MALTA sensor development

(with a focus on UK activities)

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Future UK Silicon Vertex & Tracker R&D Workshop

07/09/2022

UNIVERSITY OF OXFORD

ATLAS EXPERIMENT

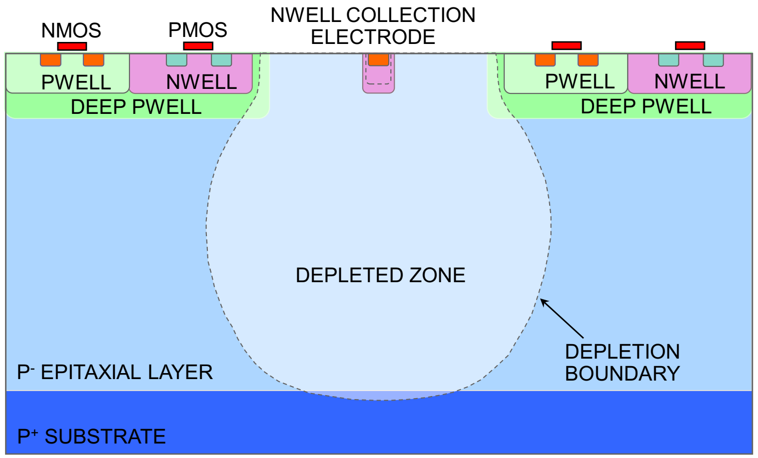
TowerJazz 180nm process

W. Snoeys, NIM A 871 (2017) 90-96

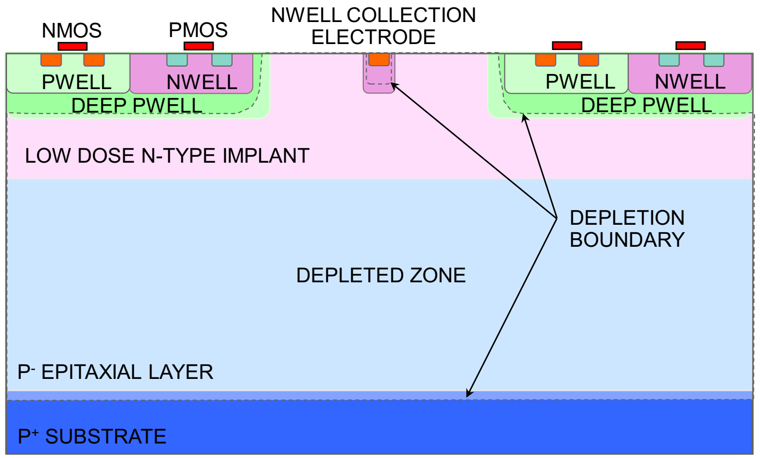
- Monolithic detectors: promising option for reducing pixel pitch, production cost and material budget for large-scale silicon pixel detectors (e.g. ATLAS)
- Problem: harsh requirements on radiation tolerance (>5e14 n/cm^2) and readout speed
- **MALTA sensor fabricated in modified TowerJazz 180nm process:**
  - Based on the standard TowerJazz design used for the ALPIDE chip for ALICE
  - Modified to include additional low dose n-type layer to improve depletion throughout entire sensor → improved speed and radiation tolerance
- MALTA pixel cell:
  - Based on small fill-factor design: small collection electrode (2-3 µm) with small capacitance (< 5fF), electronics next to electrode separated by 3.4-4 µm
  - Pixel size of 36.4 x 36.4 µm^2
  - Asynchronous readout without clock distributed to the cell

Pixel doping cross-section

Standard process



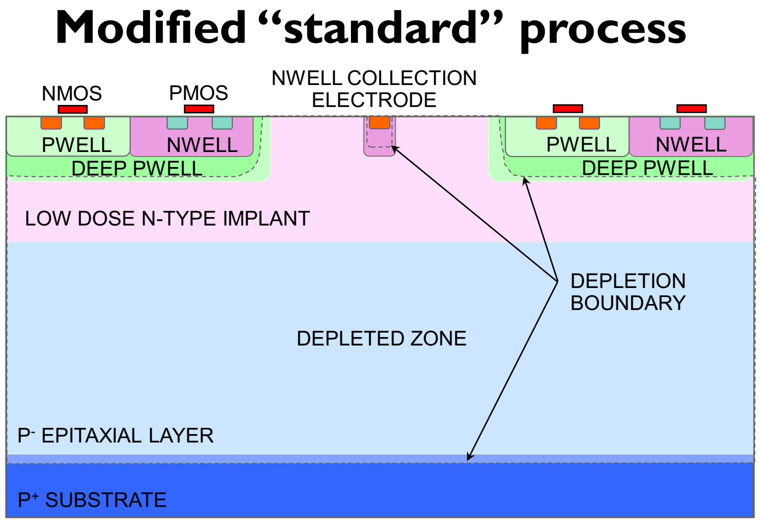
Modified "standard" process

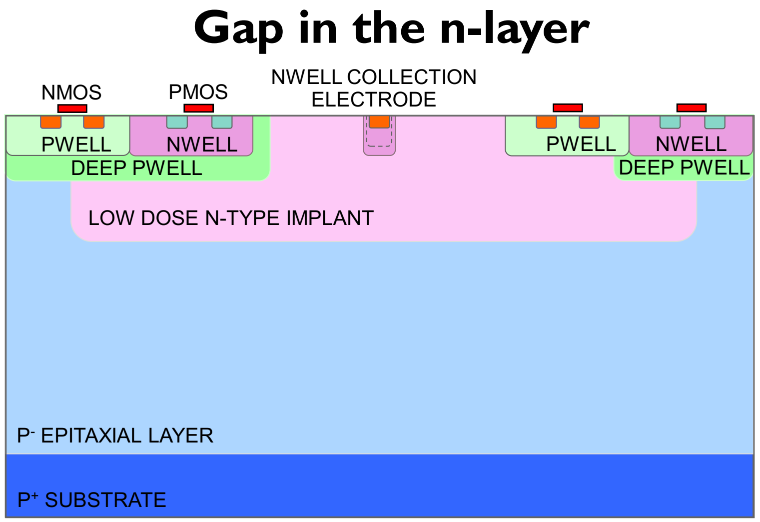


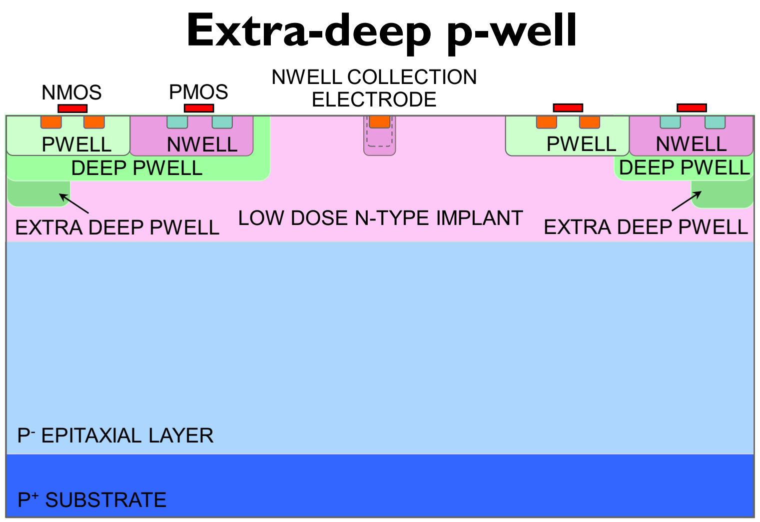
Process and substrate modifications

M. Munker, JINST 14 (2019) C05013

Additional process modifications to increase lateral field configuration and improve charge collection at the pixel edges







Substrate engineering: Use high resistivity Czochralski substrate (~3-4 kΩ cm), instead of epitaxial substrate

- Allows for higher biasing voltages and larger depletion depths (300 μm for Cz compared to ~30 μm for Epi)
- Aim for better timing resolution and higher radiation tolerance

MALTA Timeline

Mini-MALTA
- Smaller Demonstrator (5x1.7 mm^2)
- Using modified processes to improve radiation tolerance
- Improvements to RTS noise

→ **Full efficiency after 10^{15} n/cm^2 w/ modified designs**

MALTA 2
- Smaller Demonstrator (20x10 mm^2)
- New front-end and additional process modification

→ **Improved timing**

2018 | 2019 | 2020 | 2021 | 2022 | 2023

MALTA
- Full-size demonstrator (22x20 mm^2)
- Using "standard" modified TowerJazz process
- **Efficiency degradation after 10^{14} n/cm^2**

MALTA Cz
- Full-size demonstrator with slow control improvements
- Produced on Epitaxial and Czochralski substrates with different designs

→ **Larger cluster size and improved timing resolution**

MALTA 3
- Design ongoing
- To include latest process modifications and front-end
- Improve time resolution and time tagging

Mini-MALTA

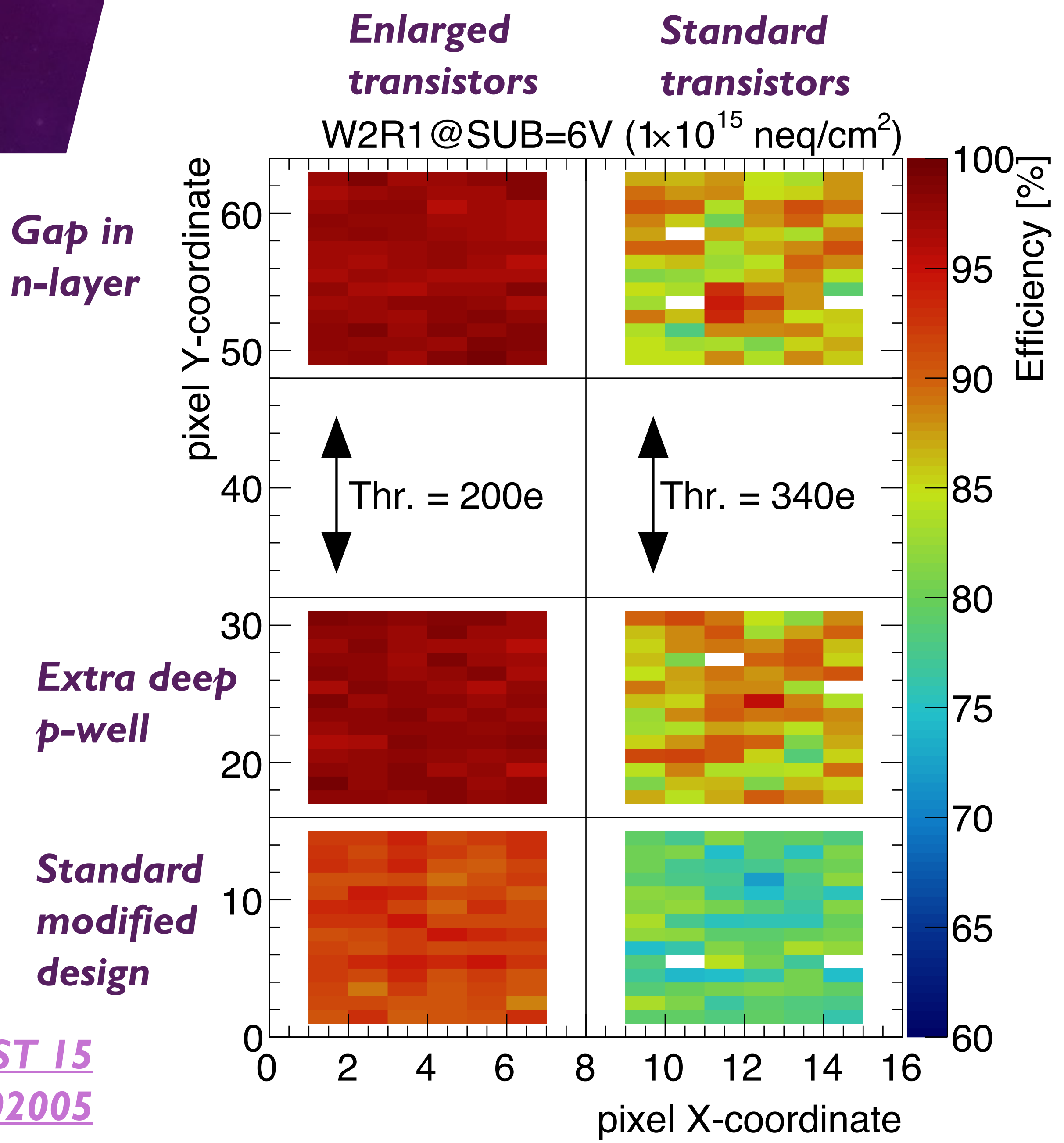
- Mini-MALTA prototype with process modifications (gap in n-layer, extra deep p-well) and different sizes of transistors
- Studied in beam test at ELSA with 3 GeV electrons

→ New designs show significant improvements

→ Enlarged transistors perform better

→ Full efficiency after 10^{15} n/cm^2 with process modifications and enlarged transistors

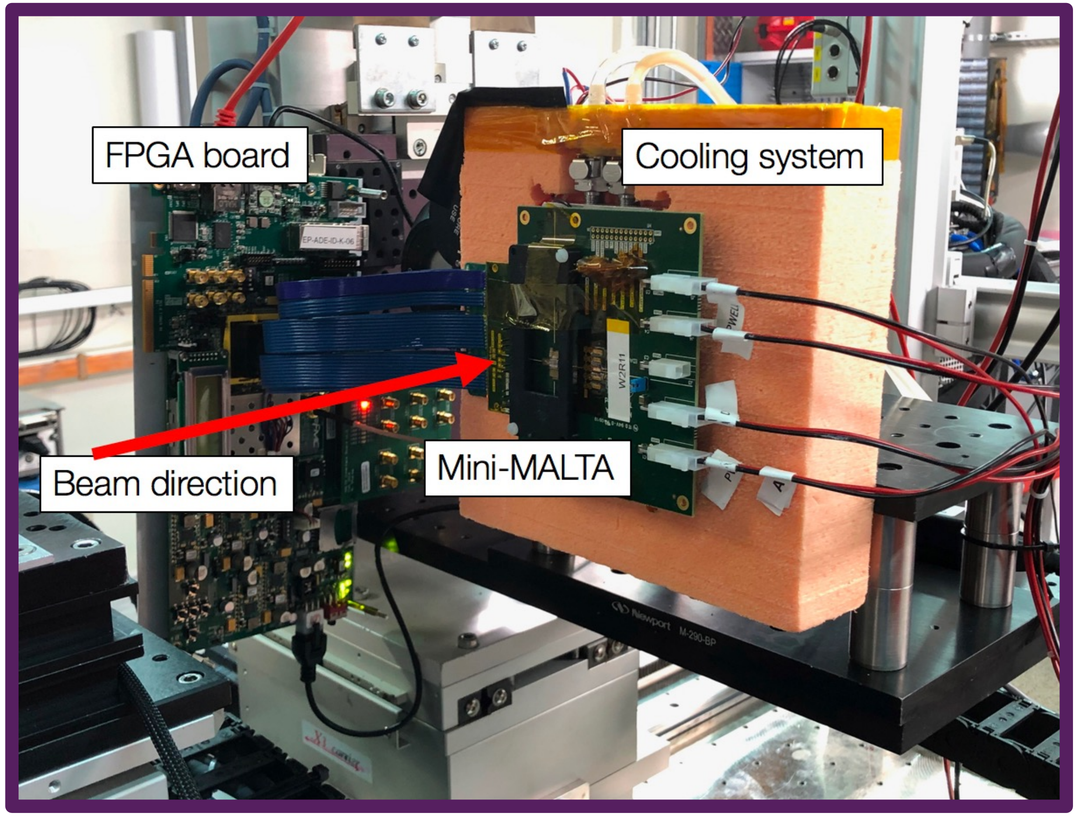
[M. Dyndal, JINST 15 (2020) P02005](#)



Mini-MALTA @ Diamond

- X-Ray beam test measurements at Diamond Light Source performed with mini-MALTA
- X-ray beam with 8 keV energy and 2 µm beam-spot
- Setup on motion stage to perform raster scan with step size of 2 µm

→ **Pixel structure and response of the different designs studied with high precision**



UK involvement: University of Birmingham, University of Oxford, diamond

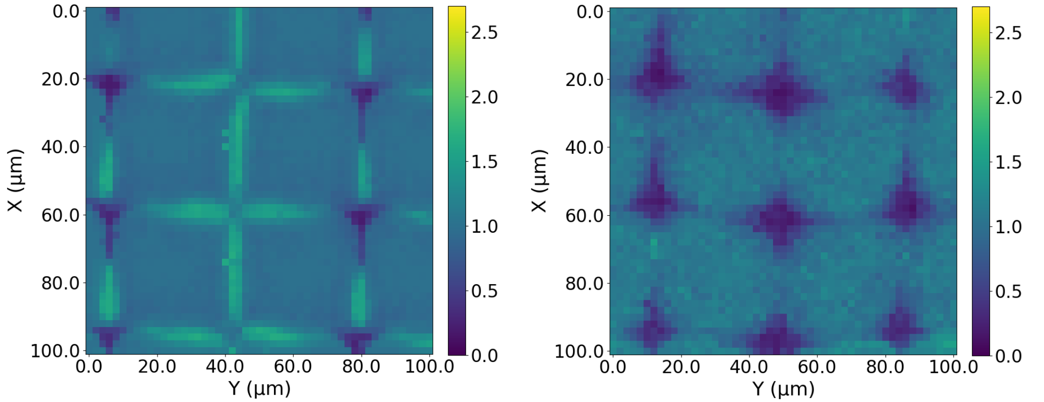
- Measurement of relative pixel response: response of pixel to photons with respect to the pixel center

→ Can obtain high-precision measurements of the pixel shape

- Relative pixel response decreases with irradiation in standard design, especially around the pixel edges
- **New p-well and n-gap designs improve pixel performance**

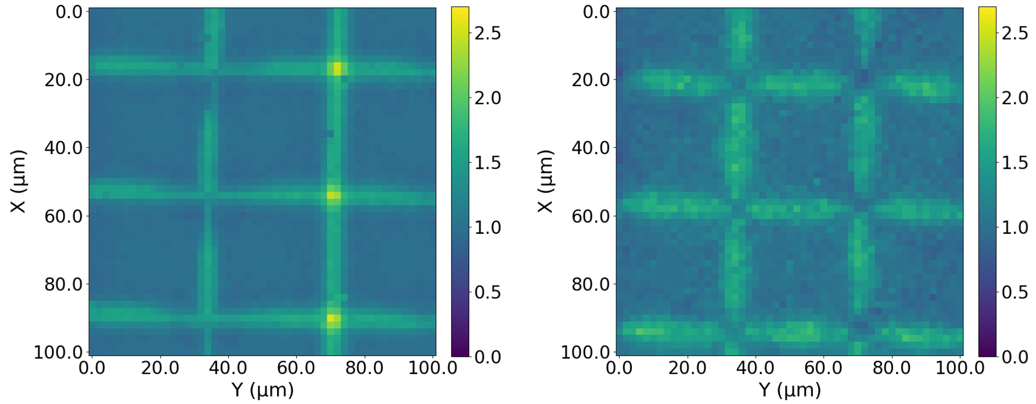
Modified "standard" process: Continuous n layer

unirradiated | 1e15 n/cm²



Modified design: Gap in n layer

unirradiated | 1e15 n/cm²



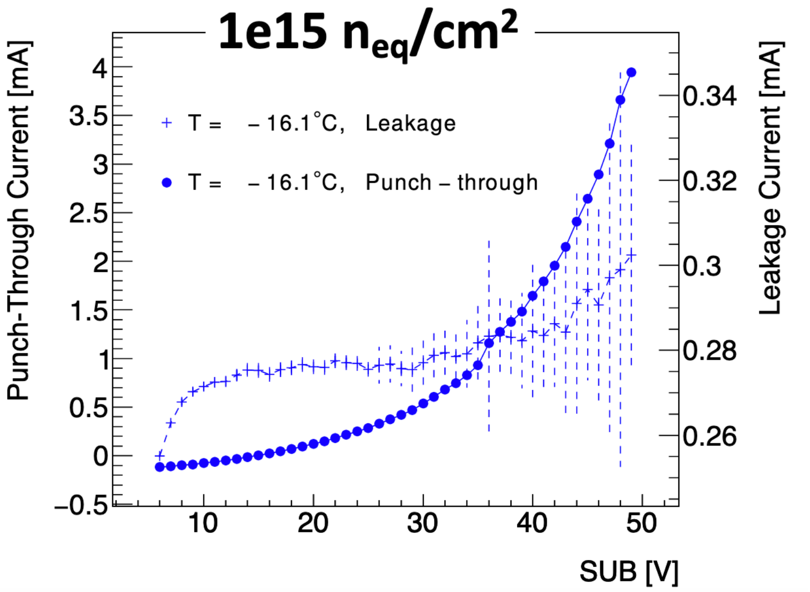
Response: (89 ± 3) % → (77 ± 4) % | (92 ± 3) % → (90 ± 3) %

Decrease | **No decrease**

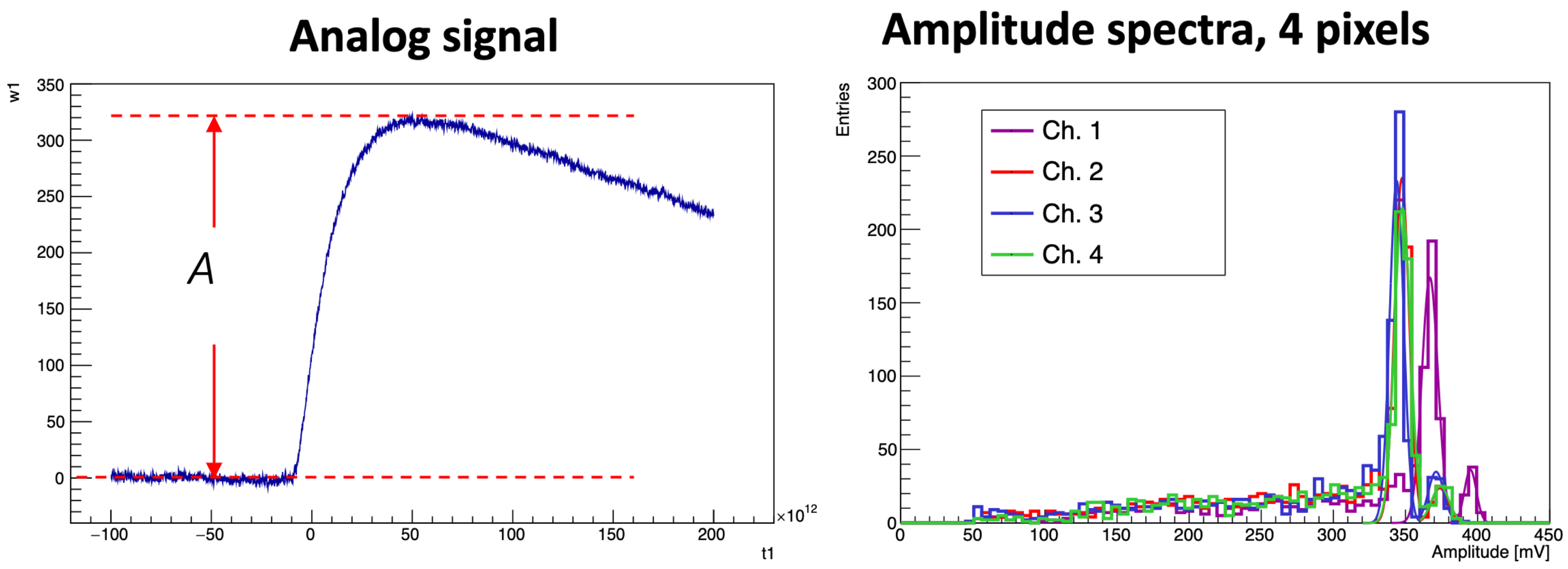
MALTA Cz – Lab measurements

UK involvement: UNIVERSITY OF BIRMINGHAM

- MALTA Cz: Full-size demonstrator with several improvements produced on Epi and Czochraski substrates
- Characterisation in laboratory measurements:
    - IV curves → voltages up to 50 V possible on Cz (vs 10-25 V on Epi) → larger depletion depth
    - Validation of performance with measurements of Fe55 on analog monitoring pixels → good performance for all designs



Currents after irradiation



Fe55 source measurements

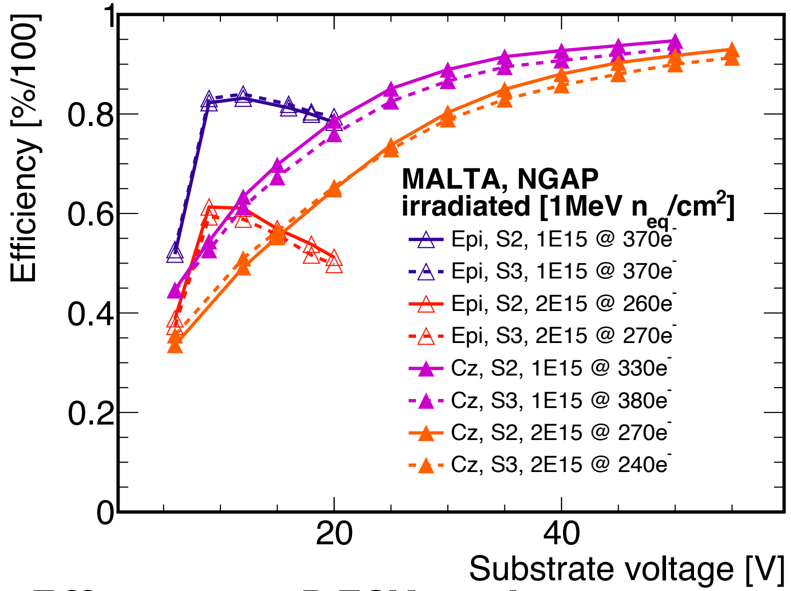
MALTA Cz efficiency

UK involvement: UNIVERSITY OF BIRMINGHAM

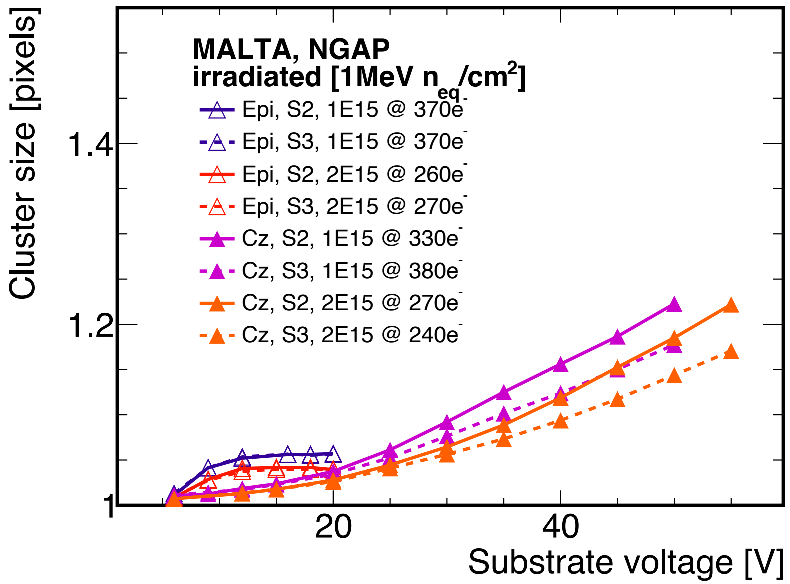
- MALTA Cz performance also measured in testbeam at DESY with 4 GeV electrons
- Cz samples: Efficiency and cluster size increase with biasing voltage - plateau in efficiency and maximum cluster size of 1.2 at -50 V

→ **Cz samples are fully efficiency at 10^{15} n/cm^2 with process modifications, at -50 V**

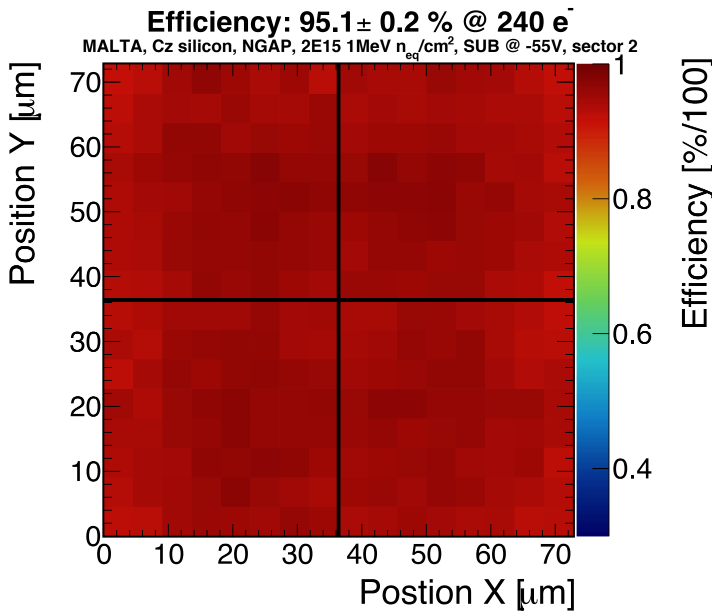
- Epi samples: Maximum cluster size of 1.05, and maximum efficiency at -12 V (with decrease in efficiency afterwards)



Efficiency in DESY testbeam



Cluster size

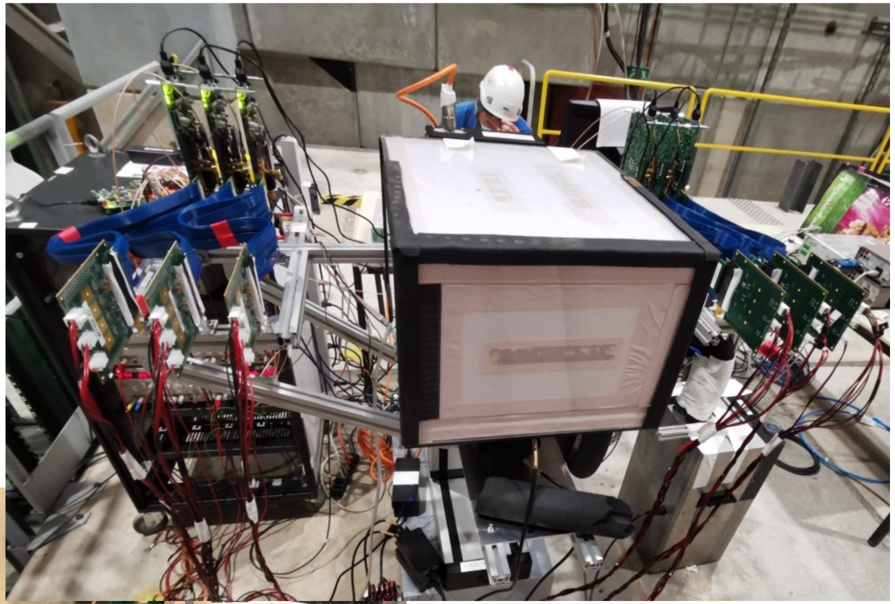


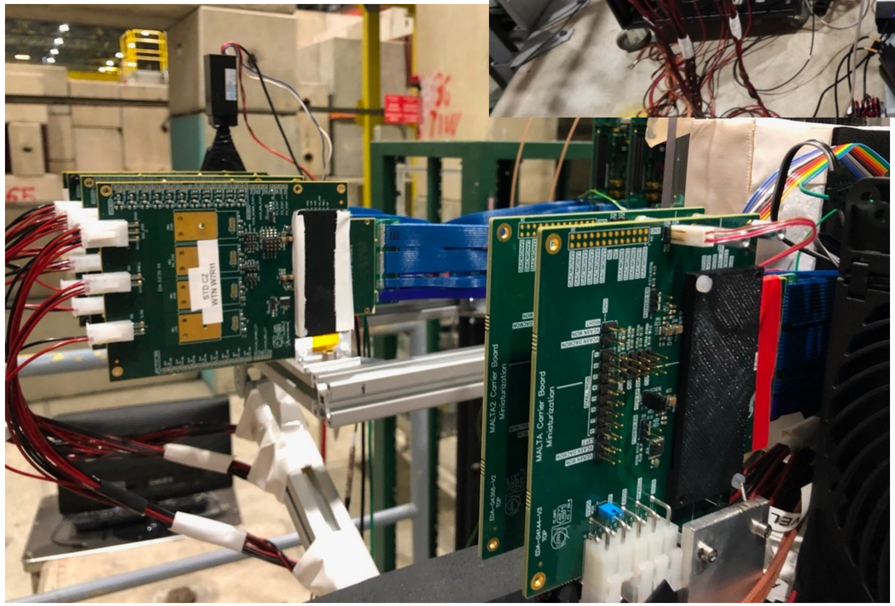
Efficiency map at 10^{15} n/cm^2

MALTA 2 & MALTA telescope

UK involvement: UNIVERSITY OF OXFORD

- MALTA2: Half-size demonstrator with improved FE and better timing
- **Custom MALTA telescope (6 planes + scintillator) at CERN SPS North Area**
- Aim: demonstrate radiation hardness and timing performance of MALTA2



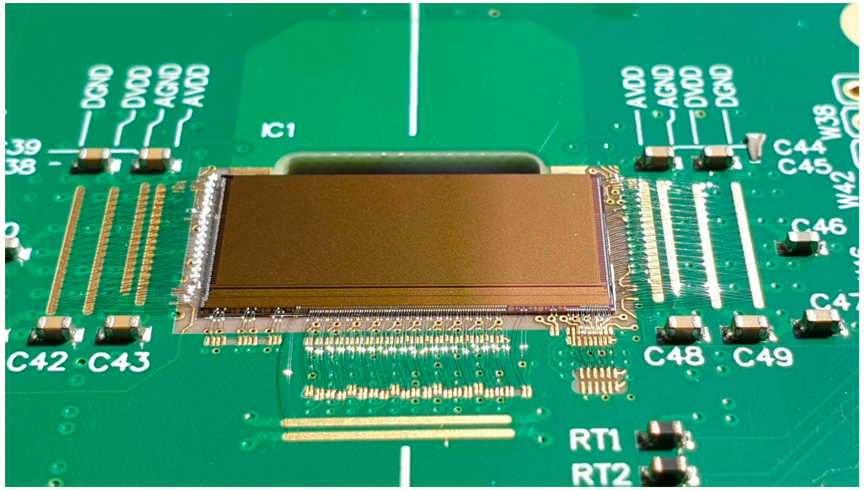


- Comparison of MALTA2 variations:
  - Flavour (structural variation)
  - Substrate type: Epi vs Czochralski
  - N-layer doping
  - Thickness

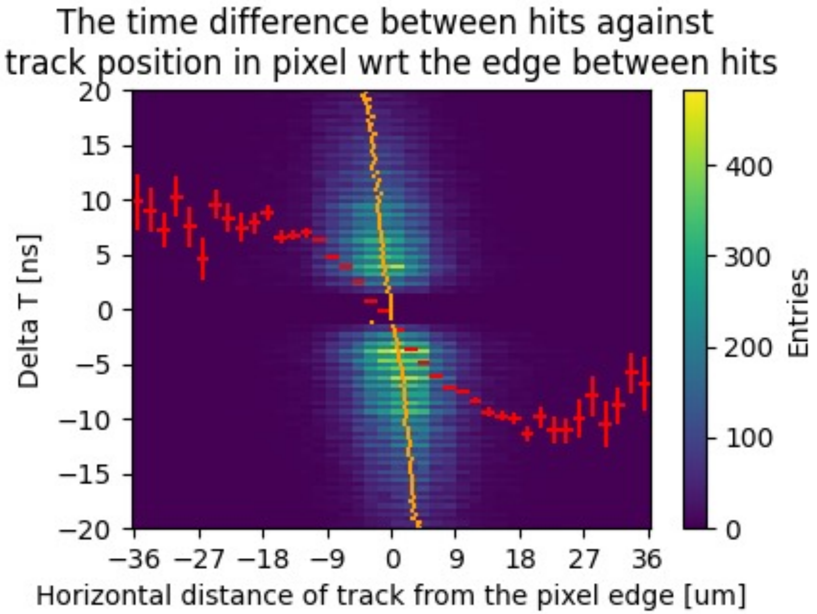
MALTA2 timing data analysis

UK involvement: UNIVERSITY OF OXFORD

- Utilisation of detailed information on telescope tracks and DUT hits
  - data structures implemented in July 2022
- Analysis of in-pixel timing resolution of MALTA2 using telescope track reconstruction
- Analysis of timing of hits within clusters
- Improvement of position precision using timing information
- Improvement of timing information using cluster information



Analysis of hits within a cluster of size 2



Column and row averages shown as red and orange points, respectively

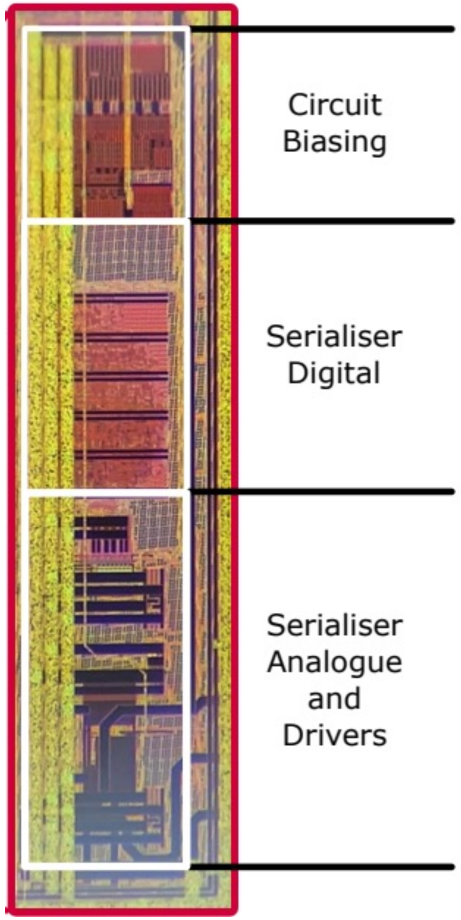
MALTA 3 IP block

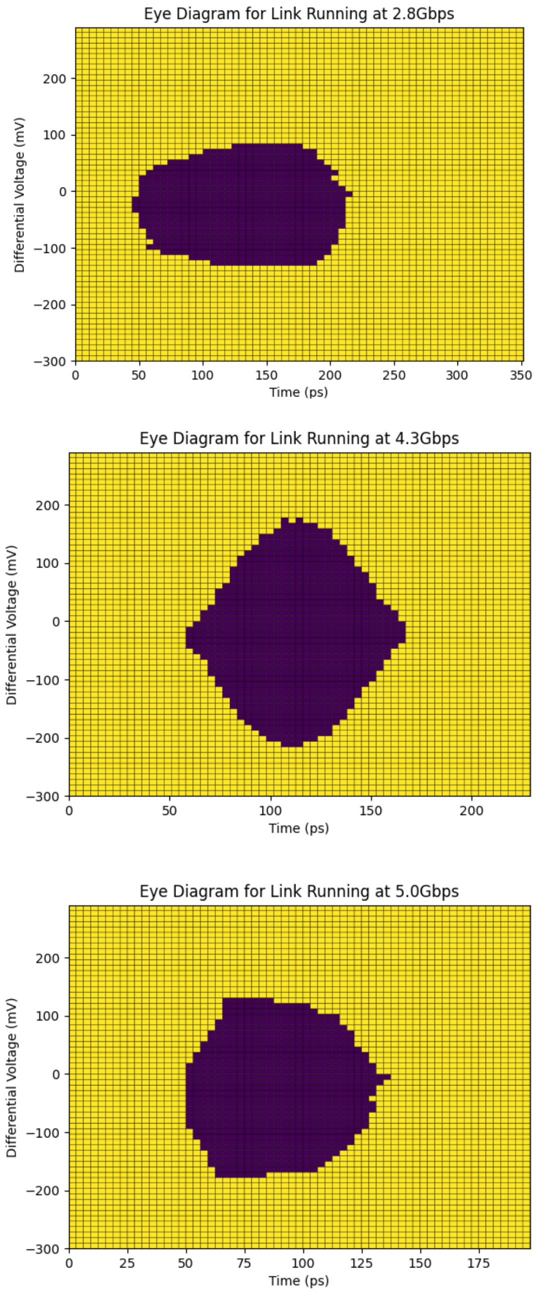
Background

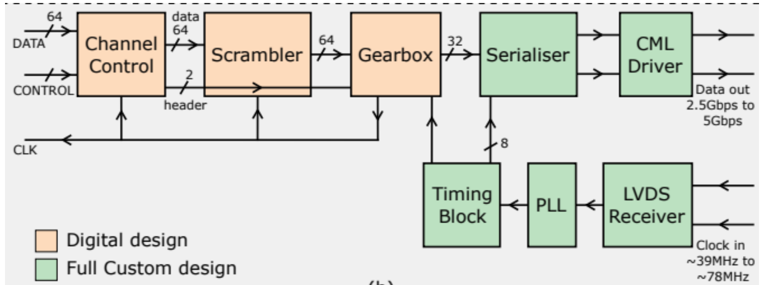
- Range of circuit blocks developed under internal STFC programme
- CERN asked to use some of the data transmission blocks for MALTA3 (5 Gbps Serialiser)

Ongoing work

- Transfer of these blocks (and associated legal agreements)
- Support to CERN in integration
- Some additional blocks (I2C interface)







(b)

UK involvement: UKRI Science and Technology Facilities Council

Conclusions

- MALTA sensors in 180 nm technology are a promising possibility of monolithic pixel detectors for the LHC and future collider experiments
- Small fill-factor pixels with 36.4 x 36.4 μm^2 pixel pitch and asynchronous readout
- Extensive production and testing programme with various small and full-size demonstrators over the past 5 years
- Additional process modifications to 180 nm TowerJazz process (gap in n-layer/extra-deep p-well) show **radiation tolerance up to 10^{15} n/cm^2**
- Substrate engineering (Cz substrate) allows for better tracking and timing resolution with increased depletion depth
- **Strong UK involvement in both testing and design at Birmingham, Oxford and RAL**

Thank you!

Questions?