Novel pixel sensors for the Inner Tracker upgrade of the ATLAS experiment at HL-LHC

ATLAS-ITk Collaboration

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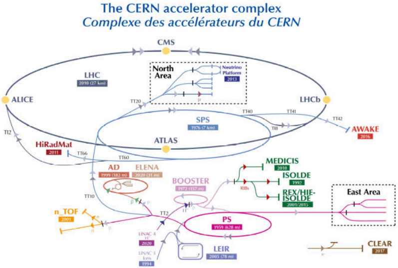
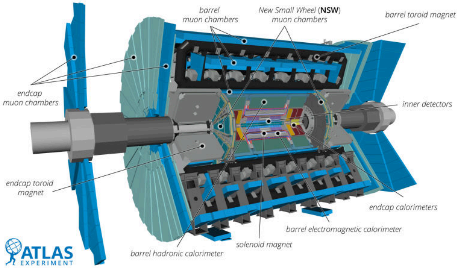
Siena 25/09/2023

HL-LHC and ATLAS upgrade



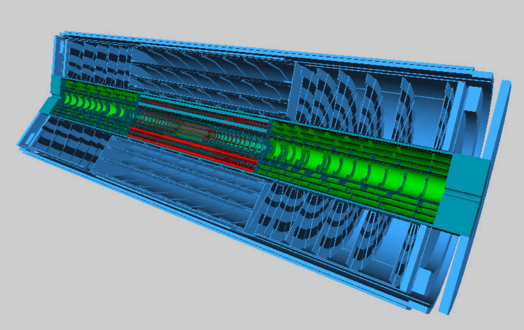


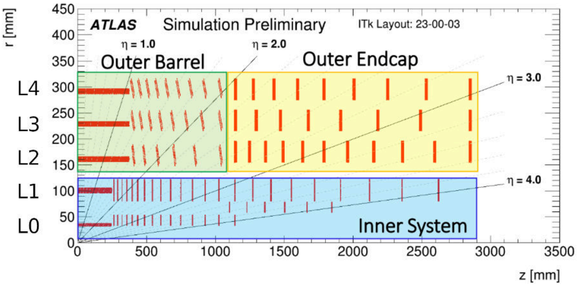
[1]

- The LHC is to be upgraded for higher luminosity ($1 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to $7.5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$), energy, number of events per bunch encounters (50 to 200) to improve probing of SM and beyond SM
- ATLAS must be able to distinguish very close particles, at high frequency
- Must withstand high irradiation fluence in its end of life (up to $2 \cdot 10^{16}\mathrm{n_{eq}}/\mathrm{cm}^2$ 1.5 safety factor)
- Need for new pixels detectors : ATLAS ITk Pixel

[1] Ewa Lopienska. "The CERN accelerator complex, layout in 2022. Complexe des accélérateurs du CERN en janvier 2022". In: (2022). General Photo. URL: https://cds.cern.ch/record/2800984.

ATLAS ITk



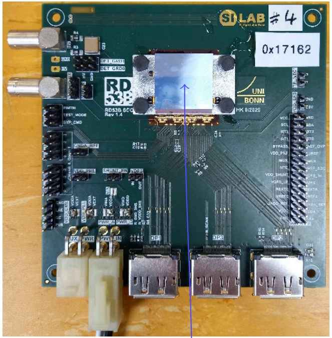


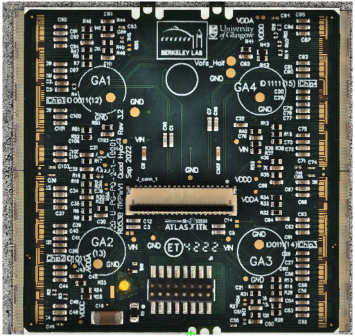
[2]

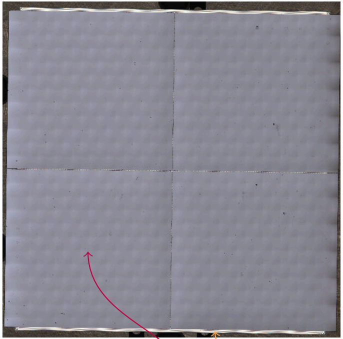
Section	Flat barrel		End caps	
Layer	Sensor type	Dimensions	Sensor type	Dimensions
L0	Triplets	3d, $25 \times 100\mu m^2$	Triplets	3d, $50 \times 50\mu m^2$
L1	Quad	Planar, $50 \times 50\mu m^2$, $100\mu m$ thickness	Quad	Planar, $50 \times 50\mu m^2$, $100\mu m$ thickness
L2	Quad	Planar, $50 \times 50\mu m^2$, $150\mu m$ thickness	Quad	Planar, $50 \times 50\mu m^2$, $150\mu m$ thickness
L3	Quad	Planar, $50 \times 50\mu m^2$, $150\mu m$ thickness	Quad	Planar, $50 \times 50\mu m^2$, $150\mu m$ thickness
L4	Quad	Planar, $50 \times 50\mu m^2$, $150\mu m$ thickness	Quad	Planar, $50 \times 50\mu m^2$, $150\mu m$ thickness

[2] *Technical Design Report for the ATLAS Inner Tracker Pixel Detector*. Tech. rep. Geneva: CERN, 2017. DOI: 10.17181/CERN.FOZZ.ZP3Q. URL: https://cds.cern.ch/record/2285585 and *Expected tracking and related performance with the updated ATLAS Inner Tracker layout at the High-Luminosity LHC*. Tech. rep. All figures including auxiliary figures are available at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024. Geneva: CERN, 2021. URL: https://cds.cern.ch/record/2776651.

ATLAS ITk





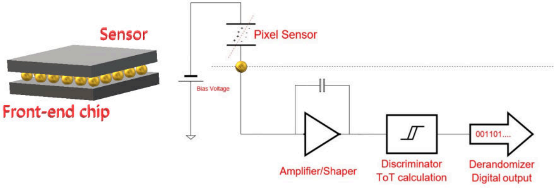


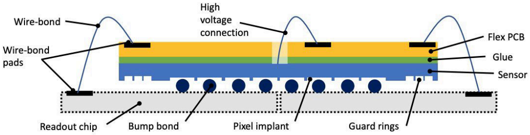
A SCC is embedding 1 sensor and 1 chip on a rigid pcb, a quad holds for 1 flexible pcb with 4 chips on 1 sensor.

ITk pixel concept

The pixels in outer layers uses $50 \times 50\mu\text{m}^2$ silicon n-in-p planar sensors with a $150\mu\text{m}$ thick substrate[3].

Those sensors are then bump-bonded to read-out front-end chips, those chips being wire-bonded to a flex pcb.





[4]

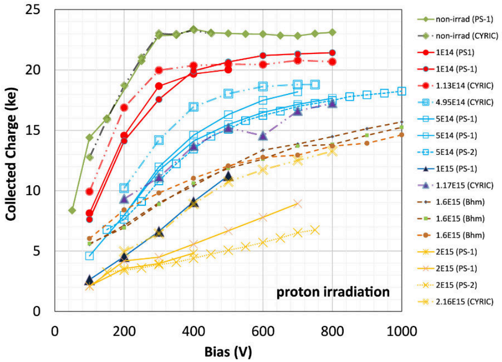
Particles passing in silicon sensor generates pairs of electrons and holes by ionization.

Charges are collected through drift phenmenon, moving in electric depletion field.

[3] Maurice Garcia-Sciveres, Flavio Loddo, and Jorgen Christiansen. ***RD53B Manual***. Tech. rep. Geneva: CERN, 2019. URL: https://cds.cern.ch/record/2665301.

[4] ***Technical Design Report for the ATLAS Inner Tracker Pixel Detector*** and Julien-Christopher Beyer. "**Optimisation of pixel modules for the ATLAS inner tracker at the high-luminosity LHC**". Mar. 2019. URL: http://nbn-resolving.de/urn:nbn:de:bvb:19-239390.

Charge collection before and after irradiation



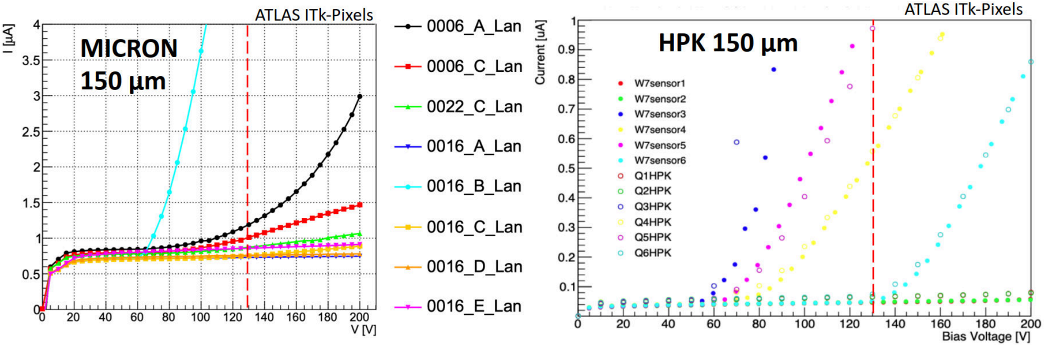
[5]

Irradiation generates defects in lattice of Si atoms

An irradiated sensor has a loss of collected charges and needs higher bias voltage

Higher bias voltage -> higher leakage current -> higher noise

[5] **Giovanni Calderini**. ***The ATLAS ITk detector for High Luminosity LHC Upgrade***. Tech. rep. Geneva: CERN, 2022. DOI: 10.1016/j.nima.2022.167048. URL: https://cds.cern.ch/record/2798838.



[6]

Breakdown voltage mostly in accordance with ITk specifications ($> \mathrm{V_{depl}} + 70\mathrm{V}$[7], $\mathrm{V_{depl}} = 60\mathrm{V}$, so $> 130\mathrm{V}$)

Low leakage current mostly in accordance with ITk specifications ($< 0.75\mu\mathrm{A/cm^2}$ at $\mathrm{V_{depl}} + 50\mathrm{V}$, chip is $2 \times 2\mathrm{cm^2}$ so $< 1.2\mu\mathrm{A}$ at $110\mathrm{V}$)

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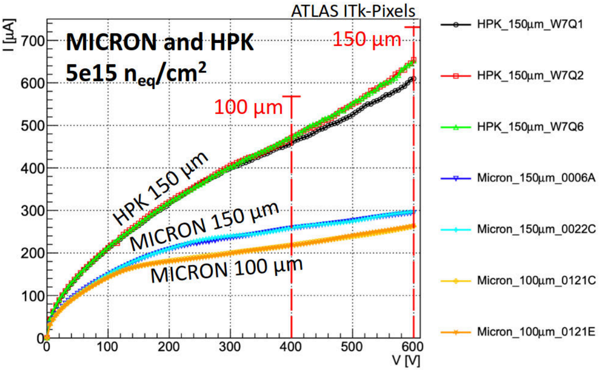
[6] Stefano Terzo and ATLAS Collaboration. "Novel pixel sensors for the Inner Tracker upgrade of the ATLAS experiment". In: (2023). URL: https://cds.cern.ch/record/2870239.

[7] Yusong Tian et al. *ATLAS ITk Pixel Pre-production Planar Sensor Characterisation for the HL-LHC Upgrade*. Tech. rep. Geneva: CERN, 2023. DOI: 10.22323/1.420.0067. URL: https://cds.cern.ch/record/2847990.



[8]

No breakdown voltage observed before 600 V (ITk specifications > 600 for $150\mu m$ thickness ones and > 400 for $100\mu m$ thickness ones)

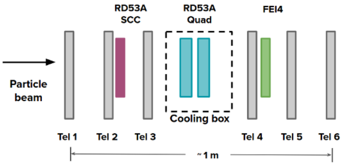
Higher leakage current but still in ITk specifications

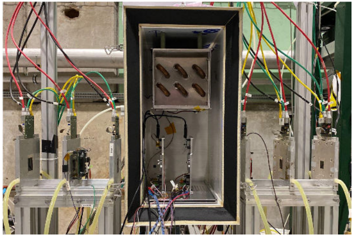
- $150\mu m$ thickness : $< 45\mu A/cm^2$, chip is $2 \times 2cm^2$ so $< 720\mu A$ at $600V$
- $100\mu m$ thickness : $< 35\mu A/cm^2$, chip is $2 \times 2cm^2$ so $< 560\mu A$ at $400V$

[8] Terzo and Collaboration, "Novel pixel sensors for the Inner Tracker upgrade of the ATLAS experiment".

To evaluate the actual tracking capability of the modules :

- Test in pion beam ($\mathrm{E} \simeq 120\mathrm{GeV}$) at CERN SPS North Area and in proton beam ($\mathrm{E} \simeq 24\mathrm{GeV}$) at PS East Area
- Device Under Test (DUT) in beam line between telescope planes (accurate track reconstruction)
- Tracks reconstructed with telescope, extrapolated to DUT, check for hits on DUTs for those tracks





[9]

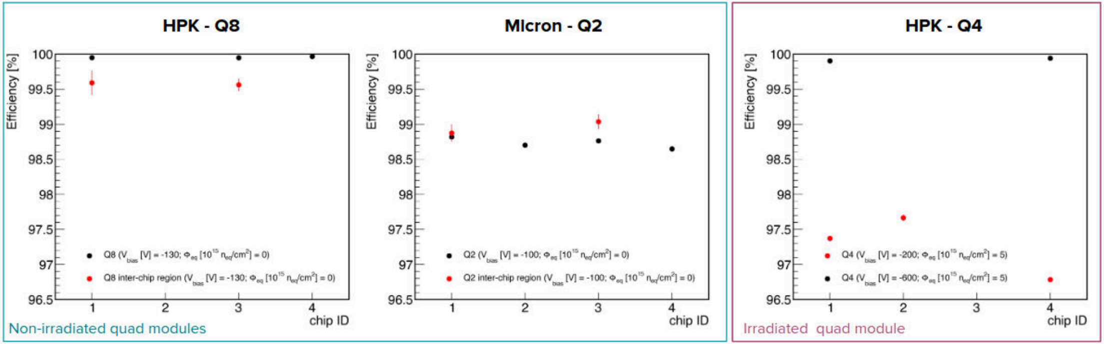
Efficiency of reconstruction : $\epsilon = \frac{\text{Number of tracks with associated cluster on DUT}}{\text{Total number of tracks intersecting DUT}}$

ITk requirements on efficiency[10] :

- Non irradiated modules : $\epsilon \geq 98\%$
- Irradiated modules : $\epsilon \geq 97\%$ at max 400V for $100\mu\mathrm{m}$ and 600V for $150\mu\mathrm{m}$

[9] Sejla Hadzic. "ATLAS ITk Pixel quad module test-beam measurements". In: (2022). URL: https://cds.cern.ch/record/2813300.
[10] Hadzic, "ATLAS ITk Pixel quad module test-beam measurements".

Hit efficiency per chip



HPK - Q8

- Chip 2 was disabled
- $\varepsilon >$ **99.9%** for all 3 measured chips
- $\varepsilon >$ **99.5% (inter-chip region)**

Micron - Q2

- All chips enabled
- $\varepsilon >$ **98.5%**

HPK - Q4

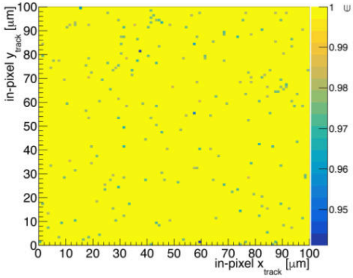
- Chip 3 was disabled
- $\varepsilon \sim$ **97.0%** (-200 V)
- $\varepsilon \sim$ **99.9%** (-600 V)

The efficiency uncertainties are statistical.

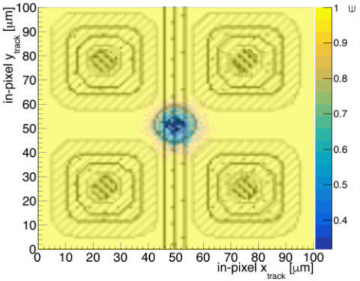
[11] Hadzic, "ATLAS ITk Pixel quad module test-beam measurements".

Hit efficiency map (50x50 μm^2 pixels)

HPK - Q8

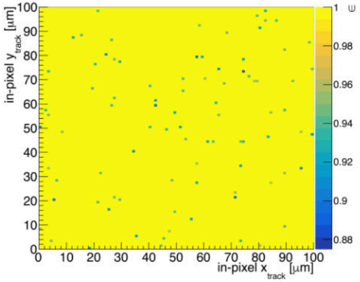


Micron - Q2



Non-irradiated quad modules

HPK - Q4



Irradiated quad module

Threshold tuning: 1500e
Bias voltage: -130 V
Leakage current: -0.2 µA
T: ~20 °C

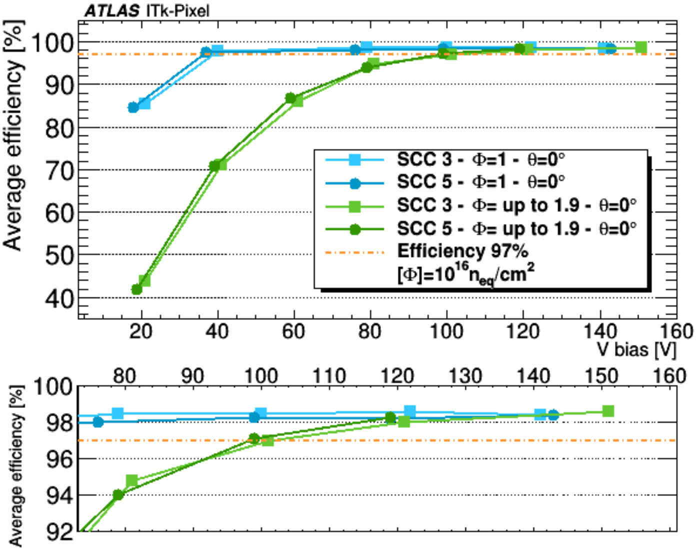
Threshold tuning: 1500e
Bias voltage: -100 V
Leakage current: -4.8 µA
T: ~25 °C

with a punch-through biasing structure

Threshold tuning: 1500e
Bias voltage: -600 V
Leakage current: -100 µA
T: ~ -30 °

[12] Hadzic, "ATLAS ITk Pixel quad module test-beam measurements".

Track reconstruction efficiency at two different fluences for 3d SCC

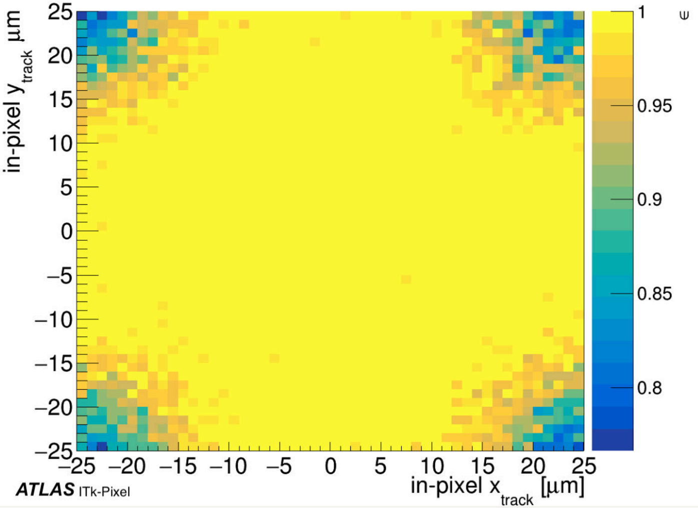


13

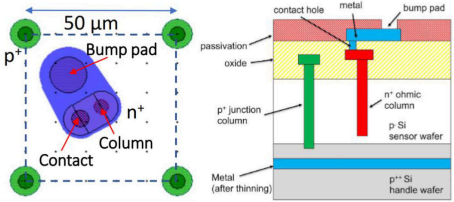
- Irradiation went from $1 . 10^{16} \mathrm{n_{eq}/cm^2}$ to $1.9 . 10^{16} \mathrm{n_{eq}/cm^2}$
- Efficiency is significantly reduced for bias under 80V
- Over 100 V efficiency regains acceptable values
- The breakdown voltage is far enough to enable reaching the 170 V bias for the 98% efficiency

[13] BTTB2023testbeamresults, 3D FBK irradiated at ultimate fluence 12 December 2022 .

In-pixel track reconstruction efficiency at ultimate fluence for perpendicular SCC5



- Mean efficiency $> 97\%$ at 100V bias
- Efficiency is lower in the corners because of design of 3d diode
- Diode p-n junction is not a plane - it is made of n+ and p+ columns in p- region
- The p+ on the corner is a ohmic column for biasing - it does not collect charges

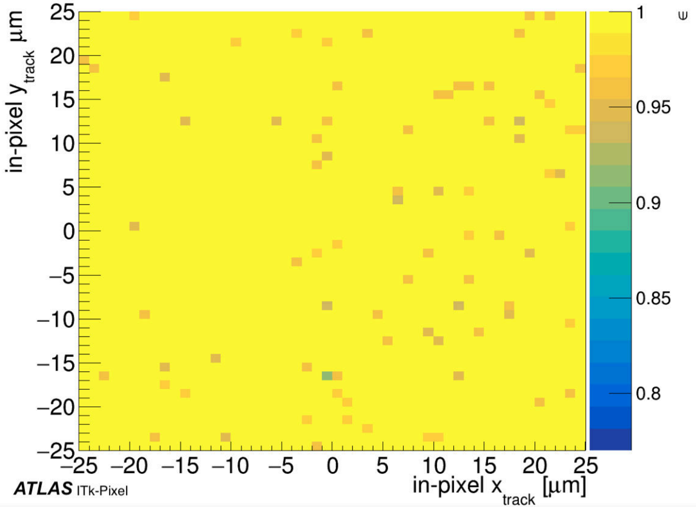


[14], [15]

[14] BTTB2023testbeamresults, 3D FBK irradiated at ultimate fluence 12 December 2022 .

[15] Alessandro Lapertosa et al. *Test of ITk 3D sensor pre-production modules with ITkPixv1.1 chip*. Tech. rep. Geneva: CERN, 2022. URL: https://cds.cern.ch/record/2834417

In-pixel track reconstruction efficiency at ultimate fluence for 15° tilted SCC5



[16]

- Mean efficiency $> 97\%$ at $90\mathrm{V}$ bias
- Efficiency is uniform as expected for tilted 3d

[16] BTTB2023testbeamresults, 3D FBK irradiated at ultimate fluence 12 December 2022 .

Summary

Sensors electrical behavior

Bias voltage compensates the charge collection efficiency decrease when irradiatied
Leakage current and breakdown voltage are within the tolerancies after reaching the final irradiation doses

Quad reconstruction

Quads were irradiated at up to $5 \cdot 10^{15} \mathrm{n_{eq}/cm^2}$
A higher bias voltage allows to reach in specification efficiency

SCC reconstruction

SCC were irradiated at up to $1.9 \cdot 10^{16} \mathrm{n_{eq}/cm^2}$
Thus having received a higher irradiation, they still meet the requirements when biased enough
Lower efficiency in corners for 3d vanishing when tilted as expected, as 3d will be tilted in detector

Conclusion

Both 3d and plannar sensors gives good results
Preproduction has been initiated