ATLAS Inner Tracker Upgrade for the HL-LHC

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The 14th International Conference on Position Sensitive Detectors

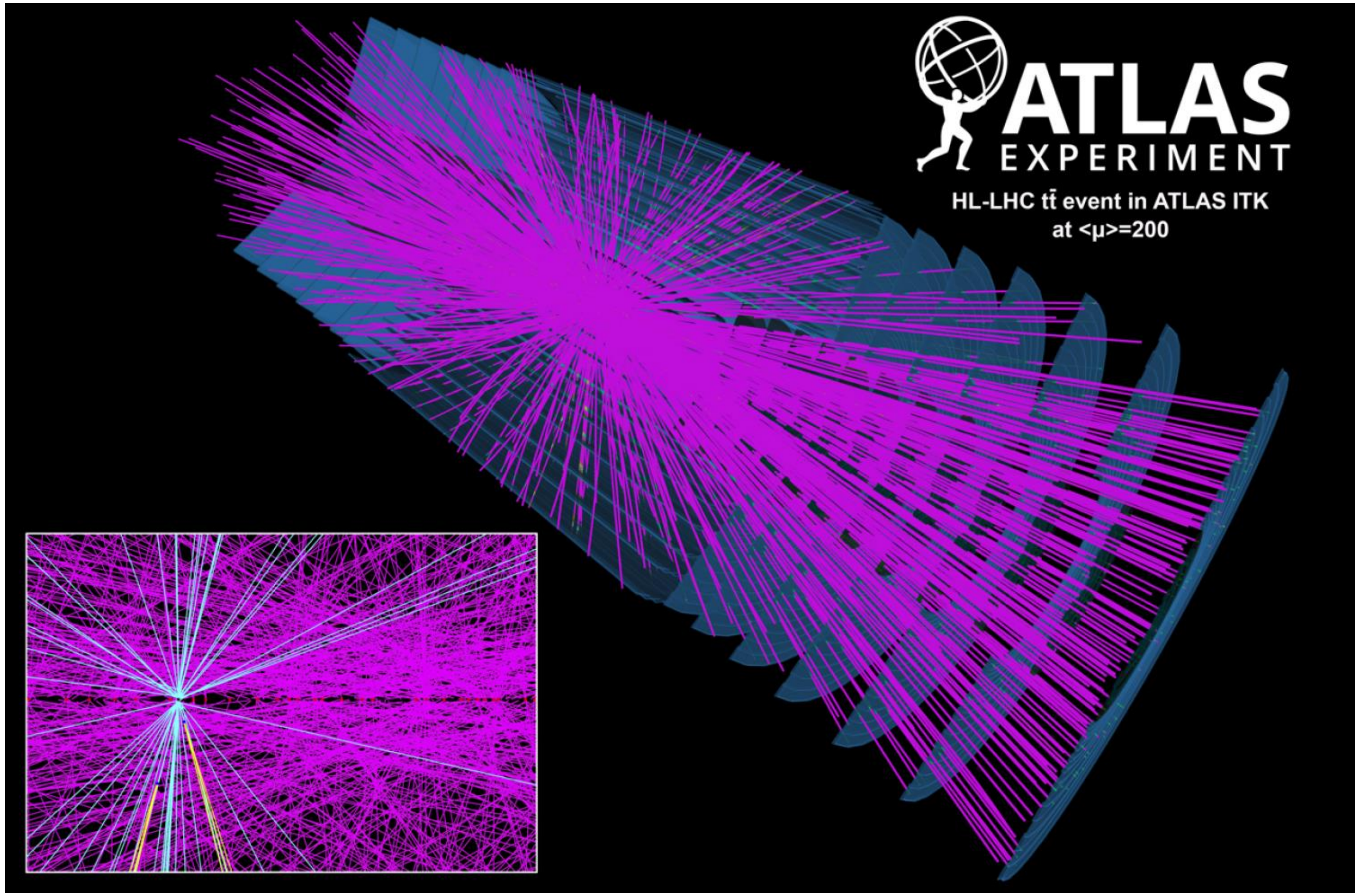
3rd September 2026, QMUL, London

ATLAS ITk

MANCHESTER 1824
The University of Manchester

Outline

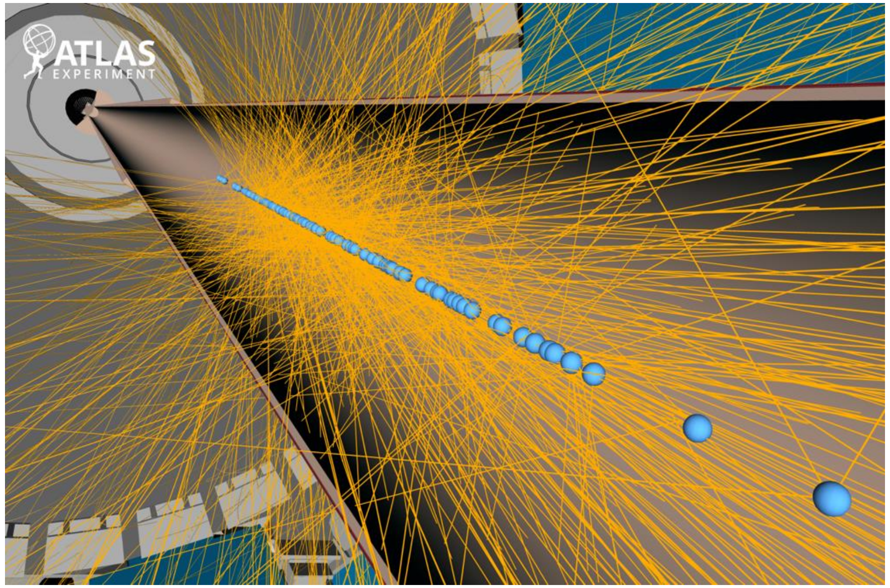
- The High Luminosity LHC
- ATLAS Upgrade. The ITk
    - Production flow
    - Modules
    - Read Out chip
    - Mechanics
- ITk Challenges
- Summary

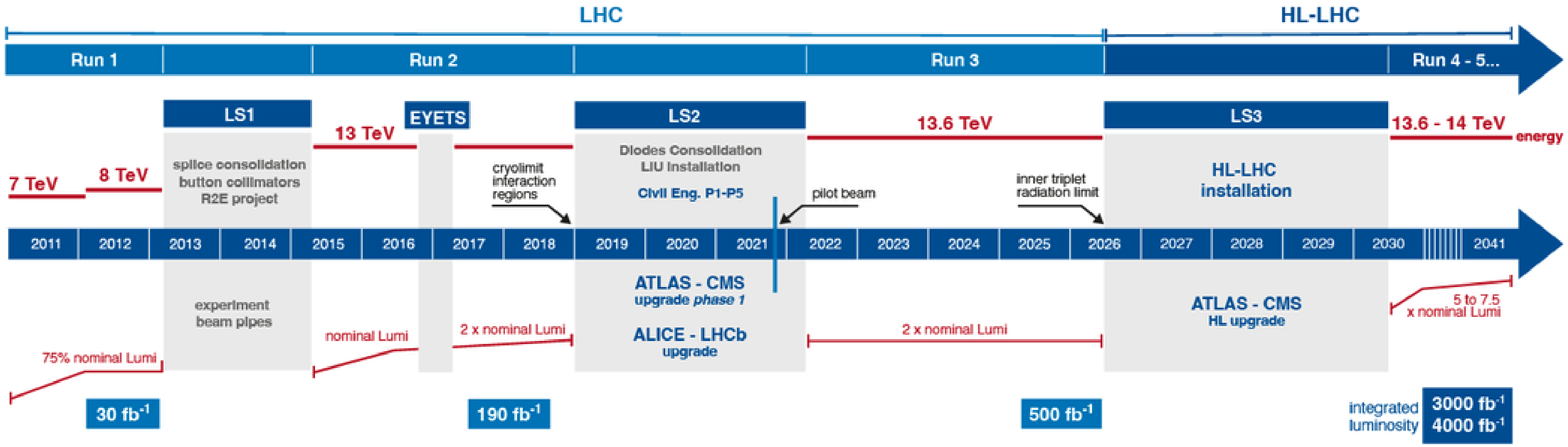


The LHC upgrade: HiLumi LHC

HiLumi

- Produce 380 millions of Higgs bosons
- Luminosity Increase:
  - $L \sim 7\text{x } 10^{34}\ cm^{-2}s^{-1}$
  - $L_{int} \sim 4000fb^{-1}$.
- 200 pile up events (~ 3.3 x LHC)
- Radiation fluence:
  - $\phi_{HL\text{-}LHC} \sim 10 \text{ x } \phi_{LHC} = 2 \text{ x } 10^{16}\ n_{eq}/cm^2$.

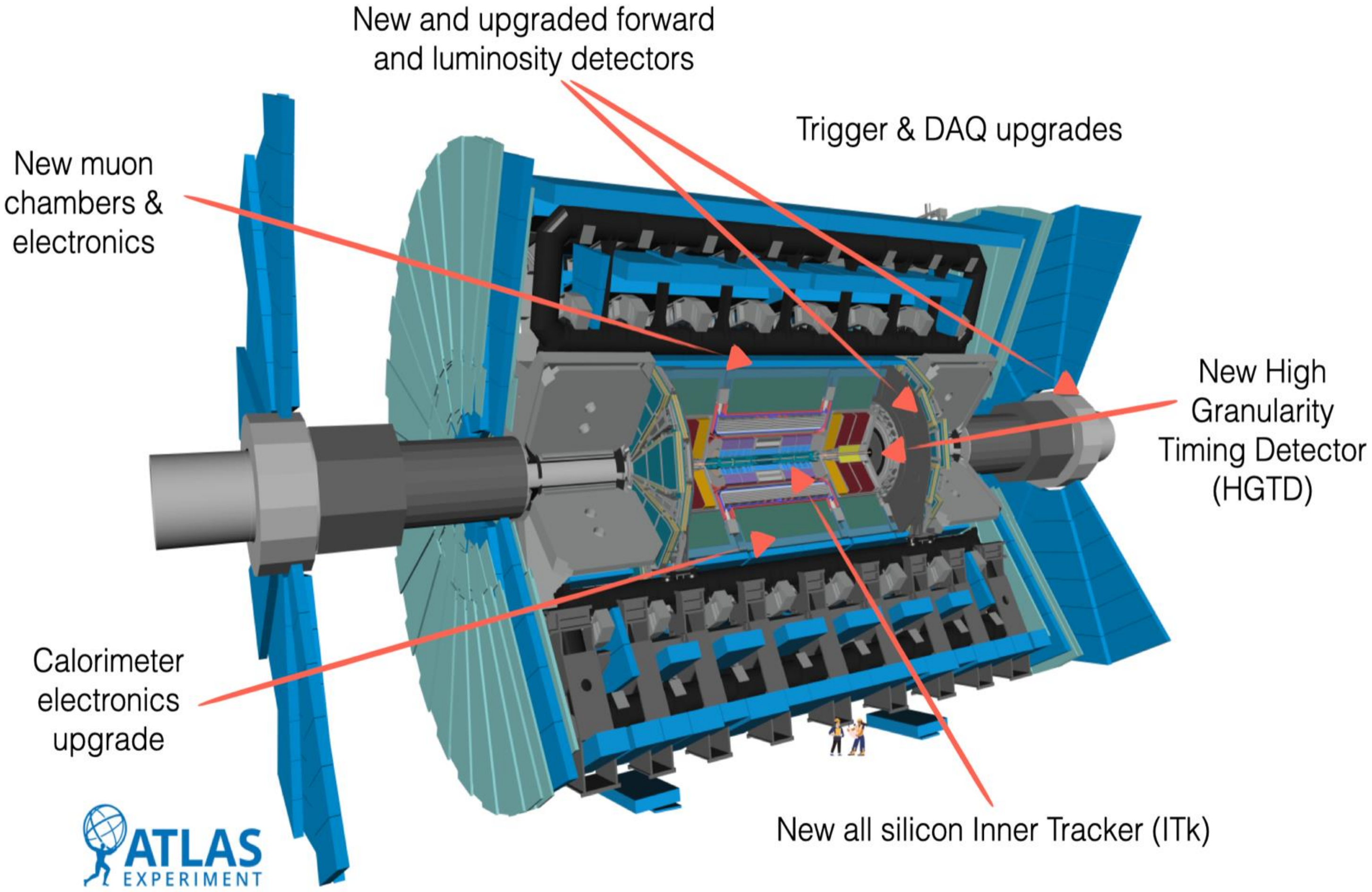




The ATLAS phase II upgrade

ATL-UPGRADE-PUB-2025-001

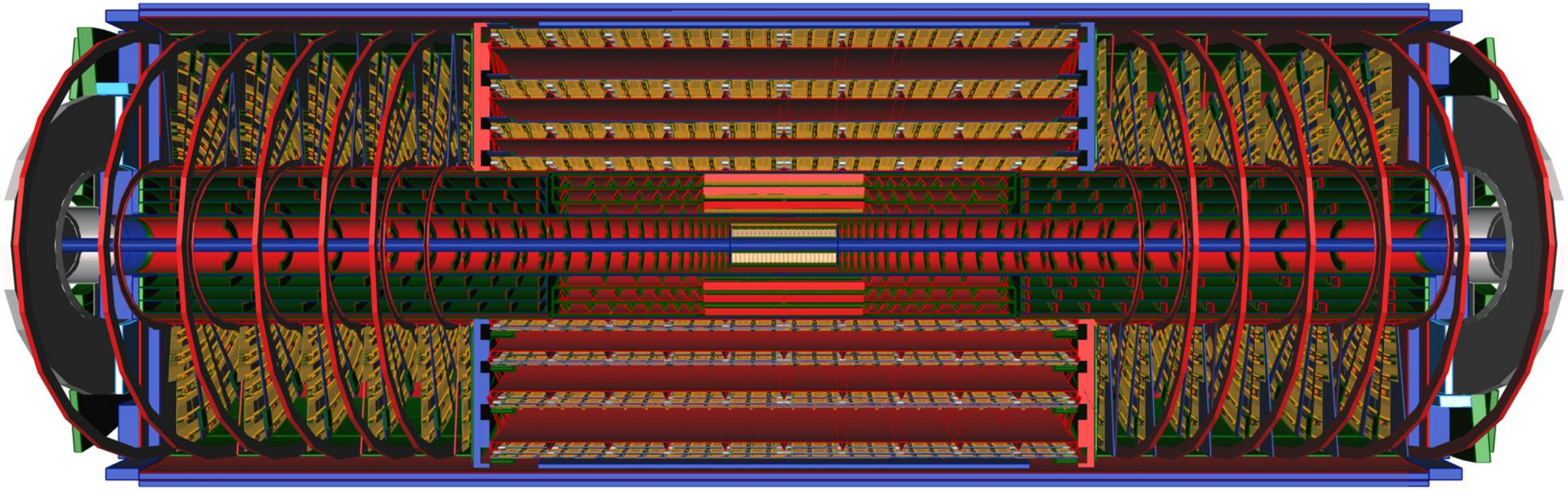
- New lumi detectors
- New muon detectors
- New detector : HGTD
- ~ 181 m^2 of a NEW all-silicon **Inner Tracker (ITk)**
    - Strip and a Pixel detector.



The ATLAS ITk

- Higher radiation resistance
- Higher granularity, ~ 5 billion pixels
- Higher data rate capability
- Low mass
- Lower operation temperature

- Coverage up to η =4
  - 5 innermost layers → pixel detector
  - 4 outermost layers → strip detector



ATL-PHYS-PUB-2021-024

The ATLAS ITk

- Higher radiation resistance
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- Coverage up to η =4
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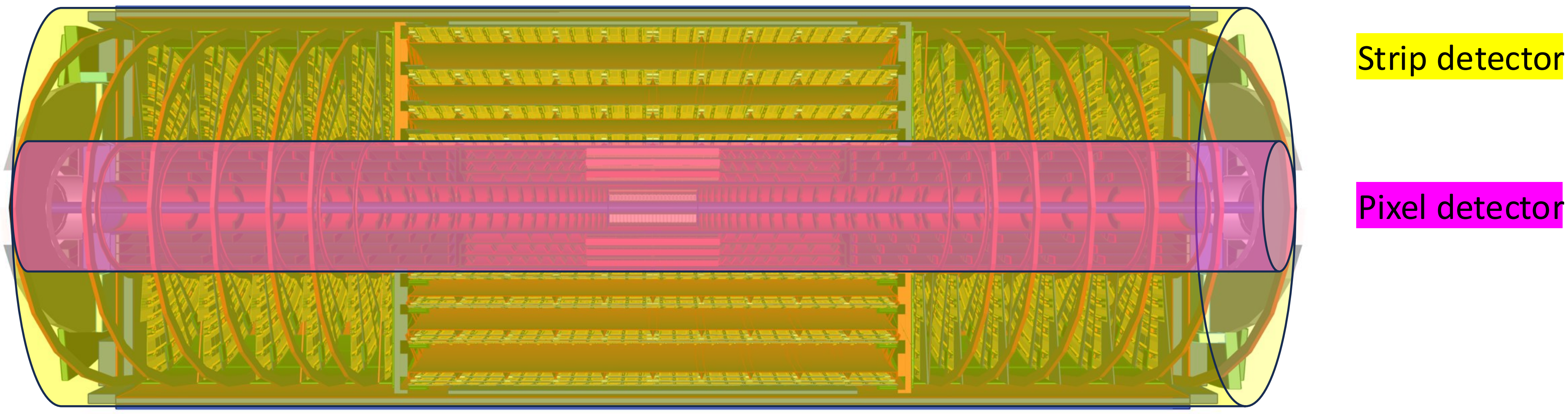
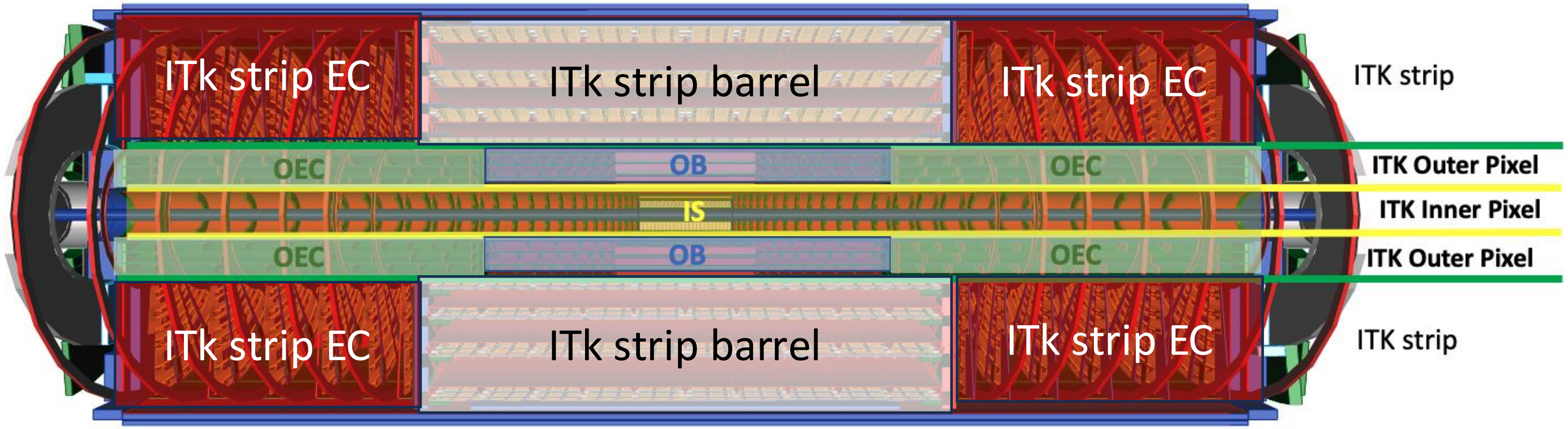


ATL-PHYS-PUB-2021-024

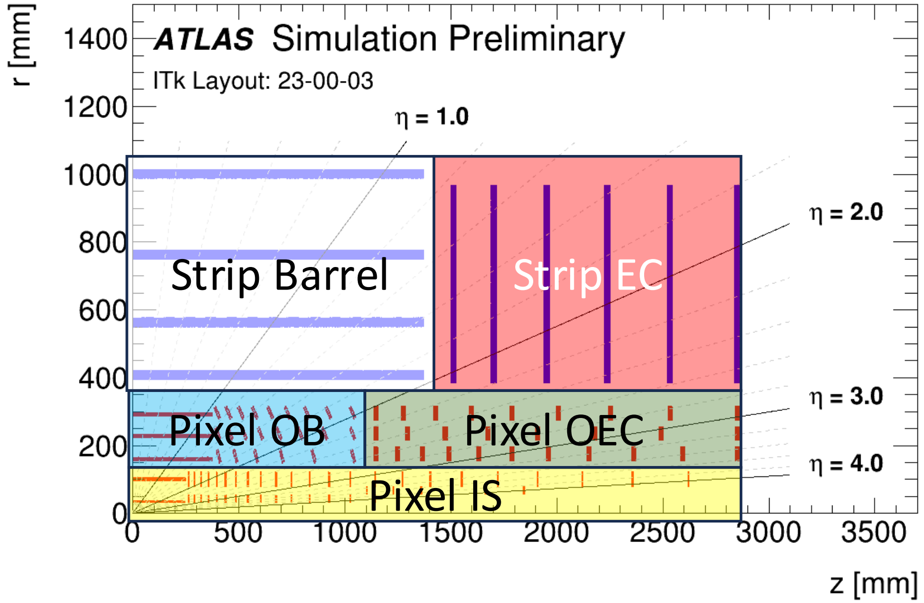
ATLAS-ITk

ATL-PHYS-PUB-2021-024

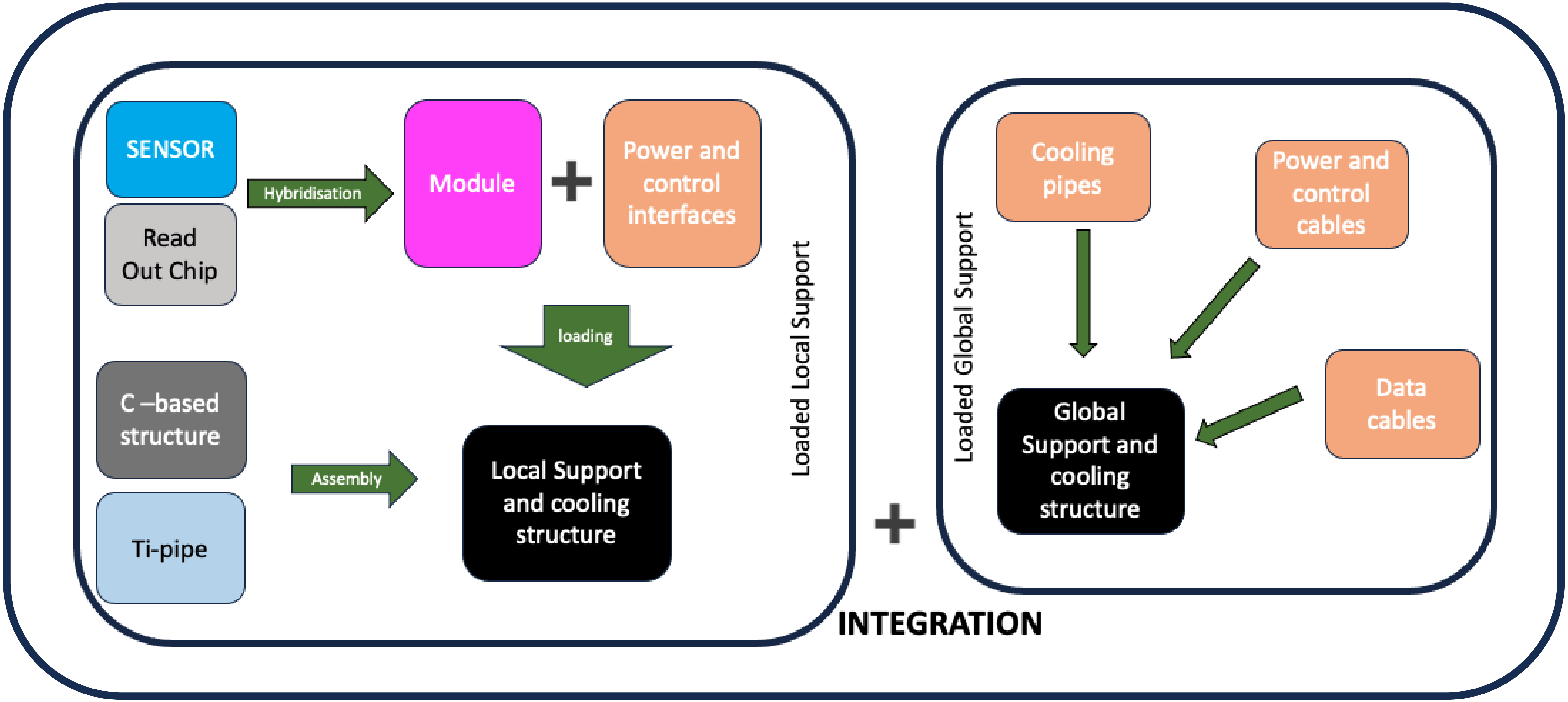
- The Strip detector has:
  - Barrel: 4 layers
  - Two endcaps: 5 layers
- The Pixel detector has three sub-detectors:
  - Inner system. To be replaced after 2000 fb $^{-1}$:
    - 2 layers of flat staves and 2-3 layers of flat rings
  - Outer system:
    - Outer Barrel: 3 layers of flat staves and inclined rings
    - 2 Outer endcaps: 3 layers of flat rings



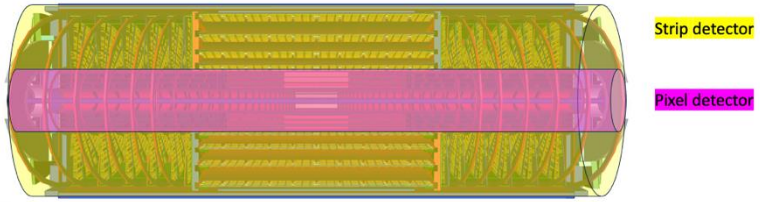
ITk Pixel = ITk-pixel Inner System + ITk-pixel Outer System = ITk-pixel Inner System + (Outer Barrel + two Outer Endcaps)



ITk production workflow. Strip and Pixel detectors



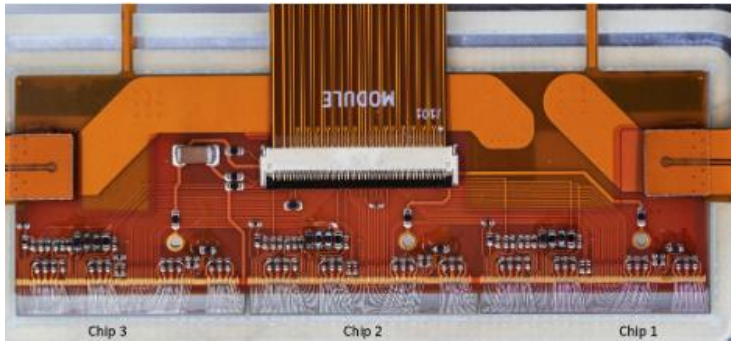
ATLAS-ITk. Pixel Modules



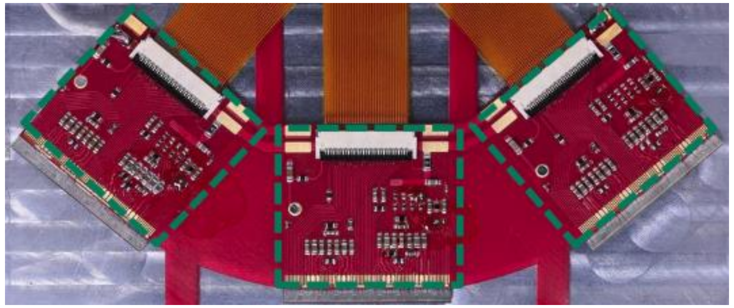
- Inner System:
  - 396 3D silicon triplet modules in Layer 0:
    - 50 x 50 μm^2 in the endcaps and 25 x 100 μm^2 in the barrel
  - 1160 n-in-p planar quad modules (50 x 50 μm^2):
    - 100 um thick on Layer 1 → barrel
    - 150 um thick on Layer 1 → Endcap

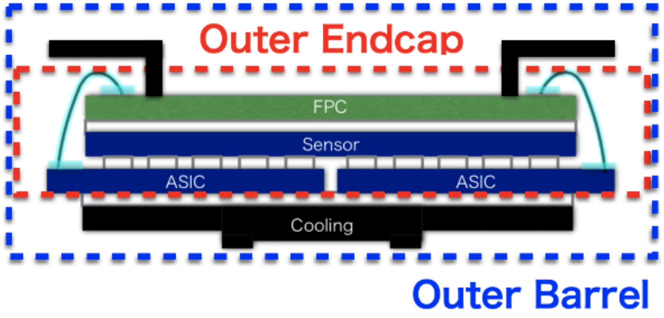
- Outer system:
  - Outer barrel: 4472 n-in-p 150 μm thick planar quad modules
  - Outer Endcaps: 2344 n-in-p 150 μm thick planar quad modules

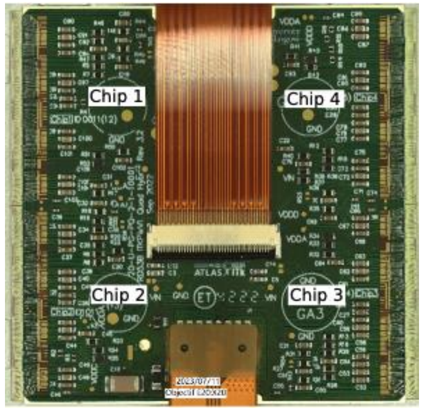
3D triplet for the Inner System barrel stave



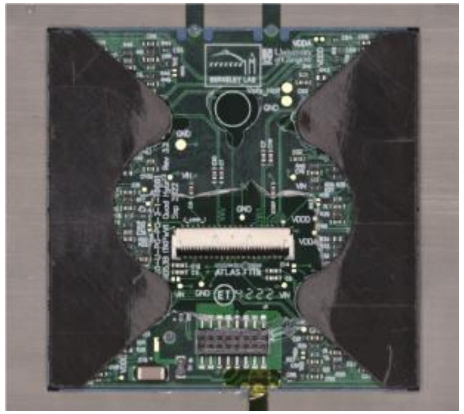
3D triplet for the Inner System endcap ring







Outer Endcaps quad module with data and power pigtails connected

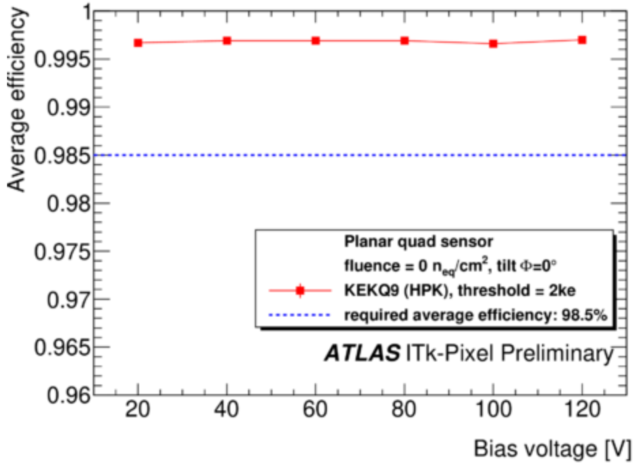


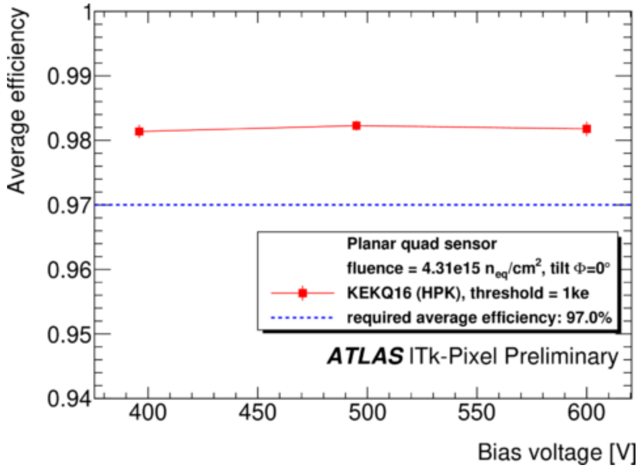
Outer Barrel quad module with carbon fibre wire bond protection

ATLAS ITk

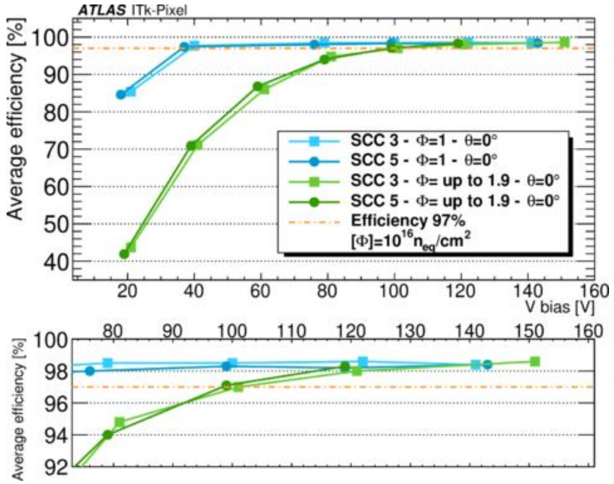
ATLAS –ITk Pixel Modules. Silicon sensors

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

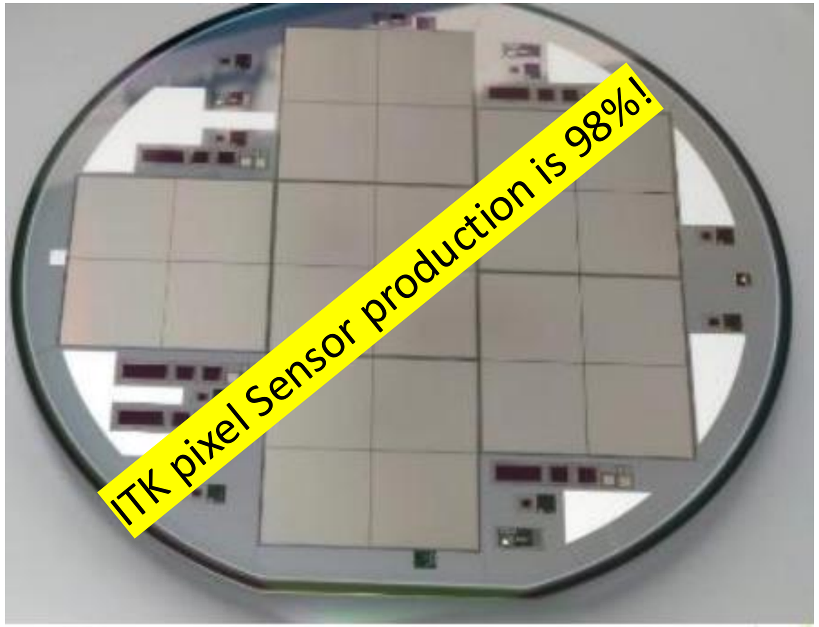




Average efficiency vs bias voltage for 150 μm thick planar sensors before (top) and after (bottom) irradiation from ITK-2023-005.

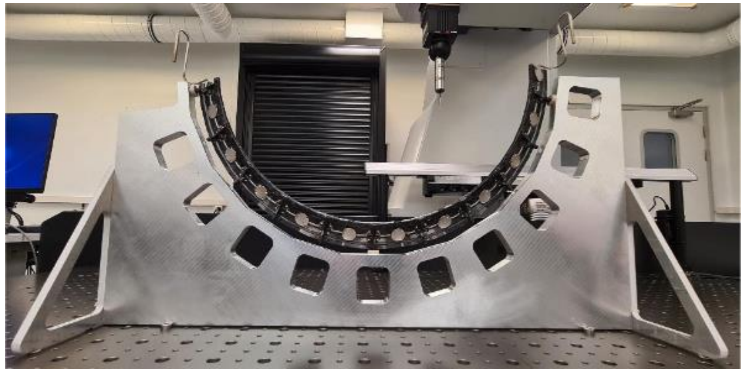


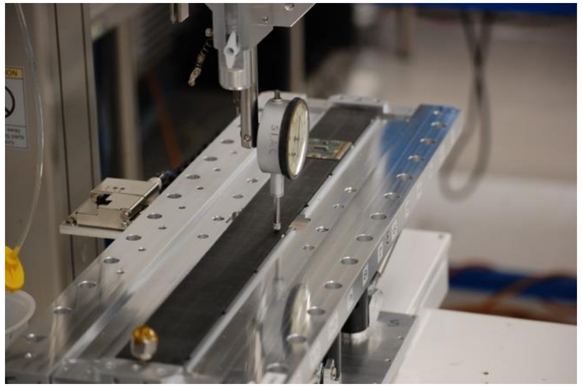
Average efficiency vs bias voltage for 3D sensors after irradiation (top). At the bottom also showing the leakage current and the breakdown voltage, Both from ITK-2022-005.

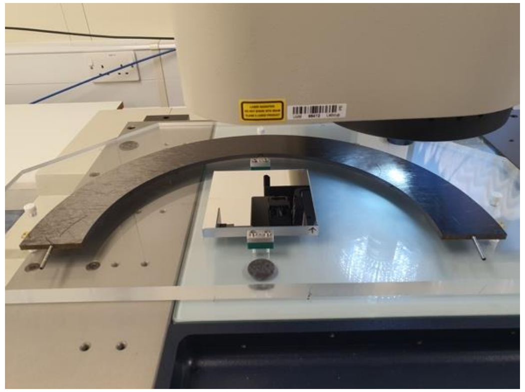


Pixel Mechanical structures. Local supports

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.

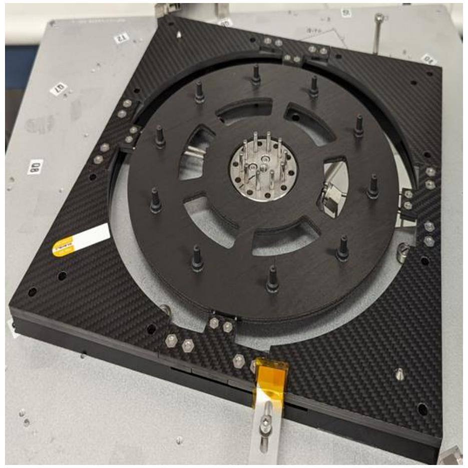






Outer Endcaps Half-ring

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

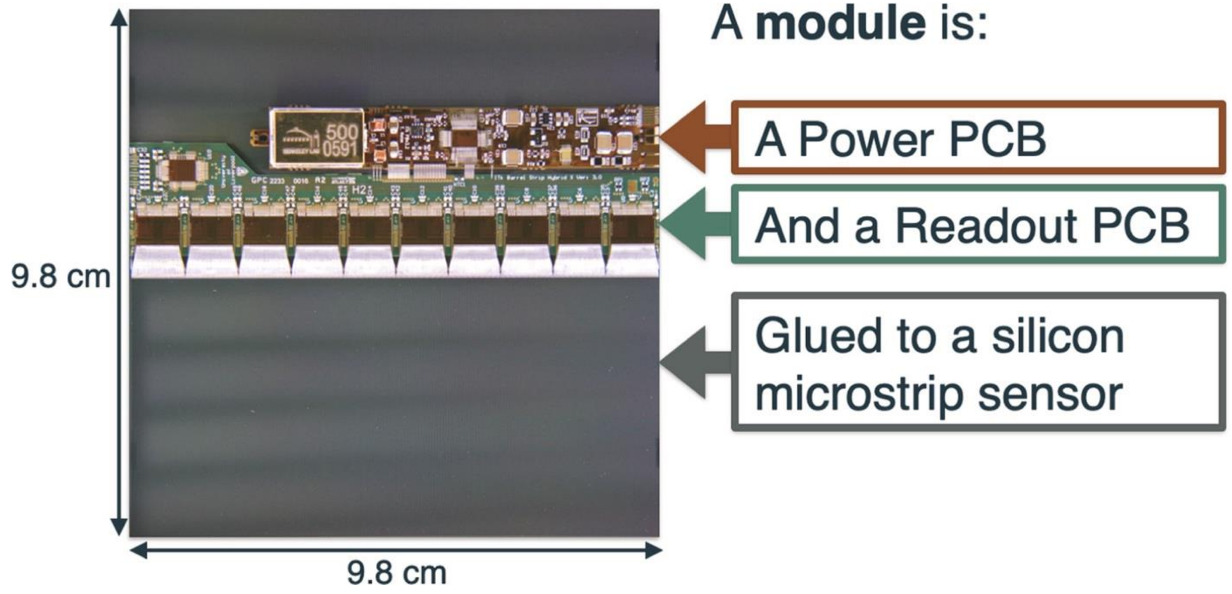


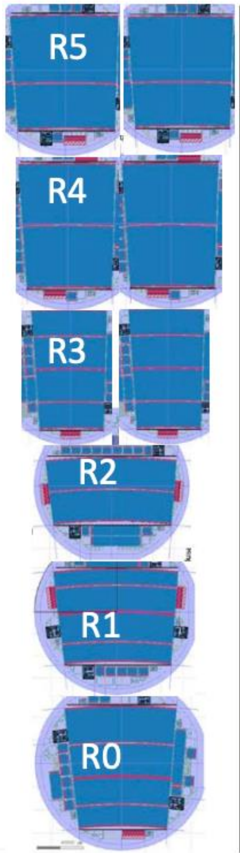
Inner system stave (top) and coupled ring (bottom)

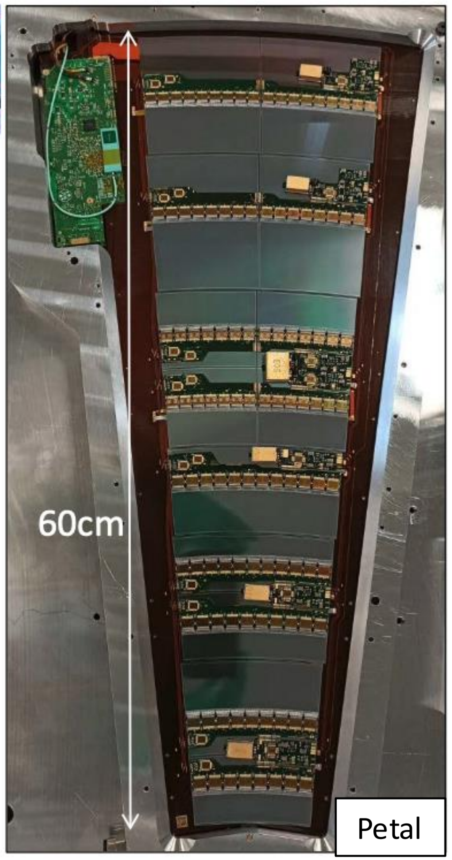
- Local supports already in production. All materials, assemblies and interfaces qualified against thermal and mechanical stresses and irradiation.
- QC protocols already in place:
    - Thermal.
    - Metrology.
    - Grounding.

ATLAS-ITk. Strip Modules

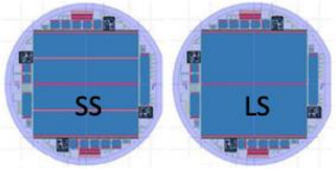
- 8 different geometry of Silicon sensors for the ITk strips are fabricated on 320 µm thick n-in-p float zone wafers
- The central region (barrel) has 1 sensor shape with 74.5 µm strip pitch and strip lengths of:
  - 23.9 mm (short strip- SS)
  - 47.75 mm (long strip- LS)
- The forward regions (endcap) have 6 sensor shapes with strip lengths from 15.1 mm to 60.2 mm with sensor pitch between 70 and 80 µm

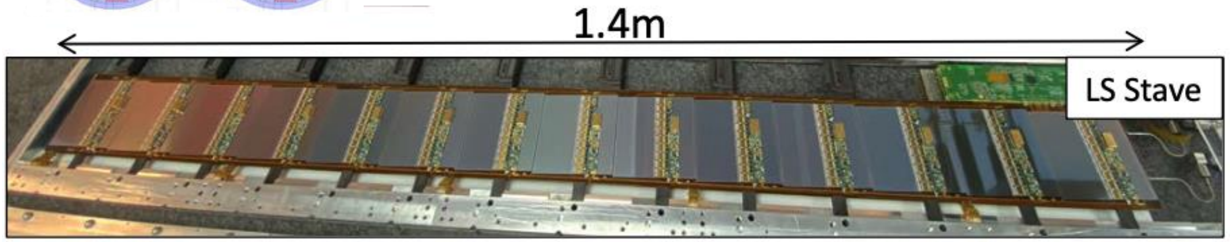






4608 modules on 384 petals

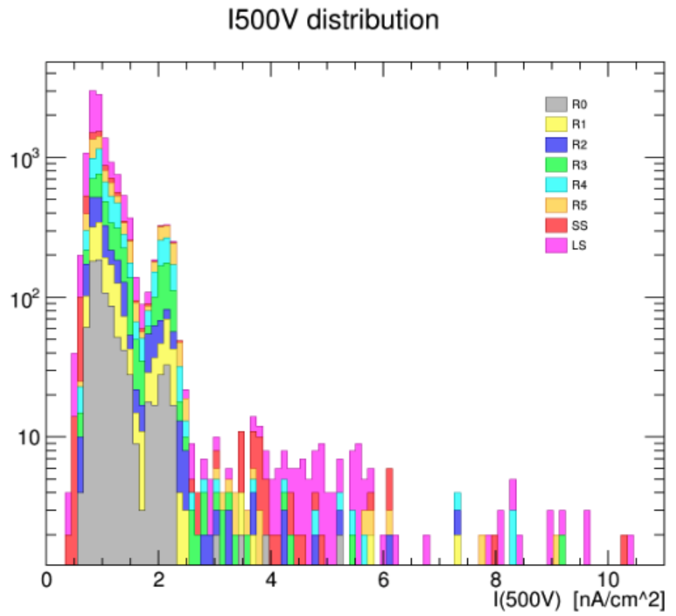




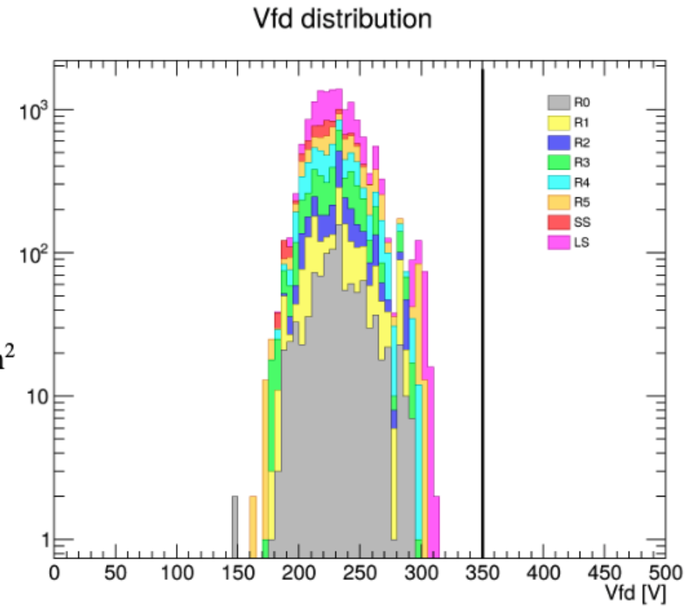
10976 moules on 392 staves

ATLAS –ITk Strip Modules. Silicon sensors

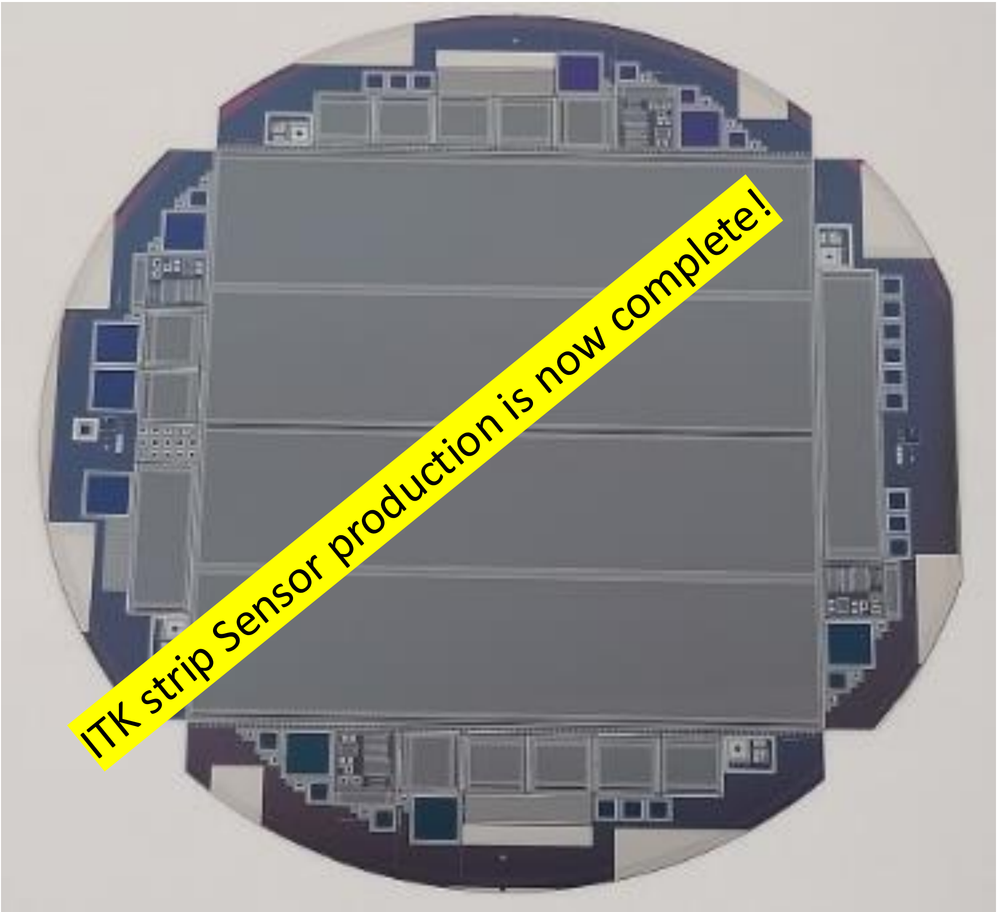
Some results on quality control of Strips sensors, more in ATL-ITK-PROC-2026-002



IV normalised leakage current at 500 V specs.: < 100 nA/cm^2

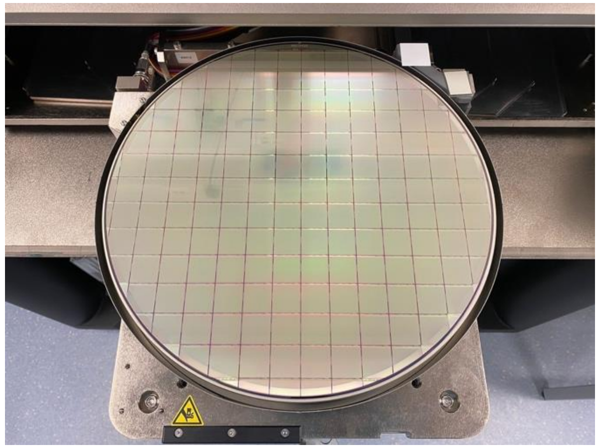


Full depletion voltage (Vfd) specs.: < 350 V



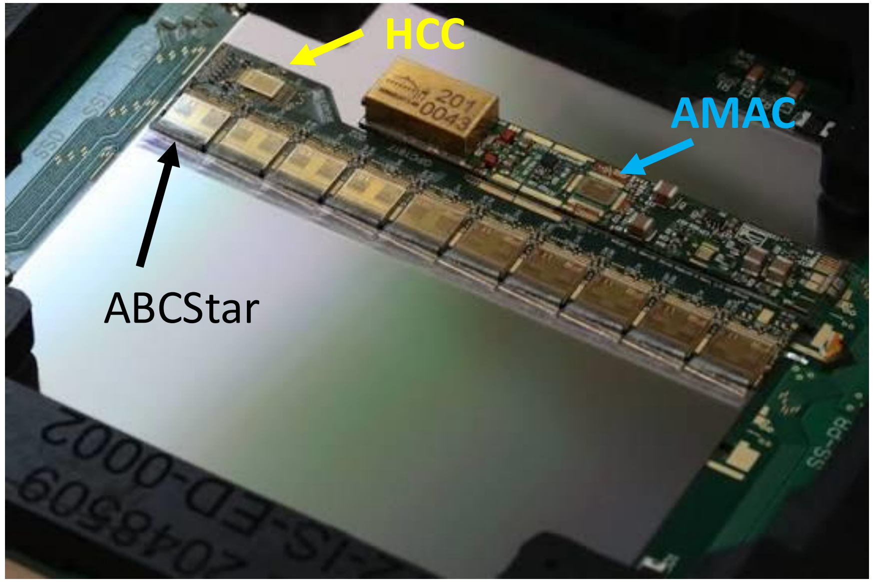
ITk (main) ASICs

- Pixel.
  - ITkPix V2
    - RD53 Collaboration
  - A total area of 2x2cm^2. 152800 pixels per chip (50x50 μm^2) pitch. High granularity.
  - Low threshold operation and cluster charge readout using Time over Threshold.
  - Sensor leakage current compensation and Single Event Error hardening.
  - 1.28Gb/s data rates → higher luminosity.
  - Data merging and Shunt LDO regulator



700 wafers (131 chips) with a 90% yield

- Strip
  - ABCStar: ATLAS Binary Chips. Read analogue signal from the sensors and provide binary output
  - HCC: Hybrid Controller Chip. Gather data from ABCStars and send clock and control signals
  - AMAC: Autonomous Monitor and Control chip. Module control and monitoring

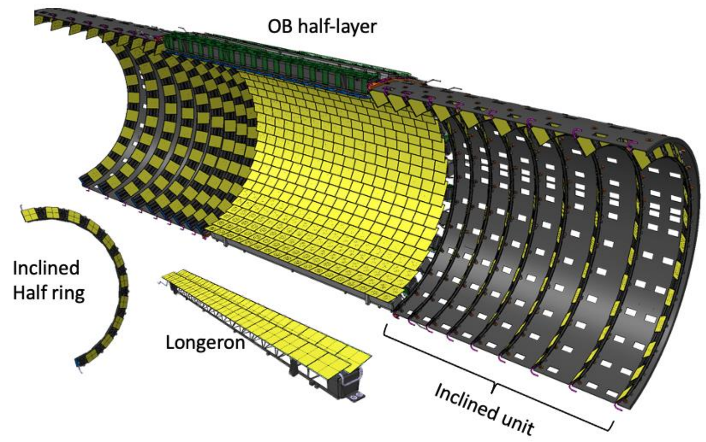


Long-strip module

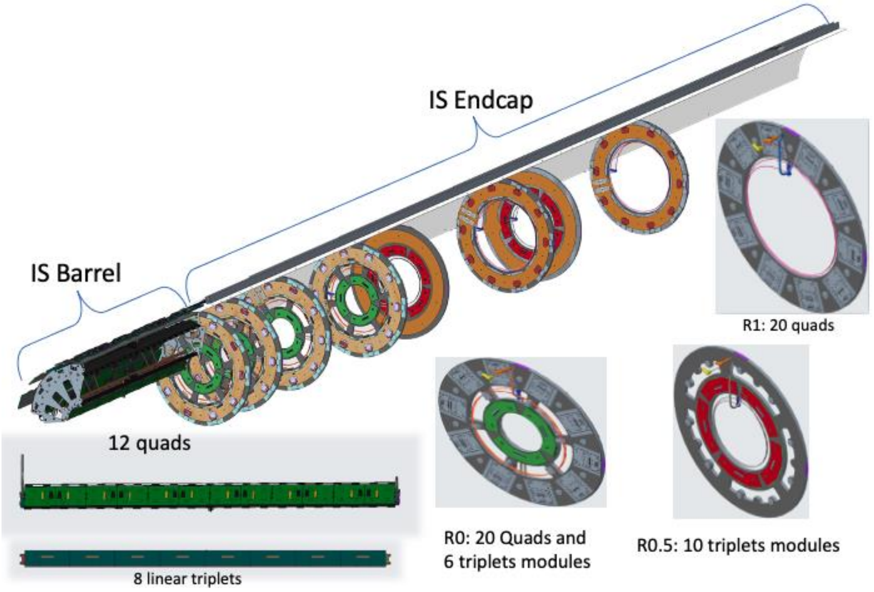
Global Mechanics. ITk pixel

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).

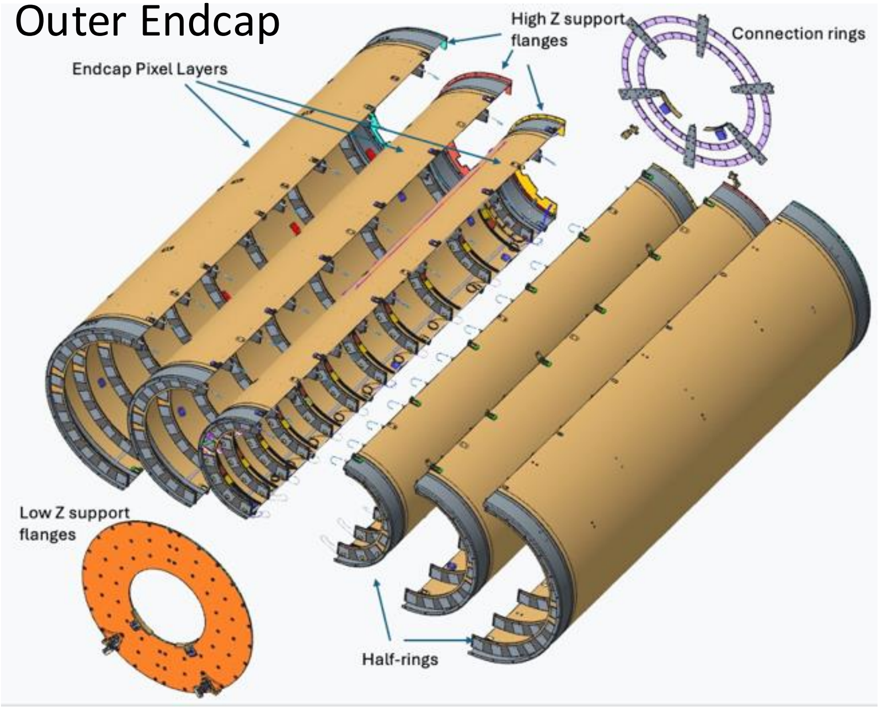
Outer Barrel half layer



Inner System Quarter-shell

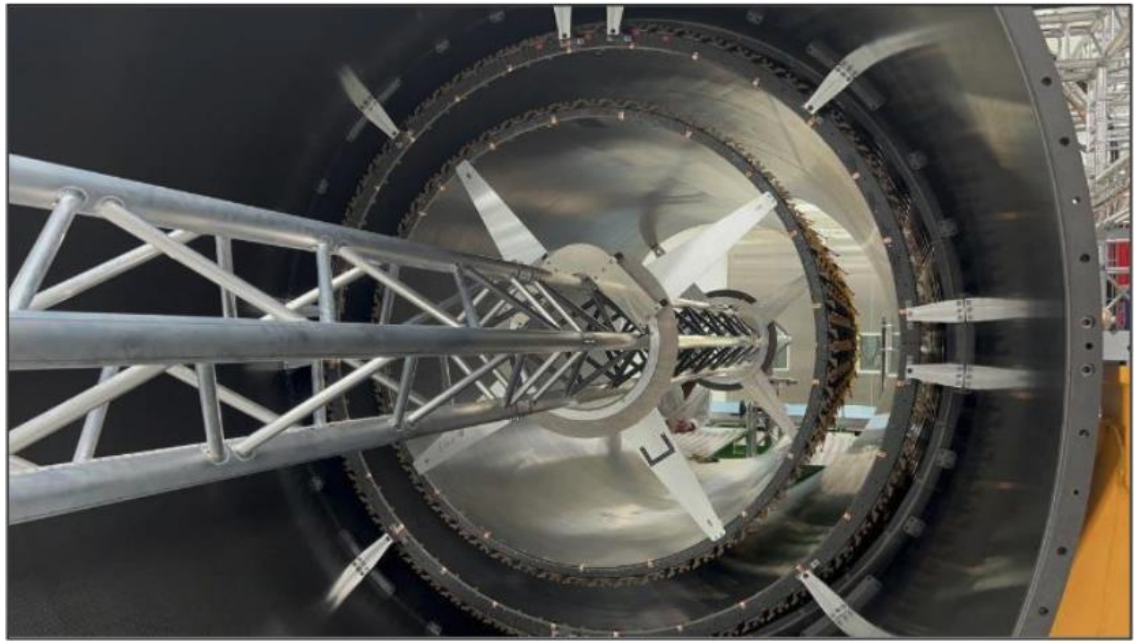


Outer Endcap



Global Mechanics. ITk strips

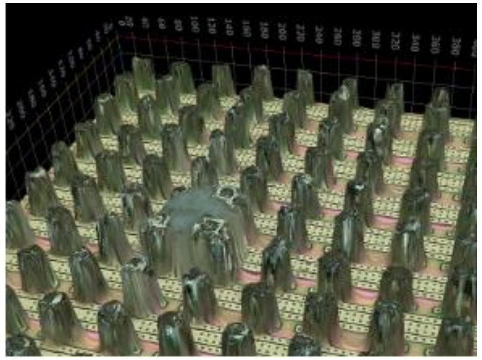
Global mechanic structures support the local supports and all the services needed in the detector: power, cooling, data lines and detector conditions (Humidity and Temperature).



ITk challenges

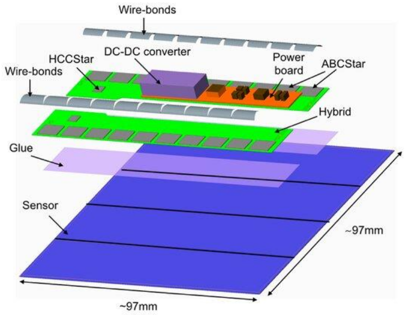
Pixel Detector

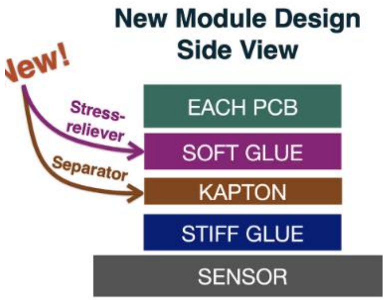
- Delamination problems due to CTE mismatches, mitigations:
  - Tuning the copper thickness in the flex
  - R&D in the hybridisation technique
  - Parylene coating.
- Sensor's bow is also a technical challenge for hybridisation vendors during prototyping.
  - Techniques are being found at vendors to overcome it.
- Core-column issues coming from debris (dicing) and impacting hybridisation, mitigated by:
  - Changing the cleaning procedures
  - Dicing technique: laser

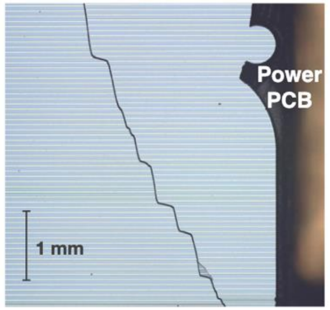


Strip Detector

- Cold noise → mechanical vibrations on the power board
- Sensor cracking after loading in the mechanical supports
- Both effects correlated to the interface between the module and the electronics:
  - Thicker glue layer reduced the cold noise
  - Softer glues (not suitable) eliminated it
  - Cracks were located near the power board
- Solution for both : The interposer
- bPOL12V failure after irradiation and T-cycling:
  - Chips with new design under production to be used on the harder irradiation areas







Project Status

- **Sensor and ASIC production is finished (or quasi) for both subsystems**
- Production ongoing:
  - Modules
  - Local supports
  - Services (cooling and electrical)
  - Global Mechanics
- Complex system testing
- Integration*
- Face any surprises along the way

Many challenges ahead until integration into ATLAS!

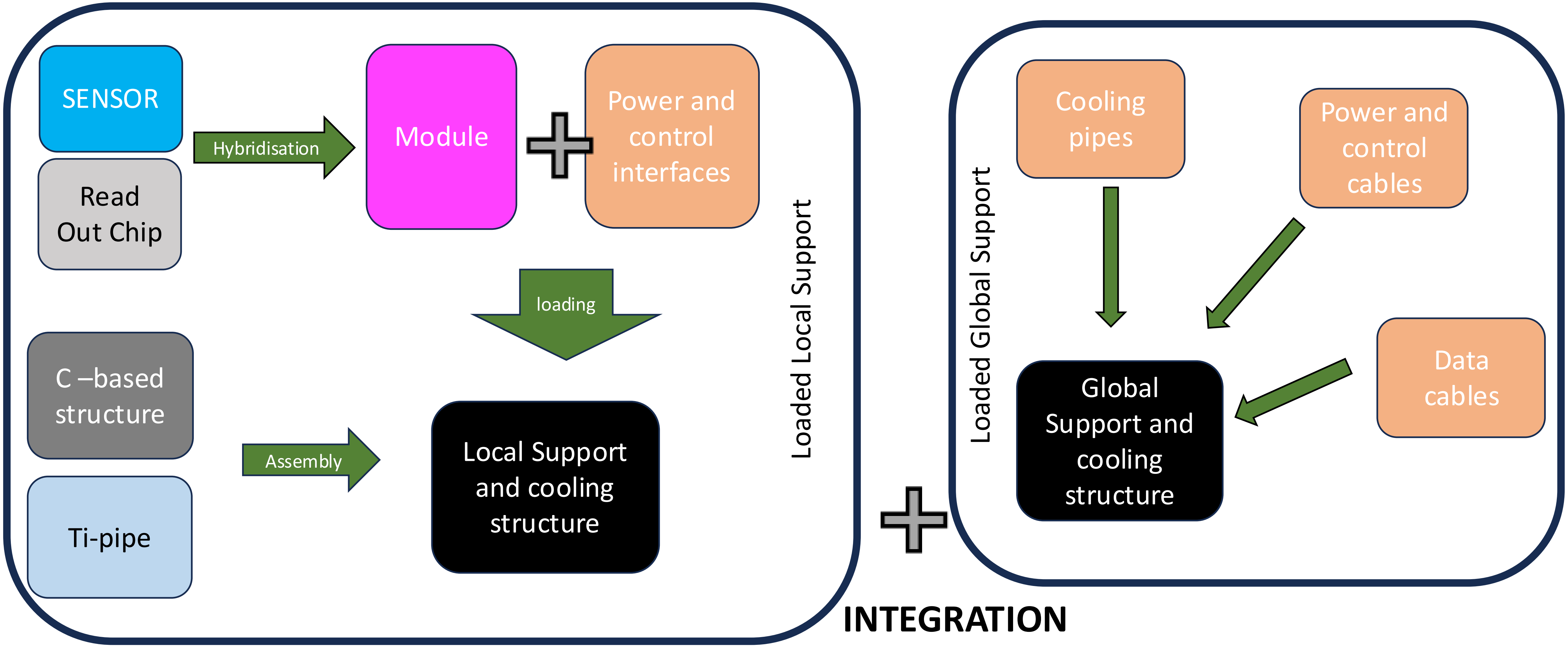
"If you want the rainbow, you gotta put up with the rain"
Dolly Parton

****It actually means that*** *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… And everything must work together, and must fit…*

Thank you very much for your attention. Questions?

Backup slides

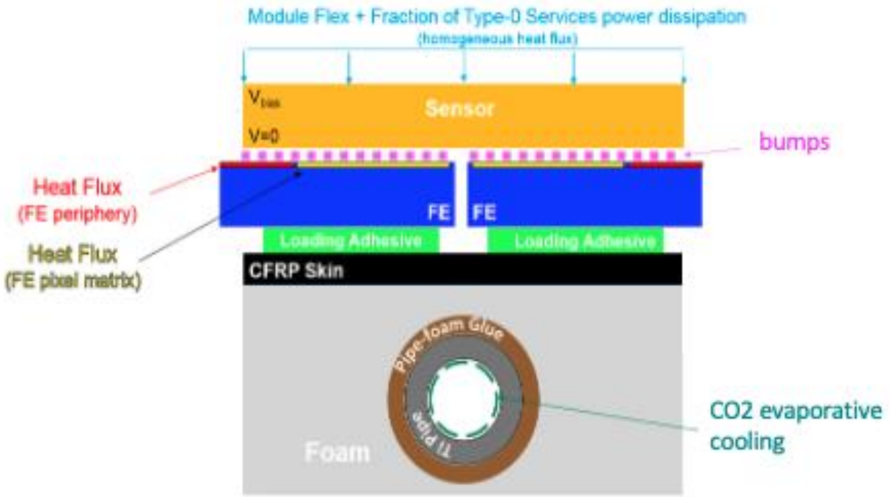
Tracker construction stages.

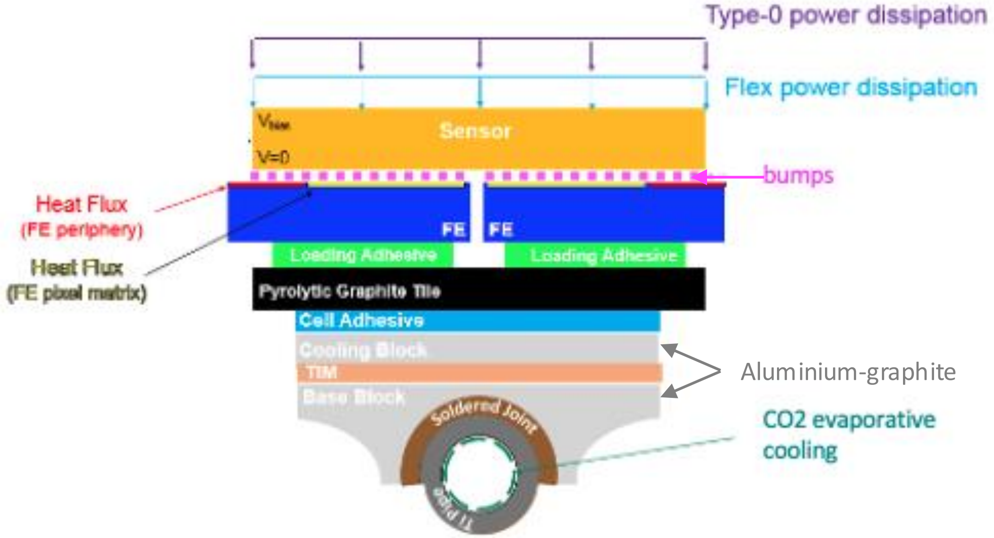


Mechanical Structures. Local supports

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



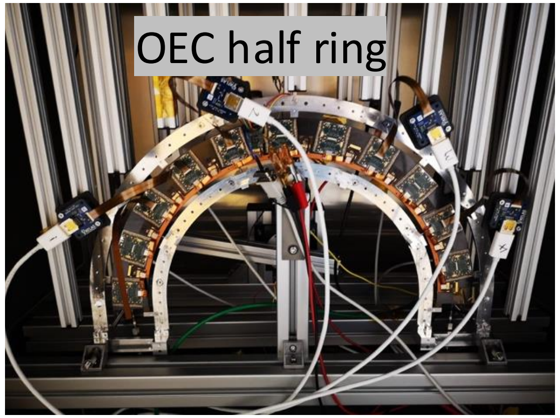


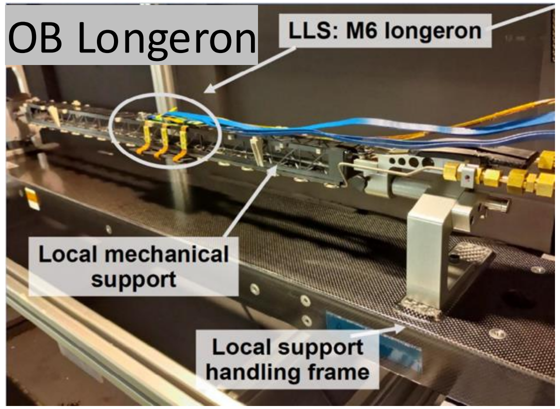
Different schematics to illustrate the different structures and materials between the silicon and the cooling pipe (the thermal path). Left: Outer Endcaps and Inner System Schematics, right: Outer Barrel

System tests

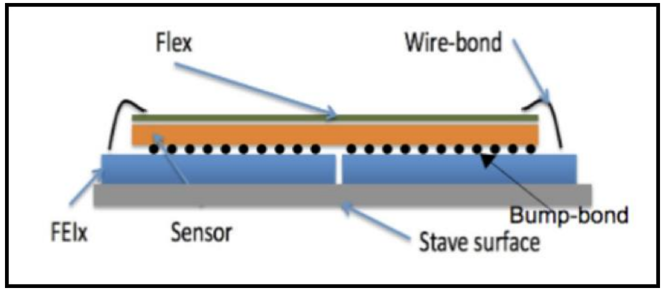
Tests performed with as many parts and as final as possible (now with RD53A prototypes, getting ready for ITkPix V1-2) :

- 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…).





Modules. Challenges.



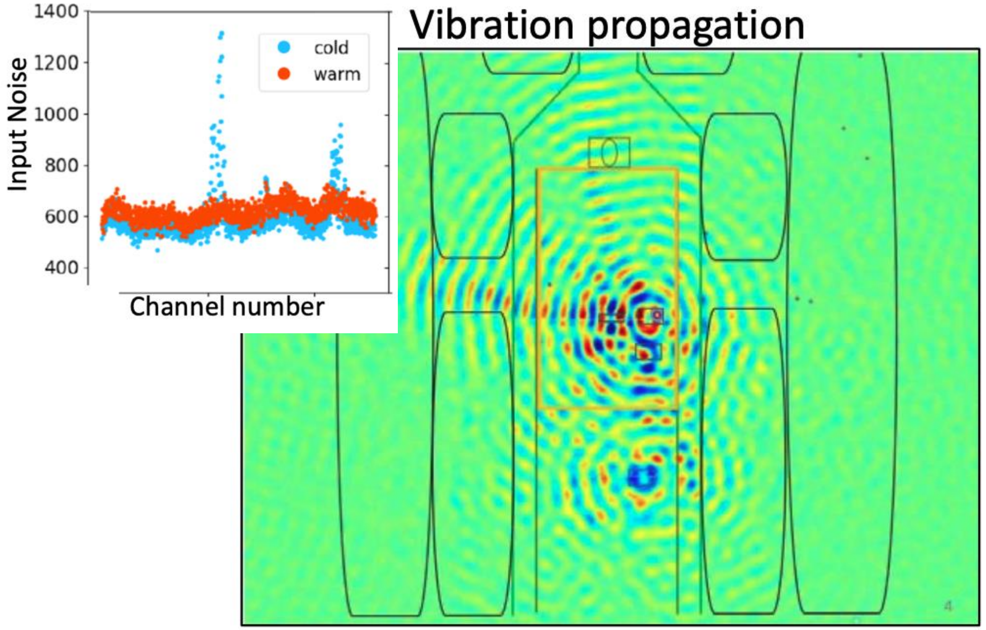
- The final module assembly contains many different materials:
  - Copper and Kapton in the flex
  - Copper and silicon (others) in the FE-chip
  - Thin silicon and aluminium in the sensor
  - Different metal alloys in the bumps
- It is then glued into a local support (carbon structure)
- All the different 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.

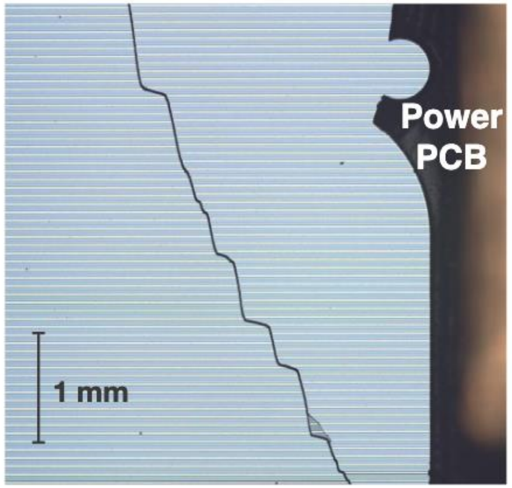
These issues are still being closely monitored and tested during pre-production.

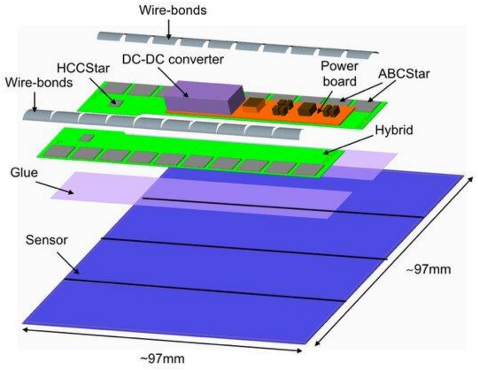
ITk strip challenges

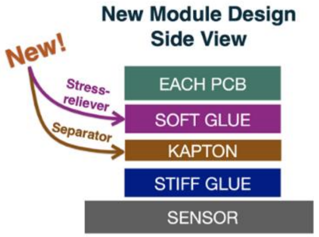
- 2022. During the testing of pre – production modules at cold temperatures (< -20 °C)
  - Noise excess → called "cold noise"
  - Mechanical vibrations in the power board
- 2023. Sensor cracking after loading in the mechanical supports
- Both effects were correlated to the interface between the module and the electronics:
  - Thicker glue layer reduced the cold noise
  - Softer glues (not suitable) eliminated it
  - Cracks were located near the power board
- Cold noise produced by vibrations of the capacitors on the power board
- Cracks due to different thermo-mechanical properties inducing stresses between the electronics and the module

- Solution for both : The interposer





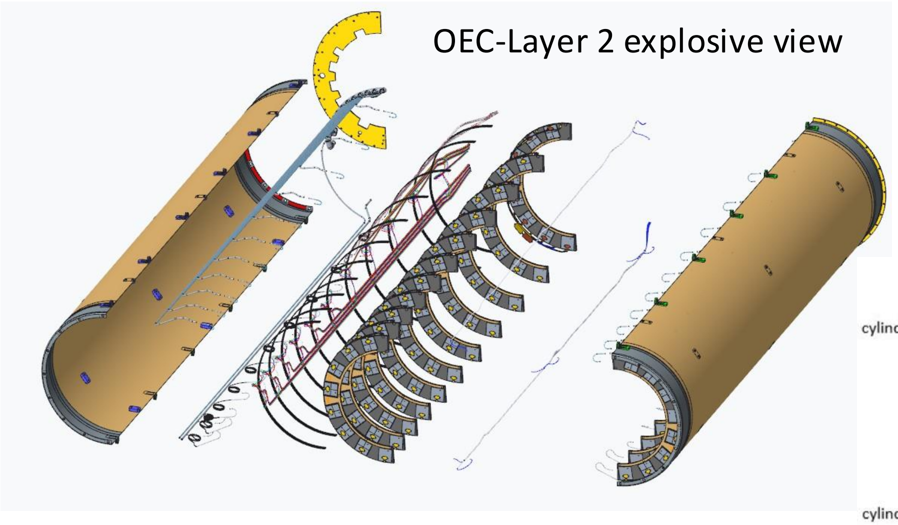




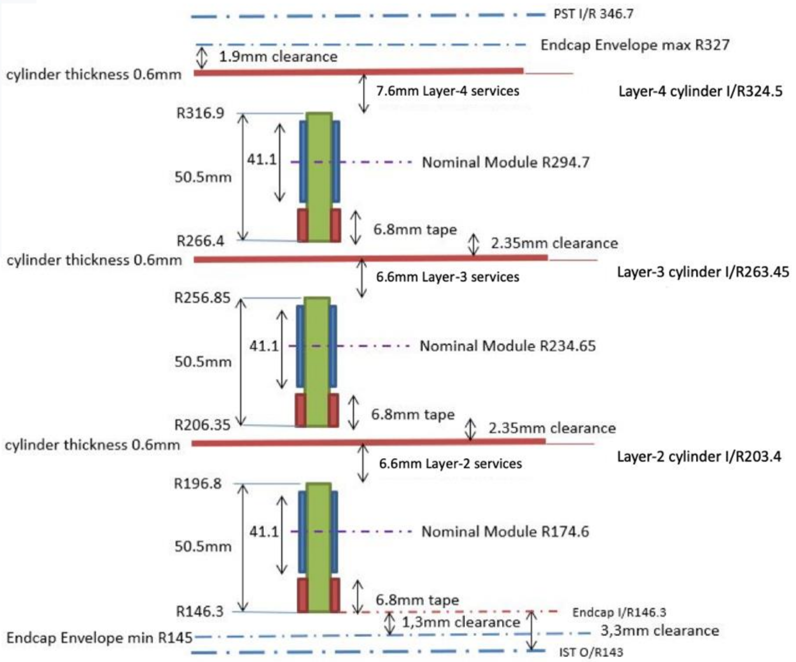
ATL-ITK-SLIDE-2024-102

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…*

Summary

- The ATLAS-ITk Detector has been designed to perform and operate under the HL-LHC challenges:
  - Low mass: carbon structures, serial powering, data merging, optical data transmission.
  - 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).
- A few busy years ahead…