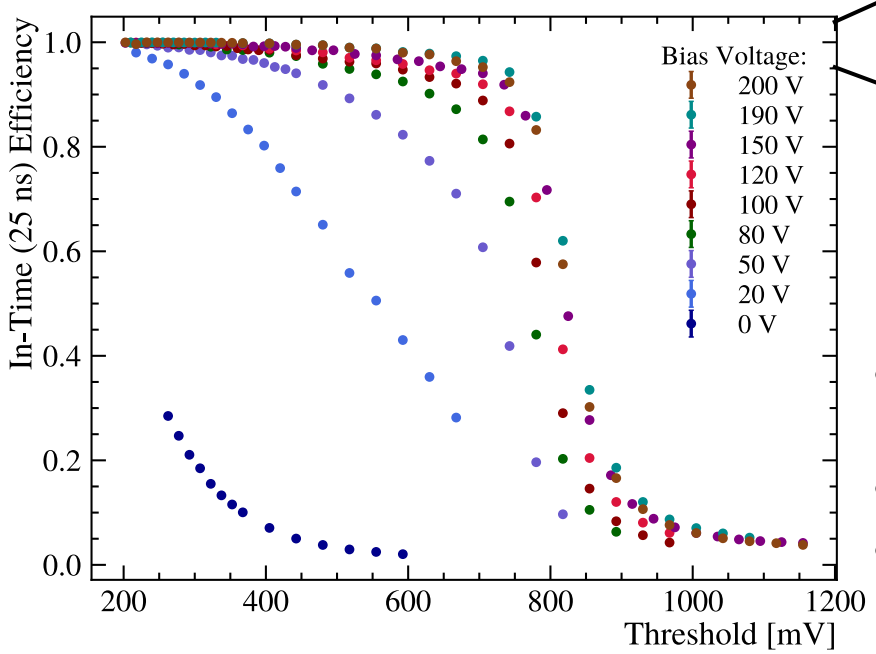
1. Build Tracks using reference telescope
2. Check DUT for hit at same time and position and associate hits
3. Calculate Hit-Efficiency = $\frac{Number\ of\ associated\ Hits}{Number\ of\ Tracks\ traversing\ the\ DUT}$
4. Calculate Time Resolution $t_{track} - t_{DUT}$
5. Calculate In-Time-Fraction = $\frac{Number\ of\ hits\ in\ 25\ ns}{Total\ number\ of\ hits}$
6. Calculate In-Time Efficiency: Hit-efficiency × In-Time-Fraction

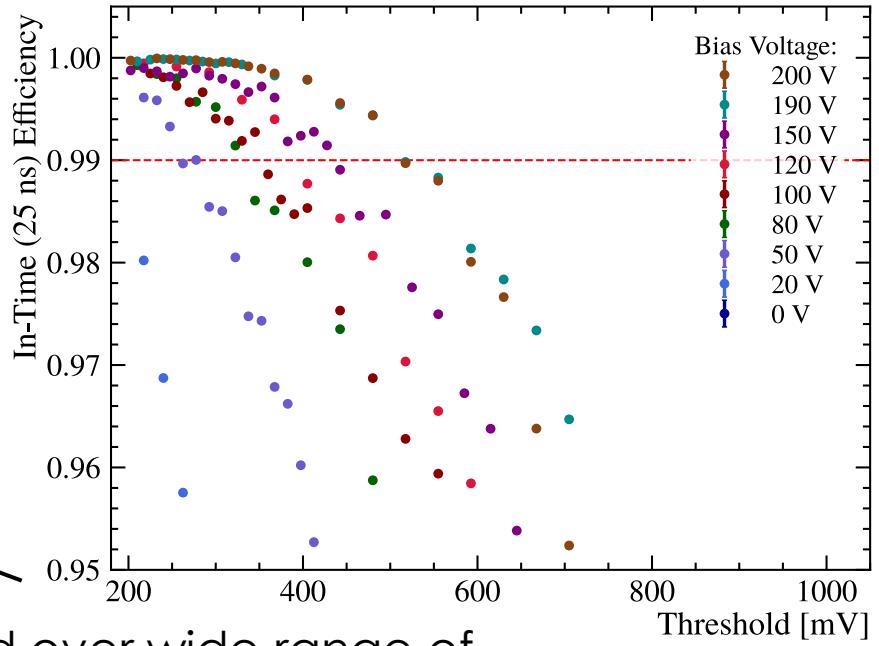
The MightyPix Sensors

Parameter	MightyPix1	LF-MightyPix	MightyPix2	LF-MightyPix2
CMOS technology	TSI 180 nm	LFoundry 150 nm	AMS 180 nm	LFoundry 150 nm
Sensor size	5 mm x 20 mm	3.5 mm x 4 mm	20 mm x 22 mm	24 mm x 10 mm
Pixel pitch	165 µm x 50 µm	100 µm x 100 µm	84 µm x 84 µm	100 µm x 110 µm
Number of pixels	29 x 320	28 x 23	244 x 240	211 x 75
Sensor thickness	100 µm – 700 µm	280 µm	100 µm – 700 µm	?
Wafer resistivity	200 – 400 Ωcm	> 2 kΩcm	200 – 400 Ωcm	?
Time-of-arrival-binning	≥12.5 ns	≥ 6.25 ns	≥ 3.125 ns	≥ 3.125 ns
ToT binning	25 ns	12.5 ns	3.125 ns	3.125 ns
Data link	1280/640/320 Mbit/s	1280/640/320 Mbit/s	4 x 1280/640/320 Mbit/s	8 x 1280/640/320 Mbit/s

LF-MightyPix: Non-Irradiated Performance

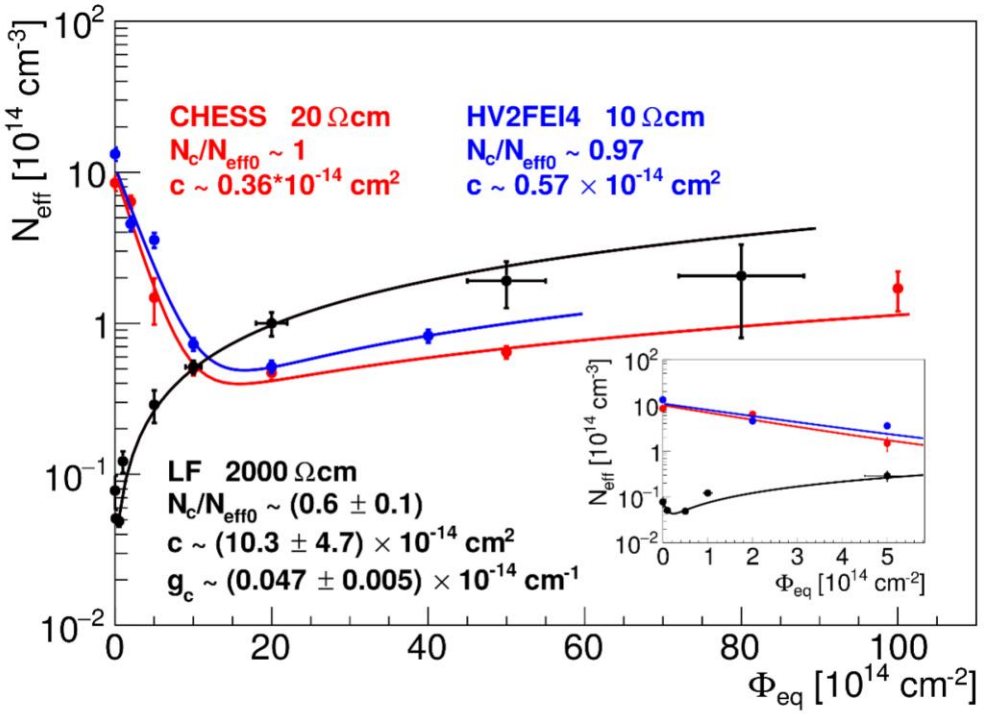
In-time efficiency for different reverse bias voltages





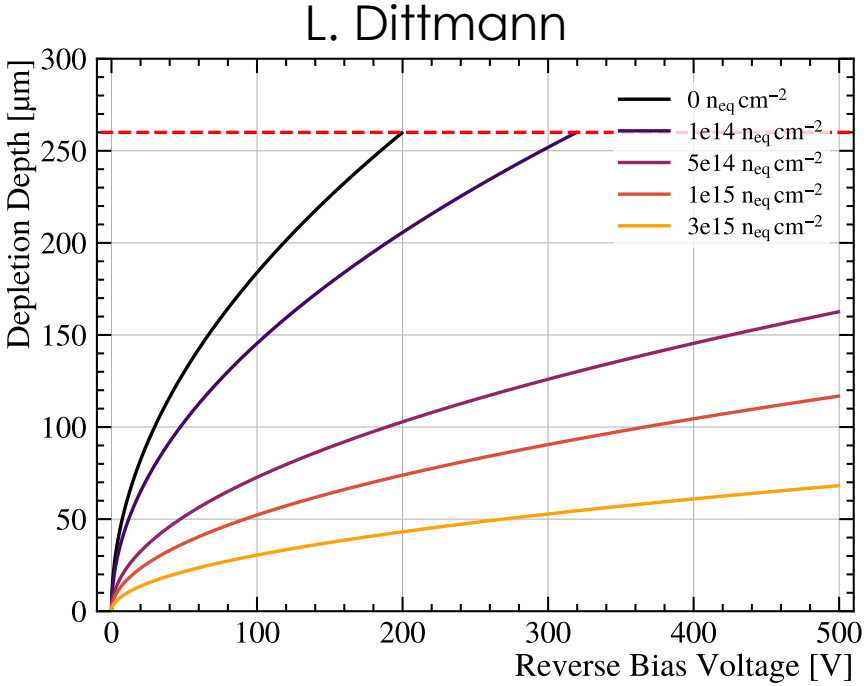
- Performance validated over wide range of measurements and reverse bias voltages
- ε_{25ns} > 99 % achieved for V_{bias} > 50 V ~ 138 µm depletion
- → no full depletion needed for excellent performance

Expected depletion after Irradiation



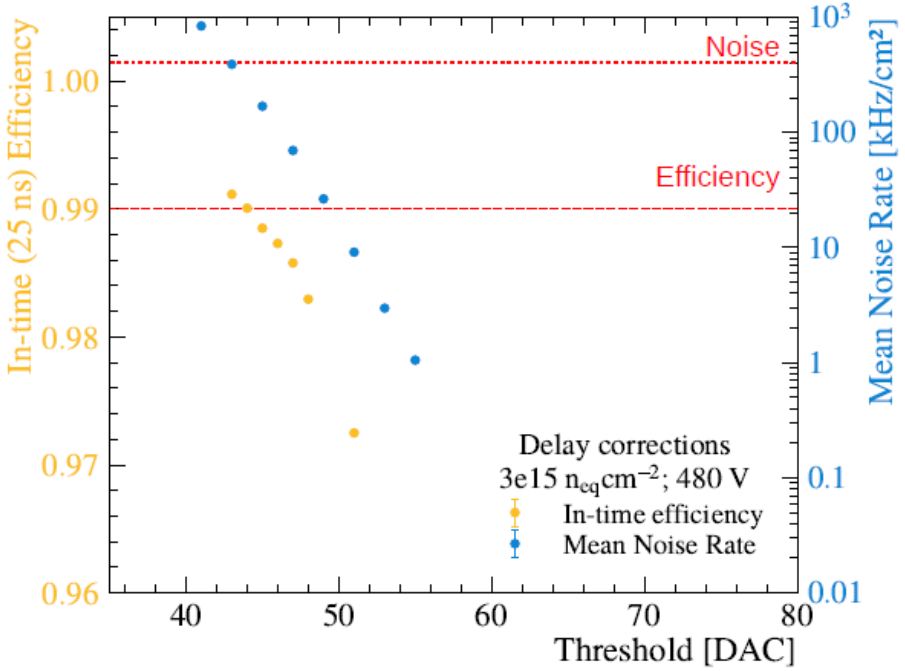
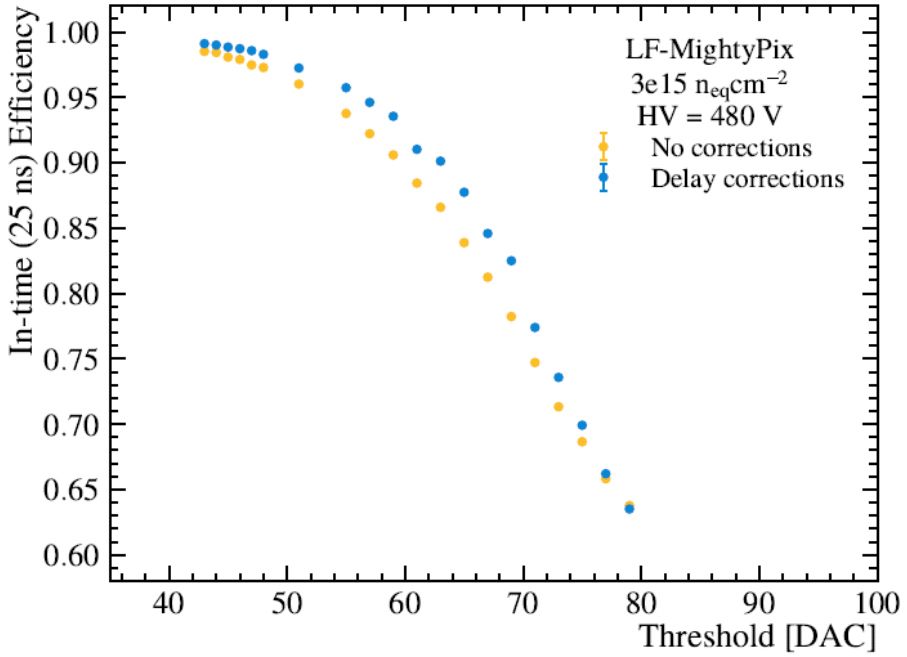
$$d \sim \sqrt{\frac{1}{N_{eff}} V_{bias}}$$

L. Dittmann



[I. Mandić et al 2017 JINST 12 P02021] here

Offline Correction for 3e15 n_{eq}/cm^2

L. Dittmann

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