Qualification of pixel detectors for the upgrade of the ATLAS Inner Detector with beam tests

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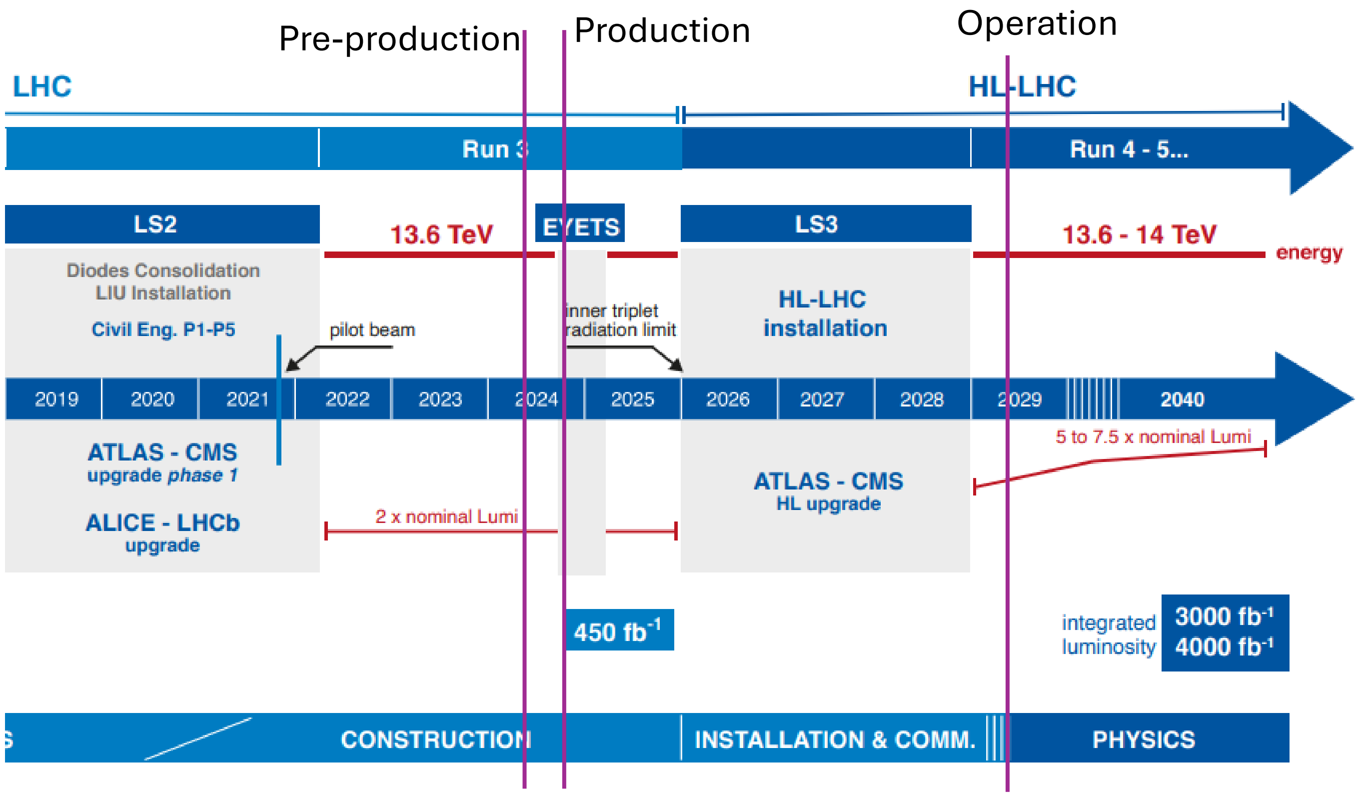
Institute for High Energy Physics

Large Hadron Collider upgrade

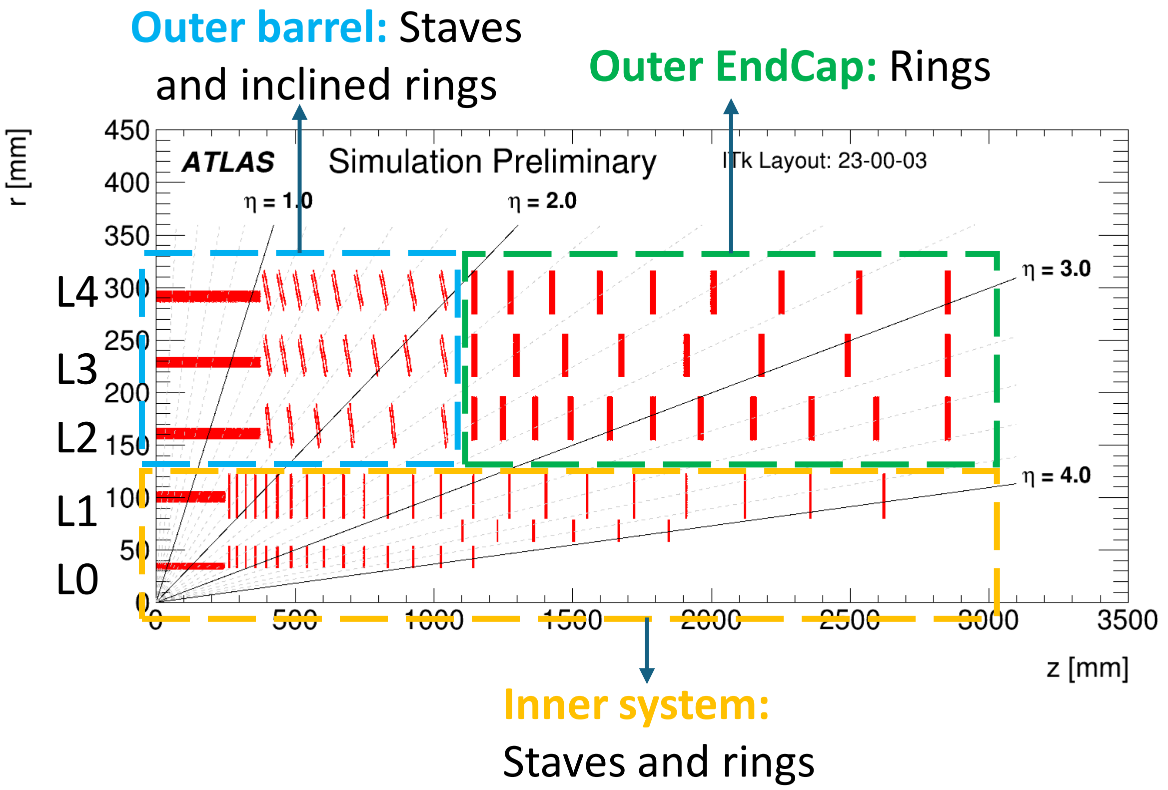
- The LHC next upgrade is the High-Luminosity LHC (HL-LHC) planned to start operation in 2029.
- It is expected to provide up to 200 proton-proton interaction per bunch crossing delivering about 4000 fb^{-1} of data over 10 years.
- An upgrade of the ATLAS detector is needed to cope with the harsher radiation levels and with a much higher number of tracks.

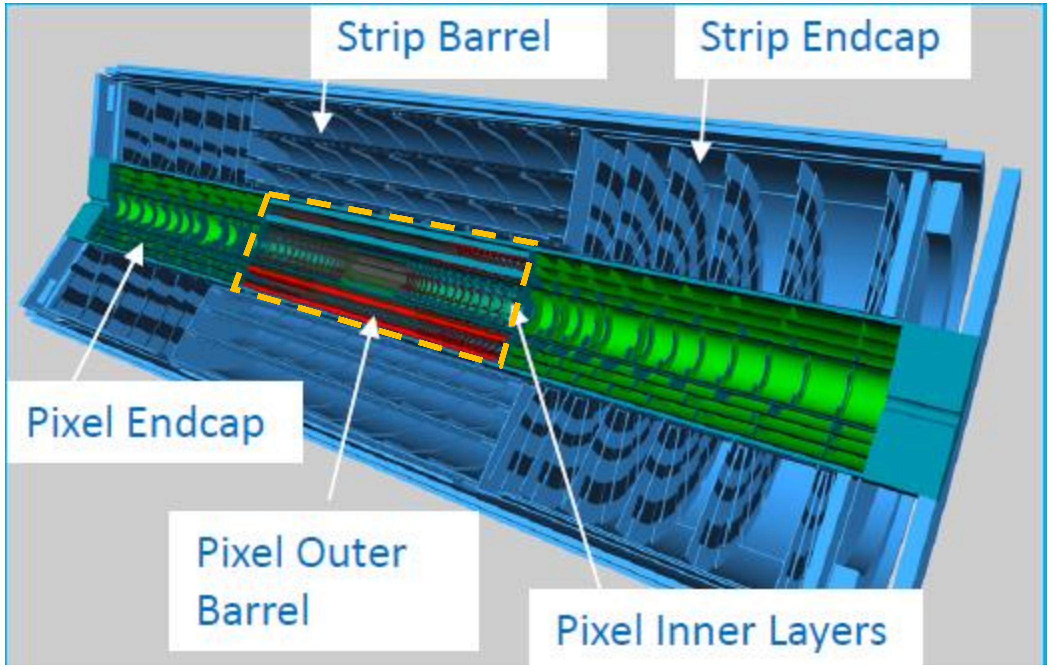


ATLAS ITk upgrade

The ATLAS Inner Detector will be completely replaced with an all-silicon Inner Tracker (ITk). The challenges for this new detector are related to:

- **Large number of tracks**
  - High pixel granularity (small pitch)
- **High radiation levels**
  - Improved radiation hardness





Left picture shows a schematic depiction of the ITk Layout,

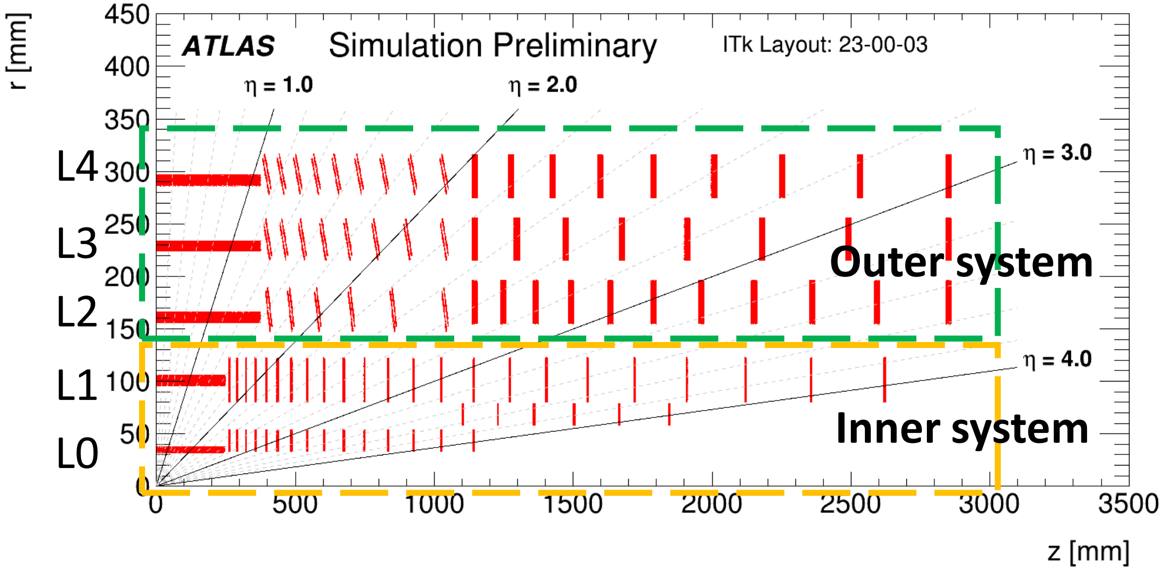
- 5 layers
  - 3D pixel sensors for the innermost layer (L0)
  - n-in-p planar silicon sensors for the other layers

ATLAS ITk upgrade

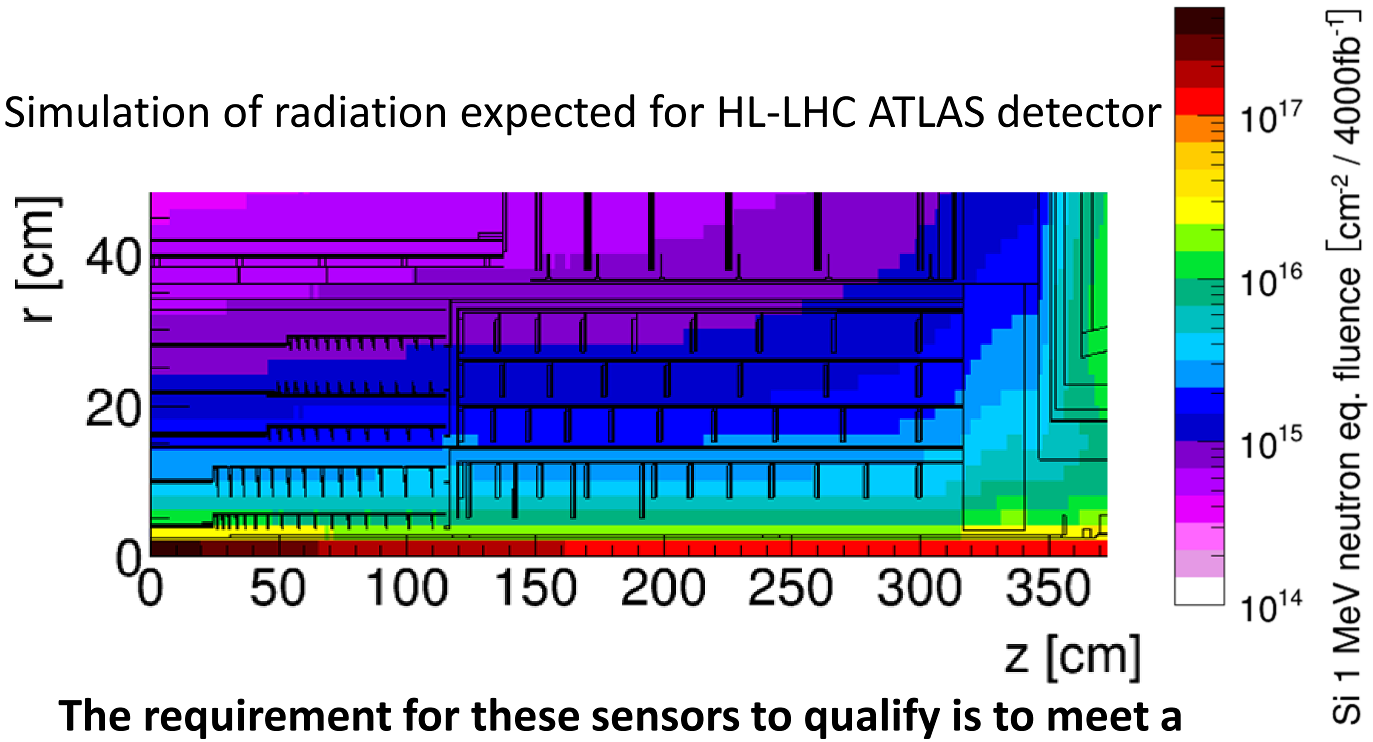
Radiation expected during the full sensor operation life:

- **Inner system:** $1.7 \cdot 10^{16}\ n_{eq}/cm^2$
- **Outer system:** $5 \cdot 10^{15}\ n_{eq}/cm^2$

Performance of pre-production sensors irradiated at these fluences going to be presented.



Simulation of radiation expected for HL-LHC ATLAS detector

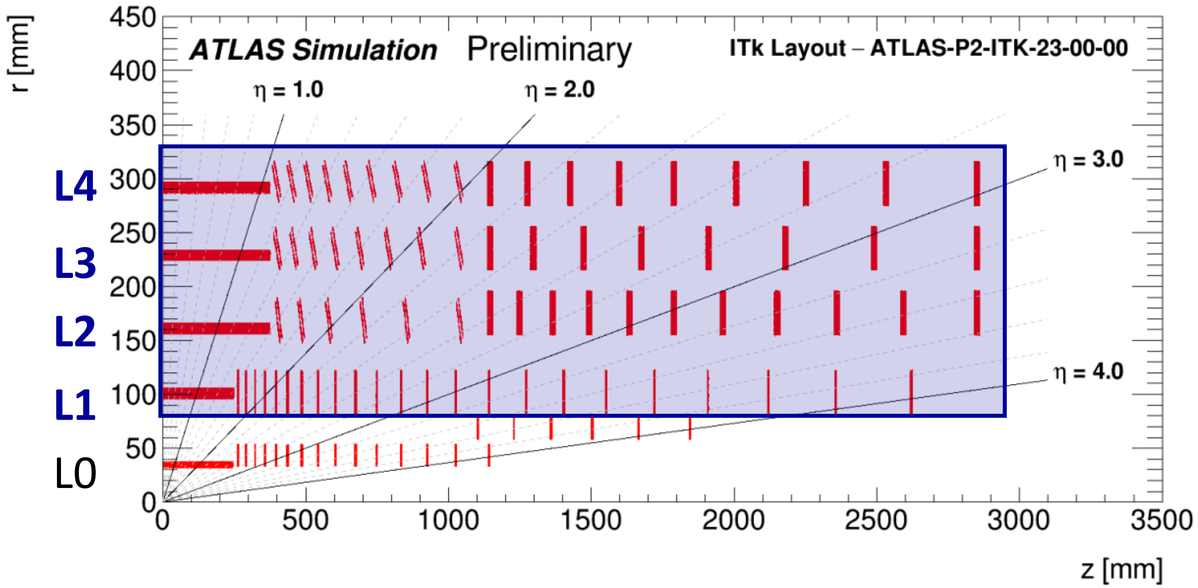


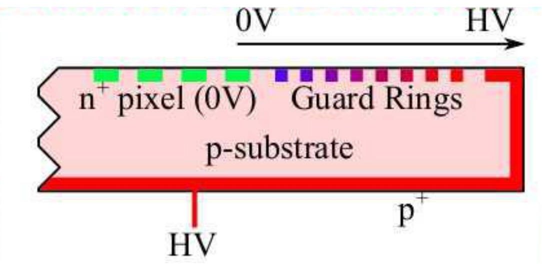
The requirement for these sensors to qualify is to meet a detection efficiency:

- **For 3D pixel sensor (L0 layer):**
  - Higher than 96% at perpendicular configuration or 97% at tilted configuration (see slide 9) after being irradiated at $1.7 \cdot 10^{16}\ n_{eq}/cm^2$
- **For planar sensors (L1-L4 layers):**
  - Higher than 97% after being irradiated at $5 \cdot 10^{15}\ n_{eq}/cm^2$

It is expected that the ITk pixel Inner system will be replace after 5 years of operation because of the radiation damage.

ITk planar sensors – quad module

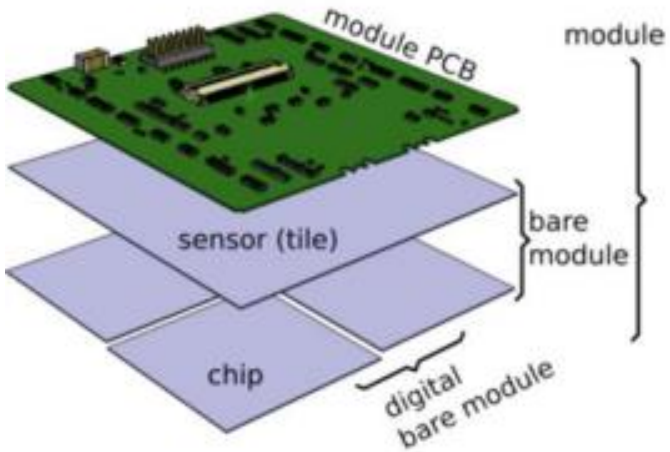


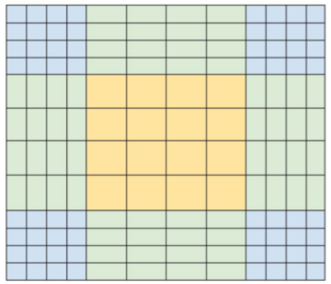


- Single side process with guardring and pixels on the top side
- Parylene protection
  - Reinforce bonds and avoid corrosion
  - Prevent discharge between sensor and front-end
- The centre of the quad sensor has larger pixels with different geometries to extend the coverage of the sensor into the inter-chip gap

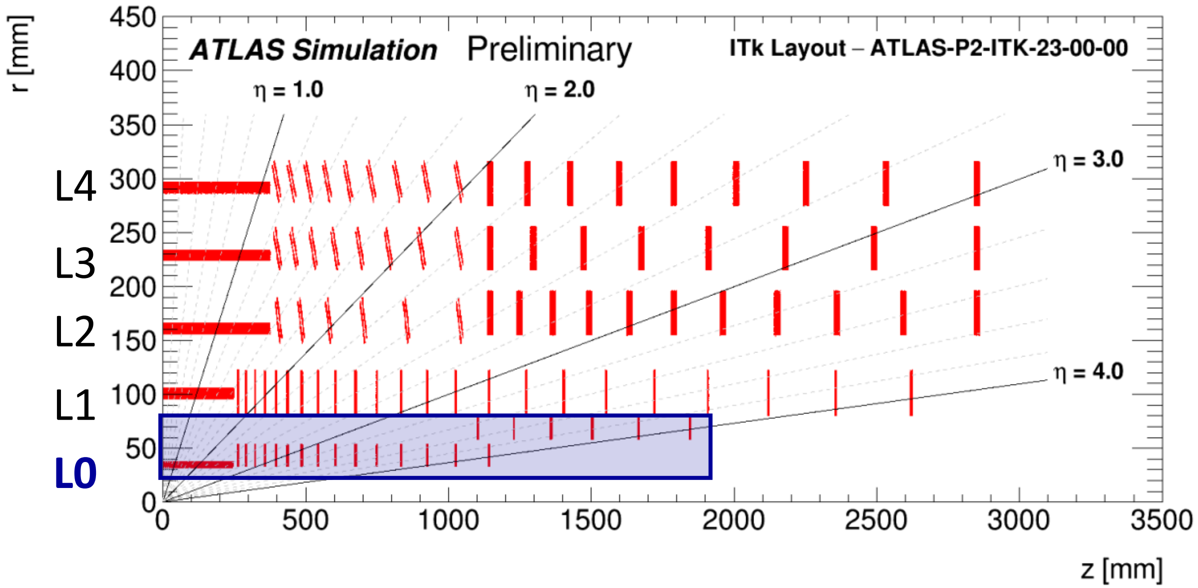
ITk pixel detector is composed by different layers:

- **L1: Inner system**
  - **Staves and rings**
    - 50x50 μm^2 pixel planar sensors **100 μm** active thickness.
- **L2-L4: Outer system**
  - **Stave and rings**
    - 50x50 μm^{2}pixel planar sensors **150 μm** active thickness.





ITk 3D pixel sensors – triplet module



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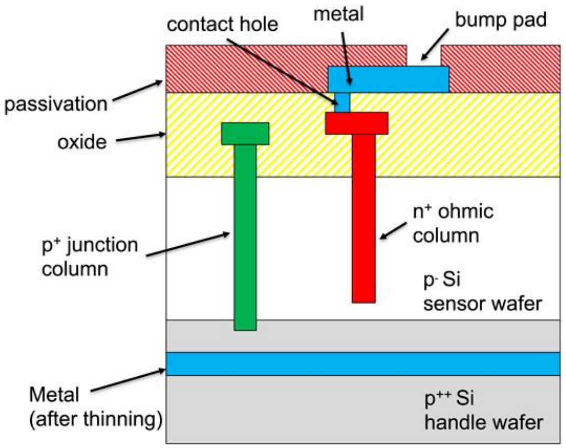
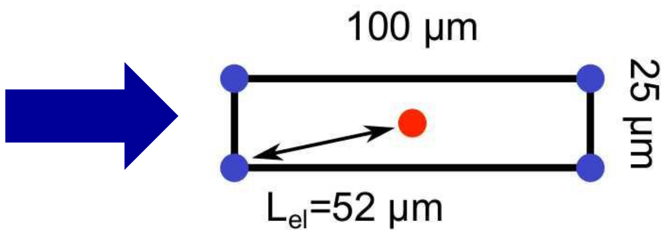
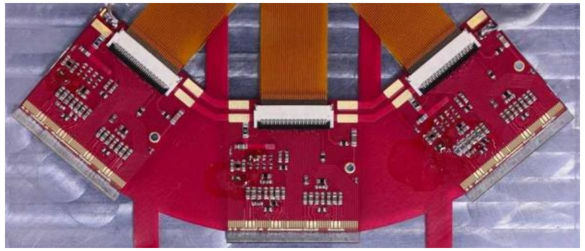


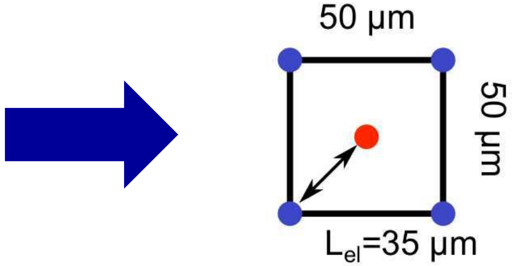
- Sigle side process
- Single read-out electrode in the center (n+ column) and four bias electrodes (p+ columns) at the corners
- Two different configurations

ITk pixel detector is composed by different layers:

- **L0: Inner most system**
  - **Staves: Linear triplets**
    - 25x100 μm^2 3D pixel sensors with 1 electrode and **150 µm** active thickness.
  - **Rings: Rings triplets**
    - 50x50 μm^2 3D pixel sensors with 1 electrode and **150 µm** active thickness.
  - **Very high radiation hardness**

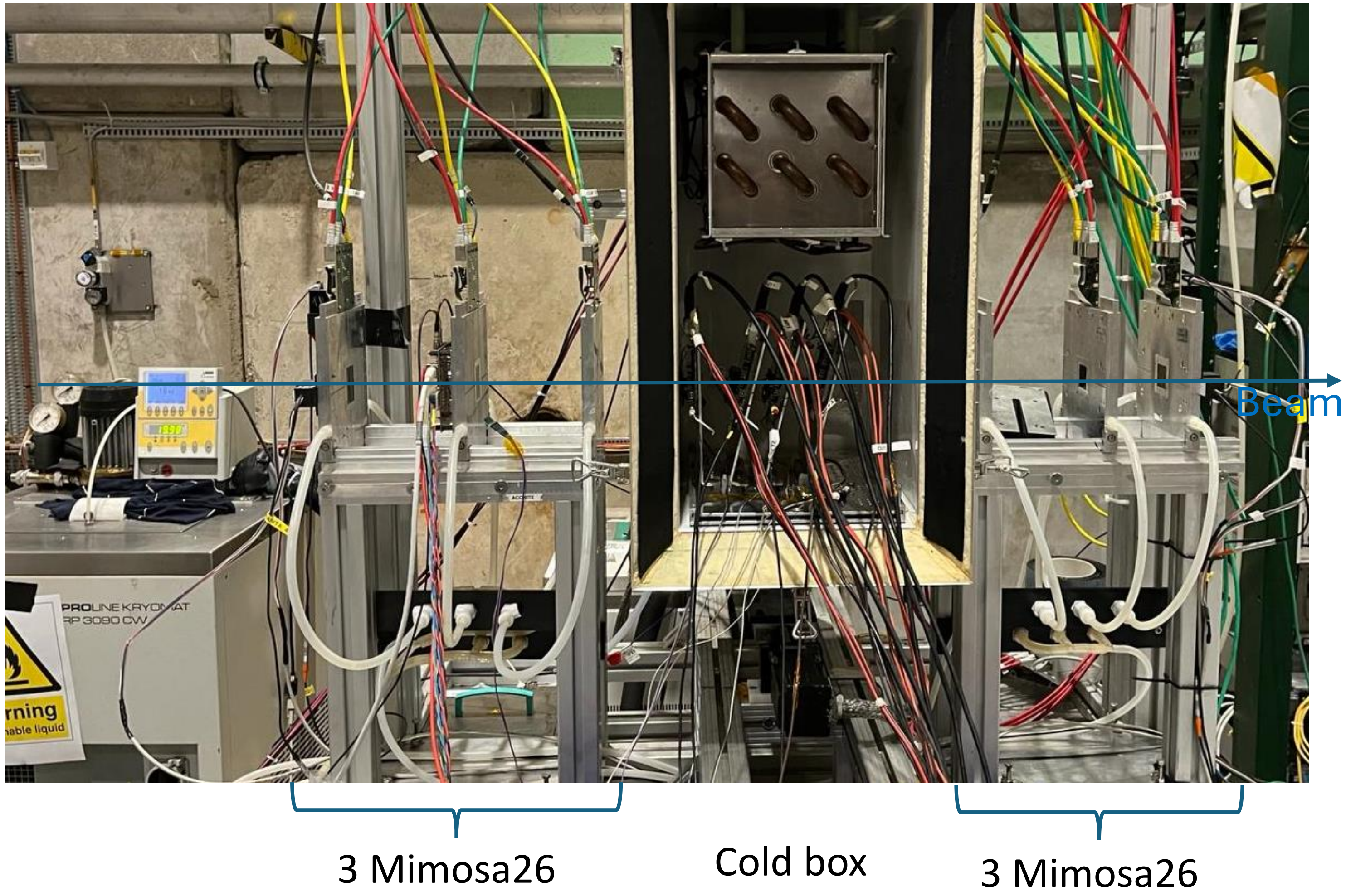




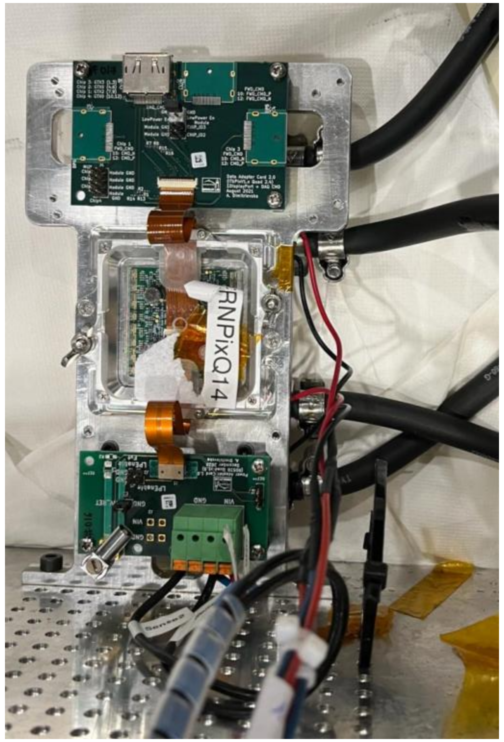


Testbeam setup at SPS-CERN

- EUDET telescope with 6 Mimosa26 planes and trigger scintillators
- FE-I4 (MMC3 readout) plane and single ITkPixV1.1 (FBK 3D sensor) for track matching.
- Results were obtained using ITkPixV1.1 chip.
- 120 GeV pions
- Cold box: 2 deep temperature chillers driving external cooling circuits with silicon oil / ethanol:
  - Liquid/air heat exchanger inside the box
  - Additional cooling circuit only for quads
  - Pre-colling nitrogen (for humidity control)

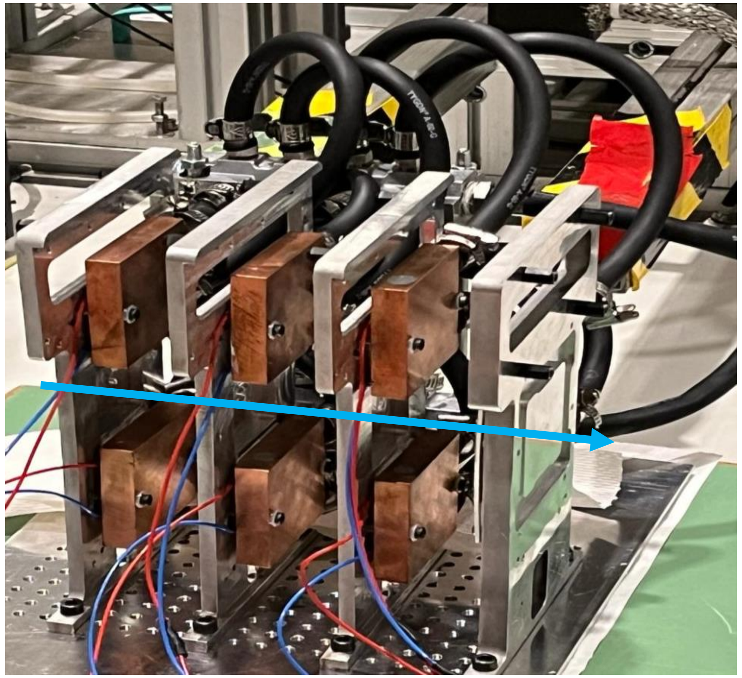


Testbeam setup at SPS-CERN



Quad module setup

- **Challenging cooling system for quads.**
  - Additional cooling circuit only for quads with ethanol or silicon oil.
  - no material is added along beam's track
- **Achieved < -15 °C on powered quad modules**

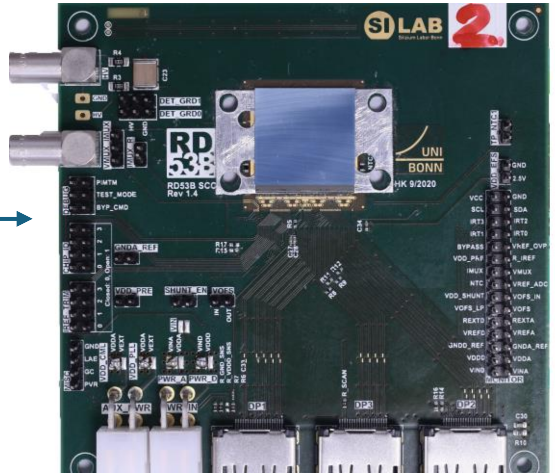


- A special frame was fabricated to support the quad in the center.
- Data adapter and power cards are located from the top and bottom connected to the module pcb by pigtails.
- The holder is directly cooled down by two Peltiers (above and below the module), each cooled down by a copper heat exchanger cooled with silicon oil/ethanol.
- **No material is added along beam's track to achieve the cooling**

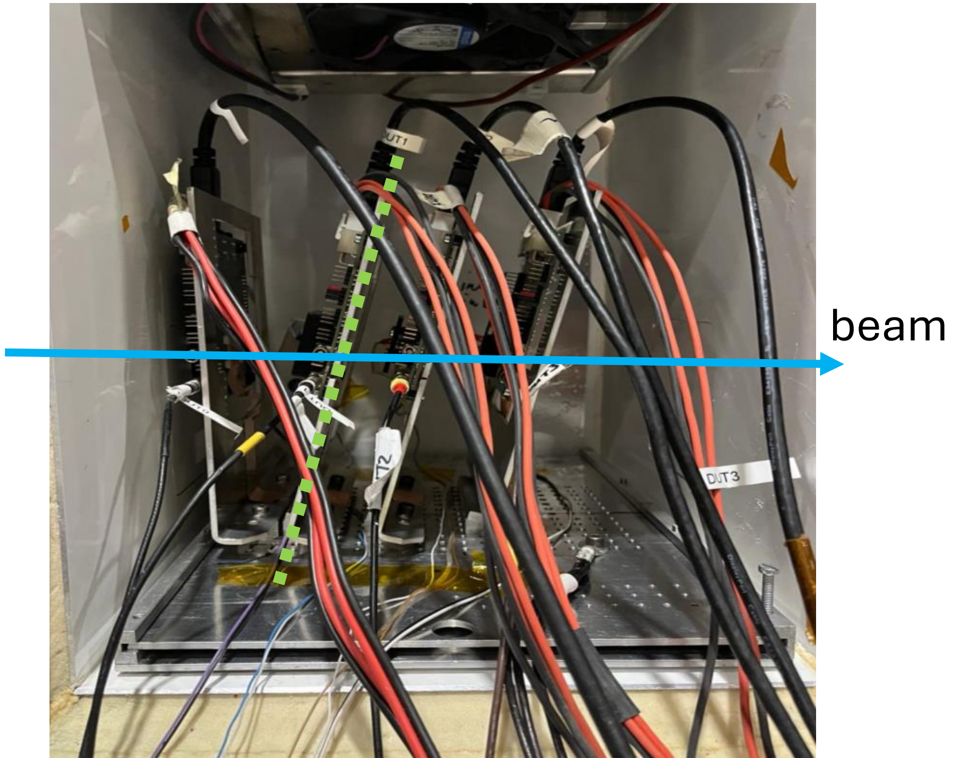
Testbeam setup at SPS-CERN

3D pixel setup

- 3D modules mounted on rigid PCB (single chip card, SCC) intended for testing individual bare module.
- Measurements were performed at different configuration angles:
  - **0° (perpendicular)**
  - **15° (To avoid column effects)**



- **Reconstruction of the events with Corryvreckan**
  - Introduce geometry of the experiment:
    - Position and inclination of the detectors
    - Pixel dimensions.
      - Default value was 50x50 μm^2
      - It was necessary to modify the program to adjust to 25x100 μm^2
  - DUT clusters are also requested to match the expected position by tracks



Modules tested during 2022/2023 testbeam

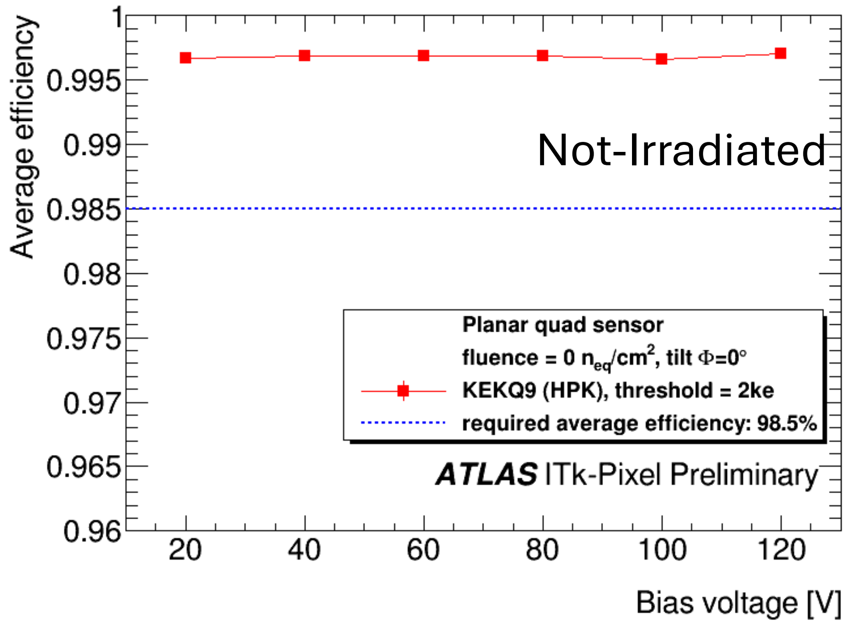
- Pre-production sensors were irradiated at:
  - KIT (23 MeV protons)
  - CERN IRRAD (24 GeV protons)
  - CYRIC (70 MeV protons)
  - Bonn (13 MeV protons)
- List of modules tested presented in this presentation:

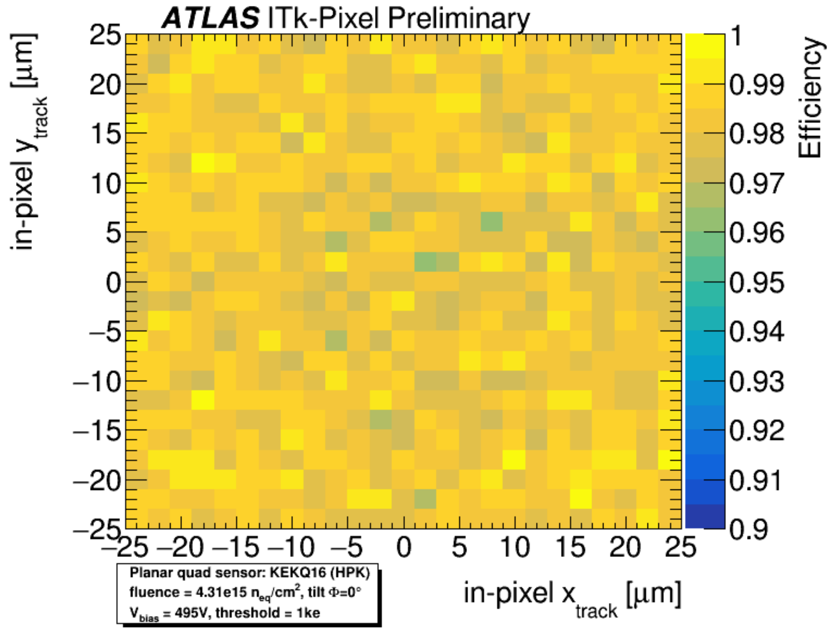
Sensor	Manufacture place	Pixel dimension [μm^2]	Serial Number	Irradiation level [$10^{16} n_{eq}/cm^2$]	Place of irradiation
3D pixel	SINTEF	50x50	1S	1	KIT
			4S	1.8 (not uniform)	KIT+IRRAD
	FBK	25x100	SCC29	1	KIT
			SCC23	2.4 (not uniform)	IRRAD
			SCC24	2.3 (not uniform)	IRRAD
		50x50	SCC3	1.7 (not uniform)	IRRAD
Planar	HPK	50x50	KEKQ9	-	Not irradiated
			KEKQ16	0.43	CYRIC

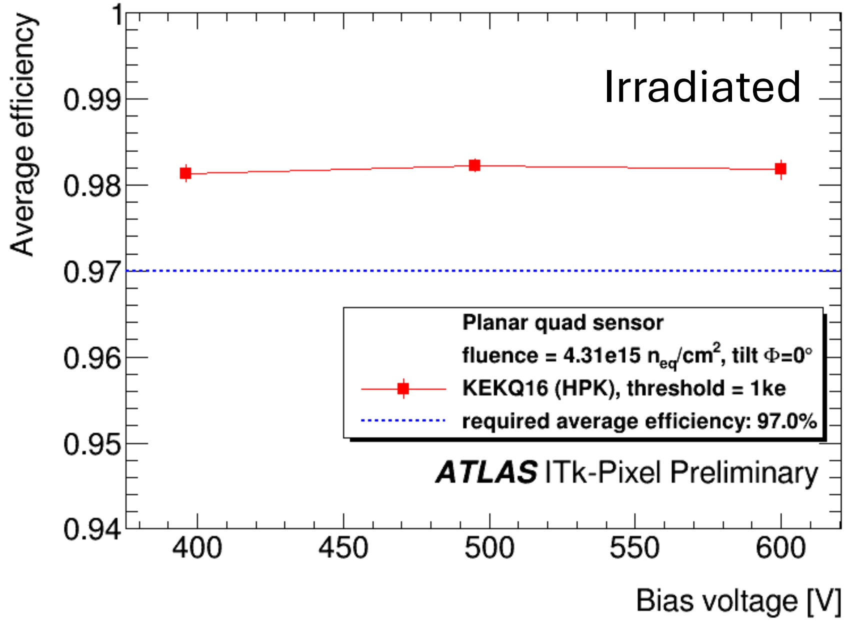
Planar sensor from FBK and Micron (100 μm and 150 μm) were tested but analysis is still in process.

HPK planar sensor

- 2 HPK 50x50 μm^2 planar sensors were tested:
  - KEKQ9 (not irradiated)
  - KEKQ16 (irradiated up to 4.3 $\cdot 10^{15}$ n_{eq}/cm^2)
- KEKQ9 reaches the 98.5% hit efficiency at 20 V.
- While KEKQ16 reaches the 97% (requeriment for irradiated sensors) at 400 V.



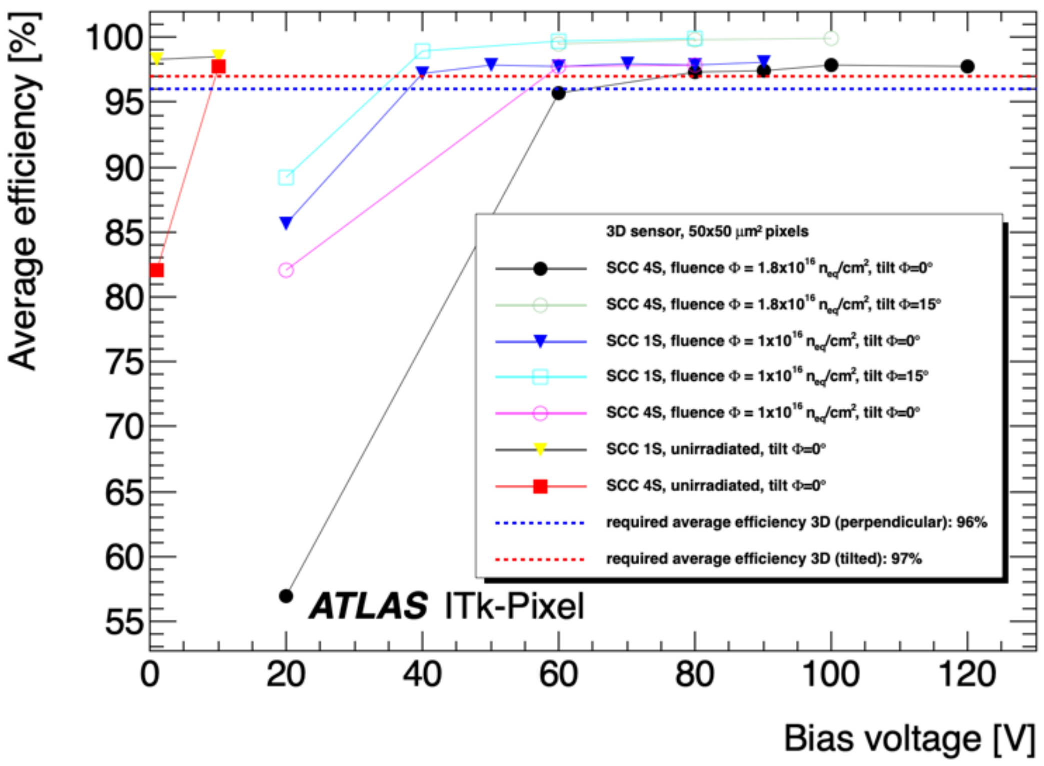


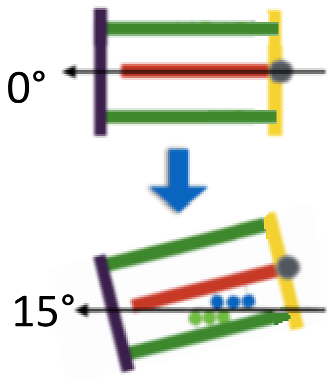


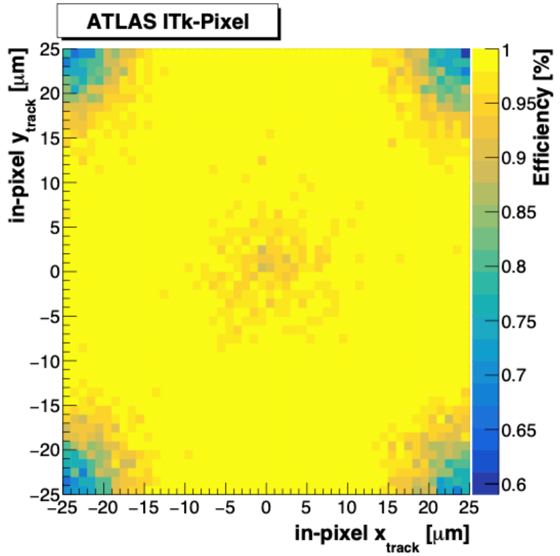
SINTEF 50x50

SINTEF 3D pixel Sensors

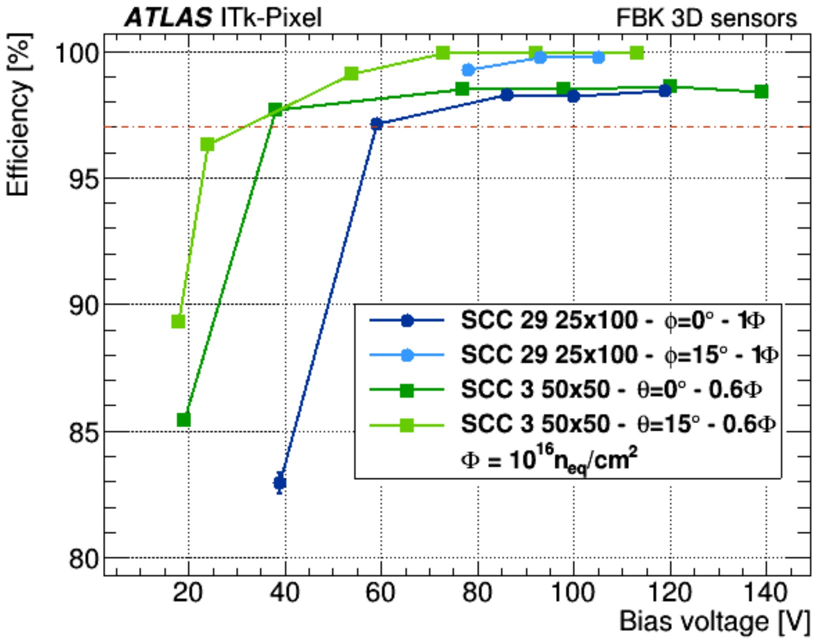
- **2 SINTEF 3D 50x50 μm² pixel sensors were tested in different conditions:**
  - **Fluences**
    - Unirradiated; $1 \cdot 10^{16}\ n_{eq}/cm^2$ and $1.8 \cdot 10^{16}\ n_{eq}/cm^2$
  - **Angles**
    - 0° (perpendicular) and 15°
- **Hit efficiency specifications is reached at $1.8 \cdot 10^{16}\ n_{eq}/cm^2$ on both angles.**
  - 97% (15°) at 60 V
  - 96% (perpendicular) at 80 V
- **Hit efficiency in the perpendicular configuration.**
  - The hit efficiency is lower in the corners and the center of the pixel cell because of the columns







FBK 3D pixel Sensors



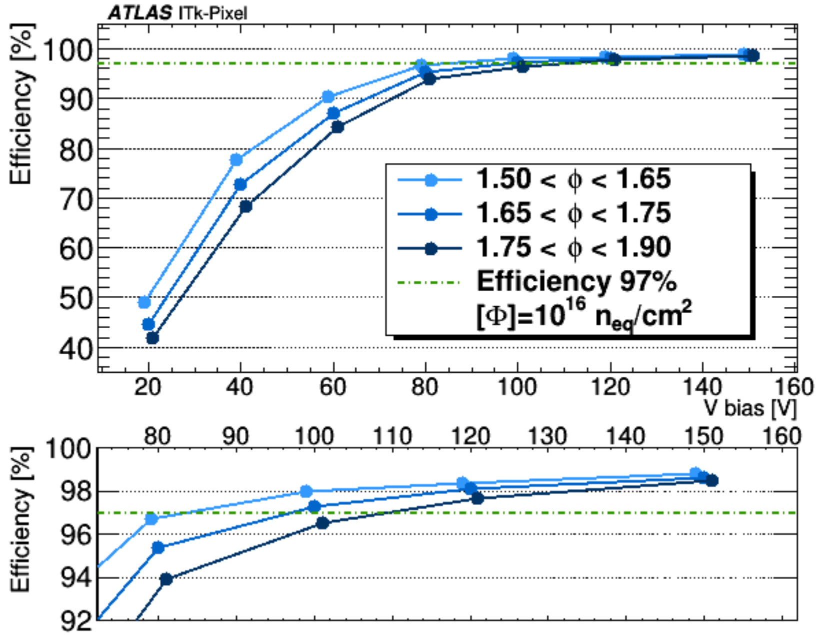
3D FBK 50x50

Upper picture:

- Hit efficiency plot for SCC29 (25x100 µm^2) and SCC3 (50x50 µm^2) perpendicular and inclined configuration.
- At 1 $\cdot 10^{16} n_{eq}/cm^2$ fluence both reached the 97% hit efficiency required at 60 V.

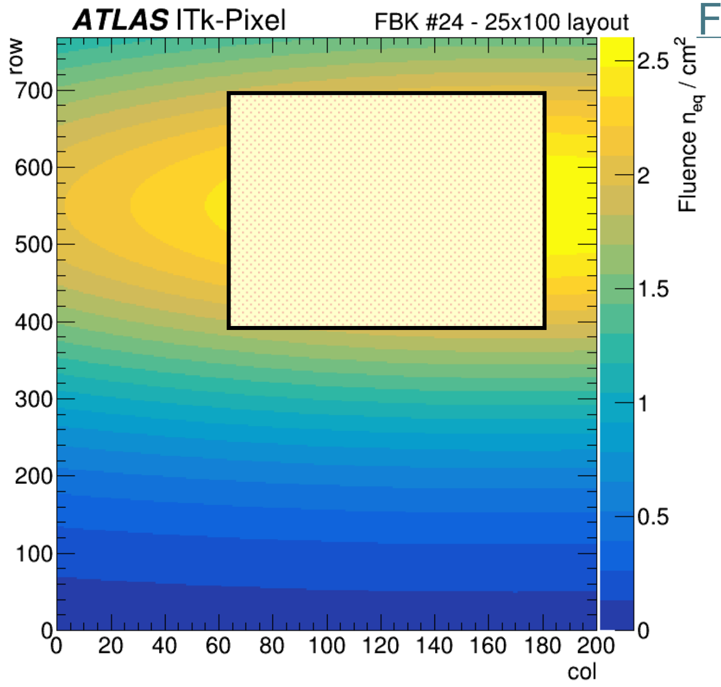
Bottom picture:

- 3D FBK 50x50 µm^2 measured at target fluences in 2022 and 2023 Irradiated at IRRAD (not uniform irradiation)
- Efficiency reached 97% at 1.7 $\cdot 10^{16}\, n_{eq}/cm^2$ with the 3% of disabled pixels at 130 V.



FBK 3D pixel Sensors

FBK 25x100



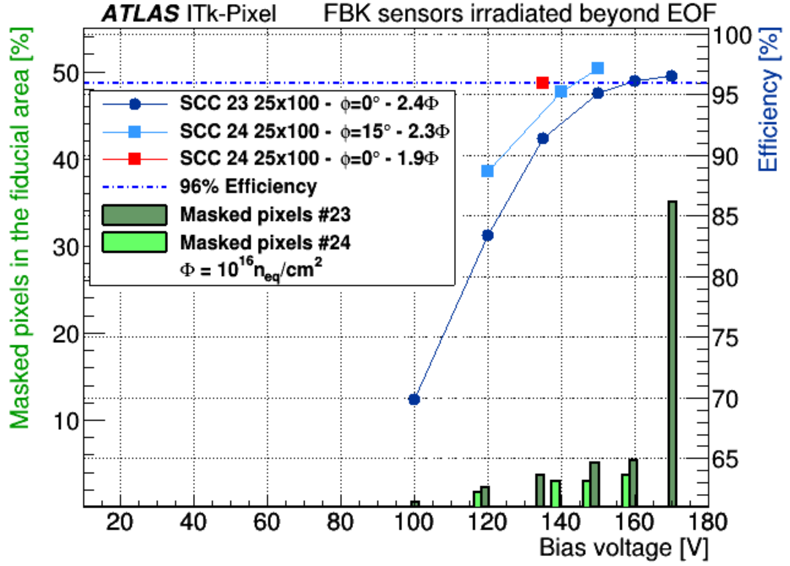
Upper picture:

- The irradiation fluency level in the SCC24 25x100 μm^2 to max. 2.4 $\cdot 10^{16}$ n_{eq}/cm^2 (mean 1.7 $\cdot 10^{16}$ n_{eq}/cm^2), similar results for SCC23.
- Picture shows the area where the testbeam experiment data was taken.

Bottom picture:

- **Hit efficiency results**
  - SCC23: Efficiency reaches 96% (normal incidence) even after irradiation at 2.5 $\cdot 10^{16}$ n_{eq}/cm^2 although with the 5% of disabled pixels at 160V that rapidly increasing at higher V_bias.
  - SCC24: Efficiency is close to 97% (inclined) in the area with mean fluence around 1.9 $\cdot 10^{16}$ n_{eq}/cm^2 with the 3% of disabled pixel at 150 V.

Beyond EOL



High number of dissable pixel because the radiation damage

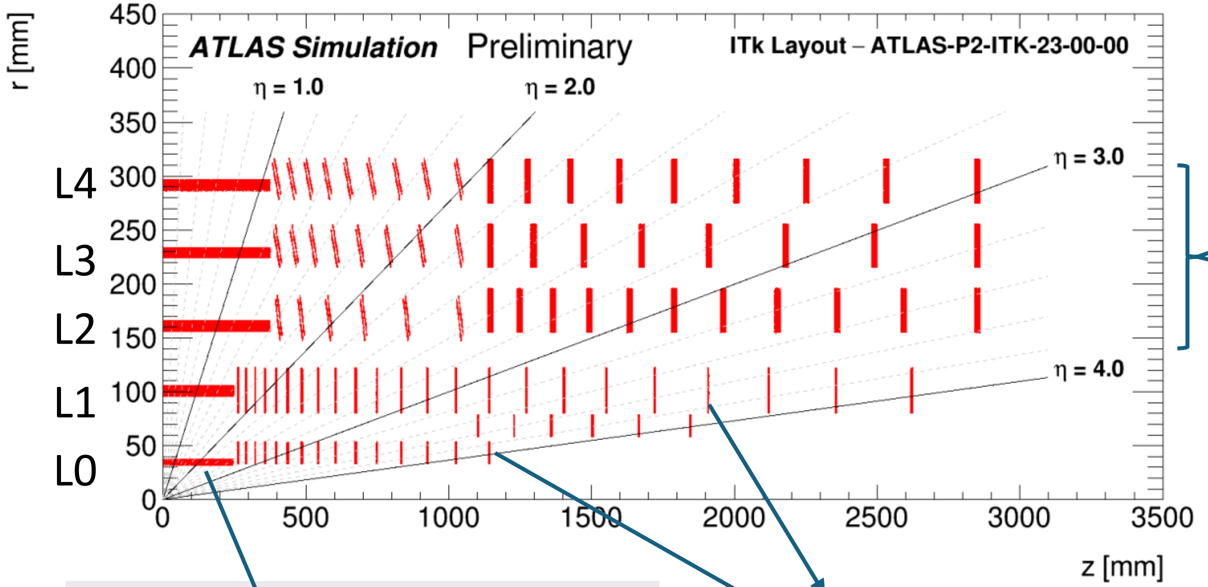
Further uniform irradiation of 25x100 3D pixel sensor is planner

Conclusion

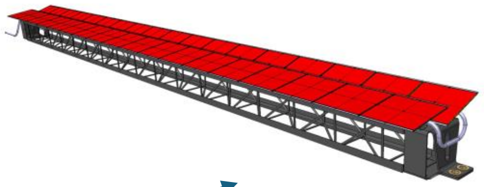
- Verification of the detection efficiency performance of the pre-production sensors was presented.
  - SINTEF 3D pixel sensor 50x50
  - FBK 3D pixel sensor 50x50 and 25x100
  - HPK 50x50 planar sensor
- 3D pixel and planar sensors meet the specifications at the corresponding irradiation fluence.
- New test beam campaign in 2024 for more measurements to confirm results, to test remaining vendor/module type combinations, to test first modules with the final chip ITkPixV2.

Thank you for your attention

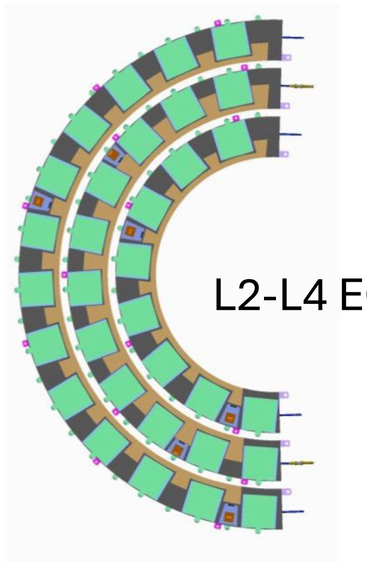
ATLAS ITk configuration



L2-L4 OB quad staves

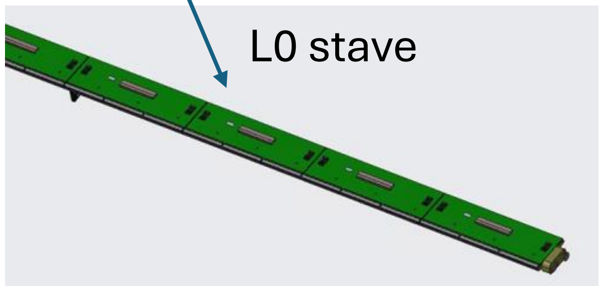


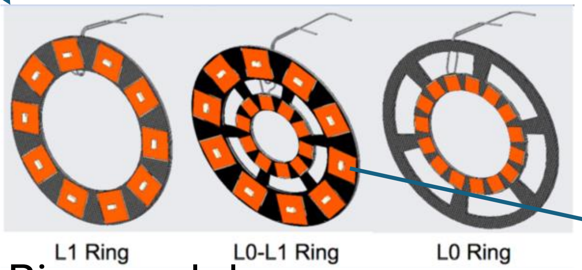
L2-L4 OB rings



L2-L4 EC rings

L0 stave





Quad module:
4 planar sensors bump
bonded to 1 FE glued to 1 PCB

Linear module:
3 bare modules on 1 pcb

Ring module
3 bare modules on 1 pcb