Performance of irradiated Digital Pixel Test Structures produced in 65 nm TPSCo CMOS process

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Pascal BECHT (Physikalisches Institut)

High-RR bi-weekly seminar

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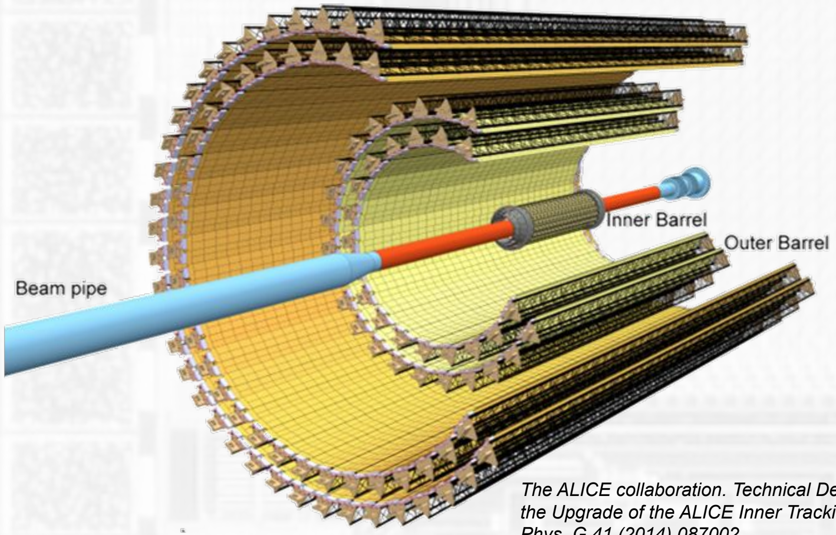
From ALPIDE to a 65 nm CMOS MAPS prototype: ALICE inner tracker upgrades

- ITS2 installed for improved tracking resolution and rate capability in LHC Run 3
- Especially true for low-momentum particles (new regions accessible)

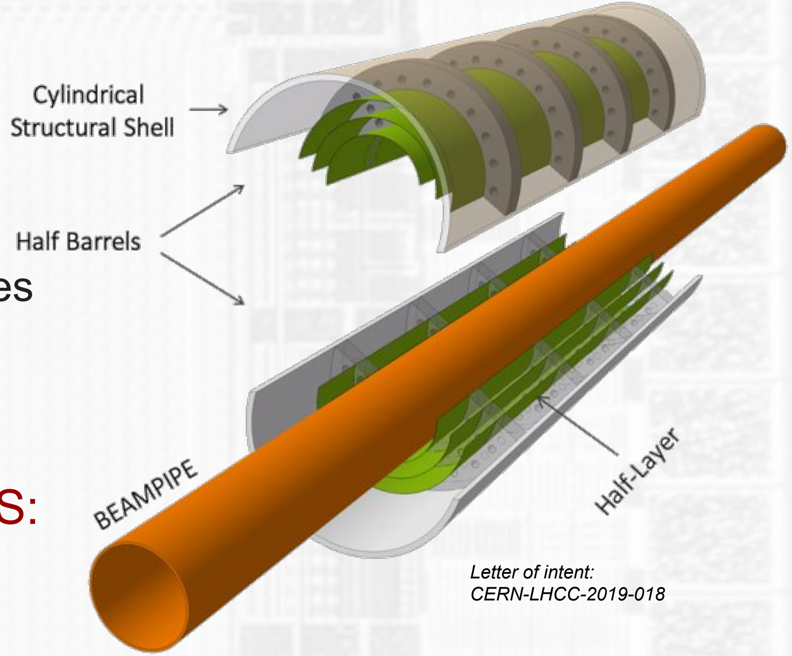


The ALICE collaboration. Technical Design Report for the Upgrade of the ALICE Inner Tracking System. J. Phys. G 41 (2014) 087002

- Powered by state-of-the-art MAPS
- **ALPIDE (180 nm technology node)**
  - ~500k pixels
  - ~30 µm x 30 µm pitch
  - In-pixel signal discrimination, i.e. digital output
  - Spatial resolution better than 5 µm
  - Optimised for low-power consumption
  - 50 µm thin chip

From ALPIDE to a 65 nm CMOS MAPS prototype: ALICE inner tracker upgrades

- Further improvement on material budget possible (wrt. ITS2 with ALPIDE sensors)
  - Improve pointing resolution by factor 2
  - Improve tracking of low momentum particles
- Get closer to the interaction point



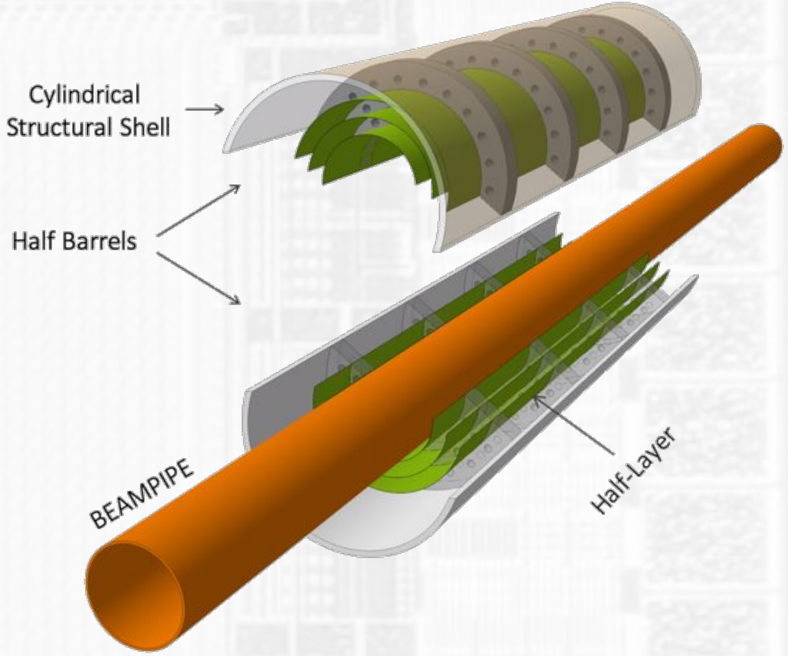
Letter of intent: CERN-LHCC-2019-018

- Move to truly-cylindrical, wafer-scale MAPS: **ITS3**
- Sensors self-supported due to bending
- Thin sensors O(30 µm)
- Cooled by air flow
- Optimised power consumption

- New generation of tracking detectors
- R&D started on new sensors to face the challenges

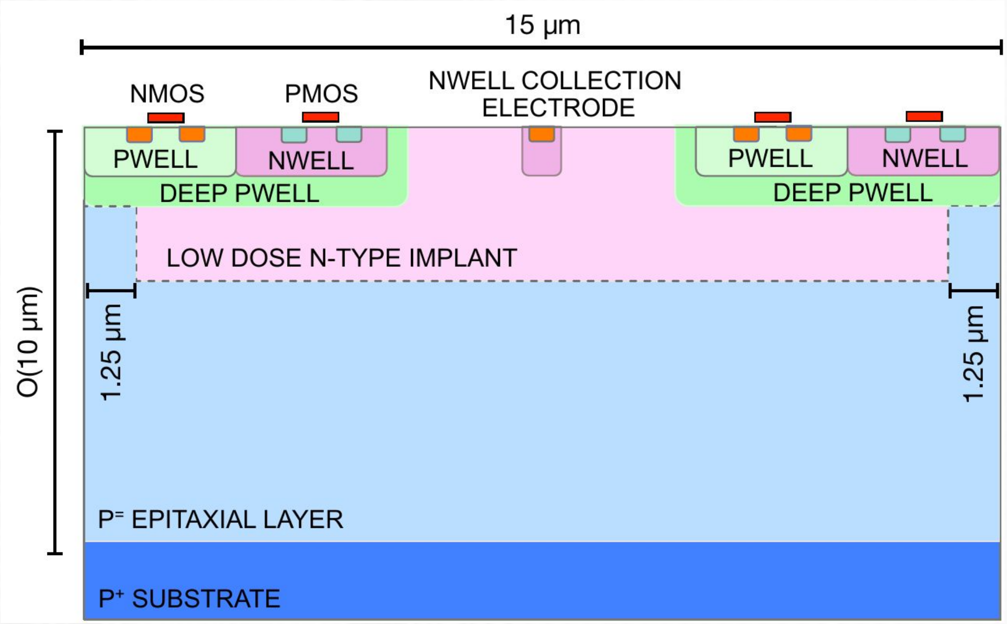
From ALPIDE to a 65 nm CMOS MAPS prototype: A new sensor for the ITS3

- 65 nm CMOS technology node is key
    - Larger available wafers (30 cm)
    - Stitching available for production of large area sensors
- Smaller feature size
    - Realise smaller pixels with in-pixel signal processing
    - Manageable occupancy at high track densities



- Small scale prototypes are available since 2021
- Multi Layer Reticle 1 (MLR1) submission
    - Joint effort of CERN EP R&D and ALICE ITS3

The MLR1 Digital Pixel Test Structure (DPTS)

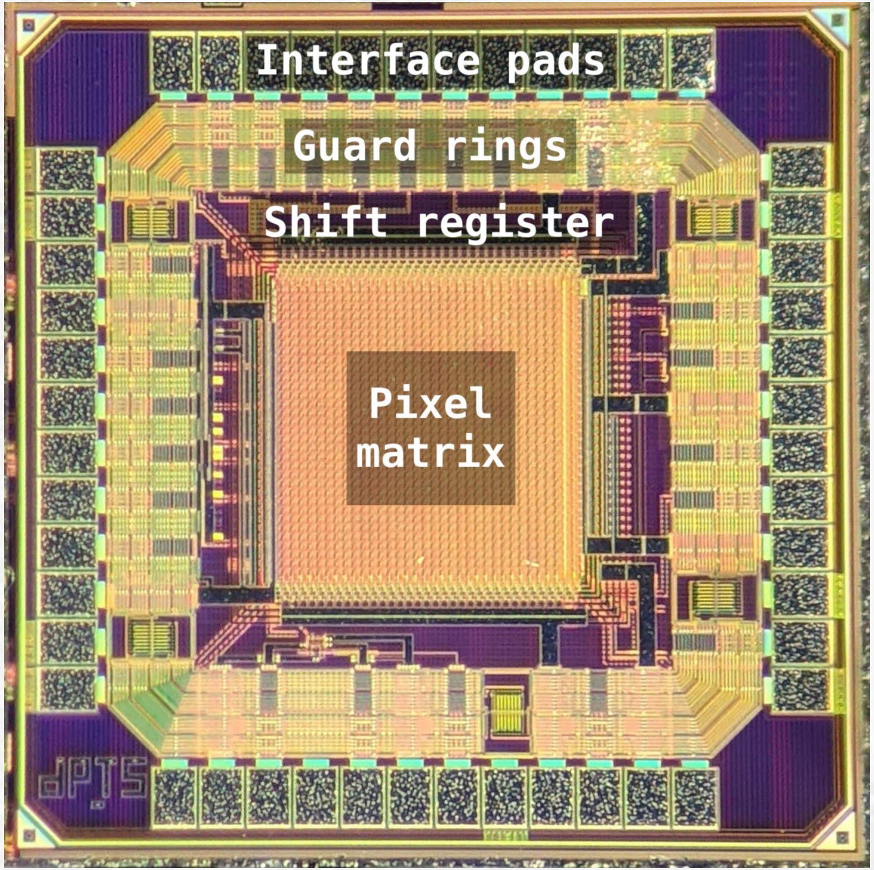


- Active epitaxial layer of ~8 µm
- Deep n-implant to fully deplete epitaxial layer

- Gaps for having a lateral field component
- Enhance charge collection in a single pixel
- Higher operating margin due to larger seed pixel signal

- Produced in “modified process”
- Pixel cross section not to scale

The MLR1 Digital Pixel Test Structure (DPTS)



- Full pixel matrix with in-pixel signal discrimination
  - Test front-end and digital building blocks
  - In-beam sensor performance characterisation
- 480 µm x 480 µm active area
- 32 x 32 pixel (15 µm x 15 µm)

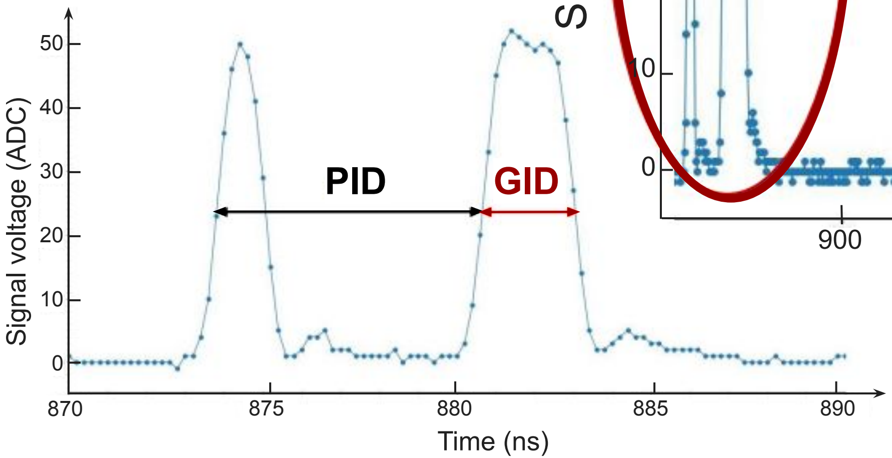
- Asynchronous digital readout (single output line)
- Time-encoded position information
- Access to signal time over threshold

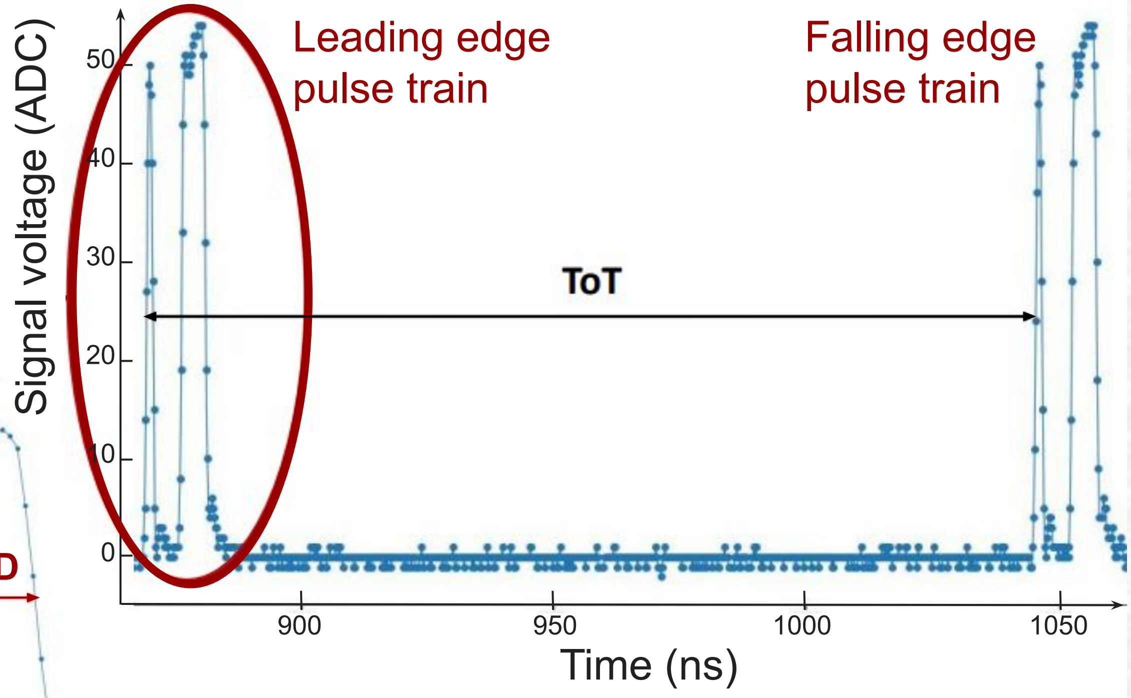
DPTS signals and position decoding

- Single pixel hit

PID: Pixel ID - pixel row

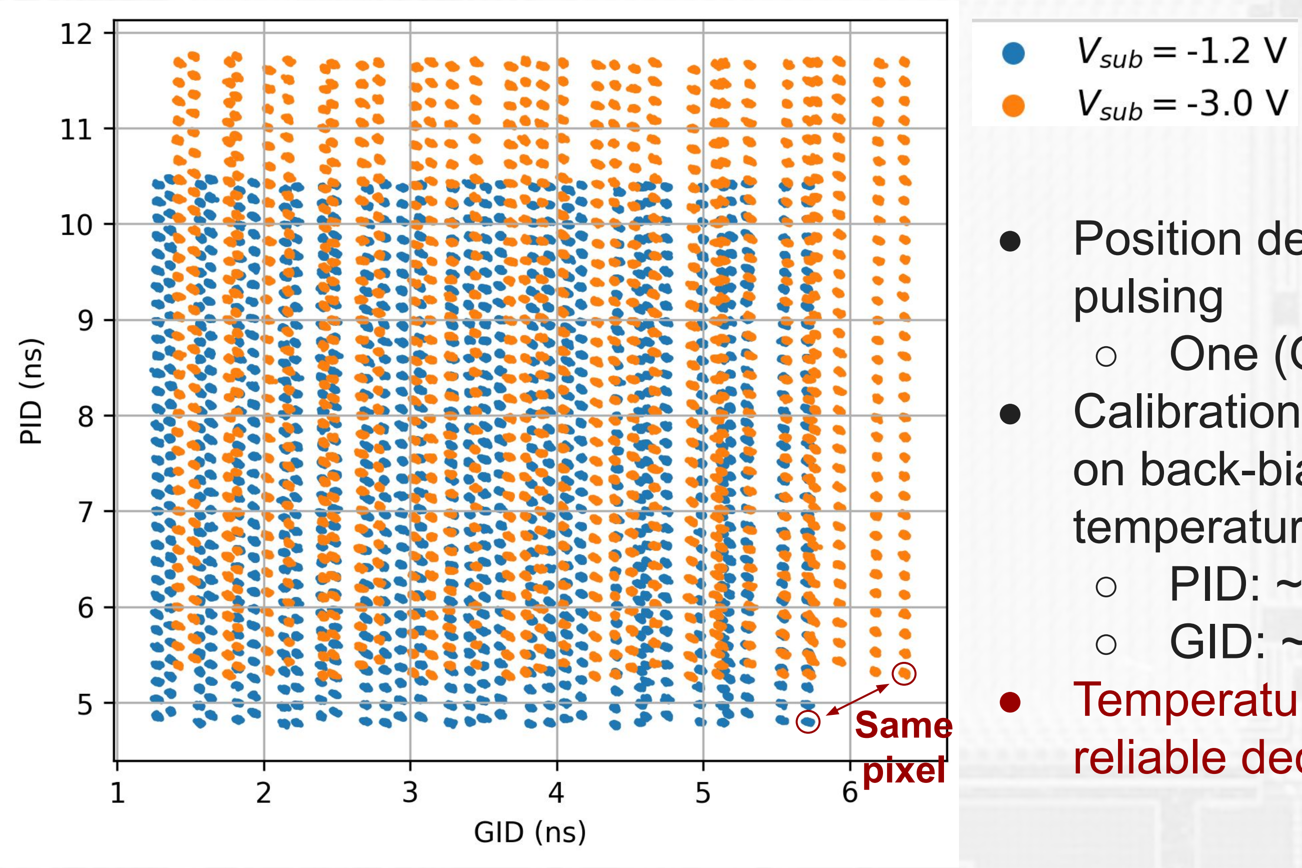
GID: Group ID - pixel column





- Multiple pixel hits may cause signal collisions

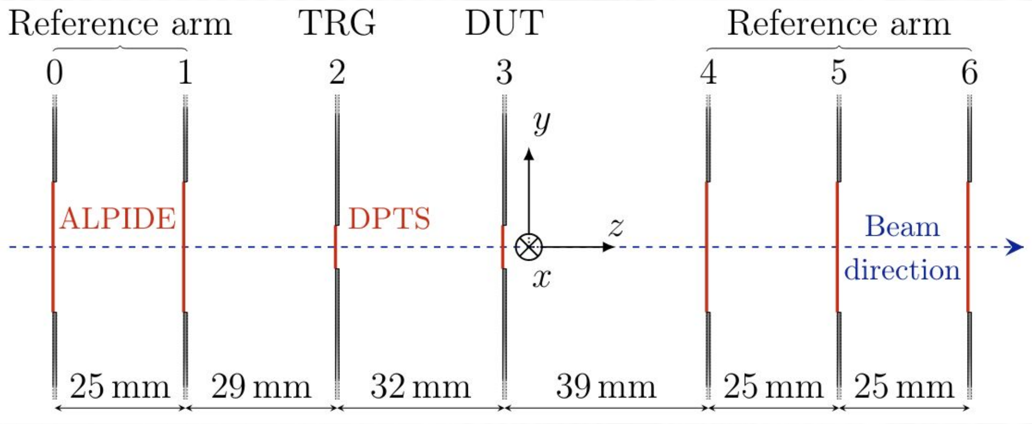
DPTS signals and position decoding

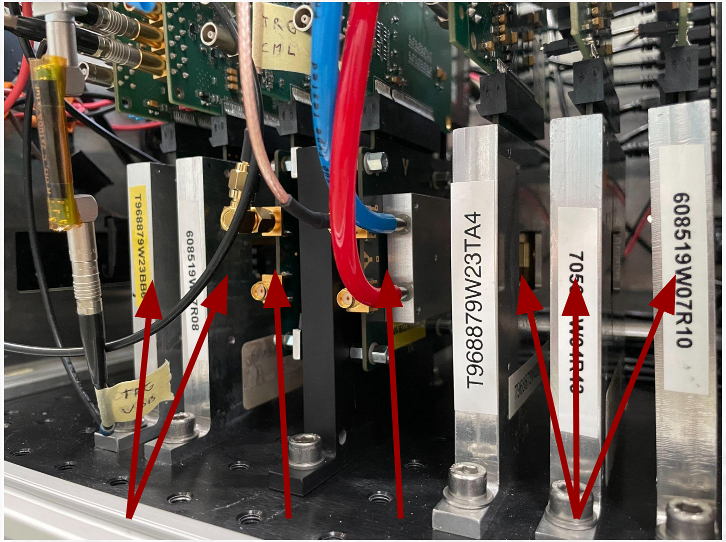


- Position decoding calibration via pulsing
  - One (GID,PID)-point per pixel
- Calibration map strongly depends on back-bias voltage and temperature
  - PID: ~0.04 ns / 5°C
  - GID: ~0.02 ns / 5°C
- Temperature control needed for reliable decoding

Multiple testbeam campaigns

- DESY
- CERN PS
  - 10 GeV/*c* positive hadrons



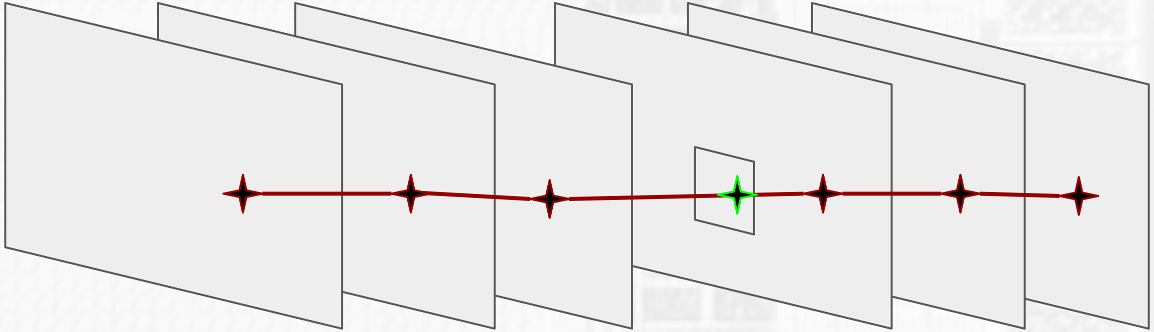


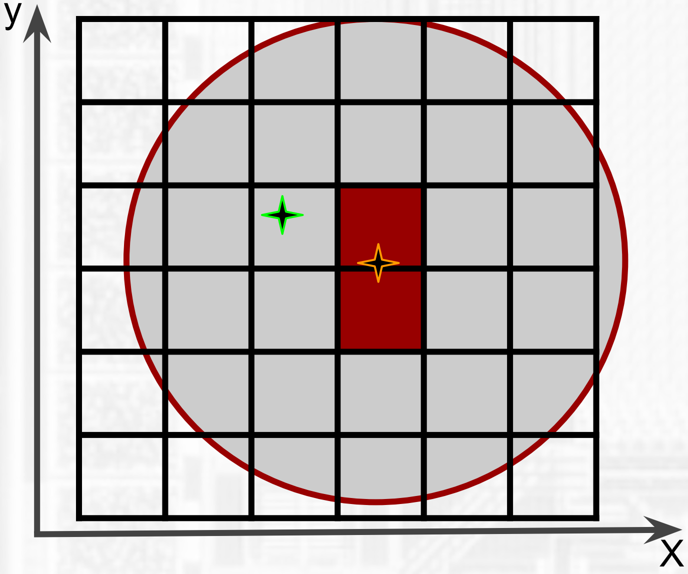
ALPIDEs TRG DUT ALPIDEs

- Temperature kept at 20°C with chiller
- In-situ fake hit rate, threshold measurements
- In-situ position decoding calibration
- DPTS waveforms read out with oscilloscope
- Data analysis with Corryvreckan
  - Alignment, Tracking, DUT association
  - **https://gitlab.cern.ch/corryvreckan/corryvreckan**

Testbeam data analysis

- Track fitting from reference planes
- GBL model used
- Multiple scattering taken into account
- Interpolation to DUT
- Associate measured DUT cluster





Efficiency calculation

- No spatial window
  - Undecodable events considered: “Signal clash”
  - Trigger mitigates false hit associations
- Time window: 1.5 µs

- Number-ratio of matched tracks and total reconstructed tracks

Testbeam data analysis

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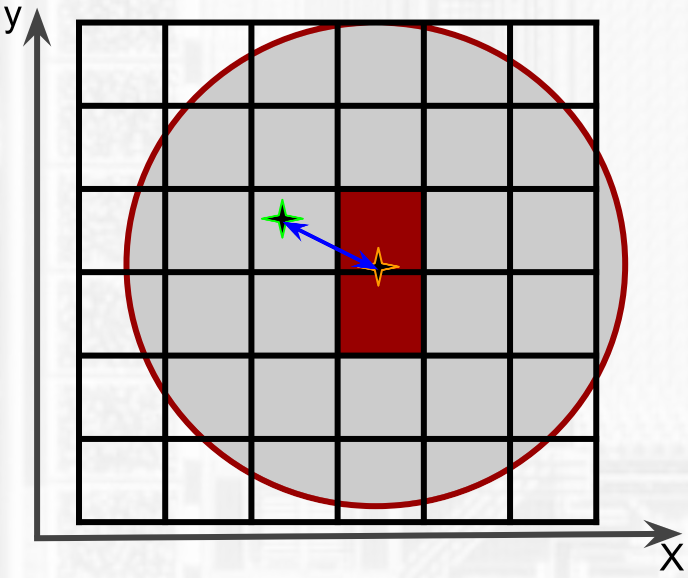
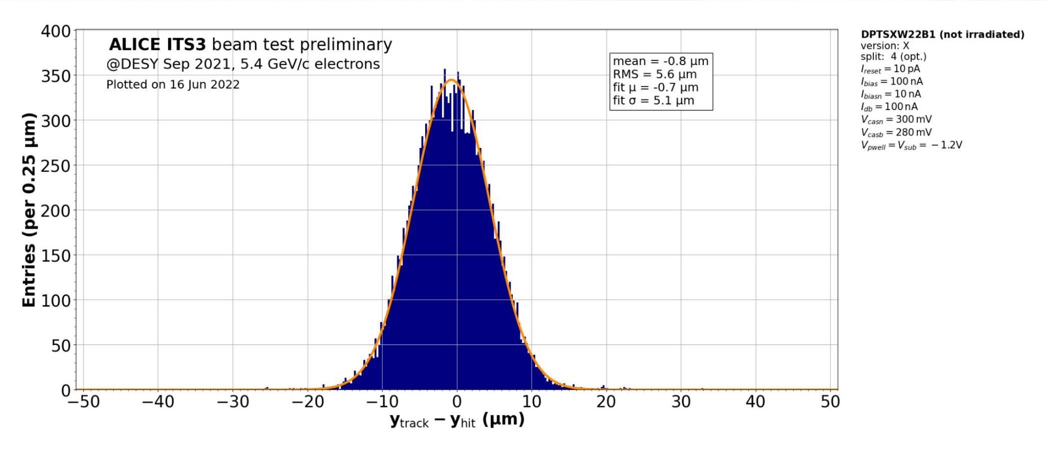


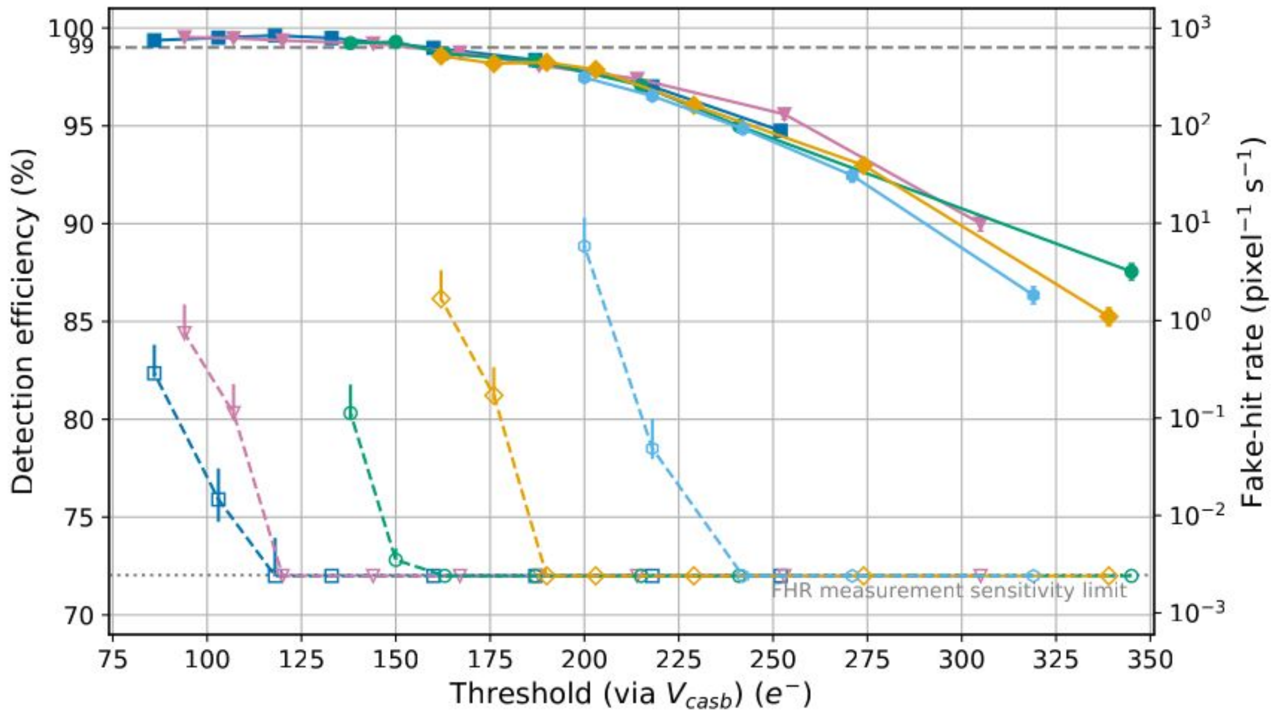
Position resolution calculation

- Spatial window: 45 µm (3 px)
- Time window: 1.5 µs



- Width of spatial residual distribution in x and y
  - Arithmetic mean
- Subtract telescope resolution from simulation: 2.43 µm

DPTS performance - Detection efficiency
Dependence on back-bias voltage (VBB)

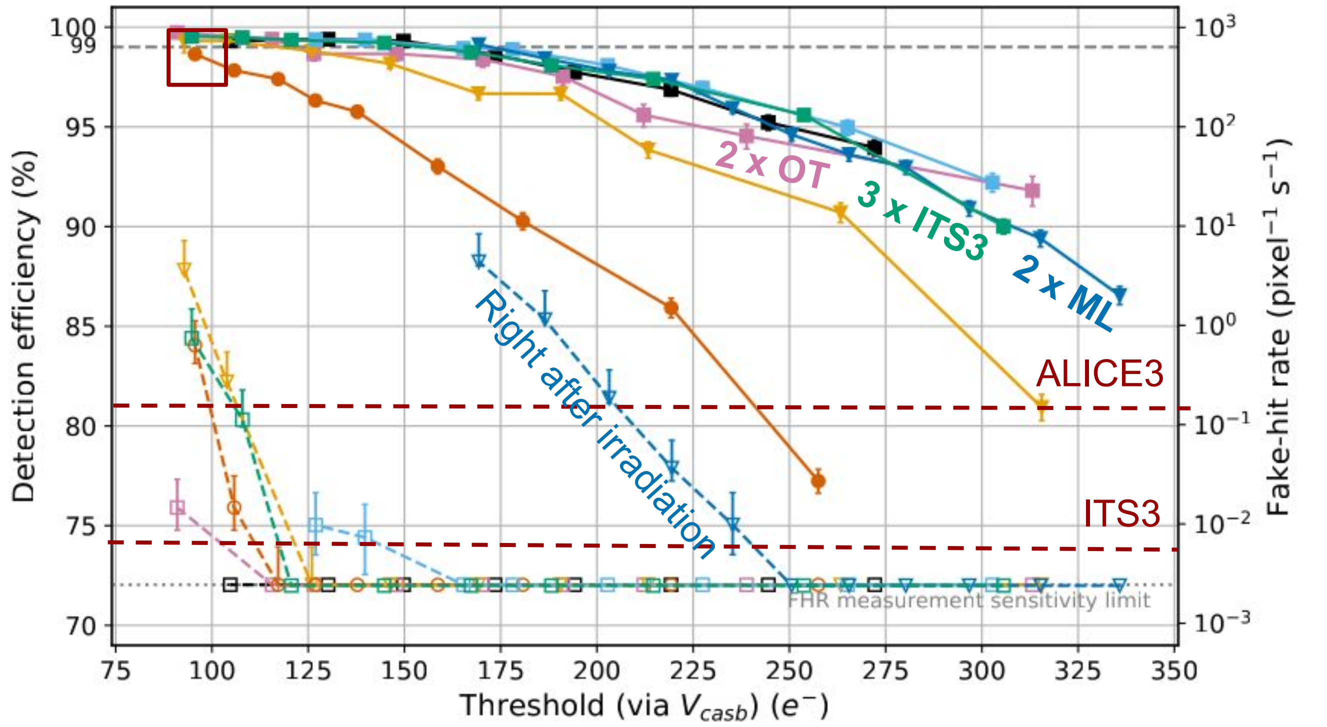


DPTS @ 10 kGy + 10^{13} 1 MeV n_{eq} cm^{-2}

Association window: 480 μm x 1.5 μs

- Detection efficiency exceeds 99% for a wide range of working points
- Manageable noise levels
  - FHR increase with lower VBB

DPTS performance - Detection efficiency
Irradiated sensors

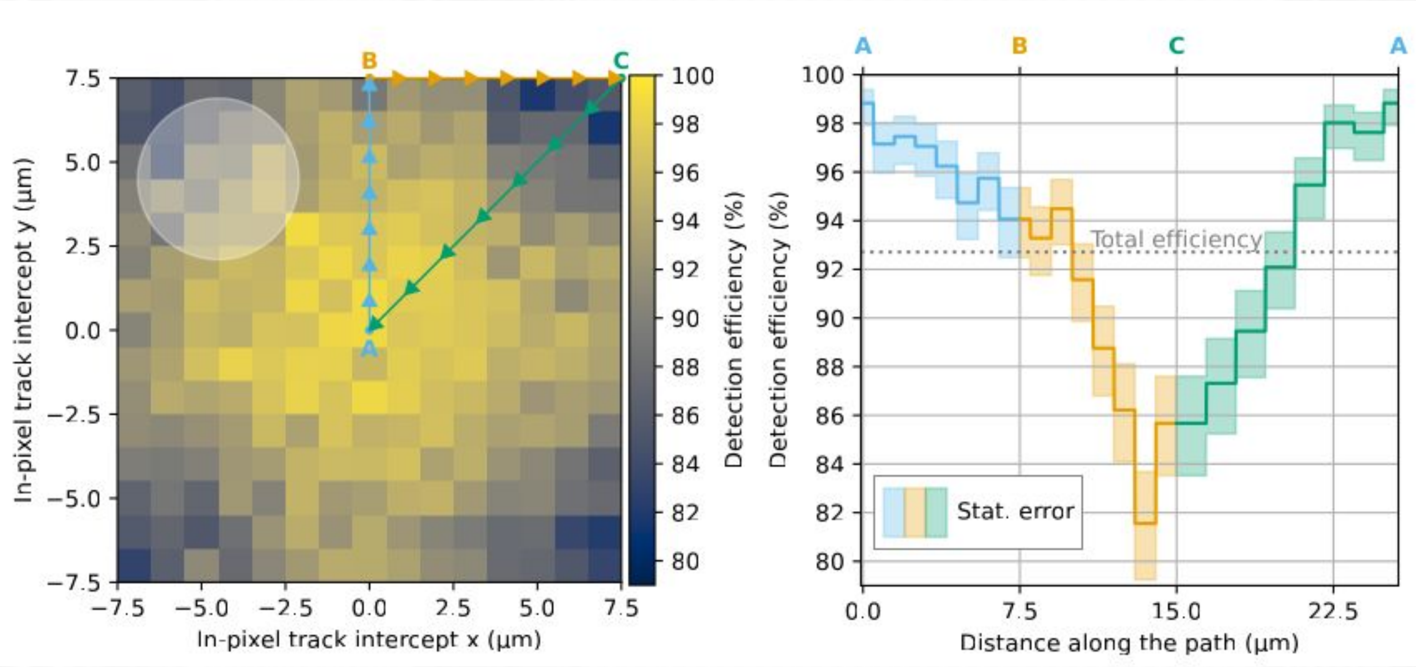


DPTS @ 20 °C (no cooling)

Association window:
480 µm x 1.5 µs

- DPTS stays efficient across different irradiation levels
- ITS3 radiation hardness requirement fulfilled

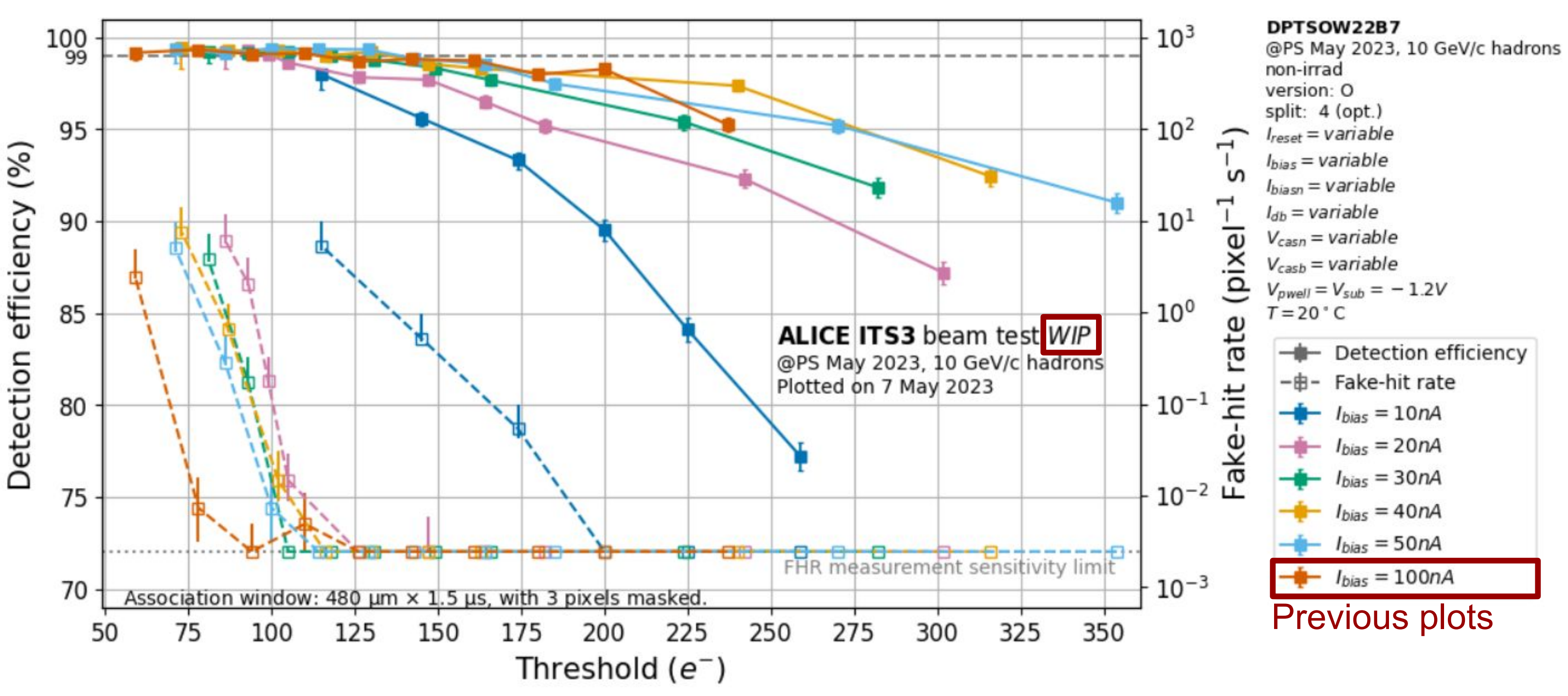
DPTS performance - Origin of detection efficiency loss



- Highest NIEL fluence: 10^{15} 1 MeV n_{eq} cm^{-2}
- Intermediate threshold: 155 electrons
- 2.4 µm track intercept uncertainty

- Lower detection efficiency with increasing distance to the collection diode
- Similar observation for non-irradiated sensor at **higher** threshold values

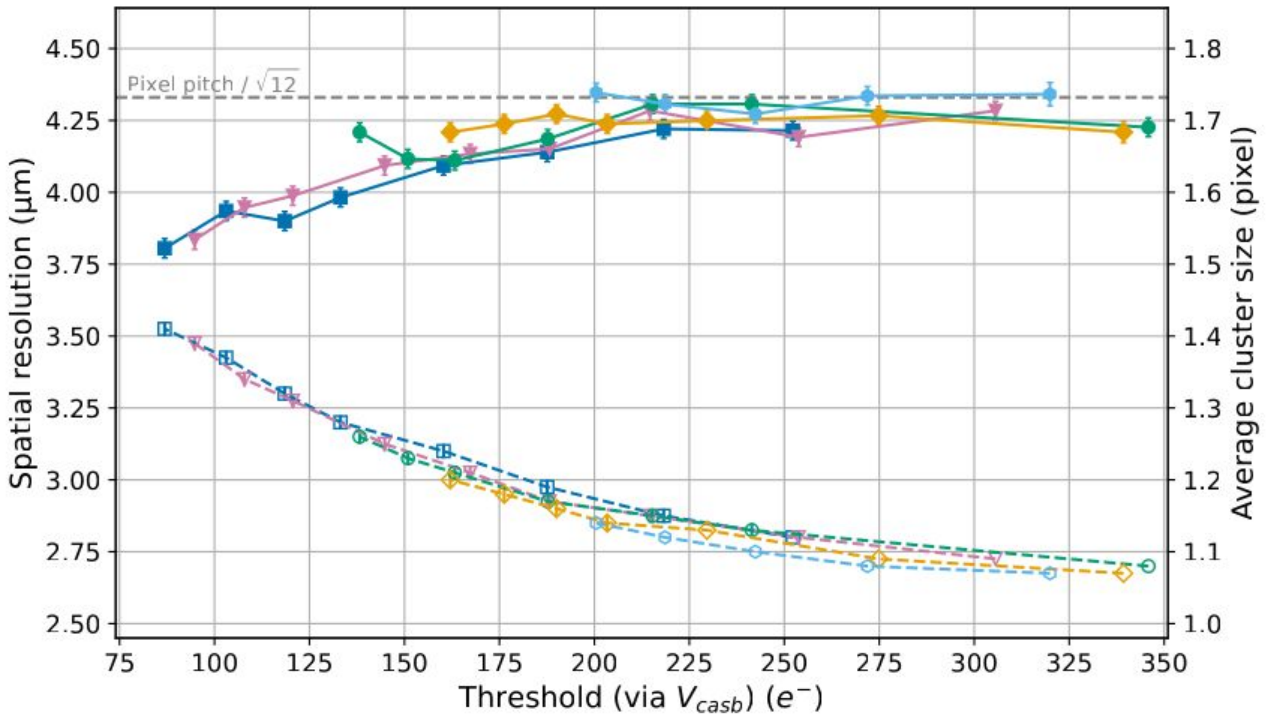
DPTS performance - Detection efficiency
Non-irradiated sensor vs. power consumption



Previous plots

- Worse noise performance with lower power consumption (IBIAS)
- Lower power consumption possible
  - IBAS=10/20 nA not performant

DPTS performance - Spatial resolution
Dependence on back-bias voltage (VBB)

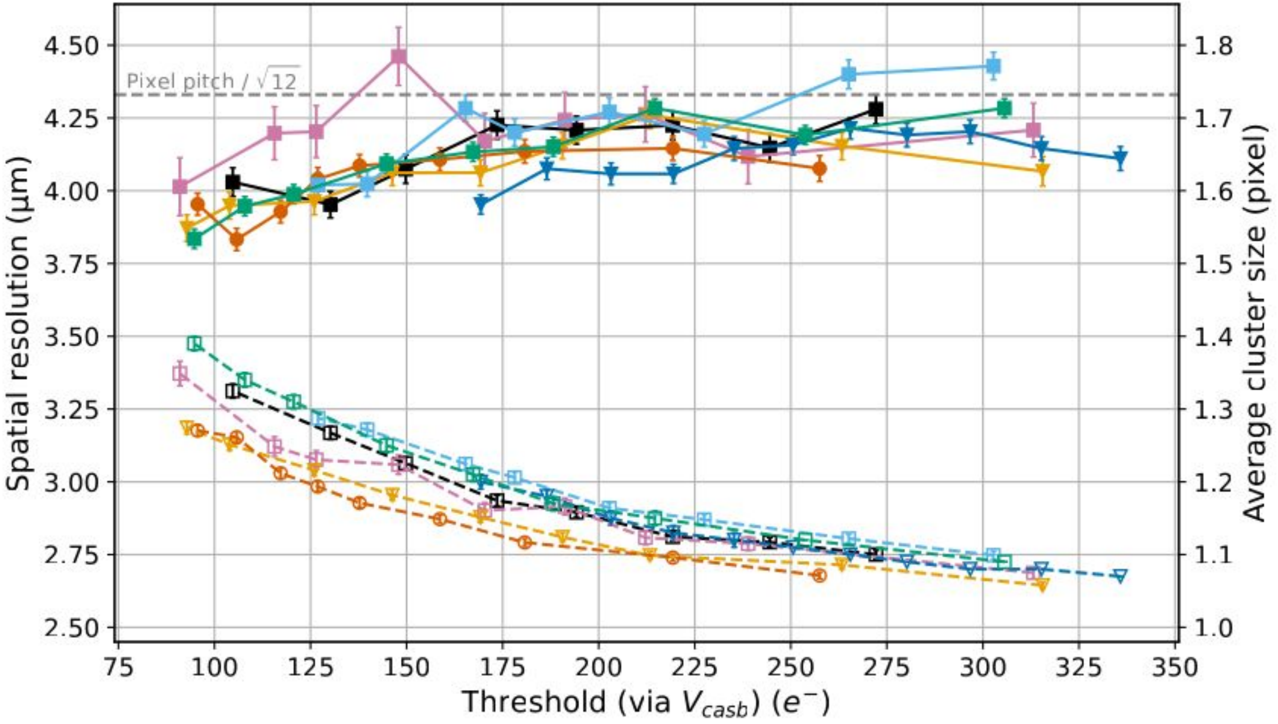


DPTS @ 10 kGy + 10^{13} 1 MeV n_{eq} cm^{-2}

Association window:
45 μm x 1.5 μs

- Dominated by small pixel size
- Spatial resolution improves with increasing cluster size

DPTS performance - Spatial resolution
Irradiated sensors



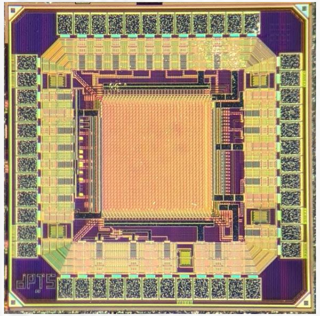
DPTS @ 20 °C (no cooling)

Association window:
45 μm x 1.5 μs

- No strong dependence on irradiation level
- Visible cluster size ordering according to NIEL dose

Summary and Outlook

- 65 nm CMOS technology qualified for MAPS used in particle/nuclear physics
- In-beam characterisation of irradiated DPTS sensors



- Operational range for high irradiation levels up to: 100 kGy and 10^{15} 1 MeV n_{eq} cm^{-2}
  - At room temperature!
  - Still reaches 99% detection efficiency
- Spatial resolution matches expectation

- DPTS characterisation paper **https://arxiv.org/abs/2212.08621**
- Additionally covers:
  - Full electrical characterisation
  - ^{55}Fe response
  - Timing resolution
- New testbeam measurements:
  - Performance vs. power consumption (ongoing)
  - Last ingredient for TDR
- Bending of DPTS sensors in progress

↓ Excellent results from MLR1 submission

- Engineering run with stitched sensors
  - Sensors have arrived at CERN

Summary and Outlook

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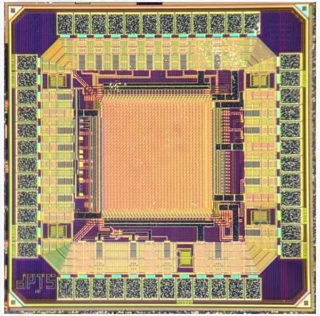
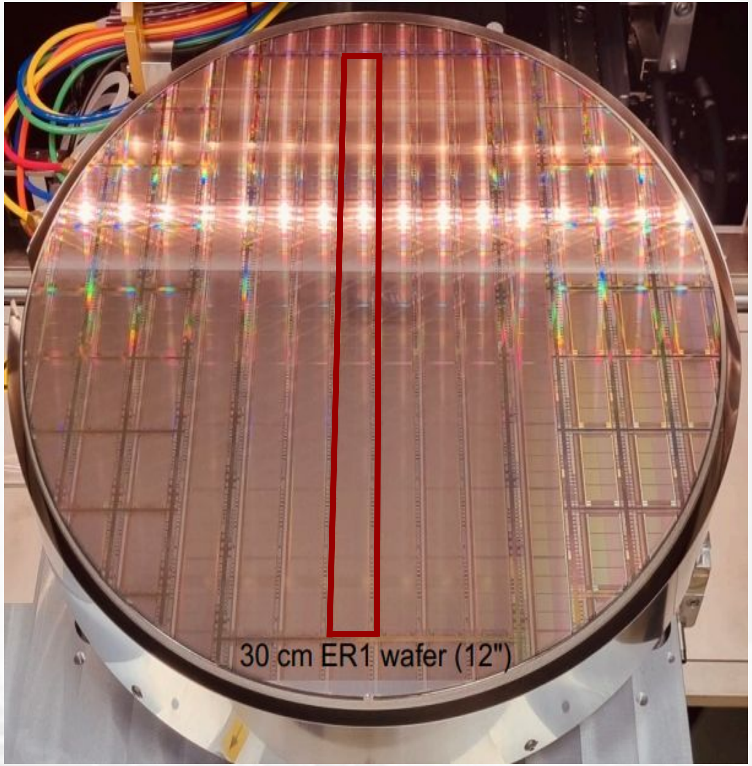


- Operational range for high irradiation levels up to: 100 kGy and 10^{15} 1 MeV n_{eq} cm^{-2}
  - At room temperature!
  - Still reaches 99% detection efficiency
- Spatial resolution matches expectation

- The show must go on:



- **First stitched sensors are alive**

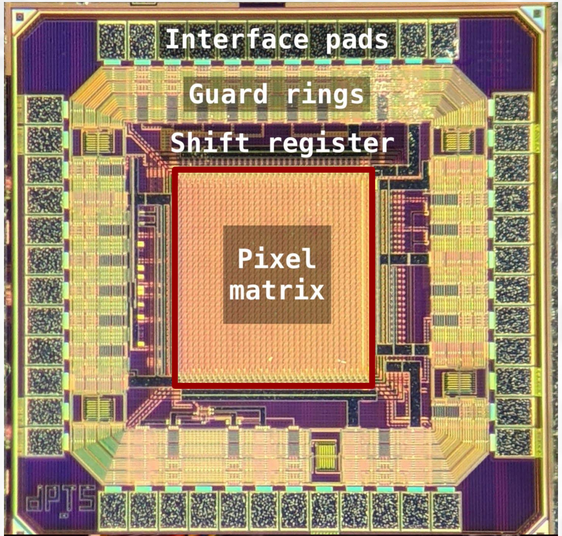
Auxiliary slides

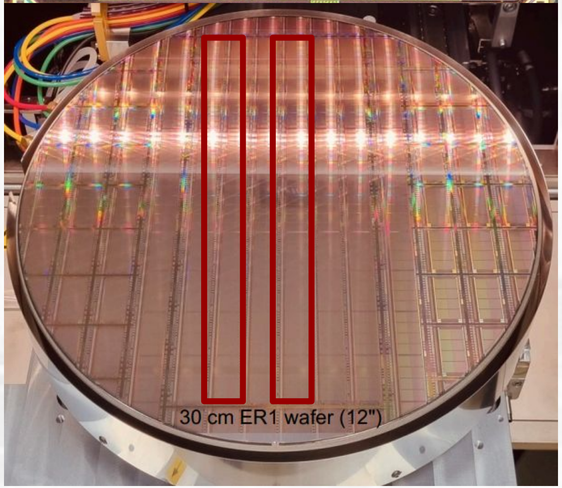
The next ALICE inner tracker upgrade: sensors

- Improve tracking performance by reduction of material budget
    - E.g. pointing resolution by factor 2
    - Especially in low-momentum regime
- Truly cylindrical pixel detector wrapped around the beam pipe
    - Closer to interaction point
    - Less mechanical support
    - New beam pipe
- Cooled by airflow
- Waferscale sensors

ITS3 implies change to 65 nm CMOS technology node

- 30 cm diameter wafers, stitching possible
- Small pixel/feature size (occupancy)
- Two submissions so far (MLR1, ER1)





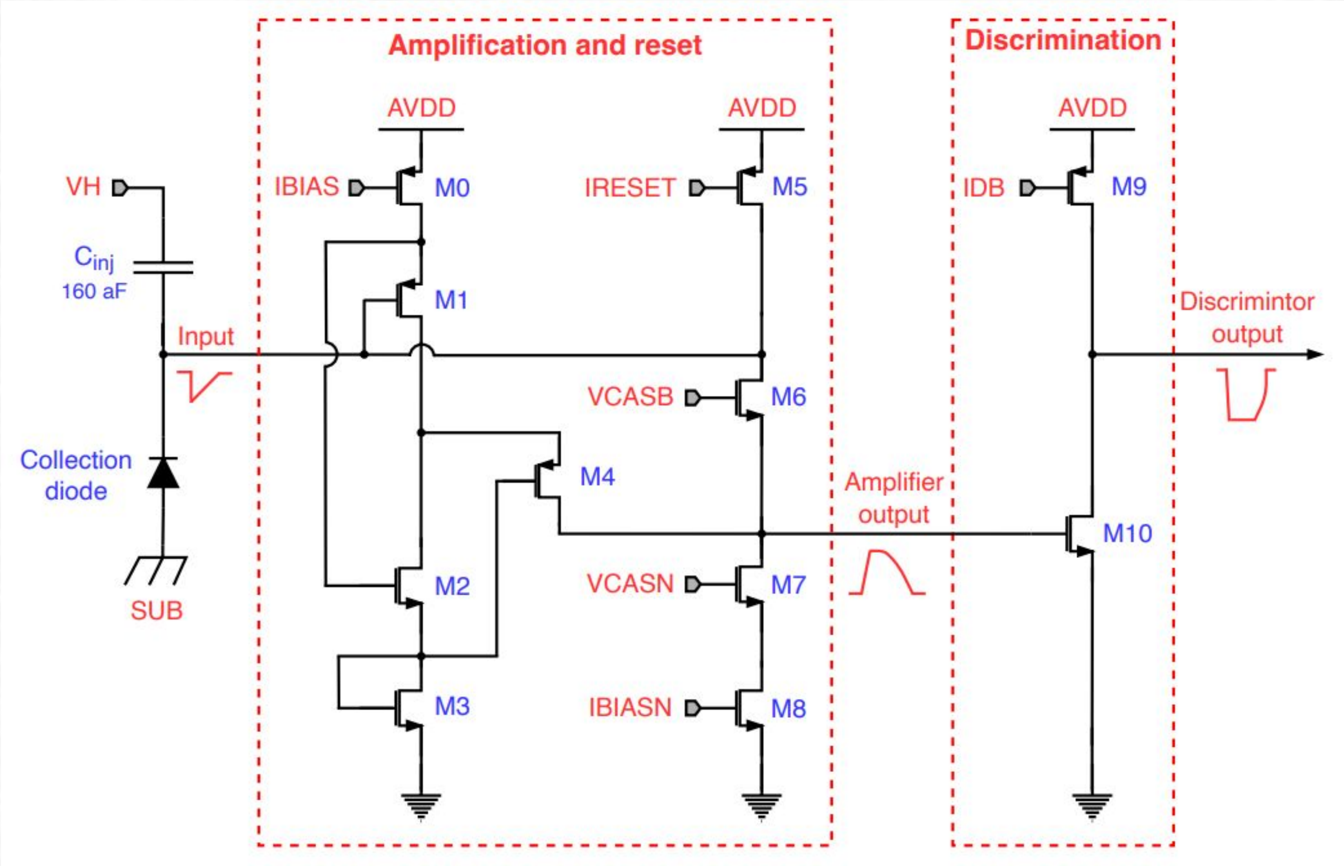
Digital Pixel Test Structure (DPTS)

- 32x32 px
- 15 µm pitch
- 480 µm x 480 µm

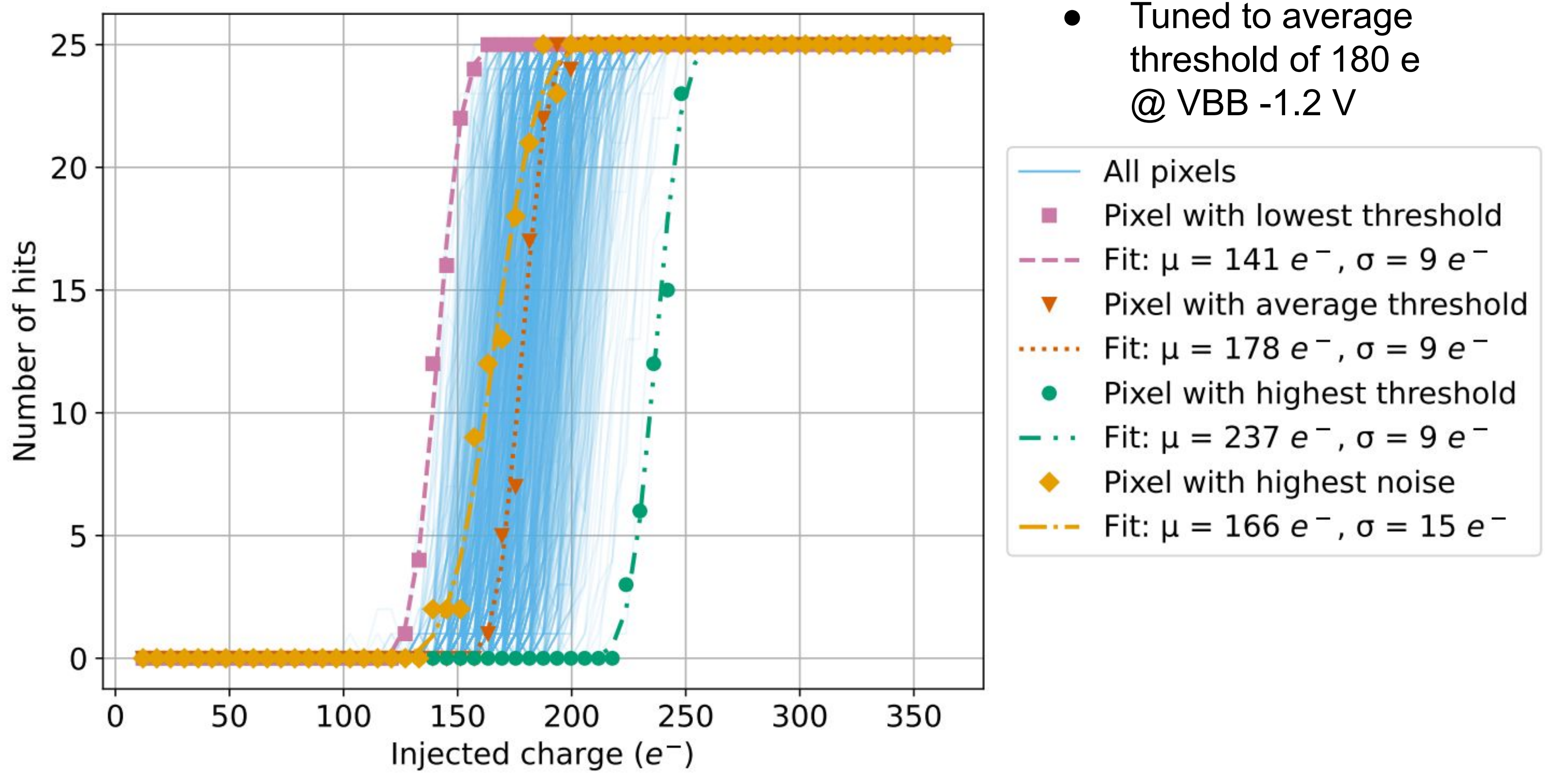
Monolithic Stitched Sensor (MOSS)

- 6.72 Mpx
- 18/22.5 µm pitch
- 1.4 cm x 25.9 cm

DPTS front-end circuitry

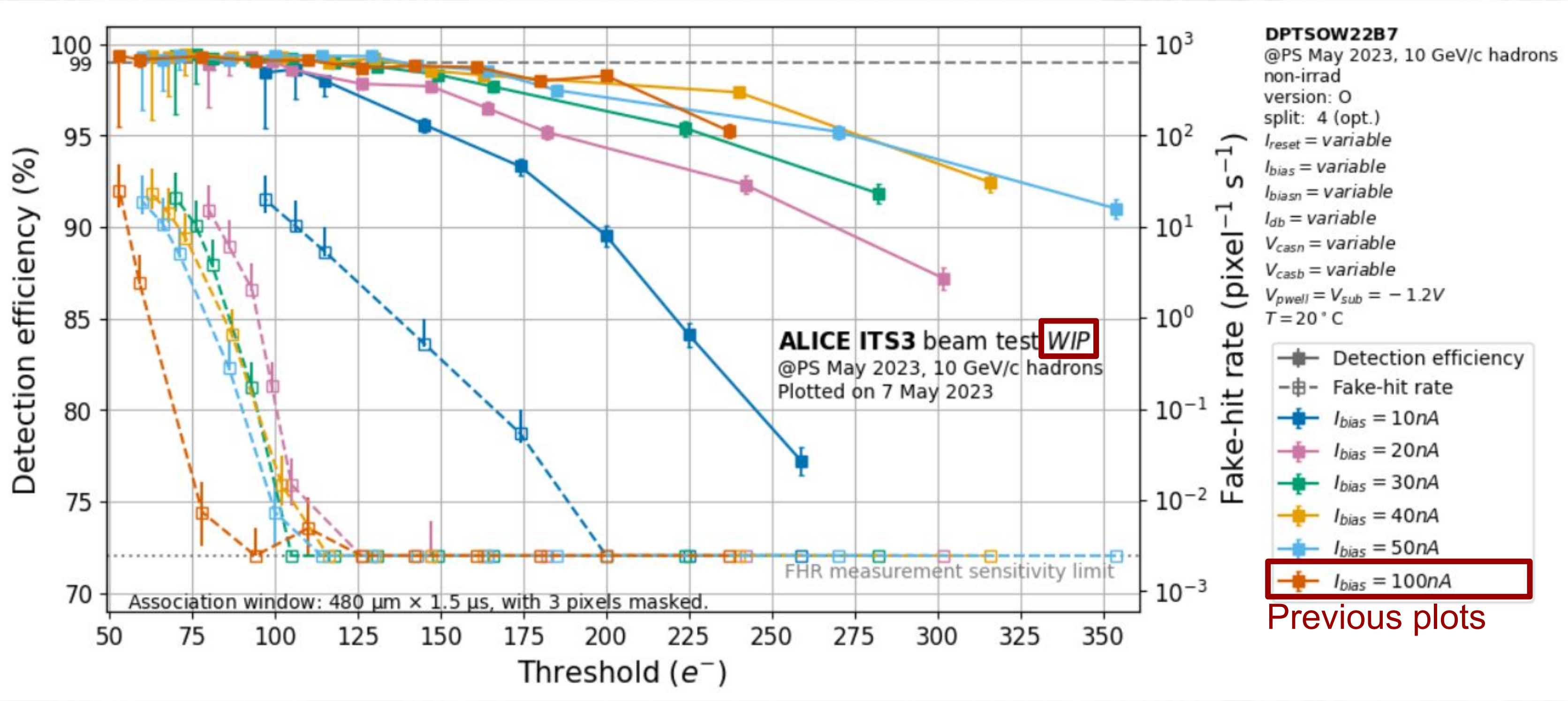


DPTS threshold measurement



- Tuned to average threshold of 180 e @ VBB -1.2 V

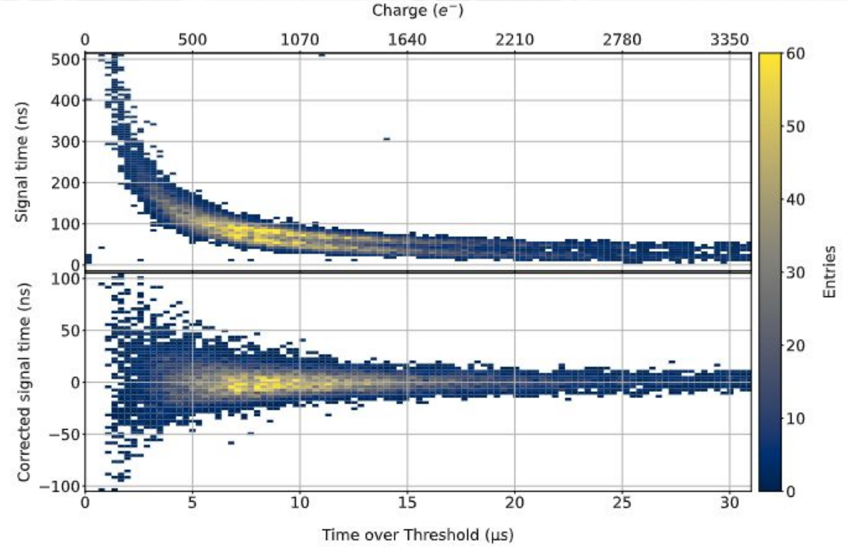
DPTS performance - Detection efficiency
Non-irradiated sensor vs. power consumption

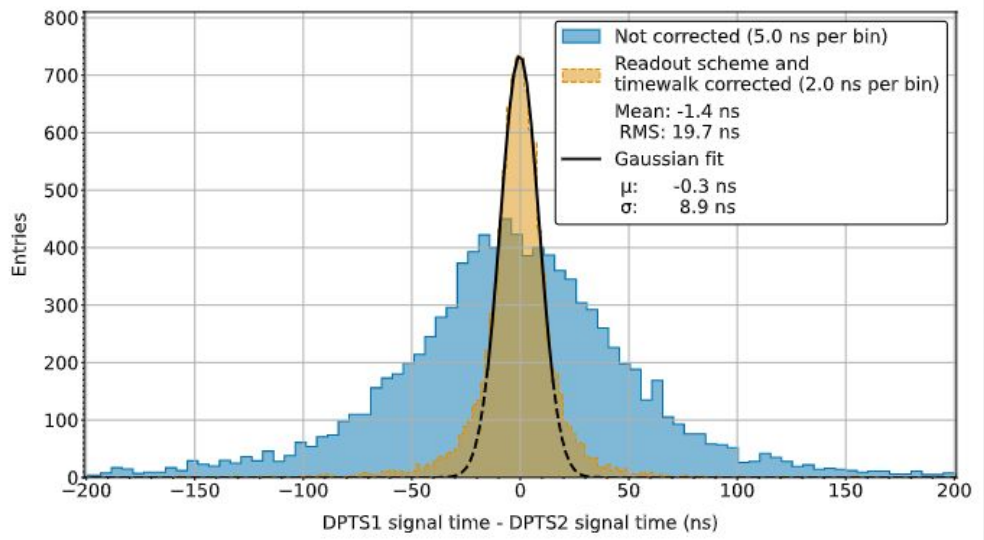


- Worse noise performance with lower power consumption (IBIAS)
- Lower power consumption possible
  - IBAS=10/20 nA not performant

DPTS time resolution

- DESY 5.4 GeV electrons

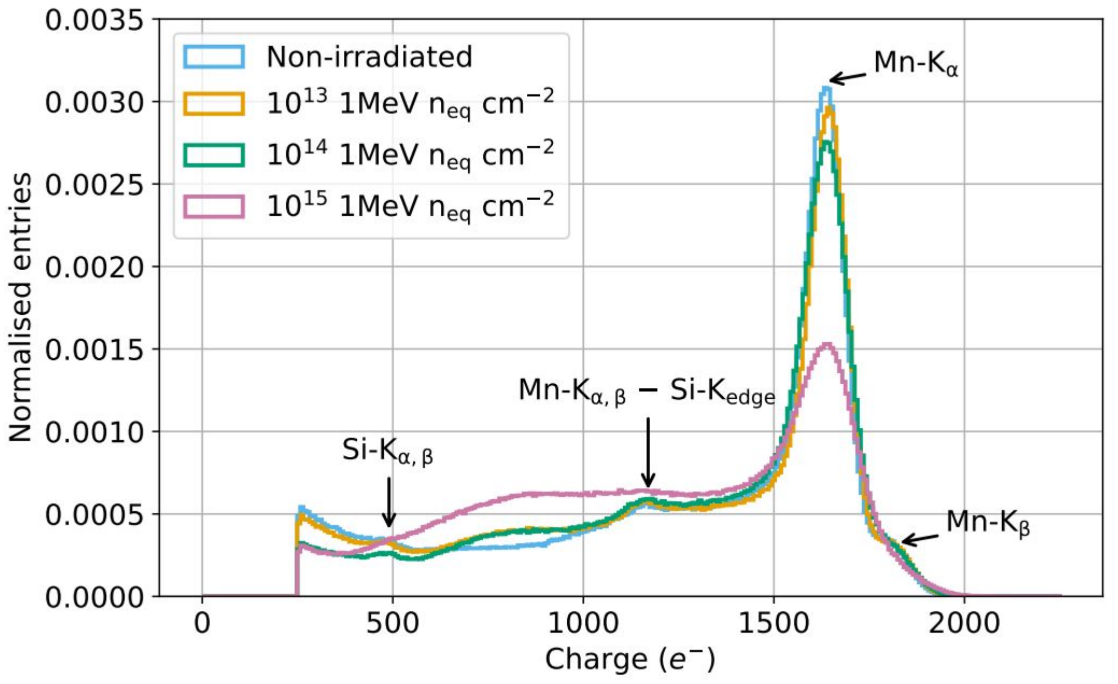




- Scintillators as absolute timing reference
- Time difference between two DPTS sensors
- Signal time needs to be corrected for:
  - Timewalk
  - Readout scheme

- **Time resolution: 6.3 ± 0.1 ns**

DPTS energy resolution with Fe55 source measurements



- Energy resolution of Mn-K_α peak

Irradiation	Resolution (%)
Non-irradiated	7.50±0.02
10^{13} 1 MeV n_{eq} cm^{-2}	22.4±0.4
10^{14} 1 MeV n_{eq} cm^{-2}	24.5±0.7
10^{15} 1 MeV n_{eq} cm^{-2}	32.7±0.7

- Degradation of the energy resolution points to distortions in the charge collection
  - Charge trapping
  - Modification of the electric fields

ITS3 pointing resolution