ATTRACT FASTPIX

Monolithic Pixel Sensor Demonstrator for sub-Nanosecond Timing in Future Vertex and Tracking Applications

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EP R&D

ATTRACT

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

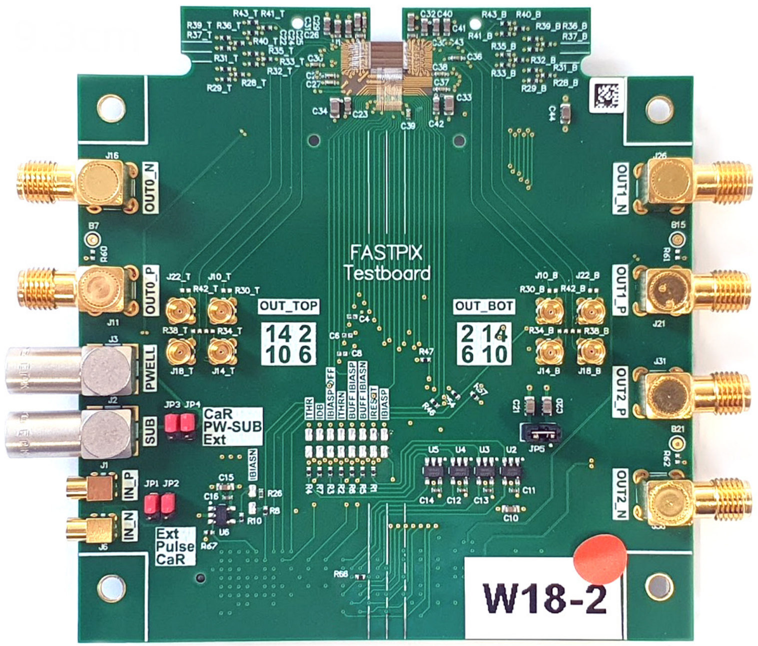
ATTRACT FASTPIX

[ATTRACT FASTPIX: Sub-Nanosecond Radiation Tolerant CMOS Pixel Sensors]

- **Monolithic pixel sensor demonstrator chip in modified 180 nm CMOS imaging process**

- **Targeting excellent spatial and temporal resolution with high detection efficiency**
  - Future high-energy and high-rate particle collider experiments
  - Technological advancements have wide-ranging applications in other fields, such as spectroscopy, microscopy, medical applications and large-scale consumer applications.

- **Design variations aiming at charge collection optimization**
  - Accelerating charge collection (precondition for radiation tolerance)
  - Uniform timing of the charge collection across the pixel



ATTRACT FASTPIX – The Pixel Cell

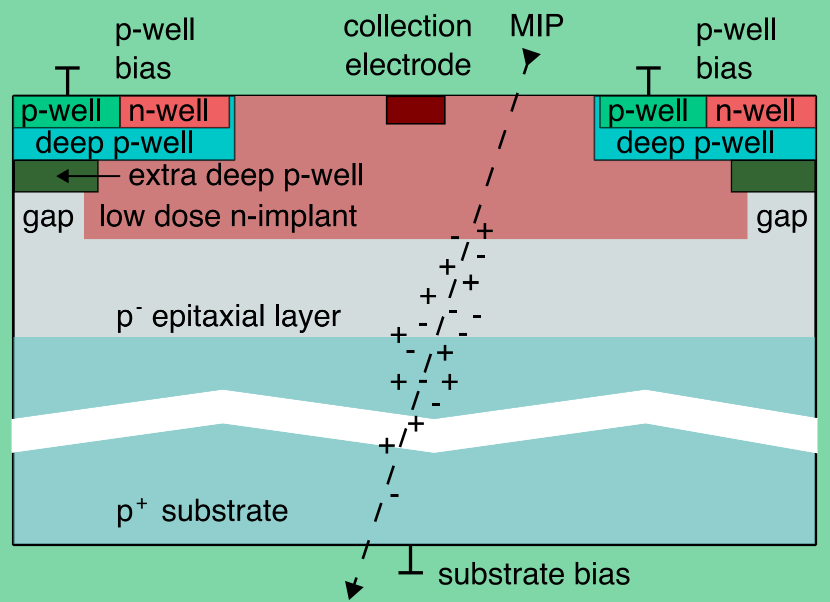
- **Small, few fF capacitance collection electrodes**
  - \+ Large signal-to-noise ratio in favor of detection efficiency and timing performance
  - – Highly non-uniform electric fields
  - – Signal charge collection time depends on in-pixel particle incidence
  - ➔ **Limiting timing and radiation tolerance for charge collection close to pixel edges**

➔ **Design modifications to overcome limitations**

- **Pixel level: implant structures at pixel edge**
  - ➔ Shape electric field to accelerate the signal charge to collection electrode
  - ➔ Uniform timing over area of pixel

M. Munker *et al* 2019 *JINST* **14** C05013

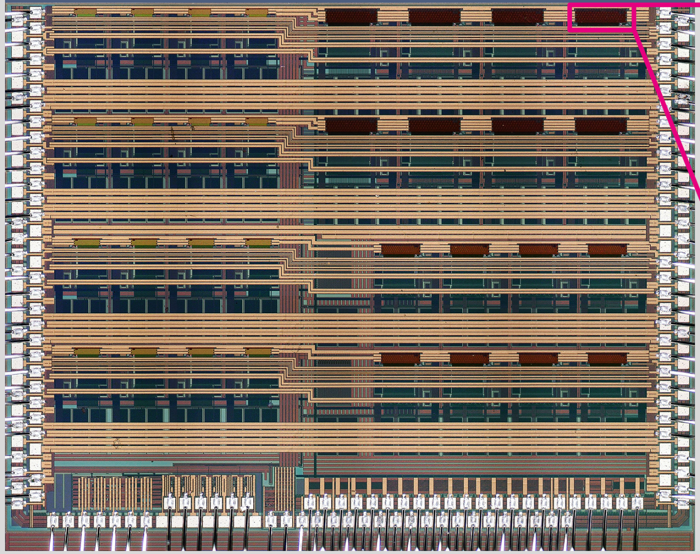
MODIFIED PROCESS



- 25 um thick epitaxial layer
- Low-dose n-implant (optional)
- Extra deep p-well (optional)
- n-implant gap (optional)

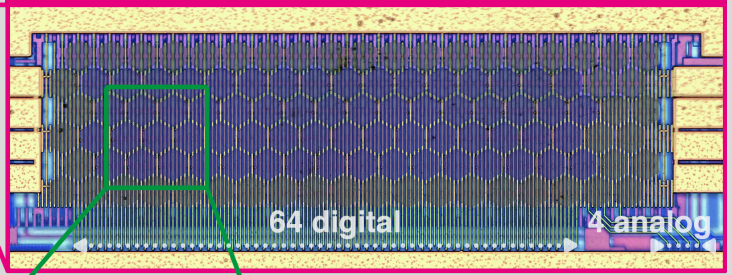
ATTRACT FASTPIX – The Sensor

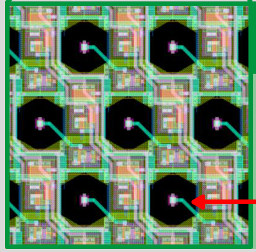
FASTPIX layout (5.3 x 4.1 mm^2)



- **4 x 8 mini matrices of 64 digital, 4 analog hexagonal pixels each**
- **Four groups with four different pixel pitches:** 8.66 µm, 10 µm, 15 µm, 20 µm

Pixel matrix layout, hexagonal grid 20µm





Pixel in the matrix

5 PMOS per pixel

n-well electrode

Different design parameters implemented per group:

- Size of collection electrode
- Geometry of implant structures
- Additional wafer-specific modifications of to sensor design

➔ **Hexagonal arrangement of collection electrodes / pixels**

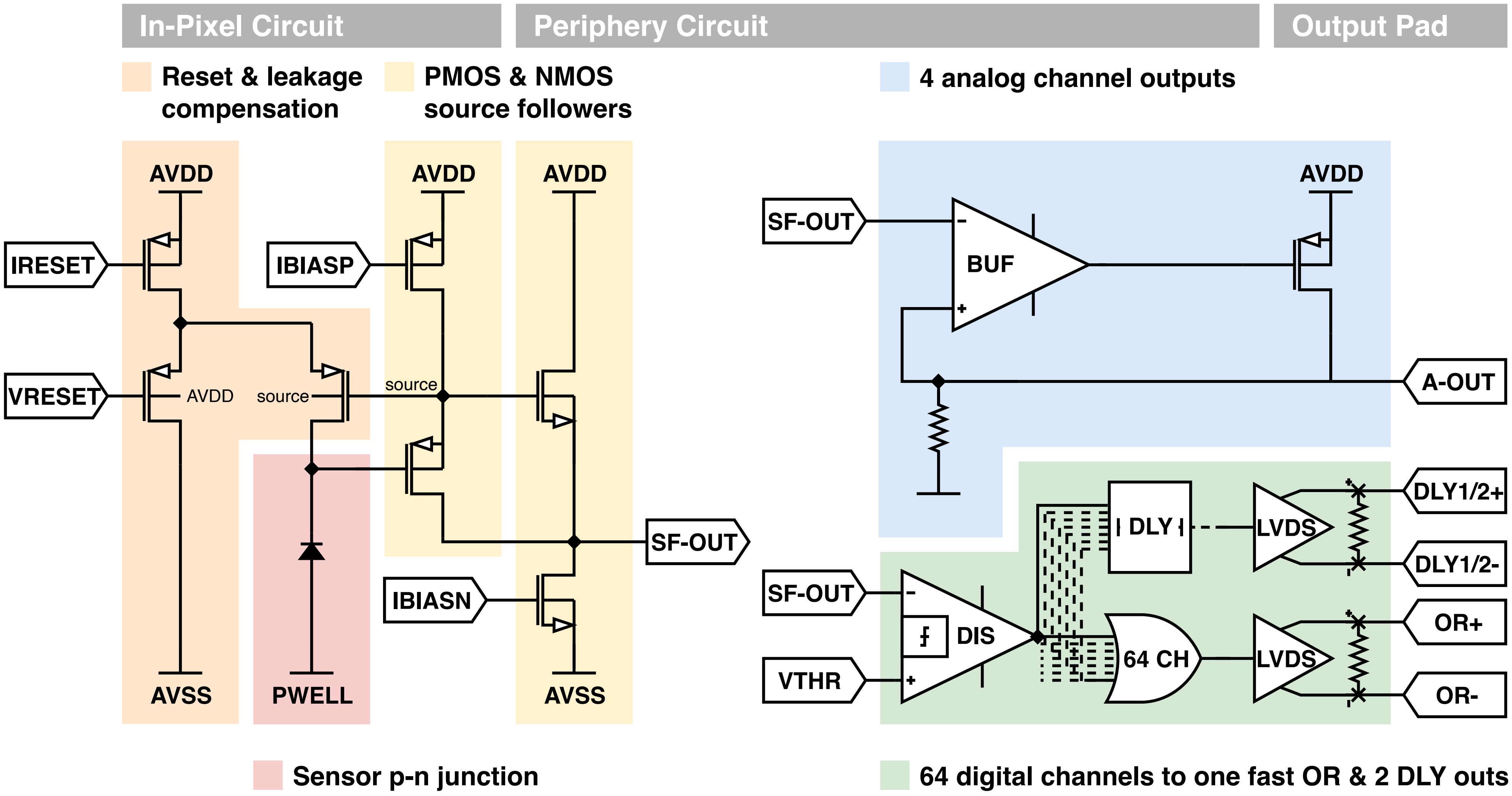
\+ Accelerates charge collection

\+ Minimizes charge sharing

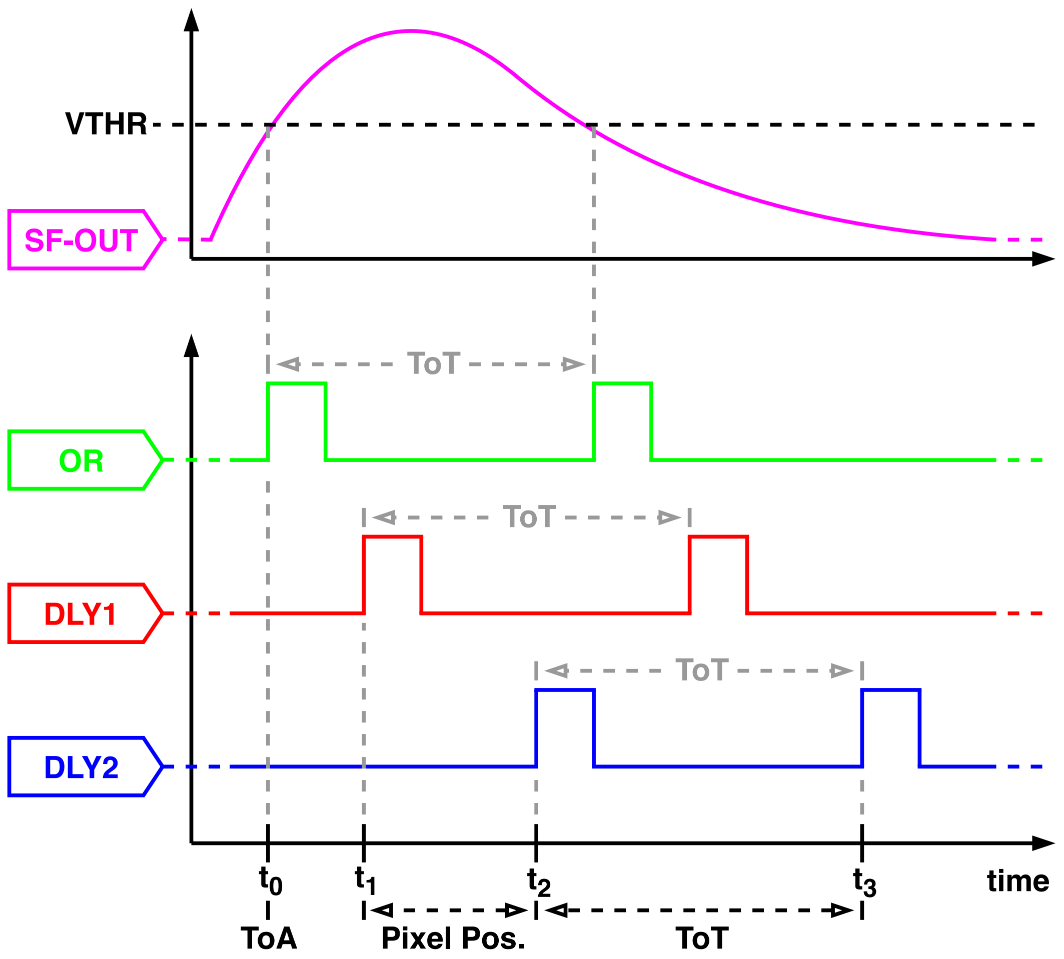
➔ **Various combinations of design modifications implemented on wafer and matrix level.**

➔ **Large parameter space of chips and matrices**

ATTRACT FASTPIX – Frontend and Periphery



Readout Architecture (Digital Channels)



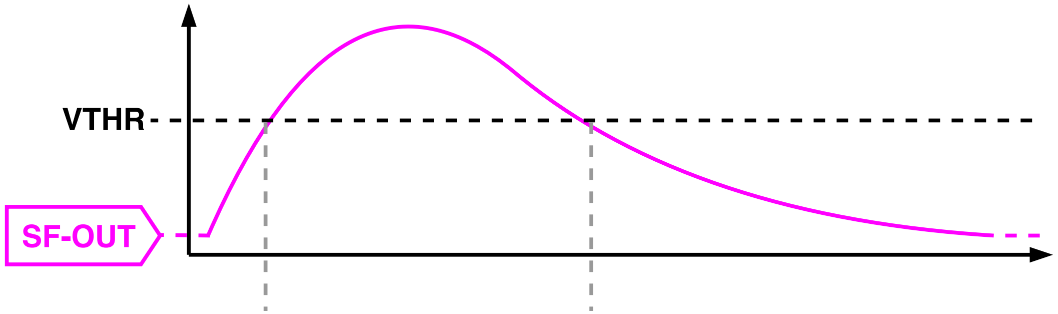
- **Asynchronous readout with oscilloscope**
- **Off-chip processing of discriminator signals**
- **Time-based position and ToT encoding on 3 channels**
  1. One direct combination of all pixels ➔ fast **OR**
  2. Delay line with 100 ps between pixels ➔ **DLY1**
  3. Similar DLY with pixels chained in opposite direction ➔ **DLY2**

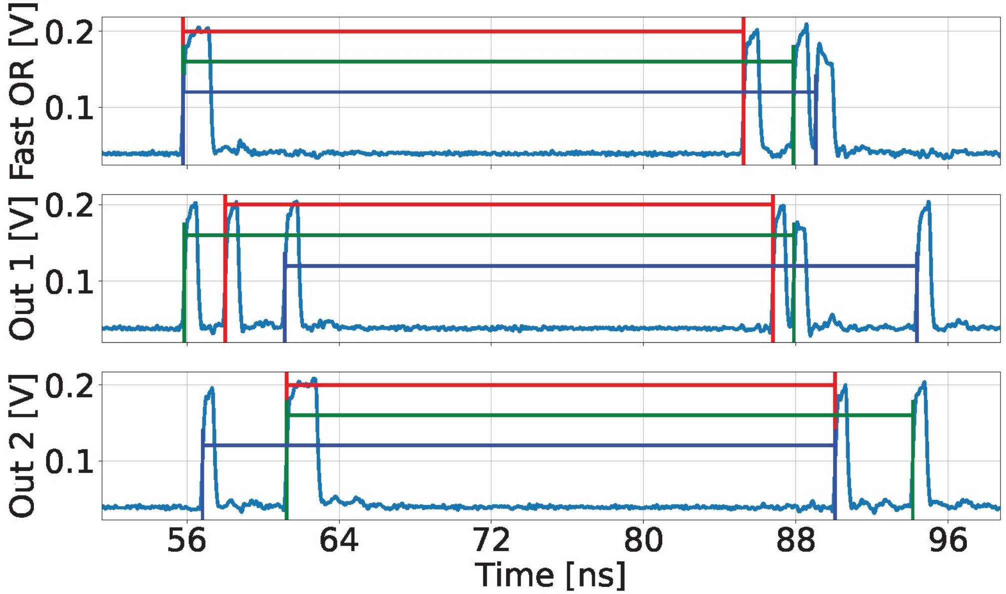
➔ Time-of-arrival (ToA): given by fast **OR** at t_0

➔ Time-over-threshold (ToT): time between e.g. t_2 and t_3

➔ Pixel position: time difference between rising edges on **DLY1** and rising edge on **DLY2**

Readout Architecture (Digital Channels)





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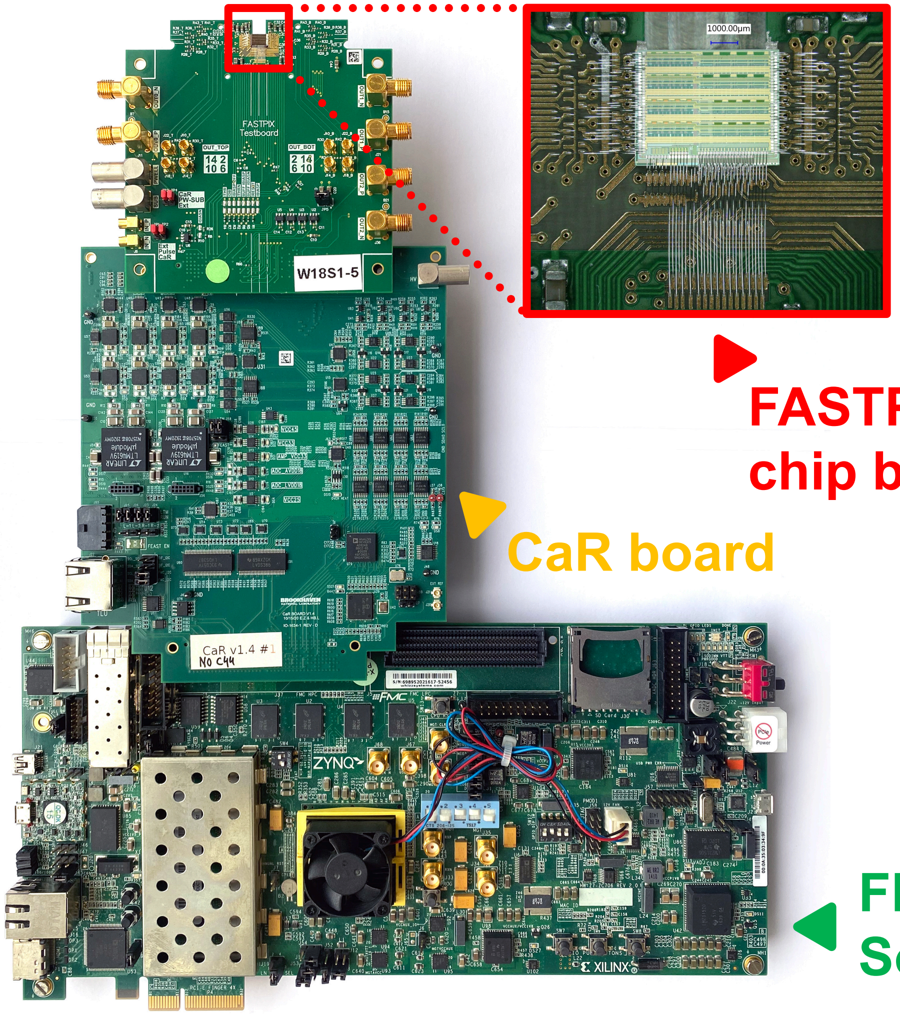
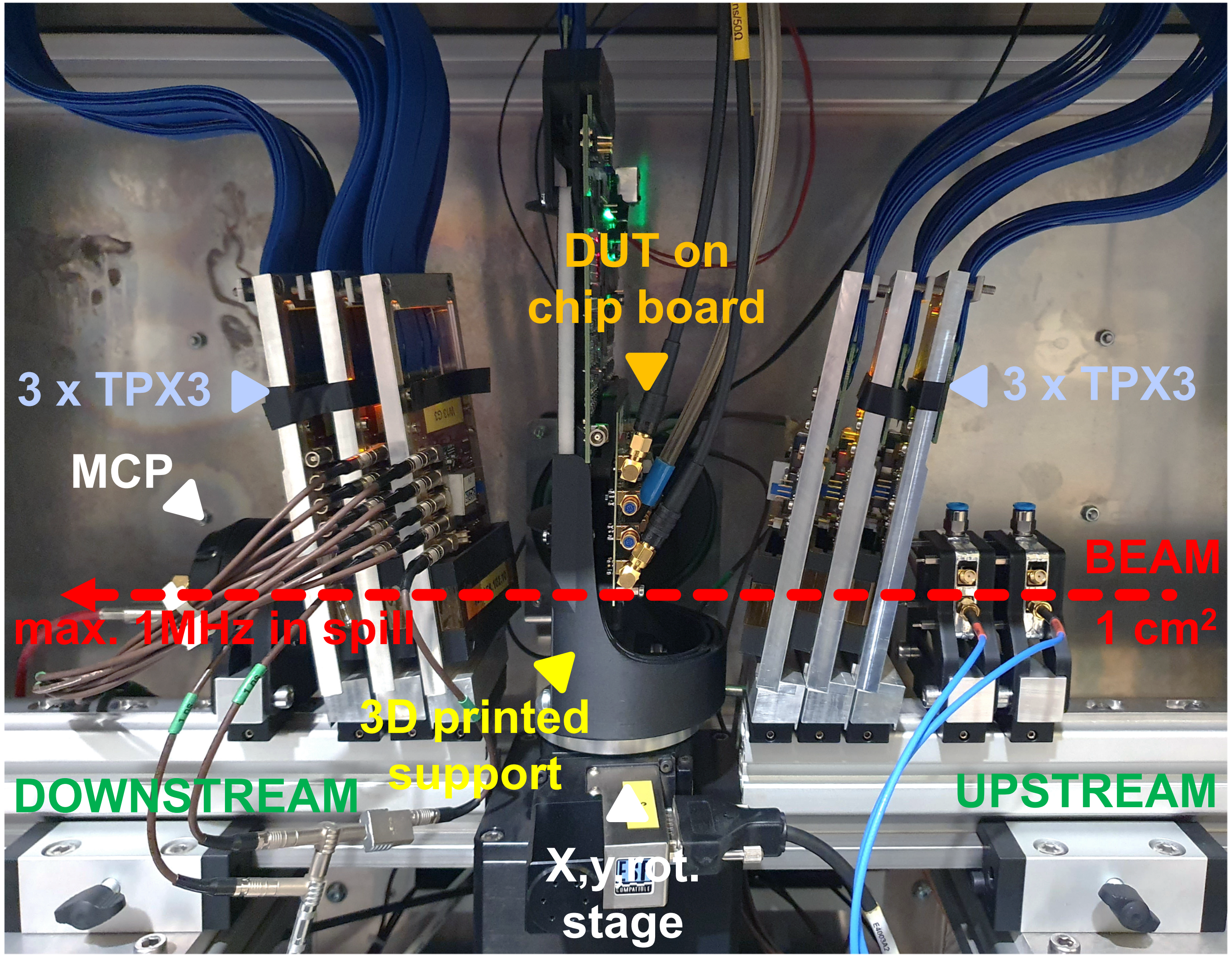
Readout and Measurement Setup



- **Caribou Data Acquisition System**
  ➔ Previous talk by Eric Buschmann on Tuesday morning

- **Stand-alone setup for initial laboratory tests and calibration**
  ➔ **FASTPIX chip board** contains wire-bonded detector, connects to readout system
  ➔ **CaR board** provides power, bias voltages and currents and configuration/control of detector
  ➔ **FPGA/SoC** runs Peary, the detector specific control firmware and data readout/processing software

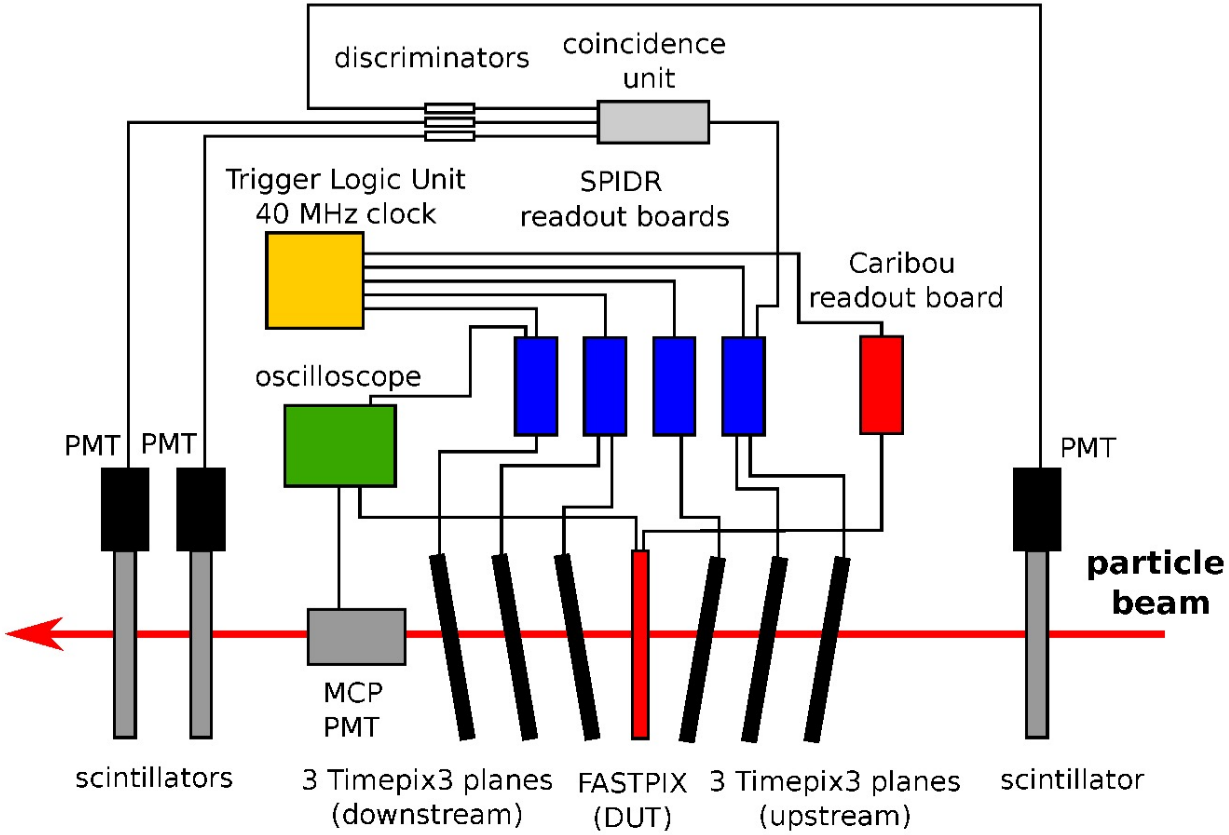
CLICdp Timepix3 Telescope Integration



- **SPS test beam H6 at 120 GeV pions**
- **Telescope arms and detectors enclosed in light-tight aluminum box**
- **DUT in between 3 upstream and 3 downstream Timepix3 (TPX3) planes**
  ➔ Tilt of planes optimized for charge sharing and spatial resolution
- **Microchannel Plate PMT (MCP-PMT) as time reference**
  - **Downstream of telescope planes** min. material in telescope acceptance

  ➔ **~$\mathcal{O}$(10 ps)** MCP-PMT timing precision

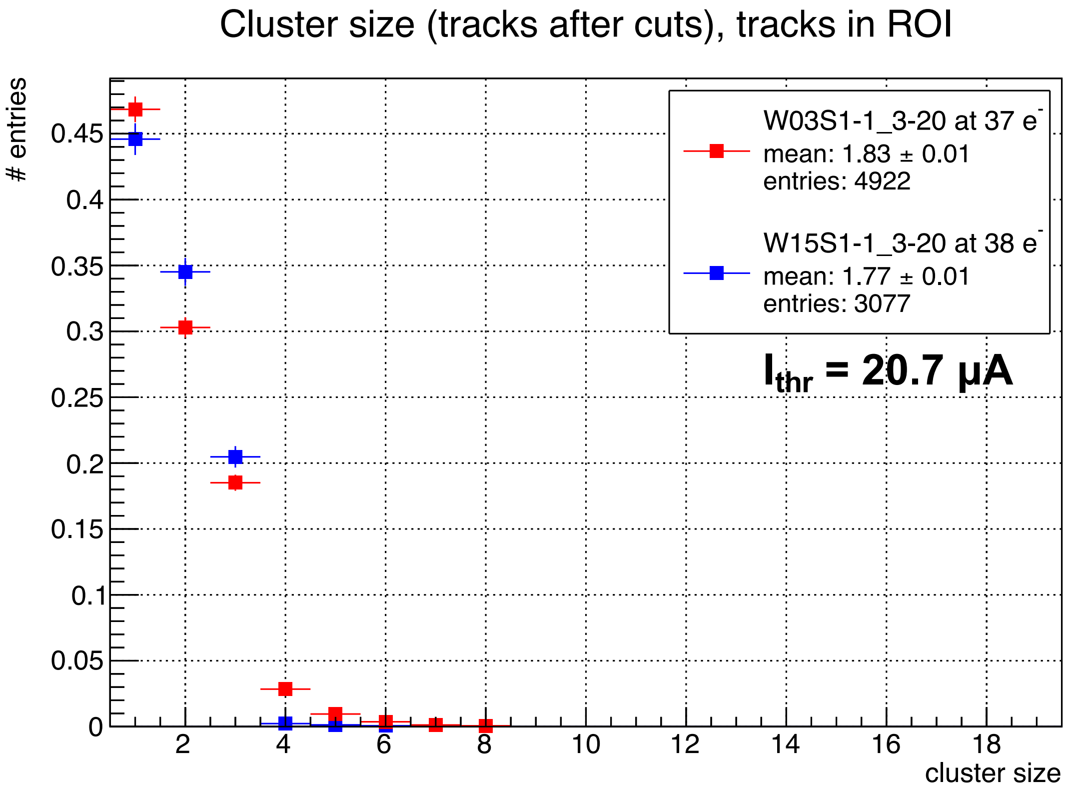
CLICdp Timepix3 Telescope Schematic



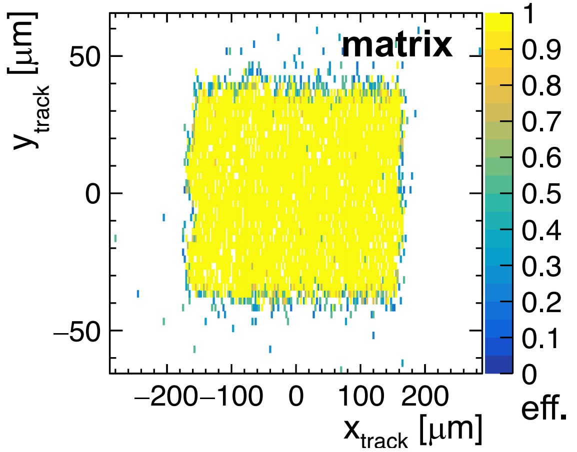
- **6 x Timepix3 connected to SPIDR readout boards**
- **Coincidence of Scintillator-PMTs is fed to TDC on a SPIDR board**

- **FASTPIX and oscilloscope controlled by Caribou and connected to telescope DAQ**
  - **FASTPIX** at -6V bias at substrate and p-wells
  - ➔ **Oscilloscope** triggers on **FASTPIX** fast **OR**
  - ➔ Triggers are fed to TDC on a **SPIDR board** for synchronization
- **Analysis with Corryvreckan reconstruction framework**
  - 2020 JINST 16 P03008
  - 2021 JPS Conf. Proc. 34, 010024
  - ➔ DLY calibration, raw data decoding scripts (C++)
  - ➔ Alignment, analysis in Corryvreckan
  - ➔ High-level analysis and plotting (Python, C++)

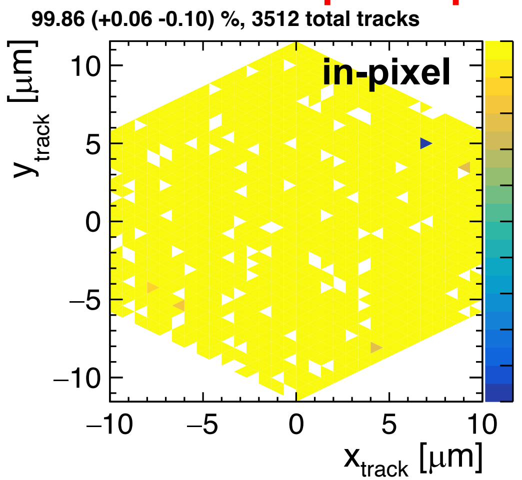
Cluster Size Distributions - 20 µm Pixel Pitch



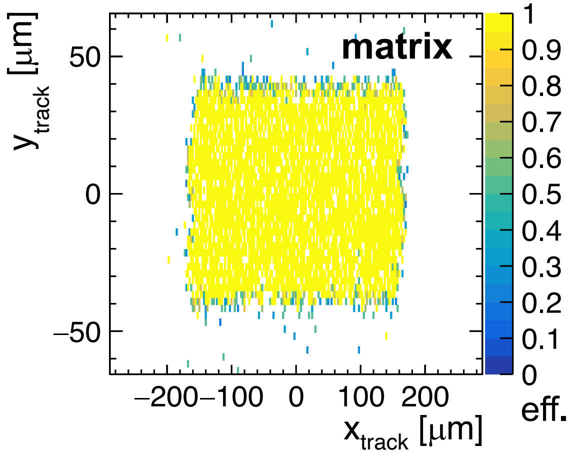
W03S1-1_3-20



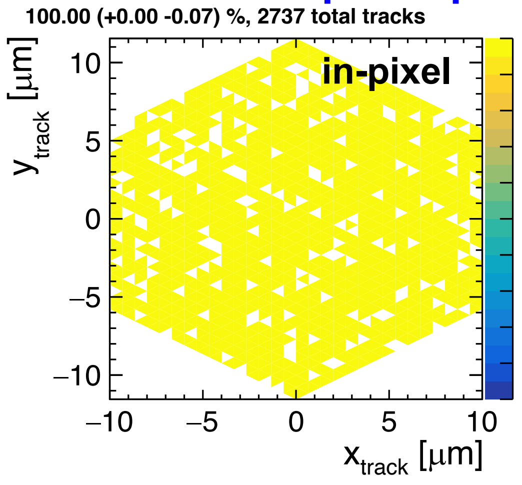
without deep n-implant



W15S1-1_3-20



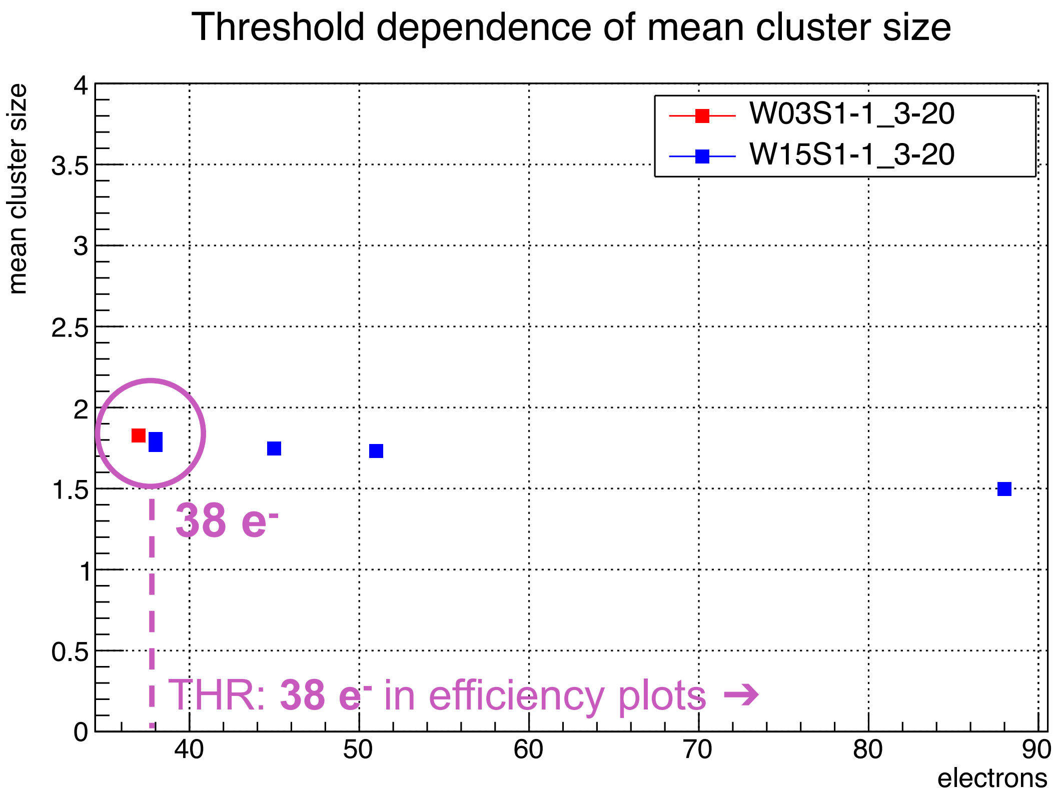
with deep n-implant



- Standard W03 vs Modified W15 for 20 µm matrix
- Global threshold of 38 electrons for both samples set by same threshold current I_{thr} on chipboard

➔ No significant difference in cluster size or efficiency

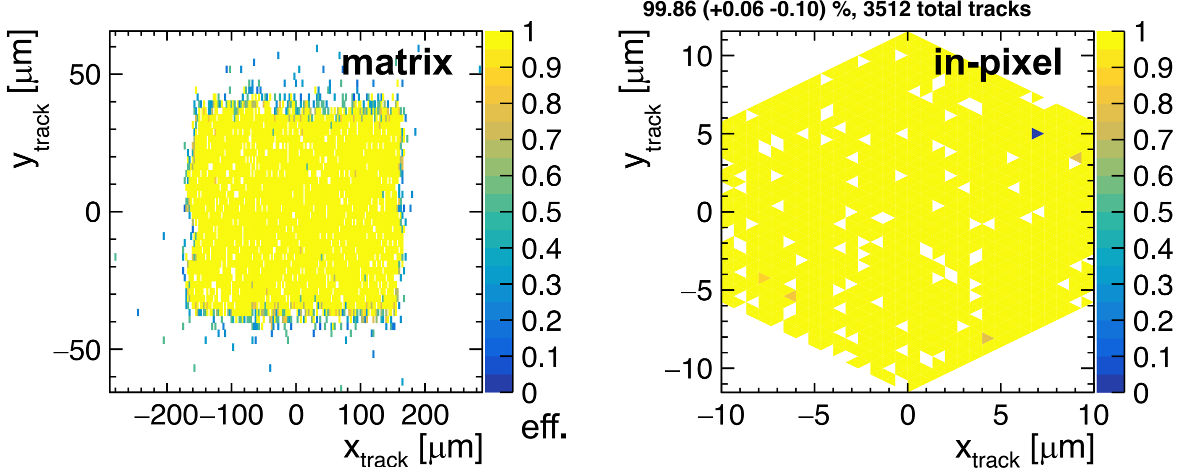
Cluster Size Distributions - 20 µm Pixel Pitch



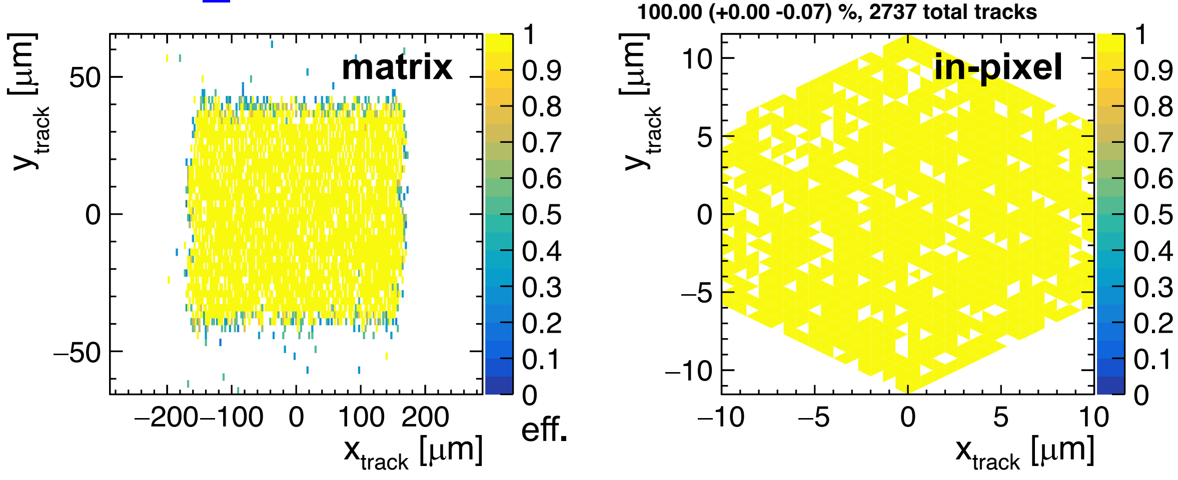
➔ Full efficiency, comparable cluster sizes for both samples at reasonable thresholds

➔ Charge sharing effects contribute most for hits near pixel border ➔ Less relevant in case of larger pixels

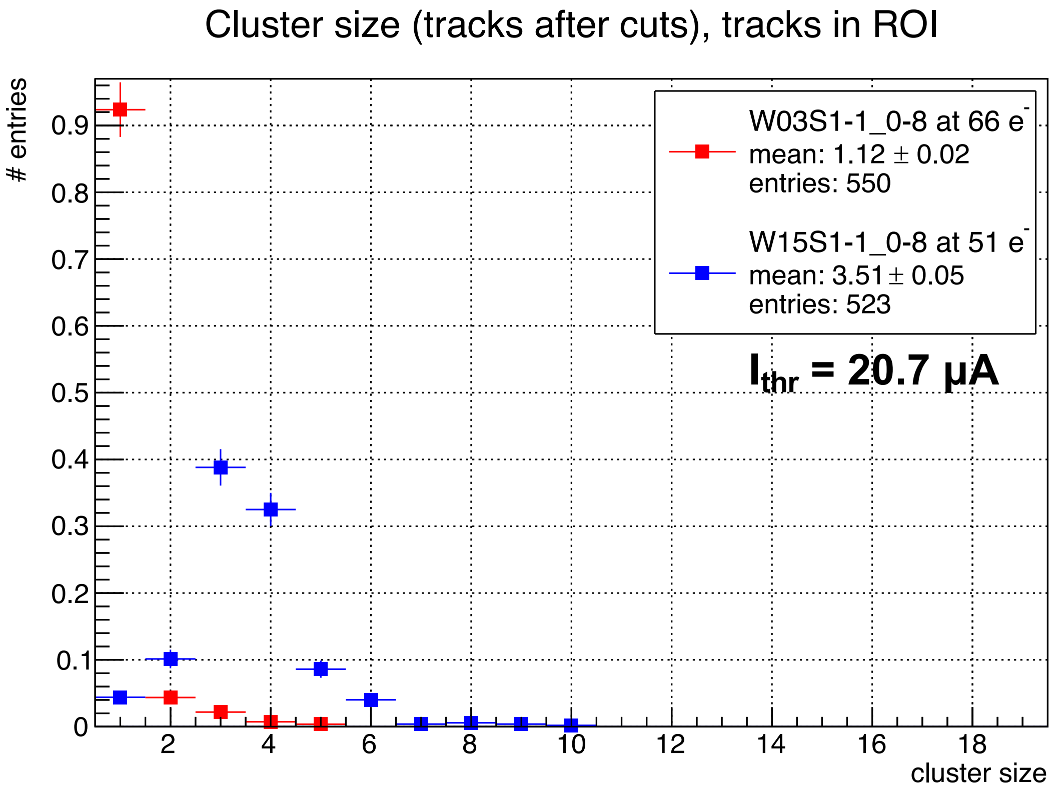
W03S1-1_3-20 **without deep n-implant**



W15S1-1_3-20 **with deep n-implant**



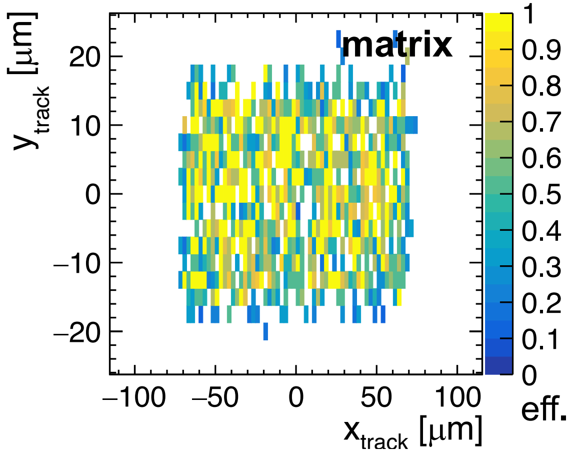
Cluster Size Distributions - 8.66 µm Pixel Pitch

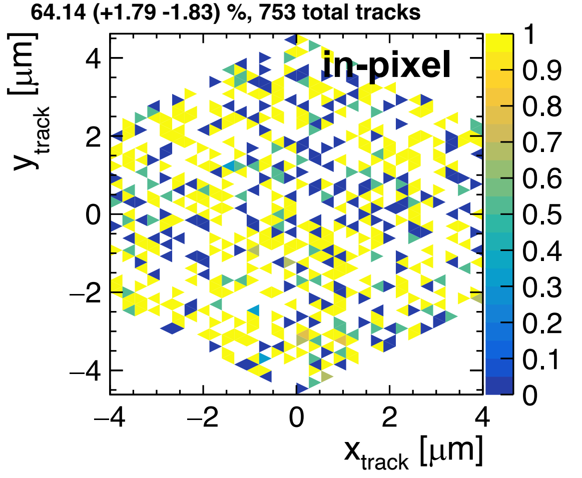


- W15 has 2.3 higher mean cluster size
- **W03 is 36% less efficient than W15 for 8.66 µm pixel pitch**

W03S1-1_0-8

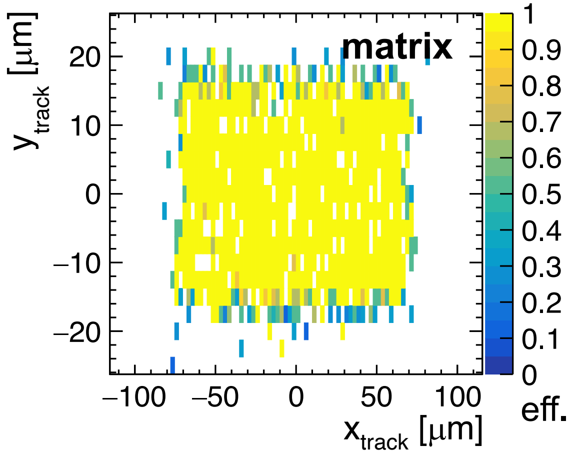
without deep n-implant

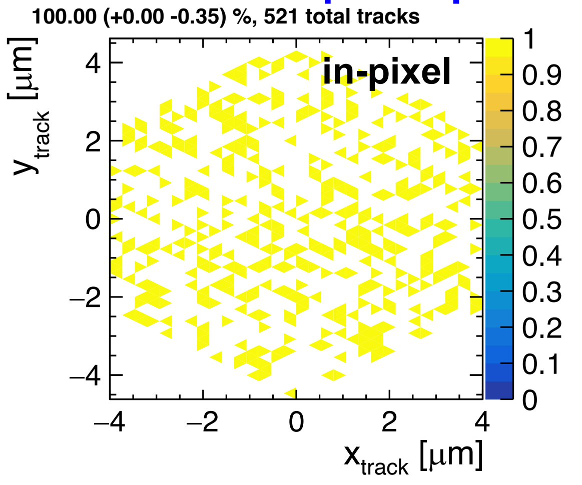




W15S1-1_0-8

with deep n-implant

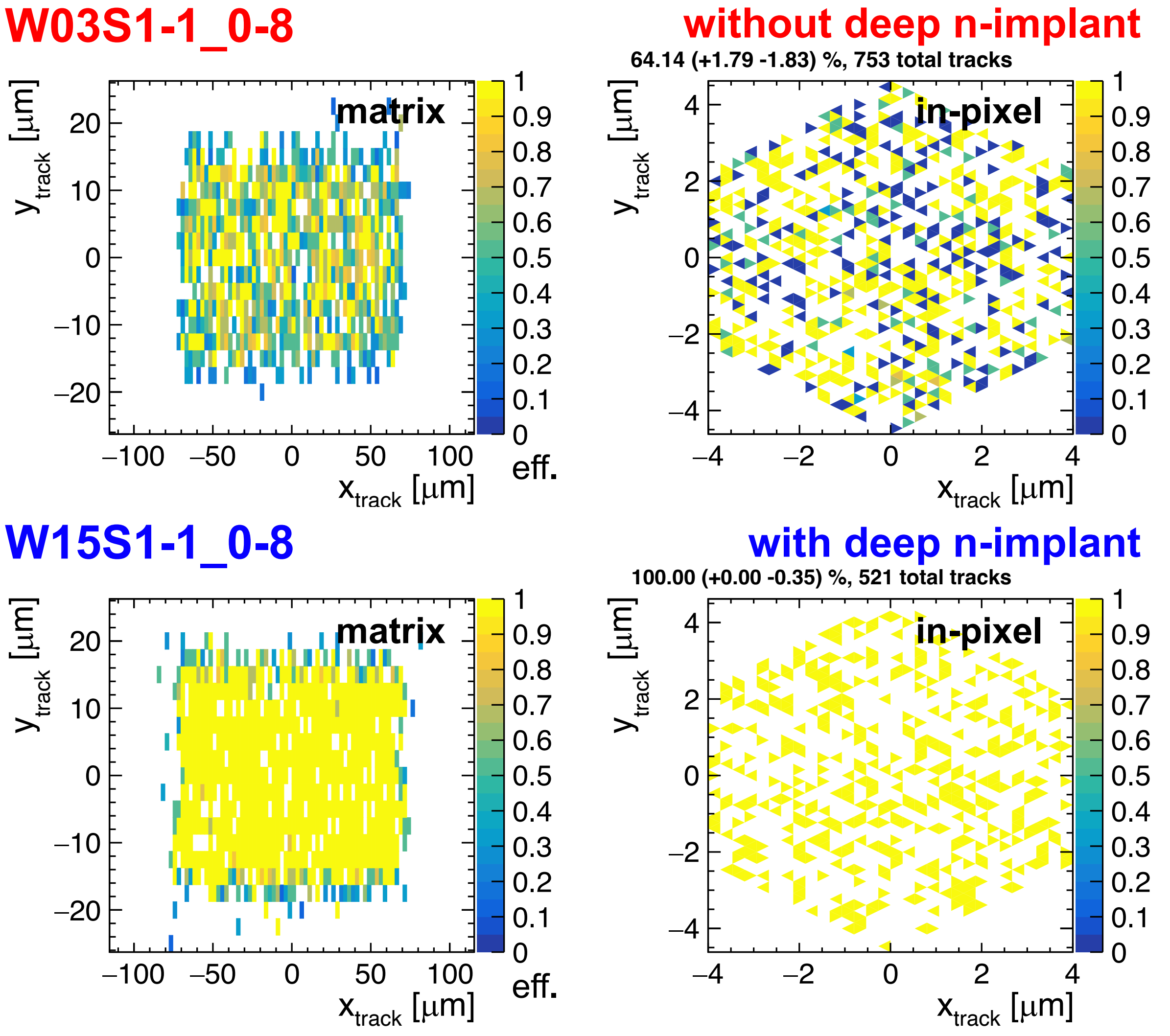




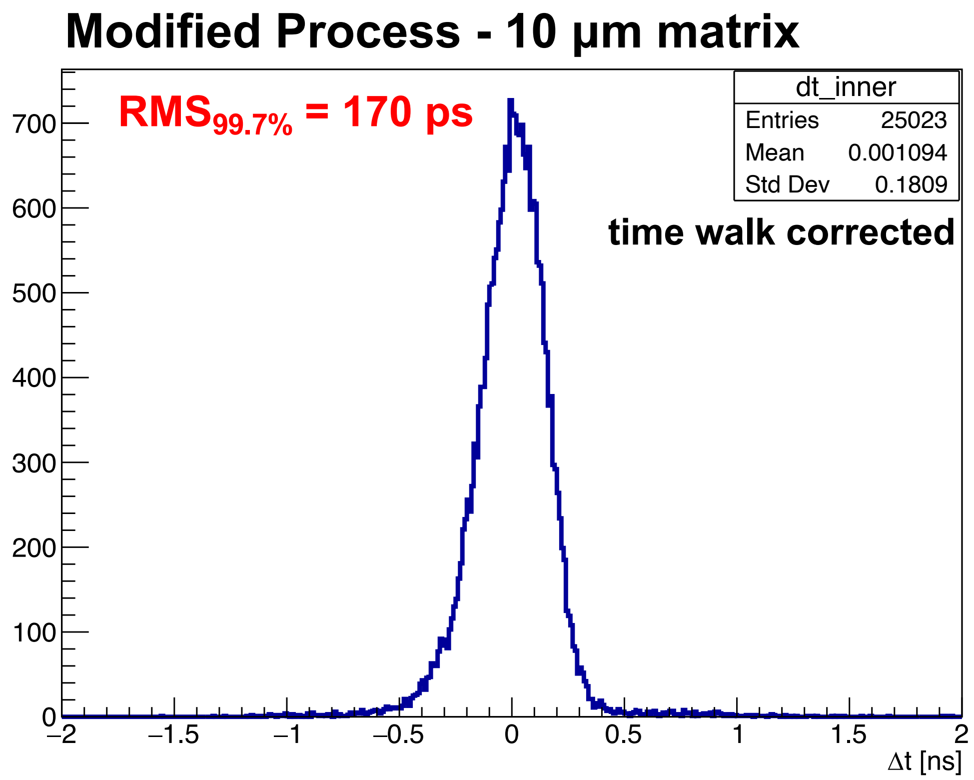
Cluster Size Distributions - 8.66 µm Pixel Pitch

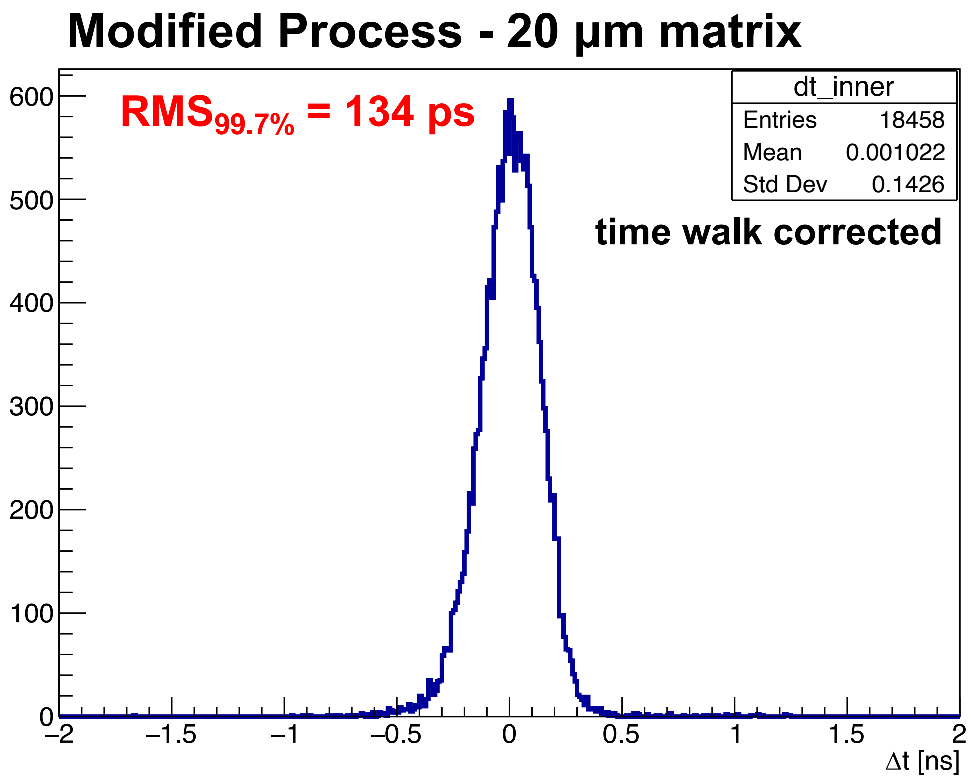
- W03 favors charge sharing due to lack of process modifications shaping electric field
- If fully efficient at the same e- threshold:
  - ➔ Increased charge sharing for standard process
  - ➔ Expected larger cluster size for standard compared to modified process
- Small pitch …
  - ➔ Increased charge sharing
  - ➔ On average smaller signal on seed pixel
  - ➔ Signal more likely to stay below threshold
  - ➔ Hit and remaining pixels in the cluster remain undetected

➔ **Process modifications of W15 help to contain the charge within single pixel ➔ give more margin for efficient operation**



Modified Process: Time Residuals



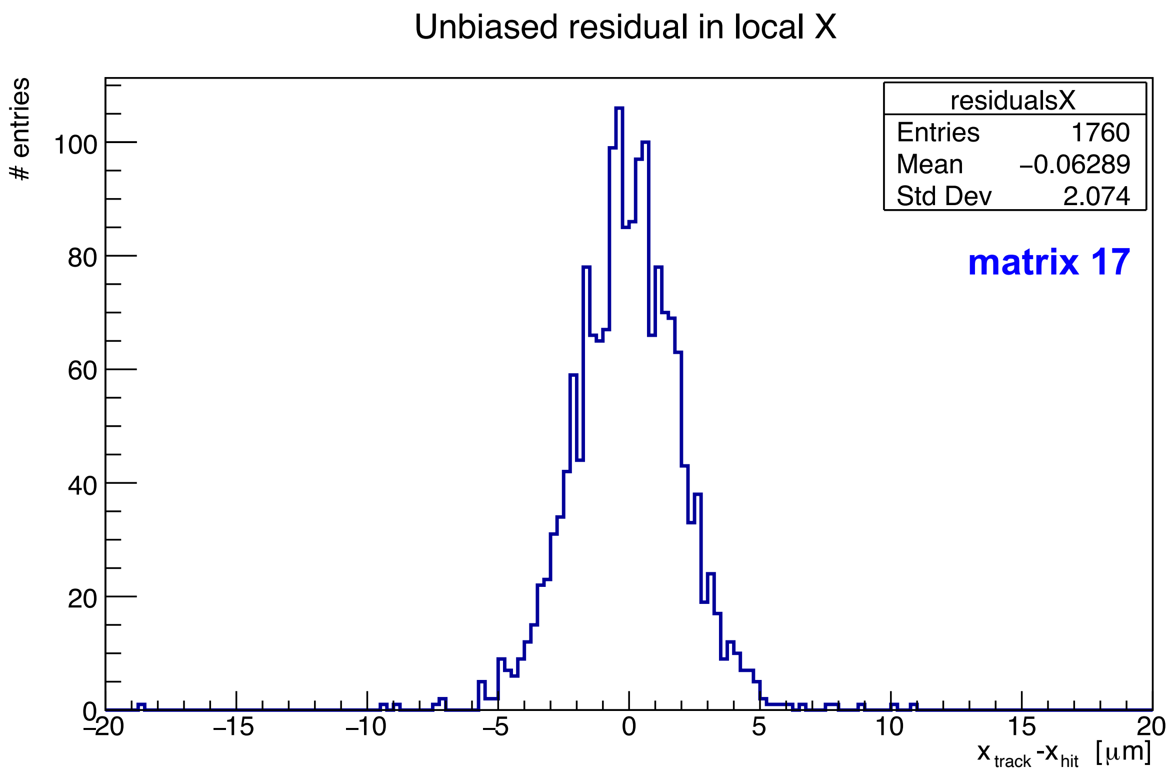


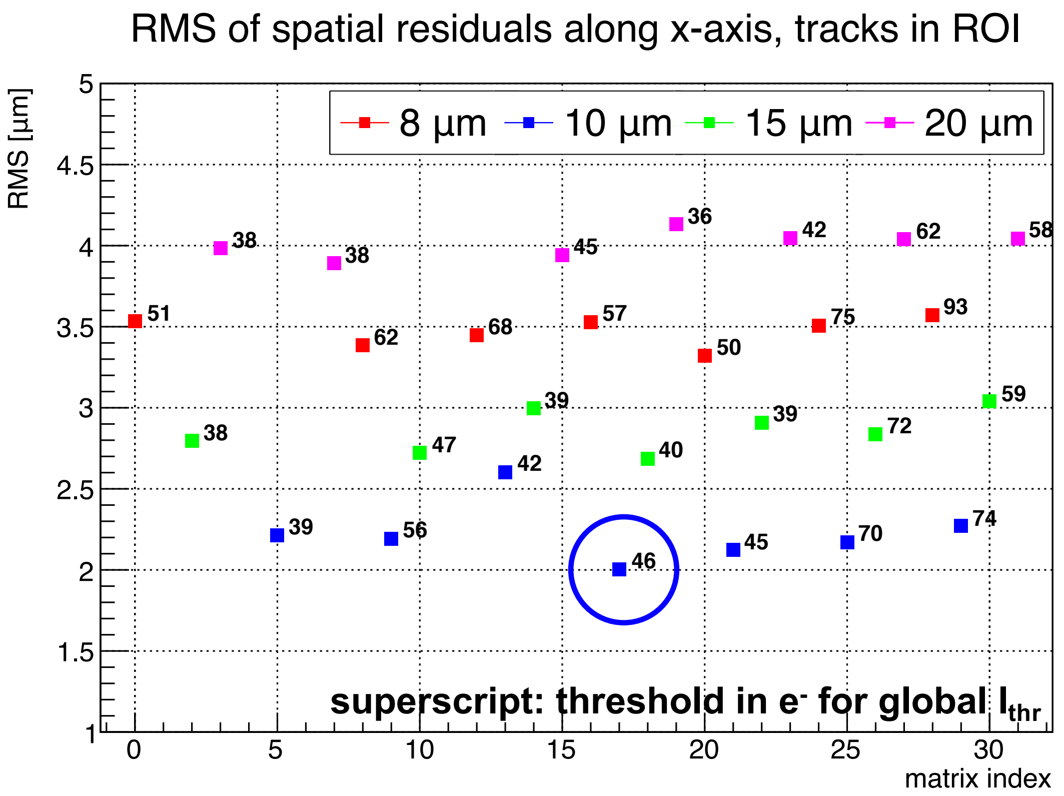
Smaller pitch ➔ shorter drift distance **but also** more charge sharing **and** larger cluster size

➔ Deteriorated time resolution for the seed pixel ➔ better performance for larger pixel pitch

➔ **FASTPIX reaches** a **timing precision of 134 ps** with 20 µm matrix in modified process

Modified Process: Spatial Residuals





RMS of spatial residuals for all matrices between 2 µm and 4.2 µm Tele. tracking resolution: Kroeger, J. CERN-THESIS-2021-167

➔ **Smaller pitch ➔ lower RMS, except 8 µm:** higher thresholds ➔ less detected charge sharing

➔ smaller cluster size ➔ neg. influence on position resolution.

➔ Telescope tracking resolution at DUT position: approx. 1.7 µm ➔ **1.0 µm – 3.8 µm spatial resolution**

Summary

- **Successful integration of FASTPIX in existing CLICdp telescope setup**
- **FASTPIX process modifications on wafer level essential for efficient operation of detector prototypes with small pixel pitch of 8.66 µm**
- **FASTPIX reaches ~$\mathcal{O}$(150 ps) timing precision for modified process**
- **FASTPIX reaches spatial resolution between 1.0 µm – 3.8 µm**

Acknowledgements

- **ATTRACT**

  FASTPIX has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222.

- **AIDAinnova**

  This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA no 101004761.

- **CERN EP R&D**

  FASTPIX and connected testing efforts are part of the CERN EP R&D programme on technologies for future experiments.

- **German Doctoral Student Programme at CERN**

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Sensor Design Optimization Before FASTPIX

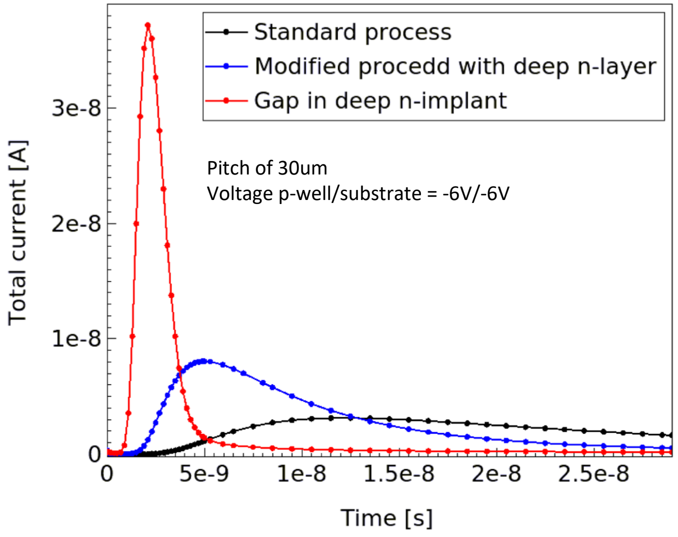
Slide taken from: M.Munker, iWoRiD 2021

Optimization performed with 3D Technology Computer Aided Design simulations (3D TCAD)

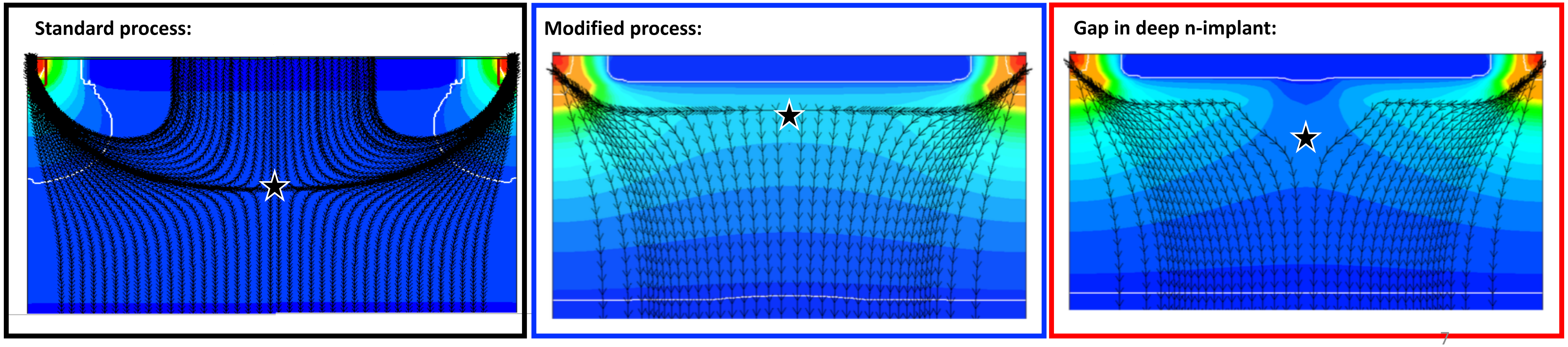
Fundamental challenges:

1. Increase and shape field significantly while maintaining small sensor capacitance
2. Limitations of circuitry on sensor and vice versa

Single pixel current pulse from transient 3D TCAD MIP simulation in pixel corner :

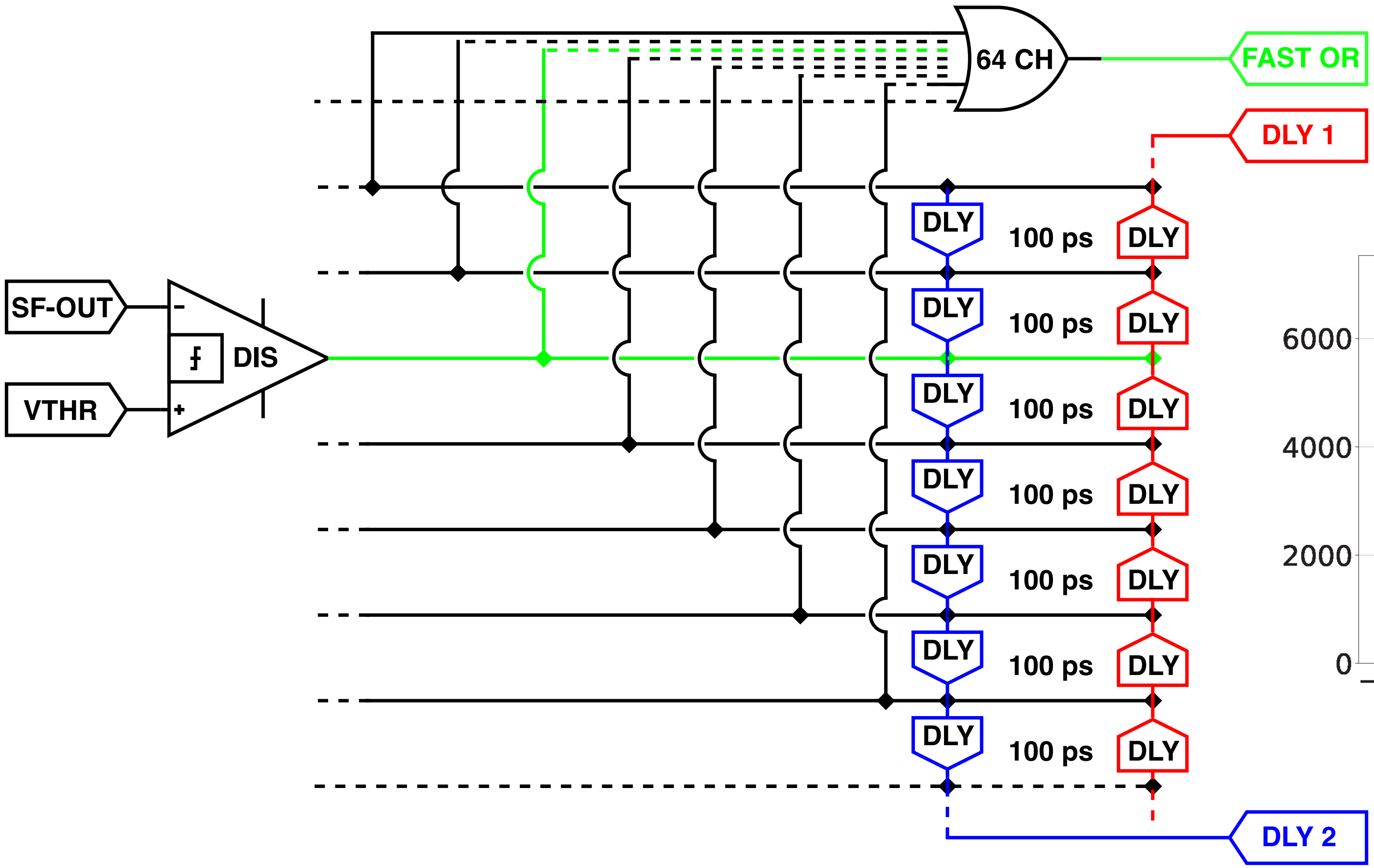


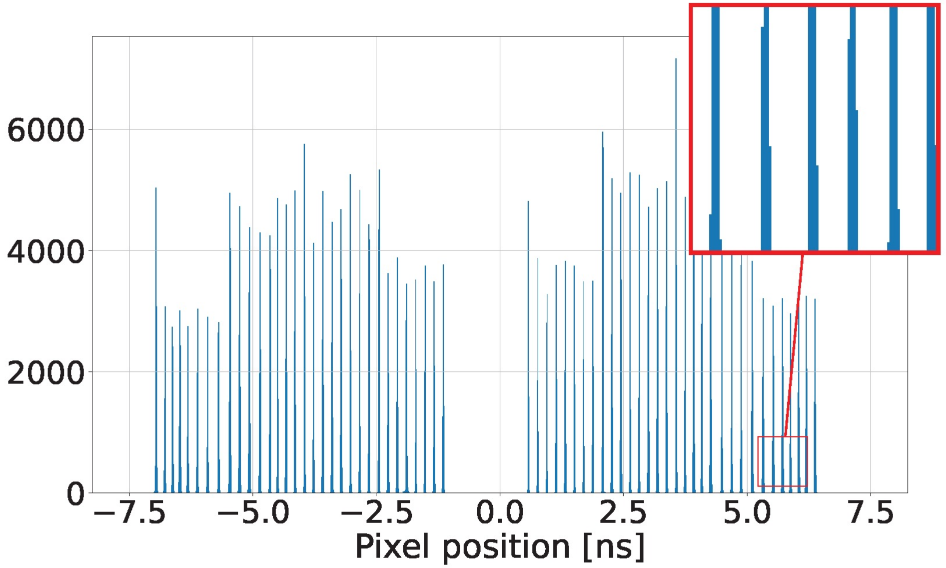
Electrostatic potential from 3D TCAD (color scale), streamlines (black arrows) and electric field minimum (star symbol):



Pitch of 36.4µm, voltage p-well/substrate = -6V/-6V

Readout Architecture





Independent Time Reference - MCP-PMT

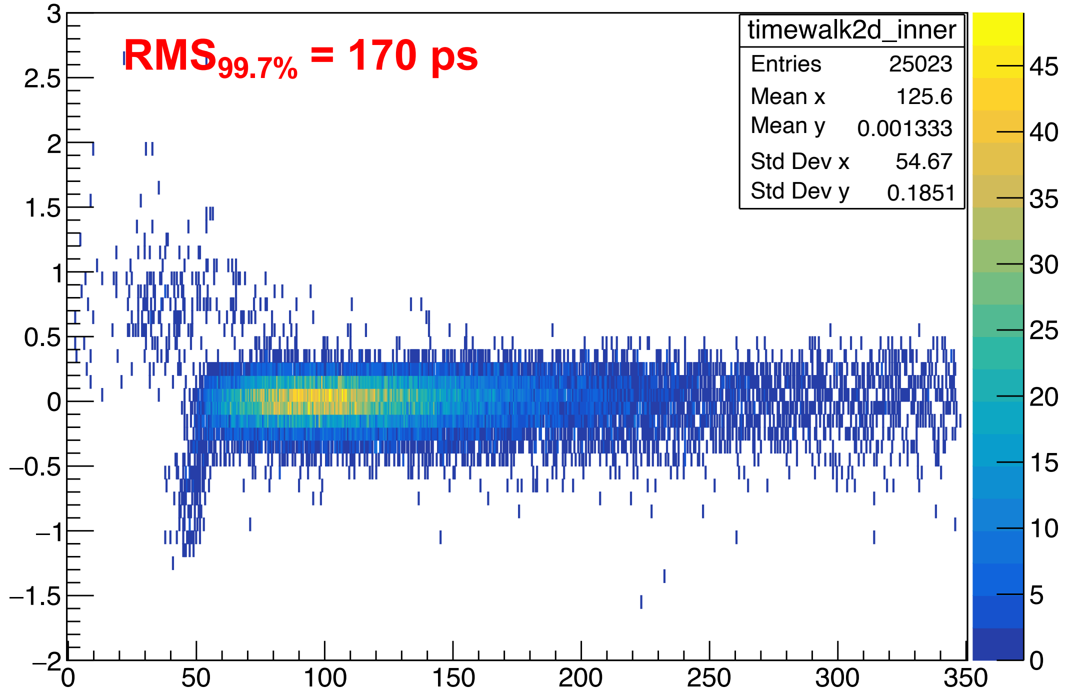
TODO: Revive link

HAMAMATSU R3809U-50 CT1742

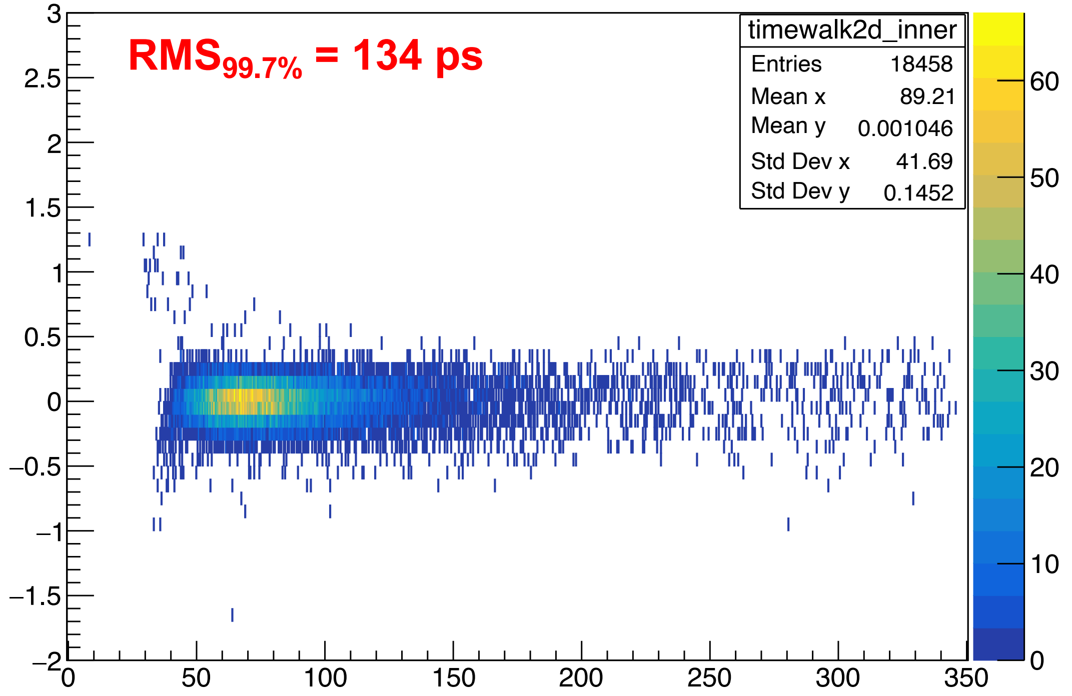
- Acceptance ~1 cm^2, expected resolution below 10 ps (see: J. Bortfeldt et al.)
- Built-in amplifier and bias-T circuit (V_{bias} = 2.6 kV) → Oscilloscope-based readout
- Custom 3D printed housing adapts to high-precision rails of telescope arms

MOD: Time Residuals with time walk correction

Modified Process - 10 um



Modified Process - 20 um

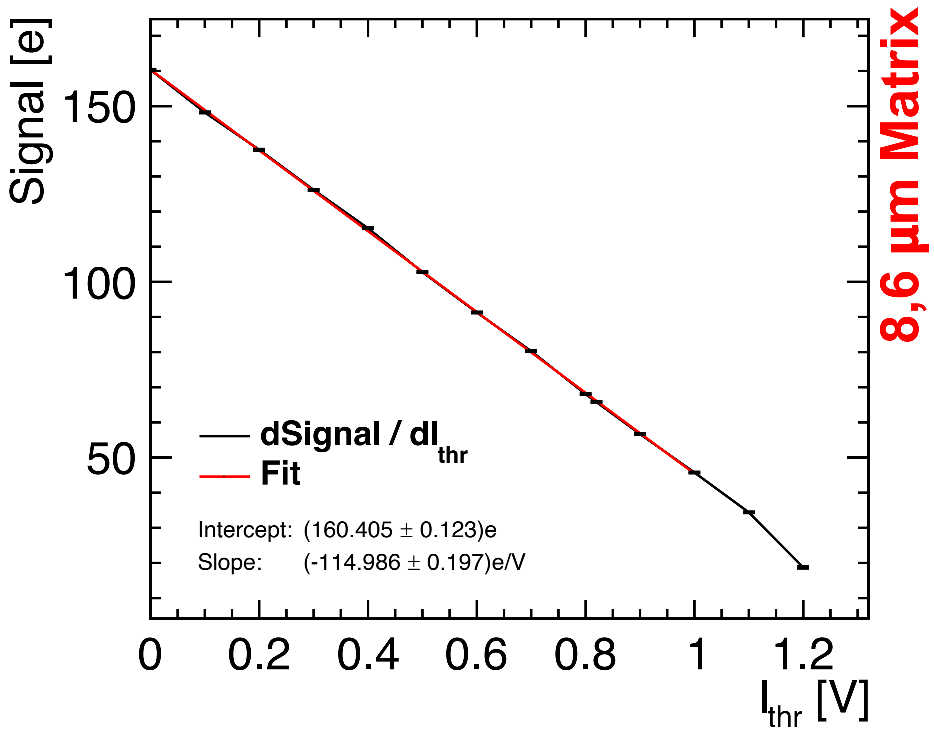


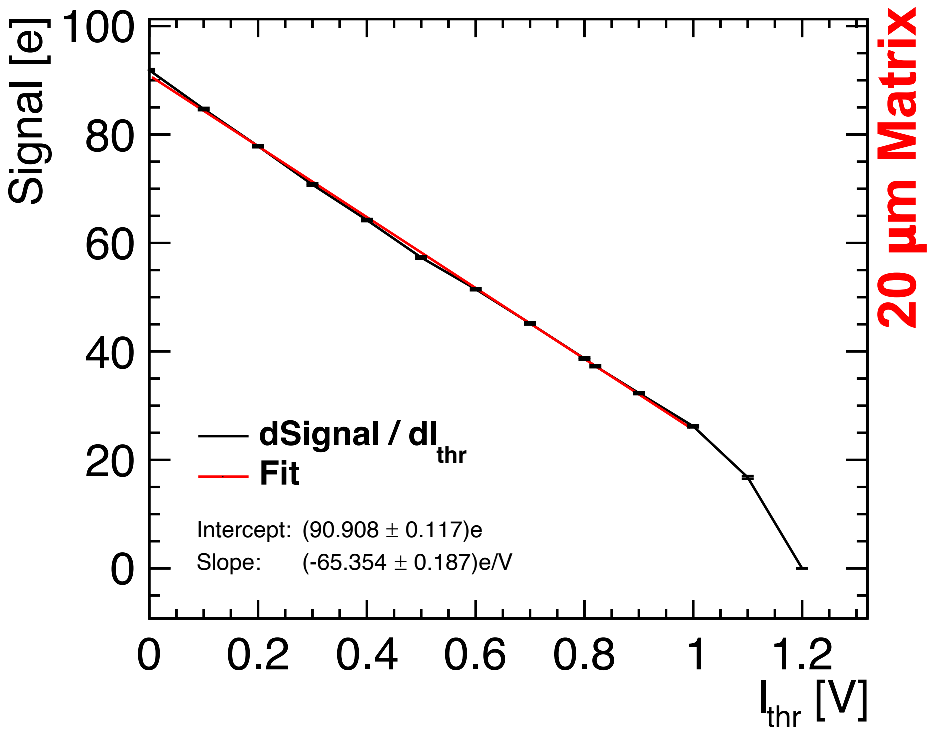
Time walk corrected time residuals for exemplary 10 um and 20 um matrix

➔ Timing performance suffers from increase in cluster size for smaller pixel pitches

➔ FASTPIX reaches a **timing precision of 134 ps**

Threshold Calibration with Test Pulses

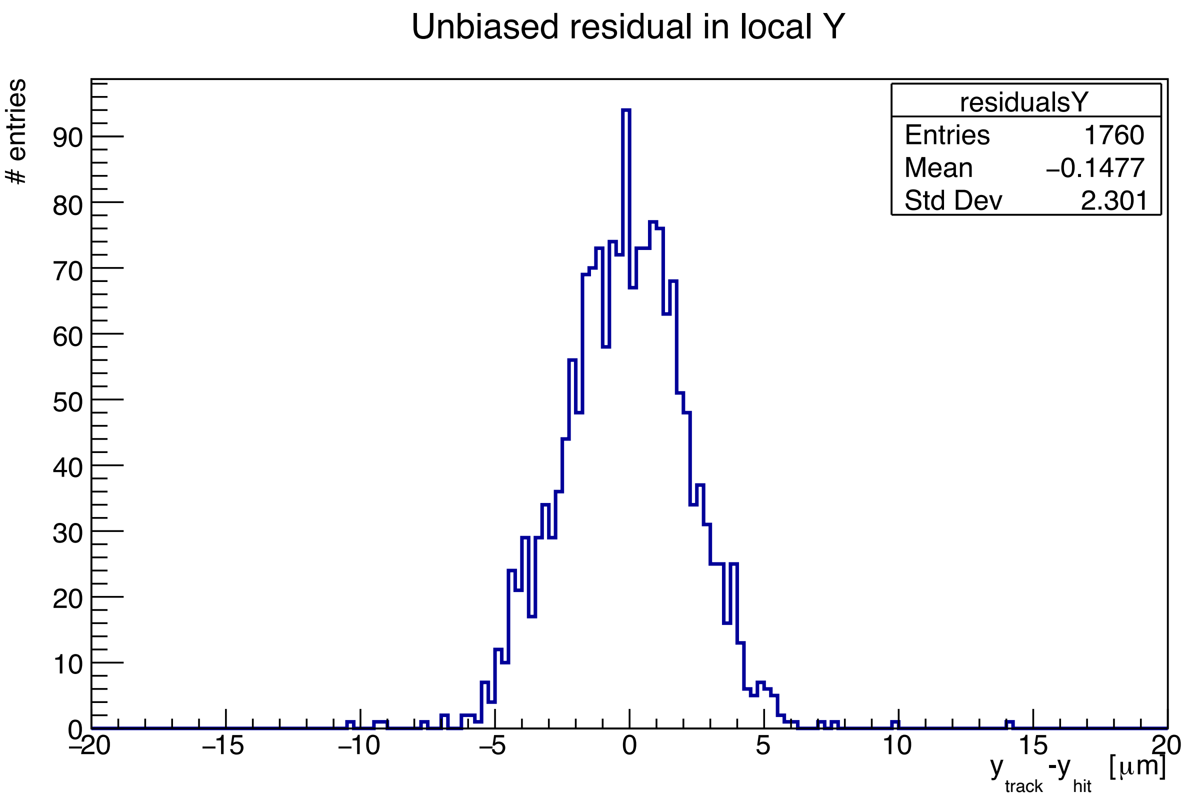


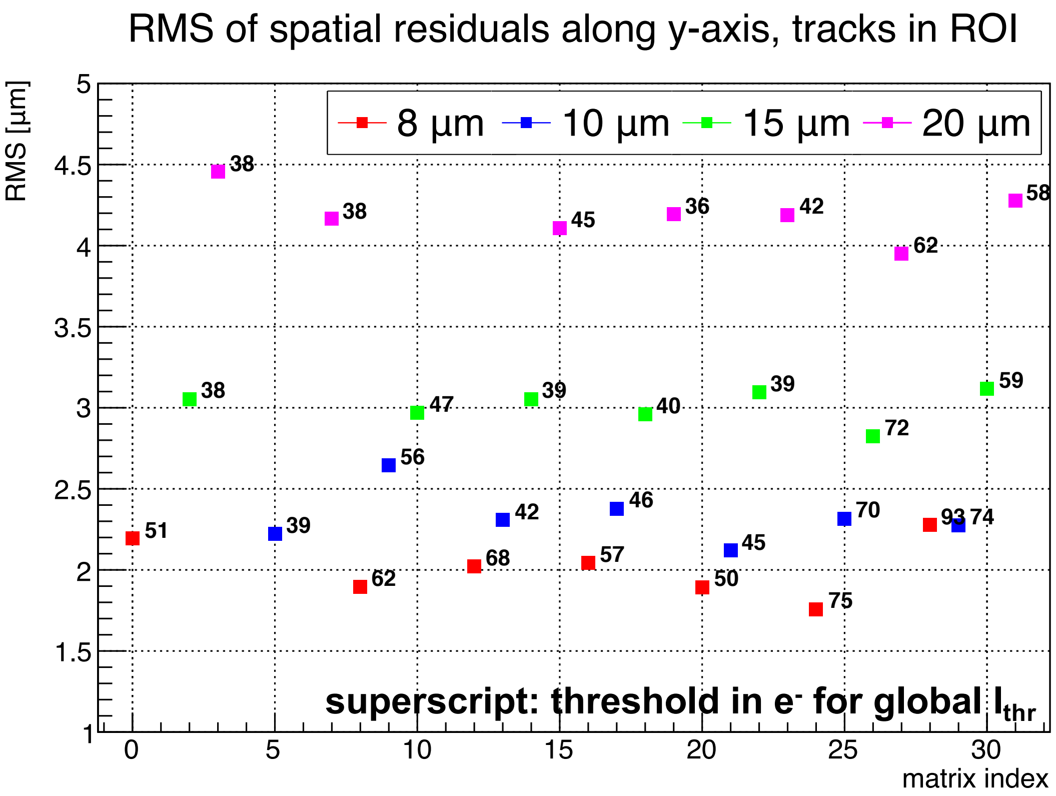


Signal in e^- is calculated using the design value of the test pulse capacitor

- Range follows approx. linear trend but fails to extend to higher electron-thresholds

Modified Process: Spatial Residuals





RMS of spatial residuals in y for all matrices between 1.7 um and 4.5 um

➔ Telescope tracking resolution at DUT position: approx. 1.7 um ➔ **Further investigation necessary.**