Development and testing of a radiation-hard large electrode DMAPS design in a 150 nm CMOS process.

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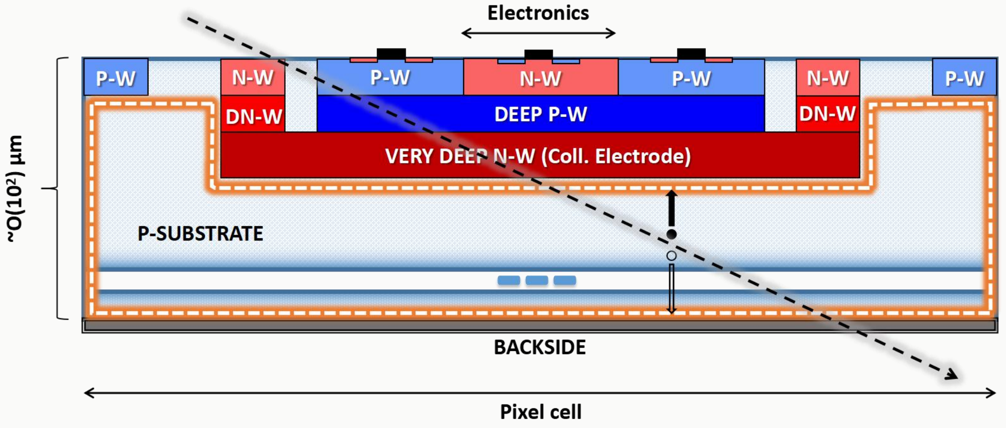
DEPLETED MONOLITHIC ACTIVE PIXEL SENSORS (DMAPS)

- Developed in commercial CMOS processes: Multiple wells to shield electronics and avoid hybridization.
  - Considerable depleted regions in highly resistive substrates: Fast charge collection by drift.

"Large Electrode" design

Large collecting well containing all the in-pixel R/O electronics

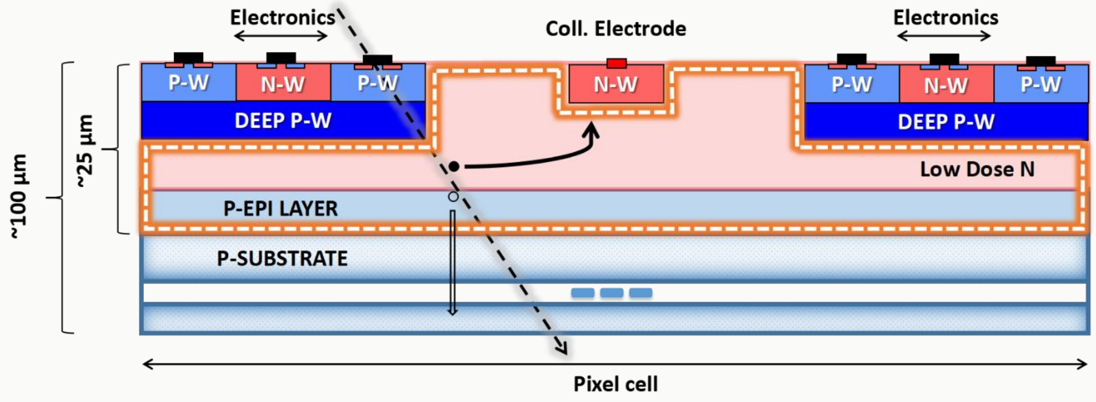


PROS: Short drift distances, strong E-field (Rad-hard).
CONS: Large sensor capacitance, high analog power.

---> Requires design efforts to optimize timing and minimize cross-coupling into the collection node.

"Small Electrode" design

Small collecting well outside the in-pixel R/O electronics



PROS: Small sensor capacitance, low power and noise.
CONS: Weak electrical field compromises rad-hardness.

---> Requires process modifications and small pixel pitch to optimize charge collection.

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DMAPS FOR HIGH ENERGY COLLIDER EXPERIMENTS

Taking the ATLAS iTK upgrade requirements as benchmark:

	ITk Outer Layer
Occupancy	1 MHz/mm²
Time Res.	25 ns
NIEL	10^{15} n_{eq}/cm^2
TID	80 Mrad
Area	O(10m²)

DMAPS would offer:

- Reduced material budget compared to hybrids.
- Cheaper and less complex module production.

The Monopix DMAPS developments

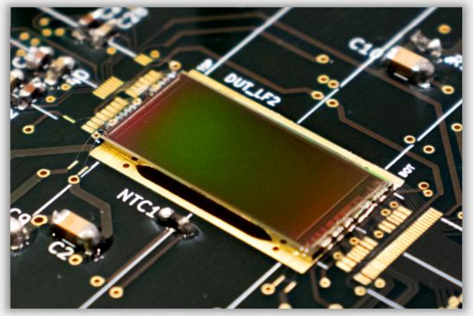
Column-Drain ("FE-I3 like") synchronous R/O architecture and fast front-end implementations

+

Design optimization to preserve charge collection after irradiation

LF-Monopix:

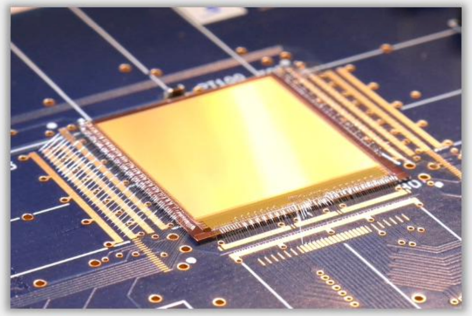
Large electrode DMAPS in LFoundry 150 nm CMOS



(This talk)

TJ-Monopix:

Small electrode DMAPS in Tower 180 nm CMOS



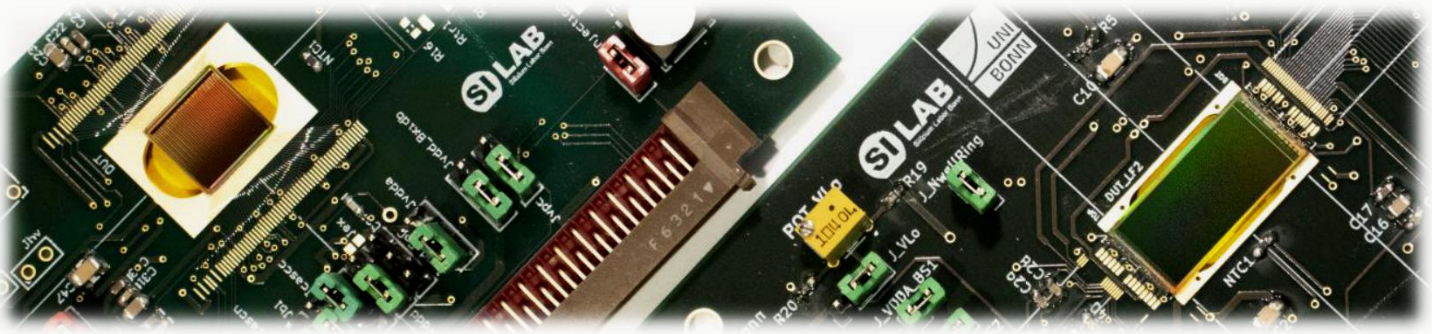
(Talk by C. Bespin)

THE LF-MONOPIX PROTOTYPES

- **Full-size (~cm²) large electrode DMAPS.**
- **Functional column-drain R/O architecture.**
- **In-pixel electronics in >2 kOhm-cm resistive substrates.**

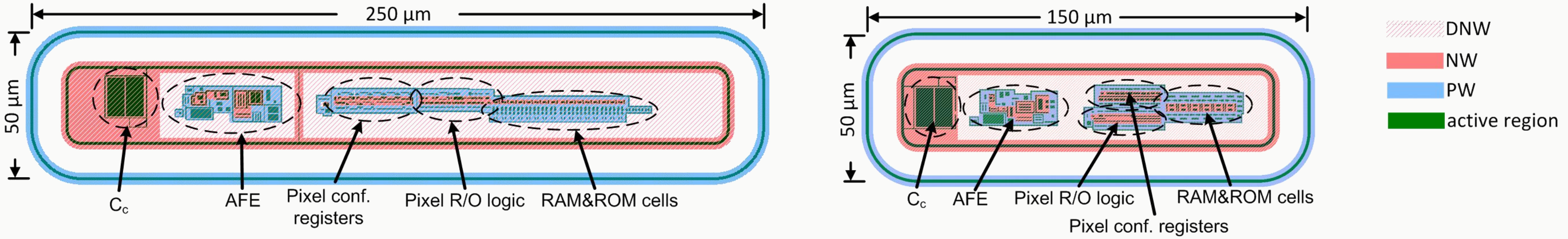
LF-Monopix1 (Mar 2017)

LF-Monopix2 (Feb 2021)



LFoundry 150 nm CMOS process

Pixel layouts (Top view):



DAQ system: Bonn's Multi-I/O 3 ("MIO3") and General Purpose Analog Card ("GPAC")

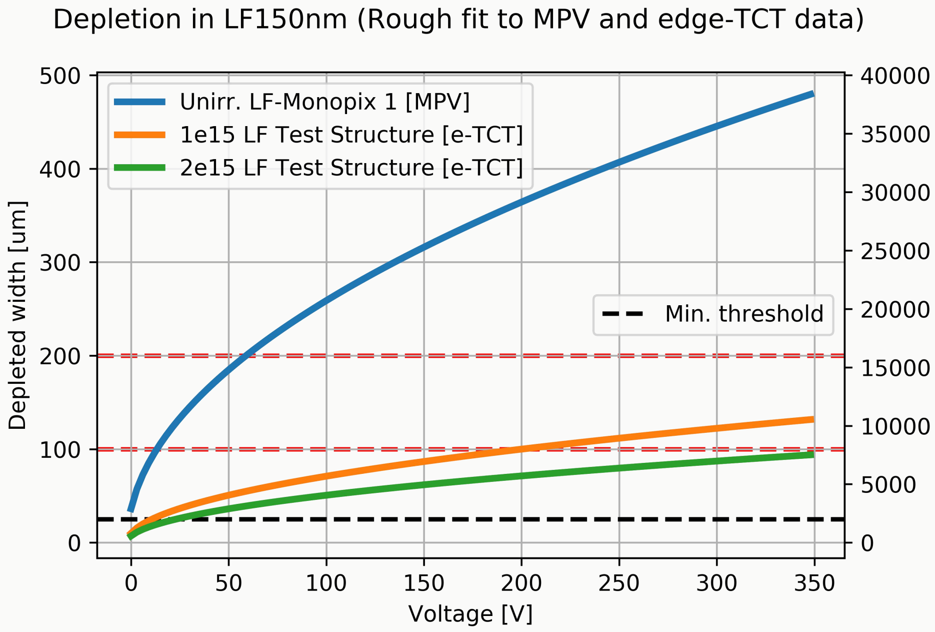
DEPLETION IN LFOUNDRY HR-SUBSTRATES

CMOS DMAPS aim to deplete the silicon bulk and collect charge <u>mainly by drift</u>

In order to do so, the **LF-Monopix** chips use:

- **A highly resistive substrate:**

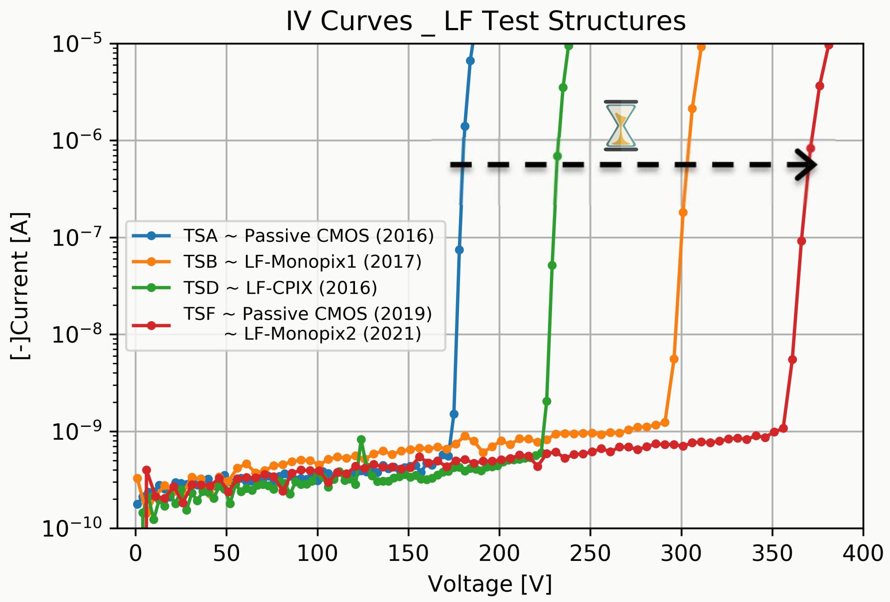
~7 kOhm-cm, Czochralski processed



(e-TcT data from: I. Mandic, L. Vigani.)

- **Large reverse bias voltages:**

Improved across LF150 prototypes



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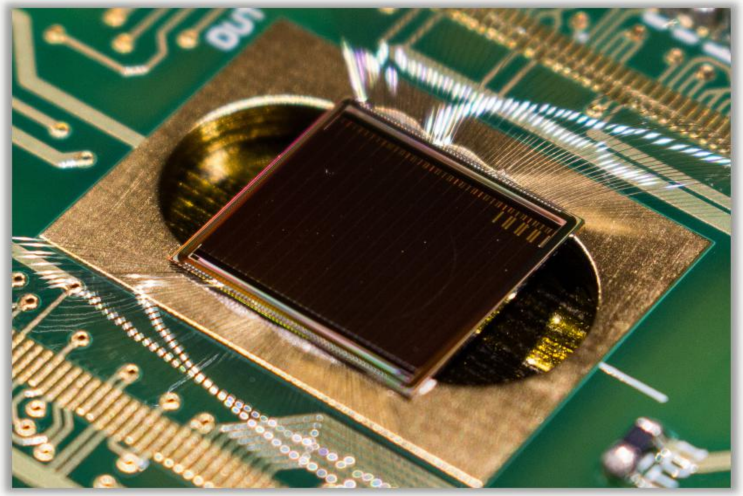
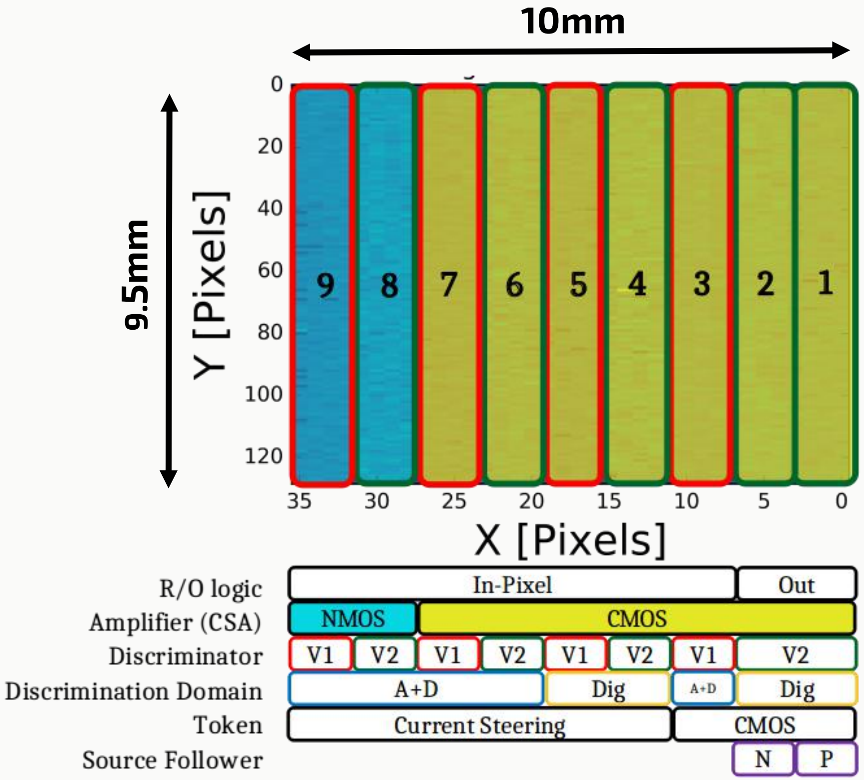
LF-MONOPIX1



- Functional **in-pixel** R/O logic.
- Large **50 x 250 µm²** pixel array (**129 rows x 36 cols**)
- Bunch-crossing clock frequency (**40MHz clock**)
- 40 MHz/160MHz CMOS or LVDS serial output.
- Timestamping: **8-bit LE/TE (ToT) @ 25 ns.**
- Power: **55 µW/pixel (~1.7W/cm²)**

Noise: ~150-200e-

Tuned Thr: ~1600 ± 100e-



Radiation-hardness and sensor layout optimized in previous prototypes ☑

Succesful design efforts for **cross-talk mitigation** in digital lines ☑

Fast and low-power CSA and discriminator implementations ☑

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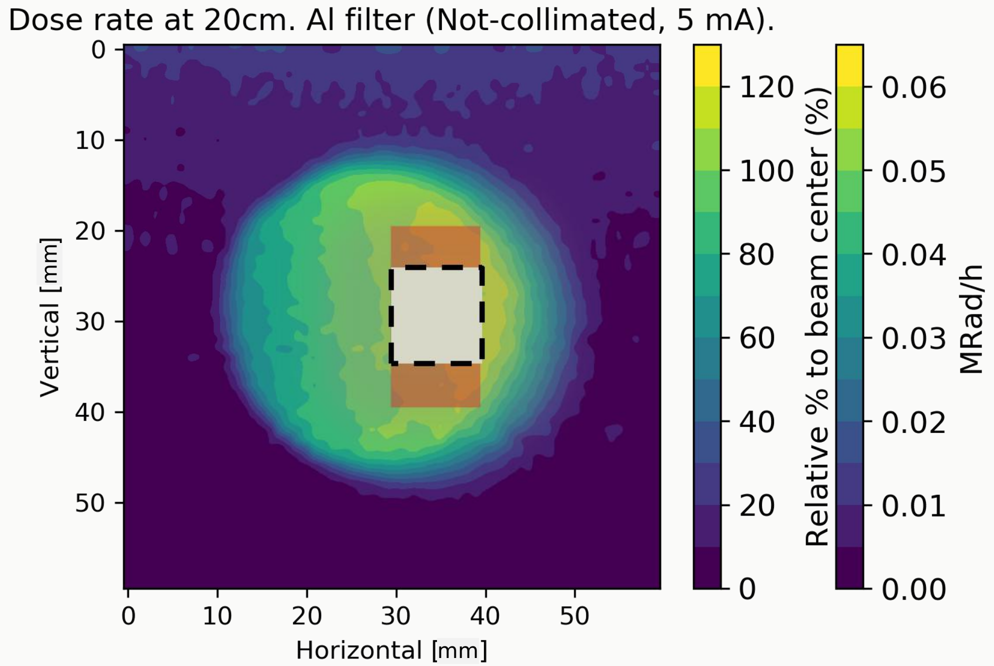
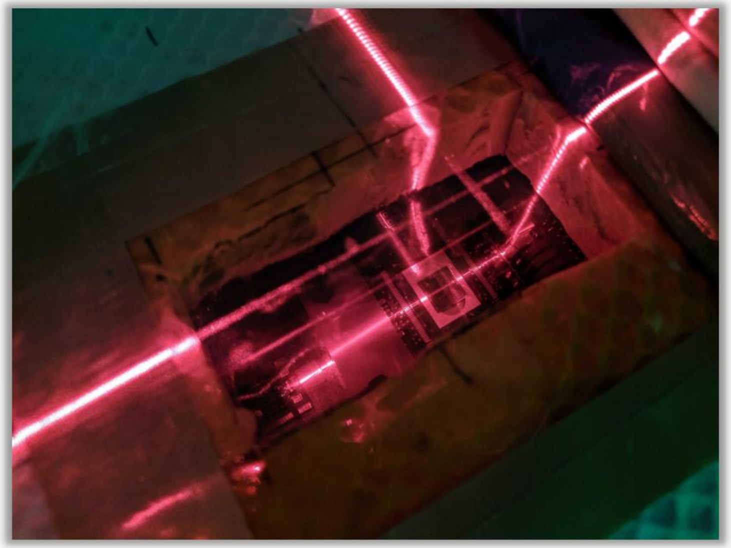
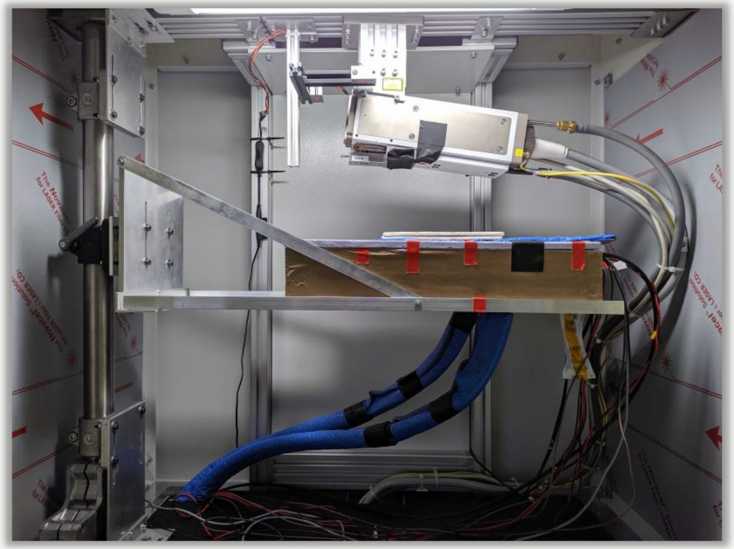
TID IRRADIATION @ SILAB BONN







- **Sample:** 100 µm thick LF-Monopix1 (Powered on)
- **X-ray tube settings:** 40 kV, 50 mA ---> 0.6 MRad/h
- **Temperature:** Cooled down with chiller through plate. 0±2 C in NTC
- **15 steps up to 100 MRad**

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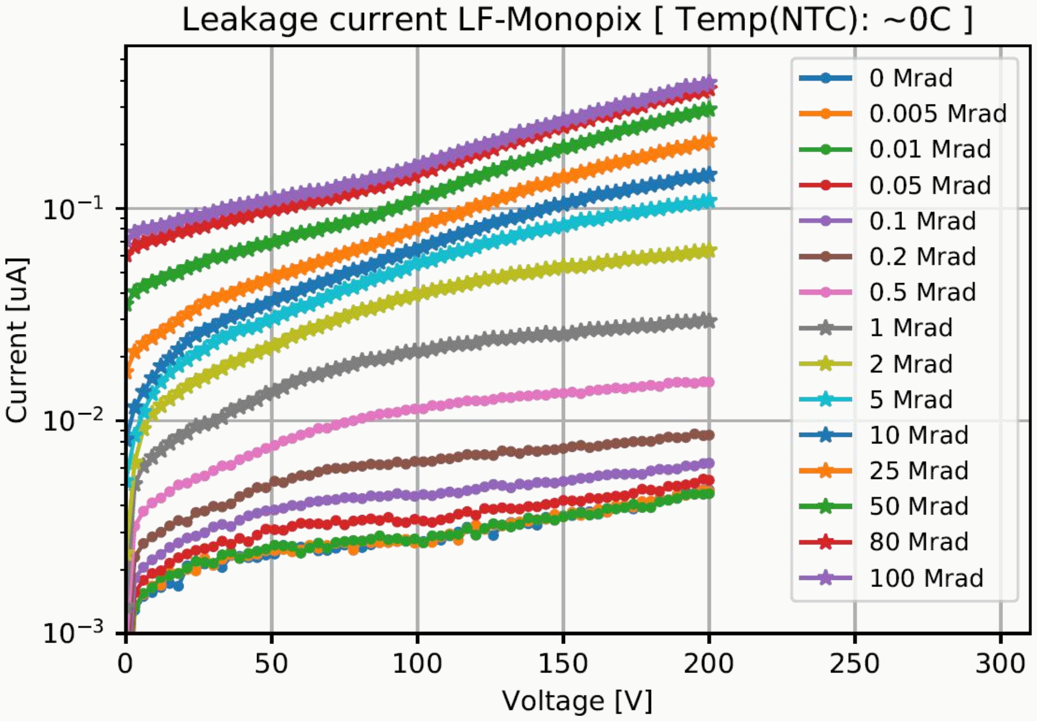
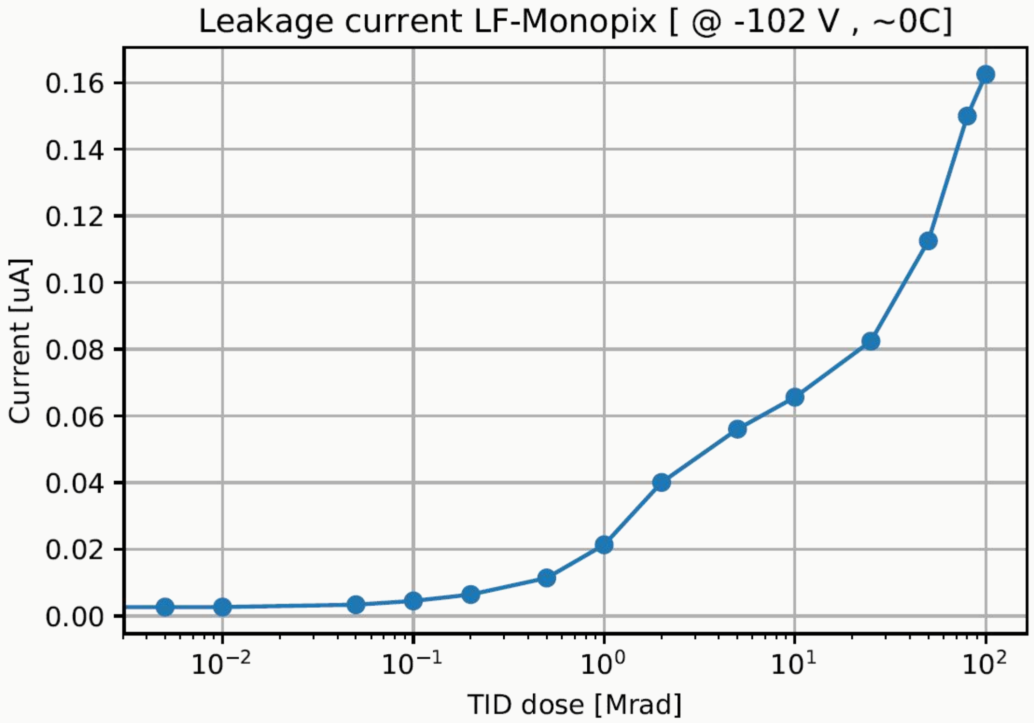
TID IRRADIATION: LEAKAGE CURRENT

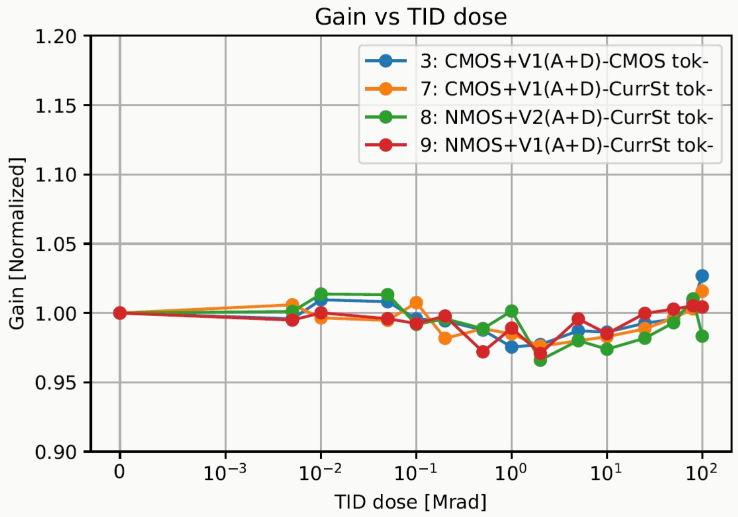




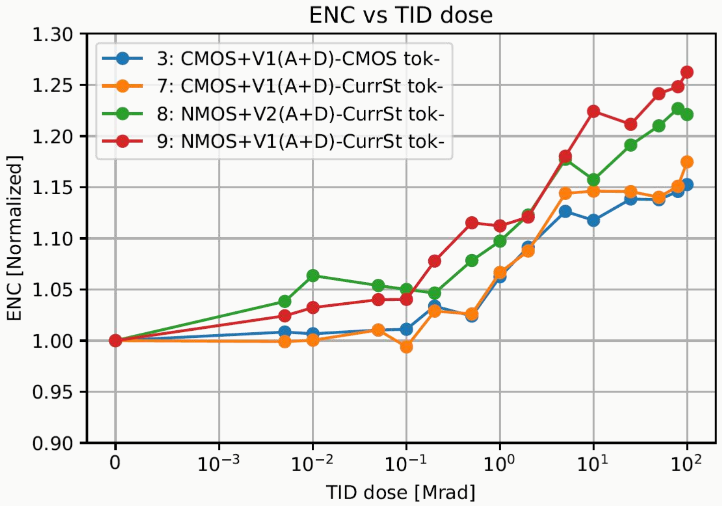
Increase of 2 orders of magnitude after 100 Mrad at 0 ± 2C temperature

TID IRRADIATION: GAIN & ENC

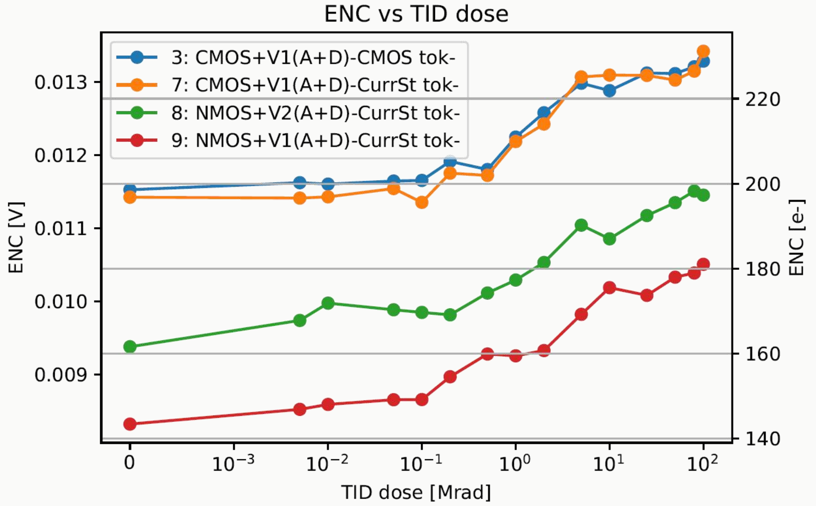
- **Relative Gain variation:** <3%



- **Relative ENC increase:** NMOS (25%) > CMOS (15%)



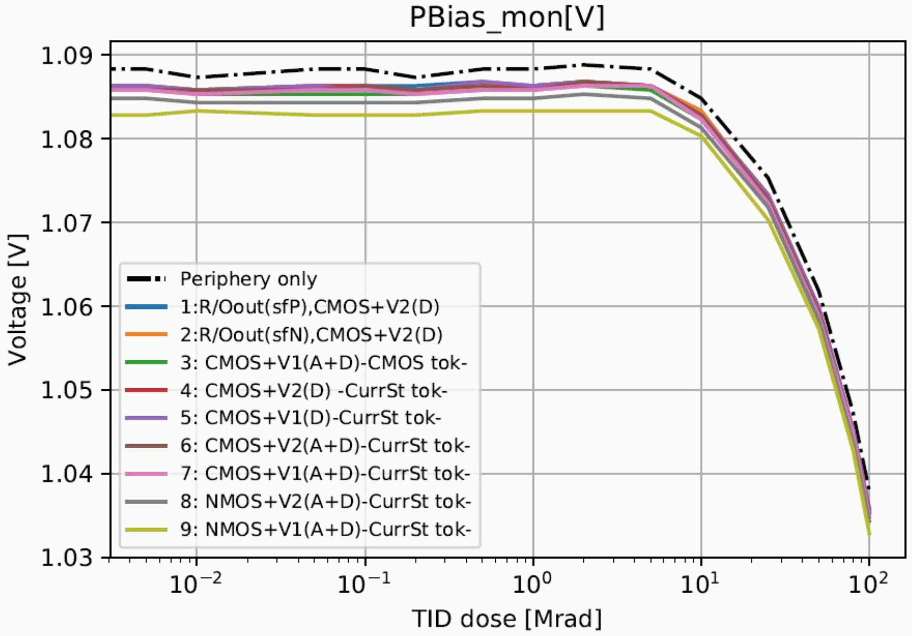
- **Nominal ENC:** CMOS > NMOS



TID IRRADIATION: DACS & DIGITAL PERFORMANCE

- **DAC Reference Current:**

Drop of 5% from 5 to 100 MRad

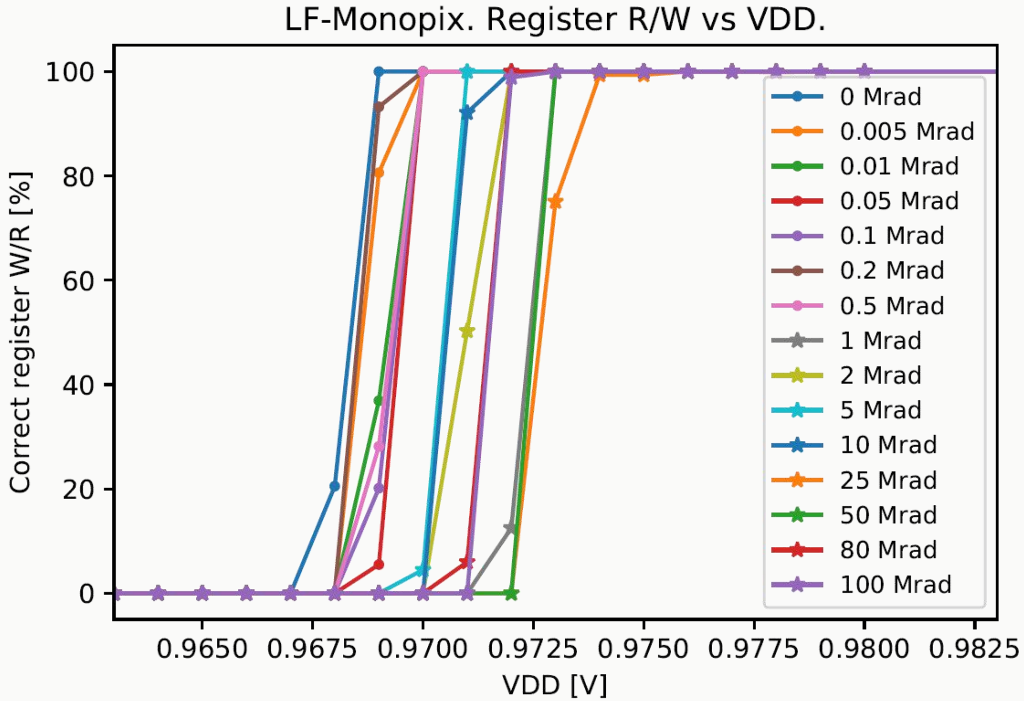


Drop of 5-10% in DAC steps

- **Shift register R/W:**

Variation < 0.5% in whole matrix

Default VDD: 1.8V



No degradation of digital performance

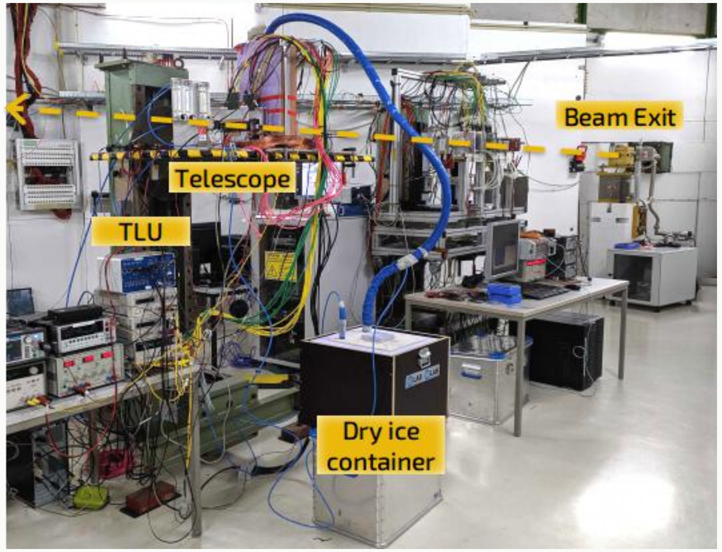
TB DATA ACQUISITION AND SAMPLING @ ELSA/DESY

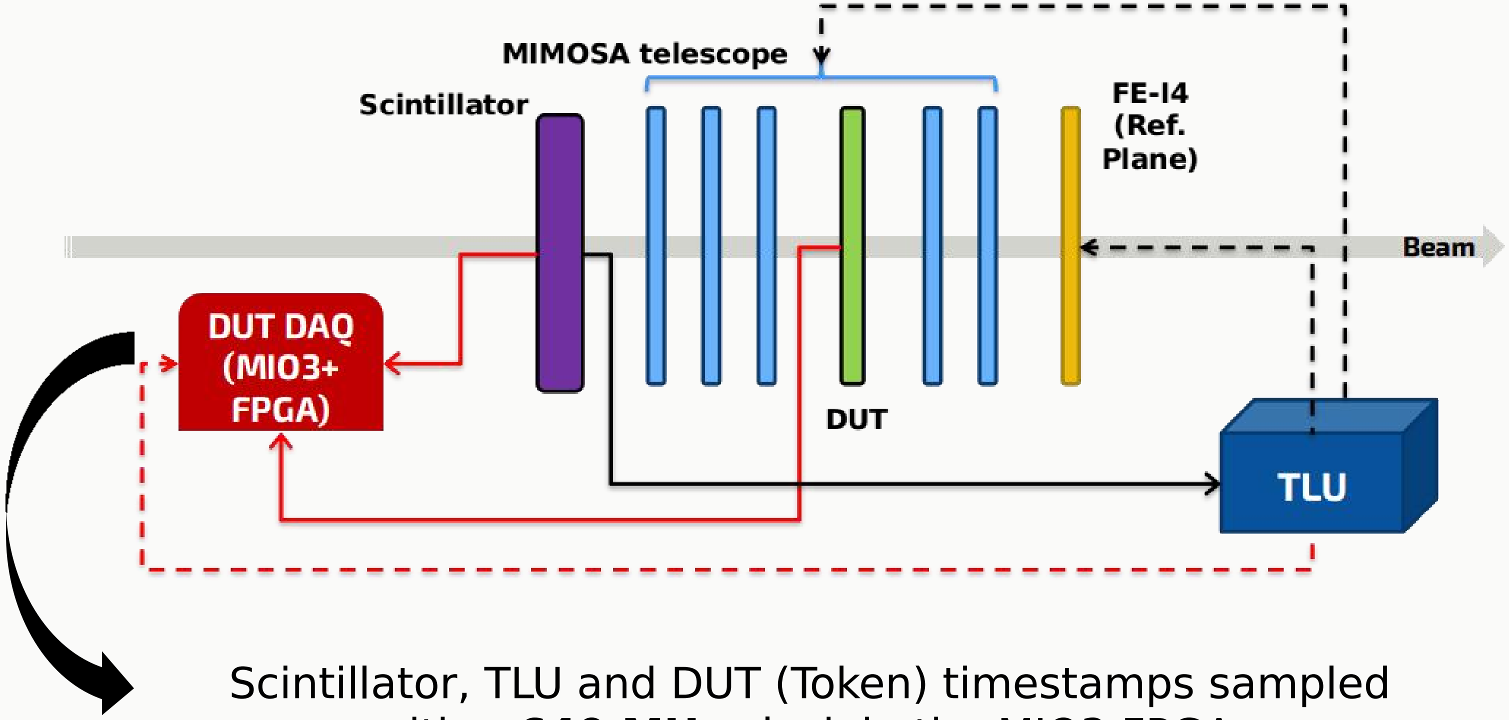
Telescope setup:

- 1 LF-Monopix1 DUT
  (200/100 µm thickness),
- 5 MIMOSA26 tracking planes
- 1 FE-I4 timing reference plane.
- Triggered by a plastic scintillator through a Trigger Logic Unit.

Beam: 5 GeV e- at DESY TB21

2.5 GeV e- at ELSA (Bonn)





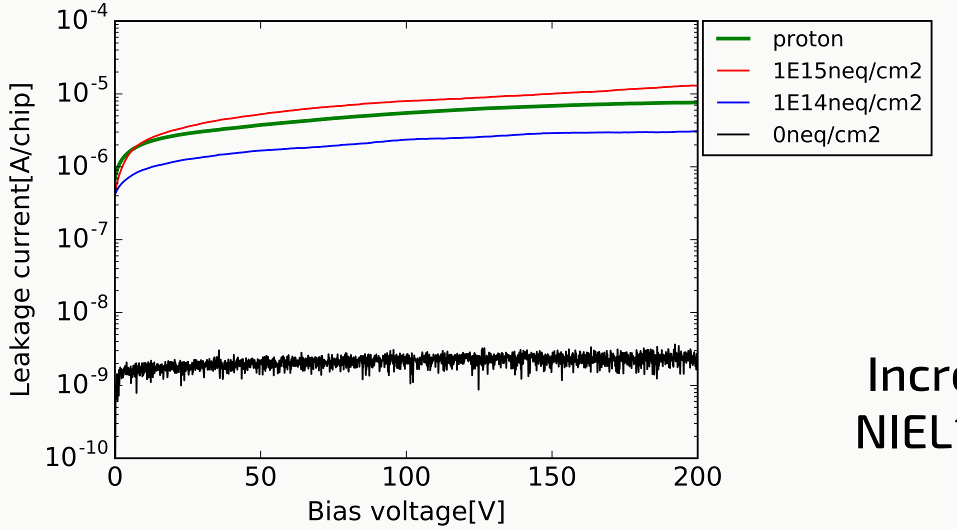
Scintillator, TLU and DUT (Token) timestamps sampled with a **640 MHz** clock in the MIO3 FPGA.

TB data analysis carried out using:
https://github.com/SiLab-Bonn/beam_telescope_analysis

NIEL: BREAKDOWN & DEPLETION IN THIN CHIPS

AIDA 2020

** Neutron irradiation in Lubljana (JSI), samples annealed for 80 mins at 60°C*

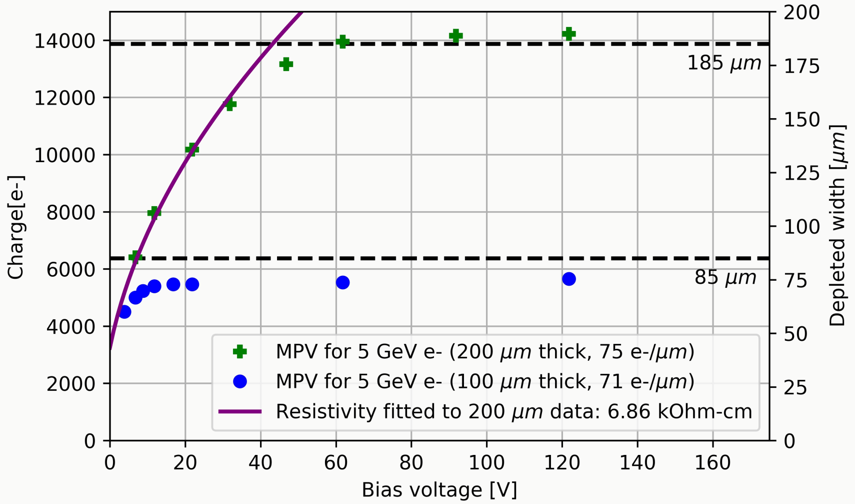


- **Breakdown voltage:**

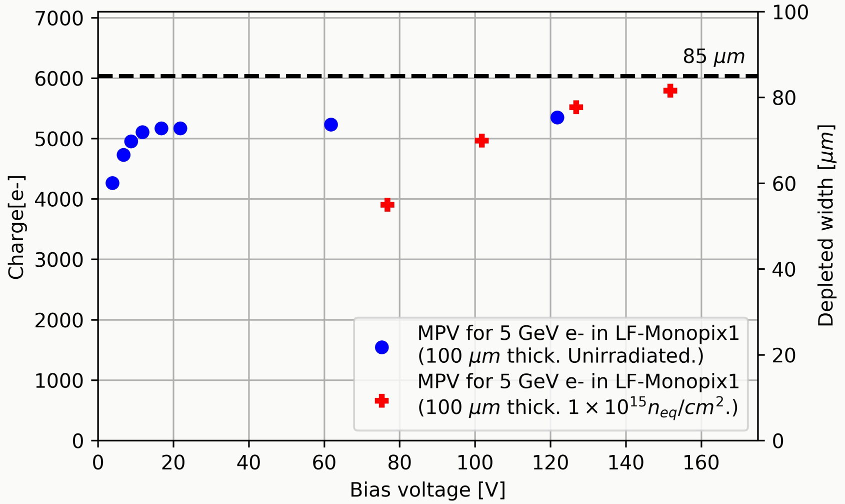
  >200V

  Increase in leakage current due to NIEL*+TID damage after irradiation

Depletion in unirradiated LF-Monopix1 (100 μm vs. 200 μm)



Depletion in LF-Monopix1 after NIEL damage (100 μm)



- **Depletion:**

  100 µm thick chips fully depleted at ~150V after $1 \times 10^{15}\ N_{eq}/cm^2$

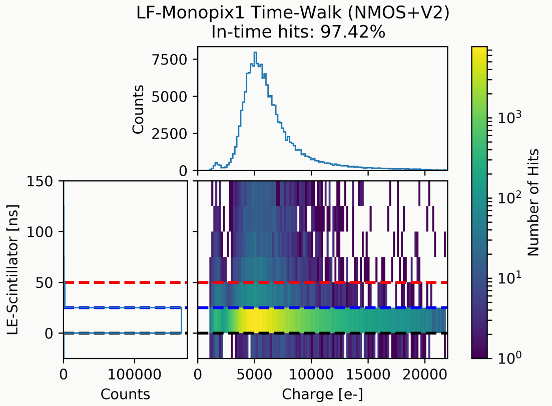
DETECTION EFFICIENCY

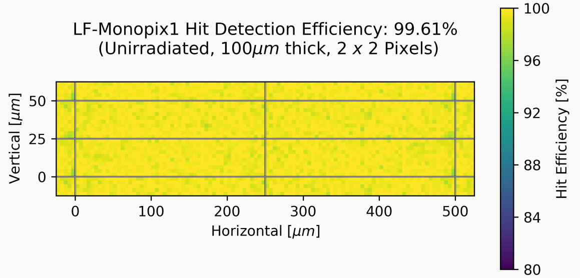
Unirradiated:

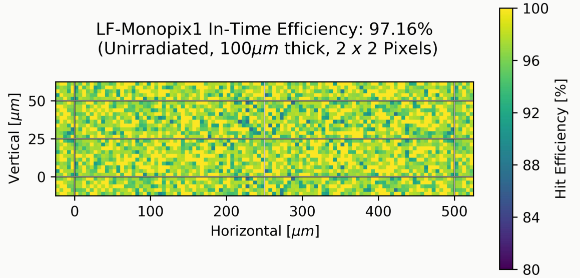
99.62%
(In-time ~97.1%)

(100 µm,
Bias: 60V,
Thr: 1885±227 e-)

Noise Occ. < **10^{-7}**





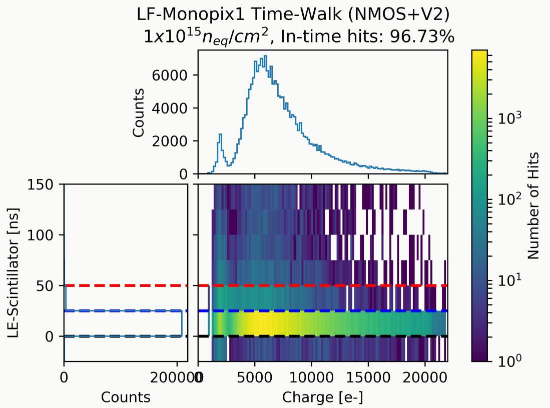


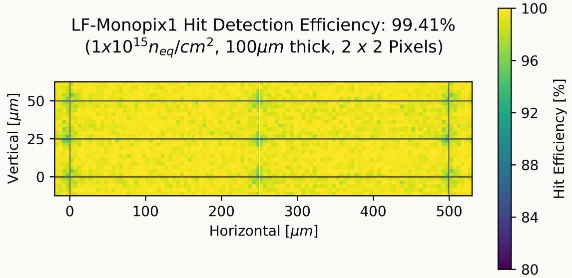
$1x10^{15}$ N_{eq}/cm^2:

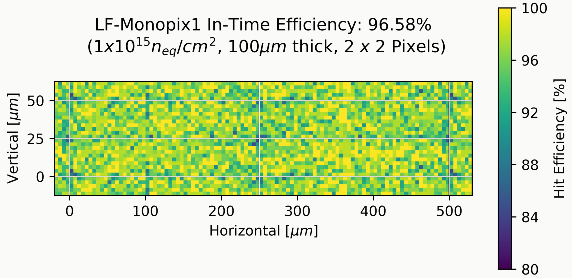
99.4%
(In-time ~96.6%)

(100 µm,
Bias: 150V,
Thr: 2336±262 e-)

Noise Occ. < **10^{-7}**







The chip's sensor and front-end still performed well after a NIEL fluence of $1x10^{15}$ N_{eq}/cm^2

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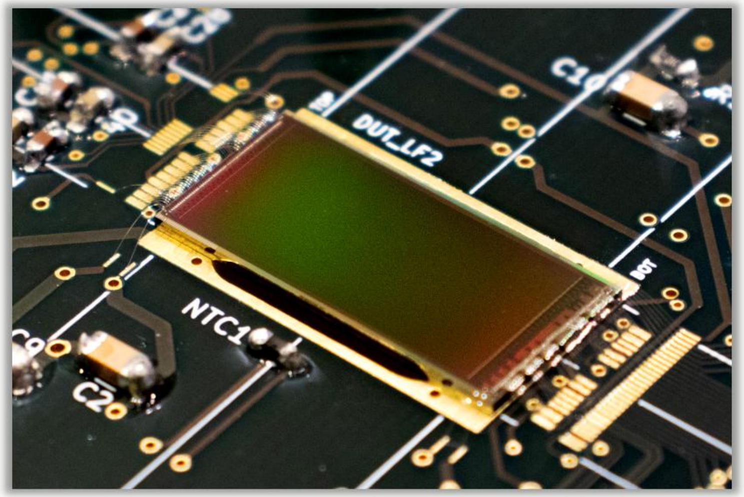
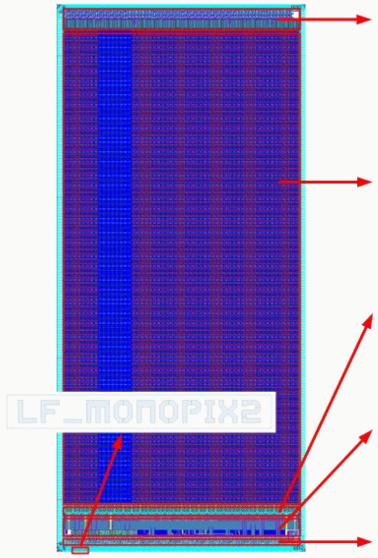
LF-MONOPIX2





- Smaller pixel pitch than LF-M1: **50 x 150 µm²**
  → Reduced C_{det}
  (ergo: lower noise & power)
  → Larger pixel array
  (**340 rows x 56 cols**)
- 40 MHz/160MHz CMOS or LVDS serial output.
- Timestamping: **6-bit LE/TE (ToT) @ 25 ns.**
- Power: ~**30 µW/pixel**
- Injection & HitOr: **Digital, at pixel level.**

Column-drain R/O in a **2 centimeter long column**, with **full in-pixel electronics** ☑

Improved pixel layout for **further cross-coupling mitigation** ☑

Most of the matrix (57%) employs the rad-hard front-end that performed best in LF-M1

New features tested in other columns:

- Bidirectional discrimination circuitry.
- CSA designs with increased gain.
- Smaller C_f (1.5 fF)

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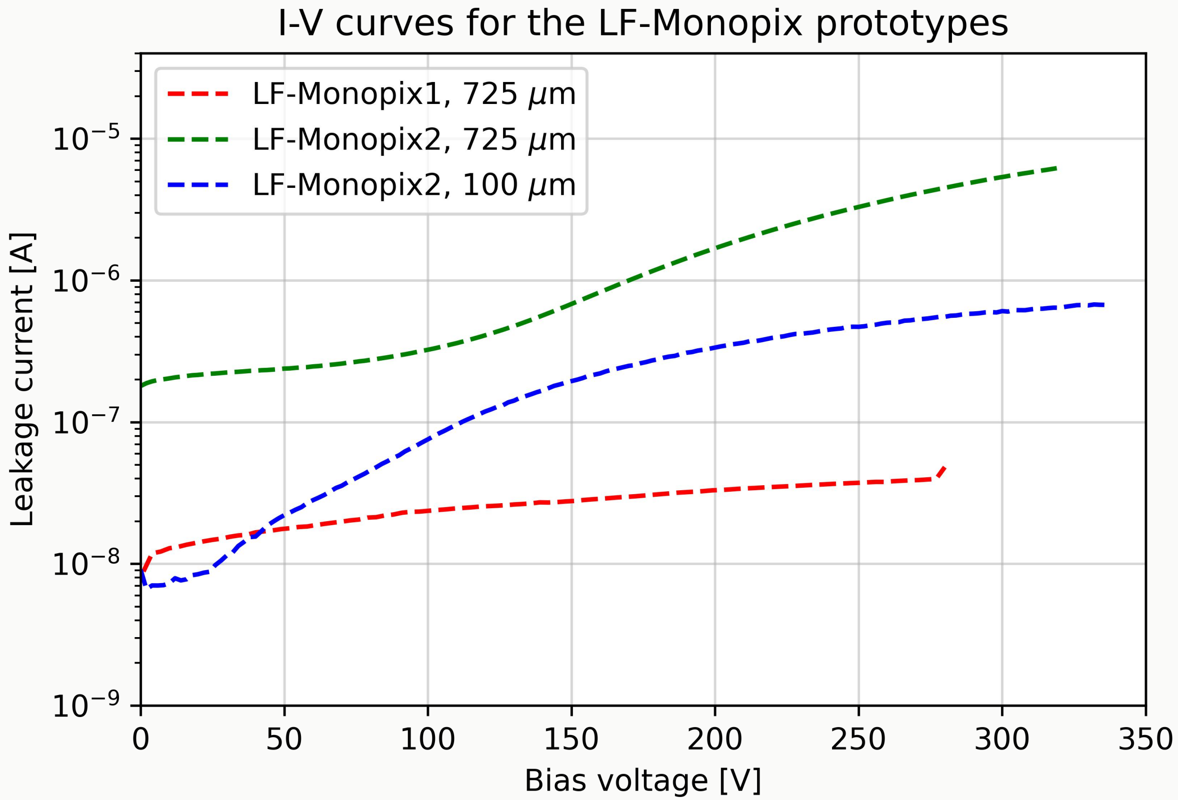
LF-MONOPIX2: SENSOR BREAKDOWN AND LEAKAGE

There was a significant improvement (>30%) in breakdown voltage from LF-M1 to LF-M2

Mainly due to guard-ring optimisation

Breakdown voltage >350V

Valid also after thinning and backside processing



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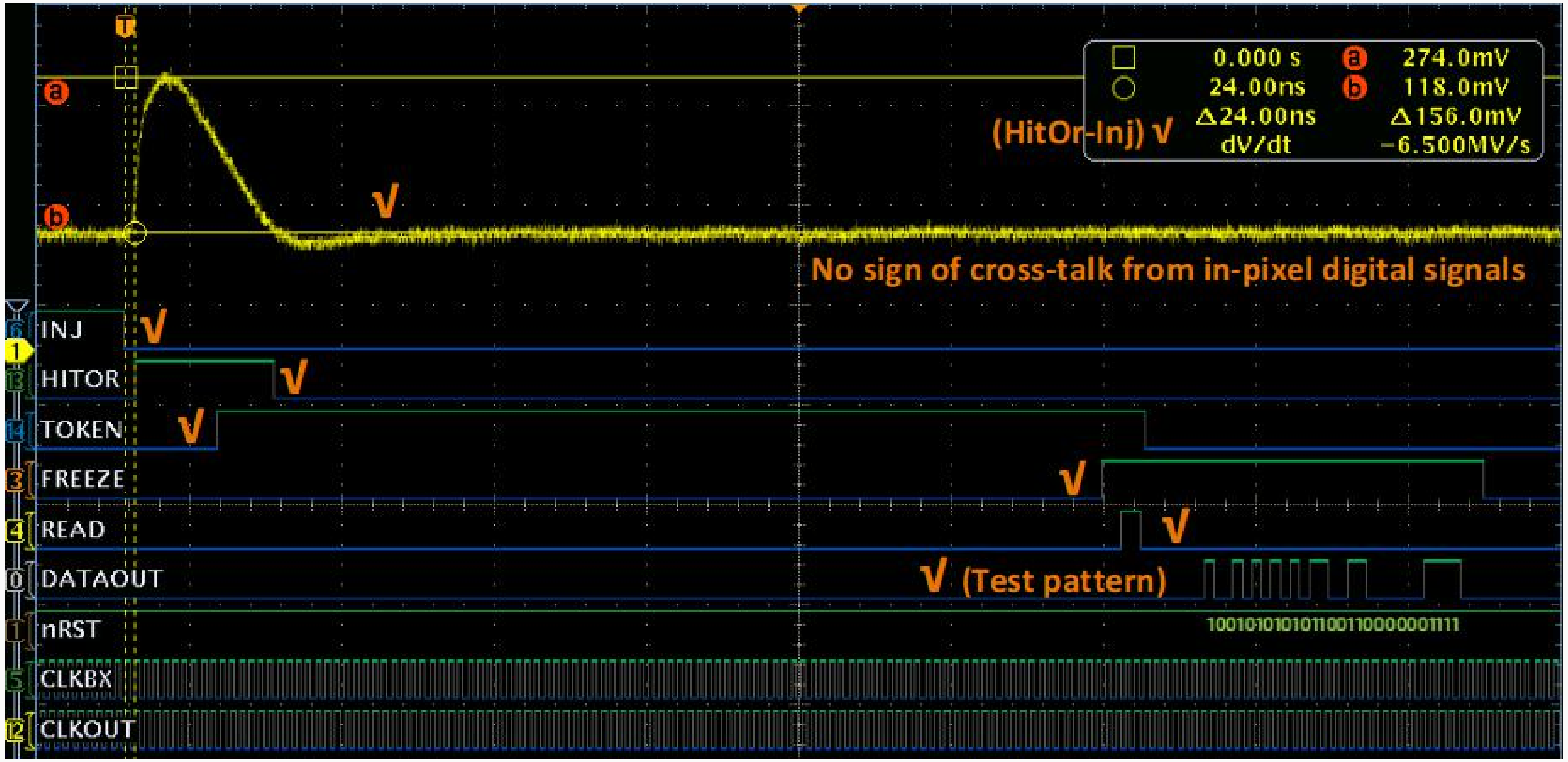
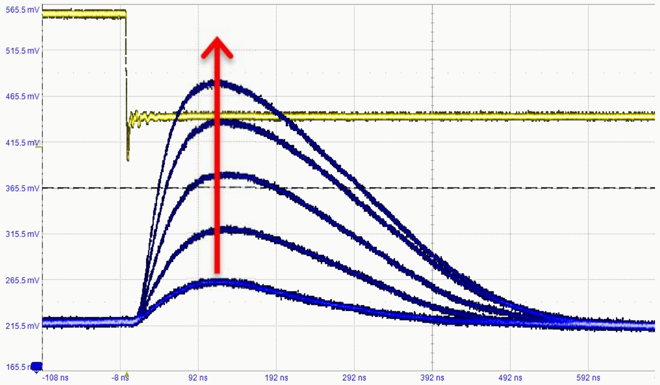
FUNCTIONAL FRONT-END, R/O AND INJECTION.

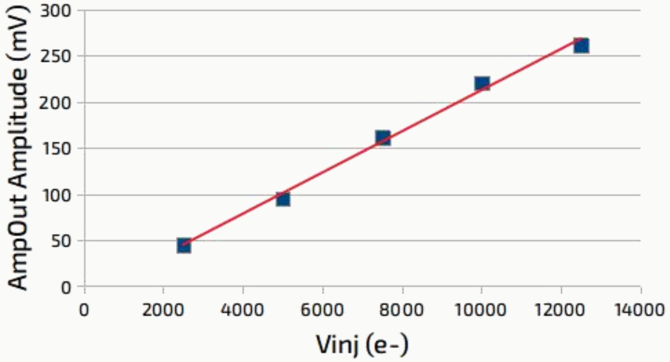
- **Correct R/O architecture operation and data output.**



Injection of 1V pulse to a single monitored pixel - 40 MHz R/O enabled

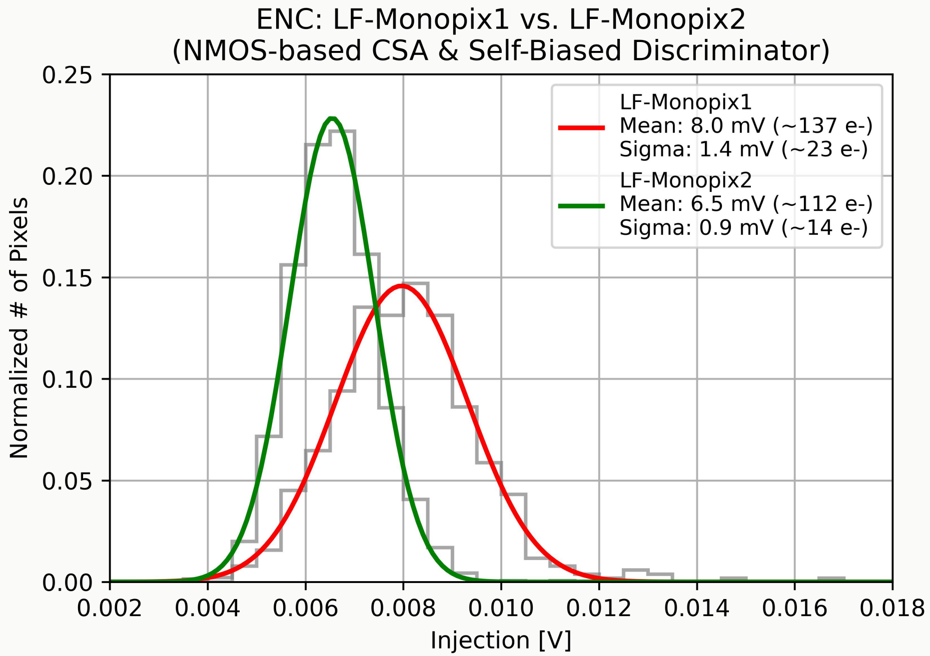
- **Linear CSA response.**





LF-MONOPIX2: ENC

- **From LF-Monopix1 to LF-Monopix2:**

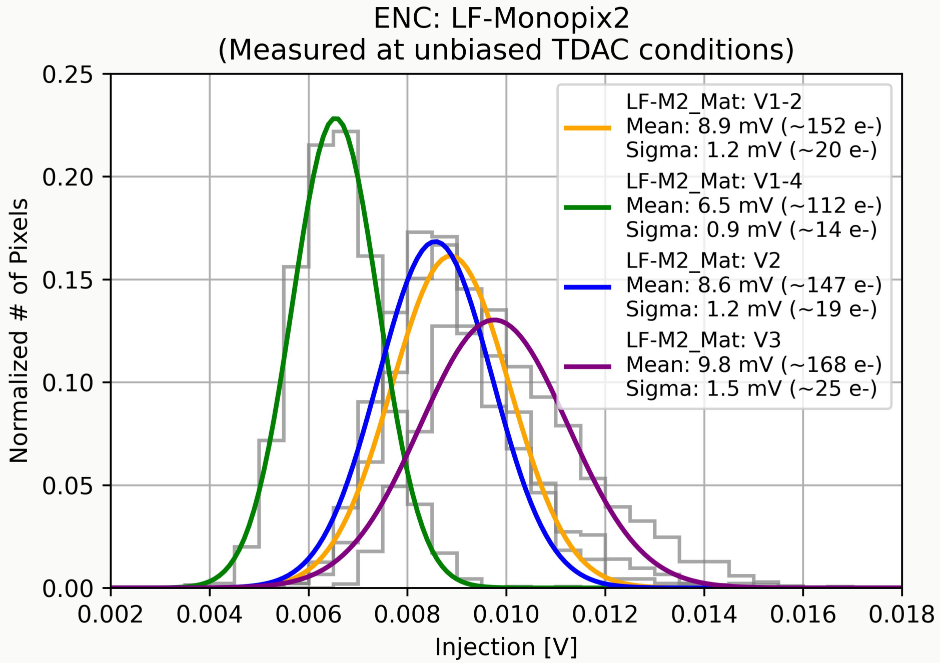


Decrease of ~20-30% in mean ENC and dispersion for the same front-end implementation

(As expected from reduced pixel pitch ~ C_d)

- **Between LF-Monopix2 flavours:**

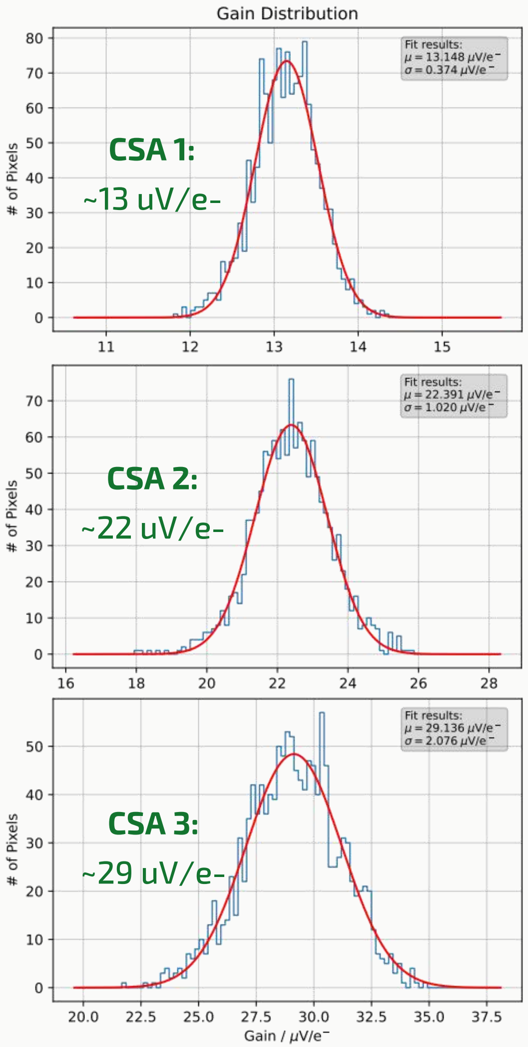
Matrix	Column	CSA	Feedback cap.	Discriminator	Logic
1-1	55 - 52	V1	1.5 fF	Bidirectional tuning	Falling
1-2	51 - 48	V1	5 fF	Bidirectional tuning	Falling
1-3	47 - 40	V1	5 f	unidirectional tuning	Rising
1-4	39 - 16	V1	5 f	unidirectional tuning	Falling
2	15 - 8	V2	1.5 fF	Bidirectional tuning	Falling
3	7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

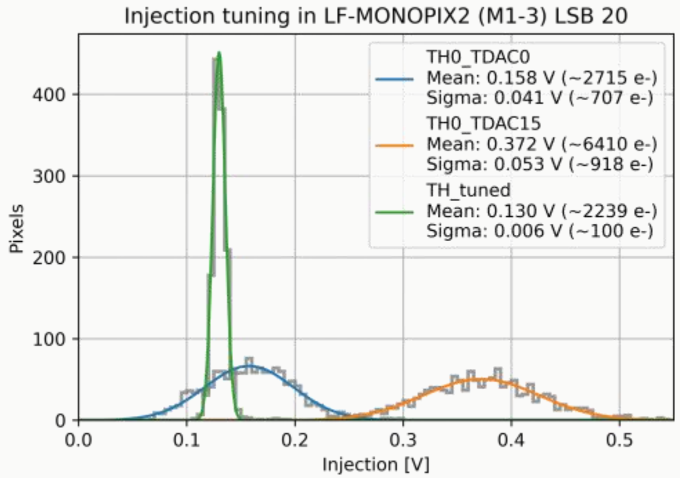


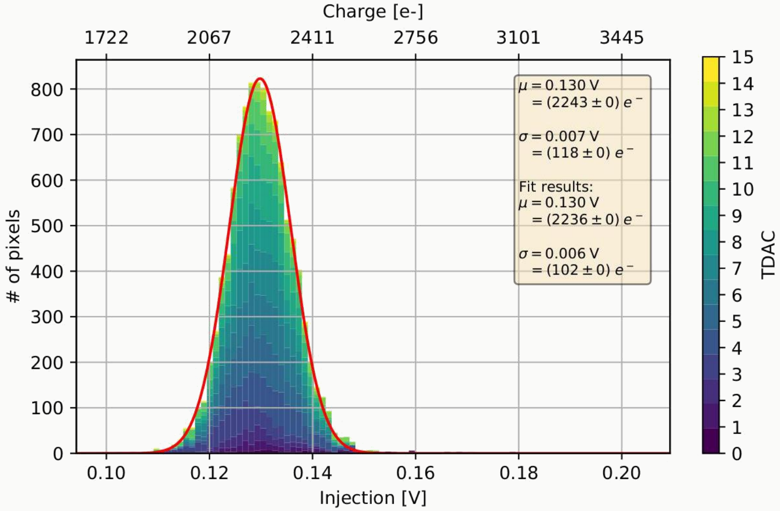
Flavours with the new "Bidirectional" tuning circuitry show a larger ENC and dispersion.

LF-MONOPIX2: FRONT-END GAIN AND TUNING

The two new CSA variants implemented in the chip ("2" and "3") show a gain 2-3 times larger than the one of the original front-end.



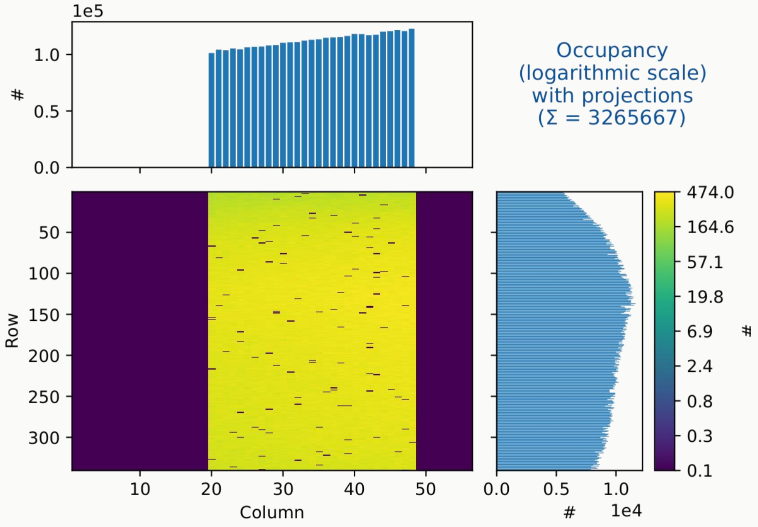


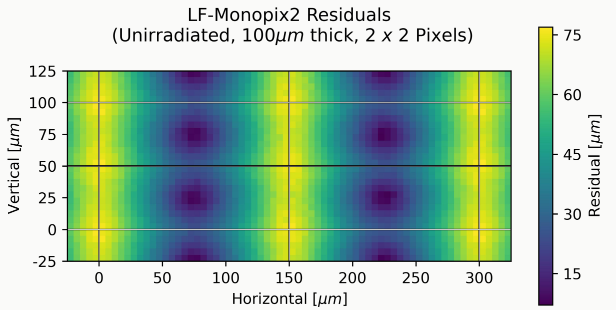


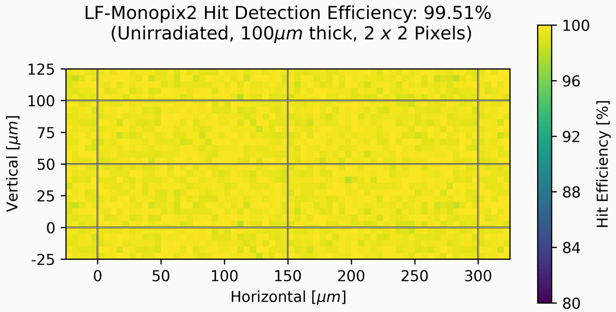
- **Threshold dispersion after tuning:** ~100 e-
- **Normally distributed TDAC values**

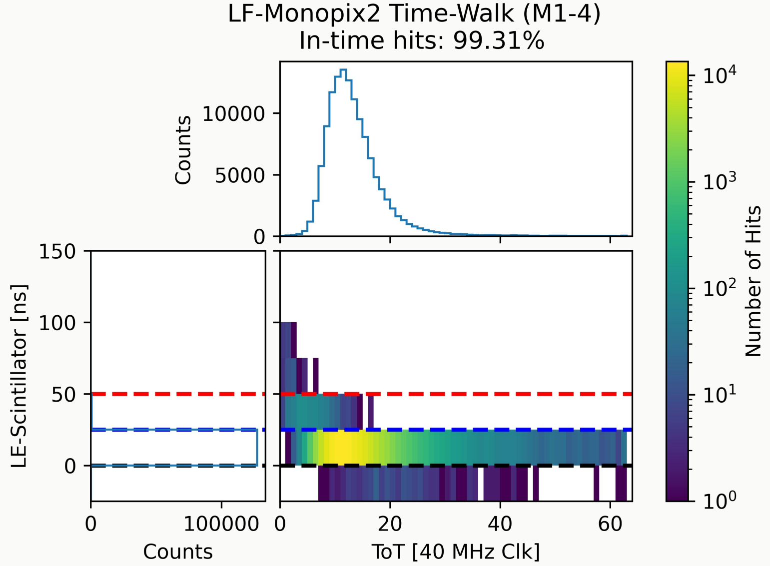
LF-MONOPIX2: (PRELIMINARY) HIT EFFICIENCY

- **Unirradiated chip exposed to 5 GeV electrons @ DESY:** Data from matrices with CSA1 and unidirectional tuning.
  (100 µm thick, Bias: 60V, Thr: 2236±102 e-) Noise Occ. < 10^{-7}









Our first test beam measurement results with LF-Monopix2 are encouraging, both in terms of hit detection efficiency and in-time hits (>99%)

➢ Upcoming: Proton irradiation and two weeks of test beam campaigns @DESY

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CONCLUSIONS

- **Fully implemented fast R/O architecture** in two large electrode DMAPS chips designed in a 150nm CMOS process and highly resistive wafers.

- X-ray irradiation and measurements in neutron irradiated samples have demonstrated that **the LF-Monopix1 prototype is radiation-hard:**
  - **Small analog and digital degradation** after 100 MRad TID dose
  - **Full depletion of thinned sensors** after neutron fluences of $1\times10^{15}\ N_{eq}/cm^2$
  - **Hit detection efficiency** after $1\times10^{15}\ N_{eq}/cm^2$ **> 99% (In-time >96%)**

- **A long column design (LF-Monopix2) with reduced pixel size is functional and shows:**
  - Increased breakdown voltage (>350V).
  - Improved cross-coupling mitigation.
  - Improved default front-end performance, as expected from the reduction in detector capacitance.
  - A uniform hit detection efficiency >99% before irradiation.

Thank you for your attention.

Questions?

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).

The measurements leading to these results have partially been performed at the Test Beam Facility in DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).