Beam Test Performance of ATLAS ITk Pixel 3D Modules irradiated up to End-of-Lifetime Fluences

Krishnan Rama[1], Andre Rummler[2] , Austin Robert Schmier[3], Bhakti Kanulai Chitroda[2], Claudia Gemme[4], Giuseppe Gariano[4], Hao Pang[5], Lola Morer Cugat[1], Martina Ressegotti[4,6], Md Arif Abdulla Samy[7] , Simone Ravera[4,6], Mahima Sachdeva[1], Matteo Ventura[4,6], Matias Nahuel Mantinan[8], Niraj Kakoty[1], Sebastian Grinstein[1], Stefano Terzo[1]

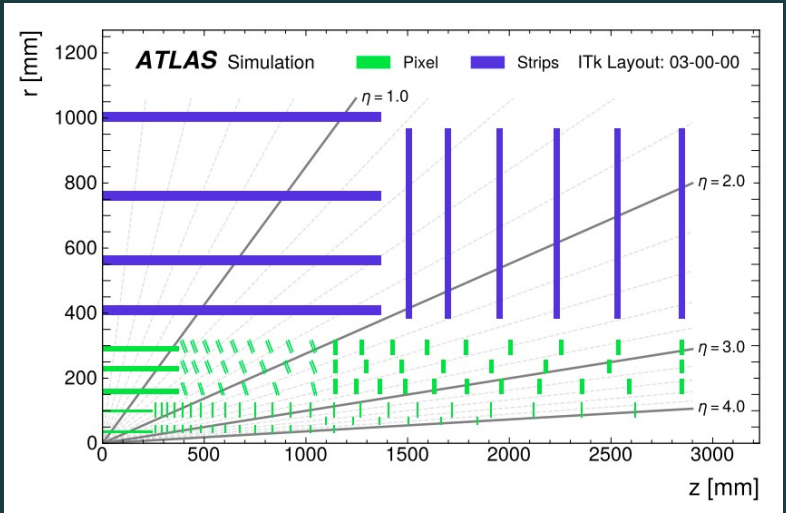
[1] IFAE, Barcelona, Spain, [2] CERN, Switzerland, [3] TIFPA, Trento, Italy, [4] INFN Sezione di Genova, Italy, [5] IRFU CEA-Paris, France, [6] Università di Genova, Italy, [7] University of Glasgow, United Kingdom, [8] University of Chicago, USA

International Conference on Technology & Instrumentation in Particle Physics

Tata Institute of Fundamental Research

February 2-6, 2026

ATLAS Inner Tracker (ITk)



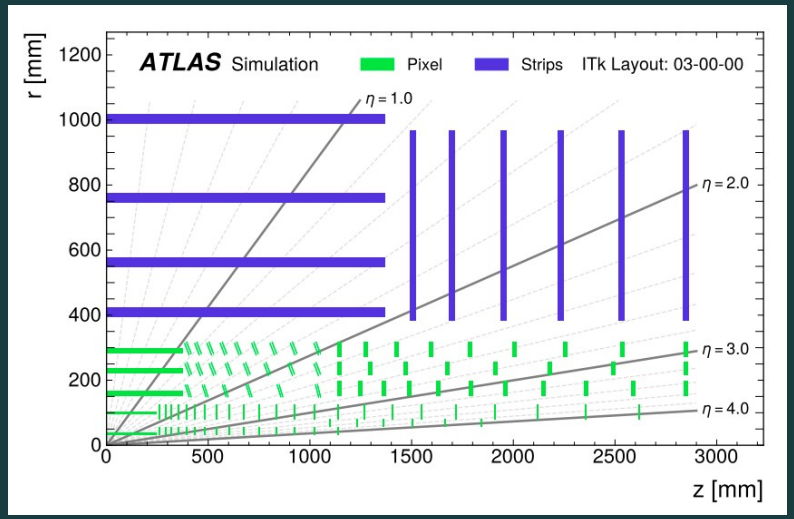
Inner Tracker (ITk) : outer strip detector
inner pixel detector

ATLAS Inner TracKer Upgrade
- Tony Affolder (Tuesday Plenary II)

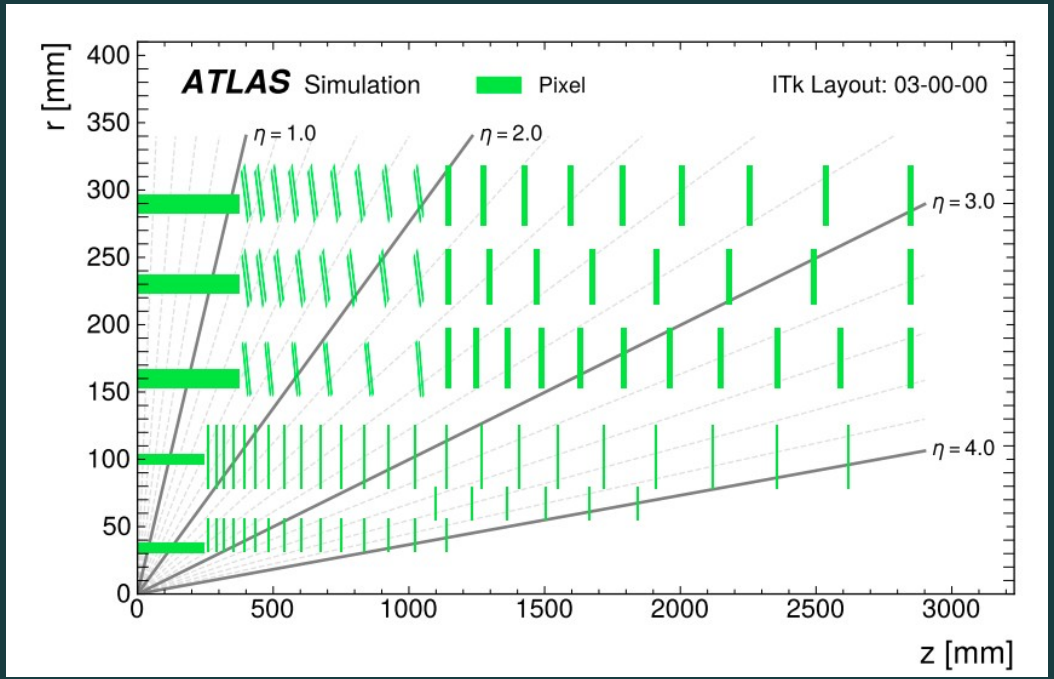
FPGA-based Emulator Platform Targeting ATLAS Phase-2 ITk DAQ System Development
- Matthias Peter Drescher (Monday Parallel V)

Getting ready for the new ATLAS ITk pixel detector: Large scale detector system tests
- Benedikt Vormwald (Today Parallel II)

ATLAS Inner Tracker (ITk)



Inner pixel detector

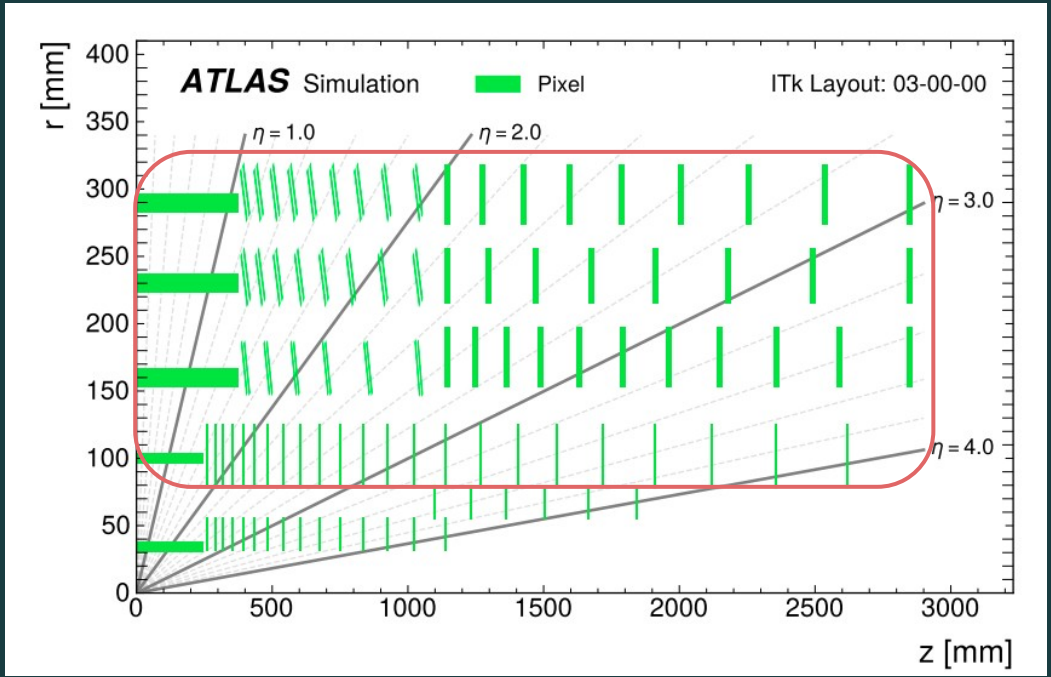


ATLAS Inner Tracker (ITk)

- Layer 1 to 4 :

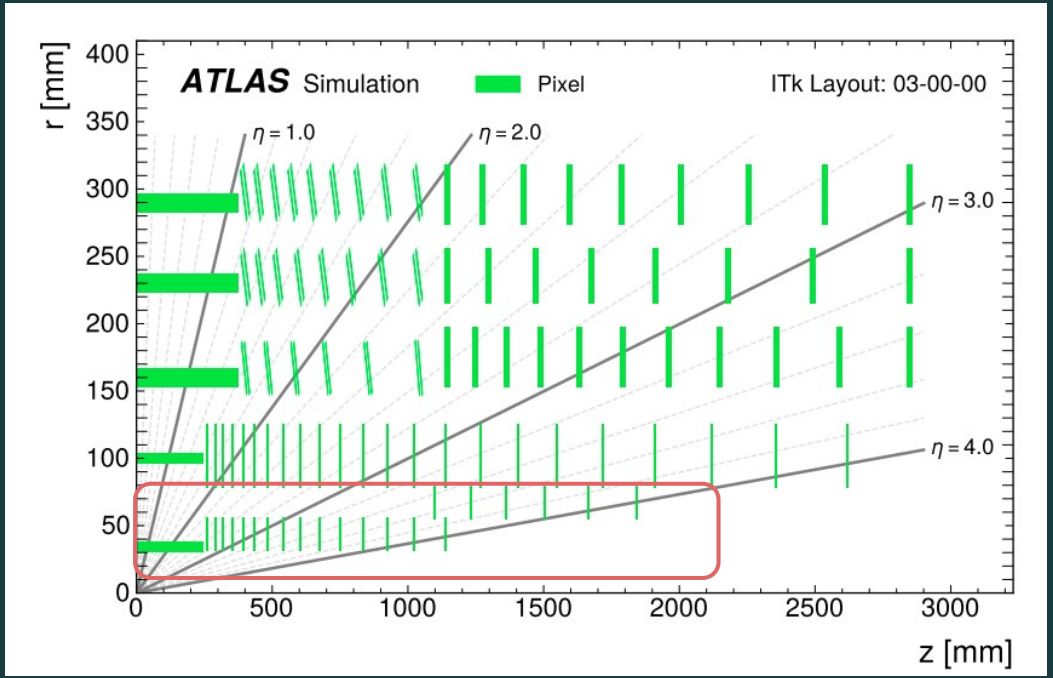
  Quad module - A flexible PCB glued and wire bonded to a quad bare module.
  Quad bare module - a planar sensor bump bonded to four ITkPix readout chips.

Inner pixel detector



ATLAS Inner Tracker (ITk)

Inner pixel detector



- Layer 0 :

  Triplet module - A flexible PCB glued and wire bonded to three single bare modules. Single bare module - a **3D sensor** bump bonded to an ITkPix readout chip.

ATLAS Inner Tracker (ITk)

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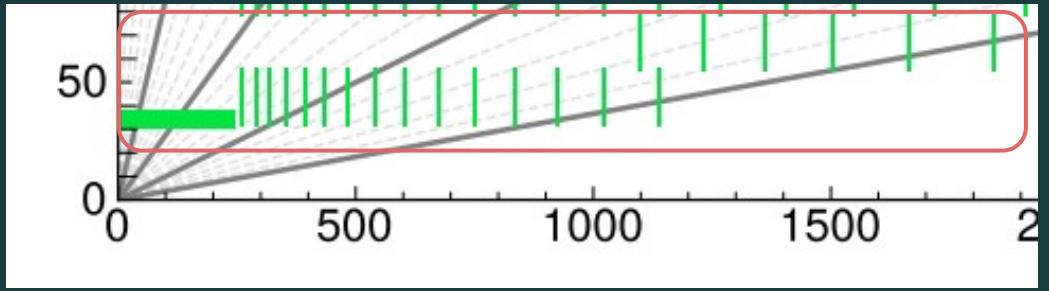
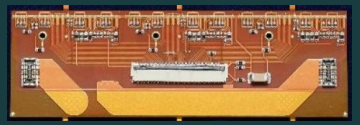
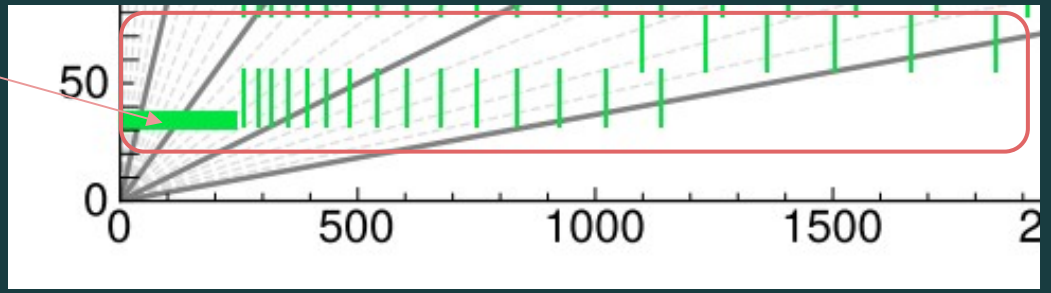


ATLAS Inner Tracker (ITk)



Barrel 0



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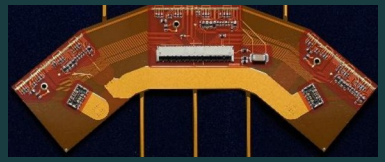
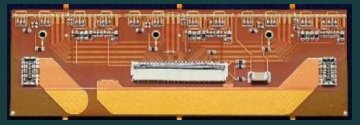
ATLAS Inner Tracker (ITk)



Ring 0



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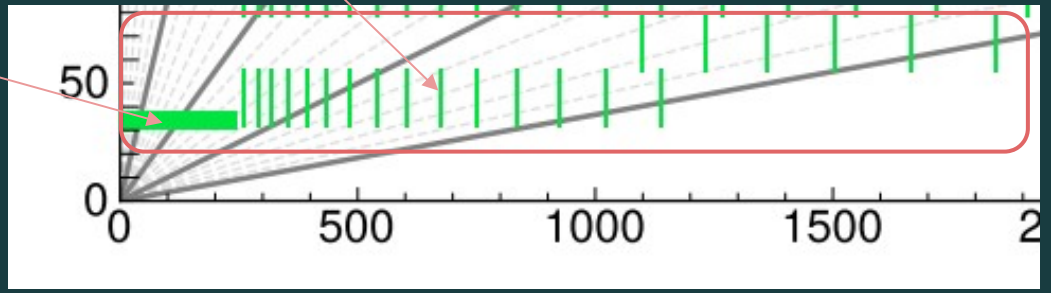
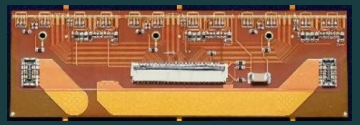
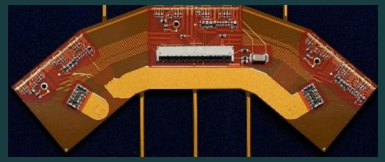


ATLAS Inner Tracker (ITk)

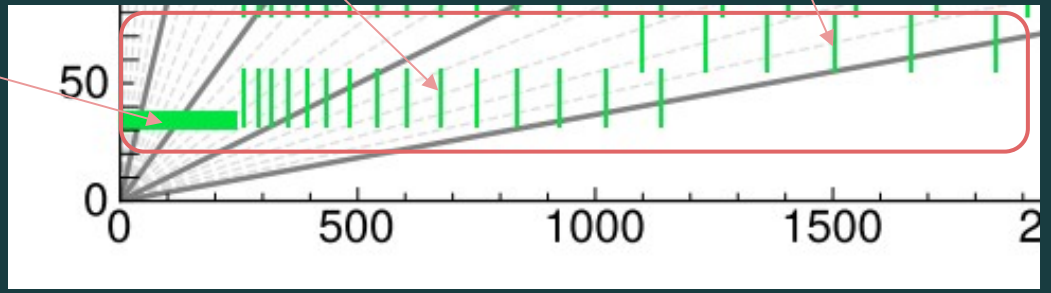


Barrel 0



Ring 0

Ring 0.5



- Layer 0 :

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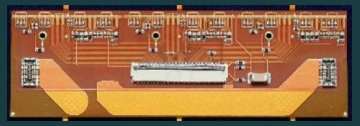
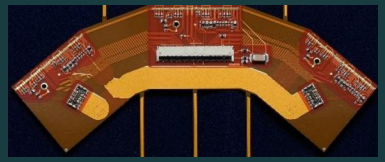
ATLAS Inner Tracker (ITk)

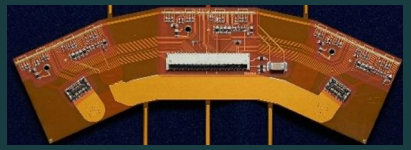
- 3D sensor technology
- Capable of withstanding fluence of more than 10^{16} n_{eq}/cm^2.



Barrel 0



Ring 0



Ring 0.5

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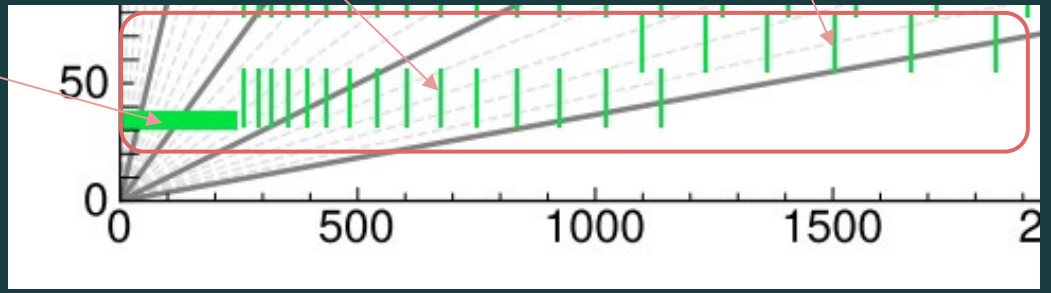
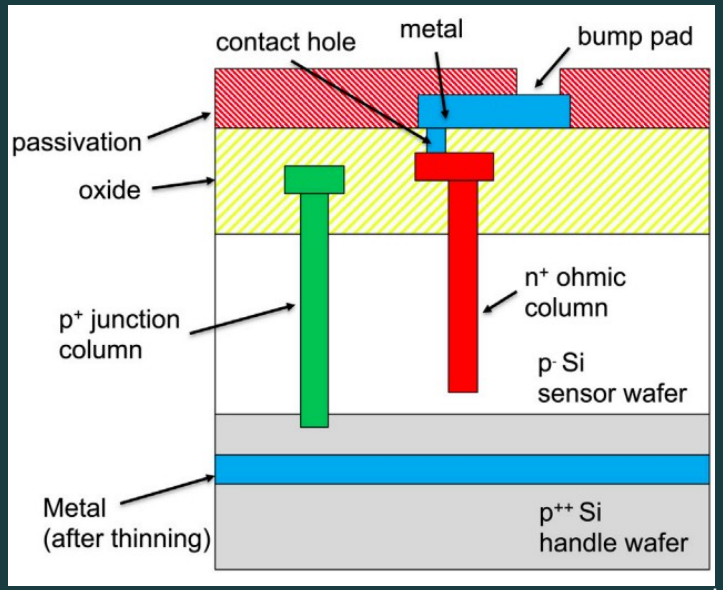


Silicon 3D sensor Technology



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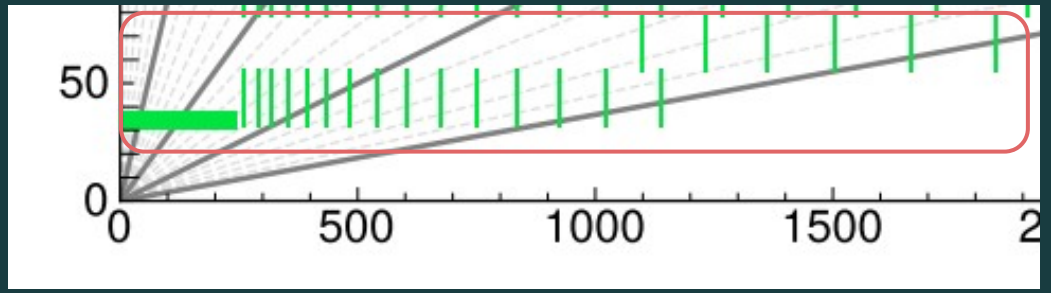
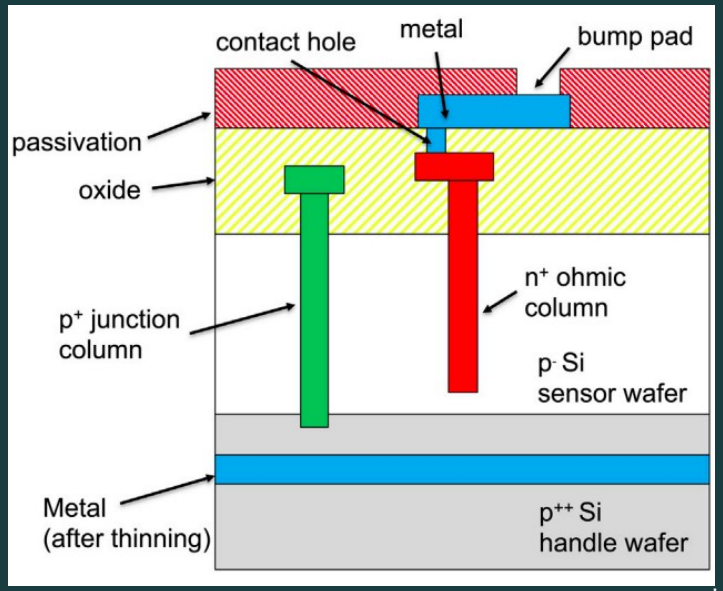


- Thickness of active region : 150 µm

*Terzo et.al., FPhy.2021.624668

Silicon 3D sensor Technology



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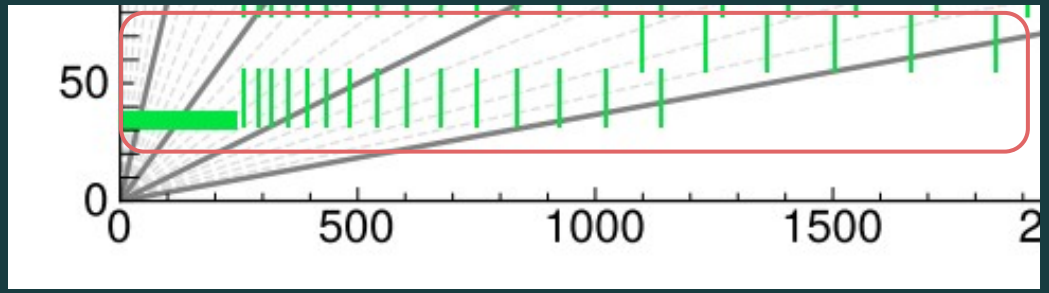

- Thickness of active region : 150 µm
- Rings and Barrel use pixel pitches
  50 µm x 50 µm and 25 µm x 100 µm

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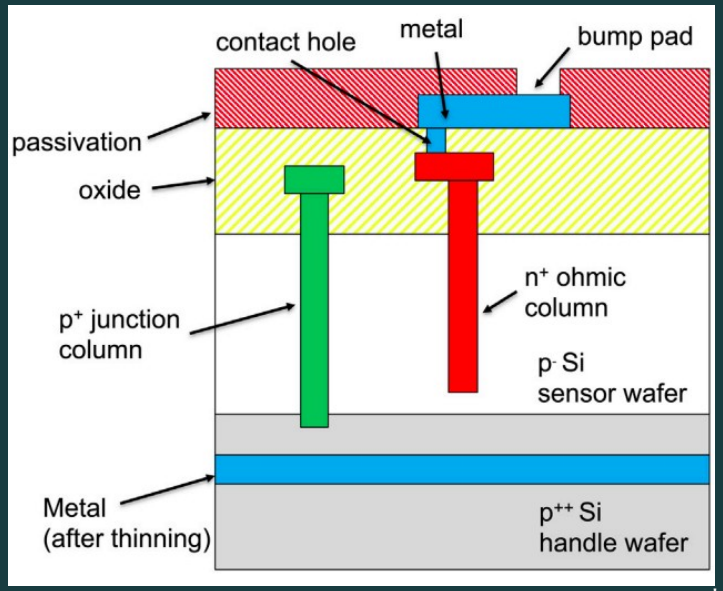
Silicon 3D sensor Technology



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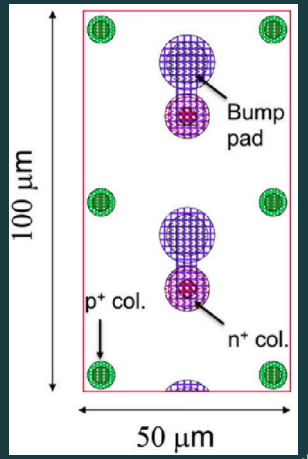
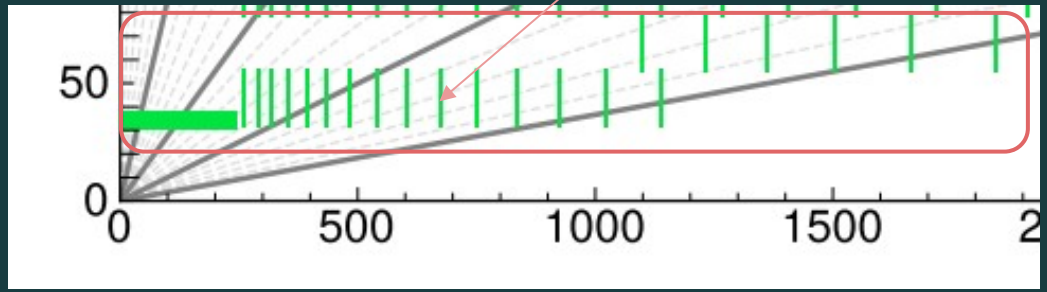


*

50 x 50



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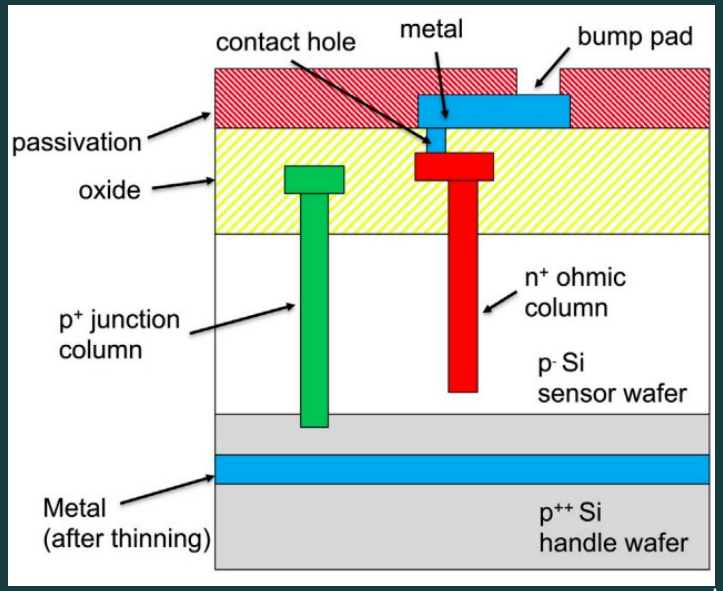

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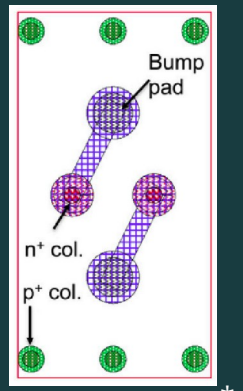
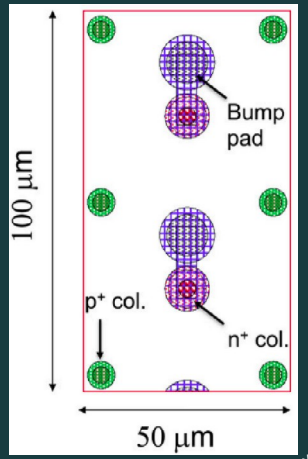


*
25 x 100



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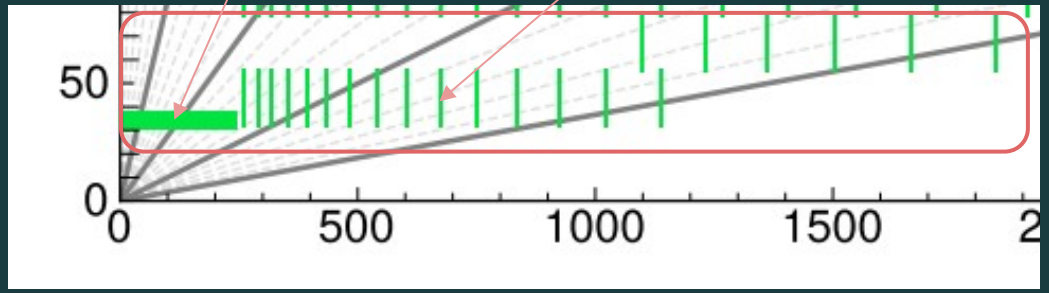

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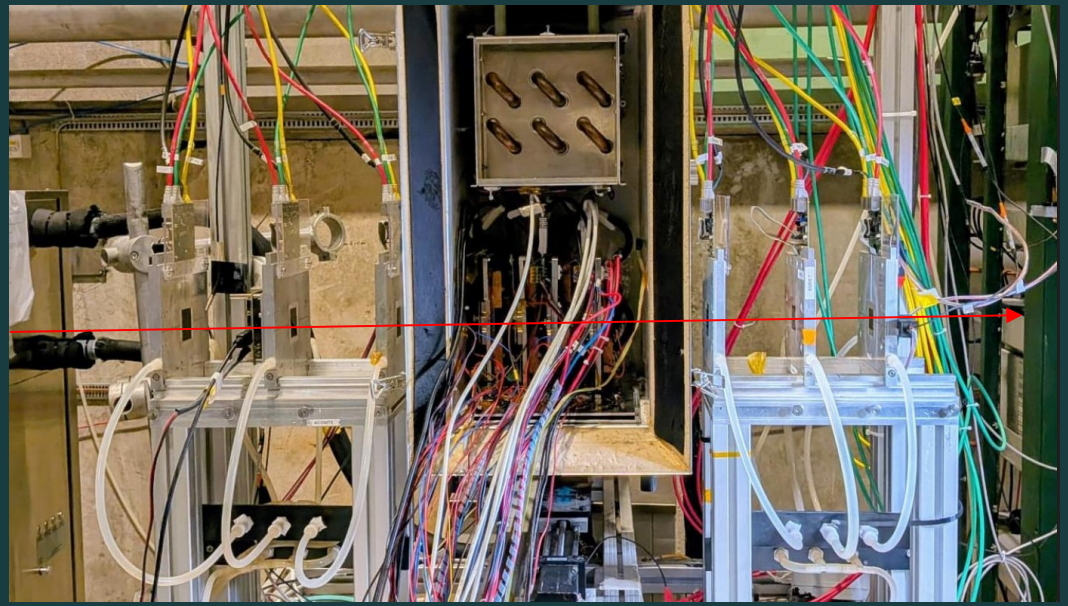
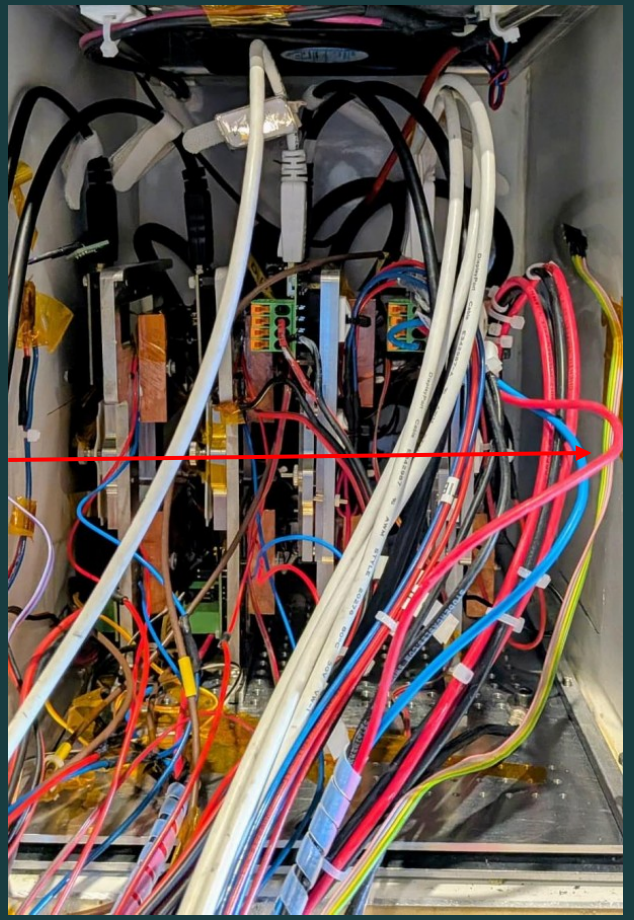
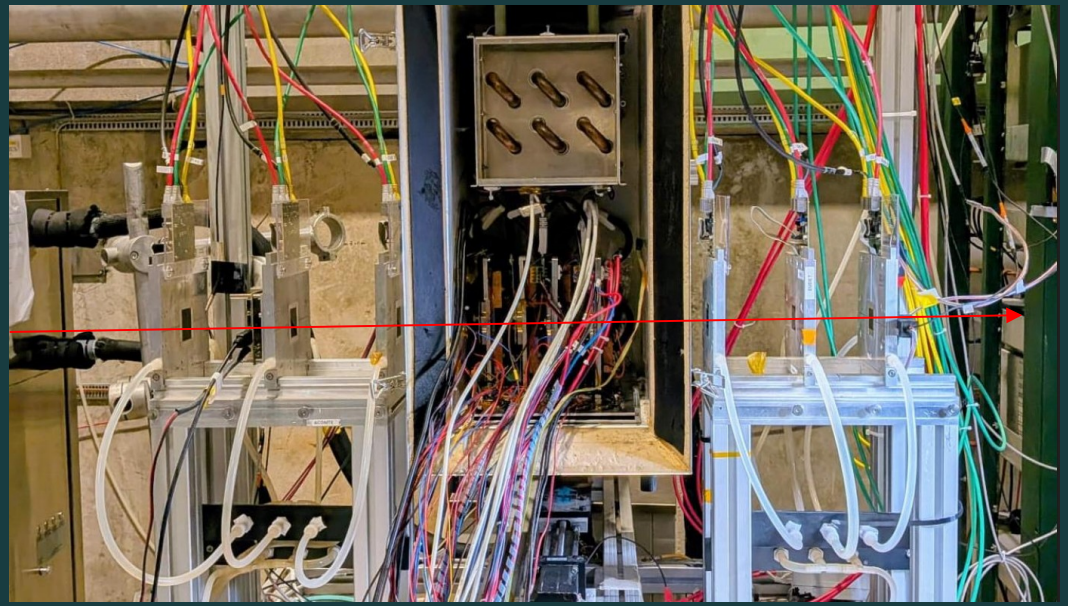
Test Beam at SPS, CERN

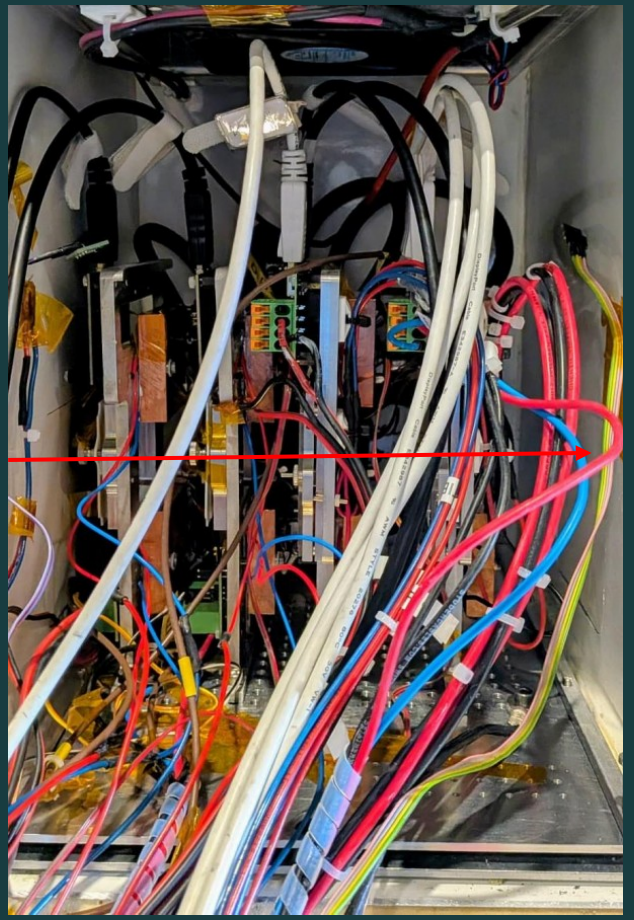




- Triplets tested during four campaigns carried out in May, July, August, November 2025.
- 120 GeV Pions

Test Beam at SPS, CERN

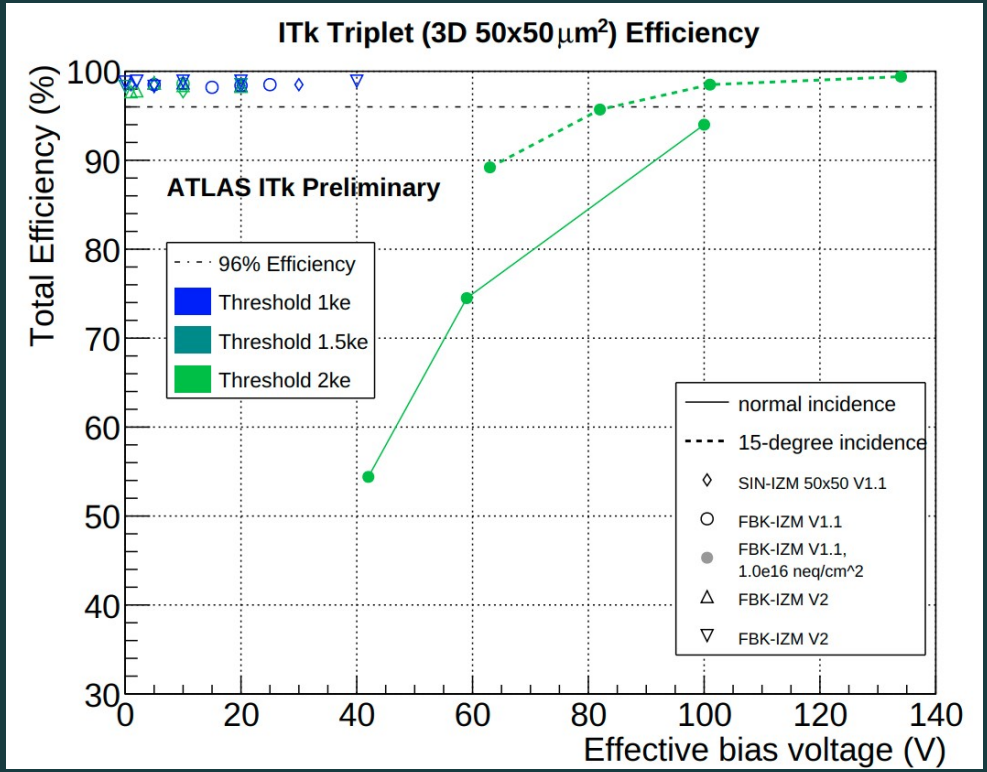




- Triplets tested during four campaigns carried out in May, July, August, November 2025.
- 120 GeV Pions
- Reconstruction and analysis using Corryvreckan software package

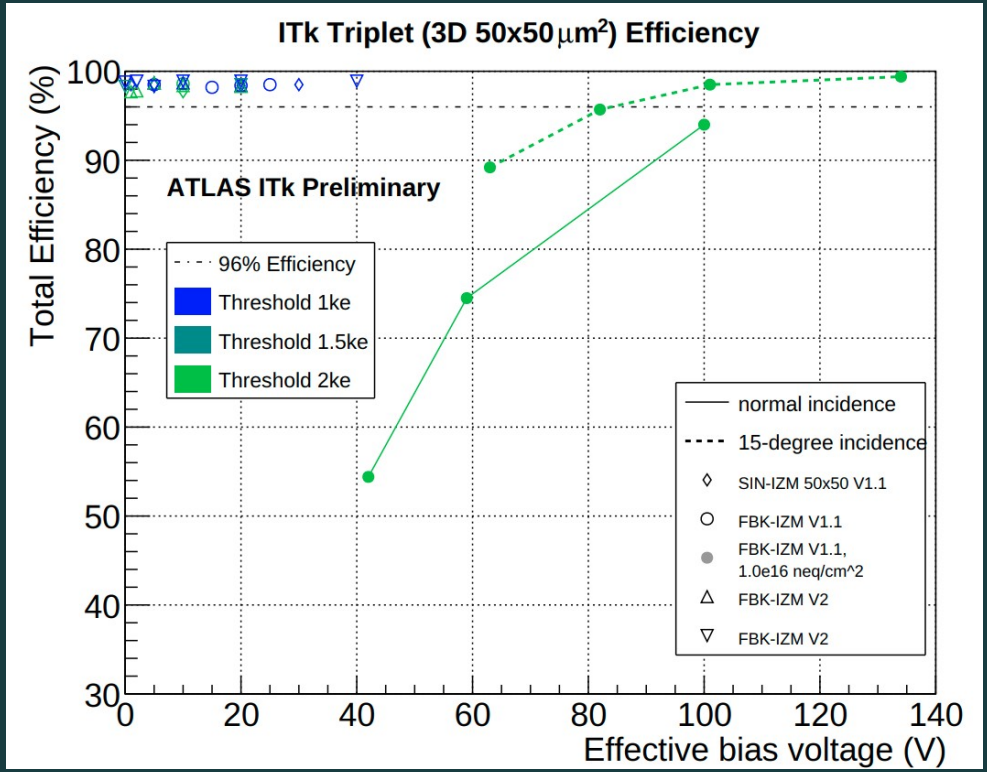
Performance of 50x50 Triplets

Unirradiated triplets have efficiency >98 (even at low bias voltages and high thresholds)



Performance of 50x50 Triplets

- Unirradiated triplets have efficiency >98 (even at low bias voltages and high thresholds)
- Expected maximum fluence after 2,000 fb^{-1} for L0 is 1.3e16 n_{eq}/cm^2. Triplets Irradiated at IRRAD, CERN.



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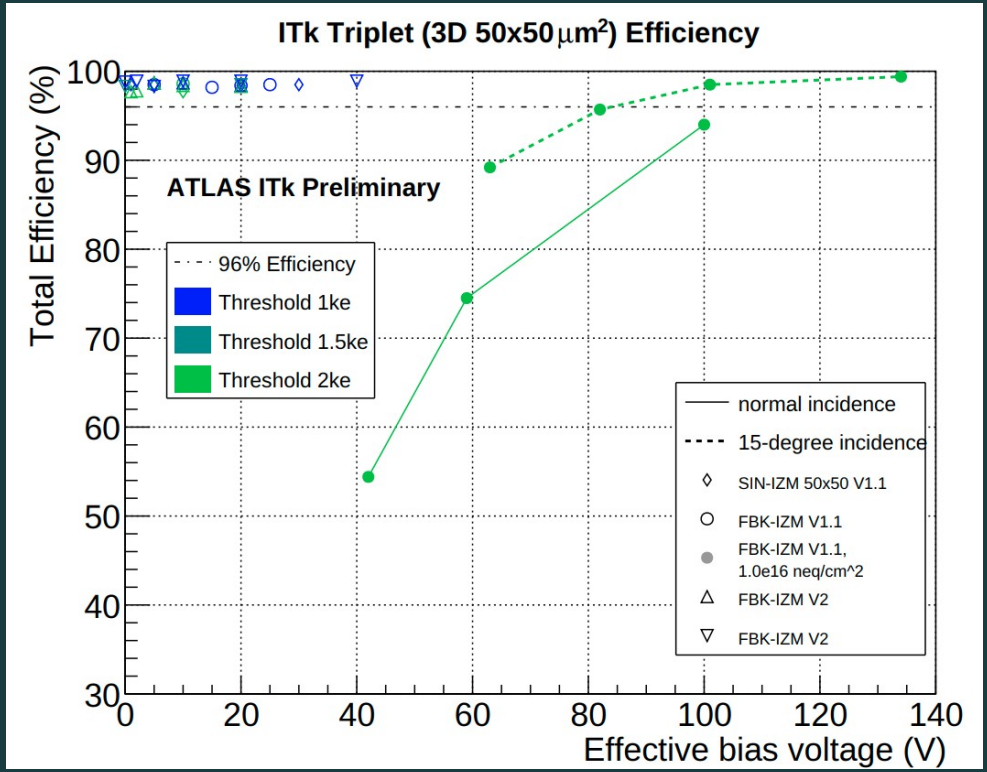

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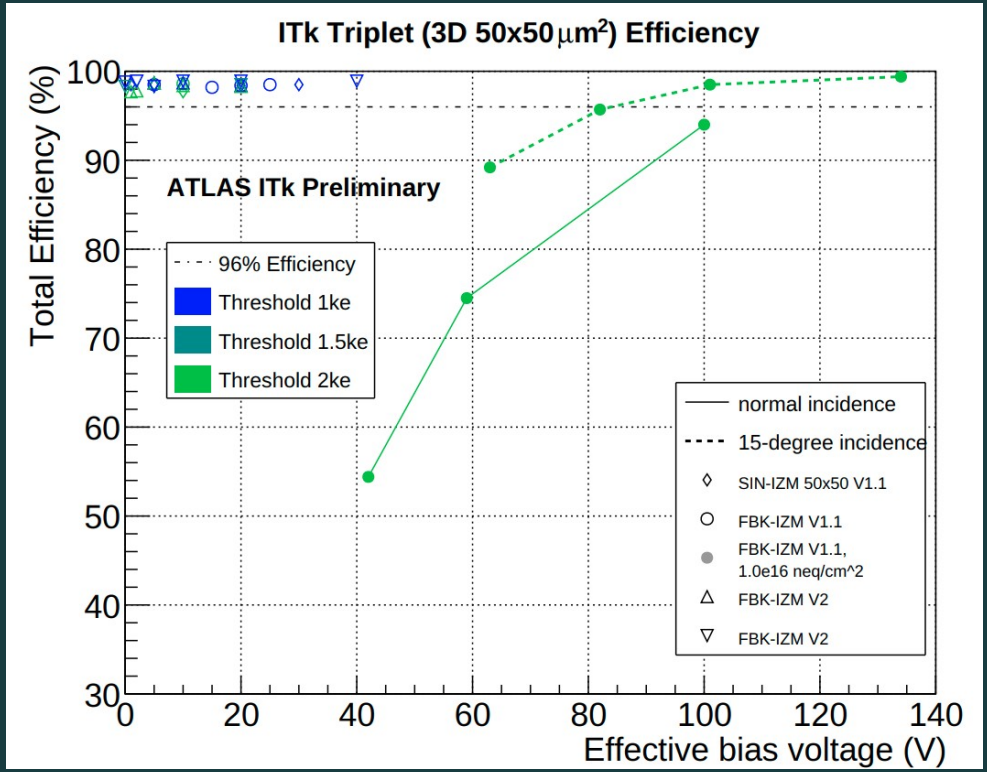
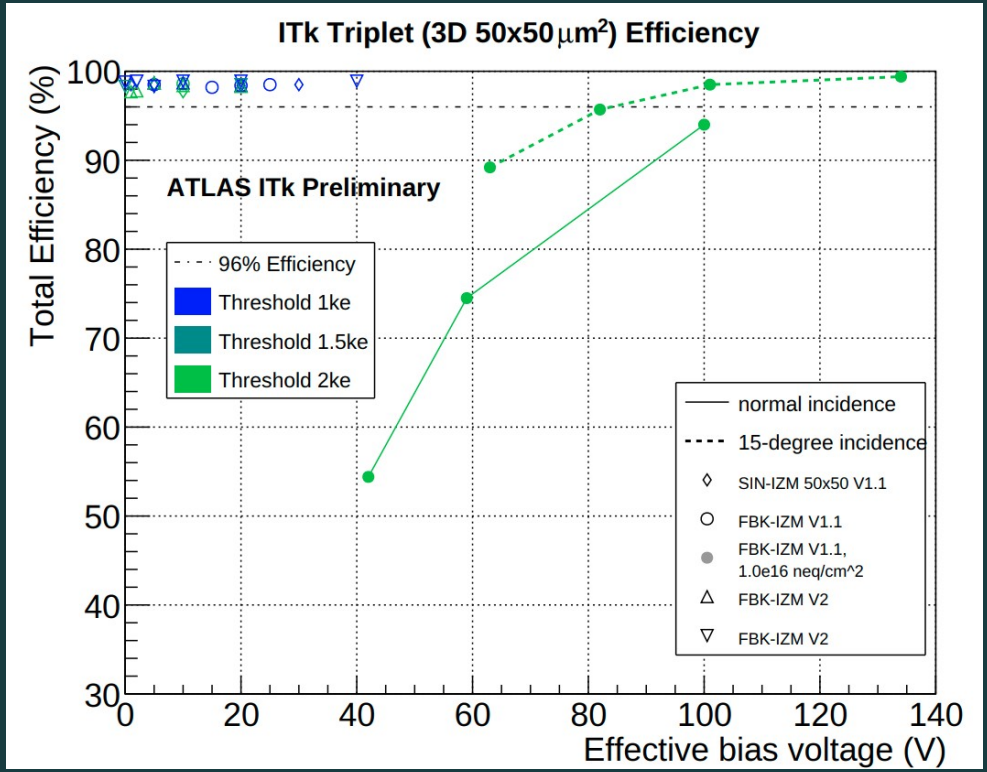
- As expected, efficiency increases when bias voltage is increased. It decreases when threshold increases as well as when irradiated
- For the irradiated triplet at normal incidence, efficiency close to 96% was achieved for threshold 1.5 ke and bias 100 V



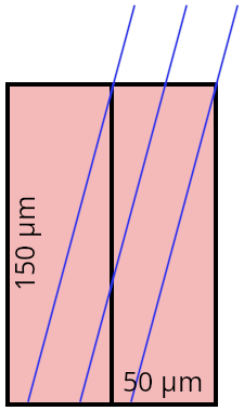
Performance of 50x50 Triplets

- The incident angle in Ring 0 and Ring 0.5 of ITk ranges from normal incidence to ~20-degrees.
- In test beam, we tested at 15-degree incident angle



Performance of 50x50 Triplets

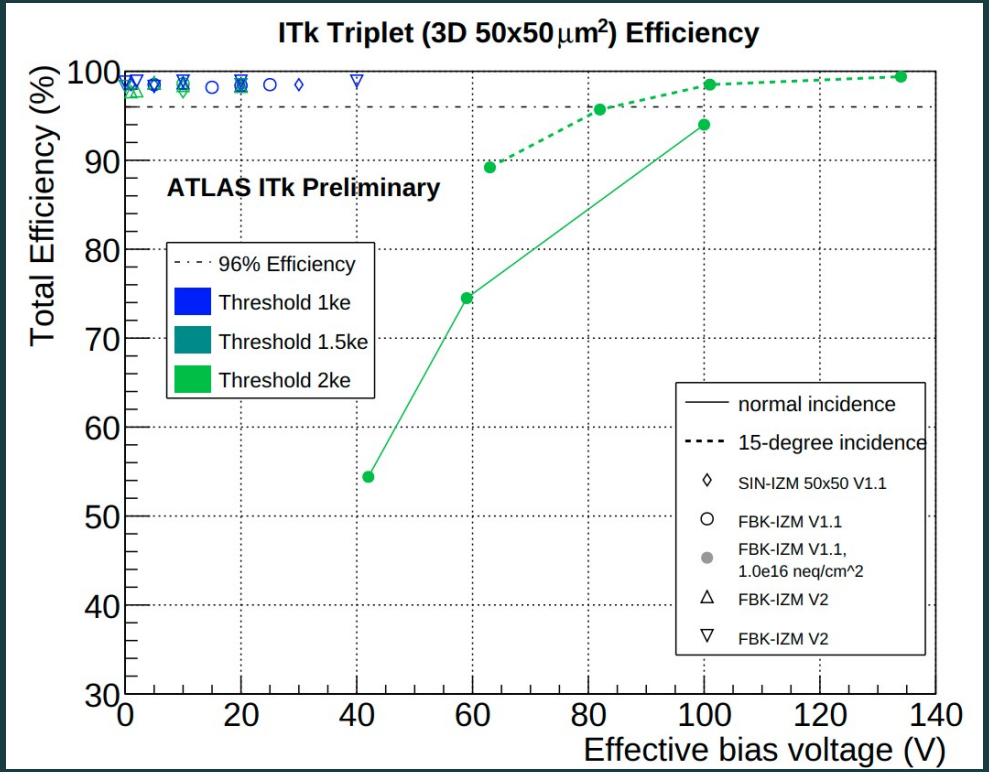
- The incident angle in Ring 0 and Ring 0.5 of ITk ranges from normal incidence to ~20-degrees.
- In test beam, we tested at 15-degree incident angle
- Efficiency increases since the effect of electrodes is reduced.



Path length in active region
= 150/Cos(15) = 155.3 µm

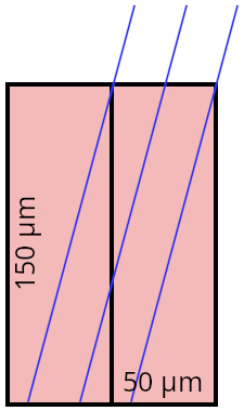
Max path length in one pixel
= 155.3 µm

In the worst scenario, path length in one pixel
= 155.3/2 = 77.6 µm



Performance of 50x50 Triplets

- The incident angle in Ring 0 and Ring 0.5 of ITk ranges from normal incidence to ~20-degrees.
- In test beam, we tested at 15-degree incident angle
- Efficiency increases since the effect of electrodes is reduced.
- The target efficiency of 96% is achieved at better conditions (lower bias voltage and higher thresholds)



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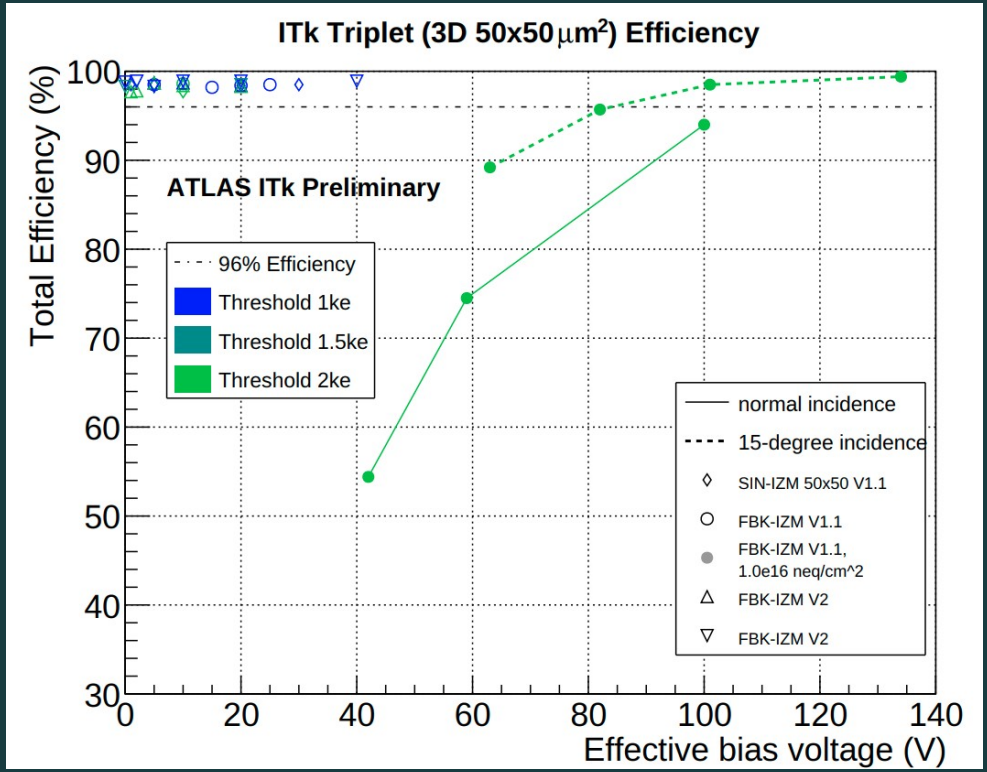
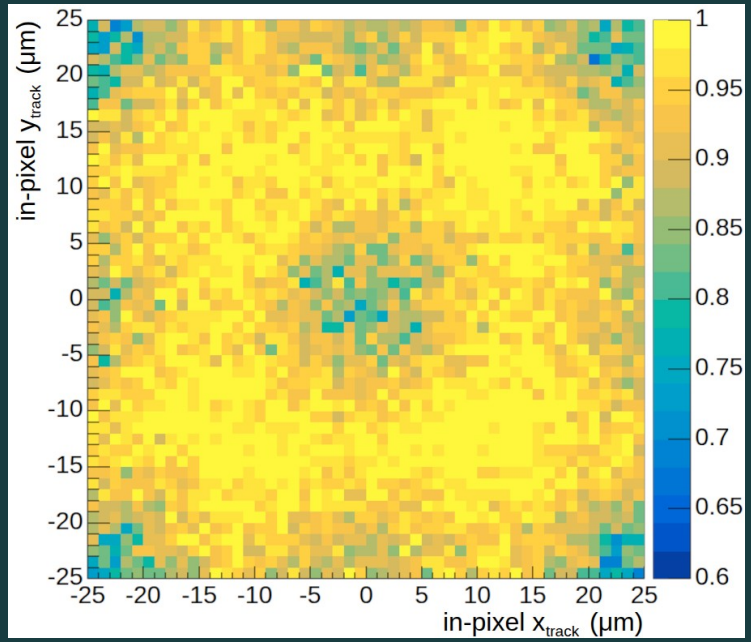
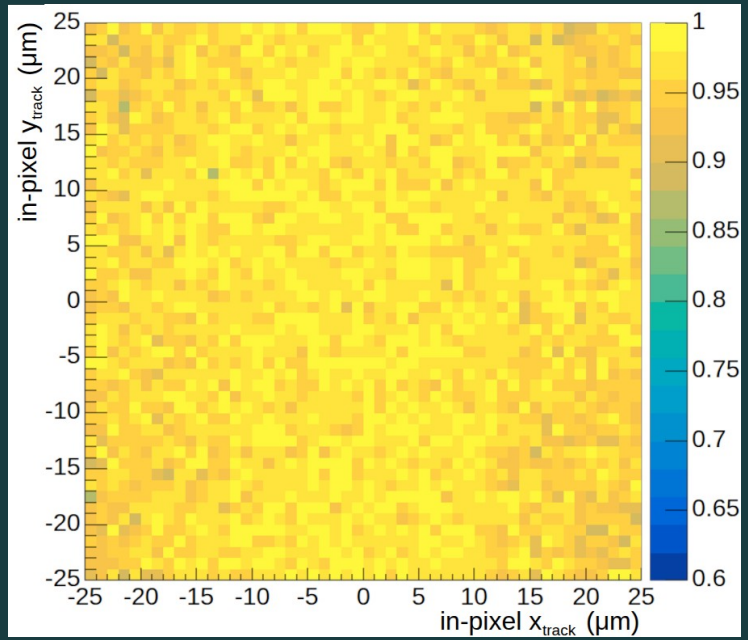


Performance of 50x50 Triplets

- Efficiency improves since the effect of electrodes is reduced.

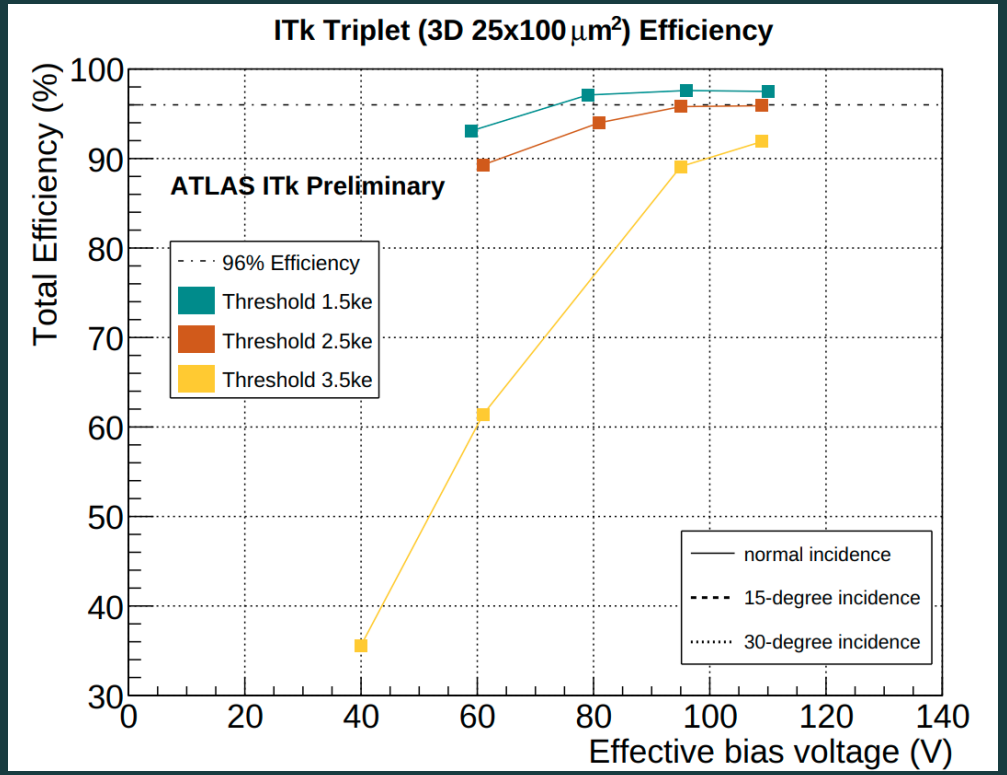


Threshold: 2 ke, Effective Bias: 100 V
Normal Incidence, Efficiency : 94.0%



Threshold: 2 ke, Effective Bias: 101 V
15-degree Incidence, Efficiency : 98.5%

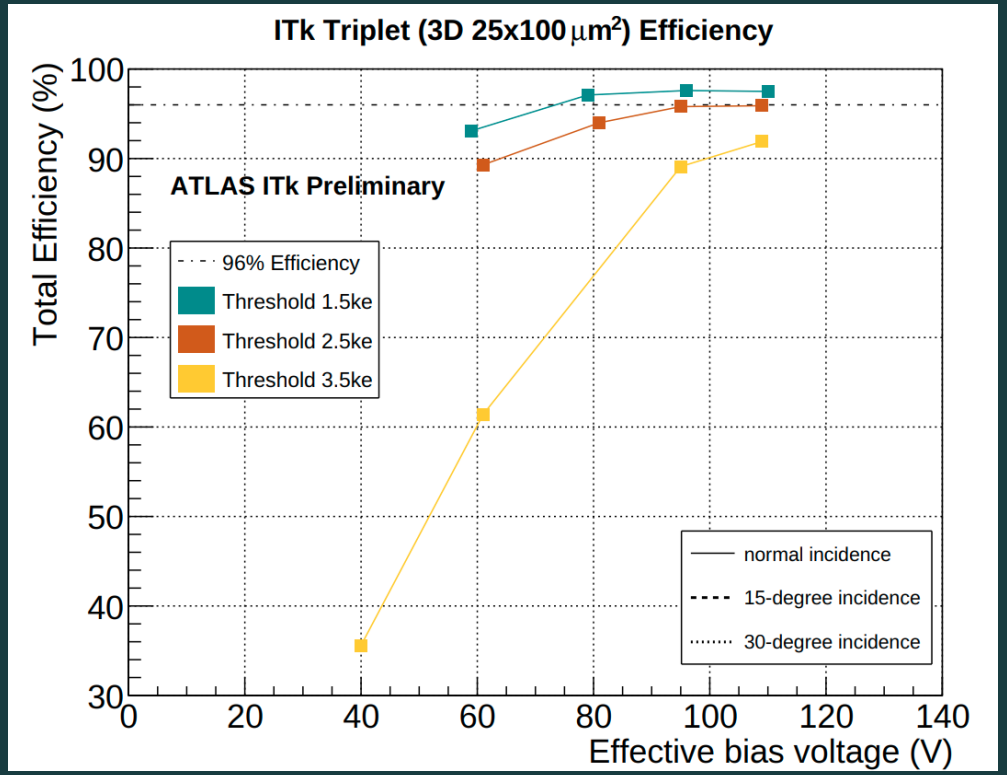
Performance of 25x100 Triplet



25x100 FBK-Leonardo Triplet irradiated to 1.1e16 n_{eq}/cm^2

Performance of 25x100 Triplet

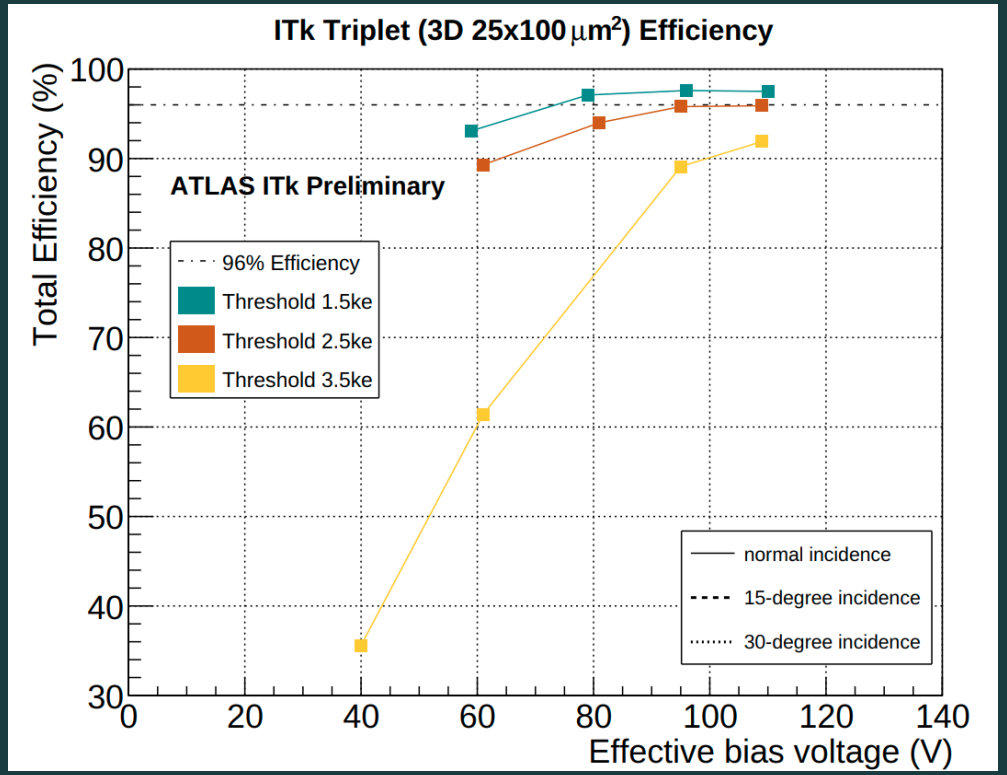
- The effect of Threshold, bias voltage on efficiency is similar to the case of the 50x50 triplets



25x100 FBK-Leonardo Triplet irradiated to 1.1e16 n_{eq}/cm^2

Performance of 25x100 Triplet

- The effect of Threshold, bias voltage on efficiency is similar to the case of the 50x50 triplets
- Since they are placed in the Barrel 0, they experience a larger variation of angle of incidence



25x100 FBK-Leonardo Triplet irradiated to 1.1e16 n_{eq}/cm^2

Performance of 25x100 Triplet

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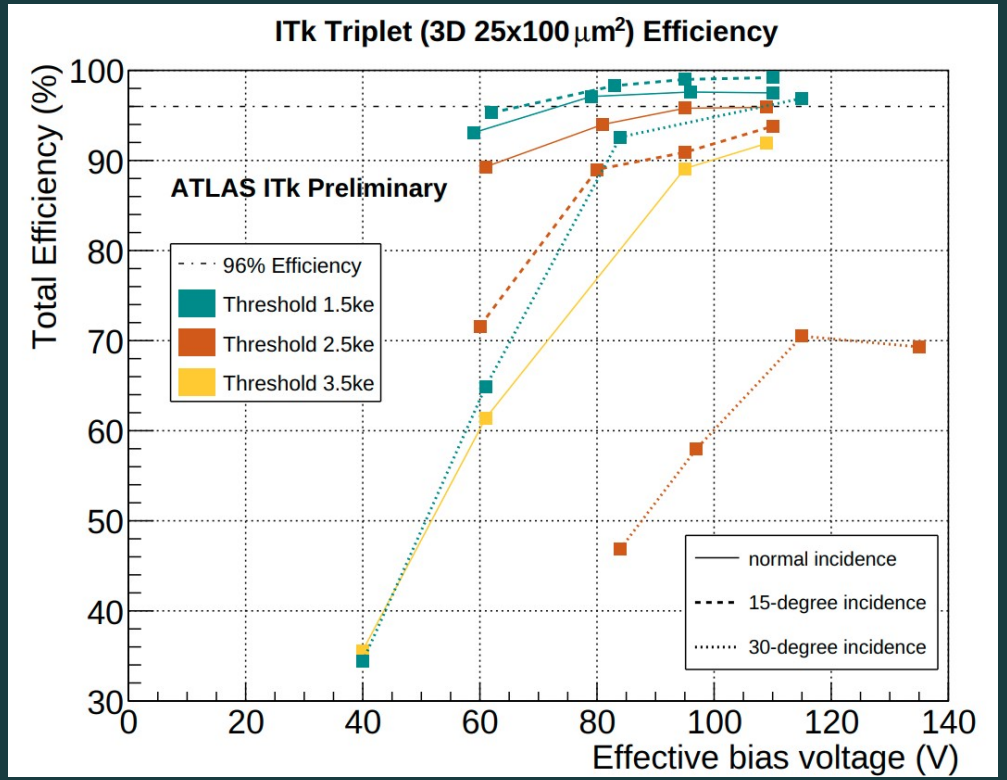
- Tested at 0, 15 and 30-degree angles along the 25 μm direction



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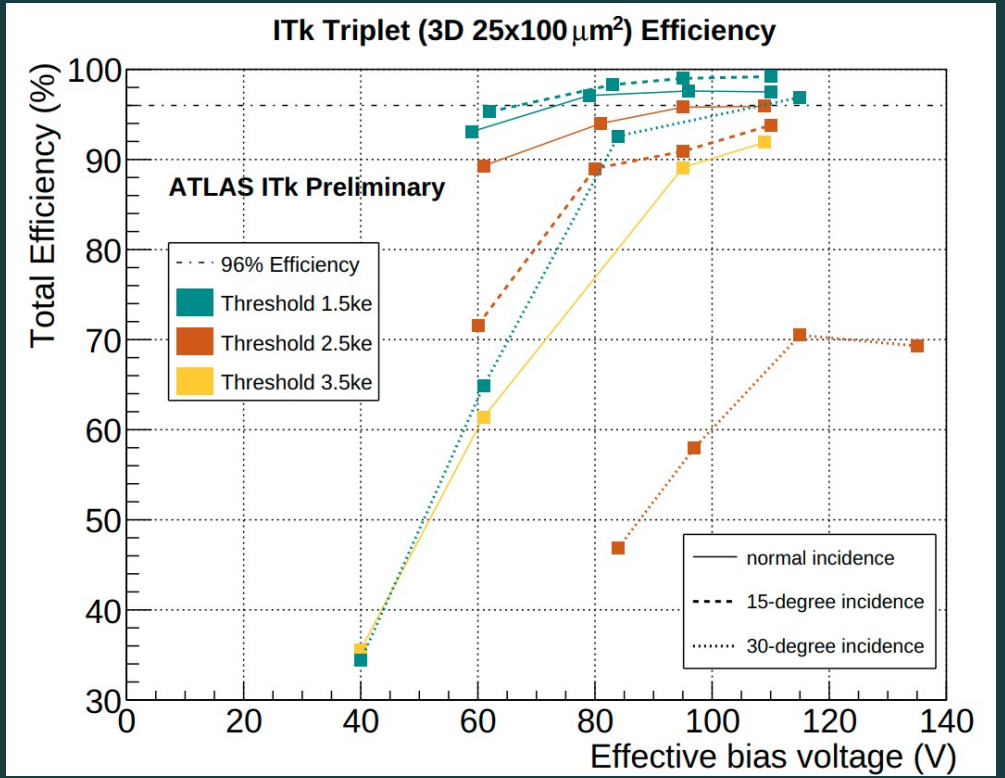
  30° : Efficiency worsens.



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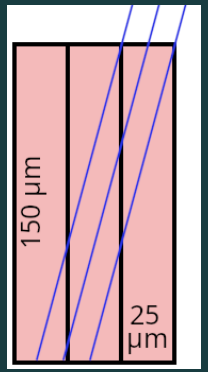
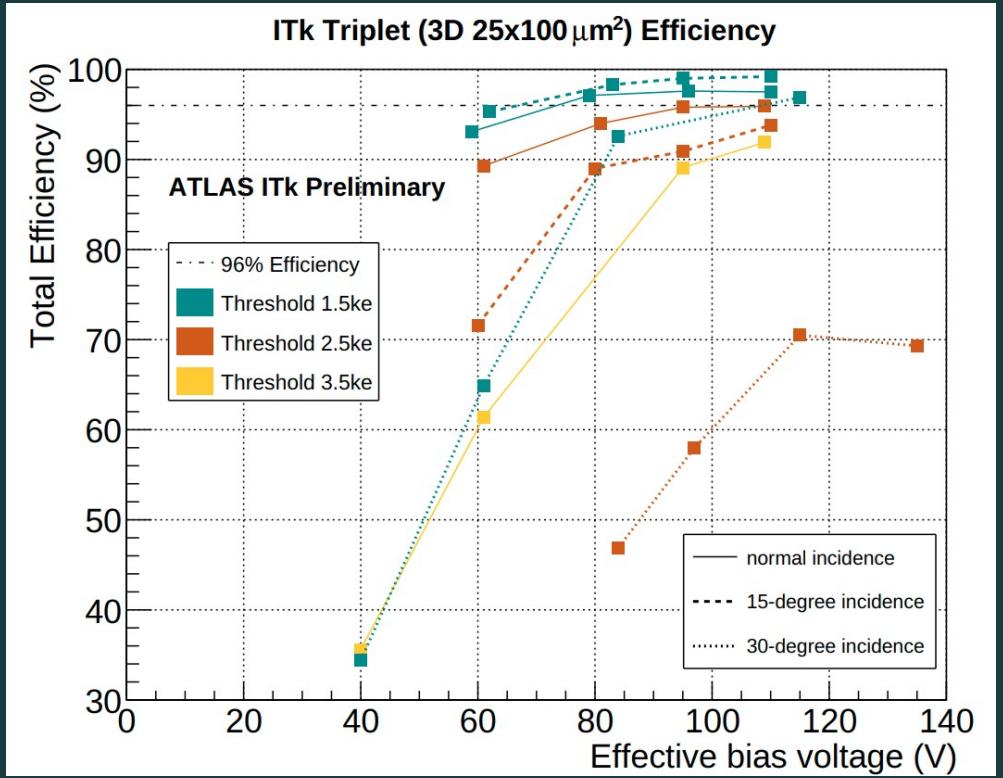


Path length in active region
= 150/Cos(15) = 155.3 μm

Max path length in one pixel
= 25/Sin(15) = 96.6 μm

In the worst scenario, path length in one pixel
= 155.3/2 = 77.6 μm



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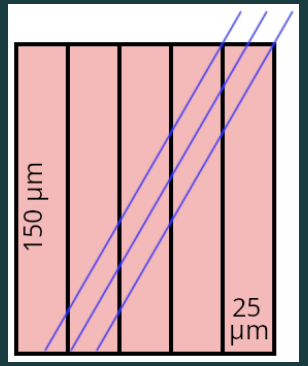
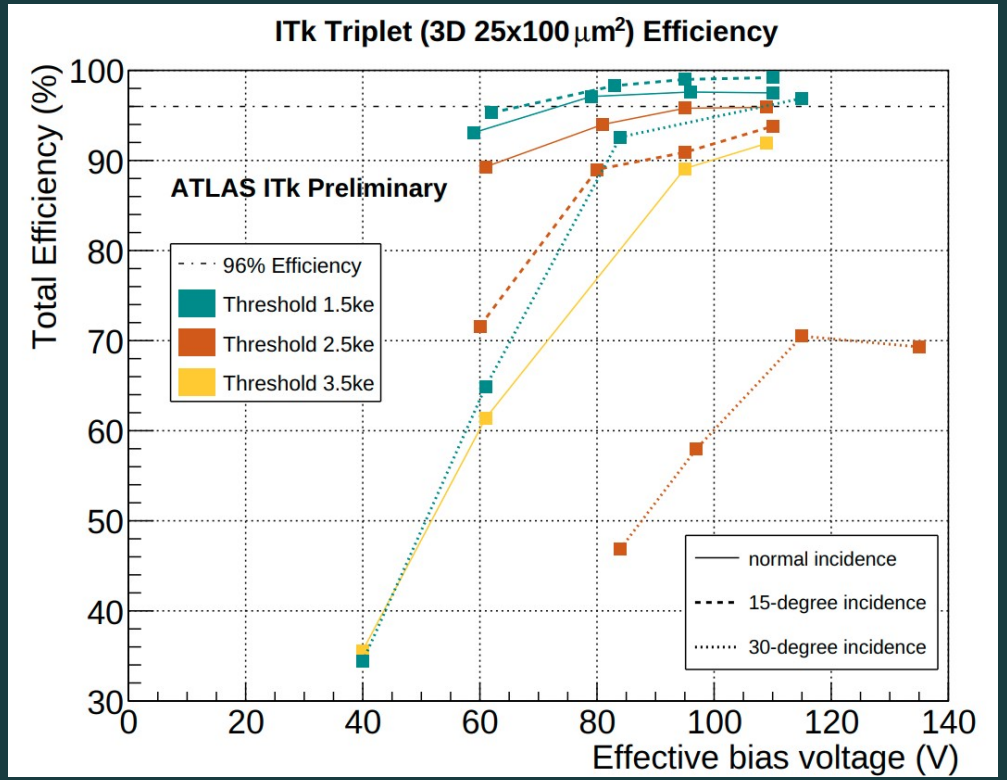


Path length in active region
= 150/Cos(30) = 173.2 μm

Max path length in one pixel
= 25/Sin(30) = 50.0 μm

We have always 2 or 3 pixels having the max path of length 50.0 μm

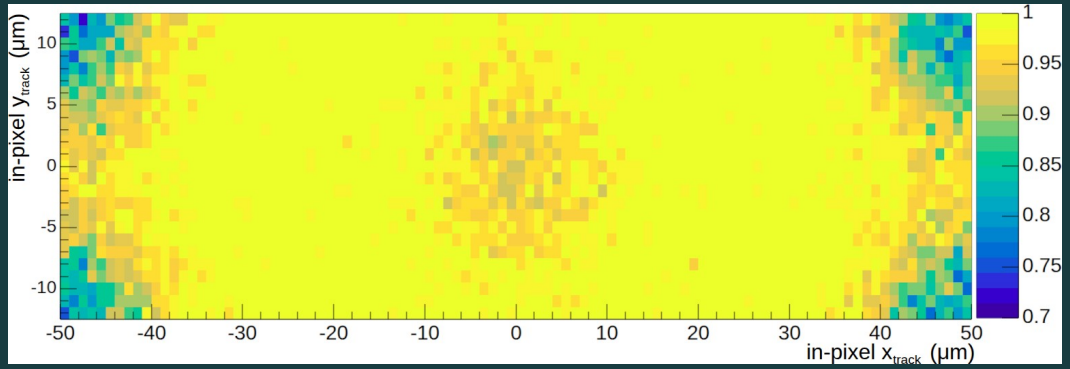


25x100 FBK-Leonardo Triplet irradiated to 1.1e16 n_{eq}/cm^2

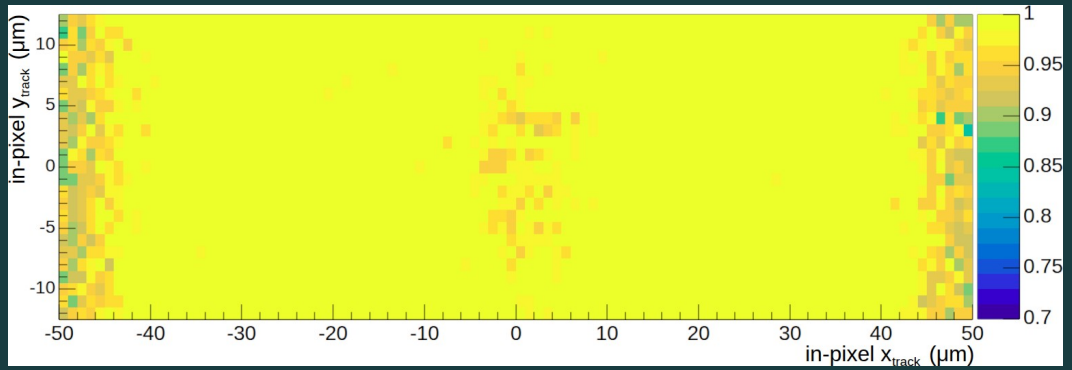
Performance of 25x100 Triplet

- Small angles: Efficiency improves at lower thresholds

Threshold: 1.5 ke
Effective Bias: 96 V
Normal Incidence
Efficiency : 97.5%



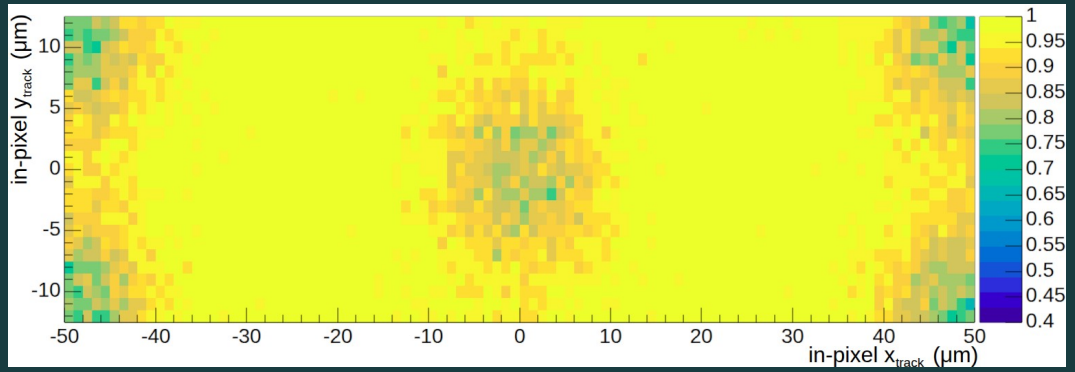
Threshold: 1.5 ke
Effective Bias: 95 V
15-degree Incidence
Efficiency : 99.0%



Performance of 25x100 Triplet

- Small angles: Efficiency worsens at higher thresholds

Threshold: 2.5 ke
Effective Bias: 95 V
Normal Incidence
Efficiency : 95.6%



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15-degree Incidence
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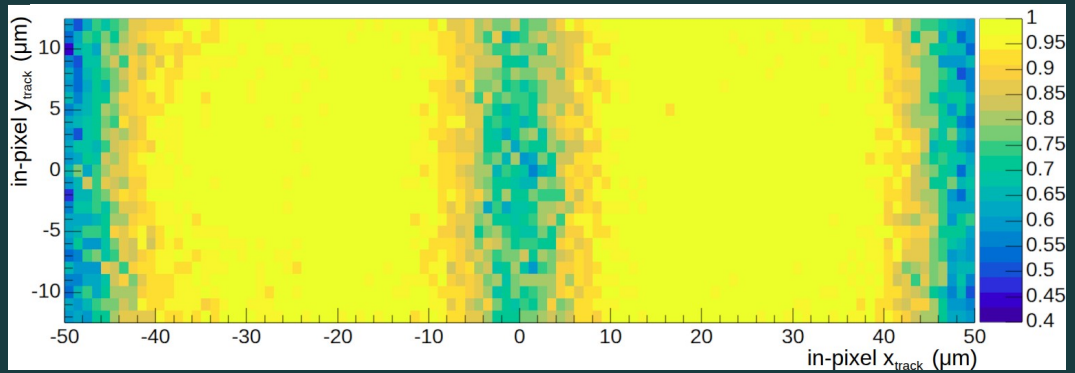
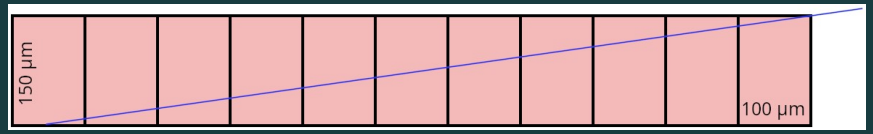


Performance of 25x100 Triplet

Large incident angle of ~82 degrees (in the plane of 100 μm) at the end of barrel

Performance of 25x100 Triplet

Large incident angle of ~82 degrees (in the plane of 100 μm) at the end of barrel



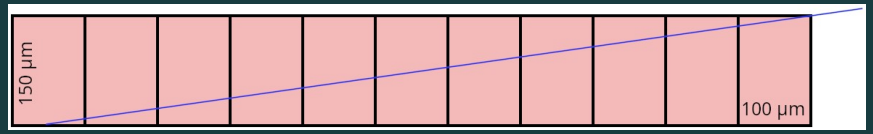
Path length in active region
= 150/Cos(82) = 1077.8 μm

Max path length in one pixel
= 100/Sin(82) = 101.0 μm

We have always many pixels having the max path of length 101.0 μm

Performance of 25x100 Triplet

Large incident angle of ~82 degrees (in the plane of 100 µm) at the end of barrel



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- The particle crossing 10 pixels increases efficiency considerably since detection can happen at any of these pixels

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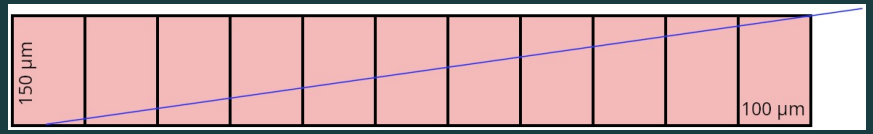

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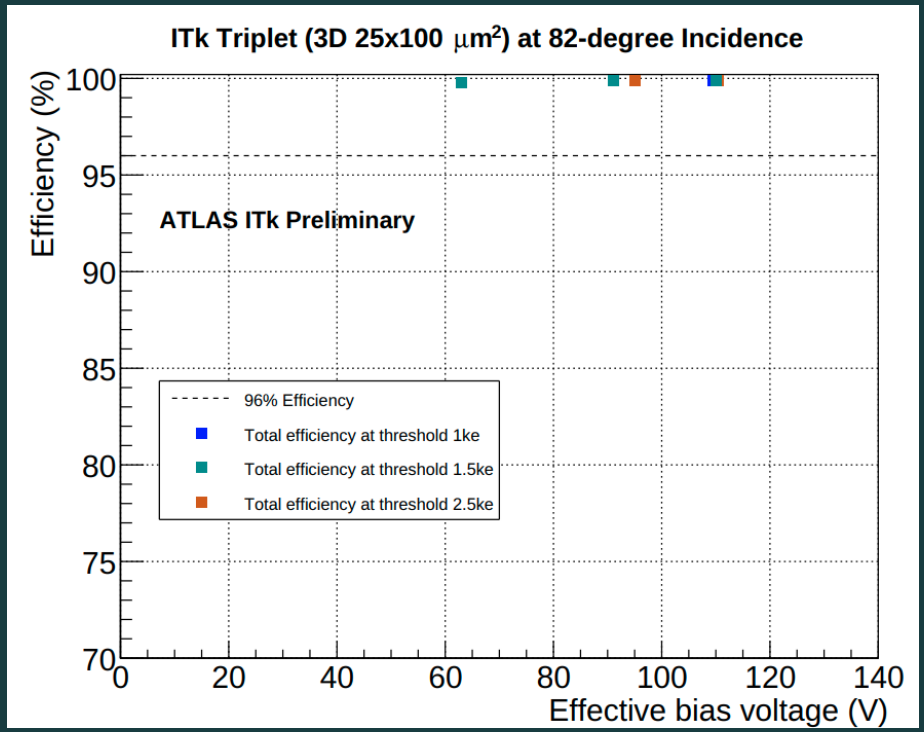
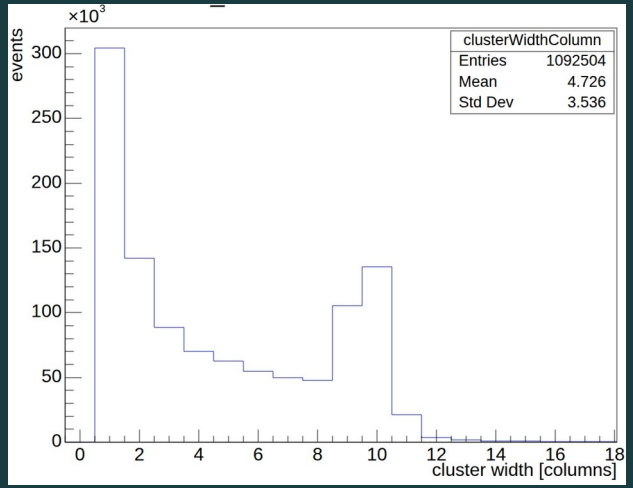
Near-100% efficiency irrespective of threshold and bias voltages

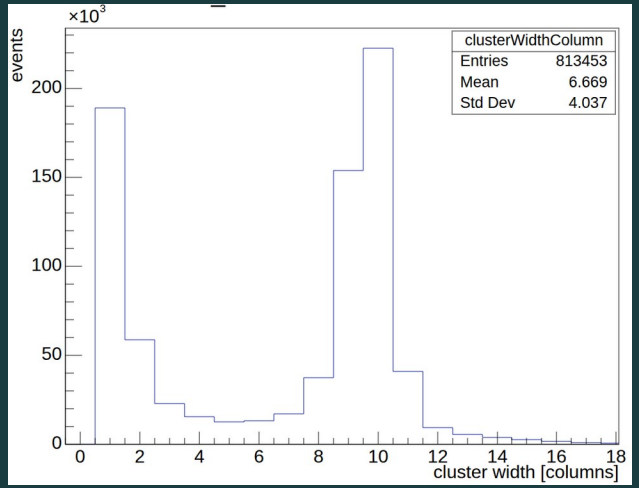


Performance of 25x100 Triplet

We can obtain single pixel efficiency by analysing cluster size.



Continuous clusters



Clusters when gaps are allowed

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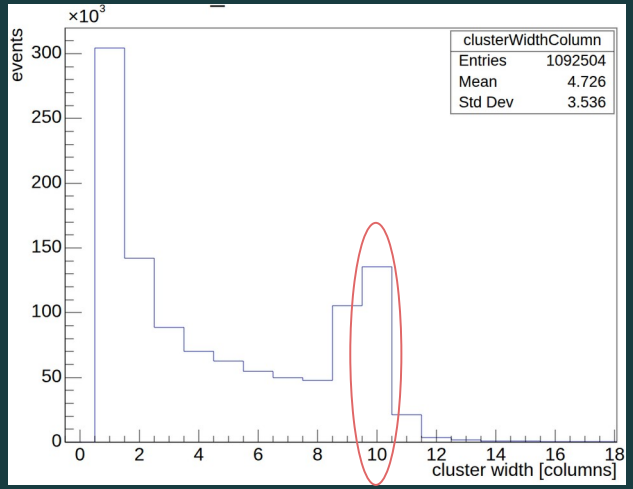

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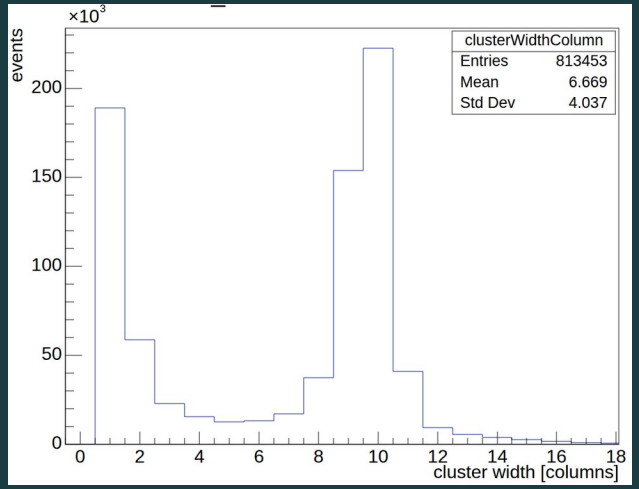

Clusters when gaps are allowed

Probability of obtaining a continuous 10-pixel cluster :

$$E^{10}$$

Performance of 25x100 Triplet

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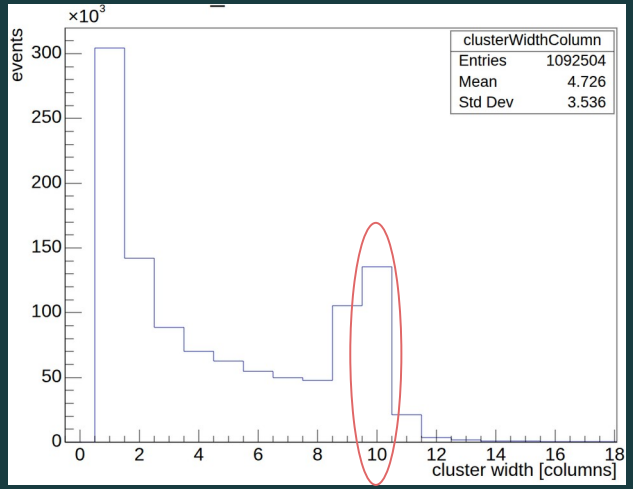

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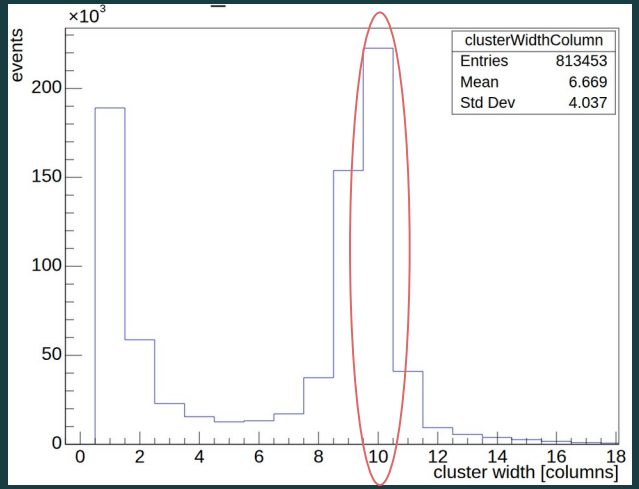


Clusters when gaps are allowed

Probability of obtaining a continuous 10-pixel cluster :

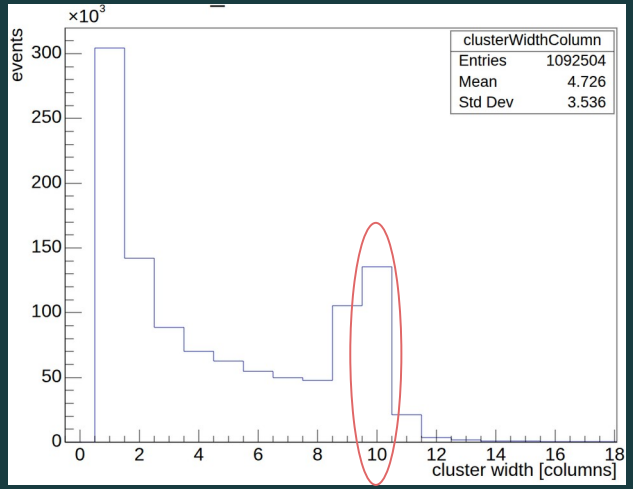
$$E^{10}$$

Probability of obtaining a 10-pixel cluster allowing gaps :

$$E^{10} + E^{9}(1-E)\,C_1^{8} + E^{8}(1-E)^{2}\,C_2^{8} + \ldots$$

Performance of 25x100 Triplet

We can obtain single pixel efficiency by analysing cluster size.



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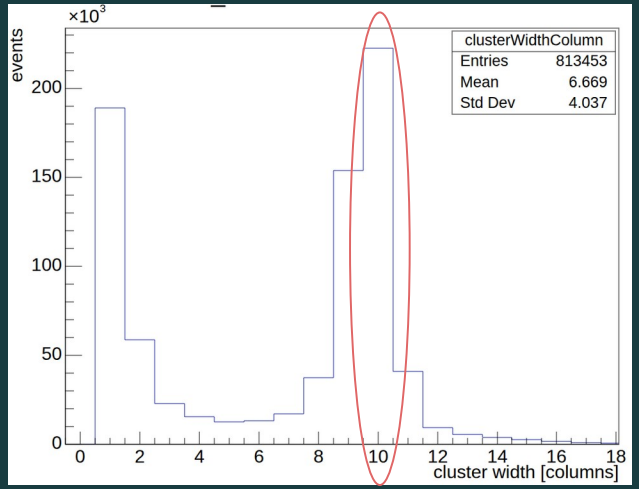


Clusters when gaps are allowed

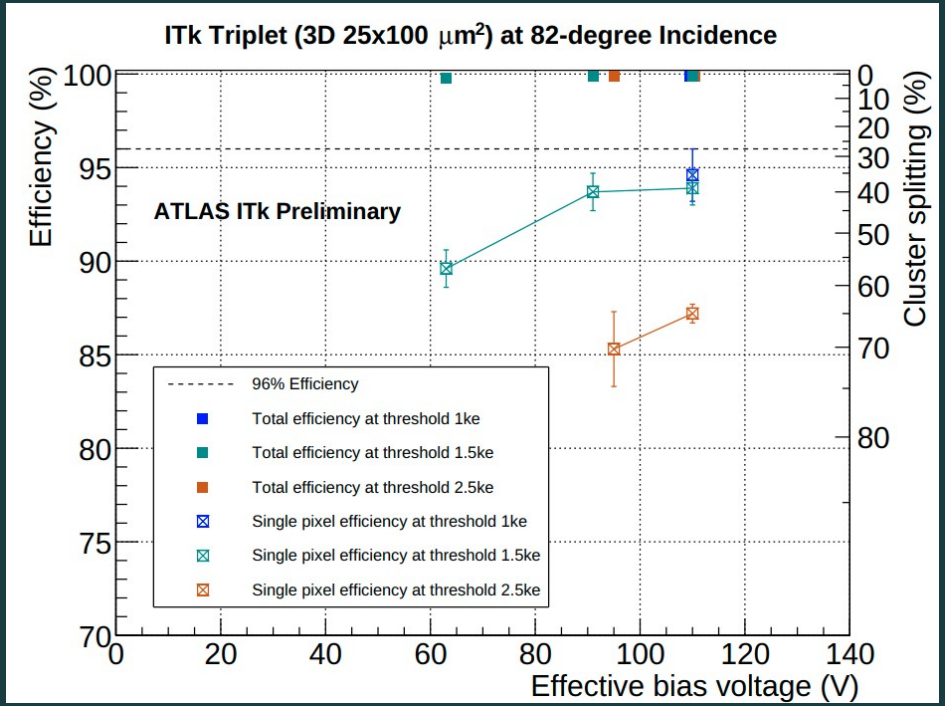
Ratio of the number of continuous 10-pixel clusters to the number of 10-pixel clusters allowing gaps :

$$E^{10}/(E^{10} + E^{9}(1-E)\,C_1^{\,8} + E^{8}(1-E)^2\,C_2^{\,8} + \dots)$$

Performance of 25x100 Triplet

Ratio
$= E^{10}/(E^{10} + E^{9}(1-E)\, C_1^{8} + E^{8}(1-E)^2\, C_2^{8} + \dots)$

- Single pixel Efficiency calculated by solving for E



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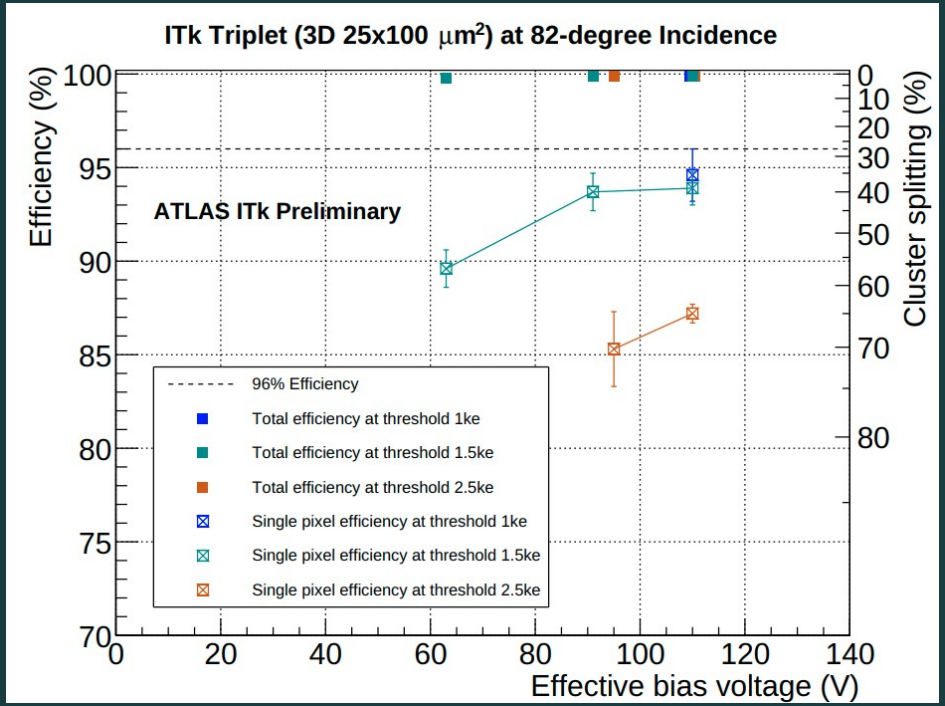
- With this technique, we can calculate efficiency without the need of tracking



Performance of 25x100 Triplet

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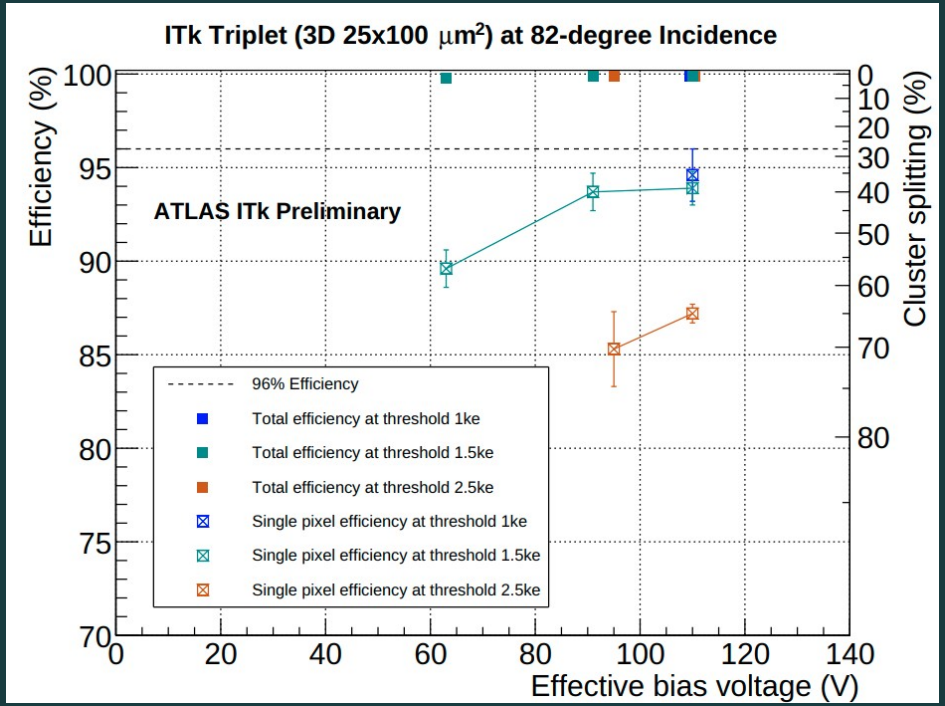
- Single pixel Efficiency calculated by solving for E
- With this technique, we can calculate efficiency without the need of tracking
- Cluster splitting (1-Ratio) gives the fraction of broken clusters obtained from a single incident particle. Relevant for the analysis of pile-up.

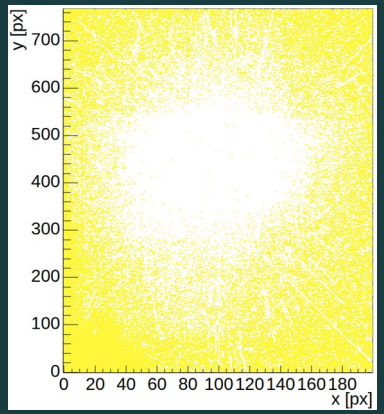


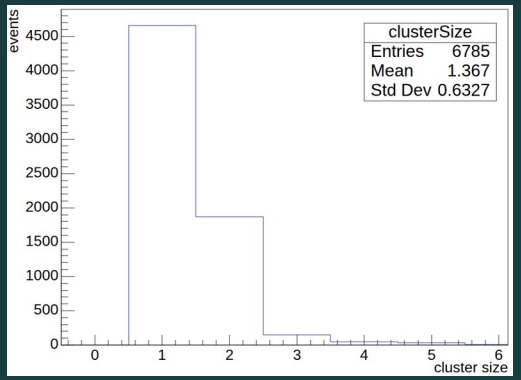
Summary

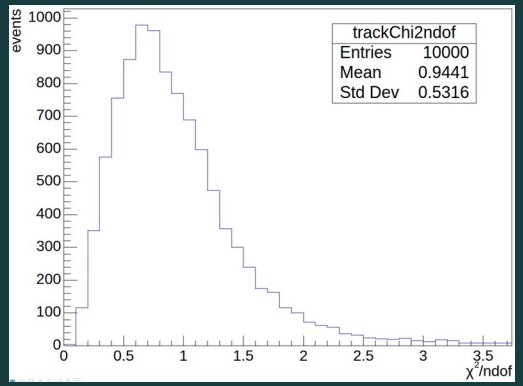
- Triplet detector modules with silicon 3D technology having 50 μm X 50 μm and 25 μm X 100 μm pixel pitches are planned to be installed in Layer 0 of ATLAS ITk.
- Preproduction triplet modules were tested under 120 GeV pions at SPS, CERN. Their efficiency was obtained using reconstruction software Corryvreckan.
- The tested modules included those irradiated to fluences comparable to the expected maximum end-of-lifetime fluence for Layer 0 of ITk.
- The dependence of efficiency on threshold, bias voltage and incident angle was studied.
- Modules achieved the target efficiency of 96% in several realistic scenarios

Backup slides

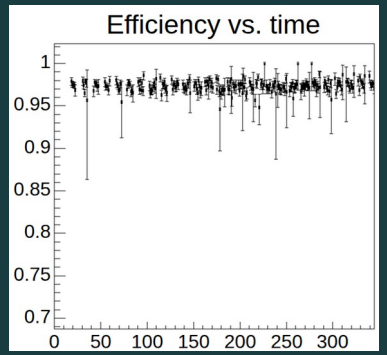
Reconstruction using Corryvreckan

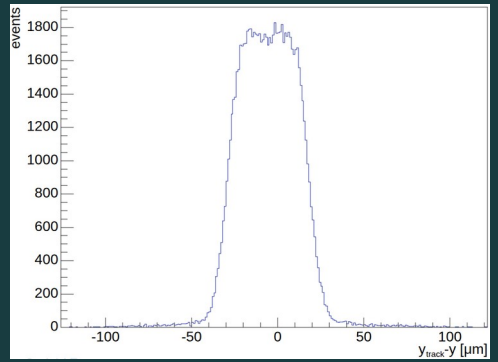




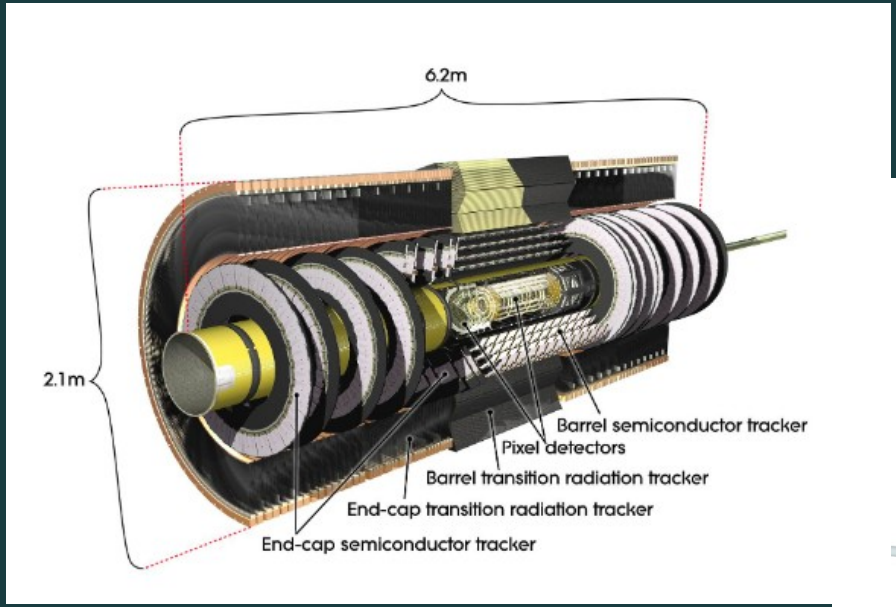


- Mask is created to identify noisy and dead pixels
- Clusters and tracks are identified
- Telescope planes (Mimosa detectors) are aligned
- DUTS (ITk triplet detectors) are aligned
- Efficiency is determined

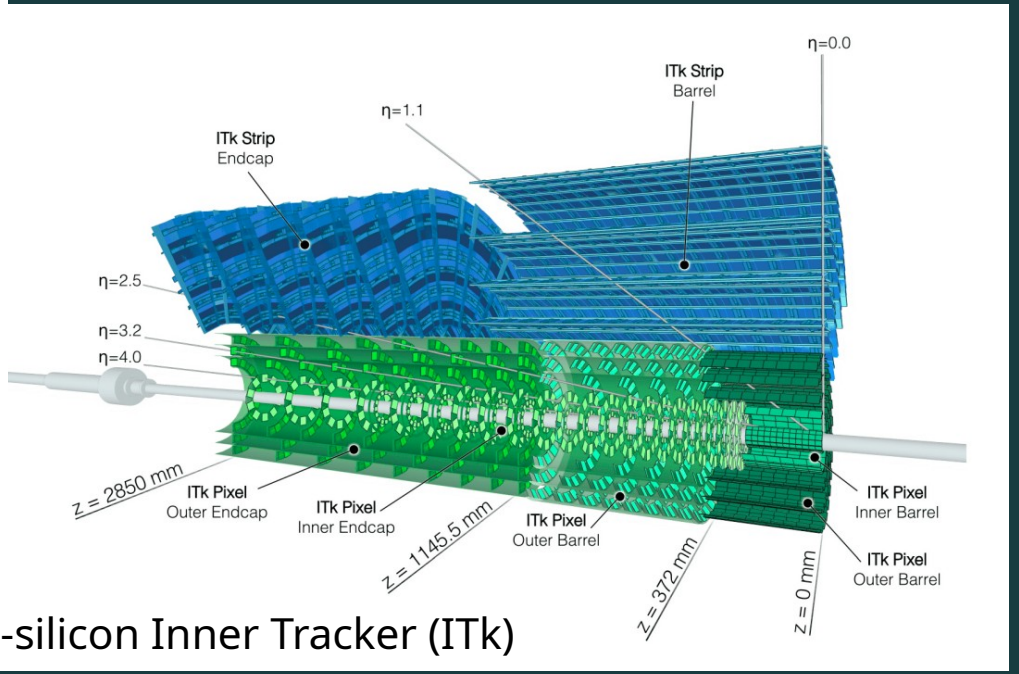




ATLAS High Luminosity upgrade

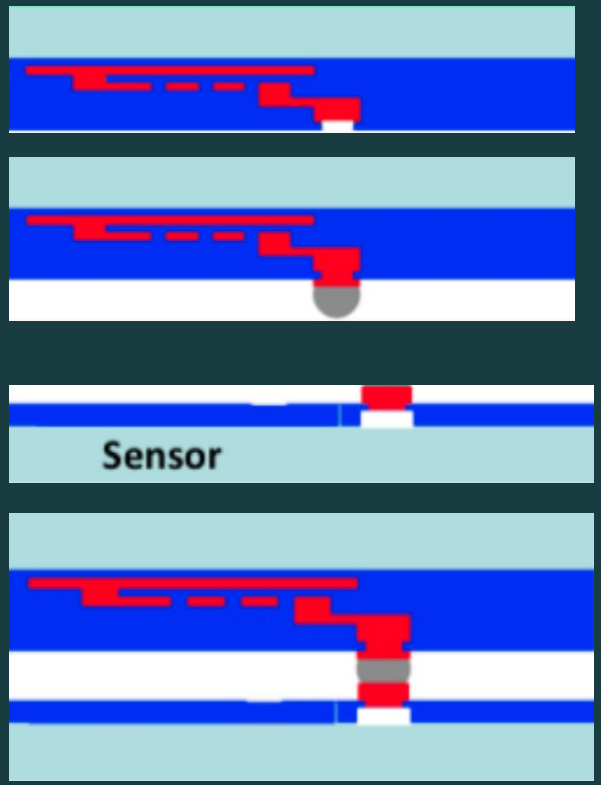


Pile-up of up to 200 expected in HL-LHC

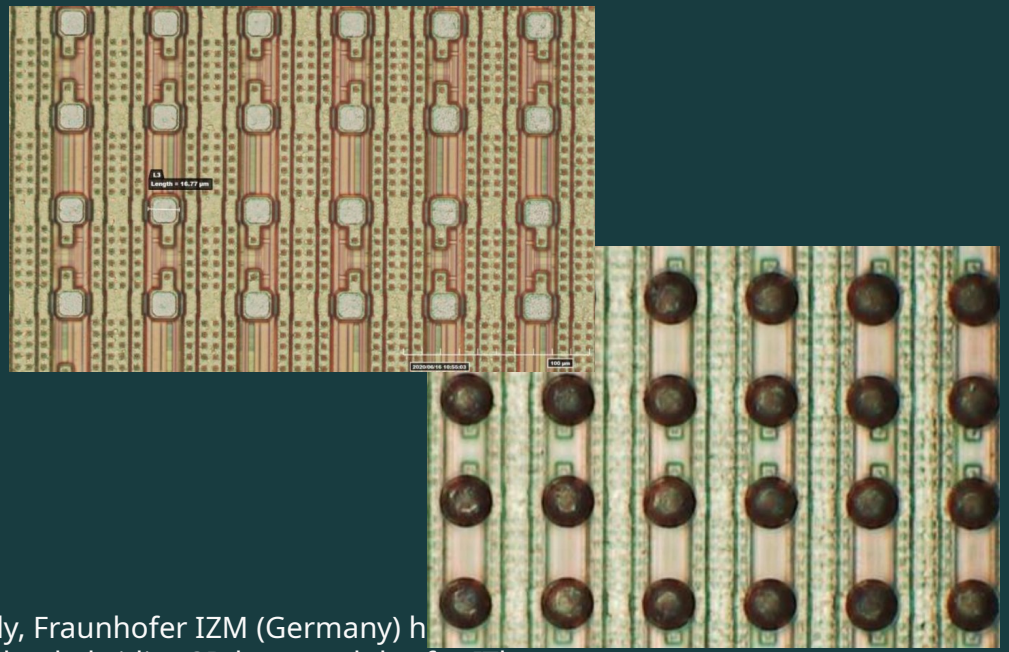


Inner detector to be replaced by all-silicon Inner Tracker (ITk)

Hybridization



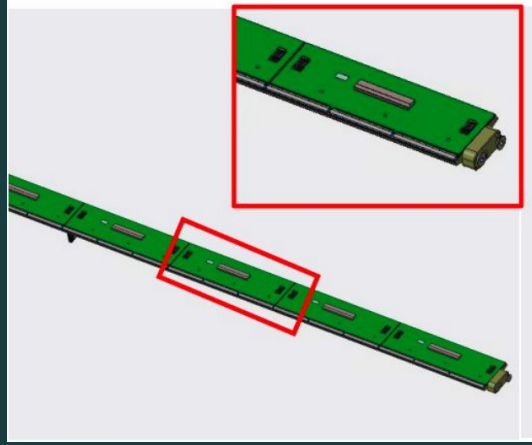
The ITkPix chip is bump bonded (flip chipping) to the sensor



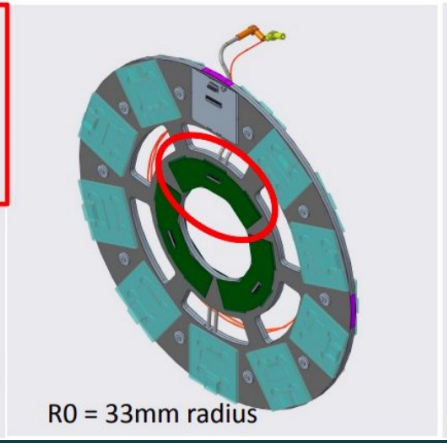
Currently, Fraunhofer IZM (Germany) h
qualified to hybridize 3D baremodules for ITk

Numbers to be built

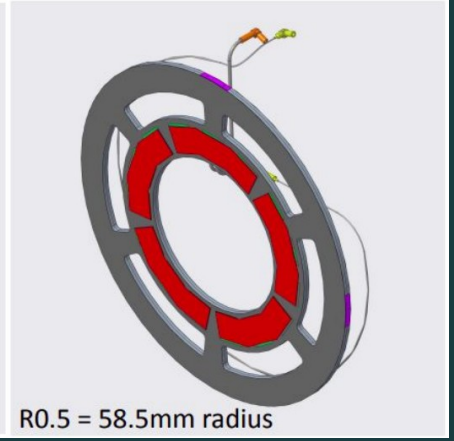
Linear Triplet (L0):
12 L0 staves x8 triplets = **96**



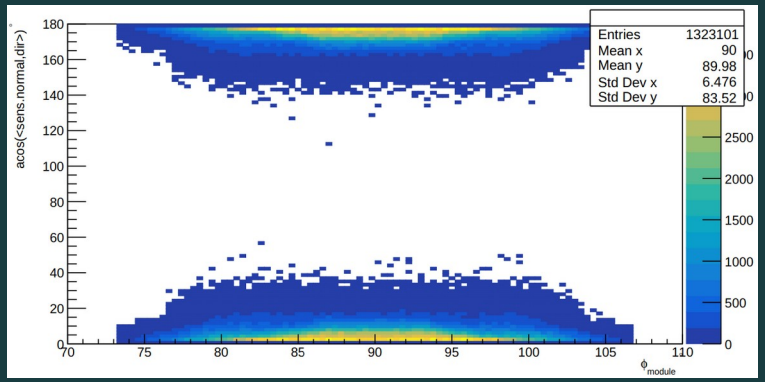
Coupled-ring Triplet (R0):
30 rings x6 triplets = **180**



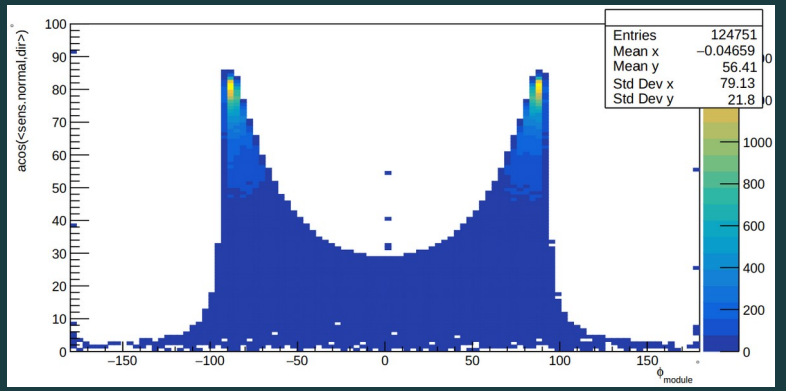
Intermediate-ring Triplet (R0.5):
12 rings x10 triplets = **120**



Simulation of incident angles



Source : Goetz Gaycken



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Loading at SLAC