

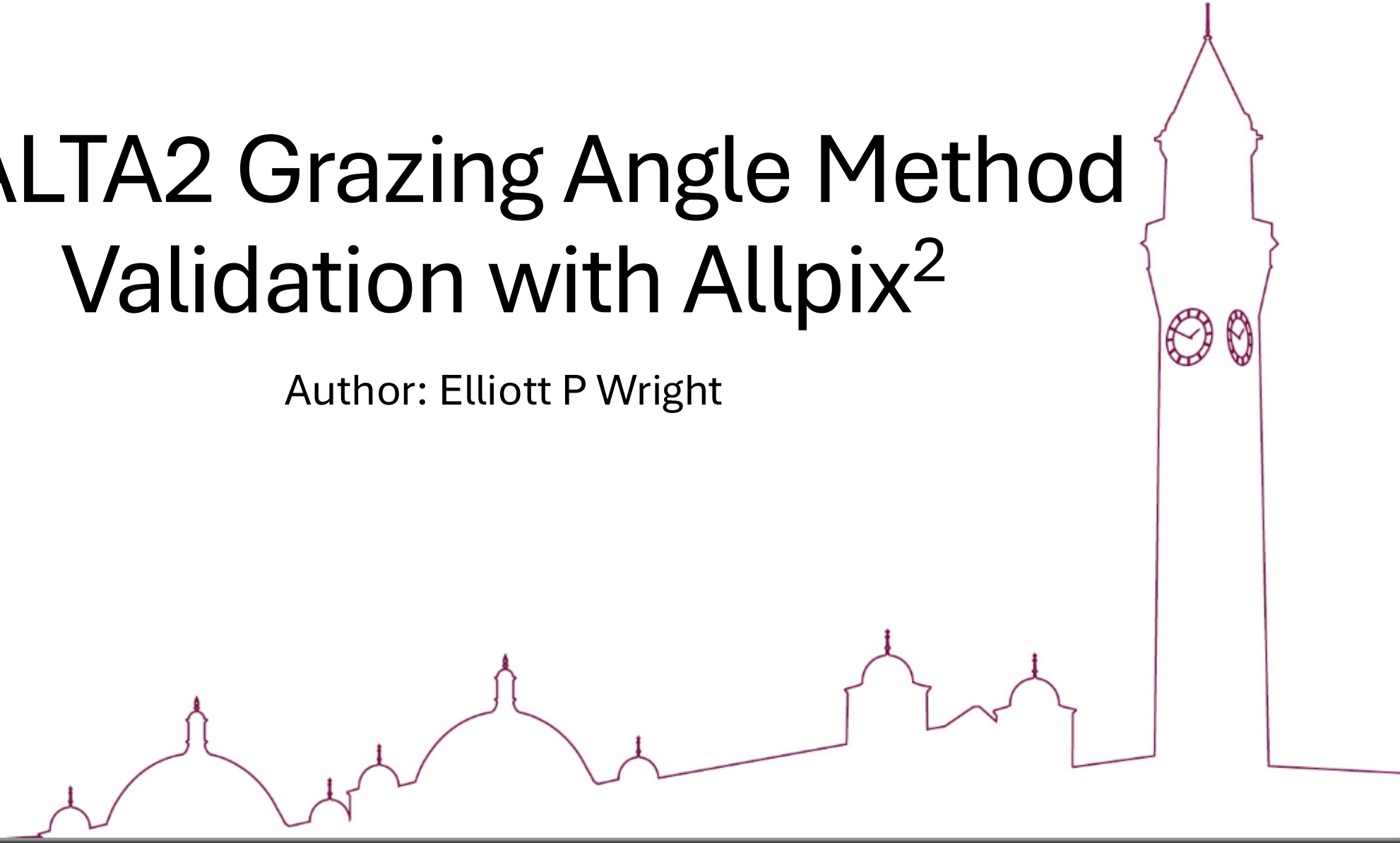


UNIVERSITY OF
BIRMINGHAM

SCHOOL OF
PHYSICS AND
ASTRONOMY

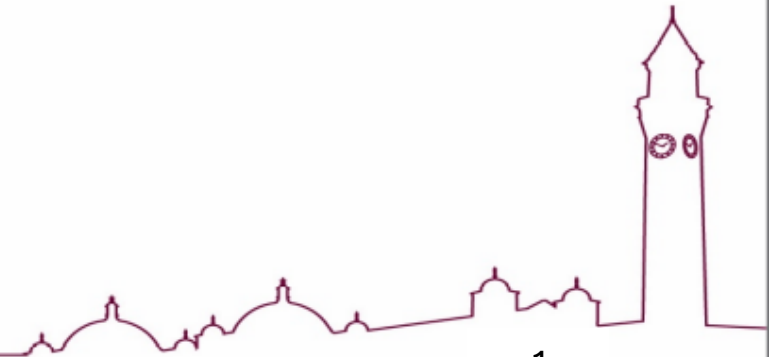
MALTA2 Grazing Angle Method Validation with Allpix²

Author: Elliott P Wright



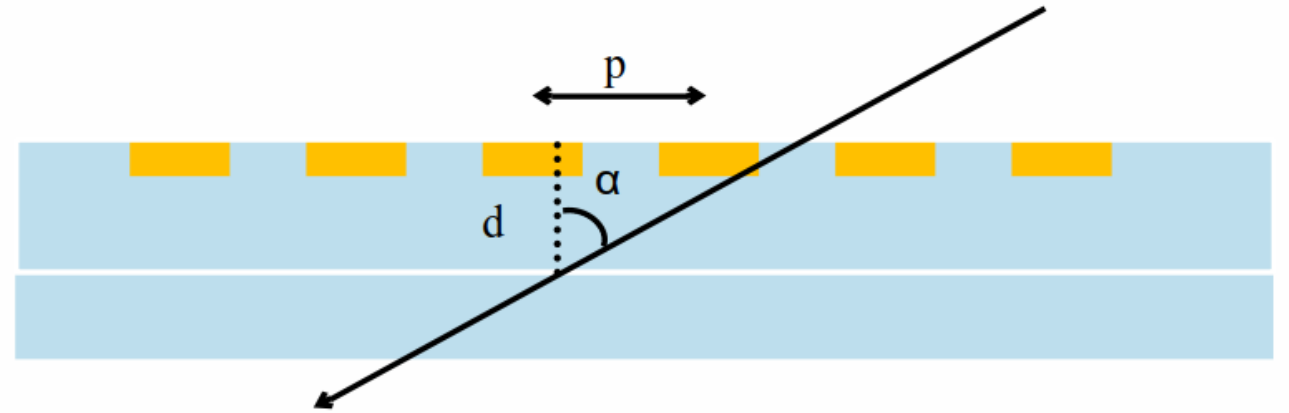
Introduction

- Validation of the grazing angle method used to calculate depletion depth using Allpix² **simulation**
 - Data already taken for a $1 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$ irradiated detector
- Simple telescope simulation with MALTA2-like sensors
- Same environmental, test beam and digitisation parameters used between the experiment and simulation
- Linear electric field applied inside sensors



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

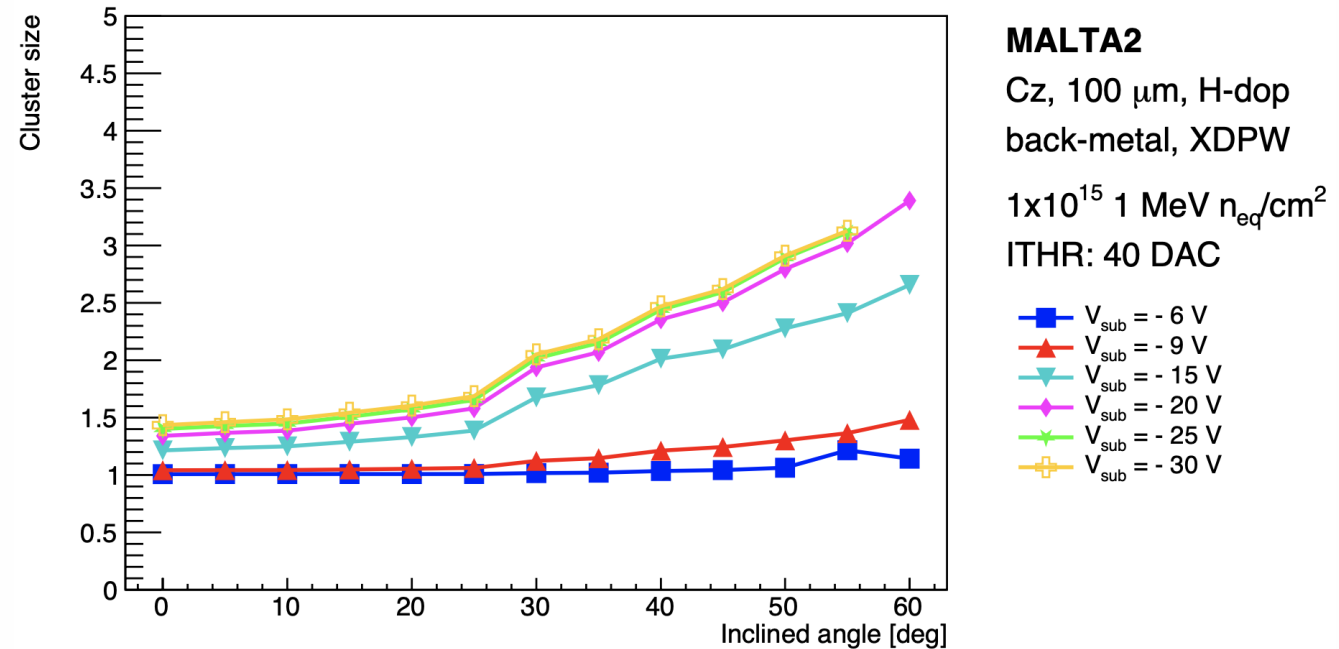


Grazing angle method: incident grazing angle α , pixel pitch p , and depletion depth d

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

The Grazing Angle Method

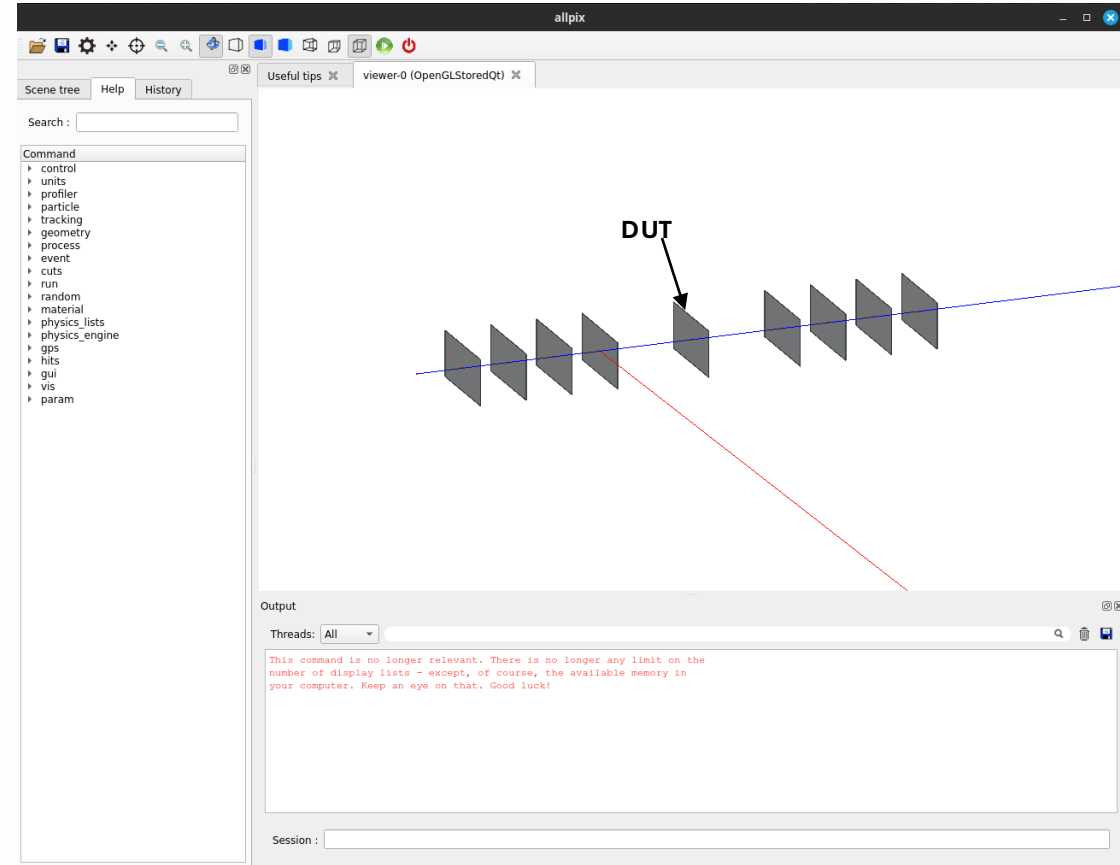
- Aim is to calculate the depletion depth
- Compare depth to what is expected to determine radiation damage
- Radiation damage changes the depletion depth
- Create a test beam of incident particles, changing sensor angle about x-axis



Cluster Size: Test beam, irradiated

Allpix²

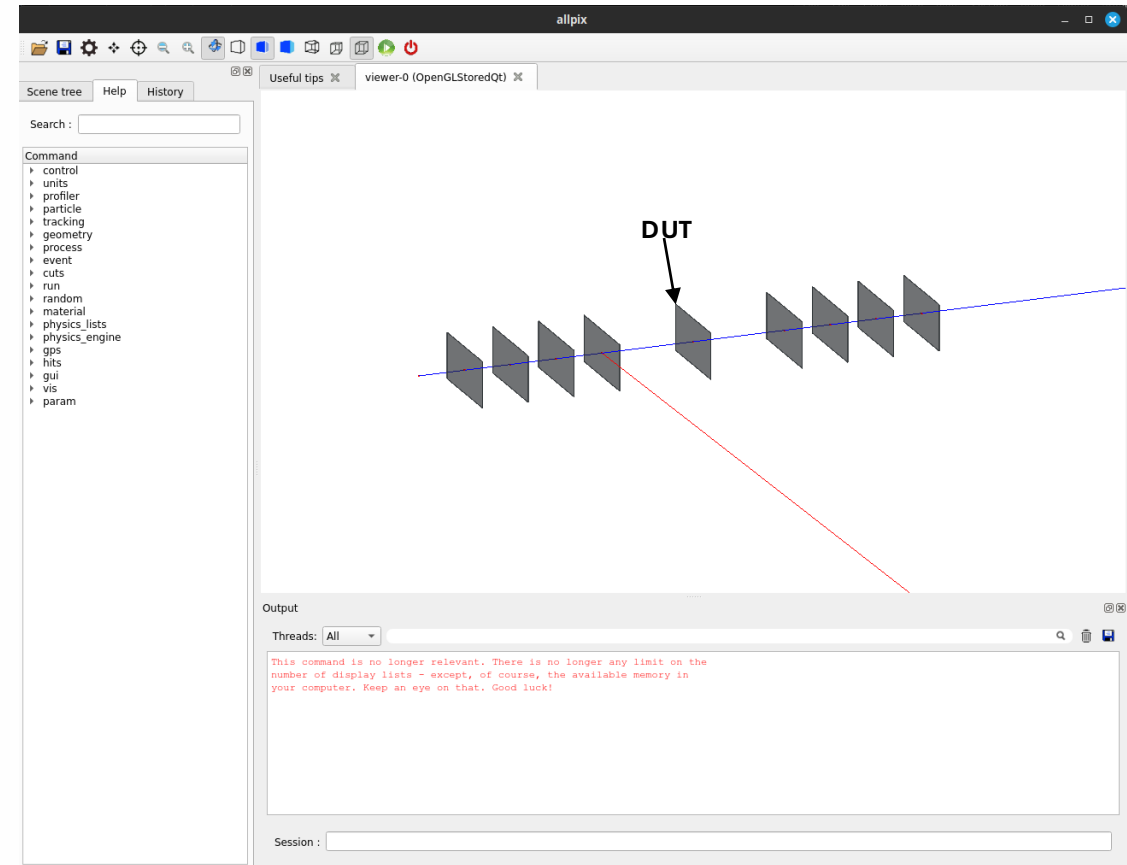
- Monte Carlo simulation software for silicon detectors based on Geant4
- Performs signal propagation and digitisation
- Visualisation capabilities
- Ease of configuration with human-readable files
- Extensive documentation:
<https://allpix-squared.docs.cern.ch/>



Allpix²: 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

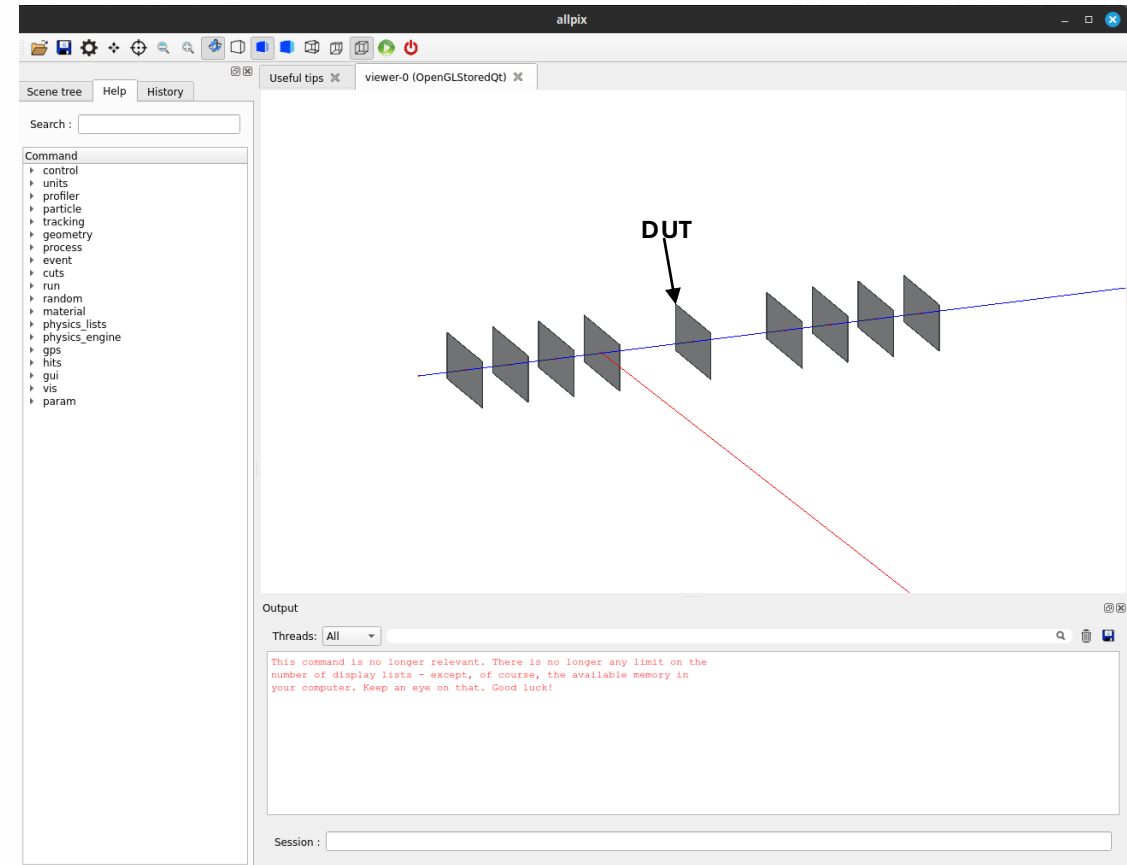


Allpix²: MALTA2 sensors (grey squares) and test beam (blue line)

Simulation Set-Up

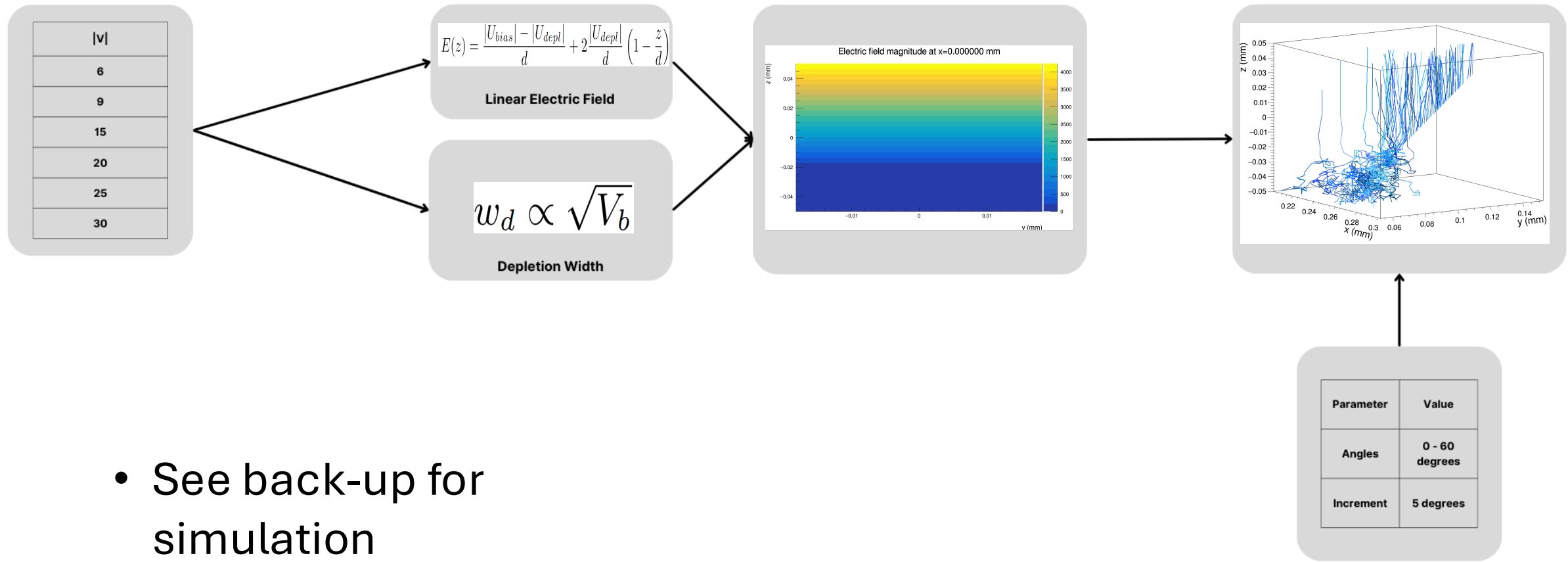
Beam Parameter	Value
Particle	Proton
Beam Energy	180 GeV

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



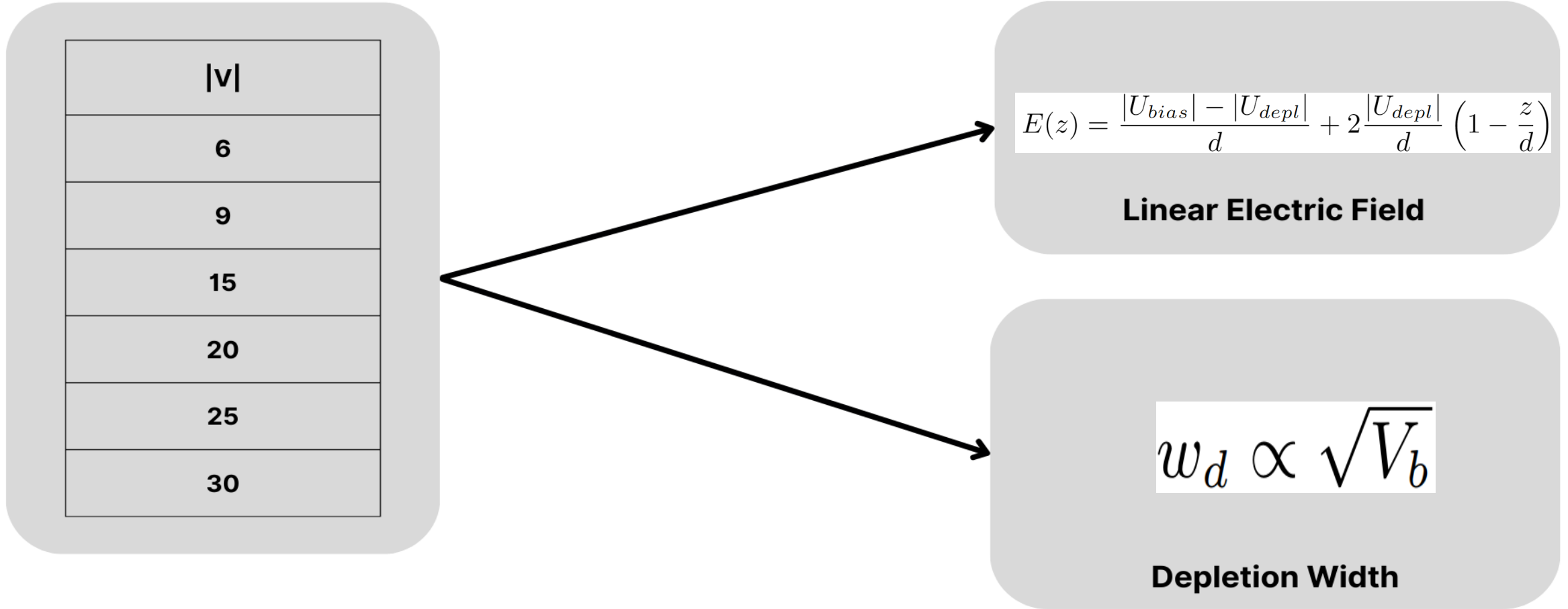
Allpix²: MALTA2 sensors (grey squares) and test beam (blue line)

Simulation Workflow



- See back-up for simulation configuration

Simulation Workflow



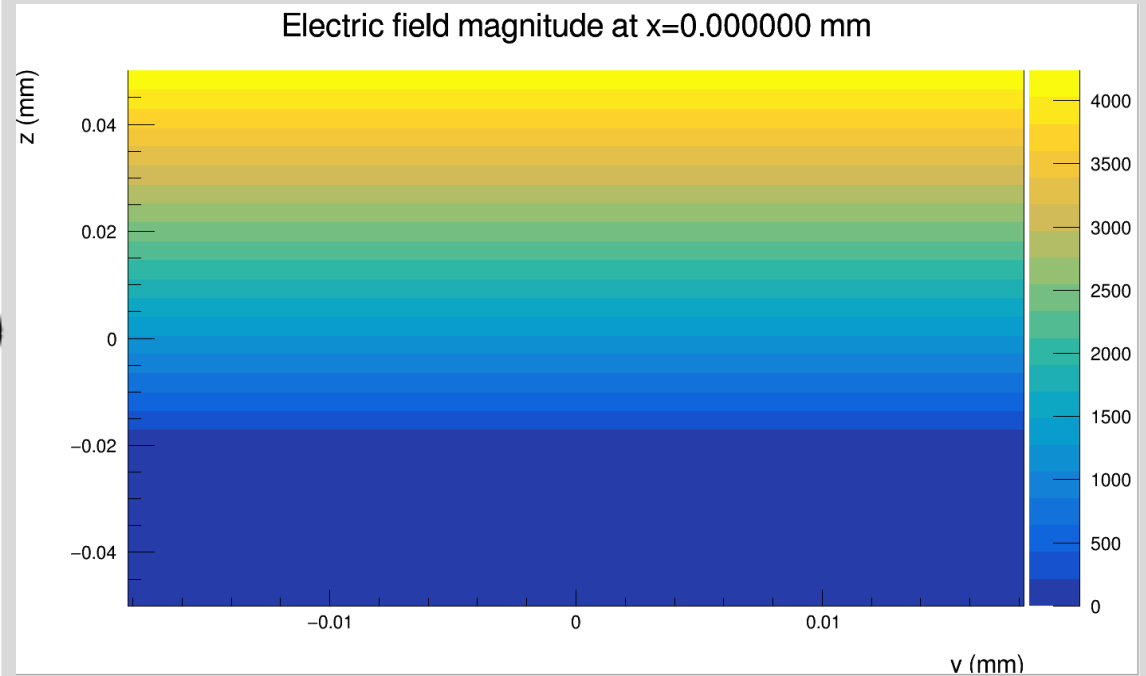
Simulation Workflow

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

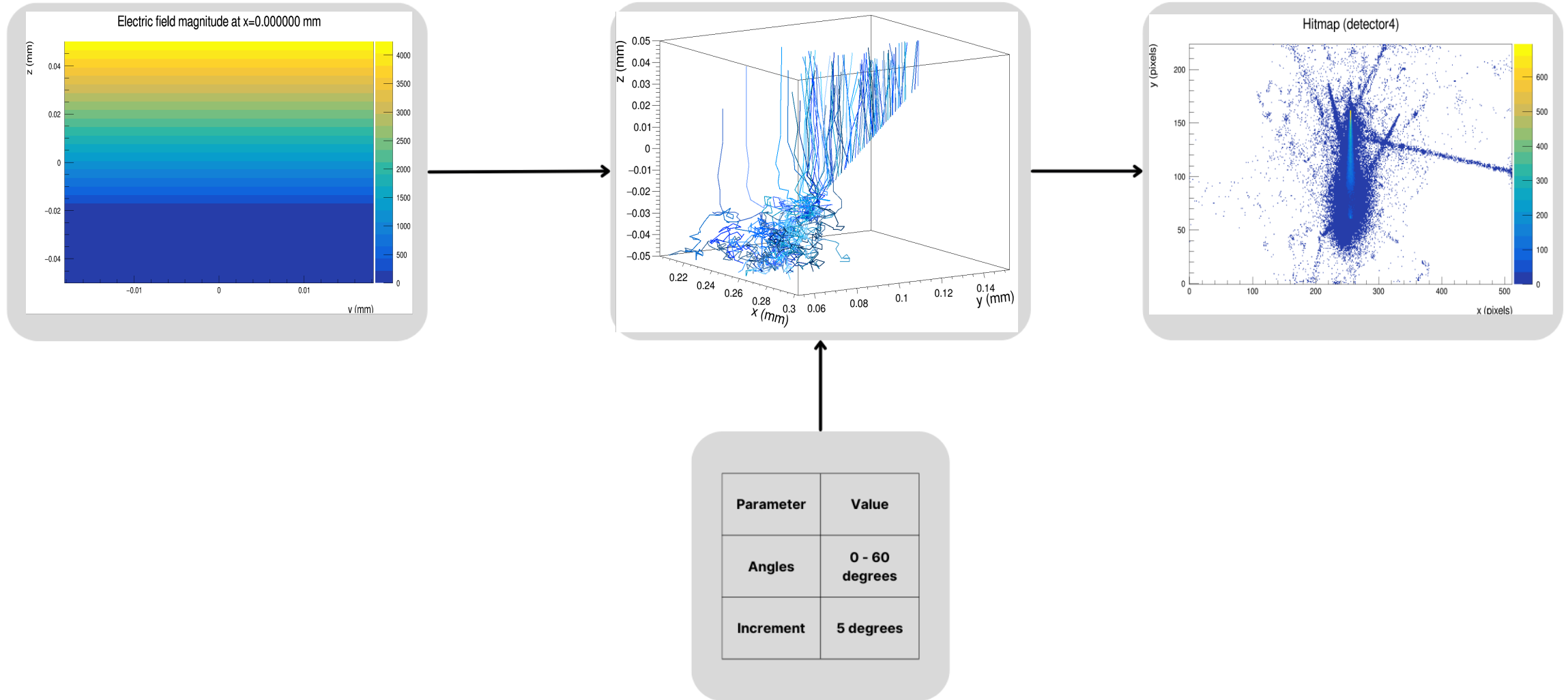
Linear Electric Field

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

Depletion Width

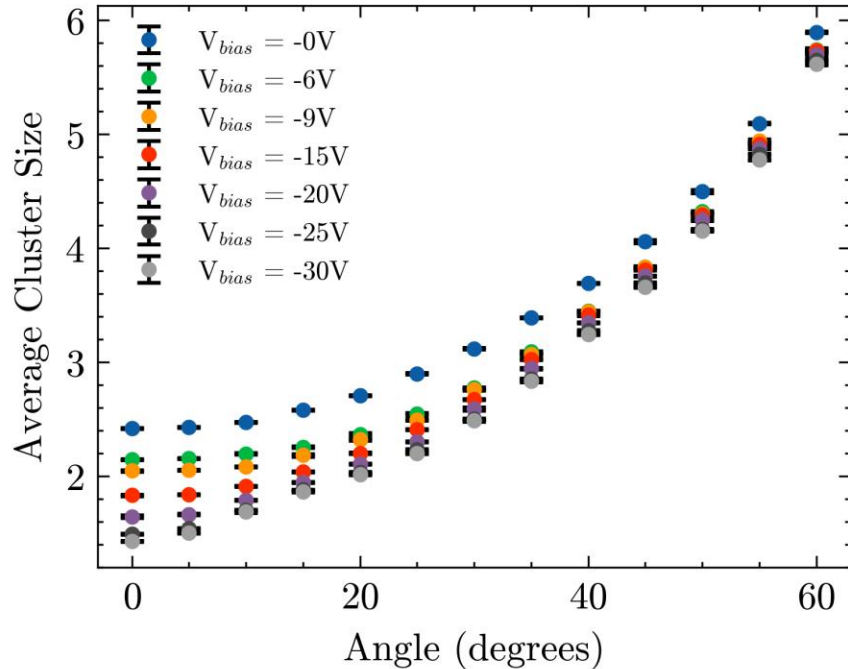


Simulation Workflow

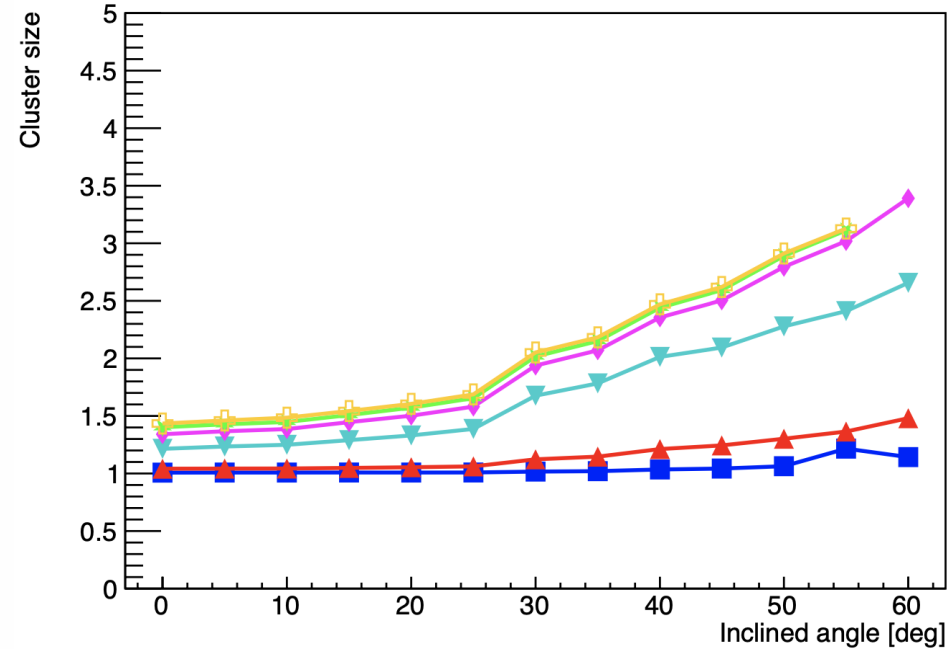


Telescope Pixel Cluster Size vs Incident Angle

Average Cluster Size vs. Angle for increasing V_{bias}



Cluster Size: Simulation, unirradiated



MALTA2

Cz, 100 μm , H-dop
back-metal, XDPW

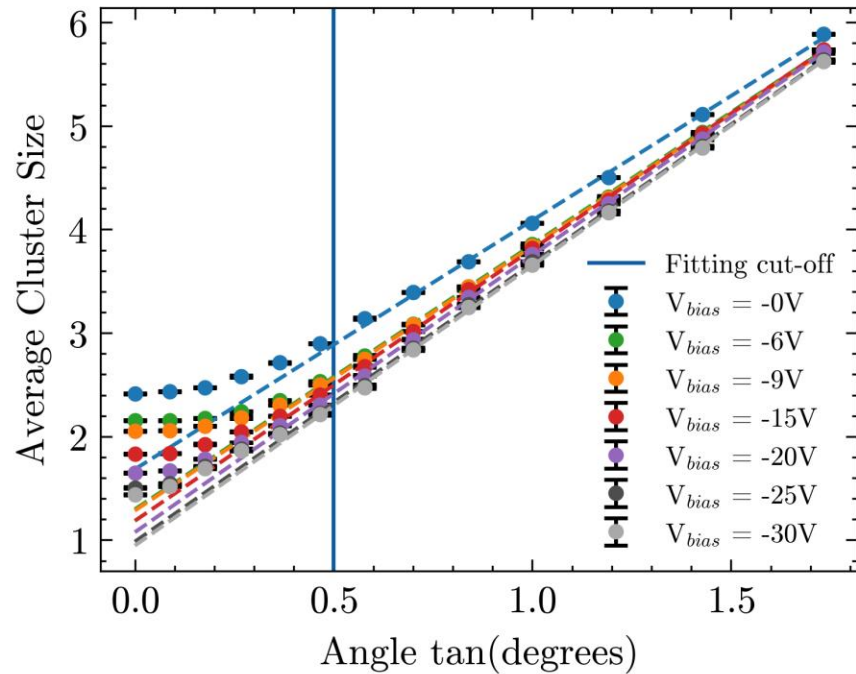
1×10^{15} 1 MeV n_{eq}/cm^2
ITHR: 40 DAC

Cluster Size: Test beam, irradiated

Linear Fit to Telescope Cluster Size Data

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

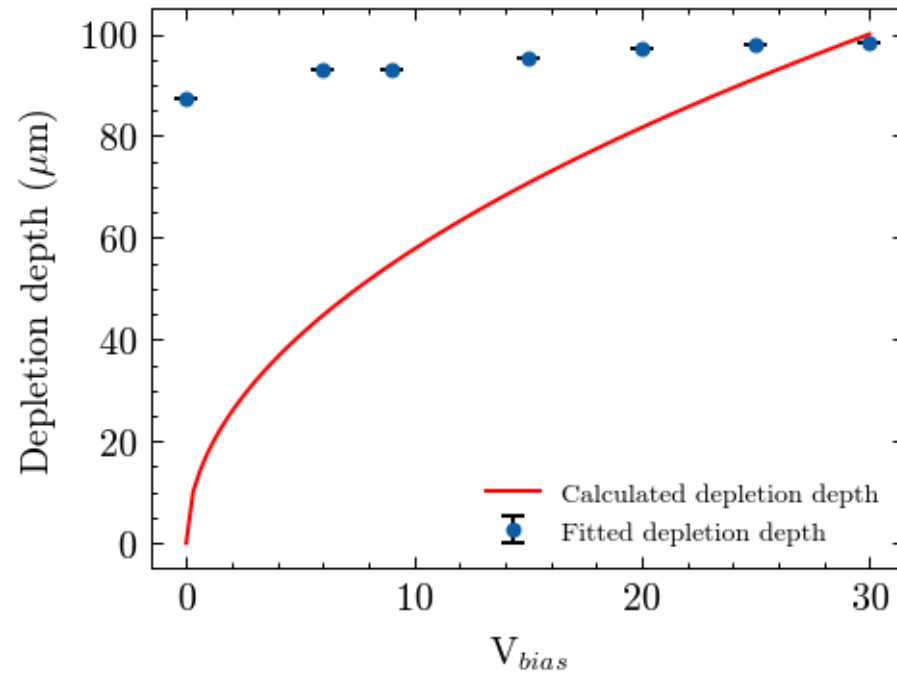
Average Cluster Size vs. Angle for increasing V_{bias}



Scaled Cluster Size: Simulation, unirradiated

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

Depletion depth vs. V_{bias}



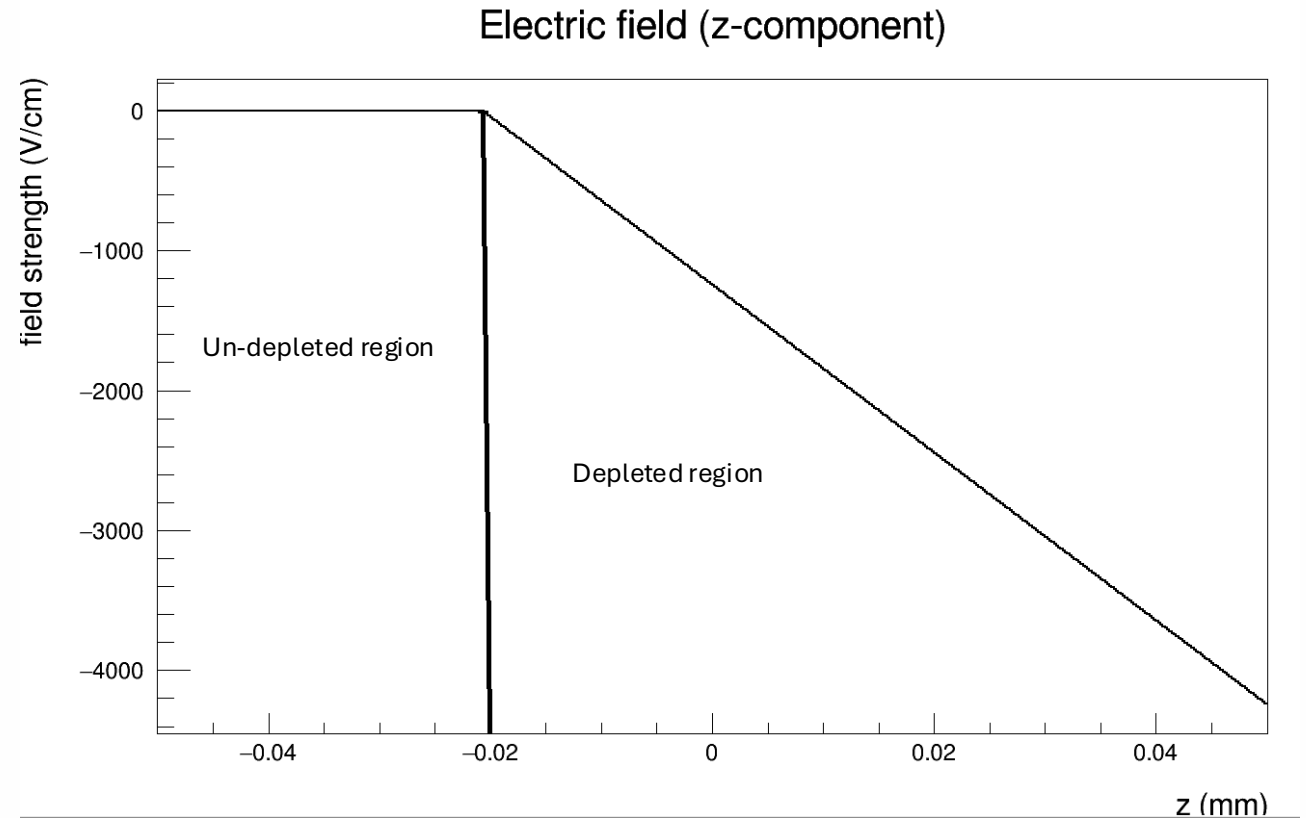
Fitted Depletion Depth: Simulation, unirradiated

Linear Electric Field Investigation

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

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

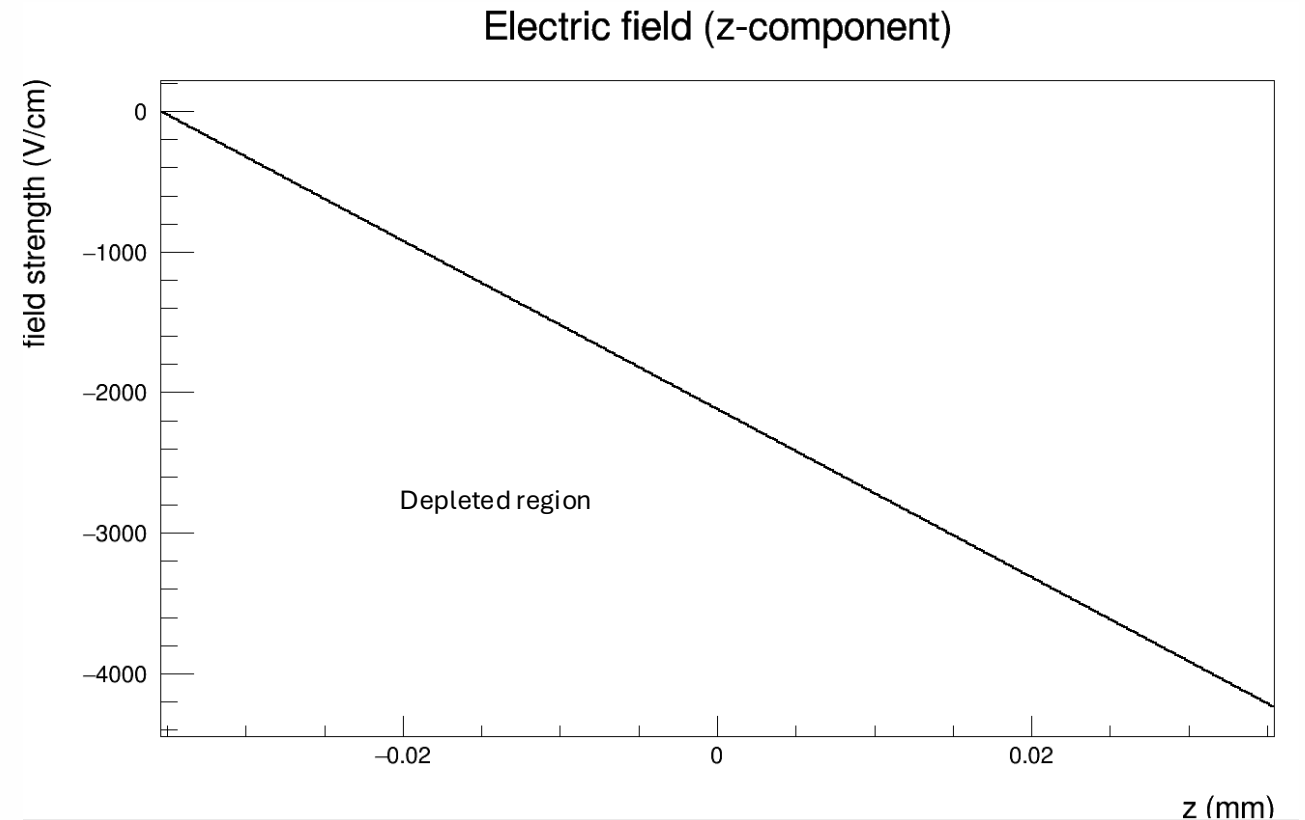
- Undepleted region produces diffusion charges
- Test diffusion charges contribution by reducing sensor thickness for given bias voltage



Electric Field: z-projection, $V_{\text{bias}} = -15\text{V}$, $V_{\text{depl}} = -30\text{V}$, full $100\mu\text{m}$ thickness

Linear Electric Field Investigation Method

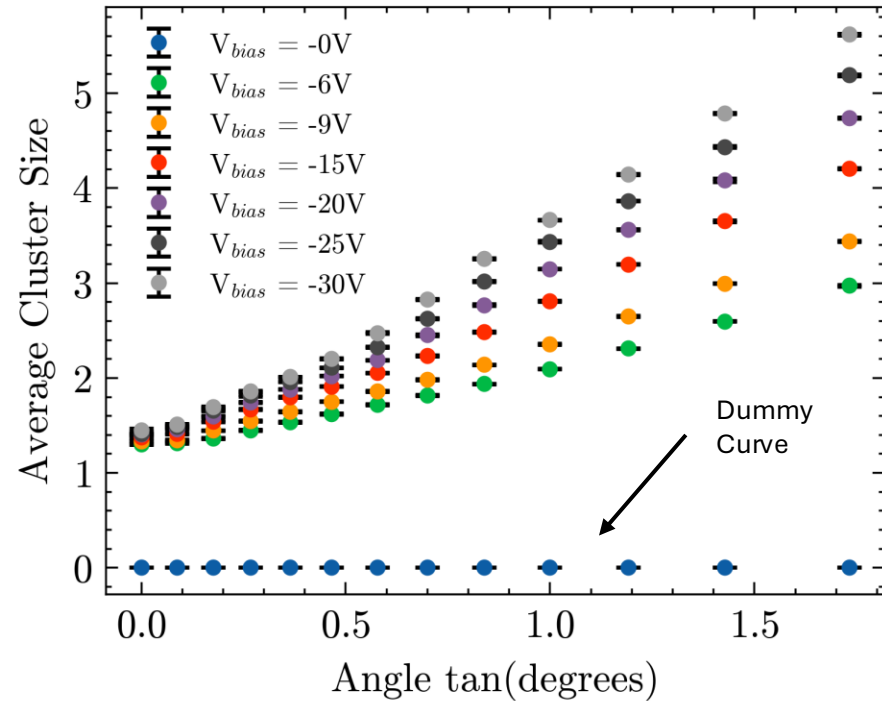
$ V_{\text{bias}} $ (V)	W_d (μm)
6	44.8
9	54.8
15	70.8
20	81.6
25	91.2
30	100



Electric Field: z-projection, $V_{\text{depl}} = V_{\text{bias}} = -15\text{V}$, $w_d = 70.8 \mu\text{m}$

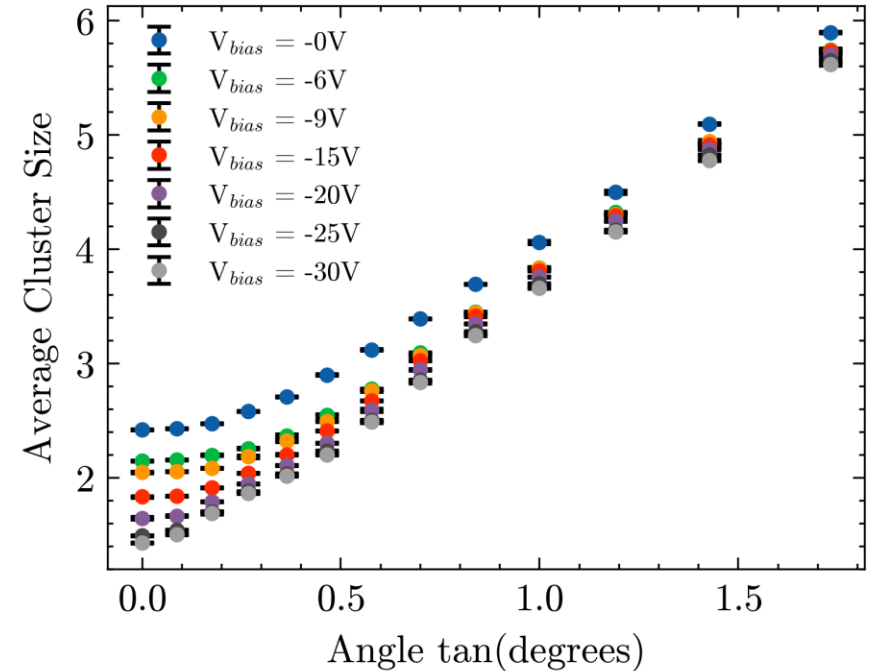
Linear Electric Field Investigation Results

Average Cluster Size vs. Angle for increasing V_{bias}



Scaled Cluster Size: Simulation, unirradiated, reduced thickness

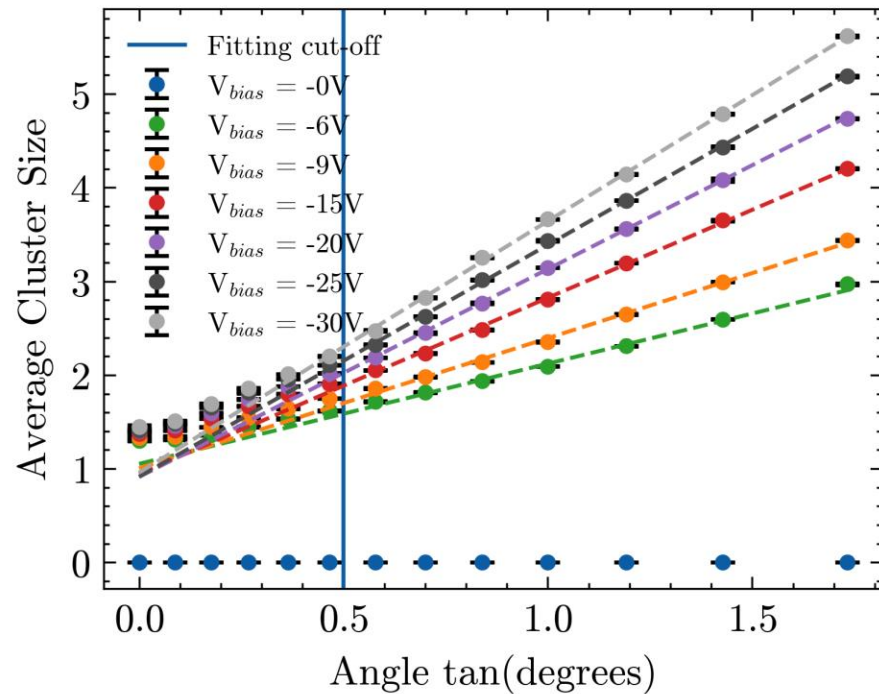
Average Cluster Size vs. Angle for increasing V_{bias}



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

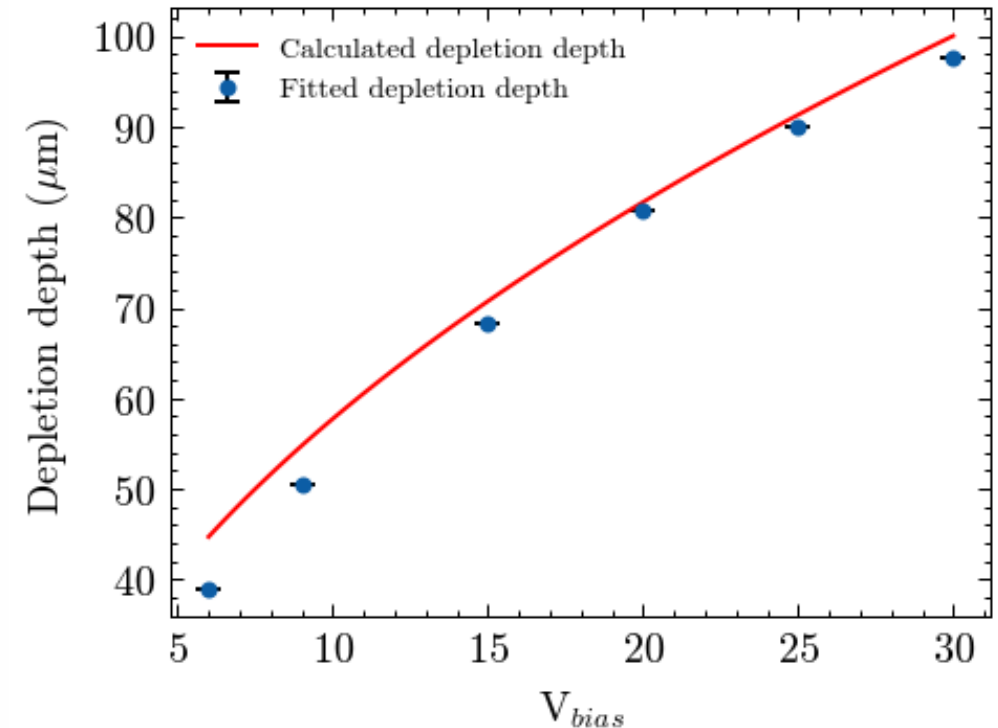
Linear Electric Field Investigation Results

Average Cluster Size vs. Angle for increasing V_{bias}



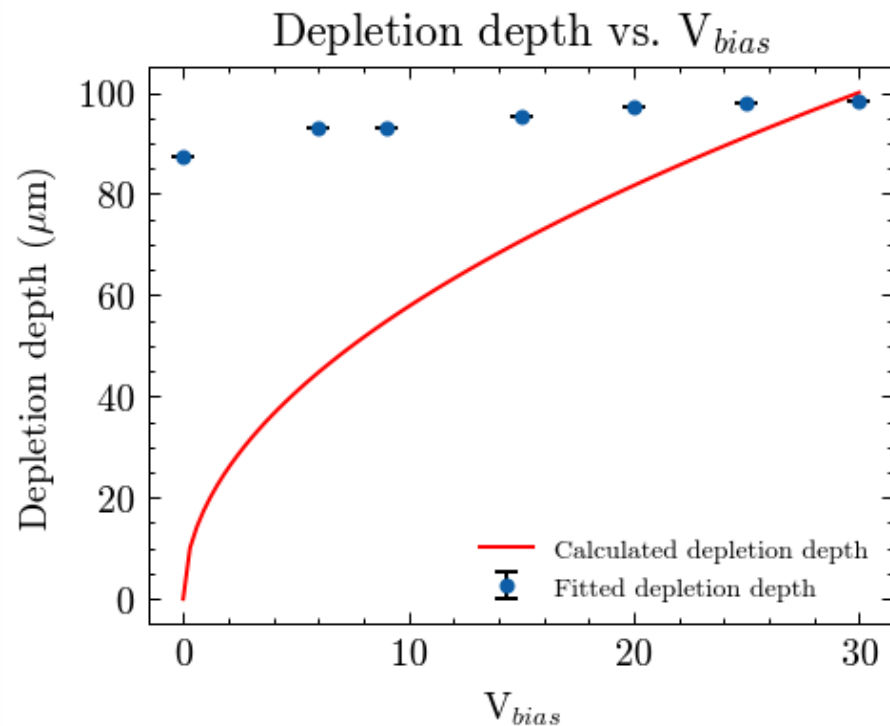
Scaled Cluster Size: Simulation, unirradiated, reduced thickness

Depletion depth vs. V_{bias}

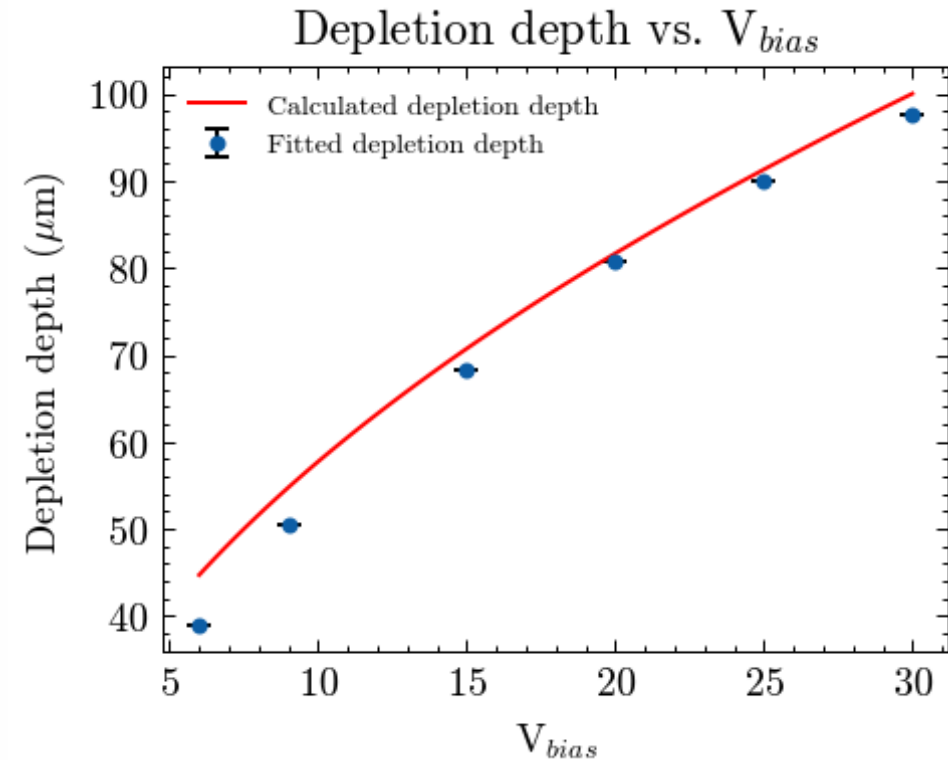


Fitted Depletion Depth: Simulation, unirradiated, reduced thickness

Linear Electric Field Investigation Results



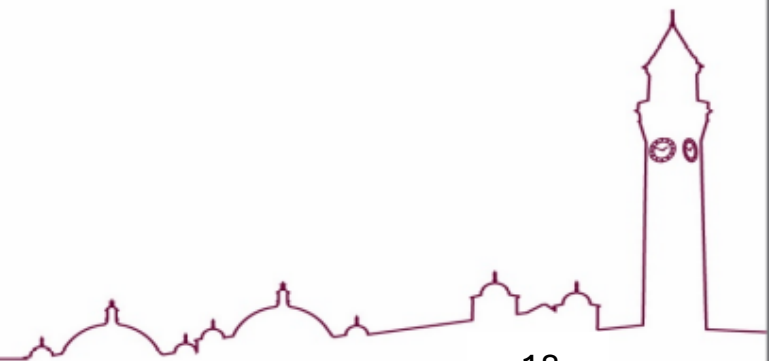
**Fitted Depletion Depth: Simulation,
unirradiated, 100 μm sensor thickness**



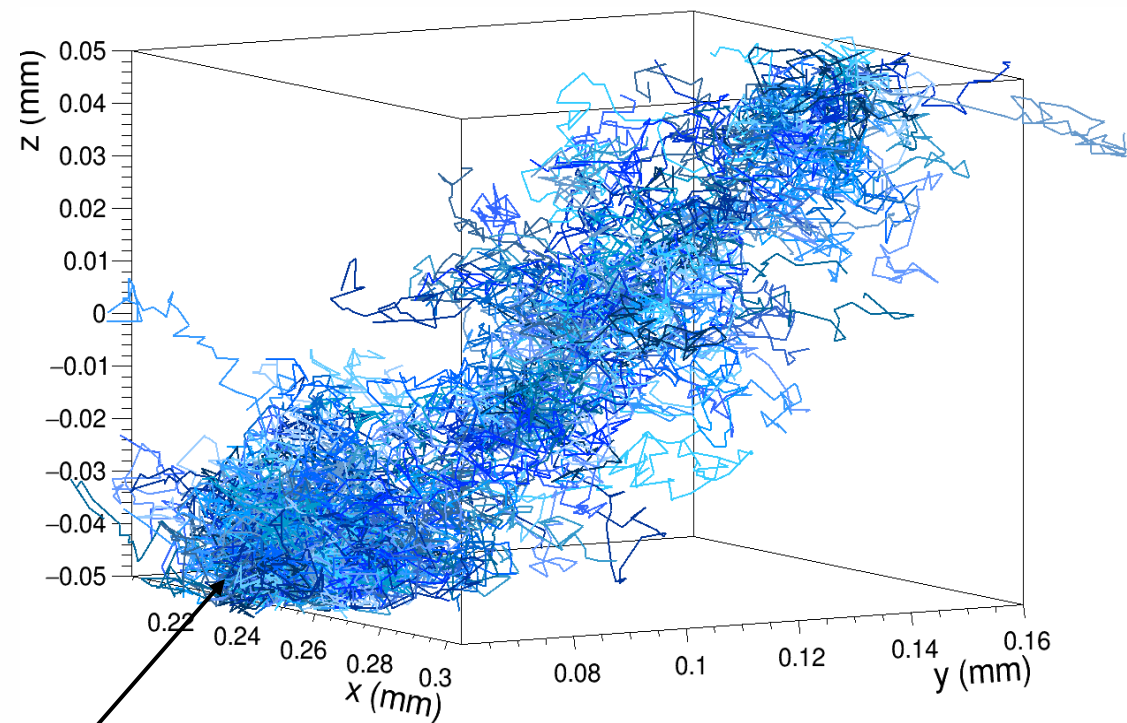
**Fitted Depletion Depth: Simulation,
unirradiated, reduced thickness**

Lineplots and Hitmaps Method

- Telescope removed to reduce spread on hitmap
- $1\mu\text{m}$ pixel pitch for increasing granularity
 - No change to digitisation threshold
- 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

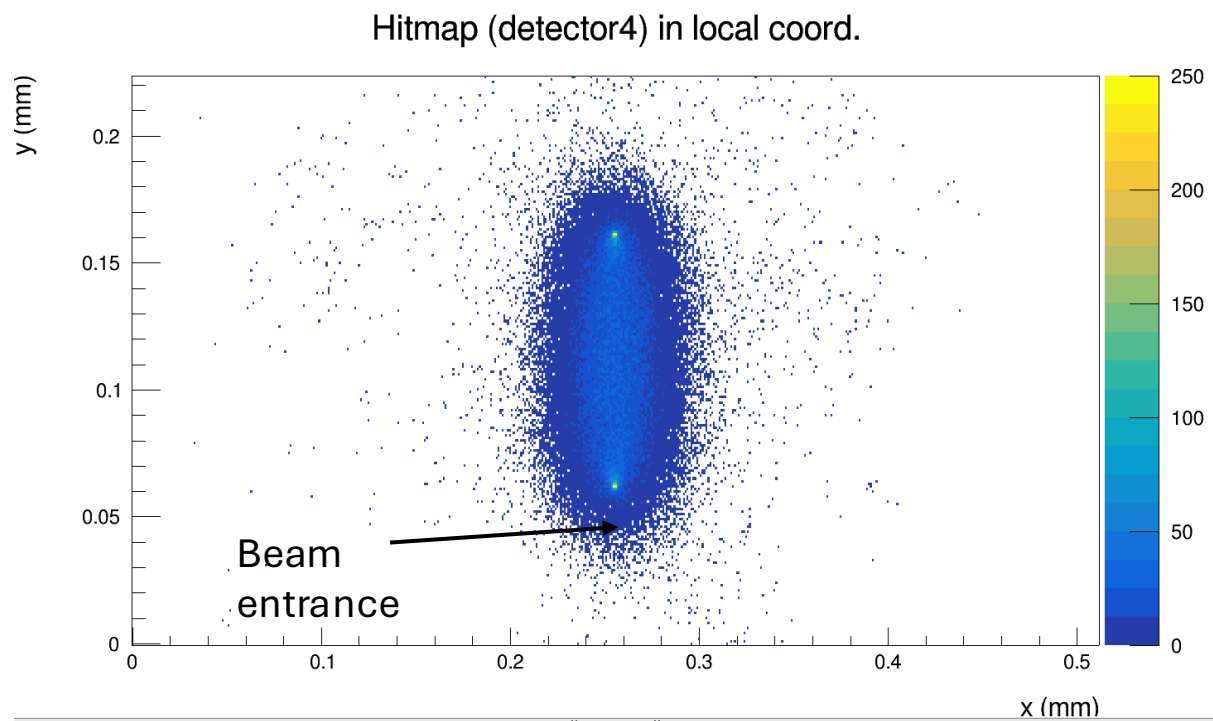


$$V_{\text{depl}} = -30\text{V}, V_{\text{bias}} = 0\text{V}$$



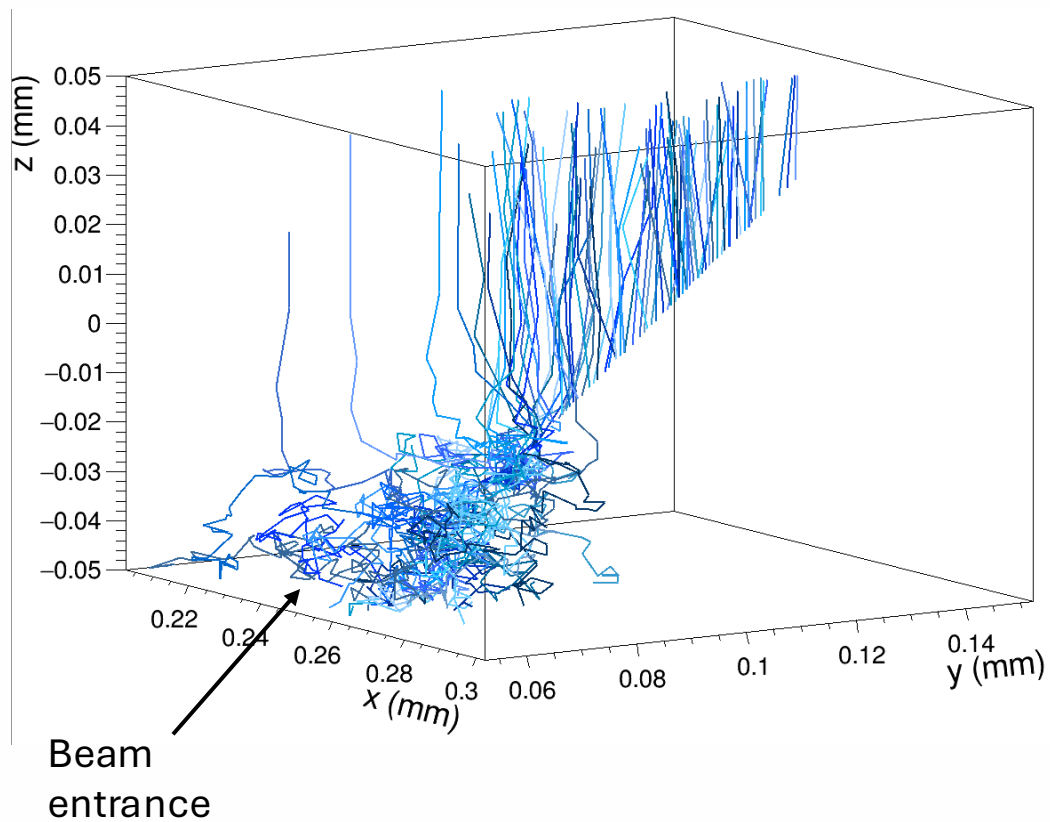
Beam
entrance

Lineplot: 45 degrees incline

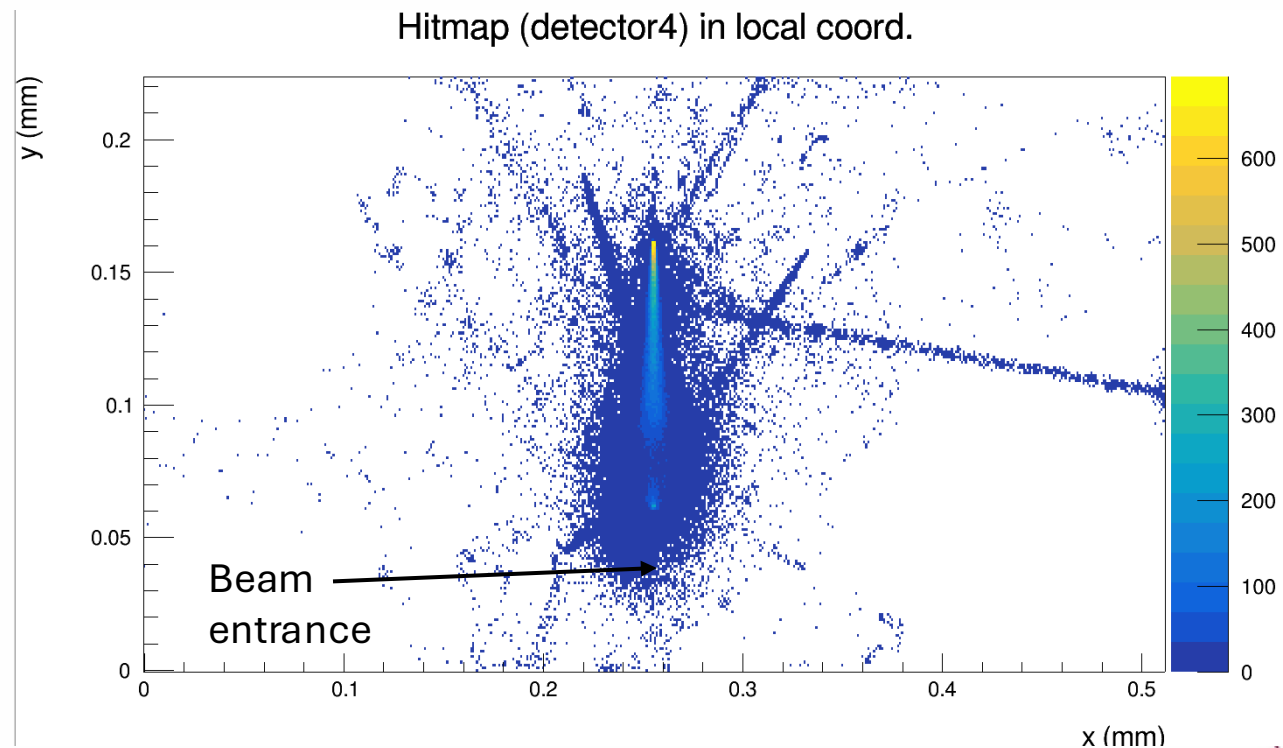


Hitmap: 45 degrees incline

$$V_{\text{depl}} = -30\text{V}, V_{\text{bias}} = -15\text{V}$$

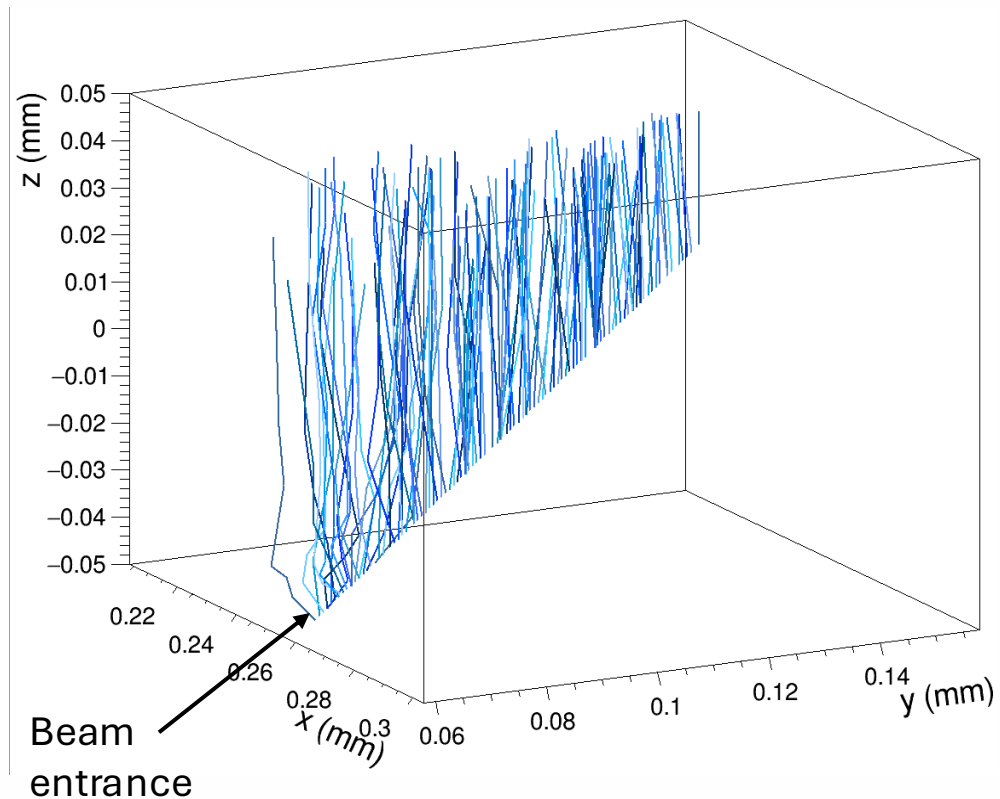


Lineplot: 45 degrees incline

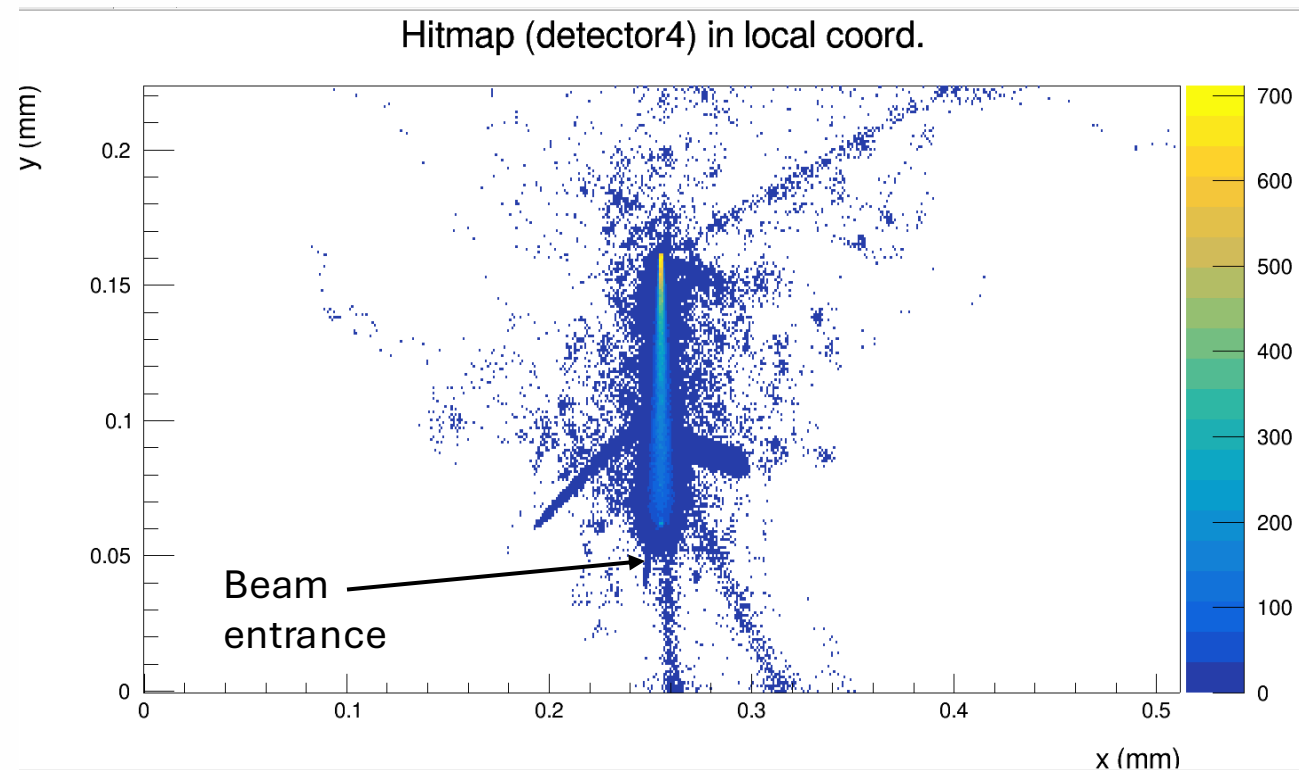


Hitmap: 45 degrees incline

$$V_{\text{depl}} = -30\text{V}, V_{\text{bias}} = -30\text{V}$$

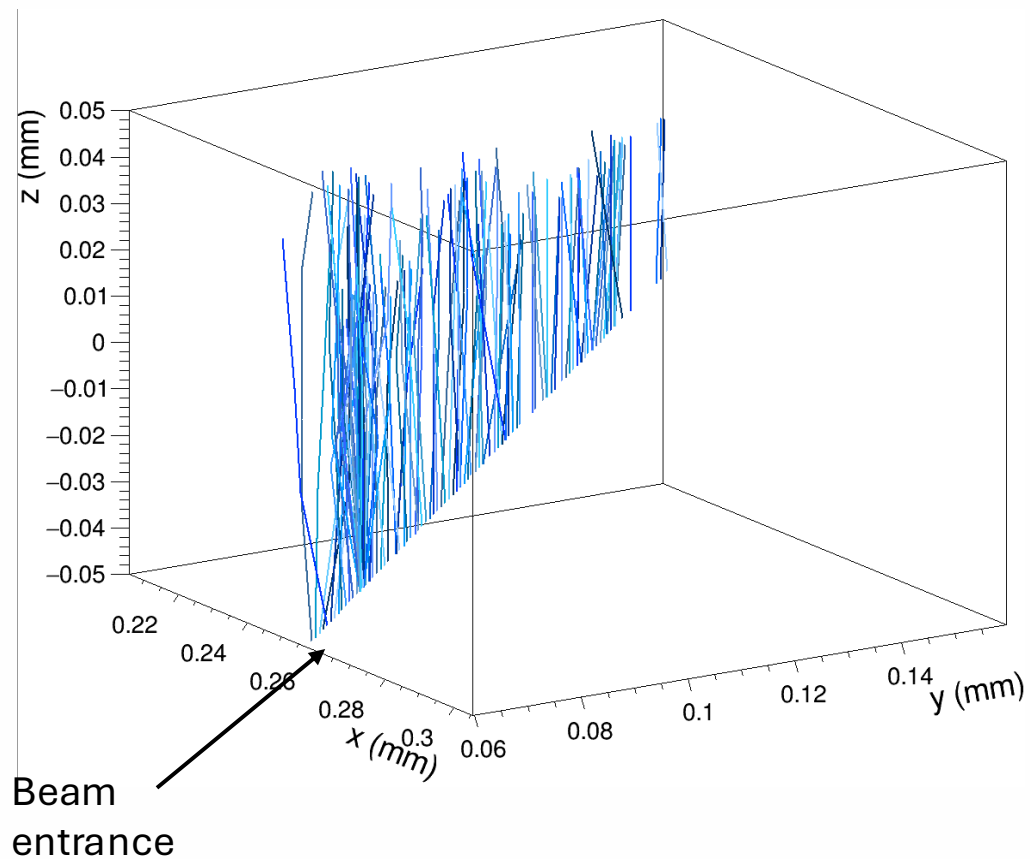


Lineplot: 45 degrees incline

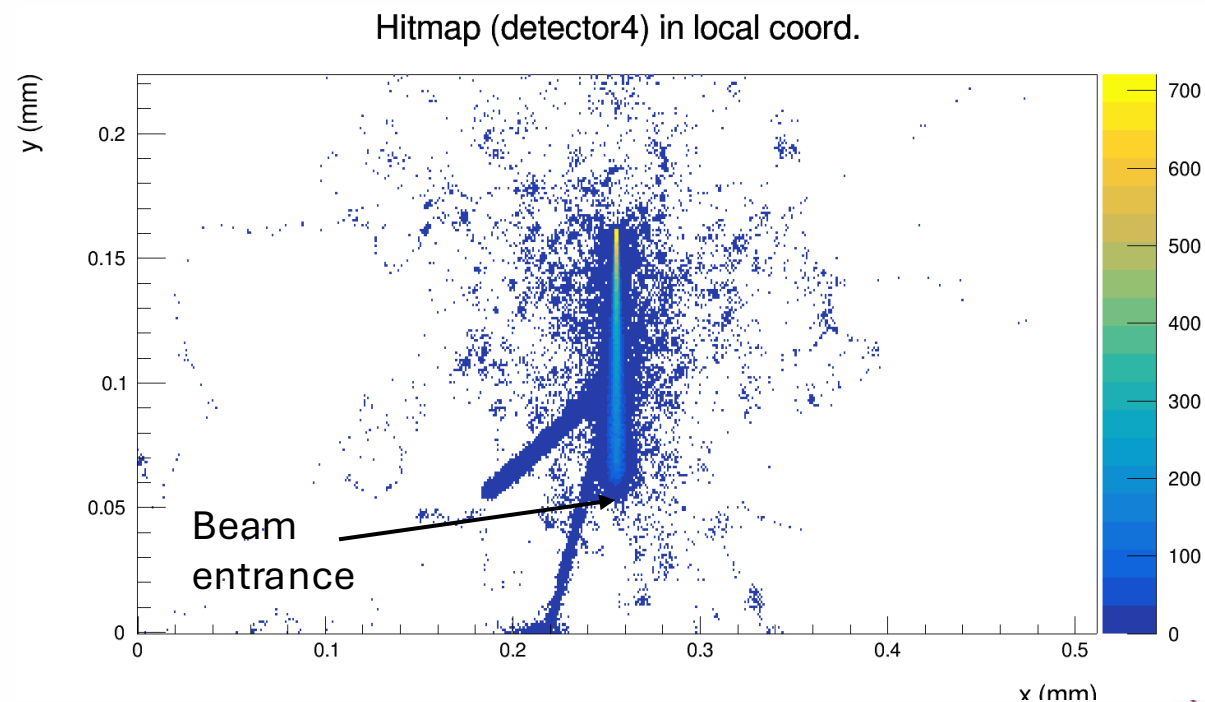


Hitmap: 45 degrees incline

$$V_{\text{depl}} = -30\text{V}, V_{\text{bias}} = -50\text{V}$$



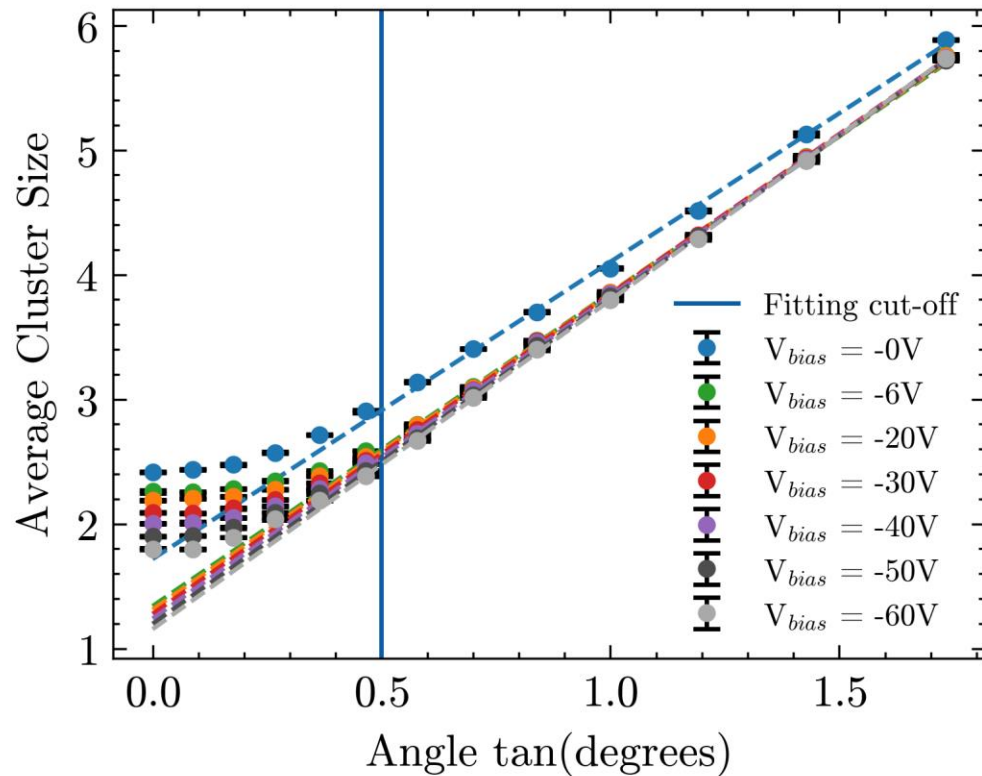
Lineplot: 45 degrees incline



Hitmap: 45 degrees incline

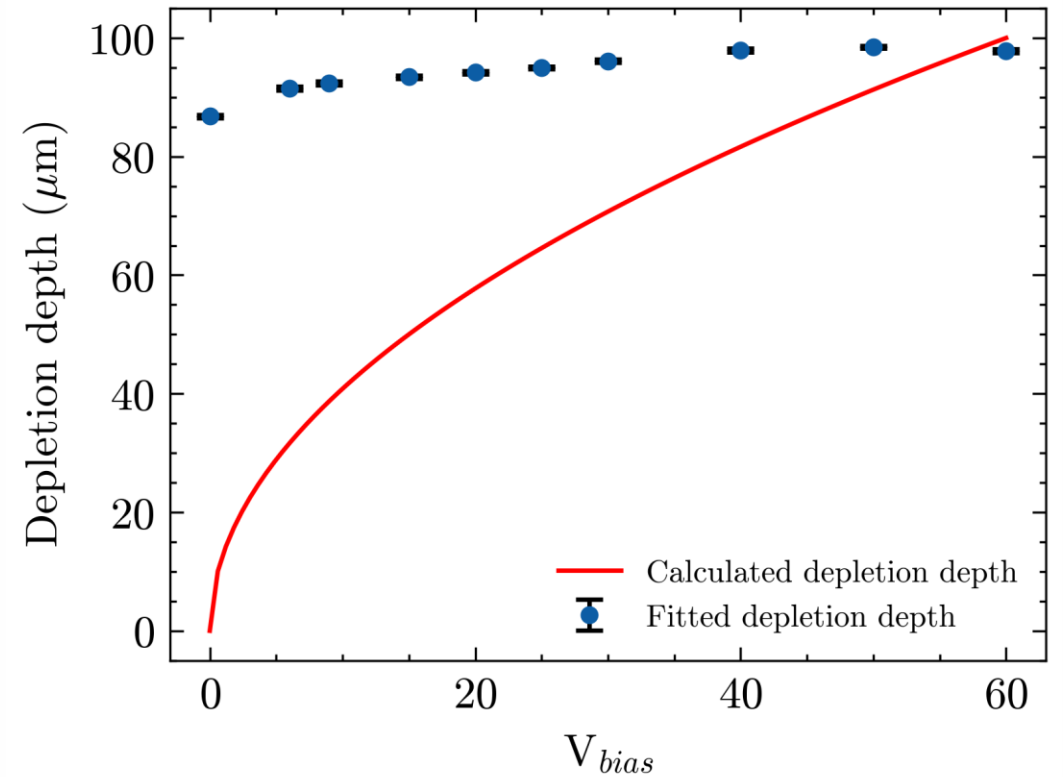
$V_{\text{depl}} = -60\text{V}$ Data

Average Cluster Size vs. Angle for increasing V_{bias}



Scaled Cluster Size: Simulation, unirradiated

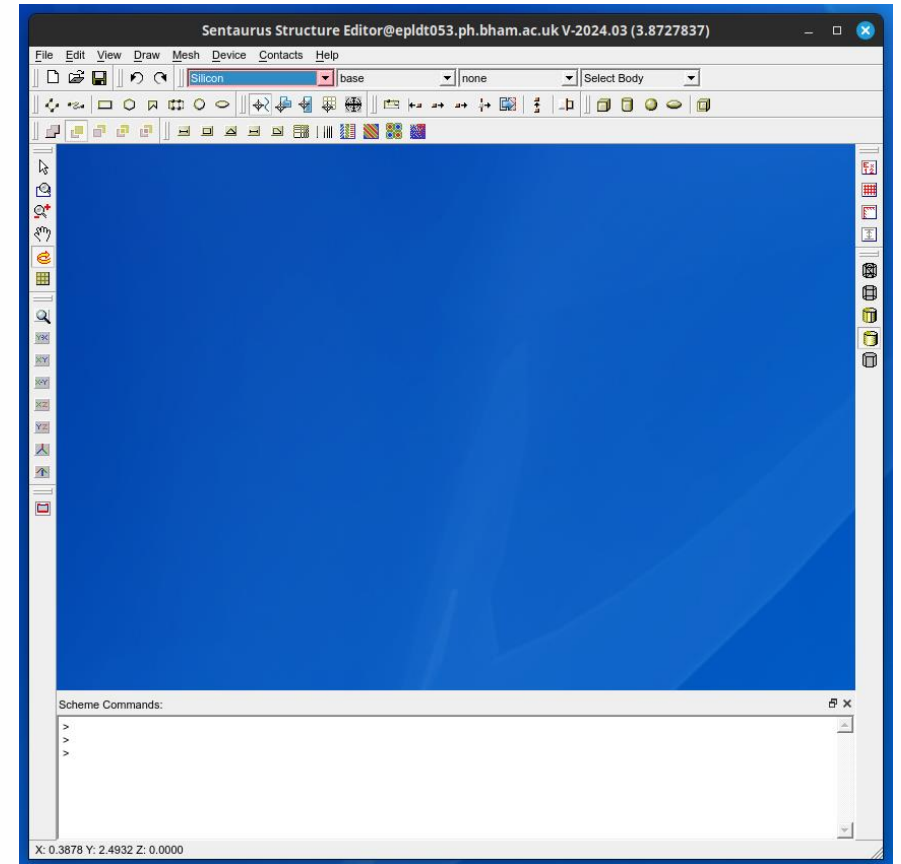
Depletion depth vs. V_{bias}



Fitted Depletion Depth: Simulation, unirradiated

Conclusions

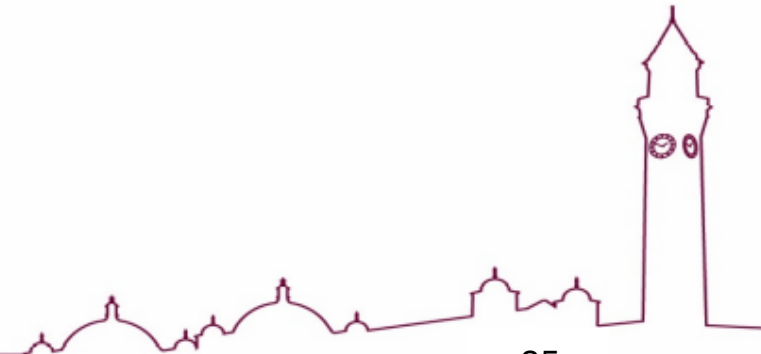
- Diffusion charges significant in clustering data at low bias voltages and incident angles
- Further study of integration time required to understand charge propagation
- Need to change the electric field linear \rightarrow mesh using TCAD software
- Long's talk will give an overview of irradiated sensor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



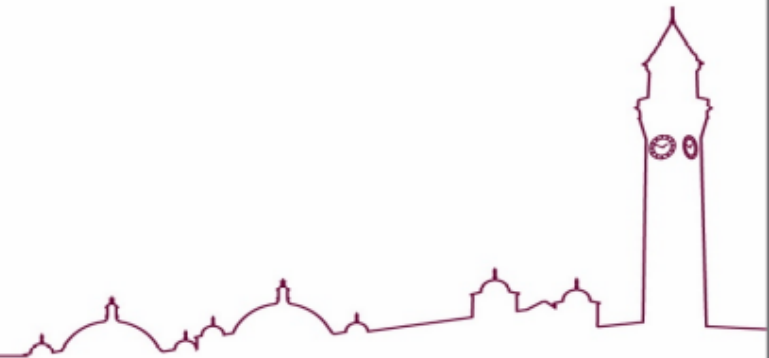
Sentaurus Structure Editor, showing lack of 3D rendering

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>

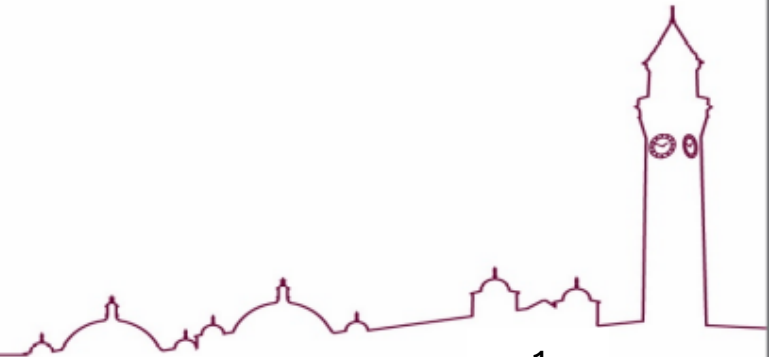


Back-up Slides



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 x 10 ¹⁵ 1 MeV n _{eq} /cm ² and 100MRad

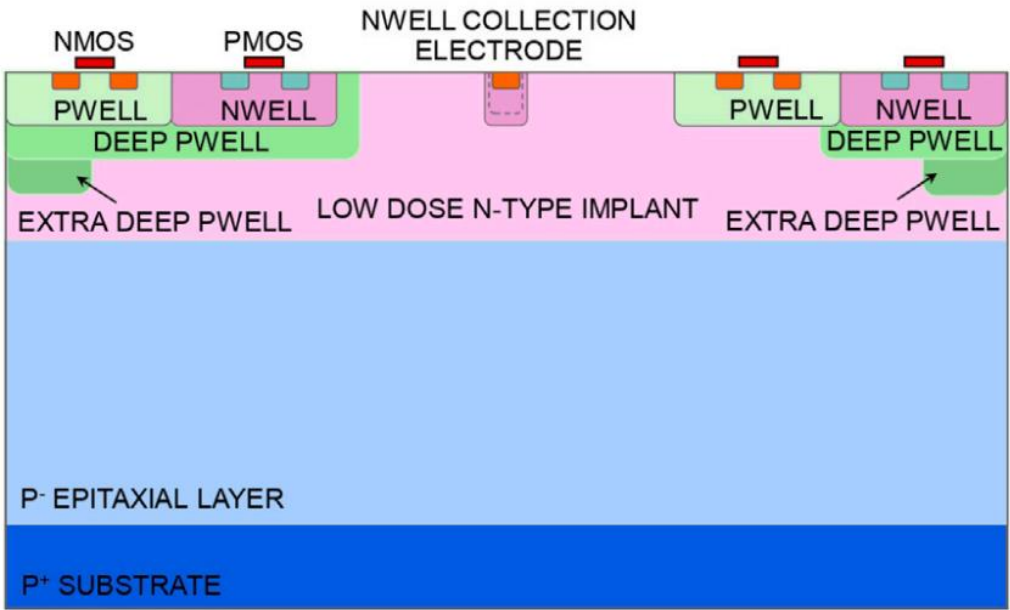


Fig. : XDPW processes MALTA2 layout with full lateral electric field and extra deep p-well [4]

Simulation set-up

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

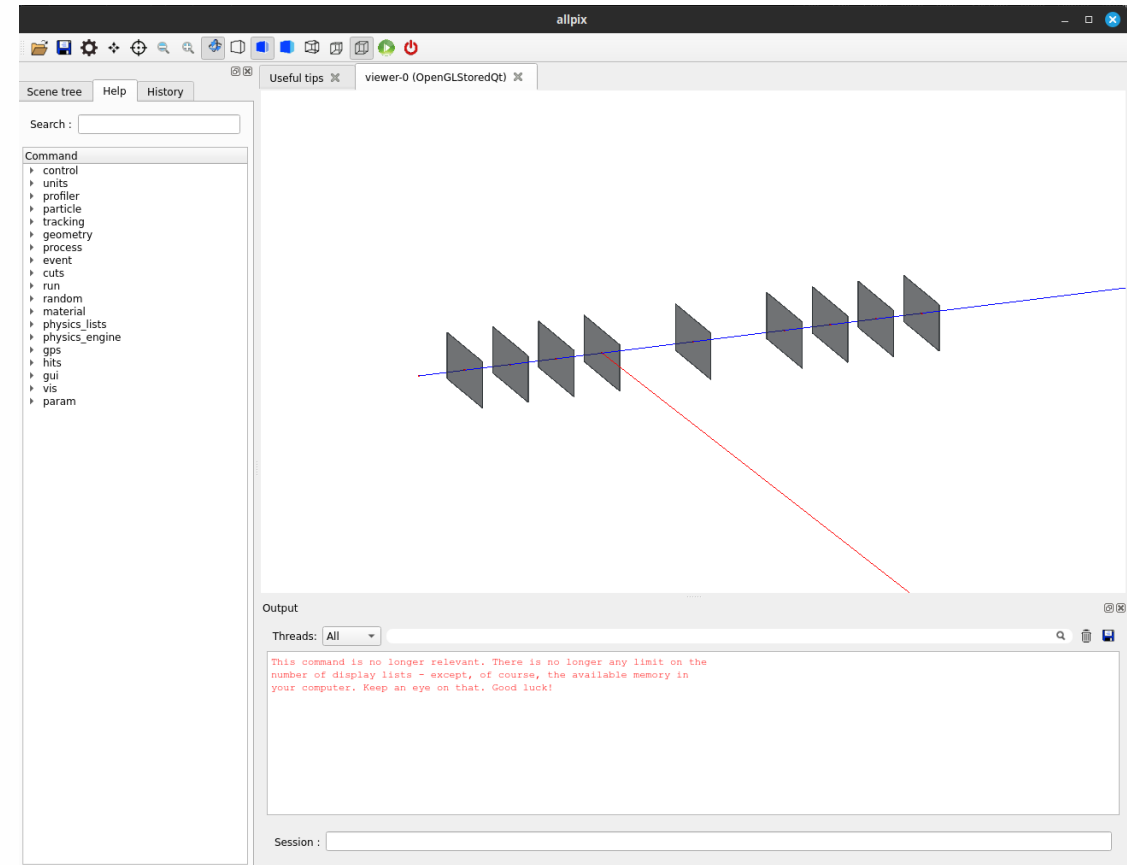


Fig. 4: Allpix-Squared simulation visualisation

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"
```

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

number_of_pixels = 512 224
pixel_size = 36.4um 36.4um

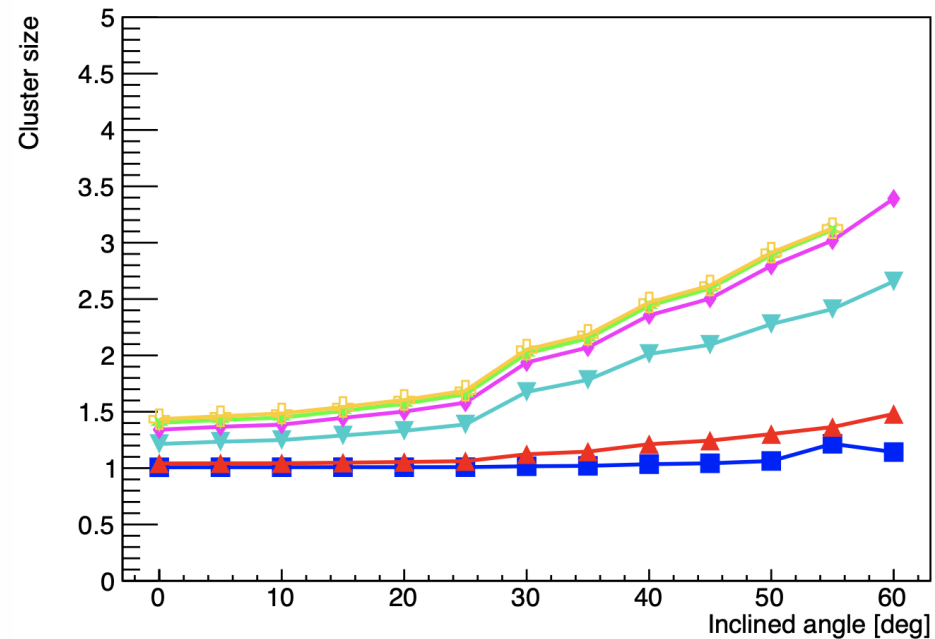
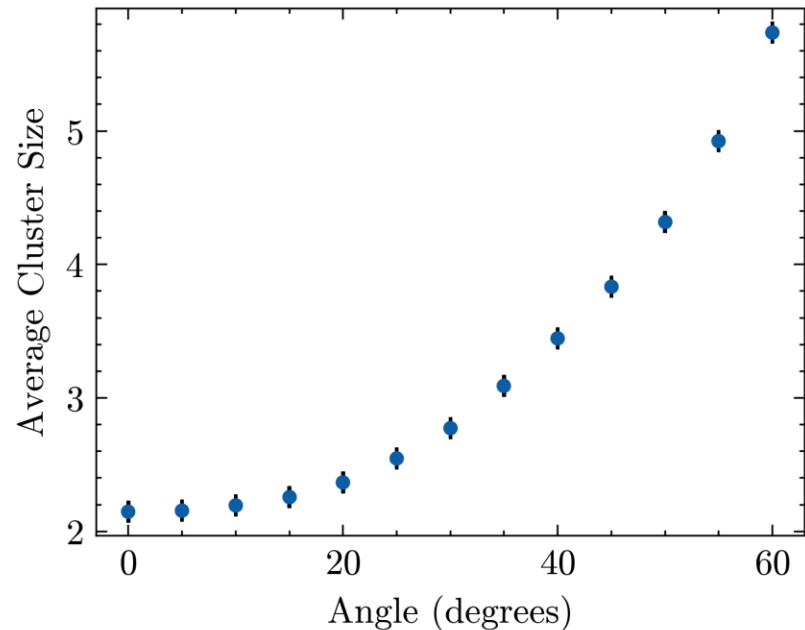
#Sensor chip size = 20.2mm 10.1168mm
sensor_thickness = 100um
sensor_excess_top = 0.9812mm
sensor_excess_bottom = 0.9812mm
sensor_excess_left = 0.7816mm
sensor_excess_right = 0.7816mm
```

Allpix²: Simulation configuration

Allpix²: Detector set-up

Telescope Cluster Size vs Incident Angle (before automation)

Average Cluster Size vs. Angle for $V_{bias} = -6V$



MALTA2

Cz, 100 μm , H-dop
back-metal, XDPW

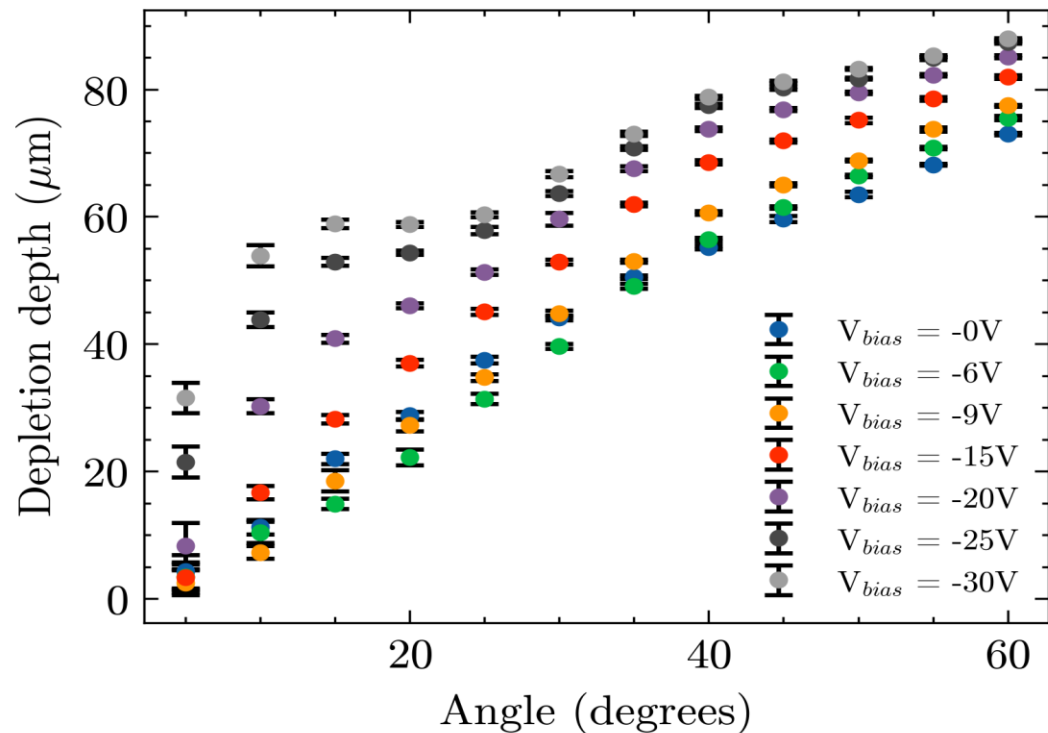
1×10^{15} 1 MeV n_{eq}/cm^2

ITHR: 40 DAC

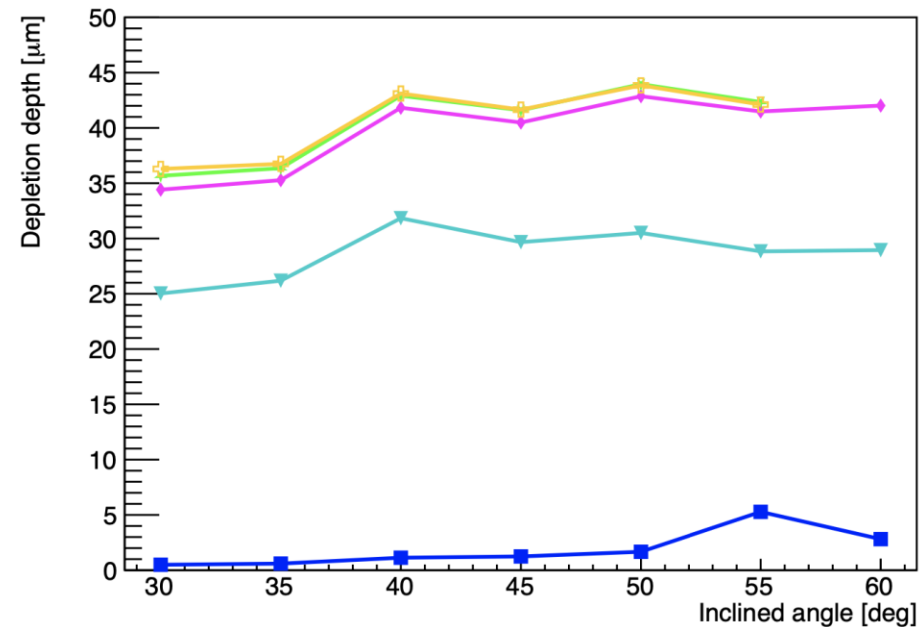
- $V_{sub} = -6V$
- $V_{sub} = -9V$
- $V_{sub} = -15V$
- $V_{sub} = -20V$
- $V_{sub} = -25V$
- $V_{sub} = -30V$

Telescope Pixel Depletion Depth vs Incident Angle

Depletion depth vs. Angle for increasing V_{bias}



Depletion depth: Simulation, unirradiated



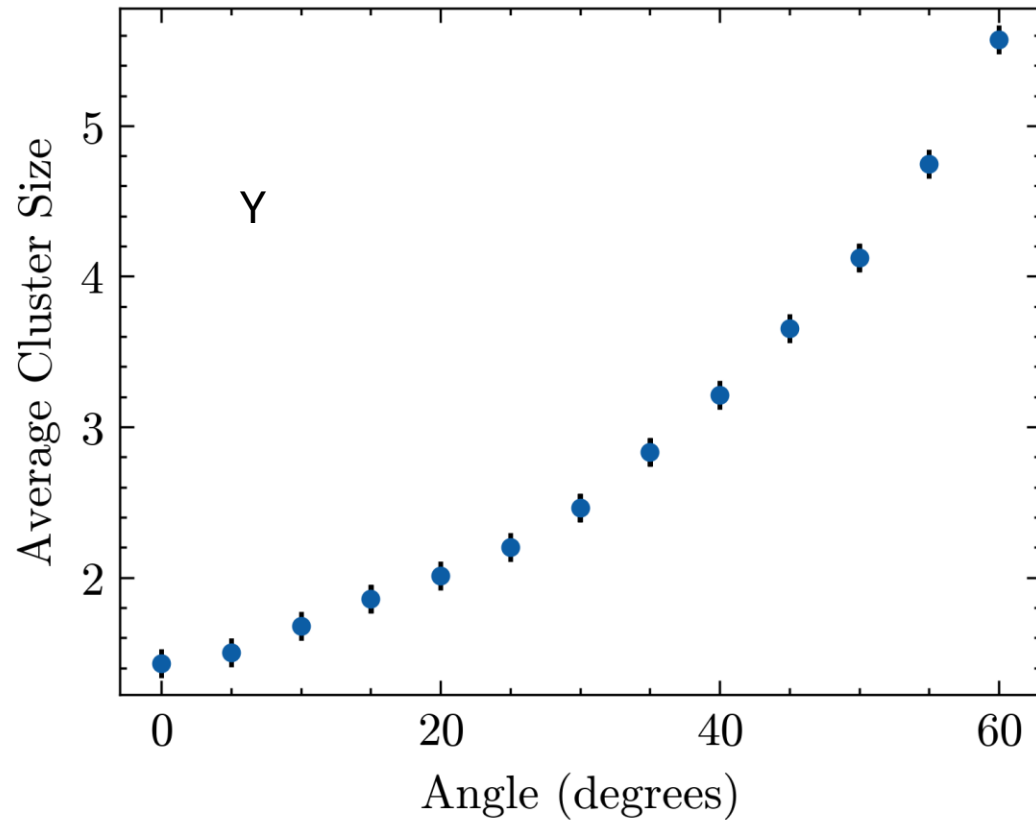
Depletion depth: Test beam, irradiated

MALTA2
Cz, 100 μm , H-dop
back-metal, XDPW
 1×10^{15} 1 MeV n_{eq}/cm^2
Threshold: 260 e^-

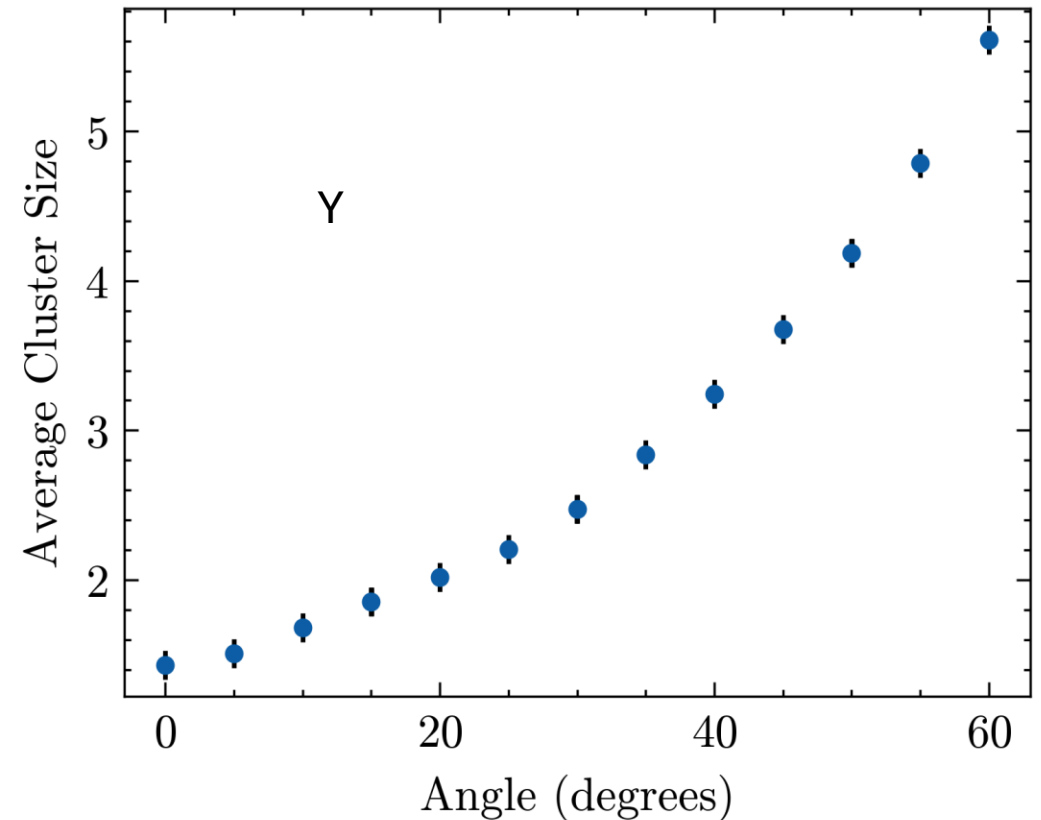
$V_{sub} = -6.0\text{ V}$
 $V_{sub} = -15.0\text{ V}$
 $V_{sub} = -20.0\text{ V}$
 $V_{sub} = -25.0\text{ V}$
 $V_{sub} = -30.0\text{ V}$

Average cluster size for $V_b = -30$ at $\text{max_depth} = 5\mu\text{m}$ and $100\mu\text{m}$

Average Cluster Size vs. Angle for $V_{bias} = -30V$

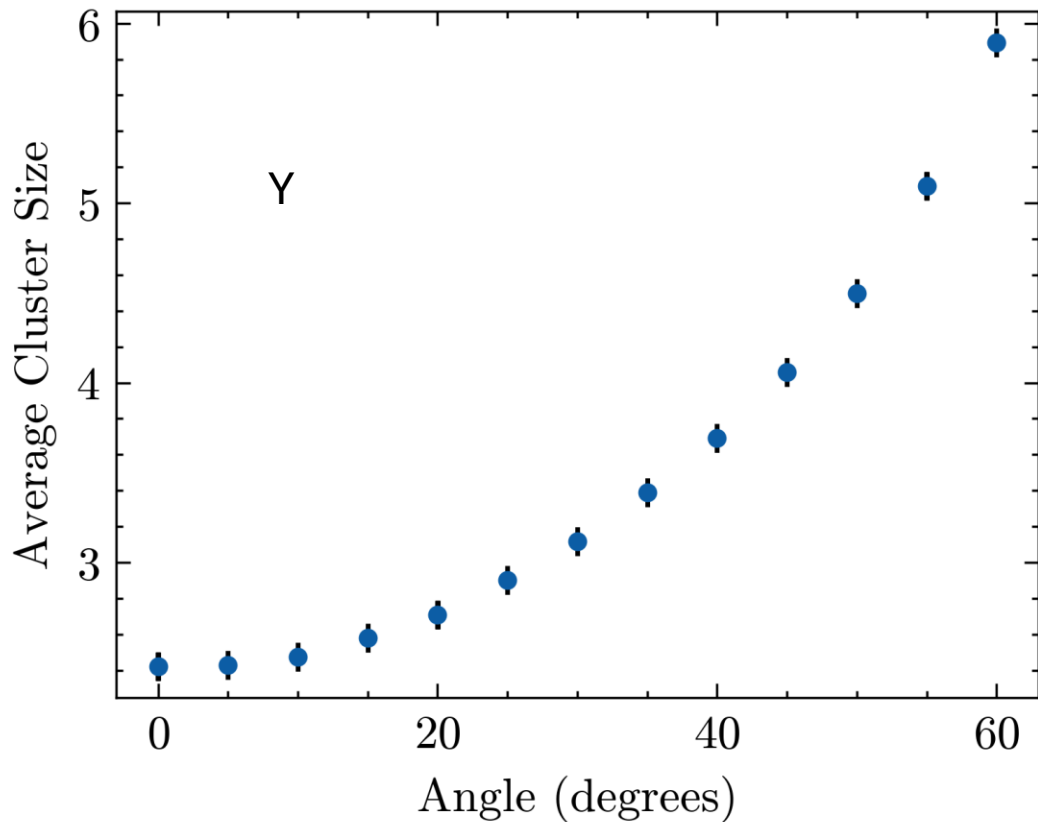


Average Cluster Size vs. Angle for $V_{bias} = -30V$

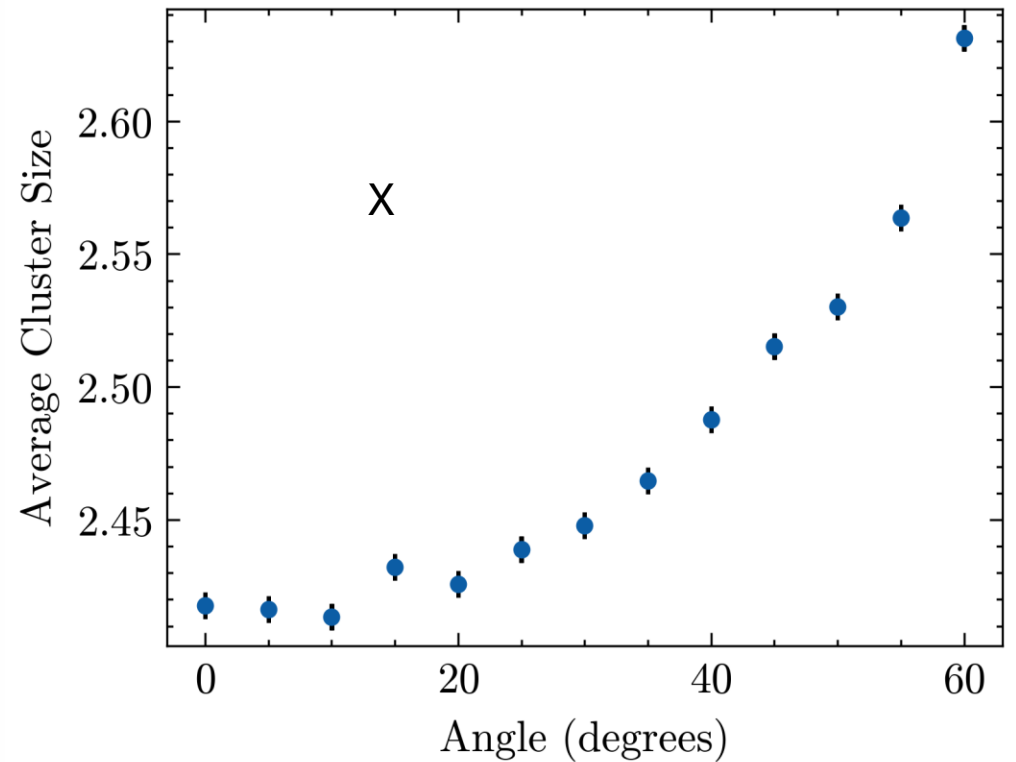


Average cluster size for $V_b = 0V$

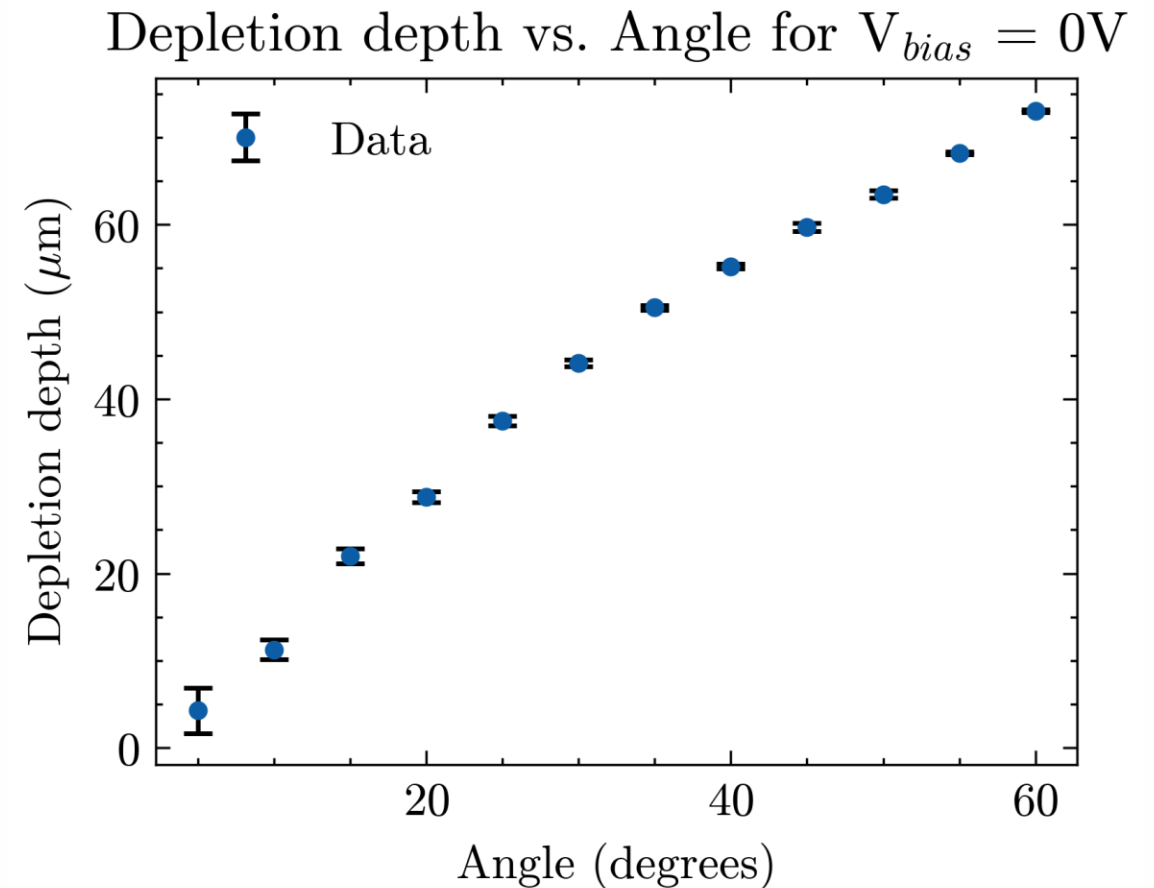
Average Cluster Size vs. Angle for $V_{bias} = 0V$

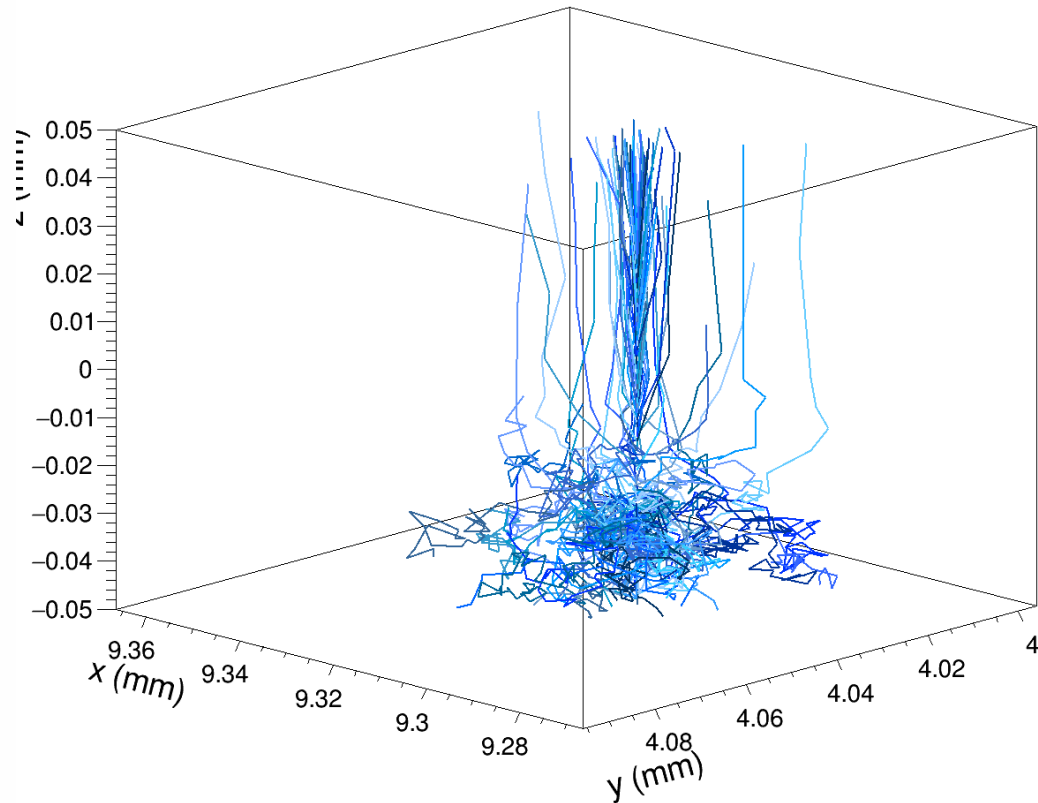


Average Cluster Size vs. Angle for $V_{bias} = 0V$

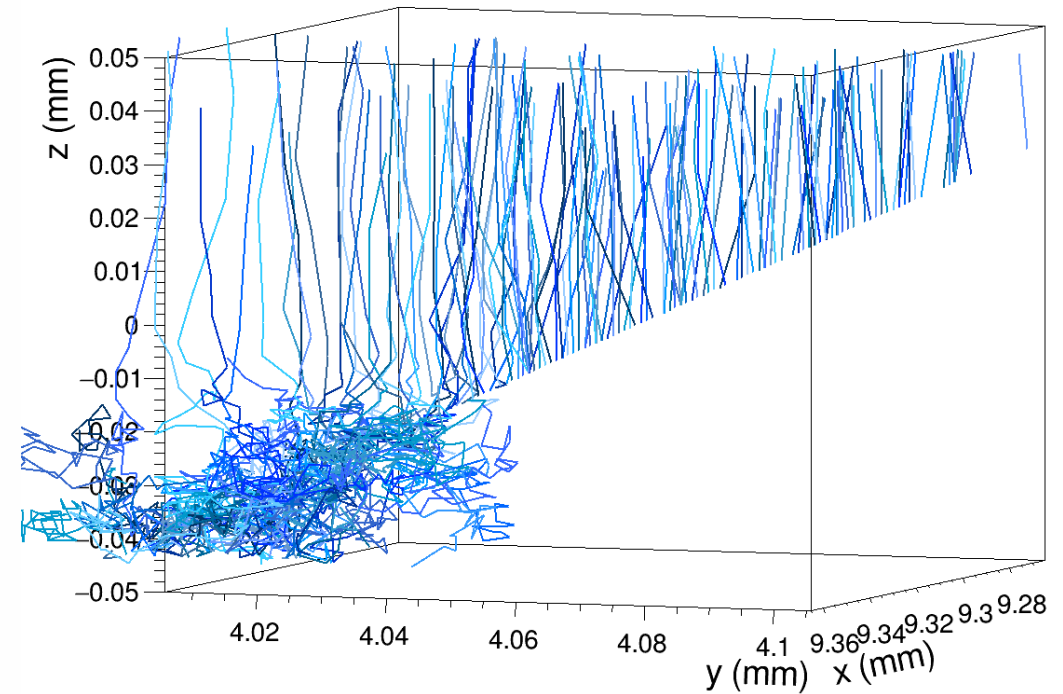


Depletion depth vs. Incident angle for $V_b = 0V$



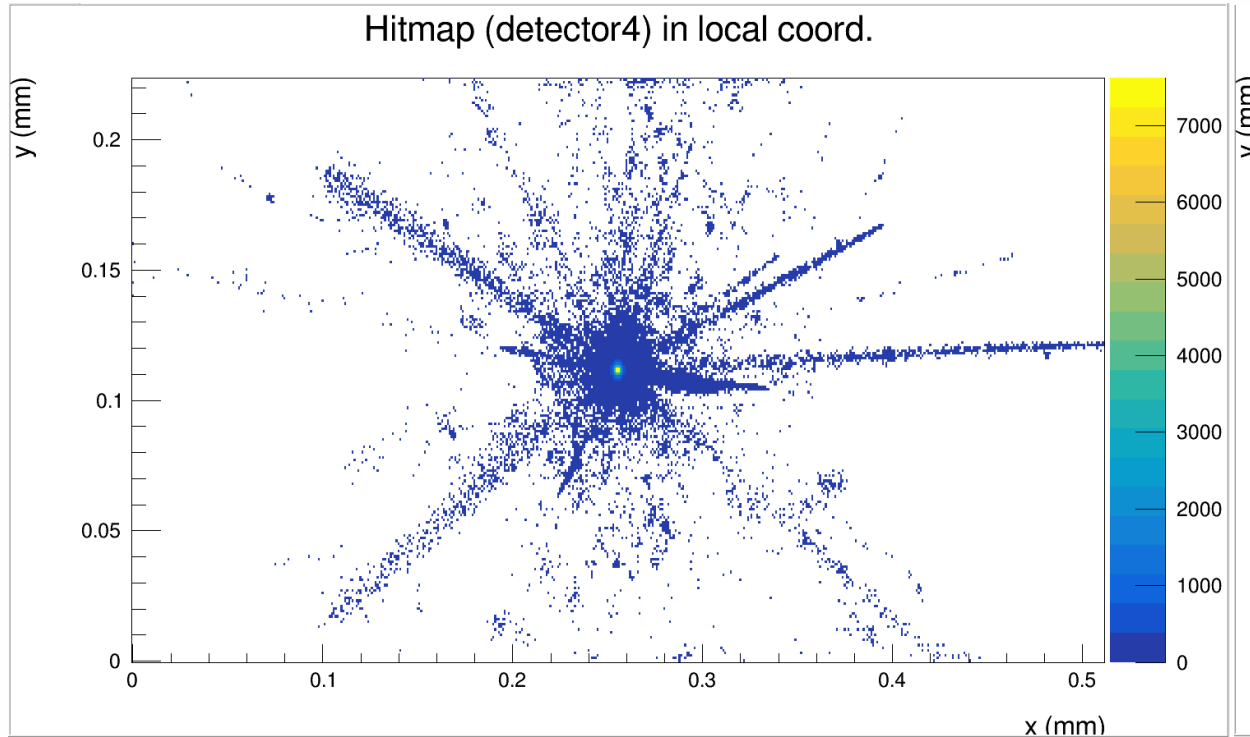


3D demonstration of electron drift and diffusion in MALTA2 DUT sensor at 0 degrees incline. A full depletion voltage of -30V is used and -15V bias.



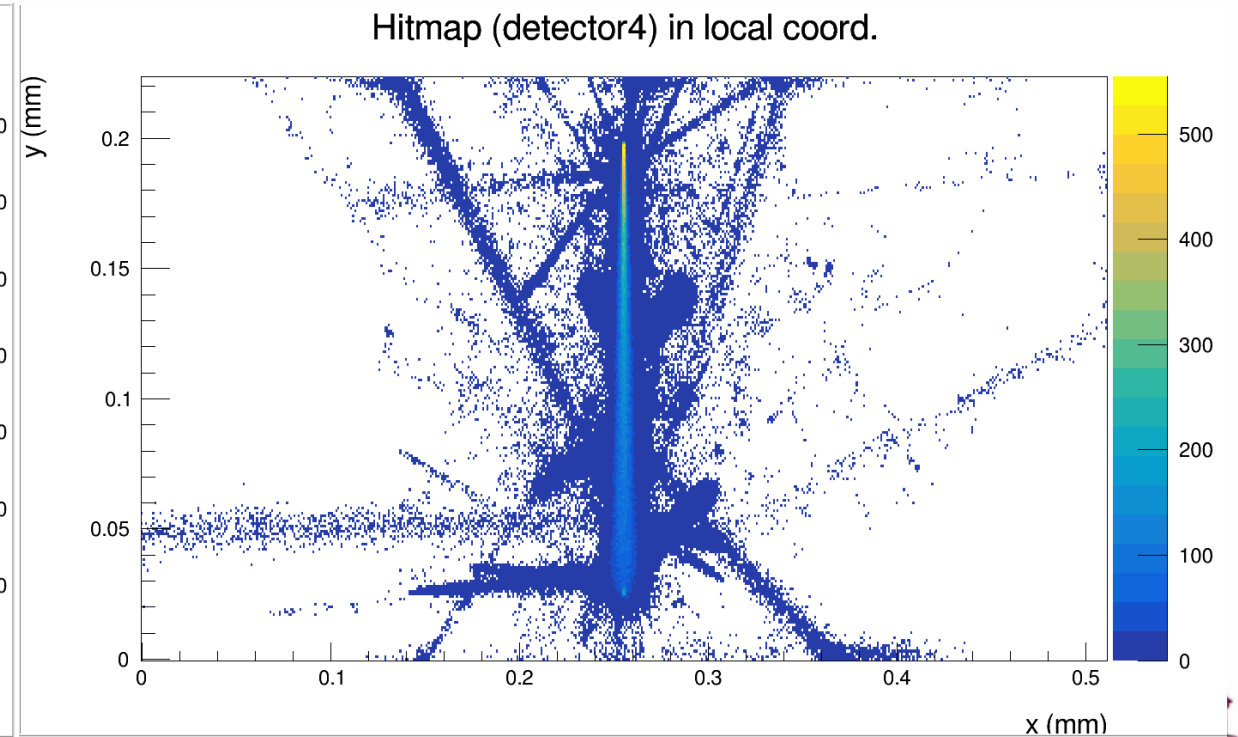
3D demonstration of electron drift and diffusion in MALTA2 DUT sensor at 60 degrees incline. A full depletion voltage of -30V is used and -15V bias.

Hitmap (detector4) in local coord.

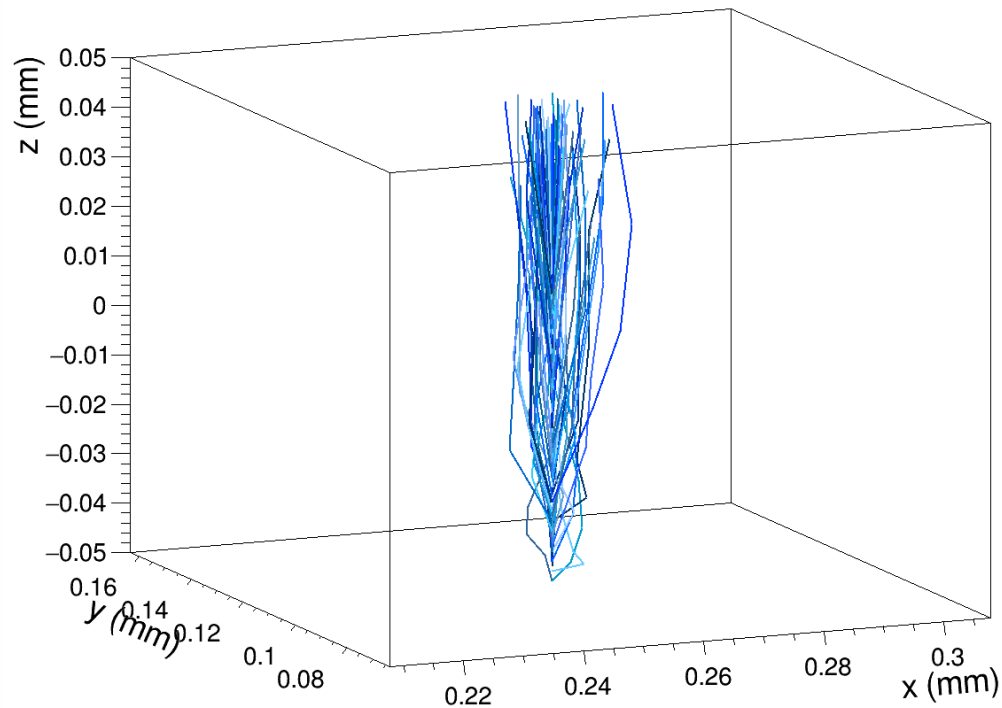


Hitmap for pixels in the MALTA2 DUT sensor at 0 degrees incline without the telescope. A full depletion voltage of -30V is used and -30V bias.

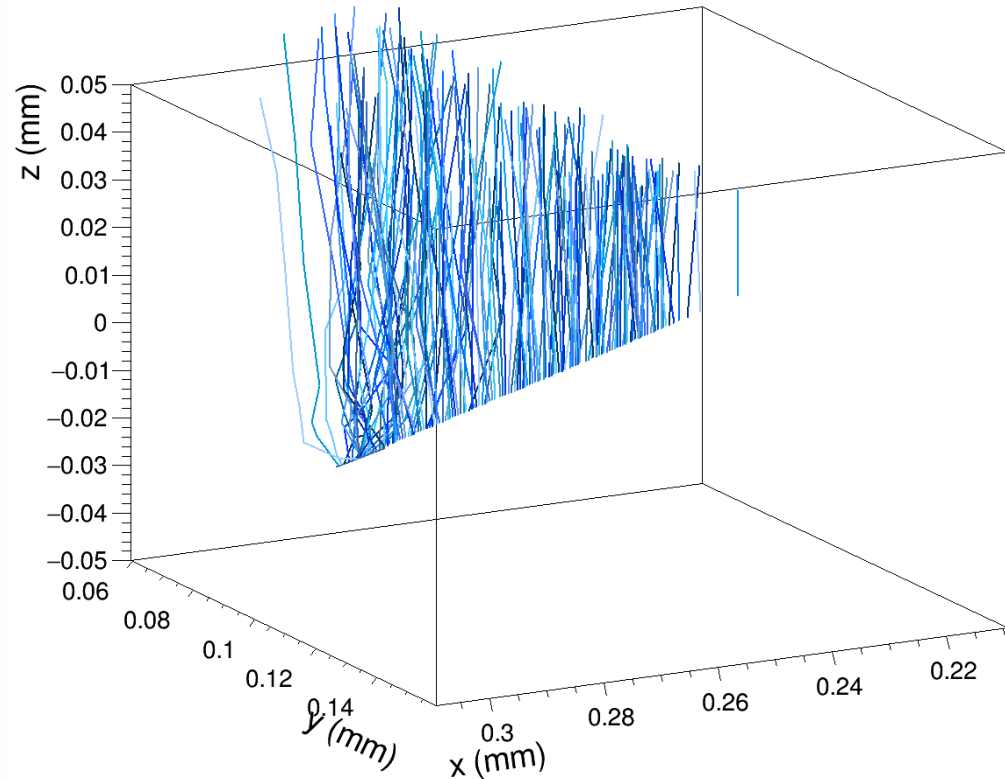
Hitmap (detector4) in local coord.



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.

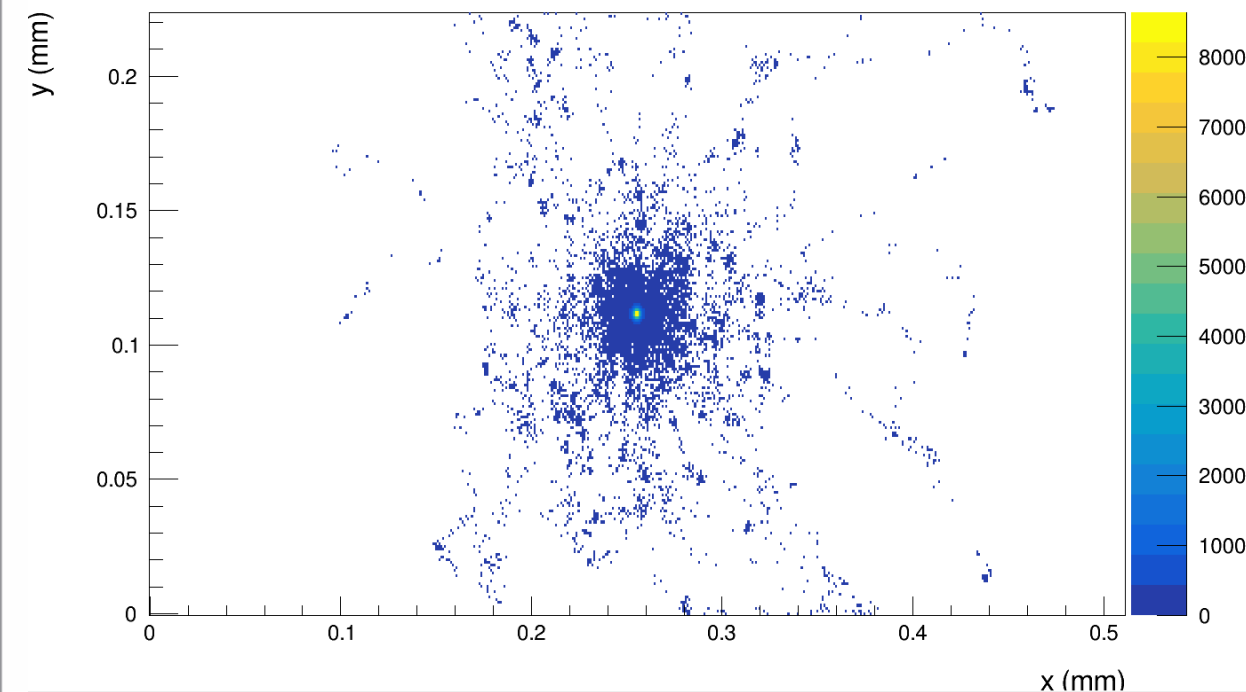


Drift and diffusion of electrons in MALTA2 DUT sensor at 0 degree incline without the telescope. A full depletion voltage of -30V is used and -30V bias.



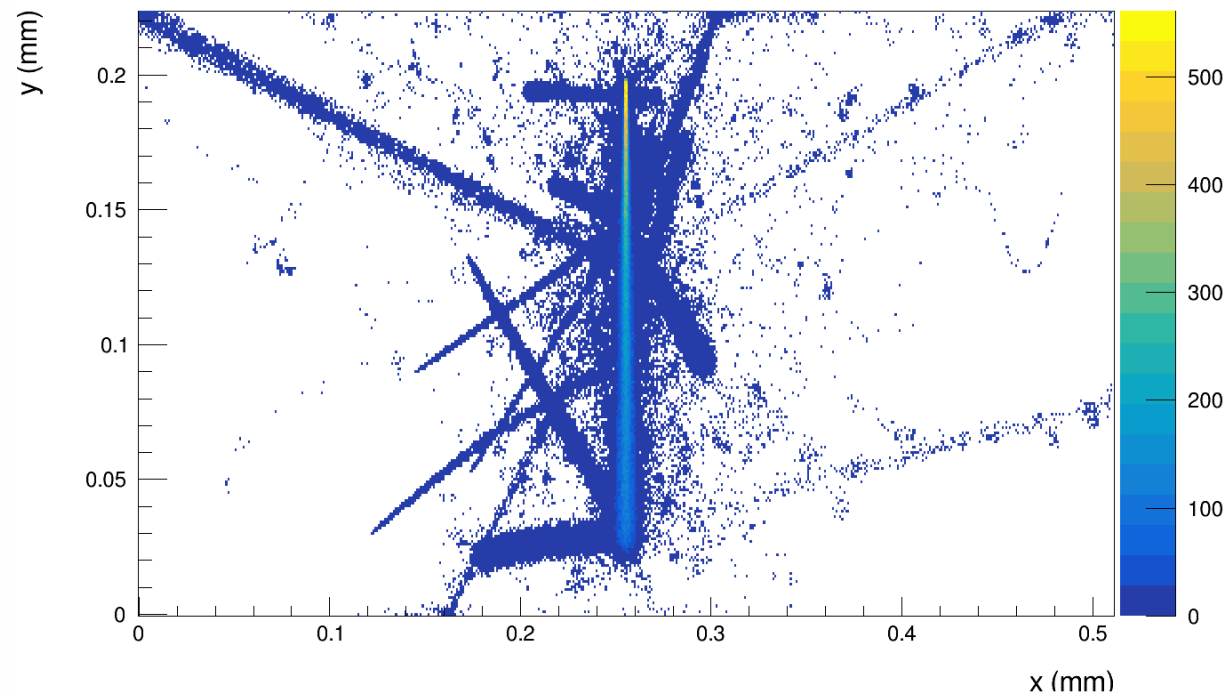
Drift and diffusion of electrons in MALTA2 DUT sensor at 60 degree incline without the telescope. A full depletion voltage of -30V is used and -30V bias.

Hitmap (detector4) in local coord.



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.

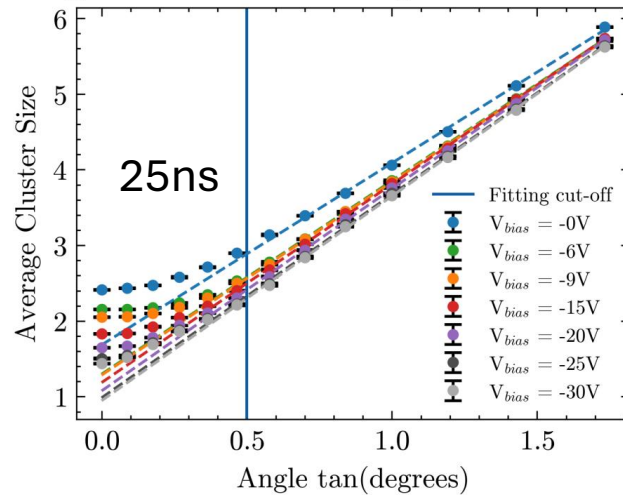
Hitmap (detector4) in local coord.



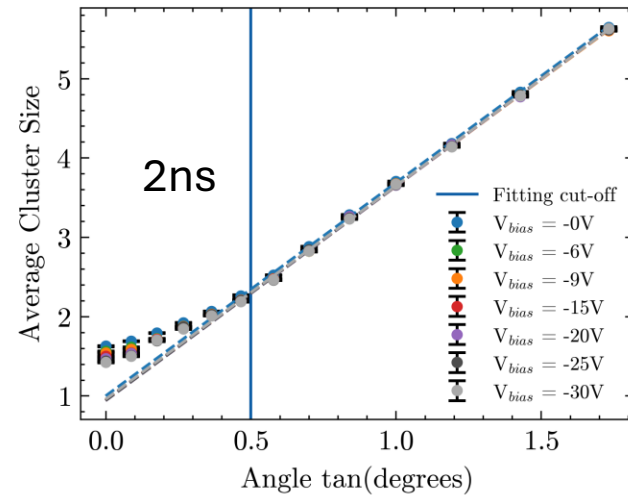
Hitmap for pixels in the MALTA2 DUT sensor at 60 degrees incline without the telescope. A full depletion voltage of -30V is used and -50V bias.

Integration Time Investigation Cluster Sizes

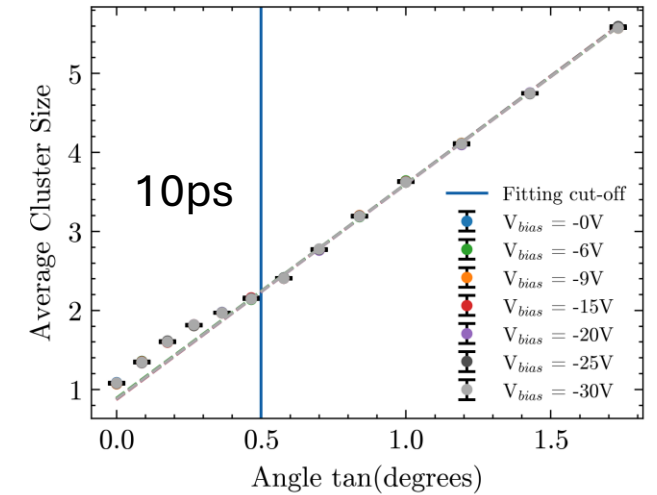
Average Cluster Size vs. Angle for increasing V_{bias}



Average Cluster Size vs. Angle for increasing V_{bias}

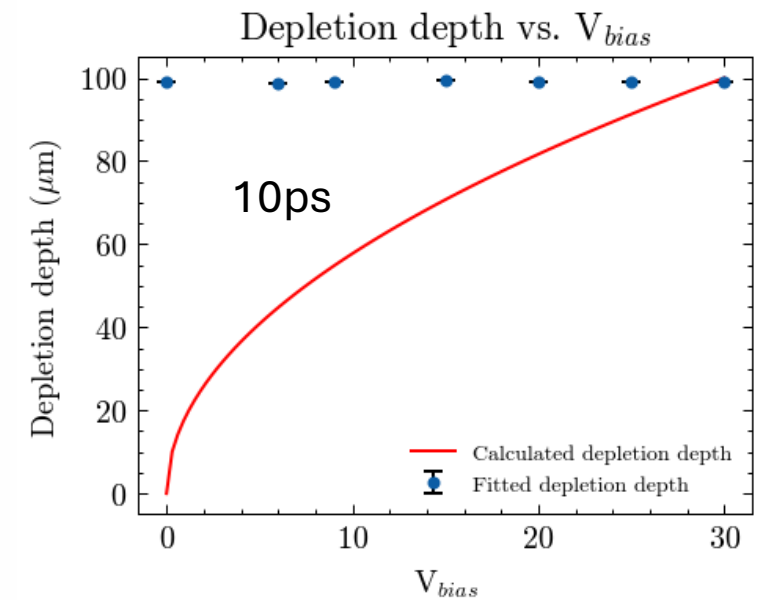
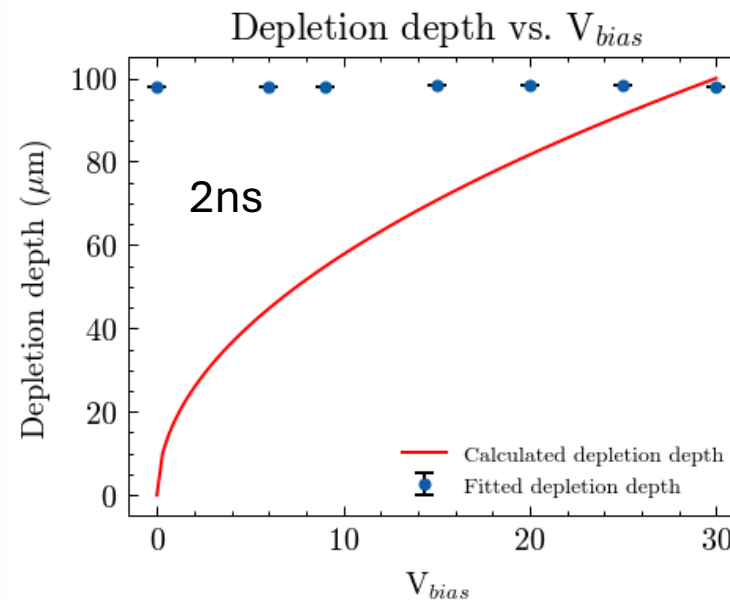
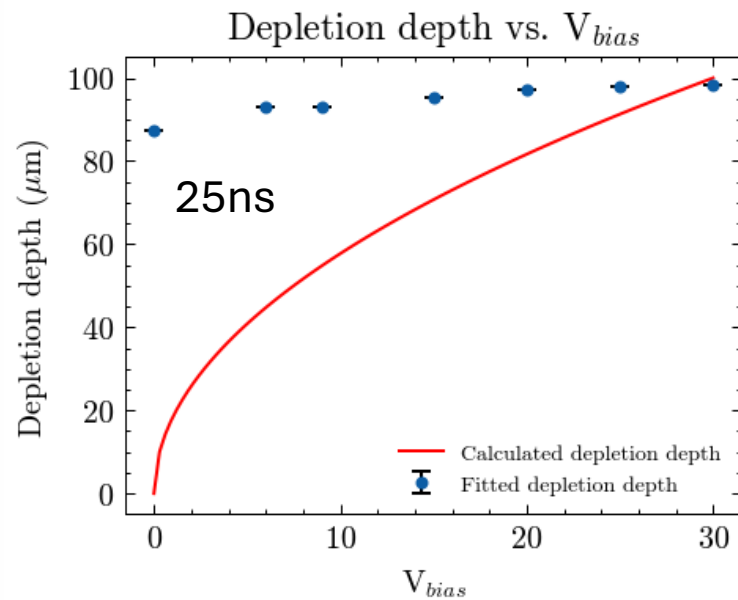


Average Cluster Size vs. Angle for increasing V_{bias}



Fitted Depletion Depth: Simulation, unirradiated, timing information

Integration Time Investigation Calculated and Actual Depletion Depth



Scaled Cluster Size: Simulation, unirradiated, timing information

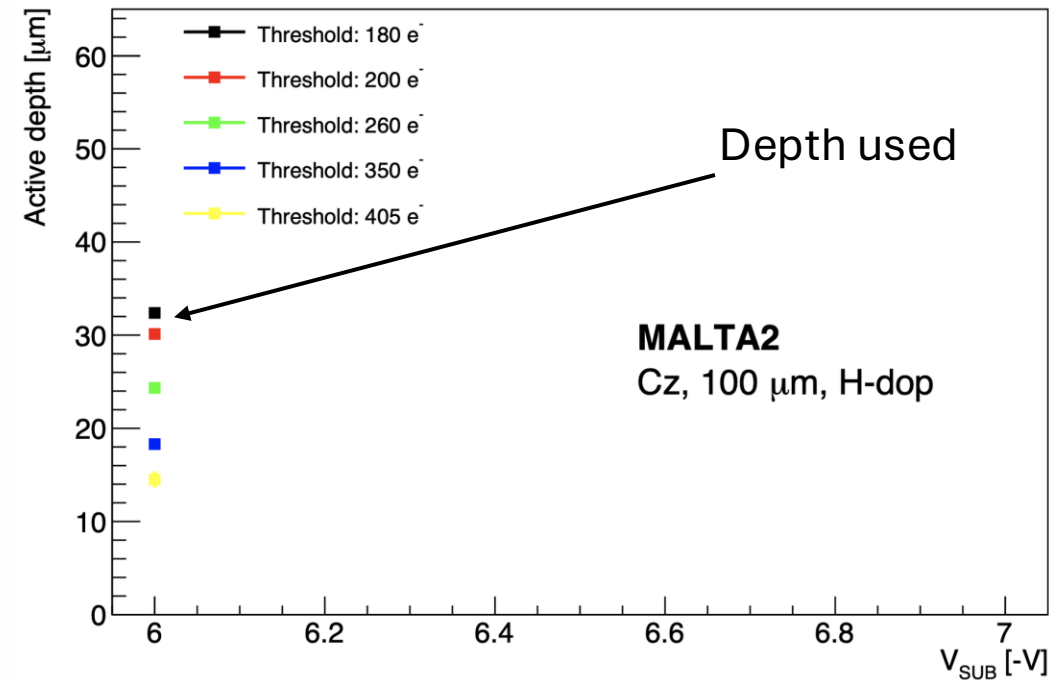
$V_{\text{depl}} = -60\text{V}$ Data

- Based on,

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

we can calculate full depletion voltage for 100 μm sensor

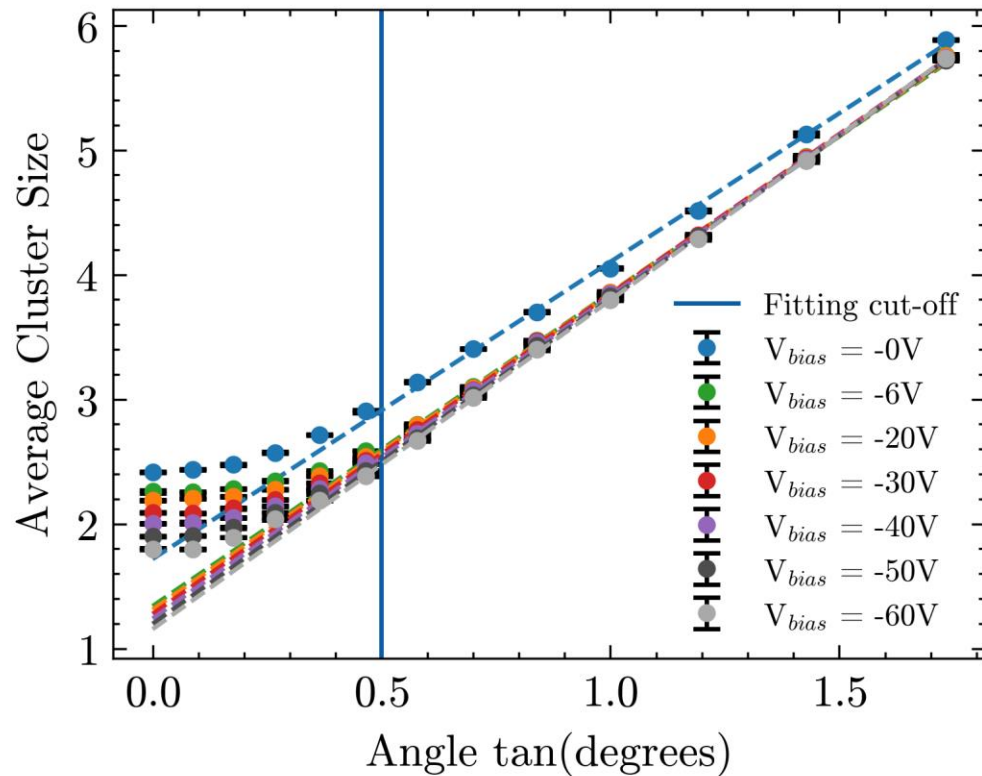
- Data taken for each bias and angle as before



Depletion Depth: Test beam, unirradiated

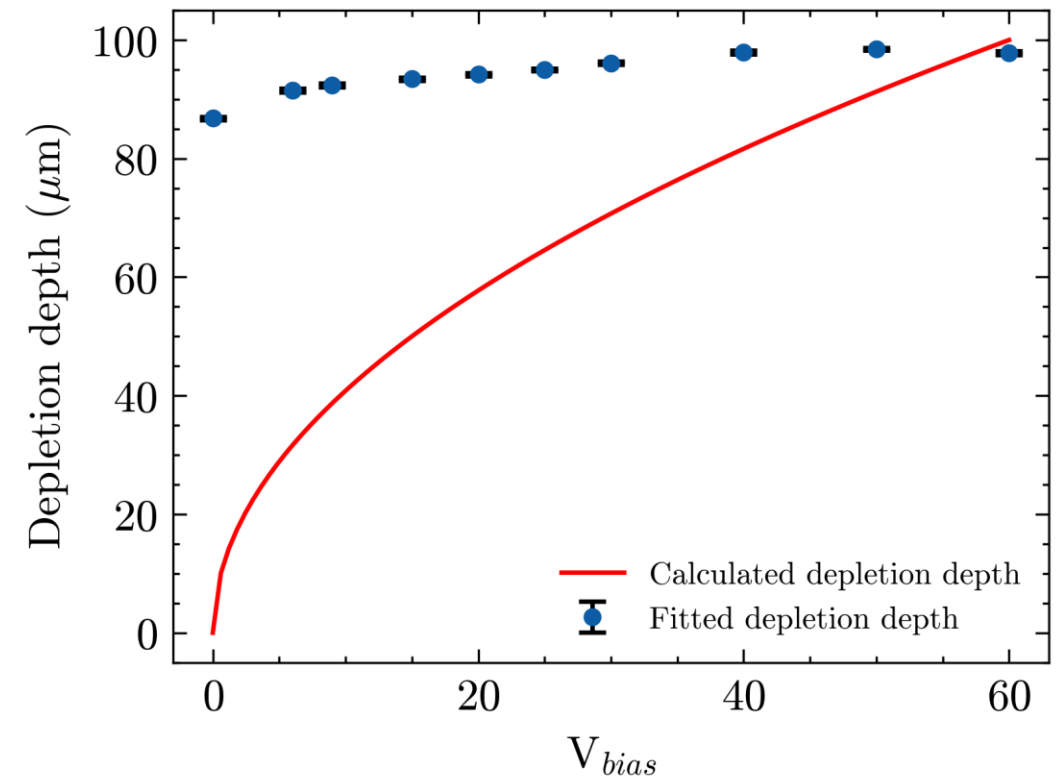
$V_{\text{depl}} = -60\text{V}$ Data

Average Cluster Size vs. Angle for increasing V_{bias}



Scaled Cluster Size: Simulation, unirradiated

Depletion depth vs. V_{bias}



Fitted Depletion Depth: Simulation, unirradiated

References

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