UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

MALTA2 Grazing Angle Method Validity

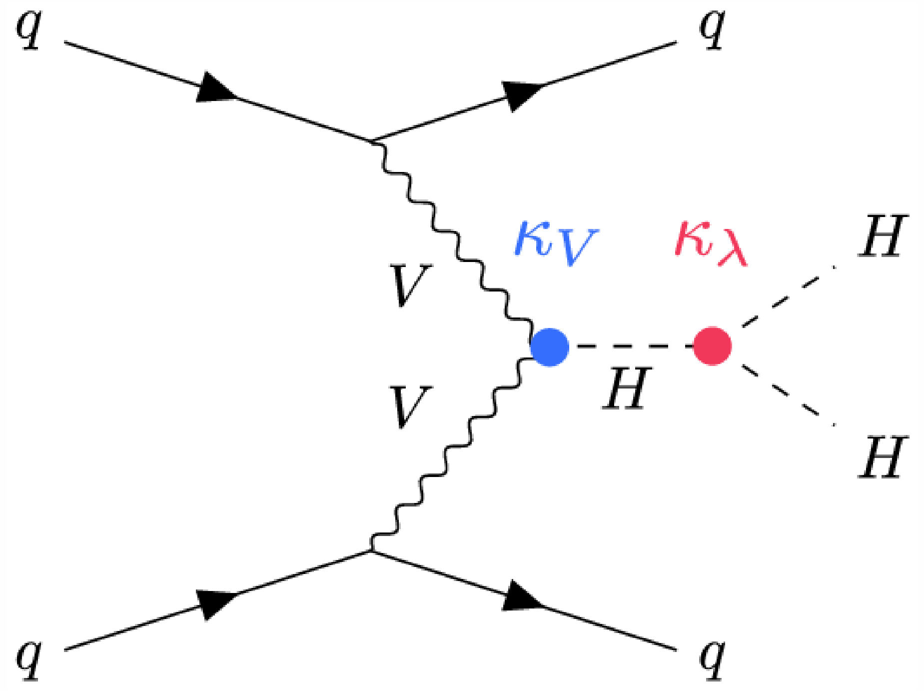
Author: Elliott P Wright

Introduction

- Validation of the grazing angle method used to calculate depletion depth using Allpix^2 **simulation**
    - Data already taken for a 1×10^{15} 1 MeV n_{eq}/cm^2 irradiated detector
- Simple telescope simulation constructed with MALTA2 sensors
- Same environmental, test beam and digitisation parameters used between the experiment and simulation
- Linear electric field applied inside sensors

HL - LHC Upgrade

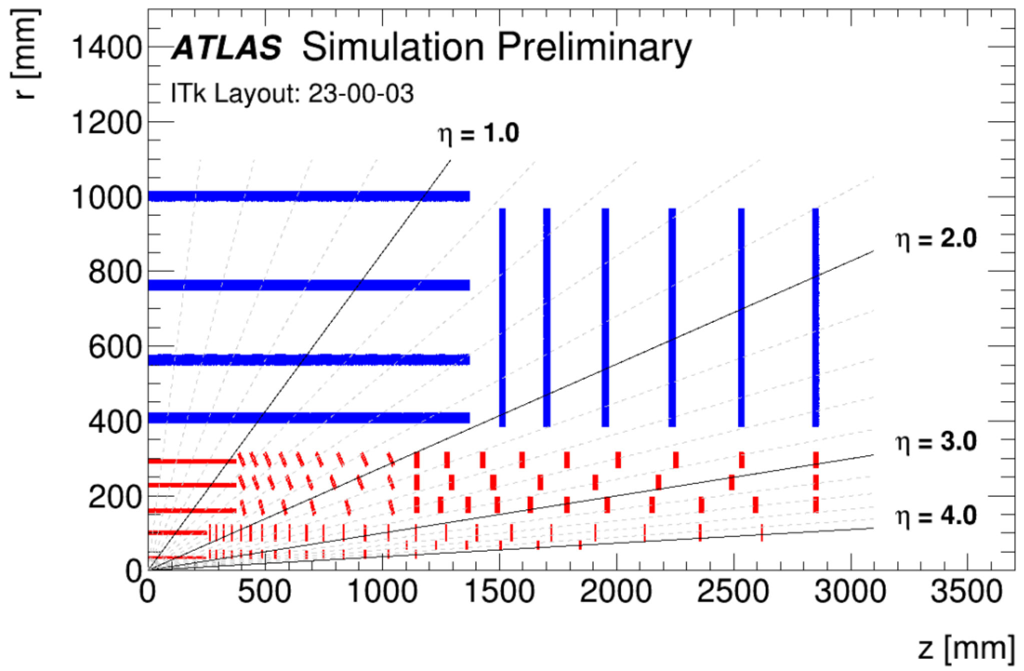
- Current LHC producing diminishing returns
- LS3 begins December 2024
- HL - LHC begins in July 2027
- Higgs physics:
    - Measurement of rare decays/production
    - Higgs mass
- Physics beyond the standard model



Higgs self-coupling: Further investigation at HL - LHC [1]

HL - LHC Upgrade

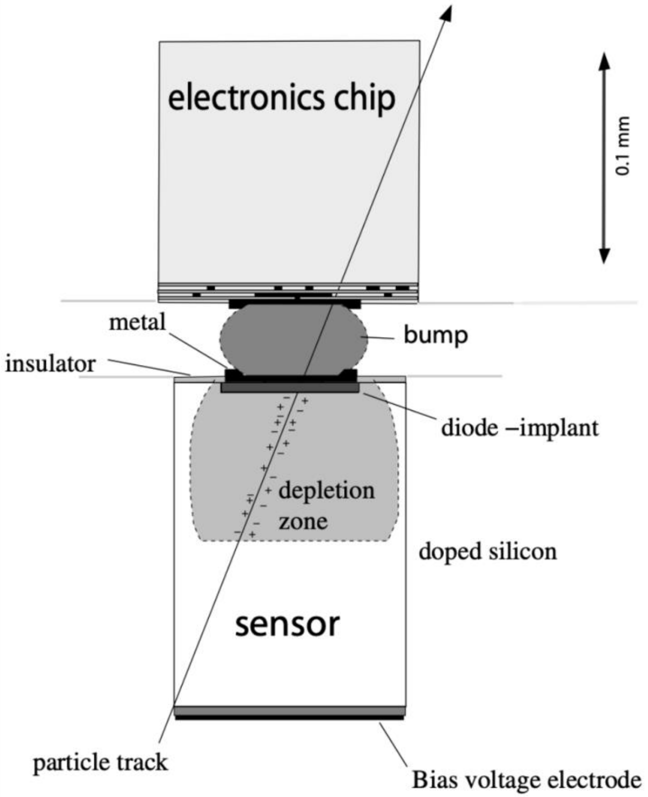
- Instantaneous luminosity increased by factor of 5 to 7.5 x 10^{34} cm^{-2} s^{-1}
- Collisions per bunch crossing 50 → 200
- Increased $|\eta|$ coverage from 2.5 → 4
- Improvements on LHC Run 2+3 Inner Detector:
  - Higher granularity (50 x 50 μm^2)
  - Greater radiation hardness
  - Lower material budget



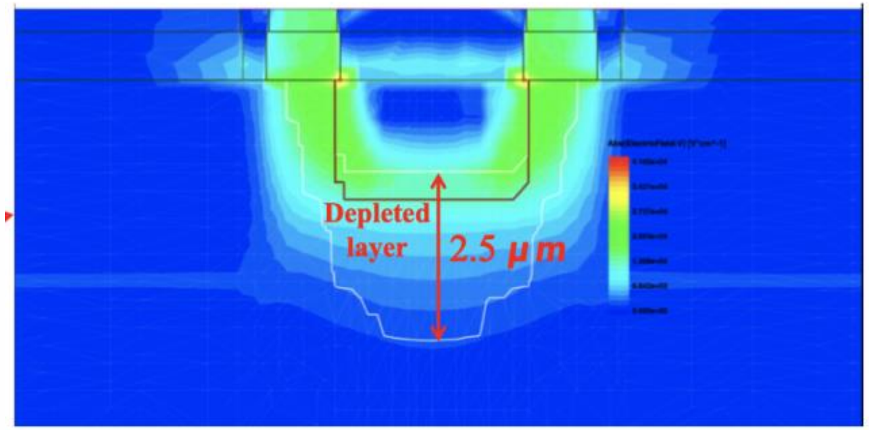
ATLAS Inner Tracker Detector (ITk): Pixel (red) and strip (blue) detector modules [2]

Hybrid Detectors

- Application Specific Integrated Circuit (ASIC)
- ASIC bump-bonded to the silicon sensor
- ASIC segmented into pixels



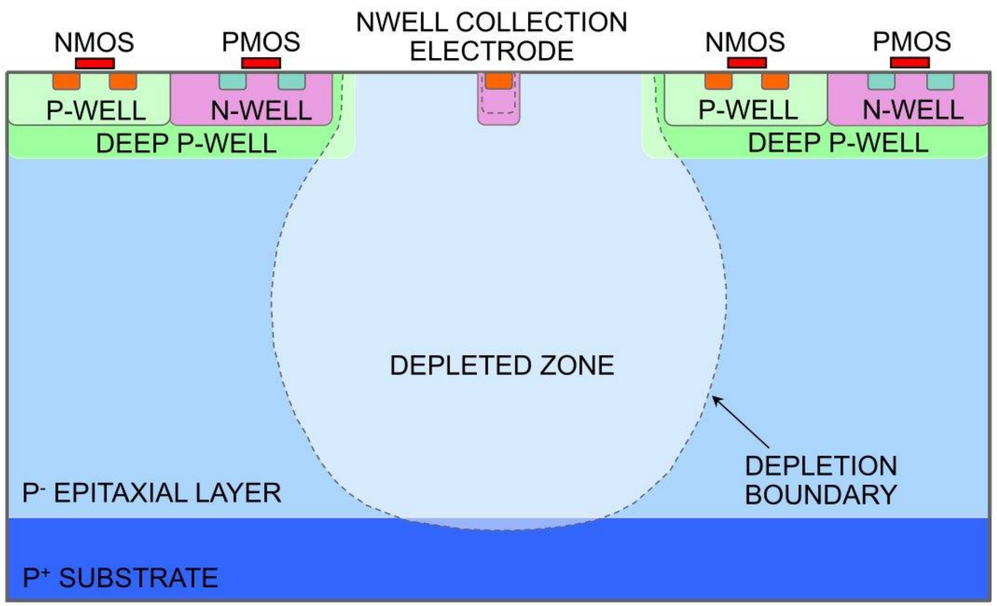
Hybrid sensor: Design



Hybrid sensor: Electric field

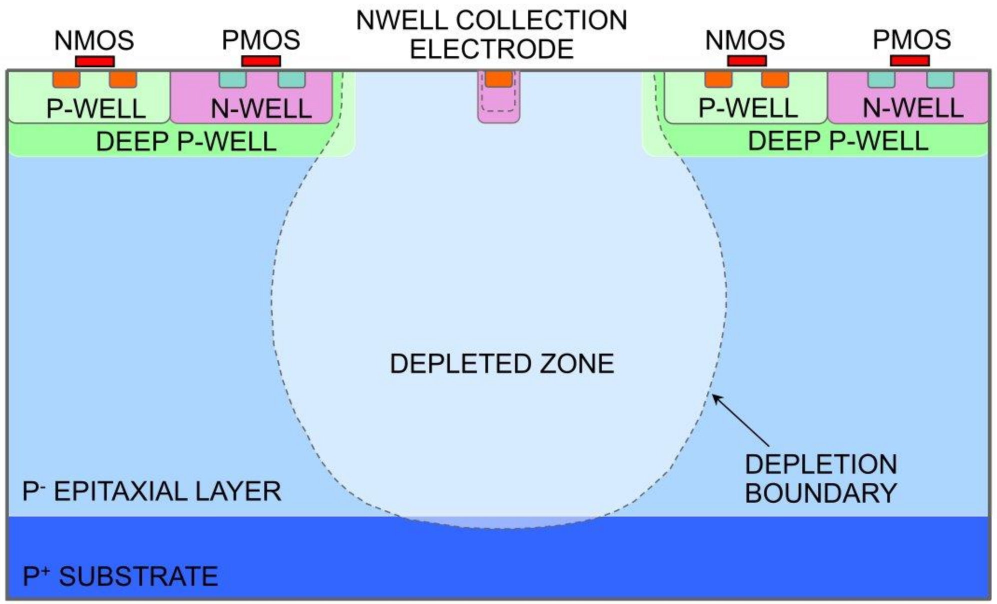
DMAPS Benefits Over Hybrid Detectors

- Depleted monolithic active pixel sensor (DMAPS)
- DMAPS CMOS sensors better than current hybrid sensors:
  - Smaller pixel pitches (36.4 x 36.4 μm^2) → greater granularity and tracking performance
  - ASIC and sensor on same chip and no glue → lower material budget
- MALTA2 not in ATLAS outermost ITk layer due to lower radiation hardness

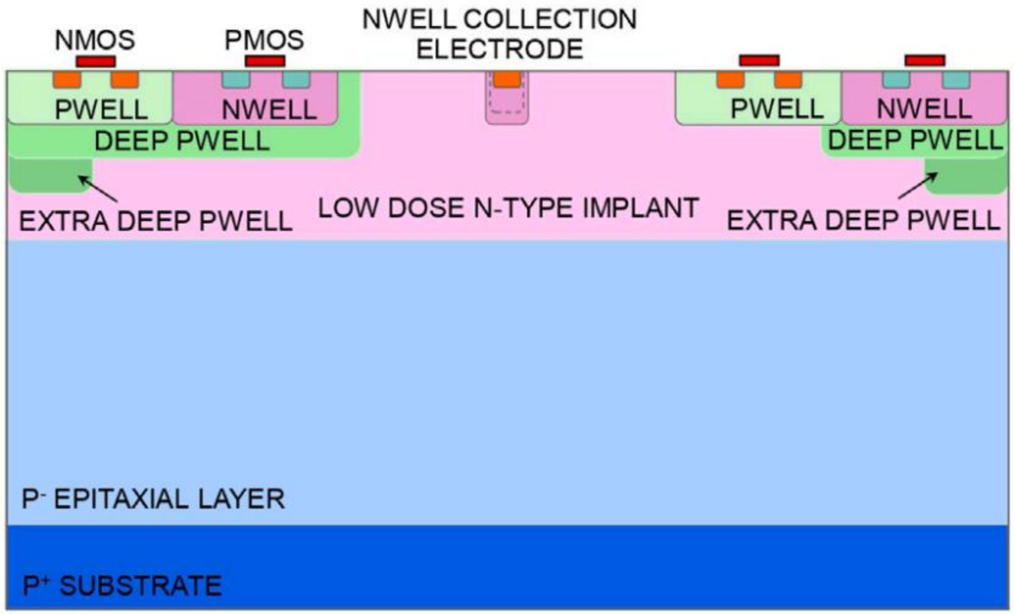


DMAPS: Standard design [3]

Standard CMOS Sensors vs MALTA2

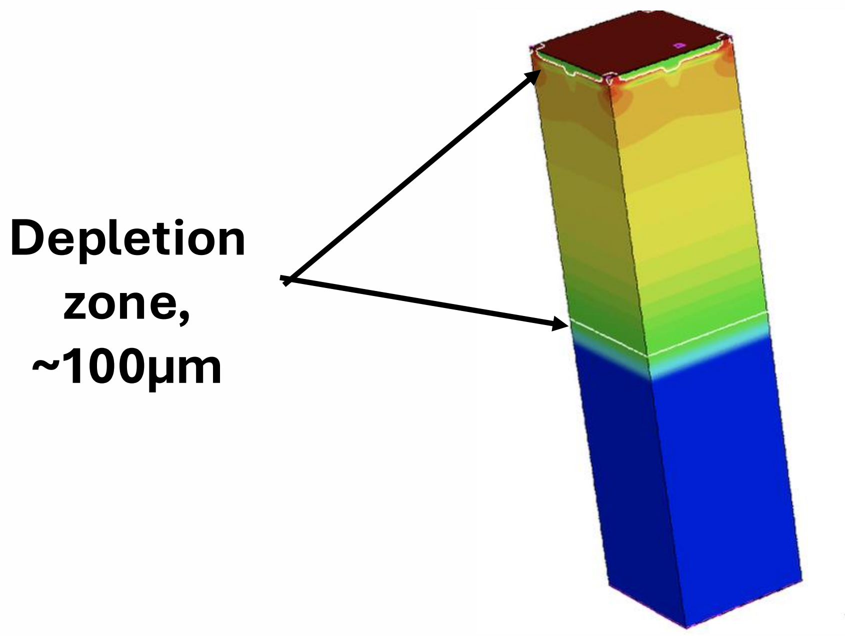


DMAPS: Standard design [3]

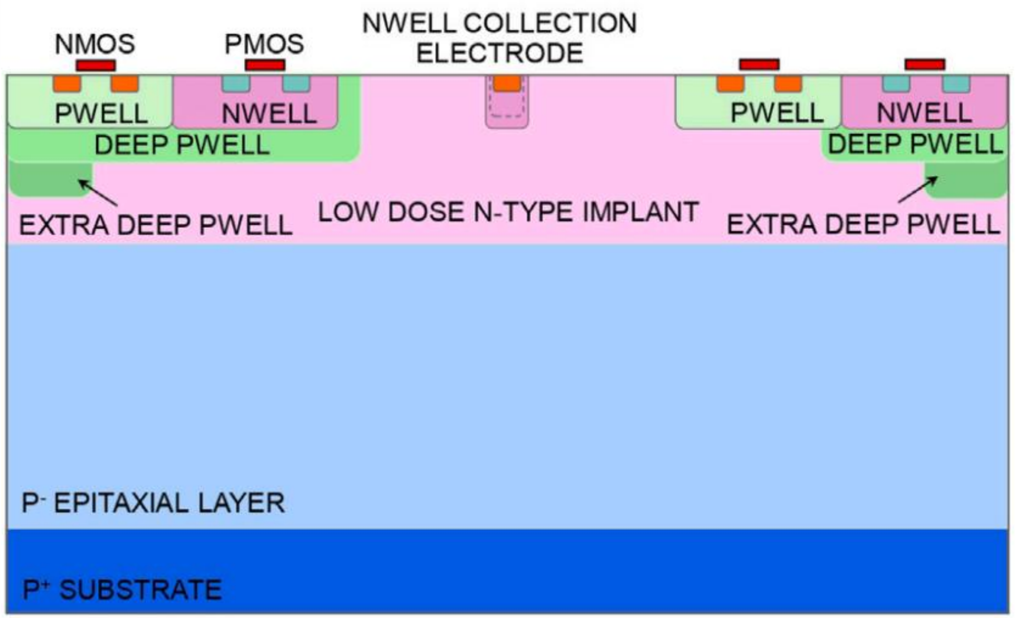


DMAPS: XDPW processed MALTA2 layout [4]

Standard CMOS Sensors vs MALTA2



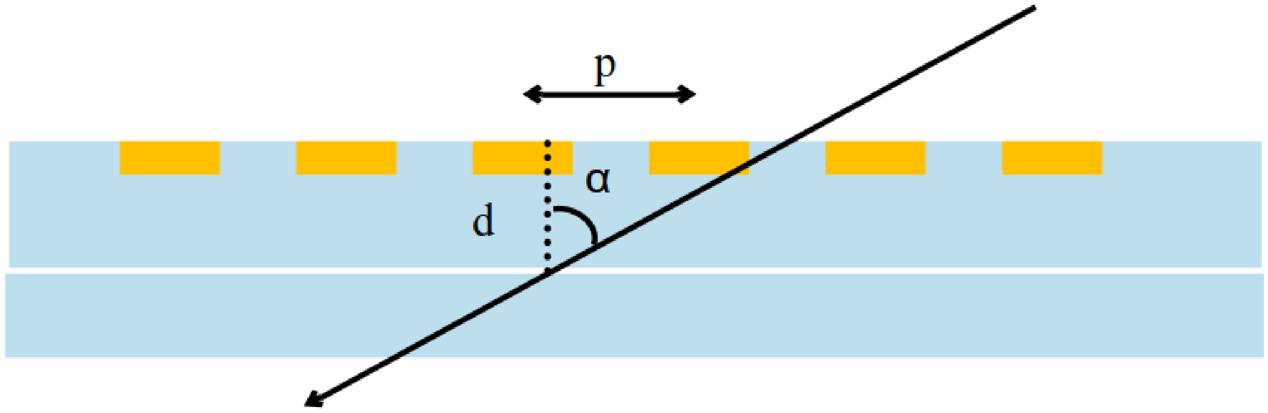
DMAPS: Electric field



DMAPS: XDPW processed MALTA2 layout [4]

The Grazing Angle Method

- Aim is to calculate the depletion depth
- Compare depth to what is expected to determine radiation damage
- Radiation damage changes the depletion depth
- Create a test beam of incident particles, changing sensor angle about x-axis

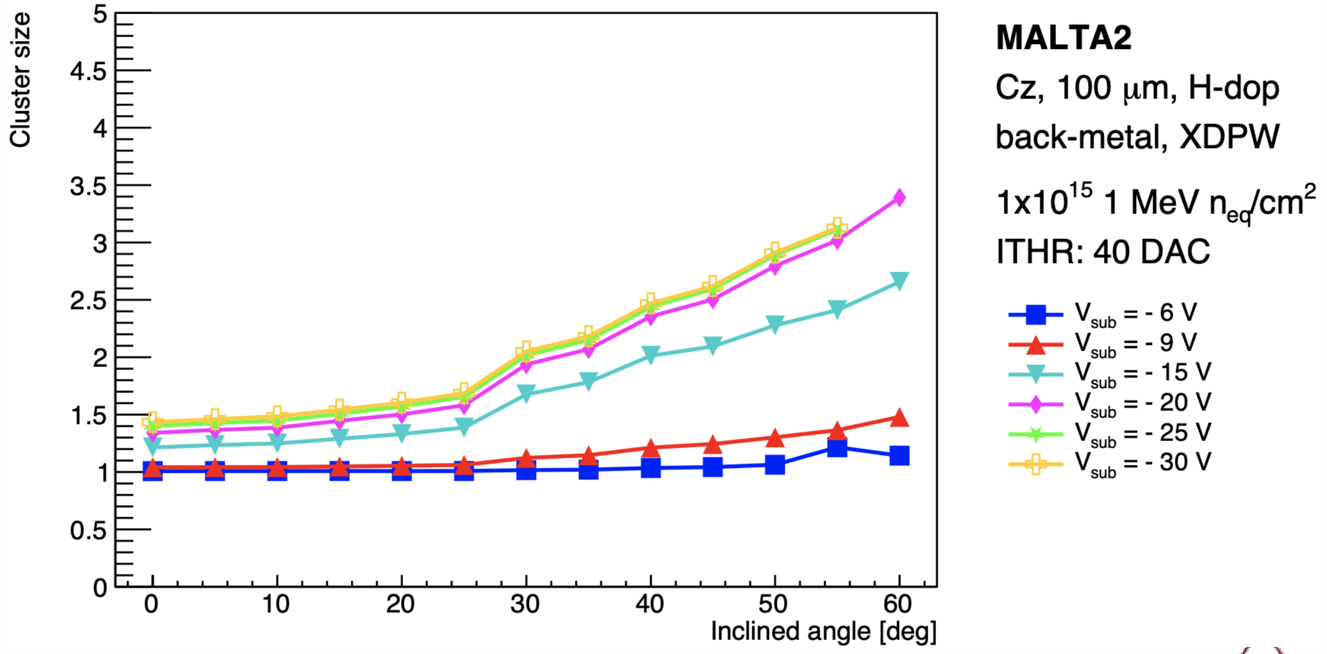


Grazing angle method: incident grazing angle α, pixel pitch p, and depletion depth d

$$Cluster(\tan(\alpha)) = \frac{d}{p}\tan(\alpha) + Cluster(0)$$

The Grazing Angle Method

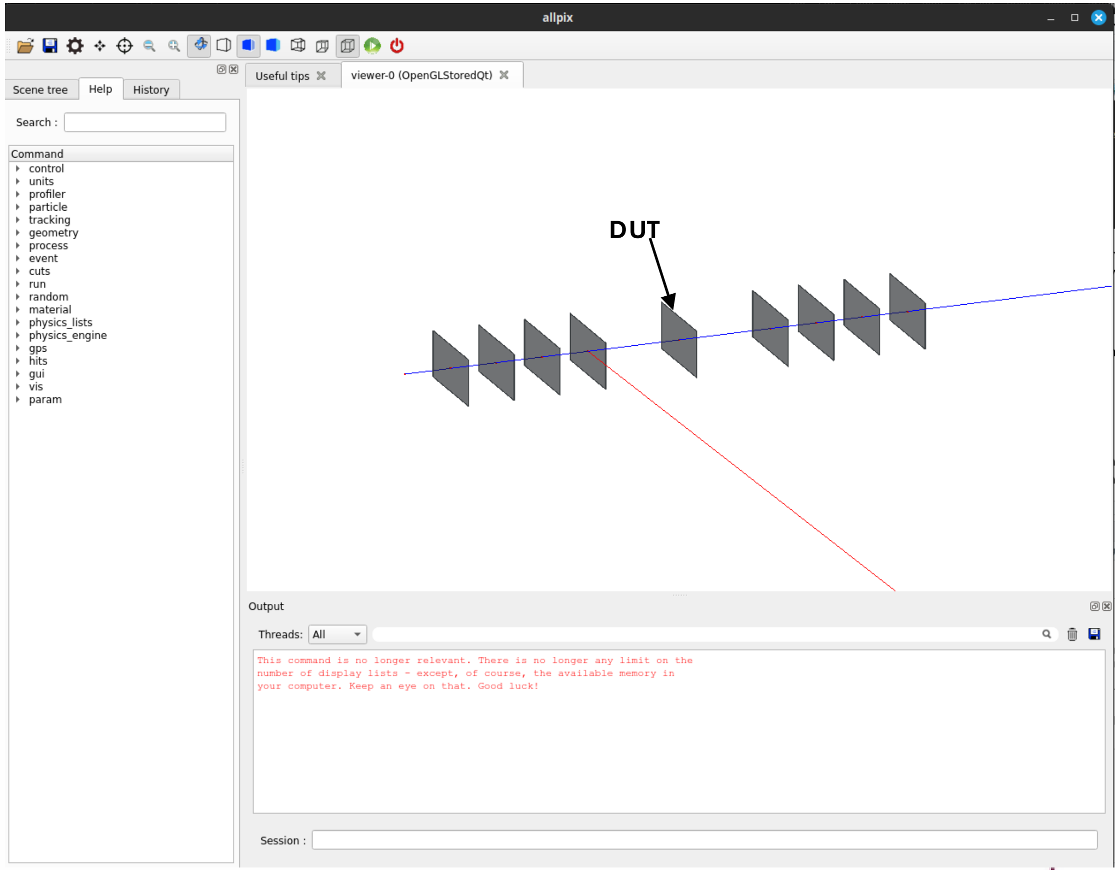
- Aim is to calculate the depletion depth
- Compare depth to what is expected to determine radiation damage
- Radiation damage changes the depletion depth
- Create a test beam of incident particles, changing sensor angle about x-axis



Cluster Size: Test beam, irradiated

Allpix^2

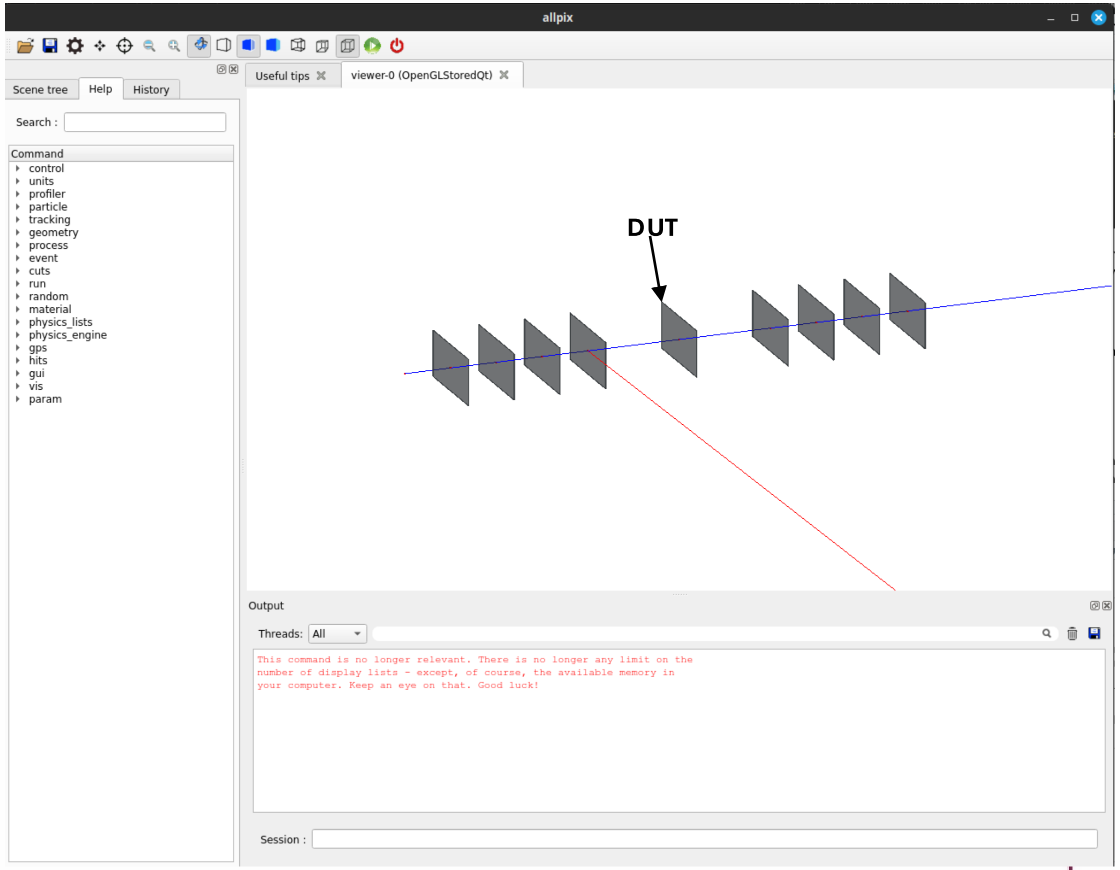
- Monte Carlo simulation software for silicon detectors based on Geant4
- Performs signal propagation and digitisation
- Visualisation capabilities
- Ease of configuration with human-readable files
- Extensive documentation: https://allpix-squared.docs.cern.ch/



Allpix^2: MALTA2 sensors (grey squares) and test beam (blue line)

MALTA2 Parameters

Parameter	Value
Sensor Dimensions	20.2 mm x 10.1168 mm
Pixel Pitch	36.4 µm 36.4 µm
Pixel Matrix	512 x 224
Sensor Thickness	100 µm
Sensor Excess	0.7816 mm x 0.9812 mm

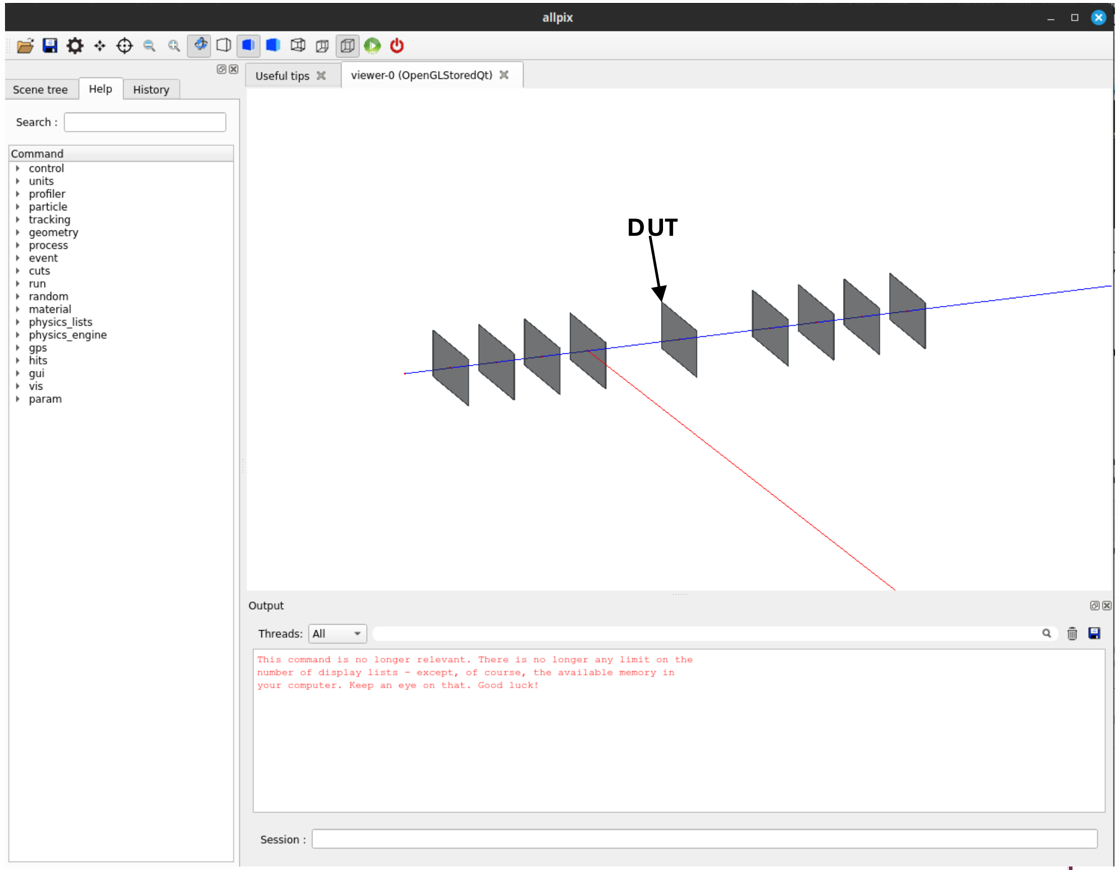


Allpix²: MALTA2 sensors (grey squares) and test beam (blue line)

Simulation Set-Up

Beam Parameter	Value
Particle	Proton
Beam Energy	180 GeV

Sensor Parameter	Value
Temperature	258.15 K
Digitisation Threshold	260 e
Depletion Voltage	-30 V (GUESS)



Allpix²: MALTA2 sensors (grey squares) and test beam (blue line)

Simulation Workflow

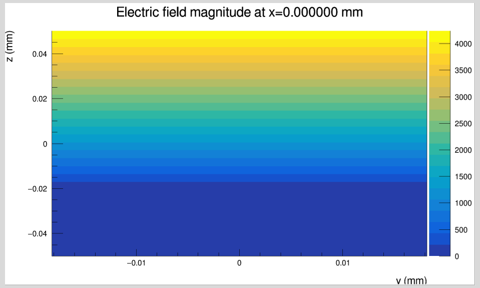
|V|
6
9
15
20
25
30

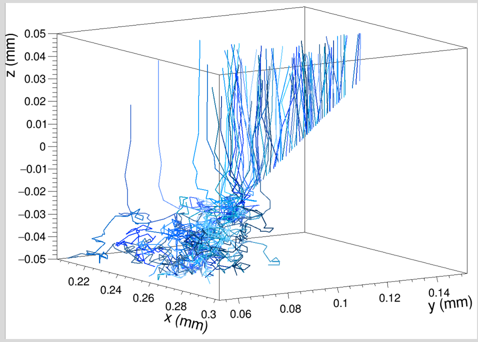
$$E(z) = \frac{|U_{bias}| - |U_{depl}|}{d} + 2\frac{|U_{depl}|}{d}\left(1 - \frac{z}{d}\right)$$

Linear Electric Field

$$w_d \propto \sqrt{V_b}$$

Depletion Width





Parameter	Value
Angles	0 - 60 degrees
Increment	5 degrees

Simulation Workflow

|v|
6
9
15
20
25
30

$$E(z) = \frac{|U_{bias}| - |U_{depl}|}{d} + 2\frac{|U_{depl}|}{d}\left(1 - \frac{z}{d}\right)$$

Linear Electric Field

$$w_d \propto \sqrt{V_b}$$

Depletion Width

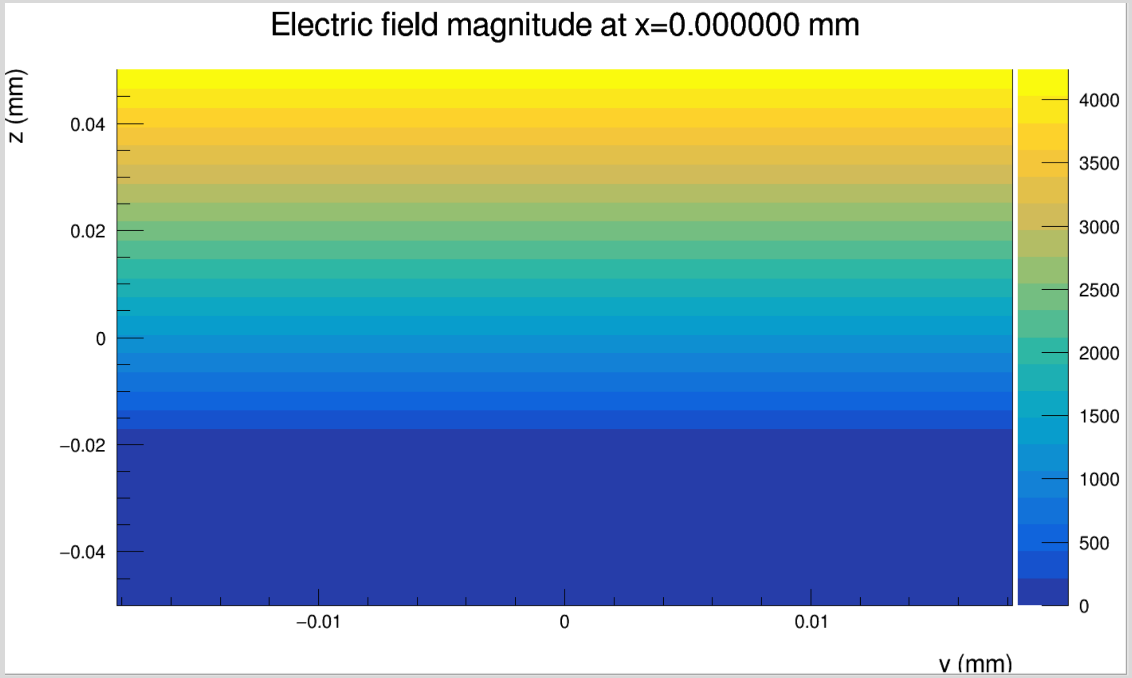
Simulation Workflow

$$E(z) = \frac{|U_{bias}| - |U_{depl}|}{d} + 2\frac{|U_{depl}|}{d}\left(1 - \frac{z}{d}\right)$$

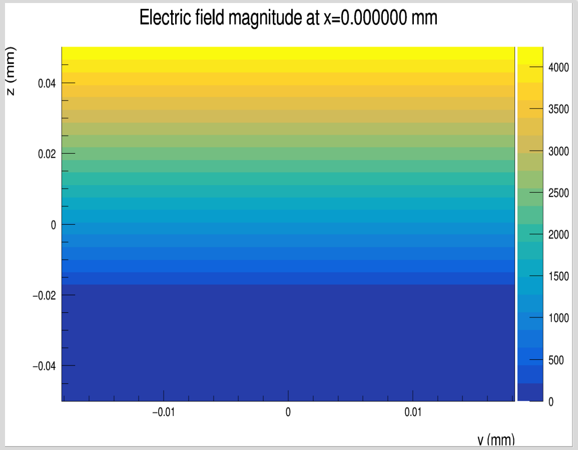
Linear Electric Field

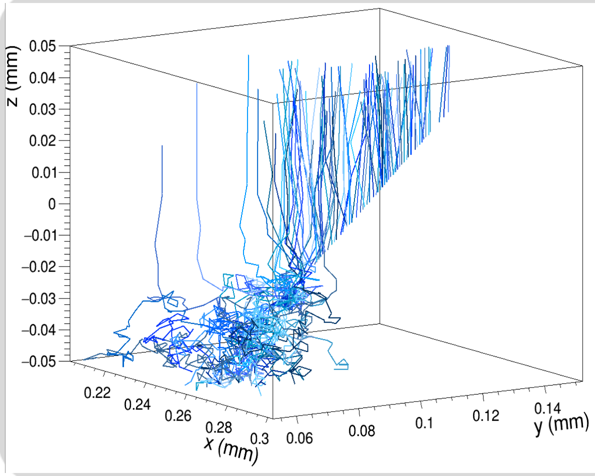
$$w_d \propto \sqrt{V_b}$$

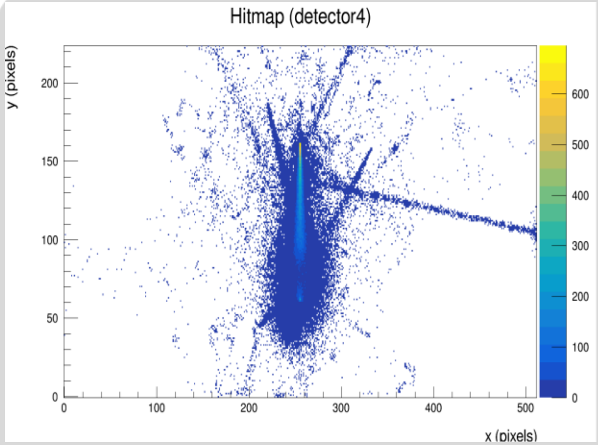
Depletion Width



Simulation Workflow







Parameter	Value
Angles	0 - 60 degrees
Increment	5 degrees

Simulation Implementation

```
[Allpix]
log_level = "INFO"
log_format = "DEFAULT"
detectors_file = "Detector.conf"
model_paths = "/home/user287/allpix-squared/Summe_Internship/"
number_of_events = 10000

[GeometryBuilderGeant4]
world_material = "vacuum"
world_margin_percentage = 0
world_minimum_margin = 2m 2m 2m

[DepositionGeant4]
physics_list = FTFP_BERT_LIV
particle_type = "Proton"
source_energy = 180GeV
source_position = 0mm 0mm -100mm
source_type = "beam"
beam_size = 10nm
beam_direction = 0 0 1
number_of_particles = 1
max_step_length = 1um
```

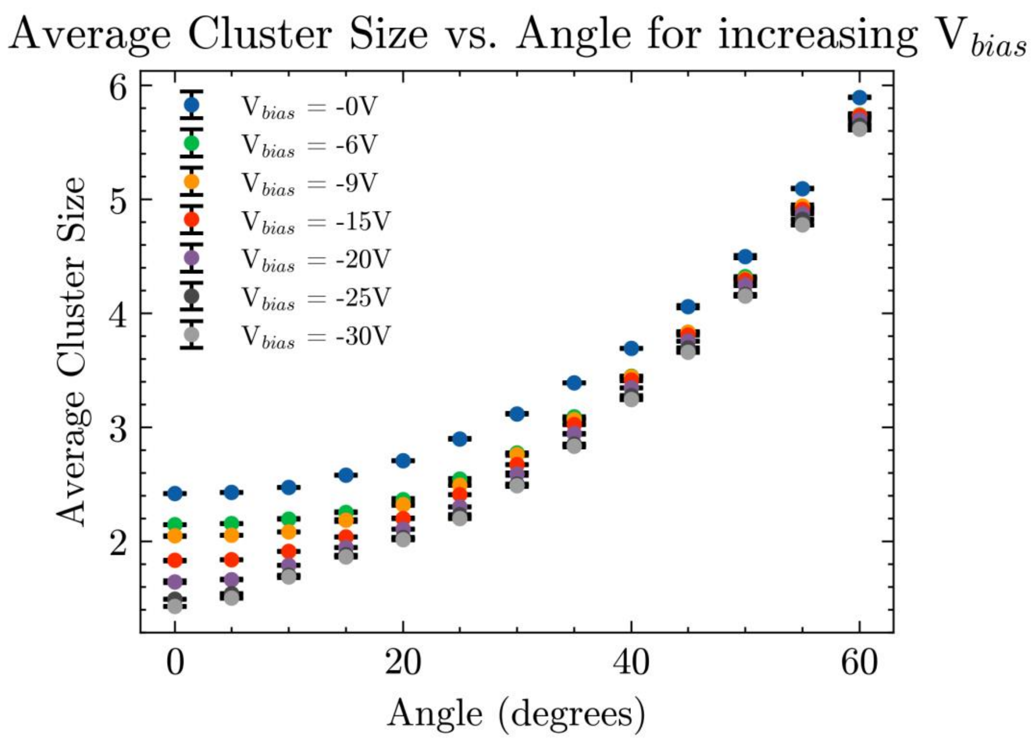
```
[ElectricFieldReader]
model = "linear"
bias_voltage = -15V
depletion_voltage = -30V
output_plots = true

[GenericPropagation]
temperature = 258.15K
charge_per_step = 100
integration_time = 25ns
output_plots = true
#output_linegraphs = true

[PulseTransfer]
max_depth_distance = 100um
output_plots = true

[DefaultDigitizer]
threshold = 260e

[DetectorHistogrammer]
name = "detector4"
```

Allpix²: Simulation configuration

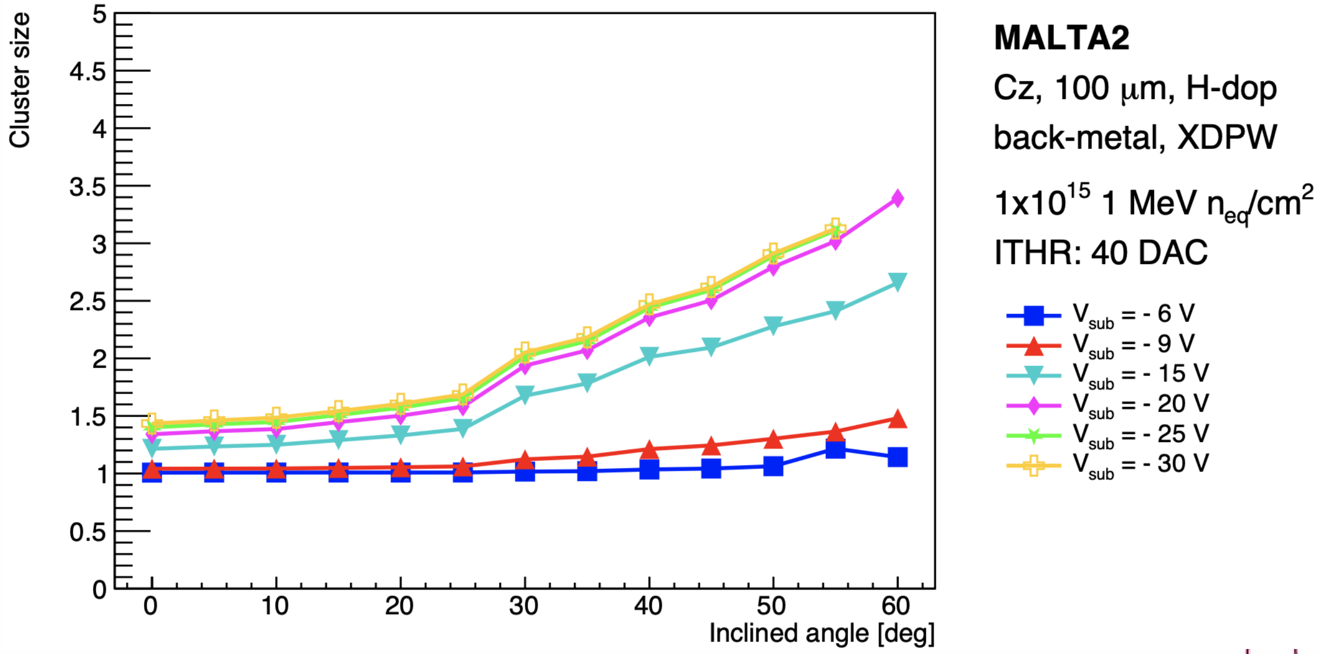
```
[detector4]
type = "alpide"
position = 0 0 550mm
orientation = 30deg 0deg 0deg
type = "monolithic"
geometry = "pixel"

number_of_pixels = 512 224
pixel_size = 36.4um 36.4um


#Sensor chip size = 20.2mm 10.1168mm
sensor_thickness = 100um
sensor_excess_top = 0.9812mm
sensor_excess_bottom = 0.9812mm
sensor_excess_left = 0.7816mm
sensor_excess_right = 0.7816mm
```

Allpix²: Detector set-up

Telescope Pixel Cluster Size vs Incident Angle

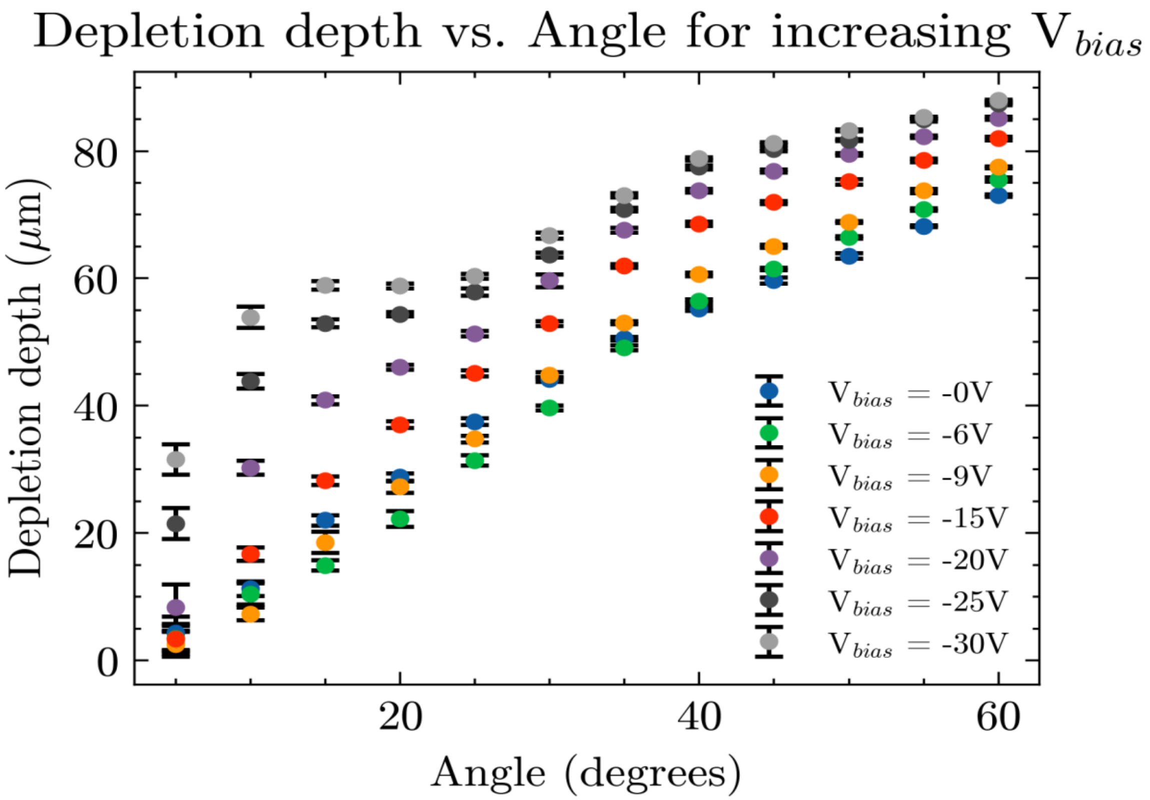


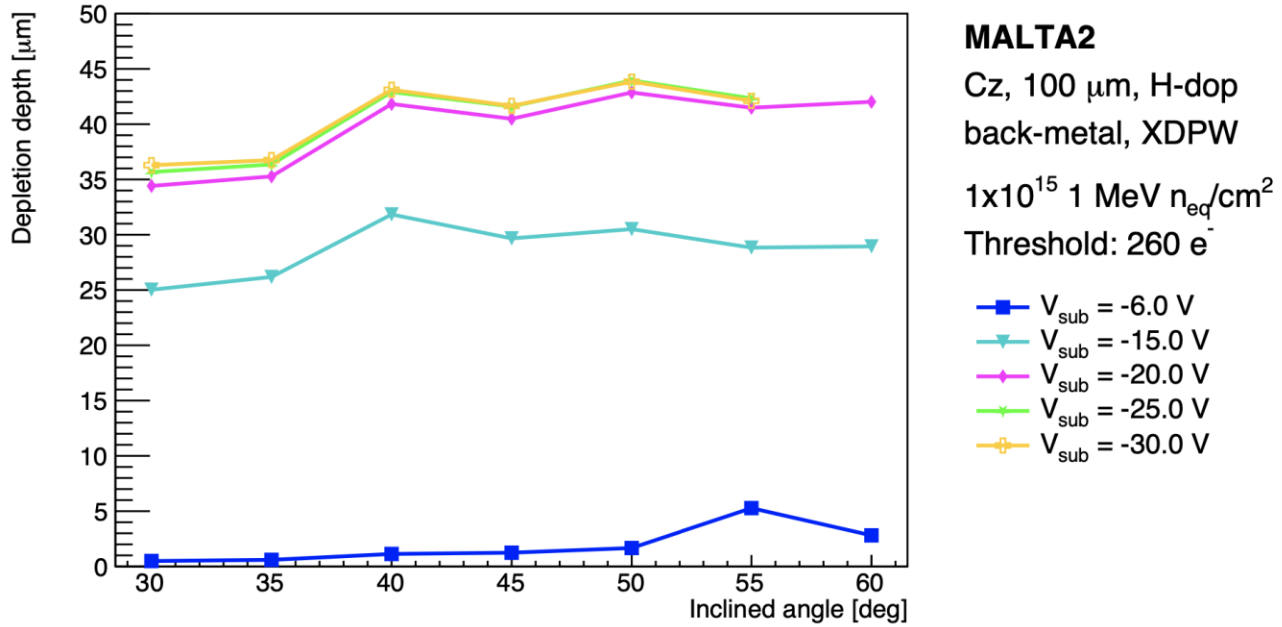
Cluster Size: Simulation, unirradiated



Cluster Size: Test beam, irradiated

Telescope Pixel Depletion Depth vs Incident Angle

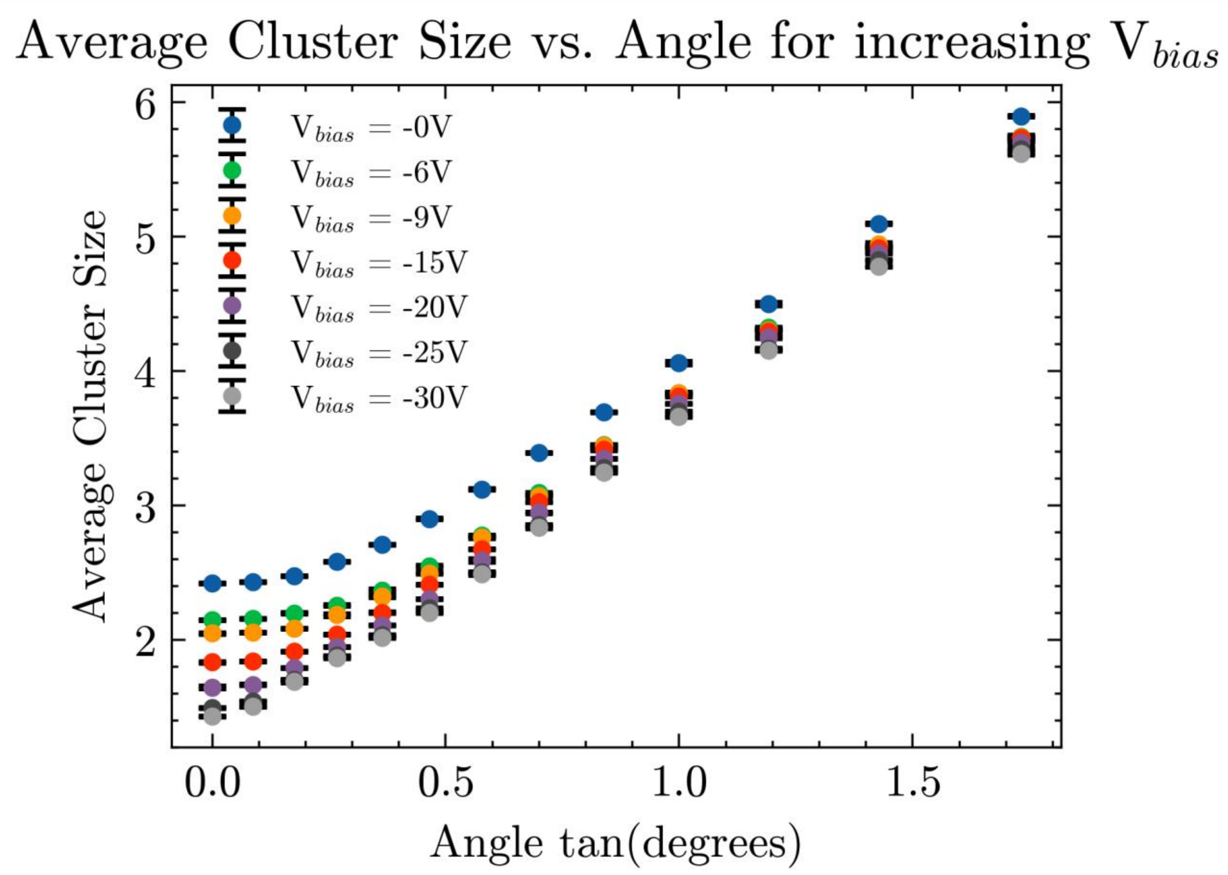




Depletion depth: Simulation, unirradiated

Depletion depth: Test beam, irradiated

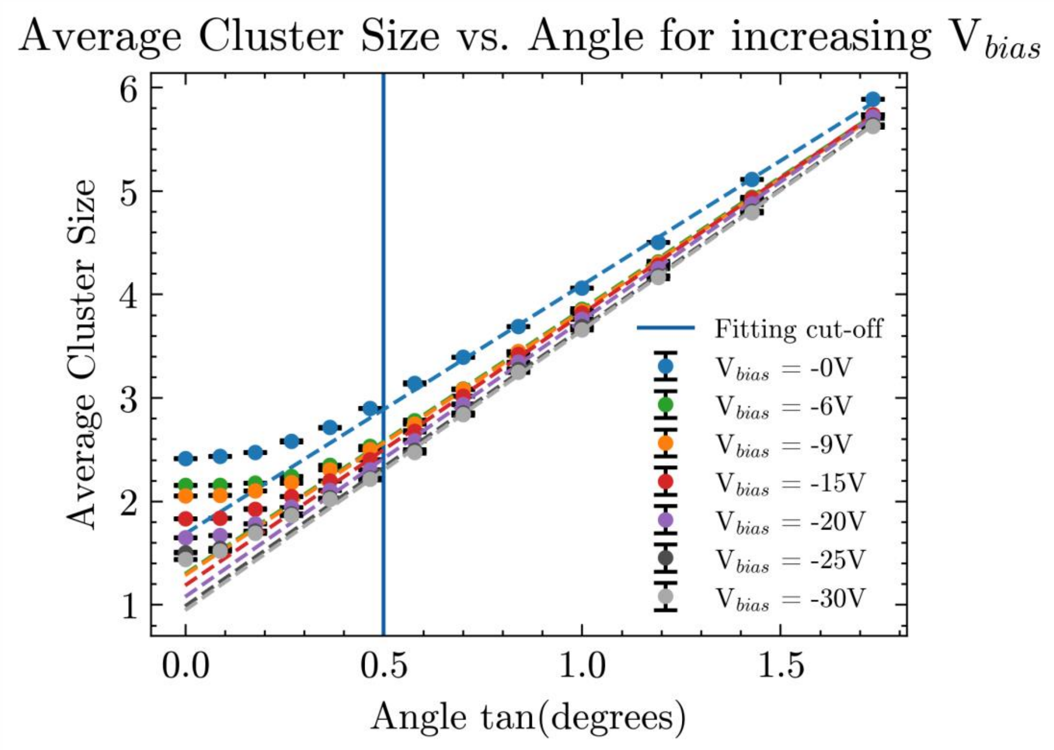
Telescope Pixel Cluster Size vs tan(Incident Angle)



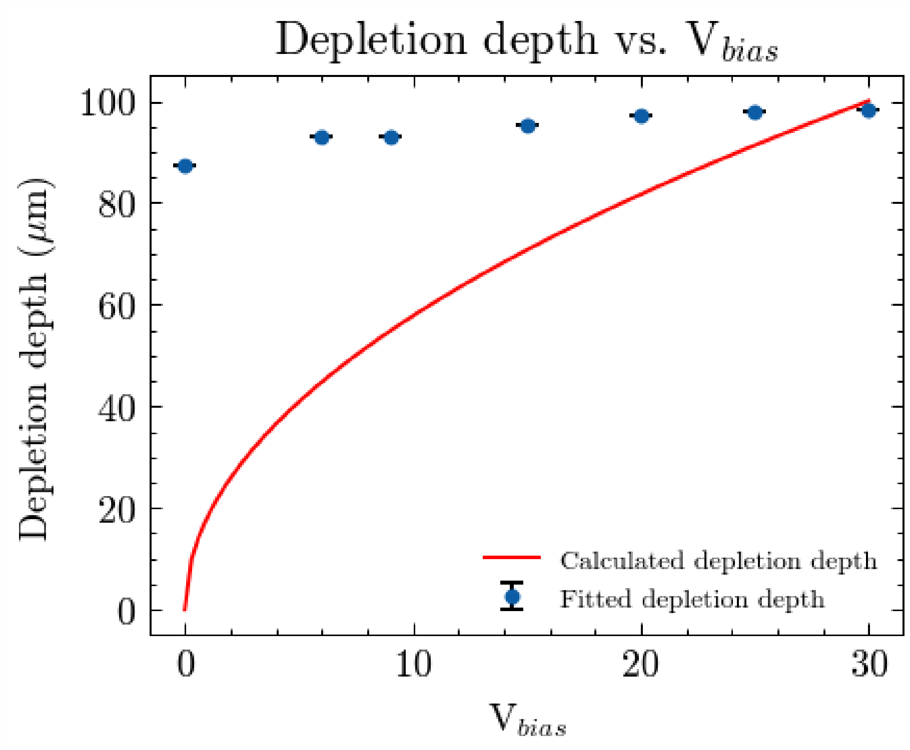
$$Cluster(\tan(\alpha)) = \frac{d}{p}\tan(\alpha) + Cluster(0)$$

Scaled Cluster Size: Simulation, unirradiated

Linear Fit to Telescope Cluster Size Data



Scaled Cluster Size: Simulation, unirradiated



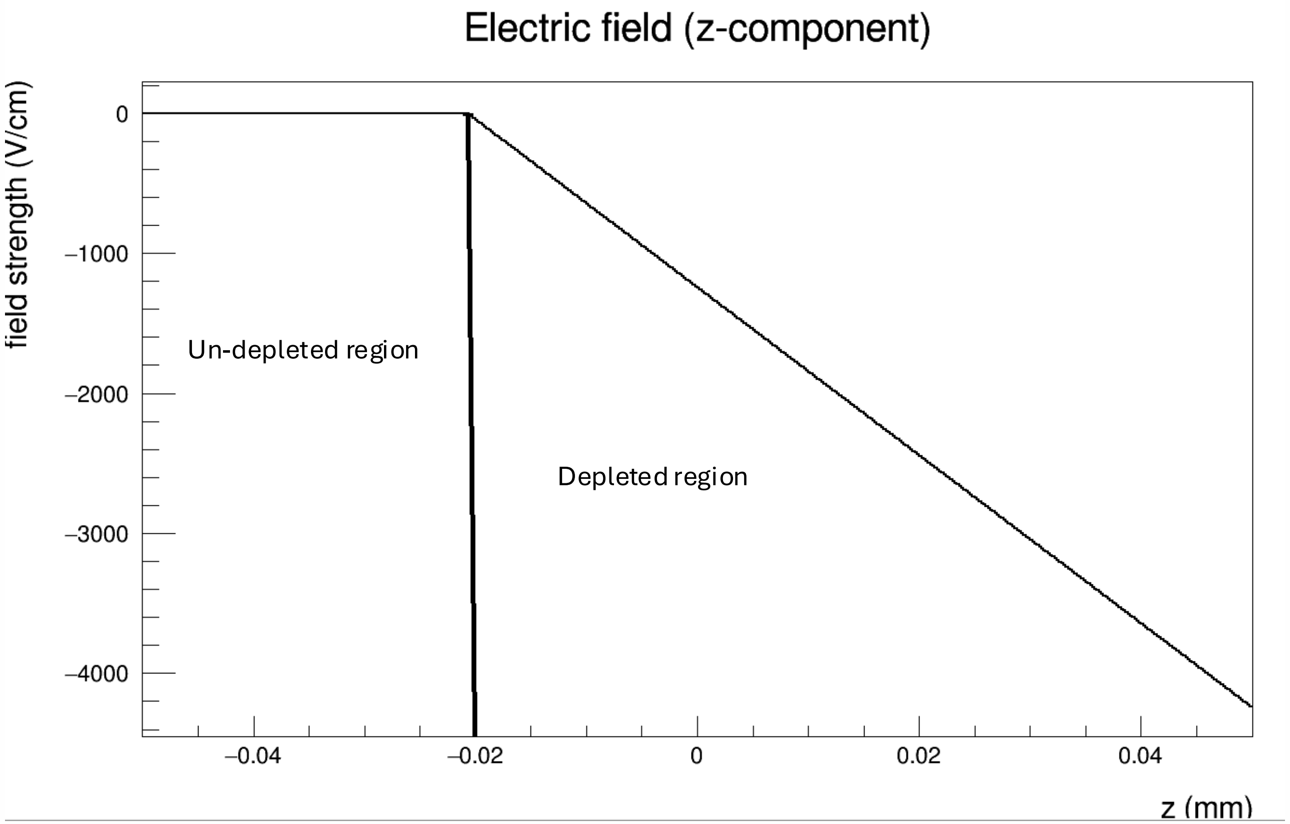
Fitted Depletion Depth: Simulation, unirradiated

Linear Electric Field Investigation

- When $V_{bias} < V_{depl}$,

$$w_d \propto \sqrt{V_b}$$

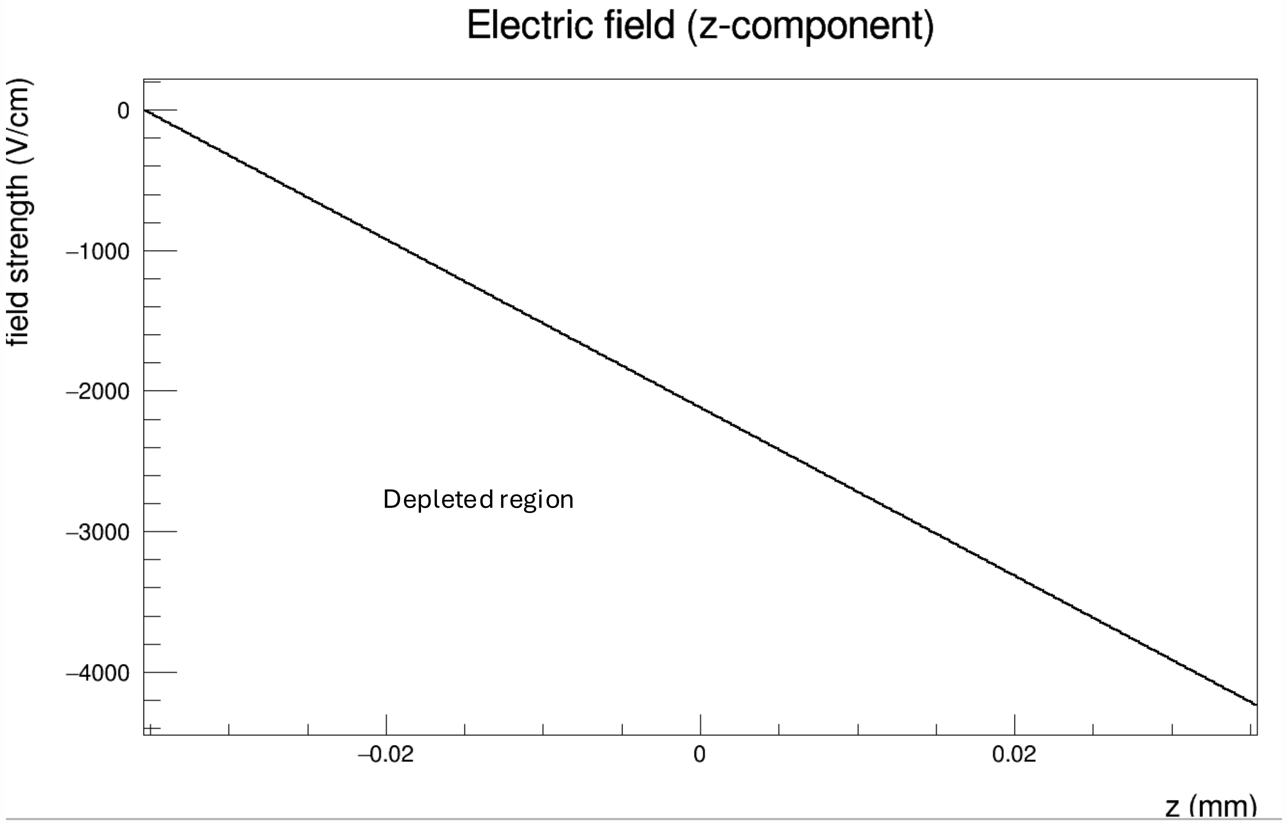
- Undepleted region produces diffusion charges
- Test diffusion charges contribution by reducing sensor thickness for given bias voltage



Electric Field: z-projection, V_{bias} = -15V, V_{depl} = -30V, full 100µm thickness

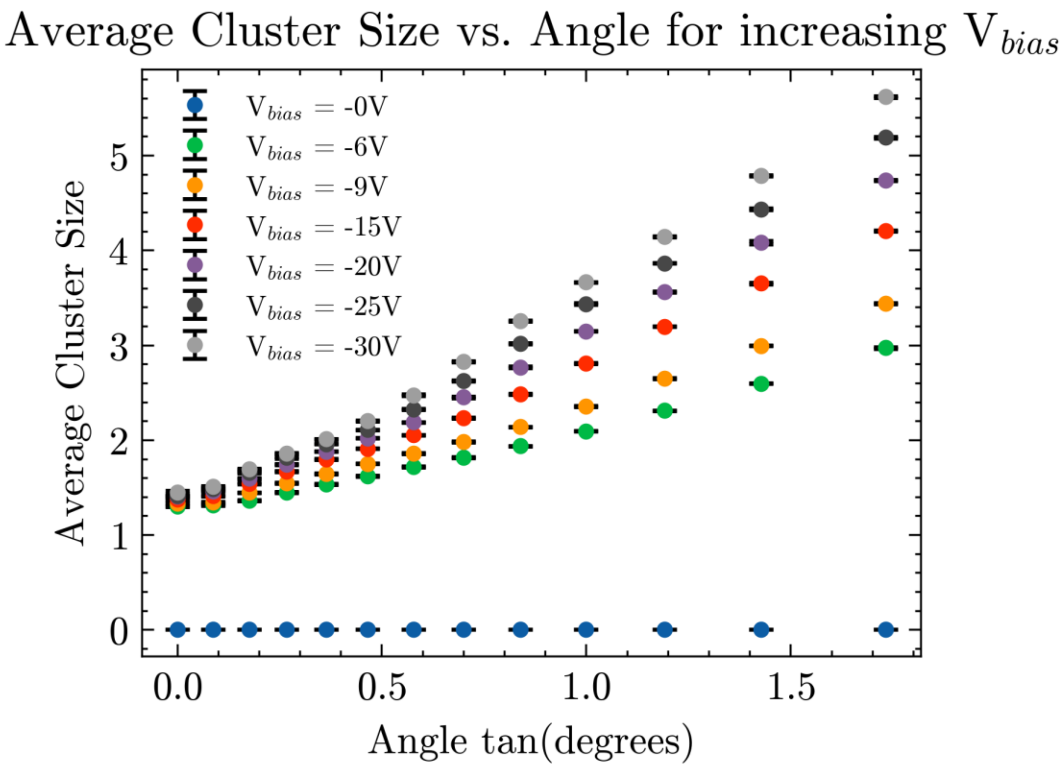
Linear Electric Field Investigation Method

$\lvert V_{bias} \rvert$ (V)	W_d (μm)
6	44.8
9	54.8
15	70.8
20	81.6
25	91.2
30	100

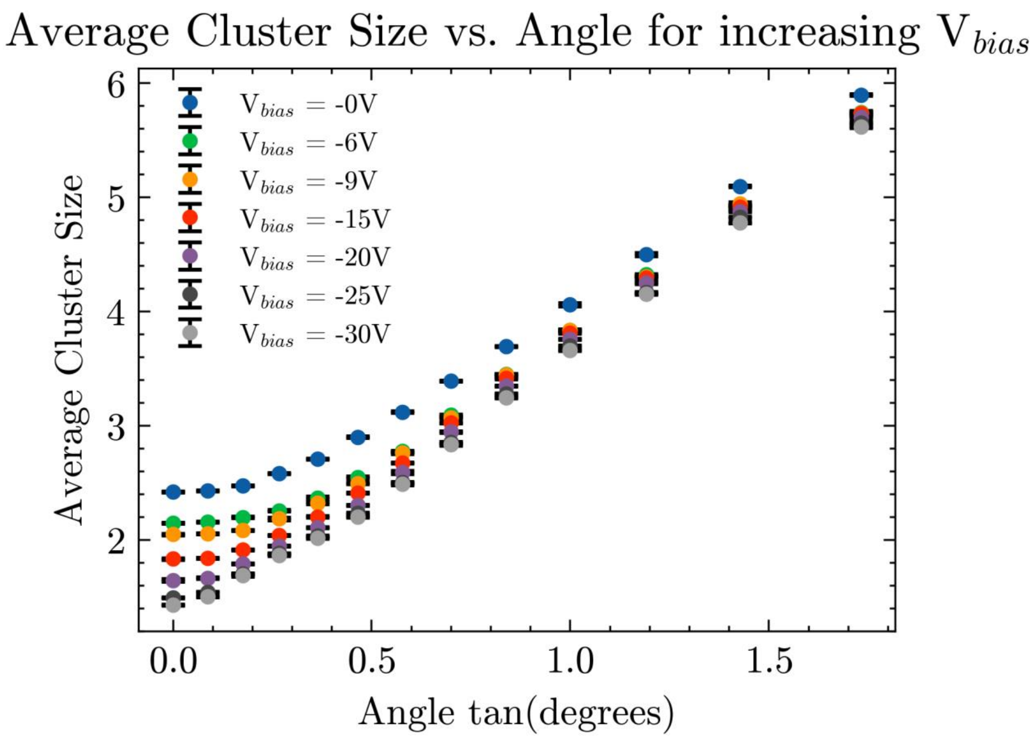


Electric Field: z-projection, $V_{depl} = V_{bias}$ = -15V, w_d = 70.8 μm

Linear Electric Field Investigation Results

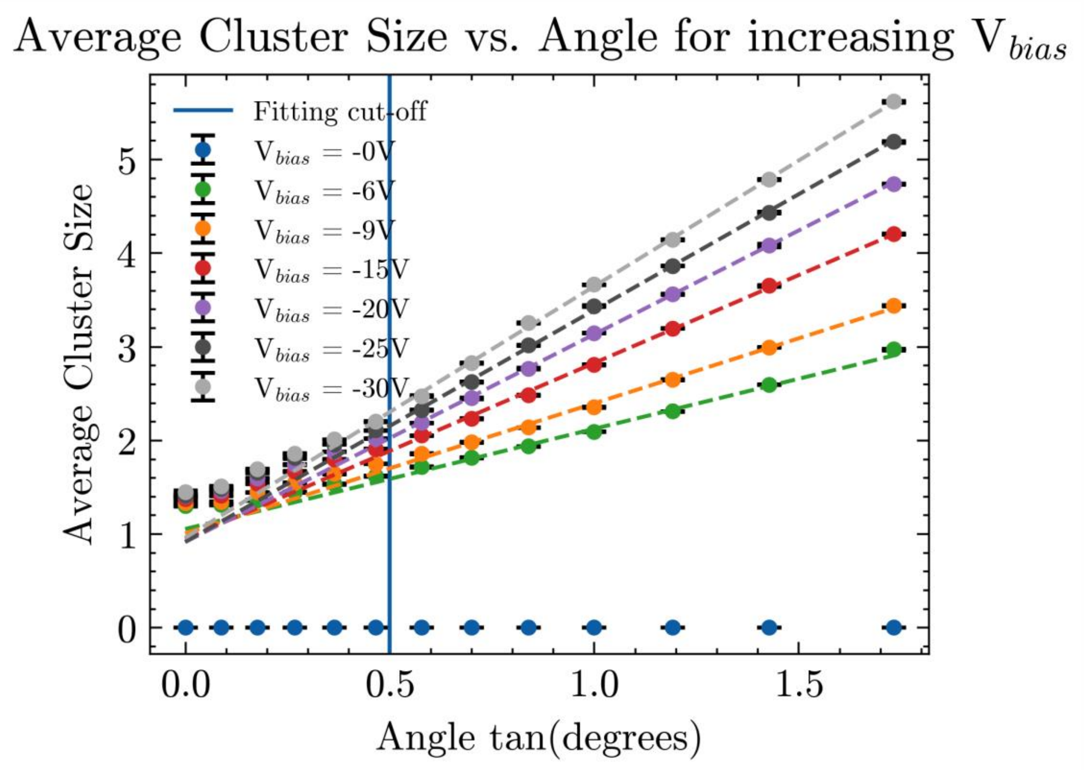


Scaled Cluster Size: Simulation, unirradiated, reduced thickness

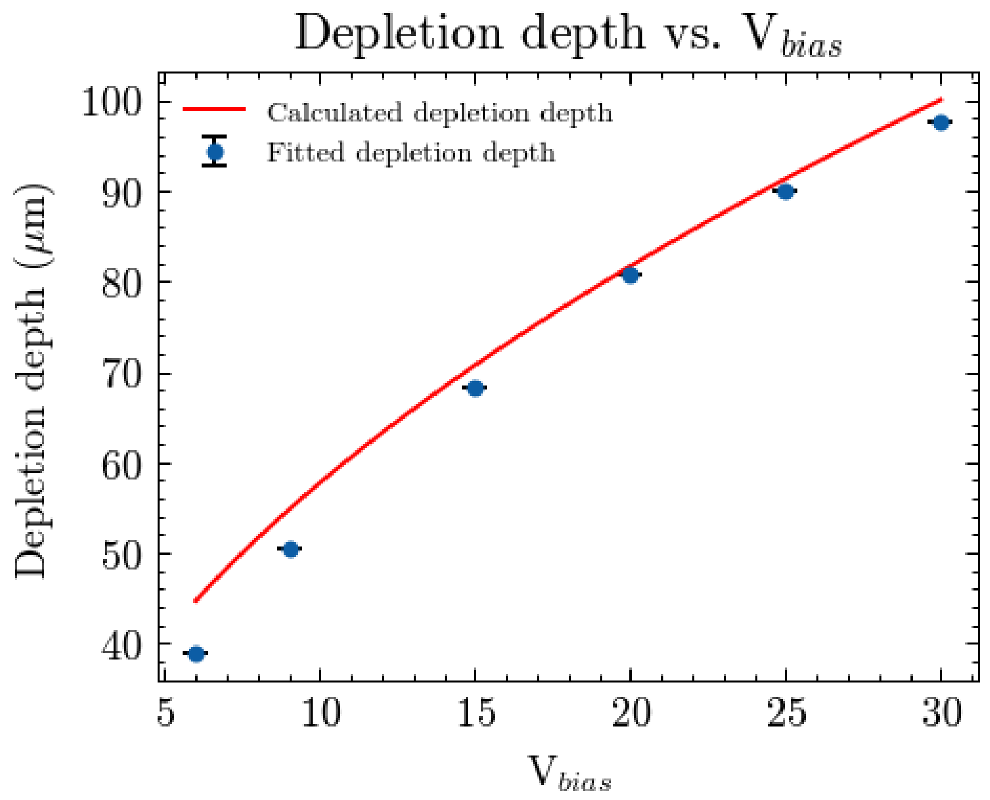


Scaled Cluster Size: Simulation, unirradiated, 100 μm sensor thickness

Linear Electric Field Investigation Results

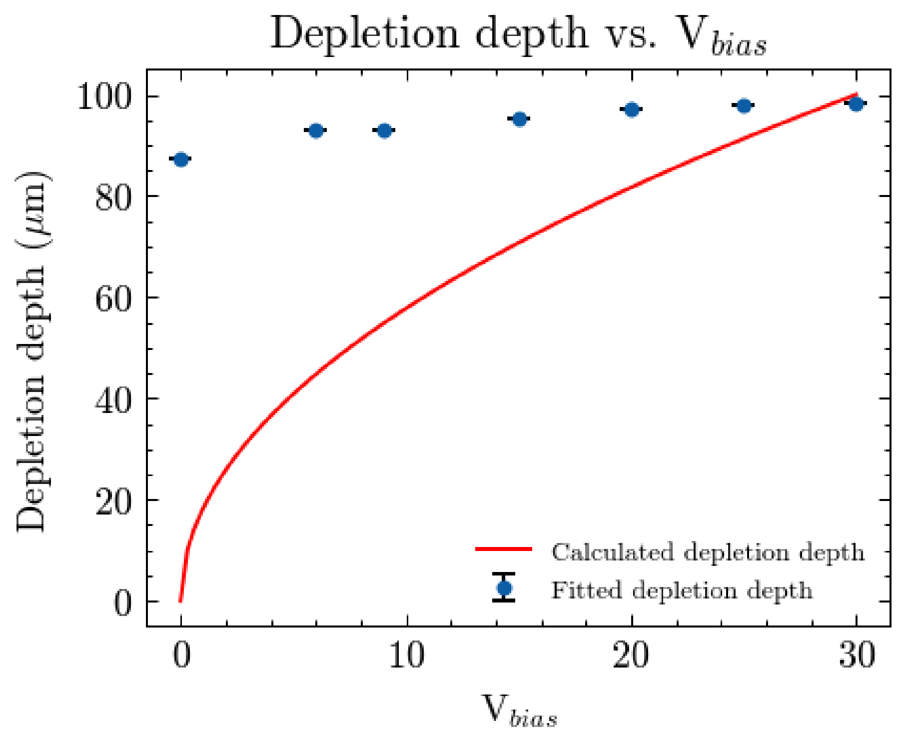


Scaled Cluster Size: Simulation, unirradiated, reduced thickness

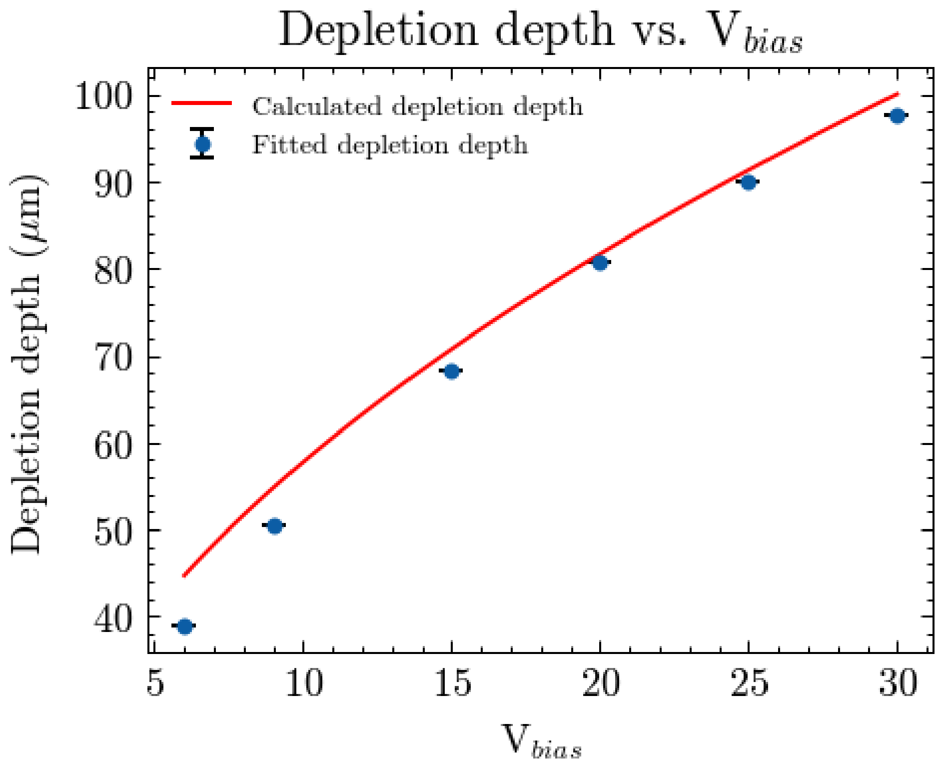


Fitted Depletion Depth: Simulation, unirradiated, reduced thickness

Linear Electric Field Investigation Results



Fitted Depletion Depth: Simulation, unirradiated, 100 µm sensor thickness

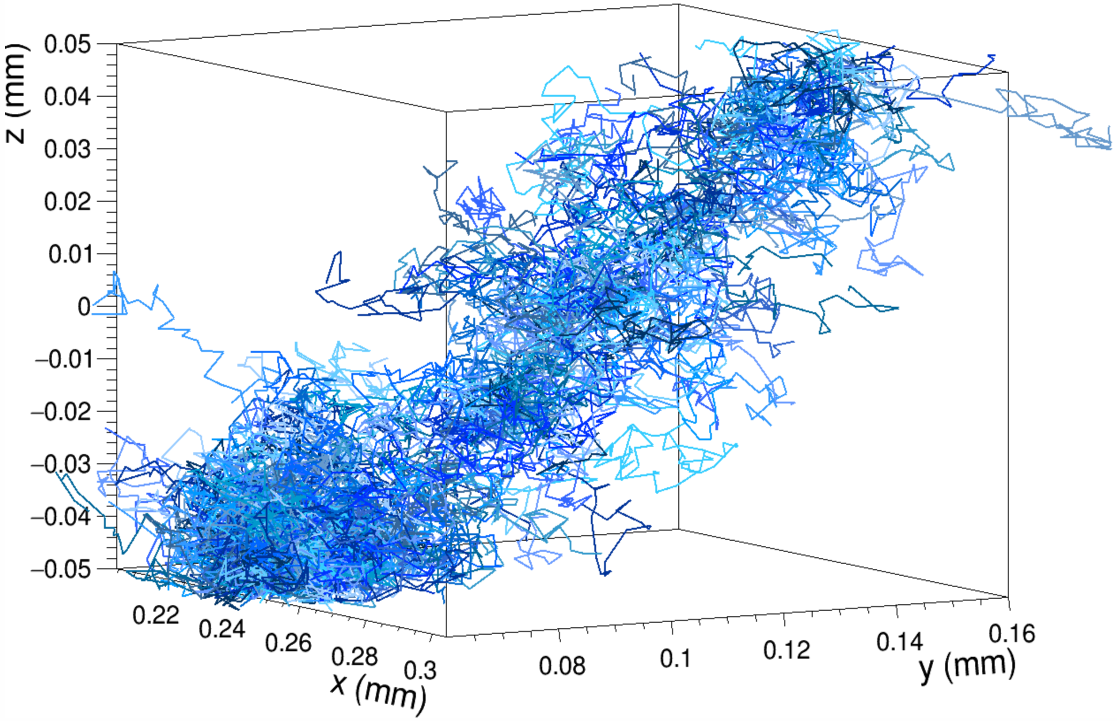


Fitted Depletion Depth: Simulation, unirradiated, reduced thickness

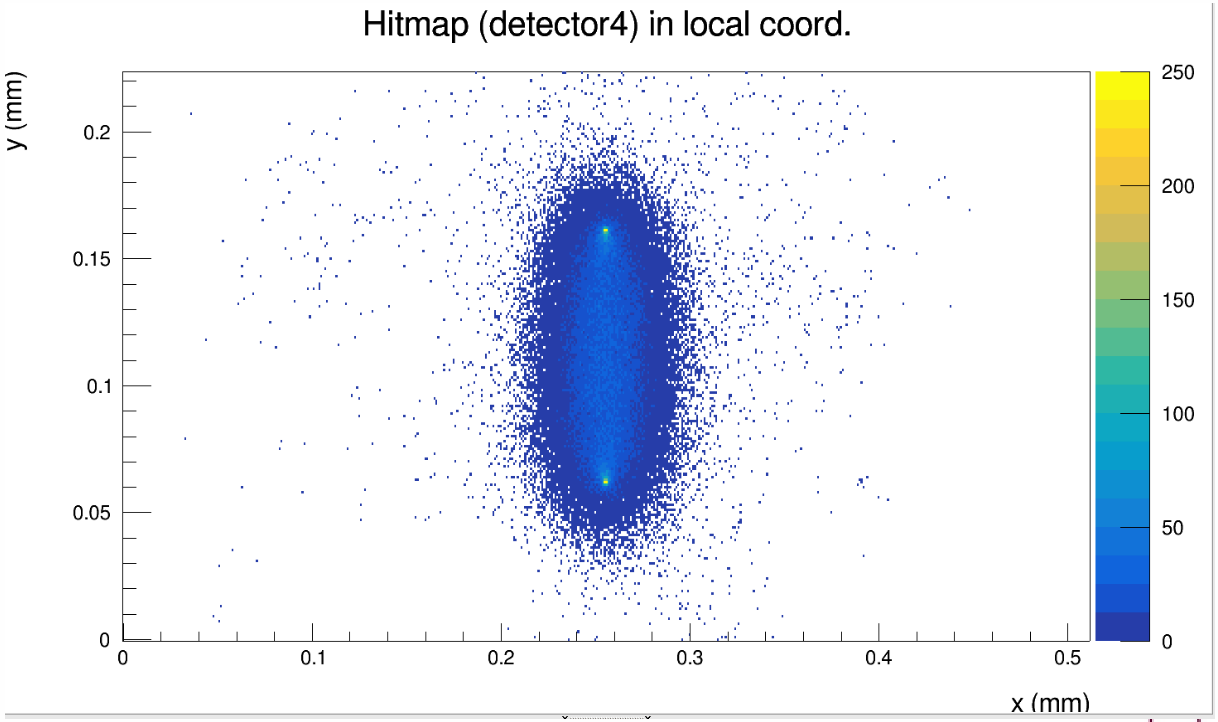
Lineplots and Hitmaps Method

- Telescope removed to reduce spread on hitmap
- 1μm pixel pitch for increasing granularity
- 10nm beam size for more repeatable hits
- 25ns integration time as standard (MALTA2 integration time)
- Data for 1 event taken to produce lineplots
- Data for 10K events taken to produce hitmaps

V_{depl}= -30V, V_{bias} = 0V

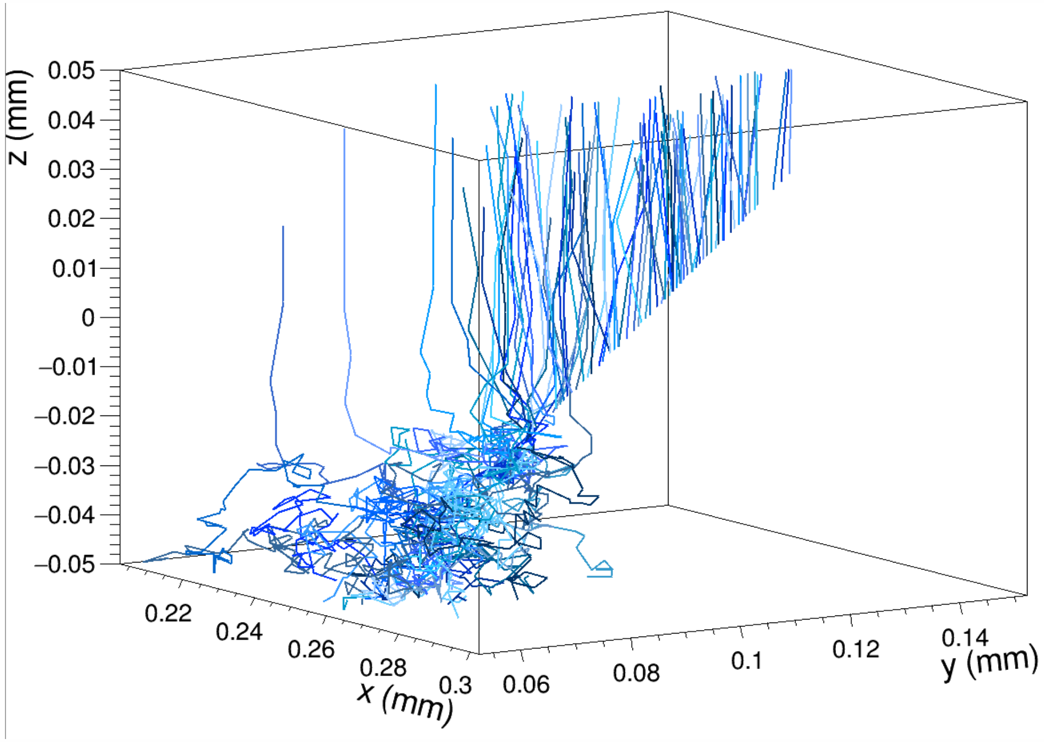


Lineplot: 45 degrees incline

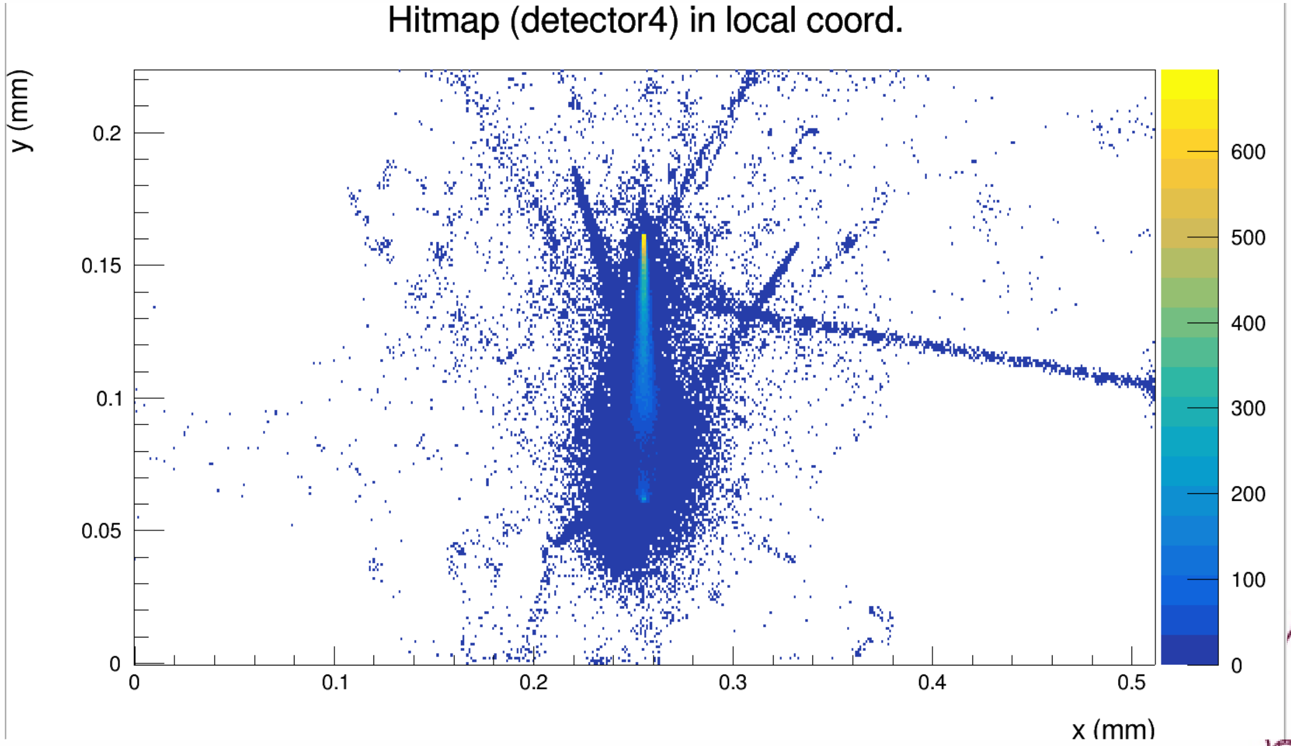


Hitmap: 45 degrees incline

V_{depl}= -30V, V_{bias} = -15V



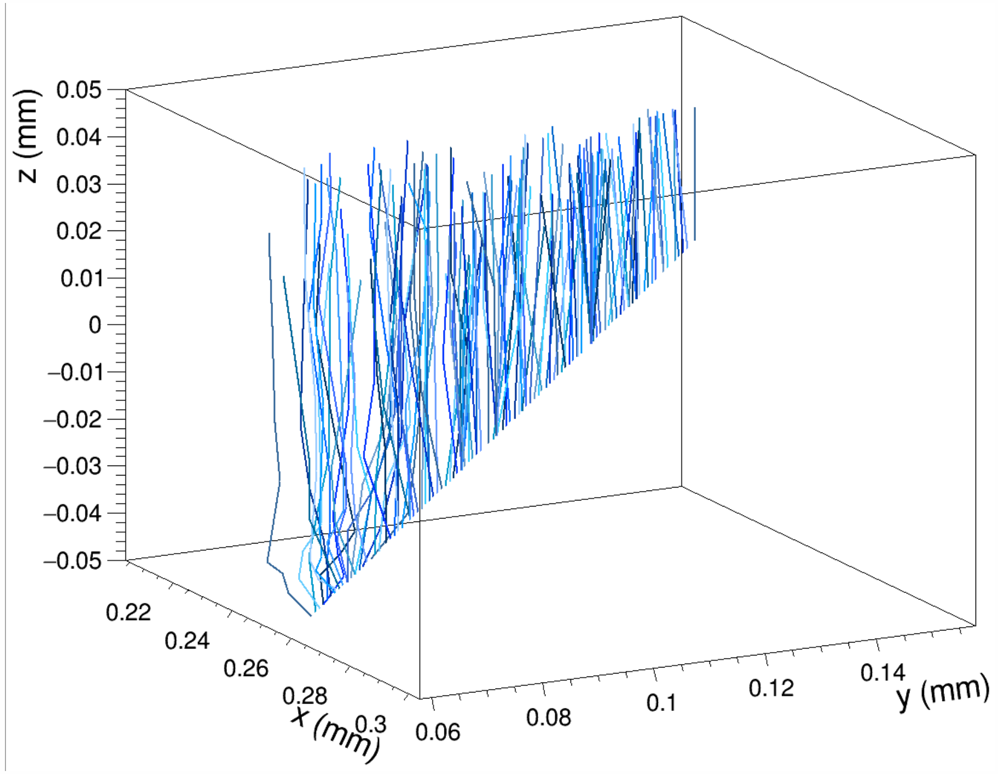
Lineplot: 45 degrees incline



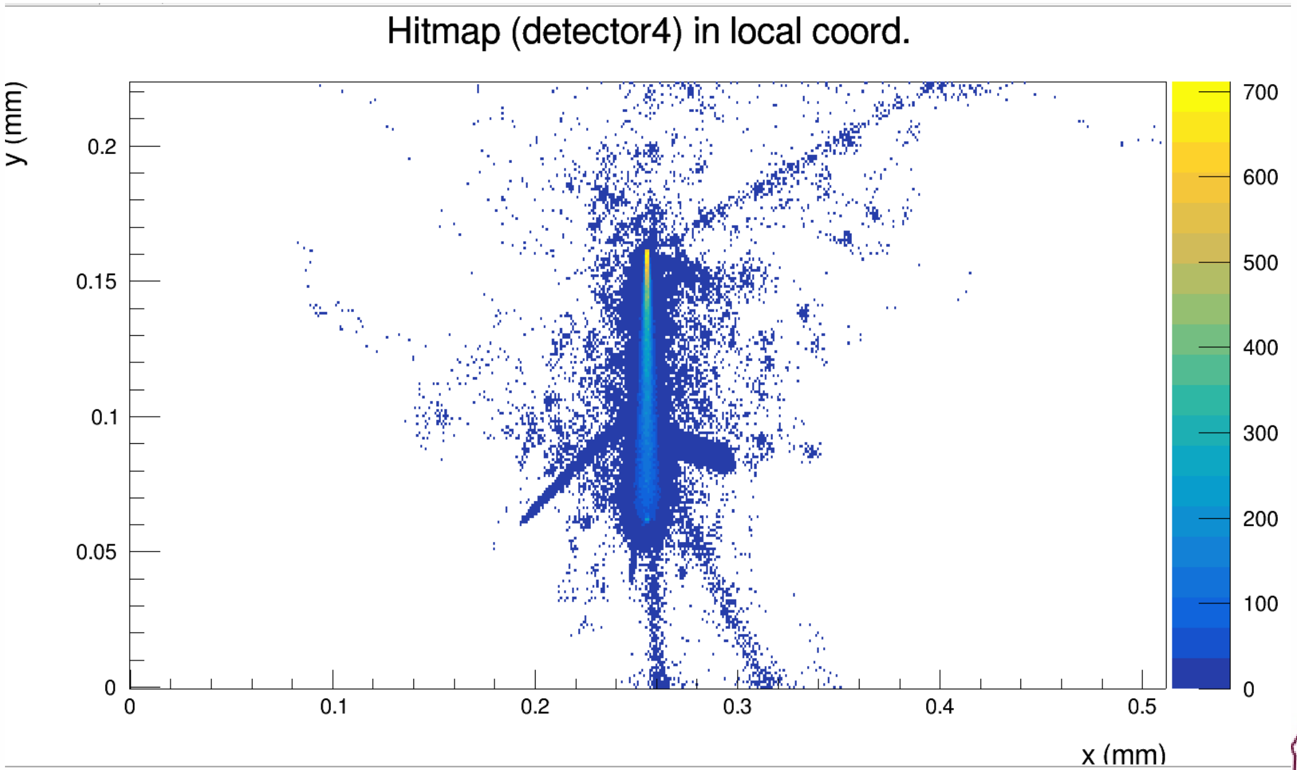
Hitmap: 45 degrees incline

Lineplot: 45 degrees incline

V_{depl}= -30V, V_{bias}= -30V

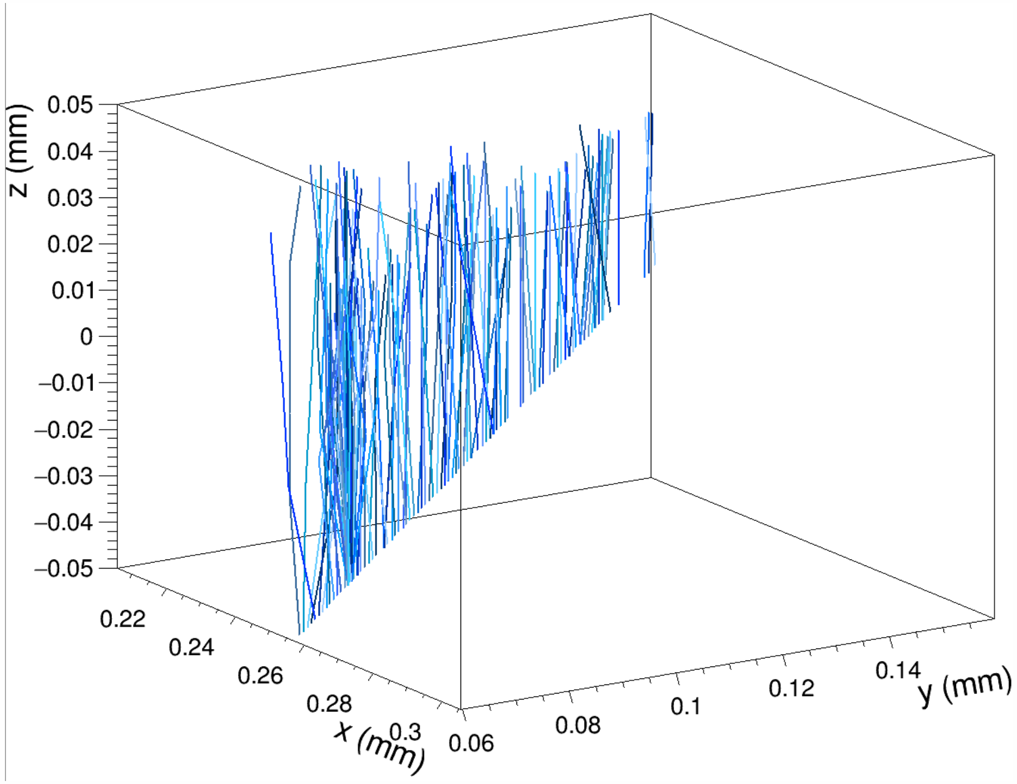


Lineplot: 45 degrees incline

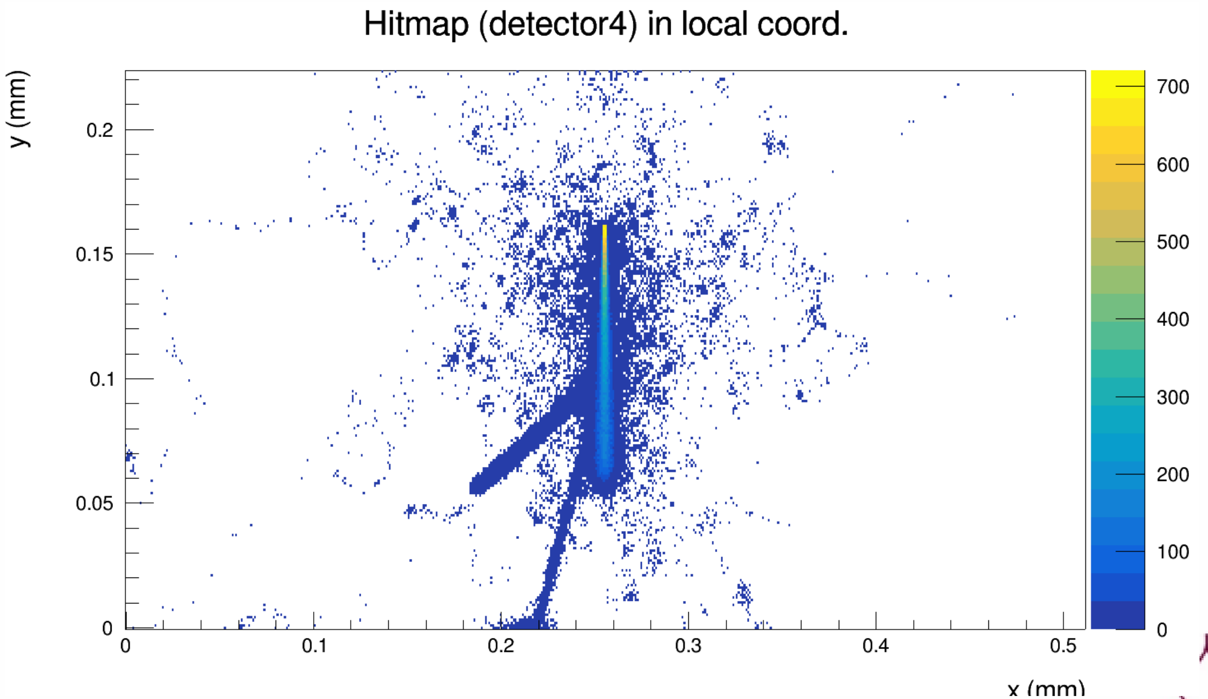


Hitmap: 45 degrees incline

V_{depl}= -30V, V_{bias} = -50V

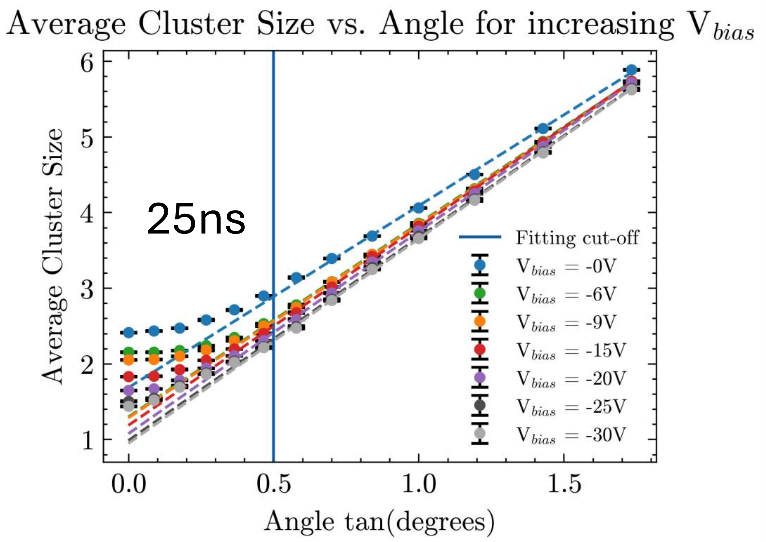


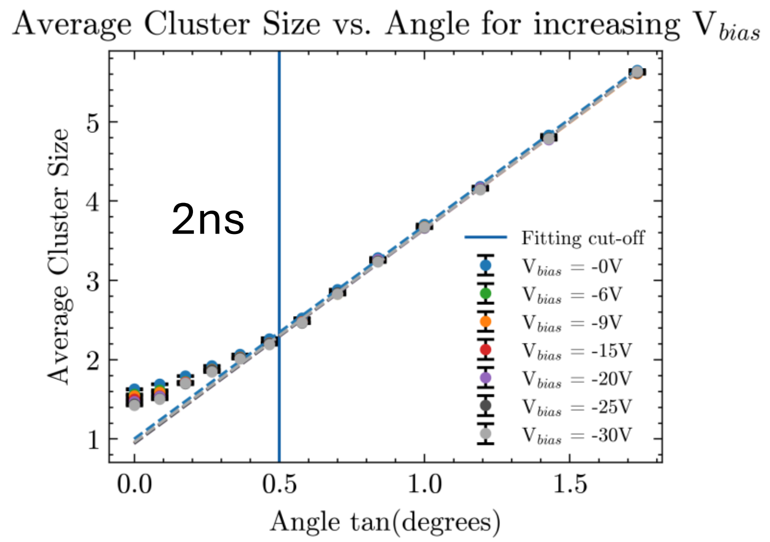
Lineplot: 45 degrees incline

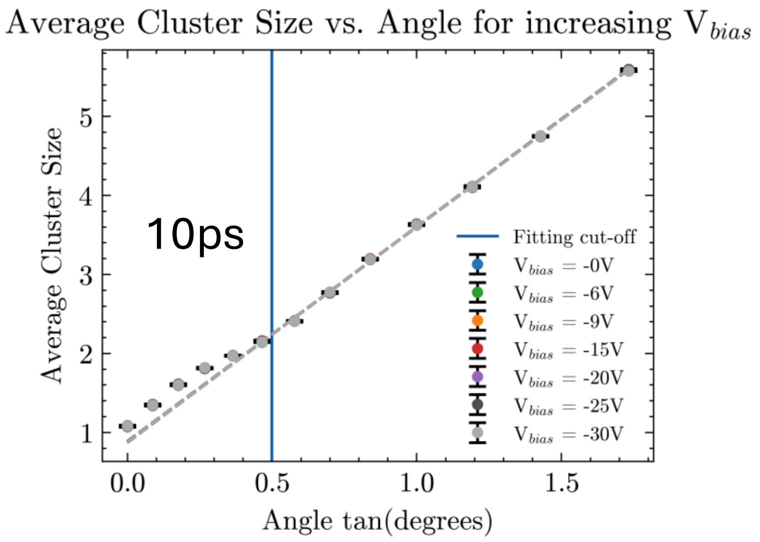


Hitmap: 45 degrees incline

Integration Time Investigation Cluster Sizes

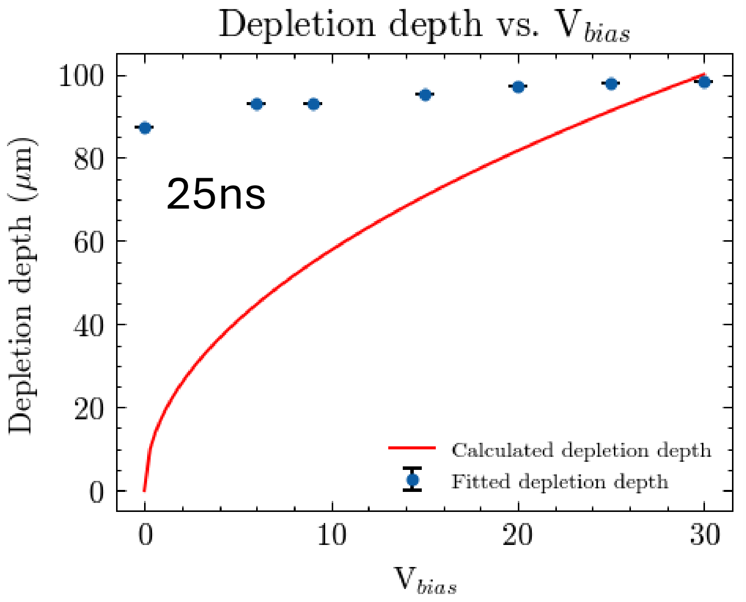


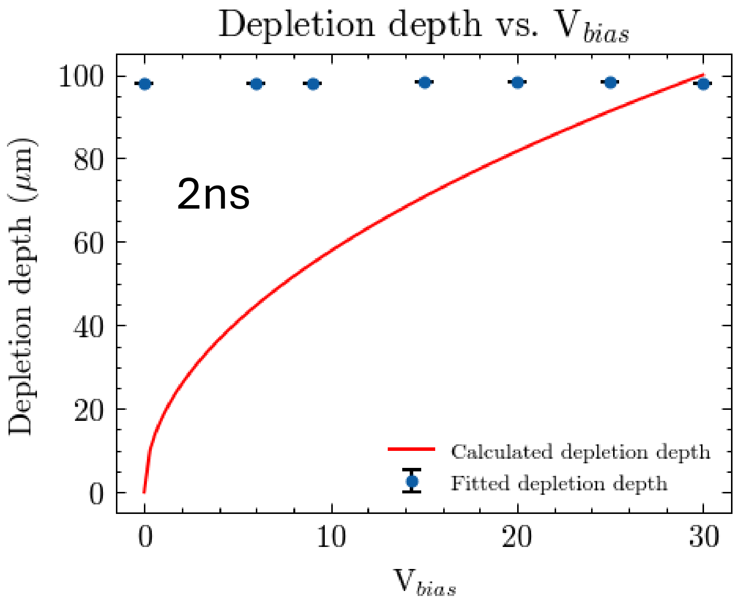


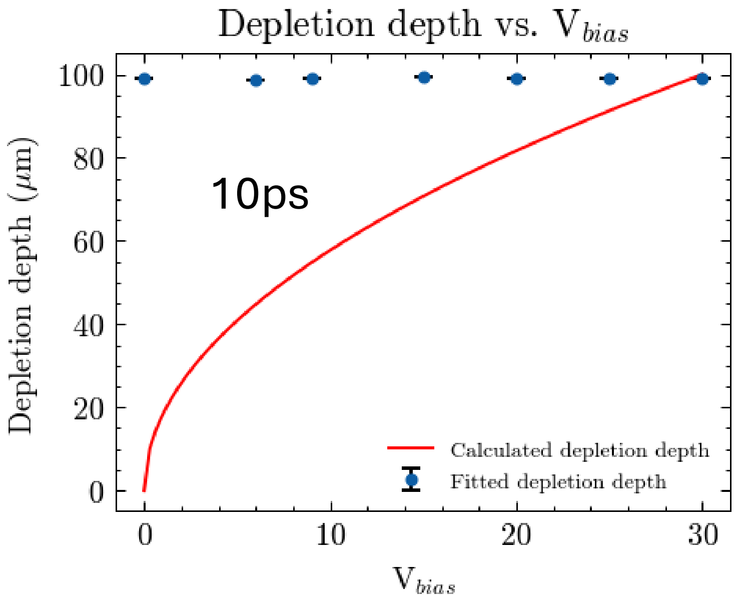


Fitted Depletion Depth: Simulation, unirradiated, timing information

Integration Time Investigation Calculated and Actual Depletion Depth

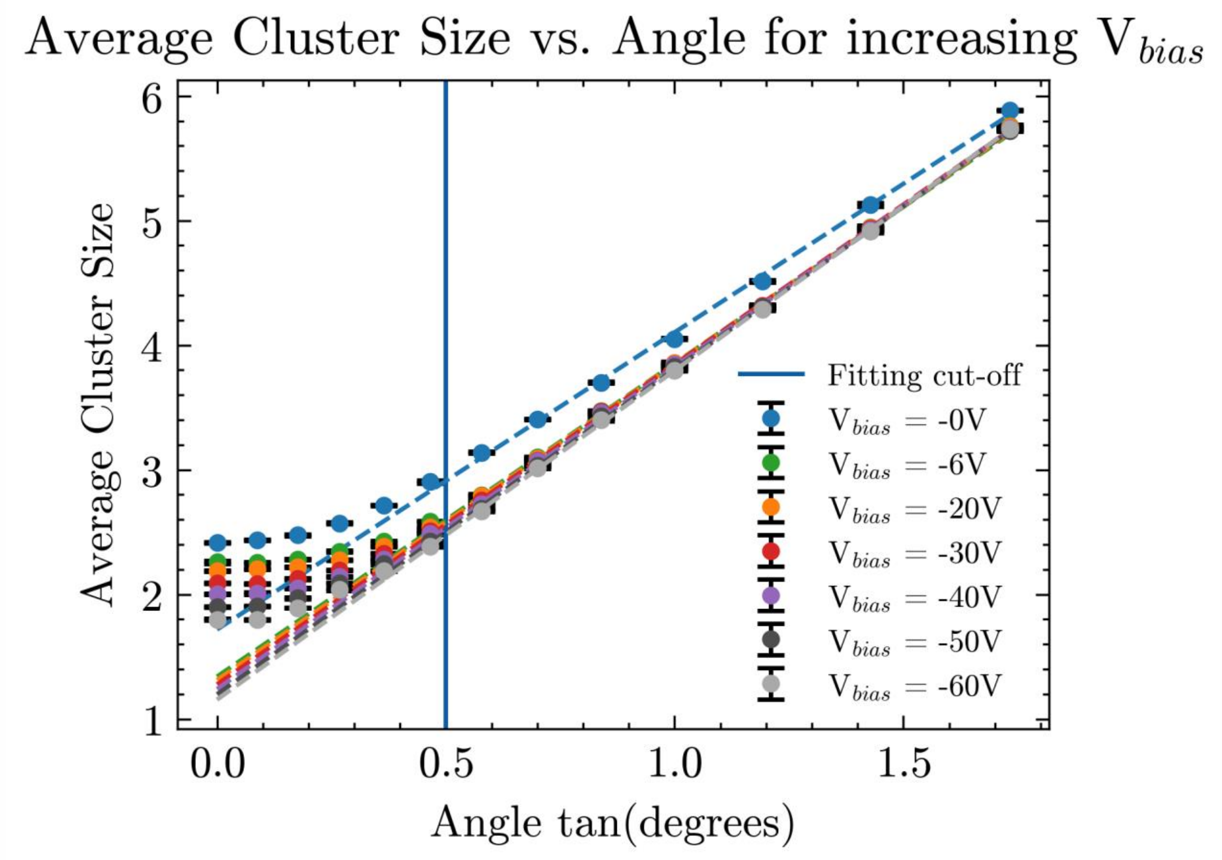




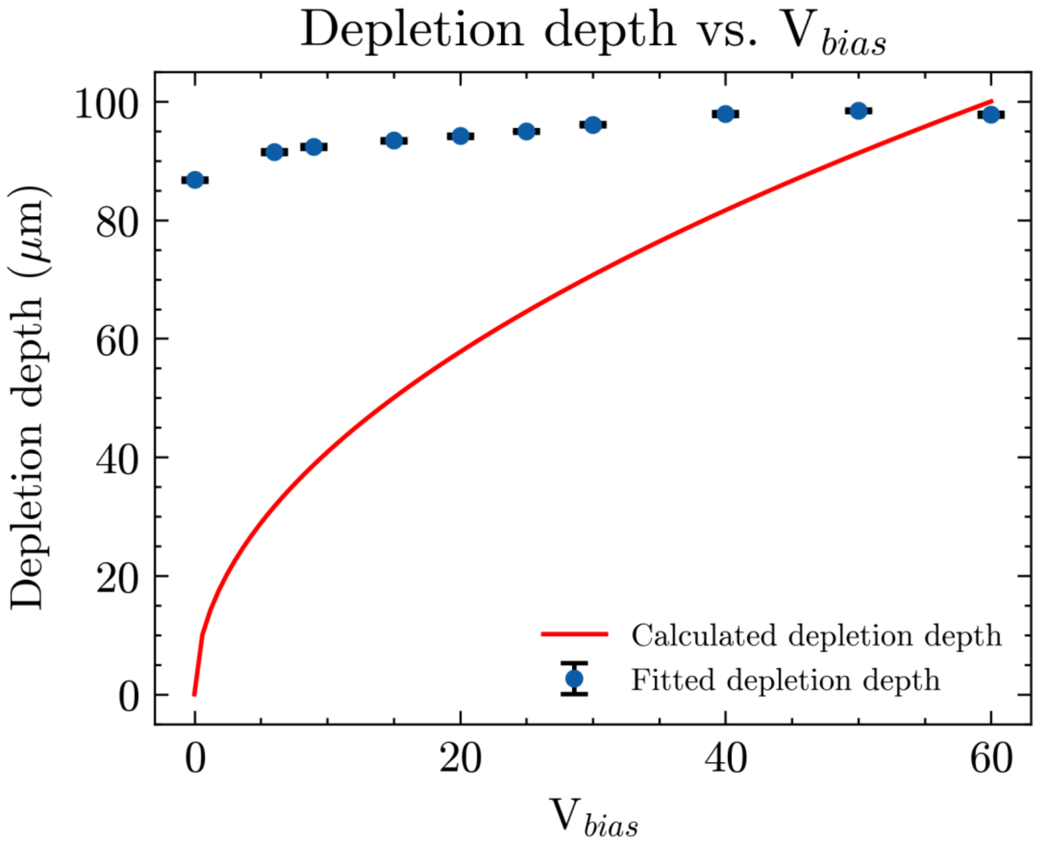


Scaled Cluster Size: Simulation, unirradiated, timing information

V_{depl} = -60V Data



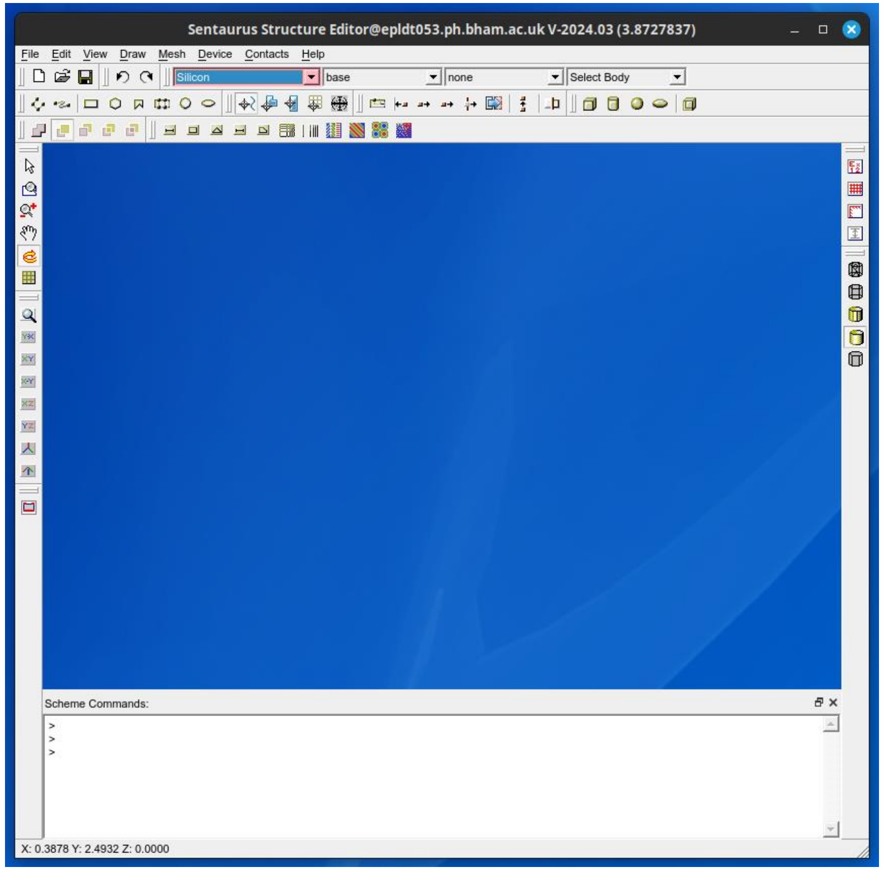
Scaled Cluster Size: Simulation, unirradiated



Fitted Depletion Depth: Simulation, unirradiated

Conclusions

- Diffusion charges significant in clustering data at low bias voltages and incident angles
- Further study of timing information required to understand charge propagation
- Need to change the electric field linear → mesh using TCAD software
- Long's talk will give an overview of irradiated sensor results



Sentaurus Structure Editor, showing lack of 3D rendering

References

- [1]: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-050/
- [2]: https://cds.cern.ch/record/2776651/files/ATL-PHYS-PUB-2021-024.pdf
- [3]: https://eprints.gla.ac.uk/270885/1/270885.pdf
- [4]: https://cds.cern.ch/record/2894529/files/Publication.pdf

Back-up Slides

Introduction (NEED TO EDIT)

- Allpix Squared simulation constructed based on example.conf
- 7 MALTA2 detectors used with detector 4 as DUT
- Full depletion voltage set to -30V
- Cluster size data obtained for 0 – 60 degrees in 5-degree increments
- Bias voltages set to -6V, -9V, -15V, -20V, -25V, -30V
- Electron threshold set to 260e
- Process automated using a Python script

The MALTA2 Sensor

Parameter	Value
Sensor Dimensions	20.2 mm x 10.1168 mm
Pixel Pitch	36.4 μm x 36.4 μm
Pixel Matrix	512 x 224
Sensor Thickness	100 μm
Sensor Excess	0.7816 mm x 0.9812 mm
Target Radiation Hardness	3×10^{15} 1 MeV n_{eq}/cm^2 and 100MRad

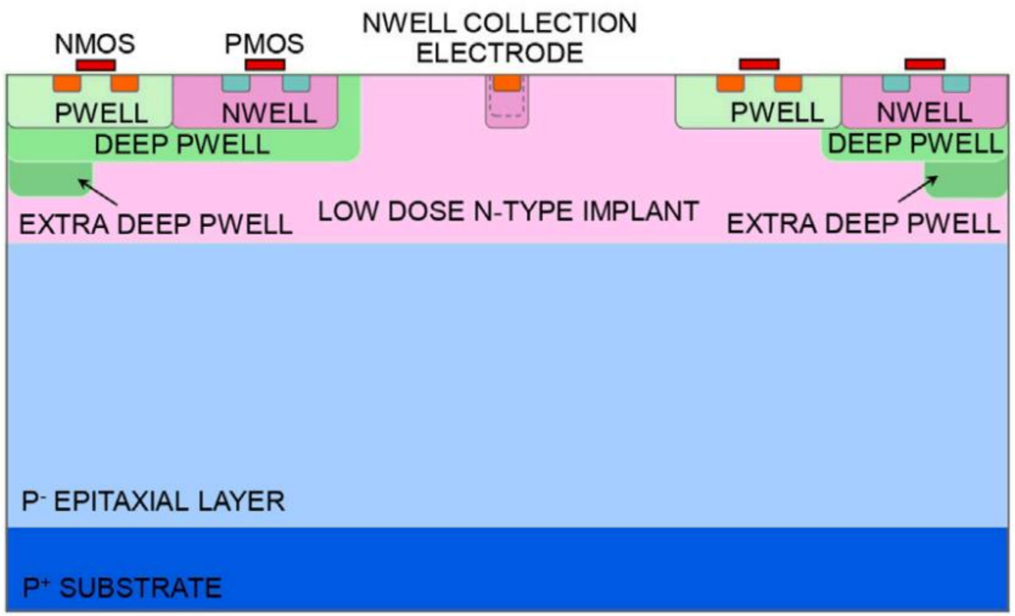


Fig. : XDPW processes MALTA2 layout with full lateral electric field and extra deep p-well [4]

Simulation set-up

Z-axis position (mm)
0
80
160
550 (DUT)
940
1020
1100

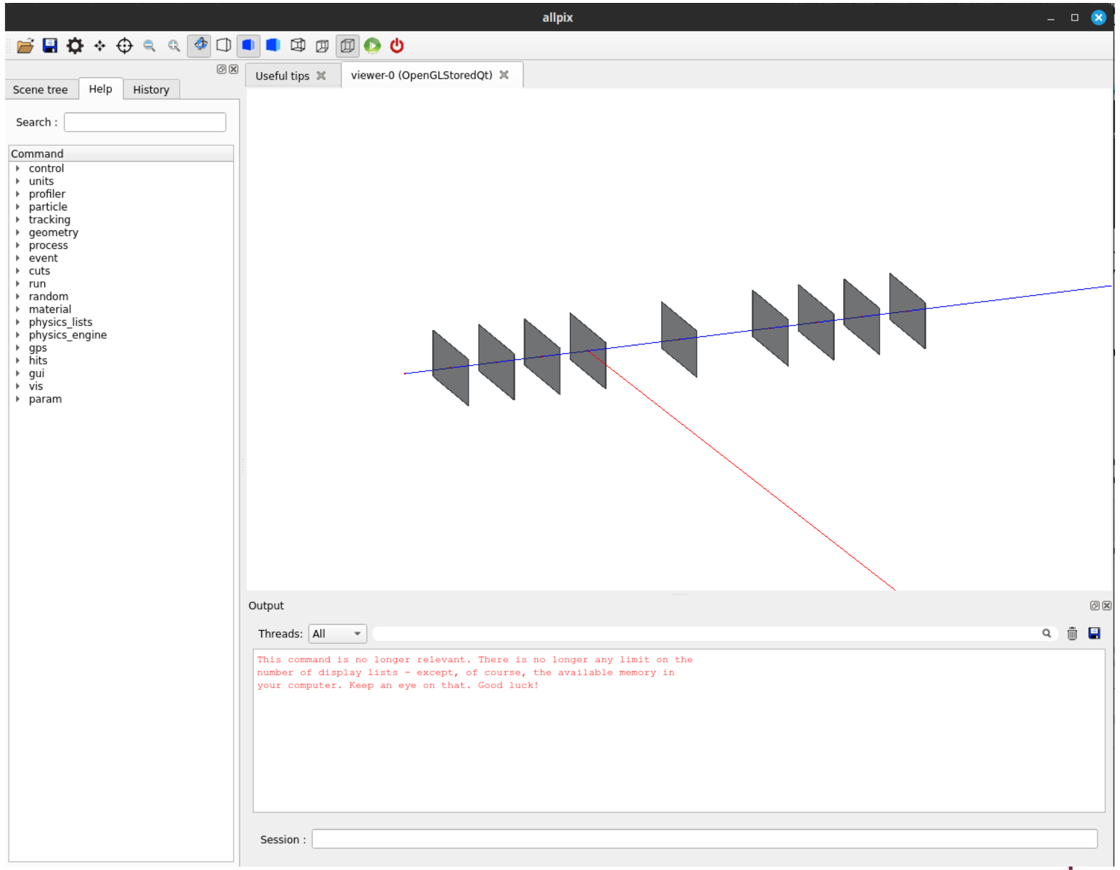
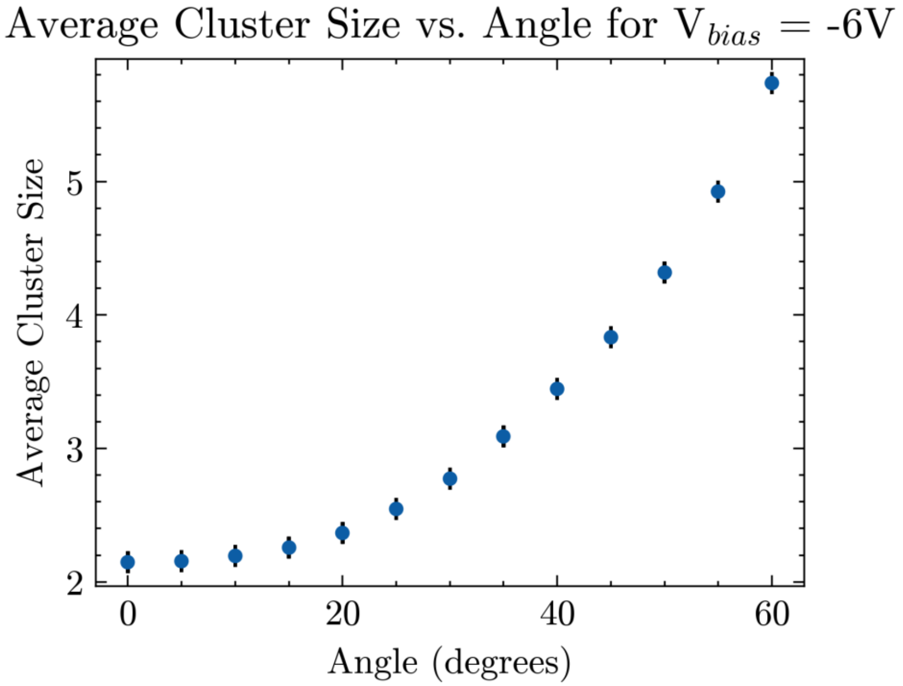
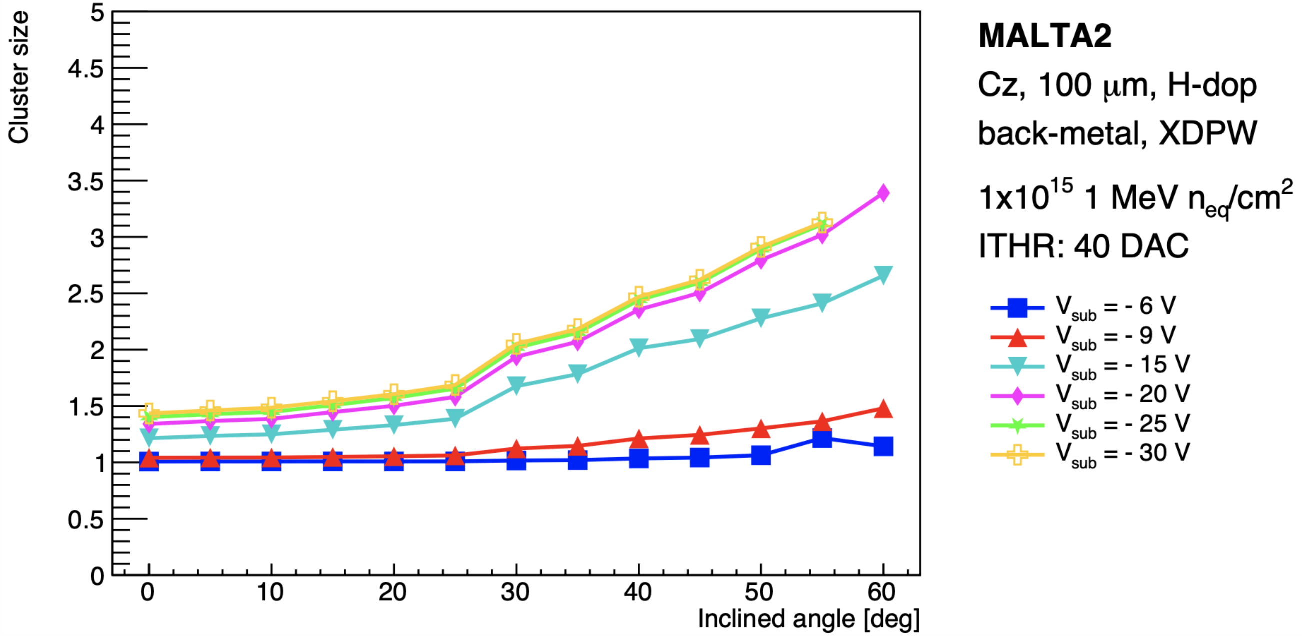


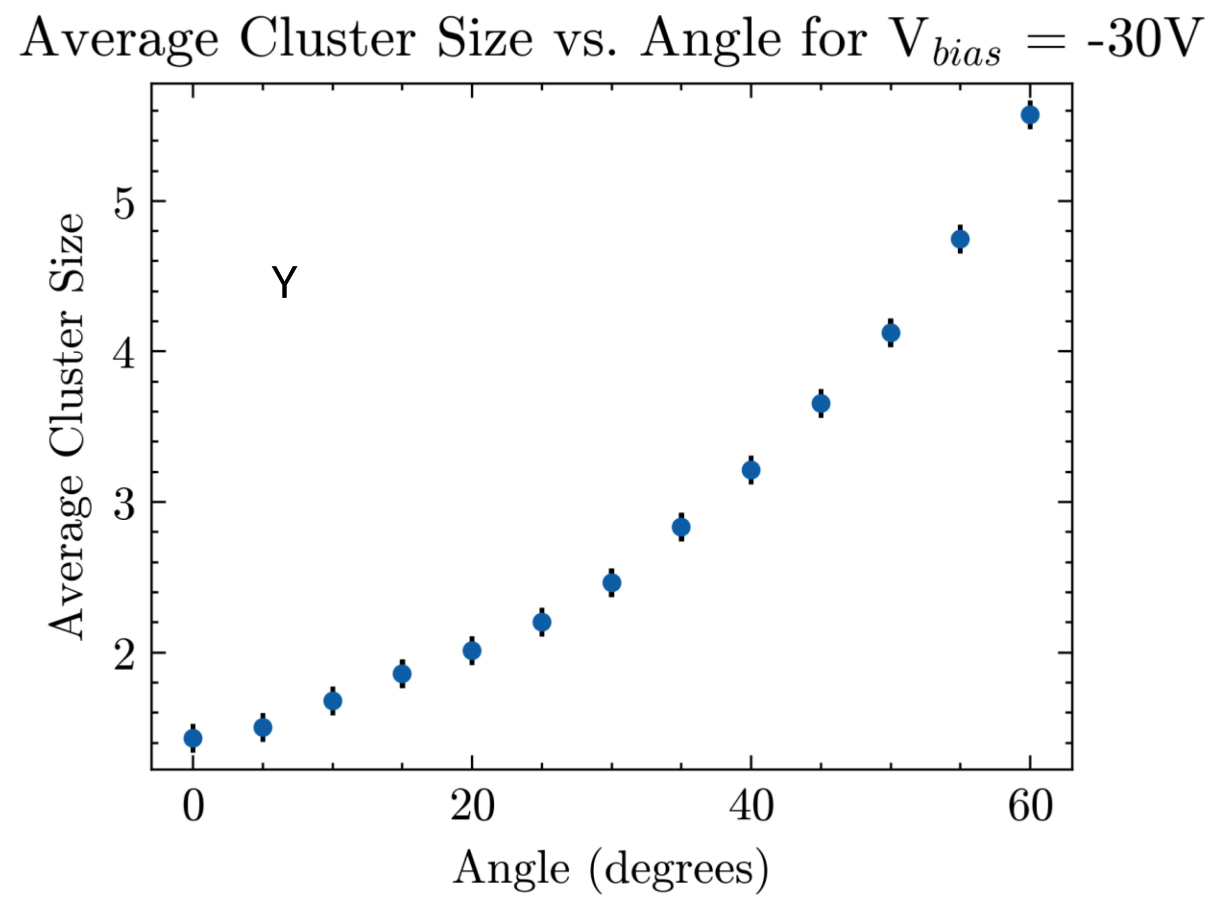
Fig. 4: Allpix-Squared simulation visualisation

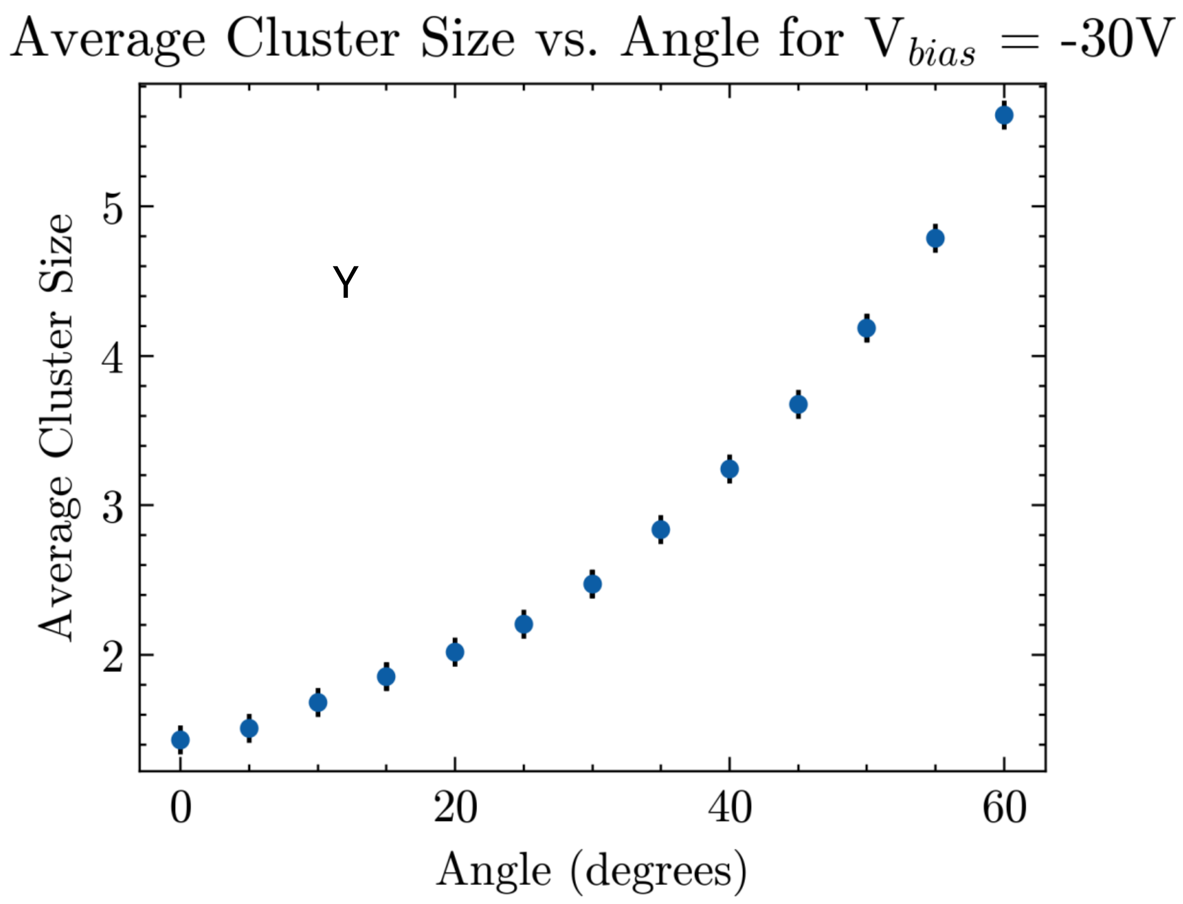
Telescope Cluster Size vs Incident Angle (before automation)



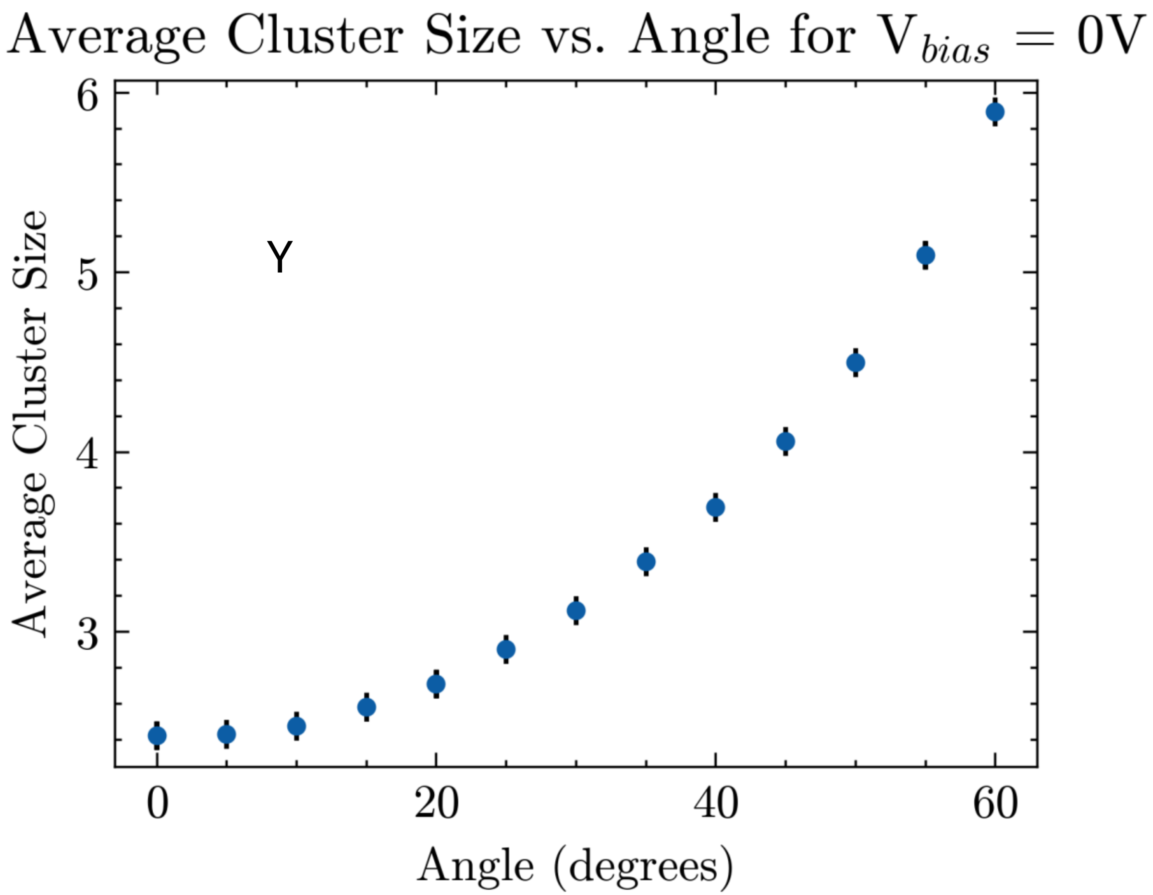


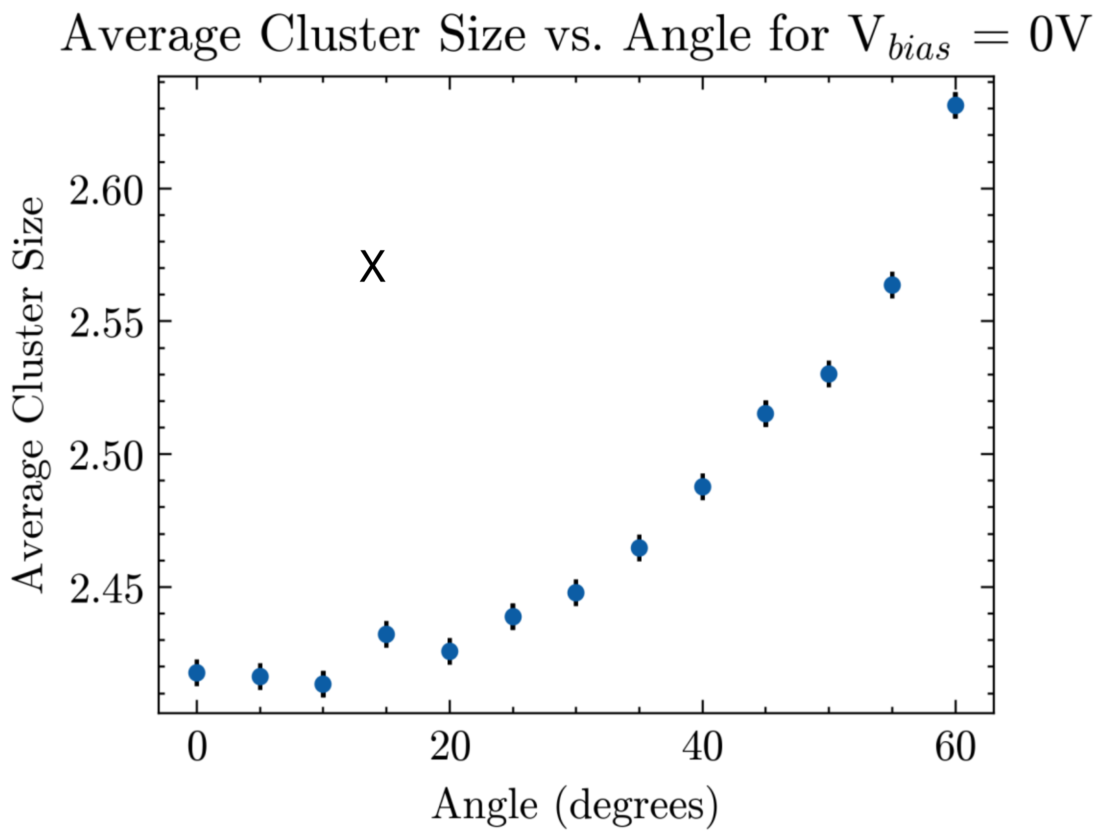
Average cluster size for V_b = -30 at max_depth = 5um and 100um



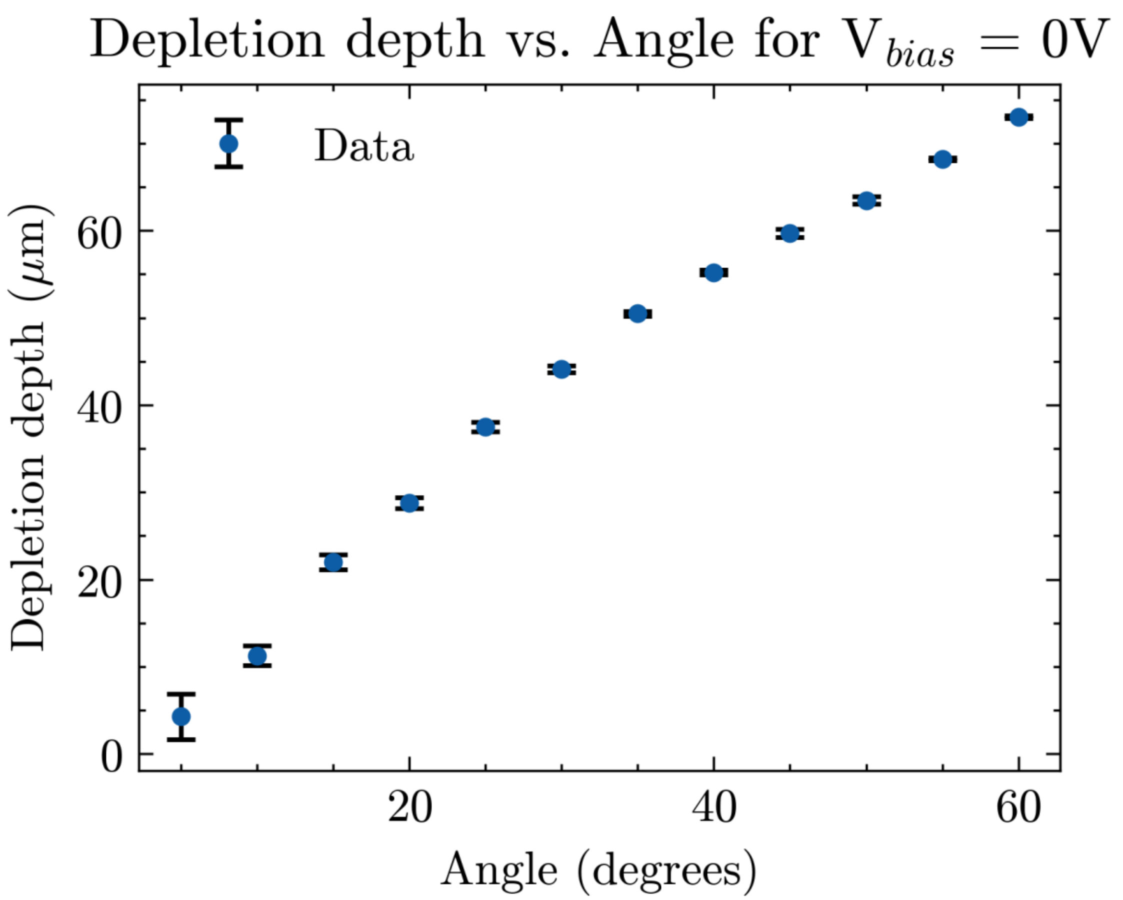


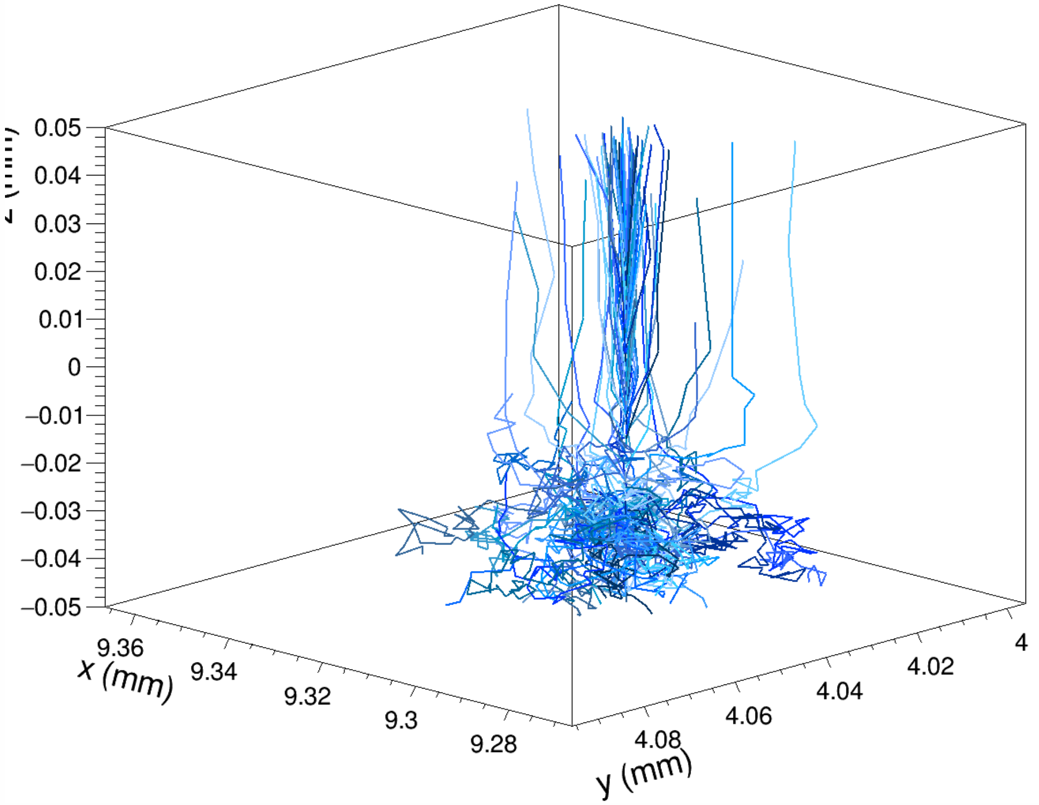
Average cluster size for V_b = 0V



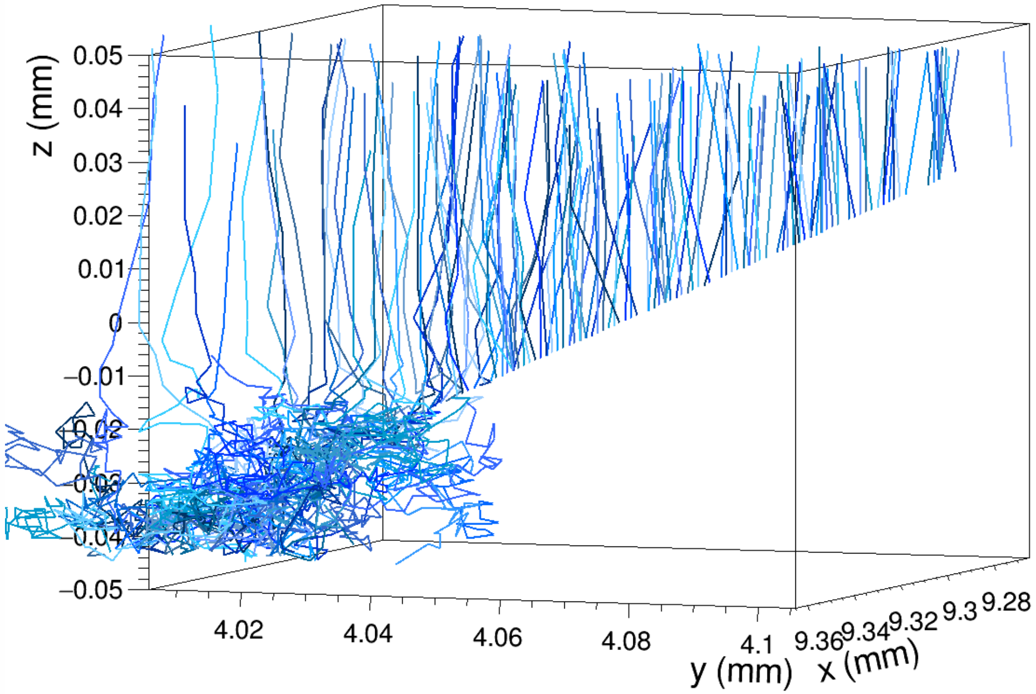


Depletion depth vs. Incident angle for V_b = 0V

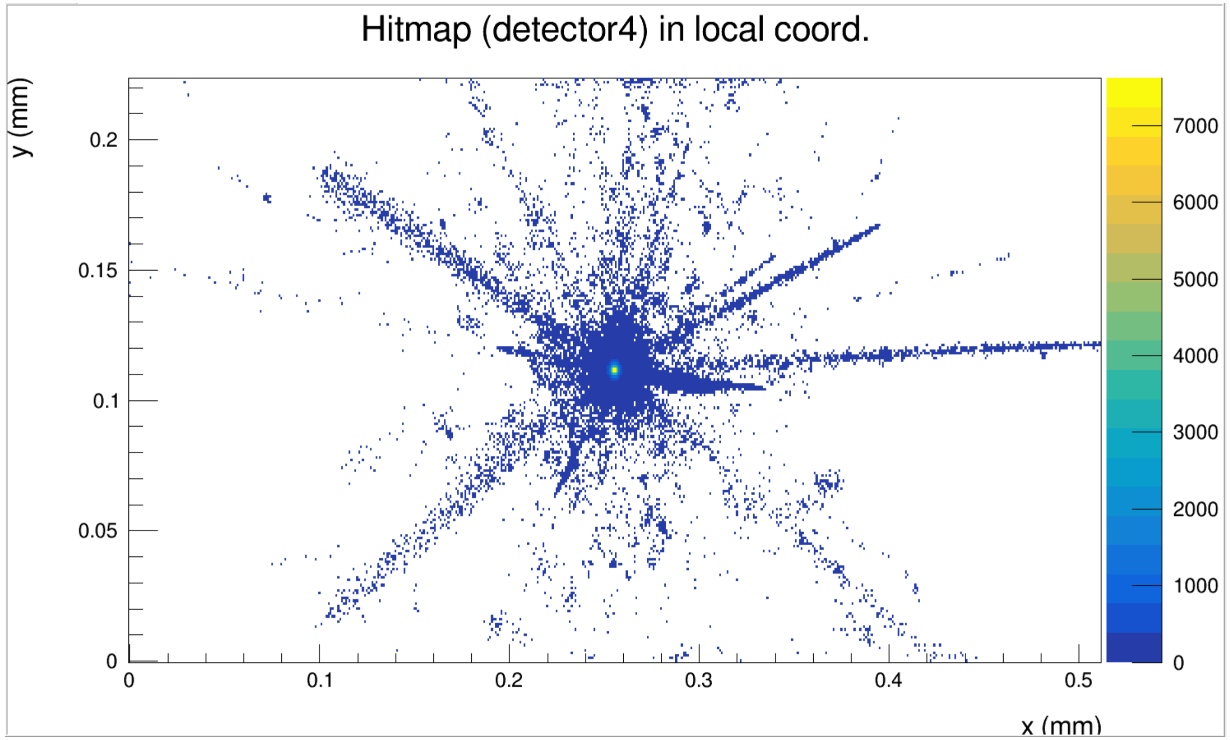




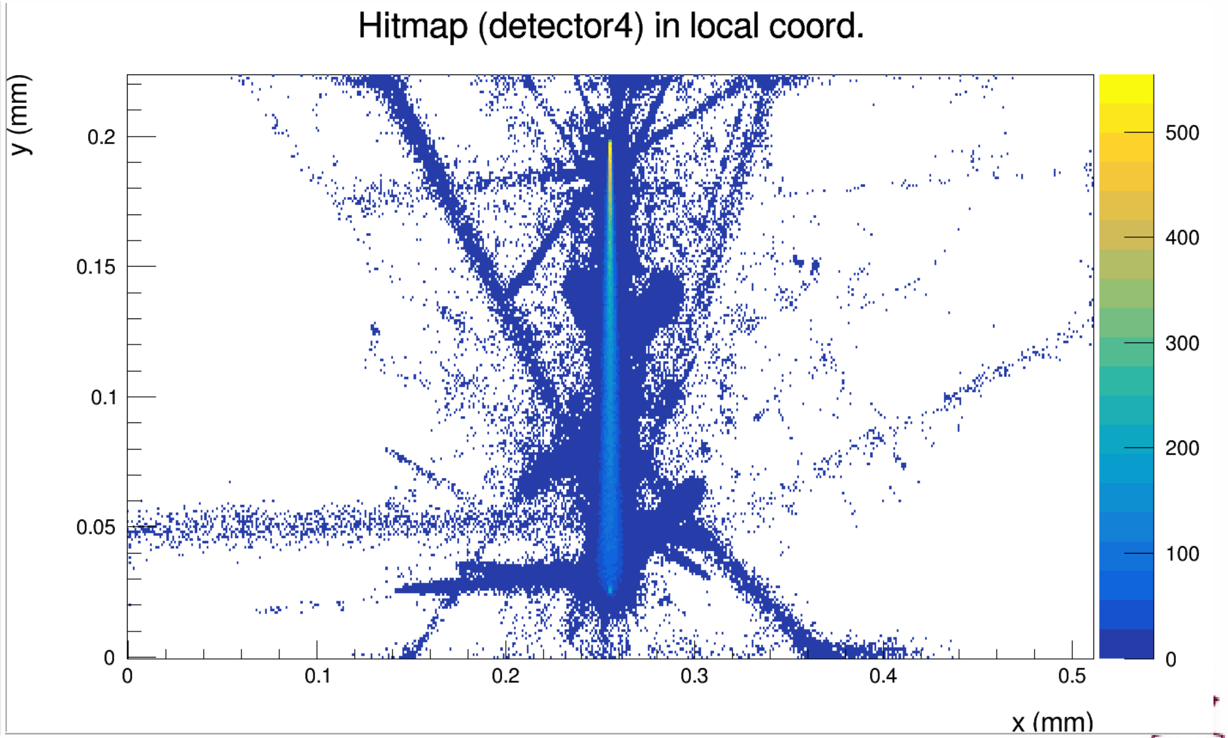
3D demonstration of electron drift and diffusion in MALTA2 DUT sensor at 0 degrees incline. A full depletion voltage of -30V is used and -15V bias.



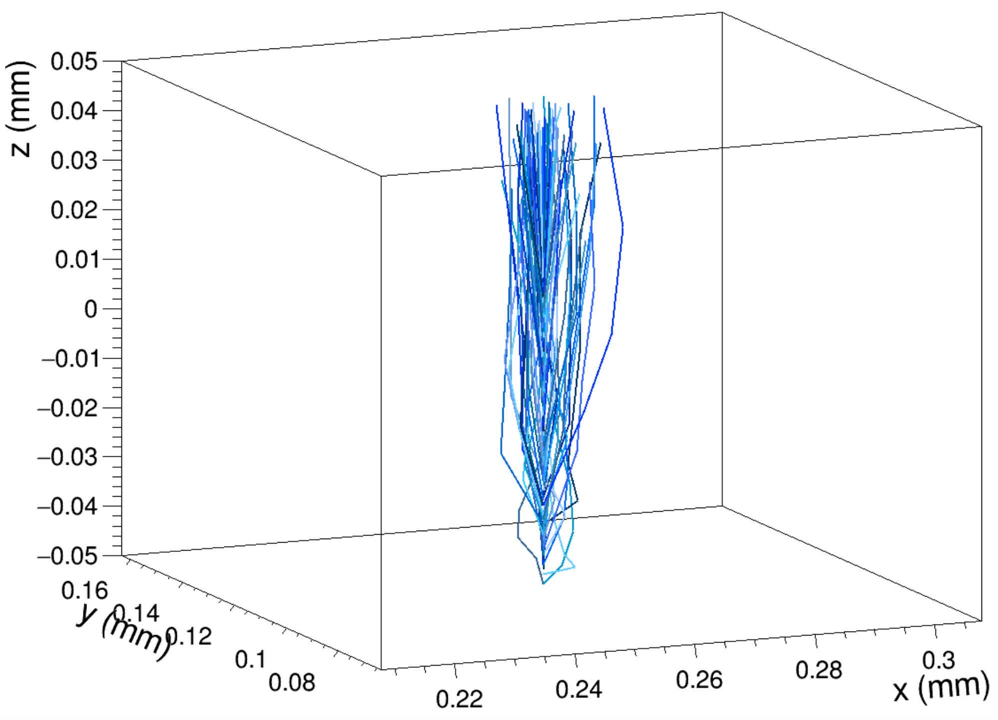
3D demonstration of electron drift and diffusion in MALTA2 DUT sensor at 60 degrees incline. A full depletion voltage of -30V is used and -15V bias.



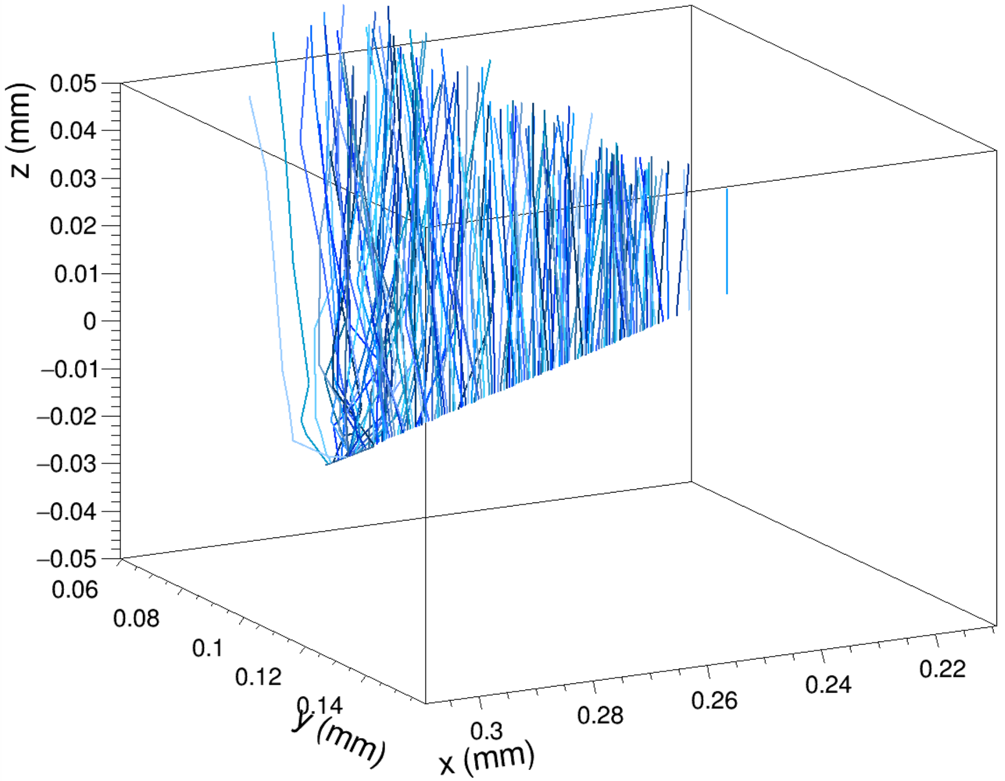
Hitmap for pixels in the MALTA2 DUT sensor at 0 degrees incline without the telescope. A full depletion voltage of -30V is used and -30V bias.



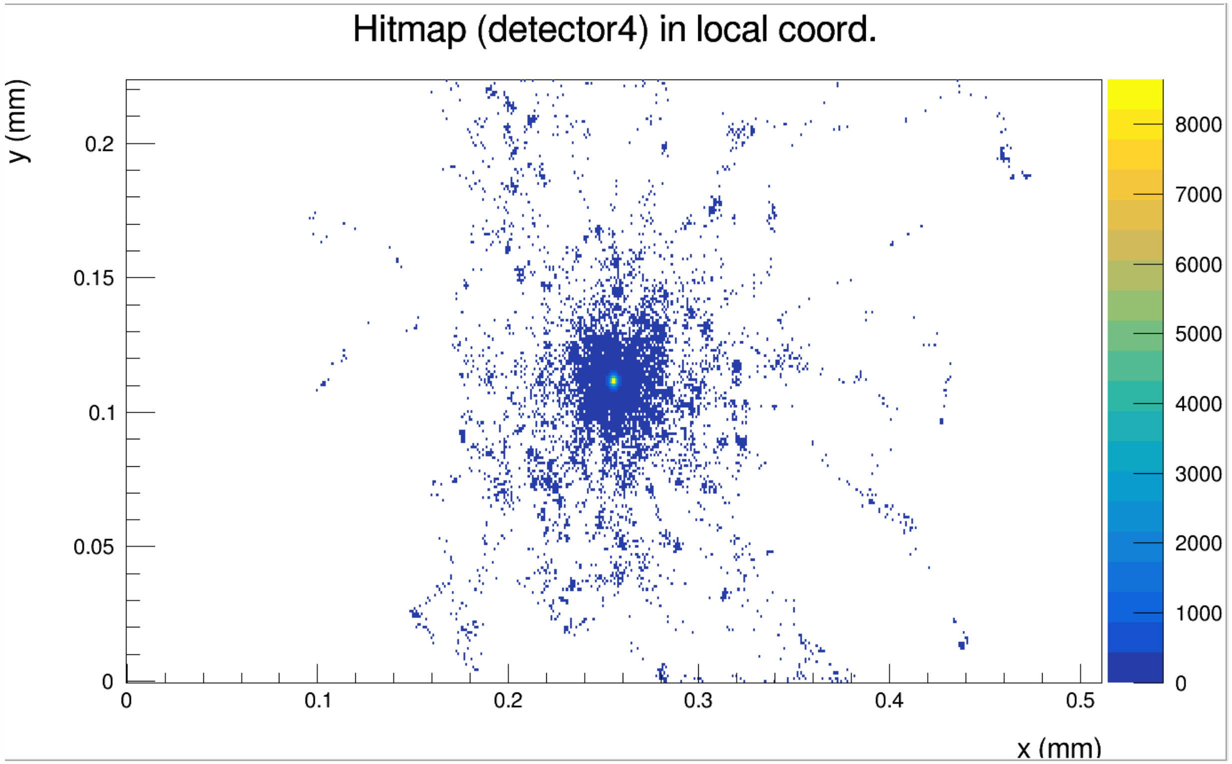
Hitmap for pixels in the MALTA2 DUT sensor at 60 degrees incline without the telescope. A full depletion voltage of -30V is used and -30V bias.



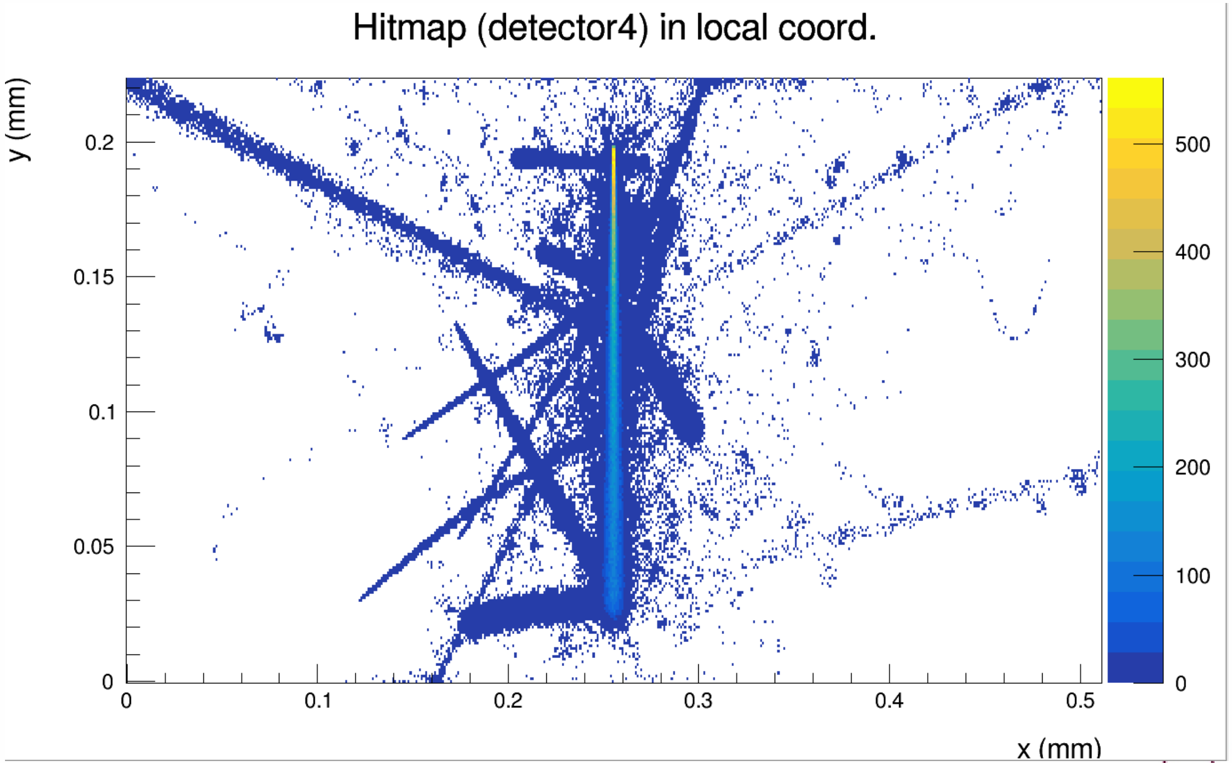
Drift and diffusion of electrons in MALTA2 DUT sensor at 0 degree incline without the telescope. A full depletion voltage of -30V is used and -30V bias.



Drift and diffusion of electrons in MALTA2 DUT sensor at 60 degree incline without the telescope. A full depletion voltage of -30V is used and -30V bias.

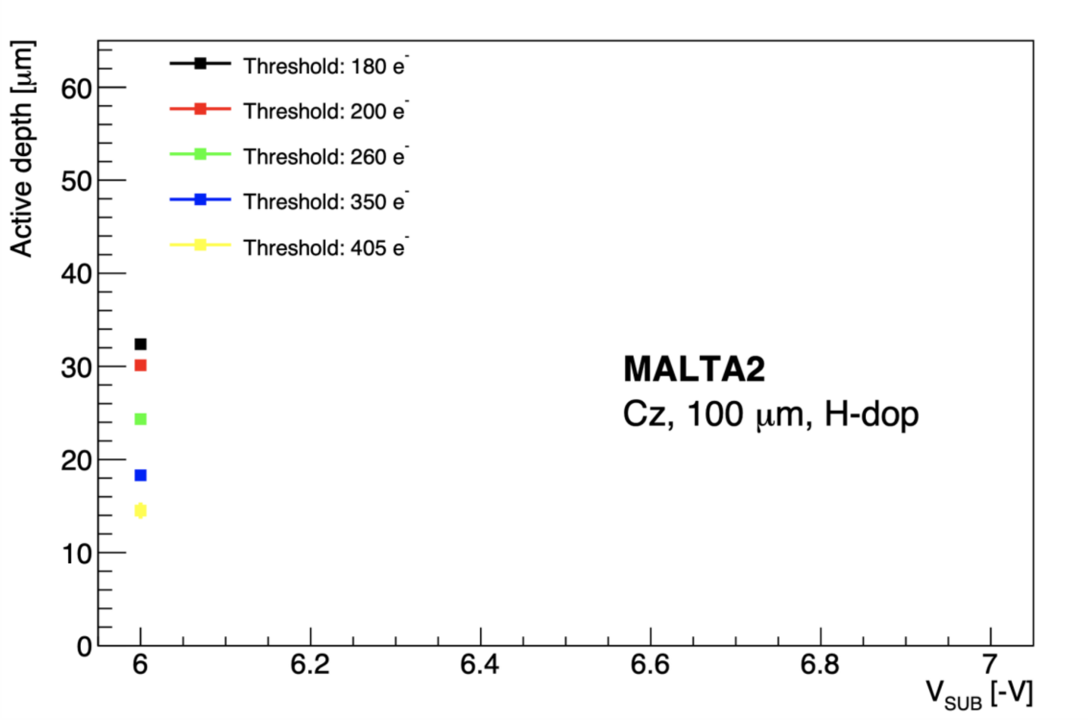


Hitmap for pixels in the MALTA2 DUT sensor at 0 degrees incline without the telescope. A full depletion voltage of -30V is used and -50V bias.

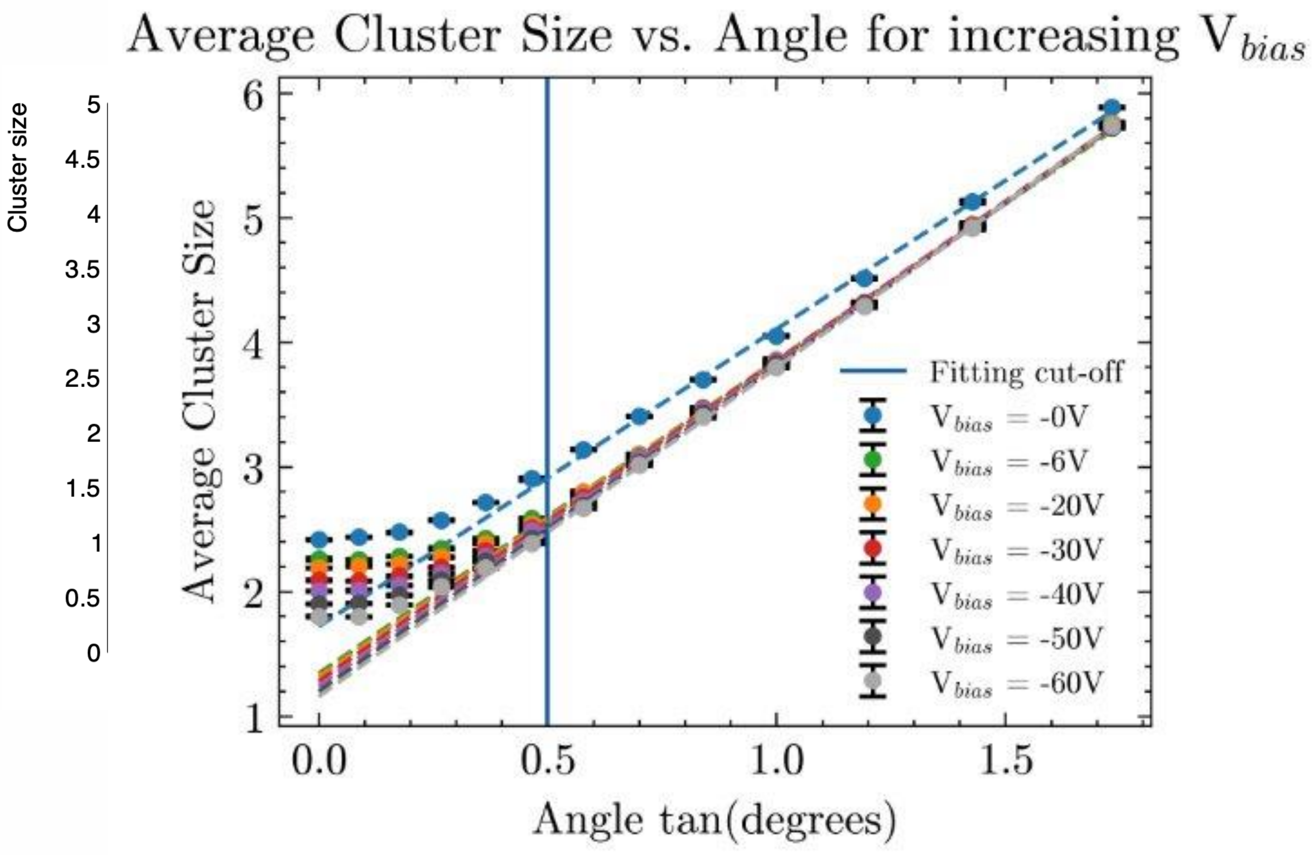


Hitmap for pixels in the MALTA2 DUT sensor at 60 degrees incline without the telescope. A full depletion voltage of -30V is used and -50V bias.

V_{depl} = -60V Data

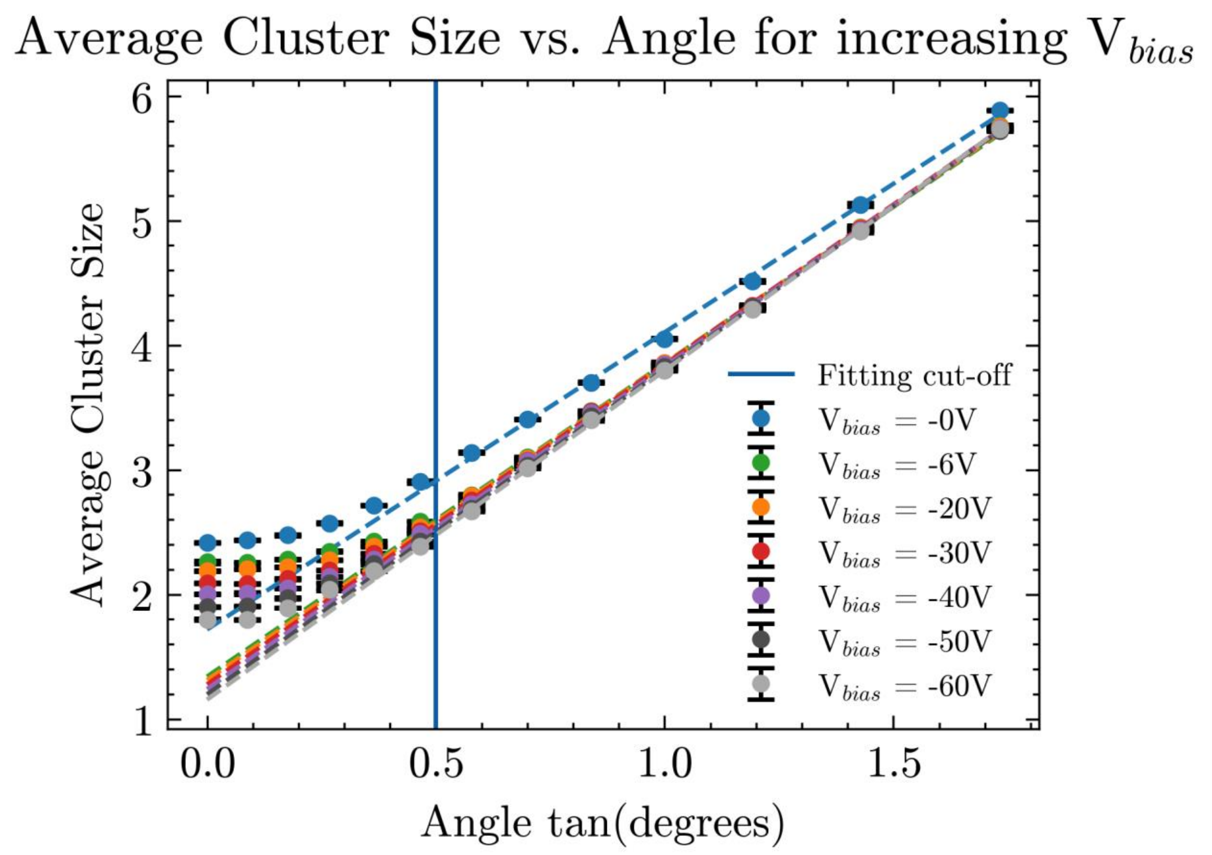


Depletion Depth: Test beam, unirradiated

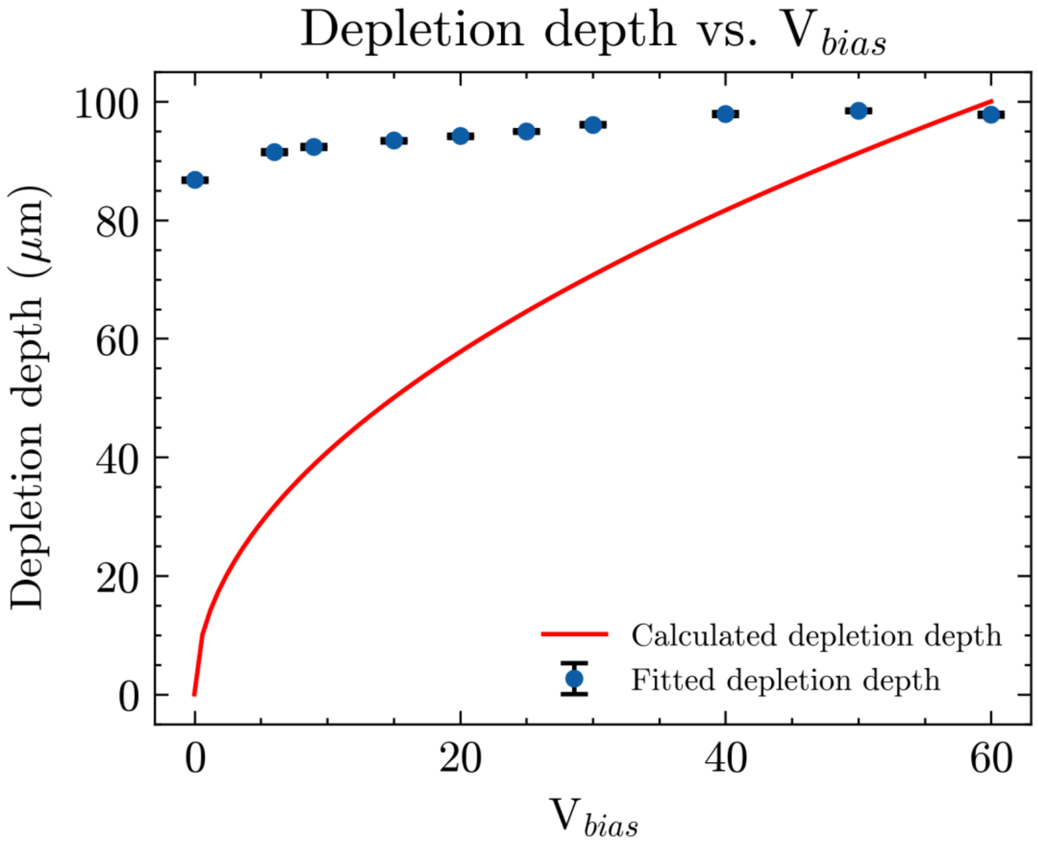


Scaled Cluster Size: Simulation, unirradiated

V_{depl} = -60V Data



Scaled Cluster Size: Simulation, unirradiated



Fitted Depletion Depth: Simulation, unirradiated

References

- [1]: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-050/
- [2]: https://cds.cern.ch/record/2776651/files/ATL-PHYS-PUB-2021-024.pdf
- [3]: https://eprints.gla.ac.uk/270885/1/270885.pdf
- [4]: https://cds.cern.ch/record/2894529/files/Publication.pdf
- https://cds.cern.ch/record/2639942/plots
- https://atlas.cern/Resources/Cheat-sheets
- https://indico.cern.ch/event/949529/attachments/2091301/3516122/The_MALTA_Sensor.pdf
- https://allpix-squared.docs.cern.ch/
- https://www.dropbox.com/scl/fi/sjxklgk3gb2z5e34875j6/tipp2021.pdf?rlkey=70at5vszowiaaq00rbk7zz8vq&e=2&st=pud9lppv&dl=0
- https://www.sciencedirect.com/science/article/pii/S0168900223007787
- https://www.sciencedirect.com/science/article/pii/S0168900215011122
- https://www.sciencedirect.com/science/article/pii/0168900294012318
- https://home.cern/news/news/physics/atlas-moves-top-gear-run-3
- https://www.sciencedirect.com/science/article/pii/S0168900222008890
- https://e-publishing.cern.ch/index.php/CYRM/article/view/1154/959
- https://e-publishing.cern.ch/index.php/CYRM/issue/view/94/69