AIDAINNOVA ANUAL MEETING 2024

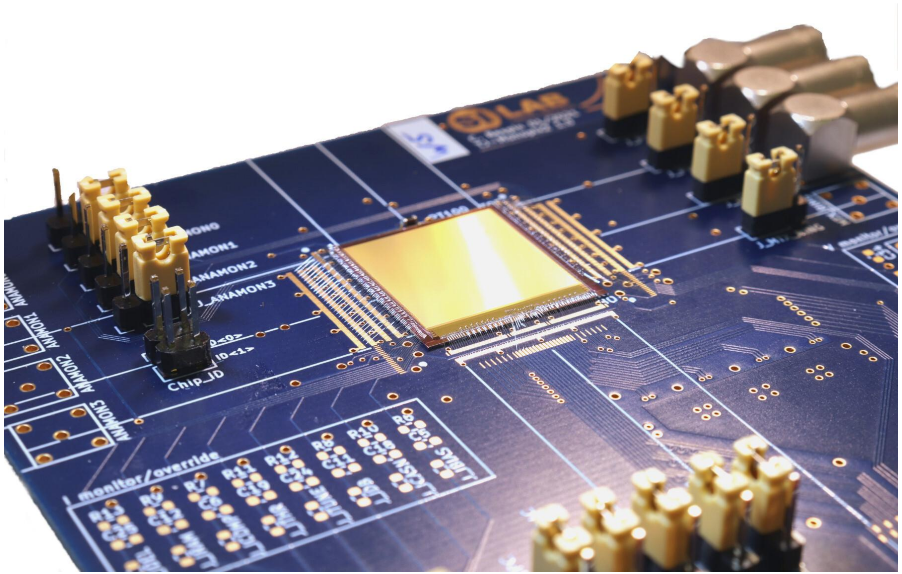
LATEST RESULTS OF THE MONOPIX DEVELOPMENT LINES

Fabian Hügging on behalf of the Monopix testing teams

TJ-Monopix2

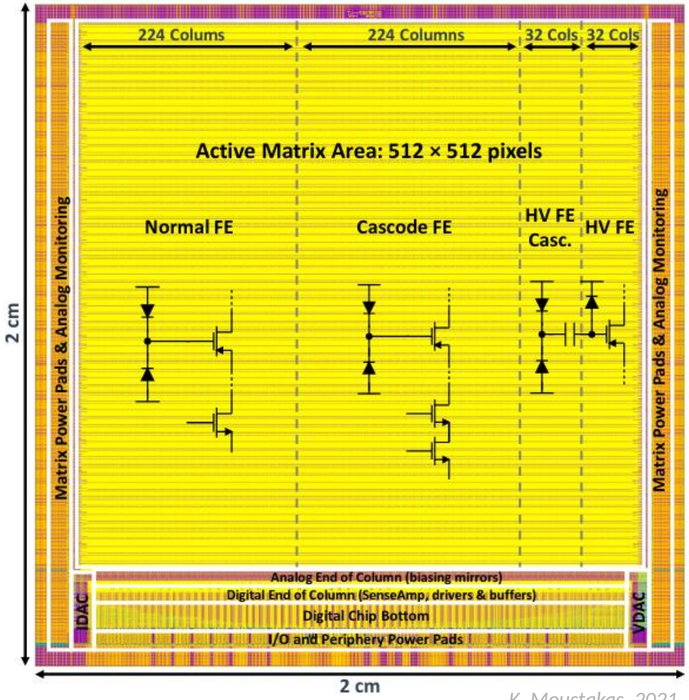
- Designed in 180 nm TowerSemiconductor CMOS technology
- 2x2 cm^2 chip size
  - 33.04x33.04 μm^2 pixel pitch
- Small charge collection electrode relative to pixel pitch
- Full scale column length with column-drain R/O architecture
- Substrate resistivity >1 kΩcm

- Baseline for a new DMAPS developed for the Belle II VTX upgrade



TJ-Monopix2 Specifications

- Improved front-end to lower noise and threshold
  - TJ-Monopix1 ~350 e- THR and ~16 e⁻ noise
    - Observed RTS noise tail
- 7 bit ToT information @ 25 ns
- 3 bit in-pixel threshold tuning
  - More in-pixel logic at smaller pixel size
- Triggerless readout
- 4 front-end variations based on proven design from predecessor:
  - Cascoded version
  - AC coupled (HV) front-ends biased via n-well

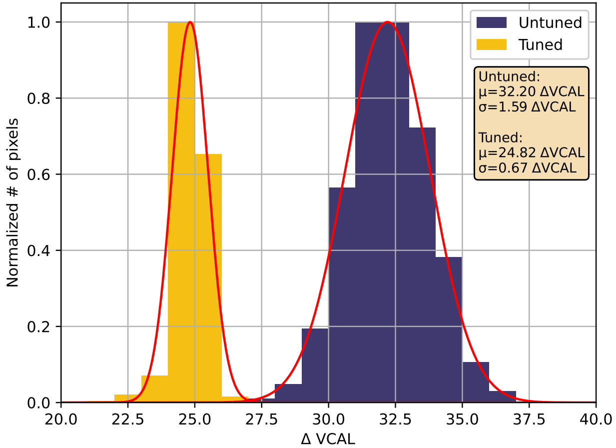


K. Moustakas, 2021

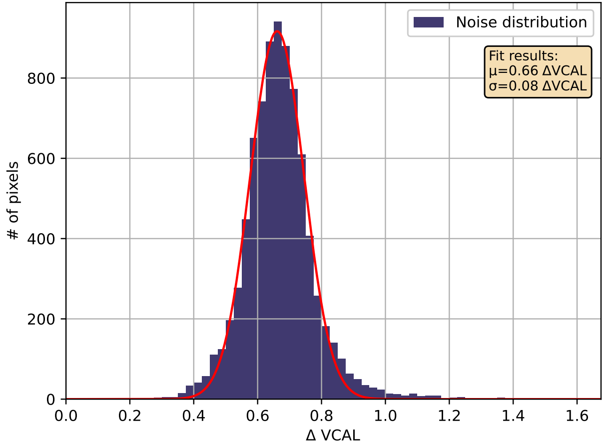
Laboratory Measurements

- Extract mean tuned **threshold of ~250 e⁻** and mean **ENC of ~6 e⁻** from s-curve scan
  - Sufficient for excellent hit-detection efficiency (MIP charge MPV >2500 e⁻)
  - Threshold dispersion significantly reduced by 3 bit in-pixel trimming
  - No RTS noise tail

Normalized threshold distribution



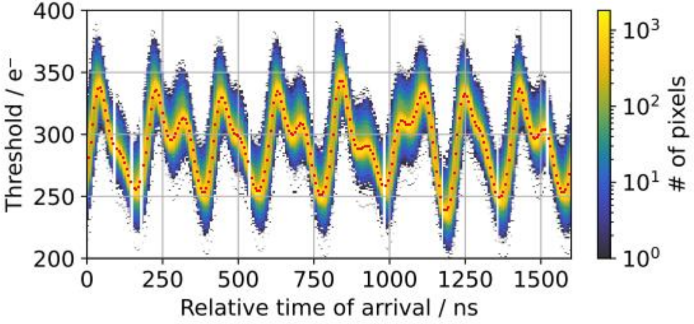
ENC distribution



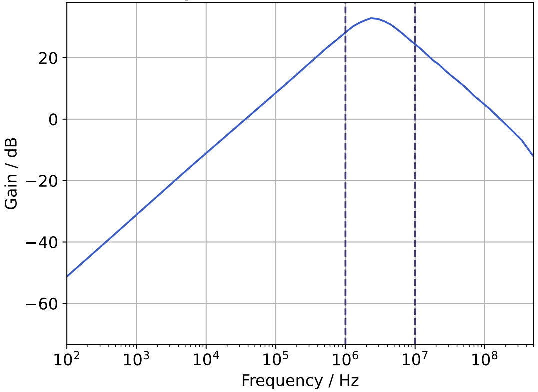
Threshold Oscillation

- Threshold depends on arrival time of signal (leading edge)
  - Amplitude O(50 e⁻) → Factor 10 larger than ENC
  - Dominant oscillation frequency roughly 5 MHz
- LE/TE sampled with 40 MHz clock in pixel
  - Bits of counter toggle in $\frac{40\ MHz}{4/8/16/\ldots}$
- Peak of pre-amplifier transfer function 2-10 MHz
  - Very sensitive to frequency of counter bit toggling
  - Cross-talk cannot be mitigated while LE/TE sampling
- Workaround for (injection based) scans:
  - Reset of 40 MHz clock with respect to injection
  - Disable LE/TE sampling and charge measurement

Threshold vs relative hit arrival time



Pre-amplifier transfer function

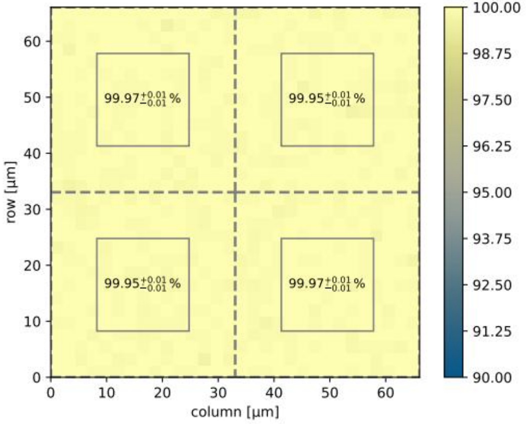


K. Moustakas, 2021

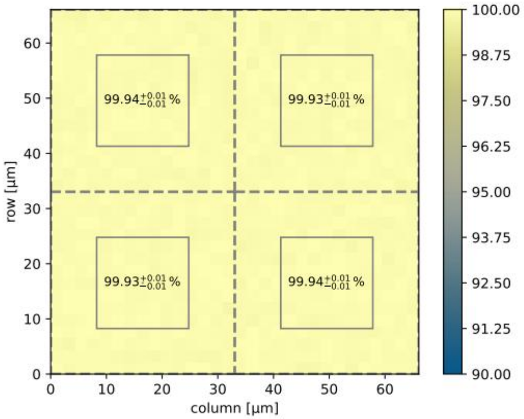
TJ-Monopix2 Hit Detection Efficiency

- Comparison of front-end variations for epi substrate with gap in n-layer
  - Measured at approx. 250 e^- threshold for all samples
    - DC coupled at -6 V bias voltage (left, middle), AC coupled +15 V bias voltage (right)
  - Uniform hit detection efficiency >99% with no losses in pixel edges

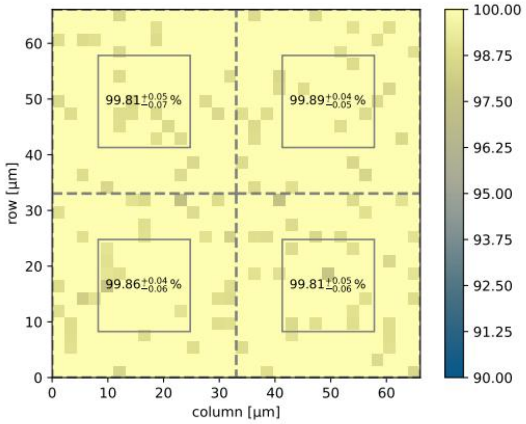
Standard FE: 99.96%



Cascode FE: 99.94%



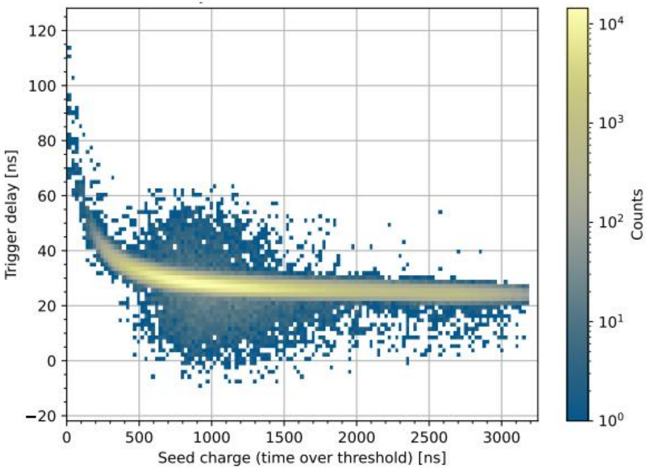
HV Cascode FE: 99.85%



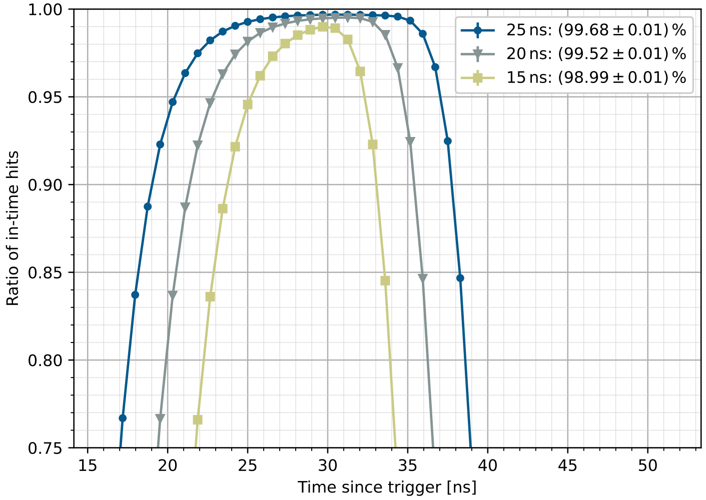
Timing Studies in Beam

- Measure delay between scintillator and HitOr signal with 640 MHz clock
- Estimate in-time ratio of hits in given time window of trigger distance distribution
- For 30 µm epi chip with n-gap modification and standard front-end:
  - **99.68% within 25 ns** (ATLAS BX frequency)

Corrected scintillator-HitOr delay

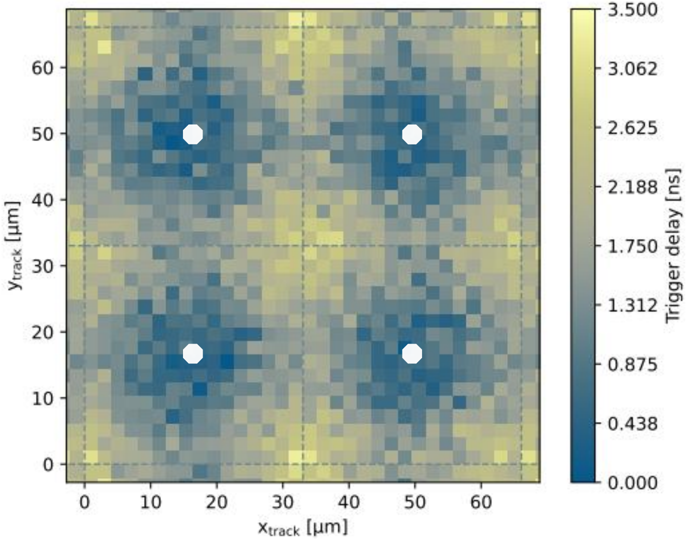


In-time ratio



In-pixel Signal Propagation

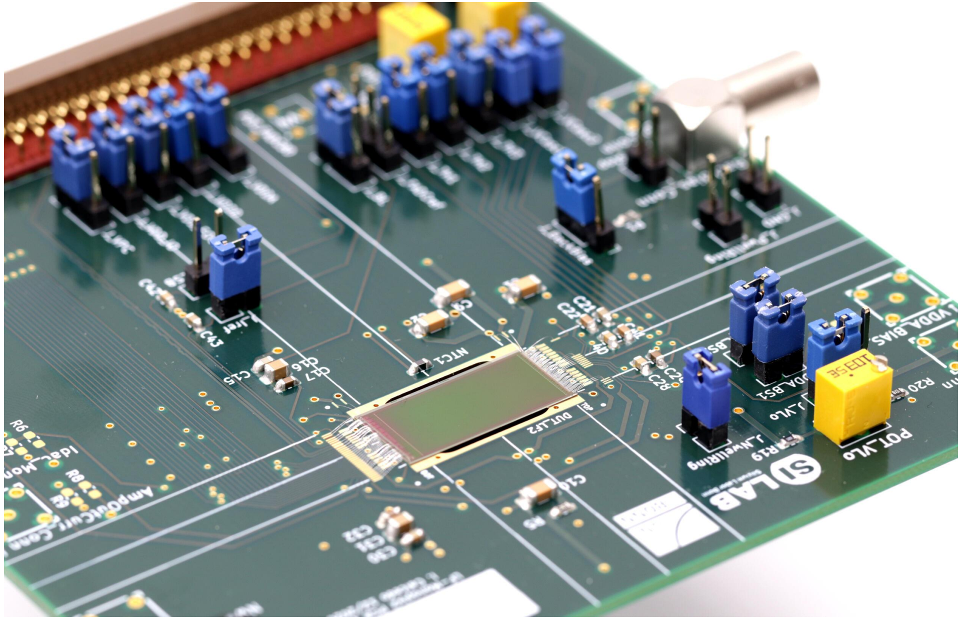
- Study in-pixel timing with telescope tracking data
- Investigate trigger delay relative to charge collection electrode
  - Electrodes indicated as white dot
- Up to 3.5 ns difference in delay due to charge propagation time to small electrode



UNIVERSITÄT BONN

LF-Monopix2

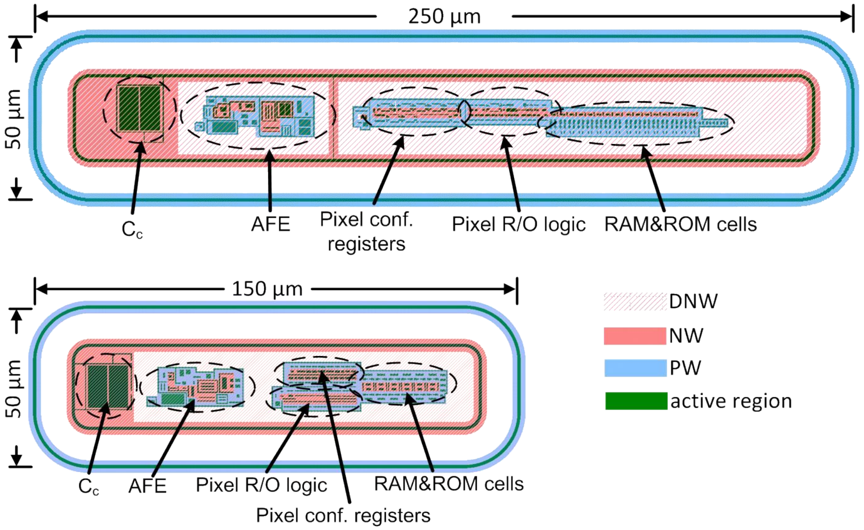
- Designed in 150 nm LFoundry CMOS technology
- 2x1 cm^2 chip size
  - 50x150 µm pixel pitch
- Large charge collection electrode relative to pixel pitch
- Full scale column length with column-drain R/O architecture
- Substrate resistivity >2 kΩcm



LF-Monopix2 Specifications

- **Full in-pixel electronics** while **reducing the pixel pitch by 40%** of predecessor
- **6 bit ToT** information @ 25 ns
- **4 bit in-pixel threshold tuning**
- 6 front-end variations available
  - Differing in CSA, feedback capacitance, tuning
- Proton irradiated samples up to 2e15 neq/cm^2 available (100 µm, backside processed)
  - Not powered during irradiation
  - Annealed 80 min @ 60 °C

LF-Monopix1 (Mar 2017)

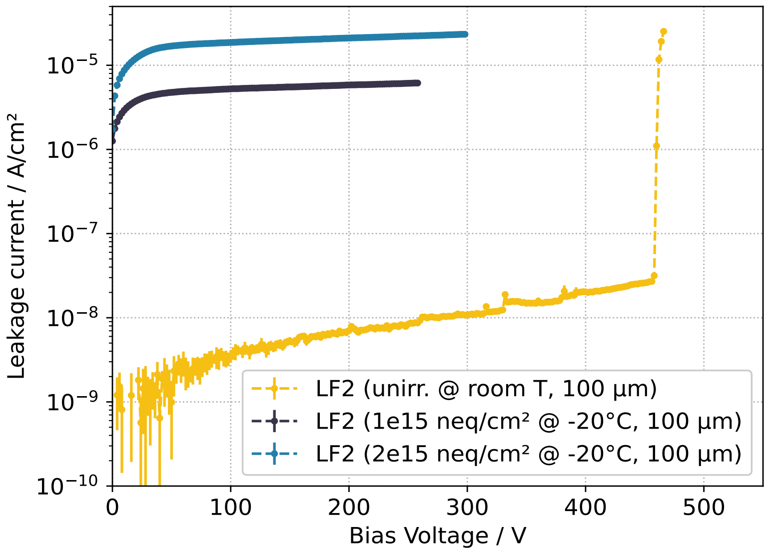


LF-Monopix2 (Feb 2021)

Leakage Current and Gain

- Measure leakage current per cm² at -20 °C environmental temperature
  - Non-irradiated at room temperature
- Breakdown at ~460 V for non-irradiated sensors
- At 100 V bias voltage:
  - Increase in leakage current ~5 µA/cm² per irradiation step of 1e15 neq/cm² fluence

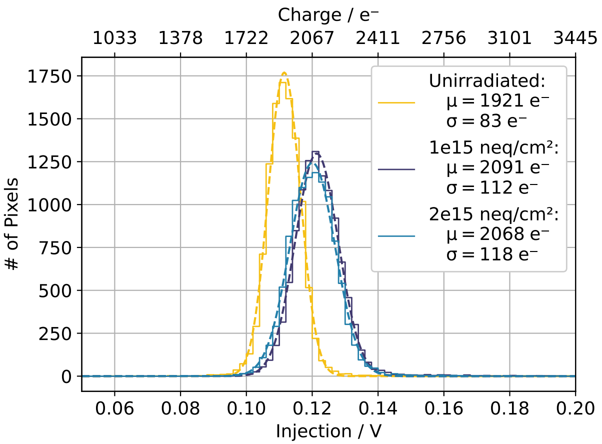
I-V curve comparison @ different fluences



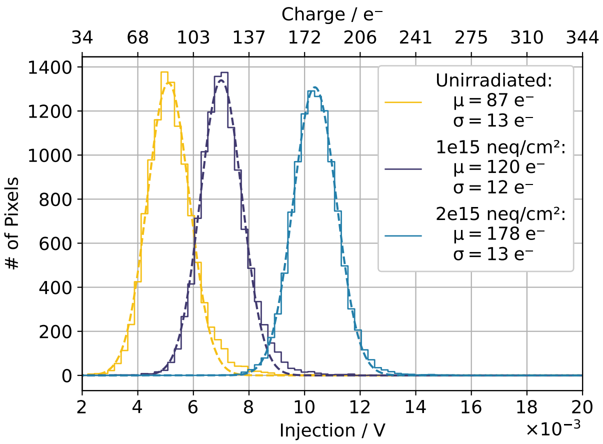
Laboratory Tests

- Operated in controlled laboratory environment @ -20 °C
- Tune-able to approx. 2 ke⁻ mean threshold at all irradiation steps
  - Expected charge MPV of MIP at full depletion around 6 ke⁻
- Ca. 40% increase in ENC per irradiation step of 1e15 neq/cm² fluence

Threshold distribution



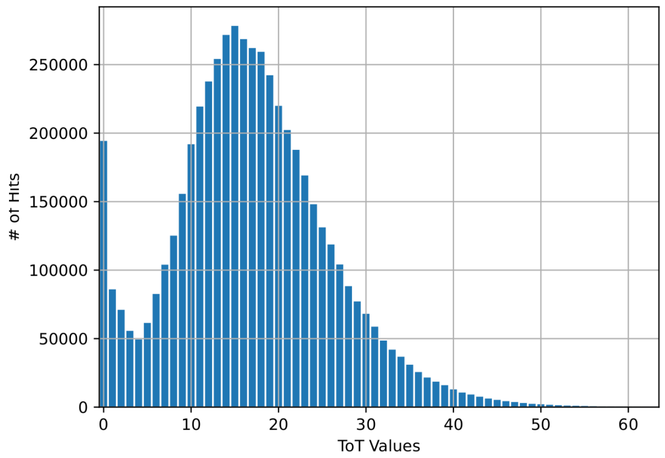
ENC distribution



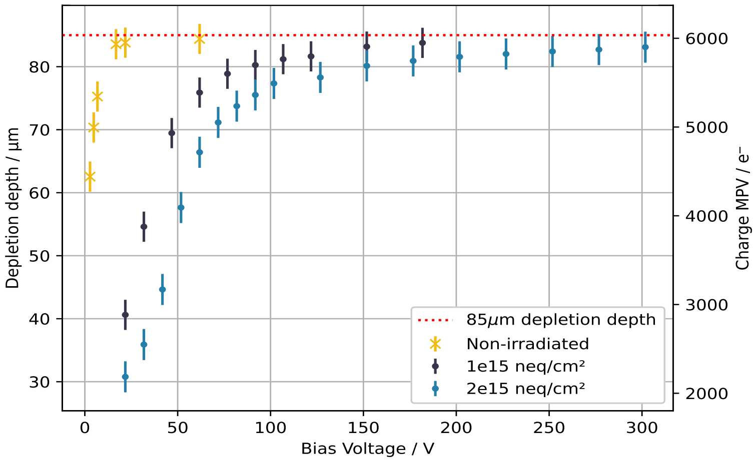
Depletion Depth of LF-Monopix2

- Extract calibrated charge MPV from Landau shaped beam spectrum
  - Measured with 5 GeV electrons at DESY
- Full depletion reached around 200 V after irradiation to 2e15 neq/cm²
  - Non-irradiated sensors fully depleted at 15-20 V

ToT beam spectrum



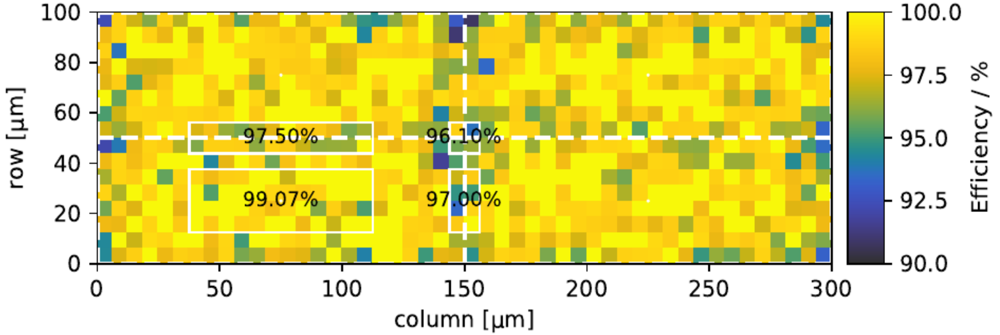
Calibrated charge MPVs



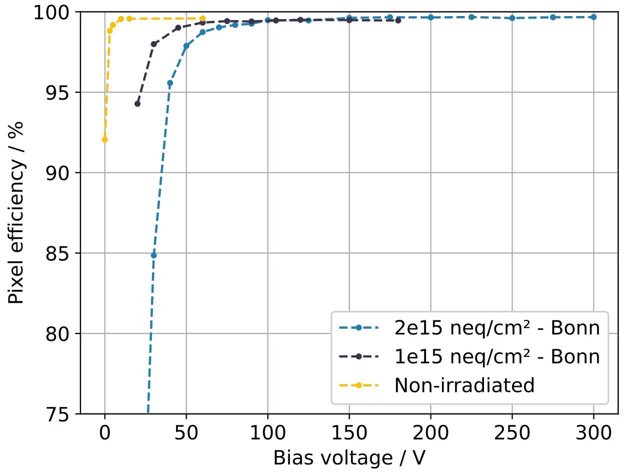
Hit Detection Efficiency Studies

- After **2e15 neq/cm²** fluence still >99 % hit-detection efficiency
  - Measured >98 % mean in-time efficiency within 25 ns window
  - Measured at 2 ke⁻ threshold and 300 V bias (full depletion)
  - Almost 1 % masked pixels due to high ENC

In-pixel, in-time efficiency
(**mean 98.35%** @ 2e15 neq/cm²)



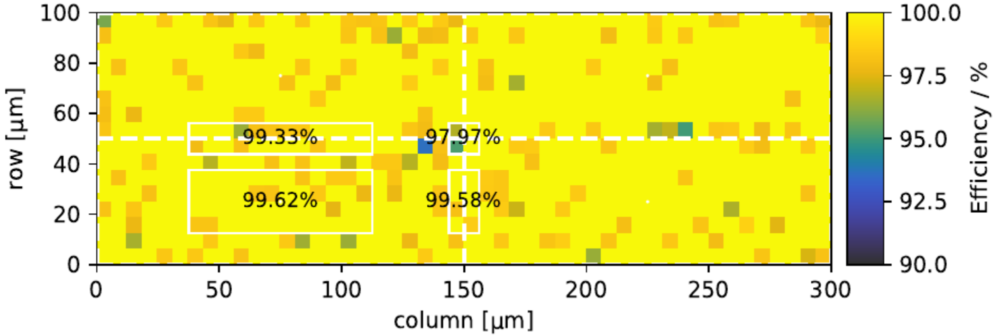
Hit-detection efficiency vs bias voltage



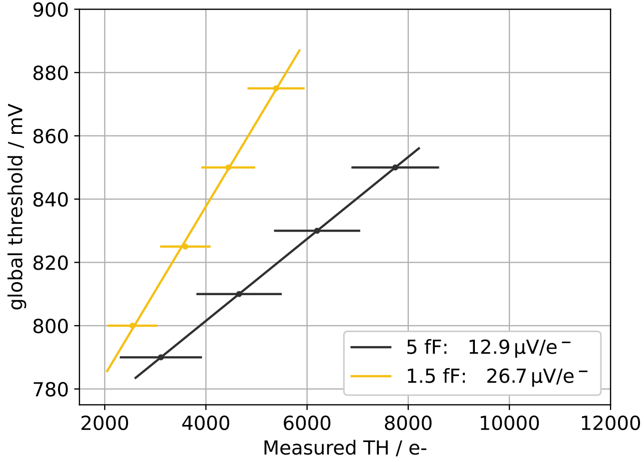
In-Time Efficiency for Higher Gain

- Compare to pixels with smaller feedback capacitance
  - Verified larger gain by measurement (at 1e15 neq/cm²)
- Higher signal gain improves timing performance
  - Mean in-time efficiency of 99.6% @ 2e15 neq/cm²
  - Only 0.5% pixels masked (smaller matrix)

In-pixel, in-time efficiency
(**mean 99.60%** @ 2e15 neq/cm²)



Measured gain @ 1e15 neq/cm² fluence



Conclusion and Outlook

- Non-irradiated **TJ-Monopix2** show hit-detection efficiencies >99.9%
  - More than 99% of hits registered within 25 ns
- **LF-Monopix2** fully operational after proton irradiation to 2e15 neq/cm²
  - >99% hit detection efficiency with ~1 % masked pixels due to high ENC

Upcoming measurements:

- Studies with neutron irradiated samples
- TID irradiation campaign in the next month(s)

Recent Publications:

- Test-beam performance of proton-irradiated, large-scale DMAPS in 150nm CMOS technology (VERTEX23) *DOI: 10.22323/1.448.0043*
- Timing performance of monolithic CMOS pixel detector front-end inn 180nm technology (PACET24) *(accepted, to be published)*
- Cross-talk of a large-scale DMAPS in 180nm CMOS technology (HSTD23) *(Submitted, under revision)*

UNIVERSITÄT BONN

Thank you for your attention!

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)

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No. 675587-STREAM, 654168 (AIDA-2020) and 101004761 (AIDA-Innova)

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.

EURO-LABS
EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

Backup