Depletion depth studies of MALTA2 a 180 nm monolithic active pixel senor

Vlad Dumitru Berlea, DESY and Humboldt University

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HELMHOLTZ

HUMBOLDT-UNIVERSITÄT ZU BERLIN

13th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD13)

DESY.

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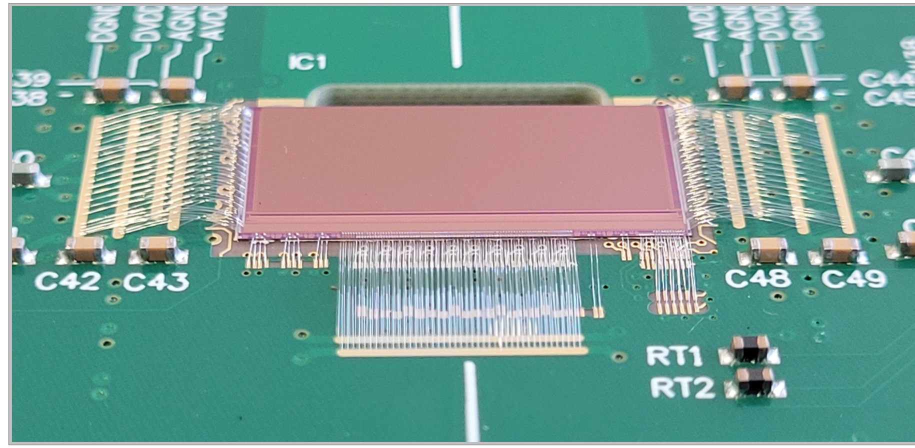
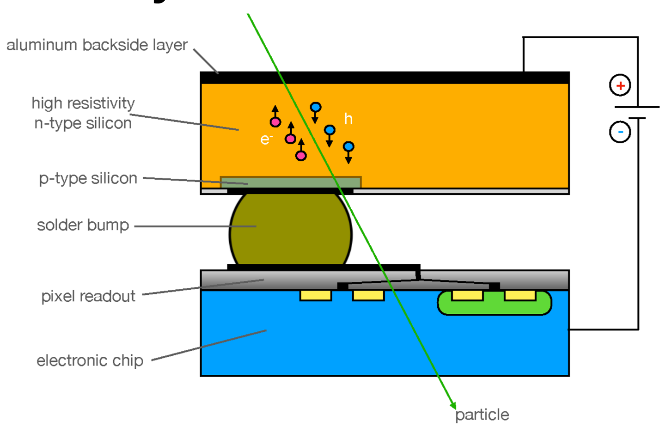
MALTA2 sensor

- **Monolithic** Active Pixel Sensor
  - 180 nm Tower CMOS process
  - 1 x 2 cm^2 sensor area
  - 256 x 512 pixels
  - 36.4 x 36.4 μm^2 pixel size

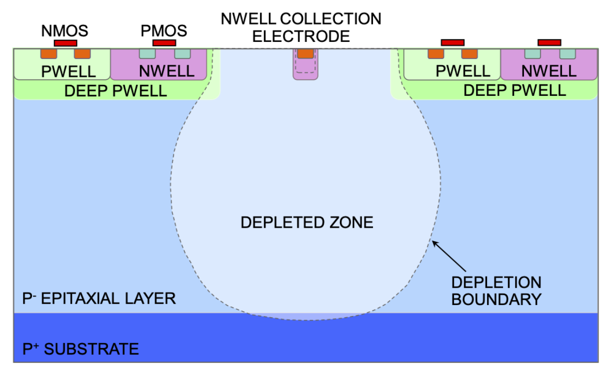


Hybrid Pixel Sensor



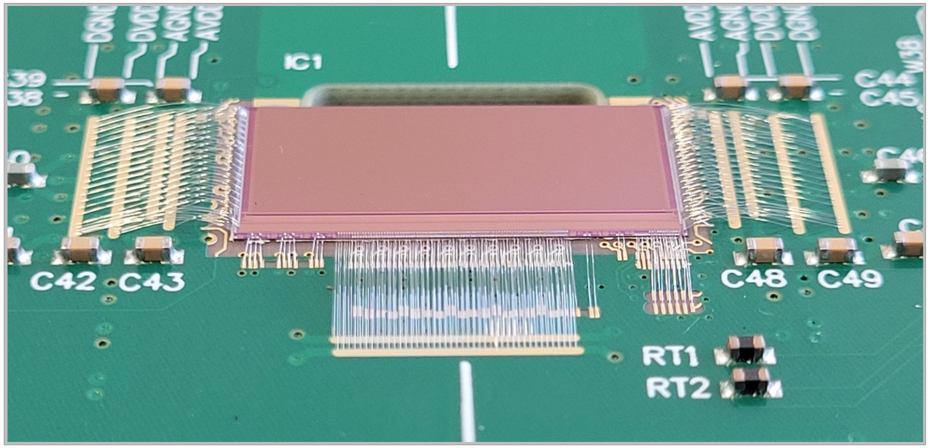
ASIC bump bonded to sensor

Monolithic Active Pixel Sensor



eg. ALPIDE monolithic chip design

MALTA2 sensor



- **Monolithic** Active Pixel Sensor
  - 180 nm Tower CMOS process
  - 1 x 2 cm^2 sensor area
  - 256 x 512 pixels
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- **Tracking** sensor for future collider experiments
  - Timing response < 2 ns G. Gustavino et al., JINST C03011
  - Radiation hardness up to 3 x 10^{15} n_{eq}/cm^2 M. van Rijnbach et al., 2308.13231
  - Low threshold (~150 e^-) and noise chip operation V. Berlea et al., IEEE TNS 2023.3313721

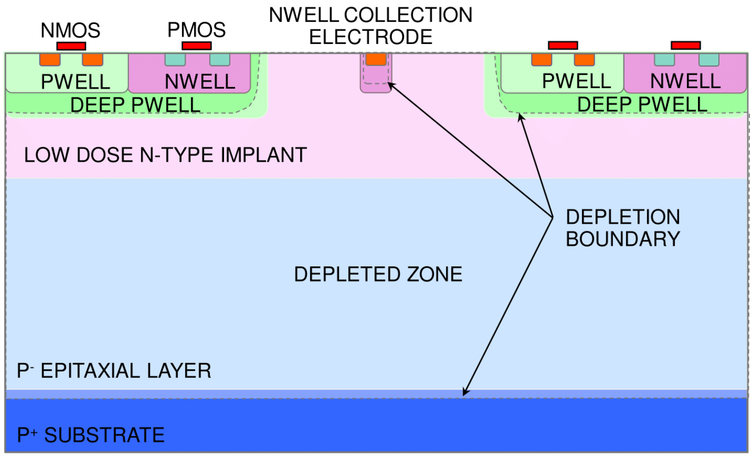
- **Asynchronous** readout architecture F. Piro et al., IEEE TNS 19222311
  - No clock propagation across pixel matrix
  - Individual hit information piped to the sensor periphery
  - High data rate (>100 MHz/cm^2)
  - No time over threshold information, only binary hit info

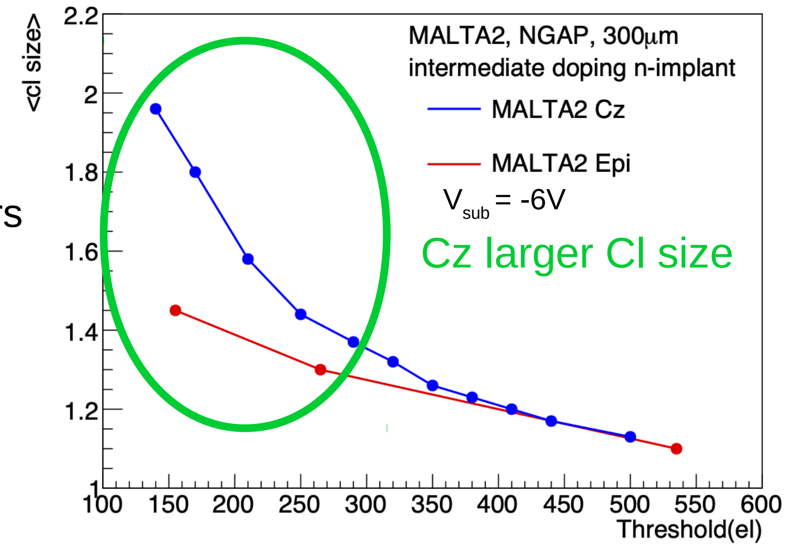
MALTA pixel

- ✗ Small, collection electrode design, 3x3 μm^2
  - <5 fF capacitance
  - ENC < 15 e$^-$
  - Low bias voltage (6 – 55 V)
  - Low power consumption (1 μW/pixel)
  - Additional low dose N-type implant

H. Pernegger et al., JINST P09018

- ✗ MALTA samples on multiple substrates
  - Epitaxial silicon (Epi): 30 μm
  - Czochralski silicon (Cz): 300, 100, 50 μm
  - Cz: more charge diffusion – larger clusters





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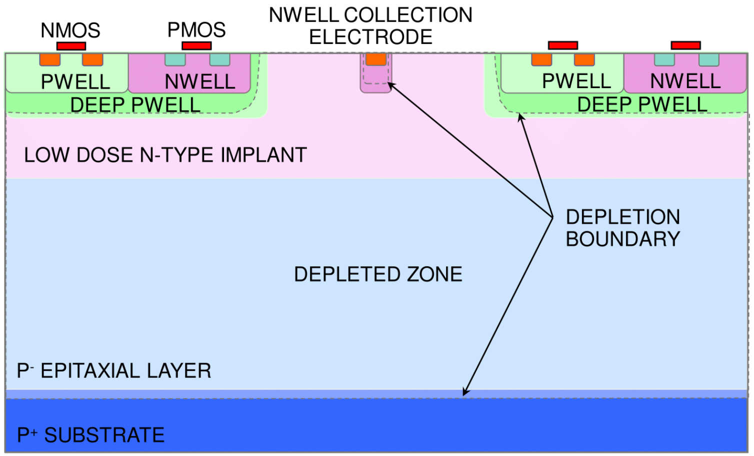

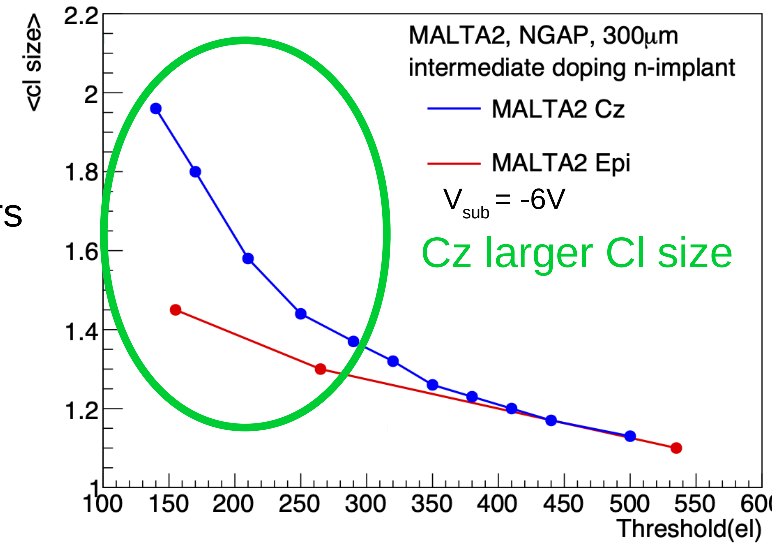

How to measure the depletion depth?

Capacitance measurements
Edge TCT
Grazing angle technique

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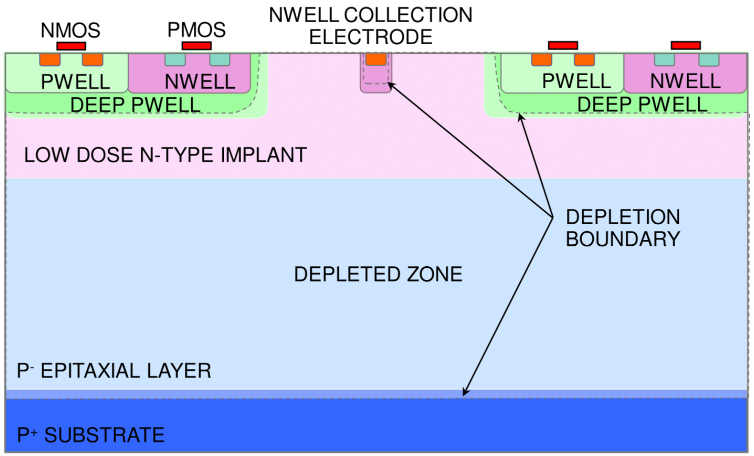

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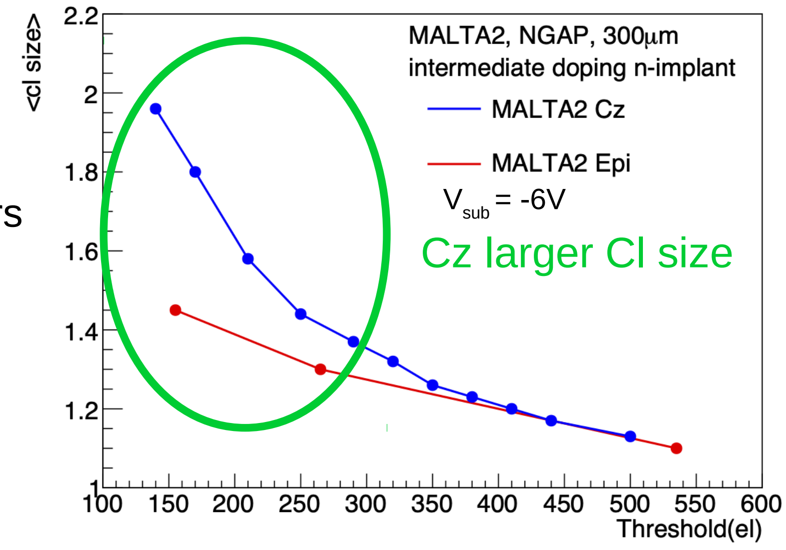
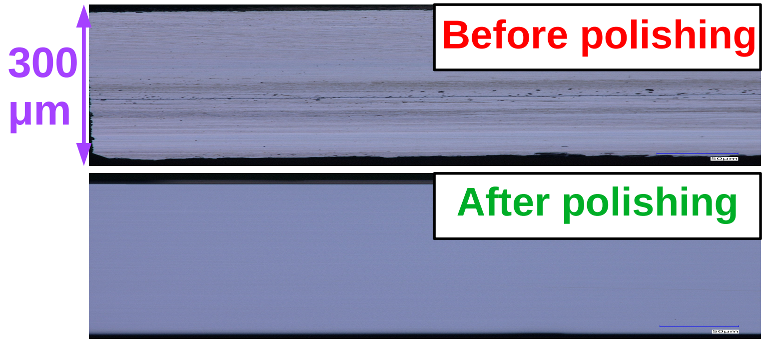


How to measure the depletion depth?

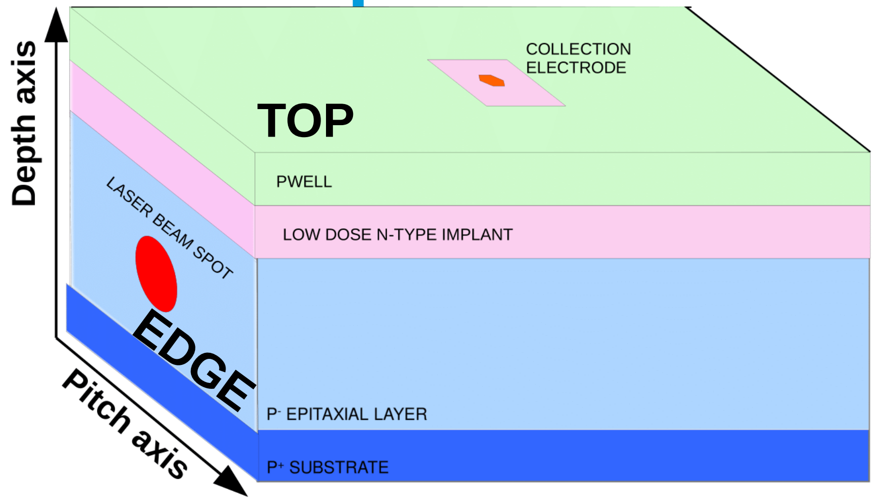
- ✗ ~~Capacitance measurements~~
- ✓ Edge TCT
- ✓ Grazing angle technique

Edge Transient Current Technique

- ✗ IR pulsed laser:
  - 1064 nm wavelength
  - 500 Hz frequency
  - ~ 4 µm beam width at focus
  - Sensor edge polish + PCB cut out



- ✗ Precise edge charge injection
  - Special analog output pixels used
  - Axis control ~ 0.2 µm precision
  - Edge scan in 2 axes: Pitch and Depth



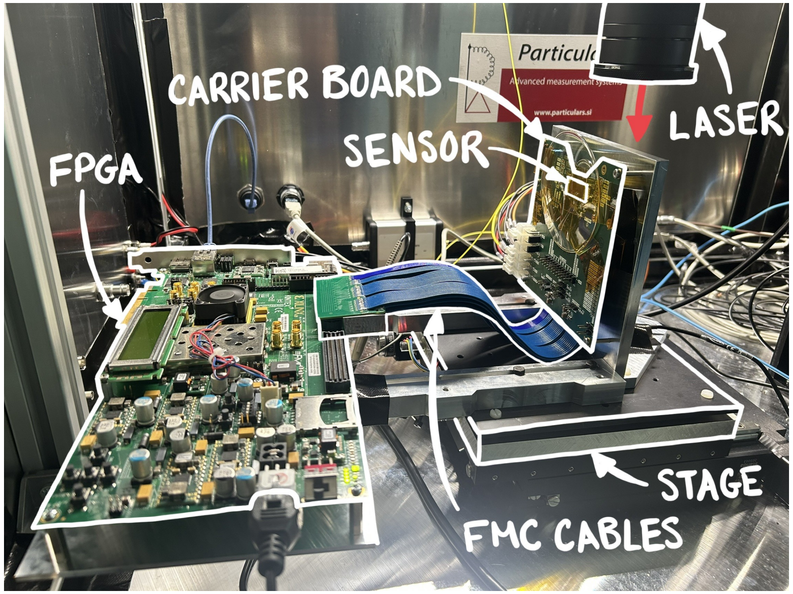
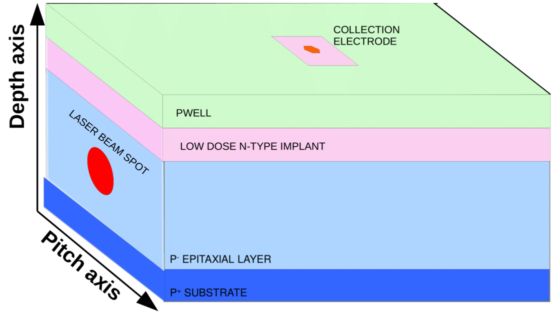
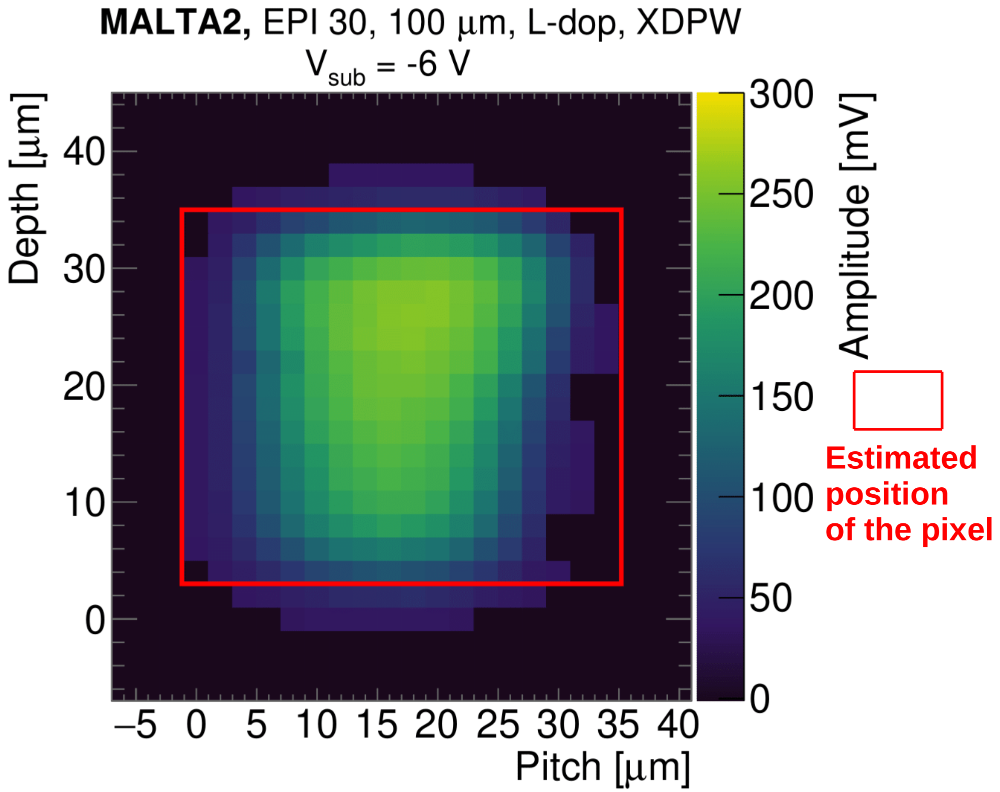


Photo by: Alex Savino, DESY Summer student, 2023

Investigation of Epitaxial sample

- 36.4 µm pitch x 30 ± 2 µm depth pixel edge
  - Top: Collection electrode
  - Left: Sensor edge
  - Right: Pixel matrix





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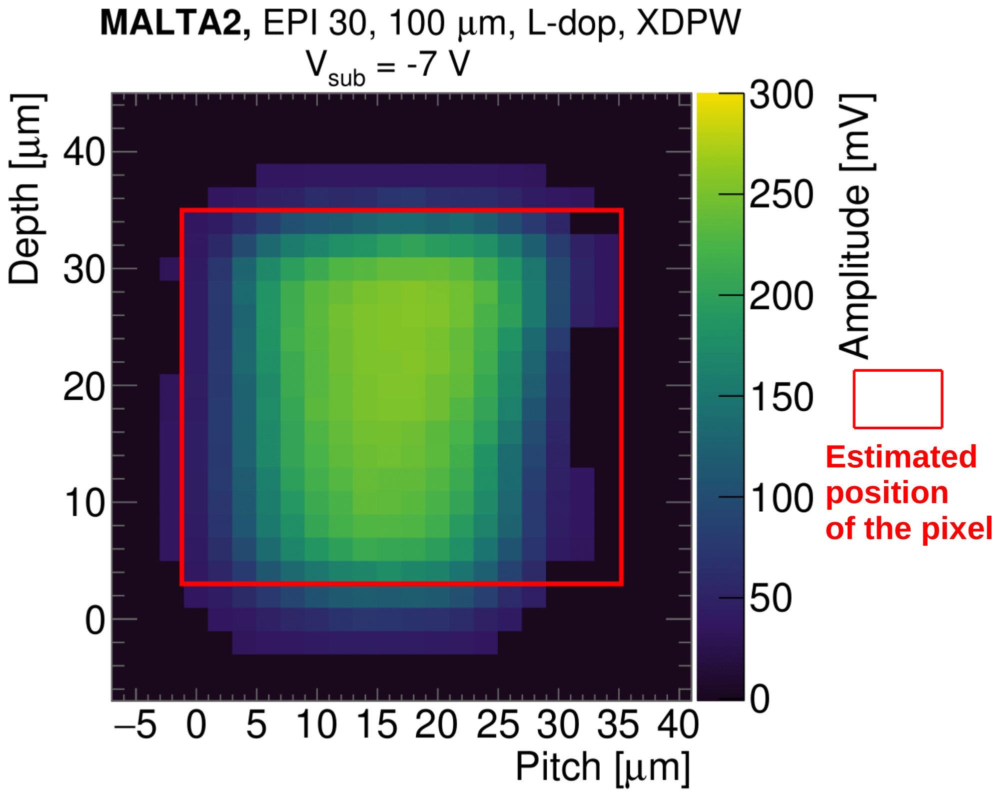

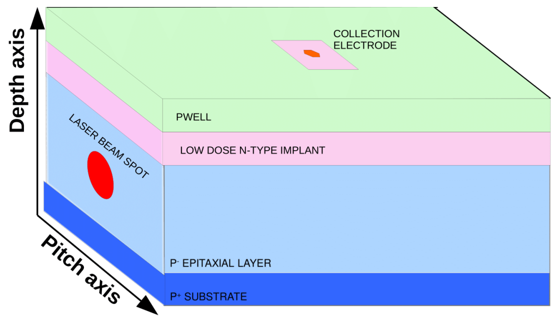

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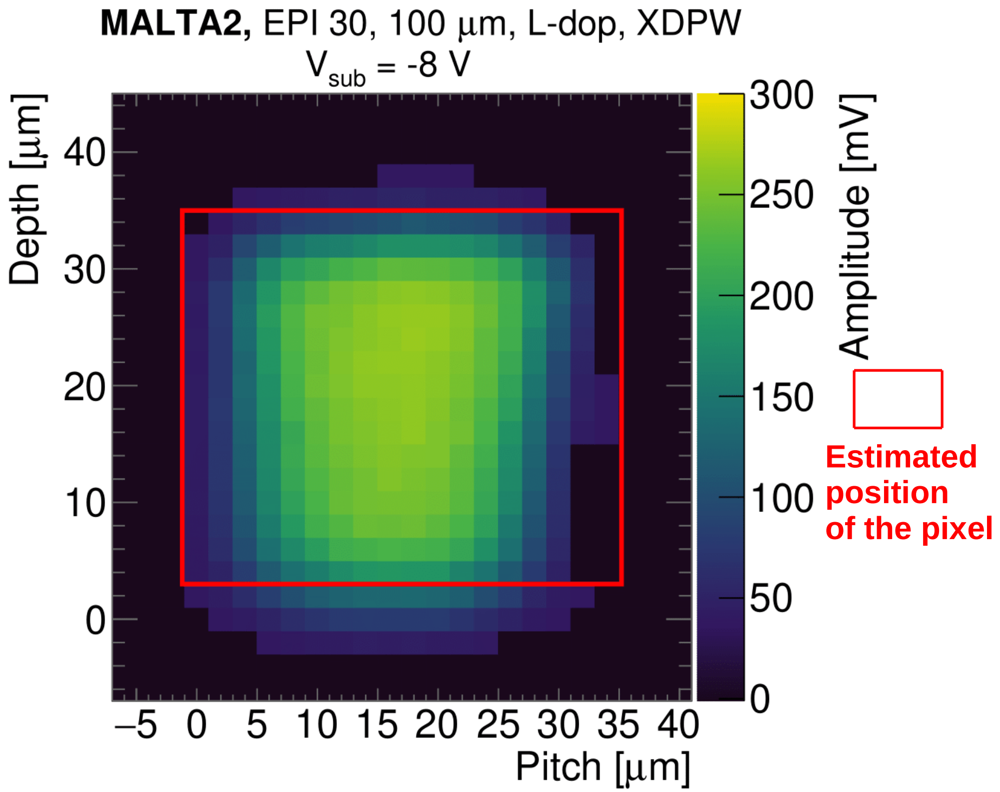

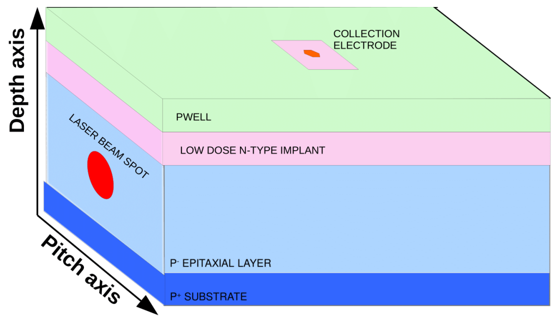

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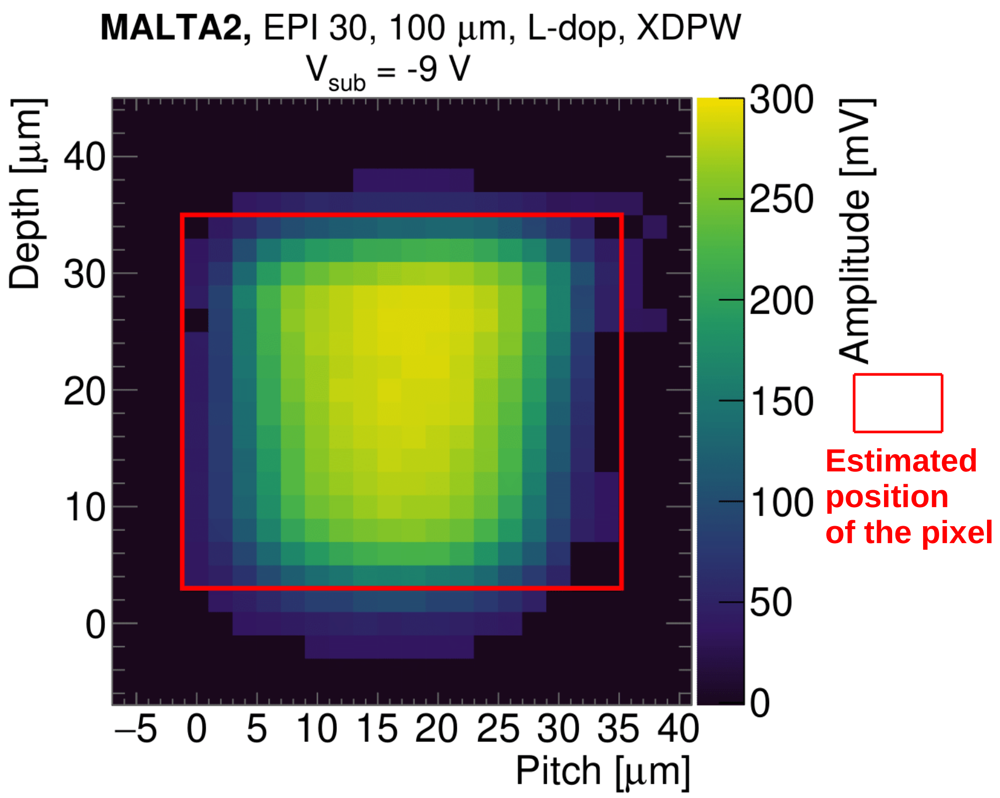

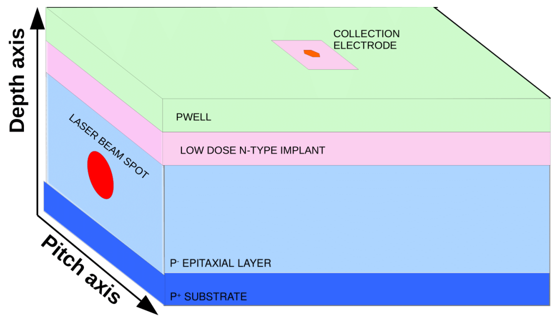

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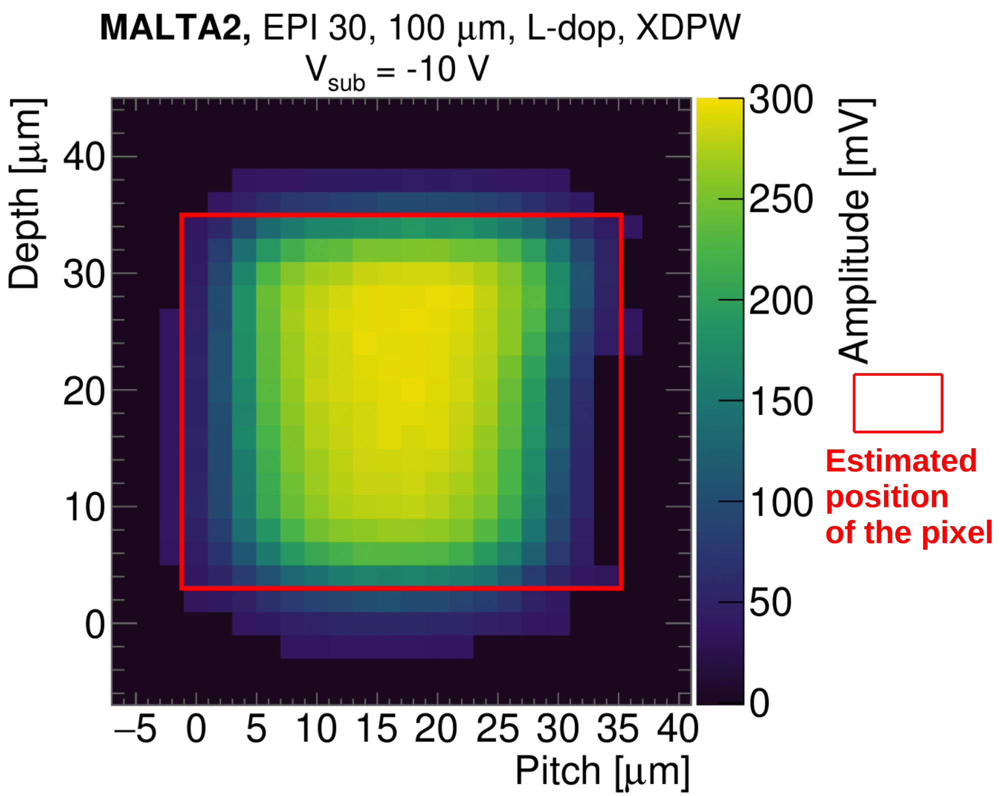

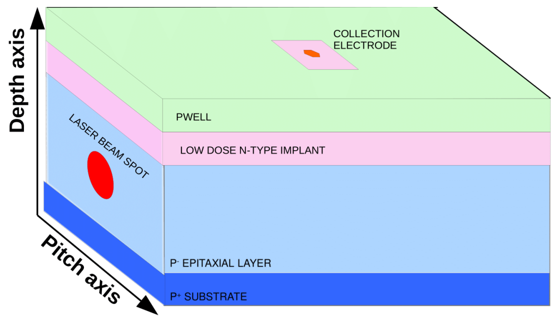

Investigation of Epitaxial sample

- 36.4 µm pitch x 30 ± 2 µm depth pixel edge
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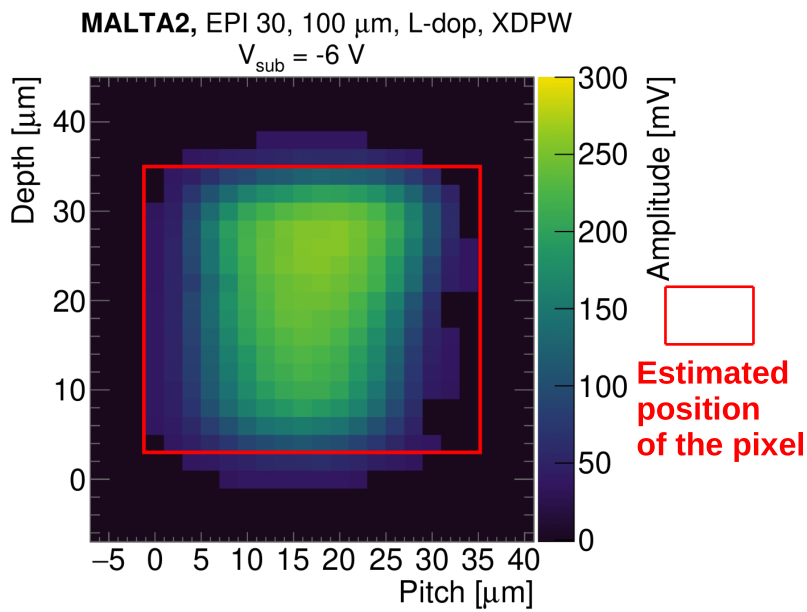
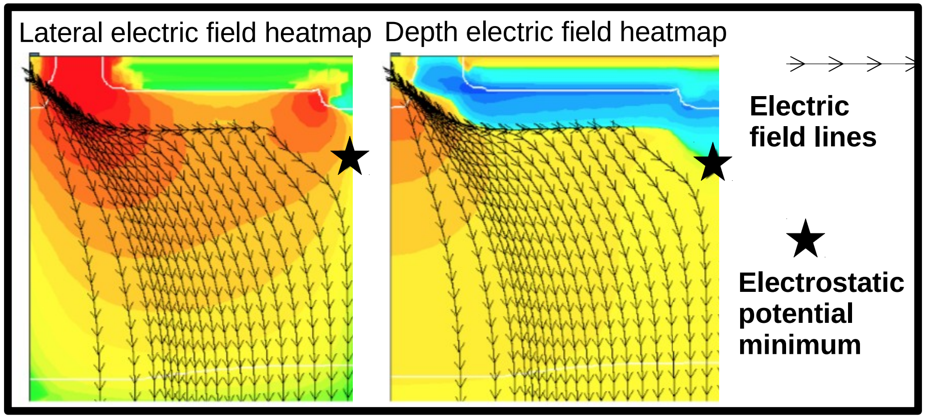
- TCAD simulations:
  - Large E field near the collection electrode
  - Decreased E field with depth

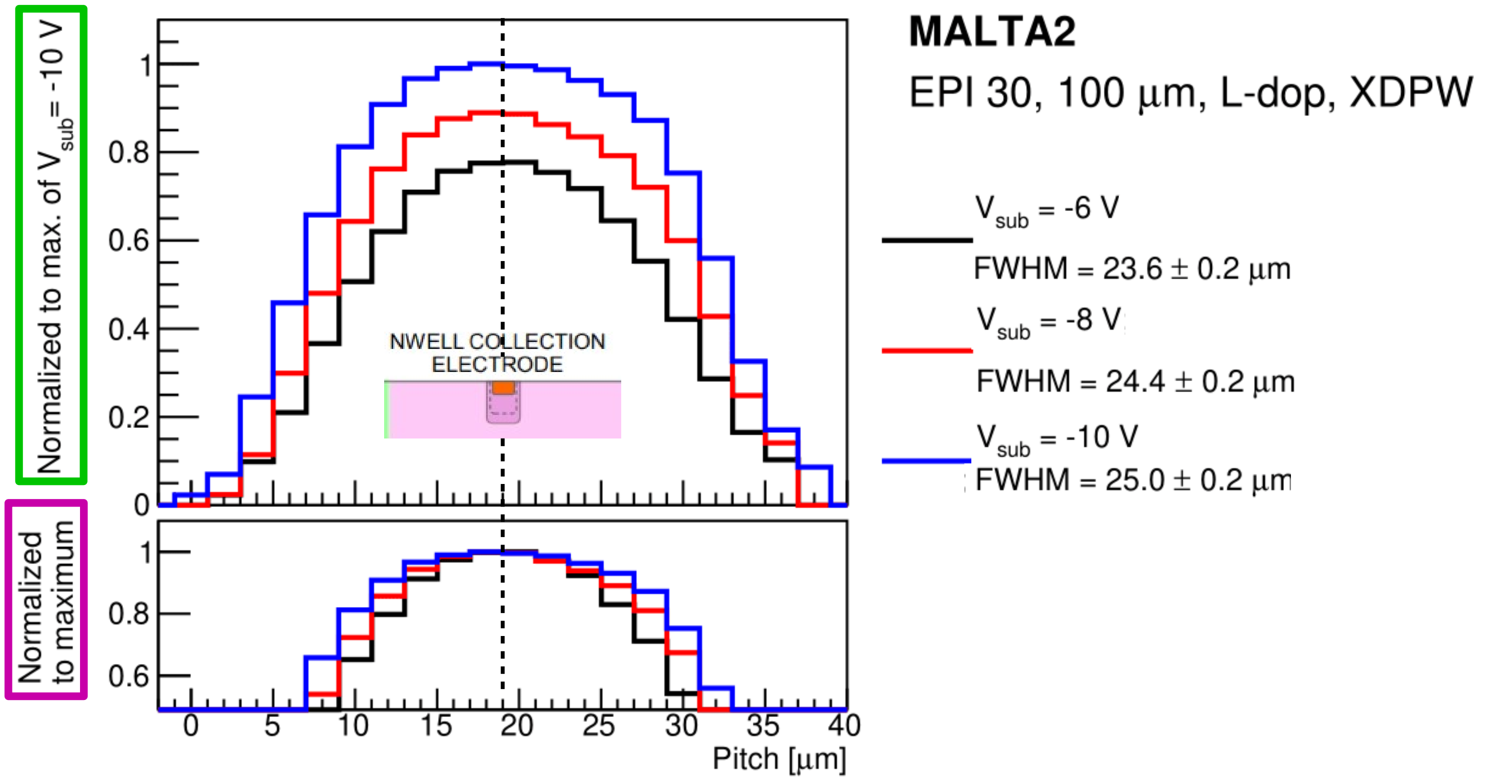


TCAD Simulations



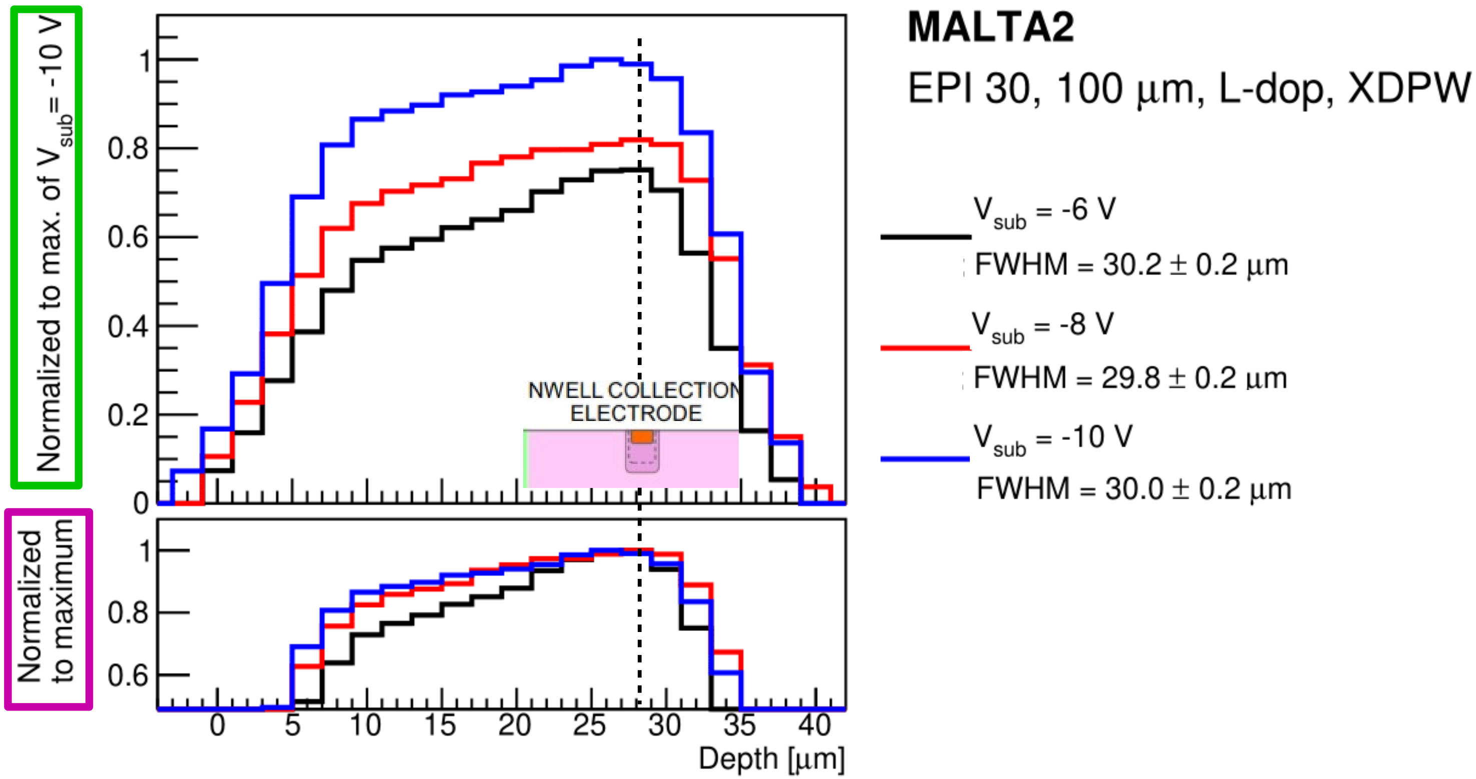
M. Munker et al., JINST C05013

Taking a better look in pitch



- Pitch and Depth projections: bias 8-10 V
  - Normalization to max. bias -10 V
  - Normalization to maximum
  - FWHM ~ depletion size ⊕ 4 µm beam width
- Pitch projection
  - Symmetric around the collection electrode
  - Lateral depletion increases with bias

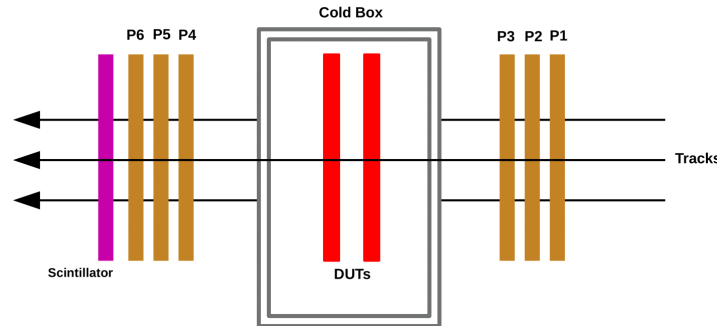
Taking a better look in depth

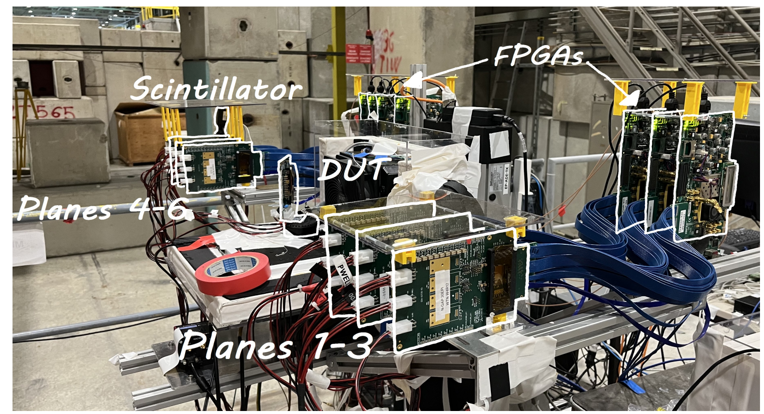


- Pitch and Depth projections: bias 8-10 V
  - Normalization to max. bias -10 V
  - Normalization to maximum
  - FWHM ~ depletion size ⊕ 4 μm beam width
- Depth projection
  - Full depletion at -6 V bias
  - "Flatter" distribution at higher bias

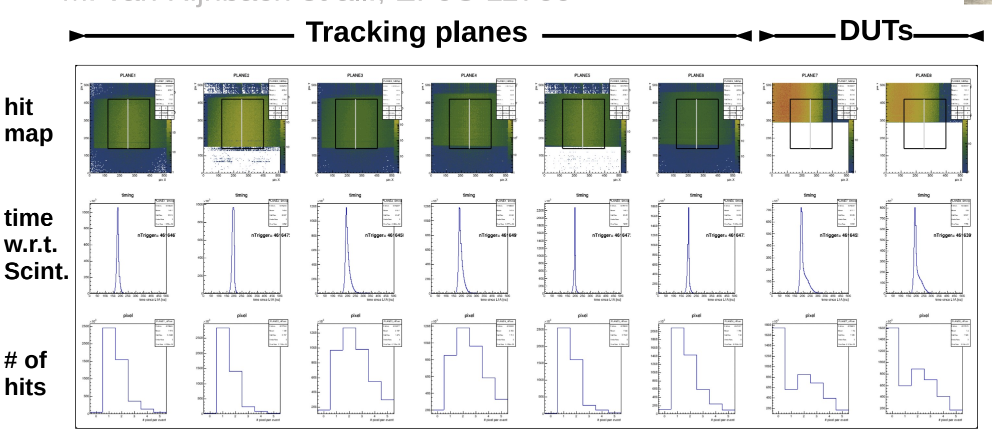
MALTA SPS Telescope

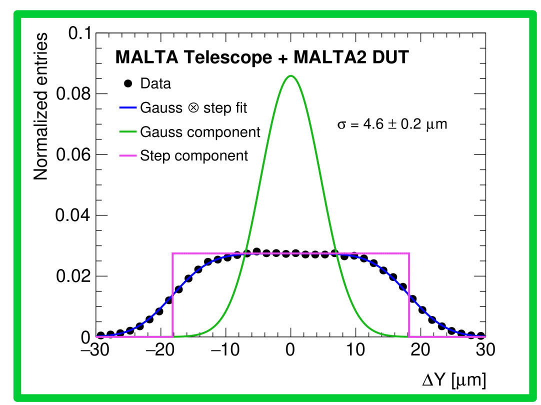
- MALTA permanent fixture at CERN, SPS
  - 180 GeV hadron beam
  - 6 tracking planes: **<5 µm** spatial resolution
  - Scintillator for precise time reference
  - Cold box: up to 2 DUTs + rotational stage
  - Flexible triggering configurations:
  - Users: BCM', ITk pixels, HGDT's LGAD
  - Online monitoring capability





M. van Rijnbach et all., EPJC 11760



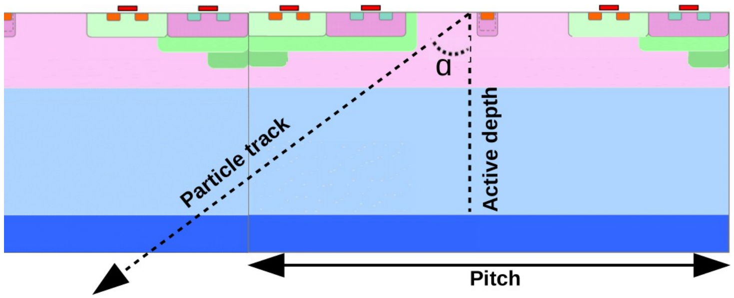


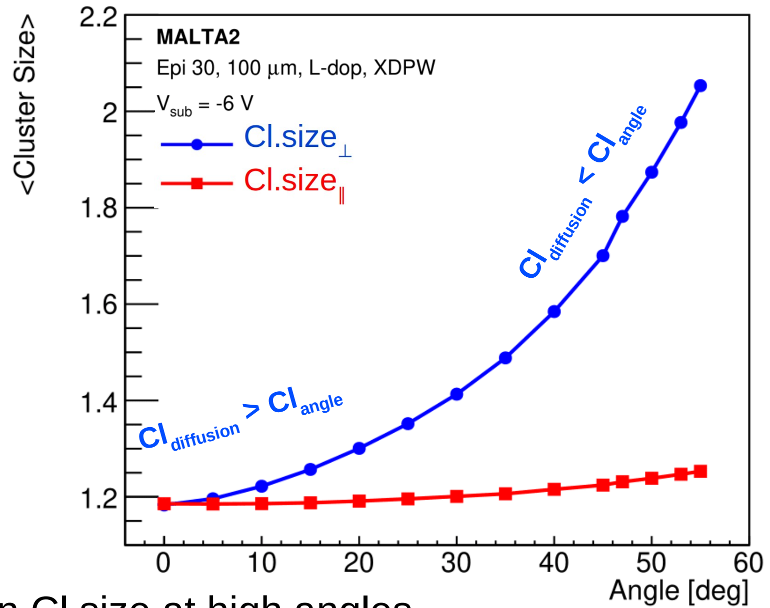
Grazing angle technique

✗ $Cl.size_{\perp}(\tan \alpha) = (d/p)*\tan \alpha + Cl.size_{\perp}(0)$

Geometrical model:

- $Cl.size_{\perp}$ – perpendicular to axis of rotation
- α – track angle
- p – pixel pitch
- d – measured active depth





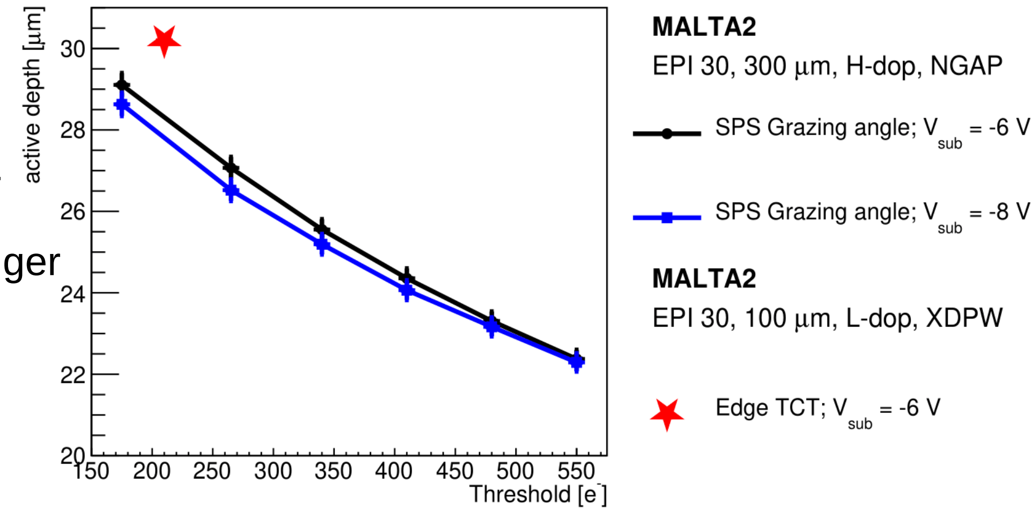
✗ Model assumes a suppressed effect of diffusion Cl size at high angles

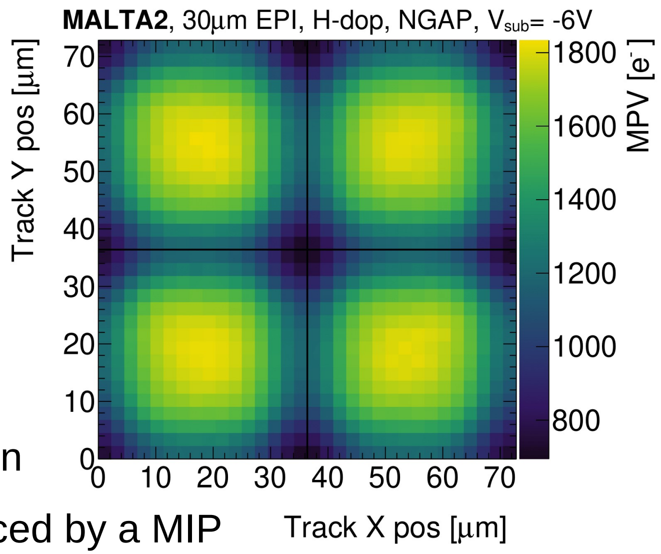
- $Cl.size_{\perp}$ ~ linear at high angles (> 30°)
- $Cl.size_{\parallel}$ - no significant increase with angle

K. Dort et al., j. nima 167413

MALTA2 Epi sample

- E-TCT & grazing angle study:
  - Active depth measured
  - SPS threshold: pixel discriminator
  - E-TCT threshold: oscilloscope trigger
  - ~ no change in act. depth w/ bias
  - Result match at lowest threshold





- Threshold dependence due to:
  - Pixel boundary charge sharing
  - Non-uniform in pixel charge collection
  - Most Probable Value of charge induced by a MIP

Conclusions

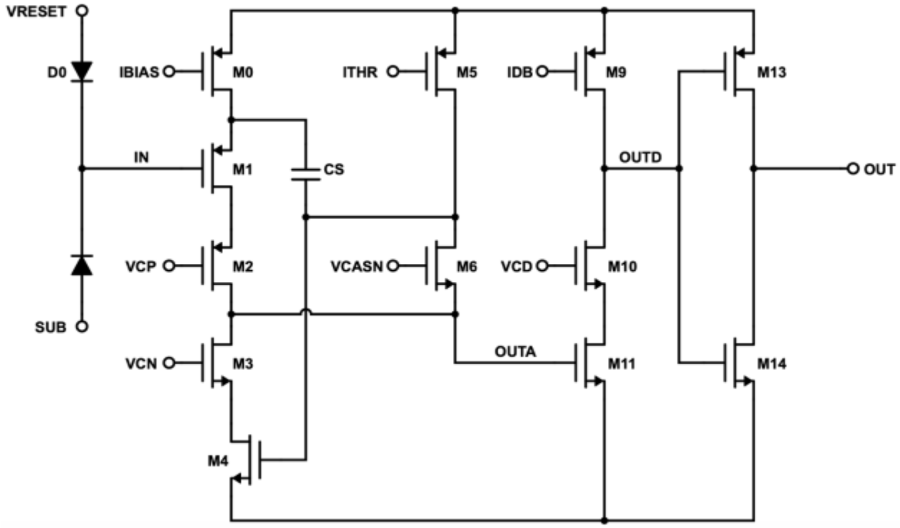
- Two methods for investigating the active depth of the MALTA2 sensor
  - Edge Transient Current Technique (E-TCT):
    - Ability to scan the pixel in depth and pitch
    - Bypasses front end effects – independent study of pixel performance
    - Edge polish of sensors, PCB redesign
    - (100% laser availability)
  - Grazing Angle Technique:
    - “Easy” integration in a test beam experiment
    - Estimation of sensor performance behavior in a test beam environment
    - Tracking corrections; Front end effects; Sensitivity only in the depth axis

- Study of MALTA2:
  - Full depth depletion at -6 V bias: ~ 30 µm
  - Increase in lateral depletion with bias: 23.6 – 25 µm
  - Grazing angle study and E-TCT results compatible at the lowest threshold
  - A lot of nice results with MALTA2 in back-up

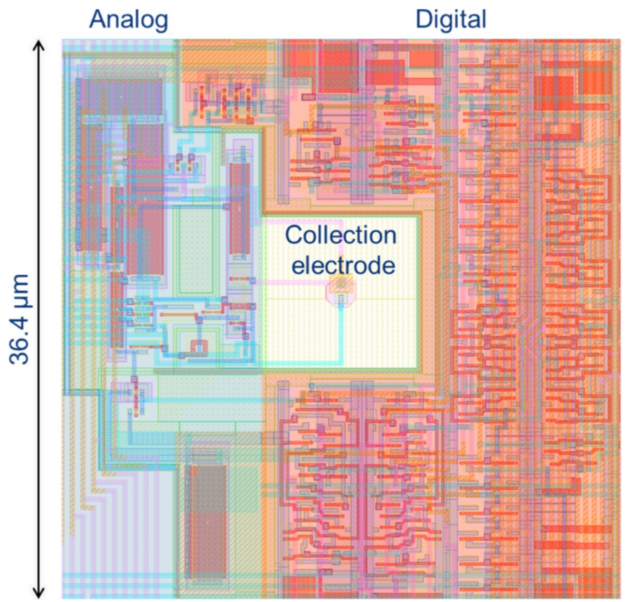
Thank you

Backup

Pixel layout



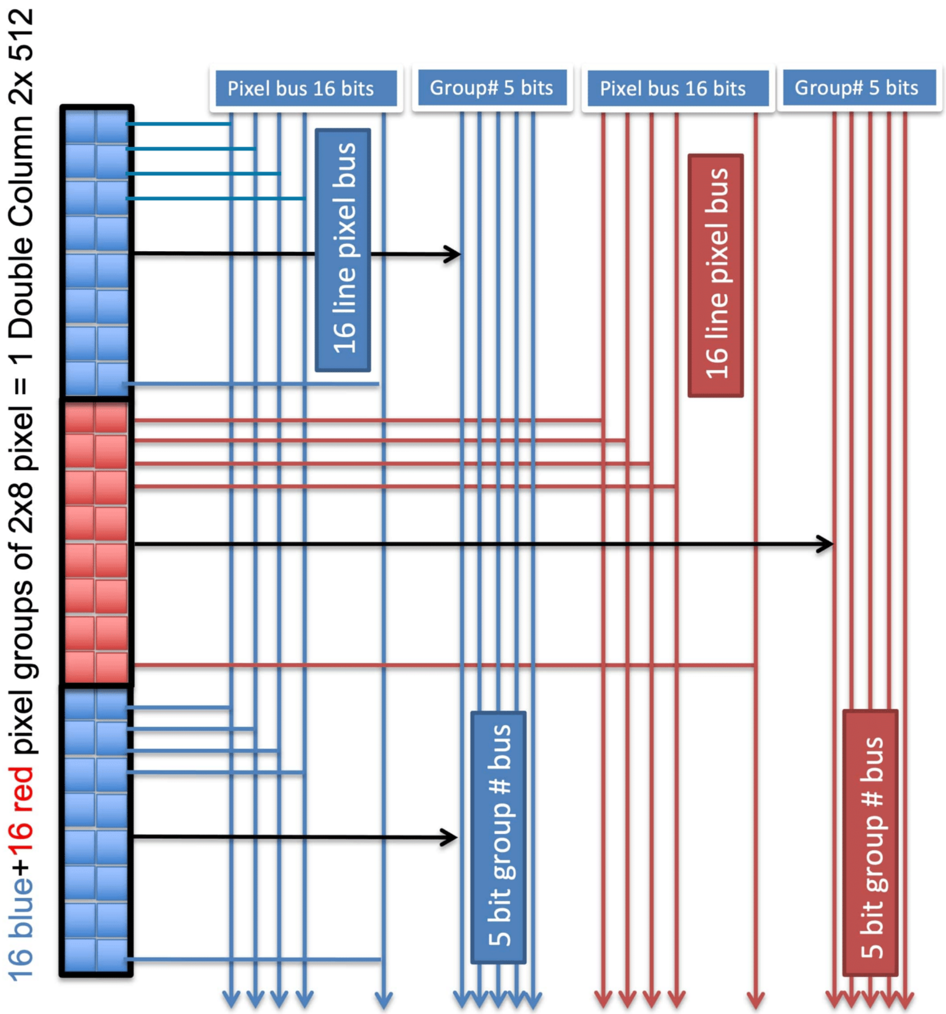
MALTA2 cascoded FE



MALTA2 pixel

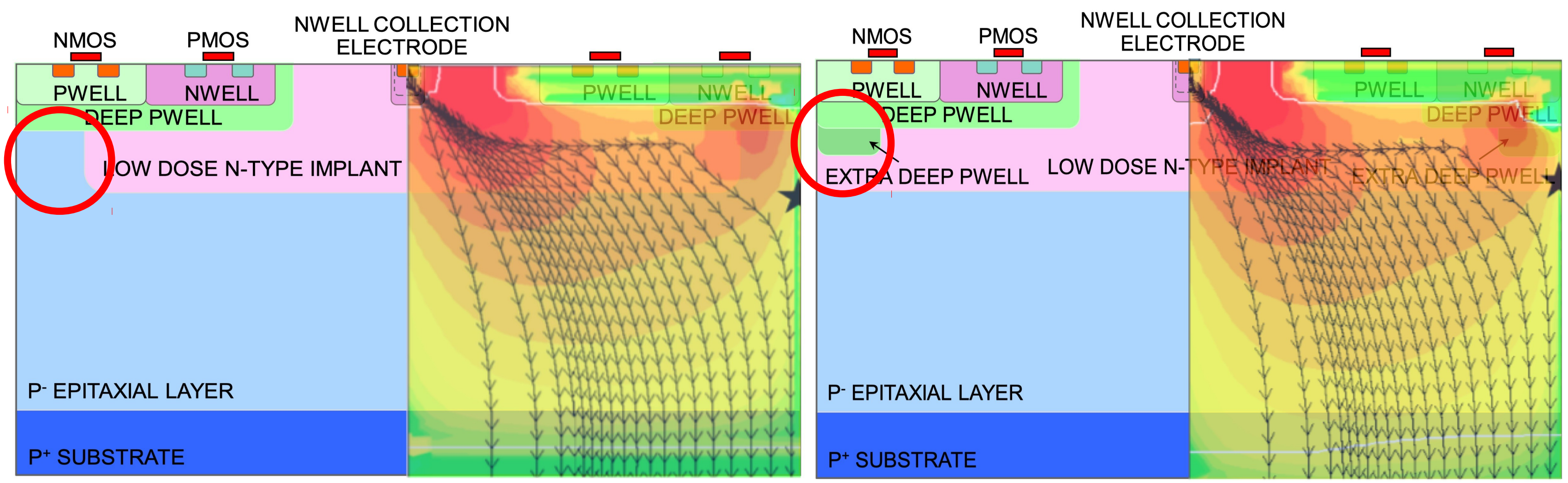
MALTA Double Column Architecture

- Double column readout
  - 2 x 8 pixel group is read out after one detects charge above threshold
  - Neighboring groups are read out on different double columns: odd and even



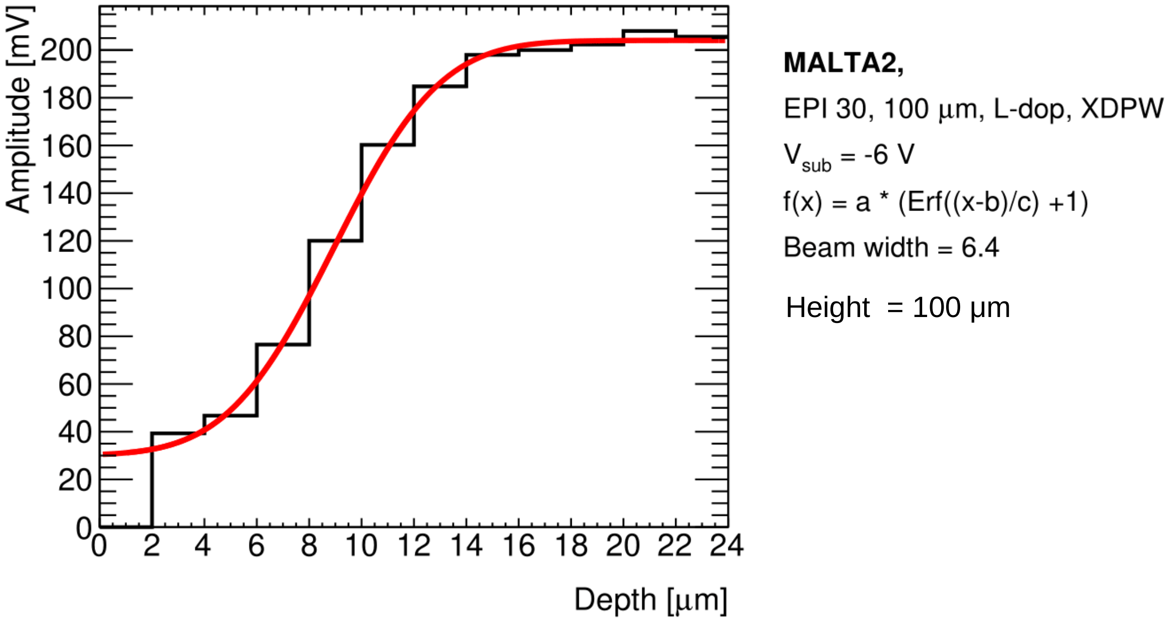
MALTA process modifications

- Process modifications to enhance the electric field
  - Gap in the low doping n-layer (NGAP)
  - Extra deep p-well implants (XDPW)

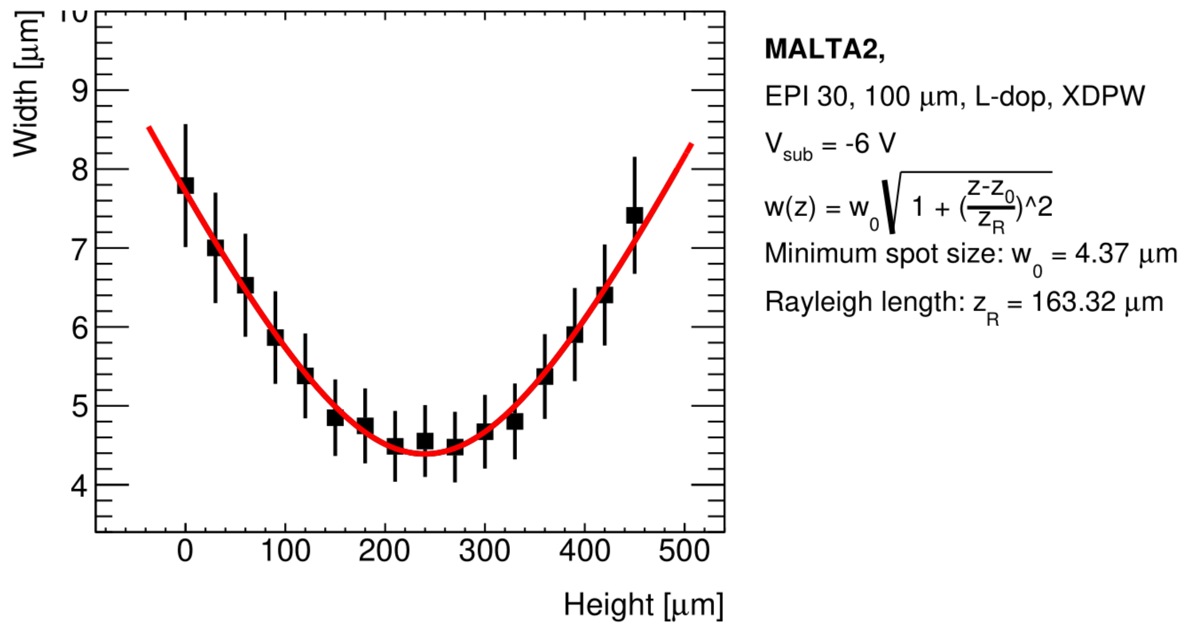


Focus finding

Turn on curve → Laser width

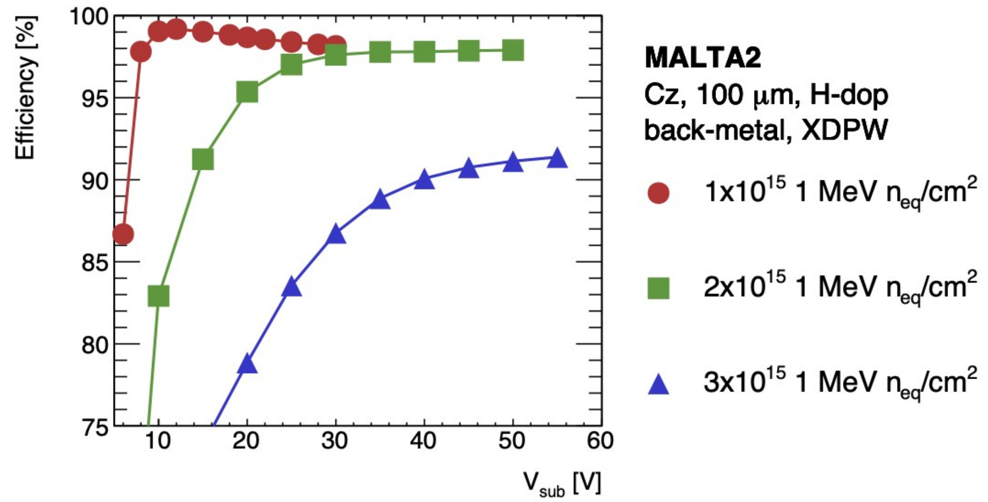


Polynomial fit of width vs height → best focus point

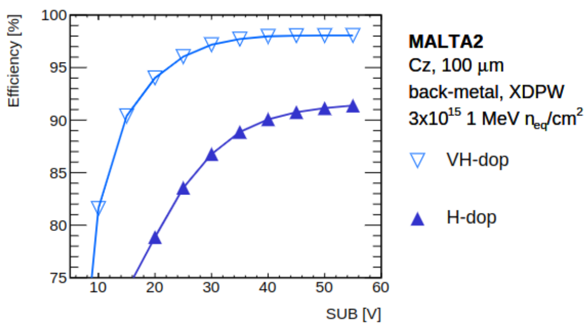


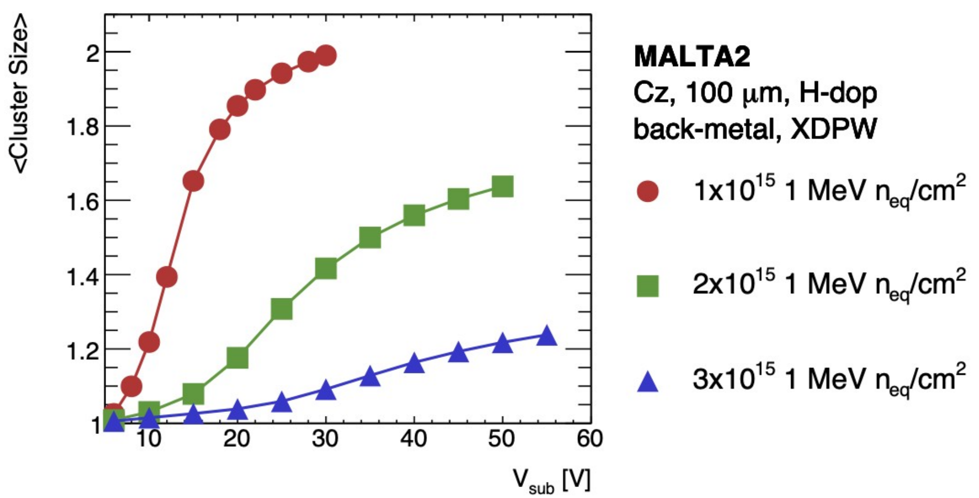
MALTA2 radiation hardness

- ✗ Three neutron irradiation doses:
  - 1 x 10^{15} n_{eq}/ cm^2
  - 2 x 10^{15} n_{eq}/ cm^2
  - 3 x 10^{15} n_{eq}/ cm^2
- ✗ Efficiency
  - Efficiency drop at lower V_{sub}
  - >95% eff. recovered for 1;2;3 x 10^{15} n_{eq}/ cm^2



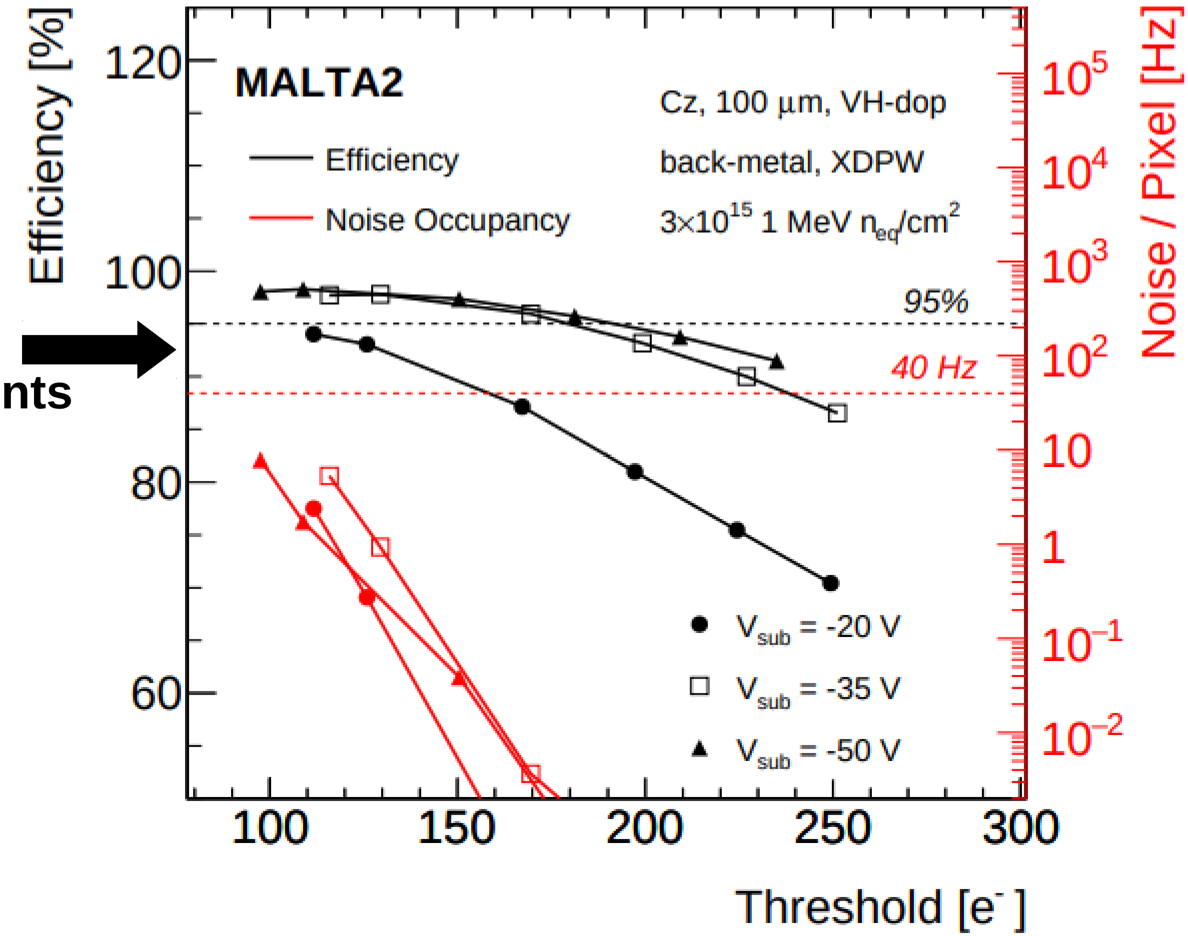
- ✗ Cluster size
  - Cl. size. ~1 at low V_{sub}
  - Increase with higher V_{sub}



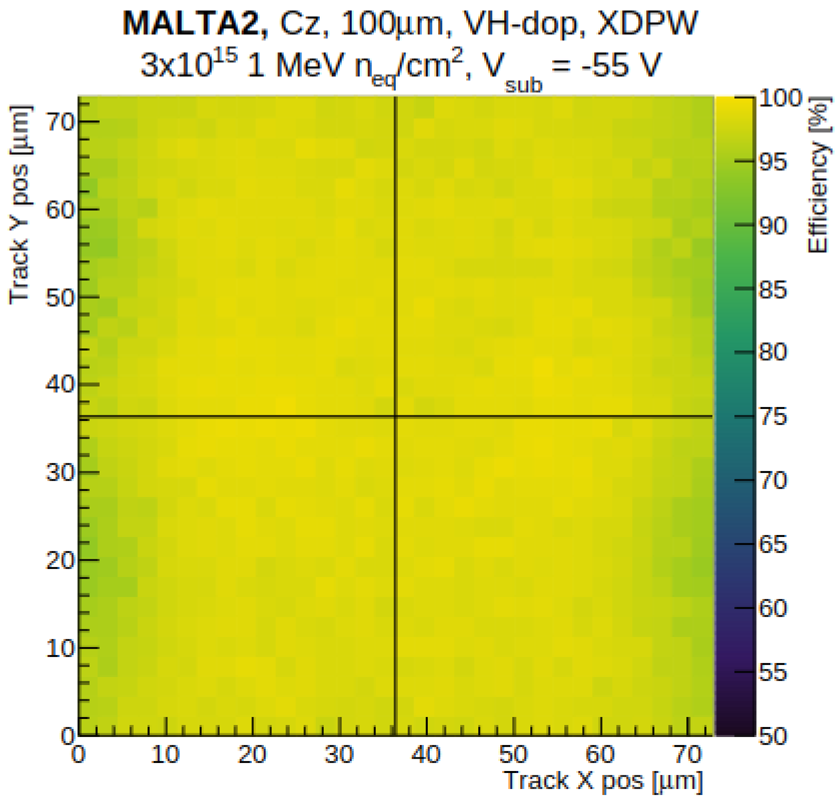


Efficiency after irradiation

ATLAS ITK Requirements



In pixel eff. after 3E15 irradiation



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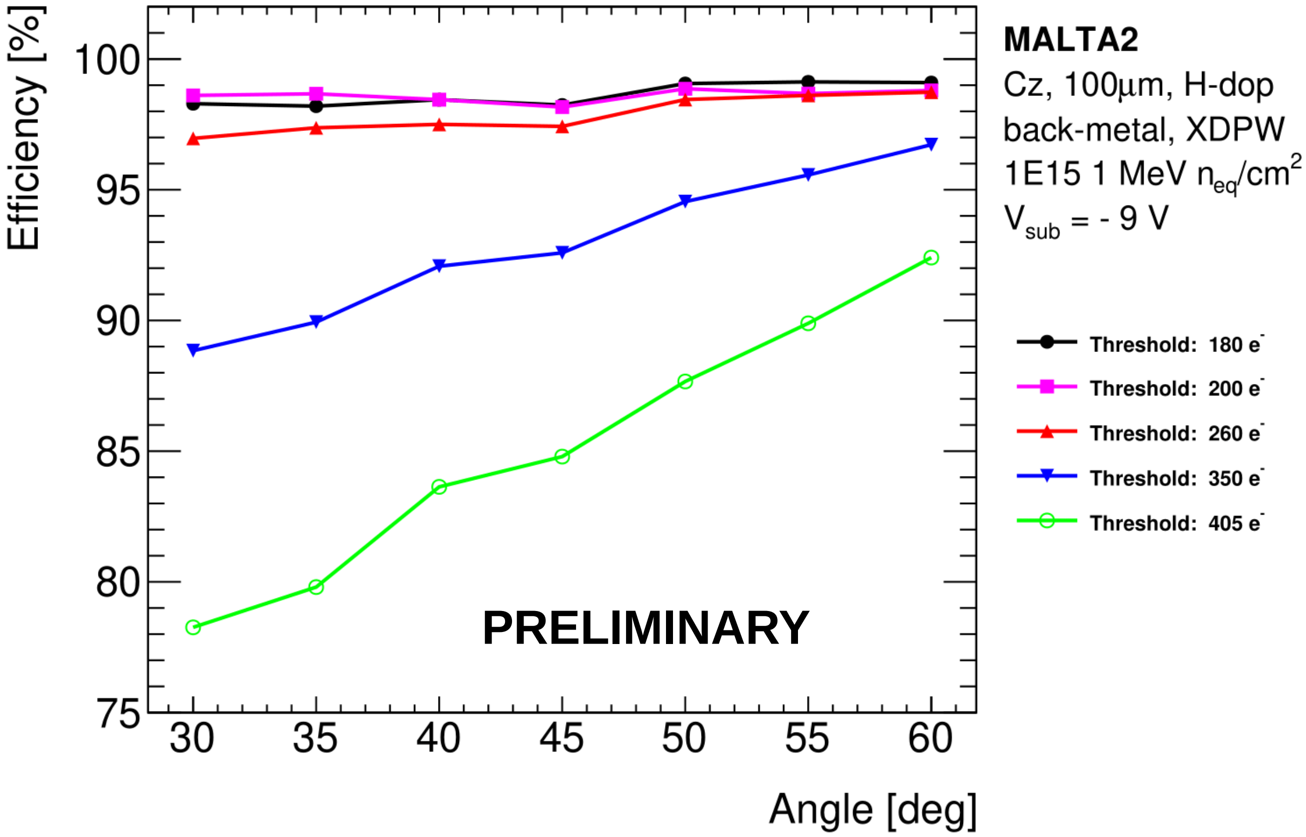
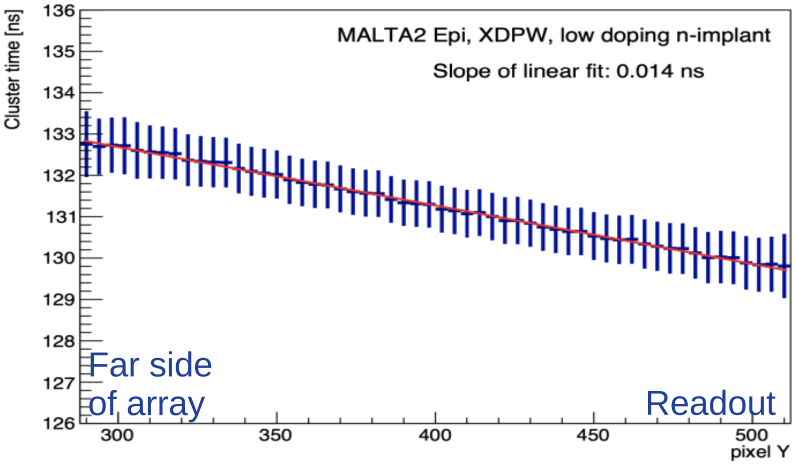


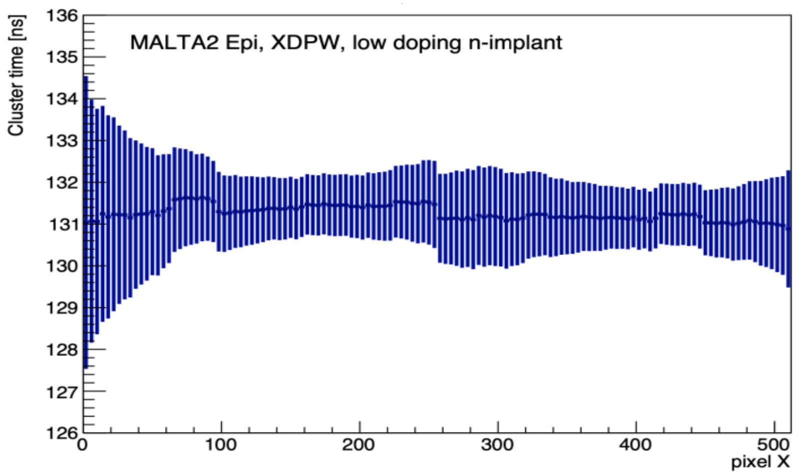
MALTA2 Timing corrections

Time of arrival of the fastest hit in a matched cluster w.r.t scintillator reference, as a function of the matrix X/Y coordinate

- **Timing corrections**:
  - **(Y)** Linear due to column time propagation (**top**)
  - **(X)** Non-uniform chip response in the row direction (**bottom**)

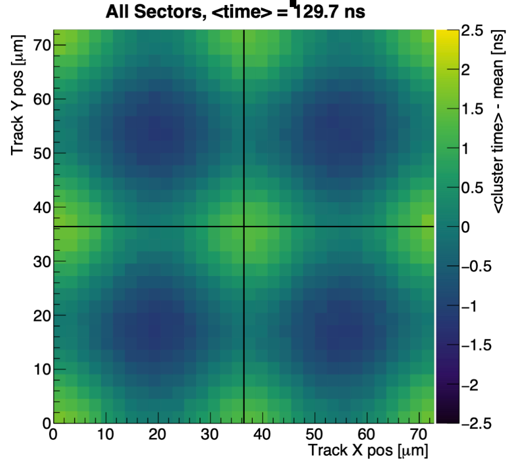
- The **timing plots** are a convolution of:
  - Electronics jitter
  - Time-walk
  - Charge collection effects
  - Scintillator jitter (500ps)
  - FPGA readout jitter (900ps)



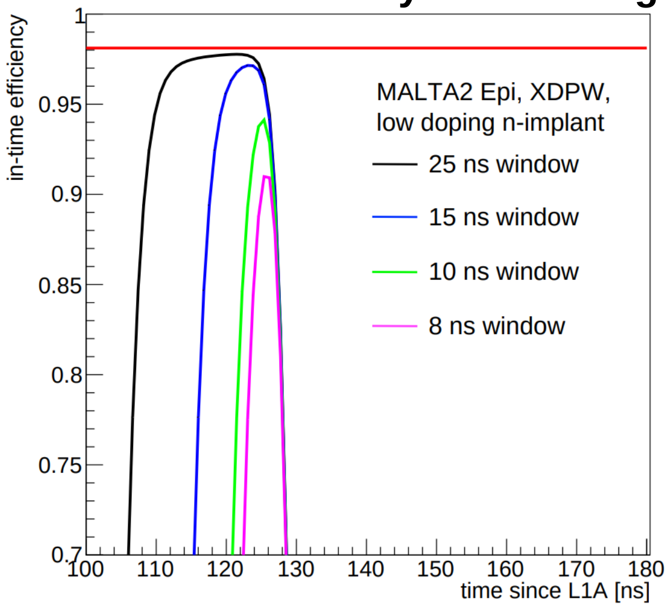


MALTA2 timing

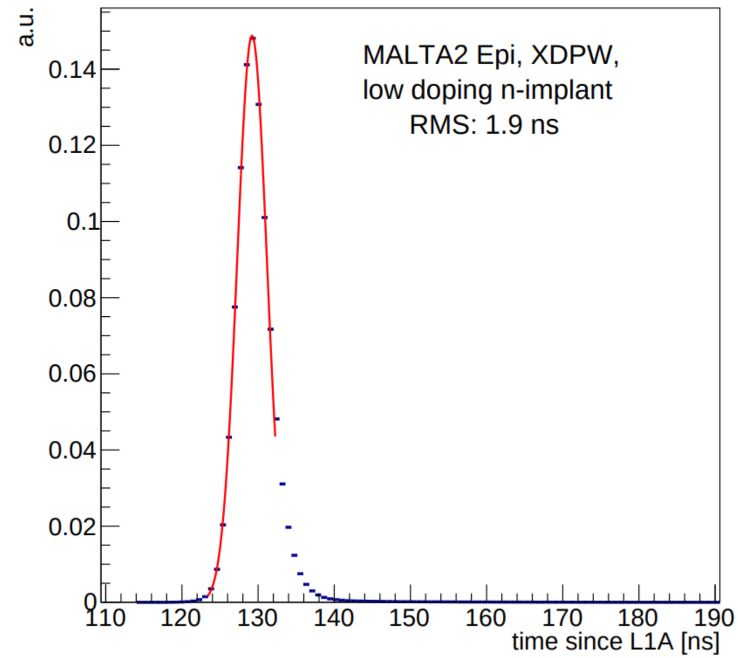
MALTA2 in-pixel timing



MALTA2 in-time efficiency for a sliding window

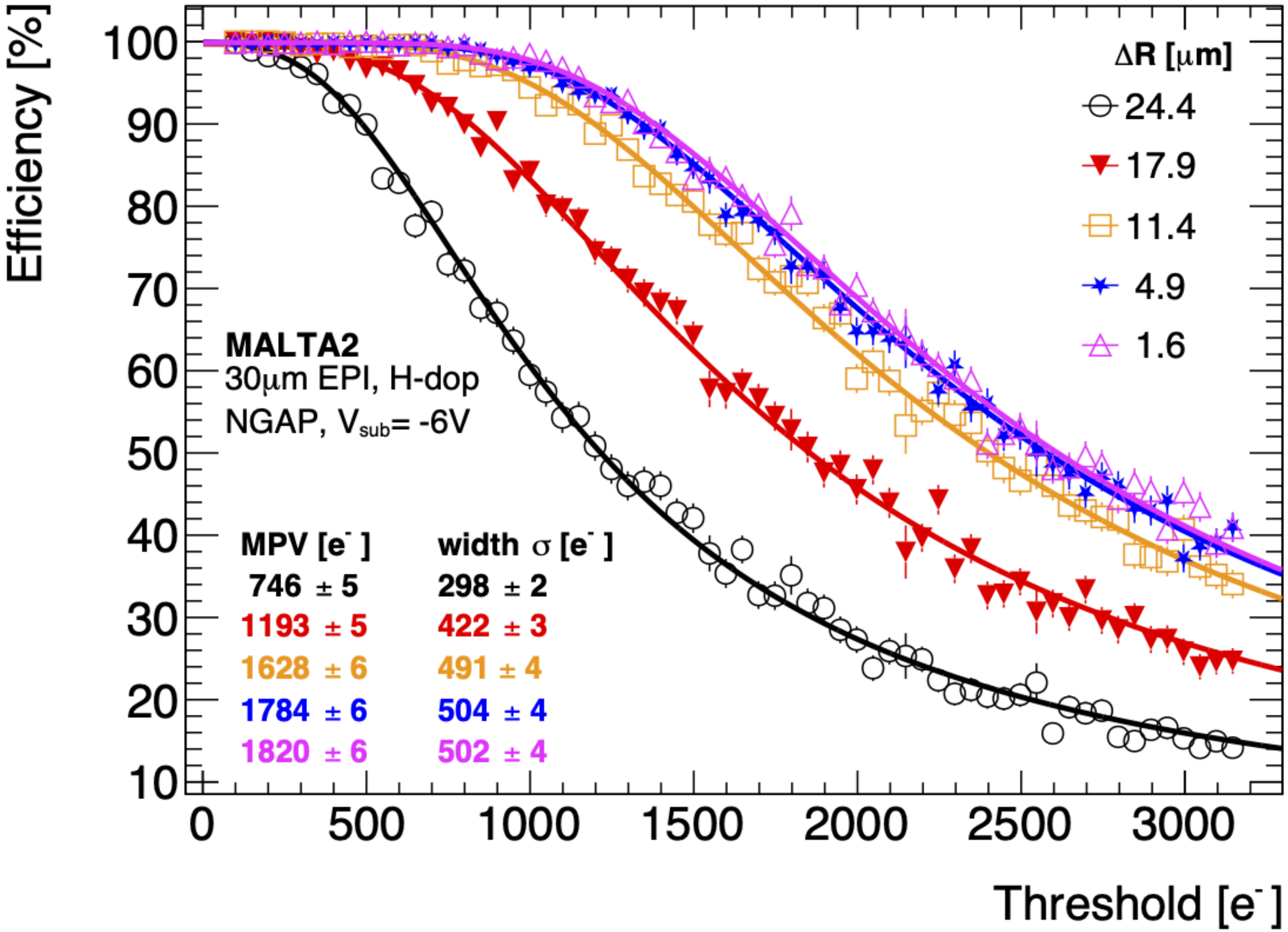


MALTA2 Time of arrival of a hit in a cluster w.r.t scintillator ref.

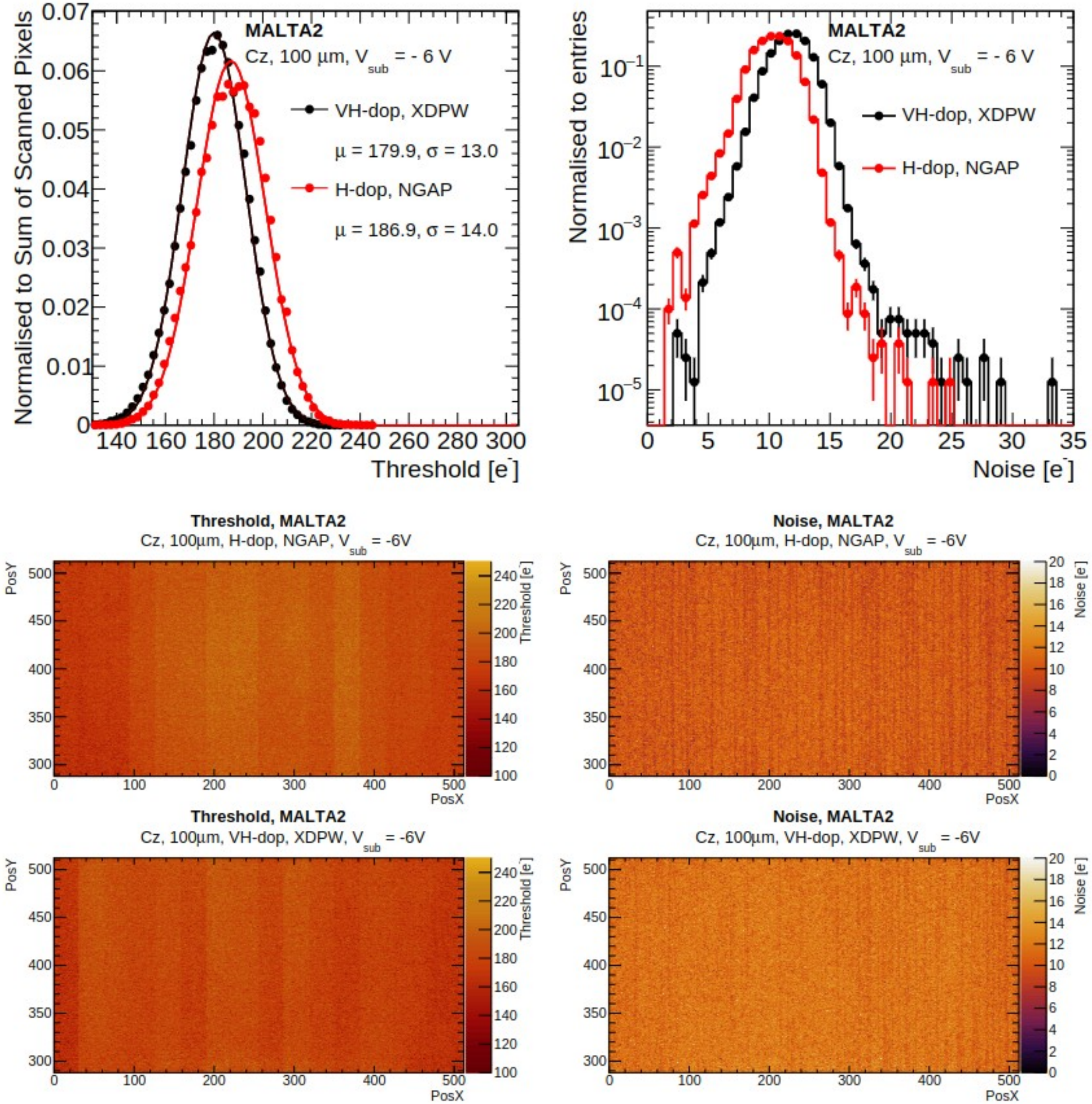


- >98% of signals withing 25ns; >90% in-time efficiency for 8ns window
- Pixel corners generate late-arriving signals; <2 ns timing resolution
- The timing plots are a convolution of:
  - Electronics jitter, sampling readout jitter, scintillator jitter
  - Time-walk
  - Charge collection effects

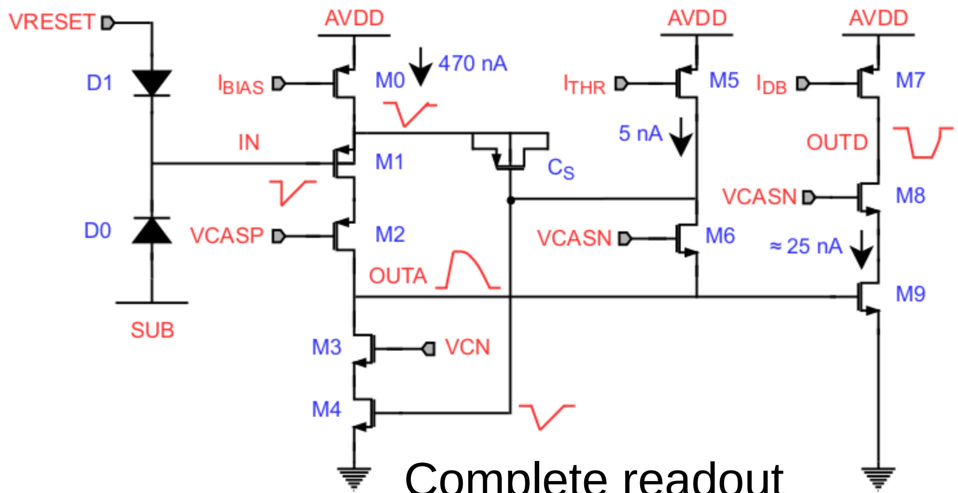
MPV derivation



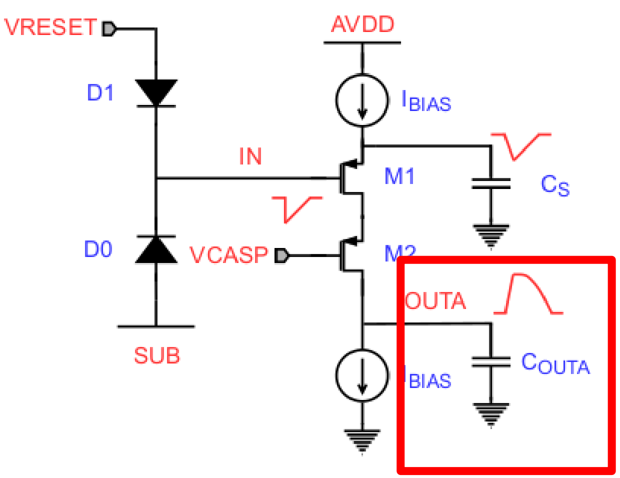
MALTA2 Threshold and noise operation



Analog monitoring



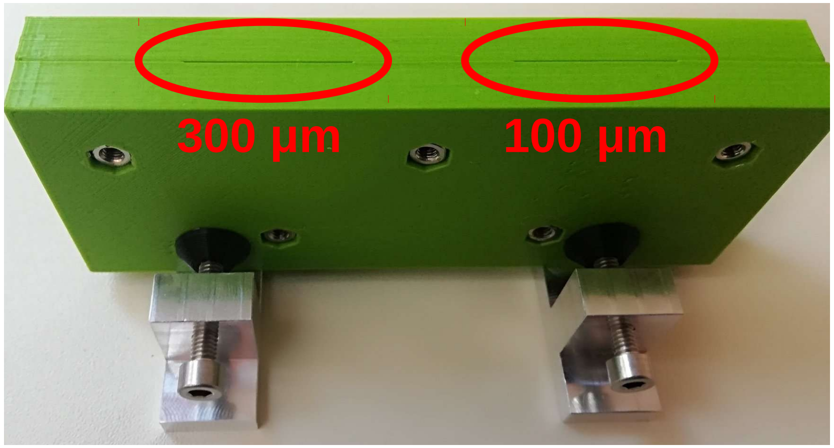
Complete readout



Simplified analog output schematic

Edge polishing

- 3D printed piece to hold up to 2 sensors:
  - 100 µm thick (EPI)
  - 300 µm thick (Cz)



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