Performance of silicon pixel detectors at small track incidence angles for the ATLAS Inner Tracker upgrade

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Test Beam Experiment Team

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  - Swagato Banerjee
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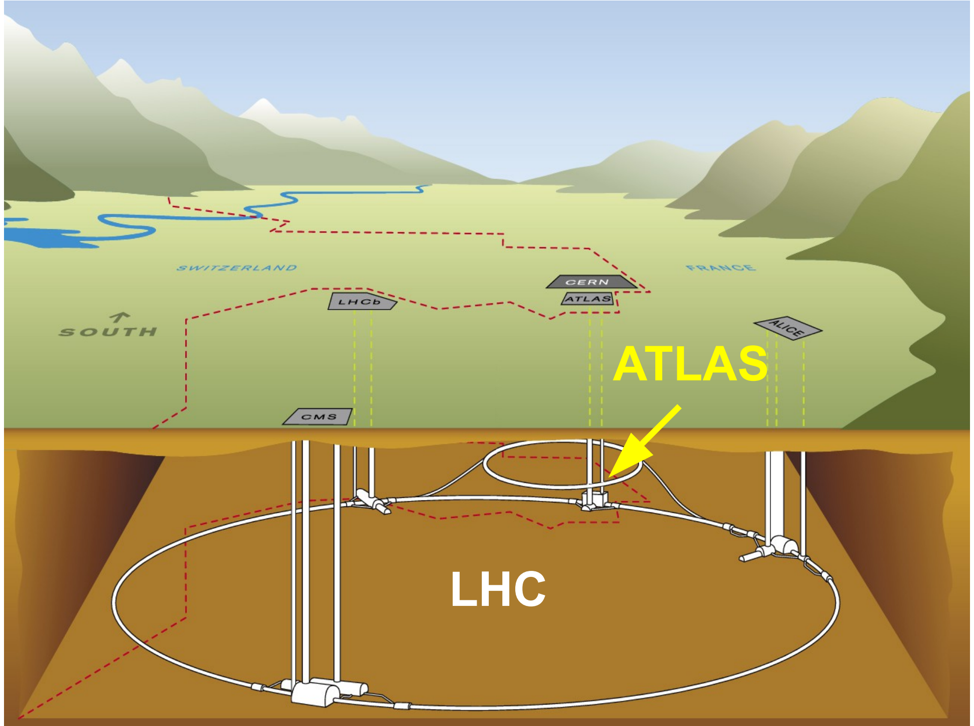
  - Andrew Hard, Laser Kaplan, Lashkar Kashif, Hongtao Yang
- With many thanks for their support at the test beams to
  - Carsten Hast (SLAC), Mathieu Benoit (Université de Genève)

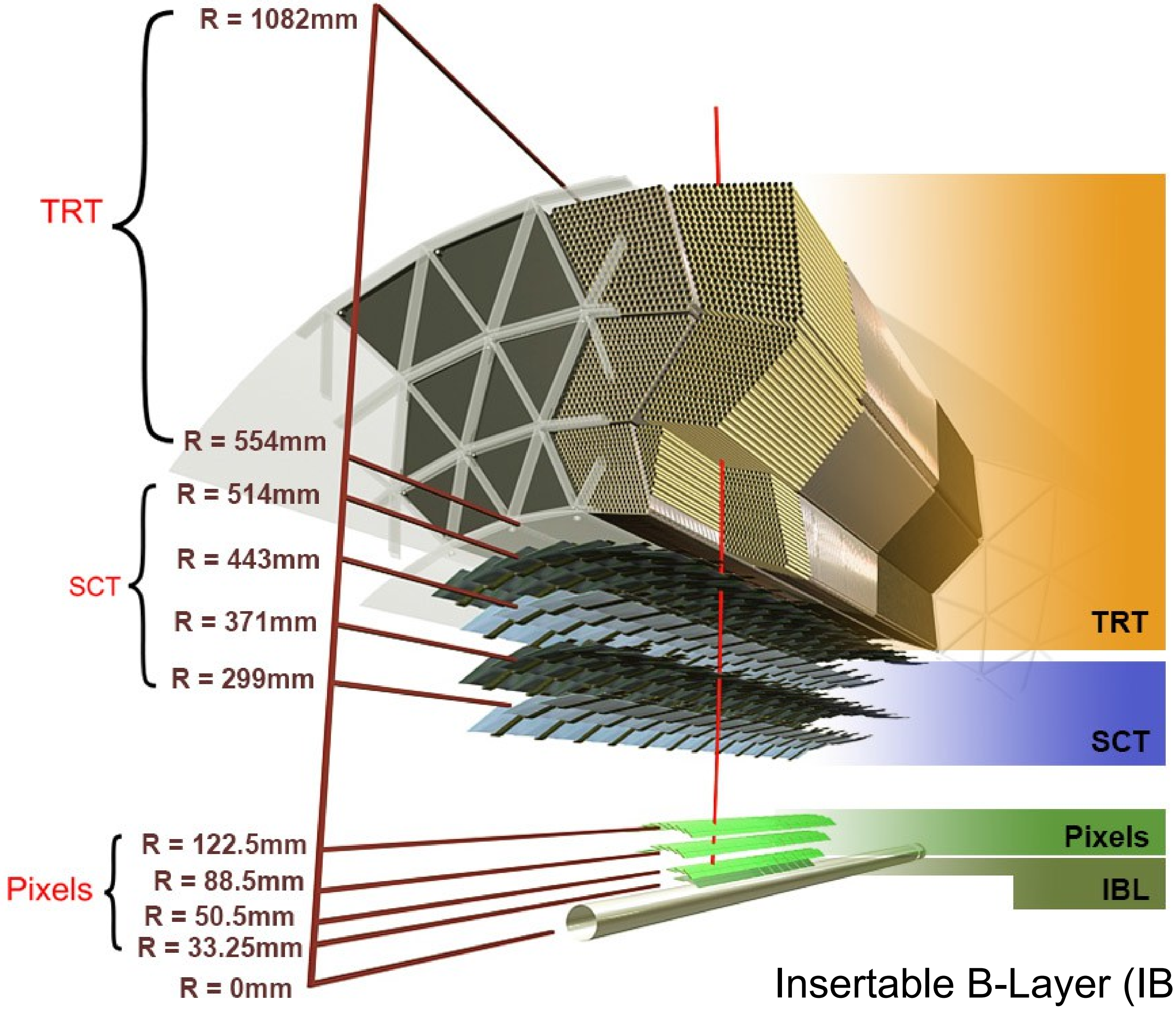
Context: High-Luminosity LHC

- The Large Hadron Collider (LHC), situated at CERN near Geneva, Switzerland, will be upgraded to the **High-Luminosity LHC** in 2024-2026
  - This accelerator will deliver proton-proton collisions at a levelled luminosity of $5 \times 10^{34}\ cm^{-2}\ s^{-1}$ and an average rate $\langle\mu\rangle$ = **200 per bunch crossing** (200 collisions per 25 ns)

- The ATLAS experiment, situated at one of the four interaction points of the LHC, will need to be upgraded to face such high collision rates



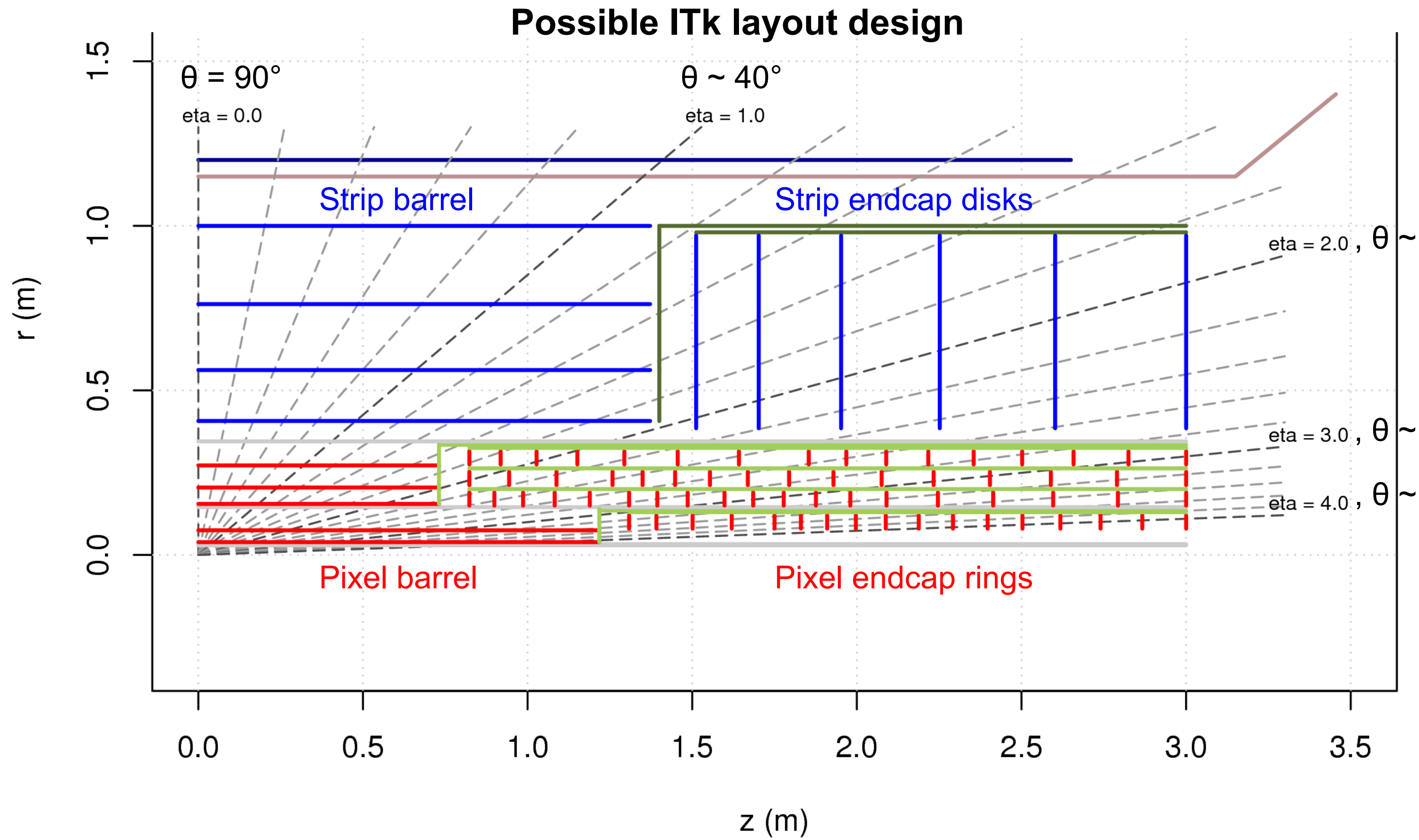
Current ATLAS Inner Detector



Insertable B-Layer (IBL):
Latest ATLAS pixel detector technology
pixel size: 50 μm x 250 μm

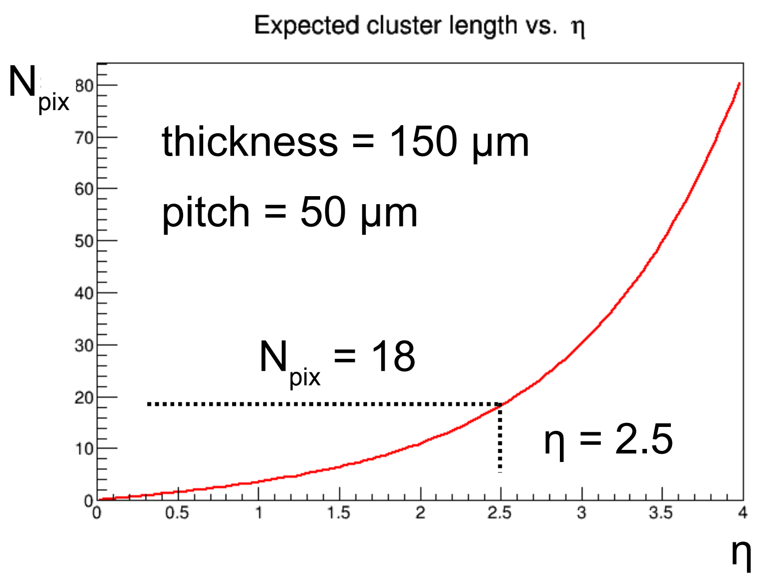
ATLAS Inner Tracker Upgrade

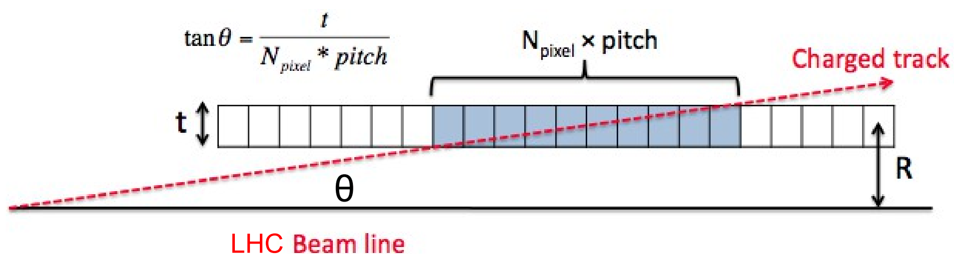
- One of the main upgrades to the ATLAS experiment will be a completely new **Inner Tracker** (ITk), made of **silicon pixel and strip detectors**
  - Currently evaluating different ITk designs; this study provides input to the discussion by characterizing the performance of a **long inner pixel barre**l to cover up to **|η| = 4**



Extended Inner Pixel Barrel Layers

- Silicon pixel detectors used for the ITk are planned to have **50 μm x 50 μm** pitch
  - With the layout shown on the last slide, we would therefore expect to measure **long pixel clusters (tracklets) at low angle θ**
  - Such long clusters provide a **measurement of θ → vertex position** using θ and R
- Main advantages of extending the inner barrel layers:
  - Improvements in tracking **efficiency** and **resolution** from having a measurement as close as possible to the interaction point
  - Potential to **reduce fake track rates** by rejecting clusters with incompatible length
    - Potential to **reduce CPU time** owing to better track seeding capability





Test beam goal:

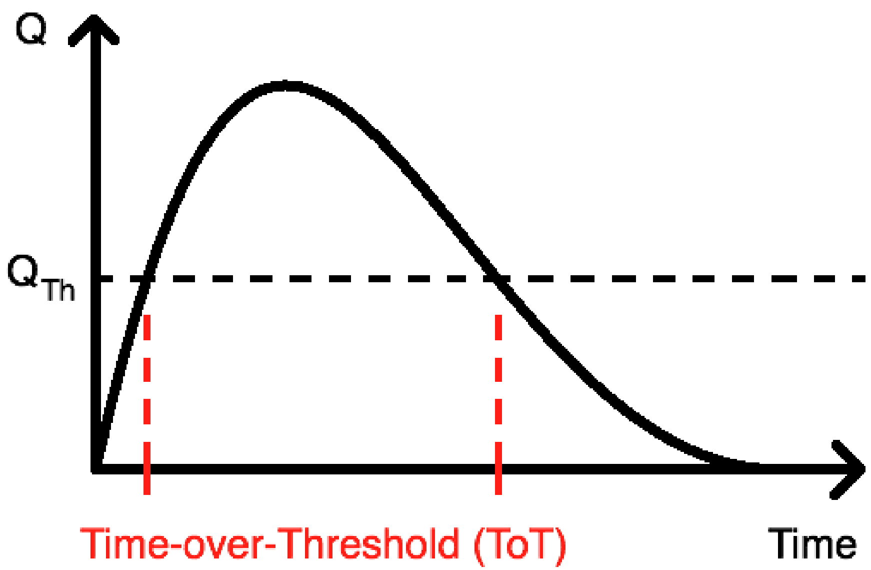
Characterize the performance of pixel detectors at very low incident angles (~2, 4, 6, 10, 15 deg.) with 10 GeV electrons (SLAC End Station A) and 180 GeV π+ (CERN SPS)

SLAC Test Beam at End Station A

Data taken in April – May 2015

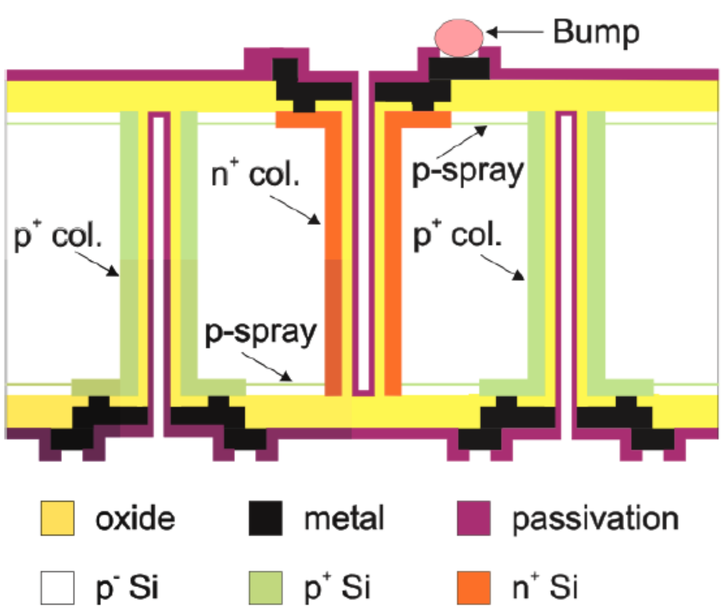
SLAC Test Beam: Devices Under Test

- Four un-irradiated Insertable B-Layer (IBL) modules under test
  - Two **double-chip planar** modules and two **single-chip 3D** modules
  - Sensor thickness: 200 μm for planar modules, 230 μm for 3D modules
  - Modules tuned to 10 Time-over-Threshold units (250 ns) at 16k electrons



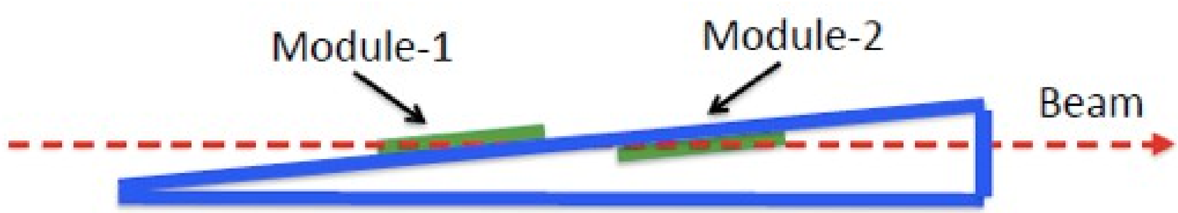
Time-over-Threshold (ToT) is measured as a multiple of the 25 ns clock signal

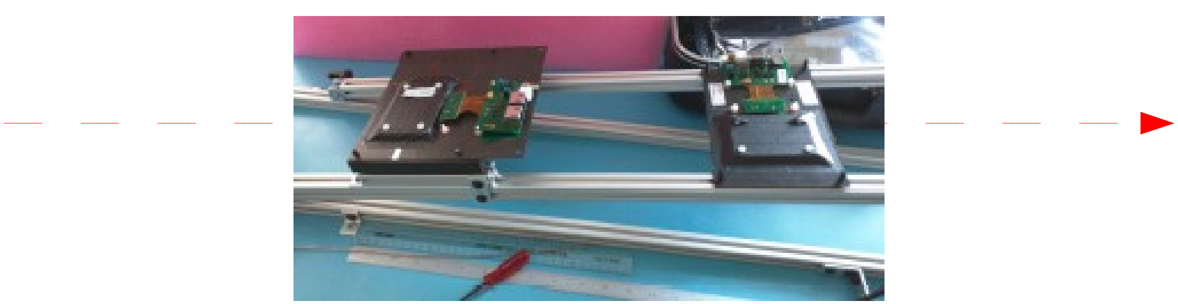
IBL 3D FBK sensor design



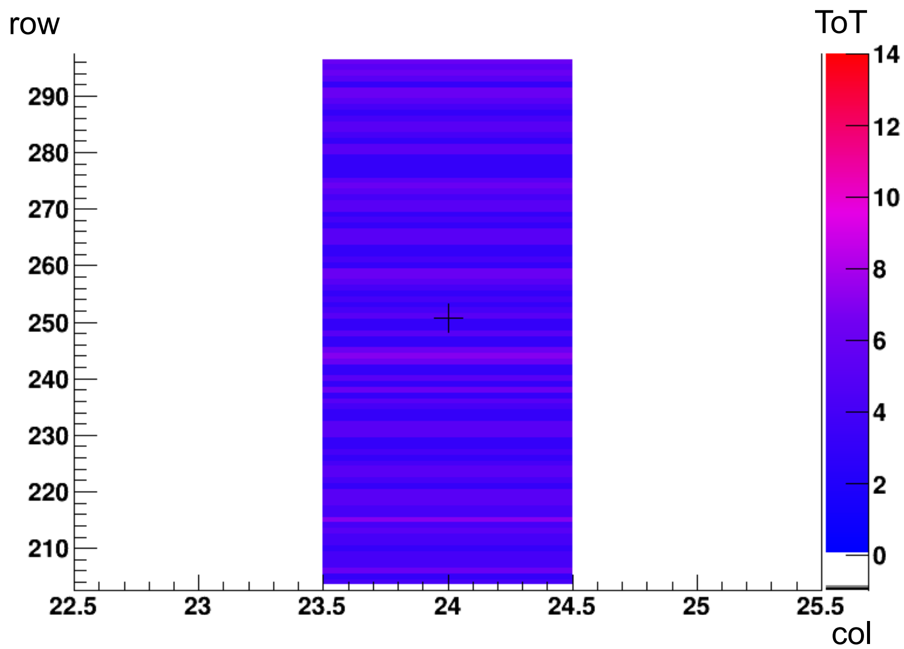
SLAC Test Beam

- Four un-irradiated Insertable B-Layer (IBL) modules under test
  - Two **double-chip planar** modules and two **single-chip 3D** modules
  - Sensor thickness: 200 μm for planar modules, 230 μm for 3D modules
  - Modules tuned to 10 Time-over-Threshold units (250 ns) at 16k electrons
- Beam: 10 GeV electrons, few-particle bunches at 5 Hz
  - Studies with beam in short pixel direction (50 μm) and long pixel direction (250 μm)





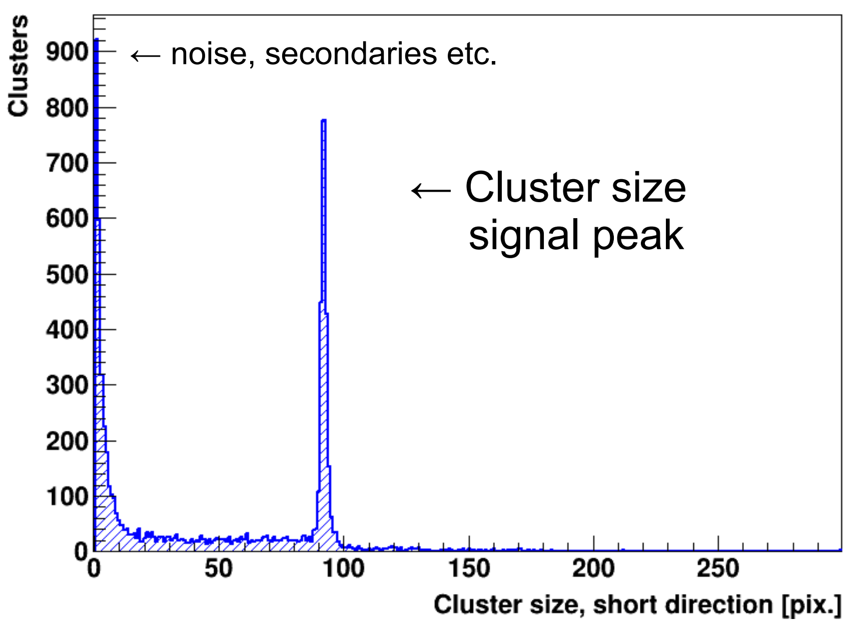
Long Pixel Clusters Observed

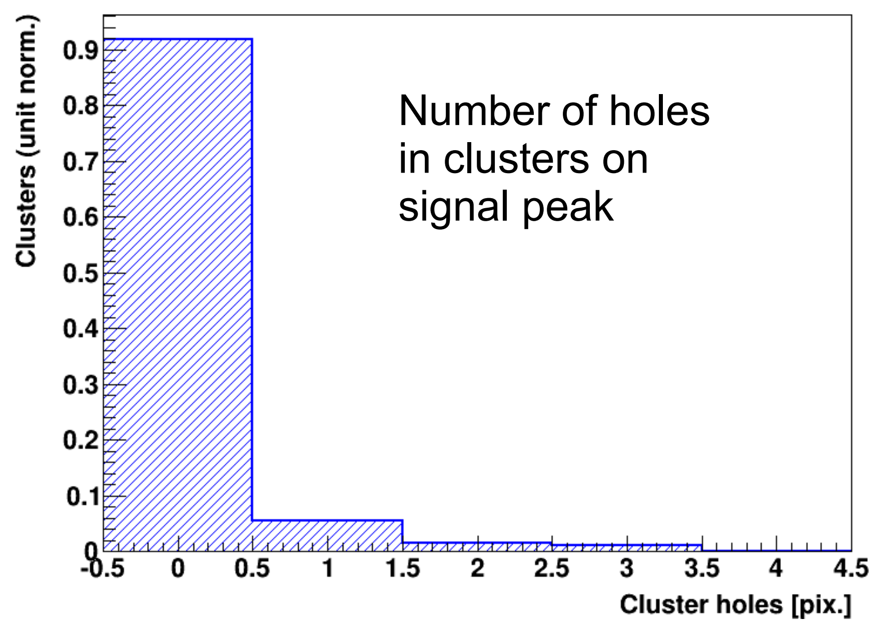


← **Typical** cluster for angle **~ 2.5 deg** (η ~ 3.8)

Planar module biased at **-120 V**,
Threshold **1000e**,
Beam in **short** pixel orientation

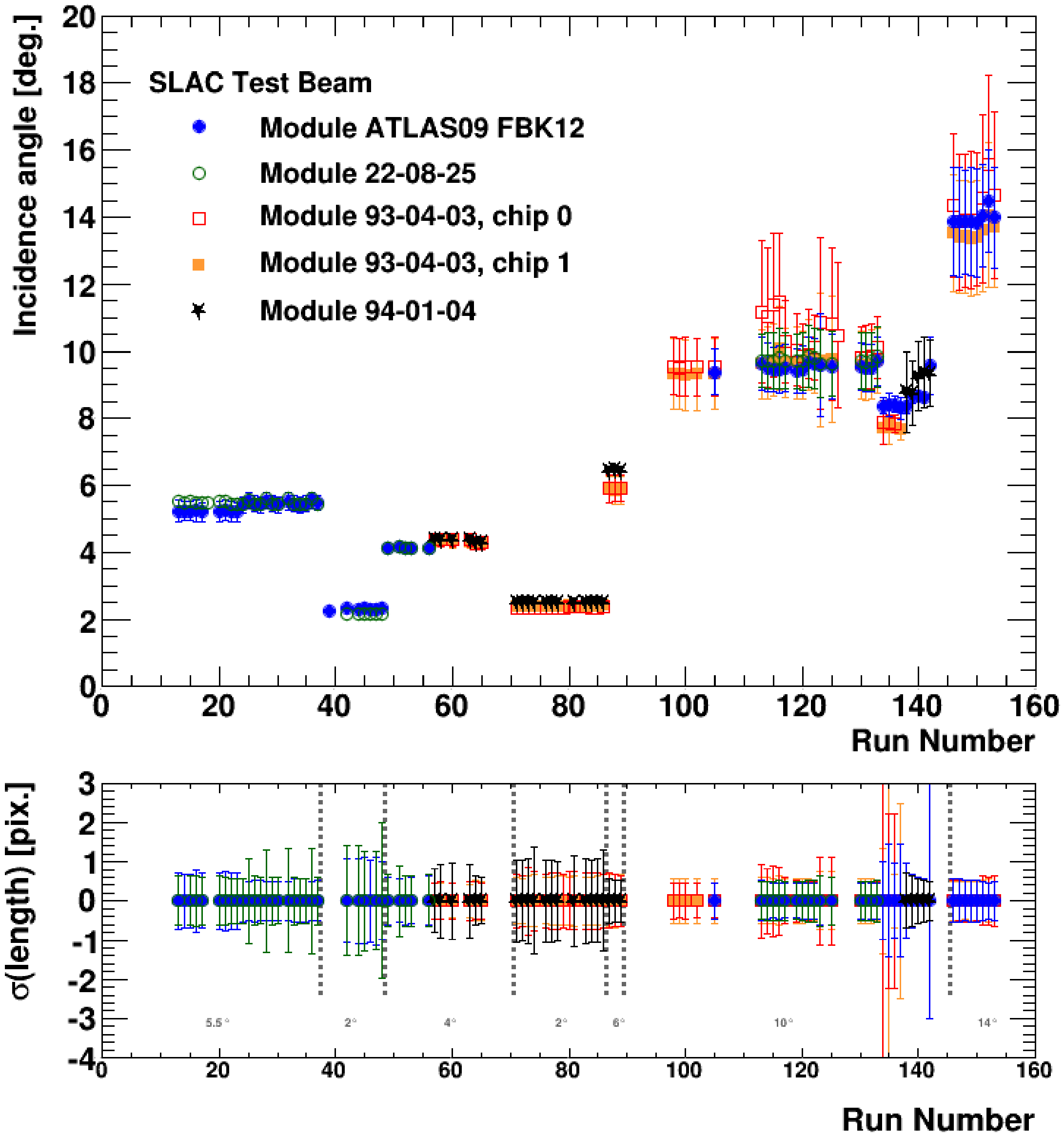
cluster size = 93, no hole



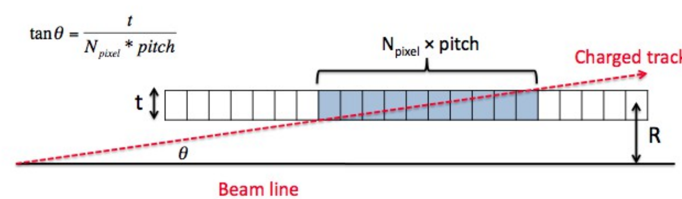


Incidence Angle Measurements

- Cluster length $\rightarrow$ **precise measurement of the incidence angle**



- In tracking context:
  measurement of θ
  $\rightarrow$ z_0 given R



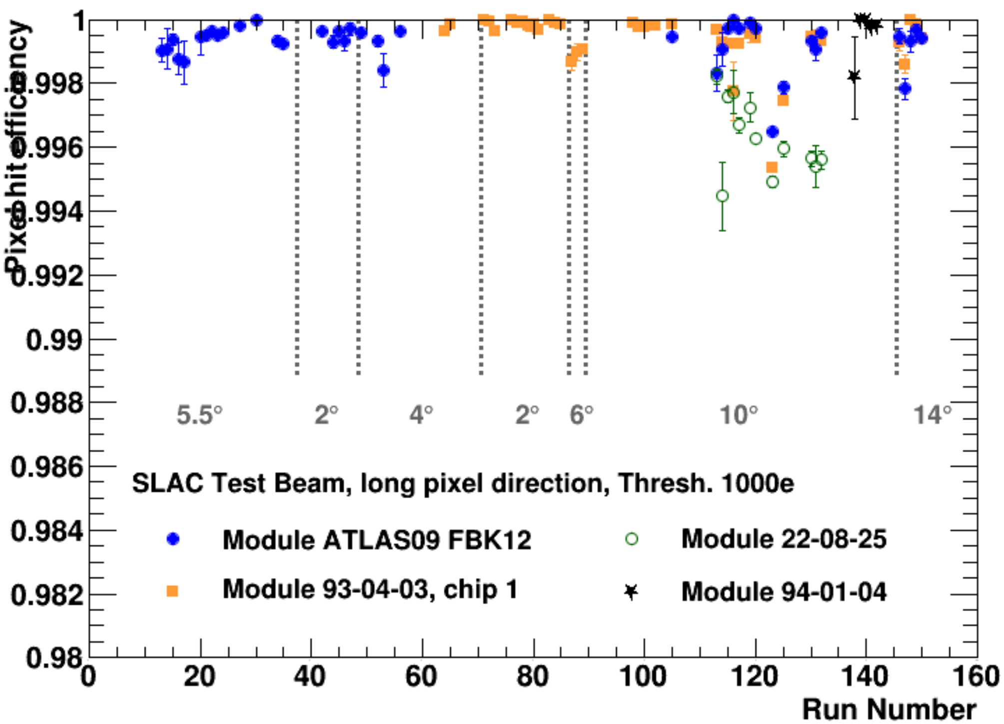
- Gaussian fit to signal peak
- **Excellent performance** achieved with all modules, especially at lowest angles
- Resolution limited by **pitch/√6** along beam direction
  [pitch/√12 for entry and exit pixels]
  - Except at 2 deg. where some scattering effects are seen

Pixel Hit Efficiency

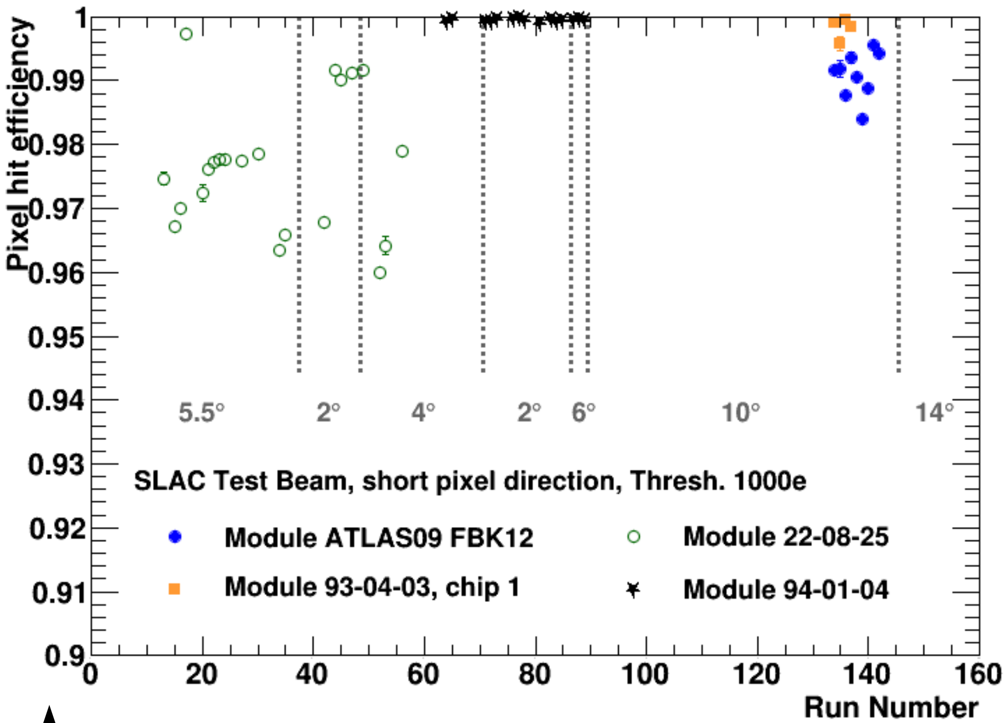
- Method: count fraction of hit pixels between first and last of cluster
  - No timing cut applied here
    - "in-time" efficiency available soon

Example: ε = 4/5 for this long cluster

Long pixel direction, Threshold 1000e



Short pixel direction, Threshold 1000e



(note different y-axis scale)

No significant contribution to efficiency from noise

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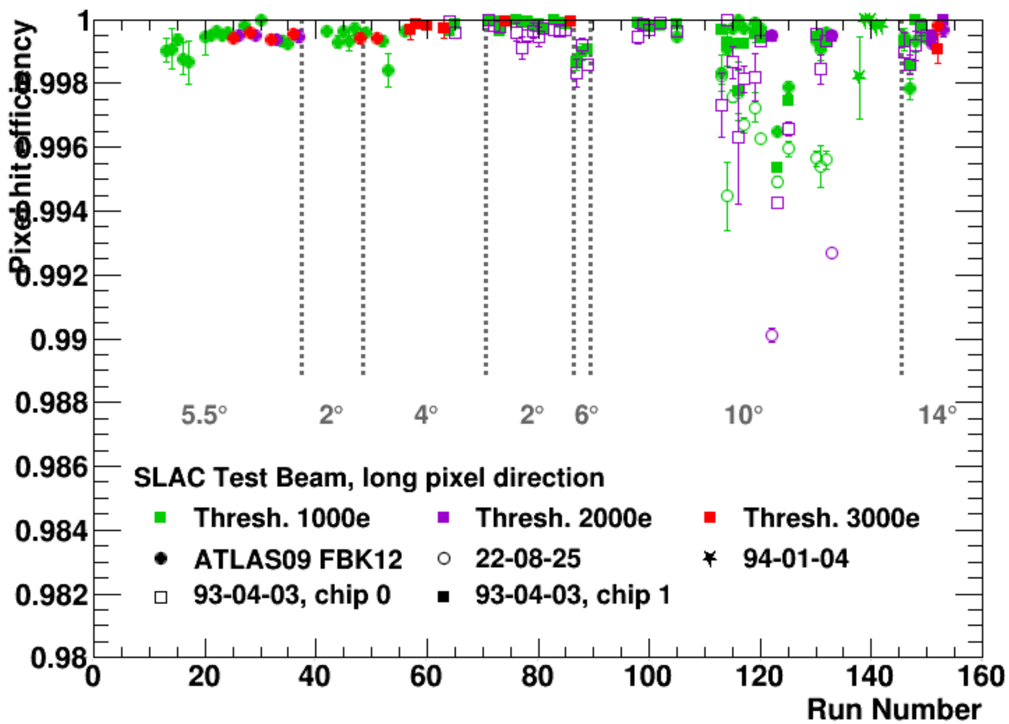
Long pixel direction, All threshold values



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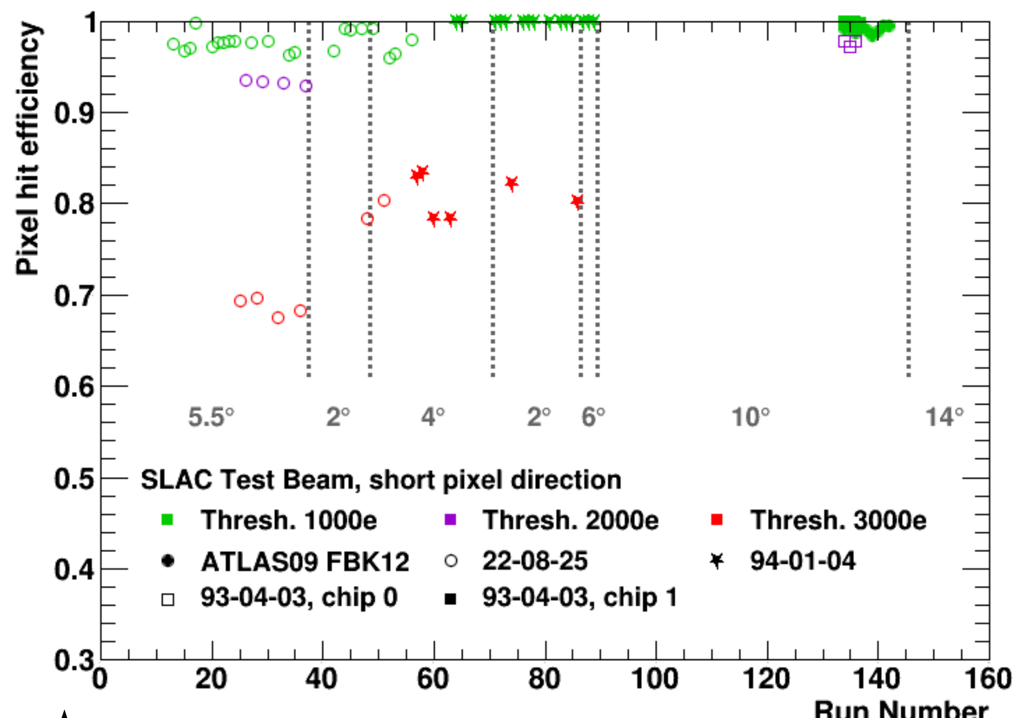

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CERN SPS Test Beam

Data taken in May 2015

FEI4 Telescope at CERN SPS

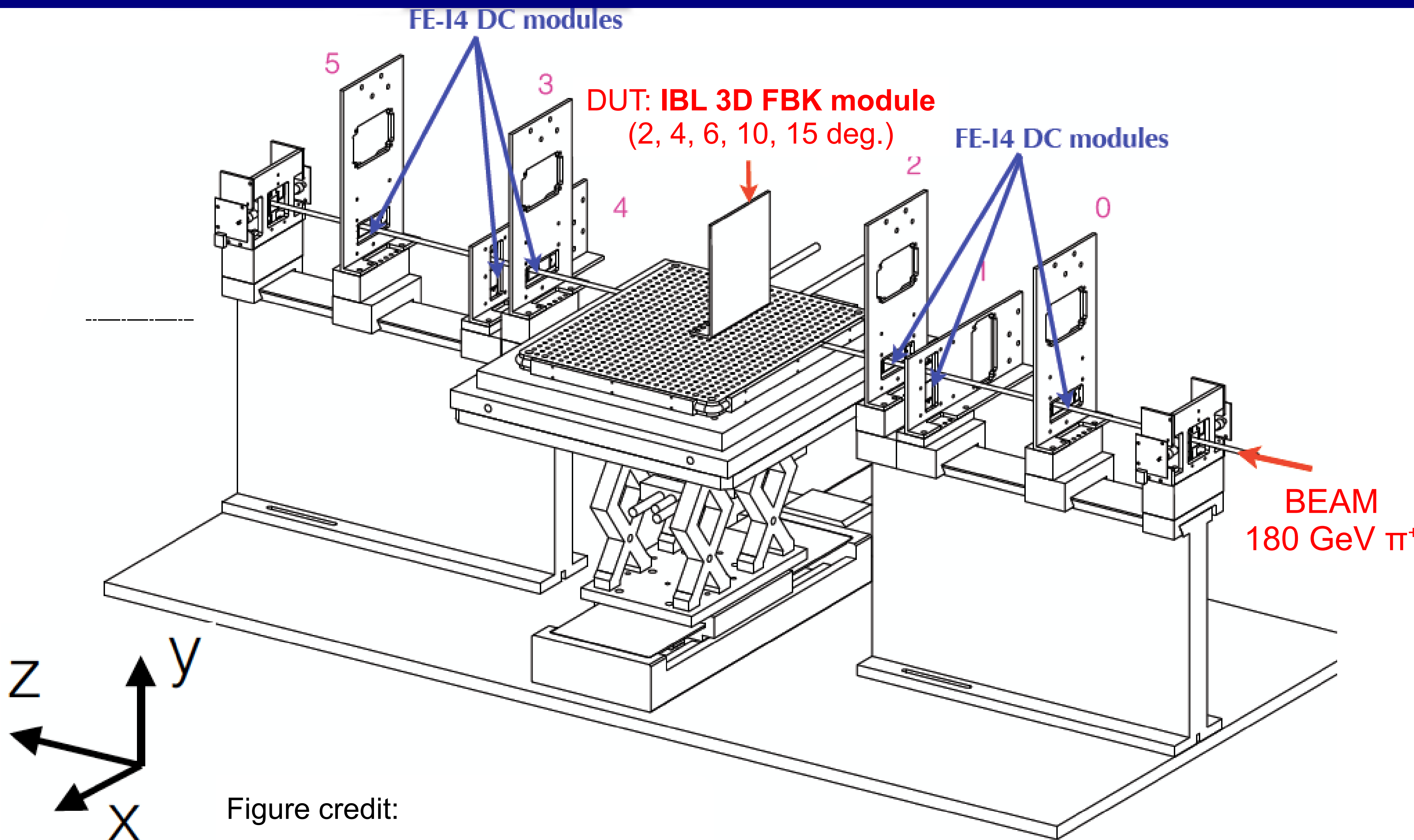
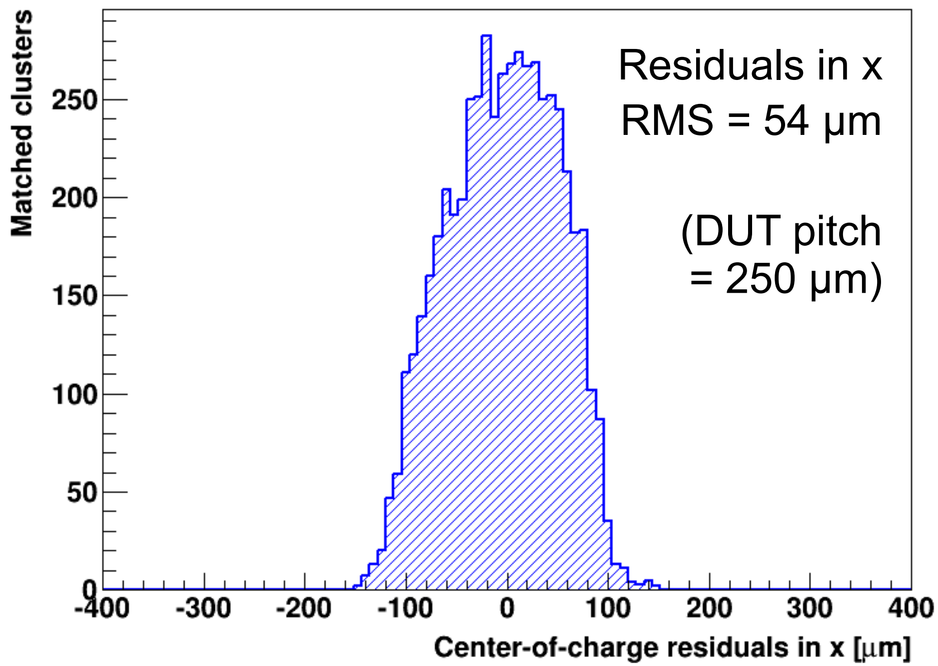
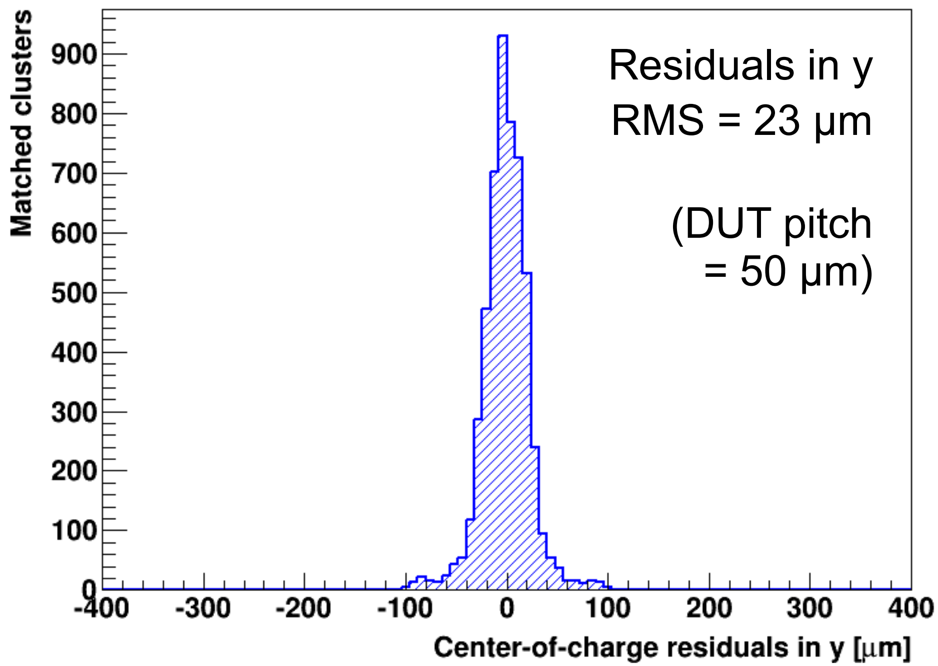


Figure credit:
JUDITH analysis software documentation

Resolution

- Tracks were measured using an FEI4 telescope
  - Reconstructed using **JUDITH software** for alignment and tracking
- Telescope resolution at DUT **~ 14 μm** in x, **~ 8.5 μm** in y
- Example residual distributions for DUT in long pixel direction
  - Rotated in y to 2 degree incident angle, bias -40 V, threshold 1000e





Incidence Angle Measurements

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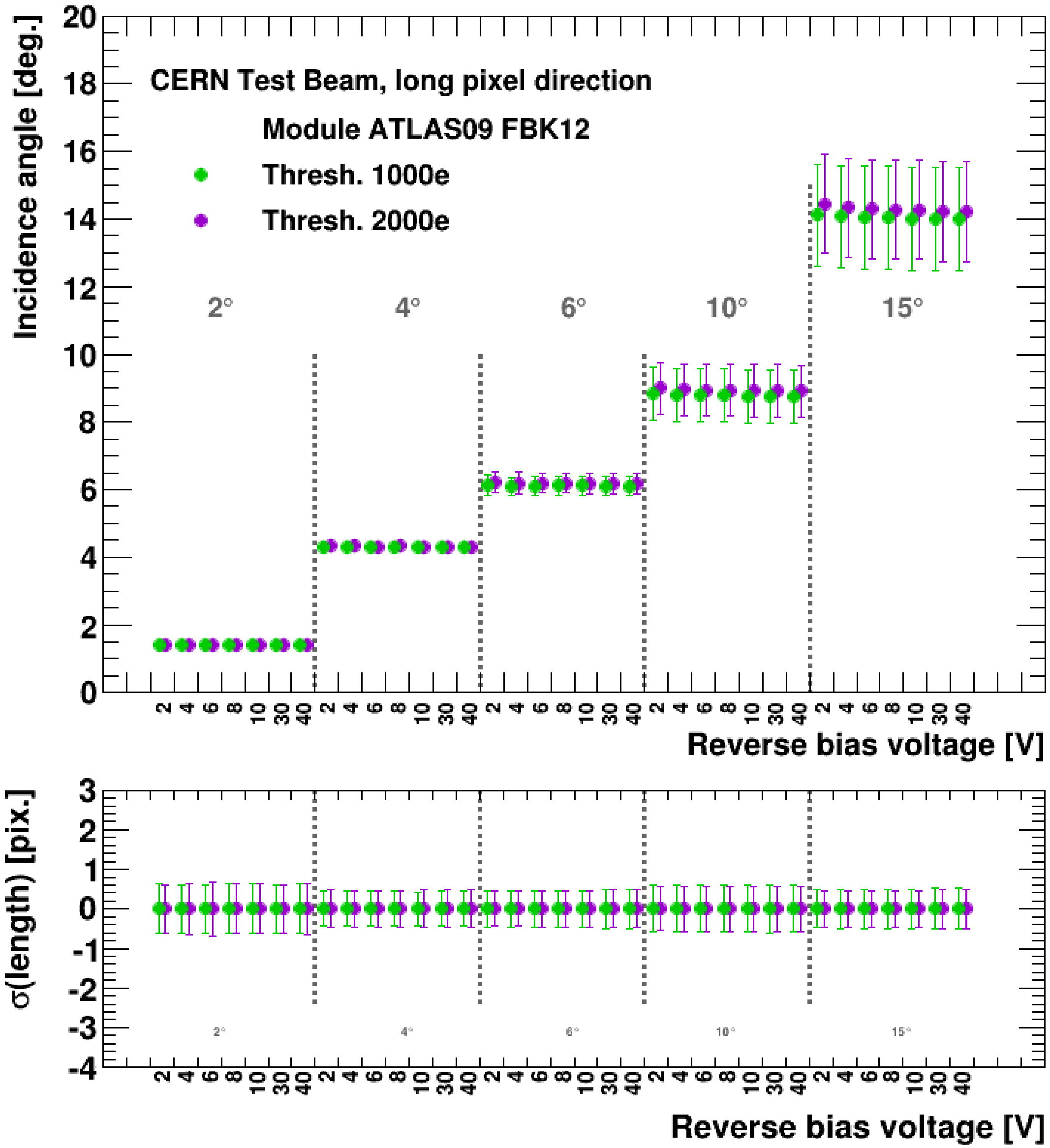

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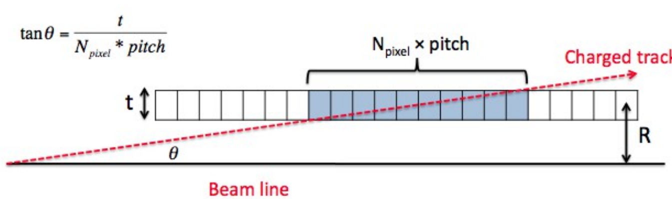
  measurement of θ
  → z_0 given R



- **Long** pixel direction
- Gaussian fit to signal peak
- **Excellent performance** independent of bias voltage
- Resolution limited by **pitch/√6** along beam direction
  [pitch/√12 for entry and exit pixels]

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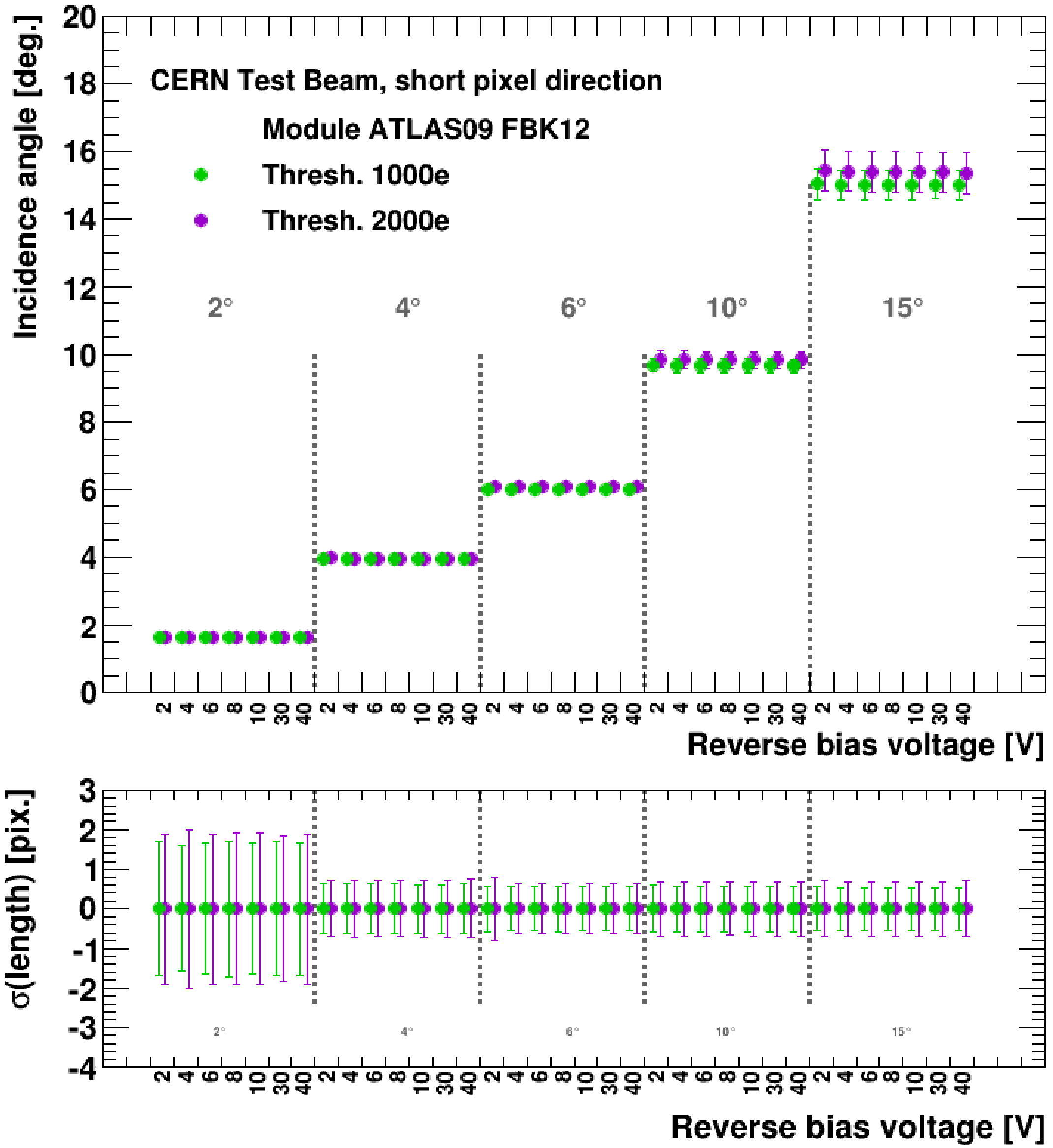

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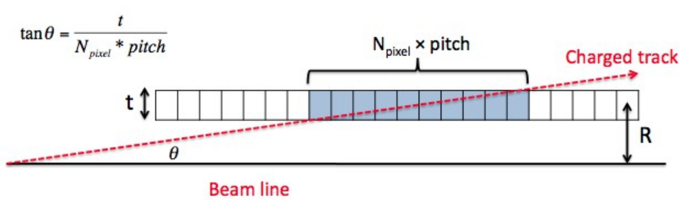

- **Short** pixel direction
- Gaussian fit to signal peak
- **Excellent performance** independent of bias voltage
- Resolution limited by **pitch/√6** along beam direction
  [pitch/√12 for entry and exit pixels]
  - Except at 2 deg. where some scattering effects are seen

Pixel Hit Efficiency

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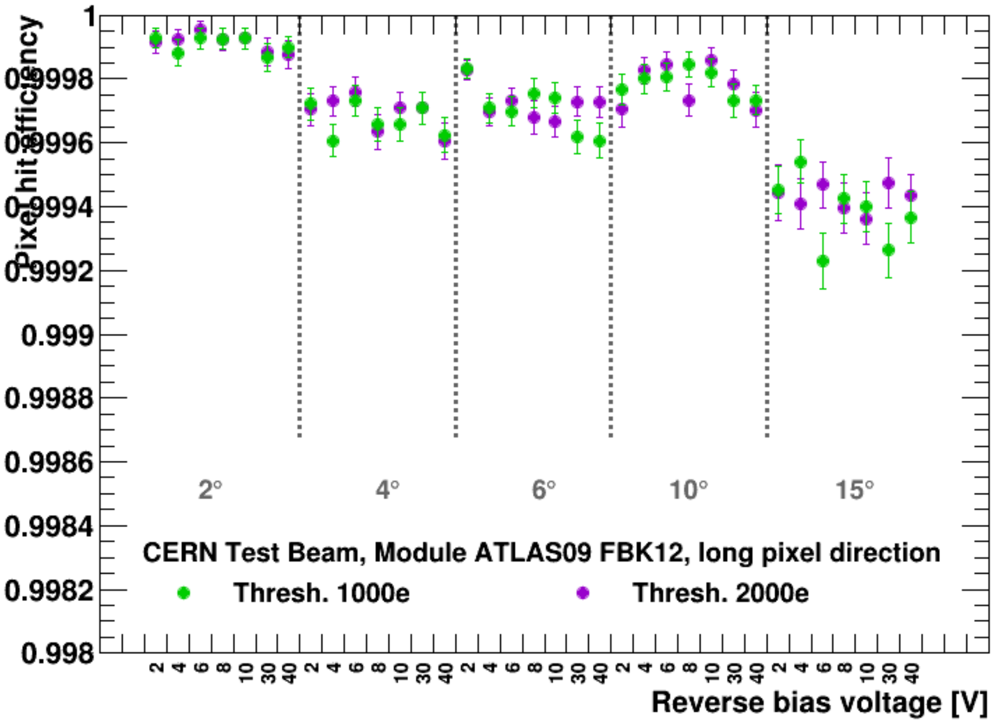
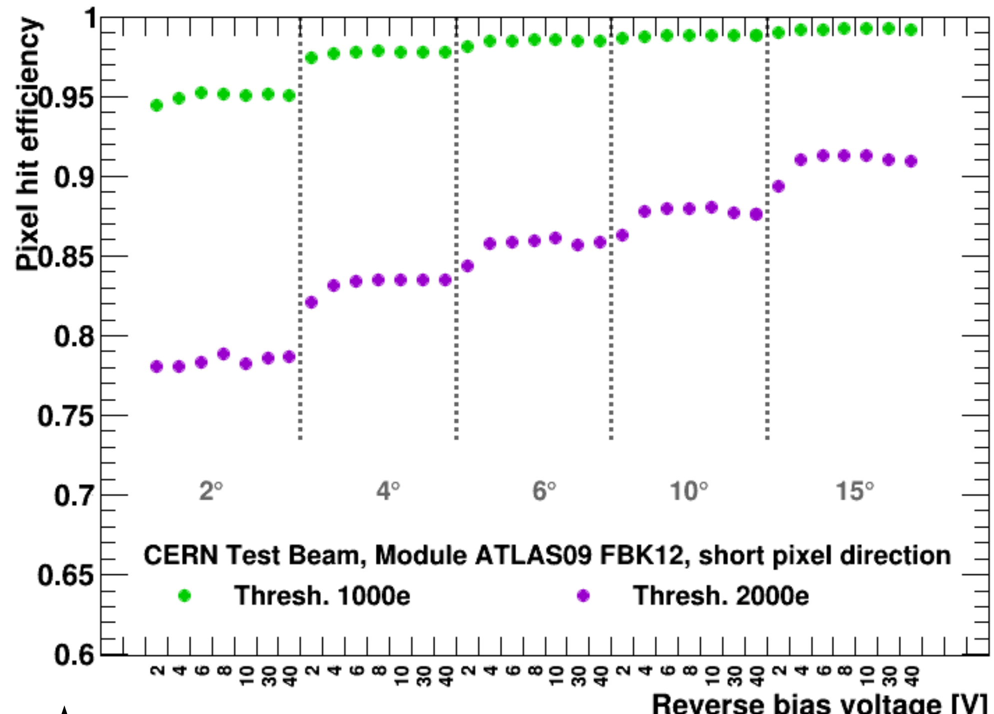
Example: ε = 4/5 for this long cluster

Long pixel direction



Short pixel direction



(note very different y-axis scale)

No significant contribution to efficiency from noise

Pixel Hit Efficiency

- Method: count fraction of hit pixels between first and last of cluster
  - No timing cut applied here
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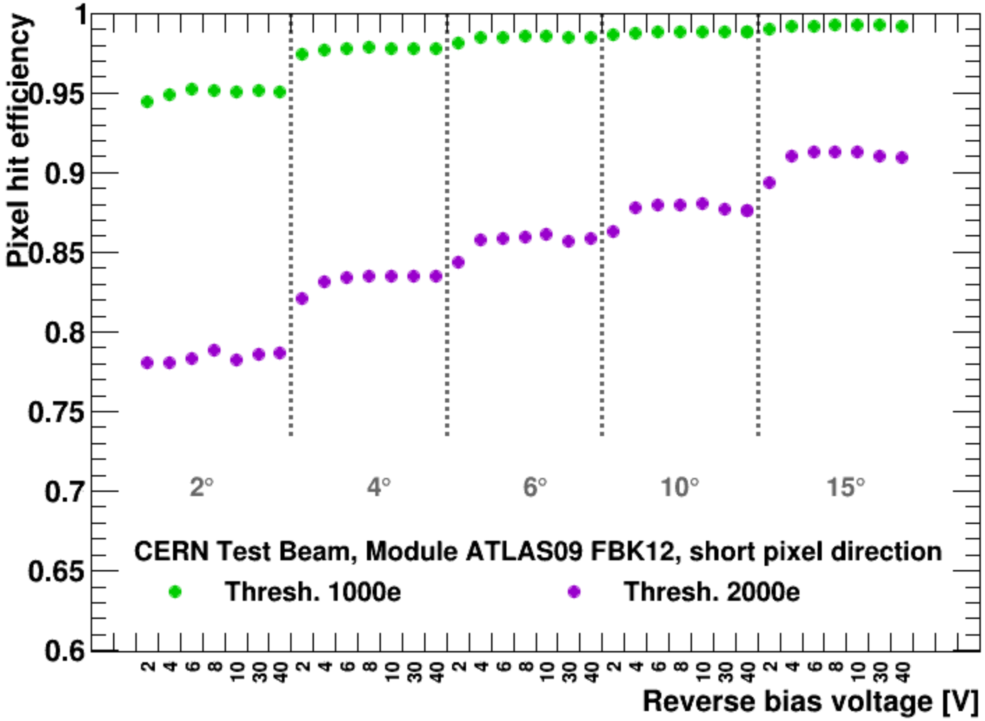
Example: ε = 4/5 for this long cluster

- Small hit inefficiencies observed for 3D modules in short pixel direction
  - Down to 95% efficiency seen at 1000e threshold
  - Down to 77% at 2000e threshold
  - No problem for long clusters as long as the threshold is low enough
  - Cause: depth effect, or charge collection effect?
    - Track analysis in short pixel direction should help answer this question

Short pixel direction

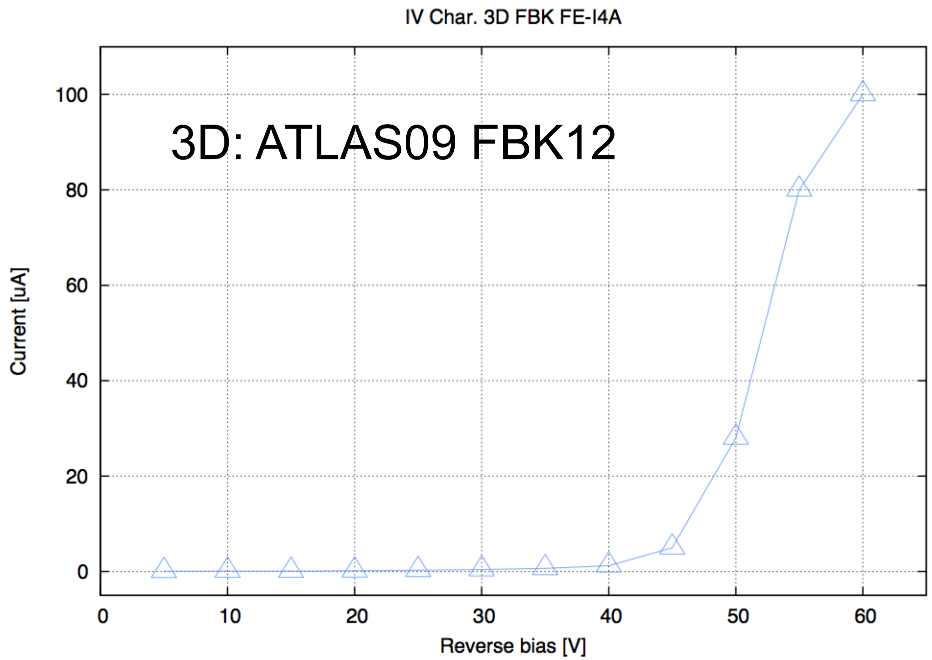


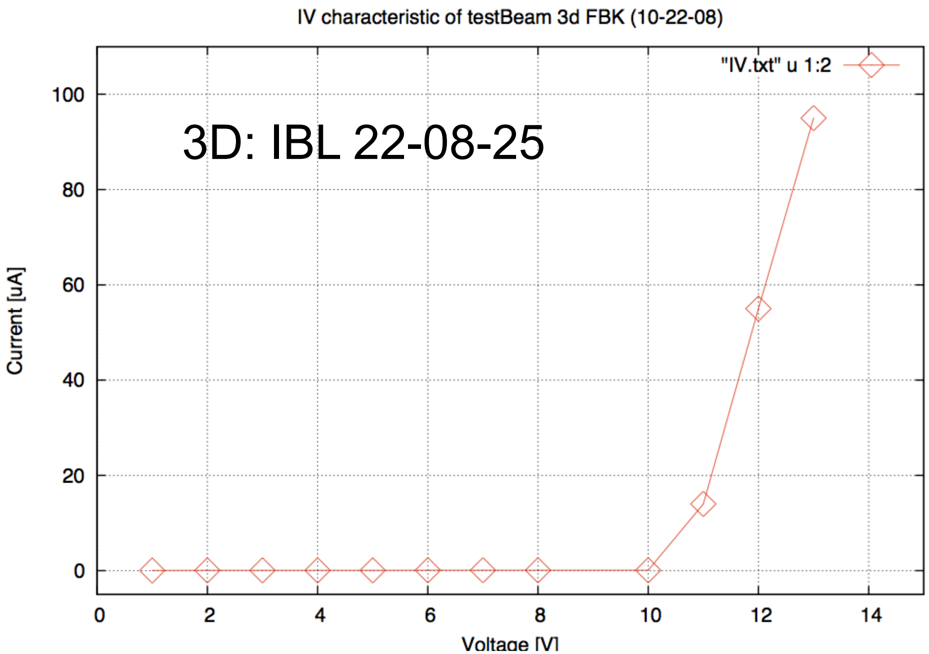
Conclusion

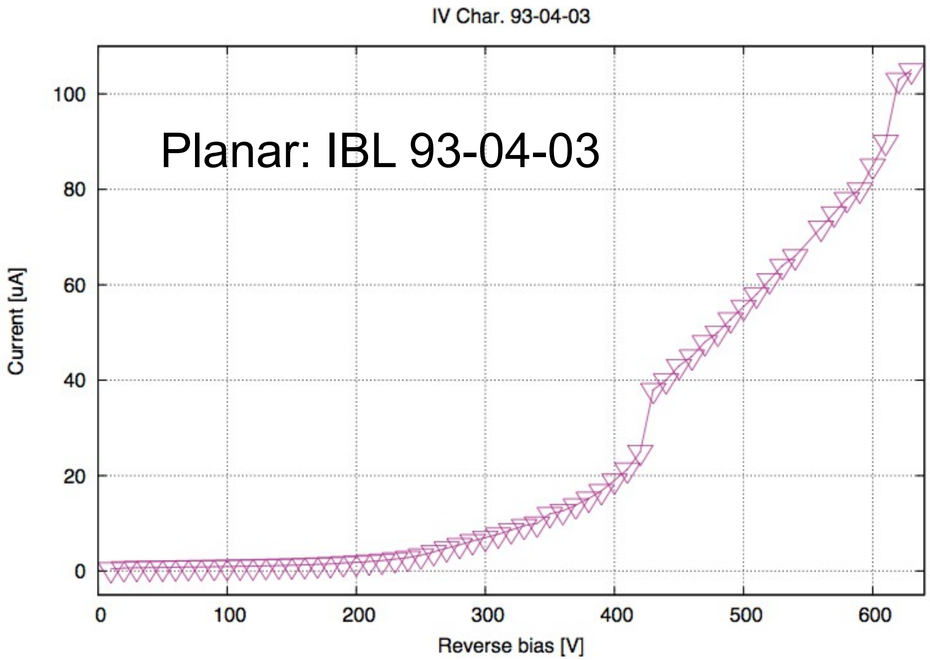
- **Test beam** results with IBL **planar and 3D modules** demonstrate excellent performance of these devices at **small incidence angles**
  - Comparable results observed with electron beam (SLAC) and pion beam (CERN)
  - Long clusters are **well-reconstructed**, especially at 1000e threshold
  - **Excellent angular resolution** using cluster size information only (e.g. 1% for $\theta \sim 2°$)
- Proof-of-concept for the **ITk extended inner barrel design**
- Next steps
  - Perform the alignment and track analysis for CERN test beam runs
    - Preliminary results are shown in supplementary material
  - Measurement of irradiated sensors down to 2 degrees incidence angle
  - Investigation of observed inefficiencies at high threshold using tracks
  - Measurement of new prototype modules with RD53 chip when available
  - Complete the design of the Inner Tracker upgrade
    - Simulation of the overall tracking performance of the proposed Pixel ITk layouts

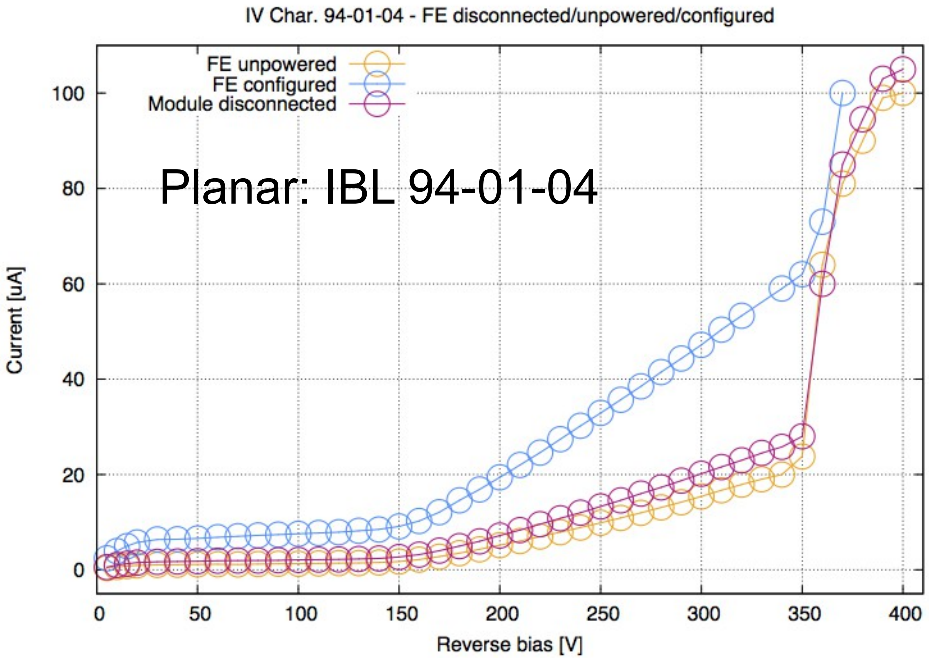
SUPPLEMENTARY MATERIAL

IV for Devices Under Test









Analysis With Tracks

- With tracks, one can also calculate the **charge collection** with respect to the **intersection** of the track with each pixel middle plane
  - Disregarding the entry and exit pixel of the long cluster
  - **Pixel local coordinate system** (note capital letters):

    X in long pixel direction, Y in short pixel direction, Z along sensor depth

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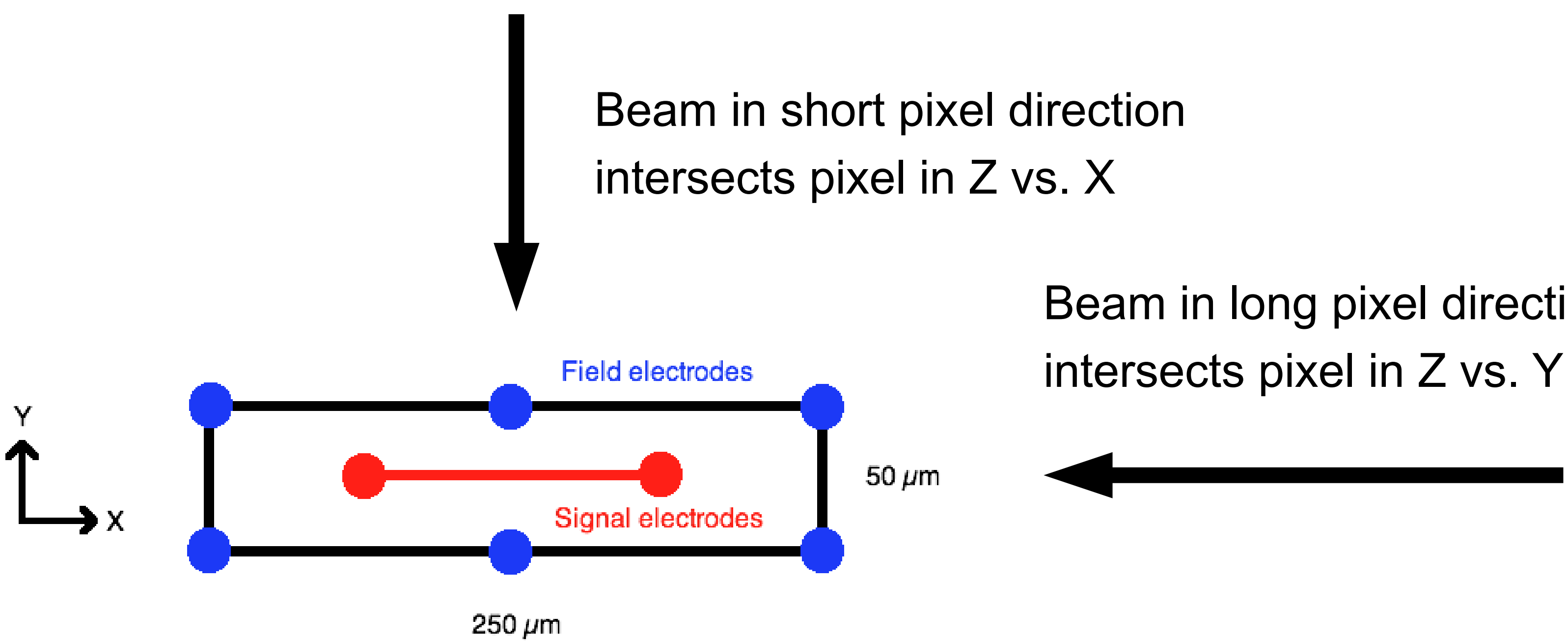
Beam in short pixel direction intersects pixel in Z vs. X

Beam in long pixel direction intersects pixel in Z vs. Y



Front view

Analysis With Tracks

- With tracks, one can also calculate the **charge collection** with respect to the **intersection** of the track with each pixel middle plane
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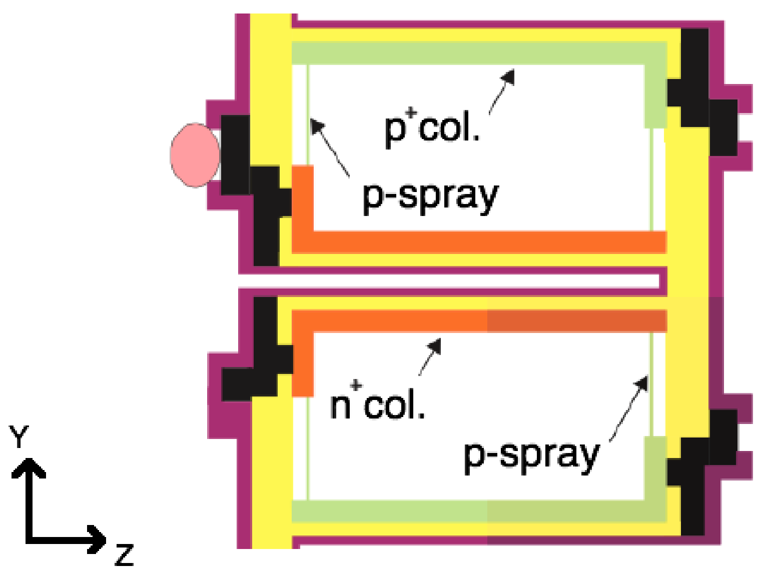
IBL 3D FBK sensor design



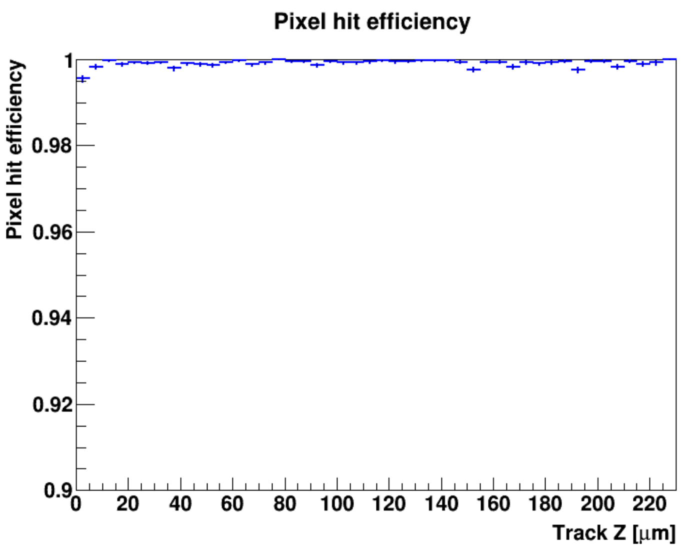
Side view

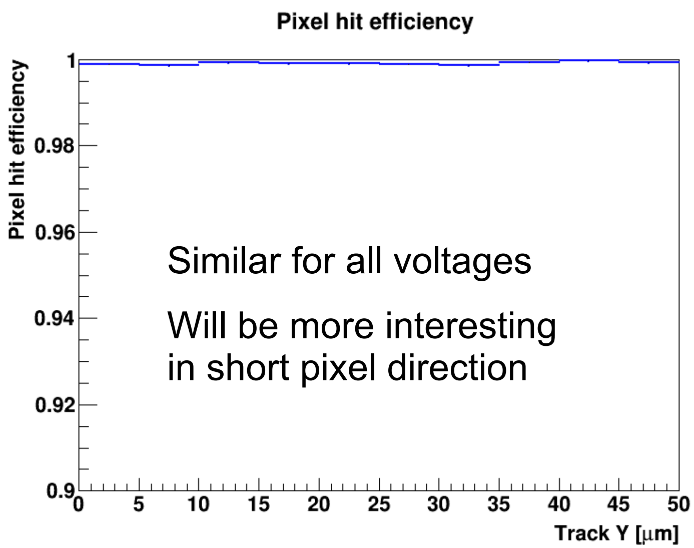
Beam in long pixel direction intersects pixel in Z vs. Y

Pixel Hit Efficiency

- With tracks, one can also calculate the **pixel hit efficiency** with respect to the **intersection** of the track with each pixel middle plane

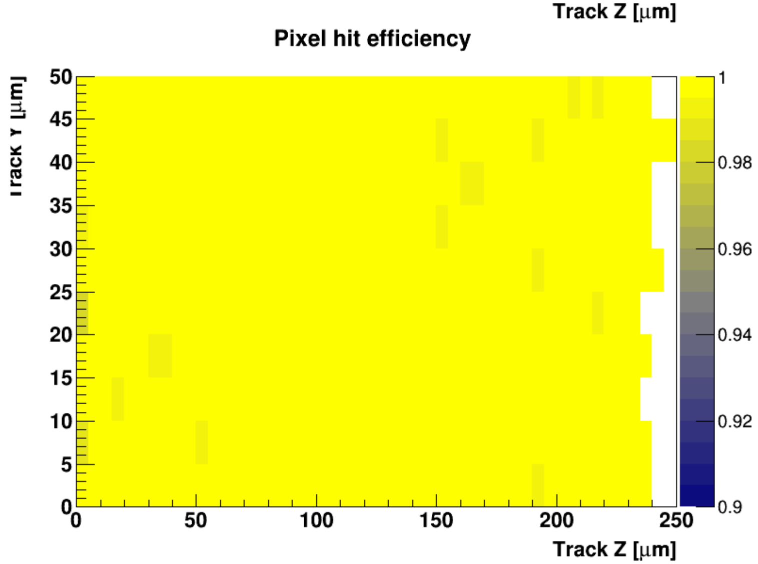
  - Beam in **long** pixel direction
  - **2 degrees**, bias -40 V
  - Threshold 1000e





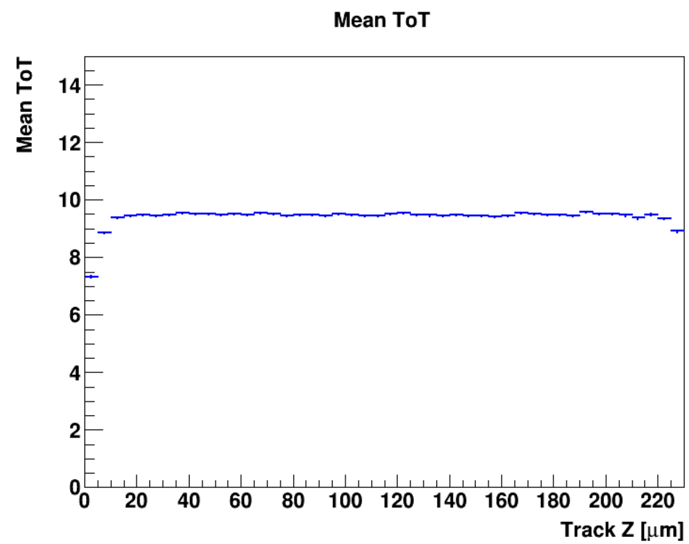
Similar for all voltages

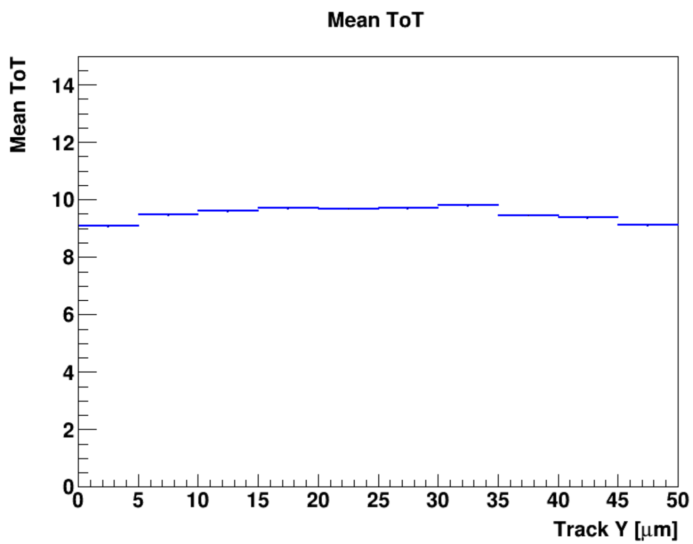
Will be more interesting in short pixel direction

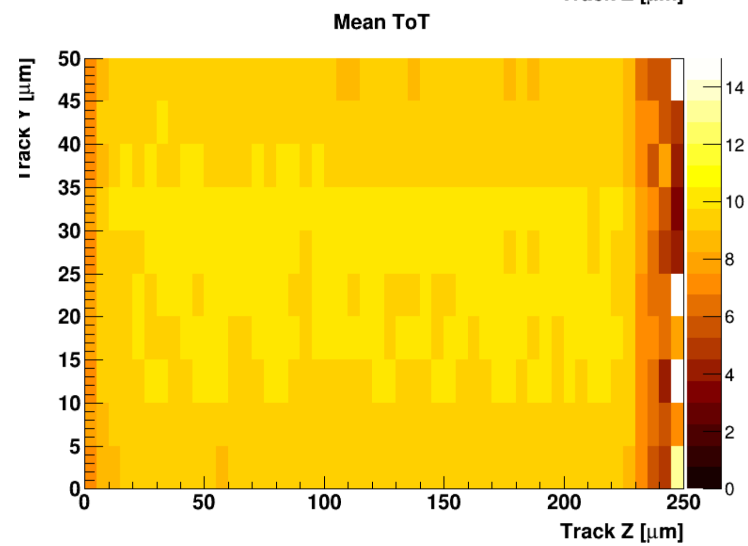


Charge Collection

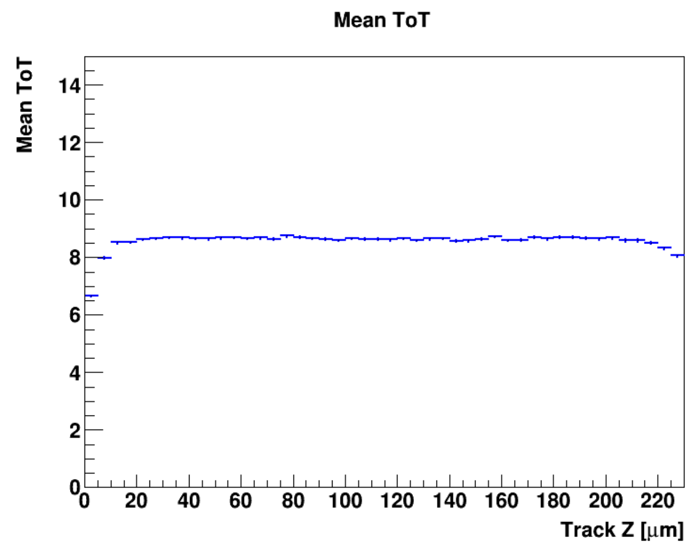
- **Mean Time-over-Threshold (ToT)** as a function of the track intersection point
  - Working toward a reliable ToT → charge calibration
    - Beam in **long** pixel direction
    - 2 degrees, bias **-40 V**
    - Threshold 1000e

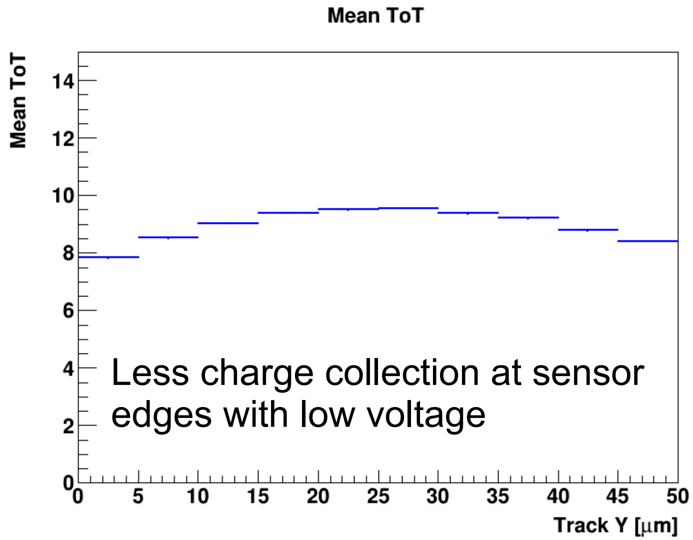


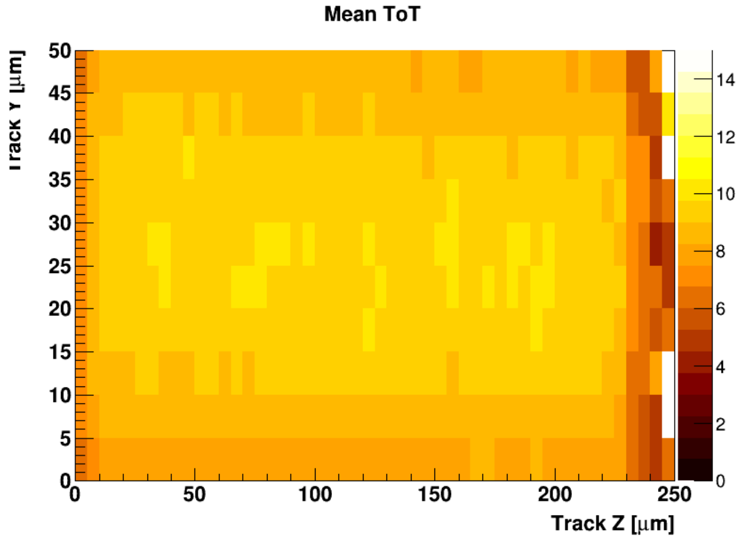




- **Mean Time-over-Threshold (ToT)** as a function of the track intersection point
  - Working toward a reliable ToT → charge calibration
    - Beam in **long** pixel direction
    - 2 degrees, bias **-2 V**
    - Threshold 1000e

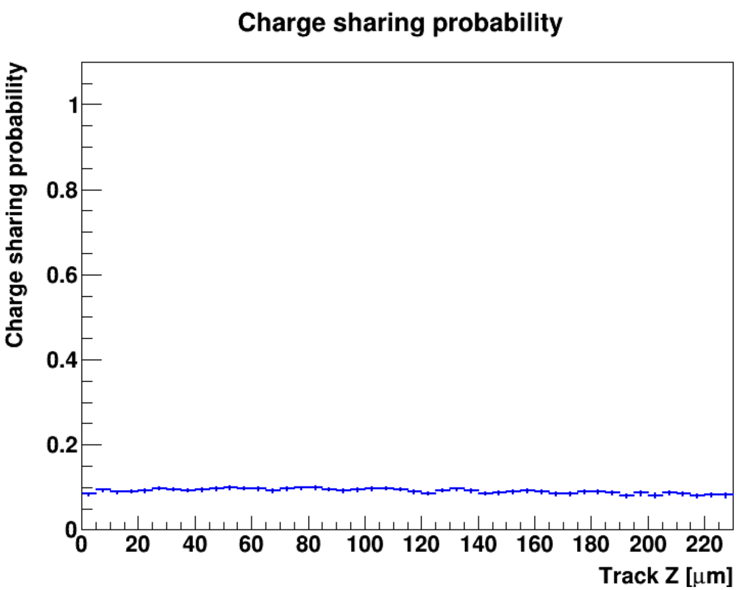


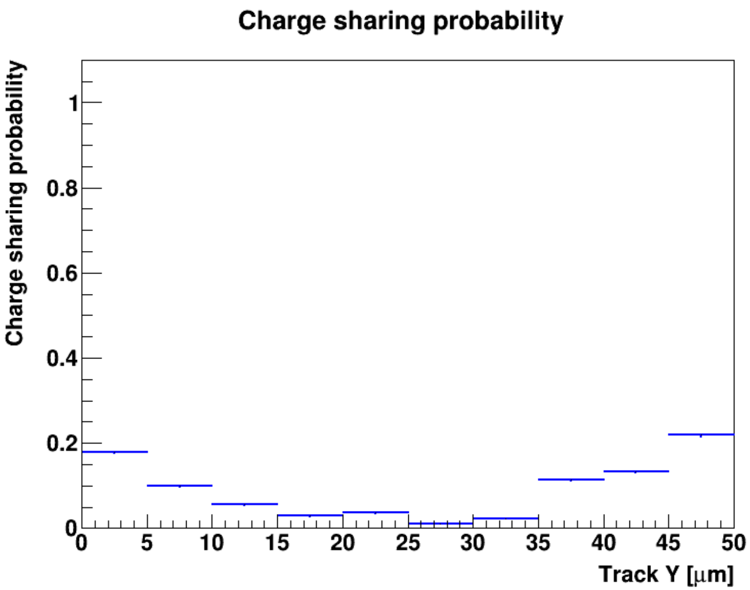


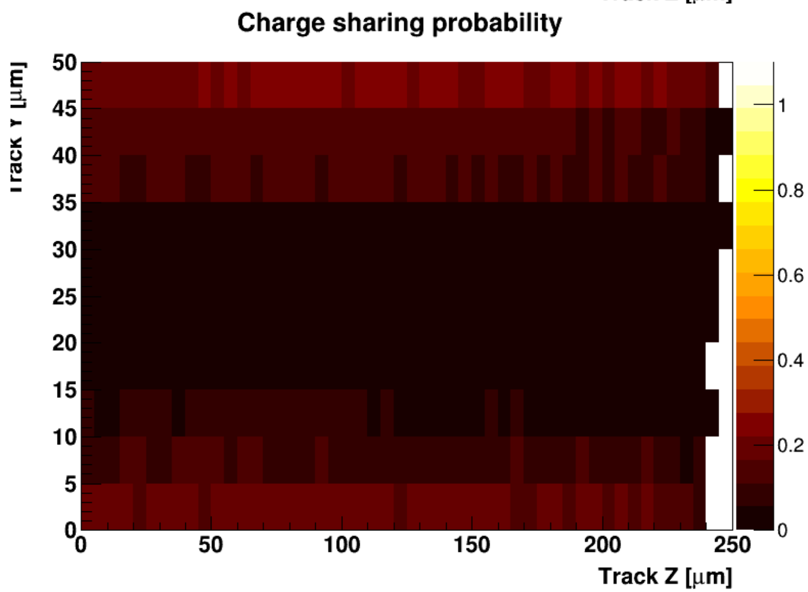


Charge Sharing

- **Charge sharing probability** as a function of the track intersection point
  - Beam in **long** pixel direction
  - 2 degrees, bias **-40 V**
  - Threshold 1000e

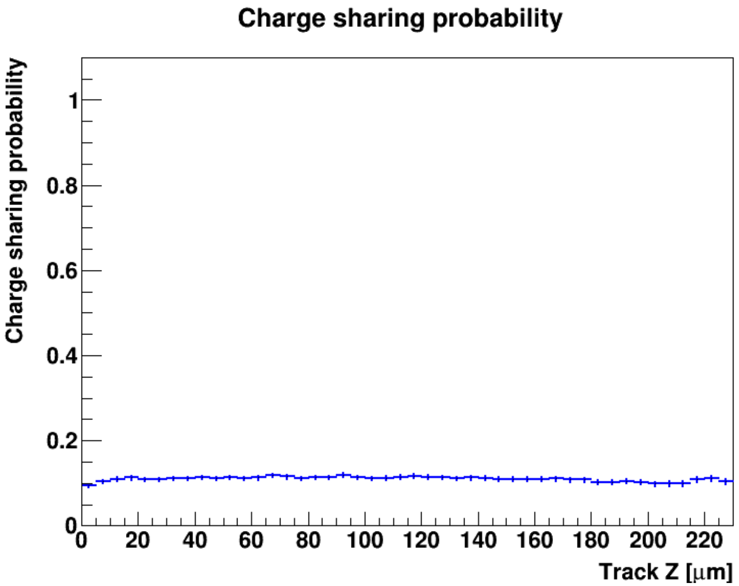


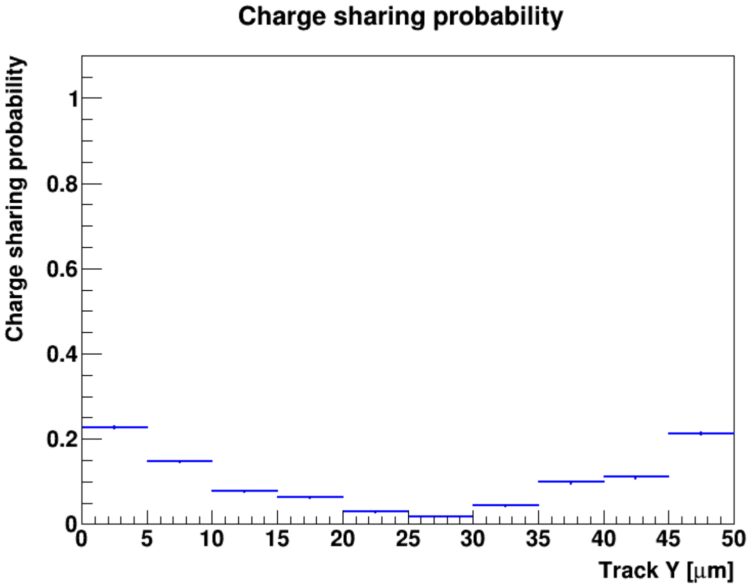


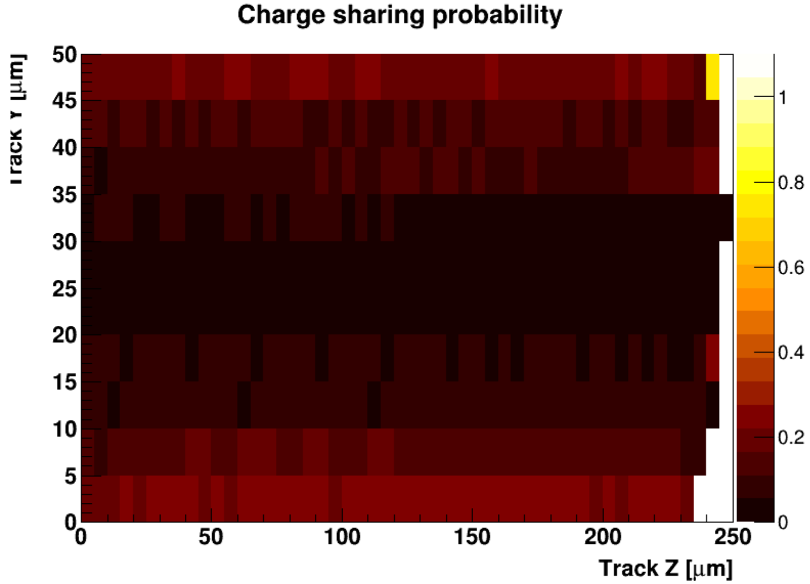


Charge Sharing

- **Charge sharing probability** as a function of the track intersection point
  - Beam in **long** pixel direction
  - 2 degrees, bias **-30 V**
  - Threshold 1000e







Charge Sharing

- **Charge sharing probability** as a function of the track intersection point
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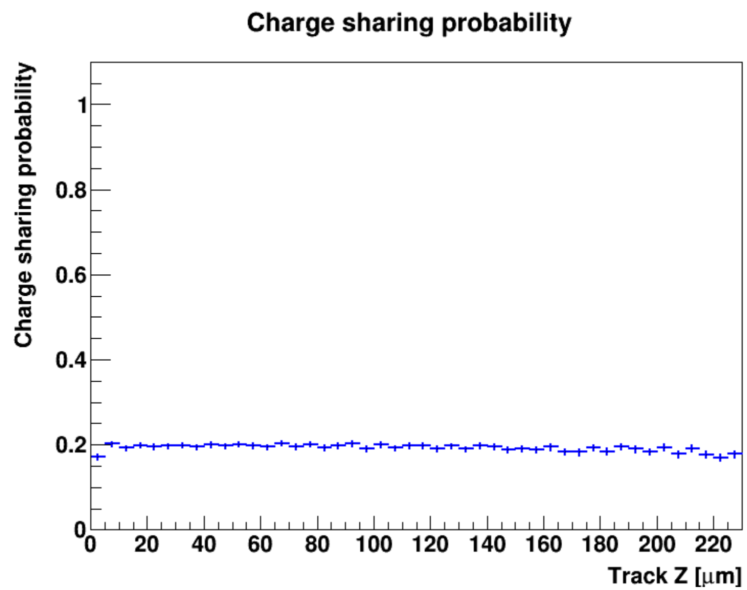
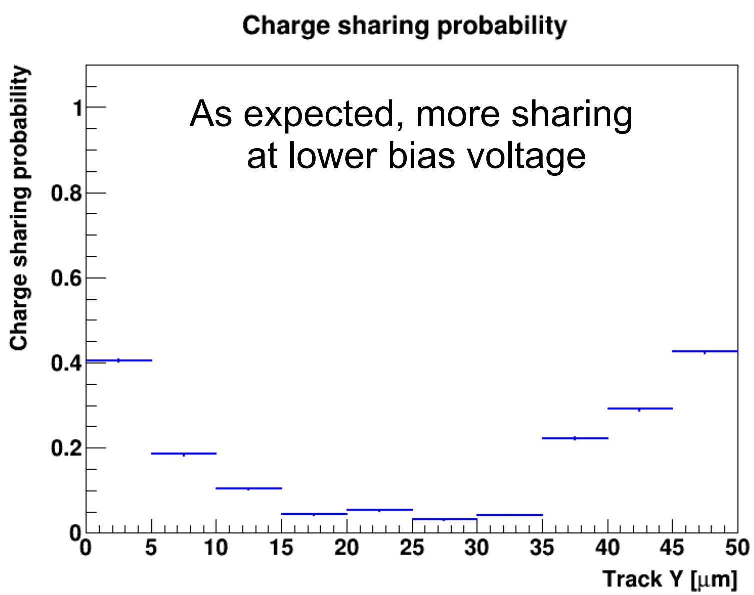
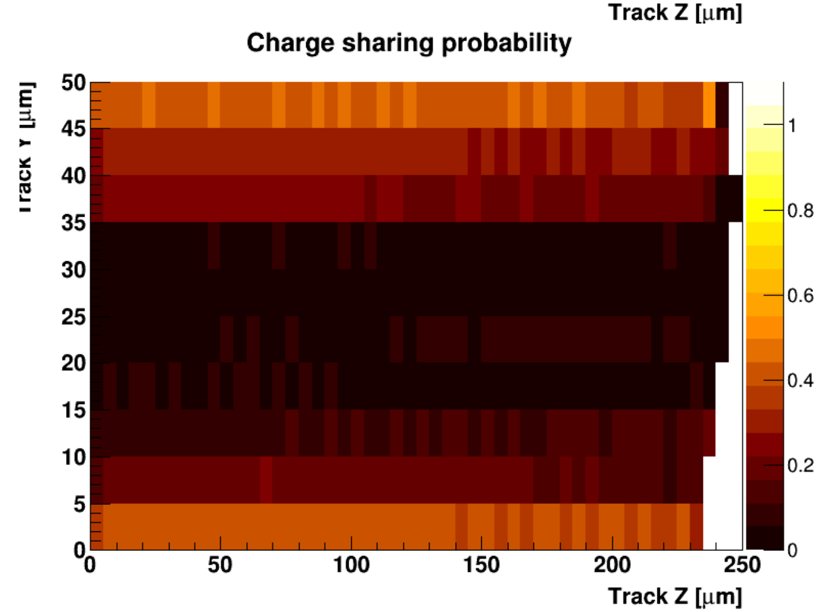
  - 2 degrees, bias **-6 V**
  - Threshold 1000e

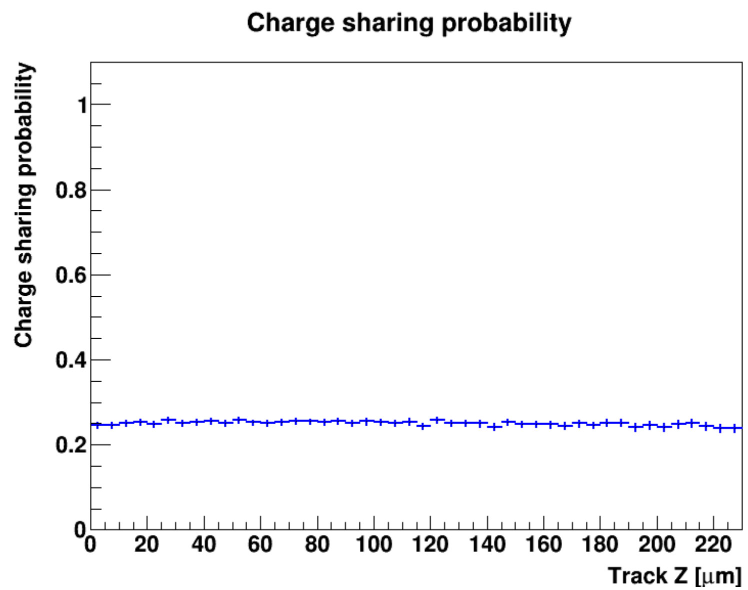


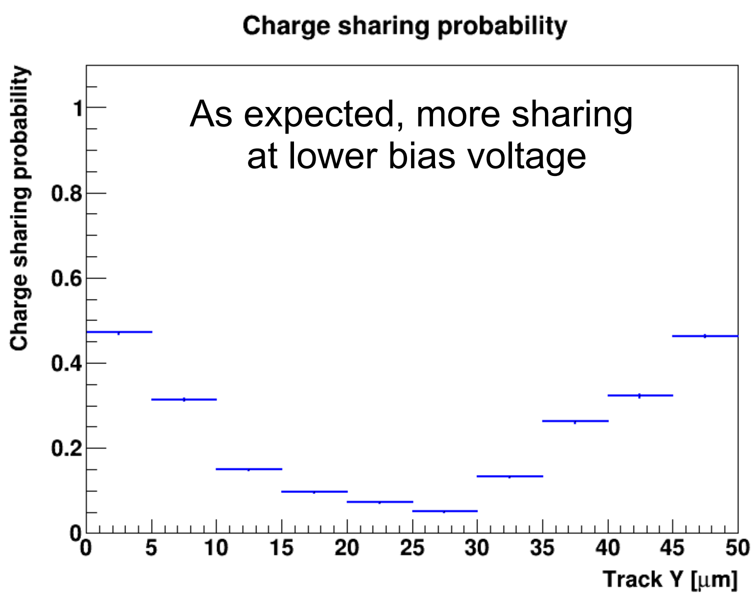


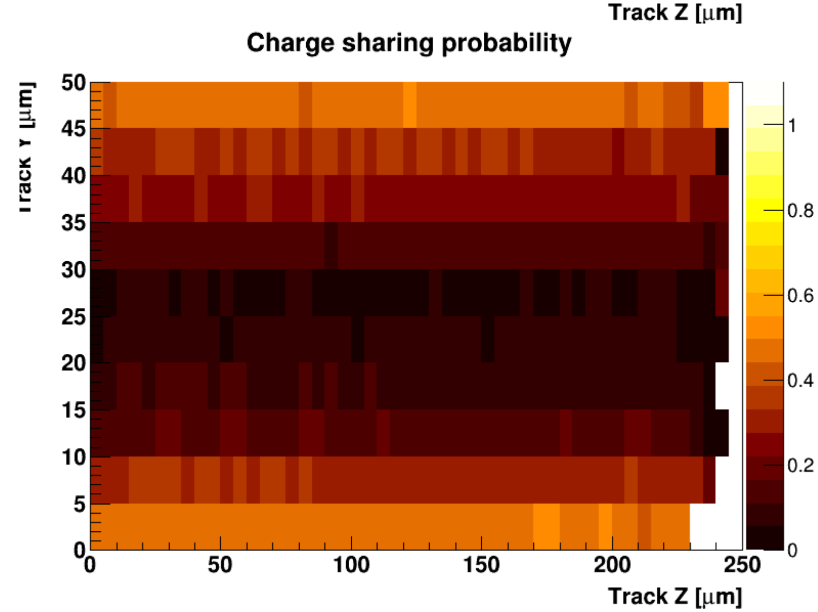


Charge Sharing

- **Charge sharing probability** as a function of the track intersection point
  - Beam in **long** pixel direction
  - 2 degrees, bias **-4 V**
  - Threshold 1000e







Charge Sharing

- **Charge sharing probability** as a function of the track intersection point
  - Beam in **long** pixel direction
  - 2 degrees, bias **-2 V**
  - Threshold 1000e