Charge reconstruction from binary hit data on irradiated MALTA2 Czochralski sensors

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MALTA sensor

Silicon tracking sensor requirements → MALTA performance:

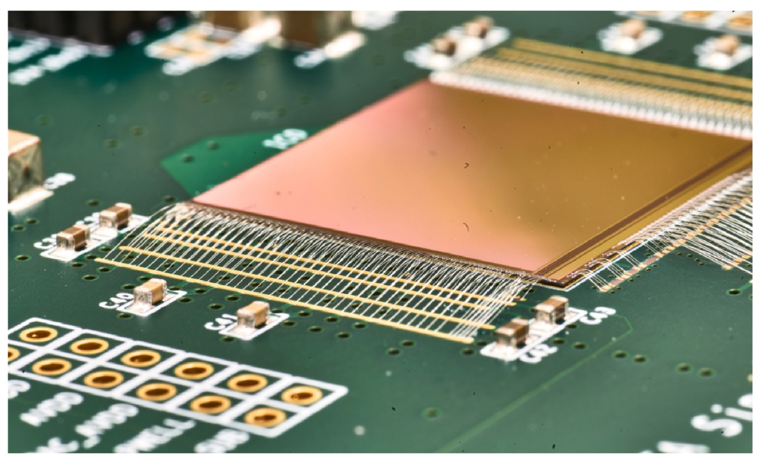
- Extreme radiation tolerance → investigated here
- Large hit rate → > 100 MHz/cm²
- High granularity → Pixel pitch 36.4 × 36.4 μm²
- Fast response time → Time resolution < 2 ns
- Very thin material → Optimisable thickness (50 to 300 μm)
- Large area coverage → Low pixel power < 1μW/pixel

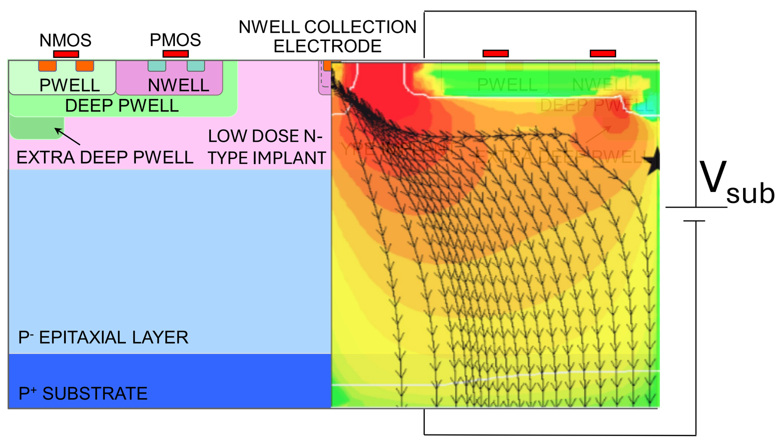
MALTA sensor specifications:

- Depleted monolithic active pixel sensor (DMAPS)
- Fabricated in 180 nm Tower CMOS imaging process
- Up to 512 x 512 pixels (2 × 2 cm²)
- Minimum threshold ~150 e⁻
- Low voltage operation (6V to 60 V)

MALTA pixel design:

- Epitaxial or Czochralski high-resistivity substrate available
- Cross-section shows Extra Deep P-Well (EDPW) modification
- TCAD simulation give complex electric field
- Variation of doping of n-type implant possible
  → investigate here **high** and **very high doping**

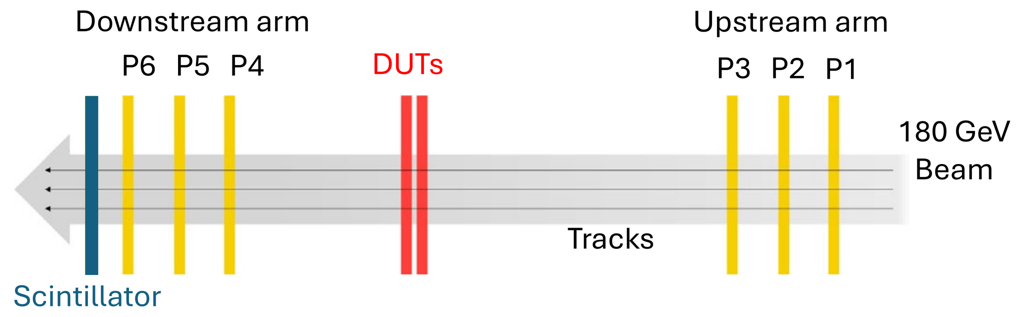




MALTA telescope at SPS

Telescope setup:

- Permanently installed at CERN SPS
- 6 MALTA tracking planes (P1-P6)
- 1 scintillator for time reference
- 2 devices under test (DUTs) in coldbox (-20°C)



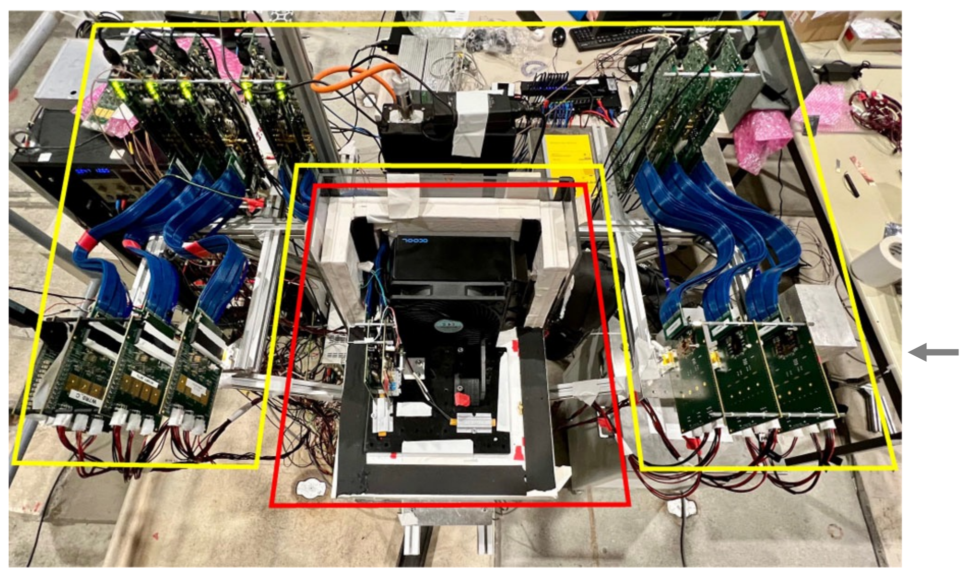
Telescope performance:

- Triggered readout at rates above 10 kHz
- < 5 μm spatial resolution → sub-pixel resolution
- 2 ns timing resolution

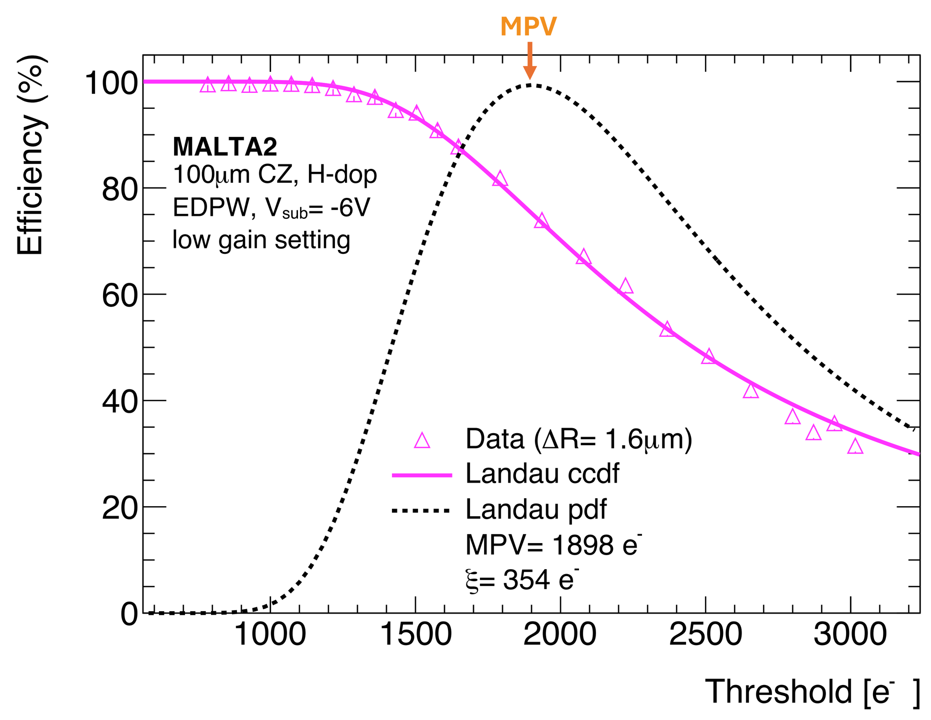
→ operation at high rates > 4×10^6 particles per spill

Sensor radiation hardness:

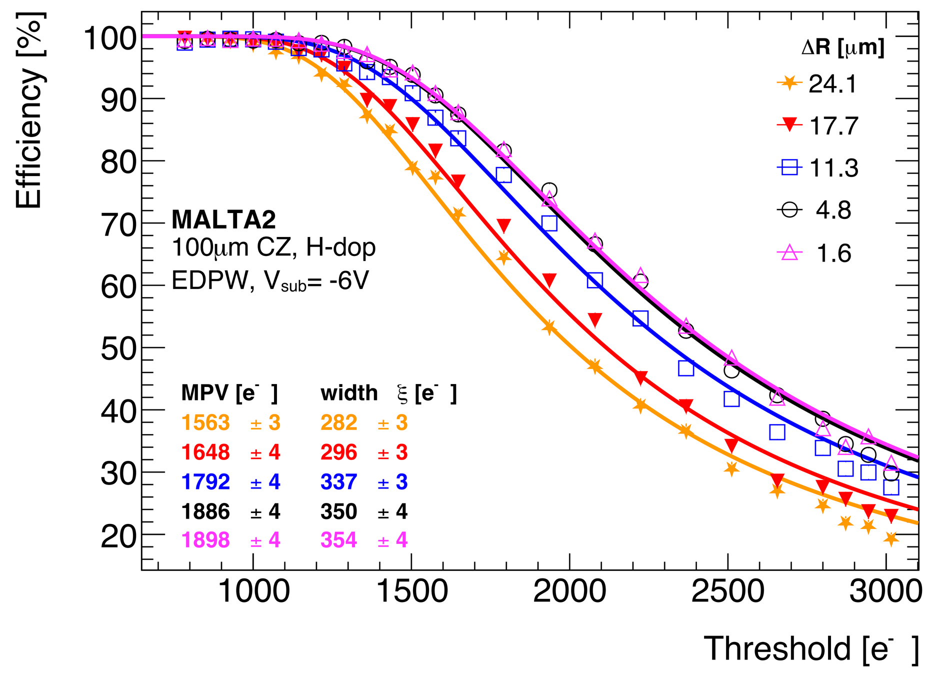
- TID radiation hardness > 100 Mrad
- NIEL radiation hard up to 3×10^{15} 1 MeV n_{eq}/cm^2
  - HL-LHC lifetime fluence about 30 cm away from ATLAS beam pipe
  - 99% efficiency and < 40 Hz noise/ pixel
  - > 95% of clusters collected within 25 ns LHC bunch crossing window



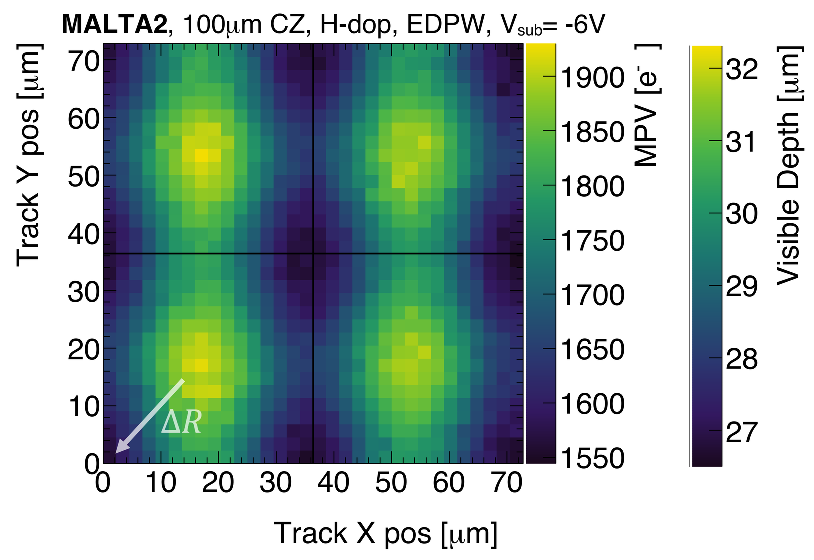
Method: Landau fit to efficiency data



- Data from MALTA2 DUT with MALTA telescope
- Low gain setting to reach higher thresholds >>150 e⁻
- **Efficiency** = $\frac{\text{Tracks detected in DUT}}{\text{Tracks reconstructed with telescope}}$
- Energy loss of charged hadrons (MIPs):
  → Landau probability density function (**pdf**)
- Fit to efficiency data
  → Cumulative Landau distribution (**cdf**)
- Most probable value (**MPV**) of Landau is
  - Maximum of **pdf**
  - Inflection point of **cdf**
  - Depends on in-pixel position→ 2×2 pixel matrix
- ΔR quantifies distance from pixel centre



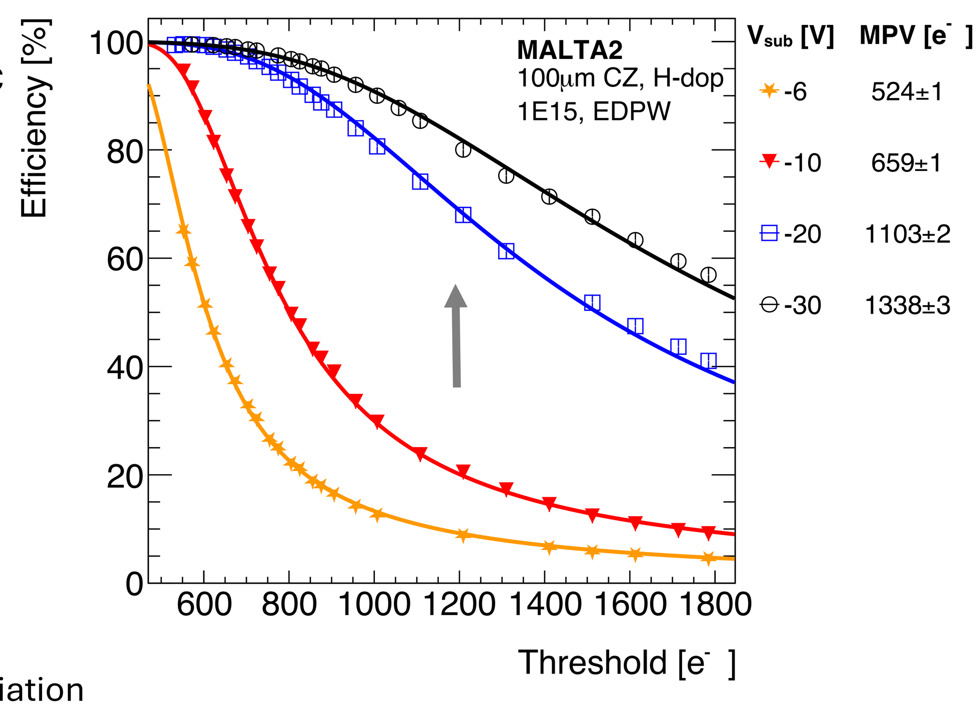
Corresponding visible depth in silicon:
→32 μm at pixel centre
→27 μm at pixel corner



Substrate voltage increase

- Sensor irradiated to 1×10^{15} 1 MeV n_{eq}/cm^2
- Stored and operated as DUT inside coldbox at -20°C

Substrate voltage increase from -6 V to -30 V
→Average efficiency increases for same threshold
→Better depletion of Czochralski substrate

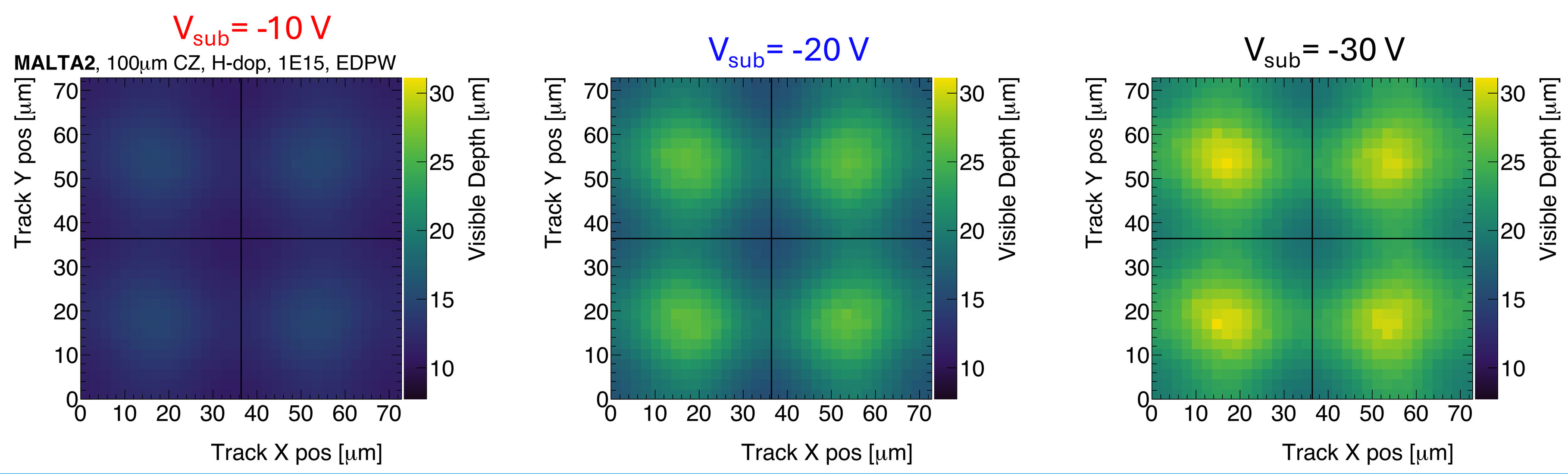


Two dimensional visible depth plots (below)

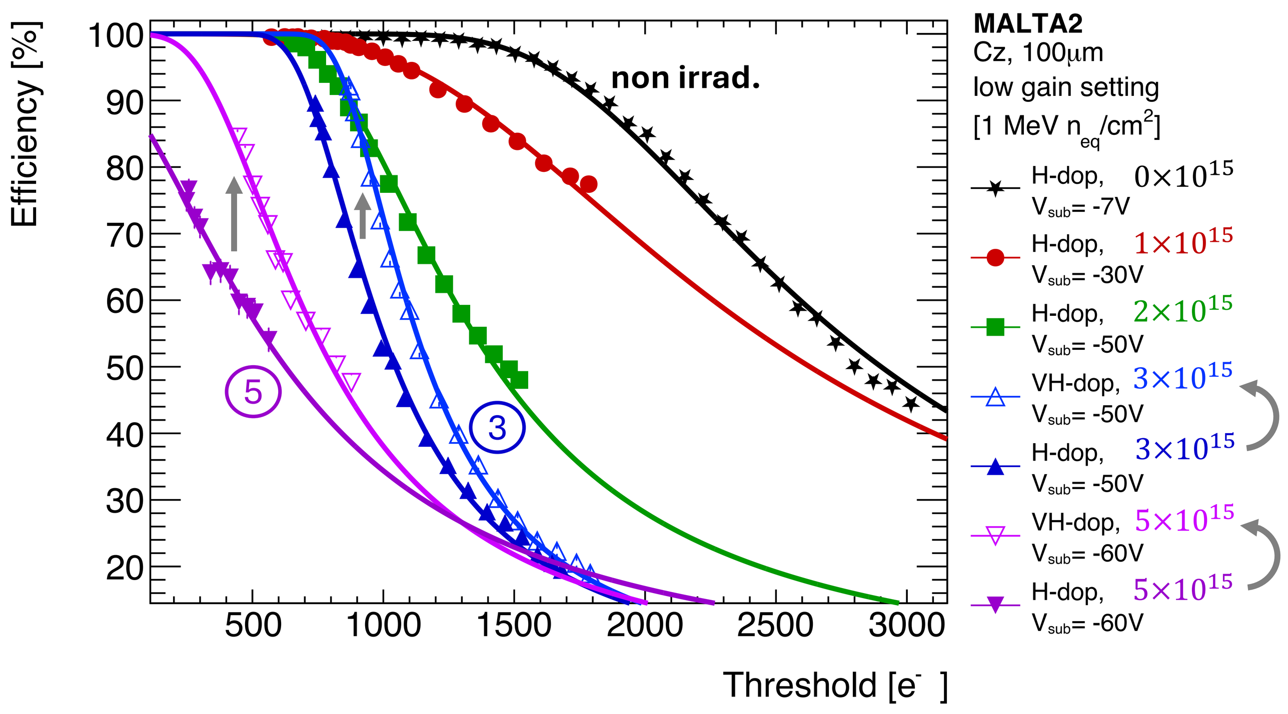
- Depth for all in-pixel regions on 2×2 pixel matrix
- At pixel centre:

V_{sub}	Vis. depth
-10 V	15 μm
-20 V	26 μm
-30 V	30 μm

→ Visible depth of same order as sensor without irradiation



Efficiency after irradiation



Higher doping of n-implant → Increase in efficiency !

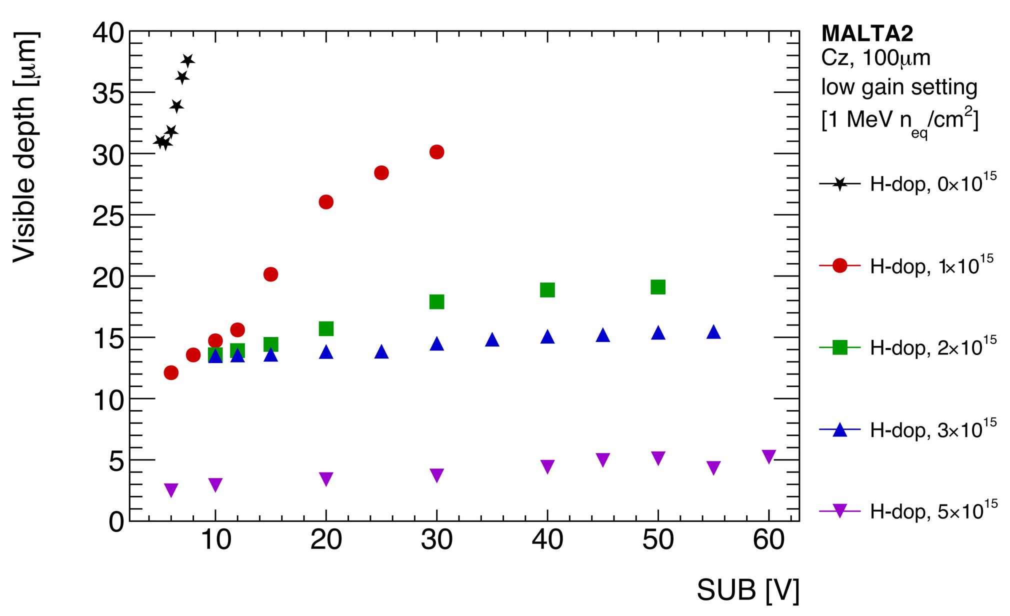
Non-ionizing energy loss (NIEL):

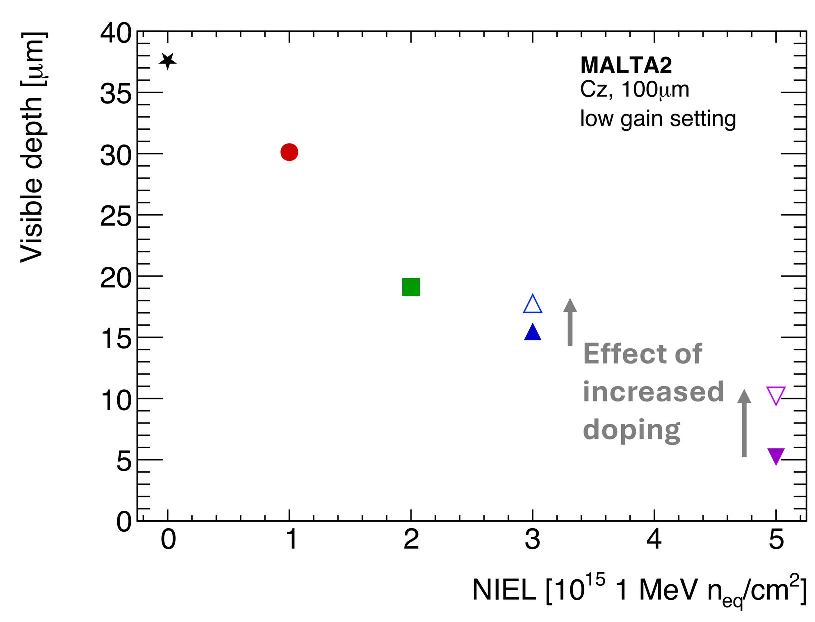
- Sensors neutron-irradiated at Triga reactor (IJS, Slovenia) to fluences of 0,1,2,3 and 5×10^{15} 1 MeV n_{eq}/cm^2
- Irradiation level indicated in circles

Irradiation behaviour:

- Larger NIEL fluence gives:
  → Smaller efficiency at same threshold
  → Smaller reconstructed charge as MPV

Result: Visible depth after irradiation





Visible depth:

- Equivalent silicon depth assuming fully efficient charge collection and no charge sharing
- Calculated from reconstructed charge (MPV) at pixel centre:
  → No charge loss due to charge sharing

Maximum depth at highest substrate voltage

- V_{sub}= -7 V for non irradiated sensor
- V_{sub}= -60 V for highest irradiation

Irradiation behaviour:

- Larger fluence
  → smaller visible depth due to degraded depletion
- Increase of substrate voltage improves depletion

Very high doping on continuous n-implant:

- Hollow markers at 3 (△) and 5 (▽) irradiation units show sensor with 70% increased n- doping

→ Recovery of visible depth due to doping

References

[1] van Rijnbach, M. et al. Radiation hardness of MALTA2 monolithic CMOS imaging sensors on Czochralski substrates. *EPJC 84, 251 (2024)*

[2] Fasselt, L. et al. Charge calibration of MALTA2, a radiation hard depleted monolithic active pixel sensor, arXiv:2501.13562 (2025)

[3] van Rijnbach, M. et al. Performance of the MALTA telescope. *EPJC* 83, 581 (2023)

[4] Meroli, S. et al. Energy loss measurement for charged particles in very thin silicon layers, *JINST* **6** P06013 (2011)

Summary & Outlook

Method of charge reconstruction from binary data:

- Measured MALTA2 hit efficiency with telescope
- Data taking at fine threshold steps
- Reconstruction of most probable charge amplitude (MPV) through Landau fit
- Quantification of visible depth in silicon

After irradiation:

- Efficiency at same threshold degrades
- Reconstructed charge and visible depth degrade

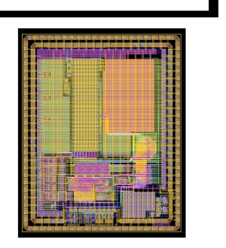
Performance after irradiation recovered by:

- Increase in substrate voltage
- Higher doping of n-implant

Coming soon:

- Sensors with even higher doping of n-implant
  → Further improves efficiency after irradiation?
- MALTA3 incorporates on-chip time-tagging
  →targets time resolution <1 ns

MALTA3



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