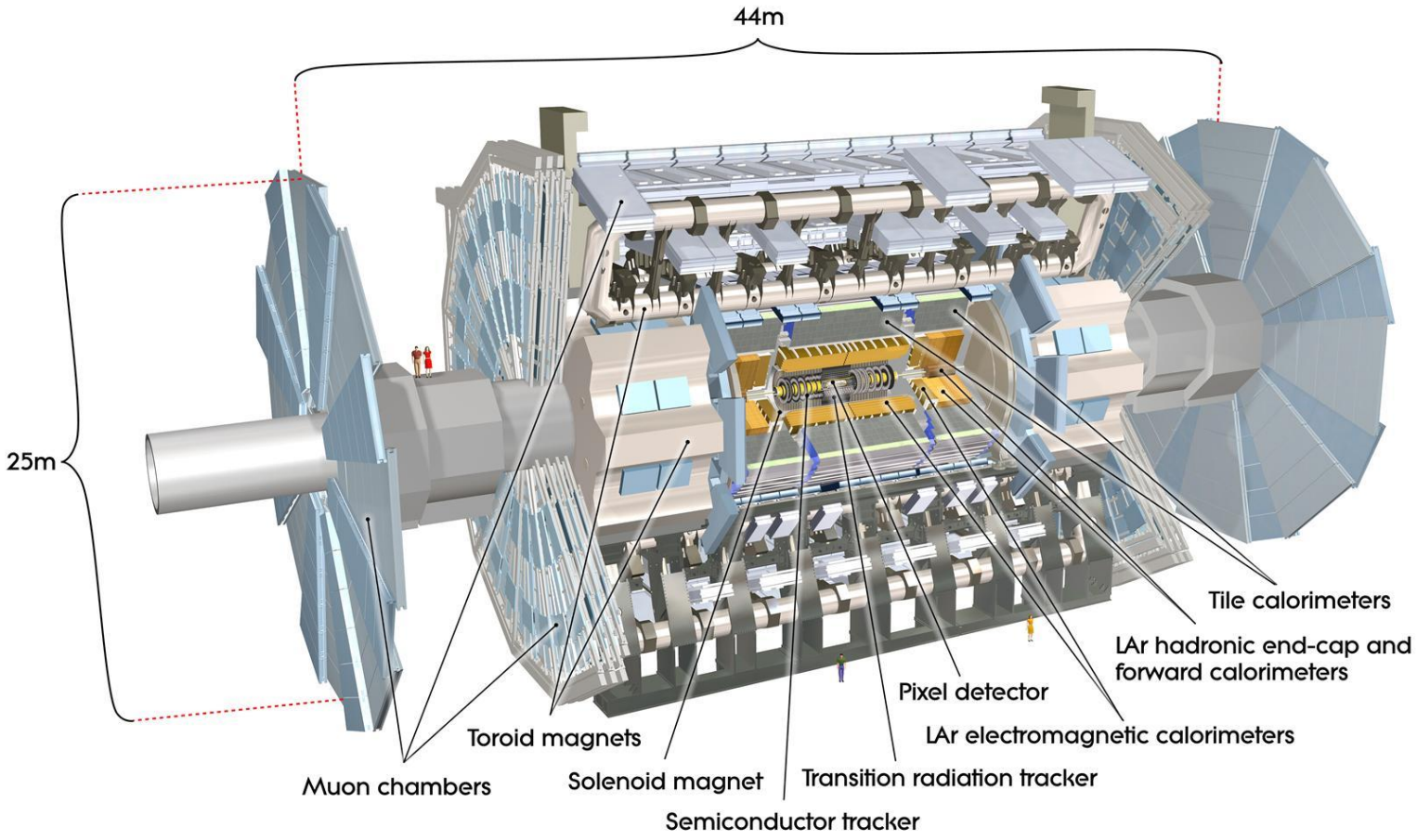
Test beam characterization of pixel modules for the ATLAS Inner Tracker Upgrade (ITk)

Dmytro Hohov on behalf of the ATLAS ITk pixel test beam collaboration

OAC, Kolymbari, Crete, Greece – **XIV ICNFP 2025** – July 17-31

Outline

- ATLAS Inner Tracker (ITk) upgrade
  - Motivation
  - Silicon pixel detector technologies
  - Layout. Modules.
- Test Beam experiment
- Test Beam results on planar sensors
- Test Beam results on 3D sensors
- Summary



ATL-TILECAL-PROC-2013-002

Motivation for the tracker upgrade

- Increased **instantaneous luminosity** up to $7.5 \times 10^{34}\ cm^{-2}s^{-1}$

  integrated luminosity will reach **4000 fb^{-1}**

  - approx. 200 simultaneous inelastic ***p-p*** collisions per bunch crossing , increase of overlap of events. → **High detector occupancy**

  - High particle densities and rate → **Radiation dose 2 x 10^{16} n_{eq}/cm^2**

Keep the same or better tracking performance → The Inner Detector **ID** will be replaced by **all-silicon tracker** Inner Tracker **ITk**.

Average pile-up events

13,4 – (2015)

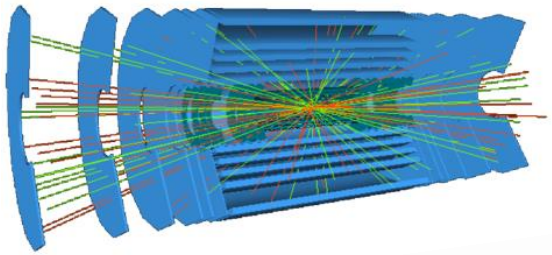
25,1 – (2016)

37,8 – (2017)

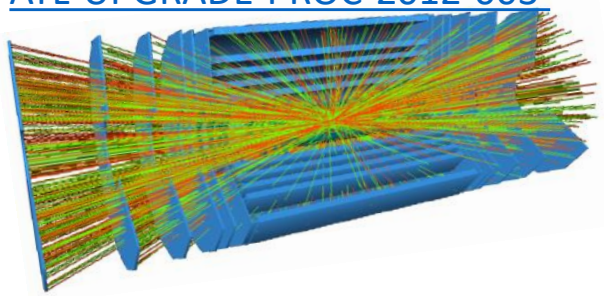
36,1 – (2018)

50-60 – (2022-2025)

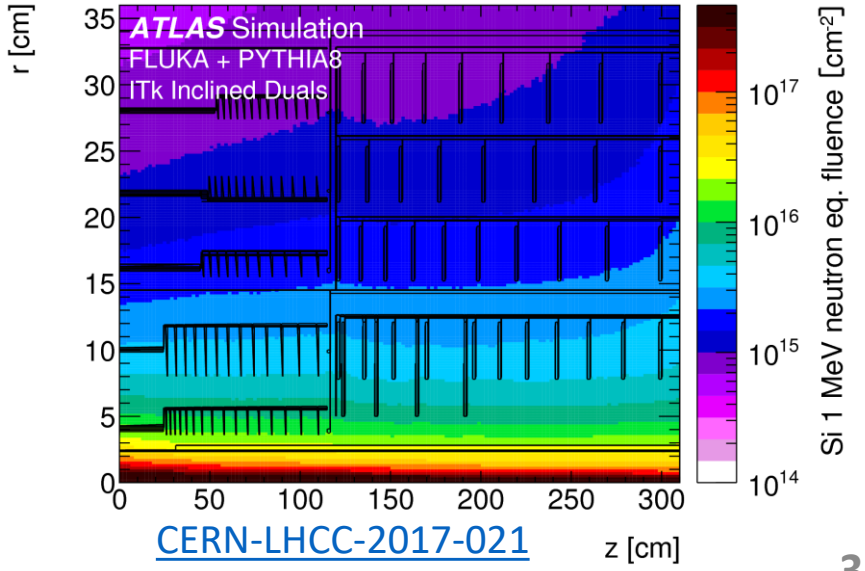
~200 – (2030)



ATL-UPGRADE-PROC-2012-003



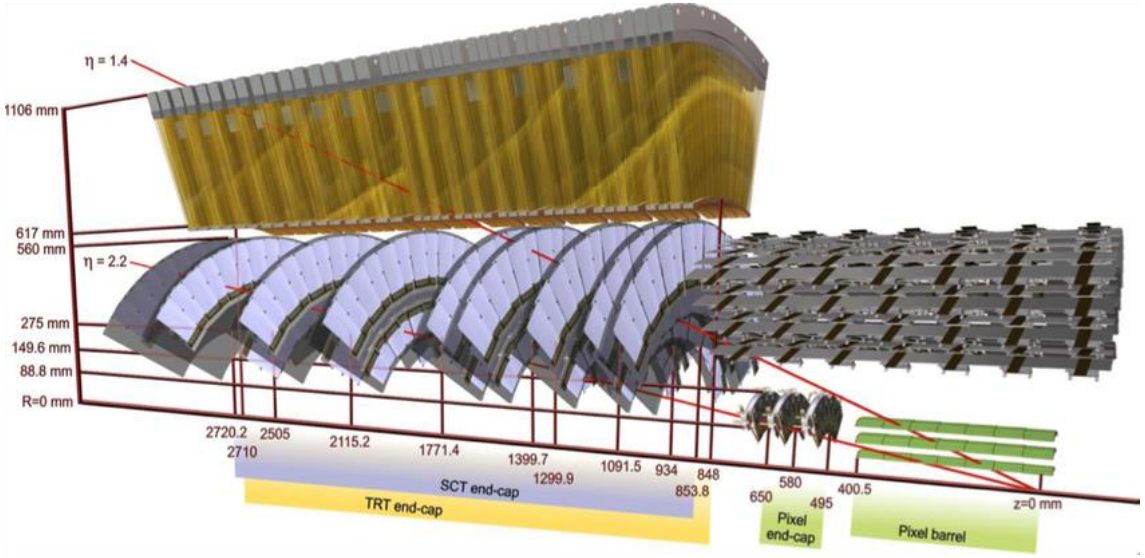
Radiation fluence



CERN-LHCC-2017-021

Inner Detector -> Inner Tracker

ID is an innermost detector, 6.2 m long and 1.2 m in radius.
Composed of **TRT, SCT and Pixel Detector**



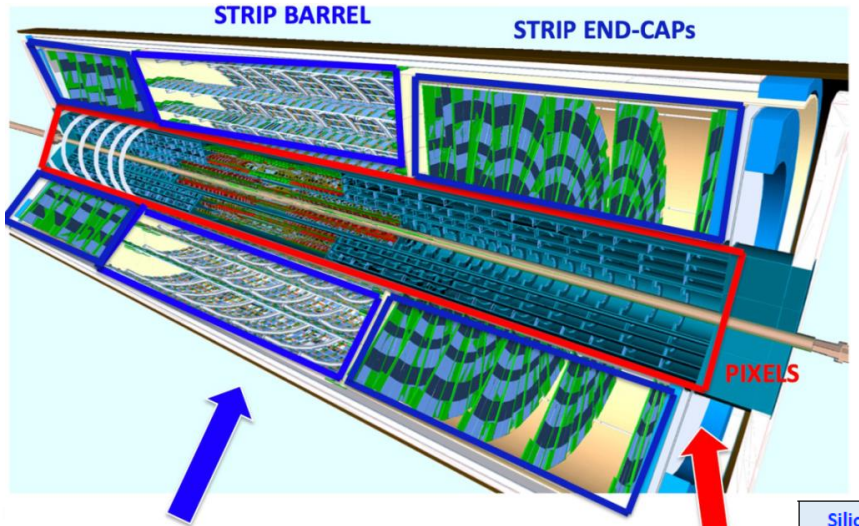
The ATLAS Collaboration *et al* 2008 *JINST* **3** S08003

Pixel Detector:

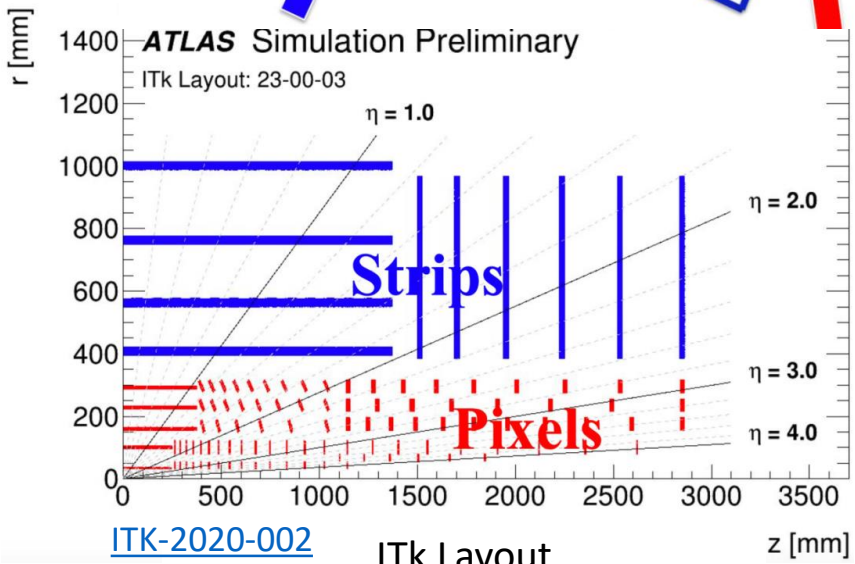
composed of 4 barrel Layers (IBL, B-Layer, L1, L2) 3 disks in two end caps, 2 m^2 of active area, $|\eta|<2.5$

92 millions of pixels, 200 (250) µm thick, pitch 50 x 250 (400) µm^2

Inner Tracker (ITk)



CERN-LHCC-2017-005



ITK-2020-002

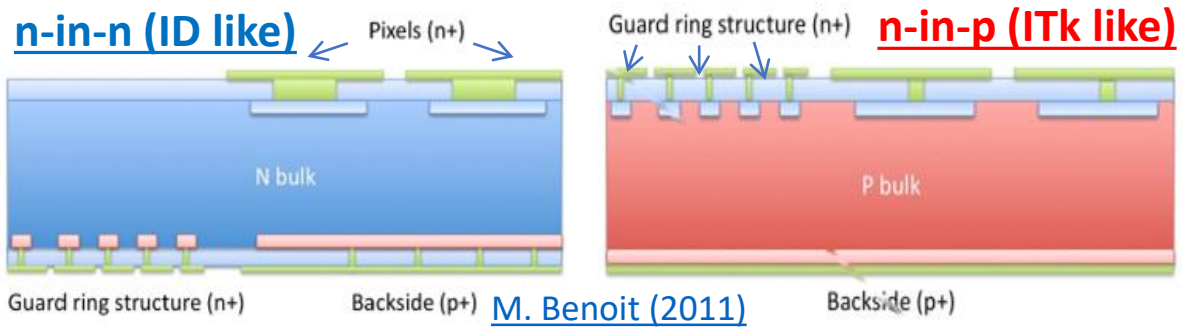
ITk Layout

Silicon Strips
Outer layers
165 m^2
17 888 modules
60 Million channels
Silicon Pixels
Inner layers
13 m^2
8372 modules
5 Billion channels

$|\eta|<4$
50x50 µm^2
25x100 µm^2

Silicon pixel detector technologies

- **Planar sensors**: highly doped implant on top of low-doped Si bulk **n-in-n** (ID), **n-in-p** (ITk)
  - ✓ Simpler production process than 3D
- **3D sensors**: highly doped Si columns (p^+ and n^+) implanted vertically through low-doped Si bulk
  - ✓ Higher electric field for the same applied voltage → low depletion voltage
  - ✓ Smaller drift time → fast response
  - ✓ Smaller drift distance (e-h path length) → less trapping probability → improved radiation hardness

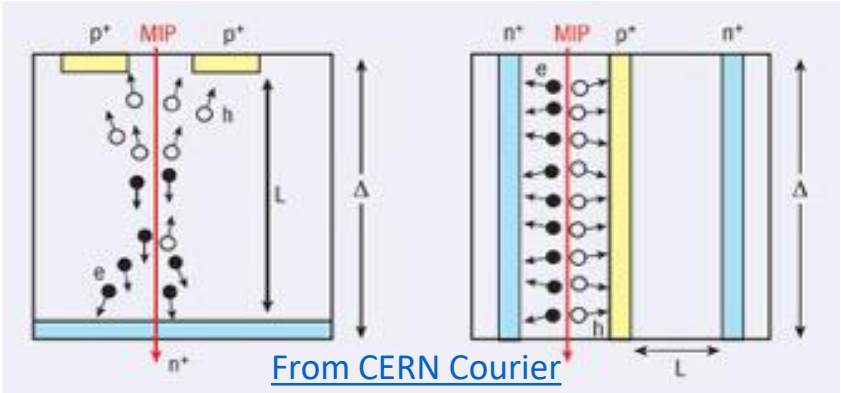


M. Benoit (2011)

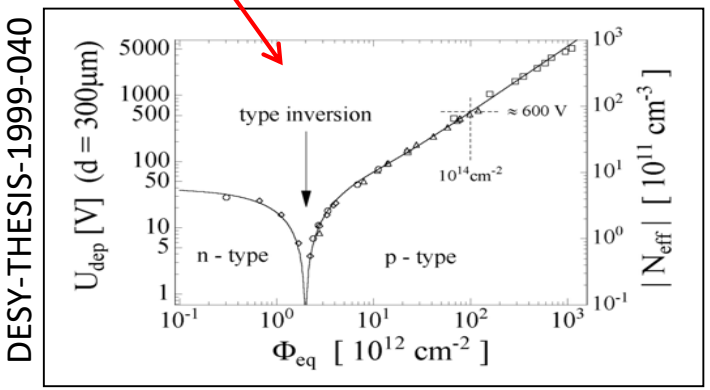
- Collect electrons
- Guard rings are not on a front side
- Double-sided processing
- Type inversion of a bulk

- Collect electrons (3 times faster than holes)
- No type inversion
- Can be operated partially depleted
- Single–sided processing
- Guard rings are on a front-end side

Planar **3D**



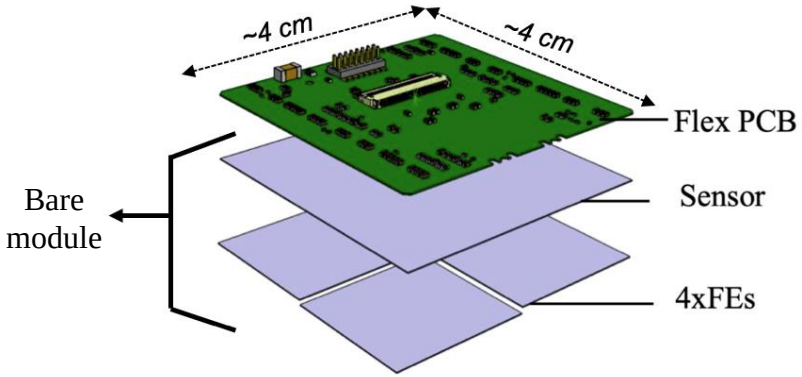
From CERN Courier



Space charge sign inversion (**SCSI**) NIM A426 (1999)

Hybrid Pixel Modules

Hybrid detector: FE readout chip connected to the sensor by bump-bonds

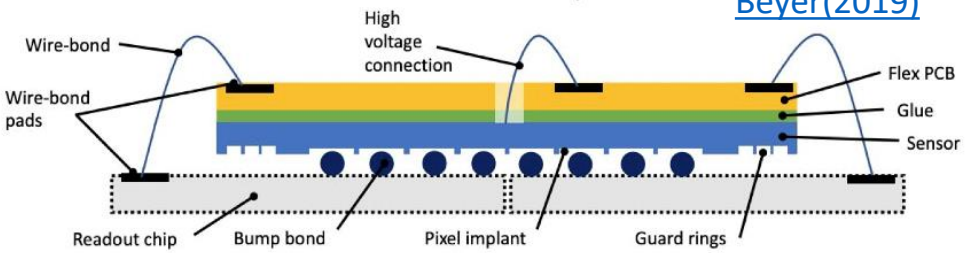


NIM A 1067

Quad module

Quad module cross-section

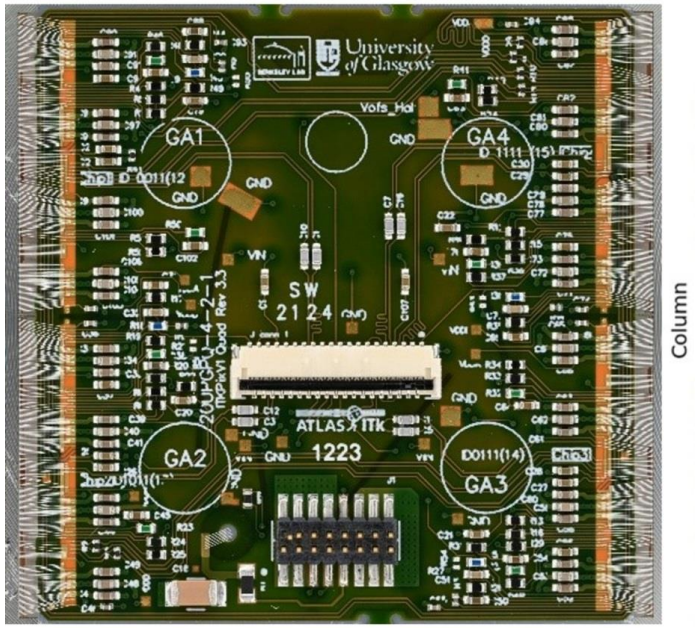
Beyer(2019)



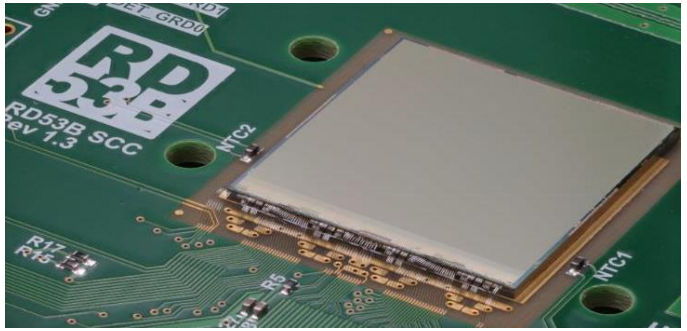
- Flexible printed circuit (Flex) for connections to LV, HV, DCS, data
- FE chip wire-bonded to the Flex

Modules:

- Triplet module: 3 (2x2 cm^2) sensors, each one with a FE chip
- Quad module: 4 FE chips attached to 1 (4x4 cm^2) sensor



Column



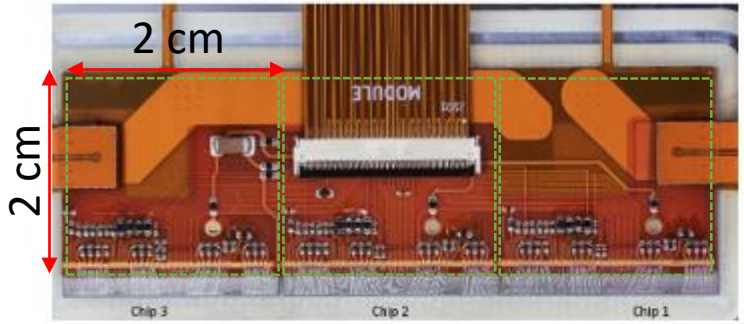
ATLAS-PHOTO-2021-045-1

Single Chip Card (**SCC**) – single FE flip-chipped to a sensor, mounted on the dedicated PCB. Not for ITk, mostly for R&D.

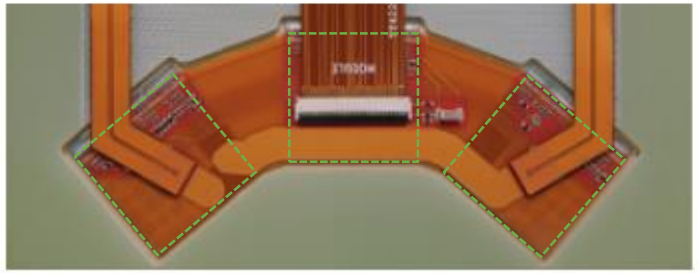
ITk Pixel Modules

Two types of modules in ITk:

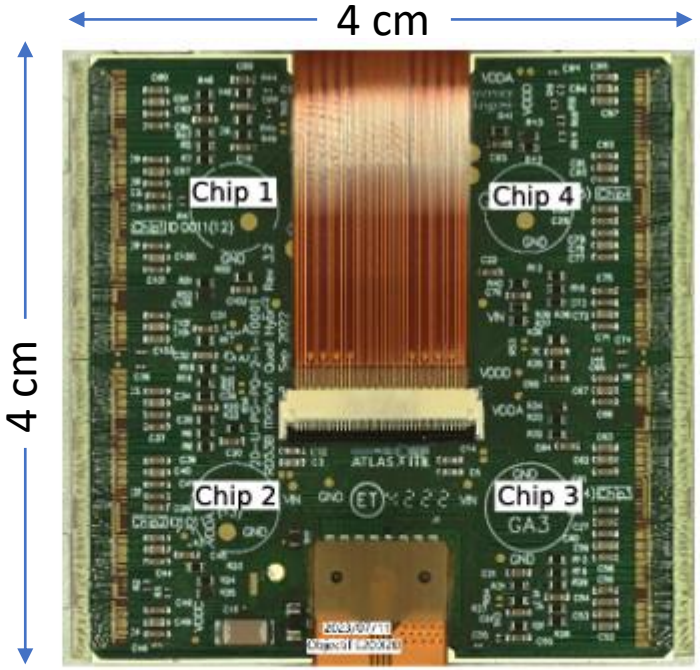
- **Quad** modules: quad bare module (4 FEs bump bonded to one sensor) + a flexible PCB
- **Triplet** modules 3 single FE bare modules connected to the same flexible PCB



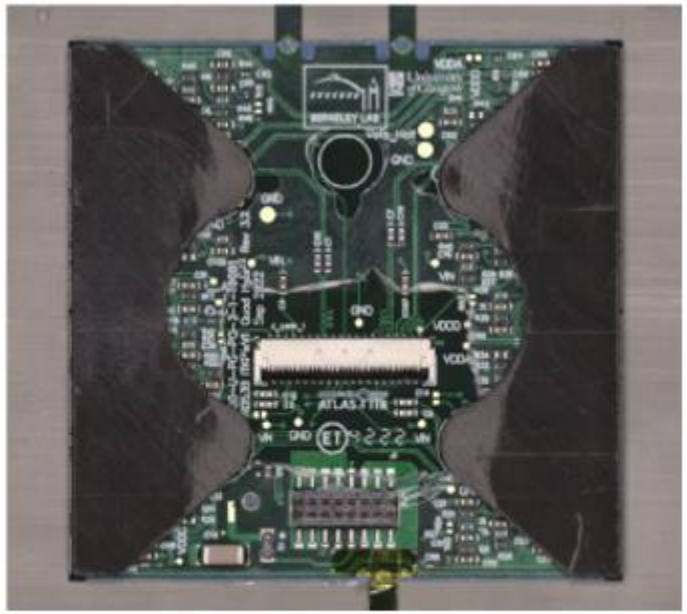
a) 3D triplet for the Inner System barrel stave



b) 3D triplet for the Inner System endcap ring



c) Inner System and Outer Endcaps quad module with data and power pigtails connected



d) Outer Barrel quad module with carbon fibre wire bond protection

ATL-ITK-PROC-2024-038

ITk Pixel Detector layout

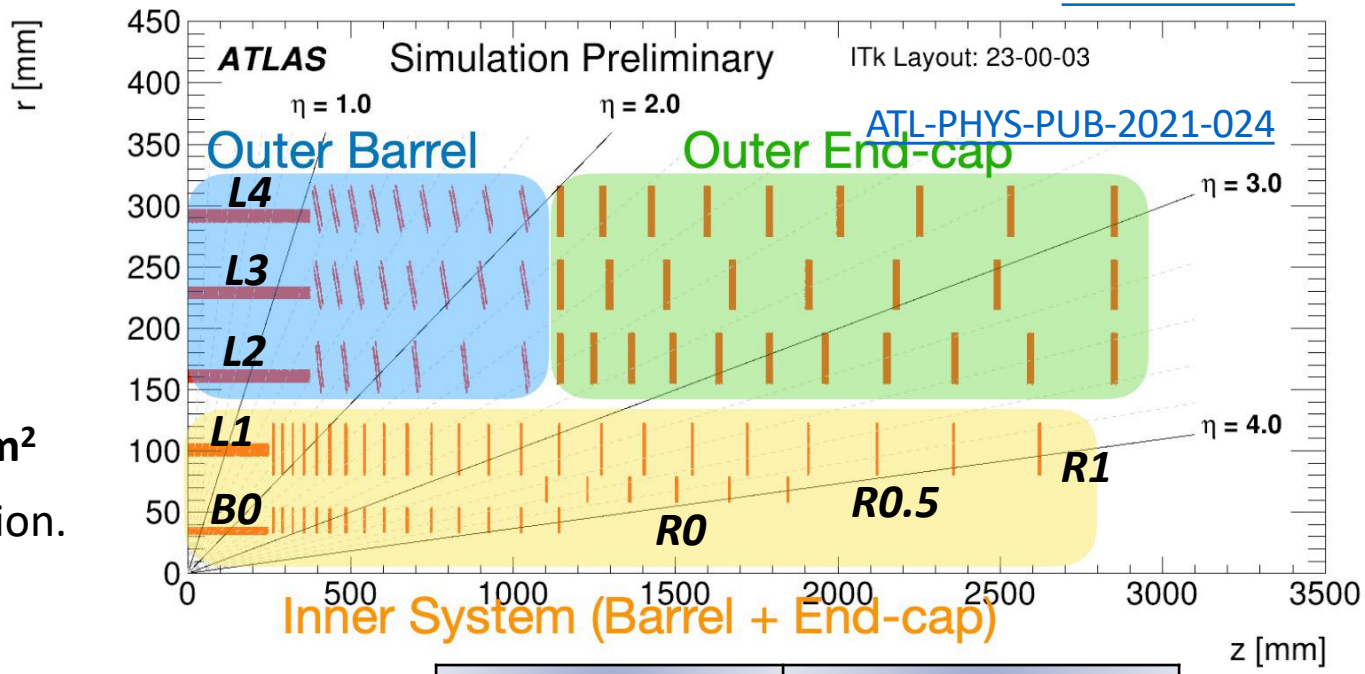
The ITk Pixel detector sensor technologies:

- *L2, L3, L4* - **Planar** n-in-p sensors (150 µm)
- *L1, R1* - **Planar** n-in-p sensors (100 µm)
- *L0* : barrel layer (*B0*) + ring layers (*R0, R0.5*) - **3D** n-in-p sensors 250 µm (150 active + 100 support)

Pixel pitch **50 x 50 µm²** in all layers, only in *B0* – **25 x 100 µm²** to improve the resolution of tracks in transverse (d0) direction.

ITk Pixel Layout

ATLAS-TDR-030



ATL-PHYS-PUB-2021-024

Inner System (*L0, L1*) - will be replaced after 2000 fb^{-1} :

- 396 3D **triplet modules** in *L0*;
- 1160 planar **quad modules** in *L1*.

Outer system (*L2, L3, L4*) :

- Outer Barrel (3 layers) : 4472 **quad modules**;
- Outer Endcap (3 ring layers) : 2344 **quad modules.**

Type	Manufacturer
planar 100 µm thick	MICRON (UK), FBK (IT)
planar 150 µm thick	MICRON (UK), HPK (JP)
3D 50x50 µm² cell	FBK (IT), SINTEF (NO)
3D 25x100 µm²cell	FBK (IT)

Hit efficiency evaluation

The sensors are required to withstand extreme radiation doses and to maintain average **hit efficiency (ε)** above 96 - 97% after a lifetime of operation of the ITk at the HL-LHC.

Hit efficiency : $\varepsilon = \frac{\text{Number of tracks with associated cluster on DUT}}{\text{Total Number of tracks intersecting DUT}}$

Modules tested so far meet ITk requirements :

- ✓ Non-irradiated : ε > 98%
- ✓ Irradiated modules :
  - 3D sensors: ε > 96% (97%) efficiency for normal (tilted 15°) incidence
  - Planar: ε > 97% efficiency at max - 400 V (- 600 V) for 100 µm (150 µm) thick sensors

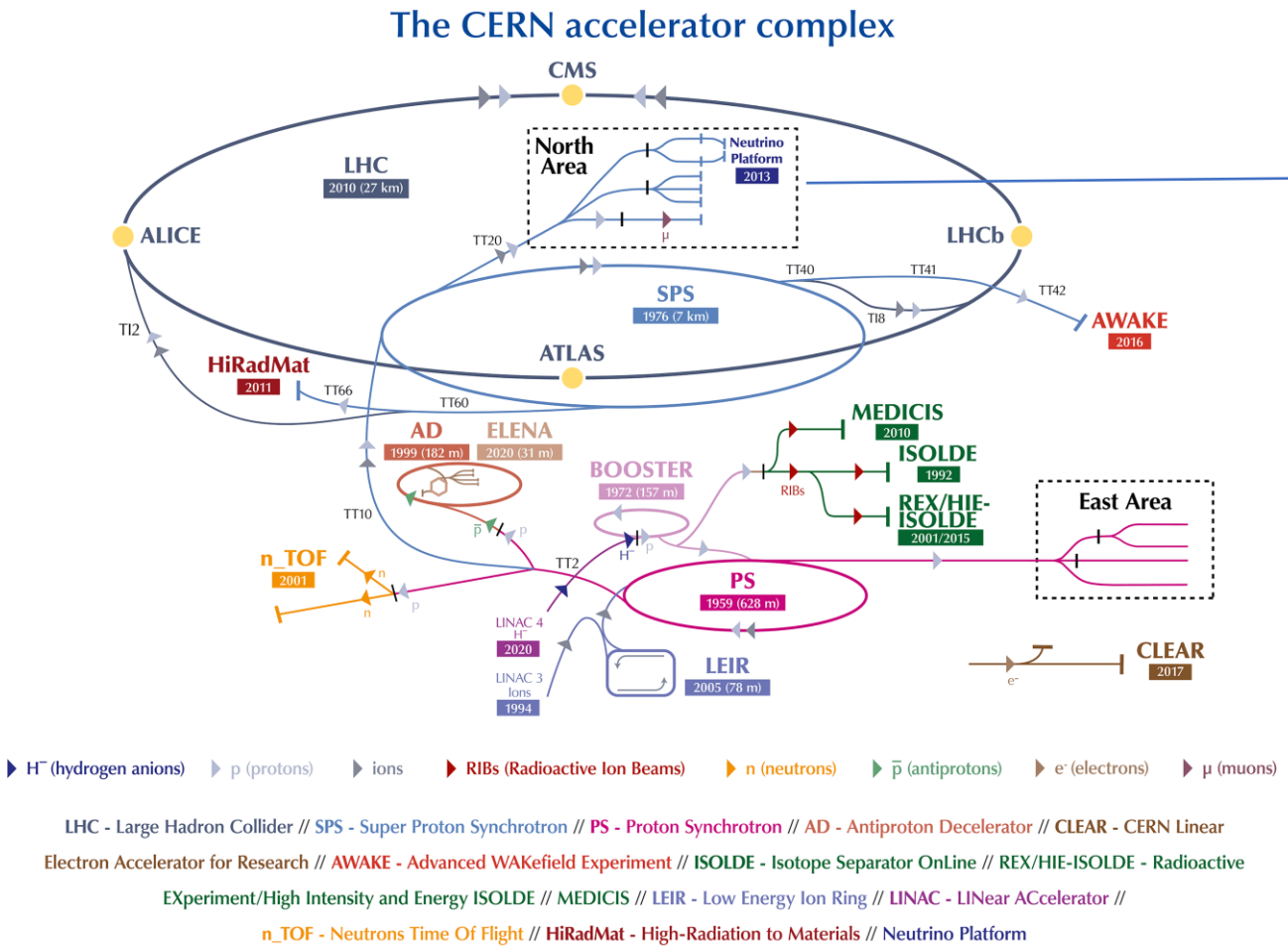
To evaluate the hit efficiency the high energy beams are used (Test Beam).

Test beam campaigns were carried out at CERN SPS beam facilities in 2024-2025. Overview of the recent test beam results on planar modules (HPK, FBK) and 3D pre-production triplets (FBK, SINTEF), with a focus on irradiated 3D SINTEF SCCs.

The Corryvreckan software framework is used for the track reconstruction and analysis of the test beam data.

- A matching radius of 100 µm used for the track reconstruction and the cluster association of the DUTs.
- The calculation of the efficiency does not use tracks through pixels that are masked or disabled, or close to masked/disabled pixels (3x3 square), hence is valid for pixels with working electronics.

Test beam facilities



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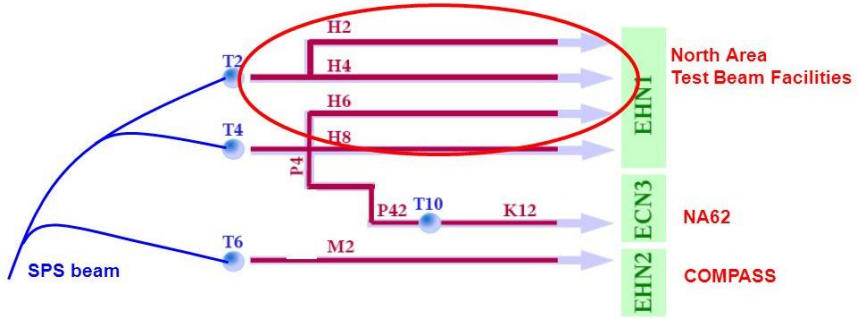
North Area



E. Gschwendtner, CERN

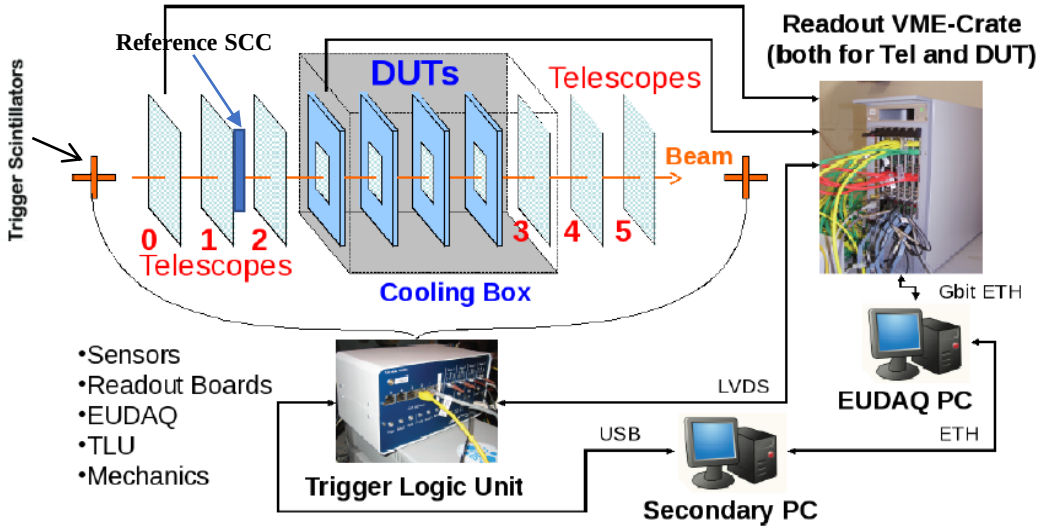
B-887, Prevessin site

- Maximum momenta: ≤ 360 GeV/c (secondary beam) or primary beams
- Particle type: primary protons or pure electrons, or pure/mixed hadrons, or pure muons

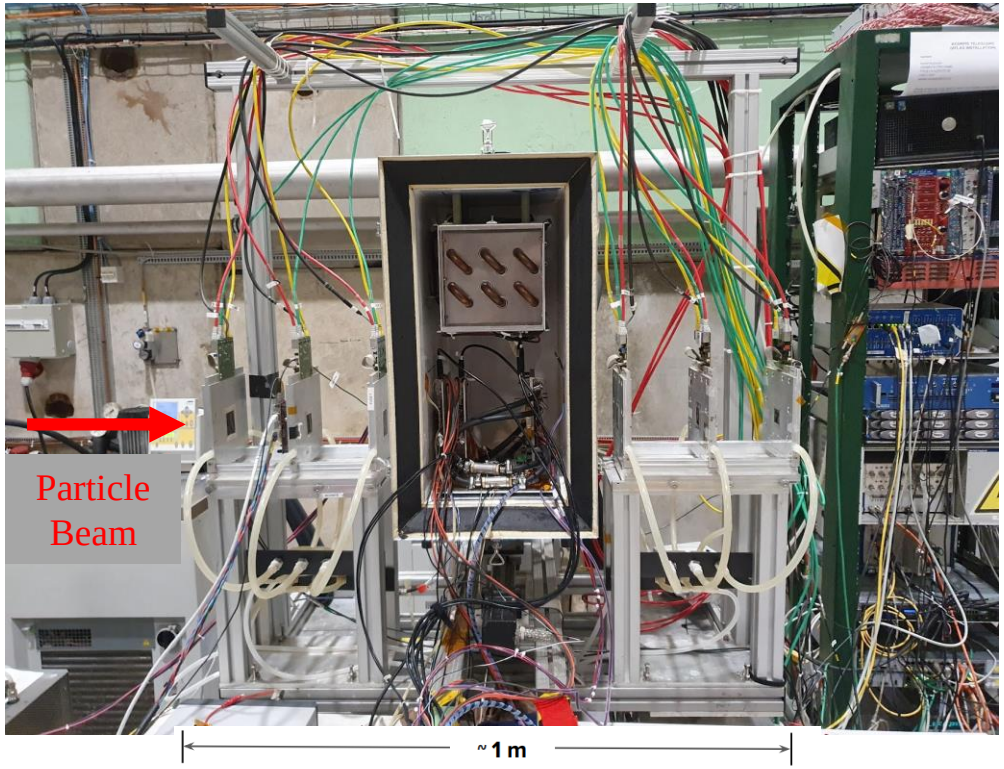
Test beam done at H6 with Pion beam (E ≃ 120 GeV)

Test Beam setup

Telescope Setup



ACONITE in H6A



EUDET telescope:

- 6 planes of monolithic active pixel sensor (MAPS) - Mimosa26 (1152 x 576), 50µm thick, with 18.4 x 18.4 µm^2 pixel size
- Spatial resolution up to 4 µm
- Pixel readout system (YARR) integrated into EUDAQV2 software framework
- Reference RD53B or/and FEI4 module for temporal coincidence
- 2 scintillators for trigger

Temperature controlled box (< - 40°C on powered modules!)

- liquid/air ethanol heat exchanger
- 2 external chillers
- Pre-cooled Nitrogen for humidity control
- Temperature and Humidity sensors

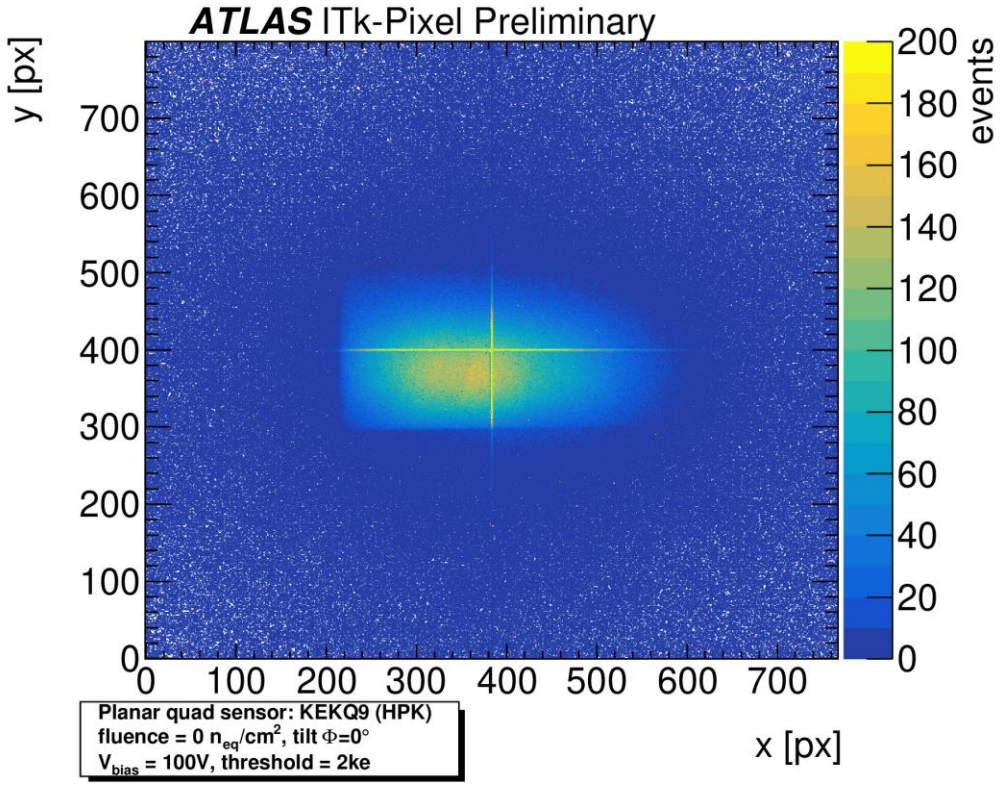
Test Beam Results of Planar Pixel Silicon Sensors

Planar sensors

Planar sensors recently has been tested:

- **Planar quad KEK (HPK) 150 µm thick sensors**
  - Pre-production quad modules: non-irradiated and irradiated to 4.31 x 10^{15} n_{eq}/cm^2
- **Planar FBK sensors 100 µm**
  - SCCs irradiated to 5 x 10^{15} n_{eq}/cm^2 (re-measured to improve data quality in Oct-2024. Improved noise masking -> significantly reduced number of masked pixels. Results are better: high hit efficiency of 99% achieved at about - 220 V. Results has to be approved by collaboration
- **Planar Micron 100 µm** flip-chipped to ITkPixV2. Non-irradiated SCC (measured in May 2025), analysis is ongoing.

Raw hit map. Quad module



Planar HPK quad results ITK-2023-005

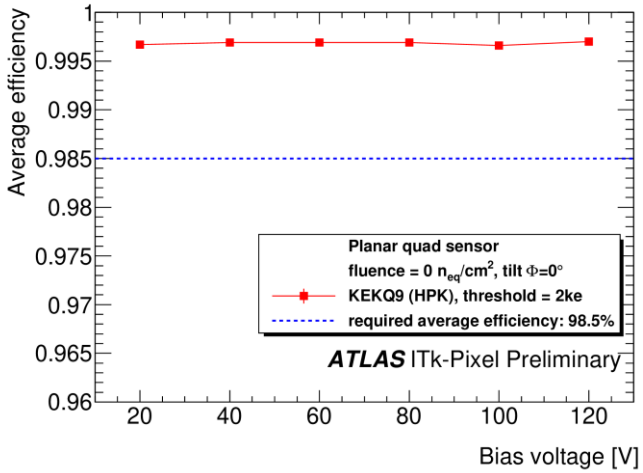
Planar HPK quad sensors results

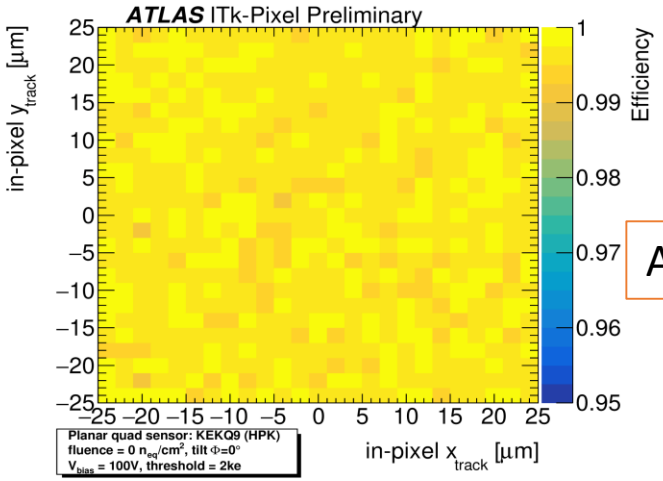
Total efficiency vs bias voltage

In-Pixel efficiency map

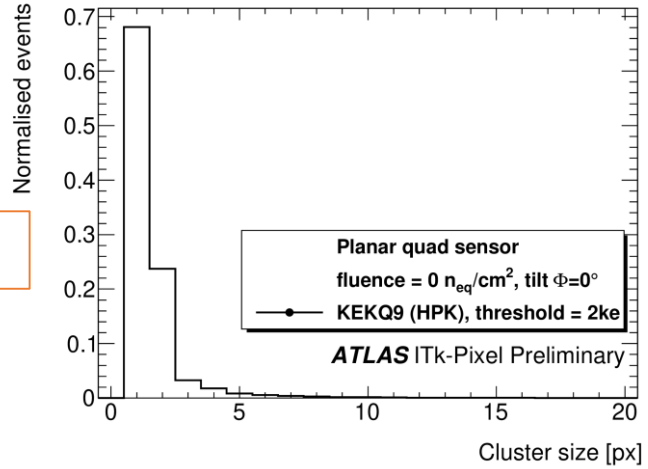
Cluster size distribution

Before irradiation

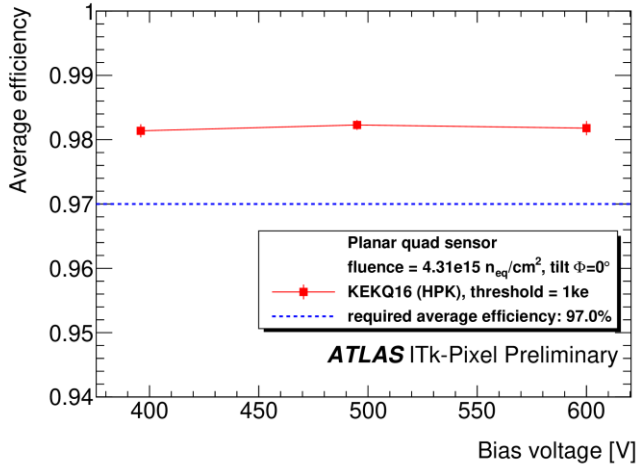


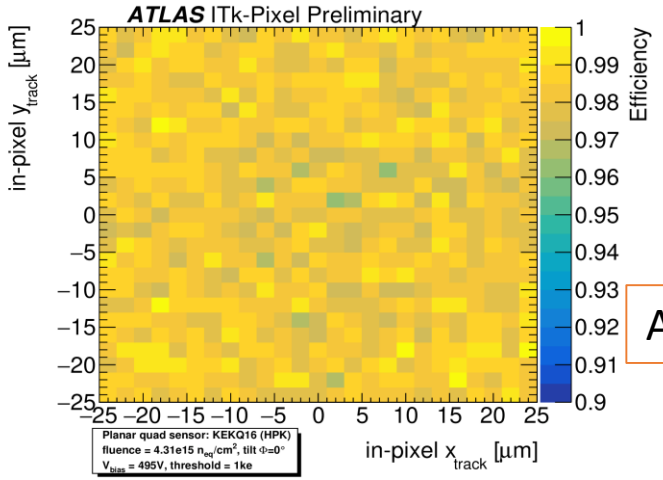


At - 100 V

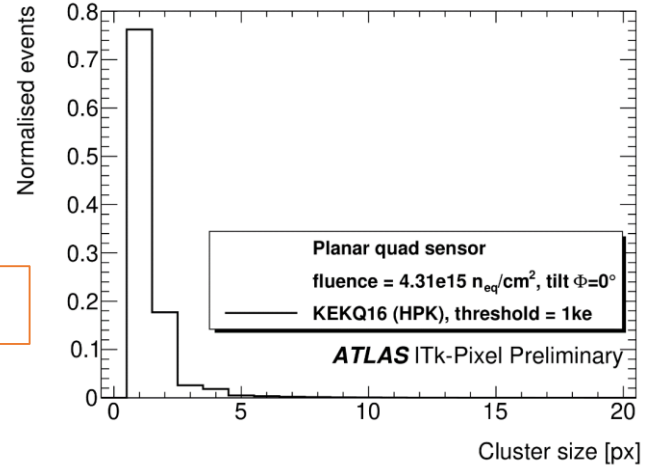


After irradiation





At - 495 V

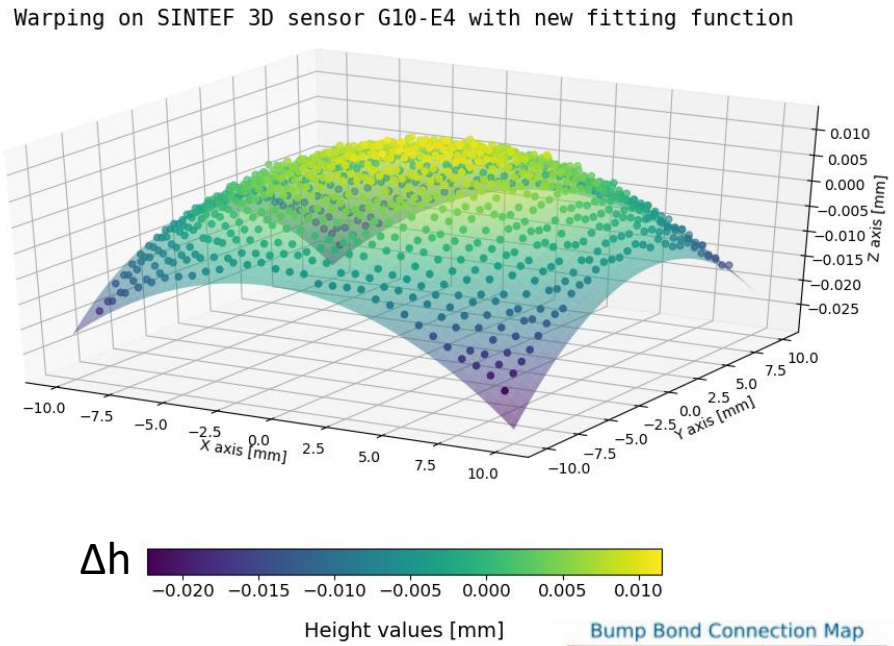


Hit efficiency specifications are met before and after irradiation. No low efficiency regions from bias structures.

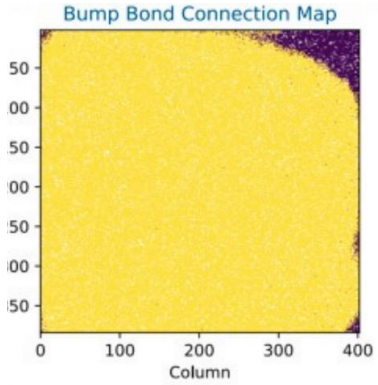
Test Beam Results of SINTEF 3D Pixel Silicon Sensors

SINTEF 3D Sensors

3D sensors manufactured by Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (**SINTEF**) have excellent electrical properties, but mechanical must be improved to increase the yield (about 70%).



Problem: excessive sensor bowing (warping) after thinning and dicing, leading to disconnected bump-bonds at the corners during the flip-chip process.

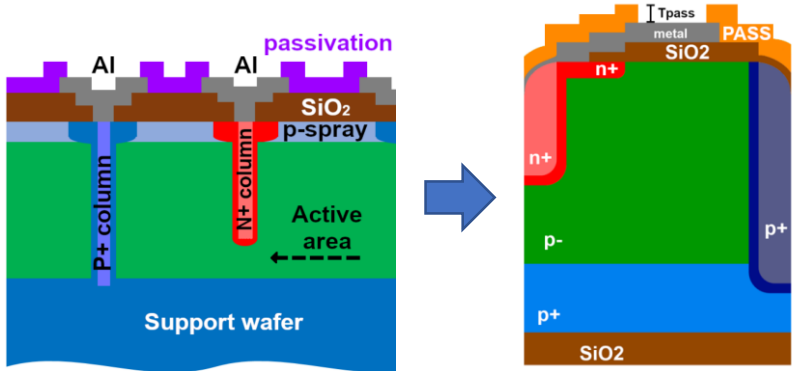


SINTEF 3D sensor design:

- 6'' Si-Si wafer type, single-sided process, 150 µm active thickness
- p^+ and n^+ electrodes radius of 3 µm
- Deep Reactive Ion Etching (DRIE)

Rework of pre-production run -> optimized passivation (modified Si_xN_y) to mitigate the stress on the sensor

ATL-ITK-PROC-2023-021



NEW PECVD PASS

Plasma-Enhanced Chemical Vapor Deposition

Original design:

- SiO_2 – 500nm
- Si_3N_4 – 250nm

New design:

- Si_3N_4 – 1000nm

Illustrations by Marco Povoli - SINTEF

Results: Bowing reduced (max Δh 15 µm -> 10 µm) -> bump-bonding successful!

Next step: Re-validation of sensor performance in test beam experiment

Irradiation facility

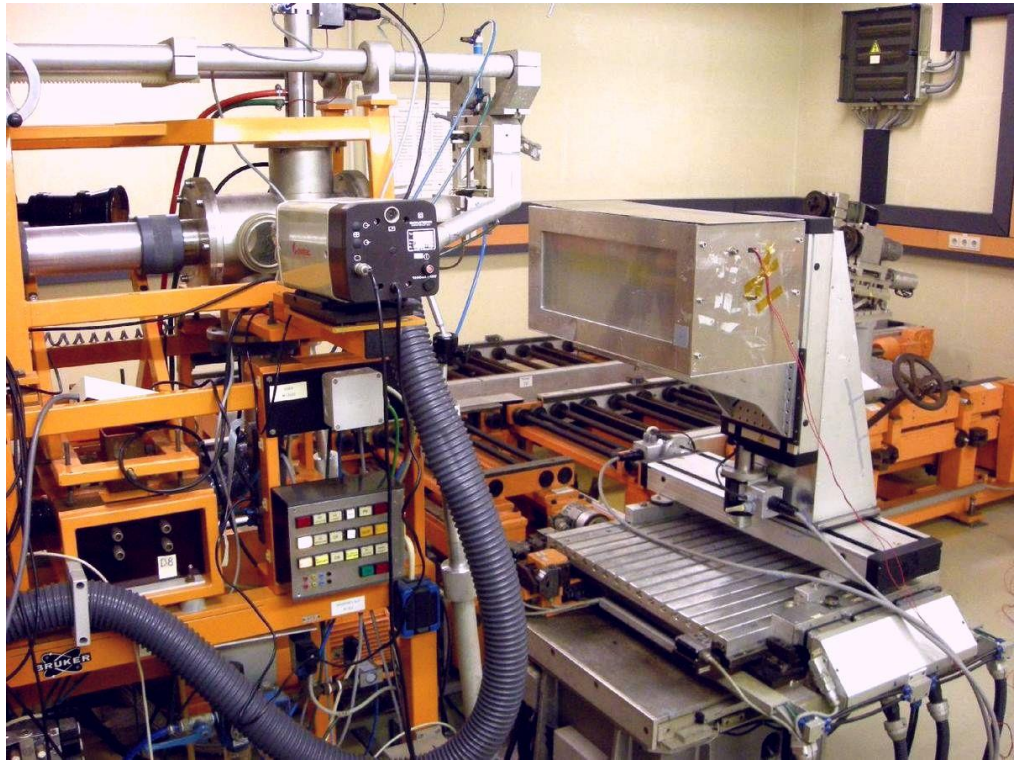
The evaluated SINTEF design was flip-chipped with ITkPixV1.1 chip (400 × 384, 153500 pixels) and irradiated at **KIT**

The Karlsruhe Proton Cyclotron:

- Proton energy at extraction: **25.3 MeV**; typical proton current: **2.0 µA**
- Beam spot ~ 7 mm (varying); Flux ~ **3 x 10^{13} p/(s·cm²)**
- Box (accessible area: ~ 40 cm x 15 cm), scanned in 1mm spaced rows
- Temperature in box: ~ **- 30°C** (cooled by cold nitrogen gas)
- Box positions and temperatures are logged
- Only silicon and aluminium materials (auxiliary electronics should be covered by an Al mask)

The module was uniformly irradiated by **23 MeV proton** beam to fluence of **1.7 x 10^{16} n_{eq}/cm²** (expected dose over its lifetime operating in ITk)

Sample box on XY-stage with beam line



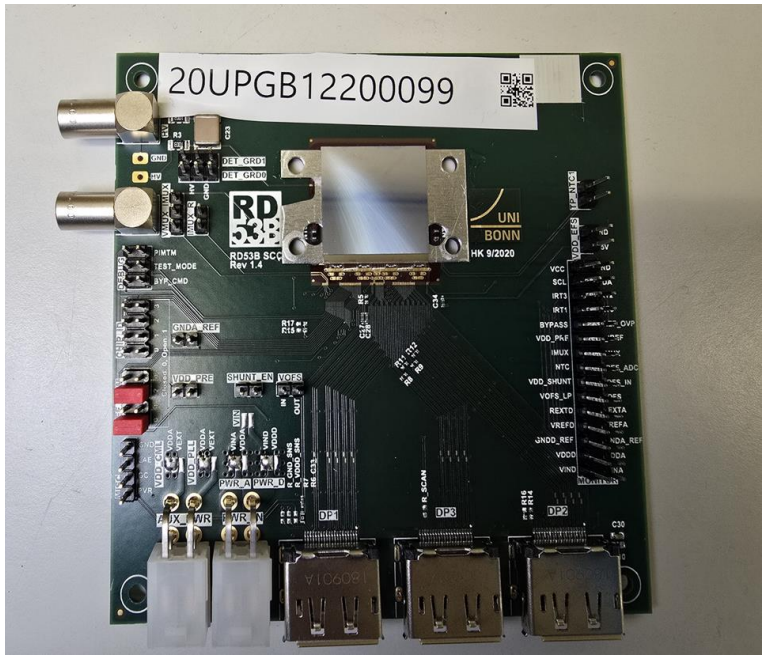
[Irradiation Center Karlsruhe]

* Hardness factor for p_{23MeV} on Si: **2.0** (i.e. 1 x 10^{14} p/cm² -> 2 x 10^{14} n_{eq}/cm²)

Test beam measurements

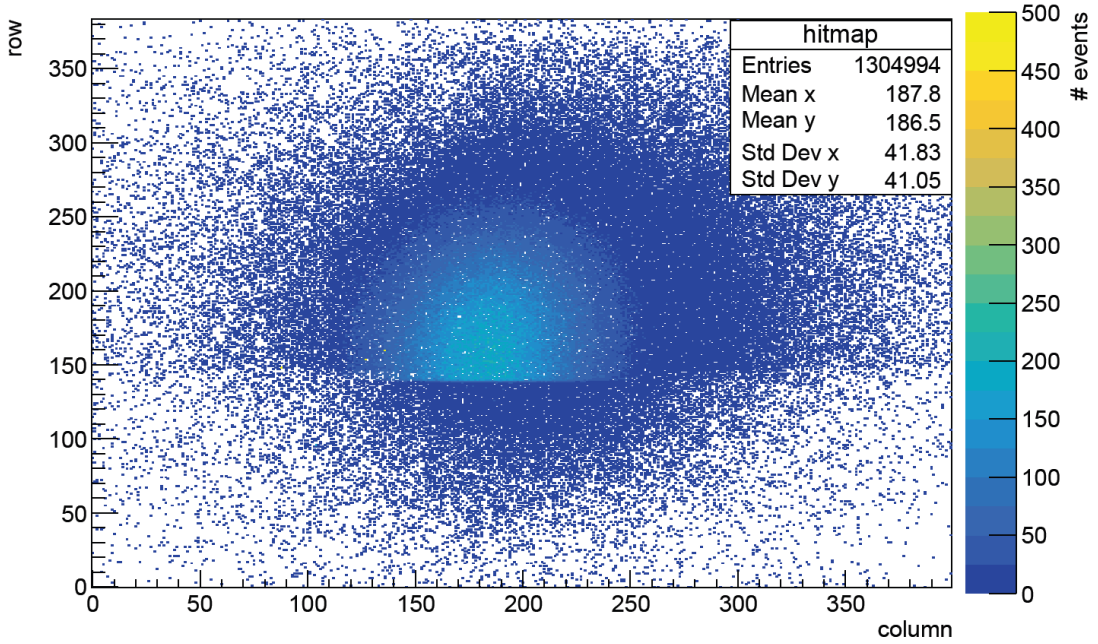
- DUT tested at **normal** incidence wrt the beam line
- Threshold set to **1000 e$^-$**
- Bias voltage range: **- 20 V to - 100 V**
- Data collected in 2024 and analyzed by Simon Huiberts

Further analysis results are shown for a bias voltage of - 65 V



Picture of 3D SINTEF module assembled on a SSC

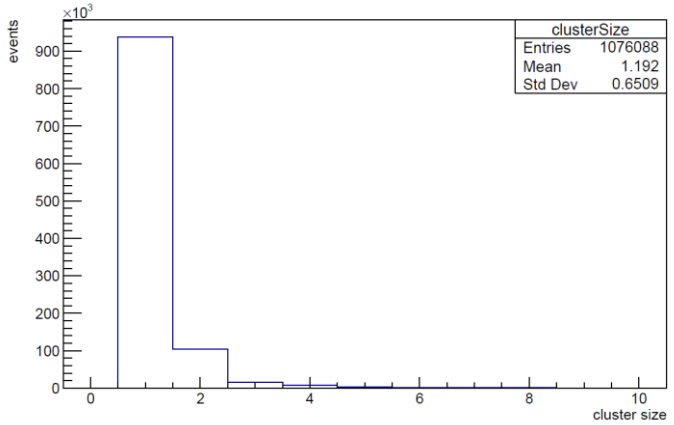
Raw pixel hit map

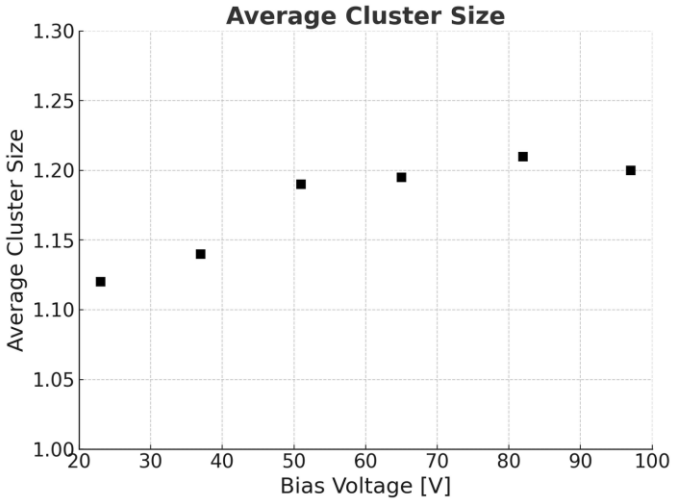


Beam well centered. Scintillator cut off about row 150
- Aligned to MIMOSA planes.

Cluster size and position resolution

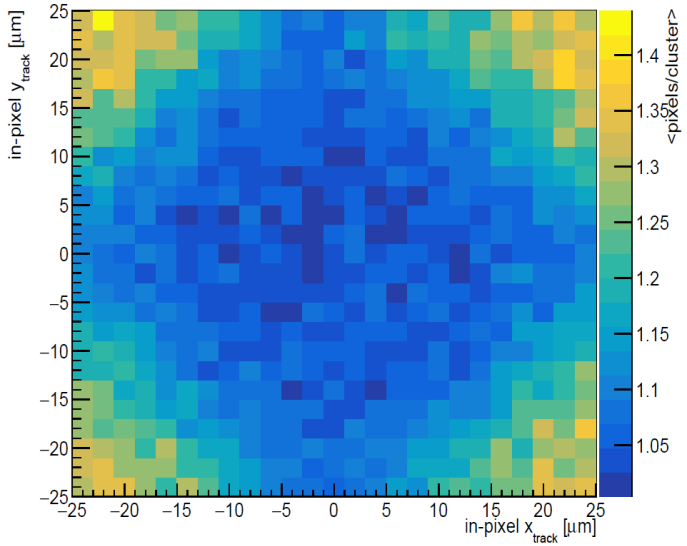
Cluster Size





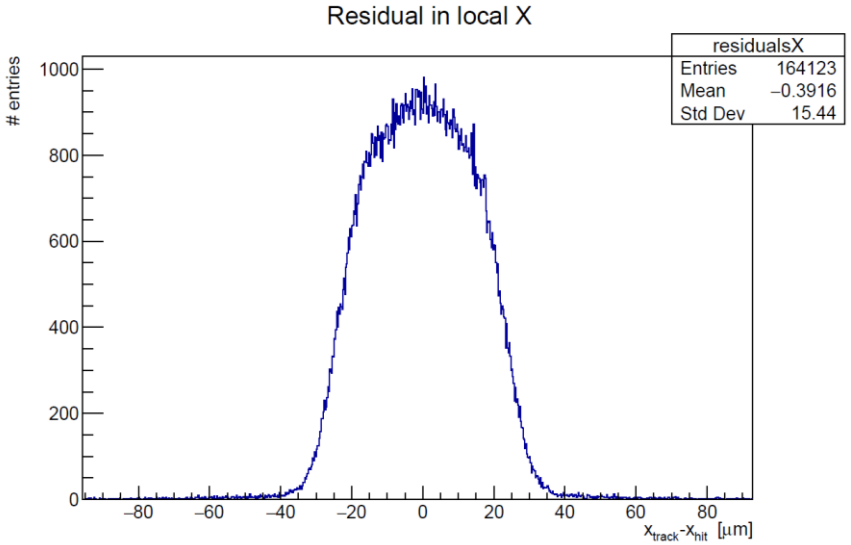
- Mostly single pixel clusters (1.1 – 1.2 pixels)
- Average cluster size increases with bias voltage

In-pixel Mean Cluster Size



- 1-pixel clusters in center
- Higher chance of 2-pixel clusters in corners
- Charge sharing
- More or less same trend for all biases

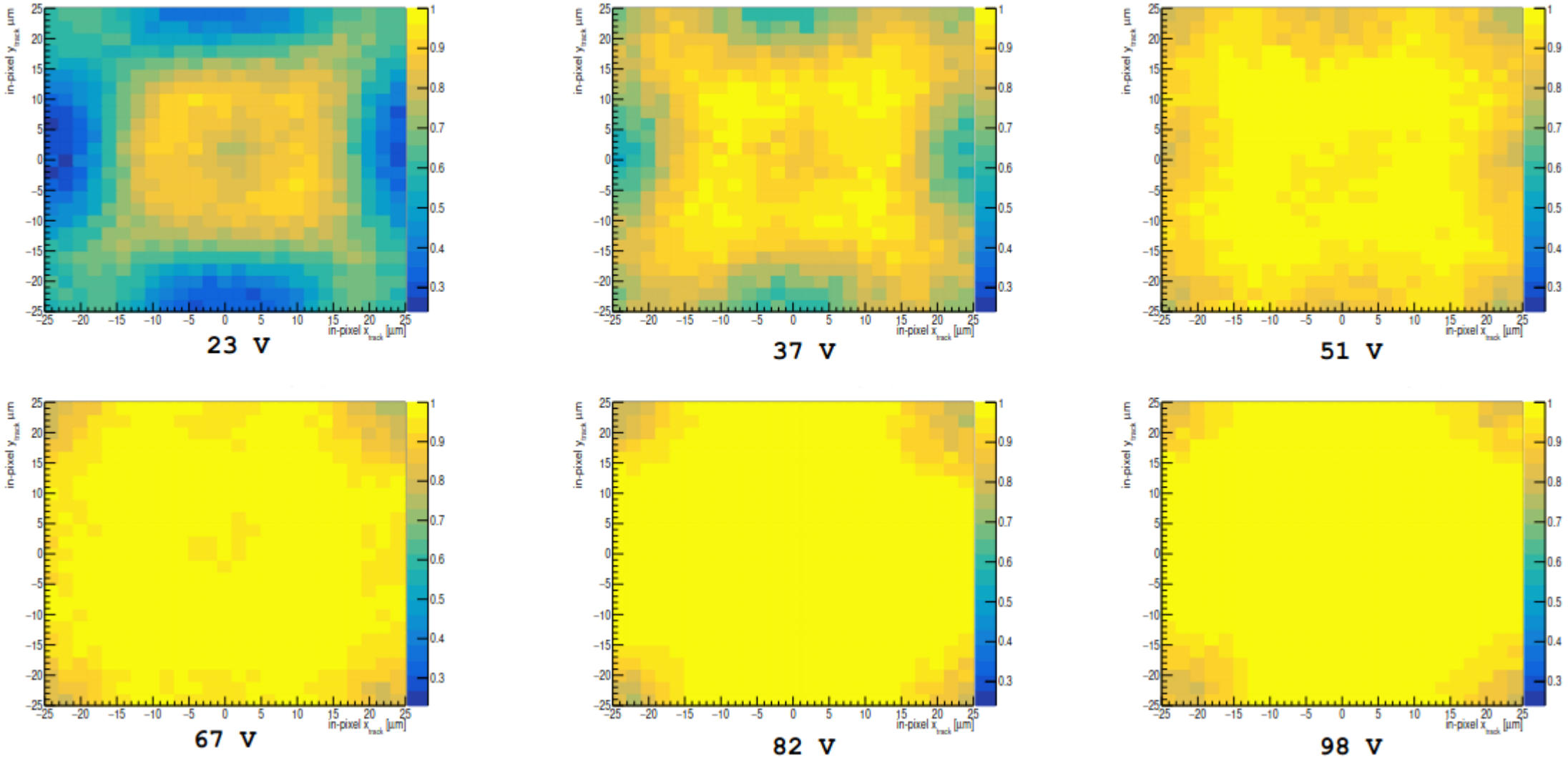
Position Resolution



- Theoretical spatial resolution:
  - $\sigma_{position} = (L/\sqrt{12}) = 14.4$ μm
- Measured resolution (Test Beam)
  - Center of gravity
  - $\sigma = 15.44$ μm
- EUDET Telescope resolution:
  - $\sigma \approx 4$ μm
- Peak due to charge sharing effects

In-pixel Efficiency Maps

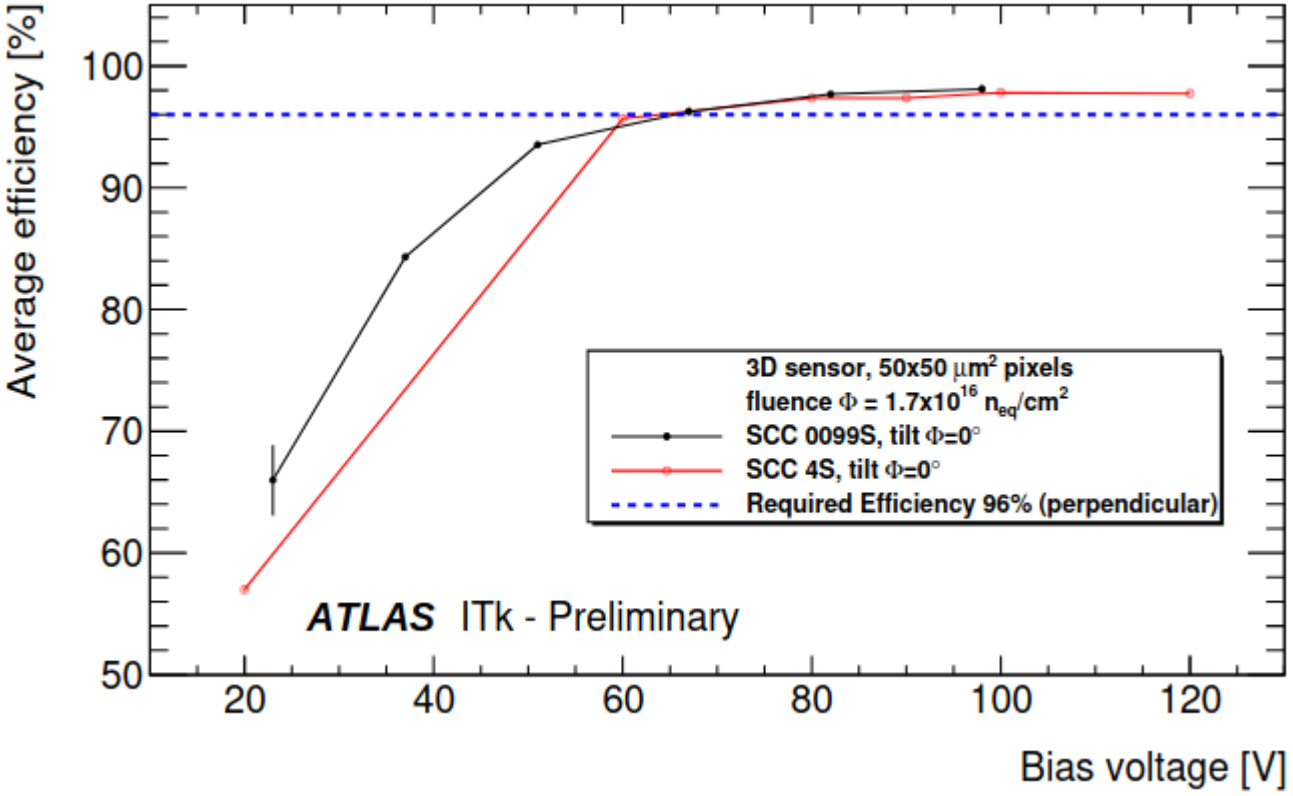
Courtesy of S. Huiberts, Bergen Uni



Efficiency results

ITK-2023-004

- The module with the new passivation (re-worked original design) SCC 0099S:
  - Reaching **96%** average efficiency at **- 70 V**
  - Up to **98%** average efficiency at **- 100 V** bias
- Efficiency results match very well with the module SCC 4S (original design)
- The module SCC 4S was irradiated to a similar fluence (1.6 - 1.8 x 10^{16} n_{eq} / cm^2 @ IRRAD (CERN)
- Tested at normal incidence wrt the beam line

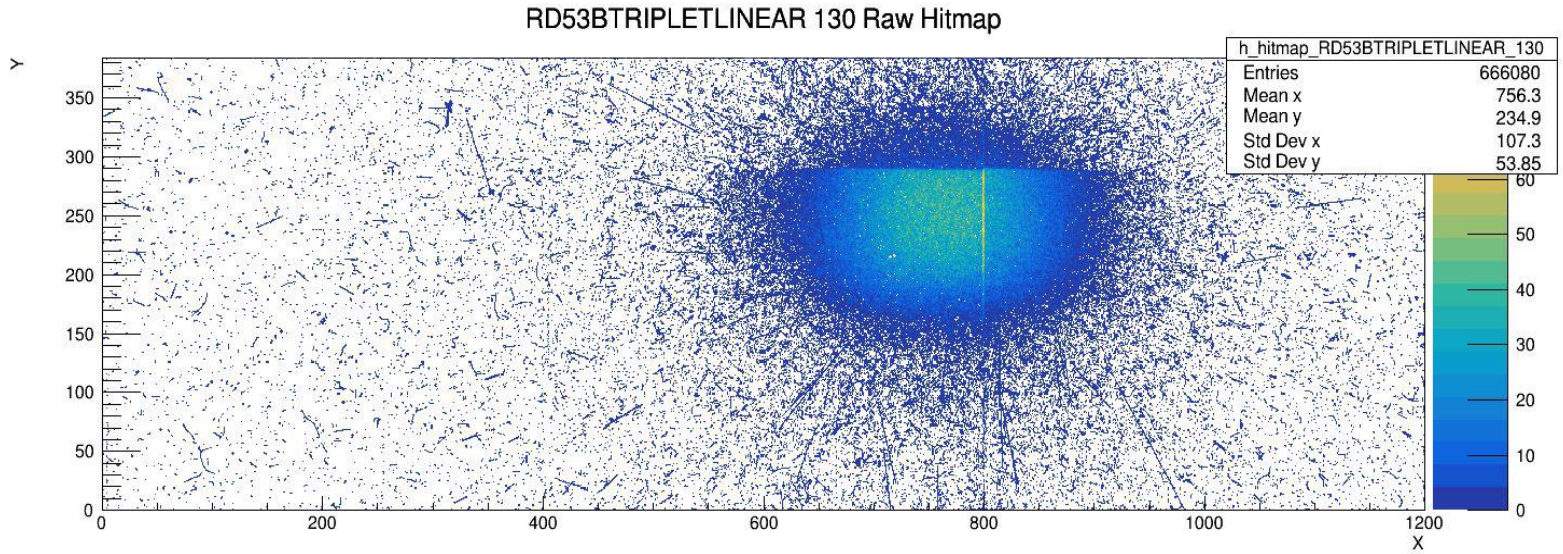


Average hit efficiency as a function of bias voltage. Comparison of the two versions.

3D triplet modules

For the first time linear triplet were measured.

- FBK and SINTEF linear triplets with ITkPixV1.1, Non-irradiated
- New triplet module holders are used
- Setting up the geometry and adjustment of software to read the raw data



Triplet on a holder

Reconstruction and analysis is ongoing. The results to be approved.

Summary

- The hit efficiency of HPK, FBK and SINTEF sensors meets specifications at required bias voltage, both before and after irradiation to about expected fluence.
  - HPK quad modules demonstrate high performance (with hit efficiency : $\varepsilon > 98\%$), no low-efficiency regions from bias structures observed.
- Irradiated FBK thin planar module have been re-measured with improved data quality. The results confirm high hit efficiency and stable operation across bias voltages. Results to be approved.
- Re-worked 3D SINTEF sensor design was successfully validated in test beam experiment. It shows improved mechanical properties and high electrical performance ($\varepsilon > 96\%$ at normal beam incidence).
  - Efficiency of the re-worked design sensor is comparable to the original design;
  - Radiation hardness remains the same as the original design.
- First test beam data were collected from triplet modules using 3D sensors (FBK, SINTEF) flip-chipped to the ITkPixV1.1 readout chip. Data analysis is ongoing.

Thank you for your attention!!!

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