# Performance and radiation hardness of Tower 180 nm MALTA monolithic pixel sensors


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*TREDI 2023* - 18th Trento Workshop on Advanced Silicon Radiation Detectors

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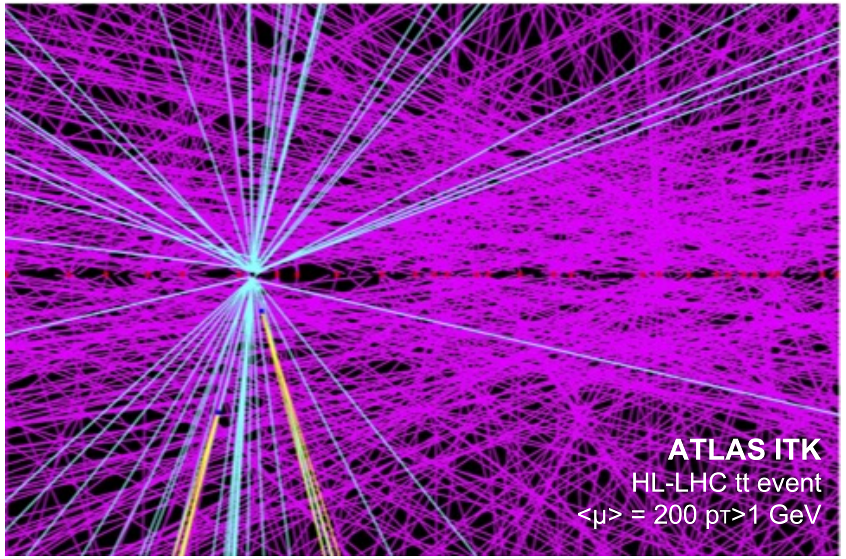
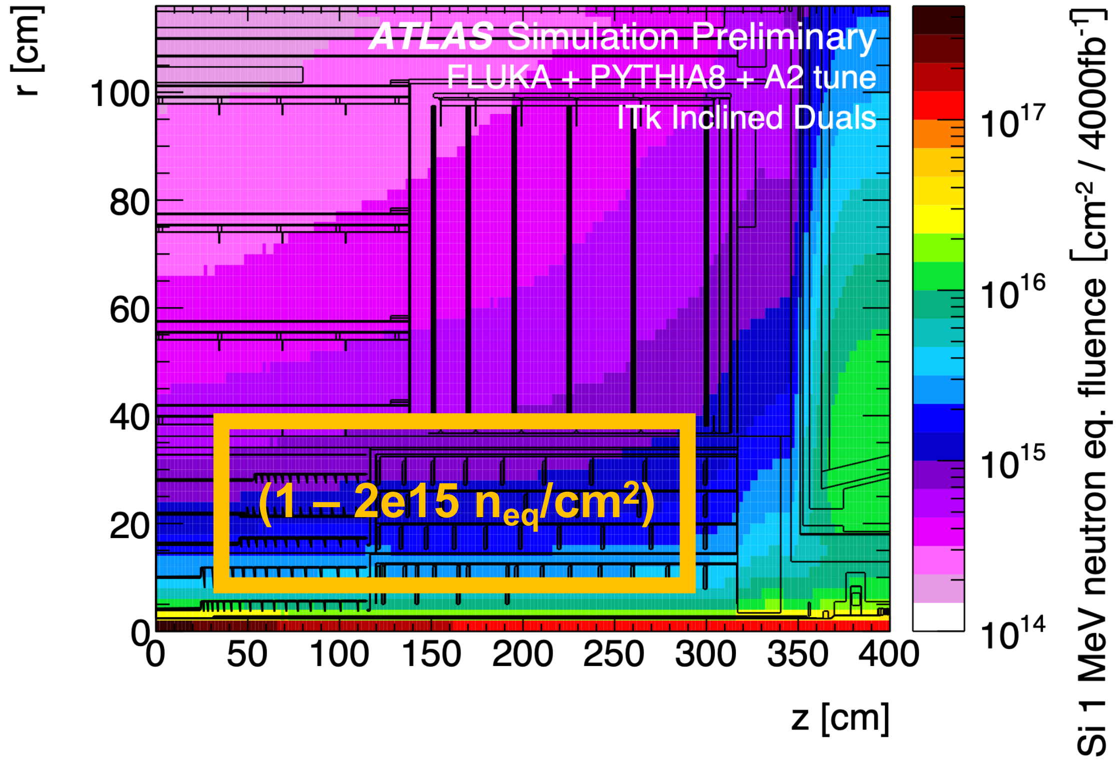
# Motivation for Monolithic pixel detectors

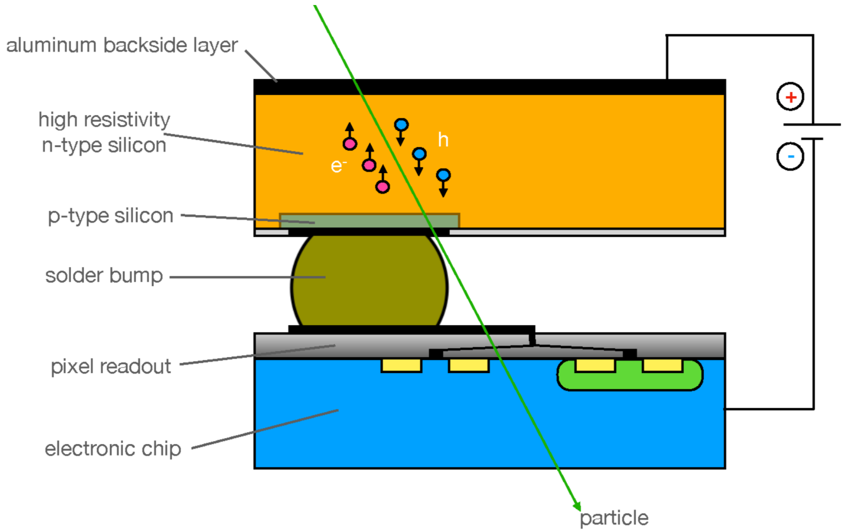
- Next generation of high-energy physics hadron experiments demanding on detectors
  - High radiation tolerance
  - High granularity (2 MHz/mm$^2$ hit rates)
  - Low material budget (cooling, power consumption)
  - Good timing response (<25 ns)
  - Large surface area -> affordable?

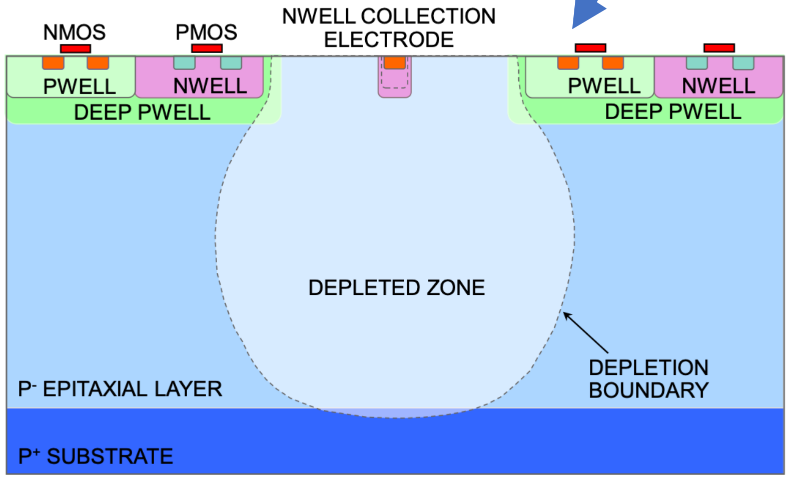


# Monolithic Active Pixel Sensors (MAPS)

**Readout electronics integrated with the sensor** in one chip




## Hybrid detectors

- ASIC bump-bonded to sensor
- Expensive bump bonding
- Well-understood radiation tolerance

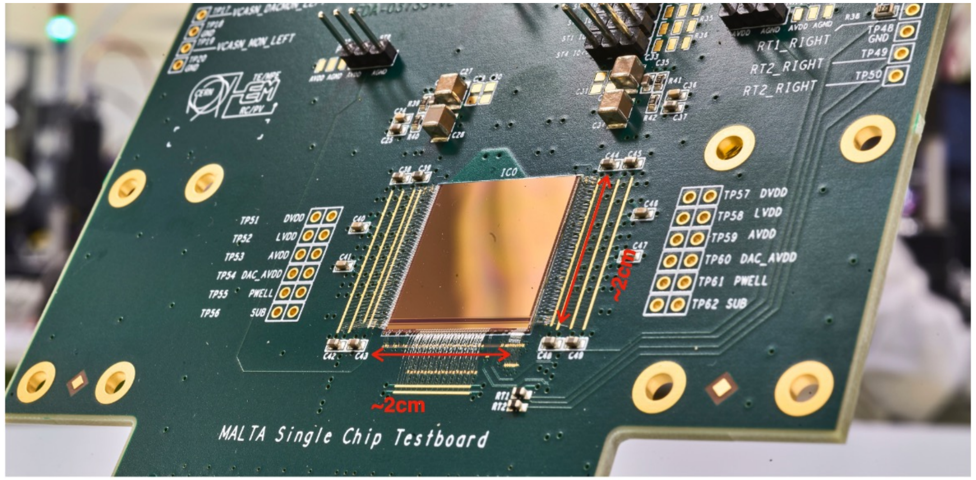
## Monolithic sensors

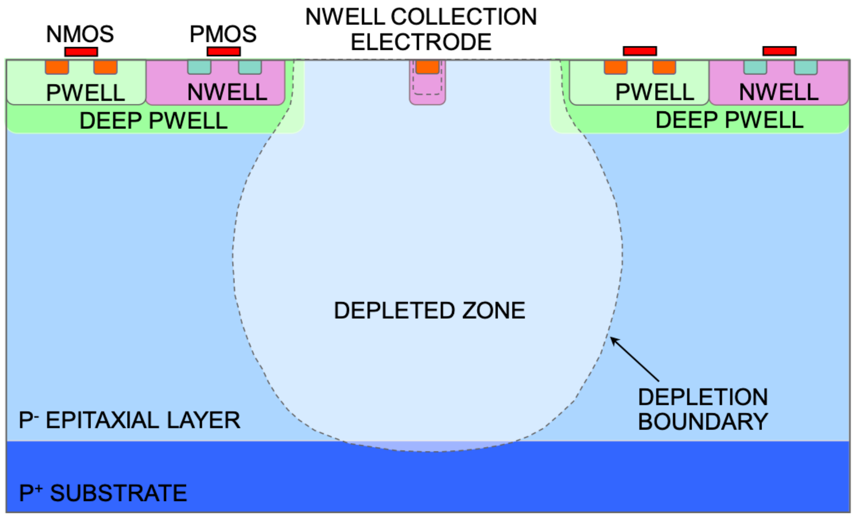
- One chip (readout + sensor)
- No bump bonding, less power needs
- Radiation tolerance needs to be studied

**Focus of this talk**

# Tower MALTA

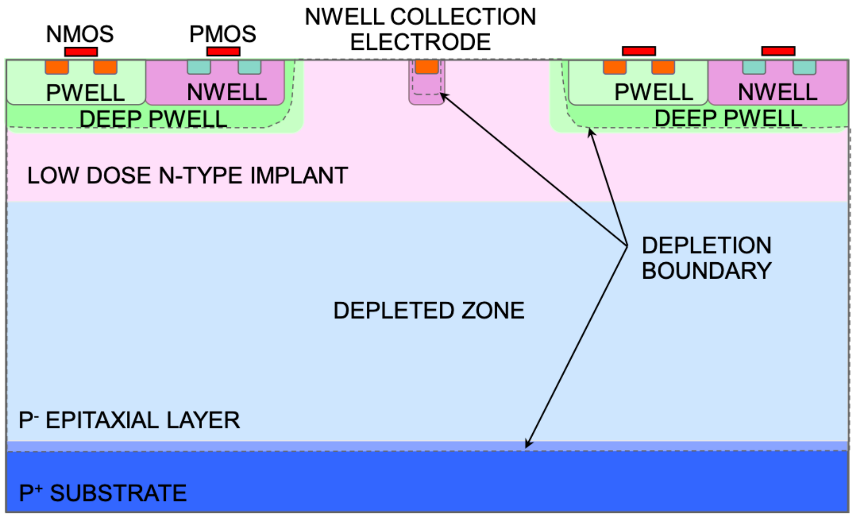
- Full-scale demonstrator to target specifications for ATLAS ITk outer layer
- 180 nm Tower Semiconductor (formerly TowerJazz) CMOS imaging technology process
  - Utilising Tower modified process




**Modified process**

- Low-dose n-type implant under p-well fully depleted pixel area
- Charge carriers pushed towards the collection electrode
- Reduces charge carrier capture probability

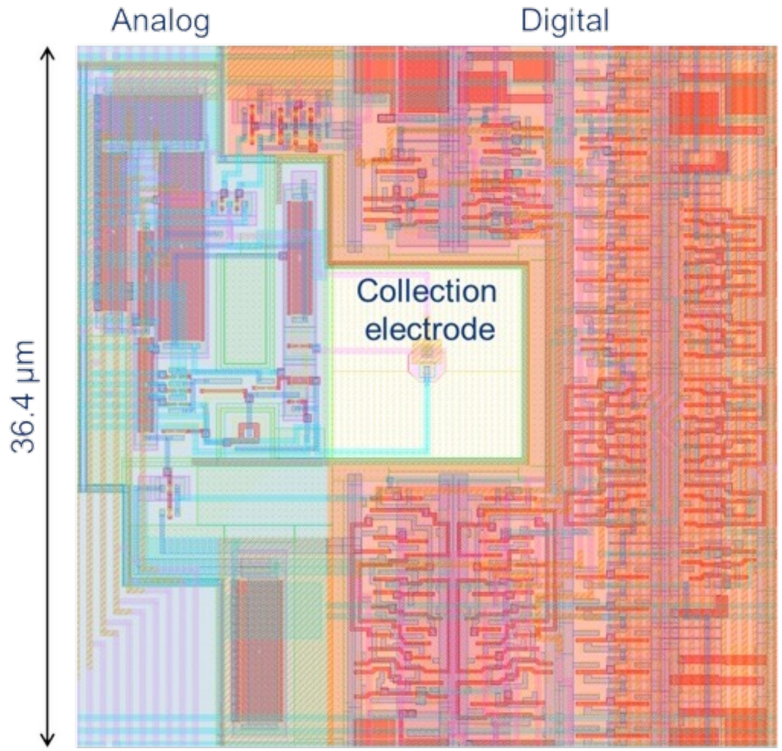



*H. Pernegger, et al, 2017 JINST 12 P06008*

# MALTA pixel and readout

- MALTA pixel pitch: 36.4 x 36.4 µm    ATLAS: 50x250/400 $\mu m^2$
- Collection electrode: 3 x 3 µm, small capacitance (5 fF)
- Low power usage: 1 µW per pixel    ATLAS: ~150 µW/pixel
  (<70 $mW/cm^2$ analog power)
- Asynchronous read-out -> no distributed clock

- Readout: **clock-less, asynchronous**
  - Parallel output signal transmission
  - Theoretical hit rate >100 MHz
  - Oversampling used for time-stamping
  - No time-over-threshold



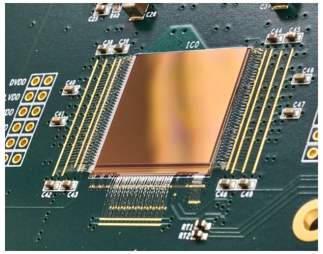

*I. Berdalovic et al, JINST, 2018, 13, C01023*

# The evolution of MALTA

**MALTA1**

Jan **2018**

Large demonstrator
$2 \times 2$ cm$^2$

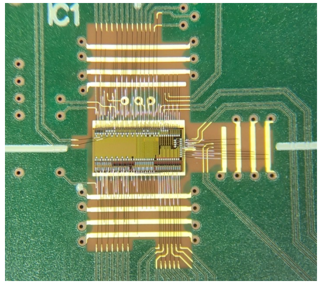


- Sensor functional, slow control issues
- Poor lateral field after irradiation

**Mini-MALTA**

Jan **2019**

Small demonstrator
$1.7 \times 0.5$ cm$^2$

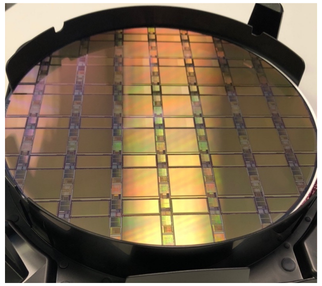



- Introduction of sensor modification
- Radiation hard, full efficiency at 1e15 $n_{eq}$/cm$^2$

**MALTA C**

Aug **2019**

Epitaxial (Epi) and Czochralski (Cz) substrates

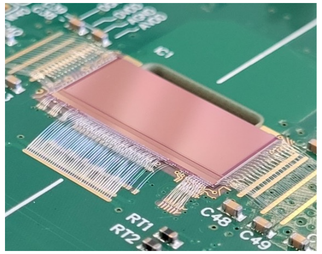


- Significant improvement of Cz substrate efficiency at high voltage after irradiation

**MALTA2**

Jan **2021**

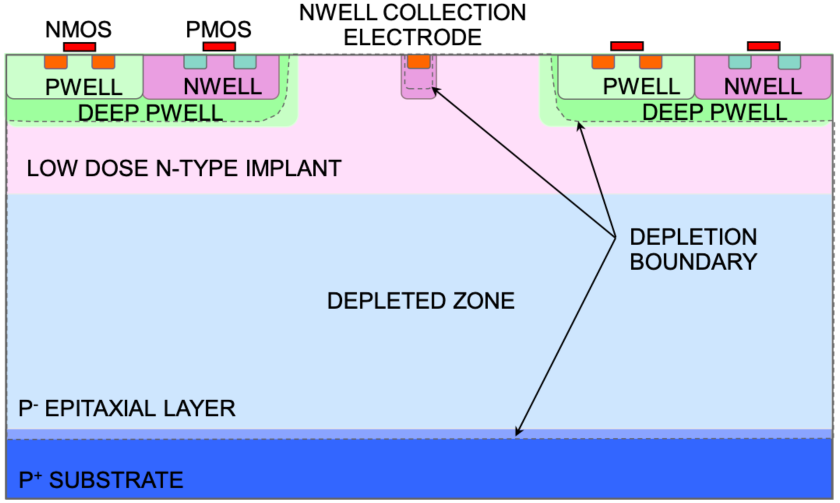
Smaller matrix
$2 \times 1$ cm$^2$




- Improved chip synchronisation
- Improved time resolution
- Improved noise performance

# Additional process modifications

**"Standard" modified process**

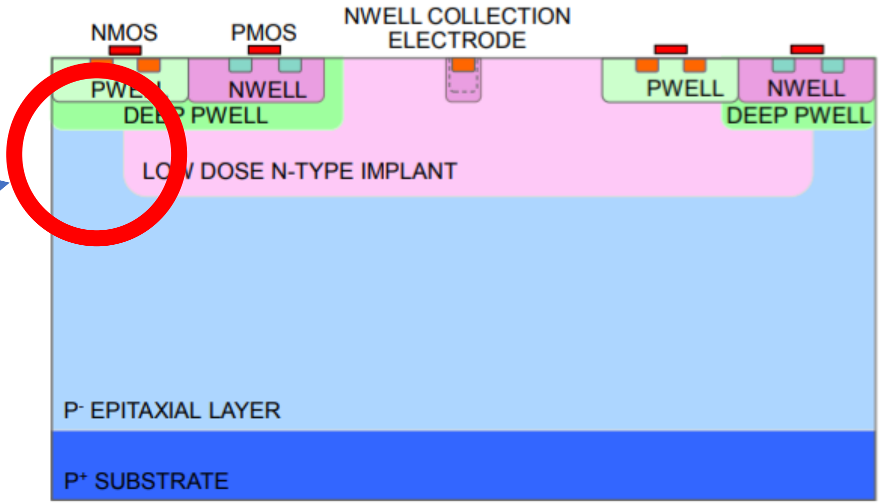



Lateral electric field not sufficient to push the deposited charge towards the small central electrode.

- Efficiency decreases in pixel corners
- Effect amplified by radiation damage

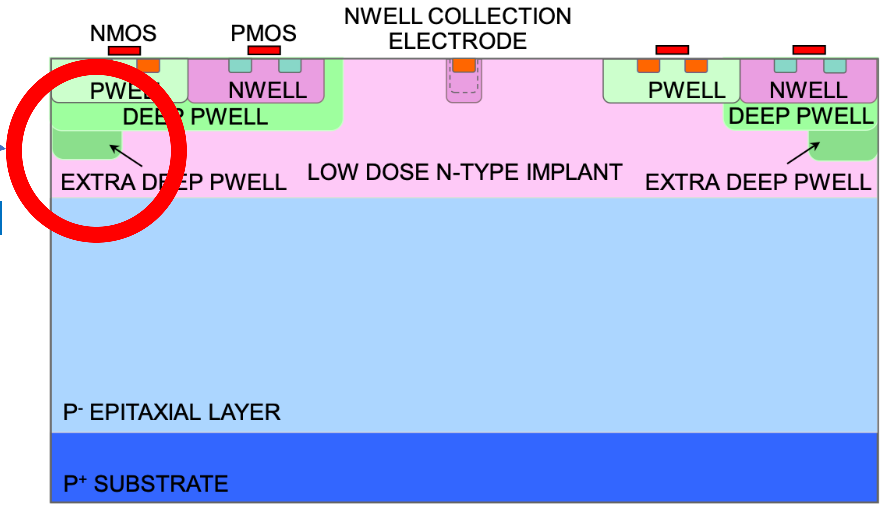
*M. Munker, JINST 14 (2019) C05013*

**N-layer gap (NGAP)**




Process modifications to improve charge collection in the pixel edges

**Extra Deep P-Well (XDPW)**



# Additional process modifications

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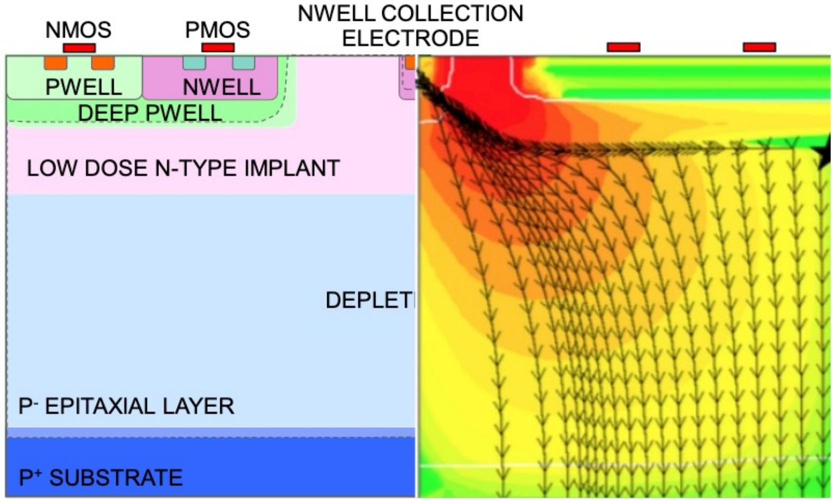


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M. Munker, JINST 14 (2019) C05013

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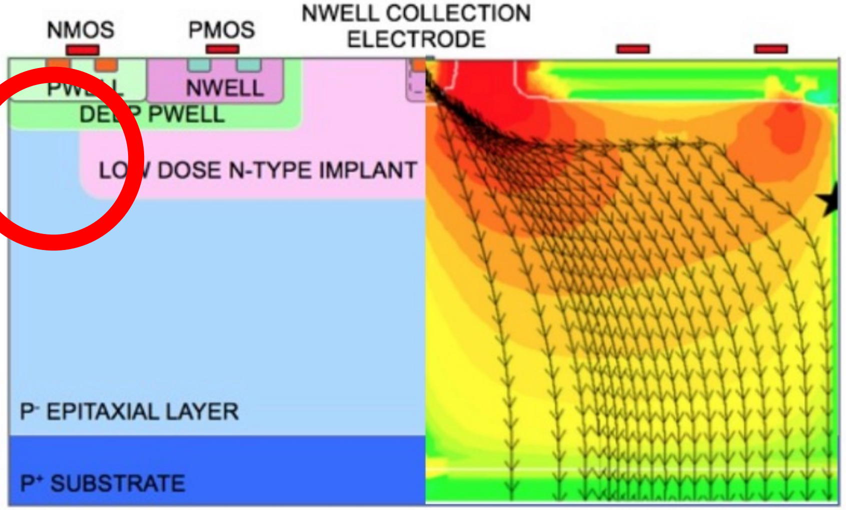


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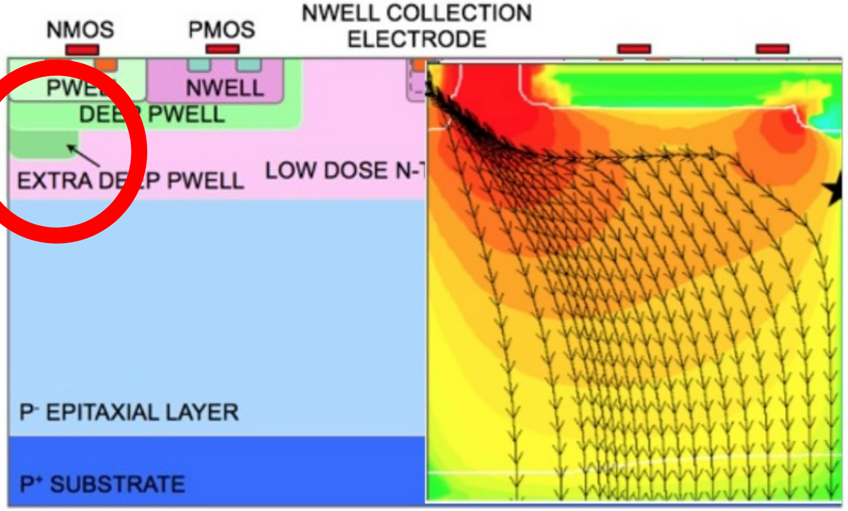
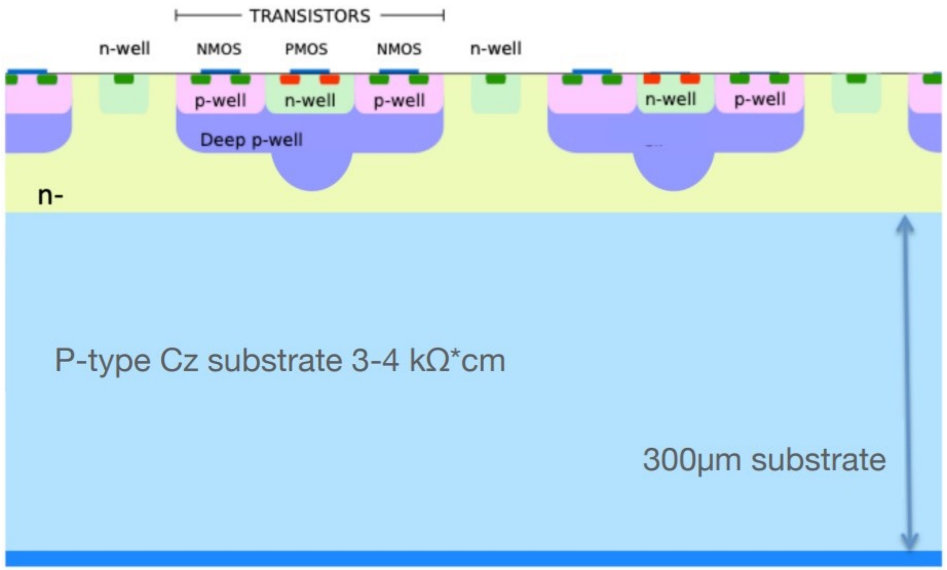


# Sensor substrate – Epitaxial and Czochralski

- Variation introduced in MALTA C – also investigated with MALTA2

- Epitaxial silicon substrate limited to 30 μm
  - High resistivity
- Czochralski (Cz) substrate (3-4 kΩ cm)
  - used for full detection volume (100 – 300 μm)
  - depletion proportional $\sqrt{V_{SUB}}$
  - results in larger cluster size
  - **enhanced radiation resistance**

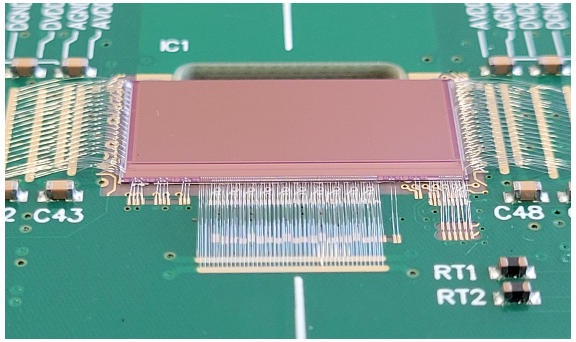


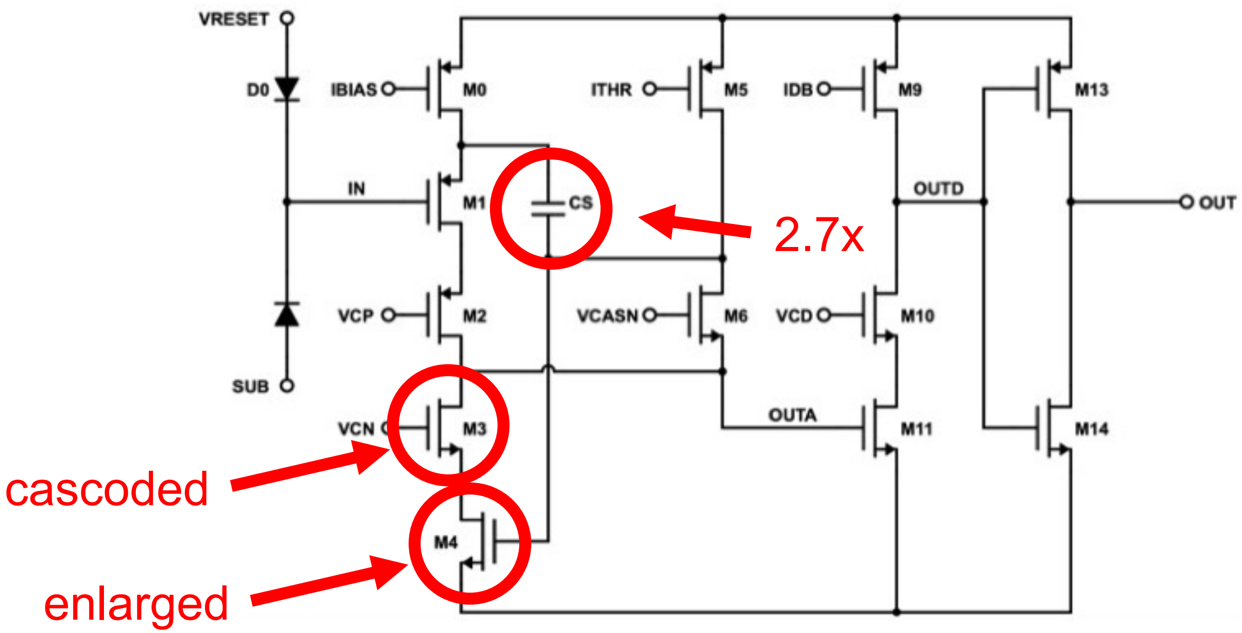

*Publication submitted to JINST, preprint available at arXiv:2301.03912*

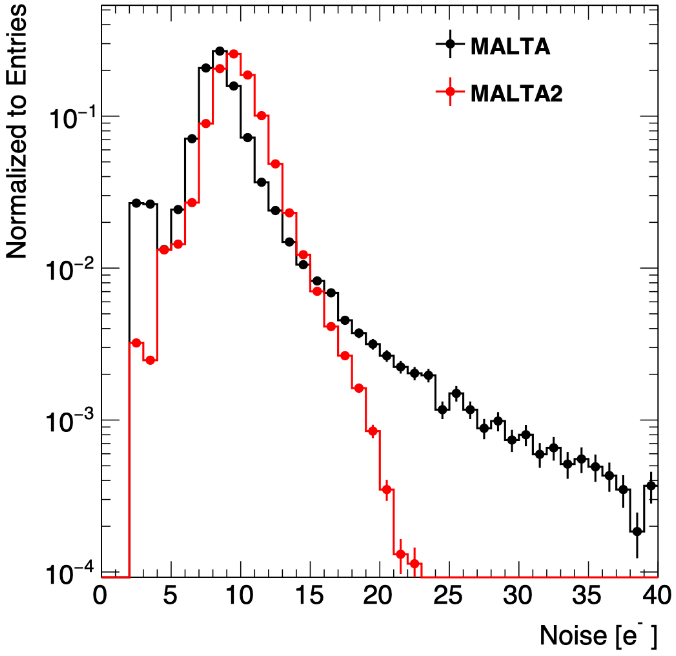
# MALTA2

F. Piro et al, TNS, 2022, vol 69, no 6

- Features 3 flavours (Standard, NGAP, XDPW) and 2 substrates (Epi and Cz)
- Readout improvements:
  - Cascoded transistor M3 -> increases gain
  - Enlarged transistor M4 -> lower noise and higher gain
- Allows for operation at lower threshold at the order of hundreds of electrons
- Significantly **improved noise performance** compared to MALTA

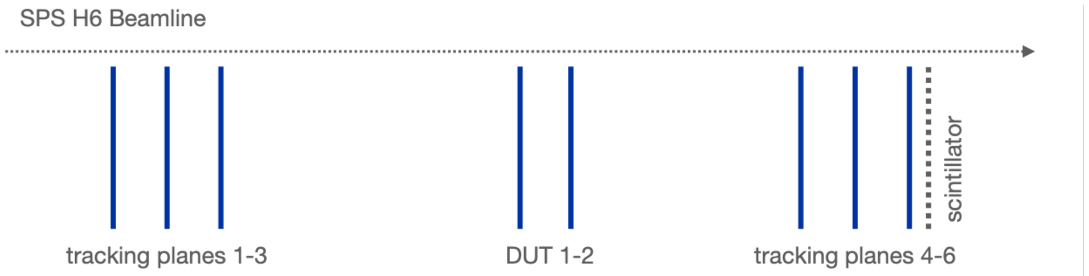


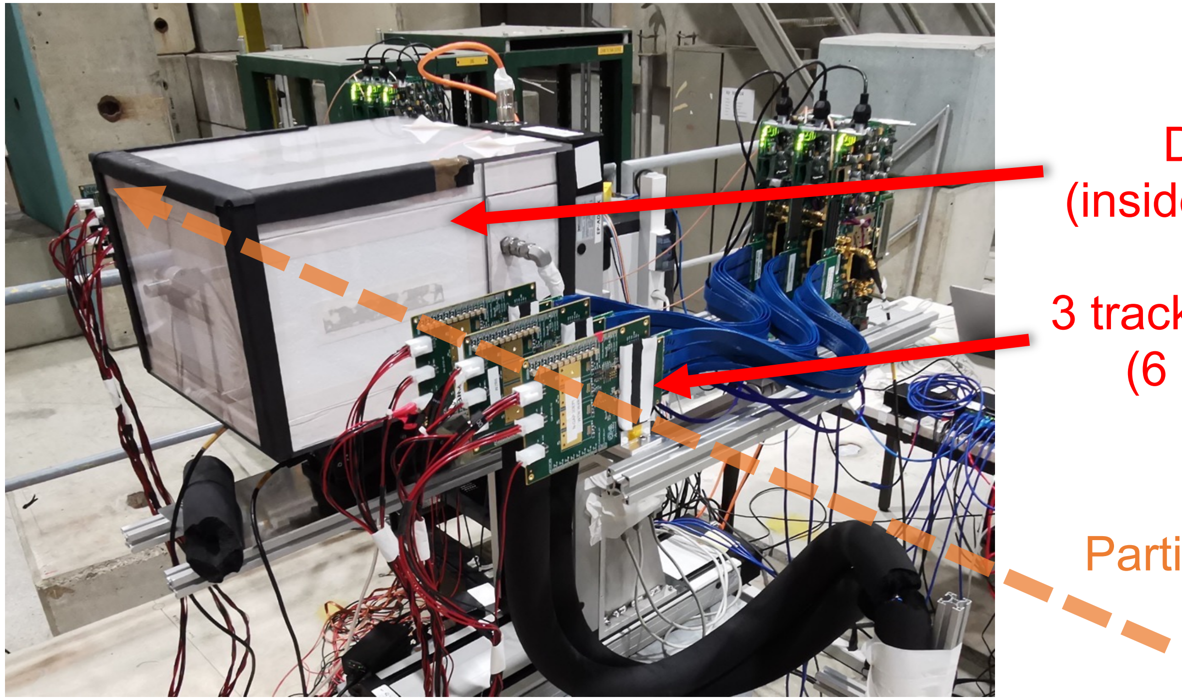



# MALTA-Telescope performance

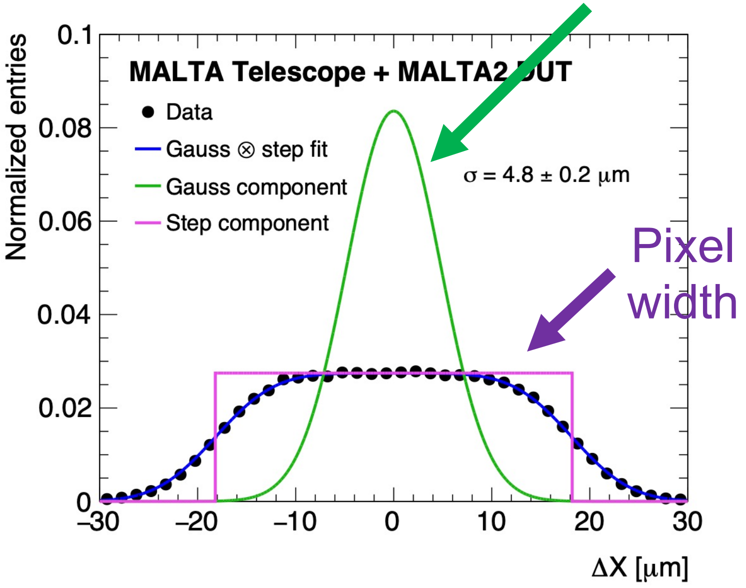
- 180 GeV proton/pion beam at SPS at CERN
- Dedicated beam telescope with flexible trigger logic
  - 6 MALTA tracking planes + scintillator for timing
- **Cold box for irradiated samples**
- Allows for two independent Devices Under Test (DUTs) simultaneously




*Average time resolution of* 2.1 ns

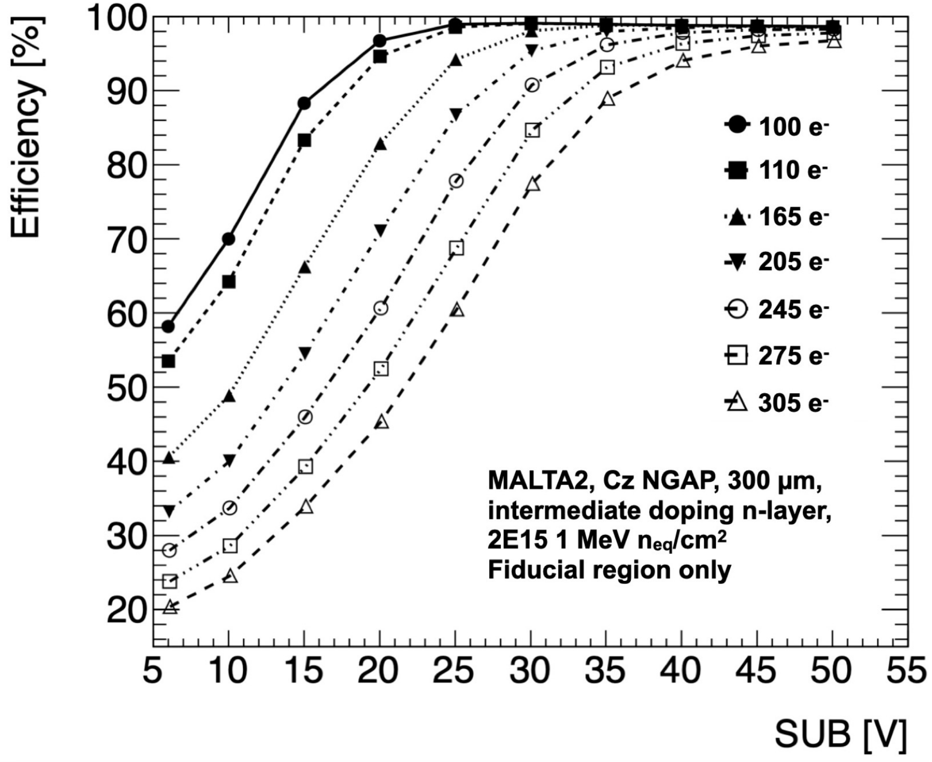
*Hit resolution on DUT* **< 5 μm**



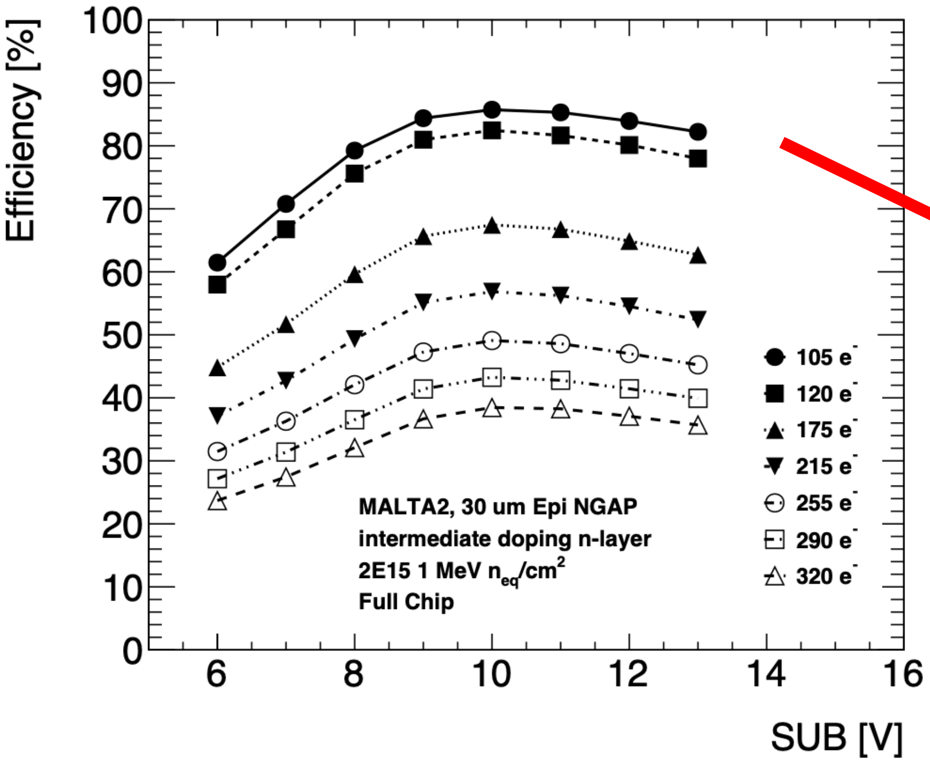
# MALTA2 – neutron irradiated – Epi vs Cz

- MALTA2 Cz shows improved efficiency after irradiation compared to Epi
  - Both samples irradiated to 2E15 1 MeV $n_{eq}cm^{-2}$

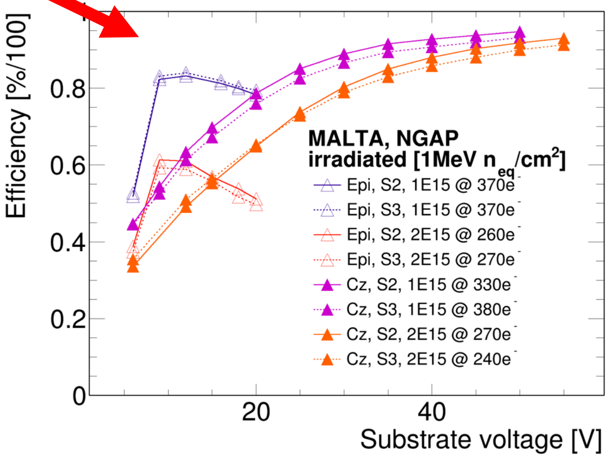
**MALTA2 Cz (conductive glue)**




**MALTA2 Epi**



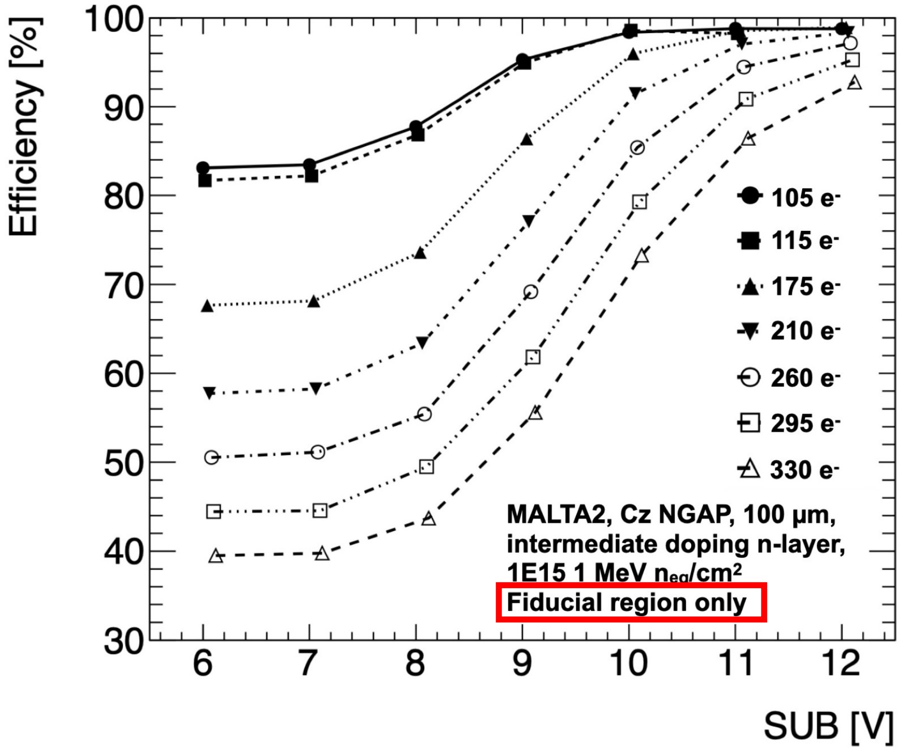

*Similar trend observed for MALTA Epi and Cz*



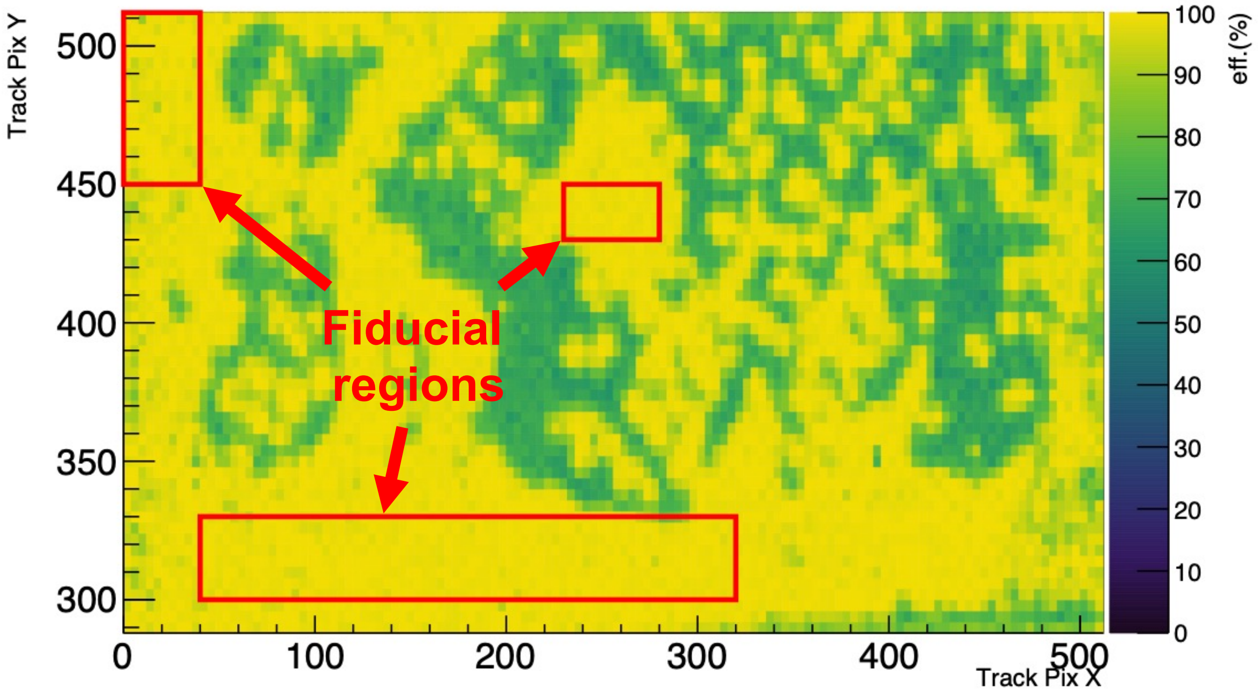

- Epitaxial sample: maximum efficiency of 86% reached at 10 V, then decreases with increasing bias

# MALTA2 – neutron irradiated – conductive glue

- Contact of MALTA2 Czochralski chip with PCB crucial for efficiency
- **Conductive glue layer applied on backside** - bubble pattern emerges due to glue inhomogeneity
- Areas with good contact achieve close to 100% efficiency at high substrate bias
    - Fiducial regions account for 10.3% of the chip

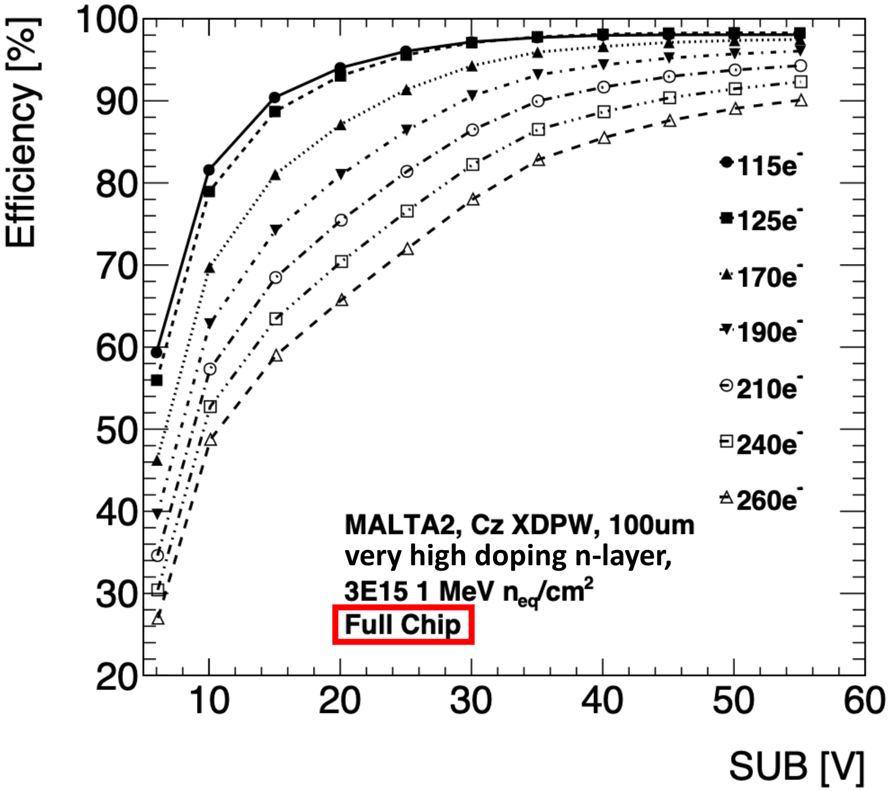


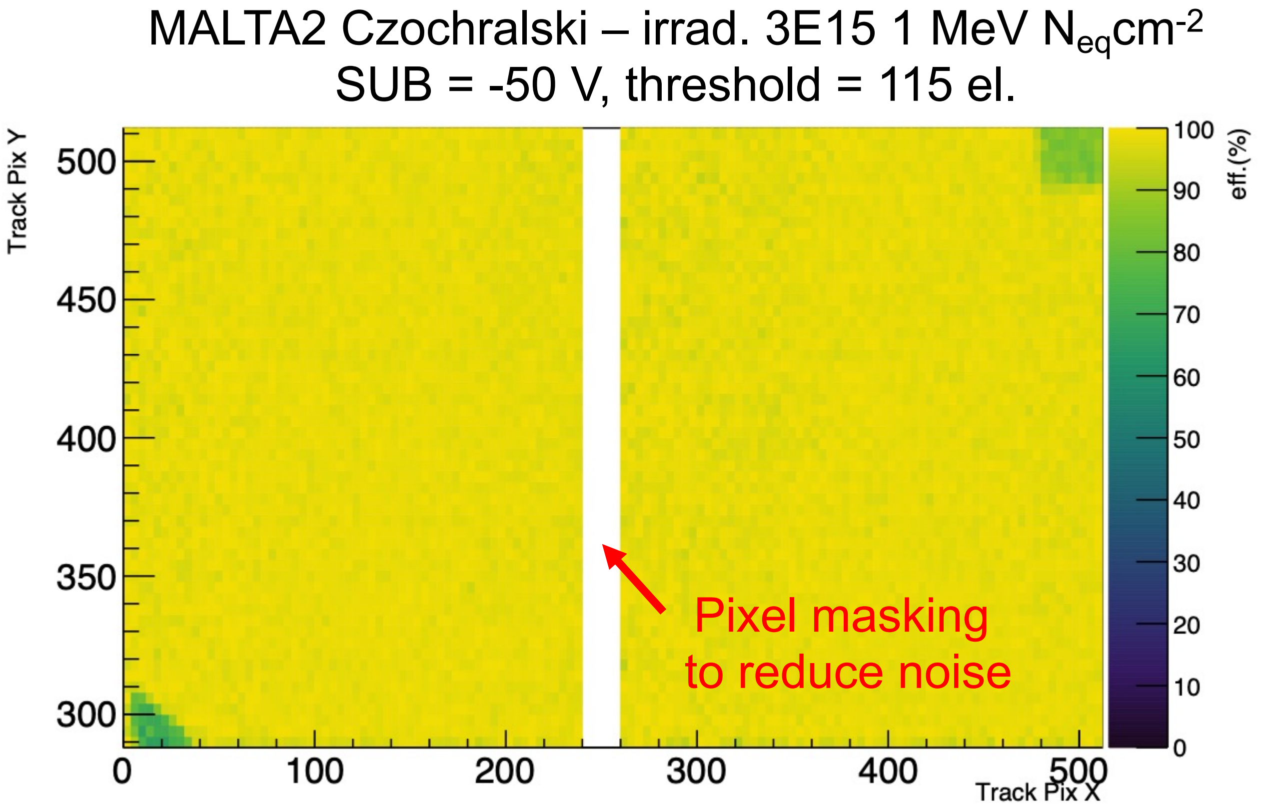

MALTA2 Czochralski – irrad. 1E15 1 MeV $N_{eq}cm^{-2}$
SUB = -12 V, threshold = 260 el.



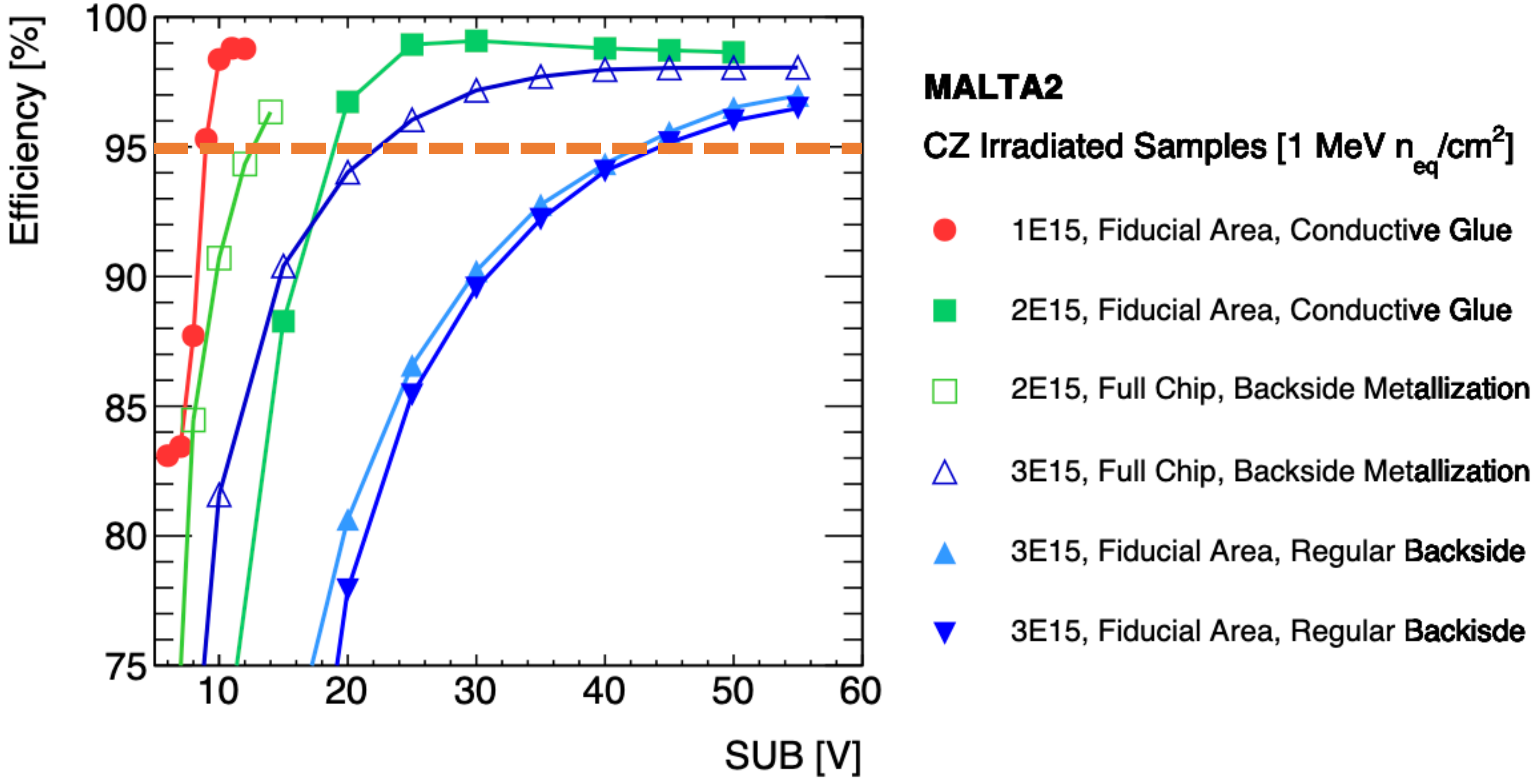
# MALTA2 – neutron irradiated – back-metallisation

- **Back metallisation applied post-dicing** to enhance contact with the substrate
- Efficiency uniformity restored across the matrix
- Chip irradiated to 3E15 $n_{eq}cm^{-2}$ reaches efficiency above 95% at high SUB and low threshold



# MALTA2 – neutron irradiated



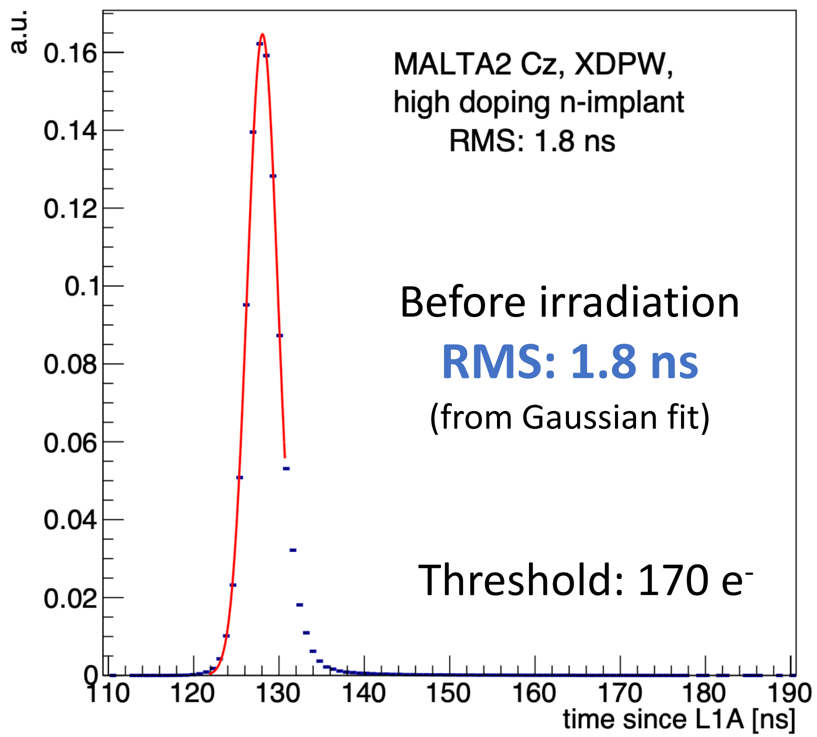

NGAP, 100 um
NGAP, 300 um
XDPW, 100 um
XDPW, 100 um
XDPW, 100 um
XDPW, 100 um

- MALTA2 Czochralski efficiency >95% **up to neutron irradiation levels of 3E15 1 MeV $n_{eq}cm^{-2}$**
  - Sufficient substrate bias voltage needed – increases with irradiation level
  - Performance enhanced by backside metallisation

# MALTA2 – neutron irradiated – timing

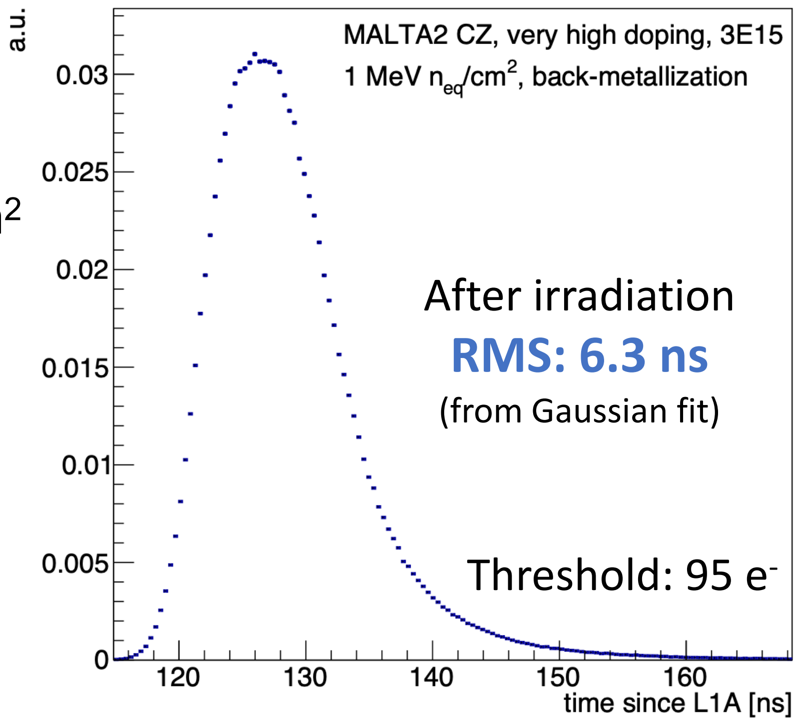
- Time of arrival of leading hit with respect to a scintillator reference
- Applied signal propagation correction
- NOT corrected for sampling jitter (0.9 ns) and scintillator jitter (~0.5 ns)

**more than 98% of the clusters are collected within 25 ns**




Neutron irradiation
3E15 1 MeV $n_{eq}/cm^2$

**more than 95% of the clusters are collected within 25 ns**



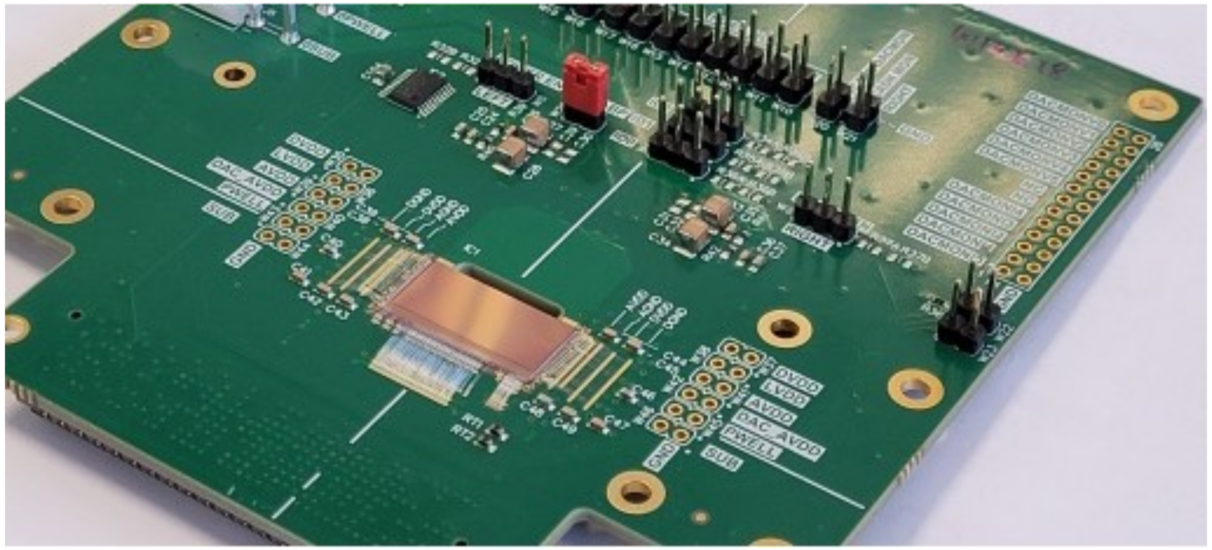
# Conclusions and Future

- MALTA2 demonstrates improvements over the previous members of the MALTA family
- Chips on Czochralski substrate show **enhanced radiation hardness** compared to Epi
- Full chip **efficiency >95% after 3e15 $n_{eq}/cm^2$** demonstrated with Czochralski sensors
- **Backside-metallisation** greatly improves efficiency of irradiated sensors
- Un-irradiated MALTA2 sensors with <2 ns timing resolution
  - After 3e15 1 MeV $n_{eq}/cm^2$ irradiation -> RMS 6.3 ns

**MALTA3 in development**

- Small demonstrator
- Data serialisation
- Improved in-pixel digital electronics
- <1 ns time-stamping in periphery
- More reliable pixel masking

MALTA3
#digital-flow-design



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- Supported by the Marie Sklodowska-Curie Innovative Training Network of the European Commission Horizon 2020 Programme under contract number 675587 (STREAM).
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# Telescope DAQ

Plane 1
MALTA Epi NGAP

Plane 2
MALTA Cz NGAP

Plane 3
MALTA Cz STD

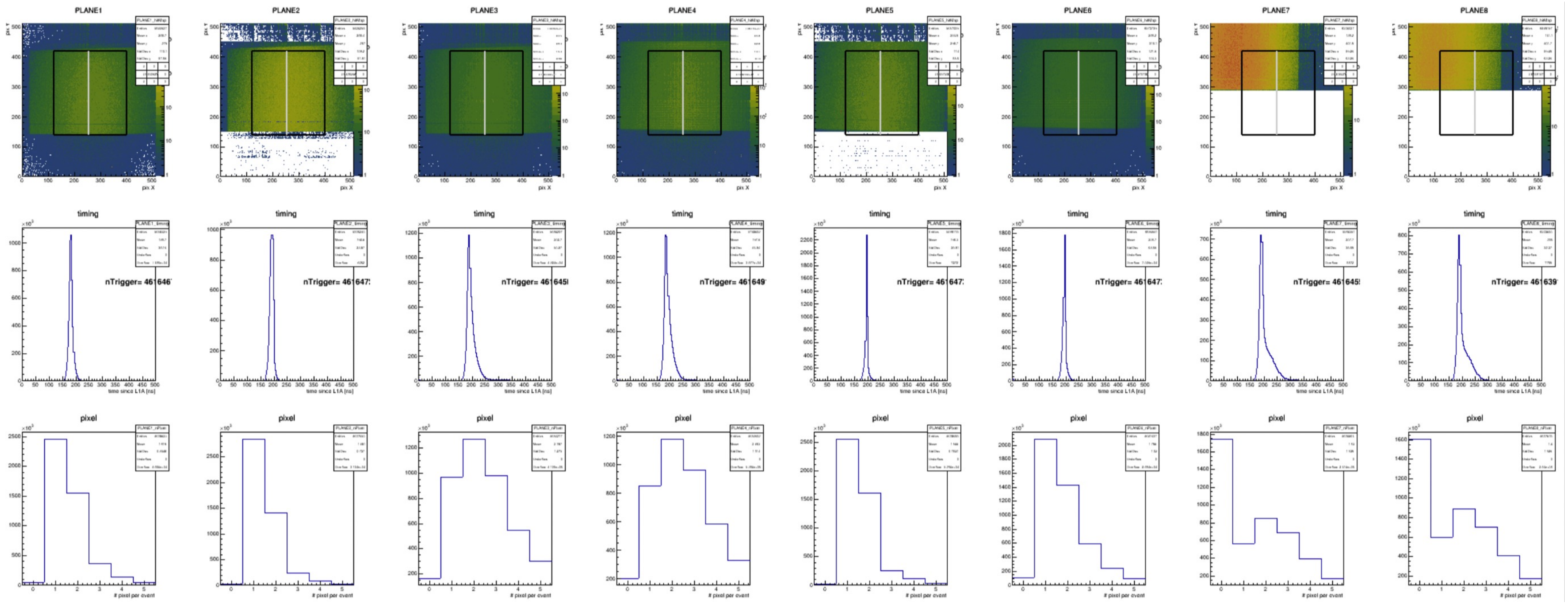
Plane 4
MALTA Cz STD

Plane 5
MALTA Cz NGAP

Plane 5
MALTA Epi STD

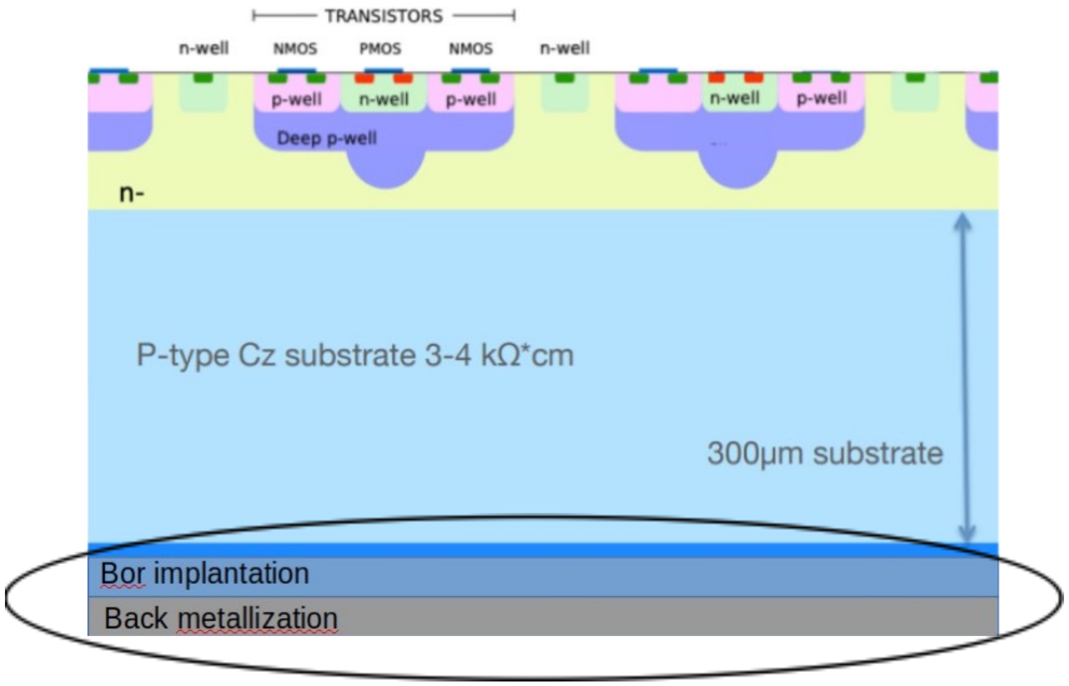
DUT1
MALTA2

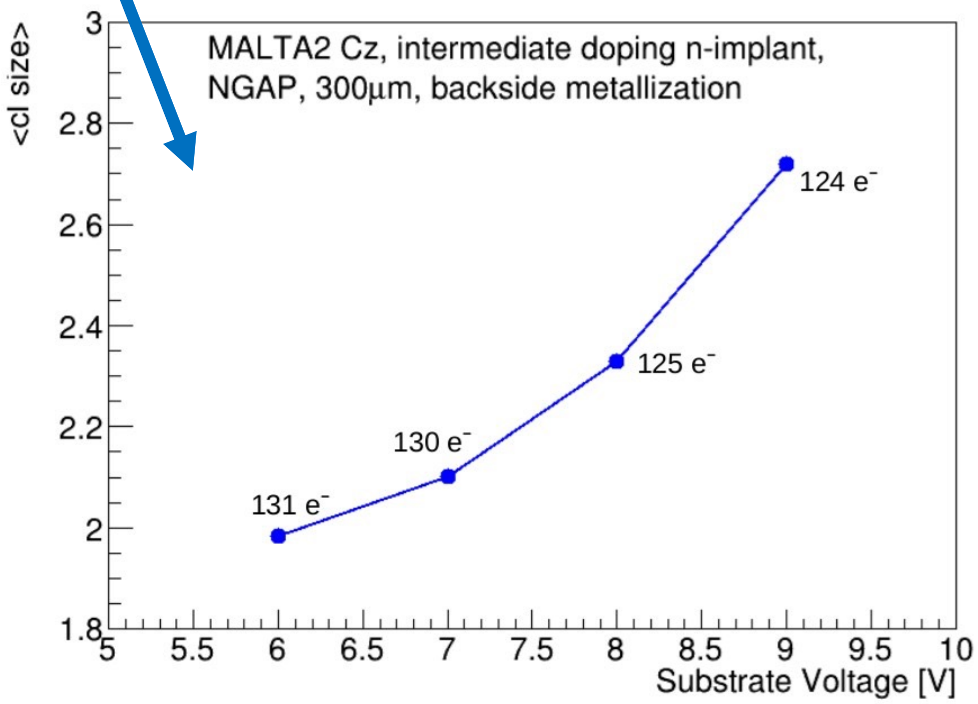
DUT2
MALTA2



# MALTA2 – back-metallisation

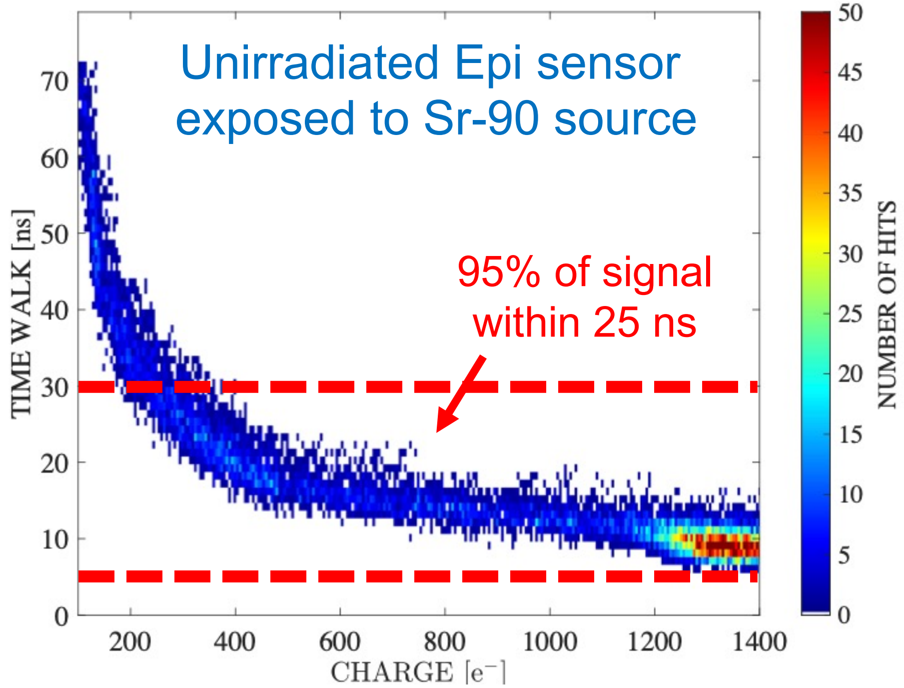
- Back metallisation leads to improved propagation of substrate voltage
- Back-metallised chips demonstrate **enhanced cluster size** as SUB voltage increased

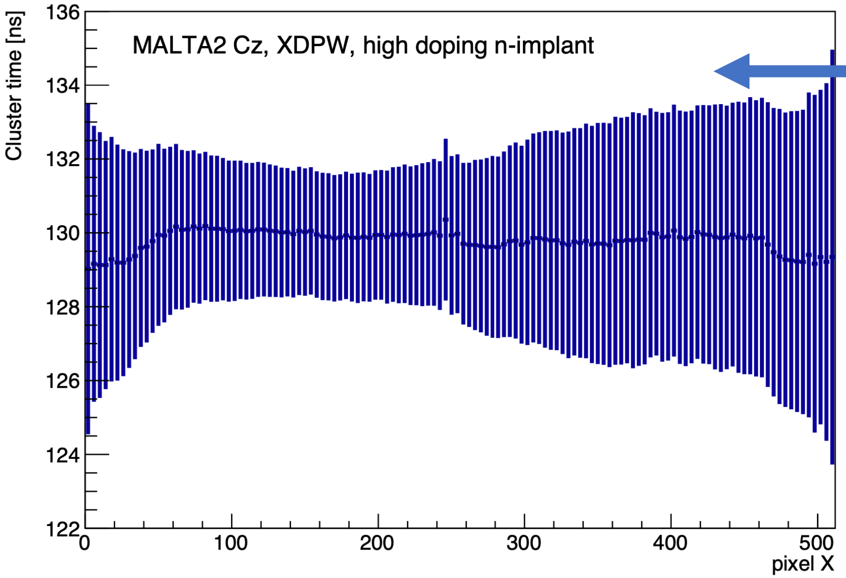


# MALTA2 – timing

- Time walk evaluated using pixels with analog output
  - Small signal arrives later -> from charge-sharing effects
  - Large charge signals with time-talk ~10 ns
- Uniformity of chip response verified both with change injection and testbeam measurements




X correction compensates for non-uniformities in chip response

Y correction due to time propagation across the column (linear behaviour)