ATLAS ITk Pixel Detector

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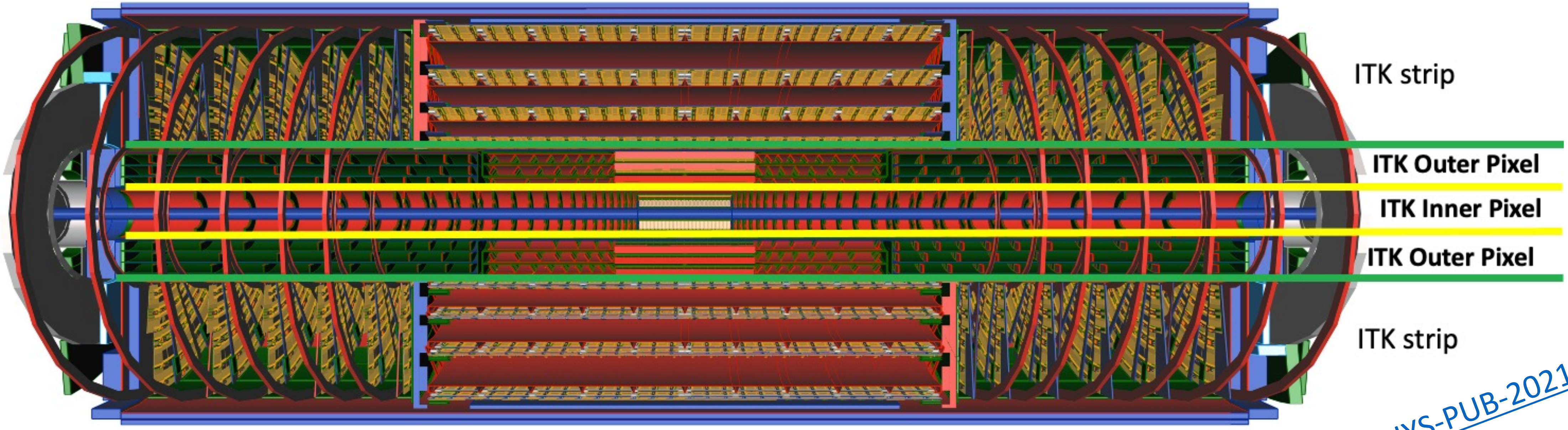
The University of Manchester

Outline

- Introduction and Motivation
- ATLAS ITk: The pixel detector
- Modules:
  - Silicon Sensors
  - Readout chip
  - Challenges
- Mechanical structures
  - Local supports
  - Global mechanics
- Integration
- System test
- Project Status
- Summary

Introduction and Motivation

- The LHC upgrade to the HL-LHC is the main motivation for the Phase II upgrade of ATLAS (see Jo Pater's presentation for more details):
  - Luminosity Increase: peak ~ 7x 10^{34} $cm^{-2}s^{-1}$, integrated ~ $3000fb^{-1}$.
  - 200 pile up events (48 in current run).
  - Radiation fluence: ϕ_{HL-LHC} ~ 10 x ϕ_{LHC} .= 2 x 10^{16} n_{eq}/cm^2.
- The ATLAS Inner Detector will be replaced by ~ 181 m^2 of an all-silicon Inner Tracker (ITk):
  - A dedicated presentation of the expected performance will be discussed in Helen Hayward's presentation this afternoon.
- The ITk will contain a Strip and a Pixel detector. The Strip detector will be presented just after me by Zhengcheng Tao.
- In this talk only the ITk-Pixel detector will be covered.

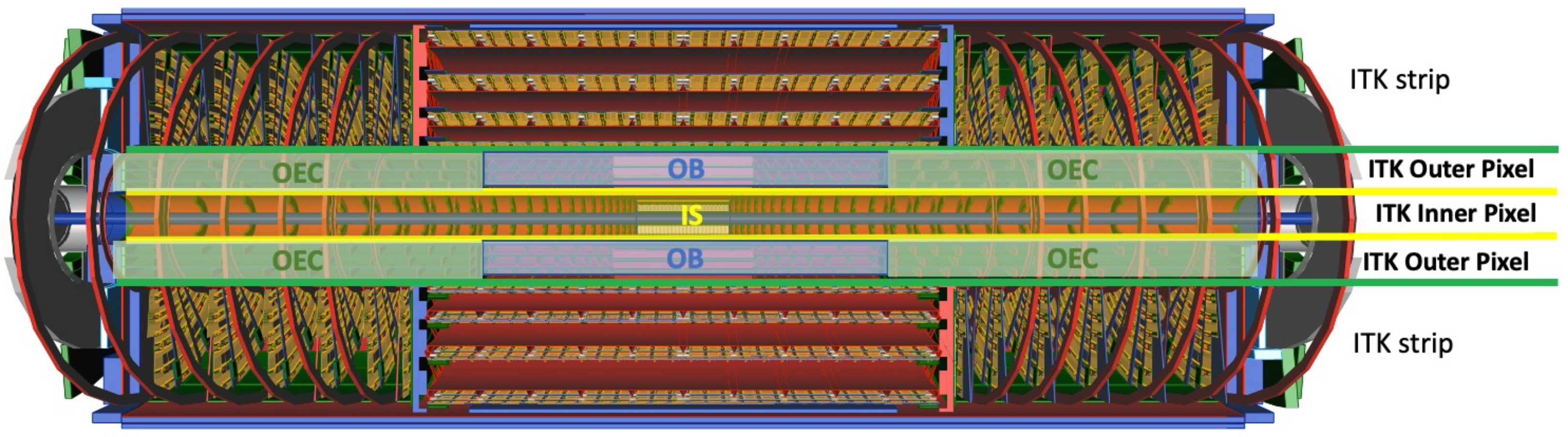


ATL-PHYS-PUB-2021-024

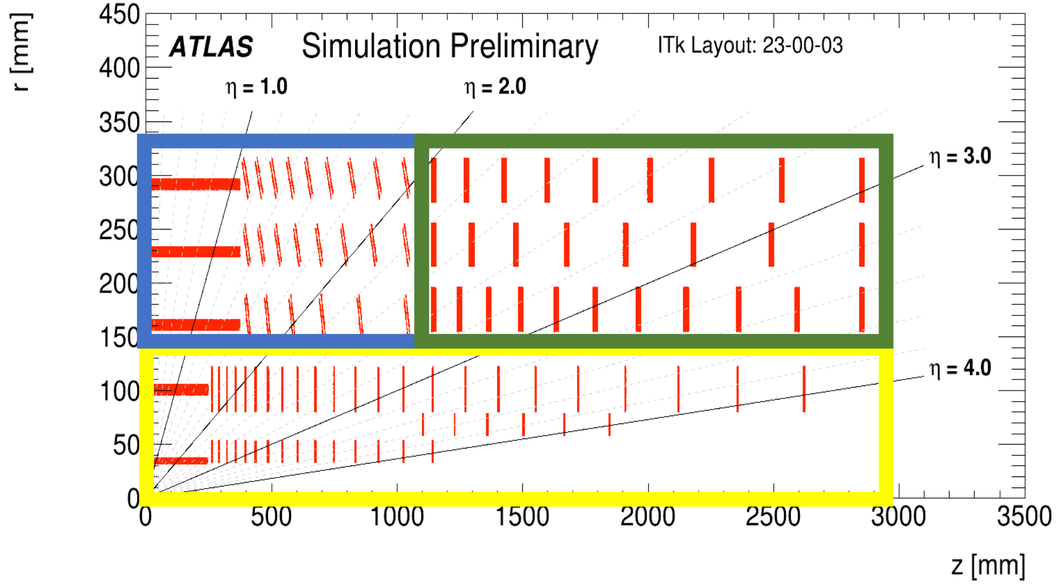
ATLAS-ITk. The pixel detector

ATL-PHYS-PUB-2021-024

- The ATLAS-ITk Pixel detector will require:
  - Higher radiation resistance.
  - Higher granularity (5G pixels).
  - Higher data rate capability.
  - Low mass (serial powering).
  - Lower operation temperature.
- It is divided in three sub-detectors:
  - Inner system. To be replaced after 2000 fb^{-1}:
    - 2 layers of flat staves and 2-3 layers of flat rings
  - Outer system:
    - Outer Barrel: 3 layers of flat staves and inclined rings
    - 2 Outer endcaps: 3 layers of flat rings

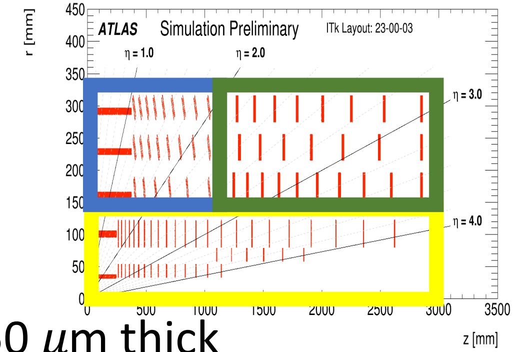


ITk Pixel = ITk-pixel Inner System + ITk-pixel Outer System = ITk-pixel Inner System + (Outer Barrel + two Outer Endcaps)



Outer Barrel
Outer Endcaps
Inner System

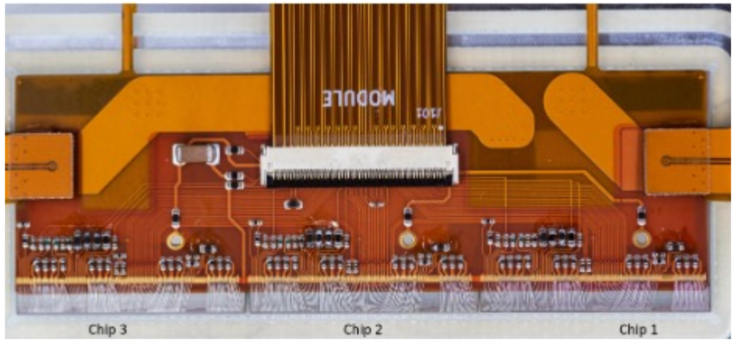
ATLAS-ITk. Hybrid Modules



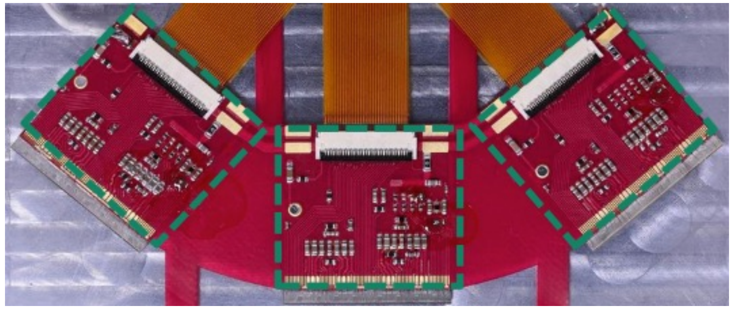
- Inner System:
  - 396 3D silicon triplet modules in Layer 0:
    - 50 x 50 μm ^{2} in the endcaps and 25 x 100 μm ^{2} in the barrel
  - 1160 n-in-p 100 μm thick planar quad modules (50 x 50 μm ^{2})

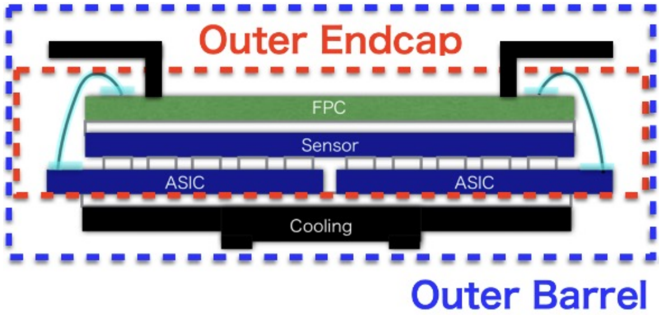
- Outer system:
  - Outer barrel: 4472 n-in-p 150 μm thick planar quad modules
  - Outer Endcaps: 2344 n-in-p 150 μm thick planar quad modules

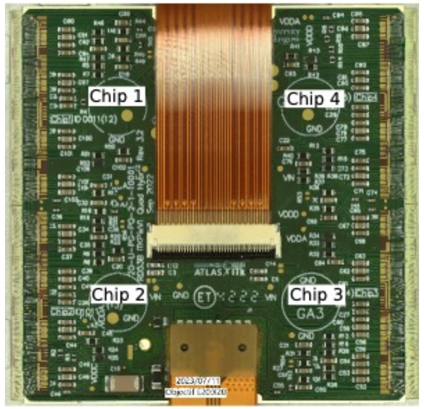
3D triplet for the Inner System barrel stave



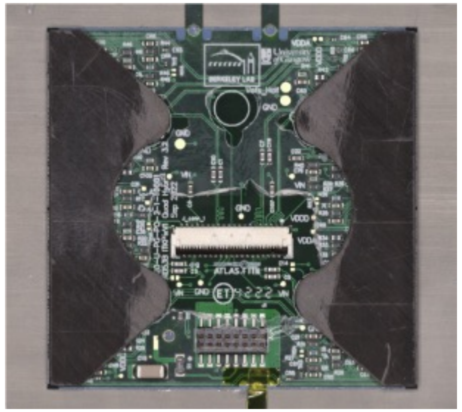
3D triplet for the Inner System endcap ring







Outer Endcaps quad module with data and power pigtails connected



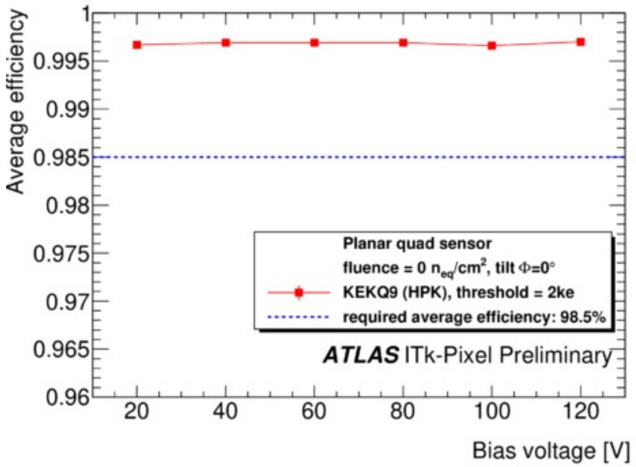
Outer Barrel quad module with carbon fibre wire bond protection

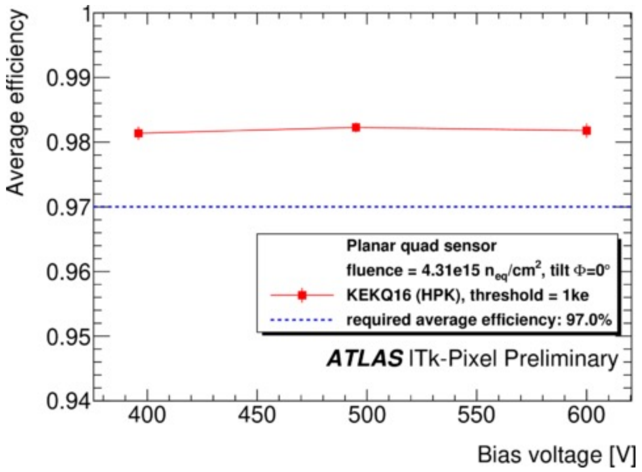
Modules. Silicon sensors

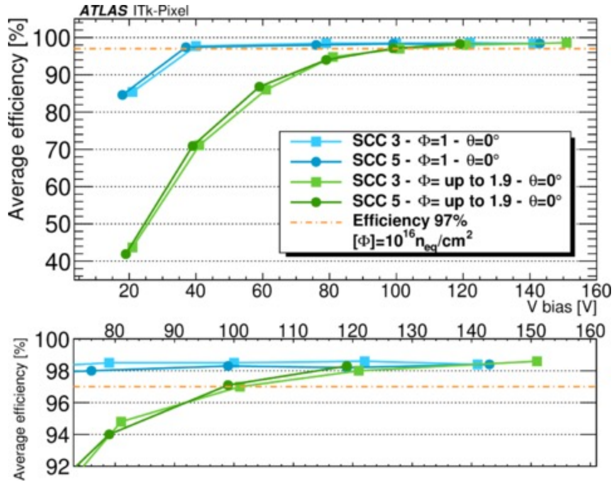
Radiation hard silicon sensor technologies: Thin planar and 3D sensors

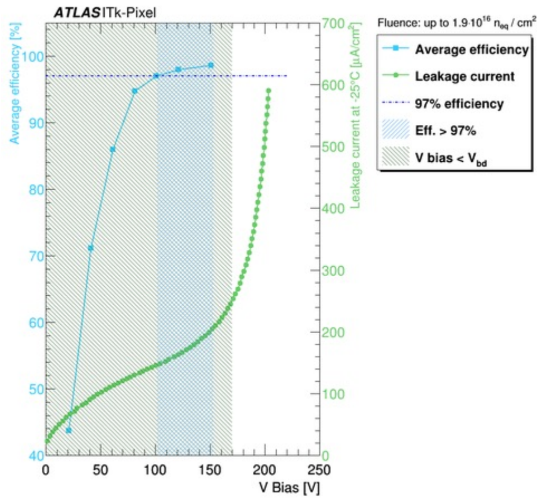
See Yusong Tian's Poster: "Characterization with test beams of ITk pixel detectors for the upgrade of the ATLAS Inner Detector"

Average efficiency vs bias voltage for 150 μm thick planar sensors before (top) and after (bottom) irradiation from ITK-2023-005.









Average efficiency vs bias voltage for 3D sensors after irradiation (top). At the bottom also showing the leakage current and the breakdown voltage, Both from ITK-2022-005.

Modules. Silicon sensors

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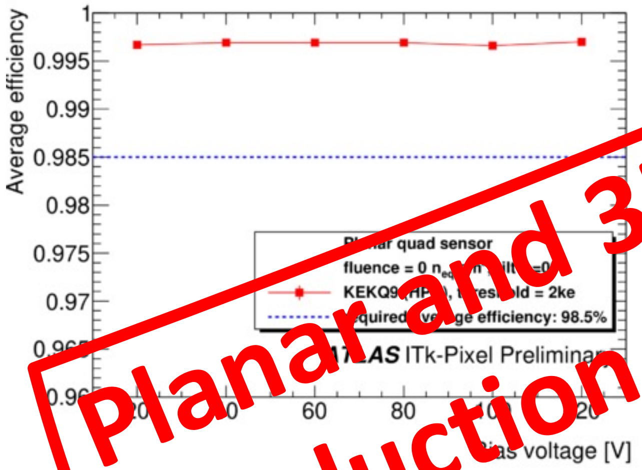
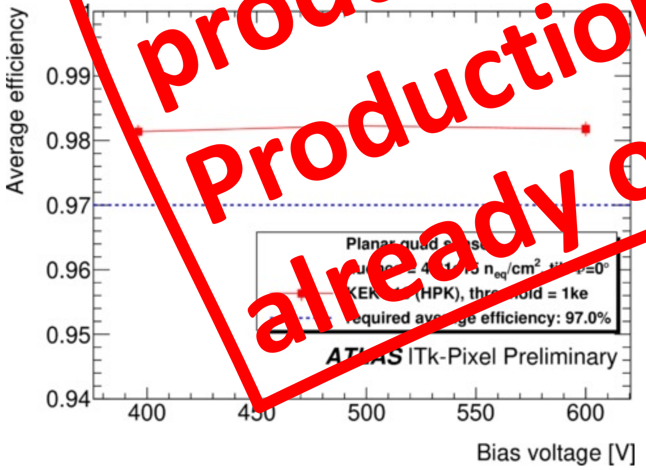
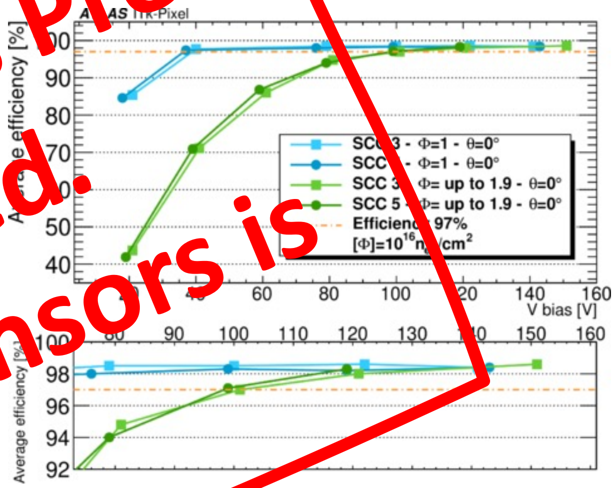
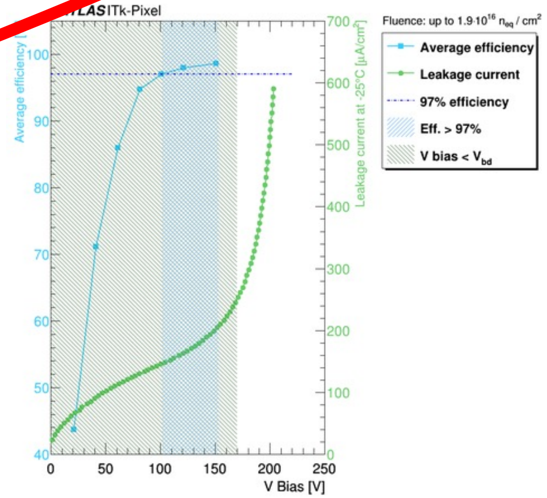








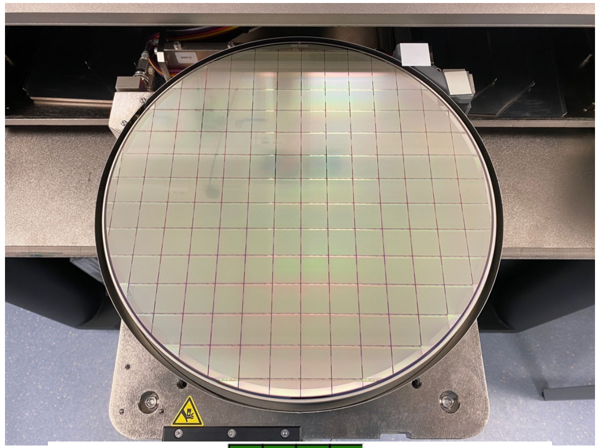
Average efficiency vs bias voltage for 3D sensors after irradiation (top). At the bottom also showing the leakage current and the breakdown voltage, Both from [ITK-2022-005].

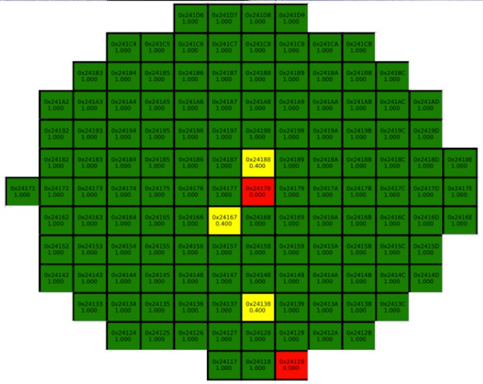
Planar and 3D sensors Pre-production completed. Production of all sensors is already ongoing!

Modules. Read Out chip: ITkPixV2

RD53 Collaboration: joint R&D for ATLAS and CMS ASIC in TSMC 65nm. Main features for ATLAS solution can be found in CERN-RD53-PUB-24-001, a simplified summary is here :

- A total area of 2x2cm^2. 152800 pixels per chip (50x50 μm^2) pitch. High granularity helps tracking in dense environments.
- Low threshold operation and cluster charge readout using Time over Threshold to increase efficiency after irradiation.
- Sensor leakage current compensation and Single Event Error hardening to cope with higher radiation damage.
- 1.28Gb/s data rates → to cope with higher luminosity.
  - 4 data links per chip at 1.28 Gb/s.
  - data compression.
- Optimisation of services:
  - Merging of chip data in module.
  - Integrated shuntLDO regulator for serial powering.





First 100 wafers (131 chips) of the final chips already probed with a 90% yield (based on digital/analogue functionality and power consumption). First modules are under assembly and testing atm.

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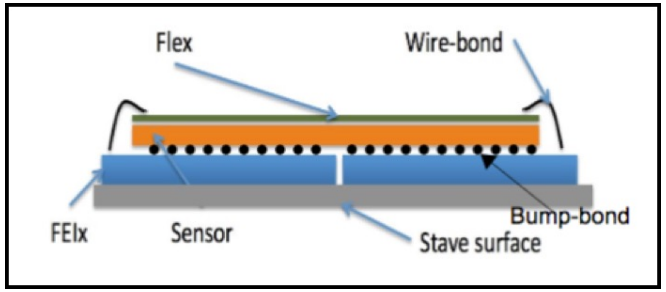
Modules. Challenges.

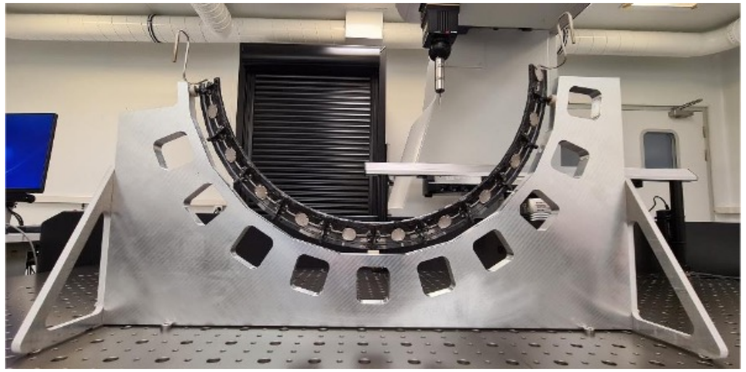


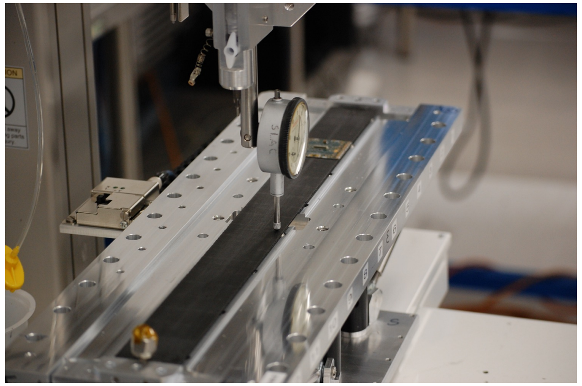
- The final module assembly contains many different materials:
  - Copper and Kapton in the flex
  - Copper and silicon (others) in the FE-chip
  - Thin silicon and aluminium in the sensor
  - Different metal alloys in the bumps
- It is then glued into a local support (carbon structure)
- All the different materials and assemblies (flex and local support) have different CTE.
  - Detector operational temperature will be -35 °C, but it varies between -45 °C and +40 °C during the life of the detector.
- Delamination problems have been found during prototyping that have been overcome by:
  - Tuning the copper thickness in the flex:
    - Enough to dissipate enough power but low to avoid inducing thermal stresses.
  - R&D in the hybridisation technique (bump bonding between the sensor and the chip).
    - Bump stress qualification → 100 cycles (-55 °C, + 60 °C)
  - Parylene coating (initially only for preventing discharging between chip and sensor) is also beneficial.
- Sensor's bow is also a technical challenge for hybridisation vendors during prototyping.
  - Techniques are being found at vendors to overcome it.
- Chips dicing can induce problems → laser dicing is the preferred solution.

These issues are still being closely monitored and tested during pre-production.

Mechanical structures. Local supports

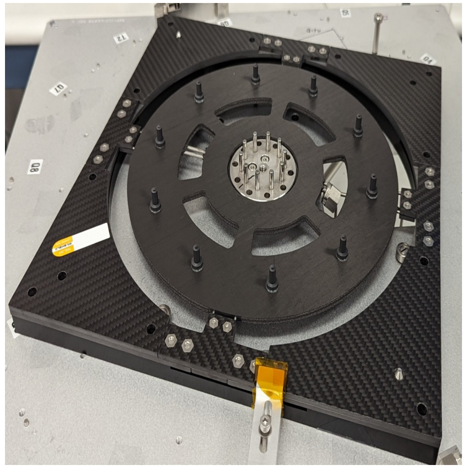
Local supports locate the modules in the experiment, support the modules and part of the services and guide the cooling next to the heat sources.





Outer Endcaps Half-ring

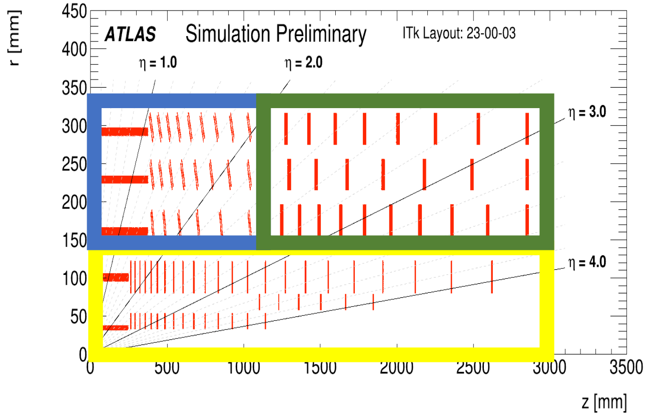
Outer Barrel inclined rings (top) and Longerons (bottom) made out of carbon composite where module cells will be loaded.



Inner system stave (top) and coupled ring (bottom)

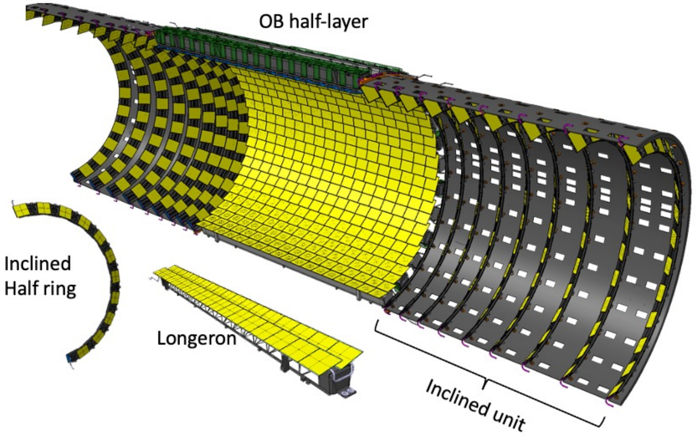
- OEC and OB Local supports already in production. All materials, assemblies and interfaces qualified against thermal and mechanical stresses and irradiation.
- QC protocols already in place:
  - Thermal.
  - Metrology.
  - Grounding.

Mechanical Structures. Global Mechanics

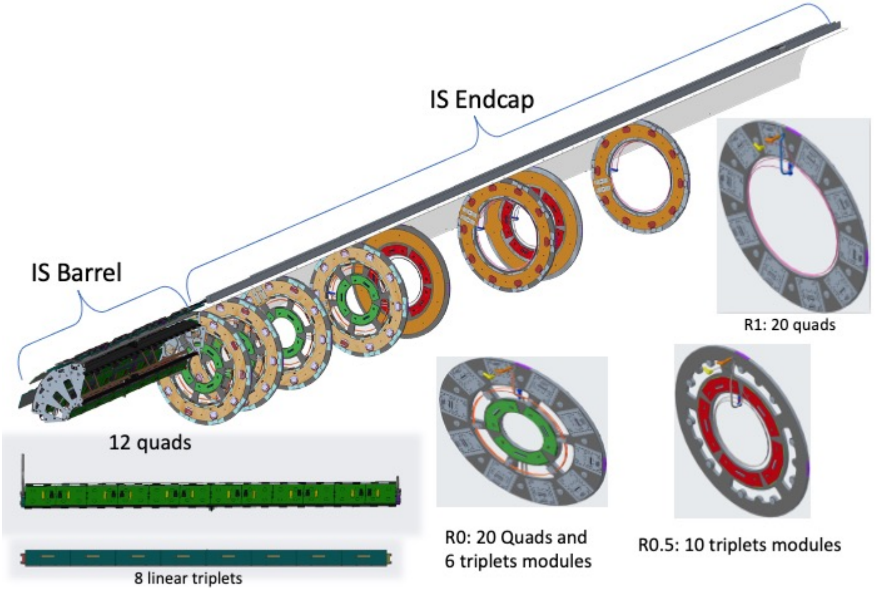


Global mechanic structures support the local supports and all the services needed in the detector: power, cooling, data lines and detector conditions (Humidity and Temperature).

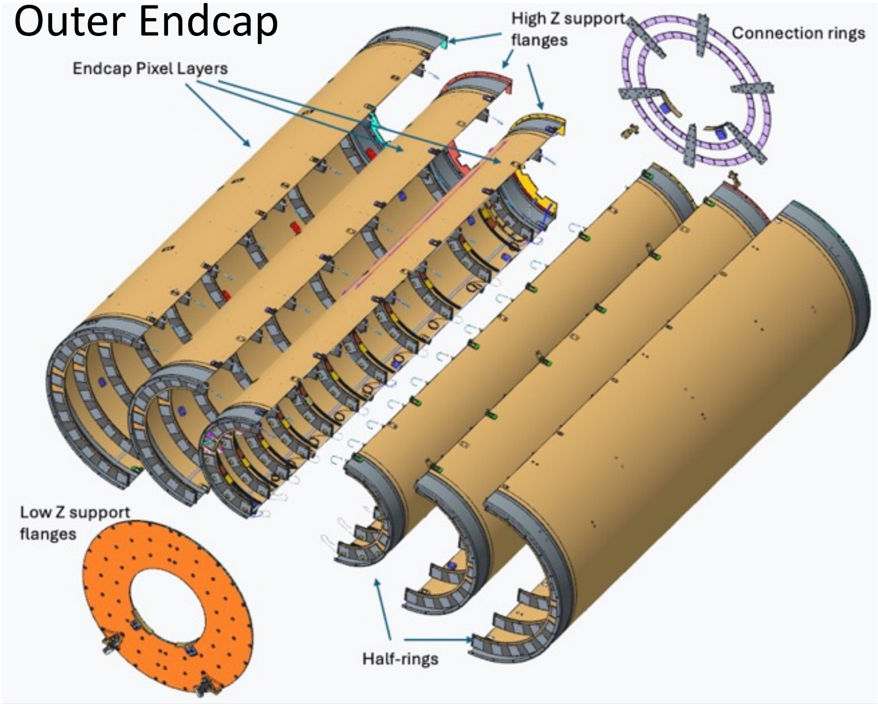
Outer Barrel half layer



Inner System Quarter-shell



Outer Endcap



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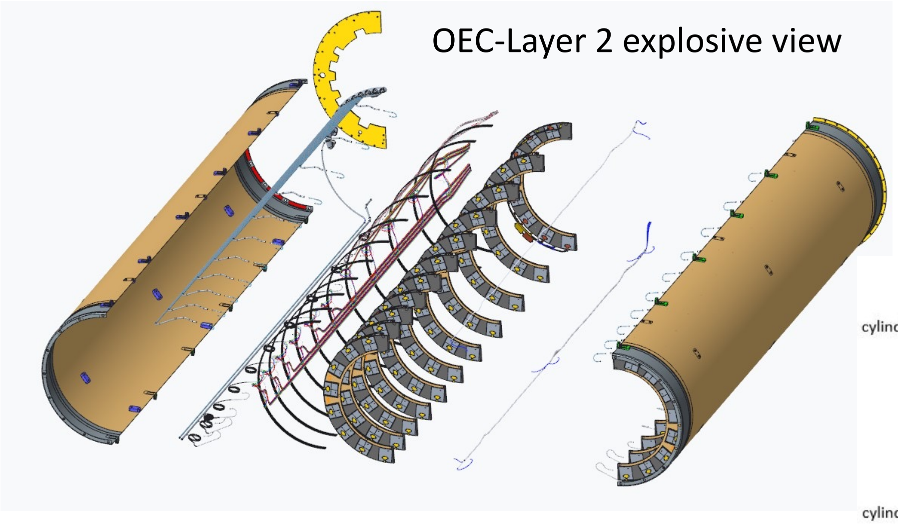
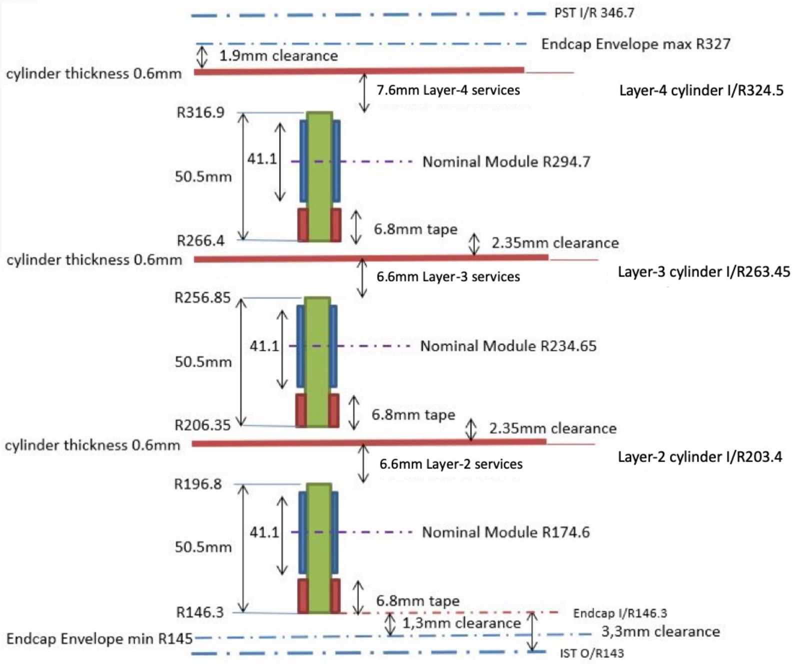
Integration *.

- Data cables
- Power cables
- Cooling pipes
- Local supports
- Detector control system (DCS):
  - Humidity and Temperature monitors
  - Interlocks
- Modules


OEC-Layer 2 explosive view



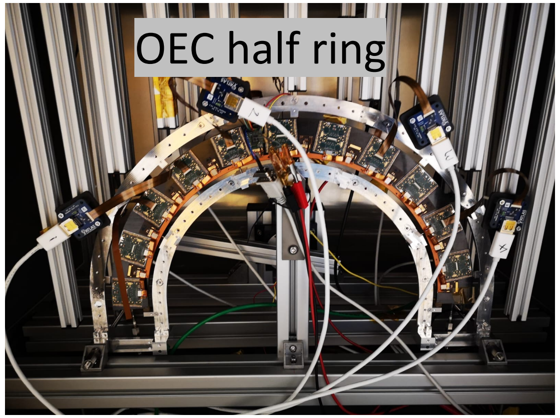
Schematic diagram of radial envelopes in the OEC

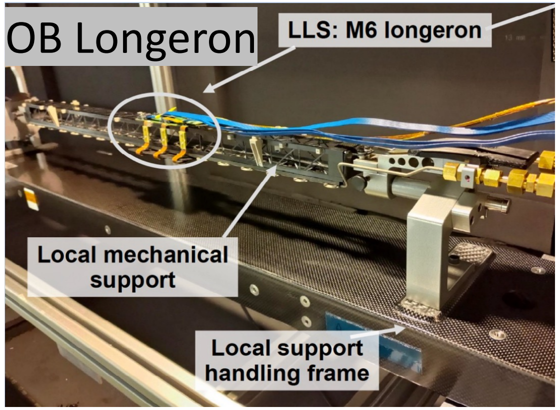
***It actually means** everything must work, must fit, you must minimise the material, increase granularity, cope with the data rate, keep the power low, make everything so when T changes over 100 ℃, nothing breaks or clashes (and things move a lot but not by the same amount)... It must survive and perform after huge radiation doses… And remember that all of these are correlated, sometimes directly, but others inversely ….. And TEST EVERYTHING! … And stay in the budget, and in the schedule…*

System tests

Tests performed with as many parts and as final as possible (now with RD53A prototypes, getting ready for ITkPix V1-2) :

- Multi-module power and readout.
- G&S optimisation.
- Data transmission with realistic chain and DAQ.
- Interference between all different elements.
- Tests at different temperature, including stability.
- Validating integration (connections, fittings, welds…).





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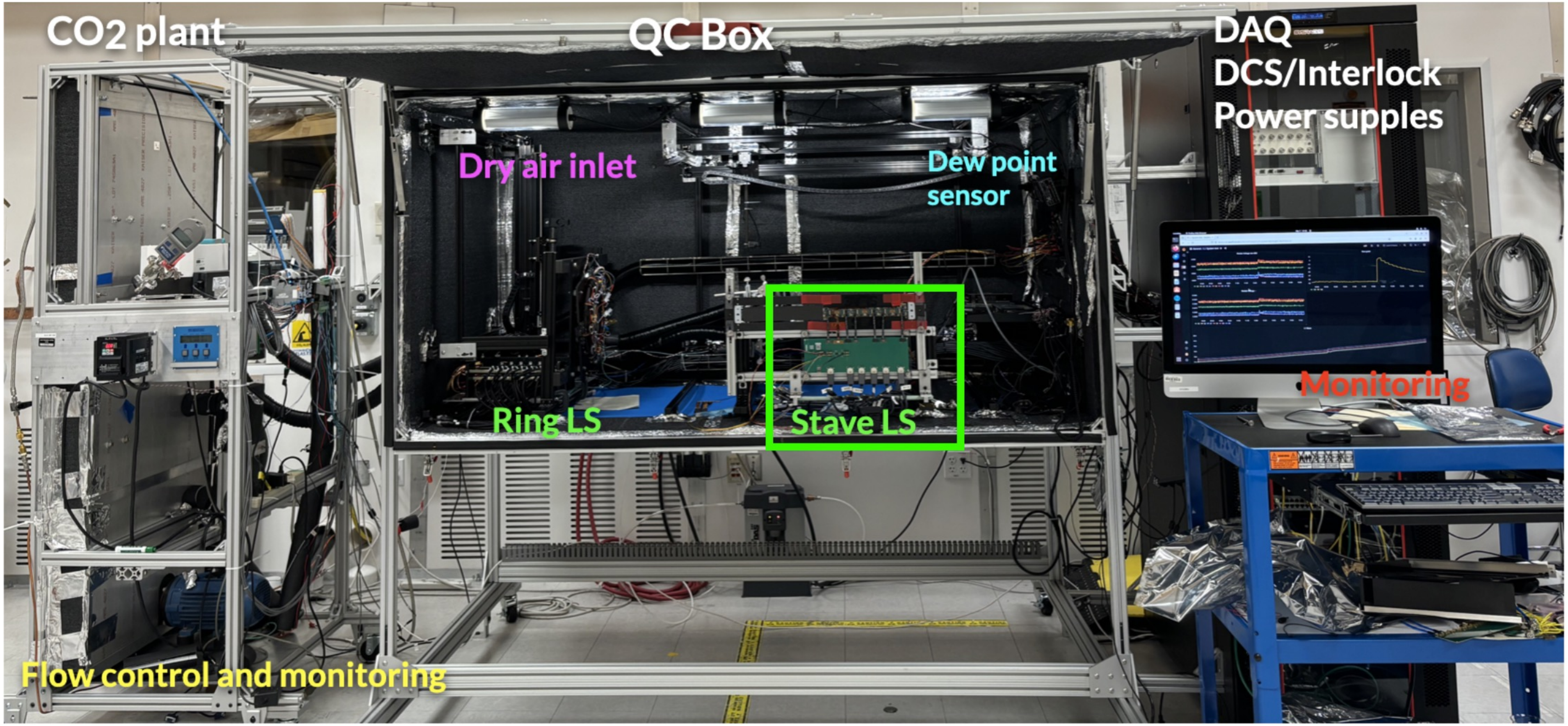
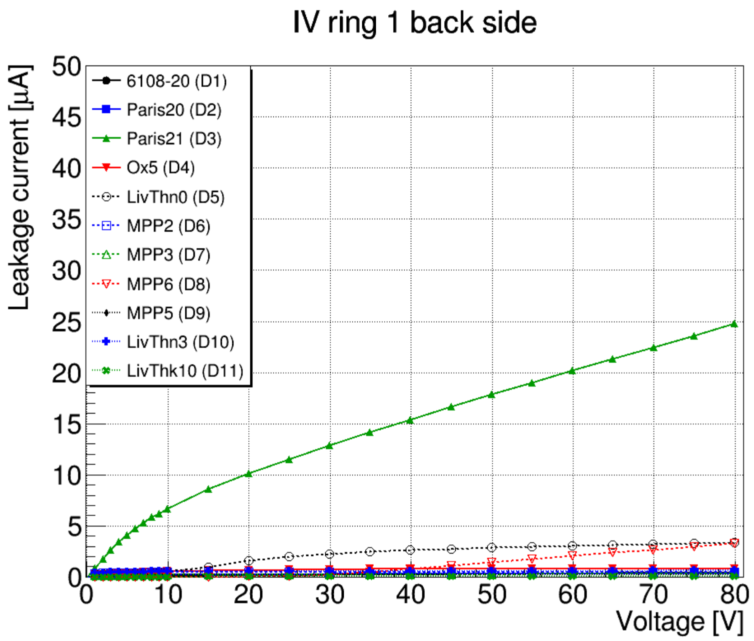


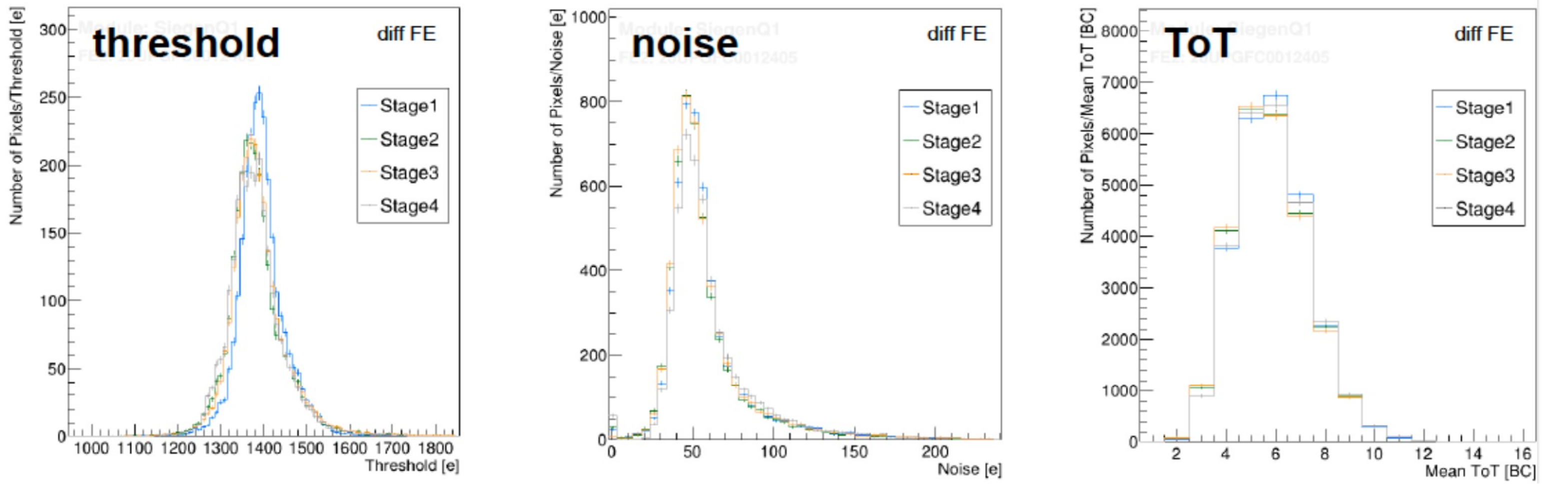
Picture of the Inner System ‘System test setup’ at SLAC.

System tests

RD53A prototypes



Leakage current measurement of one side of the Outer Endcaps half ring demonstrator



Outer barrel RD53A modules results on modules a t different stages: 1- after module production, 2- after loading on the cell, 3- after pigtail assembly, 4 – after integration in the Local support (ATL-ITK-SLIDE-2024-114).

Test with full speed: 1.28 Gb/s

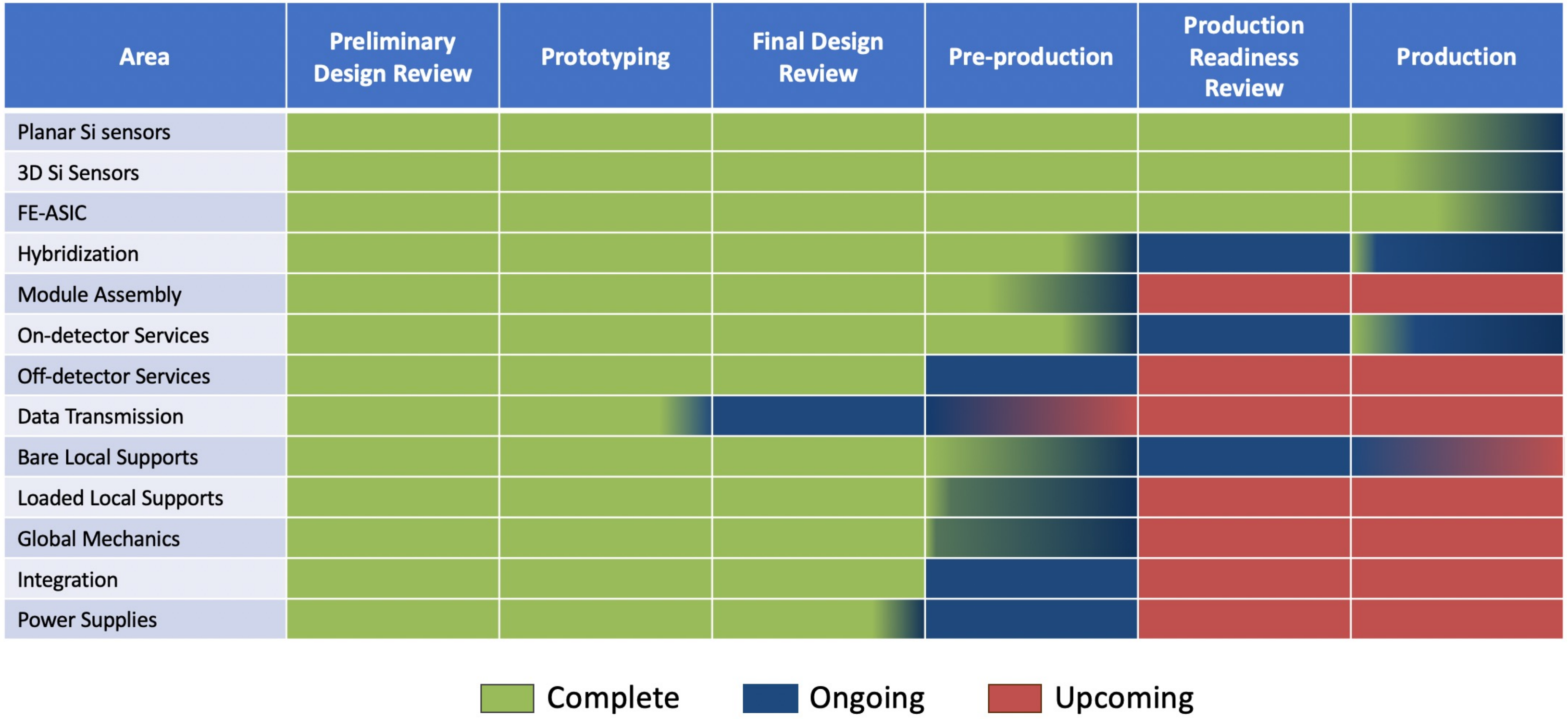
Position	FE No.	Bathtub Scenario 1		Bathtub Scenario 2		Bathtub Scenario 3	
		Step	Width (ps)	Step	Width (ps)	Step	Width (ps)
Q1	2	101	353.5	94	329	96	336
	3	101	353.5	99	346.5	102	357
	4	98	343	99	346.5	92	322
Q2	1	106	371	105	367.5	108	378

Inner system data transmission tests in 3 scenarios: 1- single data line, 2-single data line when all data lines in the module are connected, 3- single data line with all lines in the same modules and adjacent modules are enabled

ATLAS ITk

Project Status.

- Three main stages:
  - R&D: From the Preliminary Design Review (PDR) to the Final Design Review (FDR)
  - Pre-production: From FDR to the Production Readiness Review (PRR).
  - Production: From PRR to completion (2027).



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Project Status. Challenges ahead (my view)

- Move system test from RD53A prototypes to pre-production (ITkPixV1-2)
  - Including closer-to-final DAQ
  - More realistic power and data chains
- Slice test at CERN being planned and getting ready :
  - Program starting end of 2024.
  - To integrate multiple loaded local supports (2 x longerons + 1 x OEC-HR).
  - Multiple serial powering chains.
  - Move to final components as they become available:
    - Trained personnel will be critical for a smoother commissioning and operation of the final detector.
- Face any surprises along the way

Summary

- The ATLAS-ITk Pixel Detector has been designed to perform and operate under the HL-LHC challenges:
  - Low mass: carbon structures, serial powering, data merging.
  - Radiation hardness (65 nm ASIC, thin and 3D sensors…).
  - Tracking efficiency (higher granularity).
- Most of the design activities are complete:
  - only few aspects on Global Mechanics, Integration and data transmission remain.
- Prototypes and now pre-production items are tested to the most extreme conditions (expected + safety factors).
- Production of Front-end chips, sensors, hybridisation and some services and local supports already started.
- RD53A system tests are used as training and to get ready for system tests with final parts.

- A few busy years ahead…

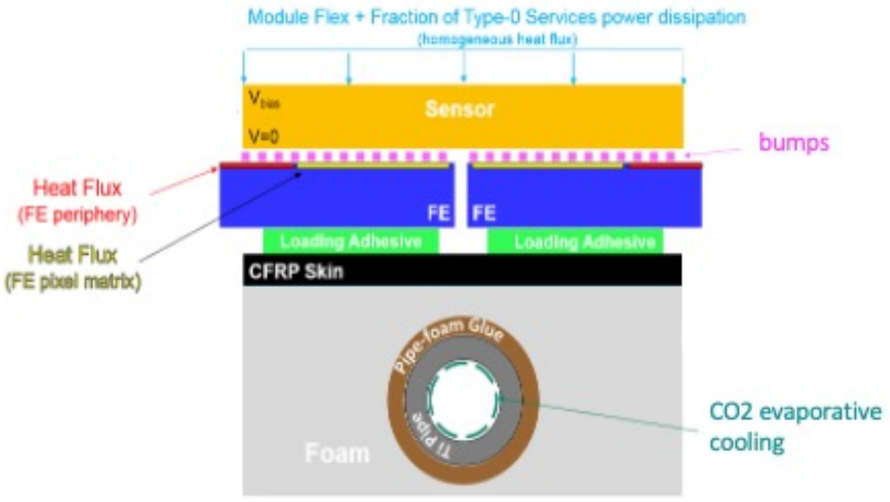
Thank you very much for your attention. Questions?

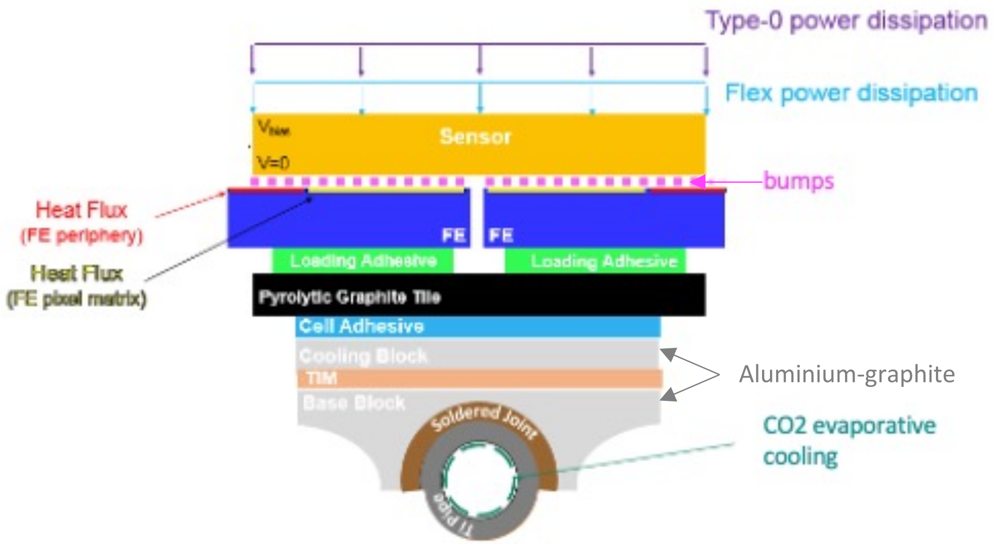
Backup slides

Mechanical Structures. Local supports

Local supports support and locate the modules, part of the services and guide the cooling next to the silicon

- Carbon based:
  - Low/Zero CTE
  - Low radiation length
  - Radiation hard
  - Good thermal and electrical conductivity





Different schematics to illustrate the different structures and materials between the silicon and the cooling pipe (the thermal path). Left: Outer Endcaps and Inner System Schematics, right: Outer Barrel

System tests

Tests performed with as many parts and as final as possible (now with RD53A prototypes, getting ready for ITkPix V1-2) :

- Multi-module power and readout.
- G&S optimisation.
- Data transmission with realistic chain and DAQ.
  - Cross talk.
  - Tuning of lpGBT (Low Power GigaBit Transceiver: serializer/deserializer device).
  - High speed verification (1.28 Gbit/s from FEs).
  - Data merging and readout of 4 Front end chips via 1 e-link and 2 e-links.
- Interference between all different elements.
- Tests at different temperature, including stability.
- Validating integration (connections, fittings, welds…).