1ST DRD3 WEEK

RESULTS AND PERSPECTIVES OF THE MONOPIX2 DEPLETED MONOLITHIC ACTIVE PIXEL SENSORS

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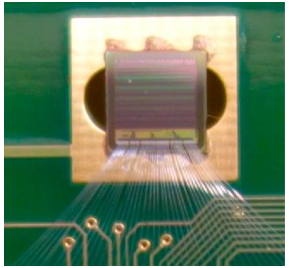
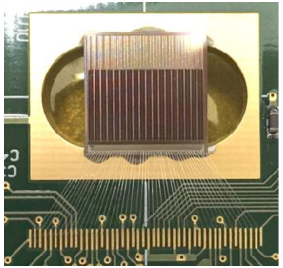
Brief Overview of Our CMOS Developments

- Started CMOS development in 2012-2013 with simple prototypes from multiple foundries
- 2016/2017: Submission of two fully monolithic large-scale designs utilizing two different technologies (LFoundry and TowerSemi) → the Monopix1 chips
  - TJ development line based on ALPIDE, in parallel to MALTA developments
  - Second iteration of both chips received in 2021
- Design and characterization were collaborative efforts driven by multiple institutes!
  - Bonn, CPPM Marseille, IRFU CEA Saclay, CERN (only TJ developments), initially also KIT

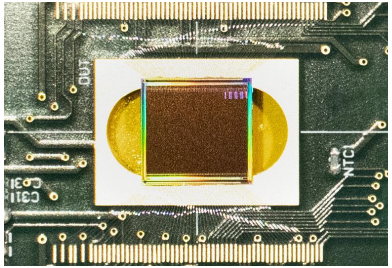
CCPD-LF (2014)



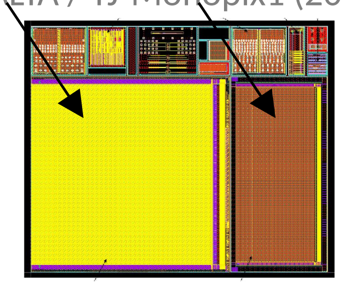
LF-CPIX (2016)



LF-Monopix1 (2017)

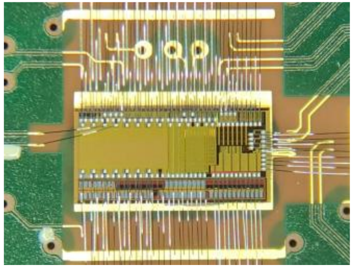


MALTA / TJ-Monopix1 (2018)



P. Freeman, 2019

miniMALTA (2018)



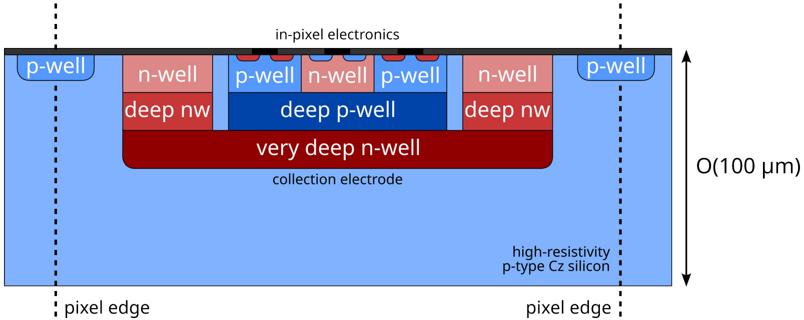
P. Freeman, 2019

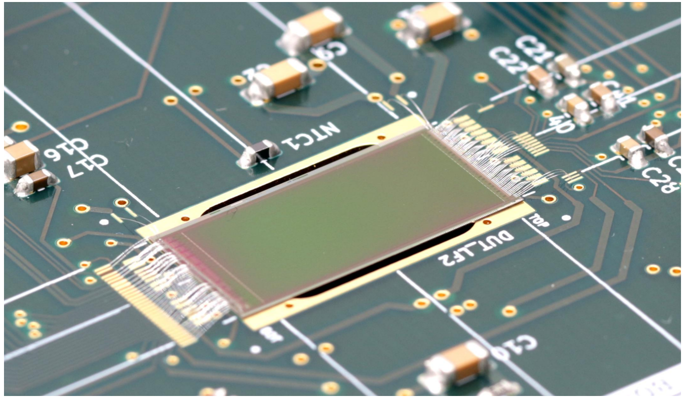
LF-Monopix Development Line

- 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)

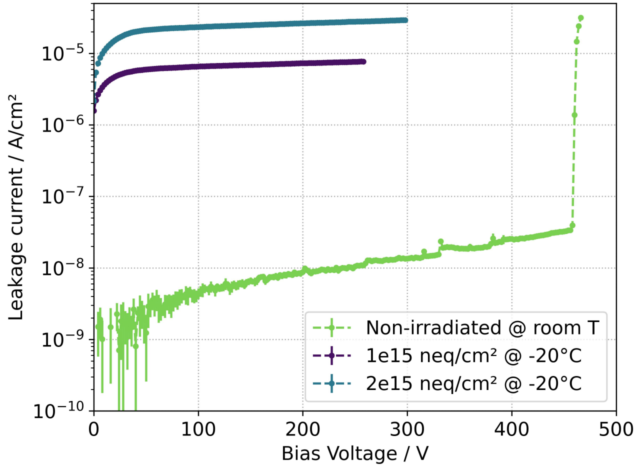




LF-Monopix2: Laboratory Test

- Breakdown voltage around 460 V before irradiation
  - No breakdown up to 300 V after irradiation
  - Facilitates high radiation tolerance
  - Increase in leakage current ca. 6 μA/cm² per 1×10^{15} neq/cm² irradiation step (@ 100 V)
- Typical operational threshold of around 2.0 ± 0.1 ke^-
  - Constant across all available fluences
  - Charge MPV of MIPs at full depletion roughly 6 ke^- (for 100 μm thickness)
- Roughly 40 % increase in ENC per irradiation step

I-V characteristics



NIEL Fluence [neq / cm²]	0	1×10^{15}	2×10^{15}
Threshold [e^-]	2040	2090	2070
ENC [e^-]	87	120	178

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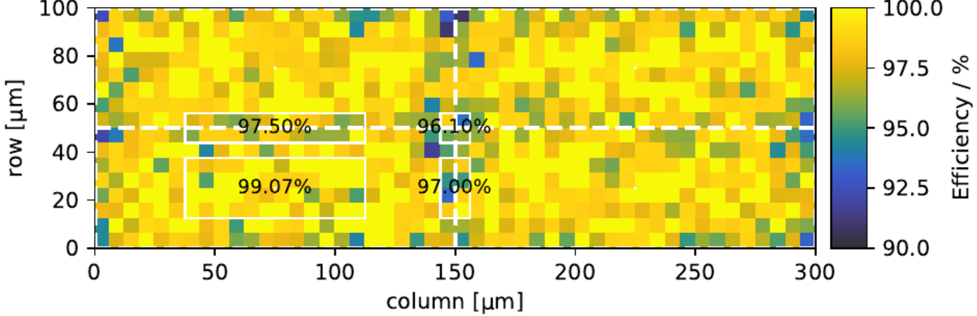
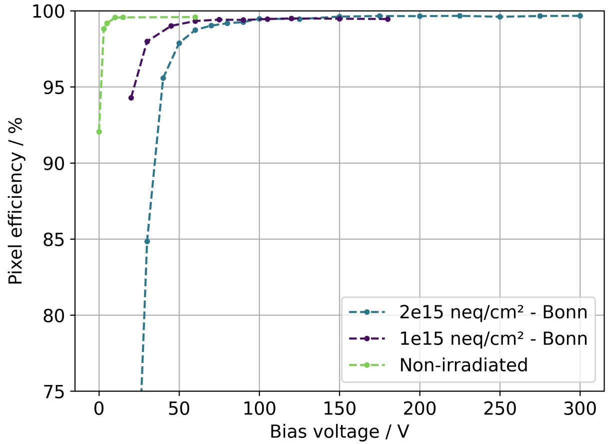
LF-Monopix2: Beam Tests

- Very high and homogeneous hit-detection efficiency >99 % for all fluences at full depletion
  - Full depletion reached around 150 V after 2 x 10^{15} neq/cm^2 of NIEL fluence
  - All samples irradiated with protons, annealed for 80 min @ 60 °C
- Mean in-time efficiency within 25 ns of >98 % after irradiation to 2 x 10^{15} neq/cm^2

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



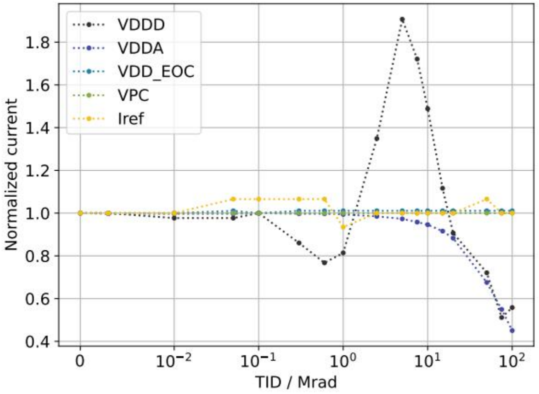
Efficiency against bias voltage



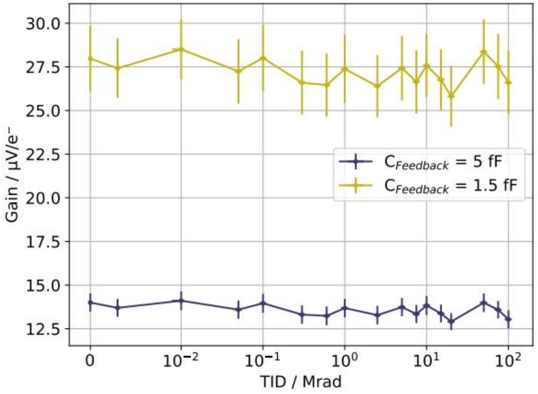
LF-Monopix2: TID Irradiation

- 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



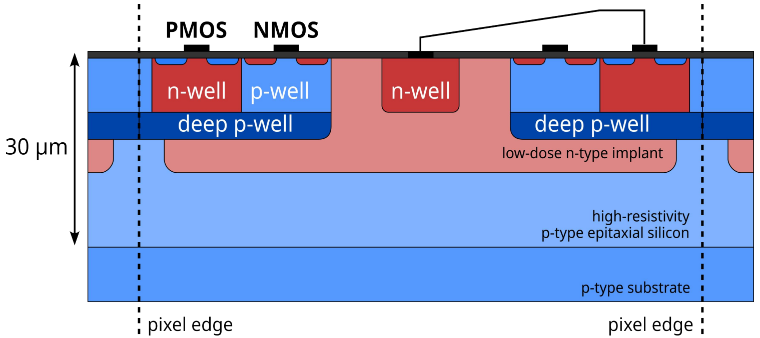
TID Fluence [Mrad]	Threshold [e⁻]	Threshold Disp. [e⁻]	ENC [e⁻]
0	2055	91	92
100	1983	108	122

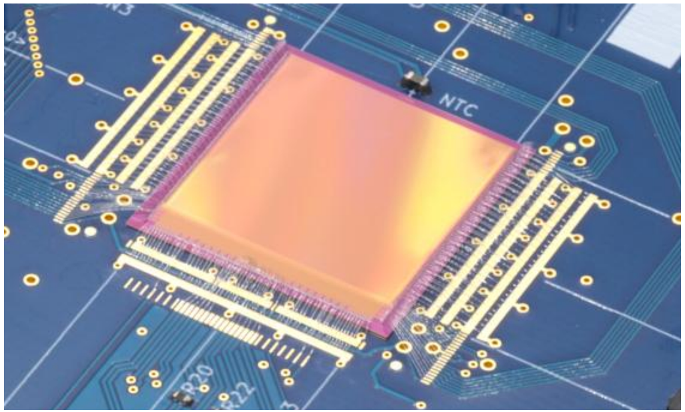
TJ-Monopix Development Line

- 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)

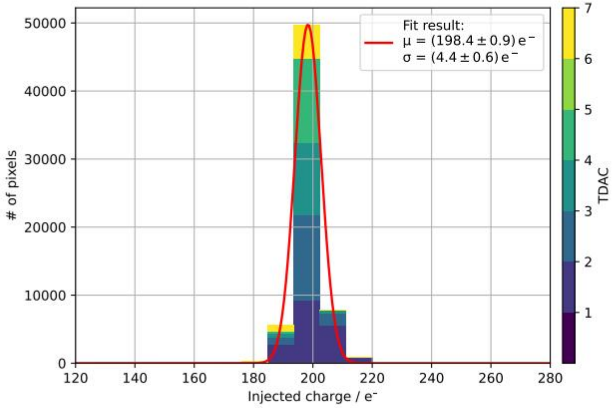




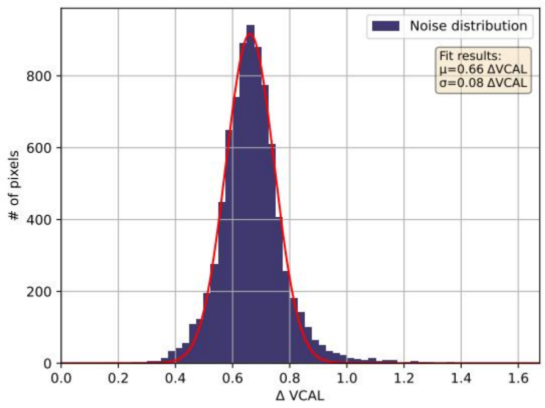
TJ-Monopix2: Laboratory Tests

- Typical operating conditions around 200 - 250 e⁻ threshold and 6 e⁻ ENC
  - Sufficient for excellent hit-detection efficiency (MIP charge MPV >2500 e⁻)
- Front-end <100 ps time resolution for MIP charge regime
  - Total time resolution including sensor contribution <1.5 ns

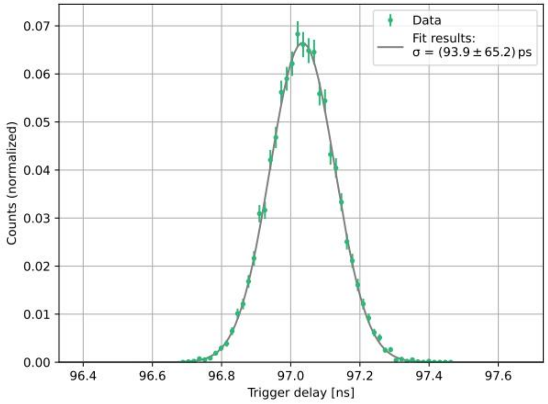
Normalized threshold distribution



ENC distribution



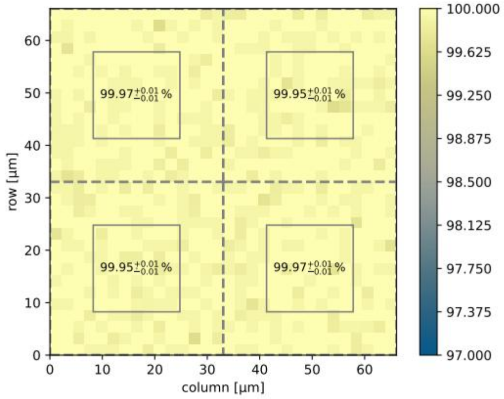
Time resolution of front-end only



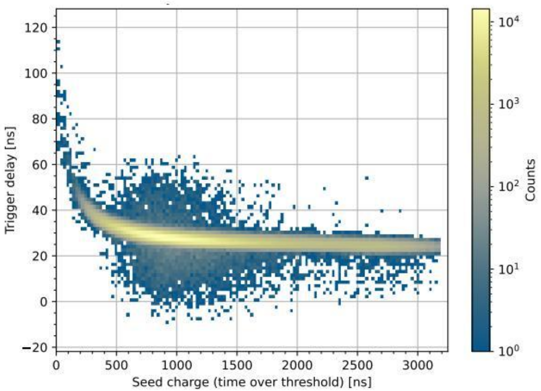
TJ-Monopix2: Beam Tests

- 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 clustering

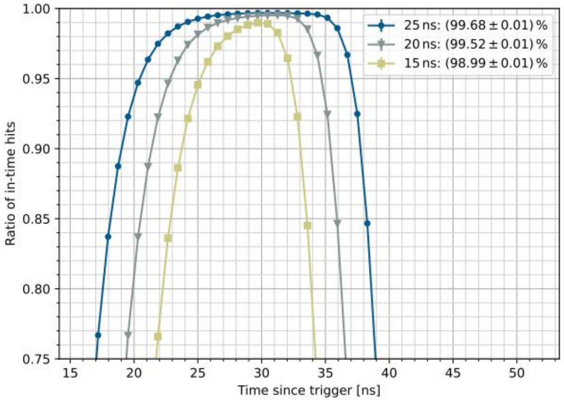
Hit-detection efficiency
(mean 99.96 %)



Corrected scintillator-HitOr delay



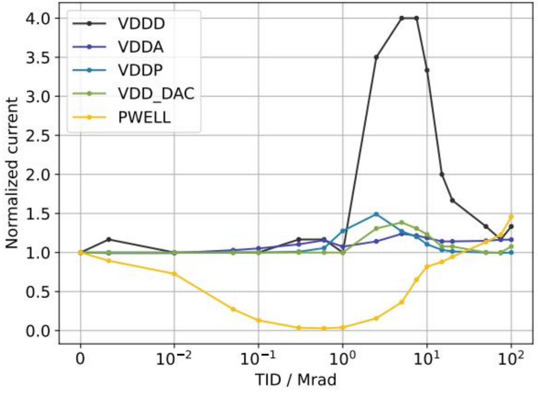
In-time ration of detected hits



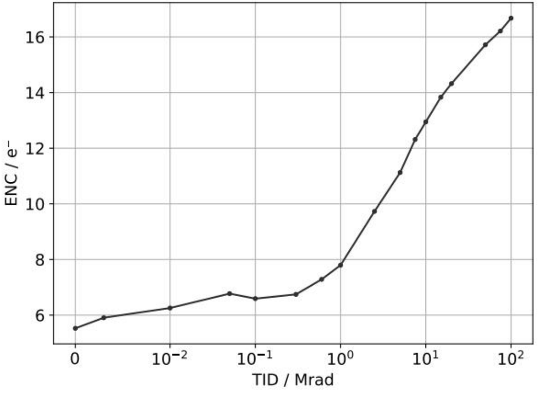
TJ-Monopix2: TID Irradiation

- 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

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 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 VXD upgrade -*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)

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Backup

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