PROGRESS IN DMAPS MONOPIX

J. DINGFELDER (U. BONN)

AND THE LF-/TJ-MONOPIX DESIGN AND MEASUREMENT TEAMS FROM

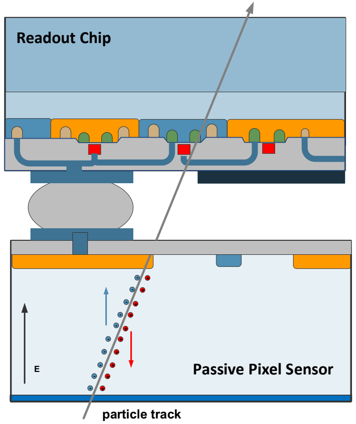
BONN, CERN, CPPM, CEA-IRFU

VERTEX 2021

SEPTEMBER 29, 2021

DMAPS - INTRODUCTION

I. Hybrid detector



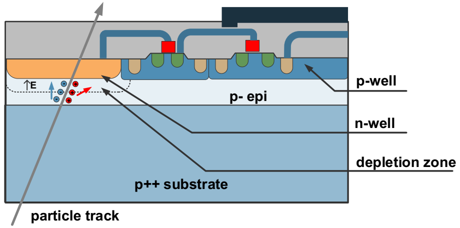
- Optimized dedicated sensor ➞ high radiation tolerance

✓

- Labor and cost intensive bump-bonding

✗

II. MAPS detector



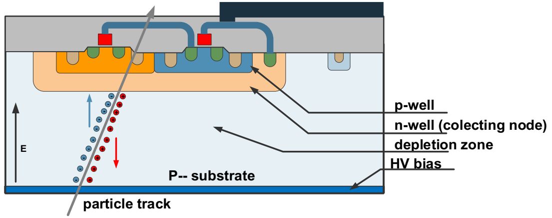
- Reduced material budget
- Lower module cost
- Larger wafers, throughput
- Fast turn-around time

✓

- The sensor volume is not fully depleted: Limited radiation tolerance

✗

III. Depleted MAPS (DMAPS) detector



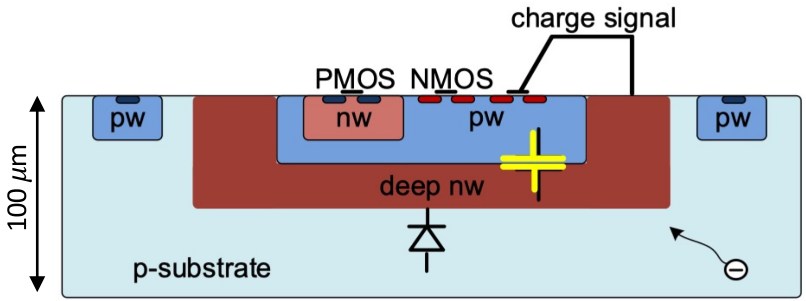
- CMOS processes offering high resistivity substrate (HR)
- High voltage biasing (HV)
- $d \sim \sqrt{\rho \cdot V}$

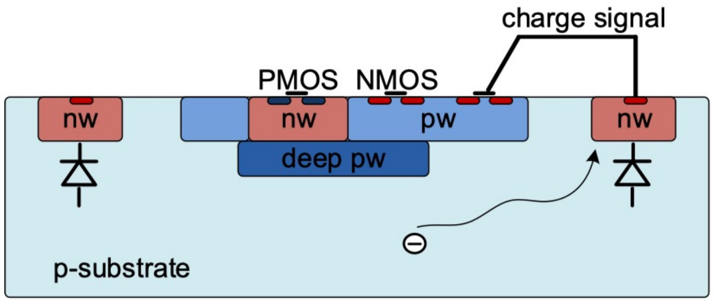
⇩

- Strong drift field
- Enhanced charge collection & radiation tolerance
- Faster charge collection

✓

LARGE VS. SMALL COLLECTION ELECTRODE





Electronics **inside** charge collection well

- **Large** collection electrode
  - short drift distances
  - few regions with low E field
  - less trapping

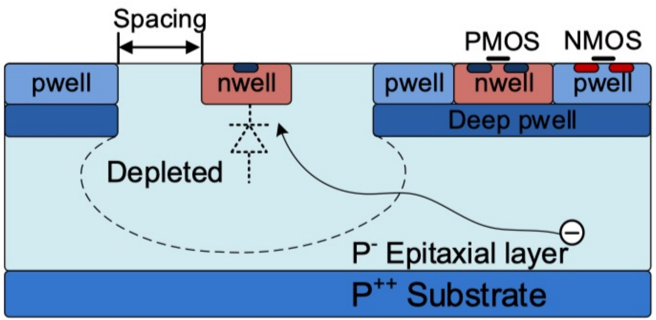
  } **radiation-hard**
- **Large sensor capacitance**
  - compromises noise and speed/power
  - risk of cross-talk (digital ⟶ sensor)

Electronics **outside** charge collection well

- **Small** collection electrode
  - longer drift distances
  - potentially regions with low E field

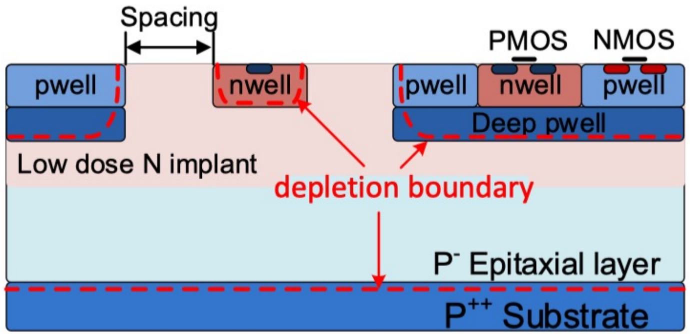
    ⇒ requires **modified process** for **radiaton hardness**
- **Small sensor capacitance** (< 5 fF)
  - lower analog power budget (noise, speed)
  - less prone to cross-talk

PROCESS MODIFICATION: TOWER JAZZ 180 NM CMOS



Standard process

- ALICE ITS type
- **High-resistivity** p-type epi (> 1 kΩ cm)
  ⇒ thickness typ. 25 μm
- Quadruple well
  ⇒ deep p-well shields n-well ⇒ **full CMOS**
- Reverse bias typ. – 6V
  ⇒ enhanced, but **not full depletion**
  ⇒ some charge collected only by diffusion
  ⇒ slow

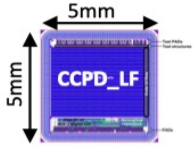


Modified process

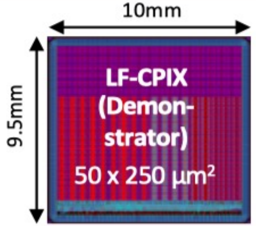
- Additional planar, low-dose N implant
  ⇒ depletion from two junction boundaries
  ⇒ **full volume can be depleted**
  ⇒ improved lateral charge collection
- Maintain **small capacitance**
- No significant circuit/layout changes

W. Snoeys et al. DOI: 10.1016/j.nima.2017.07.046

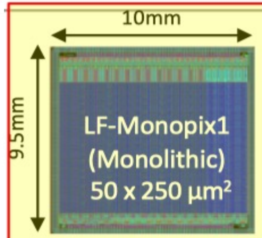
TWO DEVELOPMENT LINES



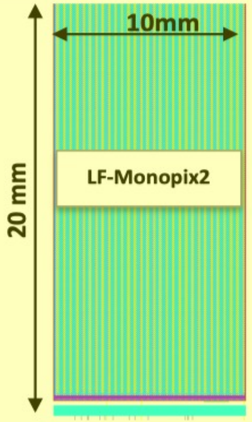
CCPD_LF
- *Subm. **Sep. 2014***
- *Fast R/O coupled to FE-I4*



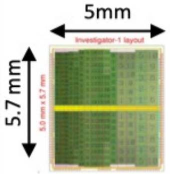
LF-CPIX (DEMO)
- *Subm. **Mar. 2016***
- *Fast R/O coupled to FE-I4*



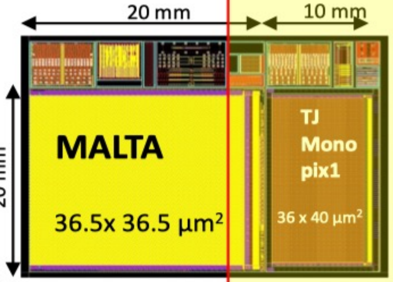
LF-Monopix1
- *Subm. **Aug. 2016***
- *Fast column drain R/O*



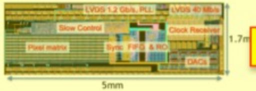
LF-Monopix2
- *subm.* **Q2/2020**
- *50 x 150 μm² pixels*
- *Full height matrix*
- *Fast column drain R/O*



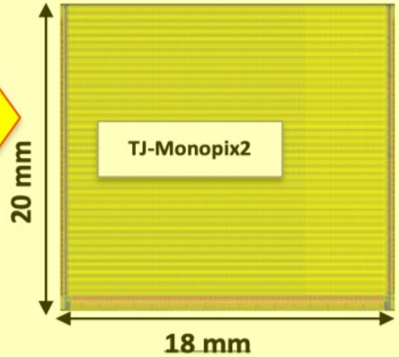
INVESTIGATOR
- ***2016***
- 8 x 8 pixel submatrices



MALTA (asynchronous) & TJ-Monopix1 (column drain)
- subm. **2018**
- large matrices
- fast asynchr & col. drain R/O



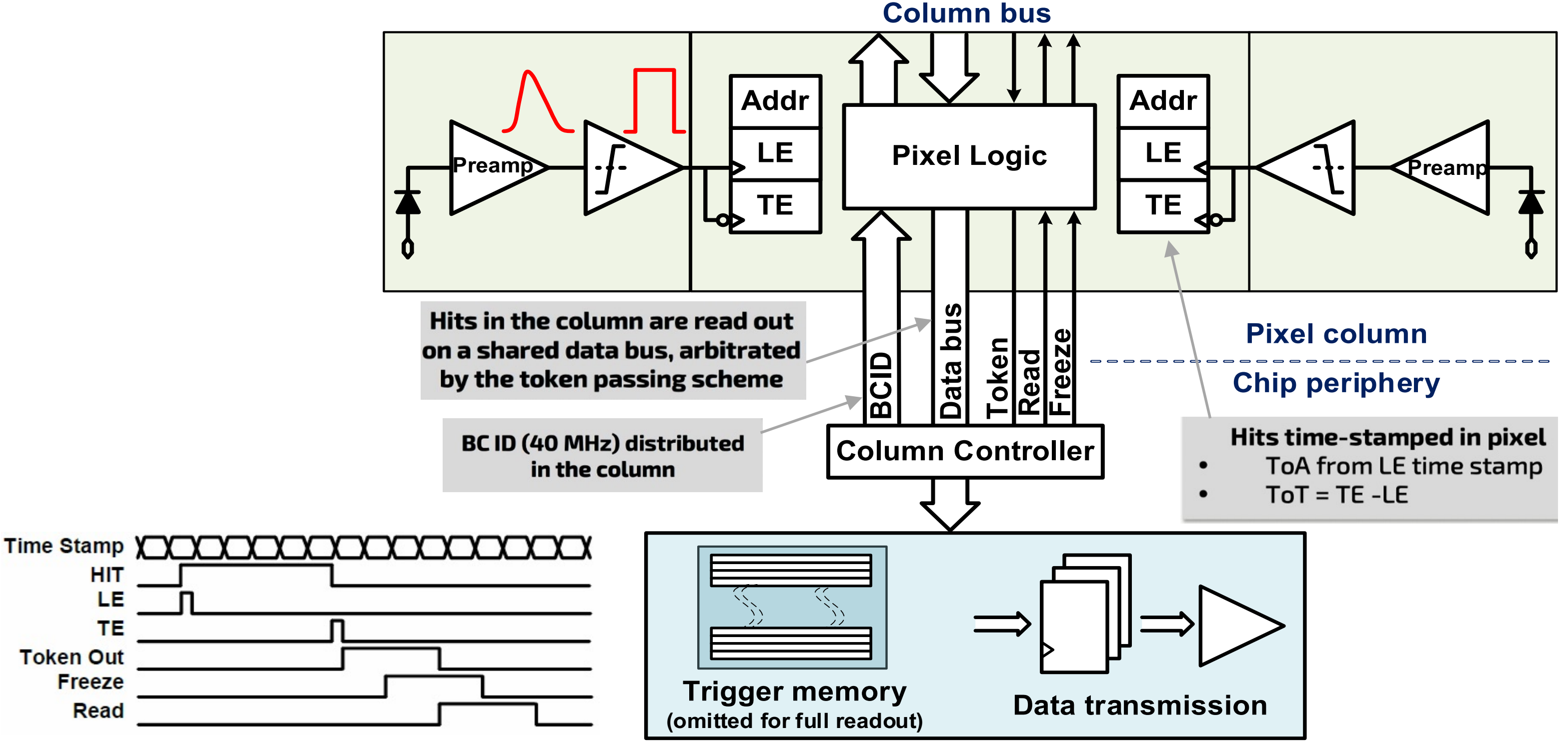
miniMALTA
- subm. **2018**
- measures for rad. hardness



TJ-Monopix2
- *subm.* **Q4/2020**
- *33 x 33 μm² pixels*
- *Full height matrix*
- *Fast column drain R/O*

READOUT ARCHITECTURE: COLUMN-DRAIN

- Derived from ATLAS FE-I3 readout chip
- Sufficient rate capability (~100 MHz/cm^2) with affordable in-pixel logic density for CMOS pixels



LFOUNDRY MONOPIX

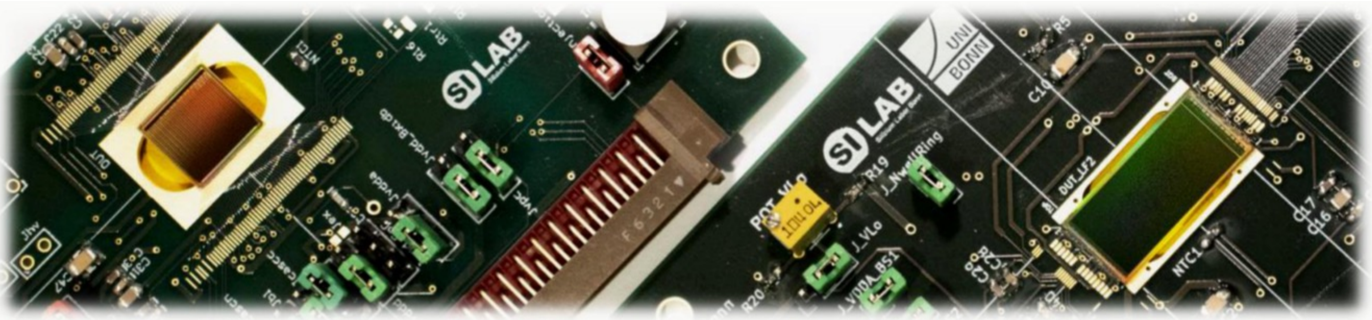
LFoundry 150 nm CMOS process

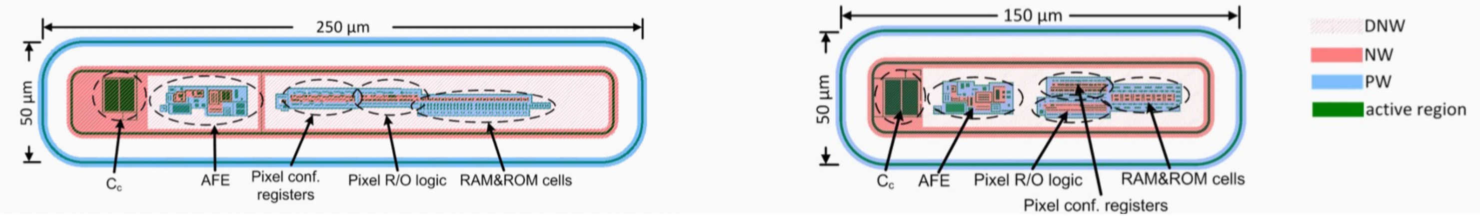
SI LAB Silizium Labor Bonn

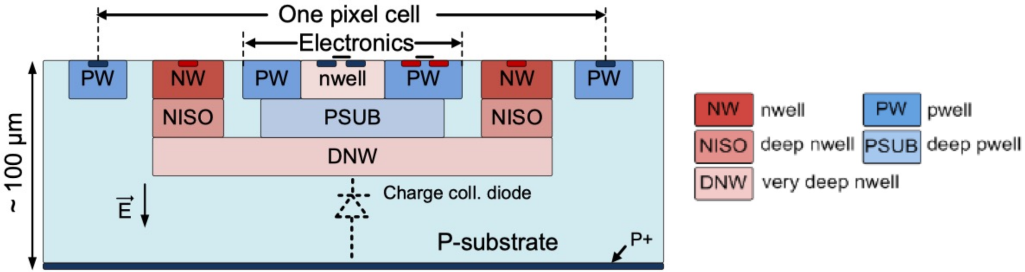
CPPM

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

LF-Monopix 1 (2017) | LF-Monopix 2 (2021)

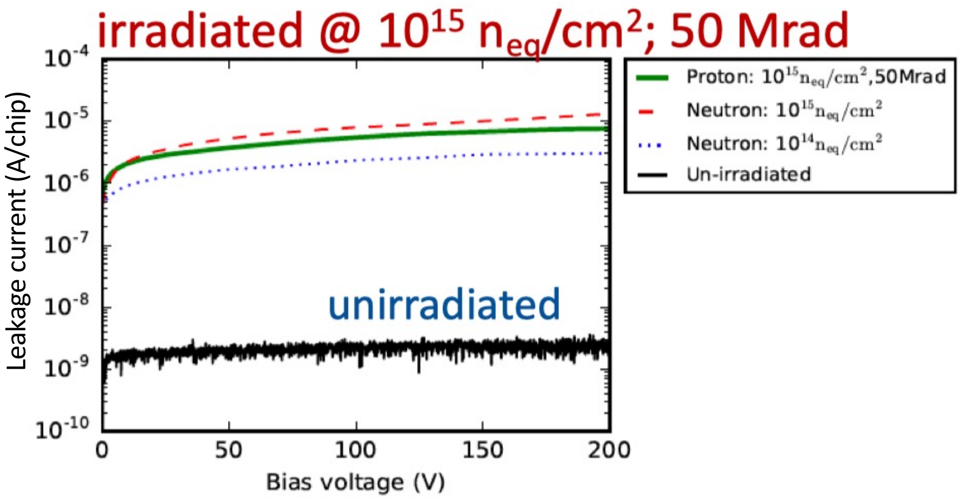


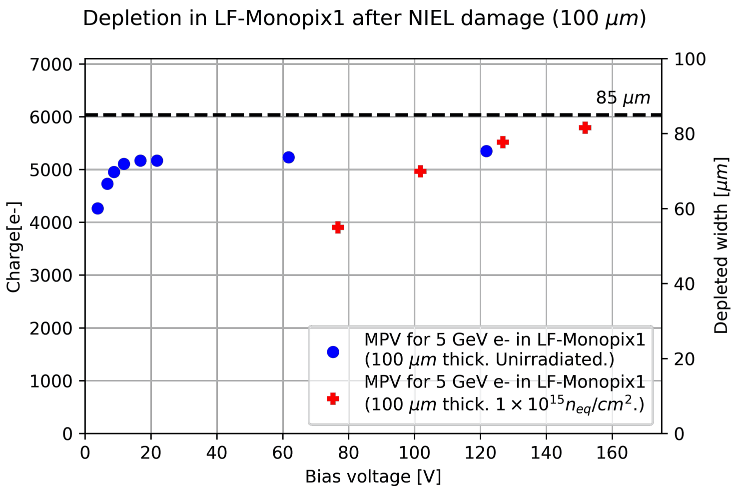




- **Large electrode**
- Resistivity > 2 kΩ cm
- Backside processing
- Voltages up to 350 V

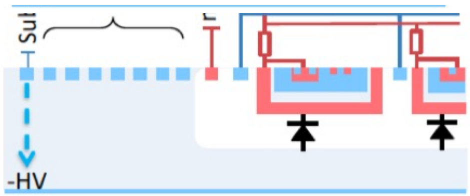
LF-MONOPIX 1: IRRADIATION – BREAKDOWN & DEPLETION





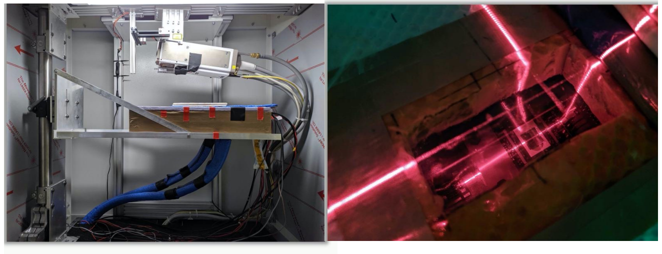
Breakdown voltage > 200 V
Increase in leakage current due to NIEL+TID damage after irradiation

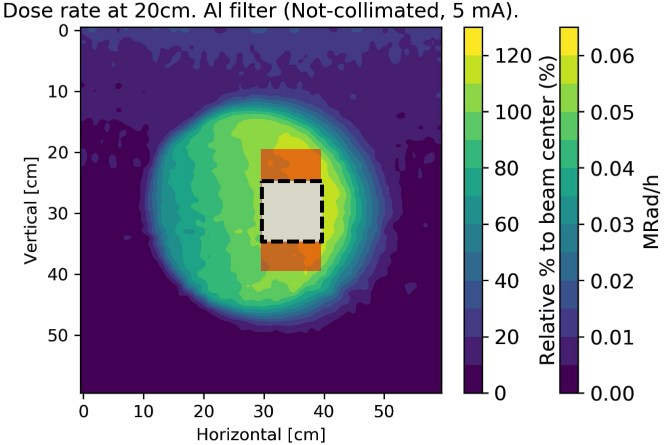
Full depletion voltage (for 100 μm):
unirradiated: ~ 10 V
irradiated: ~ 150 V

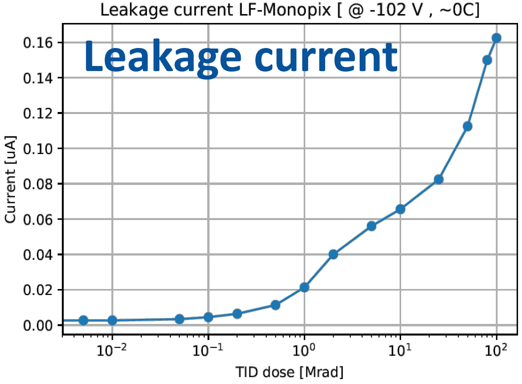


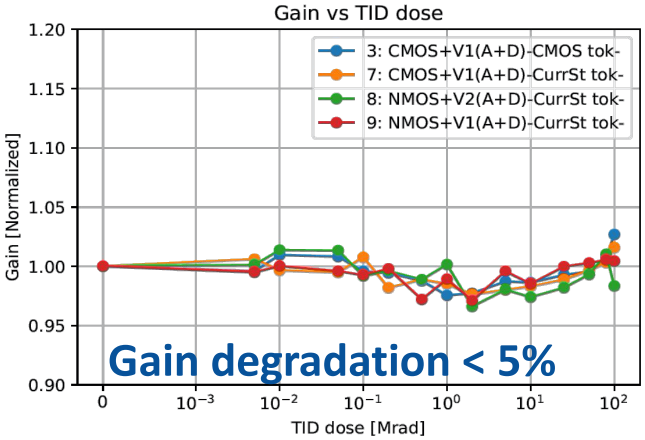
Guard-ring structure essential for high breakdown voltage (up to ~300 V)

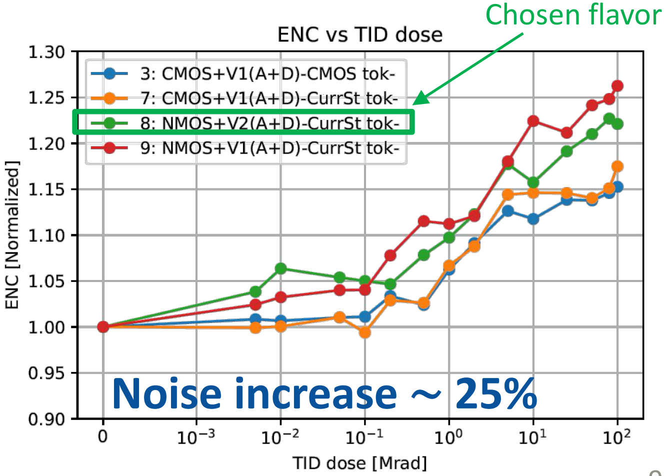
LF-MONOPIX 1: TID PERFORMANCE











- **Sample:** 100 um 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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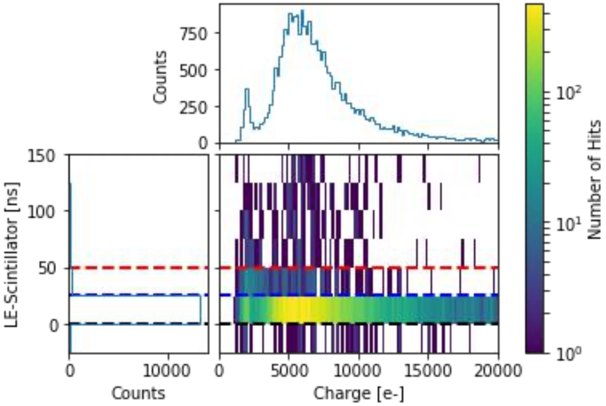
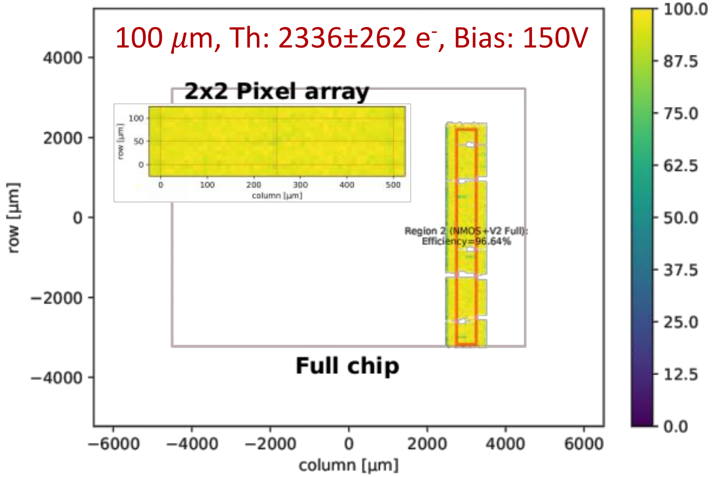
LF-MONOPIX 1: IN-TIME EFFICIENCY

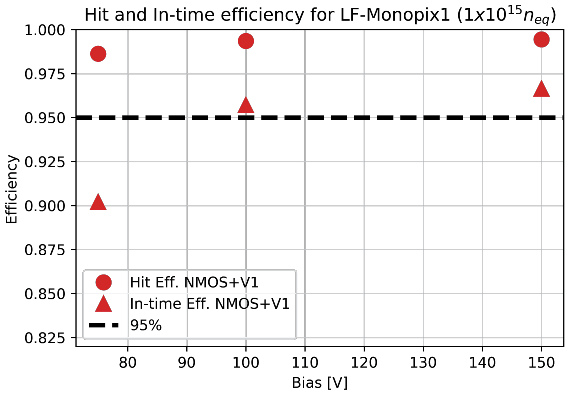
- **Hit efficiency:**
  - Unirradiated : 99.6% (100 μm, Th: 1885±227 e^-, Bias: 60 V)
  - 10^{15} n_{eq}/cm^2 : 99.4% (100 μm, Th: 2336±262 e^-, Bias: 150 V)
- **With timing (DESY test beam):**

Select only hits within first 25 ns → **In-time efficiency: 96.6%** (1×10^{15} n_{eq}/cm^2)

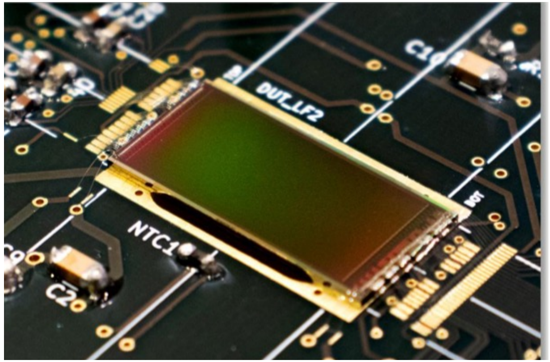
Need V_{bias} > 100 V for 95% in-time efficiency (1×10^{15} n_{eq}/cm^2)





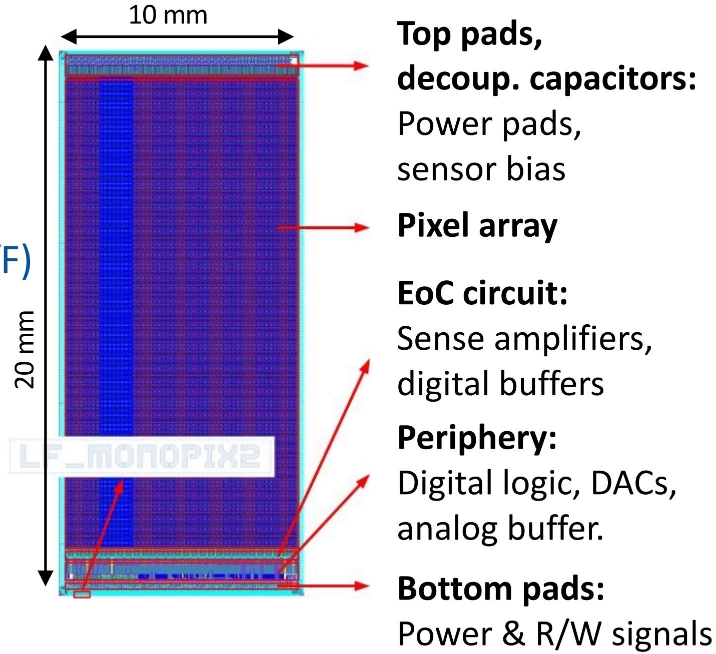


LF-MONOPIX 2



- Smaller pixel pitch: 50 × 150 μm^2
  - Reduced C_D (400 fF ⟶ 250-300 fF)
  - Larger array: 340 × 56 pixels
- Power: ∼ 30 μW/pixel

Submitted: Q2/2020, Received: Q1/2021



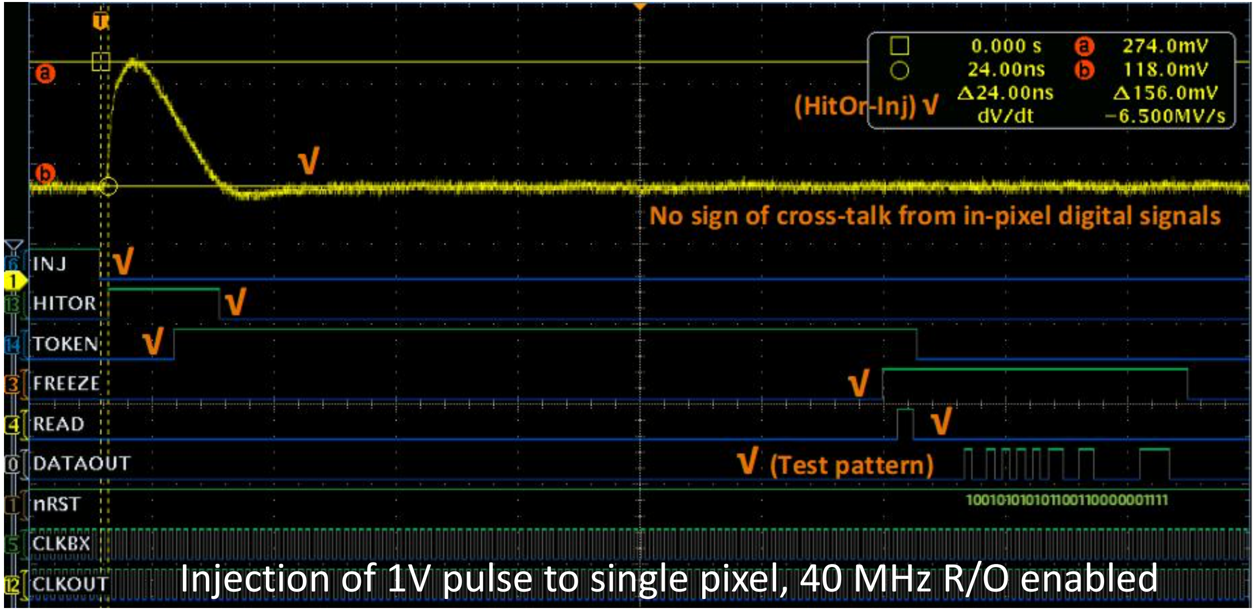
Column-drain readout in **2 cm long column**, with full in-pixel electronics

Radiation-hard Optimized FE for best timing and performance after NIEL and TID irradiation

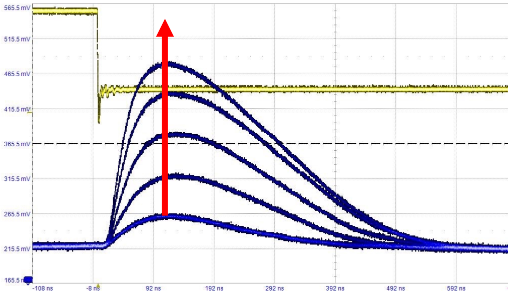
Improved pixel layout for further **cross-coupling mitigation**

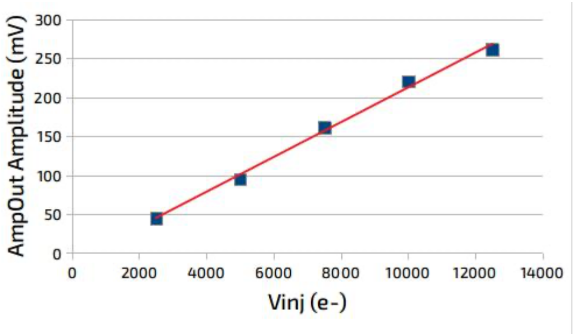
LF-MONOPIX 2: FIRST SIGNS OF LIFE

Correct readout operation and data output

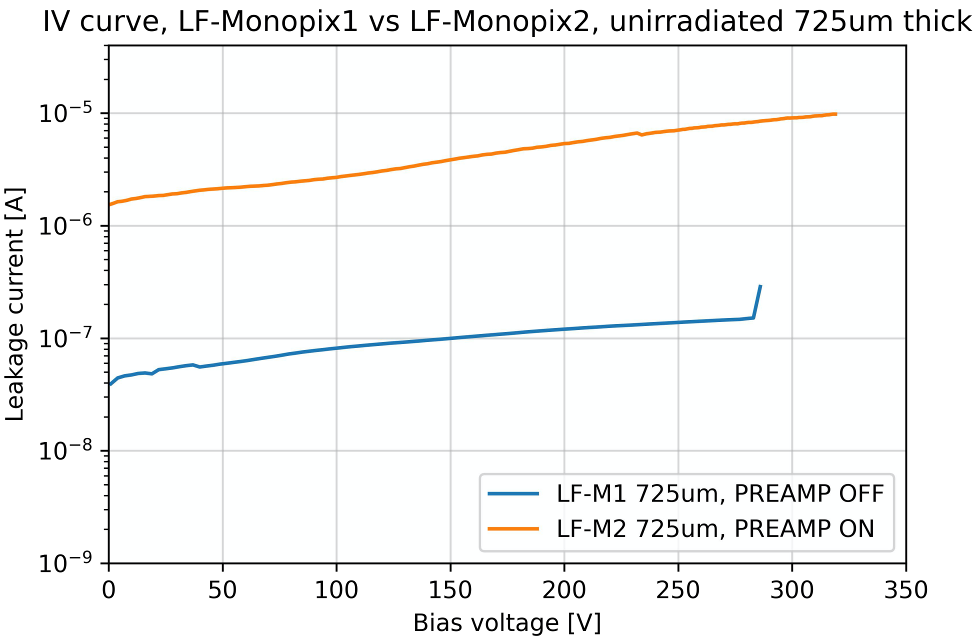


Linear CSA response





LF-MONOPIX 2: BREAKDOWN MEASUREMENT



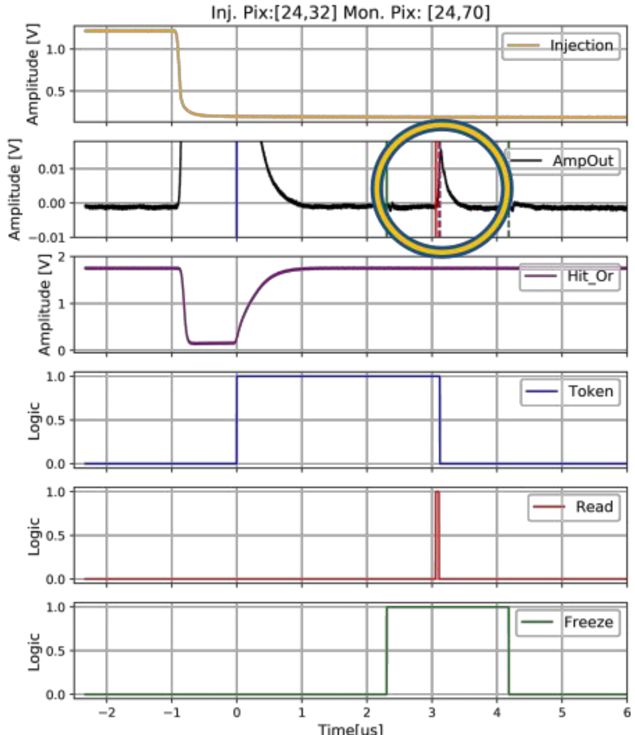
Lab measurement

at room temperature

Increased breakdown voltage from LF-Monopix 1 (280 V) to LF-Monopix 2 (**> 320 V**)

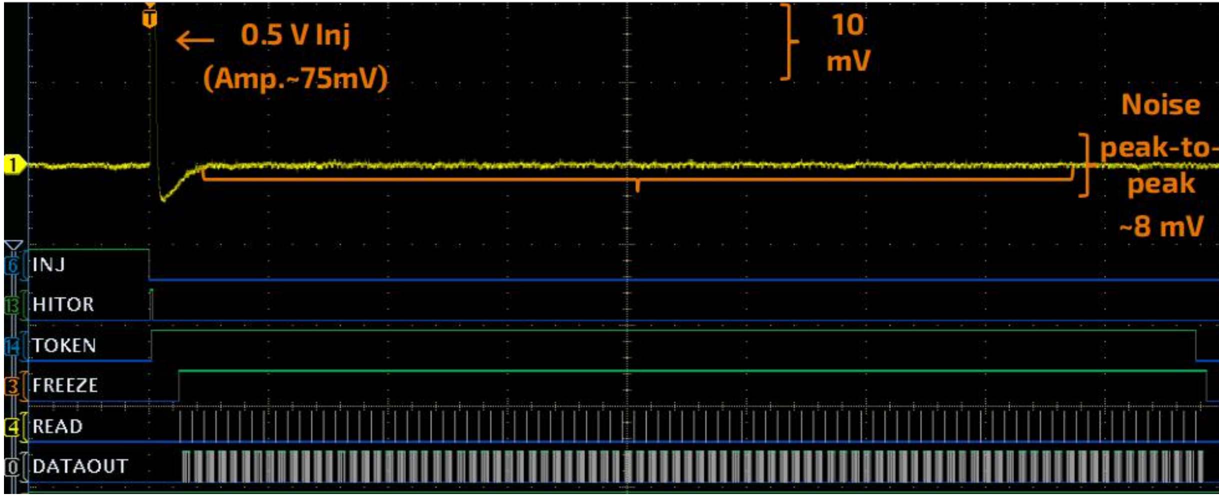
LF-MONOPIX 2: CROSS-COUPLING MITIGATION

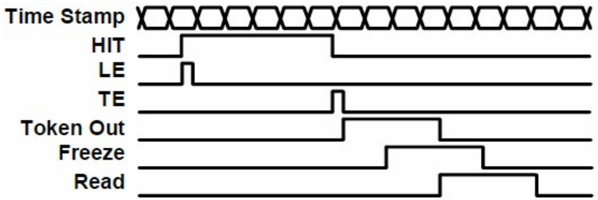
Observation in **LF-Monopix 1**:
Small **cross-coupling signal**
coincident with switching of READ inR/O



LF-Monopix 2 with **improved pixel layout**:

No sign of cross-coupling coincident with R/O digital switching while carrying signals from pixels across column

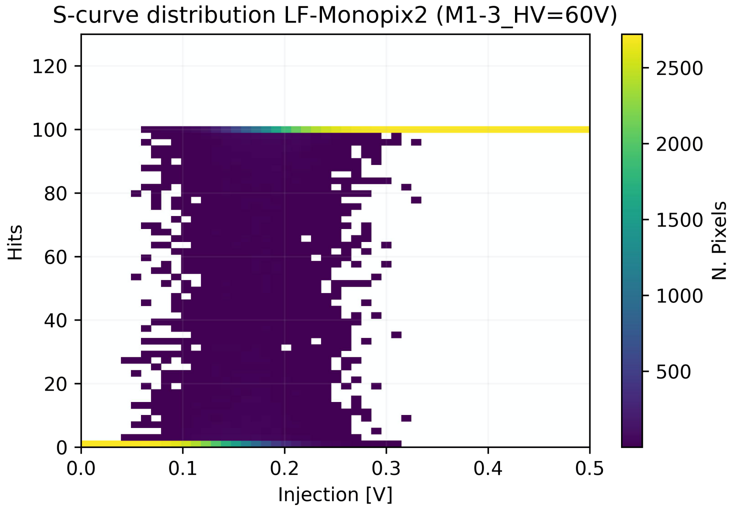


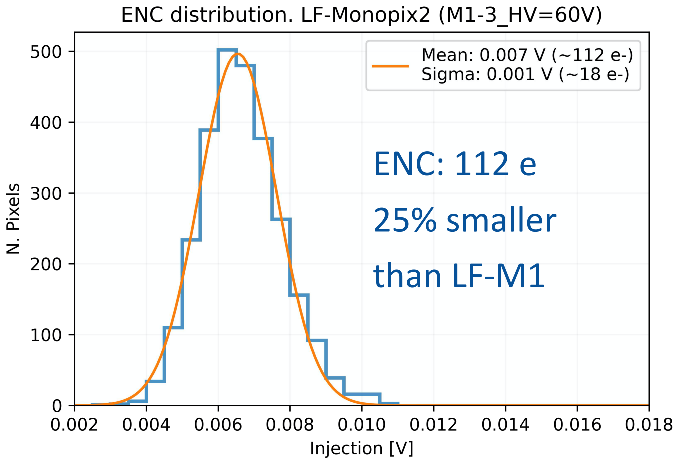


LF-MONOPIX 2: FRONT-END PERFORMANCE

Preliminary results with untuned FE,

calibrated using same C_{inj} as for LF-Monopix 1

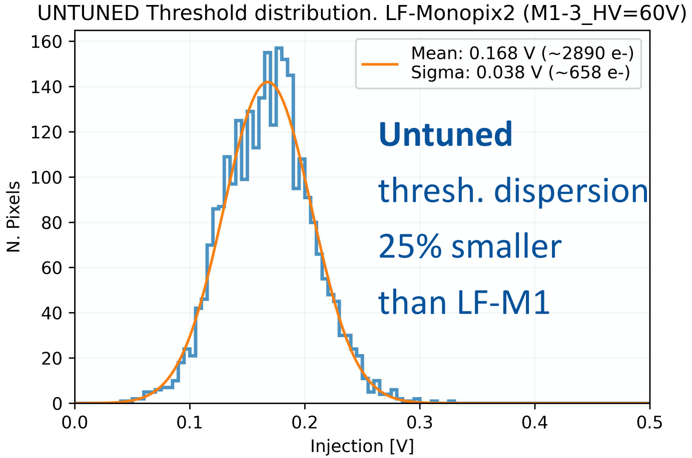




ENC: 112 e

25% smaller

than LF-M1



Untuned

thresh. dispersion

25% smaller

than LF-M1

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LF-MONOPIX: PERFORMANCE OVERVIEW

	LF-Monopix 1	LF-Monopix 2 Expected	LF-Monopix 2 Measured
Chip size	$1 \times 1\ cm^2$	$2 \times 1\ cm^2$	
Pixel size	$50 \times 250\ \mu m^2$	$50 \times 150\ \mu m^2$	
Noise	150-200 e	100-150 e	112 e
Threshold disp.	$\sim$ 100 e	80 e	untuned
Min. threshold	$\sim$ 1500 e	1000 e	$\sim$ 1000 e (TBC)
In-time threshold	$\sim$ 2000 e	1500 e	to be measured
Efficiency	97% (irrad., in-time)	> 97% (irrad., in-time)	to be measured

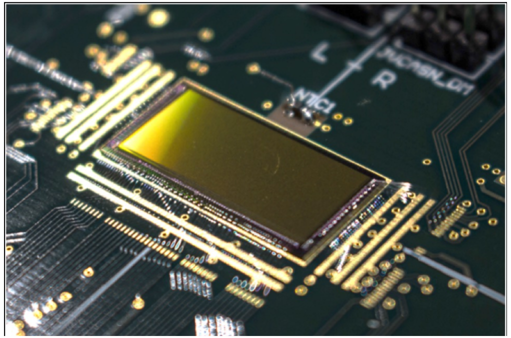
Very preliminary (1st meas.)

TOWERJAZZ MONOPIX

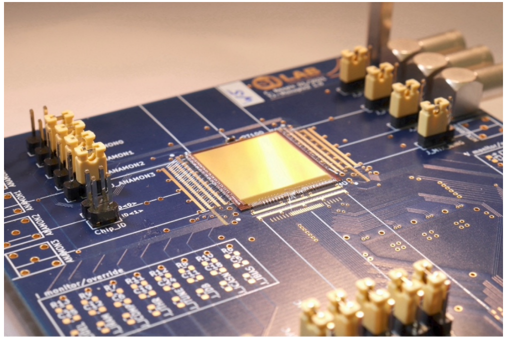
TowerJazz
180 nm CMOS
process

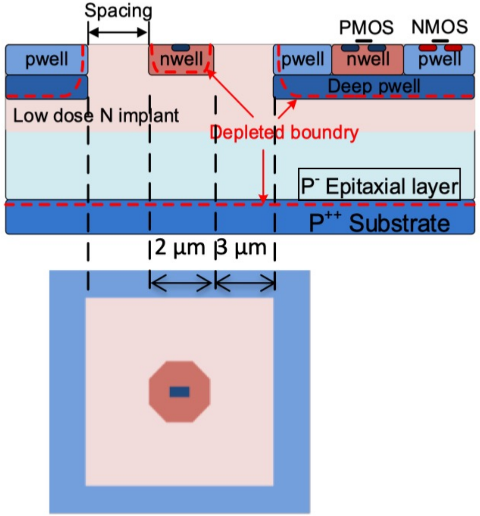
Derived from ALICE development (led by CERN)

TJ-Monopix 1 (2018)



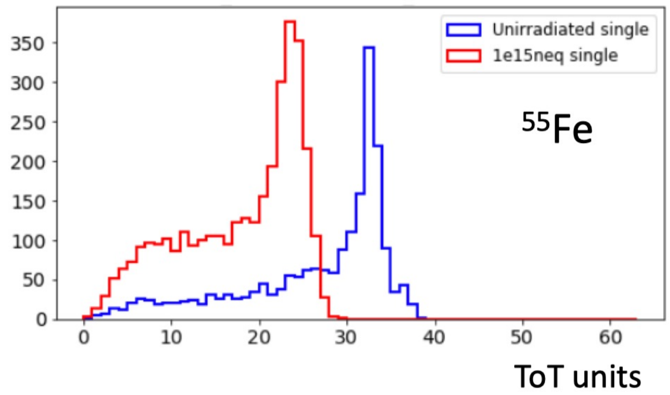
TJ-Monopix 2 (2021)

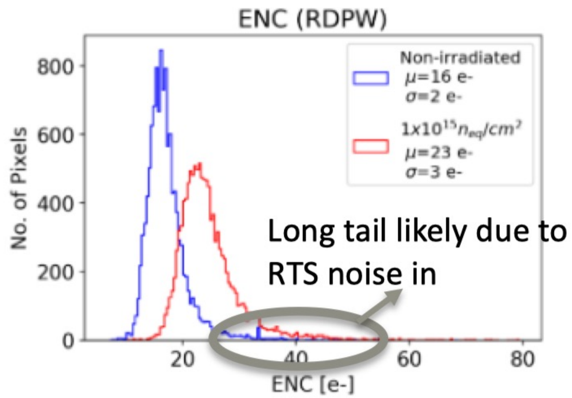


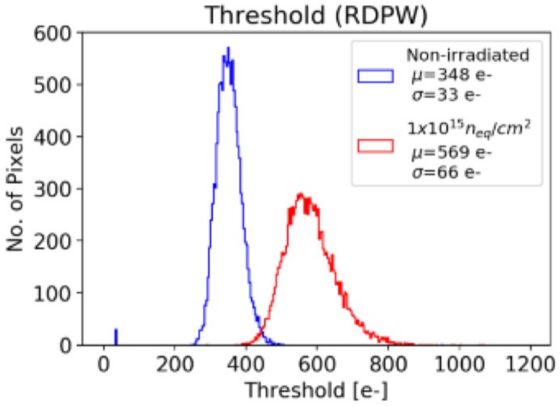


- **Small electrode**
- Small capacitance ⇒ **low power and noise**
- High-resistivity epi layer: 1-8 kΩ cm
  (epi thickness: 18-40 μm)
- **Modified process** to improve **lateral depletion**

TJ-MONOPIX 1: THRESHOLD AND NOISE







- Good noise performance:

  16 e (unirrad.) ⟶ 23 e (10^{15} n_{eq}/cm^2)

- Threshold dispersion:

  33 e (unirrad.) ⟶ 66 e (10^{15} n_{eq}/cm^2)

Need better noise and threshold tuning

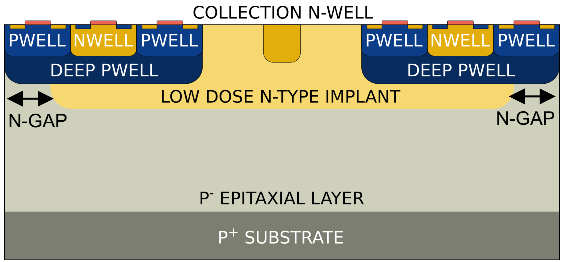
I. Caicedo et al., DOI: 10.1088/1748-0221/14/06/C06006

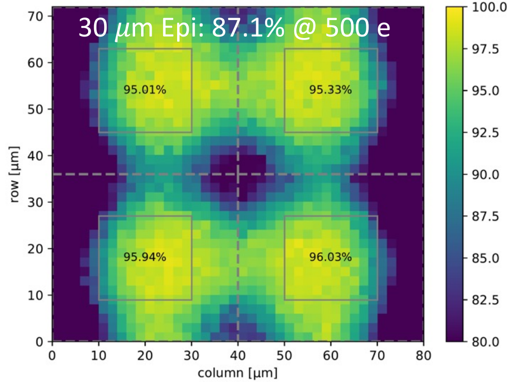
TJ-MONOPIX 1: EFFICIENCY BEFORE & AFTER IRRADIATION

- Efficiency of TJ-Monopix 1 after irradiation to $10^{15}\,n_{eq}/cm^2$ found to be only ~ 70%
- Options for improvements:
  1. **Lateral field enhancement** ⟶ **n-gap** or **extra deep p-well**
  2. **Higher input signal** ⟶ **thick Czochralski (Cz)** substrate

30 µm epitaxial layer with **"n-gap"**

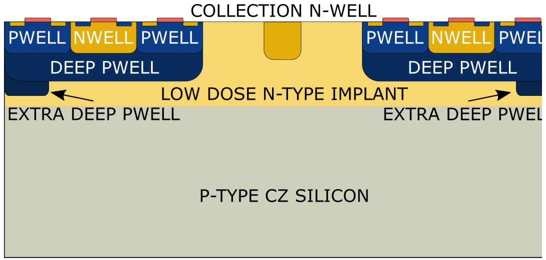
- Increase of efficiency after irradiation to $10^{15}\,n_{eq}/cm^2$: **87.1%**

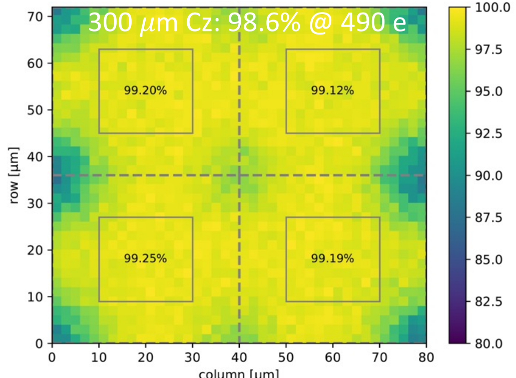




300 µm Cz substrate with **"extra dpw"**

- Almost fully efficient after irradiation to $10^{15}\,n_{eq}/cm^2$: **98.6%**

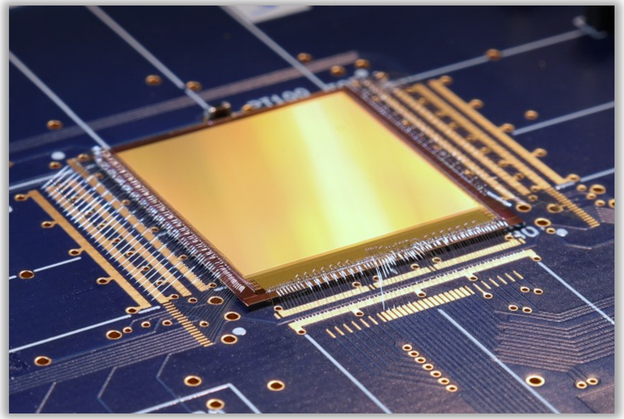




Measured by C. Bespin in 5 GeV electron beam at DESY

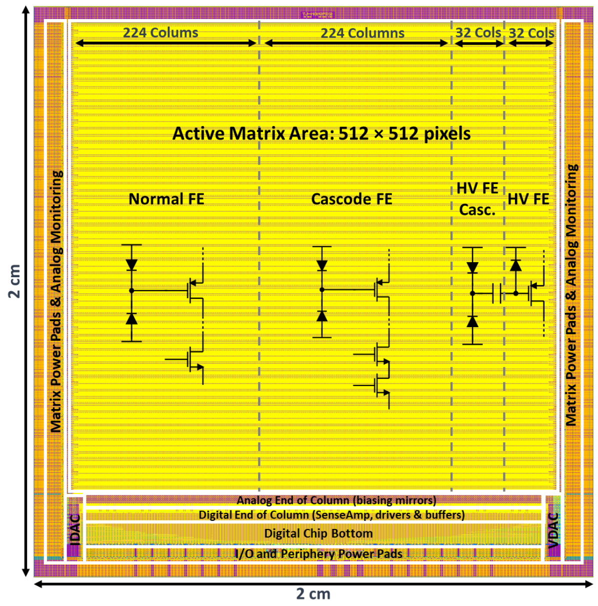
⟶ see also talk on MALTA by Carlos Solans

TJ-MONOPIX 2



- Full-scale chip: $2 \times 2\ cm^2$
- Smaller pixel pitch: $33 \times 33\ \mu m^2$
- 512×512 pixels
- Power: $\sim 1\ \mu W$/pixel

Submitted: Q4/2020, Received: Q1/2021



Larger signal
(e.g. Cz silicon)
or
lower threshold

More efficient charge collection (n-gap, extra dpw)
- Modified sensor geometry
- Optimum (smaller) cell size for given electronics

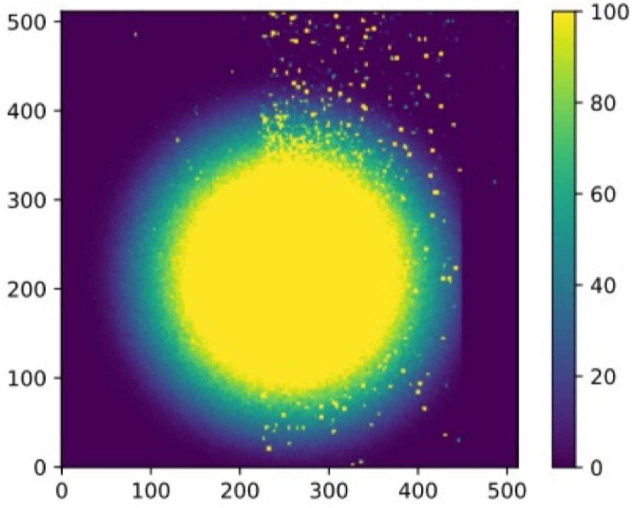
Improved FE ⇒ lower noise & threshold
- Gain increased
- RTS noise reduced
- Less threshold dispersion
- **Threshold trimming**

TJ-MONOPIX 2: FIRST MEASUREMENTS

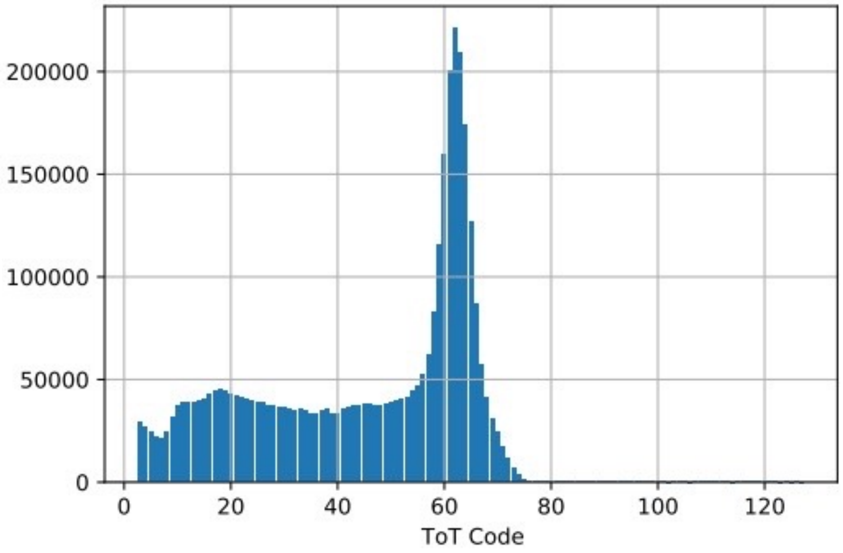
Lab measurement with Fe55 source

Occupancy

(two FE flavors activated, right one has lower threshold)



Charge spectrum



Chip works and detects radiation

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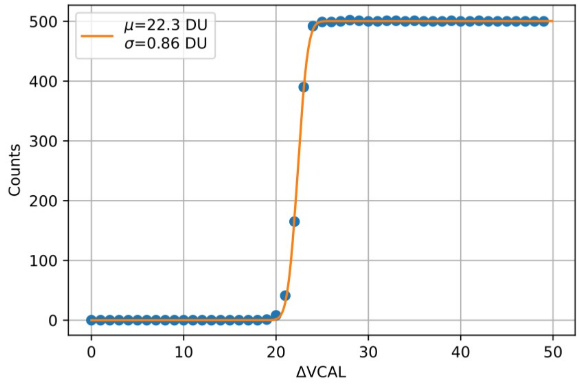
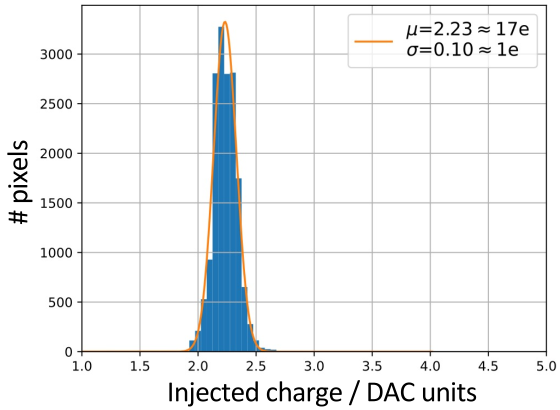
TJ-MONOPIX 2: FIRST MEASUREMENTS



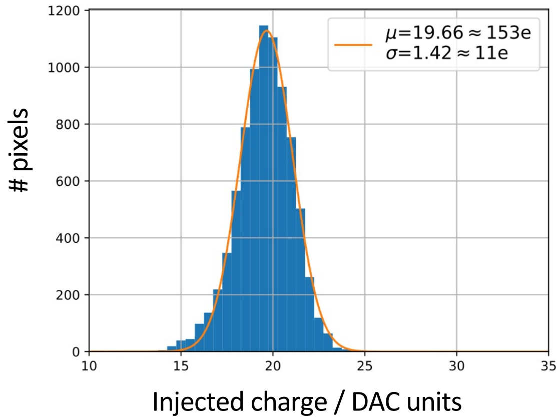
Very preliminary

Tuning not yet optimized for minimal threshold (not optimized FE settings)

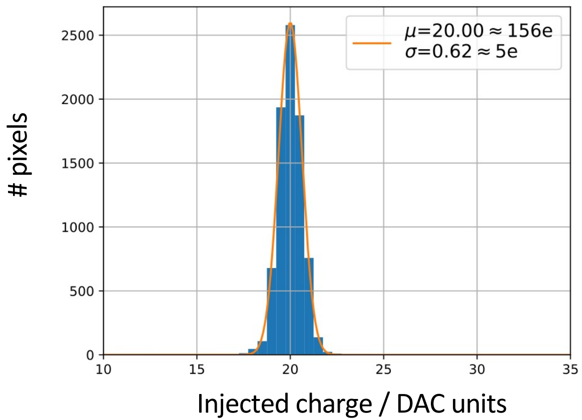
ENC



Threshold before **local tuning**



Threshold after **local tuning**



TJ-MONOPIX: PERFORMANCE OVERVIEW

	TJ-Monopix 1	TJ-Monopix 2 Expectated	TJ-Monopix 2 Measured
Chip size	1×2 cm^2	2×2 cm^2	
Pixel size	$36 \times 40\ \mu m^2$	$33 \times 33\ \mu m^2$	
Noise	~ 20 e	< 10 e	17 e
Threshold disp.	~ 30 e	< 20 e	5 e
Min. threshold	~ 300 e	< 150 e	~ 150 e
In-time threshold	~ 400 e	250-300 e	to be measured
Efficiency	~ 70% (irrad.)	> 95% (irrad.)	to be measured

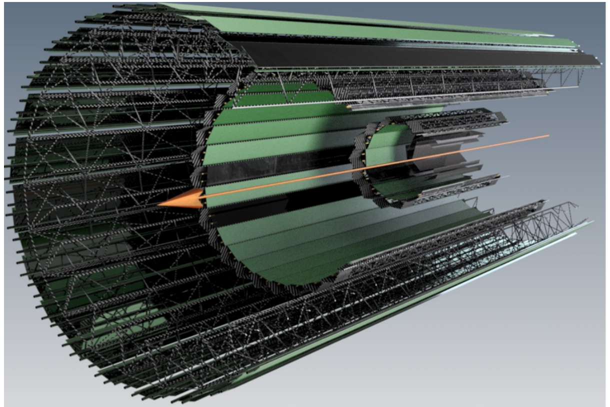
Very preliminary
(1st meas., settings not optimized)

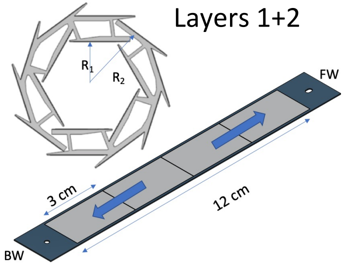
USE CASE: BELLE II VERTEX DETECTOR UPGRADE

VTX = 5-layer pixel detector with CMOS sensors

- Layers 1-2 : Self-supporting all-silicon ladders, air-cooled

  Layers 3-5: Carbon-fiber support-frame, ALICE-like staves, water-cooled
- **Low material budget** (sensor thickness ~ 50 μm):
  0.1 X_0 (L1+2), 0.3 X_0 (L3+4), 0.8 X_0 (L5)
- **Chip size = 2 × 3 cm^2, same chips in all layers**





⟶ see talk by Katsuro Nakamura

Sensor	TJMonopix-2	LFMonopix-2	Belle II
Techno	TJ-180 nm	LF-150 nm	
Pixel pitch (μm^2)	33x33	150x50	30 to 40
#Columns x #Rows	512x512	56x340	
Sensitive area (cm^2)	16.9x16.9	8.4x17	~30x20
Time Stamp (ns)	25	25	O(100)
Trigger latency (µs)	Global shutter	Continuous	5 → 10
Output charge (bits)	7	6	
Bandwidth (Mbits/s)	320		O(320)
Power (mW/cm^2)	O(200)		≤200
Hit rate (Mhz/cm^2)	>100	>100	≤150
TID kGy	1000		1000
Fluence (x $10^{13} n_{eq}.cm^{-2}$)	100	100	10

TJ-Monopix2 chosen as "workhorse" for development of new pixel sensor:

OBELIX

CONCLUSIONS

- **Next-generation Monopix 2 chips** arrived in early 2021 and are currently being intensively tested and characterized.
- **LF-Monopix 2** and **TJ-Monopix 2** are both **functioning** and (so far) show the wanted improvements.
- Fully monolithic **column-drain readout** works well.
- **Large-electrode design (LFoundry):**
  - High breakdown voltage
  - Large signal
  - High efficiency after irradiation
- **Small-electrode design (TowerJazz):**
  - Low capacitance, low noise
  - Low power
  - Can be made radiation-hard

Research and Technology Center Detector Physics

started operation in August 2021

- **TJ-Monopix 2** workhorse for **Belle II VTX upgrade** ⇒ **OBELIX chip**

ACKNOWLEDGEMENTS

- Many thanks to Christian Bespin (Bonn) und Ivan Caicedo (Bonn) for the latest TJ-/LF-Monopix 2 measurements and help with the preparation of this talk.

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

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BACKUP SLIDES

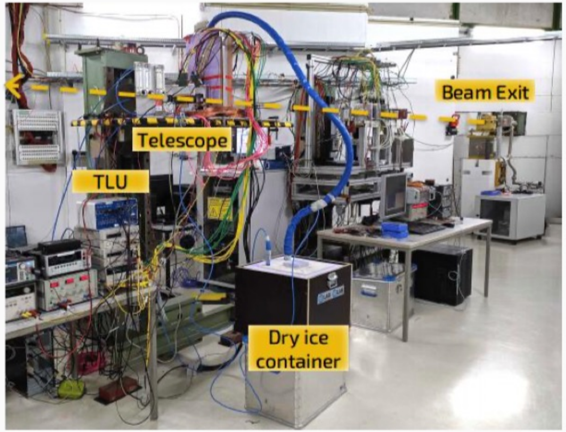
TESTBEAM MEASUREMENTS: SETUP AT DESY

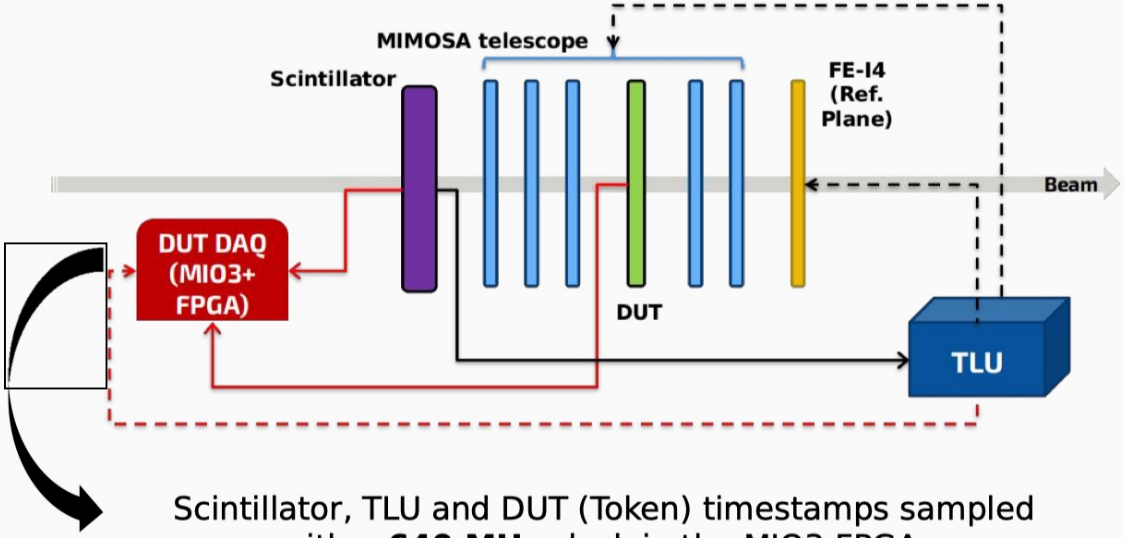
Test beam setup and data acquisition at DESY

Telescope setup:

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

Beam: 5 GeV e- at DESY TB21





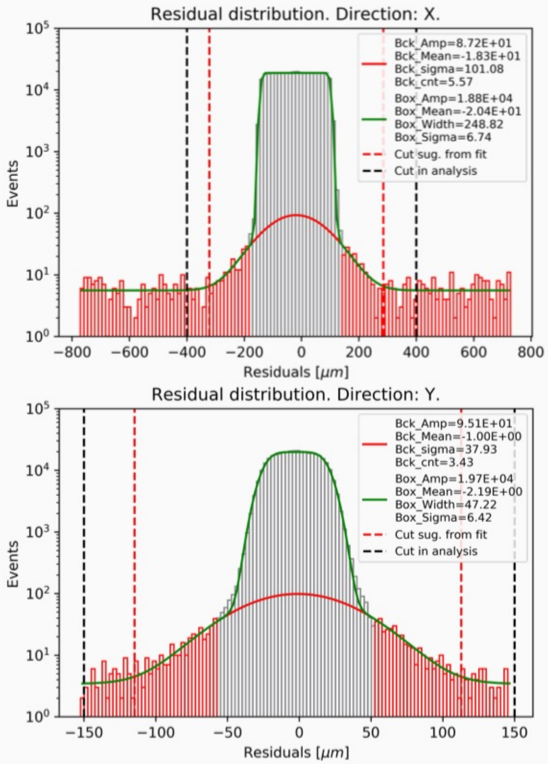
Scintillator, TLU and DUT (Token) timestamps sampled with a **640 MHz** clock in the MIO3 FPGA.

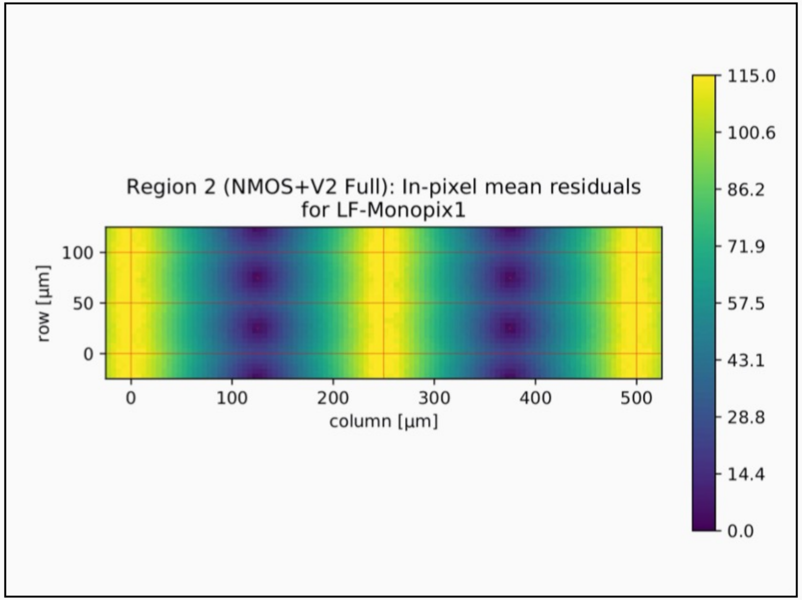
TB data analysis carried out using:
https://github.com/SiLab-Bonn/beam_telescope_analysis

From I. Caicedo (Bonn)

TESTBEAM MEASUREMENTS: DATA QUALITY

Residuals

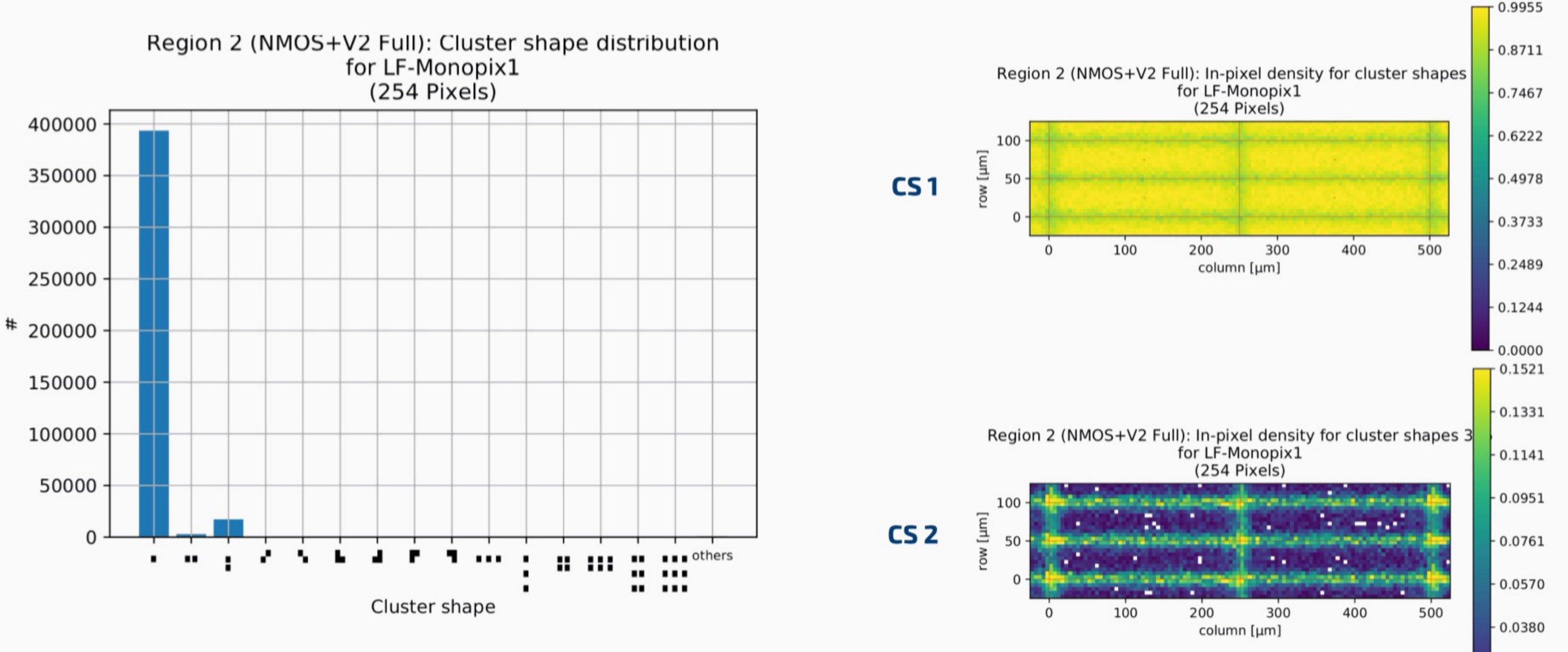




From I. Caicedo (Bonn)

TESTBEAM MEASUREMENTS: DATA QUALITY

Cluster size



From I. Caicedo (Bonn)

GUARD-RING DESIGN OF LF-MONOPIX 2

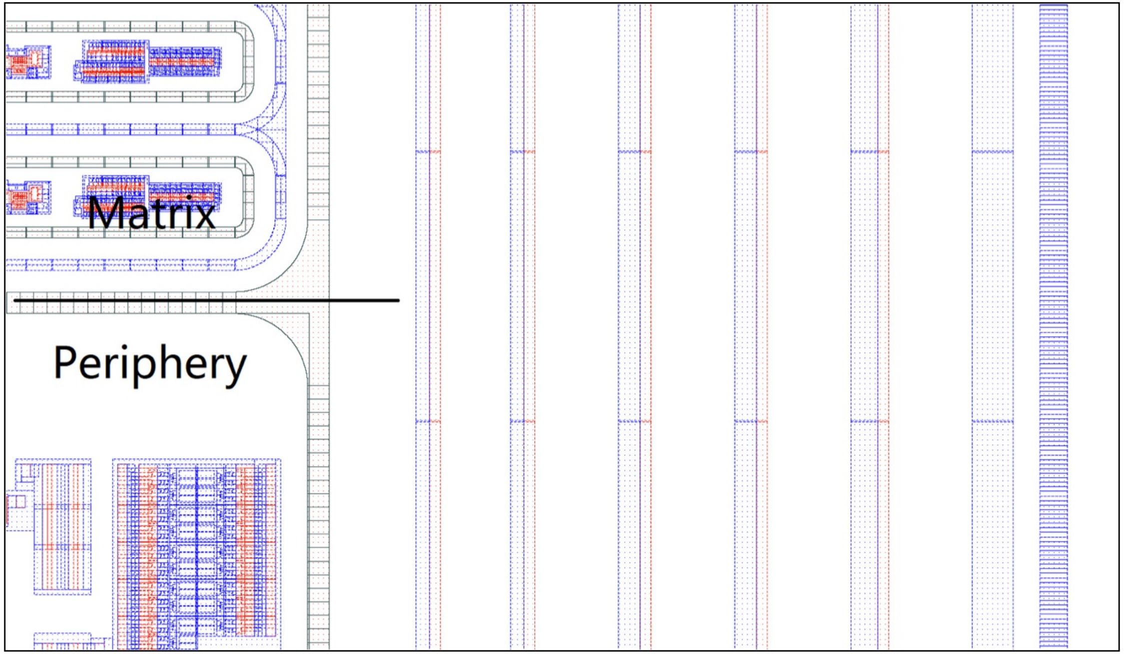
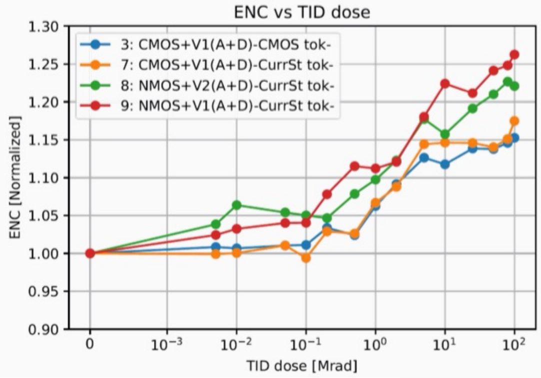


Figure 28: *Guardring design of LF-Monopix2. Red is nwell and blue is pwell. The dark green ring surrounding the matrix and periphery is a combination of nwell, niso ıd dnwell.*

TJ-MONOPIX 1: ENC - RELATIVE AND ABSOLUTE

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



- **Nominal ENC:** CMOS > NMOS