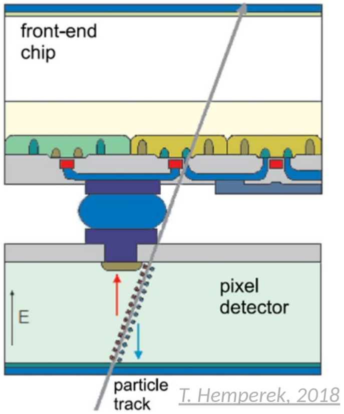
HIROSHIMA SYMPOSIUM 2023, VANCOUVER

BEAM-TEST STUDIES OF DMAPS IN 150 NM AND 180 NM CMOS TECHNOLOGY

Lars Schall, Marlon Barbero, Pierre Barrilon, Christian Bespin, Patrick Breugnon, Ivan Caicedo, Yavuz Degerli, Jochen Dingfelder, Tomasz Hemperek, Toko Hirono, Fabian Hügging, Hans Krüger, Konstantinos Moustakas, Patrick Pangaud, Heinz Pernegger, Petra Riedler, Piotr Rymaszewski, Philippe Schwemmling, Walter Snoeys, Tianyang Wang, Norbert Wermes, Sinuo Zhang

Depleted Monolithic Active Pixel Sensor

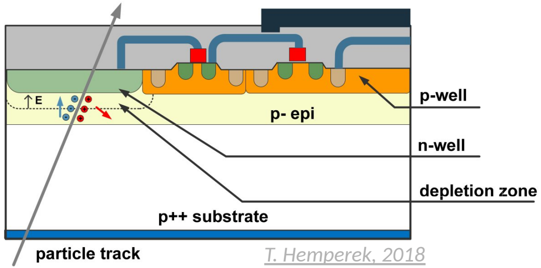
Hybrid detector



✔ Optimized individual parts
✔ High rad. tolerance

✗ Cost and labor intensive bump-bonding

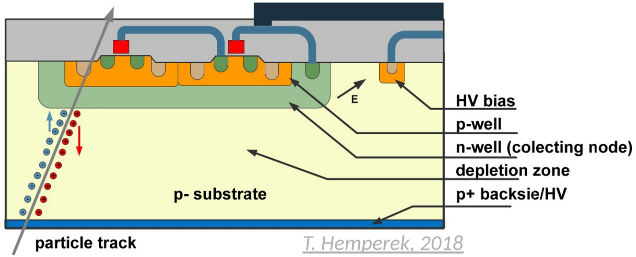
MAPS detector



✔ Reduced material budget
✔ Commercial processes:
- Fast & high volume production
- Lower module cost

✗ Sensor not fully depleted
- Not radiation hard

Depleted MAPS detector



- CMOS processes offer high-resistivity substrate
- Bias voltage capabilities (HV)

✔ Strong drift field
✔ Enhanced charge collection
→ Increased radiation tolerance

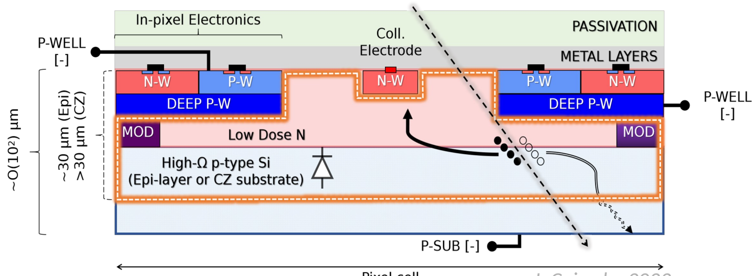
Collection Electrode Design Approaches

Small collection electrode:

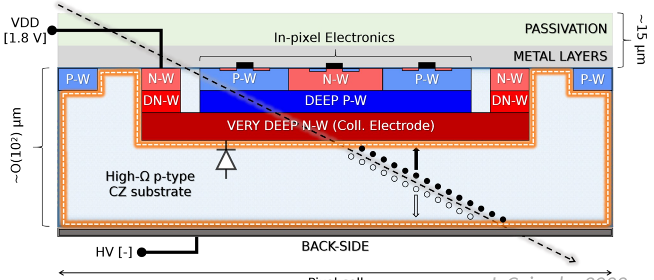
- Electronics **outside** charge collection well
- **Small sensor capacitance** (<5 fF)
  - Low analog power budget (noise, speed)
  - Less prone to cross-talk
- Longer drift distances
- Potentially regions with low E-field
  - **Need modifications** for radiation hardness

Large collection electrode:

- Electronics **inside** charge collection well
- **Large sensor capacitance** O(100 fF)
  - Compromises noise, speed, power
  - Risk of cross-talk
- Shorter drift distances
- Few regions with low E-field
  - Less trapping → **radiation hard**



I. Caicedo, 2022



I. Caicedo, 2022

Latest Monopix Prototypes

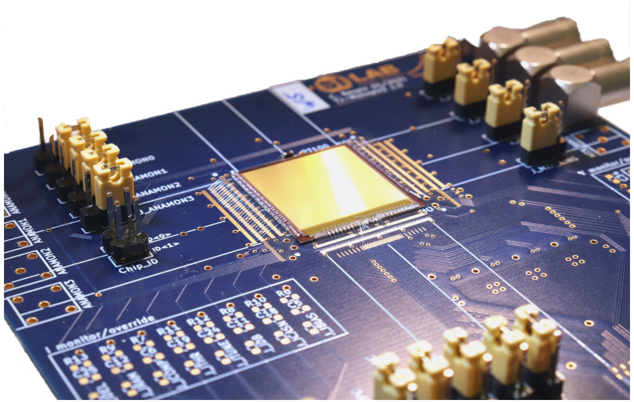
<u>TJ-Monopix2:</u>

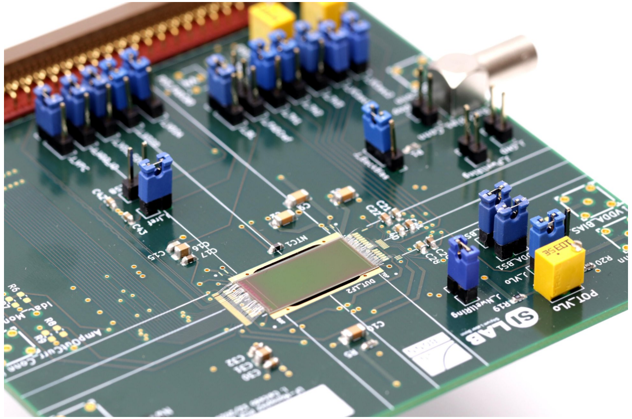
- 180 nm TowerSemi CMOS technology
- **Small** collection electrode
- ~2x2 cm² matrix with **33x33 µm²** pixel pitch
- Substrate resistivity >1 kΩcm

<u>LF-Monopix2:</u>

- 150 nm LFoundry CMOS technology
- **Large** collection electrode
- ~2x1 cm² matrix with **50x150 µm²** pixel pitch
- Substrate resistivity > 2 kΩcm

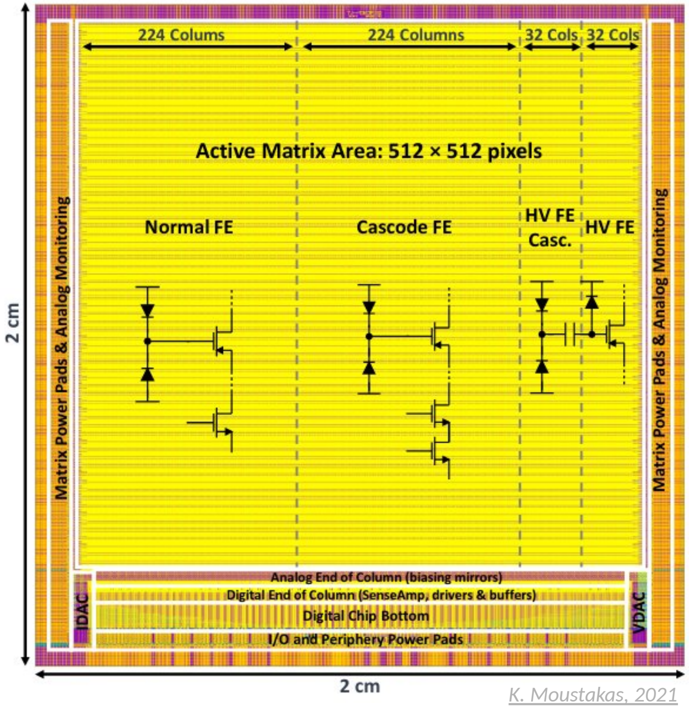
Same fast **column drain readout** architecture (FE-I3 like)





TJ-Monopix2 Specifications

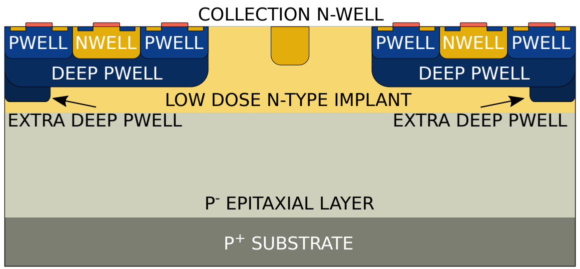
- Improved front-end to **lower noise and threshold**
  - **TJ-Monopix1** ~350 e- THR and ~16 e⁻ noise
    - Observed RTS noise tail
- **7 bit ToT** information @ 25 ns
- **3 bit in-pixel threshold tuning**
  - More in-pixel logic at smaller pixel size
- **Triggerless** readout
- 4 front-end variations based on proven design from predecessor:
  - Cascoded version
  - **AC coupled (HV) front-ends biased via collection node**
- Baseline for development of DMAPS for Belle II upgrade
  - *Upcoming talk by M. Babeluk*

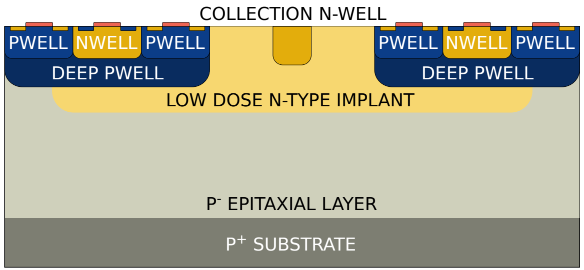


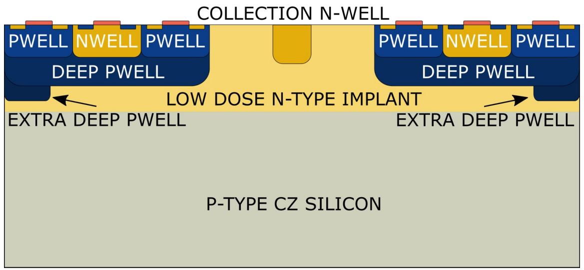
K. Moustakas, 2021

TJ-Monopix2 Modifications

- For TJ-Monopix1 *[DOI 10.1088/1748-0221/14/06/C06006]*
  - Observed **efficiency loss** to ~70% after irradiation (1e15 neq/cm²) **in pixel corners**
  - Charge loss due to E-field shaping under deep p-well
- Possible improvements:
  - Enhance lateral E-field → **n-gap** or **extra deep p-well**
  - Increase input signal → thick **Czochralski (Cz) substrate**
- All combinations available for TJ-Monopix2



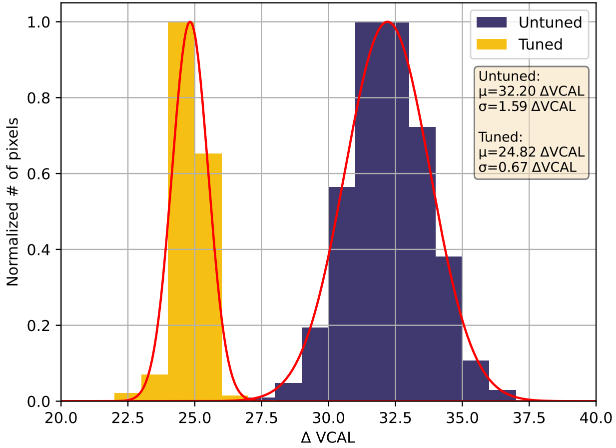




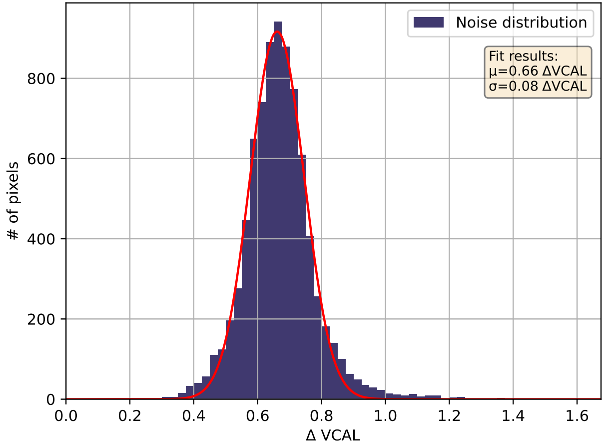
Laboratory Measurements

- 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



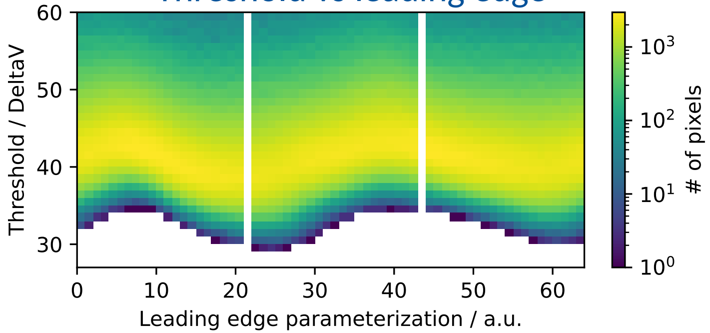
ENC distribution



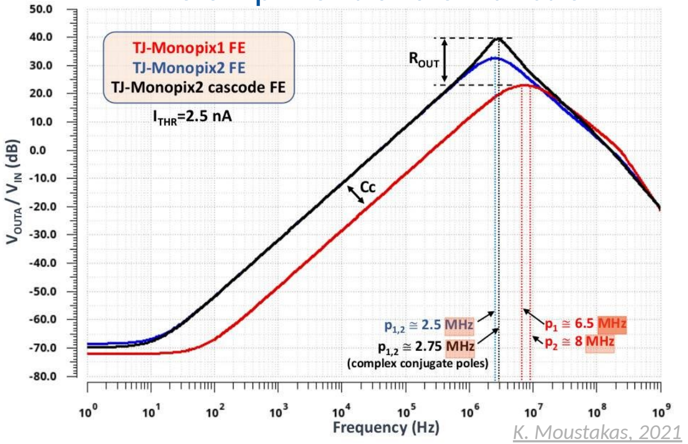
Threshold Oscillation

- Threshold depends on arrival time of signal (leading edge)
  - Amplitude O(50 e^-) → Factor 10 larger than ENC
  - Oscillation frequency ca. 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 bits toggling
  - Cross-talk cannot be mitigated while LE/TE sampling
- Workaround for injection based scans:
  - Reset of 40 MHz clock with respect to injection

Threshold vs leading edge



Pre-amplifier transfer function

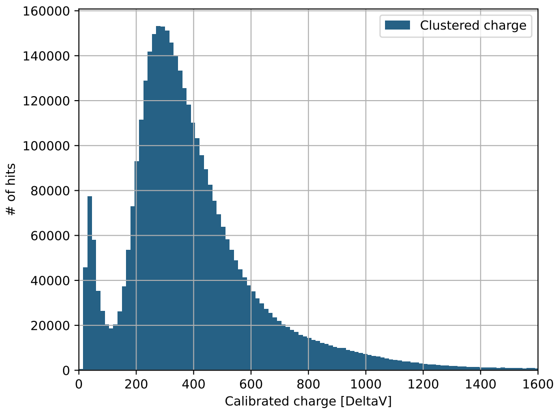


K. Moustakas, 2021

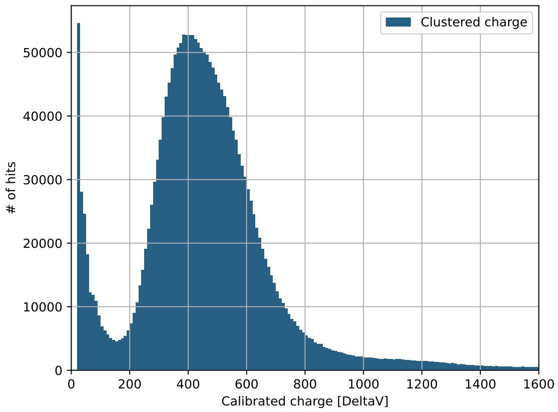
Beam Tests: Cluster Charge

- Exposed sensors to **5 GeV electron beam** at DESY
- Compare standard front-end for **30 µm Epi** and **100 µm Cz** sensor material
  - Thicker Cz material allows higher charge MPV for Cz
    - **No full depletion** reached at -6 V **for Cz**
  - **Larger average cluster size for Cz** than for Epi material

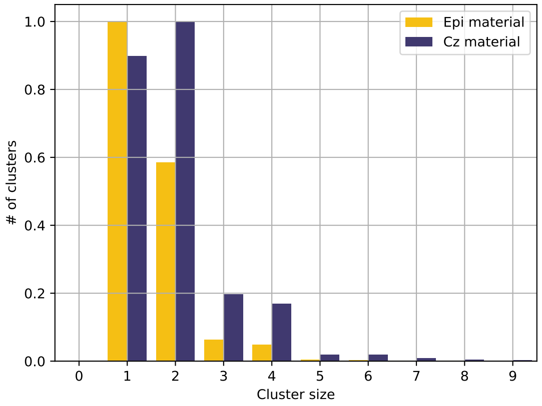
30 µm Epi: ~2700 e⁻ MPV



100 µm Cz: ~3600 e⁻ MPV



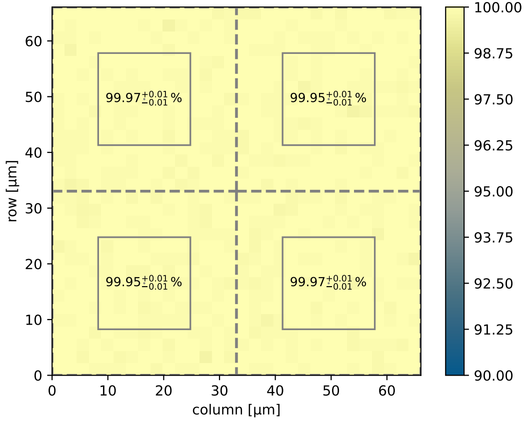
Normalized cluster size distribution



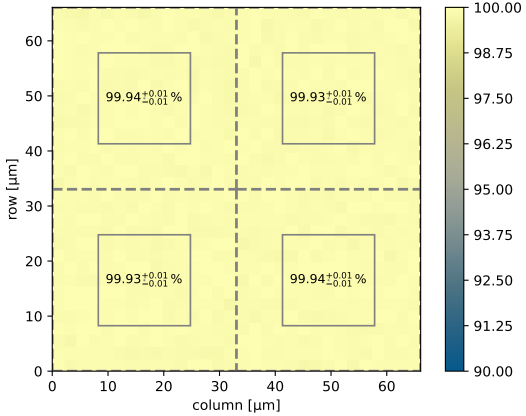
TJ-Monopix2 Hit Detection Efficiency

- 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 on PSUB/PWELL (left, middle), AC coupled +15 V on collection n-well (right)
  - **Uniform** hit detection **efficiency >99% with no losses in pixel edges**
  - Agreement between different modification types

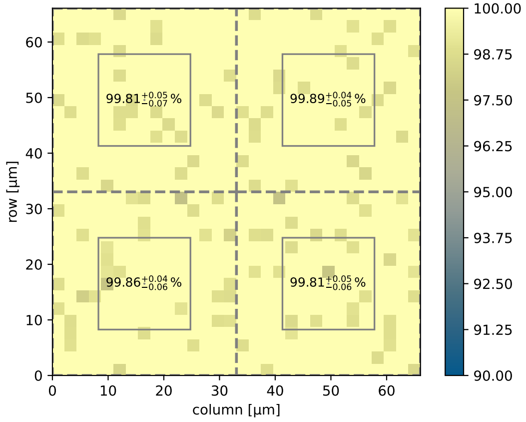
Standard FE: 99.96%



Cascode FE: 99.94%



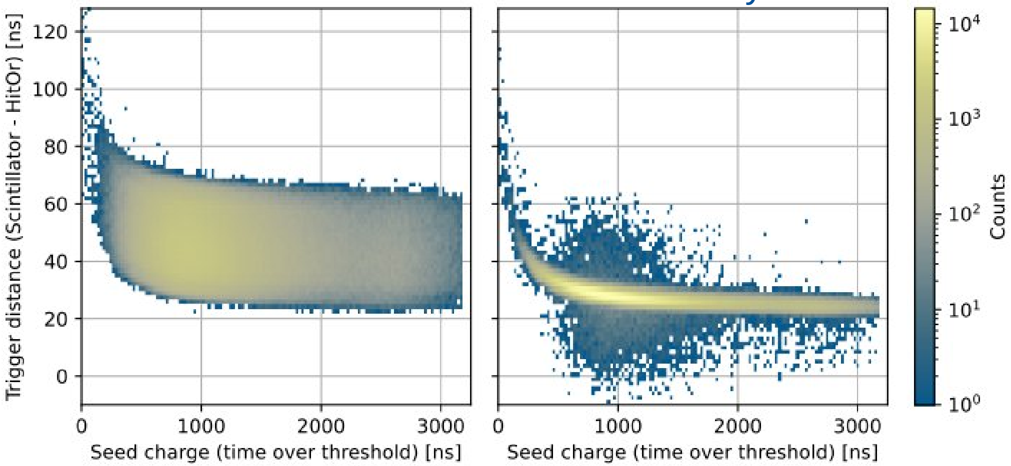
HV Cascode FE: 99.85%



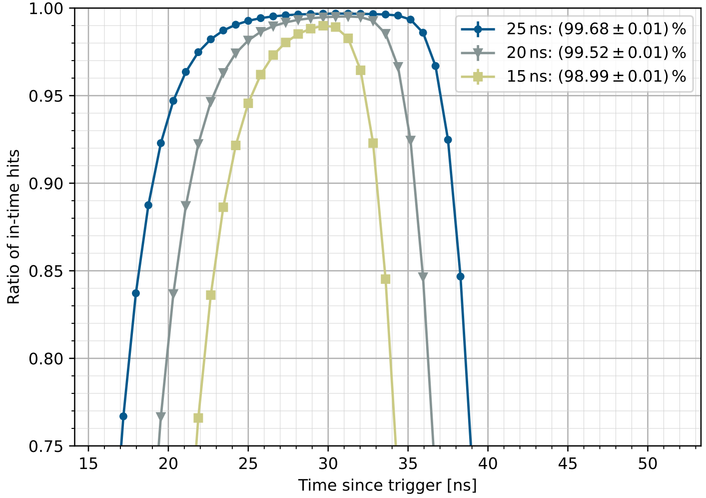
Timing Studies in Beam

- 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)

Correction of scintillator-HitOr delay



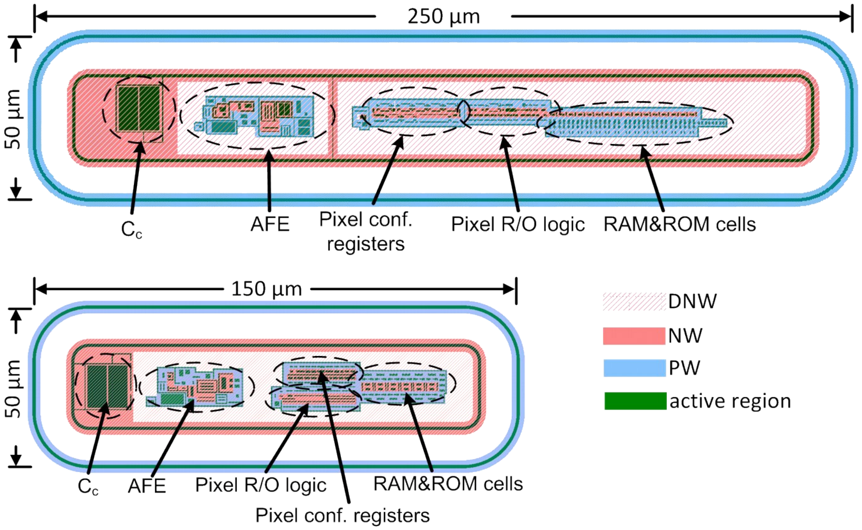
In-time ratio



LF-Monopix2 Specifications

- Full scale column length with column-drain R/O
  - **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
- Successfully thinned down to 100 µm thickness and backside processed
- Proton irradiated samples up to 2e15 neq/cm^2 available
  - Not powered during irradiation
  - Annealed 80 min @ 60 °C

LF-Monopix1 (Mar 2017)

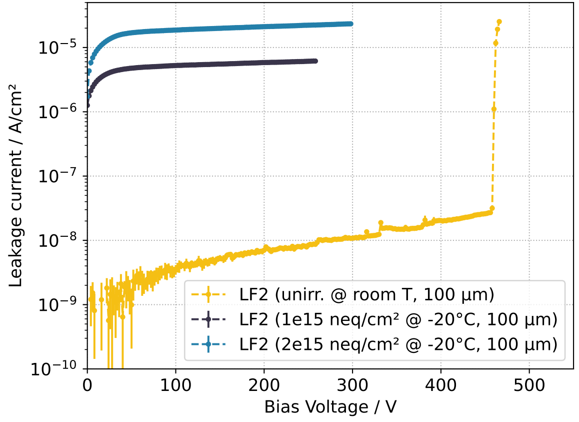


LF-Monopix2 (Feb 2021)

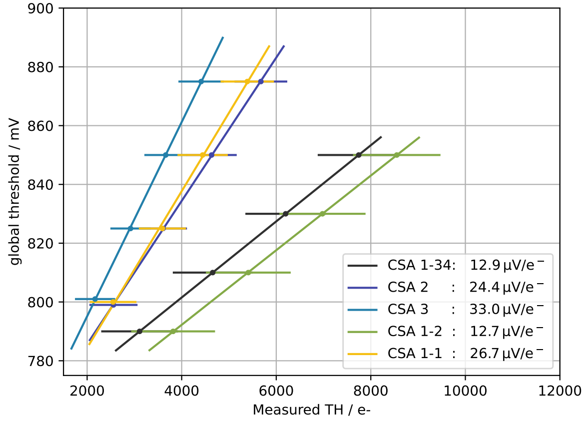
Leakage Current and Gain

- Measure **leakage current per pixel** at -20 °C environmental temperature
  - Breakdown at ~460 V for unirradiated modules
- **Increase** in leakage current **~5 µA/cm²** per 1e15 neq/cm² irradiation step at 100 V
- Extract **gain** from linear regression of untuned threshold at different global THR settings
  - Smaller feedback capacitance → larger gain (and faster rise time of LE)

I-V curve comparison @ different fluences



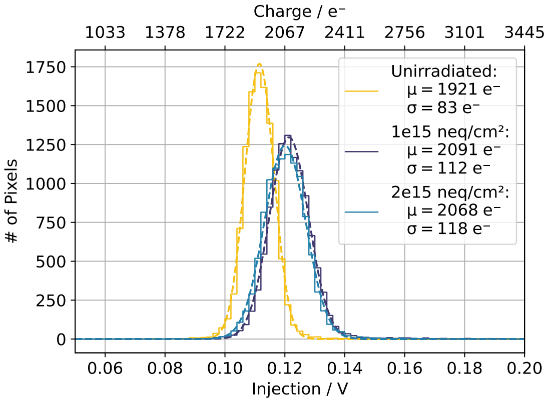
Gain **after** irradiation (1e15)



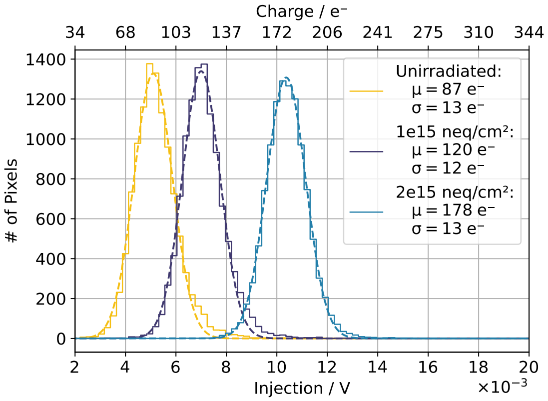
Laboratory Tests

- Operated in controlled laboratory environment @ -20 °C
- **Uniform** threshold distribution at approx. **2 ke⁻ threshold before and after irradiation**
  - Ca. 40% increase in ENC per irradiation step of 1e15 neq/cm² fluence
  - Expected charge MPV of MIP at full depletion ~6 ke⁻

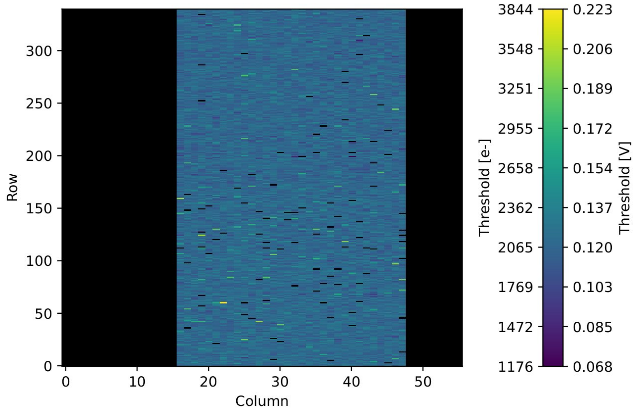
Threshold distribution



ENC distribution



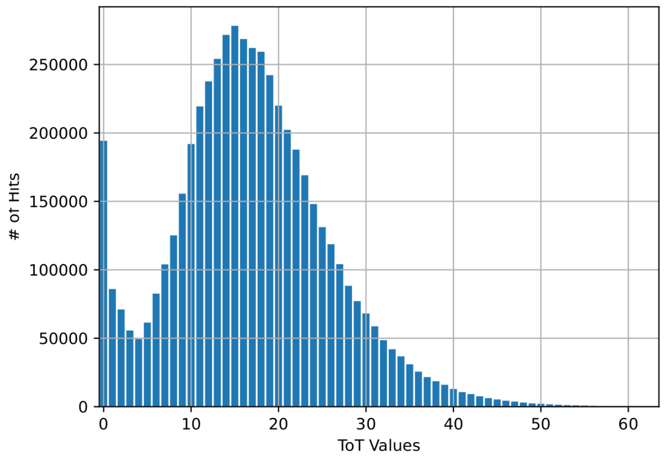
Threshold map



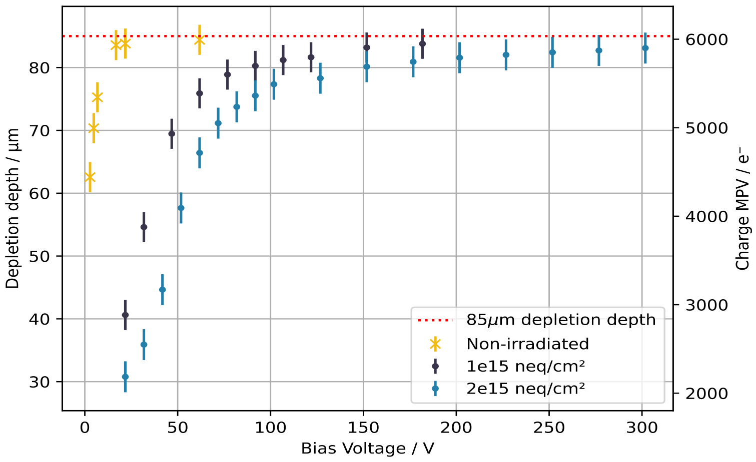
Depletion Depth of LF-Monopix2

- Get calibrated charge MPV from Landau shaped beam spectrum (**5 GeV electrons at DESY**)
- Able to fully deplete sensor after irradiation to 2e15 neq/cm²
  - *Full depletion* voltage increases from ca. 15 V to >150 V

ToT beam spectrum



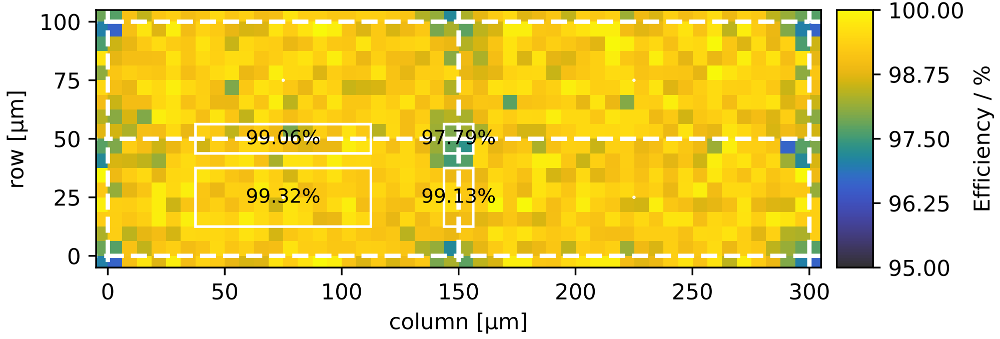
Calibrated charge MPVs



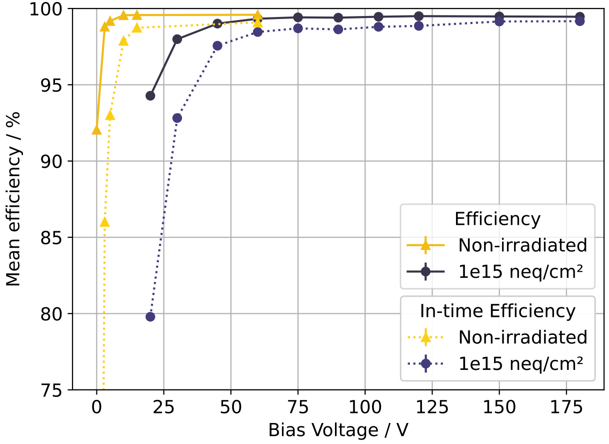
Hit Detection Efficiency Studies

- **Hit detection within 25 ns window >99% after 1e15 neq/cm²**
  - Measured at 2 ke⁻ threshold and 150 V bias
- Small drop to 97.79% in pixel corners
  - Longest drift path and charge sharing

In-pixel, in-time efficiency
(mean 99.15% @ 1e15 neq/cm²)



Efficiency vs bias voltage

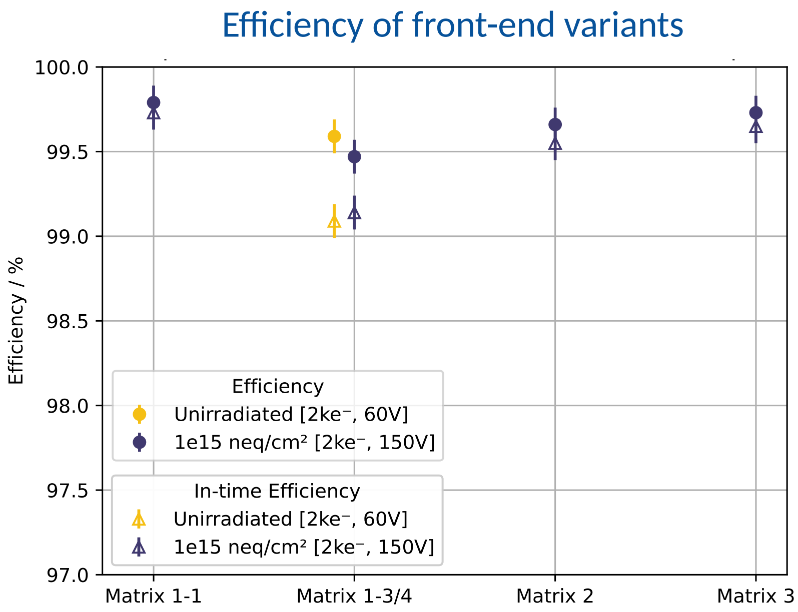


Hit Detection Efficiency Studies

- **Hit detection and in-time efficiencies >99%** for all matrices **after irradiation** to 1e15 neq/cm²
  - Measured at **2 ke⁻ threshold** and 150 V bias voltage (**full depletion**)
  - Increase in in-time ratio for larger gain front-end variants

- Result **before irradiation** as reference
  - Similar threshold of ~2 ke⁻
  - 60 V bias voltage (full depletion)

→ No significant efficiency loss after irradiation to 1e15 neq/cm²



Conclusion and Outlook

- Successful lab tests with **TJ-Monopix2** verify lower threshold and ENC than predecessor
  - **Efficiencies >99% across (available) modifications and substrate types**
  - 99.68% of events registered within 25 ns time window
- **LF-Monopix2** fully functional and efficient after **irradiation to 1e15 neq/cm² fluence**
  - **>99%** hit detection (and in-time) **efficient for all front-end variations**
  - 2e15 neq/cm² irradiated sensors show promising results

Outlook:

- Studies with neutron irradiated samples
- TID irradiation campaign planned for early 2024
- Development of new DMAPS based on TJ-Monopix2 for **Belle II** VXD upgrade (**VTX** collaboration)
  - *Upcoming talk by M. Babeluk*

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.