CMOS VERBUND MEETING

THE MONOPIX2 CHIPS

Lars Schall on behalf of the Monopix design- and testing-teams

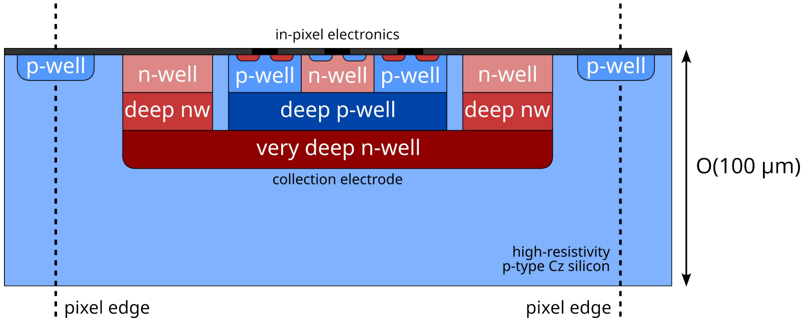
UNIVERSITÄT BONN

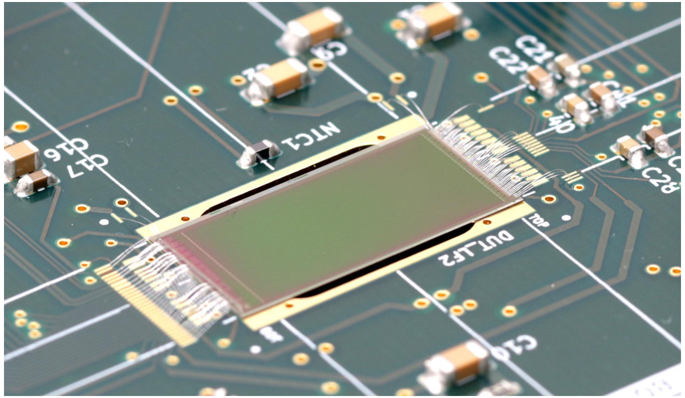
LF-Monopix Development Line

- Large collection electrode design:
  - Large sensor capacitance O(100 fF)
  - Short drift distance
  - Uniform electric field across pixel area

→ Radiation hard

- 150 nm LFoundry CMOS technology
- Substrate resistivity >2 kΩcm
- Latest DMAPS **LF-Monopix2**:
  - Large scale 1x2 cm^2 chip with 150x50 μm^2 pixel pitch
  - 6-bit ToT information, 4-bit in-pixel threshold tuning
  - Fast column drain readout architecture (FE-I3 like)





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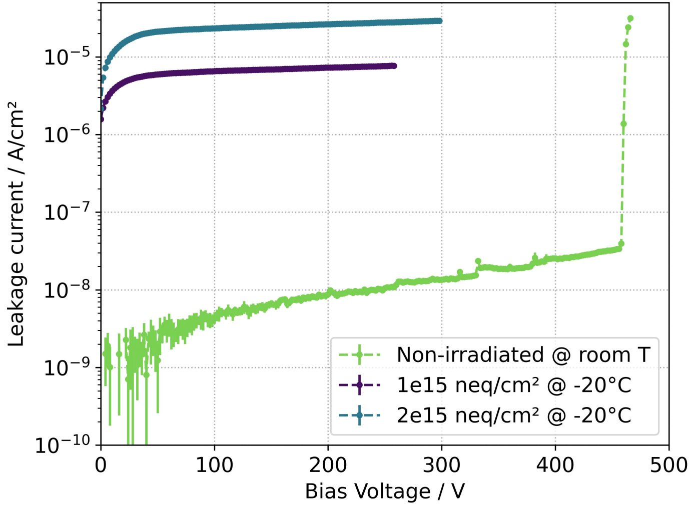
Studies with Irradiated LF-Monopix2

- NIEL Irradiated samples (100 µm thickness, backside processed) available:
  - Proton irradiated: 1 x 10^{15}, 2 x 10^{15} neq/cm² – (Bonn and Birmingham irradiation sites)
  - Neutron irradiated: 5 x 10^{14}, 1 x 10^{15}, 2 x 10^{15} neq/cm² – (Ljubljana irradiation site, tests ongoing)
  - All samples are annealed (80 min @ 60 °C)
- Breakdown voltage around 460 V before irradiation
  - No breakdown up to 300 V after irradiation
    - Sufficient for full depletion after irradiation
  - Facilitates high radiation tolerance
  - Increase in leakage current ca. 6 µA/cm² per 1 x 10^{15} neq/cm² irradiation step (@ 100 V)

I-V characteristics



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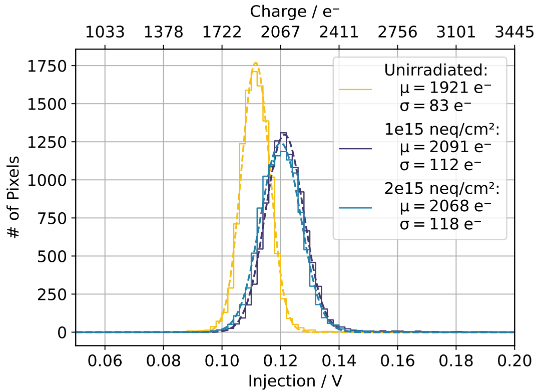
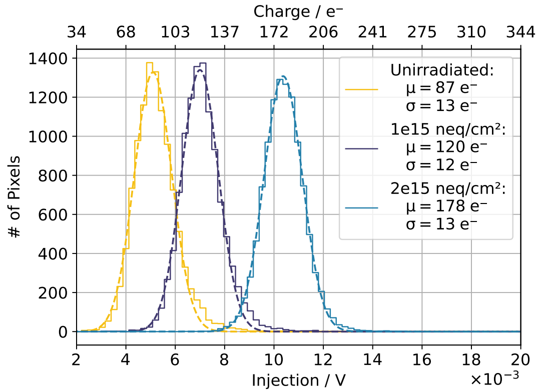
Laboratory Characterization

- Operated in controlled laboratory environment @ -20 °C
- Typical operational threshold of around 2.0 ± 0.1 ke$^-$
  - Still achievable at highest available NIEL fluence
  - Charge MPV of MIPs at full depletion roughly 6 ke$^-$ (for 100 µm thickness)
- ENC more than doubles after 2 x 10^{15} neq/cm^2 proton irradiation

Threshold distribution



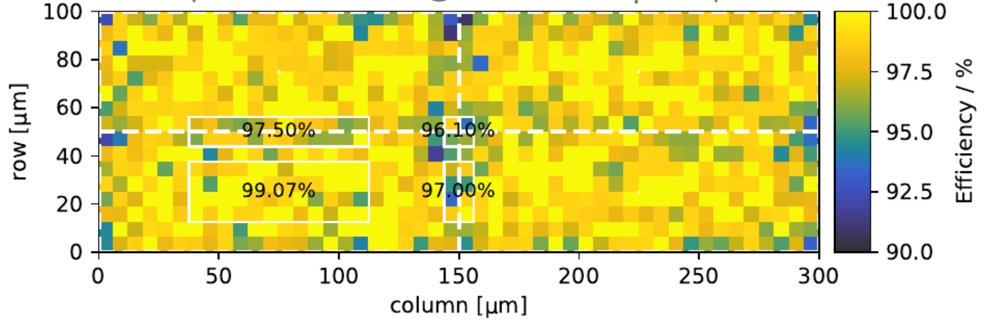
ENC distribution



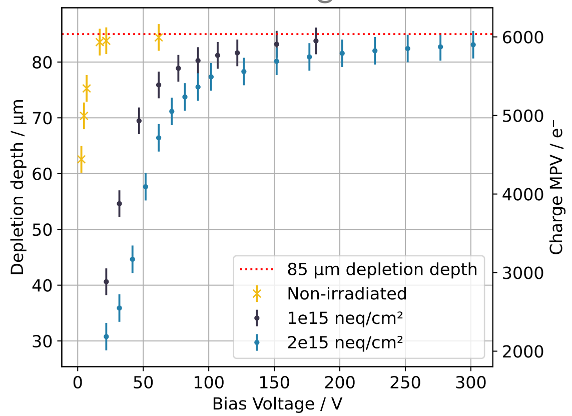
Beam Tests at DESY

- Get calibrated charge MPV from Landau shaped beam spectrum
  - Reach full depletion after 2 x 10^{15} neq/cm² fluence
  - Required voltage increases from 15 V to >150 V
- Very high hit detection efficiency >99 % achievable for all fluences
- >98 % mean in-time efficiency (25 ns) at highest fluence

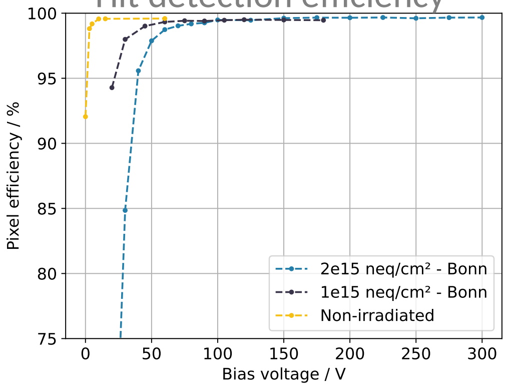
In-time, in-pixel efficiency
(mean 98.35 % @ 2 x 10^{15} neq/cm²)



Calibrated charge MPVs



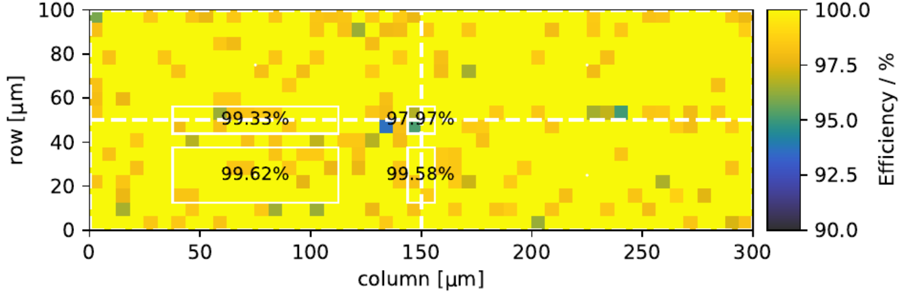
Hit detection efficiency



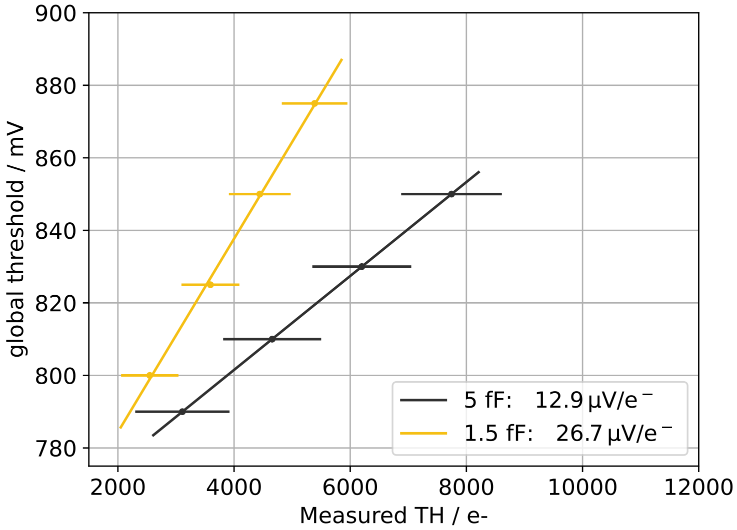
In-time Efficiency for Higher Gain

- Pixels with smaller feedback capacitance implemented on the chip
  - Expected higher gain confirmed by measurement after
- Higher signal gain improves timing performance
  - Mean in-time efficiency of 99.6%
  - Ca. 0.5% pixels masked

In-time efficiency for large gain pixels
(mean 99.60 % @ 2 x 10^{15} neq/cm²)



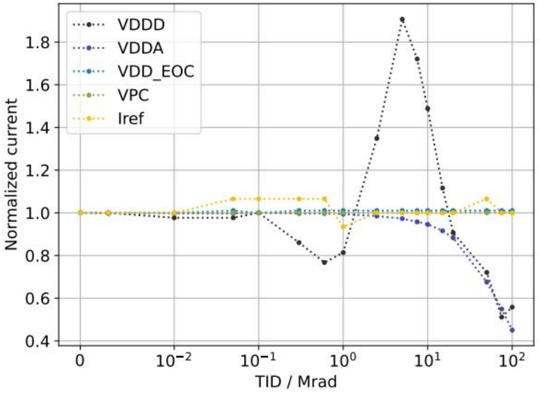
Measured gain @ 1e15 neq/cm²



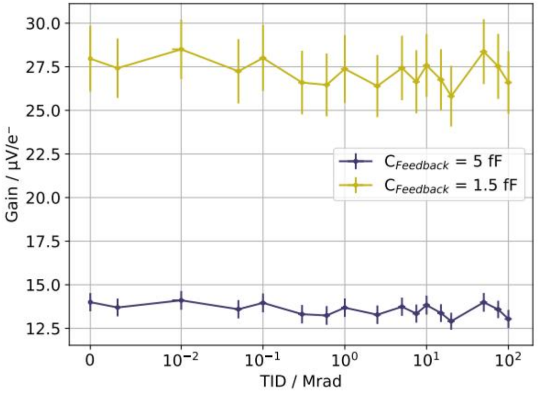
LF-Monopix2: TID Irradiation

- Irradiated up to 100 Mrad total ionizing dose, fully responsive throughout the entire campaign
  - Expected peak in VDDD current around 1 – 10 Mrad, drop in VDDA current towards high doses
  - No change or drop in gain observable throughout irradiation
- Typical operational threshold and threshold dispersion reachable after 100 Mrad and annealing

Power consumption vs TID



Gain vs TID



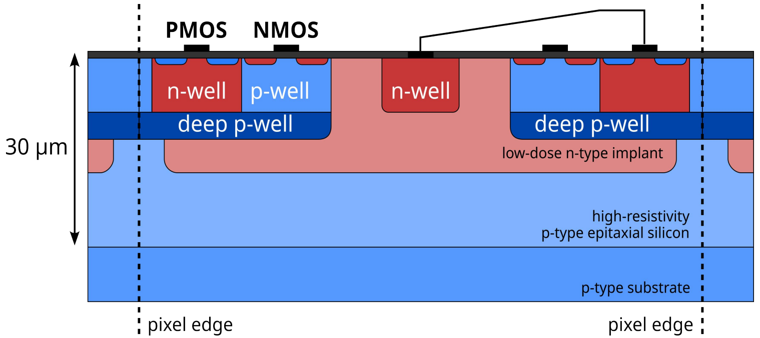
TID Fluence [Mrad]	Threshold [e^-]	Threshold Disp. [e^-]	ENC [e^-]
0	2055	91	92
100	1983	108	122

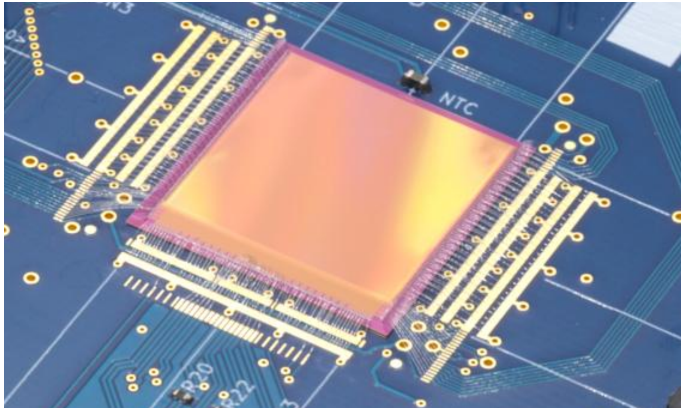
TJ-Monopix Development Line

- Small collection electrode design:
  - Small sensor capacitance (<5 fF)
  - Longer drift distances
  - Potentially regions with low electric field

→ Low power and low noise operation

- 180 nm TowerSemi CMOS technology
- Substrate resistivity >1 kΩcm
- Latest DMAPS **TJ-Monopix2**:
  - Large scale 2x2 cm^2 chip with 33x33 μm^2 pixel pitch
  - 7-bit ToT information, 3-bit in-pixel threshold tuning
  - Fast column drain readout architecture (FE-I3 like)

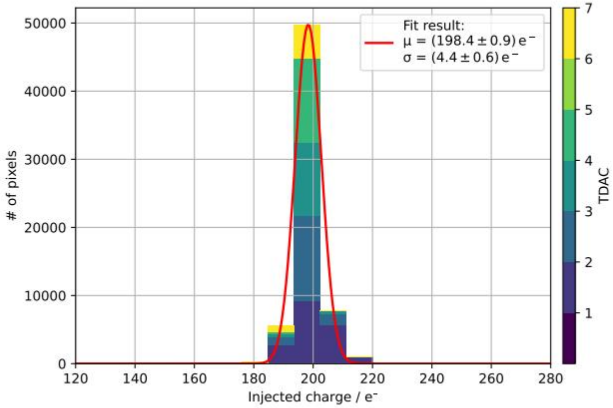




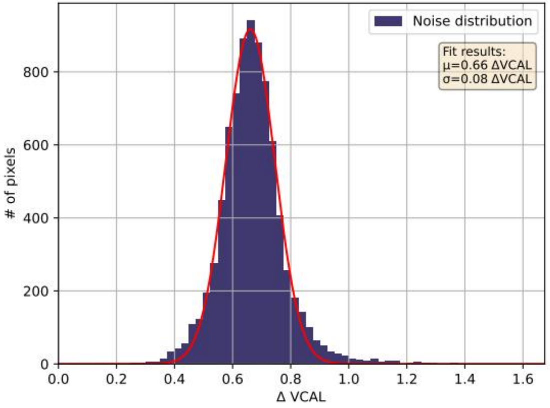
Laboratory Tests

- Typical operating conditions around 200 - 250 e^- threshold and 6 e^- ENC
  - Sufficient for excellent hit-detection efficiency (MIP charge MPV >2500 e^-)
- Measure FE timing response with analog charge injection, no sensor dependent contribution
  - Front-end <100 ps time resolution for MIP charge regime

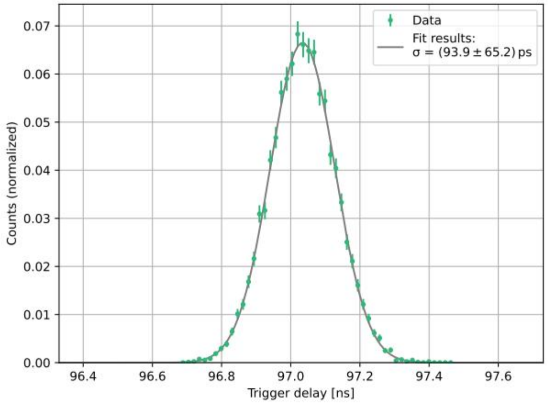
Normalized threshold distribution



ENC distribution



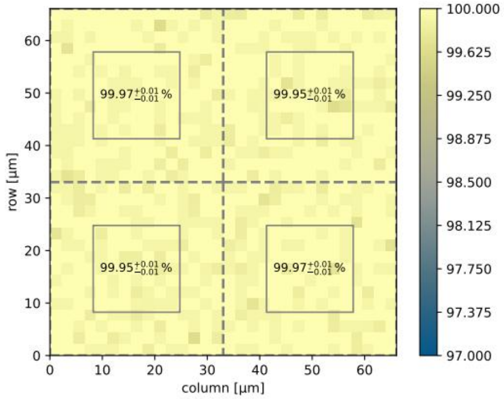
Time resolution of front-end only



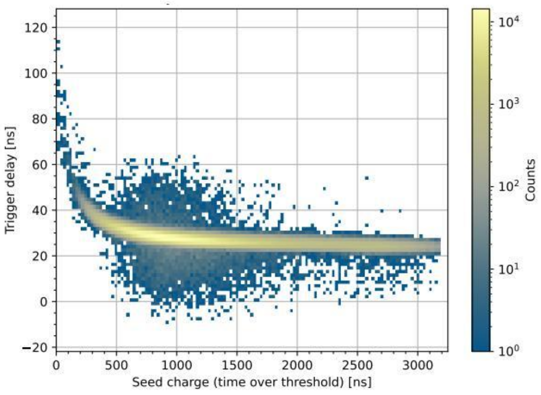
Beam Tests

- Very uniform hit-detection efficiency >99.9 % before irradiation
- 99.68 % of hits within a 25 ns window, still 99 % within 10 ns window
- Achievable spatial resolution <9 µm with charge weighted clustering

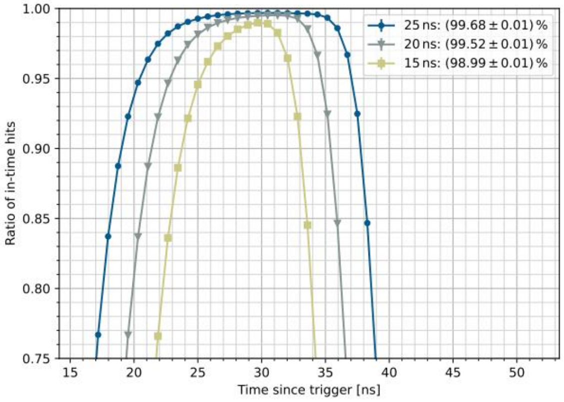
Hit-detection efficiency
(mean 99.96 %)



Corrected scintillator-HitOr delay



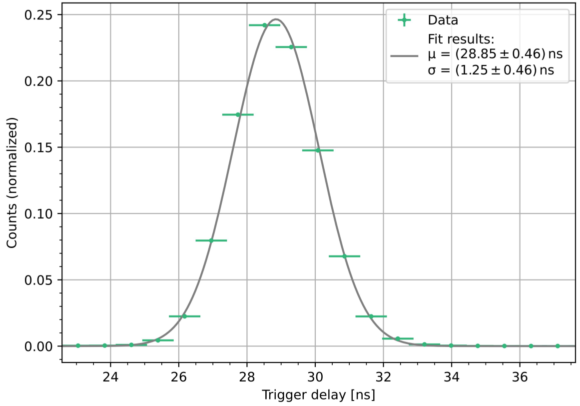
In-time ration of detected hits



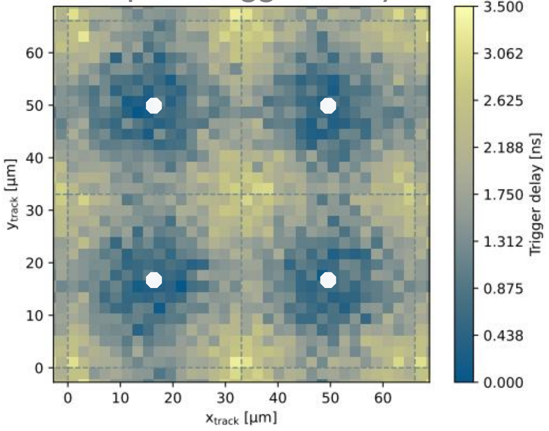
Timing in Beam

- Correct time walk based on amplitude offline
  - Total time resolution 1 – 2 ns (depending on FE variant and chip)
  - Uncertainty limited by available TDC module (640 MHz)
  - Started development of high-resolution TDC (<100 ps binning) module in FPGA
- Study 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

Total time resolution



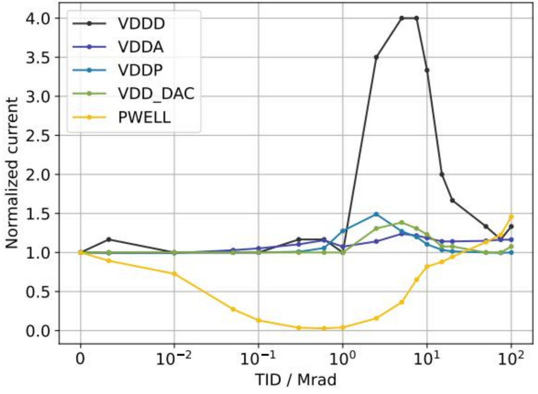
In-pixel trigger delay



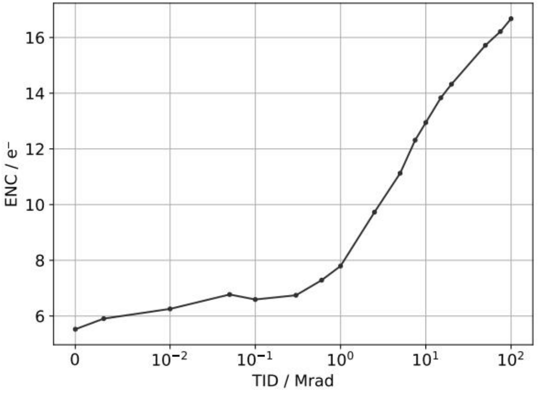
TID Irradiation

- Irradiated up to 100 Mrad total ionizing dose, fully responsive throughout the entire campaign
  - Peak in current around 1 – 10 Mrad, highest relative increase for VDDD
  - Periphery biggest absolute contributor to power consumption
  - Still <20 e^- ENC after 100 Mrad before annealing
- Typical operational threshold still reachable after 100 Mrad and annealing

Power consumption vs total dose



ENC vs total dose



TID Fluence [Mrad]	Threshold [e^-]	Threshold Disp. [e^-]	ENC [e^-]
0	230	5	6
100	245	5	13

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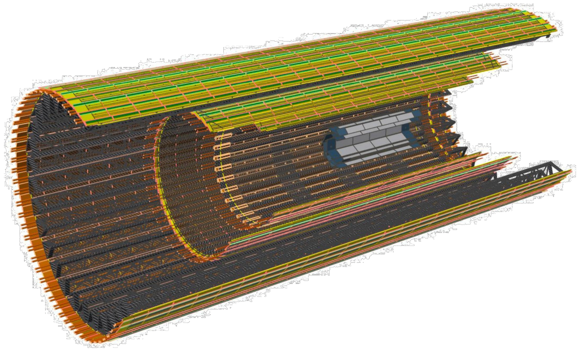
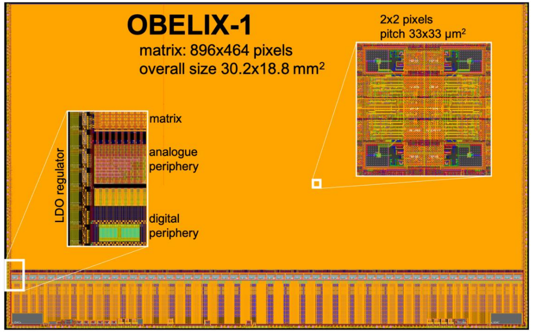
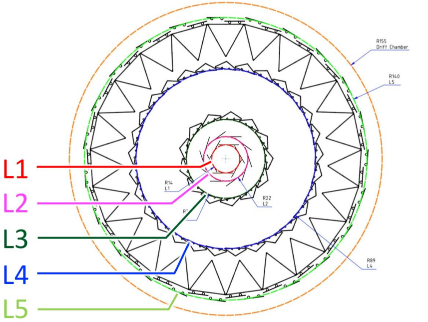
Perspective of TJ-Monopix2

- Belle II vertexing detector (VTX) upgrade planned for LS2 (2028)
- 5 layer all silicon with identical DMAPS across all layers
  - L1 & L2: Air cooled all silicon ladders
  - L3 to L5: Carbon fiber support structure with liquid cooling
- New DMAPS based on TJ-Monopix2: **O**ptimized **BEL**le II p**IX**el sensor
  - Matrix inherited completely
  - LDO regulators designed by FH Dortmund
  - OBELIX-1 to be submitted Fall 2024







Conclusion & Outlook

LF-Monopix2:

- Excellent radiation hardness without significant performance degradation up to 2 x 10^{15} neq/cm^2 NIEL fluence and 100 Mrad TID
  - Further irradiation up to 5 x10^{15} neq/cm^2 NIEL fluence and >100 Mrad TID planned

TJ-Monopix2:

- Very low noise and low threshold operation with excellent spatial resolution
- >99 % hit-detection efficiency and very high in-time ratio >99 % within 25 ns
- Fully functional after 100 Mrad TID
  - Characterization of irradiated samples up to 1.5 x 10^{15} neq/cm^2 NIEL fluence ongoing

Perspectives:

- New DMAPS based on TJ-Monopix2 under development for Belle II VTX upgrade proposal

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.

Backup

Beam Test Setup

- Beam tests at DESY (1 - 6 GeV e^- beam)
- Typical beam test setup:
  - EUDET-type beam telescope
  - Trigger-scintillator
  - Time reference plane
  - Trigger logic unit
  - DUT
- Irradiated DUTs are cooled to -20°C