VERTEX 2023, SESTRI LEVANTE

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

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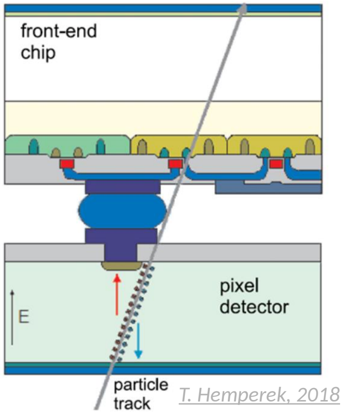
Depleted Monolithic Active Pixel Sensor

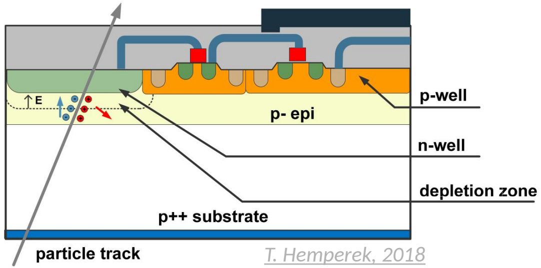
Hybrid detector



✔ Optimized individual parts
✔ High rad. tolerance

✗ Cost and labor intensive bump-bonding

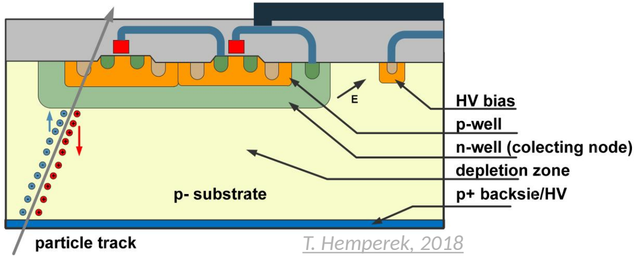
MAPS detector



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

✗ Sensor not fully depleted
- Not radiation hard

Depleted MAPS detector



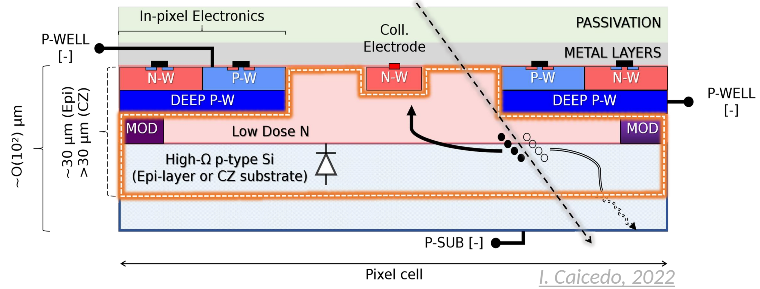
- CMOS processes offer high-resistivity substrate
- Bias voltage capabilities (HV)

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

Collection Electrode Design Approaches

Small collection electrode:

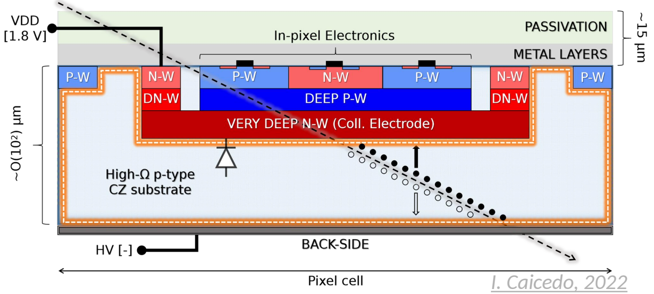
- Electronics **outside** charge collection well
- **Small sensor capacitance** (<5 fF)
  - Low analog power budget (noise, speed)
  - Less prone to cross-talk
- Longer drift distances
- Potentially regions with low E-field
  - **Need modifications** for radiation hardness



I. Caicedo, 2022

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**



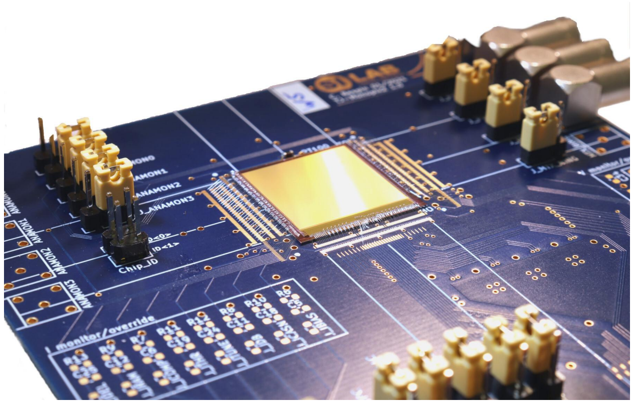
I. Caicedo, 2022

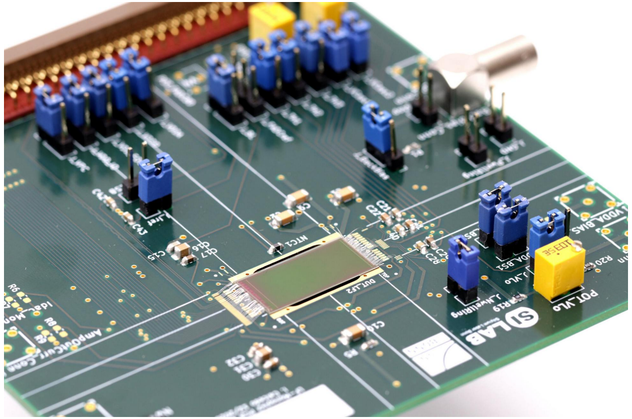
Latest Monopix Prototypes

TJ-Monopix2:
- 180 nm TowerSemi CMOS technology
- **Small** collection electrode
- ~2x2 cm^2 matrix with **33x33 μm^2** pixel pitch
- Substrate resistivity >1 kΩcm

LF-Monopix2:
- 150 nm LFoundry CMOS technology
- **Large** collection electrode
- ~2x1 cm^2 matrix with **50x150 μm^2** pixel pitch
- Substrate resistivity > 2 kΩcm

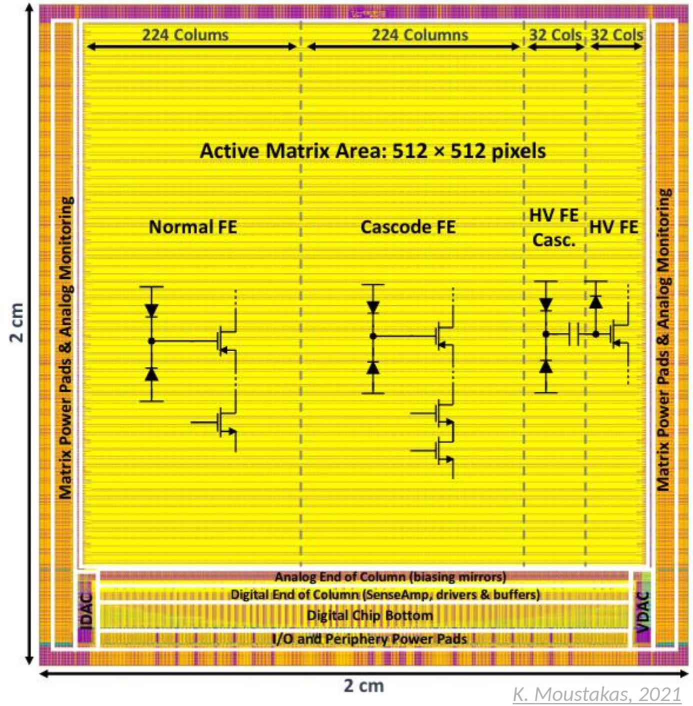
Same fast **column drain readout** architecture (FEI-3 like)





TJ-Monopix2 Specifications

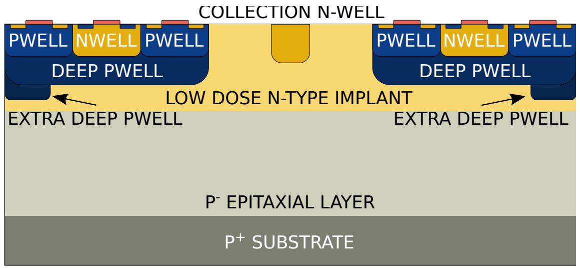
- Improved front-end to **lower noise and threshold**
  - **TJ-Monopix1** ~350 e- THR and ~16 e⁻ noise
    - Observed RTS noise tail
- **7 bit ToT** information @ 25 ns
- **3 bit in-pixel threshold tuning**
  - More in-pixel logic at smaller pixel size
- **Triggerless** readout
- 4 front-end variations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

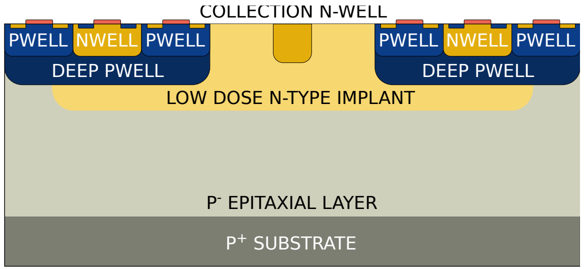


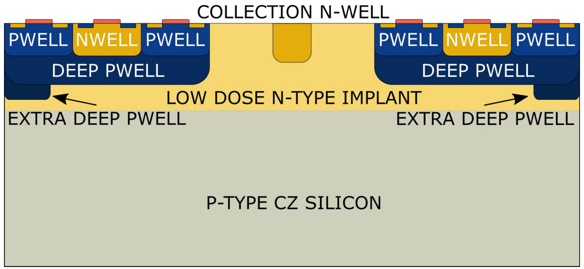
K. Moustakas, 2021

TJ-Monopix2 Modifications

- For TJ-Monopix1 *[DOI 10.1088/1748-0221/14/06/C06006]*
  - Observed **efficiency loss** to ~70% after irradiation (1e15 neq/cm^2) **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



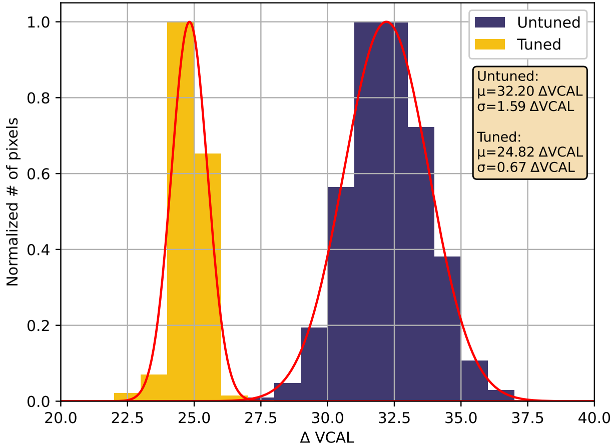




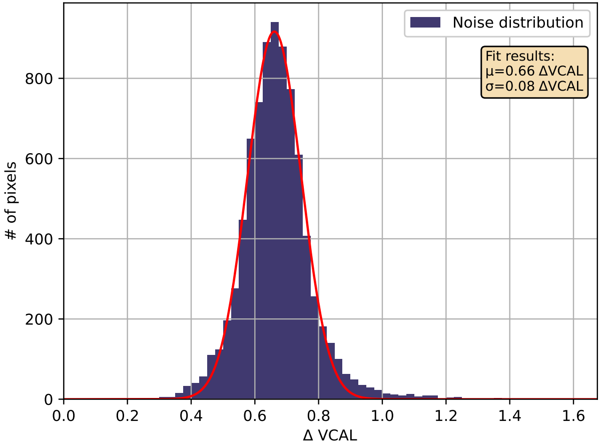
Laboratory Measurements

- 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** *(see also upcoming talk by G. Gustavino)*

Normalized threshold distribution



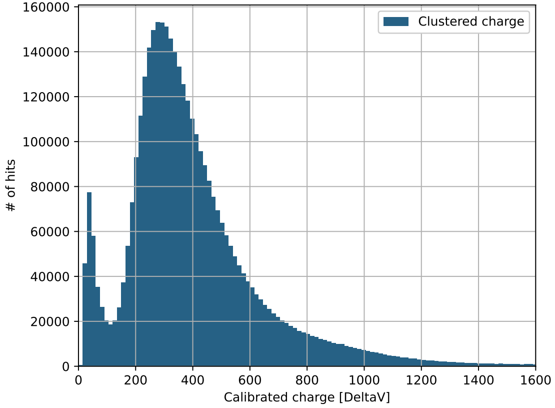
ENC distribution



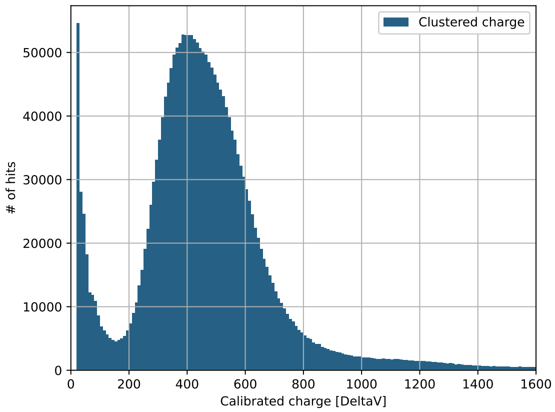
Beam Tests: Cluster Charge

- Measured **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

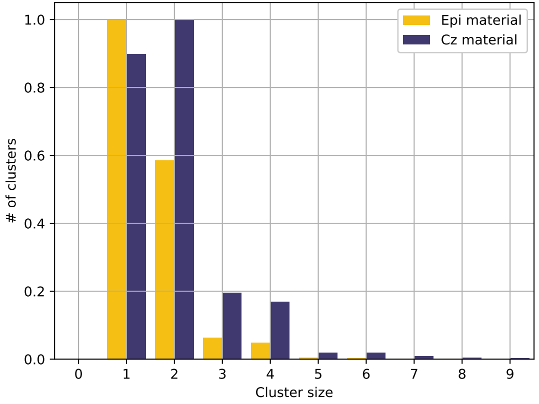
30 µm Epi: ~2700 e⁻ MPV



100 µm Cz: ~3600 e⁻ MPV



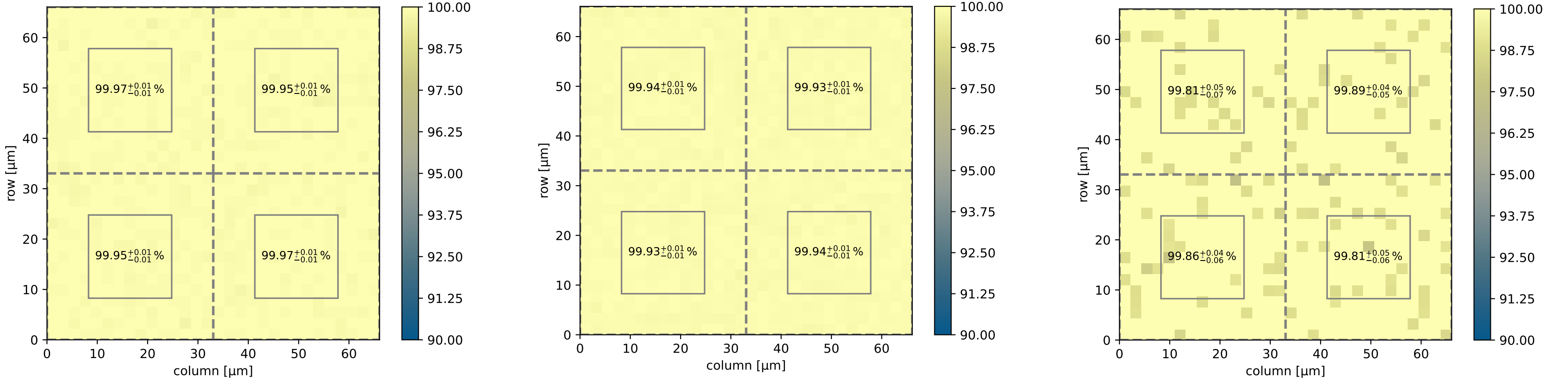
Normalized cluster size distribution



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 n-well (right)
  - **Uniform** hit detection **efficiency >99% with no losses in pixel edges**
  - Agreement between different modification types

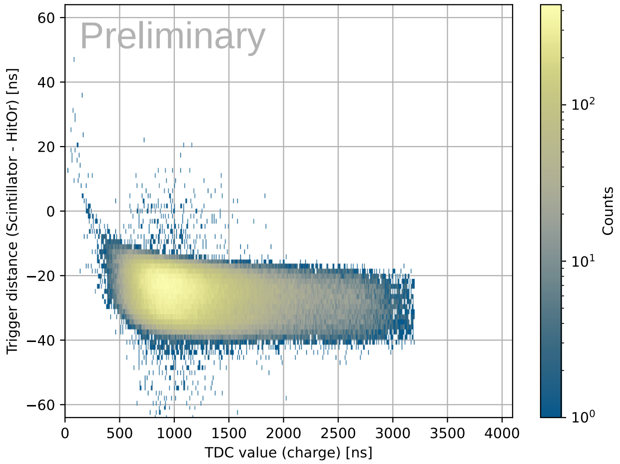
Standard FE: 99.96% **Cascode** FE: 99.94% **HV Cascode** FE: 99.85%



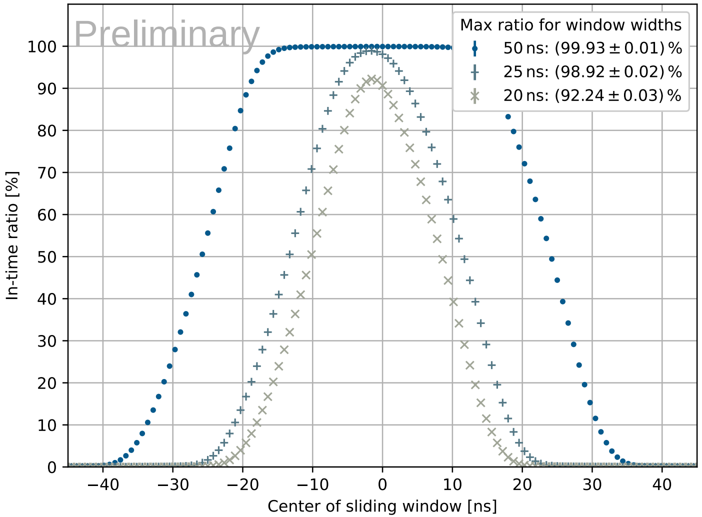
Timing Studies

- 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 **Epi** material with **n-gap** modification and **standard front-end**:
  - **98.92% within 25 ns** (ATLAS BX frequency)

Corrected scintillator-HitOr delay

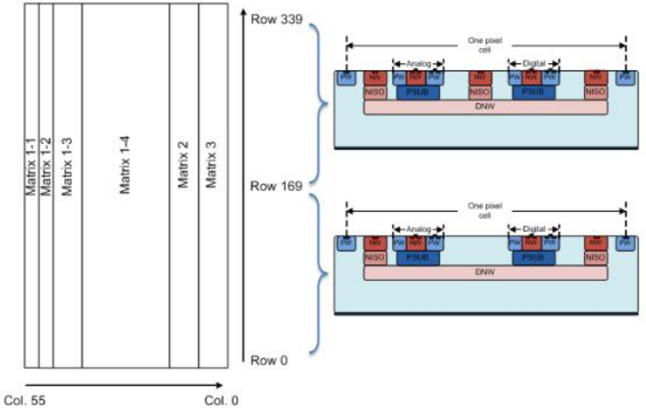


In-time ratio

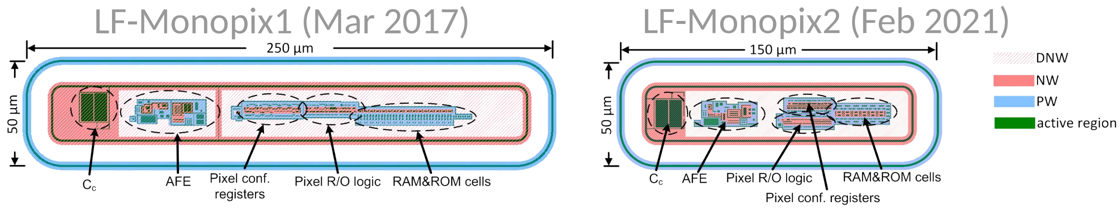


LF-Monopix2 Specifications

- Improved pixel layout to mitigate cross-talk
- 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



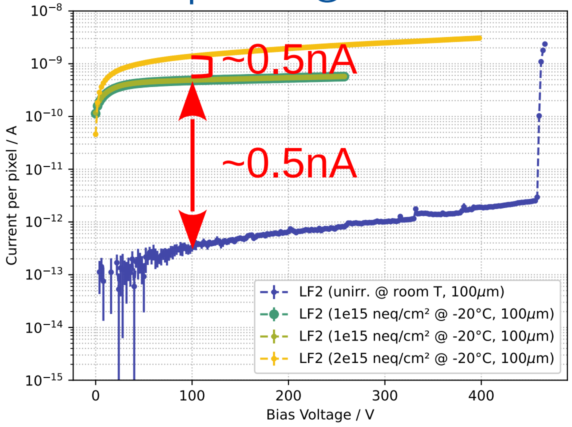
Matrix	Column	CSA	Feedback cap.	Discriminator	Logic
1-1	55 - 52	V1	1.5 fF	Bidirectional tuning	Falling
1-2	51 - 48	V1	5 fF	Bidirectional tuning	Falling
1-3	47 - 40	V1	5 fF	unidirectional tuning	Rising
1-4	39 - 16	V1	5 fF	unidirectional tuning	Falling
2	15 - 8	V2	1.5 fF	Bidirectional tuning	Falling
3	7 - 0	V3	1.5 fF	Bidirectional tuning	Falling



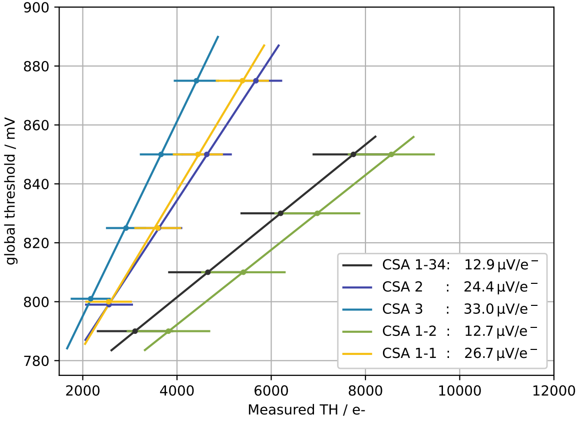
Leakage Current and Gain

- Measure **leakage current per pixel** at -20 °C environmental temperature
  - Breakdown at ~460 V for unirradiated modules
- **Increase** in leakage current **per pixel ~0.5 nA** per 1e15 neq/cm² irradiation step
- 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



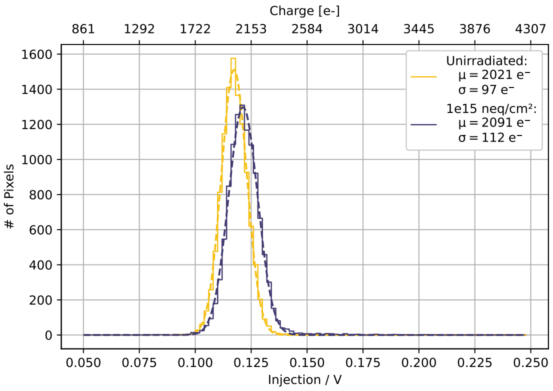
Gain **after** irradiation (1e15)



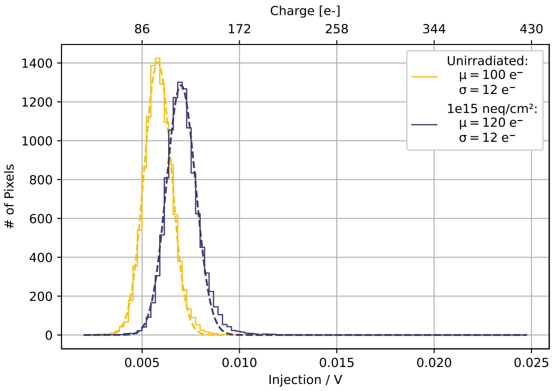
Laboratory Tests

- Irradiated chip operated at -20°C, unirradiated at room temperature
- **Uniform** threshold distribution at approx. **2 ke$^-$ threshold before and after irradiation**
  - 20% increase in ENC after irradiation
  - Expected charge MPV of MIP at full depletion ~6 ke$^-$

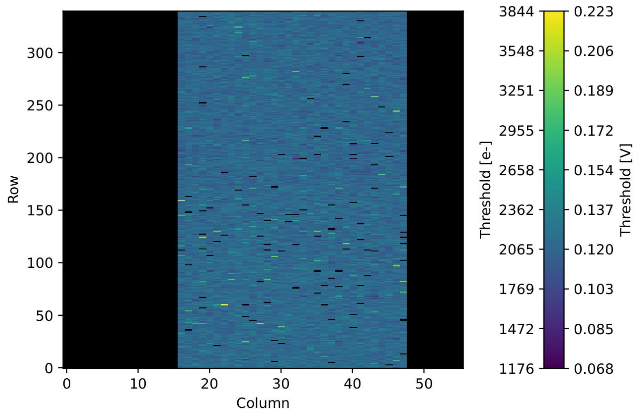
Threshold distribution



ENC distribution



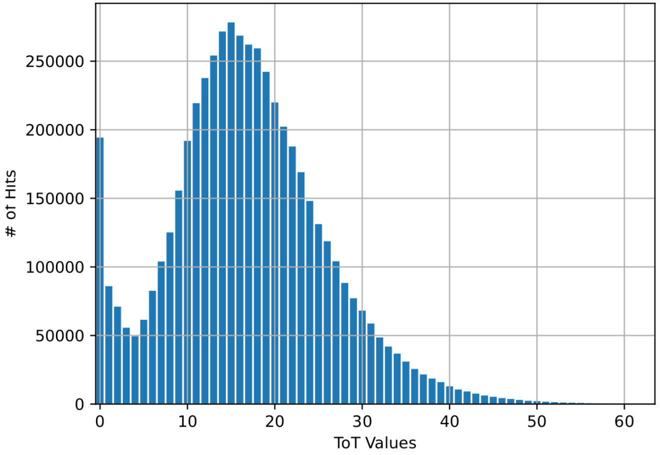
Threshold map



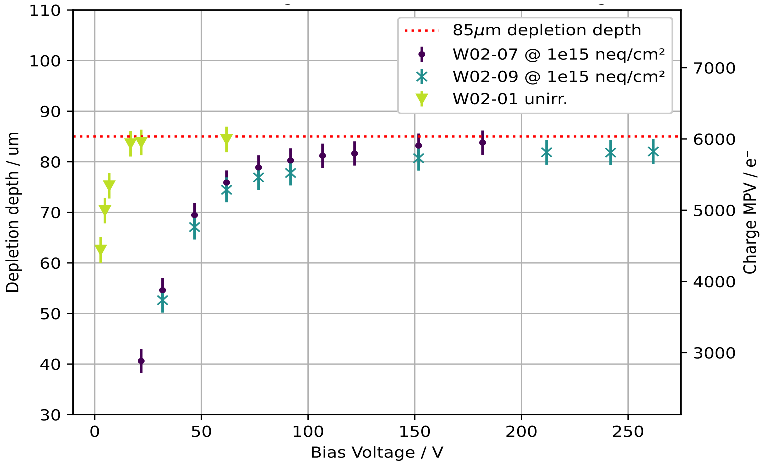
Depletion Depth of LF-Monopix2

- Get calibrated charge MPV from Landau shaped beam spectrum (**5 GeV electrons at DESY**)
- Necessary voltage for full depletion increases from ~15 V before to >100 V after irradiation to 1e15 neq/cm²
  - Depletion depth profiles after irradiation in good agreement

ToT beam spectrum



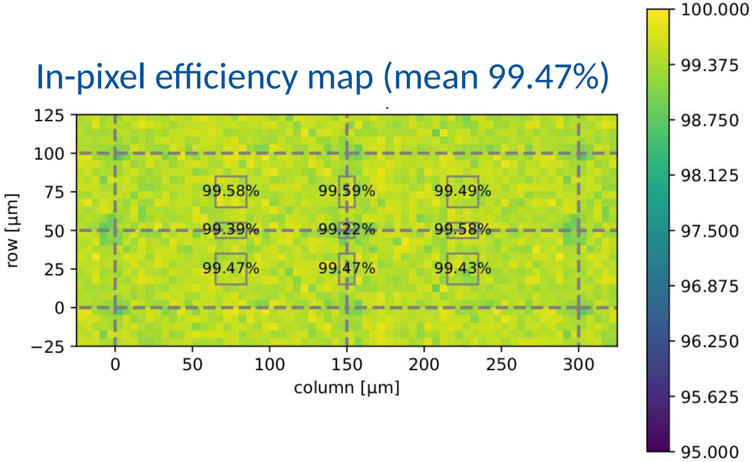
Calibrated charge MPVs



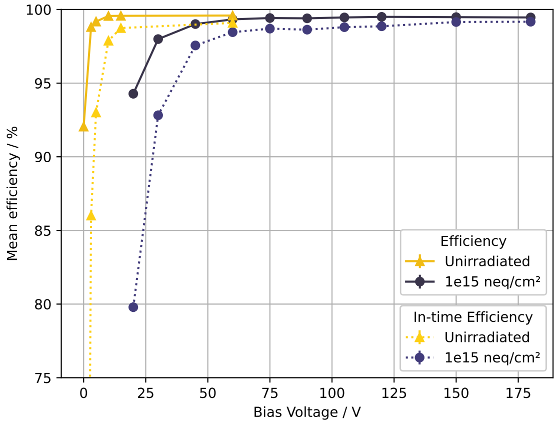
Hit Detection Efficiency Studies

- **Uniform** hit detection **efficiency across matrix**
  - **1e15 neq/cm²** irradiated chip measured at **2 ke⁻ threshold and 150 V bias**
- No charge loss in pixel corners or other patterns
- Verified decrease in efficiency for lower bias voltages

In-pixel efficiency map (mean 99.47%)



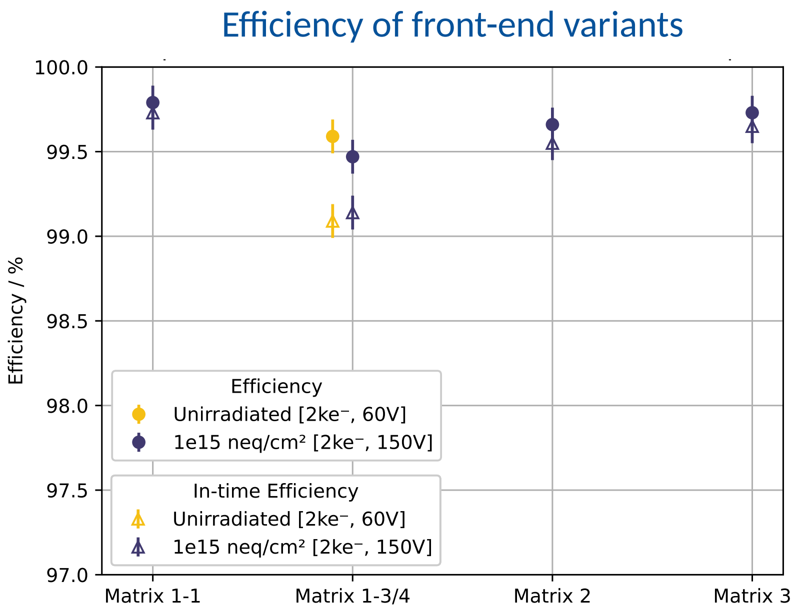
Efficiency vs bias voltage



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**
  - 98.92% of events registered within 25 ns
- **LF-Monopix2** fully functional and efficient after **irradiation to 1e15 neq/cm²**
  - **>99%** hit detection (and in-time) **efficient for all front-end variations**
  - 2e15 neq/cm² irradiated sensors still under investigation

Outlook:

- Upcoming testbeam campaign next week at DESY with irradiated devices
- TID irradiation campaign planned for early 2024
- Development of new DMAPS based on TJ-Monopix2 for **Belle II** VXD upgrade (**VTX** collaboration)
  - *Previous talk by D. Xu*

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)

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