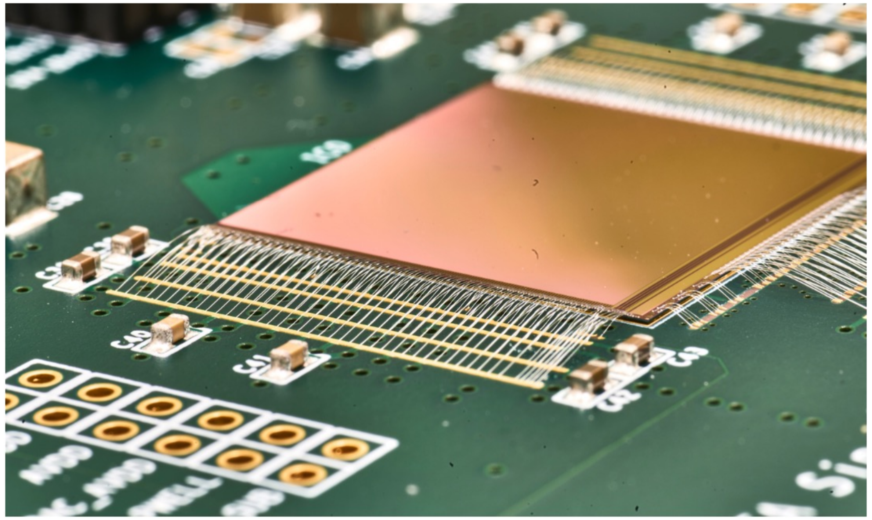
Radiation hardness and timing performance of MALTA monolithic Pixel sensors in Tower 180 nm

1st DRD3 week on Solid State Detectors R&D WG/WP1

Lucian Fasselt **17 June 2024**



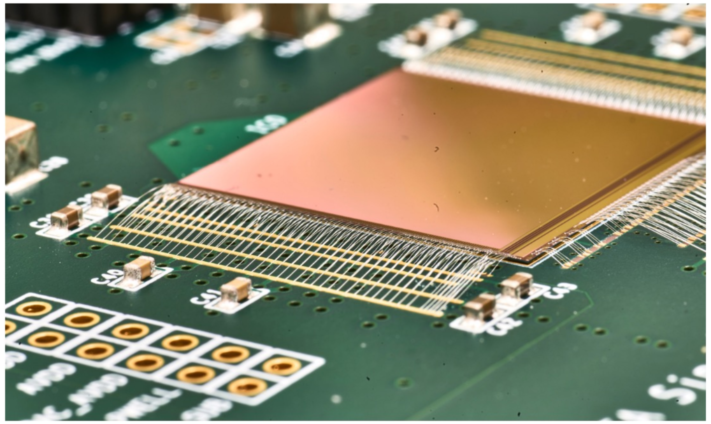
Content

- MALTA beam telescope @ CERN SPS
- Radiation hardness at $3\times10^{15}\ n_{eq}/cm^2$
- Timing resolution ~ 2 ns
- Depletion depth studies
- MALTA3

P. Allport (Birmingham), I. Asensi Tortajada (CERN), P. Behera (IITM), D.V. Berlea (DESY), D. Bortoletto (Oxford), C. Buttar (Glasgow), F. Dachs (CERN), V. Dao (CERN), G. Dash (IITM), D. Dobrijevic (Zagreb, CERN), L. Fasselt (DESY), L. Flores Sanz de Acedo (CERN), M. Gazi (Oxford), L. Gonella (Birmingham), V. Gonzalez (Valencia), G. Gustavino (CERN), S. Haberl (CERN, Innsbruck), T. Inada (CERN), P. Jana (IITM), K. Kotsokechagia (CERN), L. Li (Birmingham), H. Pernegger (CERN), P. Riedler (CERN), W. Snoeys (CERN), C.A Solans Sanchez (CERN), T. Suligoj (Zagreb), M. van Rijnbach (CERN), M. Vazquez Nunez (CERN, Valencia), A. Vijay (IITM), J. Weick (CERN), S. Worm (DESY)

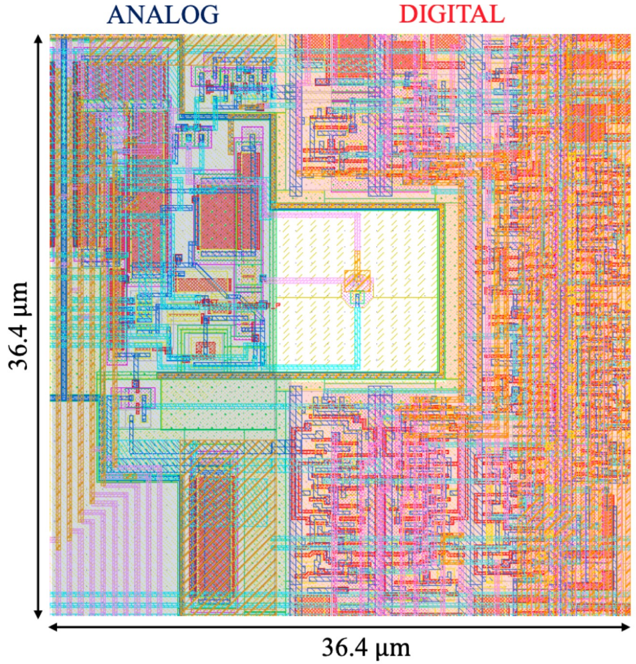
Origin of MALTA

Based on R&D for ALPIDE



MALTA Chip

- 180 nm Tower CMOS imaging process
- 512 × 512 pixels
- Originally conceived for ATLAS pixel detector upgrade for HL-LHC
- Timing response **within 25 ns**
- Radiation hard up to **3×10^{15} n_{eq}/cm^2**
  (ALPIDE < 10^{14} n_{eq}/cm^2)
- Asynchronous readout of binary hit info
  (see talk tomorrow 9 am by C. Solans)
- No TOT, only binary hit info
- High data rate **>100 MHz/cm^2**



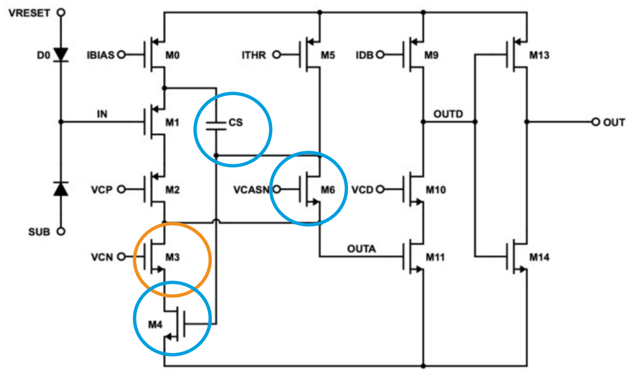
MALTA Pixel

- $36.4 \times 36.4\ \mu m^2$ pixel size
- Thickness down to 50 μm (up to 300 μm)
- $3\times3\ \mu m^2$ small collection electrode
  → Small capacitance (< 5 fF)
  → ENC < 15 e^-
- Low voltage (6 - 30 V)
- **Low power** (1μW/pixel)

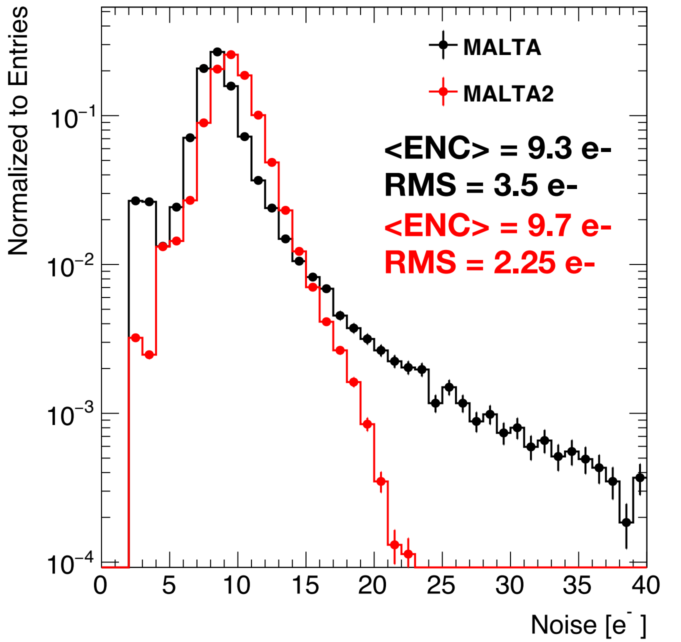
MALTA2 modifications

- Improved Front-end
  - Enlarged transistors
  - Cascode stage
  - → Lower noise
  - → Higher gain

F. Piro et al., TNS 69 (2022)



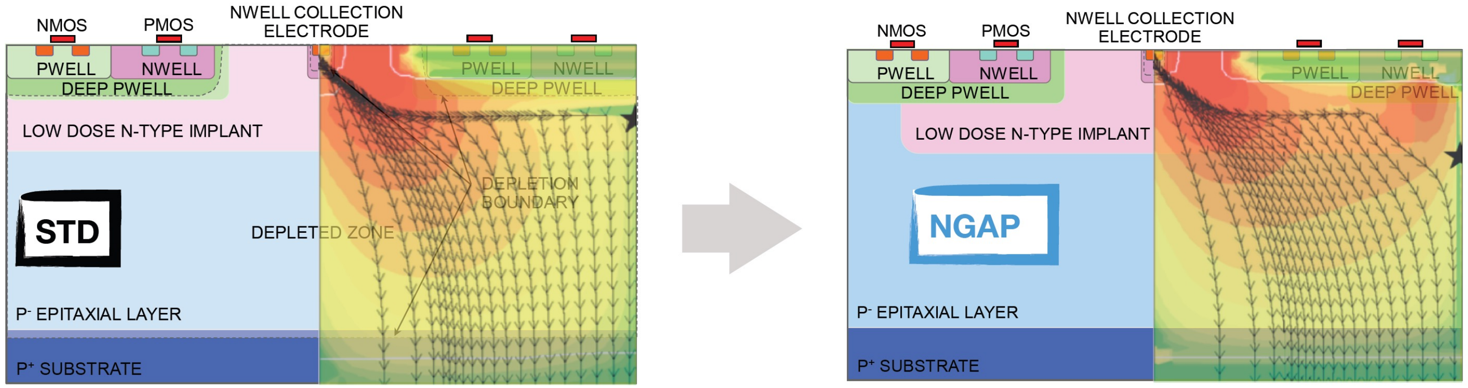
G. Gustavino et al., (VERTEX2023)048



- Pixel variants: Gap in n-layer (NGAP) or extra deep p-well (XDPW)
  - → **Improved** E-field and charge collection in pixel corners

- Epitaxial silicon (30 μm active) in 50 μm thick sensor for minimal material
- **Czochralski substrate** (100 to 300 μm)
  - Larger cluster size
  - Larger substrate voltage applicable
  - → Improved radiation hardness

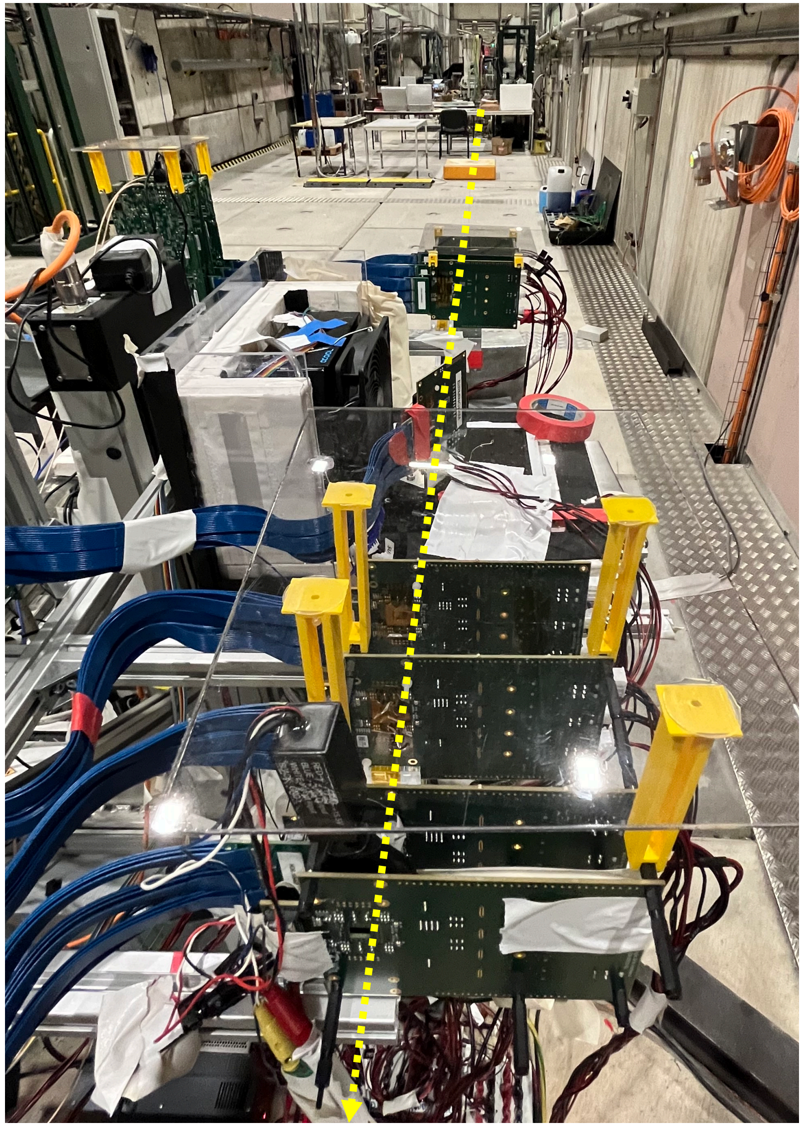
M. Munker et al., *JINST* C05013

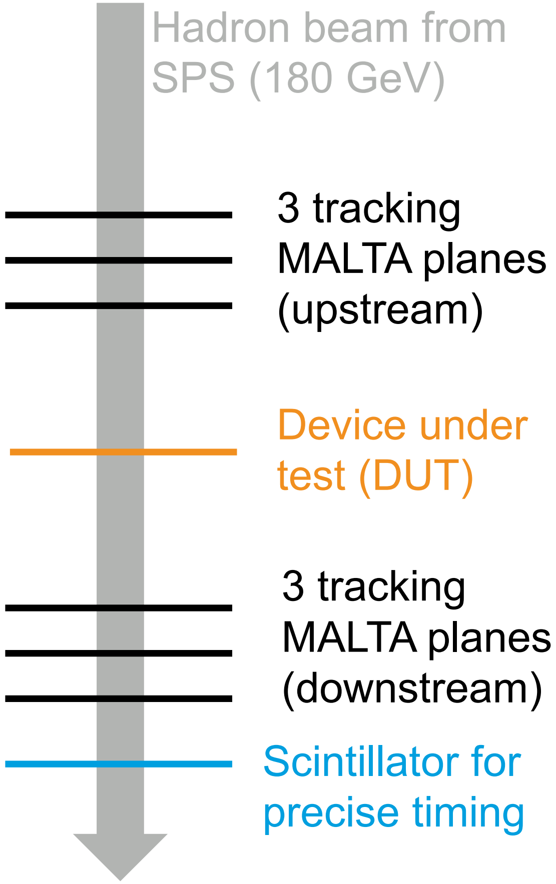


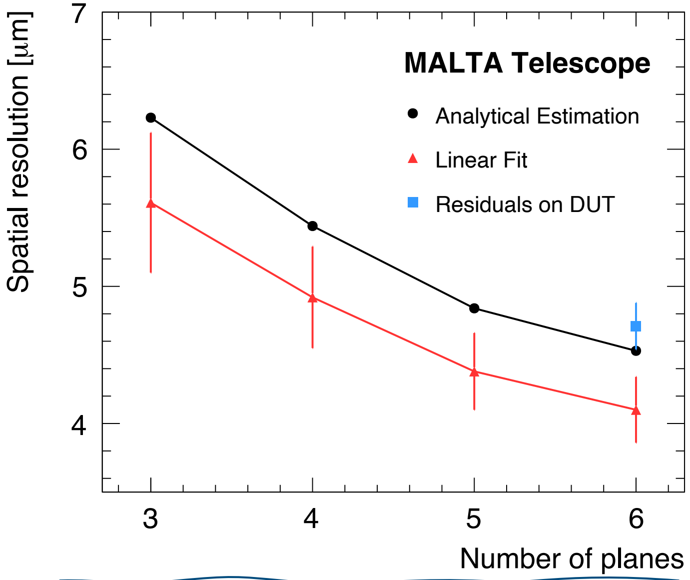
Gap in the low dose N-type implant

EPJC 83 (2023) 7, 581

MALTA telescope @ SPS

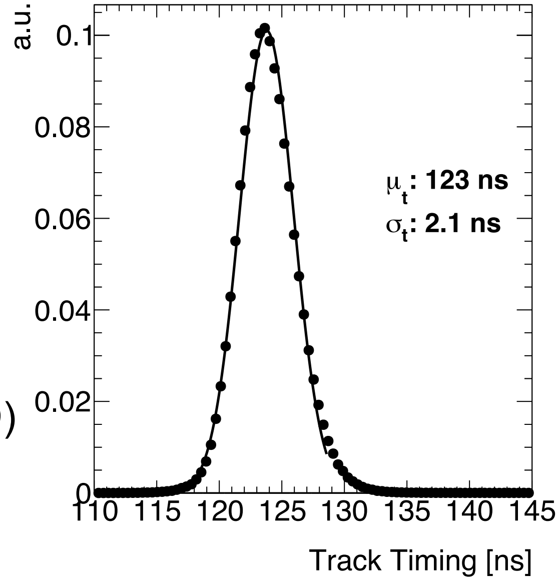






spatial resolution: $\sigma_s = 4.5\ \mu m$
time resolution: $\sigma_t = 2.1$ ns
→ Reference for DUT

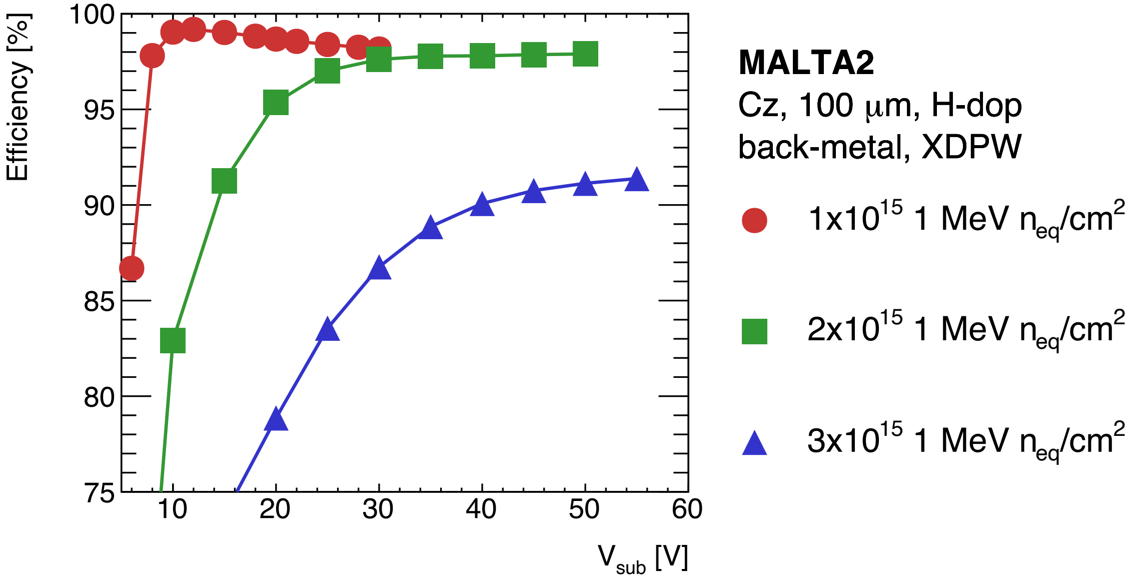
- permanently installed at SPS
- Up to 2 DUTs (in coldbox)
- used by other groups for their sensor characterization (e.g. BCM',ATLAS ITk pixel, HGTD)
- low X_0 telescope for material measurement via multiple scattering with PS T9 e- beam



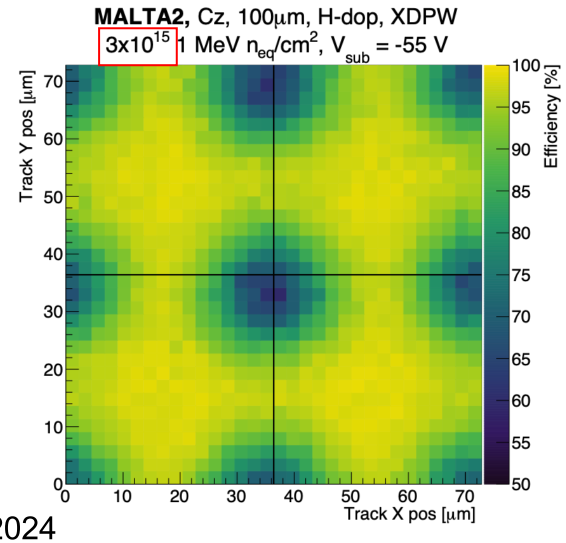
B. Moser et al., ATL-ITK-SLIDE-2023-598

MALTA2 irradiation study up to $3\times10^{15}\ n_{eq}/cm^2$

Efficiency > 90 % recovered by substrate voltage increase



- Backside metallisation
  → good voltage propagation to substrate across chip
- Efficiency loss at pixel corners



[G. Gustavino et al., (VERTEX2023)048](#)

[M. van Rijnbach et al., Eur. Phys. J. C **84**, 251 (2024)](#)

MALTA2 irradiation study up to $3\times10^{15}\ n_{eq}/cm^2$

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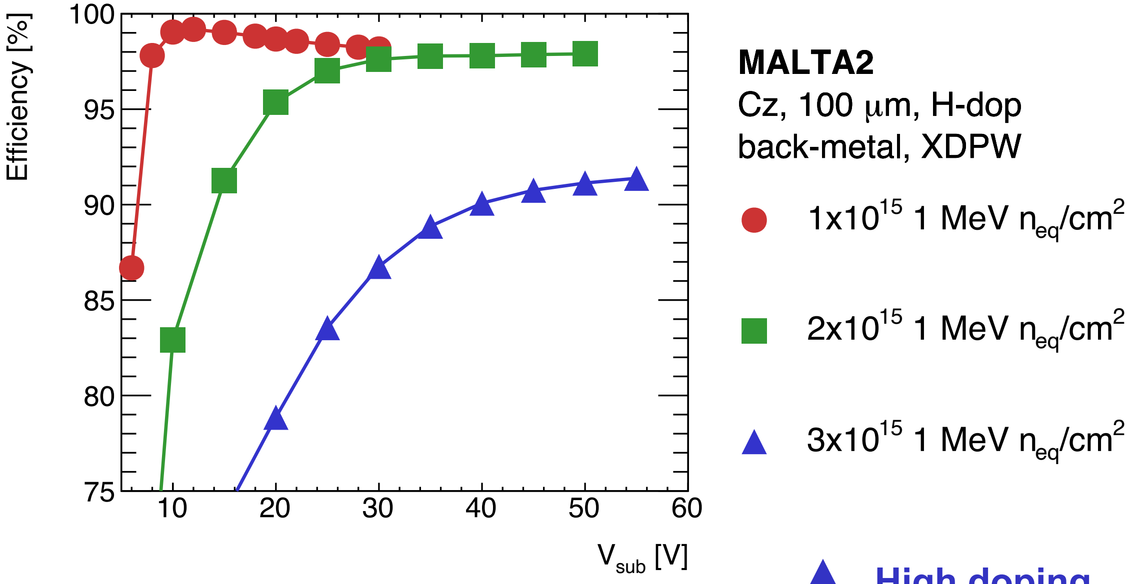
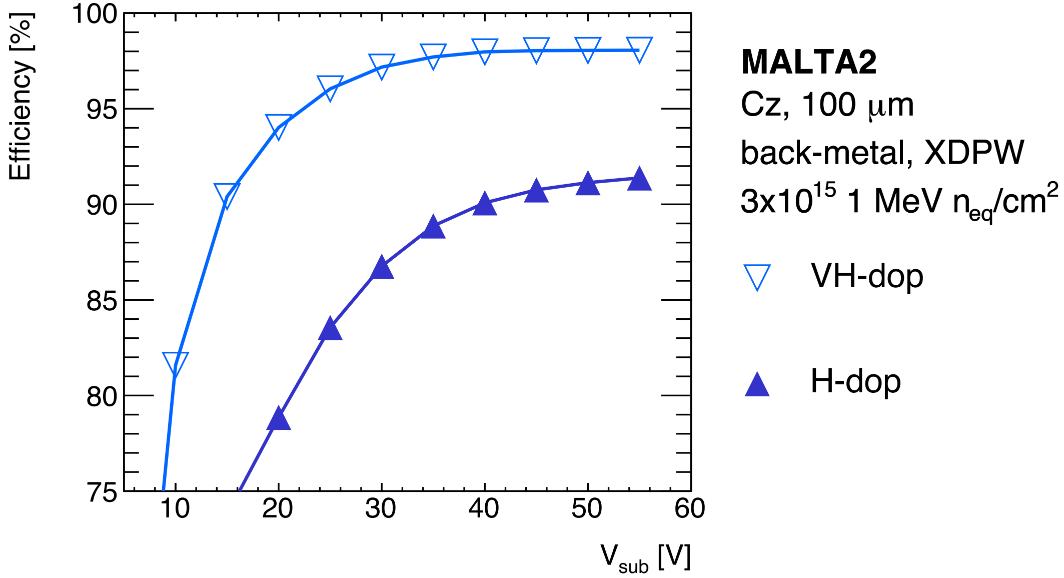
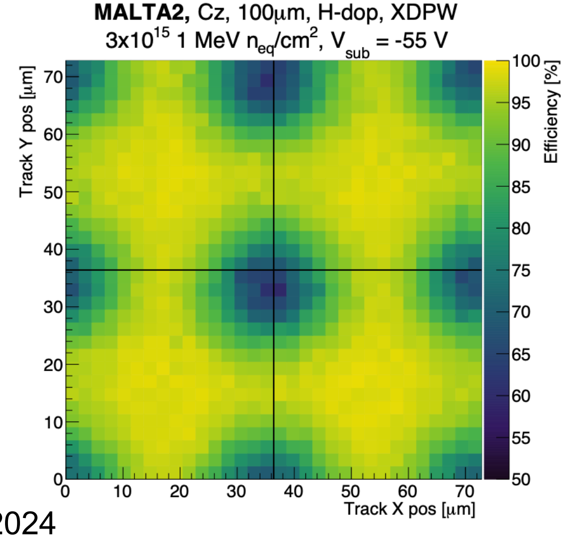


Efficiency > 95% recovered for higher doping on continuous n-layer

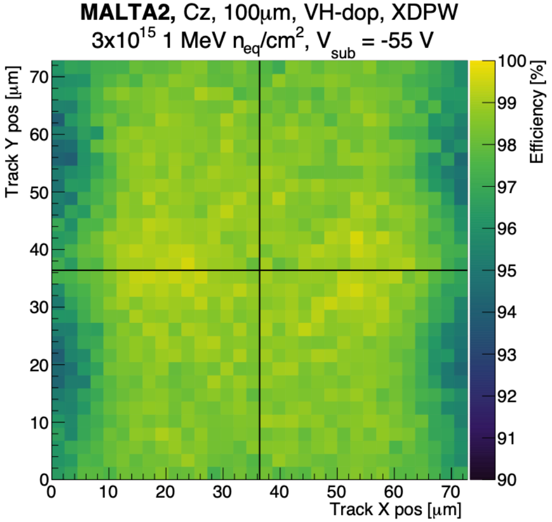


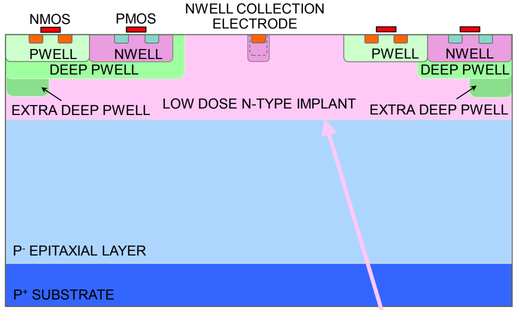
- Backside metallisation
→ good voltage propagation to substrate across chip
- Efficiency loss at pixel corners

▲ High doping



▽ Very high doping





- VH-doping* of n-type implant improves charge collection at pixel corners
  → Improved latteral depletion

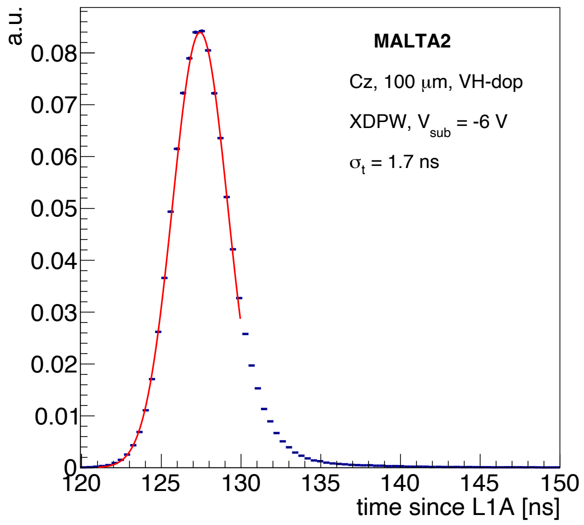
**the doping level refers to the relative difference in implantation dose, approximately 70%.*

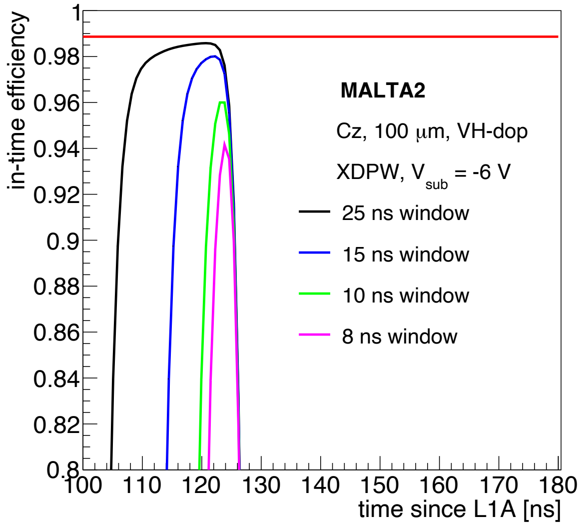
G. Gustavino et al., (VERTEX2023)048

M. van Rijnbach et al., Eur. Phys. J. C **84**, 251 (2024)

MALTA2 Timing

Before irradiation



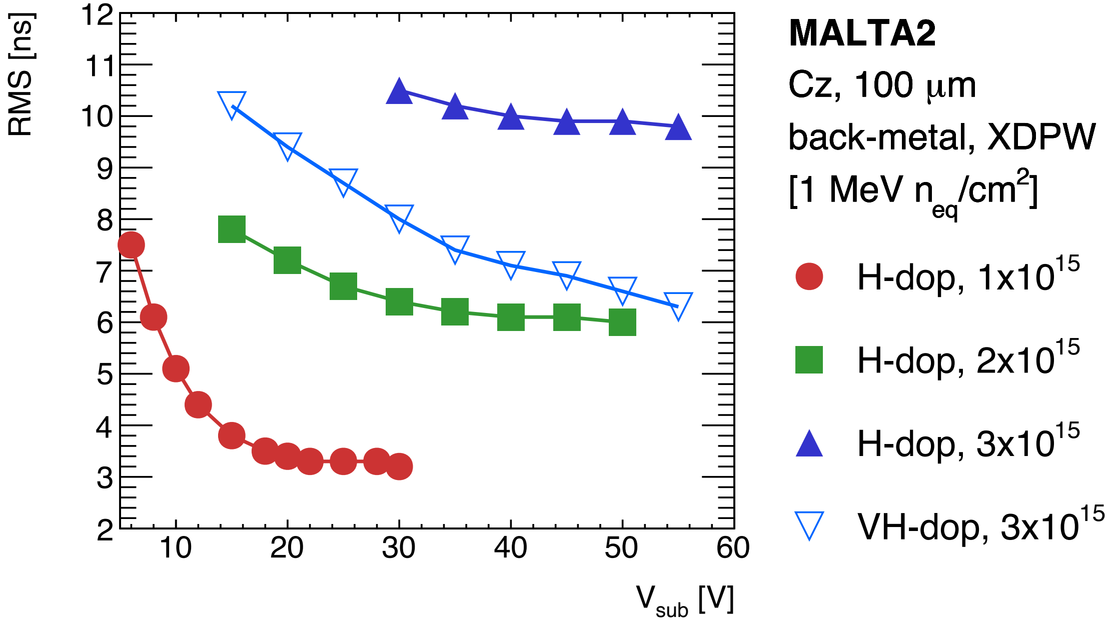


Time since L1A: Time of arrival of leading hit in a cluster w.r.t. scintillator reference

- **σ_t= 1.7 ns**
  - scintillator jitter (~0.5 ns)
  - FPGA readout jitter (~0.9 ns)
  - Correction for signal propagation

- > 98% of hits collected within 25 ns window
- > 90% of hits collected within 8 ns window

After irradiation



Timing deteriorates with irradiation

- due to charge trapping
- slow collection from pixel corners

Timing improves for

- Increase in substrate bias voltage

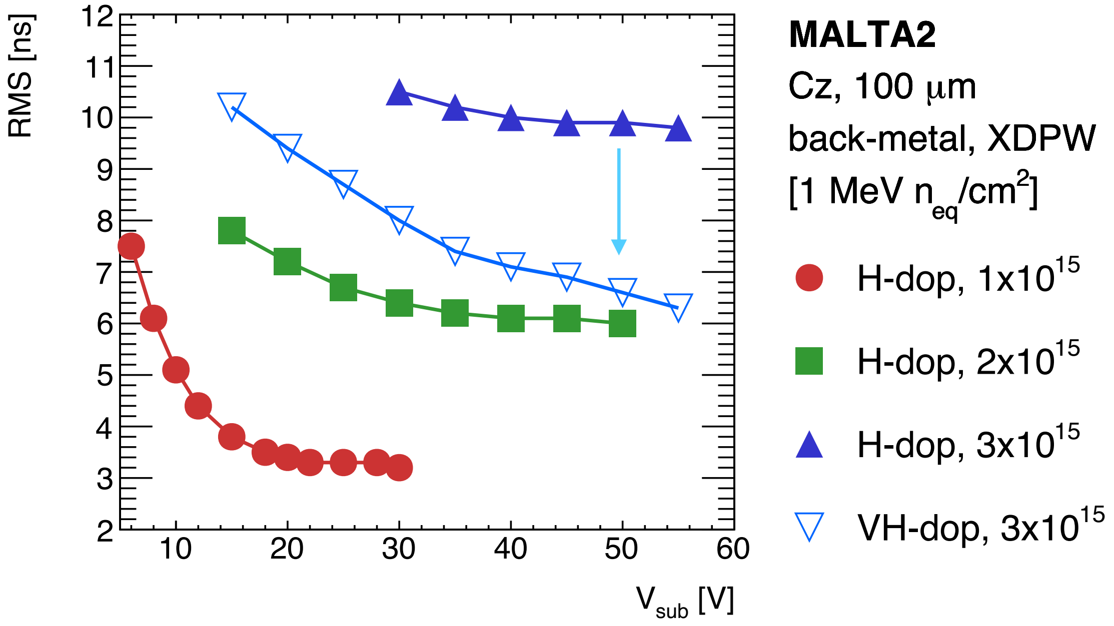
G. Gustavino et al., (VERTEX2023)048

M. van Rijnbach et al., Eur. Phys. J. C **84**, 251 (2024)

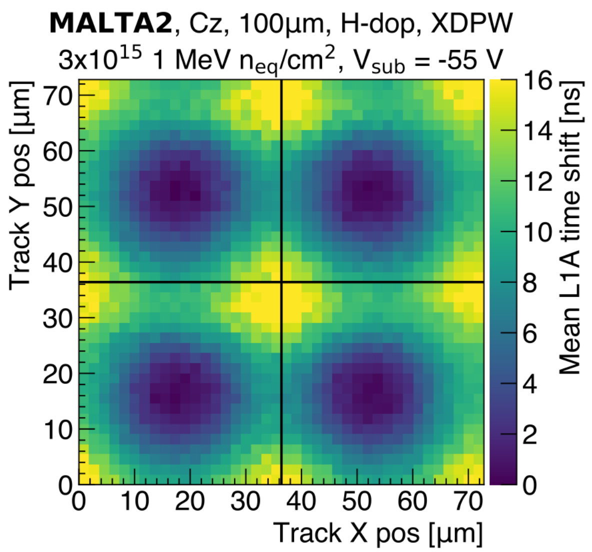
MALTA2 Timing

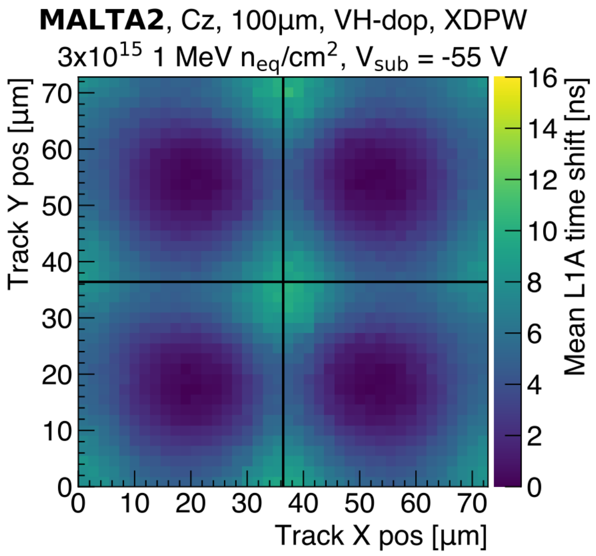
MALTA2 fulfills ATLAS ITk requirements in terms of efficiency and noise at $3\times10^{15}\ n_{eq}/cm^2$

After irradiation



▲ **High doping** ▽ **Very high doping**





Timing deteriorates with irradiation
- due to charge trapping
- slow collection from pixel corners

Timing improves for
- Increase in substrate bias voltage
- Very high doping prolongs „life-time“ of continuous n-layer
  - → 95 % of hits collected within 25 ns (for 3×10^{15}!)
  - → greater homogeneity of the mean time of the hit across the pixel

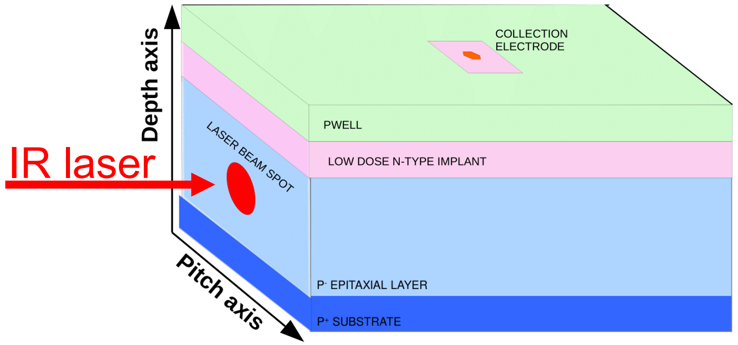
G. Gustavino et al., (VERTEX2023)048
M. van Rijnbach et al., Eur. Phys. J. C **84**, 251 (2024)

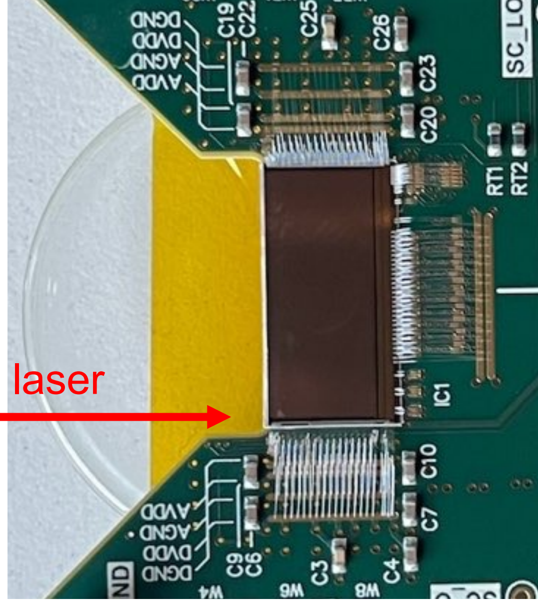
Edge-TCT

Aim of study: Find depletion depth and cross check grazing angle studies with non irradiated, 30 µm epitaxial sensor
IR laser (1064 nm, 500 Hz, ~4 µm beam width at focus)

- Special PCB with free access to edge
- Polished sensor edge
- Analog pixels readout with oscilloscope

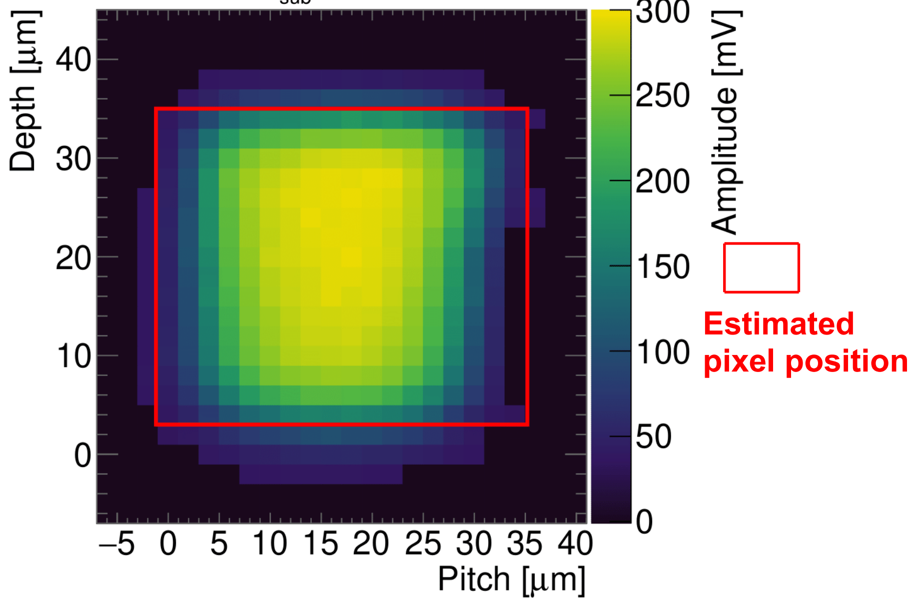
→ Active depth of ~30 µm (as expected for epitaxial sample)
→ Agrees with grazing angle studies



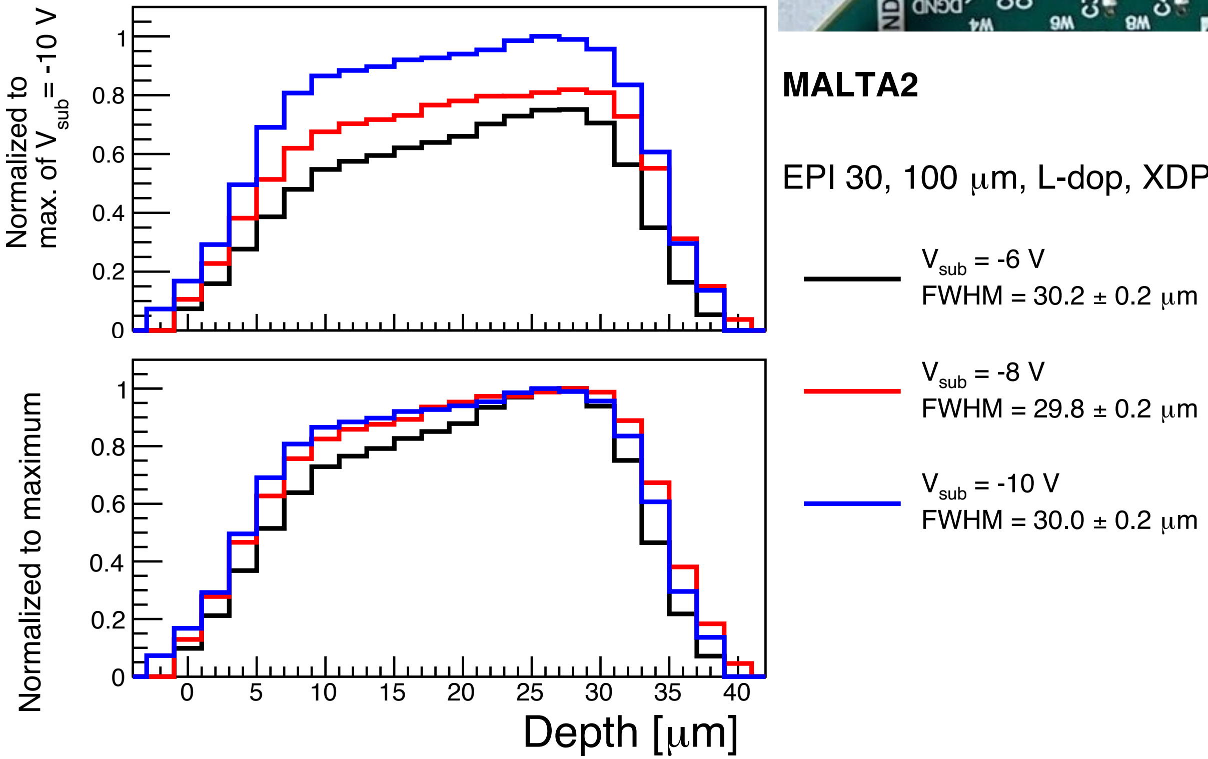


Pixel cross section through edge

MALTA2, EPI 30, 100 µm, L-dop, XDPW
V_{sub} = -10 V



Amplitude projection on depth axis



V. Berlea et al., NIMA 1063 (2024) 169262

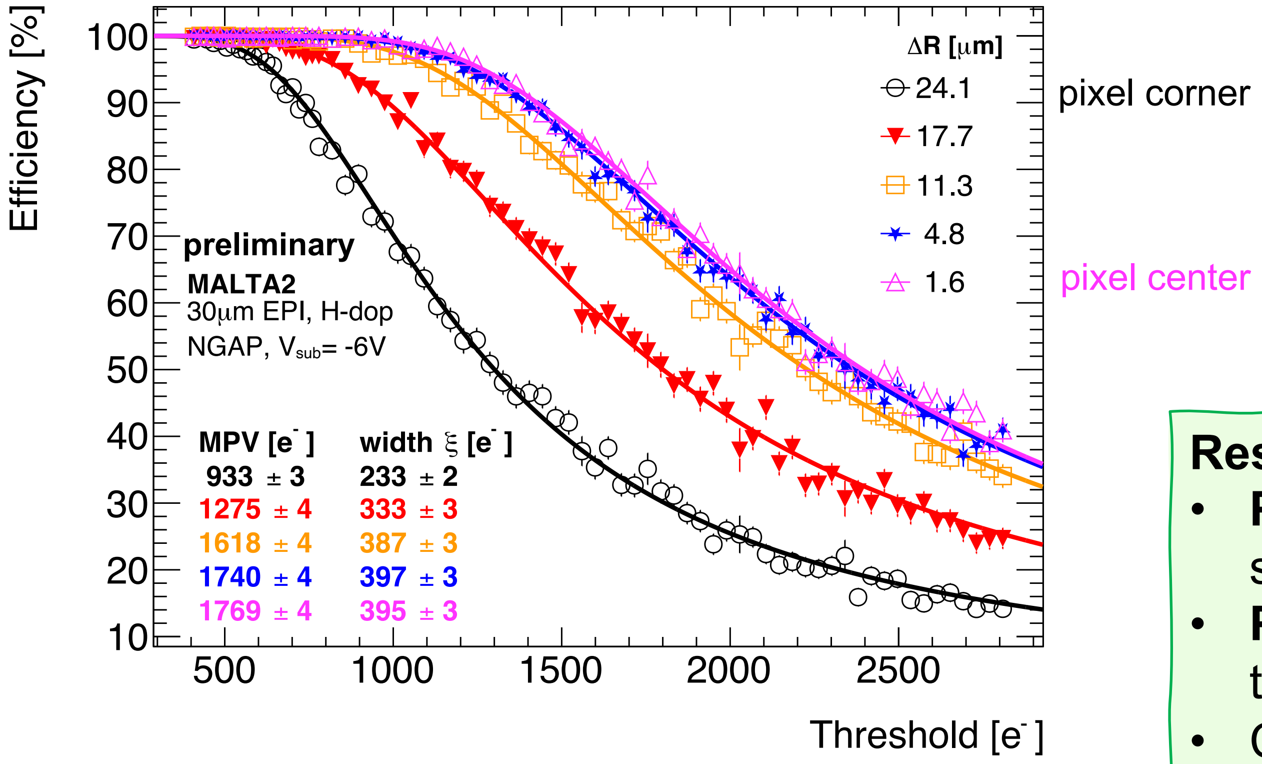
Seed amplitude reconstruction from digital testbeam data

MALTA preliminary

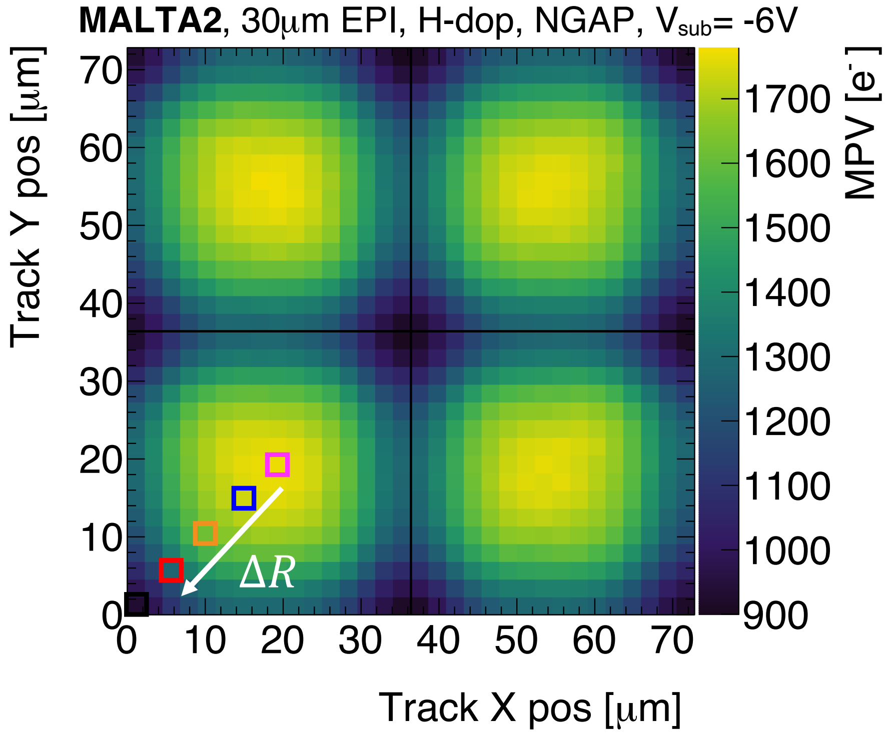
Aim of study: Understanding charge collection in complicated pixel
Method: Cumulative Landau distribution fitted to efficiency spectrum

- Amplitude reconstructable as most probable value (MPV)
- $\sigma_{track} = 4.5\ \mu m$ < **pitch** $36.4\ \mu m$ → In-pixel resolution
- ΔR is distance to electrode at pixel center

Selection of in-pixel regions along pixel diagonal



In-pixel regions projected onto 2×2 pixel matrix



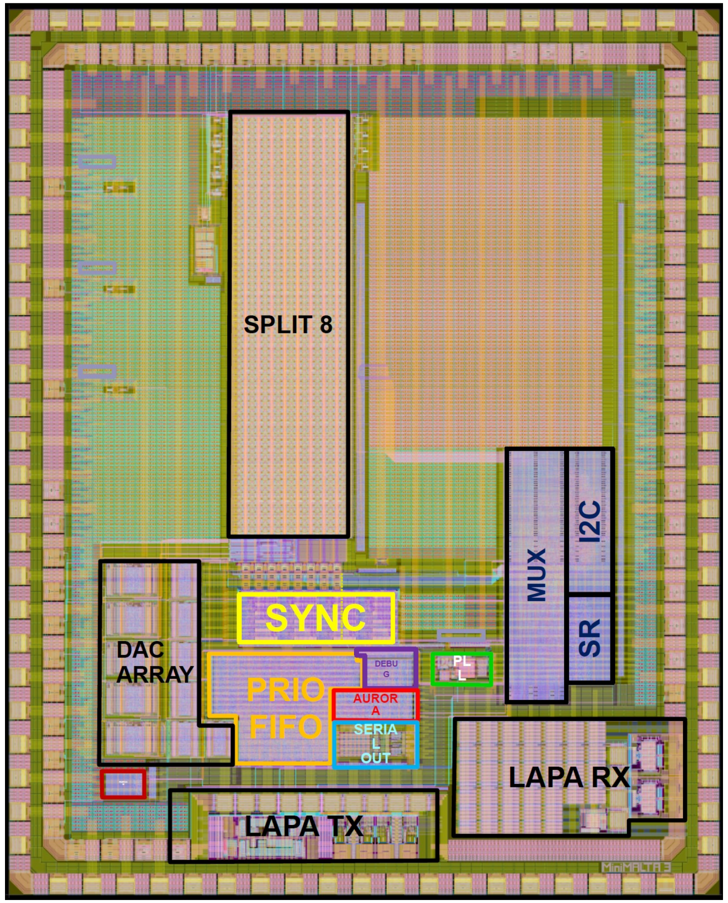
Results:

- **Pixel center: ~1800 e-** collected → **30.2 μm** active silicon depth (**as expected** for EPI sample)
- **Pixel corner: ~900 e-** due to charge sharing and tracking uncertainty
- Charge reconstructed from **binary** data!
- Alternative to E-TCT or grazing angle studies

D. Dobrijević et al., JINST 18 C03013 (2023)

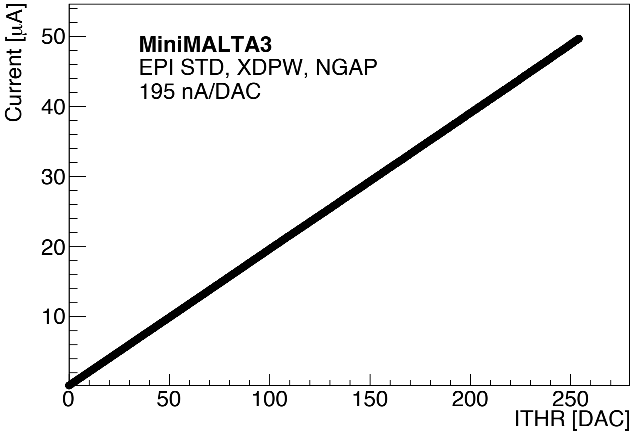
Mini-MALTA3

- 5×4 mm^2 demonstrator with 64 × 48 pixels
- Pixel size 36.4 × 36.4 μm^2 (same as MALTA2)
- Same front-end as MALTA2, no clock over the matrix
- Integrate **time-stamping** and **data serialiser on chip** in periphery
- Time-stamping logic at 1.28 GHz (for MALTA2 done in FPGA)
  → **aiming for sub-nanosecond** on-chip timing resolution
- Synchronization memory with 0.78 ns time resolution
- Fast clock generation with STFC PLL from 80 MHz clock
- Serialized high-speed output



Testing of the chip:

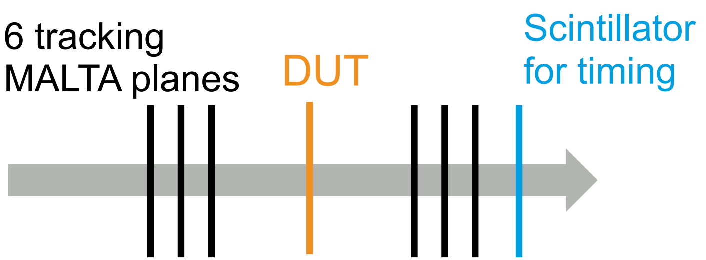
- arrived late 2023
- powered and consumption is within expected values
- Responding to the shift register slow control
- DAC scan results as expected



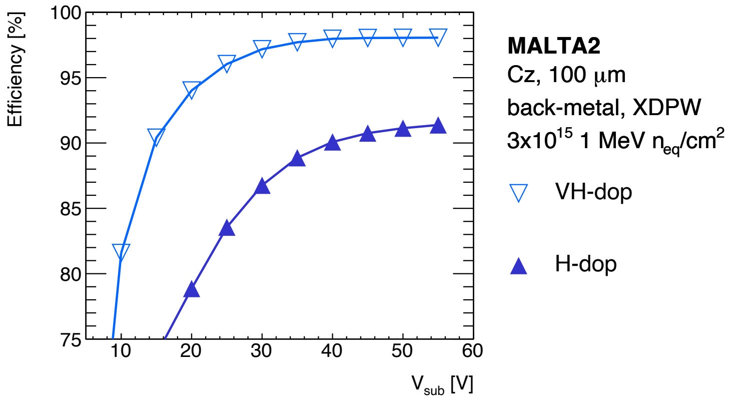
More details:
"Radiation hard read-out architectures" (WG1 C. Solans) Tue 9:00

Summary

MALTA beam telescope @SPS with $\sigma_s = 4.5\ \mu\text{m}$ & $\sigma_t = 2.1\ \text{ns}$

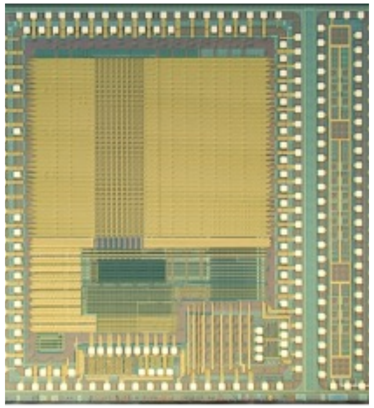


MALTA2 shows radiation hardness up to $3\times10^{15}\ n_{eq}/cm^2$
- > 98% efficiency
- > 95% of clusters collected within 25 ns (LHC bunch crossing window)
- Fulfills ATLAS ITk requirements for efficiency and noise



Depletion depth studies:
- Edge-TCT
- Grazing angle studies
- Amplitude reconstruction from binary hit data

MALTA3:
- Time-stamping logic on chip @ 1.28GHz aiming for **sub-nanosecond** timing
- Serialised data output in view of future detector integration



Future developments:
“Radiation hard read-out architectures” (WG1 C. Solans) Tue 9:00
“Interconnections and multi-chip flex developments” (WG7 A. Sharma) Wed 13:30

Latest publications

M. van Rijnbach et al., Radiation Hardness of MALTA2 Monolithic CMOS Sensors on Czochralski Substrates, Eur. Phys. J. C 84 (2024) 251, link

D.V. Berlea et al., Depletion depth studies with the MALTA2 sensor, a depleted monolithic active pixel sensor, NIM A 1063 (2024) 169262, link

F. Dachs et al., Quad-module characterization with the MALTA monolithic pixel chip, NIM A 1064 (2024) 169306, link

C. Solans et al., MALTA monolithic Pixel sensors in TowerJazz 180 nm technology, NIM A 1057 (2023) 168787, link

F. Dachs et al., Development of a large-area, light-weight module using the MALTA monolithic pixel detector, NIM A 1047 (2023) 167809, link

H. Pernegger et al., MALTA-Cz: A radiation hard full-size monolithic CMOS sensor with small electrodes on high-resistivity Czochralski substrate, JINST 18 (2023) P09018, link

J. Weick et al., Development of novel low-mass module concepts based on MALTA monolithic pixel sensors, JINST 18 (2023) C04003, link

D. Drobijevic et al, Future developments of radiation tolerant sensors based on the MALTA architecture, JINST 18 (2023) C03013, link

G. Gustavino et al., Timing performance of radiation hard MALTA monolithic pixel sensors, JINST 18 (2023) C03011, link

V. Berlea et al, Radiation hardness of MALTA2, a monolithic active pixel sensor for tracking applications, TNS 70 (2023) 2303-2309, link

M. van Rijnbach et al., Performance of the MALTA Telescope, Eur. Phys. J. C 83 (2023) 581, link

CERN · University of Oxford · Universitat de València · DESY. · University of Zagreb · Technische Universität Darmstadt · Indian Institute of Technology Madras · University of Glasgow · Humboldt-Universität zu Berlin · universität innsbruck · University of Birmingham

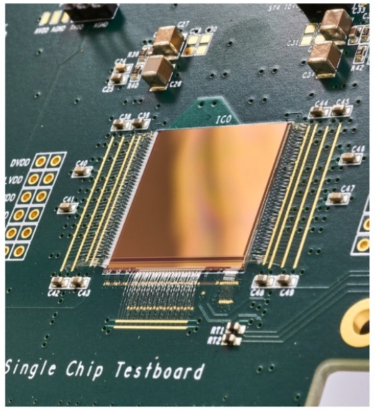
Backup

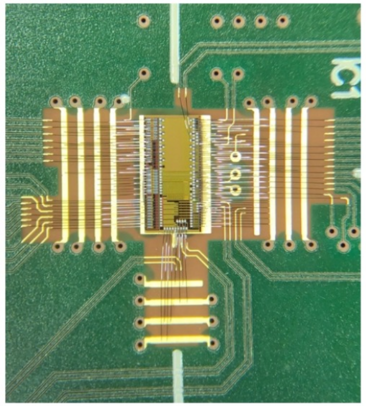
MALTA history

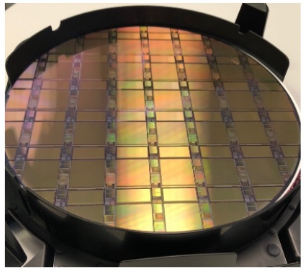
Based on R&D for ALPIDE

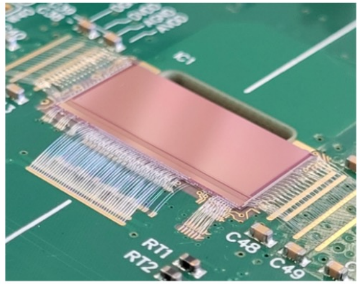
STREAM

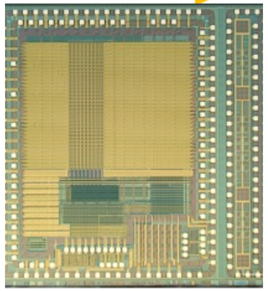
AIDA Innova WP5 and CERN EP R&D WP 1.2





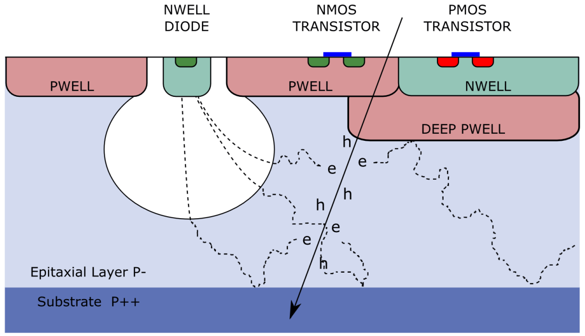




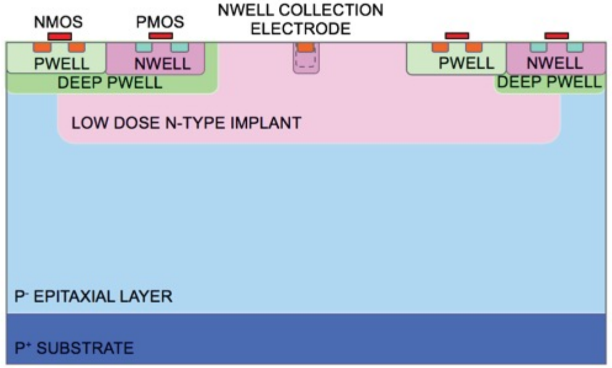


MALTA1 & MLVL	Mini-MALTA	MALTA C	MALTA 2	MALTA 3
Jan 2018	**Jan 2019**	**Aug 2019**	**Jan 2021**	**2023**
Large demonstrator Asynchronous readout Electrode size and reset mechanism evaluation	Small demonstrator Process and mask modification	Slow control improvements on EPI and Czochralski substrates	New front-end Additional process modification	Large matrix Time tagging
Poor lateral field after irradiation	Full efficiency after 1e15 n/cm^2	Enlarged cluster size and improved time resolution on Czochralski	Improved time resolution and on chip synchronization	

Technology	180 nm Towerjazz
Sensor area	9×18 mm^2
Pixel pitch	36.4×36.4 μm^2
Thickness	50 - 300 μm

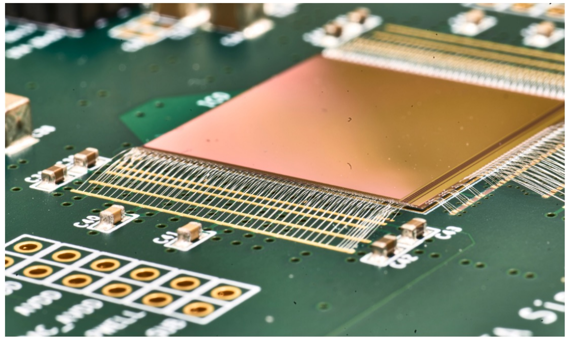


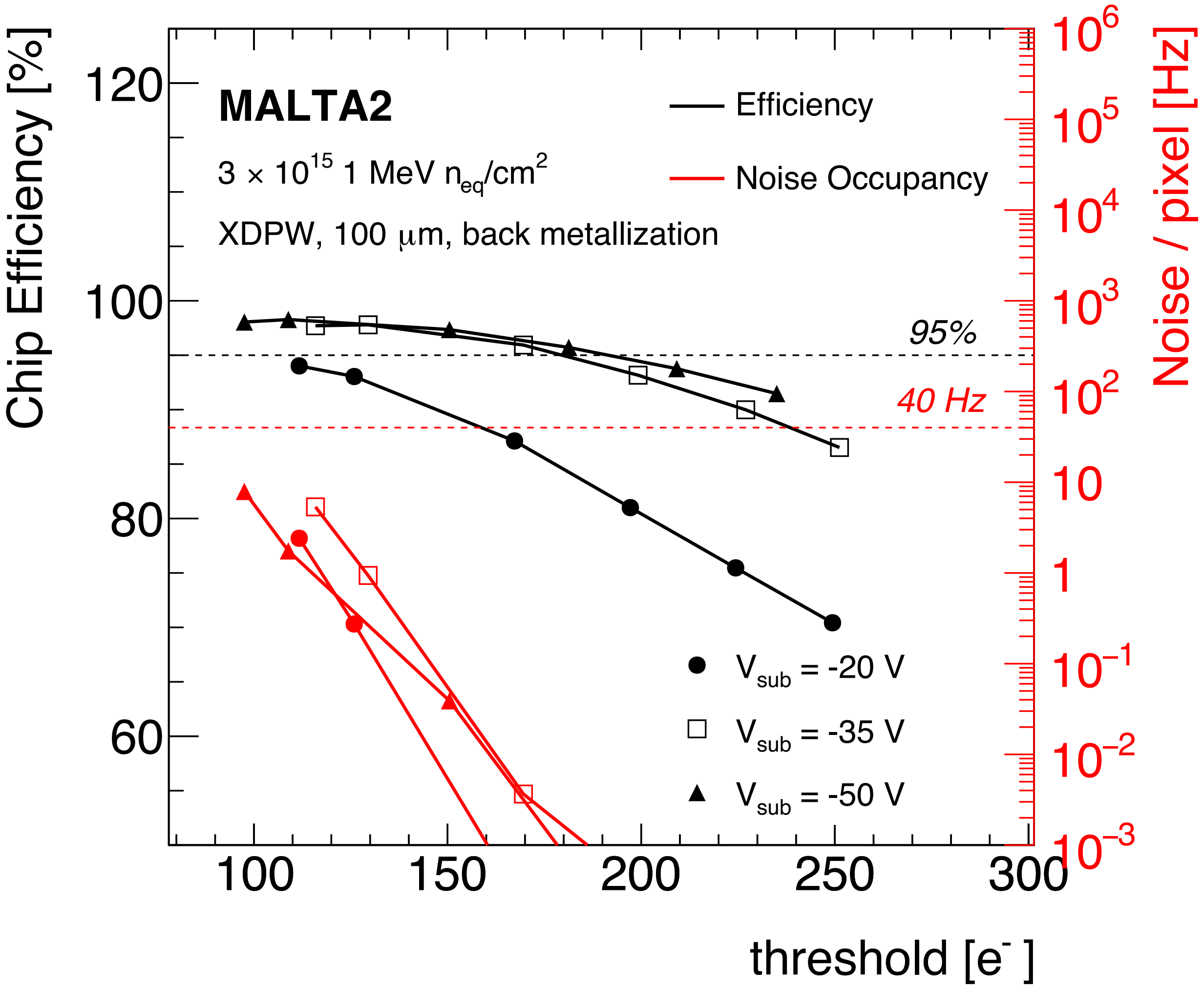
Additional implant increases depletion zone and electric field



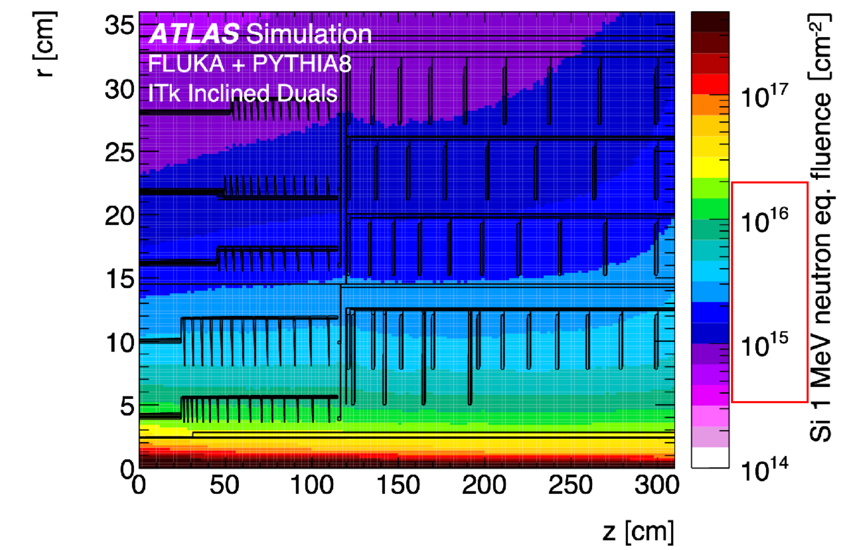
MALTA2 Performance

Irradiation summary





Fluence distribution for the ATLAS ITk

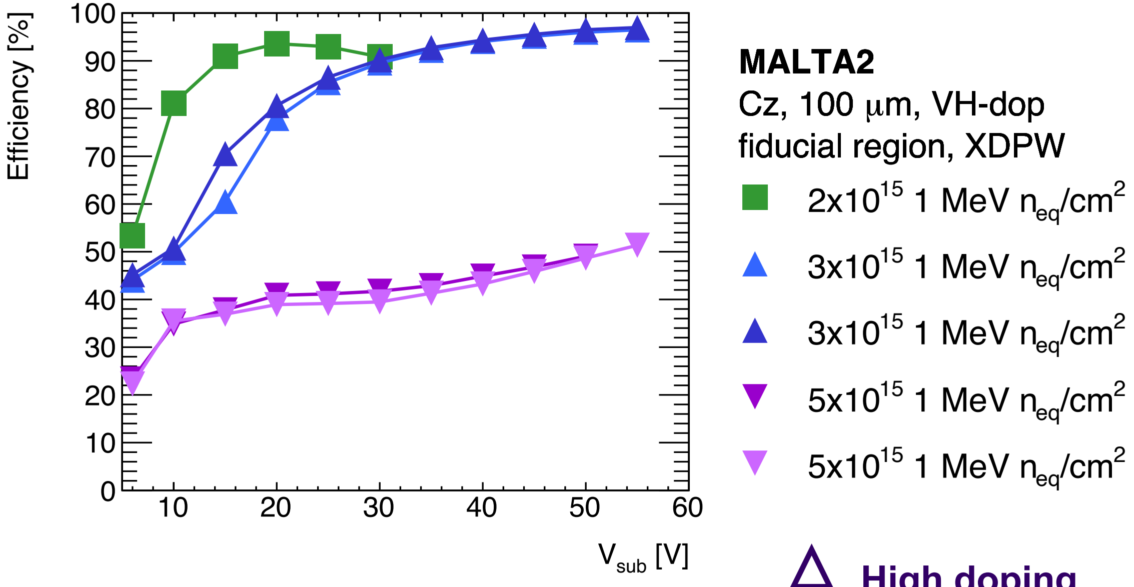


Fulfills requirements for ATLAS HL-LHC ITk pixel upgrade in terms of:

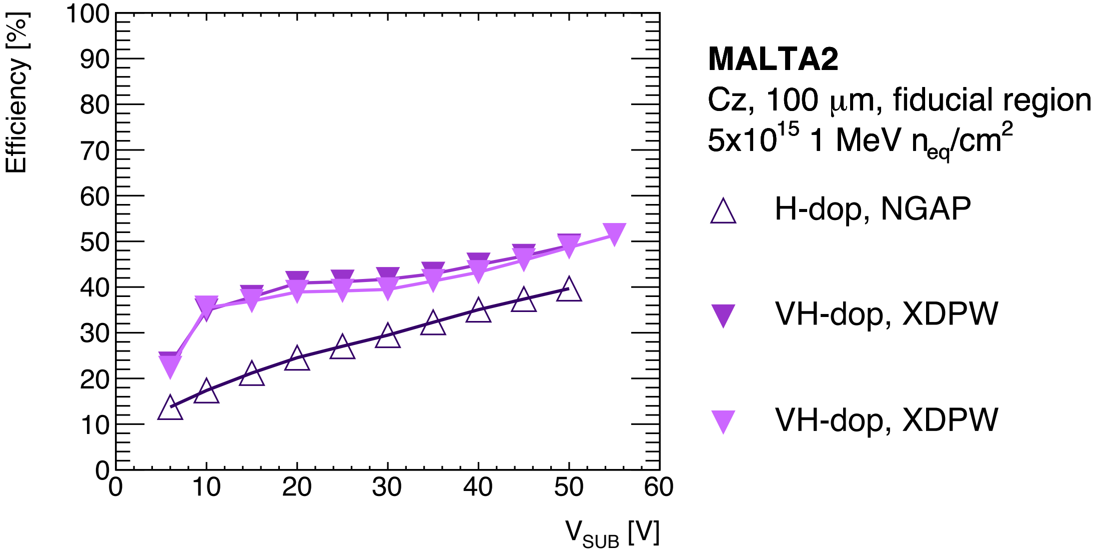
- Radiation hardness up to 3×10^{15} n_{eq}/cm^2 (~ HL fluence 10 cm from beam pipe)
- Efficiency > 95%
- Noise rate < 40 Hz
- Timing resolution of 2.1 ns

MALTA2 irradiation study up to $5\times10^{15}\ n_{eq}/cm^2$

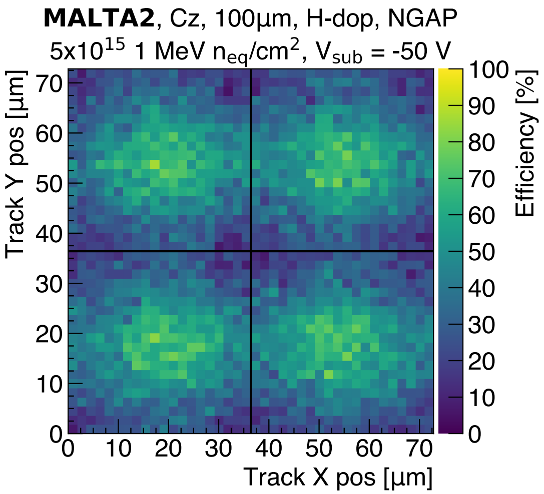
Efficiency ~35 % recovered by substrate voltage increase



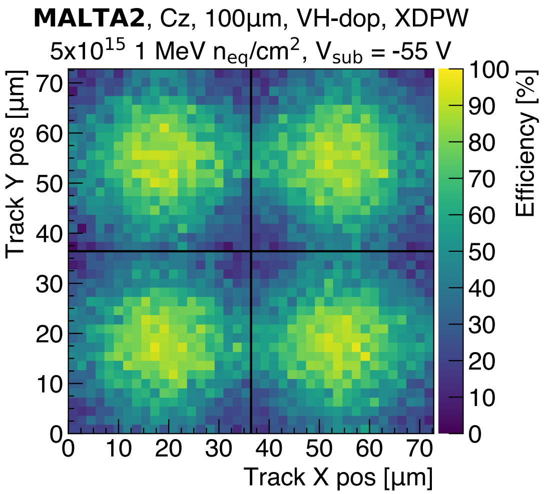
Efficiency ~50% recovered for higher doping on continuous n-layer

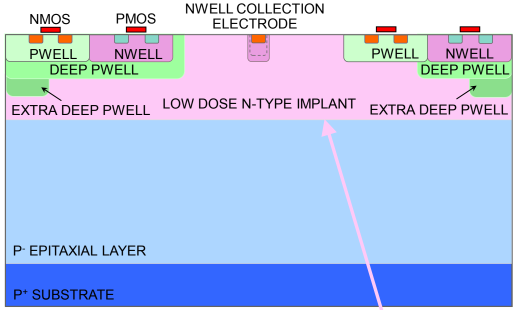


△ High doping



▼ Very high doping

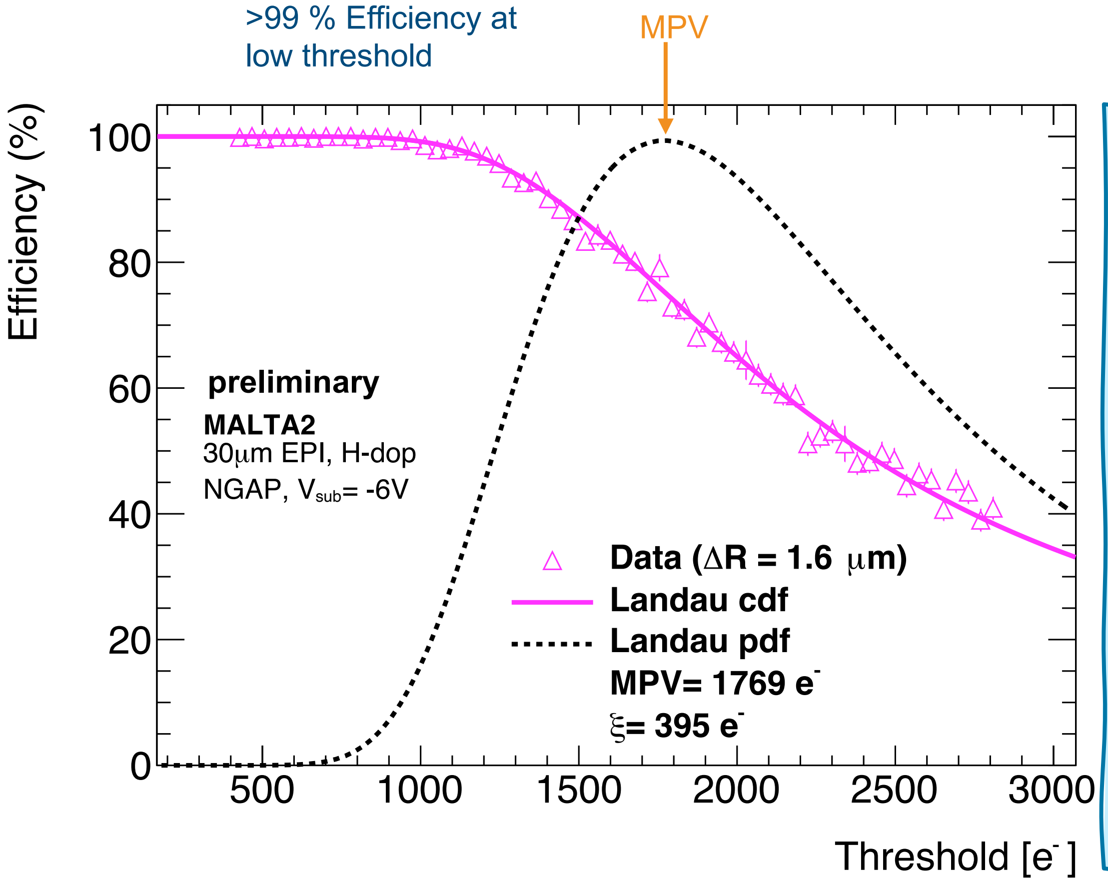




- VH-doping* of n-type implant improves charge collection at pixel center and corners
  → Improved overall depletion

**the doping level refers to the relative difference in implantation dose, approximately 70%.*

Amplitude reconstruction method from binary data



- Reconstruct tracks with telescope
- Efficiency = $\frac{\text{Tracks detected in DUT}}{\text{Tracks reconstructed with telescope}}$
- Energy loss of charged hadrons (MIPs): Landau probability density function (**pdf)**
- Cumulative Landau distribution (**cdf**) fitted to efficiency data
- Most probable value (MPV) of Landau is
  - Maximum of **pdf**
  - Inflection point of **cdf**