ATLAS ITk

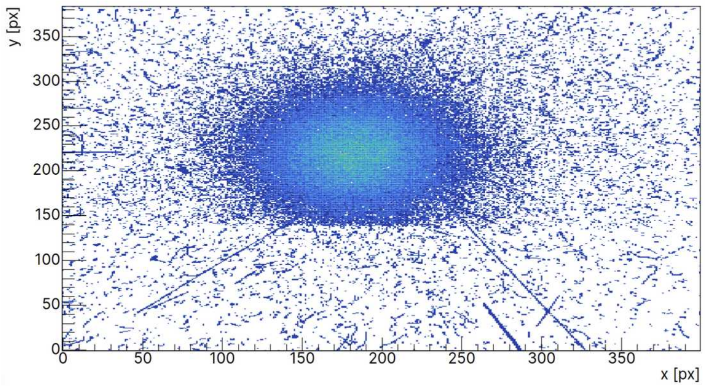
Characterization of Pixel Detectors with Test Beams for the Inner Tracker Upgrade of the ATLAS

VERTEX 2023

19th October 2023

André Rummler

On-behalf of the ITk Pixel collaboration



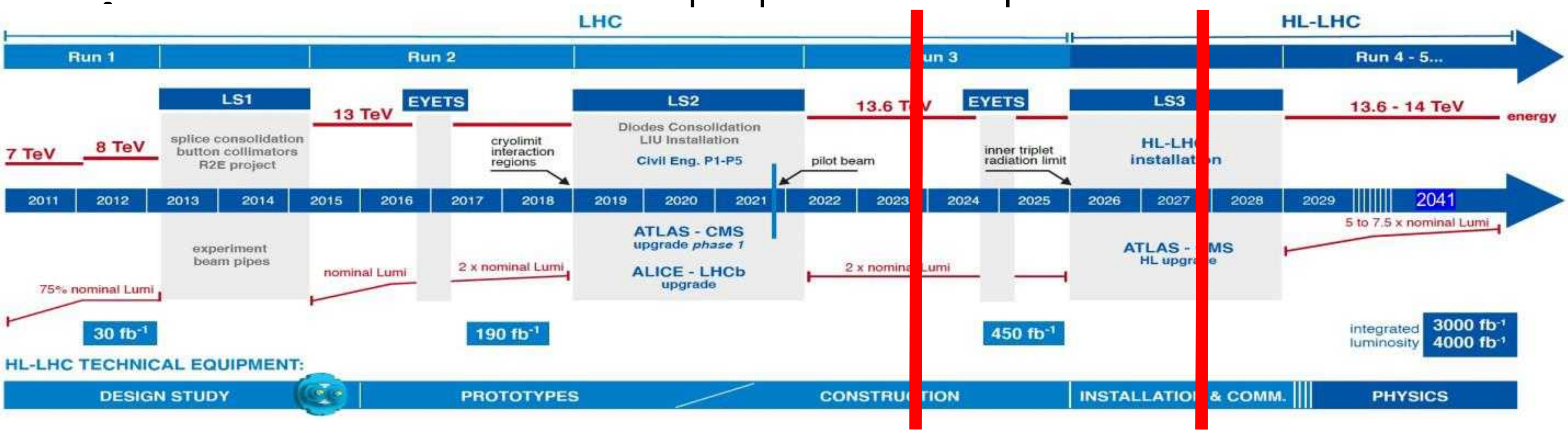
This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.

CERN

HL-LHC and ATLAS upgrade

- HL-LHC upgrade is under construction and will provide after LS3 primarily a peak luminosity increased by more than a factor 3 to $7.5 \cdot 10^{34}$ cm^{-2} s^{-1}
- Pile up (events per bunch crossing) will increase from maximum 50 to maximum 200
- The current ATLAS Inner Detector cannot cope with these conditions and another 20+ years of operation would exceed massively the current detector's life expectancy

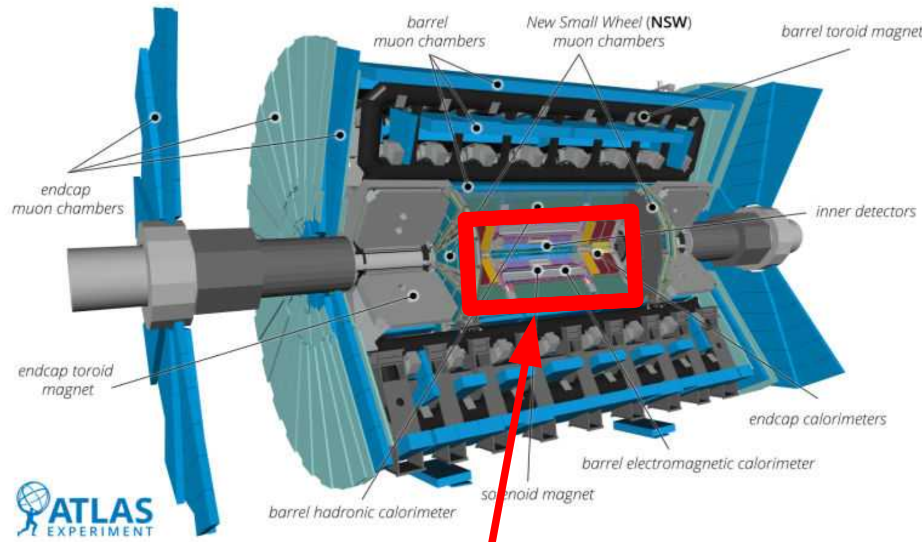
pre-production → production



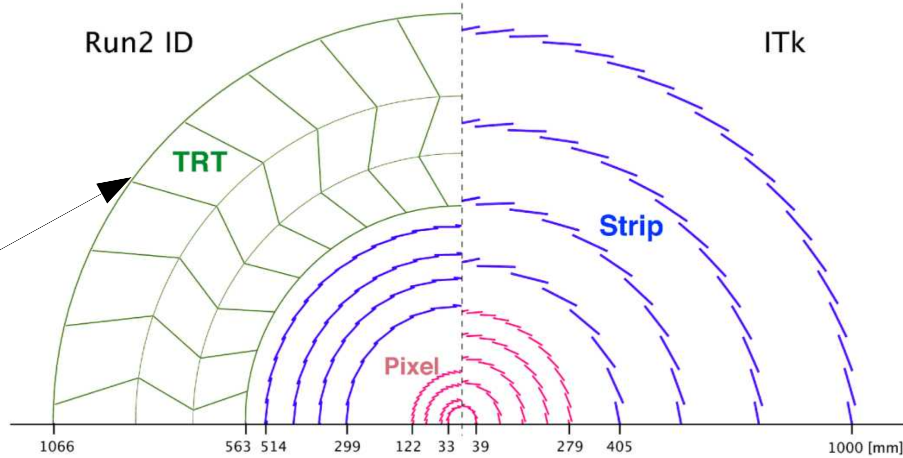
Now Insertion ITk

ITk Overview

- The current ATLAS Inner Detector will be replaced by a new full silicon detector
- The Inner Tracker (ITk) will consist of the pixel and the strips detector
- Pixel forward coverage increase: η<2.5 to η<4
- Resulting in total in a factor 10 larger active surface: 1.9 m^2 to 13.5 m^2



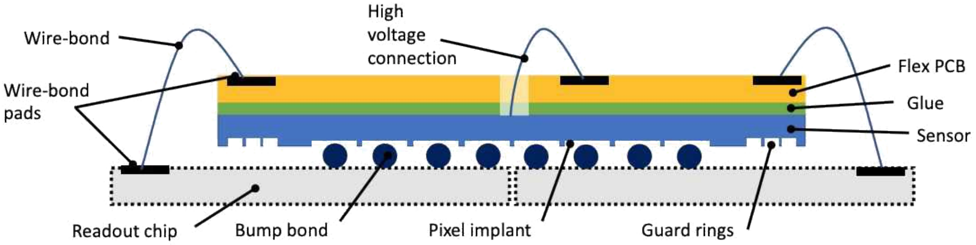
Far more details in the ITK Pixel overview talk by Joleen Pater on Tuesday



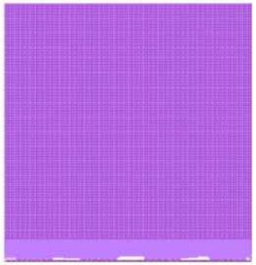
gas detector

ITk Pixel Modules

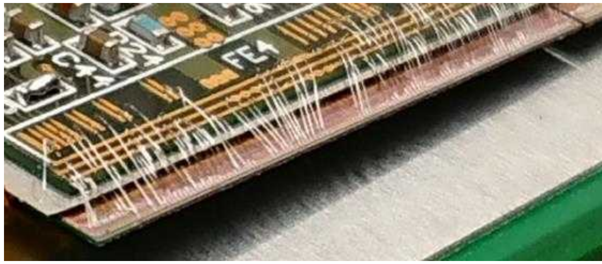
- Pixel modules are mounted on staves and rings with embedded CO_2 cooling: <-25° C on sensor (max. -45°C coolant)
- Hybrid sensor modules consisting of one sensor tile with one or four readout chips connecting each pixel cell by a bump ball
- ITKPix (RD53) as readout chip
- On the sensor tile a flex PCB is attached by glue which connects the readout chips by wire bonds
- Another flex (pig tail) attached to it realizes the connection to the exterior through the stave flex

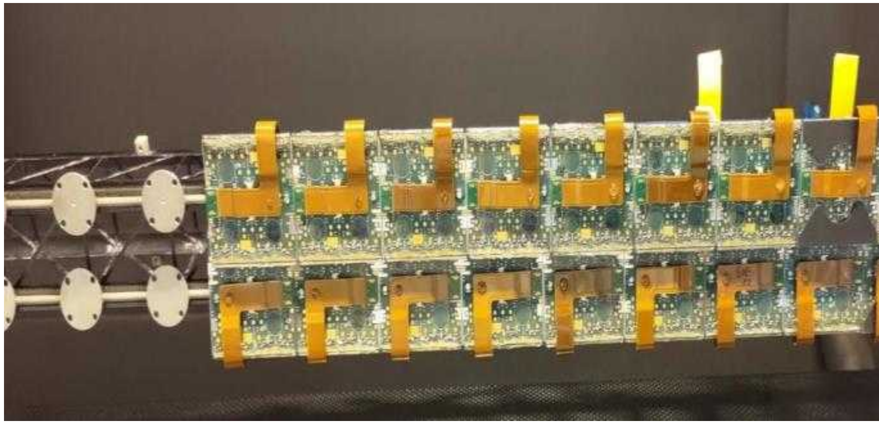


20mm (400 rows)



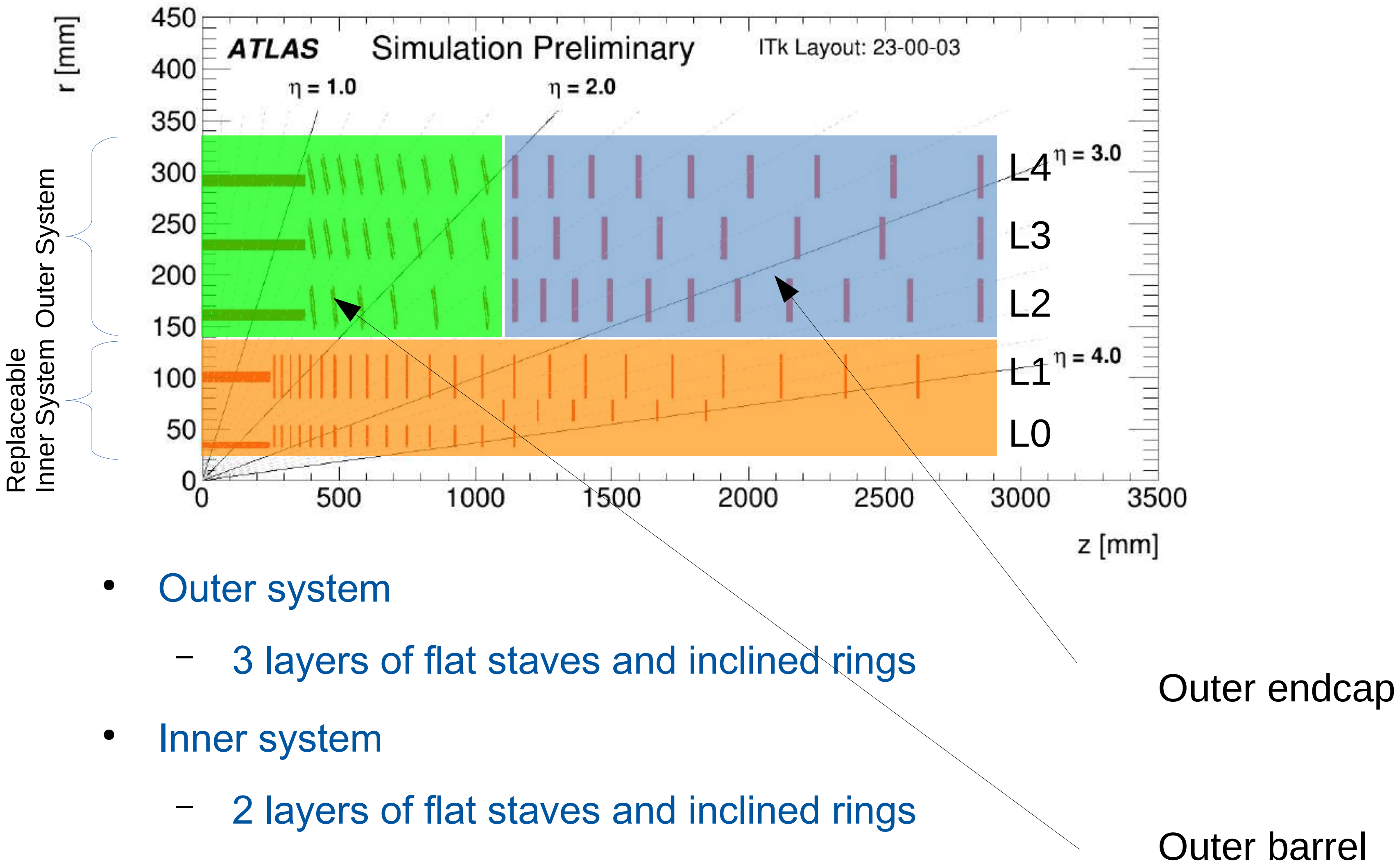
20mm (384 columns)





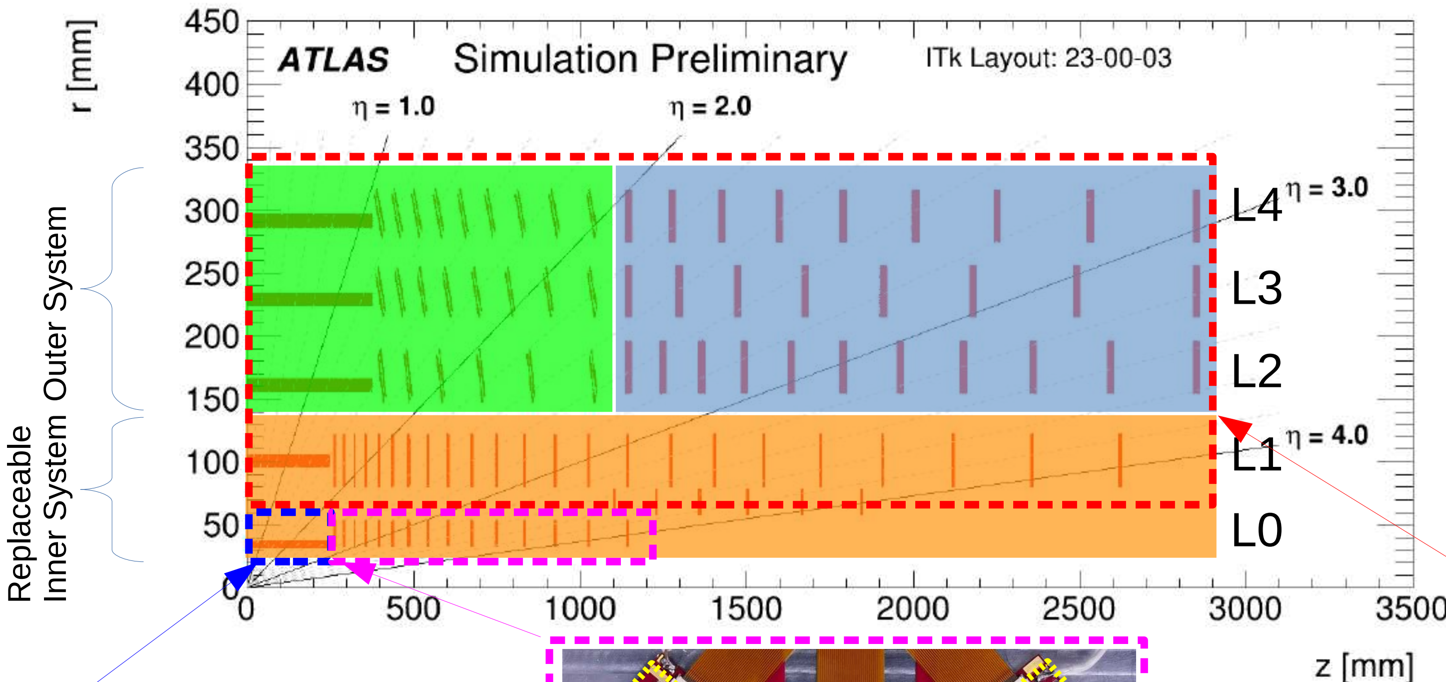
ITk Pixel Structure

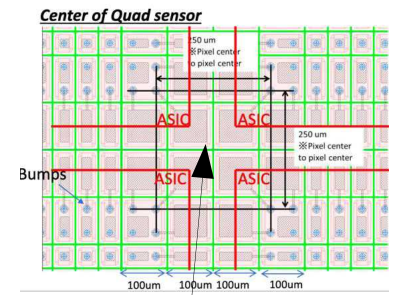
ATL-PHYS-PUB-2021-024



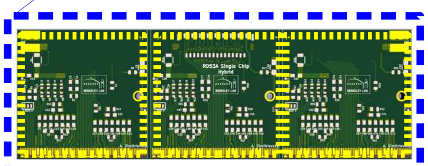
- Outer system
  - 3 layers of flat staves and inclined rings
- Inner system
  - 2 layers of flat staves and inclined rings

Pixel module types

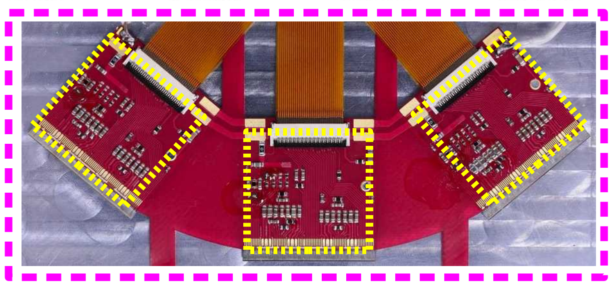




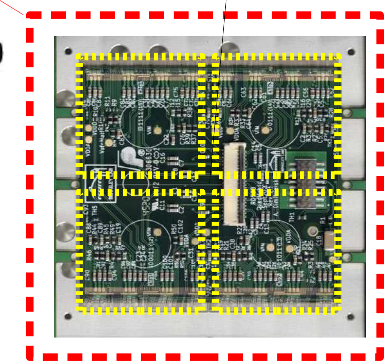
inter pixel region between read out chips covered with larger pixels



Triplet module barrel

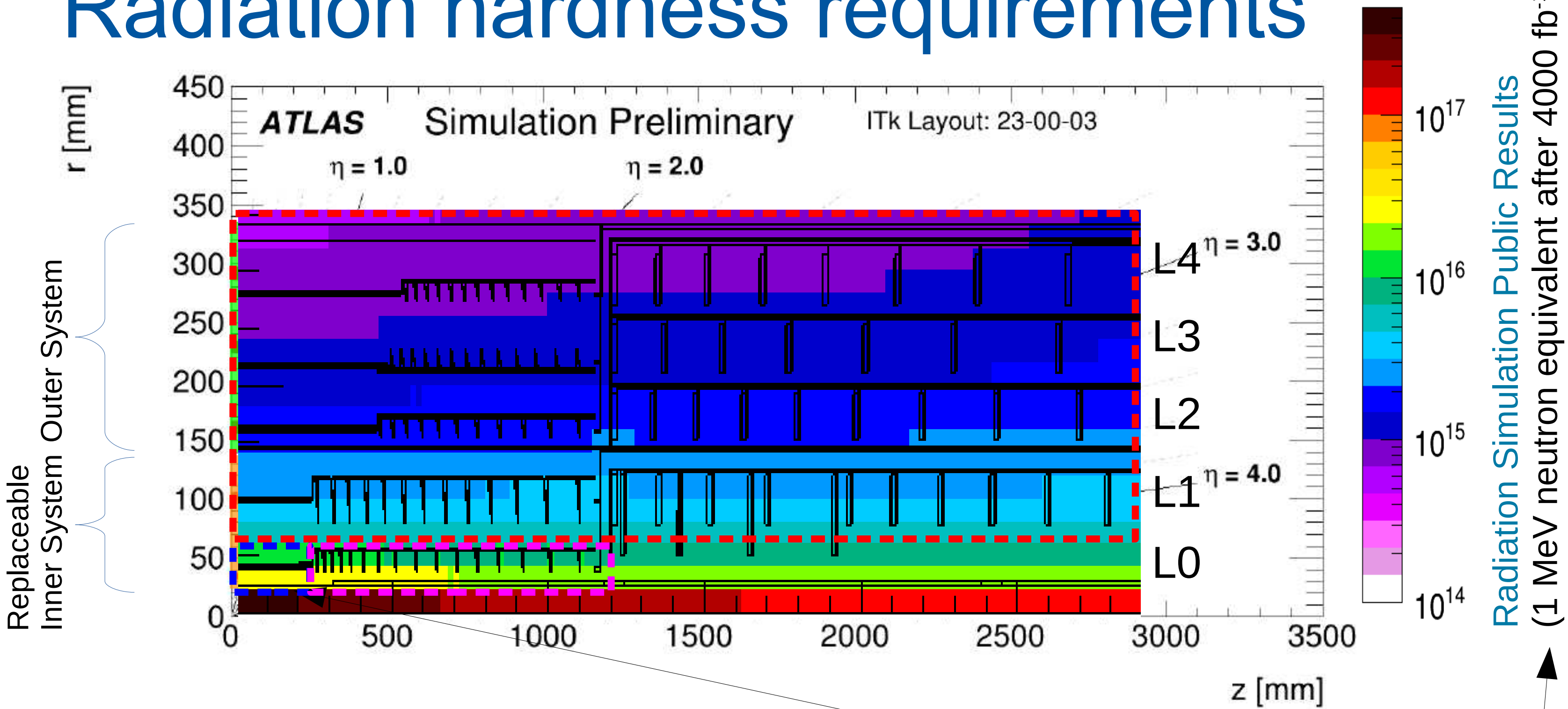


Triplet module end cap



Quad module

Radiation hardness requirements

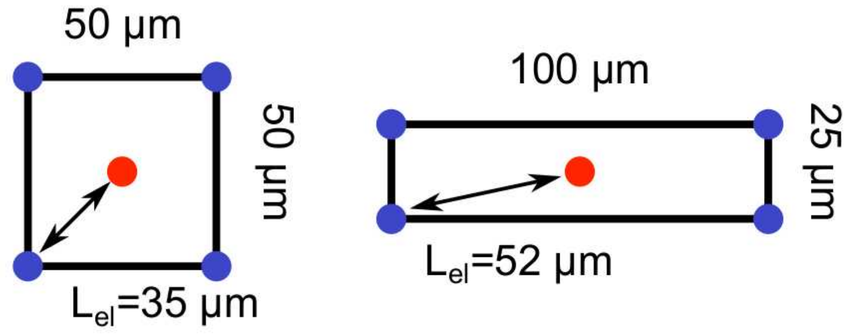


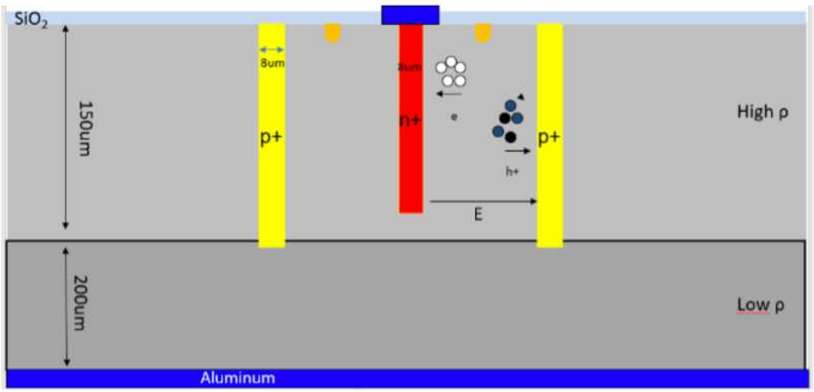
- Outer system
  - $5 \cdot 10^{15}$ n_{eq} cm^2 with safety factors
  - 6816 planar quad modules with 150 µm thick sensor, 50 µm x 50 µm pixels
- Inner system
  - $1.7 \cdot 10^{16}$ n_{eq} cm^2 with safety factors
  - Inner 2 layers will be replaced after half the run time
  - L0: 1188 3D single modules (25 µm x 100 µm 2 for flat and 50 µm x 50 µm for the endcaps)
  - L1: 1200 planar quad modules with 100µm thick sensor, 50 µm x 50 µm pixels

Ten years ~10^{17}
→ replacement after ~5 years

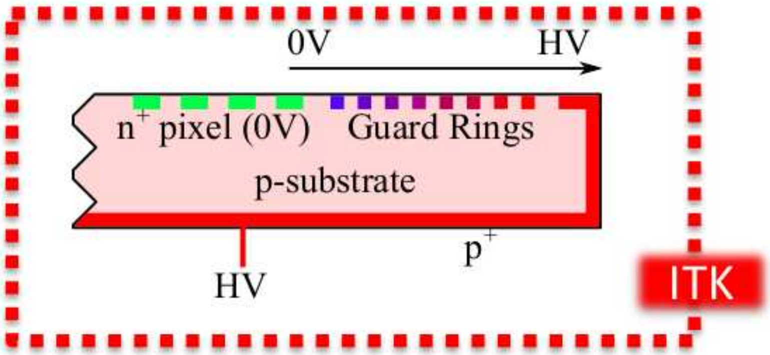
3D Sensors

- 3D sensors in the inner most region (L0 and corresponding rings) as:
  - Very high radiation hardness at low bias voltage
  - Higher cost due to technical complexity
  - Potentially higher capacity/noise
- 150 µm active wafer (high resistivity p^-) bonded to a 100 µm handling wafer (thinned after production)
- Both n^+ readout columns and p^- bias columns etched from the same side
- 25 µm x 100 µm pixel cells in barrel for improved impact resolution
- Manufacturers chosen: FBK and SINTEF

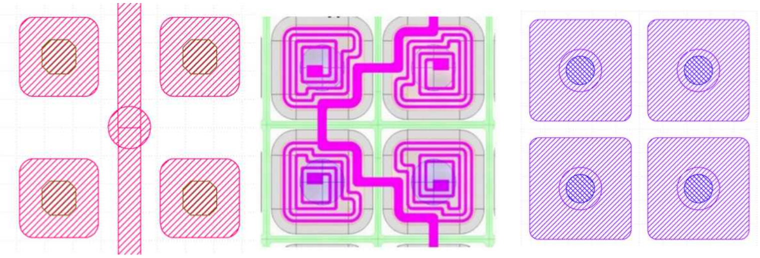




Planar Sensors



- Planar sensors in the Outer System:
  - Reduced radiation hardness requirements
  - Lower cost
- N-in-p wafers single side processed with 100 µm bulk thickness in L1 and 150 µm in the outer layers
  - Thinner bulk reduces material budget and increases charge collection
  - Thicker bulk increases the yield
- Isolation (p-spray vs p-stop) and testing (punch through, bias rail/resistor, temporary metal) according to vendor preferences
- Manufacturers chosen: FBK, MICRON and HPK



punch through MICRON | bias rail HPK | temporary metal FBK

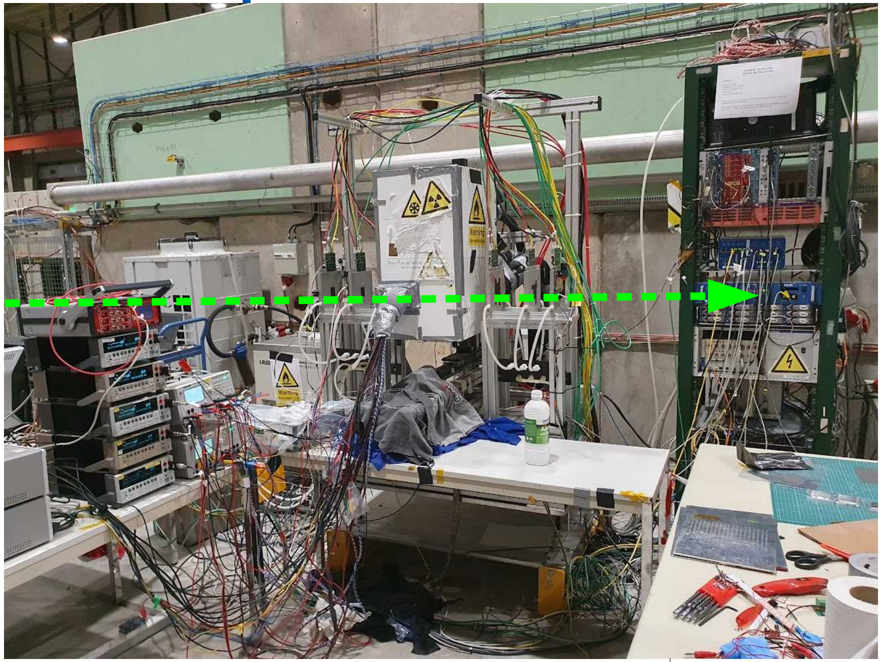
Section	Flat barrel		End caps	
Layer	Module type	Sensor properties	Module type	Sensor properties
L0	Triplet (straight)	3d, 25x100 μm^2	Triplet (arc)	3d, 50x50 μm^2
L1	Quad	Planar, 50x50 μm^2, 100 µm bulk	Quad	Planar, 50x50 μm^2, 100 µm bulk
L2	Quad	Planar, 50x50 μm^2, 150 µm bulk	Quad	Planar, 50x50 μm^2, 150 µm bulk
L3	Quad	Planar, 50x50 μm^2, 150 µm bulk	Quad	Planar, 50x50 μm^2, 150 µm bulk
L4	Quad	Planar, 50x50 μm^2, 150 µm bulk	Quad	Planar, 50x50 μm^2, 150 µm bulk

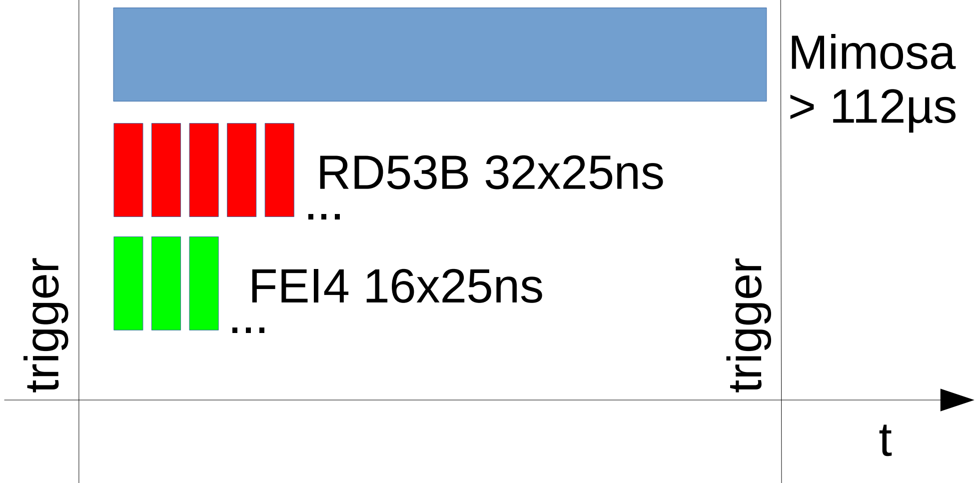
Sensor Type	Pixel Size [μm^2]	Bulk Thickness [µm]	Manufacturer	Bump Vendor
3d	50x50	150+handling	SINTEF	combinations of ADVACAM HPK IZM LEONARDO
			FBK	
	25x100		FBK	
planar	50x50	100	FBK	
			Micron	
		150	Micron	
			HPK	

data taking until end of September; analysis ongoing

Test Beam Experimental Setup

- ACONITE telescope (hodoscope) located in the SPS H6 beam line
  - EUDET telescope with 6 Mimosa26 planes and trigger scintillators with a pointing resolution of >3 µm
  - 120 GeV pions
  - FE-I4 (MMC3) plane and ITkPixV1.1 SCC (FBK) for track matching/ referencing → checked with both
  - Reconstruction with Corryvreckan using extended geometry class





Jansen, H., Spannagel, S., Behr, J. et al. Performance of the EUDET-type beam telescopes. EPJ Techn Instrum 3, 7 (2016). https://doi.org/10.1140/epjti/s40485-016-0033-2

D. Dannheim et al., "Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data", J. Instr. 16 (2021) P03008, doi:10.1088/1748-0221/16/03/P03008, arXiv:2011.12730D.

Test Beam Experimental Setup

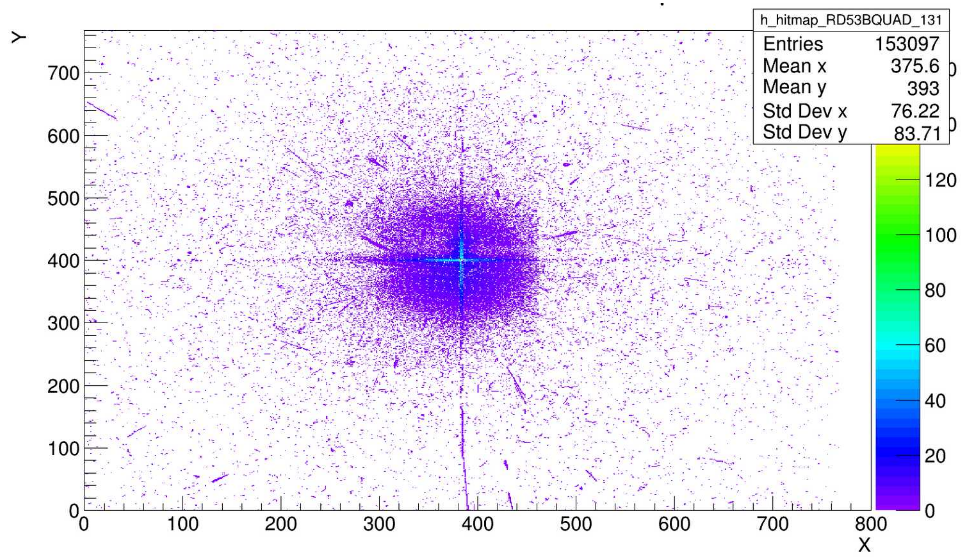
- Cold box
  - 2 deep temperature chillers driving external cooling circuits with silicon oil / ethanol:
    - Liquid/air heat exchanger inside the box
    - Nitrogen (for humidity control) pre-cooling
    - Optional direct cooling circuit for quads

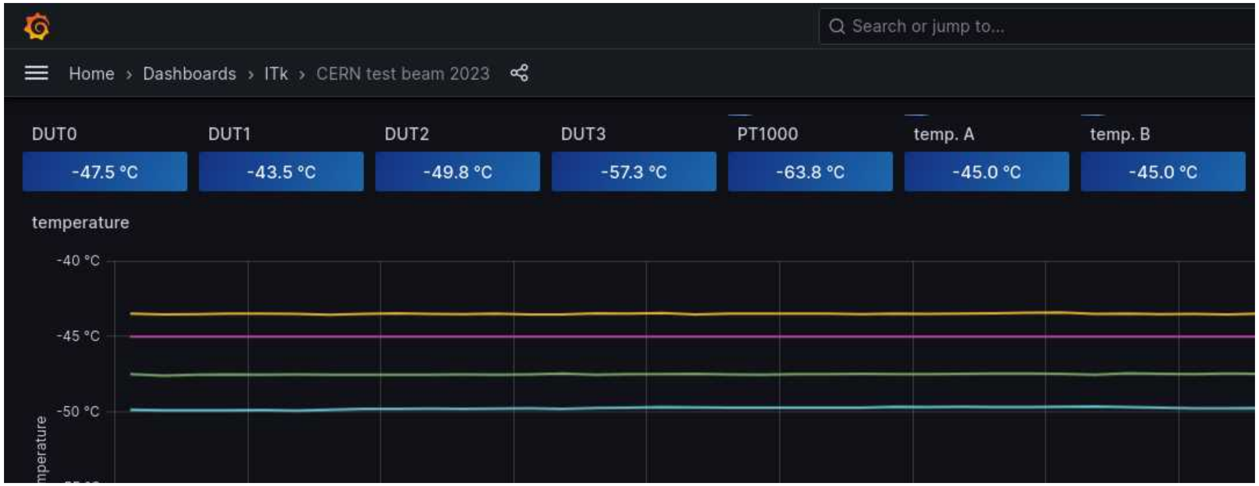
  - Achieved <-40°C on powered quad modules which is challenging due to the nature of test beam setups (no stave; no permanent connection) → reserves for various future tests
- 3D modules and planar single chip modules mounted on rigid PCBs intended for tests only while the planar quad modules were on flex PCBs
- Readout with YARR/OHIO card fully integrated into EUDAQ1
- Data taken with pre-production modules on rigid and flex PCBs irradiated at KIT (23 MeV protons), CERN IRRAD (24 GeV protons), CYRIC (70 MeV protons), Bonn (13 MeV protons)

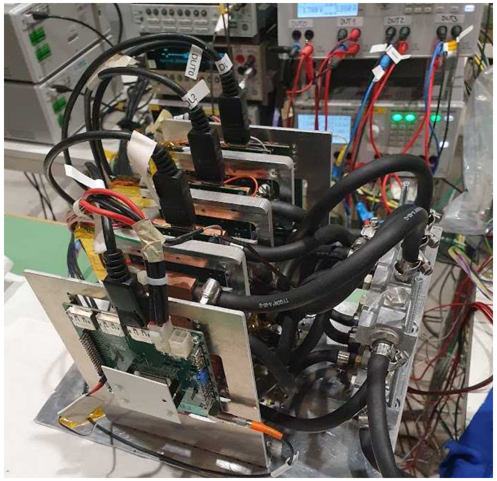
Planar sensor modules

- Data taken with
  - FBK planar
  - HPK planar
  - Micron planar 100 µm

  in September
  → analysis ongoing
- Preview...

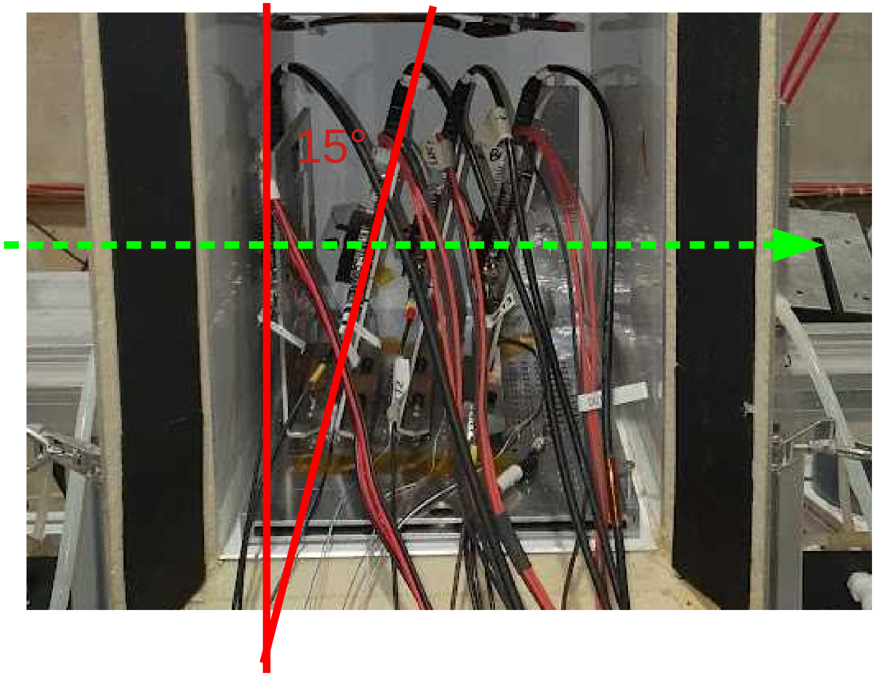


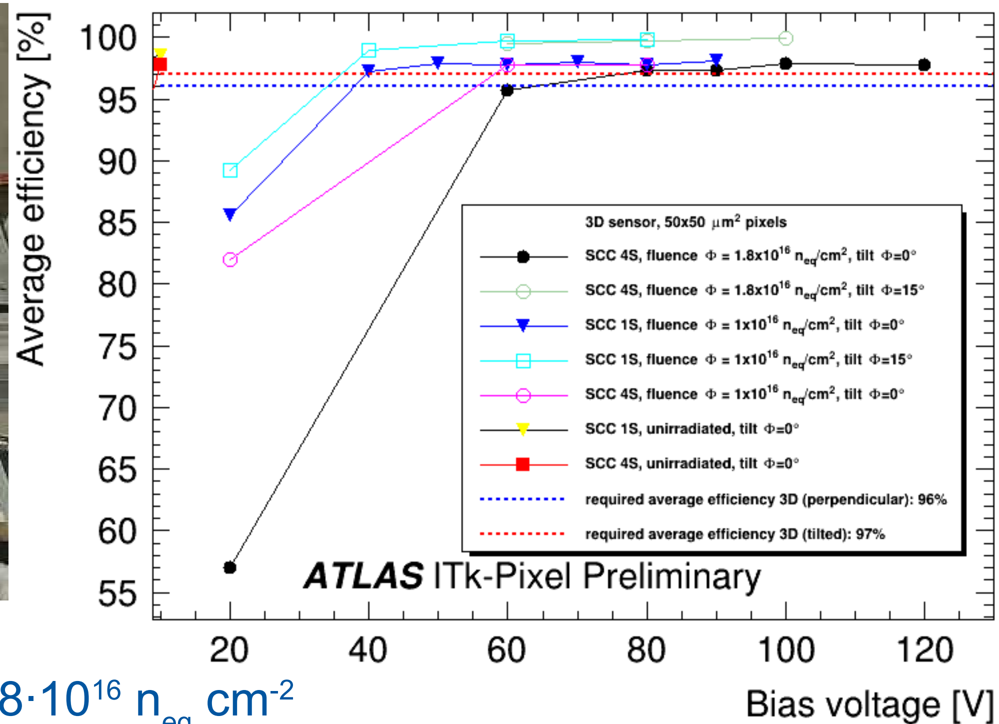




3D SINTEF 50 µm x 50 µm

see poster by Simen Hellesund

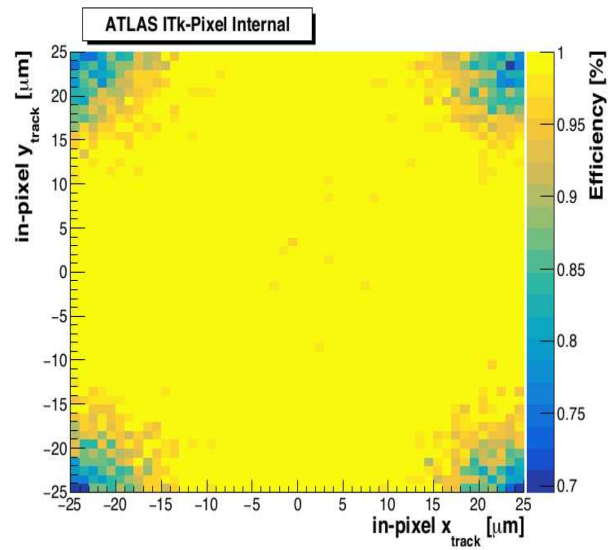


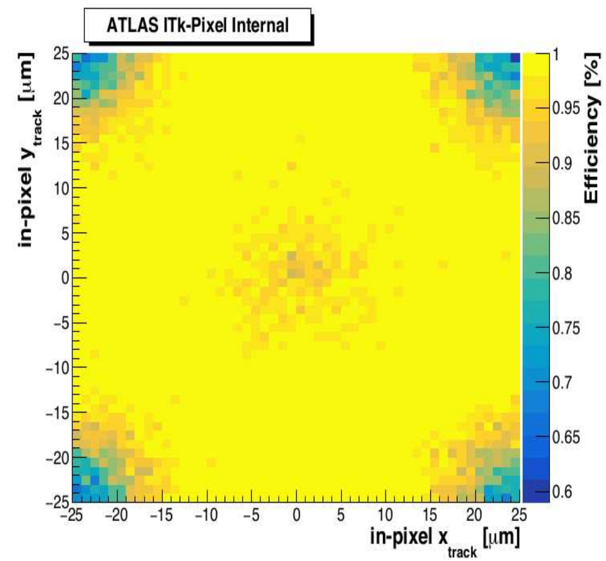


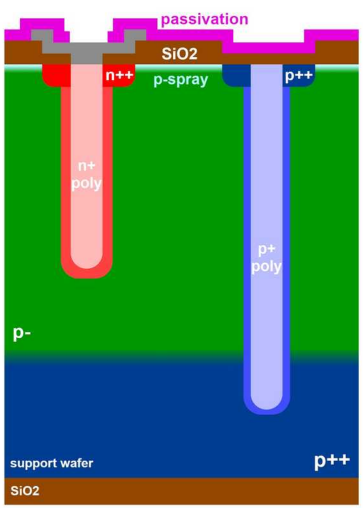
- Fulfills required hit efficiency after $1.8 \cdot 10^{16}$ n_{eq} cm^{-2}
  - >97% (15°) at 60V
  - >96% (perpendicular) at 80V
- Higher efficiency expected in inclined state particularly for 3D sensors
- Staged irradiation / measurement: KIT (SCC 1S, SCC 4S), IRRAD (SCC 4S) (highly inhomogeneous; average value in this case)

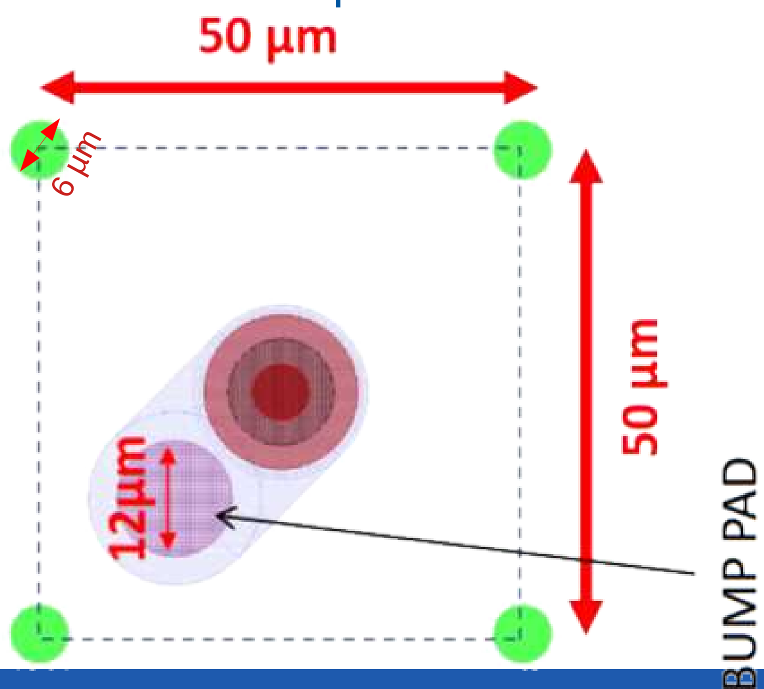
3D SINTEF 50 µm x 50 µm

- In-pixel efficiency 100% for unirradiated modules with exception of bias p^+ columns at 55-85%
- After irradiation readout electrode area in the middle if the pixel cell: 90%
- Only relevant for perpendicular incident angle which are not the foreseen operation conditions



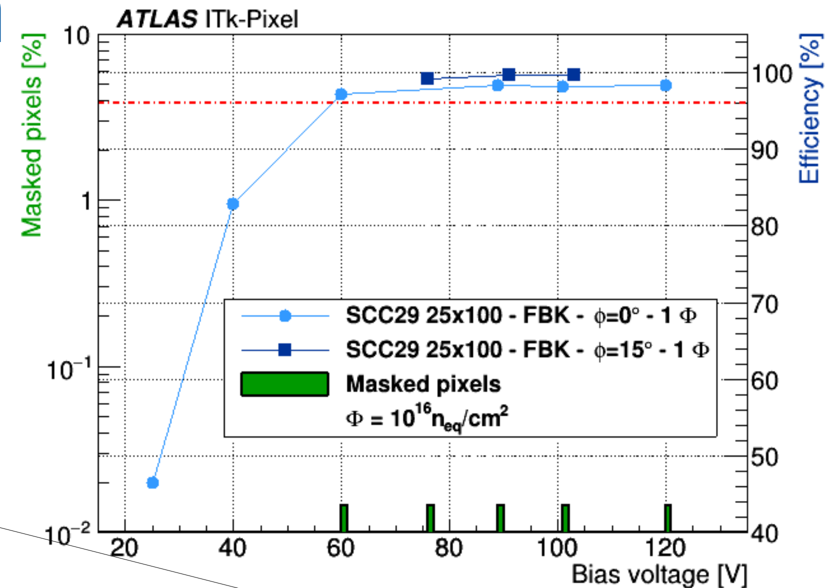


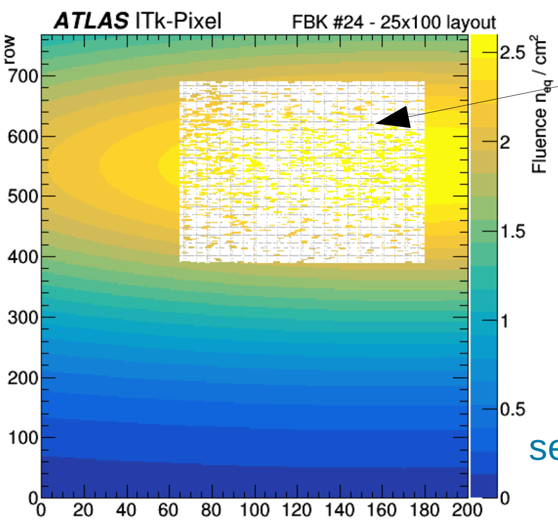




3D FBK 25 µm x 100 µm

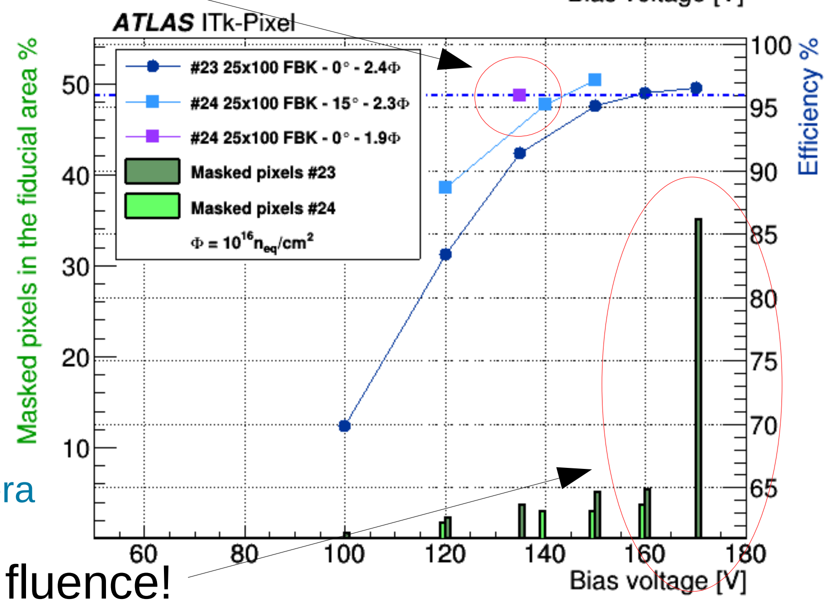
- Irradiation at KIT to $1.0 \cdot 10^{16}$ n_{eq} cm^{-2}
  - Efficiency >97% at 70V with less than 0.1% pixels disabled
- Irradiation at IRRAD to max. $2.4 \cdot 10^{16}$ n_{eq} cm^{-2} (mean $1.7 \cdot 10^{16}$ n_{eq} cm^{-2})
- Efficiency >97% at 130V with less than 3% pixels disabled for selection with $1.9 \cdot 10^{16}$ n_{eq} cm^{-2}





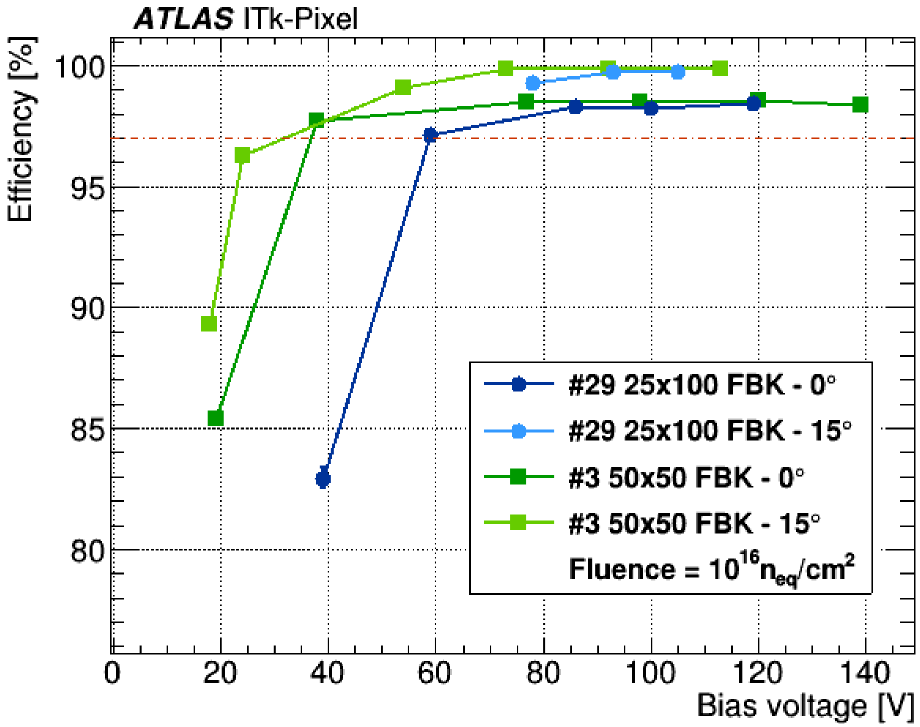
Triggered area IRRAD very inhomogeneous irradiation! measured with Al foil activation

see poster by Simone Ravera



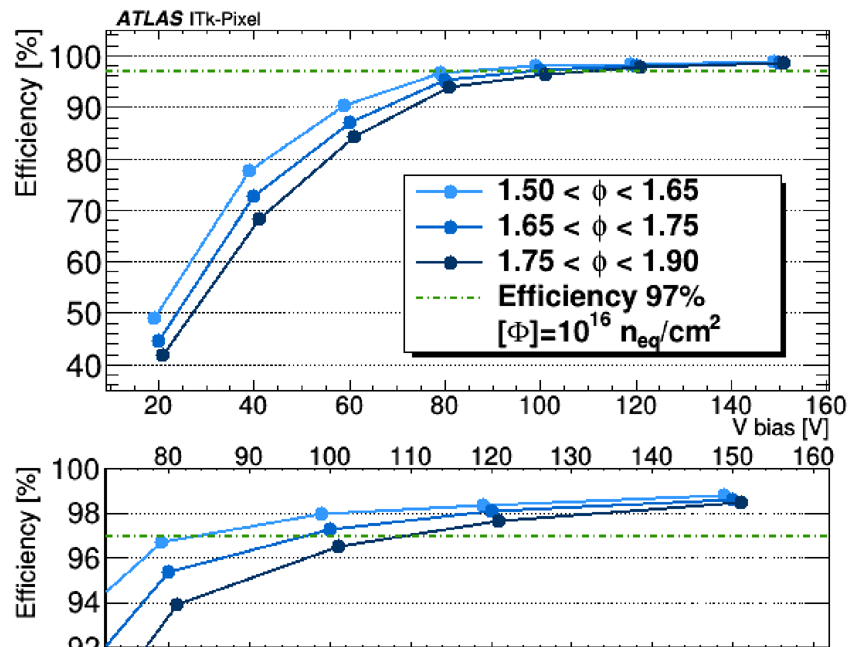
Not operational here but 30% beyond end-of-life fluence!

3D FBK 50 μm x 50 μm



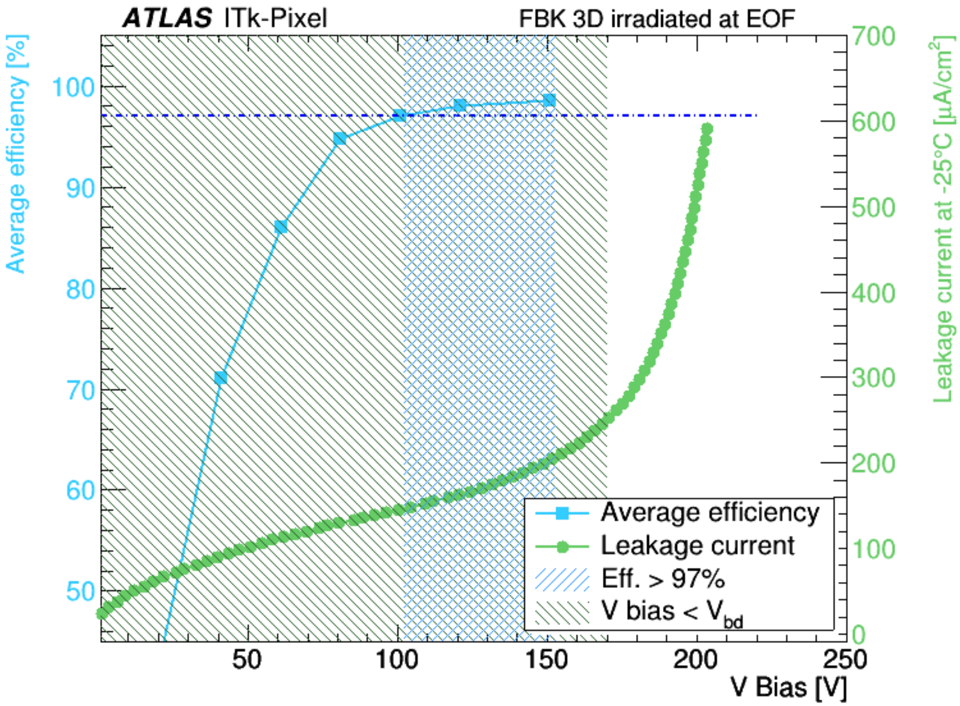
- 3D FBK 50 μm x 50 μm measured at target fluences in 2022 and 2023
- Irradiated at IRRAD

- 3D FBK 50x50 μm^2 efficiency >97% at 50V
- Irradiation to 10^{16} n_{eq} cm^{-2} in Bonn
- 50x50 μm^2 requires slightly lower bias voltage than 25 μm x 100 μm

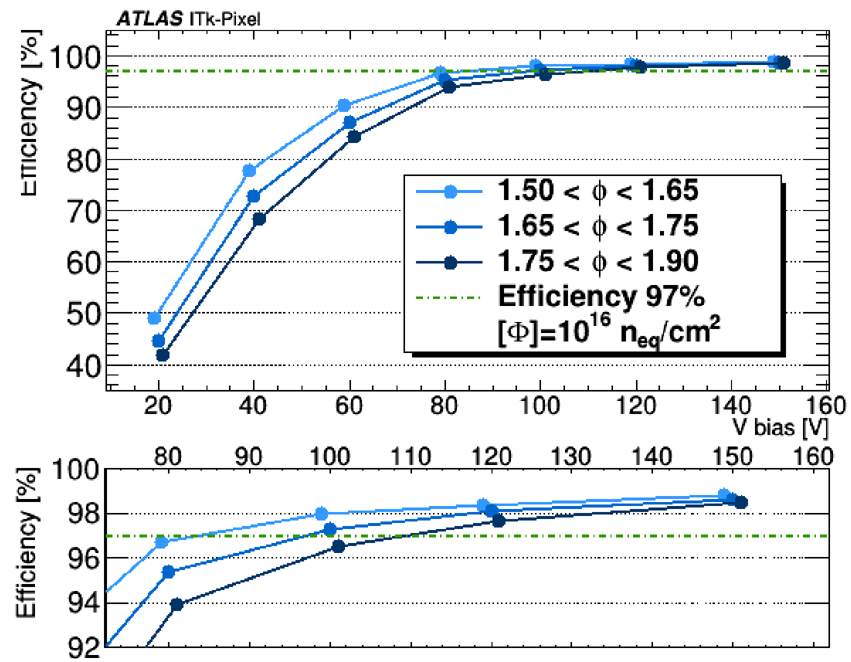


"Qualification of the first pre-production 3D FBK sensors with ITkPixV1 readout chip", PoS Pixel2022 (2023) 025

3D FBK 50 µm x 50 µm



- 3D FBK 50 µm x 50 µm measured at target fluences in 2022 and 2023
- Irradiated at IRRAD
- 97% at 120V-150V with 3% masked pixels maximum



"Qualification of the first pre-production 3D FBK sensors with ITkPixV1 readout chip", PoS Pixel2022 (2023) 025

Summary

- The ITk Pixel detector is currently in the pre-production phase moving towards production
- The following sensor flavors were measured in form of single or quad chip modules equipped with ITkPixV1.1 readout chip:
  - SINTEF 3D 50 µm x 50 µm ✓
  - FBK 3D 50 µm x 50 µm ✓
  - FBK 3D 25 µm x 100 µm ✓
  - FBK and MICRON Planar 50 µm x 50 µm, 100 µm bulk
  - HPK Planar 50 µm x 50 µm, 150 µm bulk
- Charge collection efficiency vs bias has been demonstrated to be fully compliant for the 3D sensors
- Outlook:
  - Finish analysis of planar data
  - Complete outstanding measurements (MICRON 150 µm, additional voltage points at proper fluence areas)
  - ITkPixV2 equipped modules to arrive next year which will have e.g. ToT operational
  - Further specialized measurements such as magnetic field under discussion for digitizer and radiation damage studies

Backup