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TRENTO WORKSHOP 2022 FREIBURG

DEPLETED MONOLITHIC ACTIVE PIXEL SENSORS (DMAPS) FOR HIGH RADIATION AND HIGH RATE ENVIRONMENTS

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And the LF-/TJ-Monopix Design and Measurement Teams from
Bonn, CERN, CPPM, CEA-IRFU

Depleted Monolithic Active Pixel Sensors

- Want **minimal material budget** in high radiation and high rate environments
  → **Monolithic pixel detector** combining sensor and readout chip in one wafer

- Require **radiation hardness** to levels of 10^{15} neq/cm^2
  - Only achieved by depletion using high bias voltage

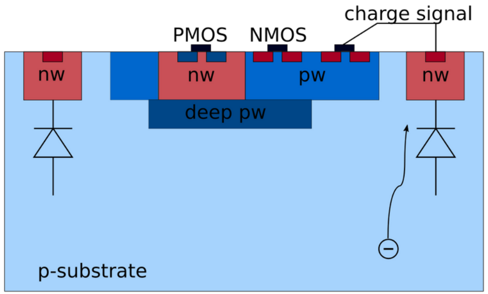
  → **High-resistivity substrate** with high voltage capabilities

- Availability of **commercial CMOS processes** with such materials
  → Fast and high volume production, less complex

Small VS Large Collection Electrode

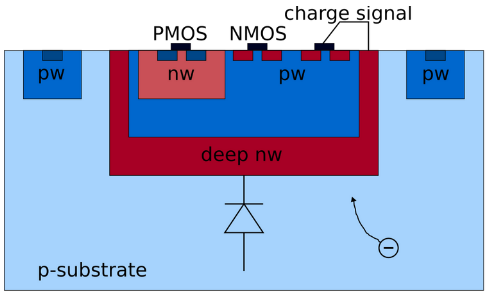
Small collection electrode:

- Electronics **outside** charge collection well
- **Small sensor capacitance** (< 5 fF)
  - Low analog power budget (noise, speed)
  - Less prone to cross-talk
- Longer drift distances
- Potentially regions with low E field
  - **Modification needed** for radiation hardness



Large collection electrode:

- Electronics **inside** charge collection well
- **Large sensor capacitance** O(100fF)
  - Compromises noise and power/speed
  - Risk of cross-talk
- Short drift distances
- Few regions with low E field
  - Less trapping → **radiation hard**



The Monopix Chips

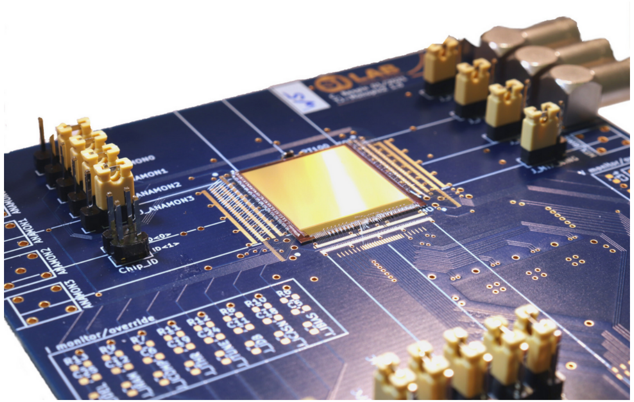
<u>TJ-Monopix2:</u>

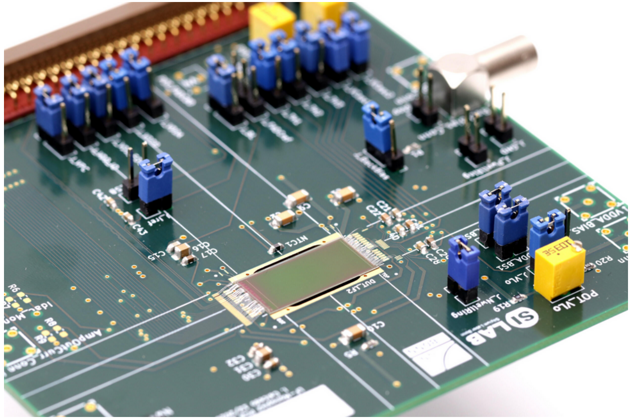
- 180nm TowerJazz CMOS Technology
- **Small** collection electrode
- ~2x2 cm² matrix with **33x33 µm²** pixel pitch
- Substrate resistivity ~1 kΩ/cm

<u>LF-Monopix2:</u>

- 150nm LFoundry CMOS Technology
- **Large** collection electrode
- ~2x1 cm² matrix with **50x150 µm²** pixel pitch
- Substrate resistivity > 2 kΩ/cm

Same fast **column drain readout** architecture (FEI-3 like)





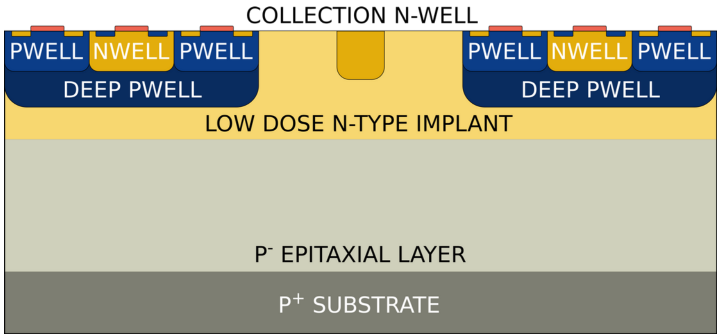
TJ-Monopix1: Recap

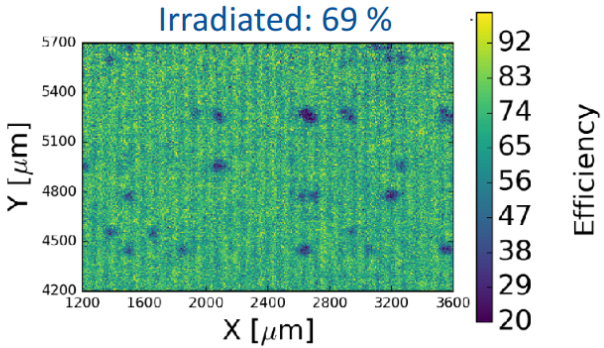
- Based on ALICE ITS pixel detector ALPIDE

- Modified existing process to increase radiation hardnesss

  → Add n-type layer
  W. Snoeys et al. DOI: 10.1016/j.nima.2017.07.046

- Still observe **significant efficiency loss** to ~70% after irradiation to $1x10^{15}$ neq/cm^2
  - Charge loss due to E field shaping under deep p-well

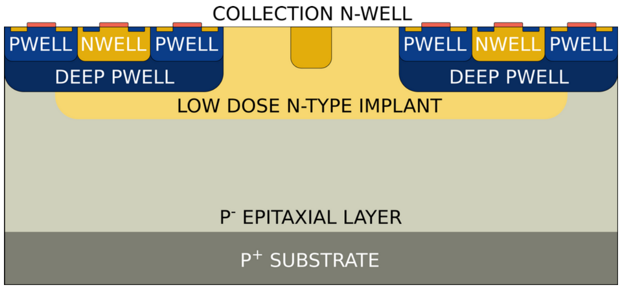


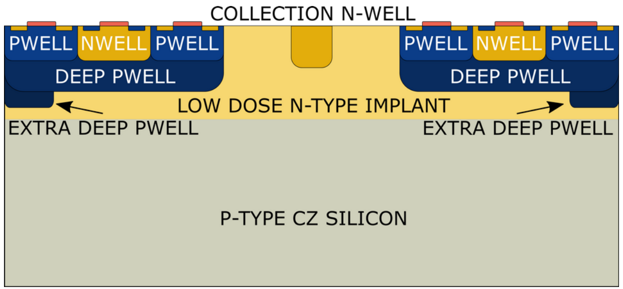


TJ-Monopix1: Recap

- Possible improvements:
  1) Lateral E field enhancement → **n-gap** or **extra deep p-well**
  2) Higher input signal → **thick Czochalski (Cz) substrate**

- Compare **30 µm epitaxial chip with n-gap** and **300 µm Cz chip with additional deep p-well**
  - From simulation and measurements n-gap and additional deep p-well work equally well



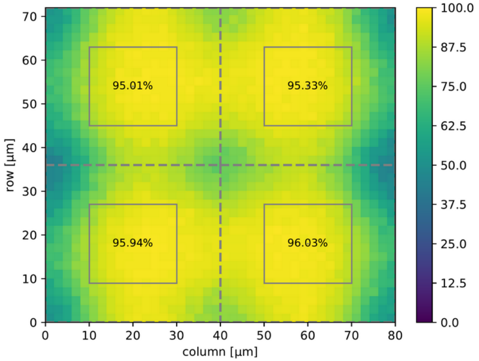


TJ-Monopix1: Recap

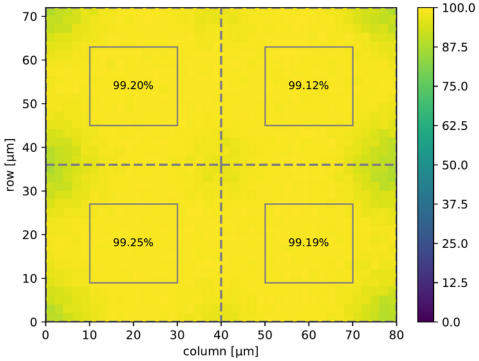
- Testbeam results of 5 GeV electron beam at DESY
- Increase in efficiency after irradiation to 10^{15} neq/cm^2 to:
  - **87.1%** for **30 µm** epitaxial chip with n-gap
  - **98.6%** for **300 µm** Cz chip with deep p-well

→ TJ-Monipix1 efficient if enough charge compared to threshold is created

30µm Epi: 87.1% @ TH=500e$^-$



300µm Cz: 98.6% @ TH=490e$^-$



TJ-Monopix2: Design

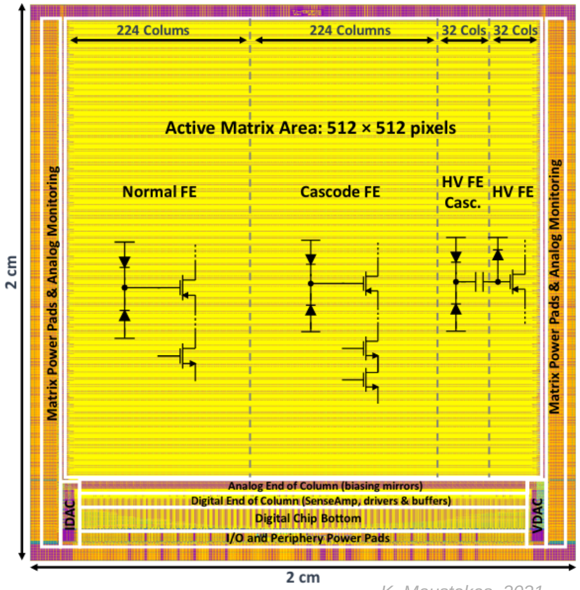
- **Increase chip size** (2x2 cm²) while **reducing pixel pitch** (33x33µm²)
- Improve FE to **lower noise and threshold**
- Extend ToT information from 6 to 7 bit
- 3 bit **in-pixel threshold tuning**

  → More in-pixel logic at smaller pixel size

- Command-based slow control from RD53B
- Four **LVDS lines for I/O** (additional 2 for debugging)
- **8b10b encoded data stream** with hit and register data

  → Use BDAQ53 readout board developed for RD53

  → Small and easy lab setup

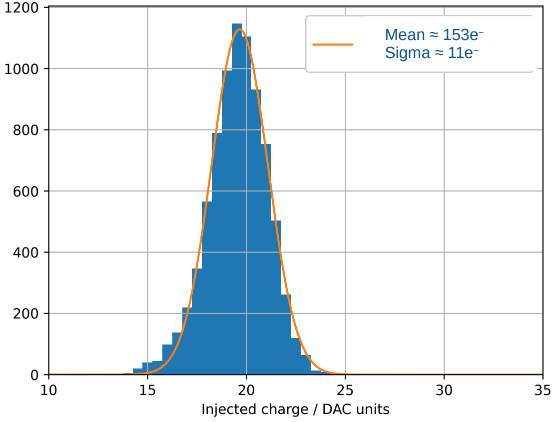


K. Moustakas, 2021

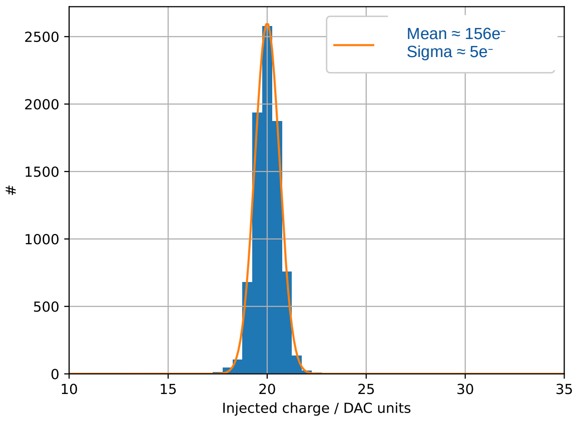
TJ-Monopix2: First Measurements

- First lab tests checking ENC and threshold
- Threshold tuning works, dispersion improves
  - Expected MIP MPV ~1.5 - 2 ke⁻ at full depletion for ~30 µm silicon
  - **Not** minimum achievable threshold

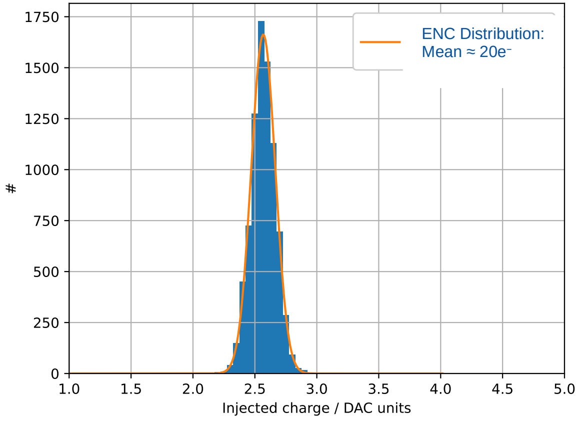
Threshold dist. **before** tuning



Threshold dist. **after** tuning



ENC distribution



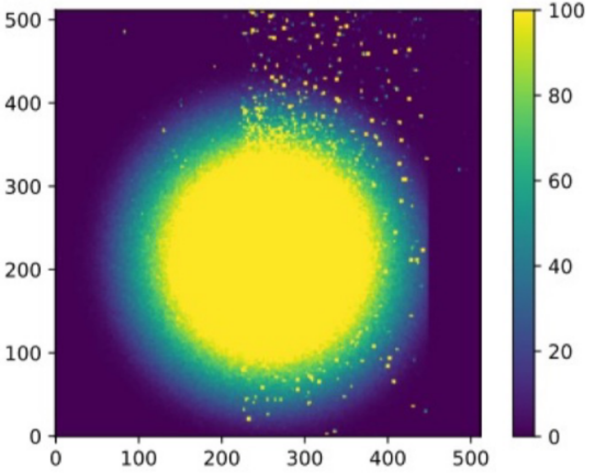
TJ-Monopix2: First Measurements

Successfully run source scan using ^{55}**Fe source**:

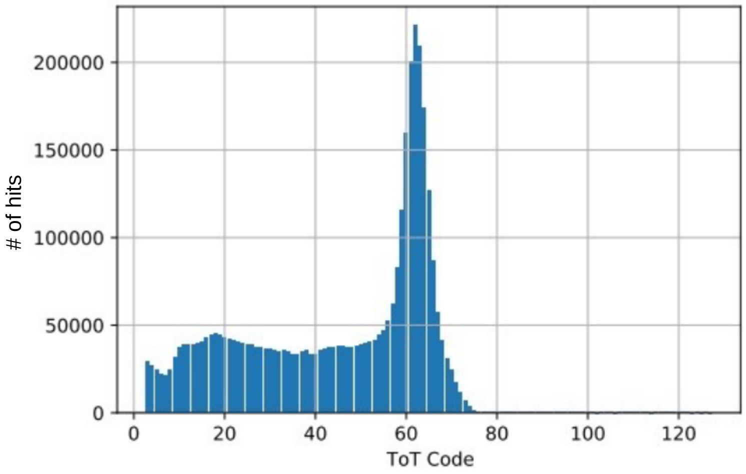
- Two FE flavors, right half has lower threshold

→ Chip works and detects radiation

Occupancy map



Charge spectrum



TJ-Monopix2: Use Case

DMAPS candidate for **Vertex detector upgrade** of **Belle II**

- **5 layer pixel detector** with CMOS sensors:
  - Layer 1-2: Self supporting all-silicon ladders
  - Layer 3-5: Carbon-fiber support frame, ALICE like staves
- **Low material budget** (sensors thinned to ~50 µm)

→ TJ-Monopix2 chosen as prototype for development of new pixel sensor **OBELIX** for **VTX proposal**

(also see upcoming talk by M. Babeluk)

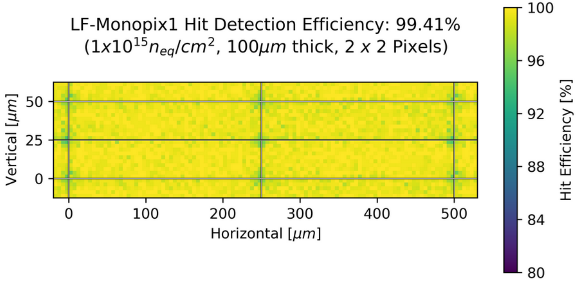
Sensor	TJMonopix-2	LFMonopix-2	Belle II
Techno	TJ-180 nm	LF-150 nm	
Pixel pitch (μm^2)	33x33	150x50	30 to 40
#Columns x #Rows	512x512	56x340	
Sensitive area (cm^2)	16.9x16.9	8.4x17	~30x20
Time Stamp (ns)	25	25	O(100)
Trigger latency (µs)	Global shutter	Continuous	5 → 10
Output charge (bits)	7	6	
Bandwidth (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 ($\times 10^{13} n_{eq} \cdot cm^{-2}$)	100	100	10

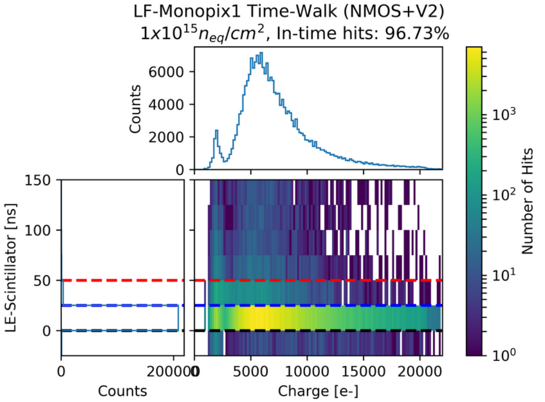
LF-Monopix1: Recap

- First DMAPS *(2016)* with full in-pixel electronics and column drain readout
- **TID hard** tested up to **100 Mrad**
- After irradiation to **$1x10^{15}$ neq/cm²**:
  - Uniform **hit detection efficiency** of **~99.4%**
  - **In-time efficiency ~96.6%**

- *But:*
  - Column length half of final target
  - Large pixel pitch of 50x250 µm²
  - Observed cross-talk from one digital signal into collection node

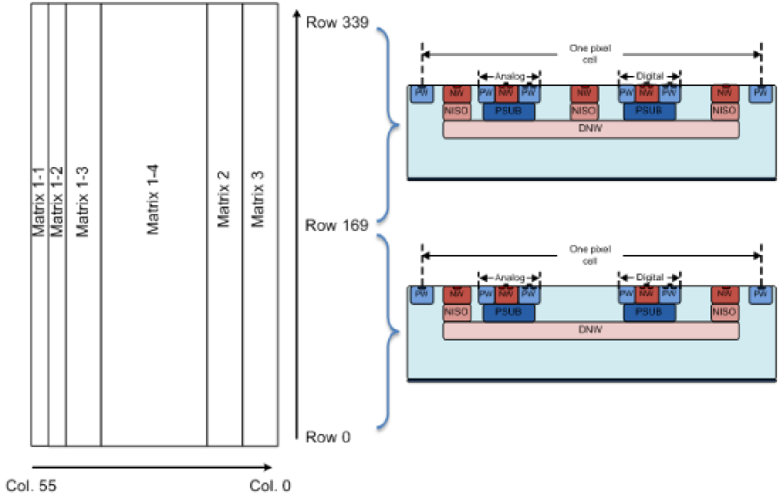
→ **LF-Monopix2**





LF-Monopix2: Design

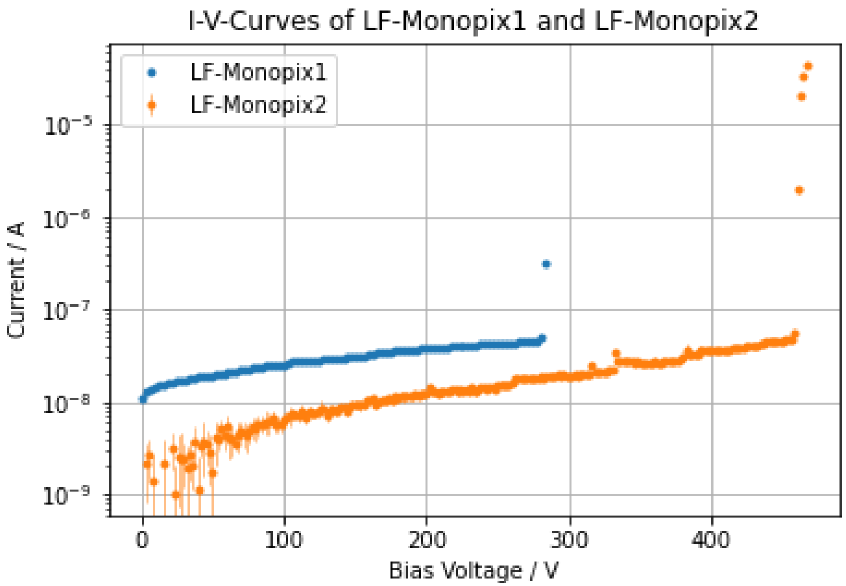
- Large collection electrode
- **Increase chip size** (2x1 cm²) while **reducing pixel pitch** (50x150 µm²)
- Total of 7 matrices with 3 CSA types
  - CSA1 proven design from LF-Monopix1
- 6 bit ToT information
- 4 bit **in-pixel threshold DAC**
  - Two different tuning circuit designs
- 40MHz / 160MHz CMOS or LVDS serial output



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 fF	unidirectional tuning	Rising
1-4	39 - 16	V1	5 fF	unidirectional tuning	Falling
2	15 - 8	V2	1.5 fF	Bidirectional tuning	Falling
3	7 - 0	V3	1.5 fF	Bidirectional tuning	Falling

LF-Monopix2: I-V Curves

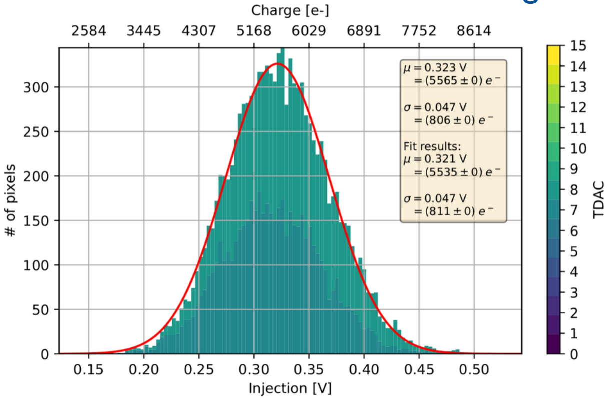
- Wafers successfully thinned down to 100 µm and backside processed
- For all tested chips **breakdown voltage above 350 V**
  - Significant improvement to LF-Monopix1
  - Fluctuations at low voltages due to limited current range of SMU



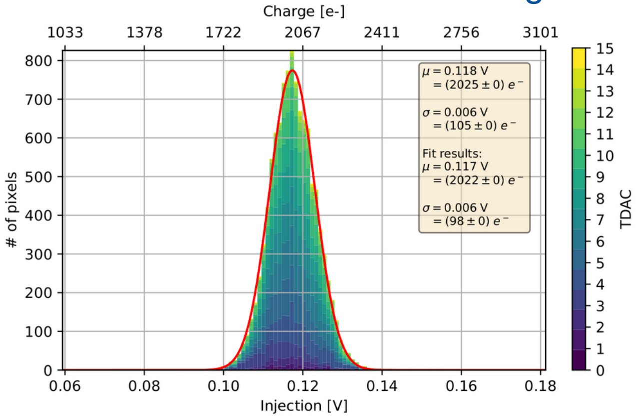
LF-Monopix2: Threshold Tuning

- 4 bit in-pixel threshold DAC
- Threshold dispersion improves after tuning (*here: 32 columns of CSA1*)
  - Expected MIP MPV ~6 ke⁻ (100 µm silicon)
- Mean ENC (~100 e⁻) as expected

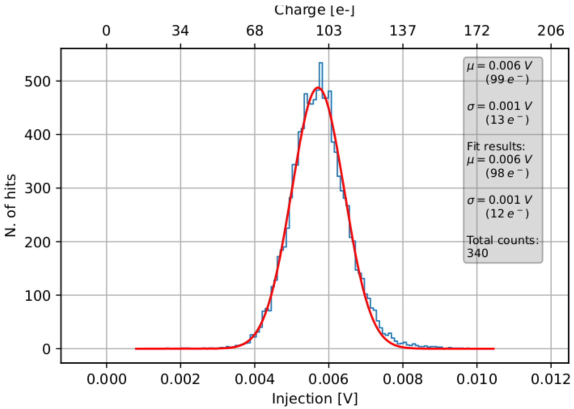
Threshold dist. **before** tuning



Threshold dist. **after** tuning



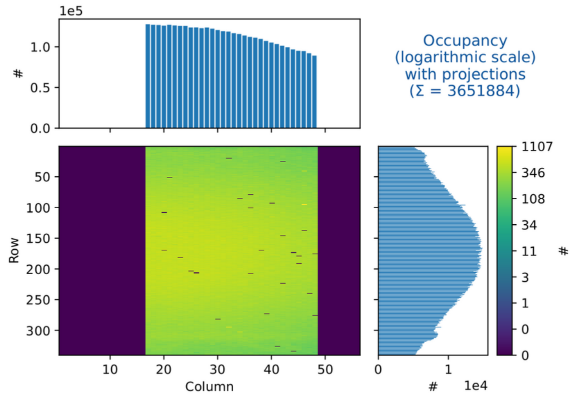
ENC distribution

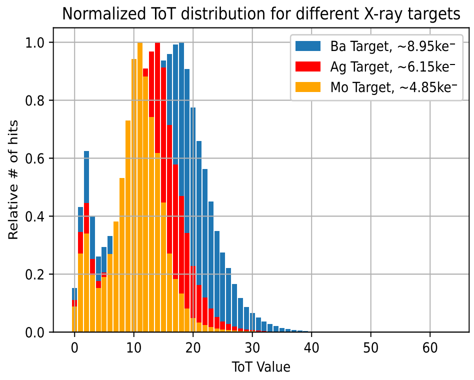


LF-Monopix2: Source Scan and Calibration

- Use ^{241}Am source with variable x-ray target
- Chip matrices 1-3 & 1-4 (Col. 16-48) tuned to approx. **2ke⁻ threshold**
- Occupancy map and ToT distribution as expected
  - Sensor fully illuminated
  - ToT increases according to X-ray energy of targets

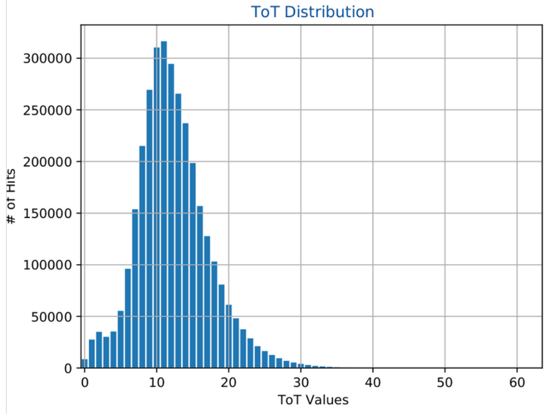
→ Preliminary LF-Monopix2 **C_Inj ~ (2.90 ± 0.25) fF**

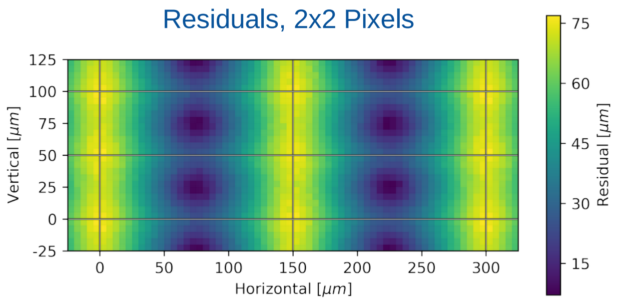


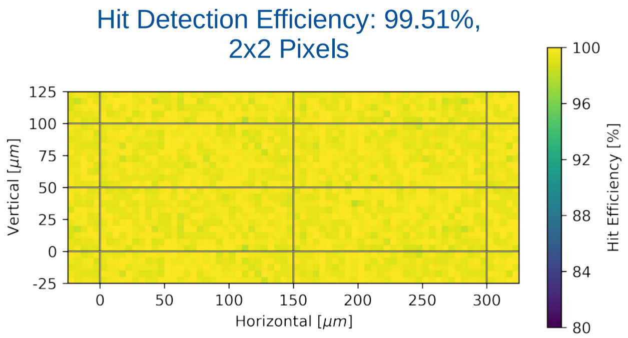


LF-Monopix2: Efficiency

- **Preliminary** results from first LF-Monopix2 **testbeam at DESY** (5 GeV electrons):
  - 100µm thick chip at 60V bias, unirradiated
  - Threshold ~2.2ke⁻
- ToT and residual distribution as expected
- Uniform hit detection efficiency >99%







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Conclusion and Outlook

- Successfully **modified TJ-Monopix1** sensor to counter efficiency loss after irradiation
- **TJ-Monopix2** is working and used as prototype for **Belle II VTX Upgrade**
- **LF-Monopix2** fully operational
  - Promising uniform hit detection efficiency >99% before irradiation after first testbeam
- Upcoming **testbeam campaigns** for both DMAPS
  - More detailed efficiency and irradiation studies to come

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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