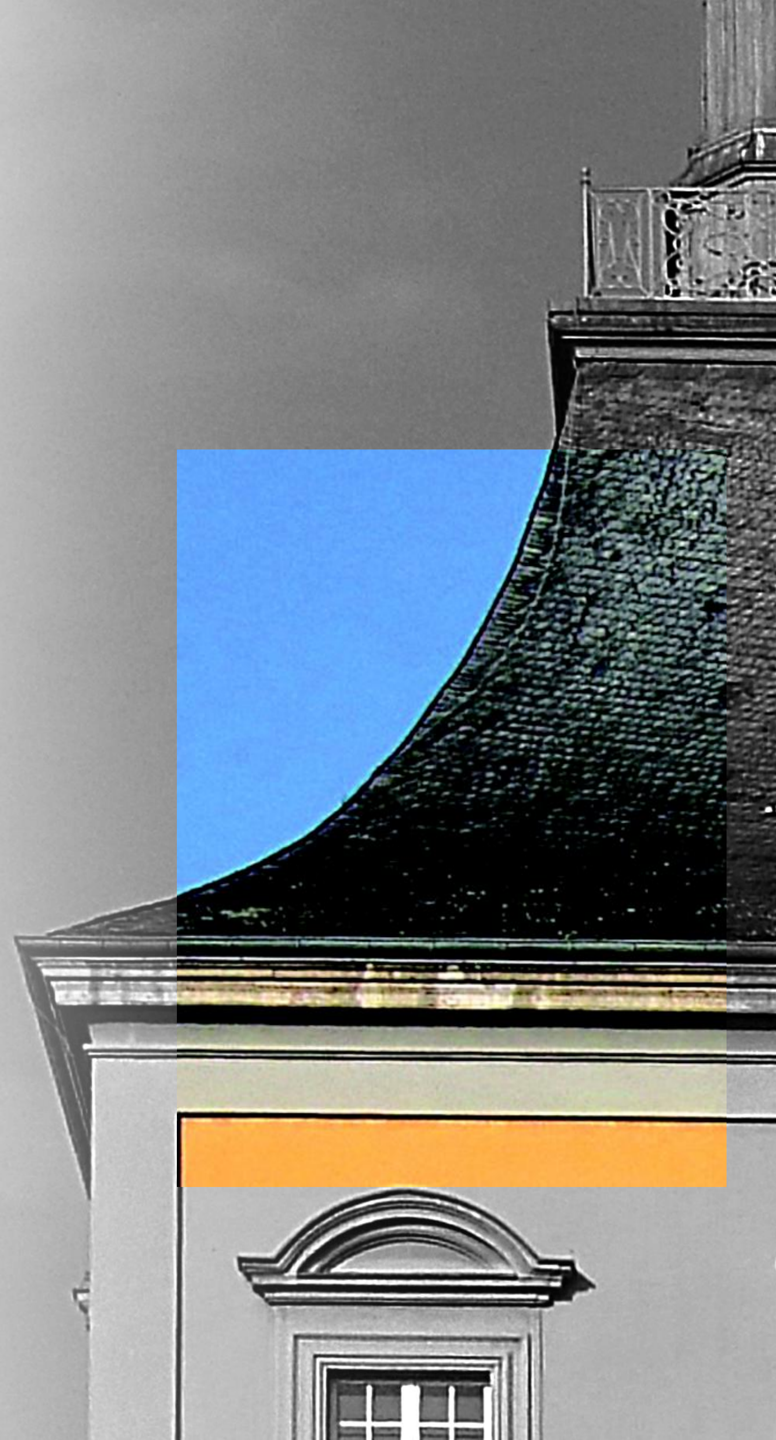
# Characterization and radiation-hardness of the LF-Monopix2 DMAPS prototype

**Ivan Caicedo***, C. Bespin, J. Dingfelder, T. Hemperek, T. Hirono, F. Huegging, H. Krueger, P. Rymaszewski, L. Schall, T. Wang, N. Wermes, S. Zhang
(University of Bonn)

M. Barbero, P. Barrillon, P. Breugnon, N. Destaing, L. Drexler, A. Habib, P. Pangaud, A. Rozanov ( Aix Marseille University, CNRS/IN2P3, CPPM)

Y. Degerli, F. Guilloux, P. Schwemling (IRFU CEA-Saclay)

*caicedo@physik.uni-bonn.de



# DEPLETED MONOLITHIC ACTIVE PIXEL SENSORS (DMAPS)

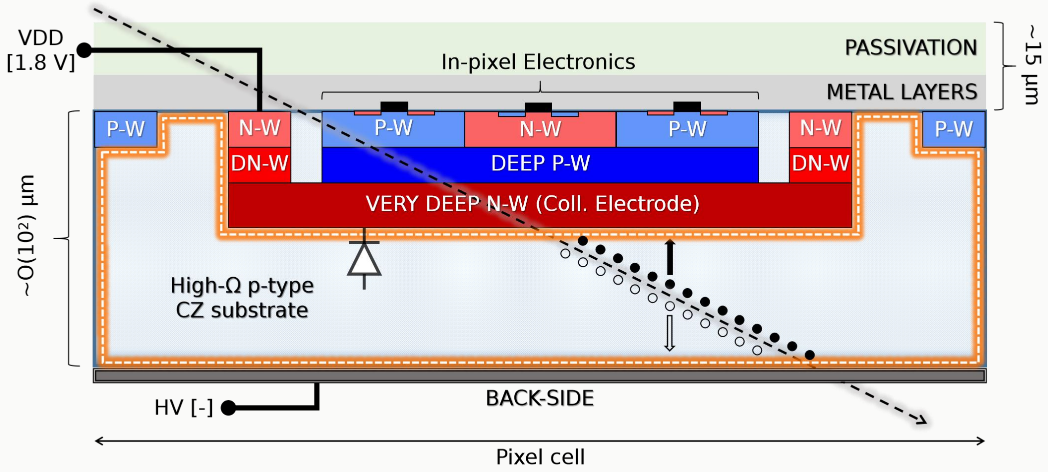
- **Sensor, front-end and readout electronics in a common silicon unit**

- **Commercial CMOS processes:**
  Multiple wells to shield electronics

- **Considerable depleted regions in highly resistive substrates:**
  Fast charge collection by drift

## "Large Electrode" design

Large collecting well containing in-pixel circuitry




**PROS:** Short drift distances, strong E-field (Rad-hard)
**CONS:** Large detector capacitance, high analog power and ENC

$$\tau_{CSA} \propto \frac{1}{g_m}\frac{C_d}{C_f} \qquad ENC^2_{thermal} \propto \frac{4}{3}\frac{kT}{g_m}\frac{C_d^2}{\tau}$$

*---> Requires design efforts to optimize timing and minimize coupling of digital activity into the collection node.*

# DMAPS FOR HIGH ENERGY COLLIDER EXPERIMENTS

Taking the requirements of future HEP experiments as benchmark:

| | ITk Outer Layer | Belle II VTX |
|---|---|---|
| **Occupancy** | 1 MHz/mm² | 1.5 MHz/mm² |
| **Time Res.** | 25 ns | O(100) ns |
| **NIEL** | $10^{15}$ $n_{eq}/cm^2$ | $5\times10^{14}$ $n_{eq}/cm^2$ |
| **TID** | 80 Mrad | 100 Mrad |
| **Area** | O(10m²) | O(3m²) |

**DMAPS would offer:**

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

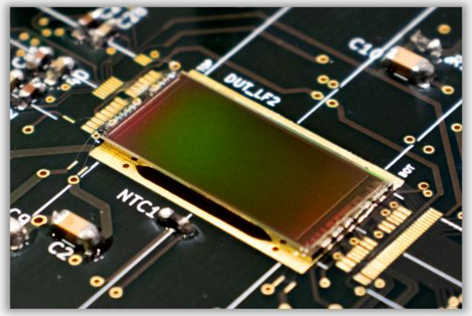
**The Monopix DMAPS developments**

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

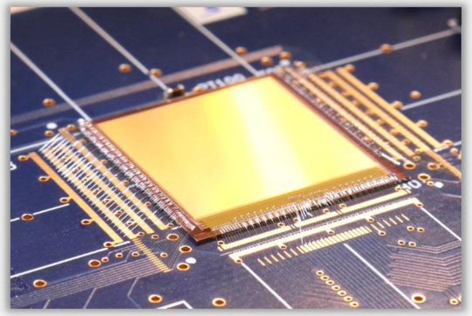
**+**

**Design optimization to preserve charge collection after irradiation**

**LF-Monopix:**
Large electrode DMAPS in LFoundry 150 nm CMOS



**TJ-Monopix:**
Small electrode DMAPS in Tower 180 nm CMOS



**Later talk by C. Bespin**

# THE LF-MONOPIX PROTOTYPES

Barbero et al. https://doi.org/10.1088/1748-0221/15/05/P05013
Dingfelder et al. https://doi.org/10.1016/j.nima.2022.166747

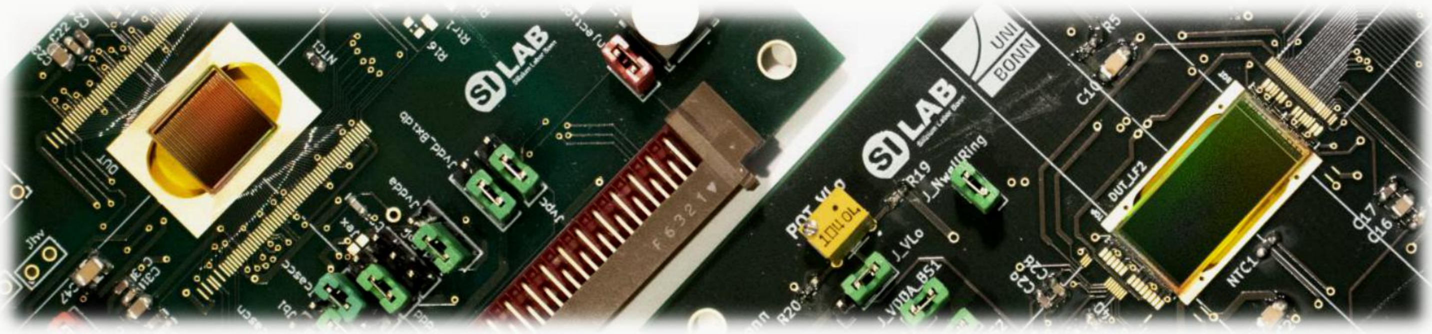
**LFoundry**
**150 nm CMOS** process

SI LAB Silizium Labor Bonn

CPPM — Irfu - CEA Saclay, Institut de recherche sur les lois fondamentales de l'Univers

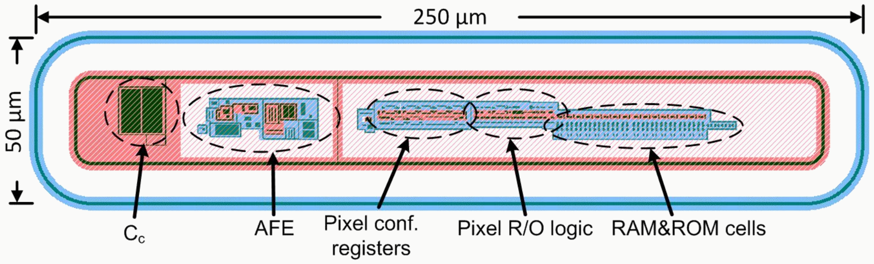
**LF-Monopix1** (Mar 2017)

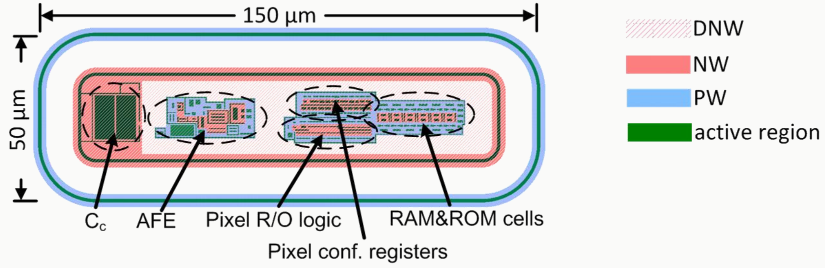
**LF-Monopix2** (Feb 2021)



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

Pixel layouts (Top view):



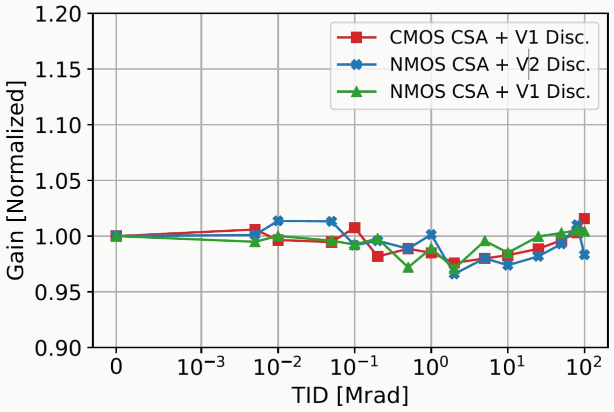




**Design strategies for LF-Monopix2:** Next talk by Tianyang Wang

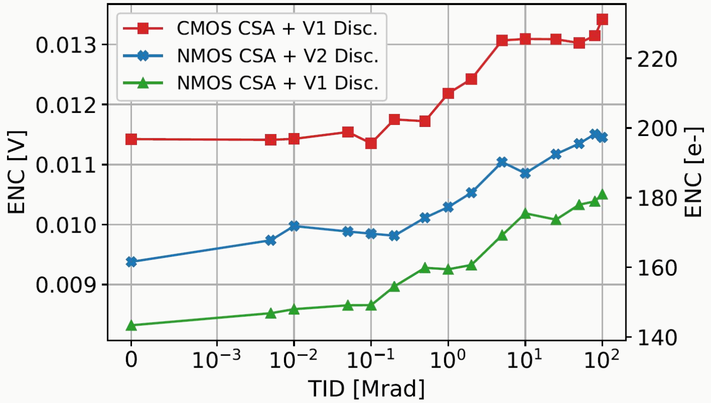
# LF-MONOPIX1: RADIATION HARDNESS

## TID up to 100 Mrad

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



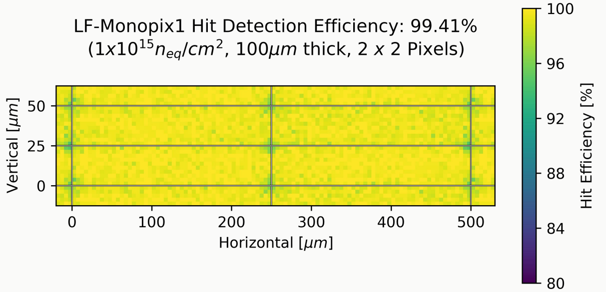

- **ENC increase:** NMOS CSA (25%), CMOS CSA (15%)

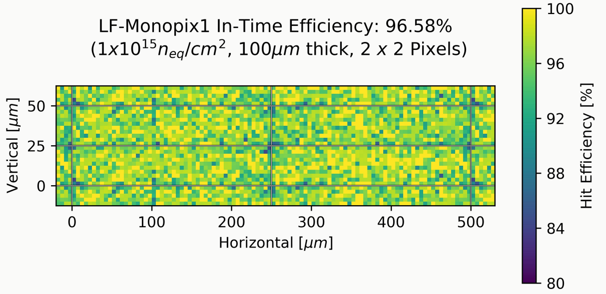


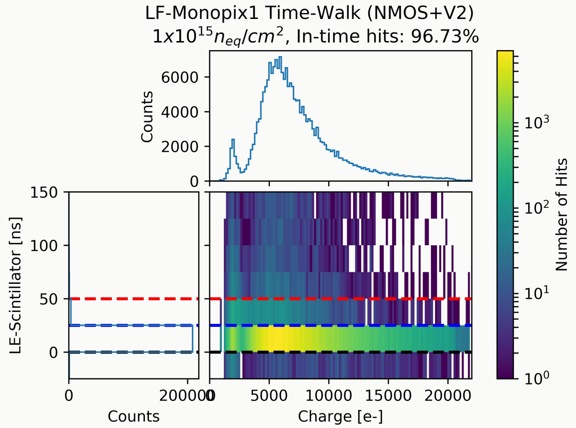

## NIEL up to 1x10$^{15}$ $N_{eq}/cm^2$

- **Hit efficiency:** ~99.4% (in-time: ~96.6%)

(100 µm thick | Bias: 150 V | Threshold: 2336±262 e$^-$ | Noise Occ. < 10$^{-7}$)

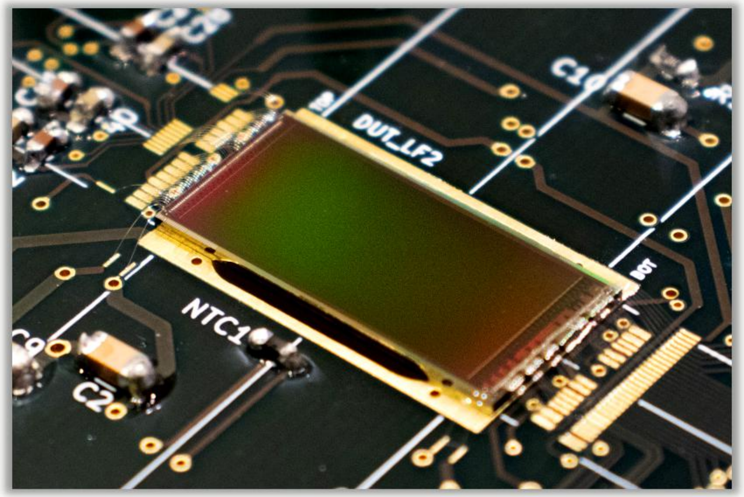


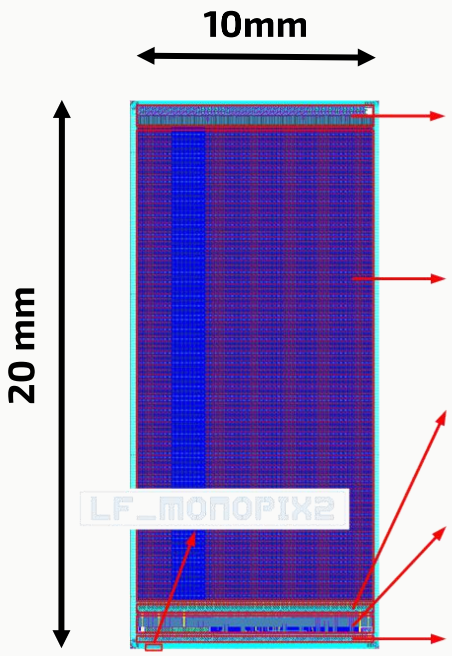




Caicedo et al. http://10.1016/j.nima.2022.167224

# LF-MONOPIX2




**Top pads, decoup. capacitors:** Power pads, sensor bias.

**Pixel array (340 x 56)**

**EoC circuit:** Sense amplifiers, digital buffers.

**Periphery:** Digital logic, DACs, analogue buffer.

**Bottom pads:** Power & R/W signals.

- Smaller pixel pitch than LF-M1: **50 x 150 µm²**
  → Reduced $C_{det}$ (~250 fF)
- Larger pixel array (**340 rows x 56 cols**)
- 40 MHz / 160 MHz CMOS or LVDS serial output.
- Timestamping: **6-bit LE/TE (ToT) @ 25 ns**
- Analog power: ~28 µW/pixel **(370 mW/cm²)**
- New injection & HitOr circuitry: **Digital, at pixel level**

Column-drain R/O in a **1.7 centimeter long column**, with **full in-pixel electronics**

☑

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

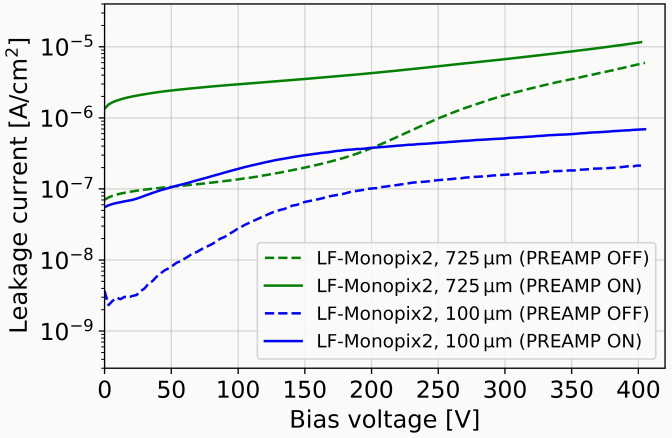
☑

**Inherited and improved a fast rad-hard front-end**
(CSA with NMOS input transistor
+
fast discriminator)

New features to be tested:

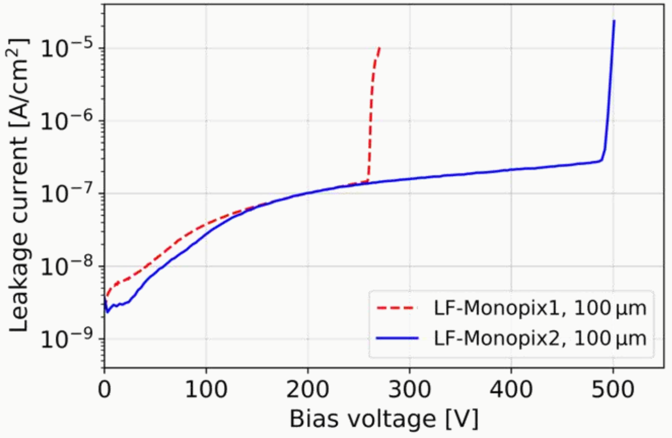
- Increased tuning range
- Benefits of smaller $C_f$ (1.5 fF)

# SENSOR THINNING AND BREAKDOWN




## Succesful wafer thinning and back-side processing

- Leakage current: <1 µA/cm²
- No early breakdown

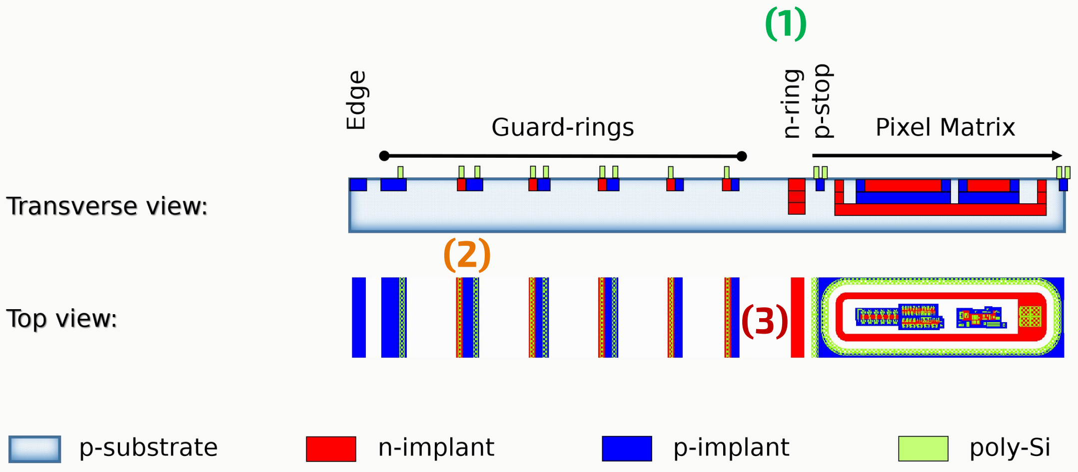



## Improved breakdown voltage in LF-Monopix2

## (~ 460- 500 V)

due to guard-ring optimization

## What changed from LF-Monopix1 to 2?

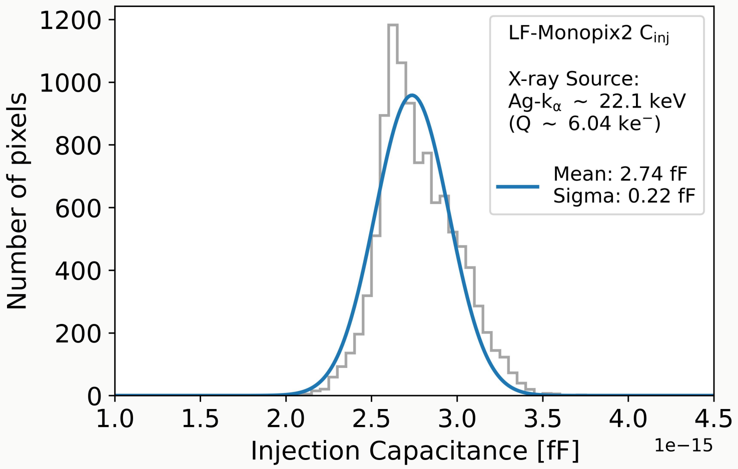


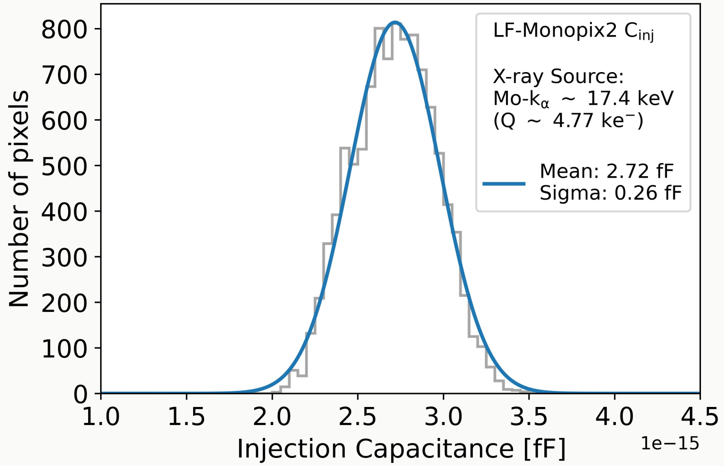

- Adding Deep N-well on innermost n-ring **(1)**
  - P+N combination in guard-rings **(2)**
- Reduction of guard-ring number -> Increase in spacing between n-ring and 1st g. ring **(3)**

# CALIBRATION OF THE INJECTION CIRCUIT

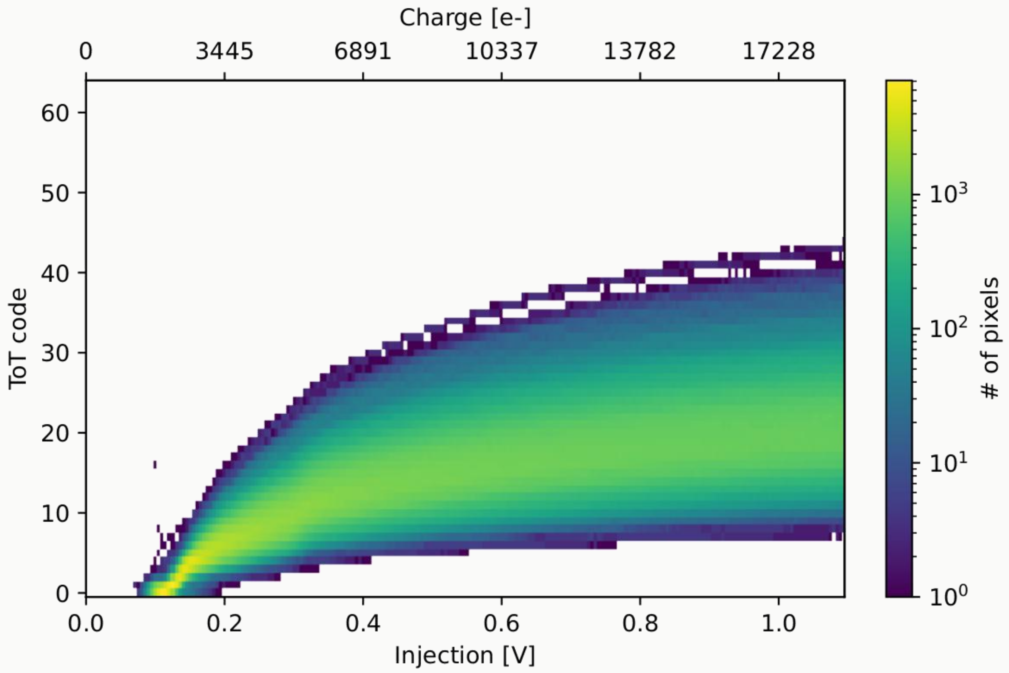
Comparing (per pixel) the mean ToT for a known injection voltage and well-defined fluorescence peaks:

**$C_{inj}$ ~ 2.73±0.24 fF**



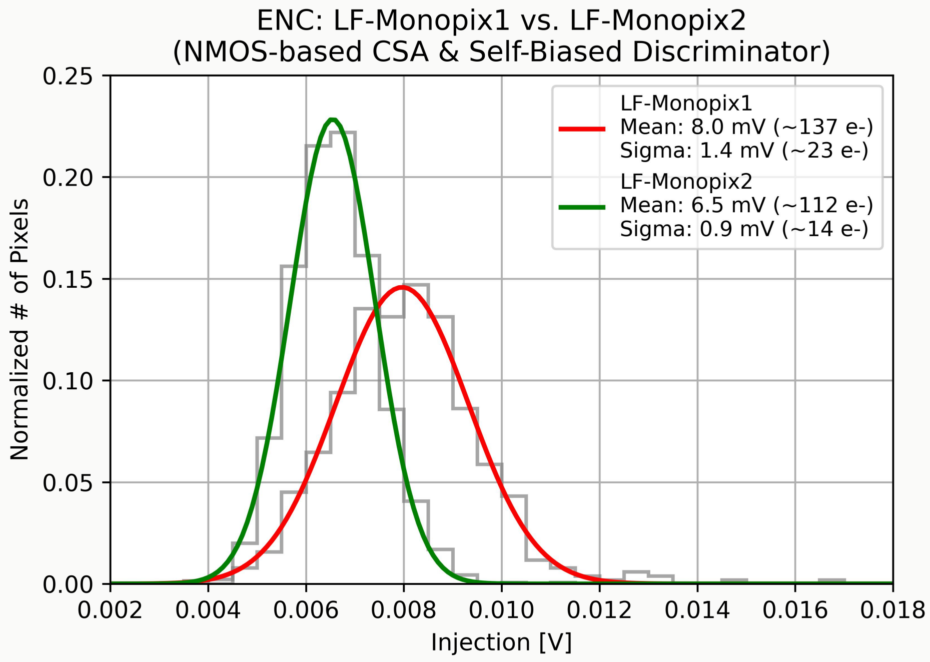




**Each pixel's ToT response can be calibrated to charge**



# ENC & GAIN

## ENC from LF-Monopix1 to LF-Monopix2




**Decrease of ~20-30% in mean ENC and dispersion**

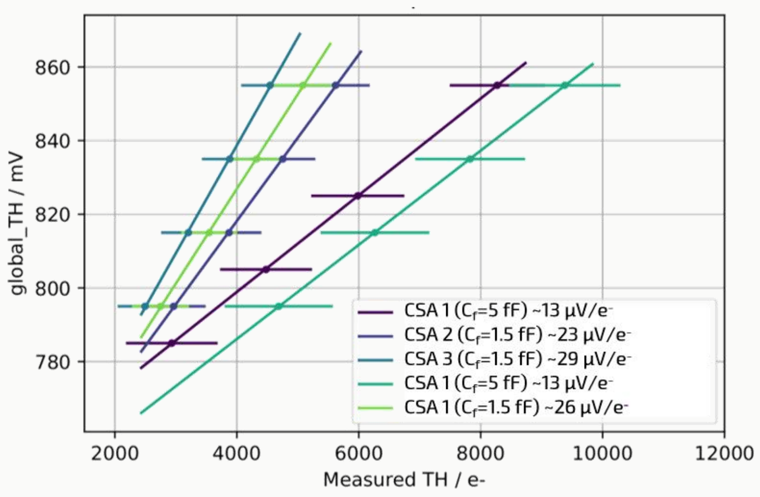
for the same front-end implementation

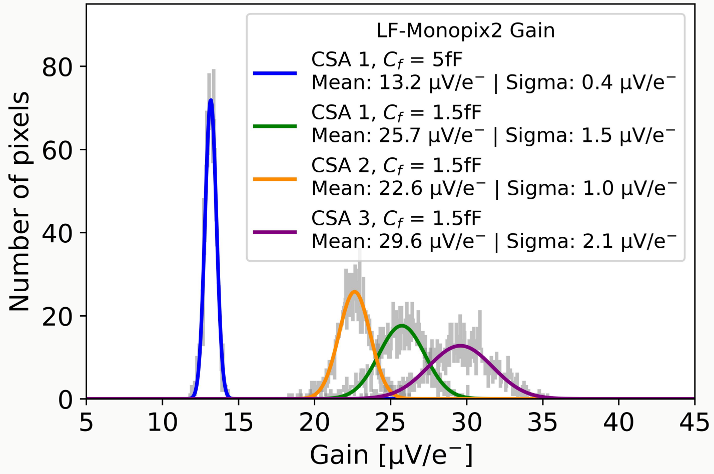
(As expected from smaller pixel ~ $C_d$)

$$\mathrm{ENC}^2 = a_{\mathrm{shot}}\,\tau + a_{1/\mathrm{f}}\,C_D^2 + a_{\mathrm{therm}}\,\frac{C_D^2}{\tau}$$

## Gain

$$V_{csa} = \frac{Q}{C_f + \frac{C_d + C_f}{A_{csa}}}$$



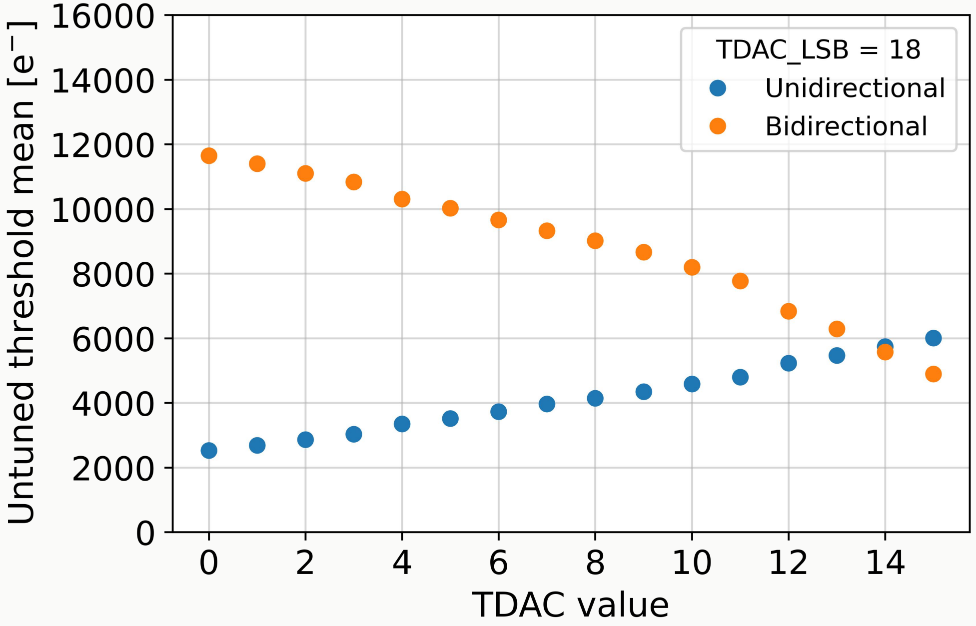

- Linear gain response
- Both old and new CSAs benefit from a smaller $C_f$

# FRONT-END TUNING

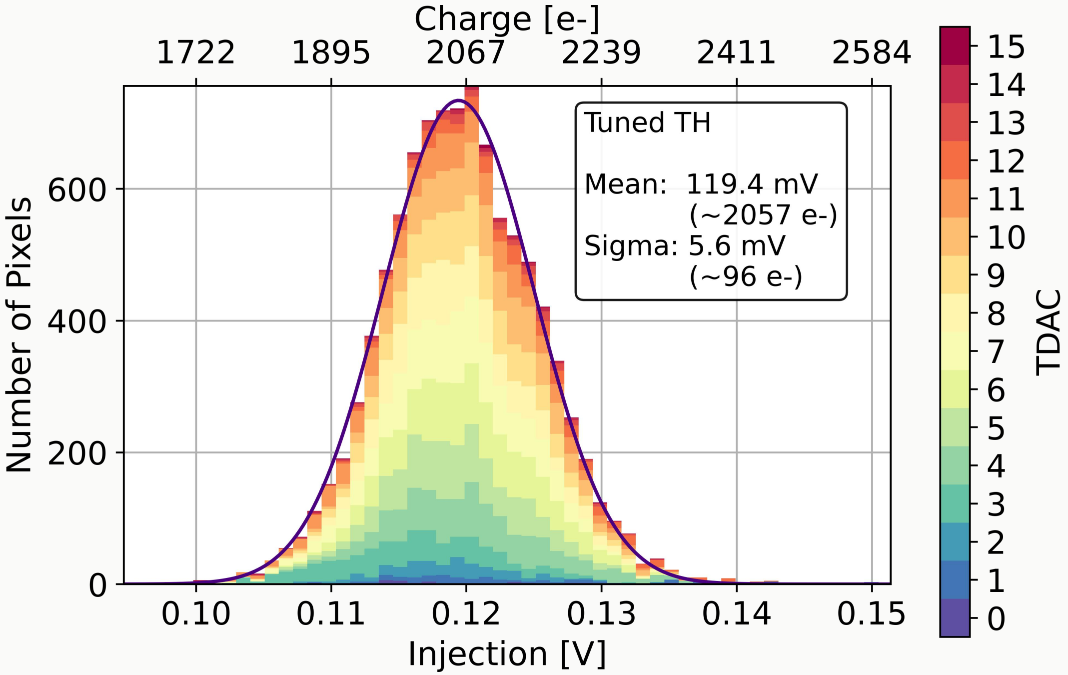
→ **Original threshold dispersions ~600-750 e⁻**

**Two threshold tuning circuit schemes:**

- Current source for unidirectional polarization
- Current source and sink for bidirectional polarization (~2 times the tuning range for same LSB)




**Tuned threshold dispersion ~100e⁻**



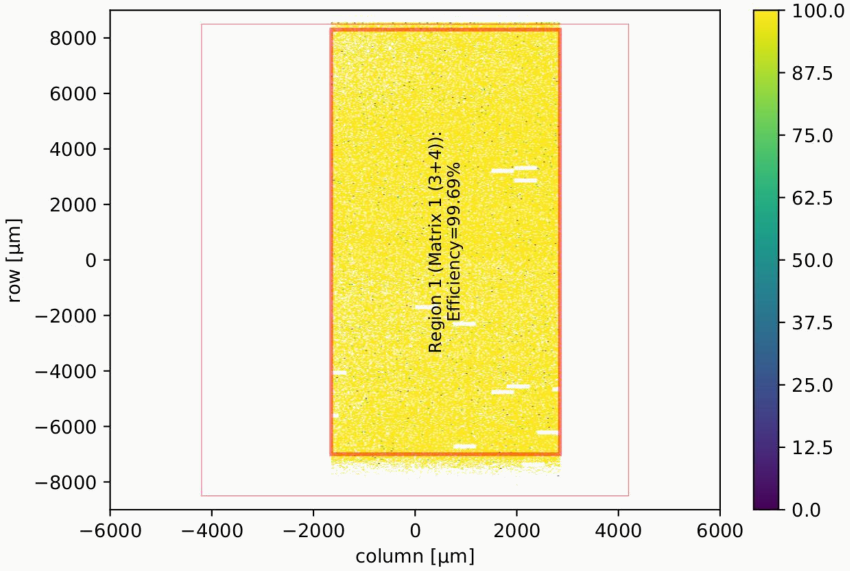

- Normally distributed TDAC values
- Only 1/3 of the maximum TDAC bias current

# HIT & IN-TIME EFFICIENCY

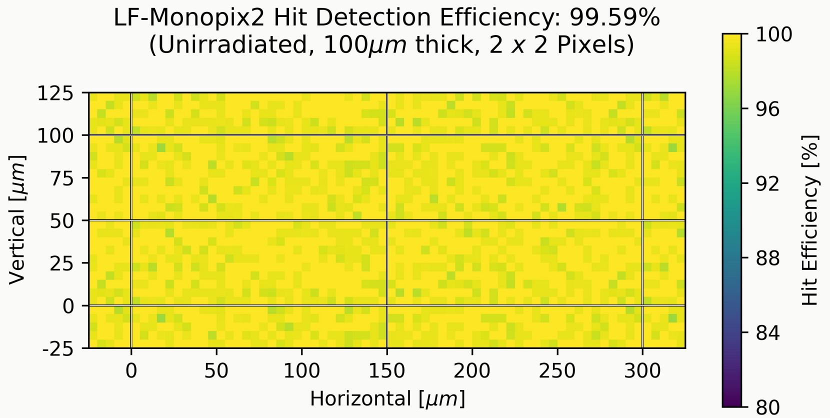
- **Unirradiated chip exposed to 5 GeV $e^-$ @ DESY**

(100 µm thick | Bias: 60V | Mean threshold ~2ke$^-$ | Noise Occ. < $10^{-7}$)

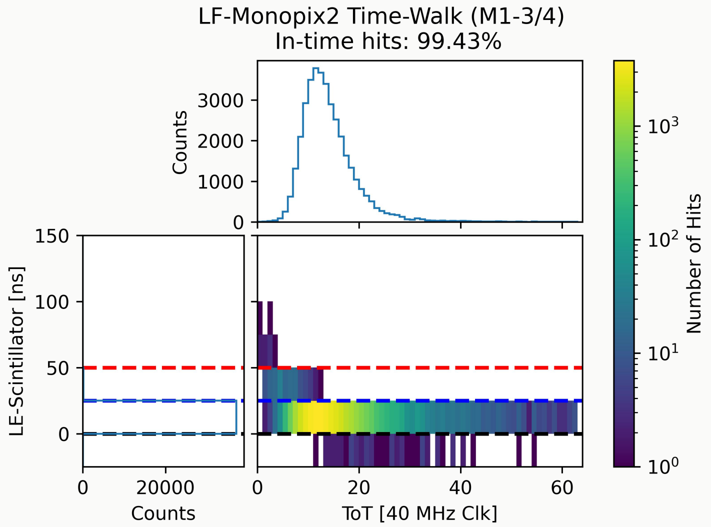
**Efficiency map of the full matrix**




**Efficiency projected onto a 2x2 pixel array**




**Time-walk distribution of seed pixels in efficient events**




- **Hit detection efficiency and in-time events >99%**
- **~2.5% improvement in in-time efficiency (at the same threshold) with respect to LF-M1**

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

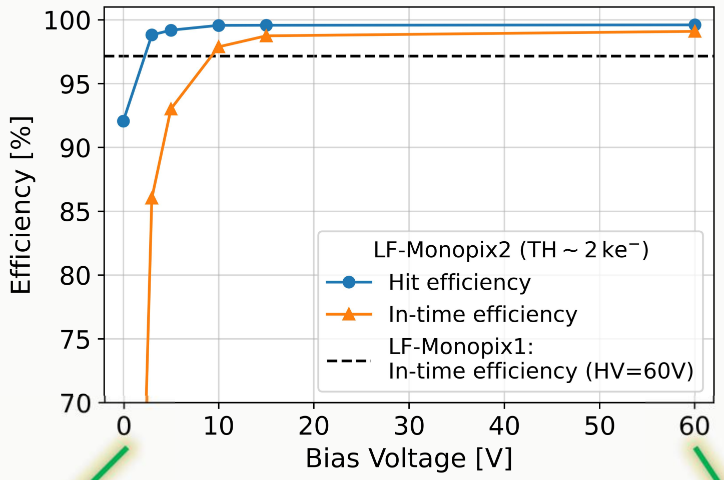
# HIT & IN-TIME EFFICIENCY

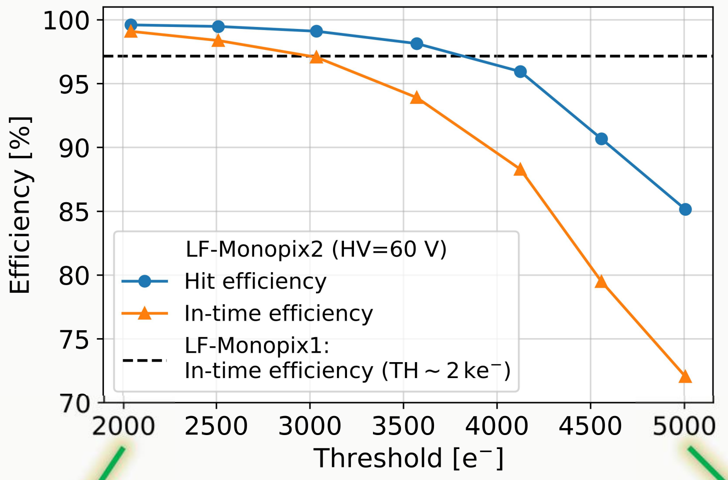
- **Variation with bias voltage:**

MIP signal dependent of the depleted volume

- **Pronounced drops in pixel corners:**

Charge sharing



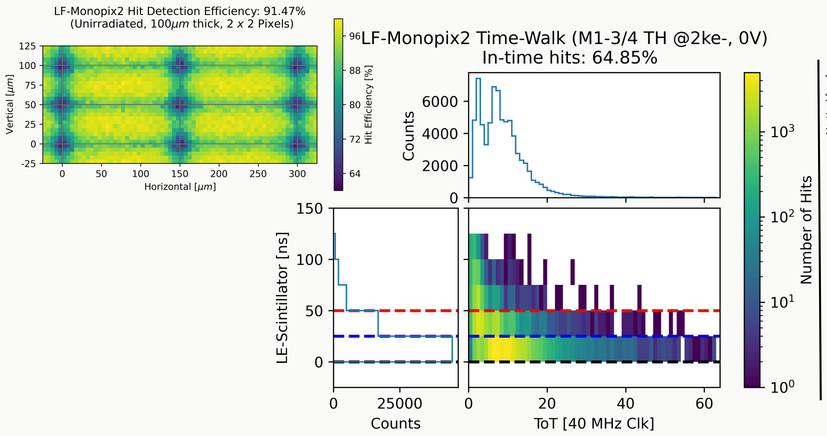



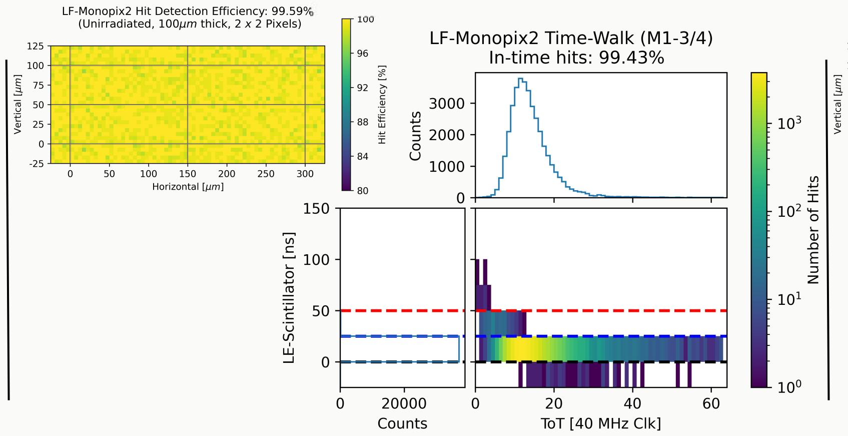

- **Variation with threshold:**

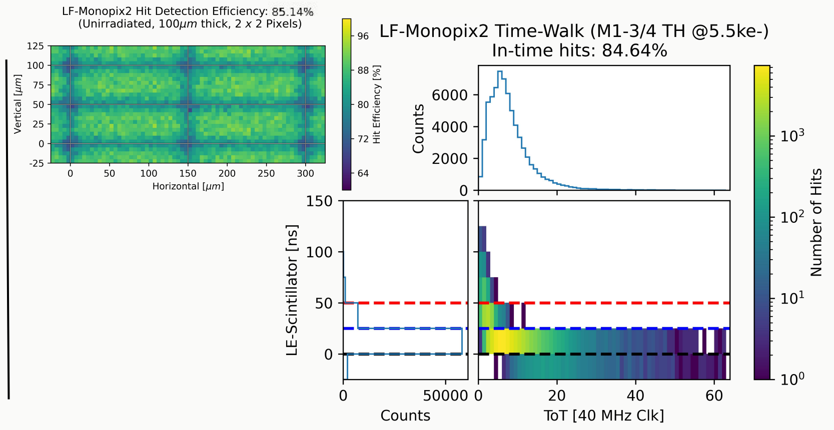
Cut on MIP signal

- **Timing dependency:**

Front-end away from its operation point. (Signal ~6ke-, TH ~1.5ke-)



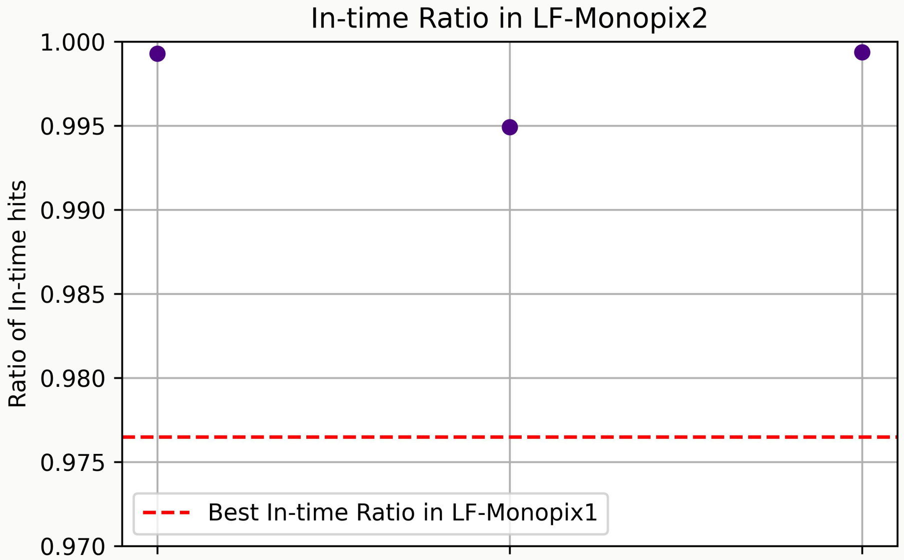



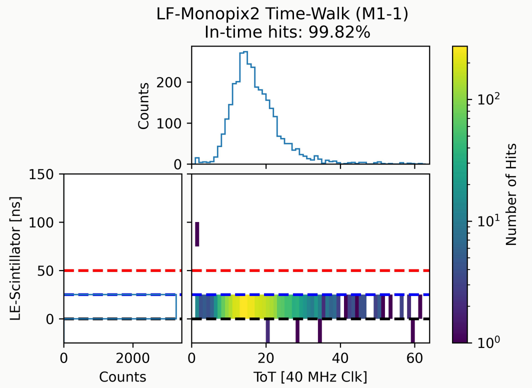
# TIMING VS FEEDBACK CAPACITANCE

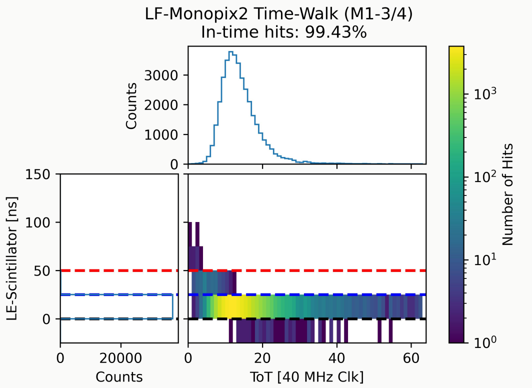
**The increase in gain results in all efficient events detected within 25 ns**

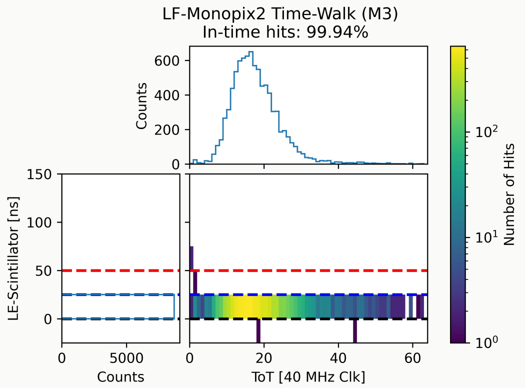
( Bias: 60V |
Mean threshold ~2ke)




| CSA 1 ($C_f$=1.5 fF) | CSA 1 ($C_f$=5 fF) | CSA 3 ($C_f$=1.5 fF) |
|---|---|---|



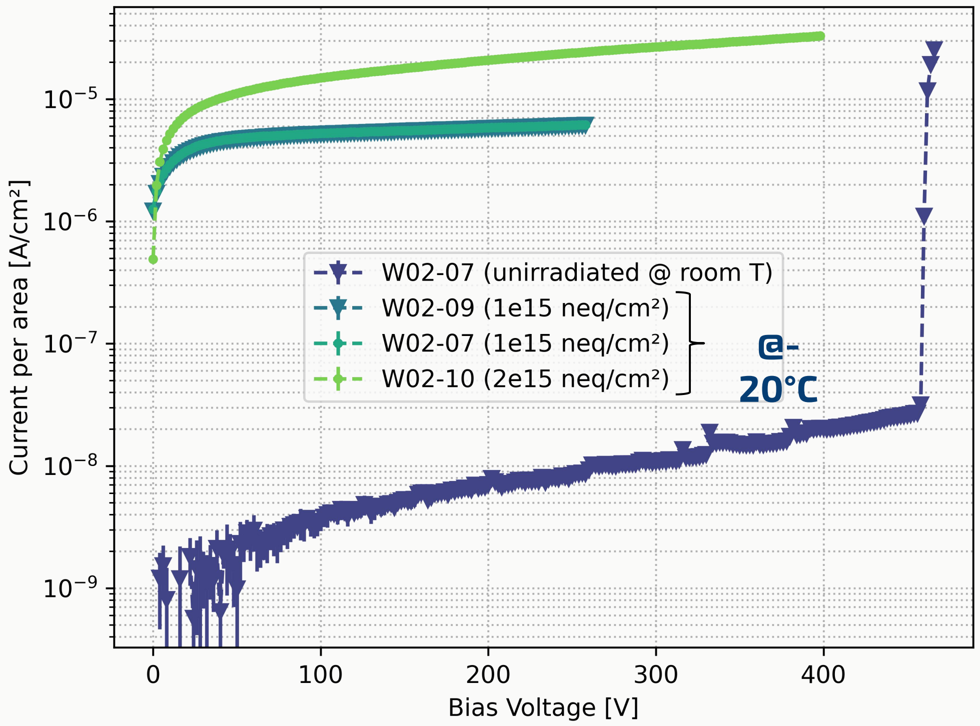



# NIEL DAMAGE: LEAKAGE CURRENT & ENC

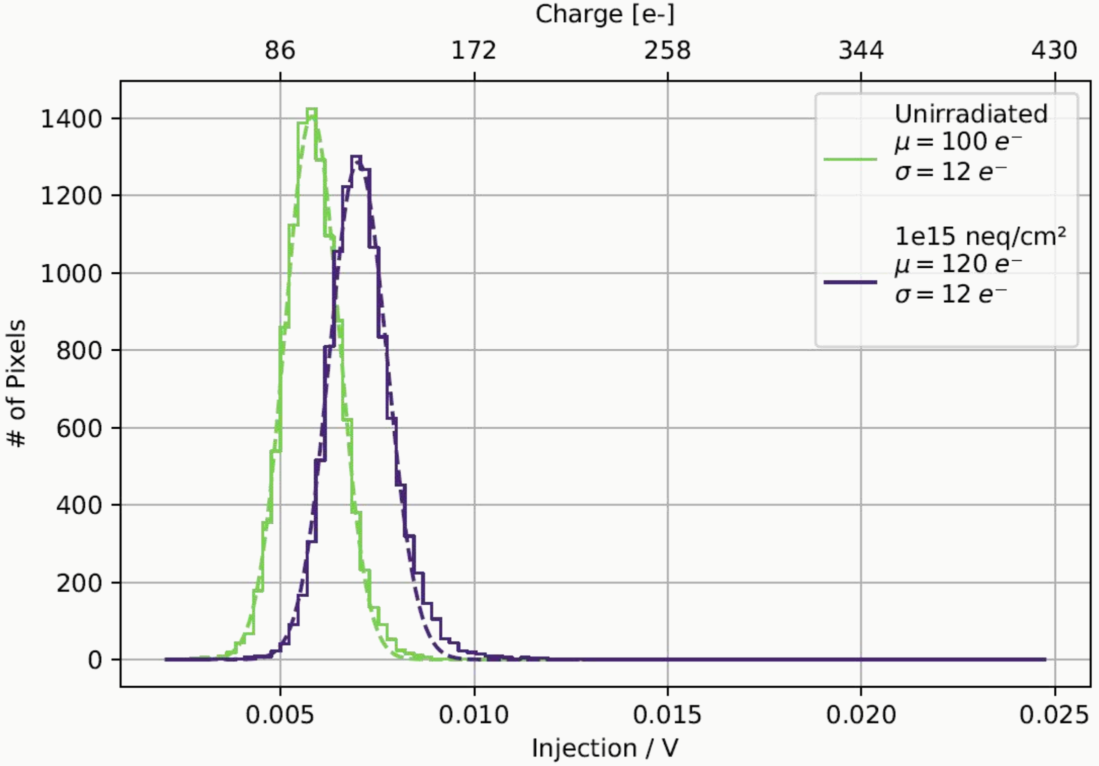
**NIEL → Generation/Recombination levels in band gap → Higher leakage current → Higher ENC**

- Samples irradiated with protons up to fluences of $1 \times 10^{15}$ $n_{eq}/cm^2$ (Bonn) and $2 \times 10^{15}$ $n_{eq}/cm^2$ (MC40 Birmingham)

**Leakage current after NIEL fluence of $2 \times 10^{15}$ $n_{eq}/cm^2$** ~30 µA/cm² (@400V)



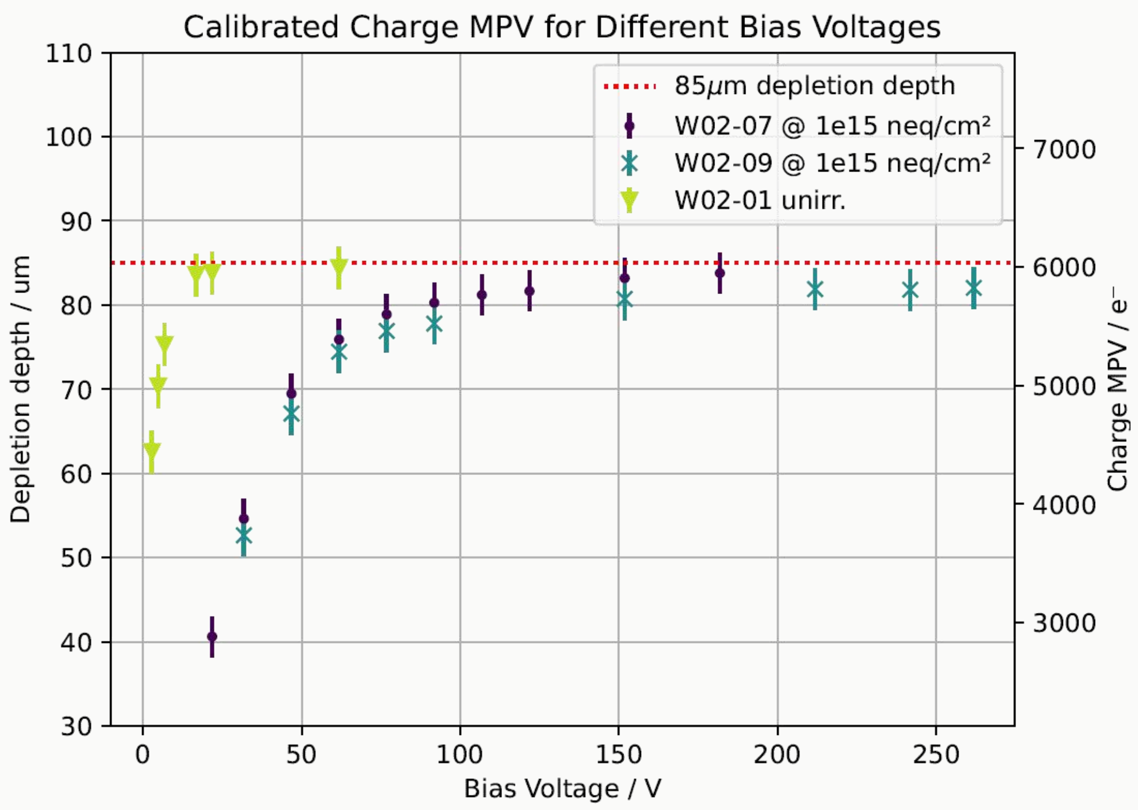

**15-20% increase in ENC due to higher bulk leakage current**



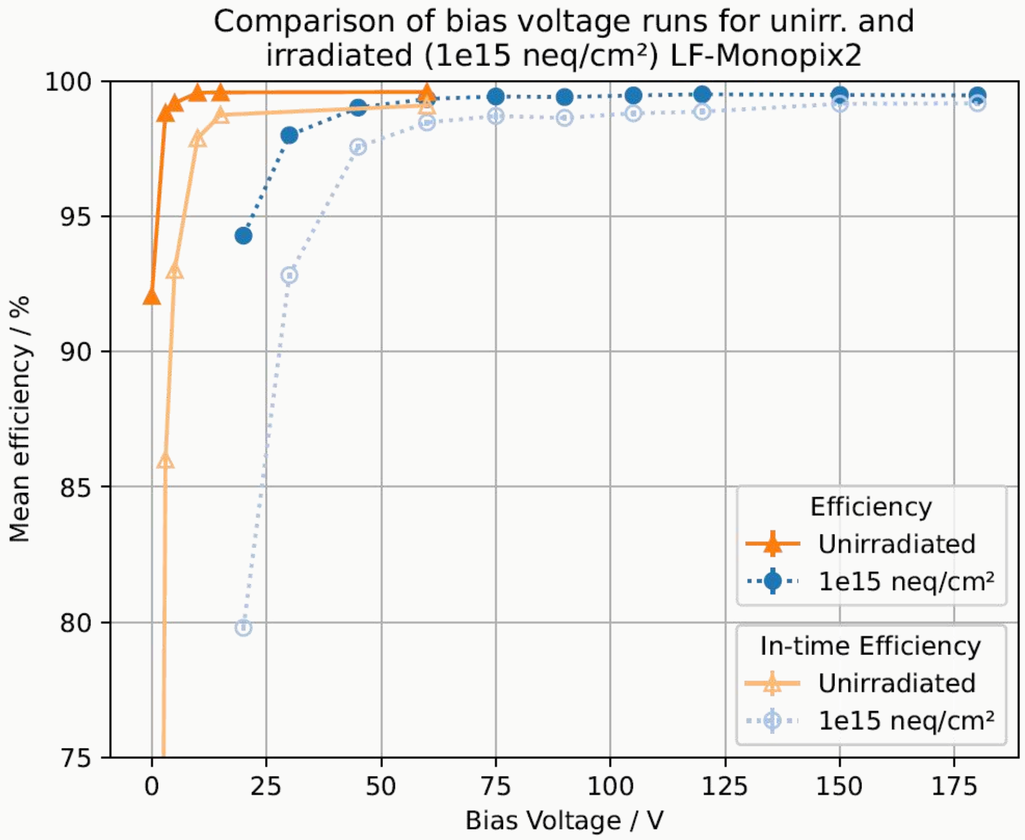
# NIEL DAMAGE ($1X10^{15}$ $N_{EQ}/CM^2$): DEPLETION

**NIEL → Change of effective doping concentration → Larger voltage required for full depletion**

## 85 µm thick Si: Fully depleted from ~150 V



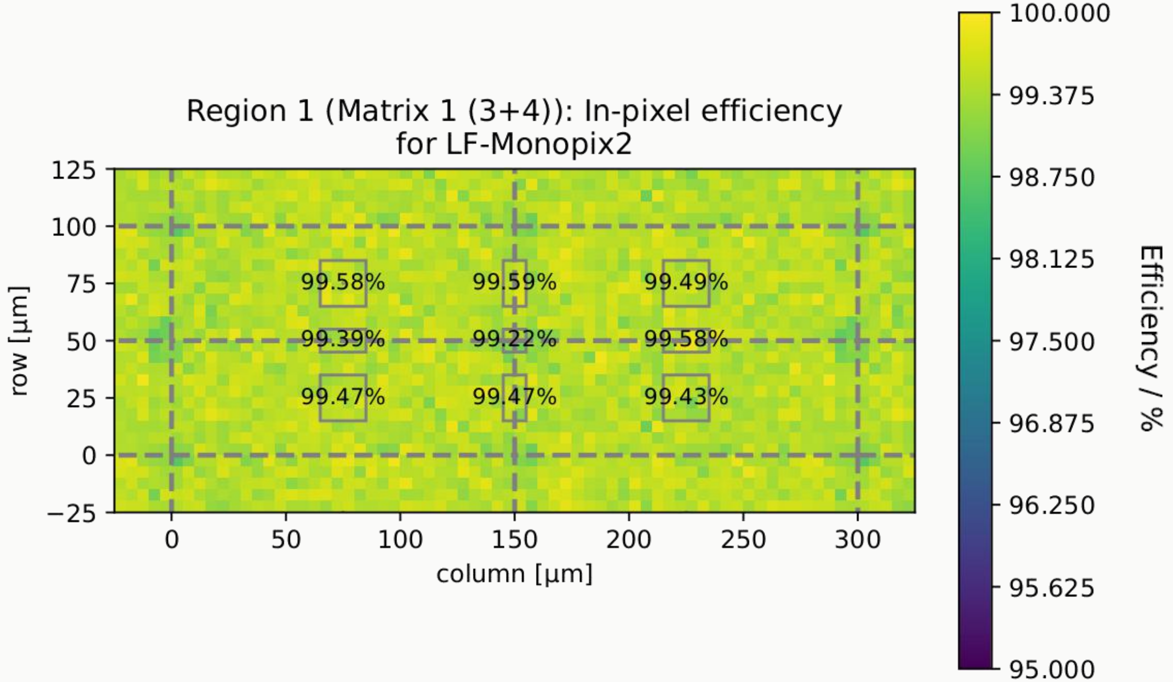

## Efficiencies before & after irradiation



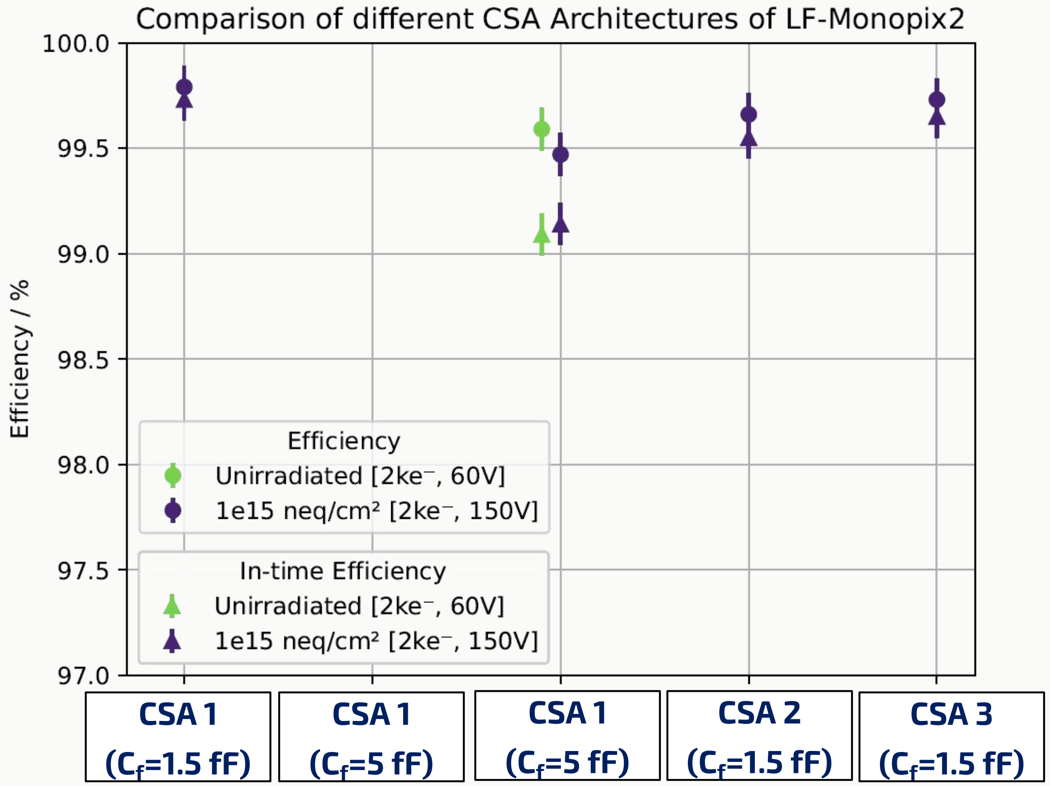
# NIEL DAMAGE ($1X10^{15}$ $N_{EQ}/CM^2$): HIT & IN-TIME EFFICIENCY

**Mean hit detection efficiency of 99.5% for a fully depleted sensor**

( Bias: 150 V | Mean threshold ~2ke)




**Hit detection efficiency >99% in all front-ends and timing performance preserved**



# PERFORMANCE OVERVIEW

| | LF-Monopix1 | LF-Monopix2 |
|---|---|---|
| **CMOS process** | LFoundry 150 nm | |
| **DMAPS type** | Large collection electrode | |
| **P-type substrate** | CZ (>2 kΩ-cm) | |
| **Signal MPV [ke$^-$]** | 6 (85 μm) | |
| **Pixel pitch [μm$^2$]** | 250 x 50 | 150 x 50 |
| **Column length [mm]** | 6.5 | 17 |
| **Analog power [μW/pixel (mW/cm$^2$) ]** | ~45 (360) | ~28 (370) |
| **ENC [e$^-$]** | 150-200 | 90-130 |
| **TH. Dispersion [e$^-$]** | ~1000 → (Tuned) 100 | ~600-750→ (Tuned) 100 |
| **Max. Bias Voltage [V]** | 260 - 300 | 460 - 500 |
| Irrad Level<br>**Hit (in-time) Efficiency [%]** | NIEL, 1x10$^{15}$ $N_{eq}$/cm$^2$ (neutrons)<br>[TH~2.3 ke$^-$]<br>99.4 (in-time ~97) | NIEL, 1x10$^{15}$ $N_{eq}$/cm$^2$ (protons)<br>[TH~2 ke-]<br>99.5 (in-time >99) |

# CONCLUSIONS & OUTLOOK

- Fully functional DMAPS in 150 nm CMOS process and large electrode pixel design
- Column-drain readout architecture in a 1.7 centimer-long column
- All signal processing and R/O electronics placed within a 150 x 50 μm$^2$ pixel (without signs of digital coupling)
- Detection and in-time (25 ns.) efficiency > 99% after proton fluence of 1x10$^{15}$ $N_{eq}$/cm$^2$
- **Current outlook:**
    - **Next week:** Test beam (DESY) for samples exposed to higher NIEL fluence (2x10$^{15}$ $N_{eq}$/cm$^2$)
    - **Second half of 2023:** X-ray irradiation to assess TID tolerance of new front-ends

# Thank you for your attention.

# Questions?

This project has received funding from the Deutsche Forschungsgemeinschaft DFG (grant WE 976/4-1), the German Federal Ministry of Education and Research BMBF (grant 05H15PDCA9) and the European Union's Horizon 2020 Research and Innovation programme under grant agreements 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) and the E3 beam-line of the electron accelerator ELSA operated by the university of Bonn.

*This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.*