# ATLAS Inner Tracker Upgrade Pixel Detector

Umberto Molinatti on behalf of the ITk-pixel collaboration

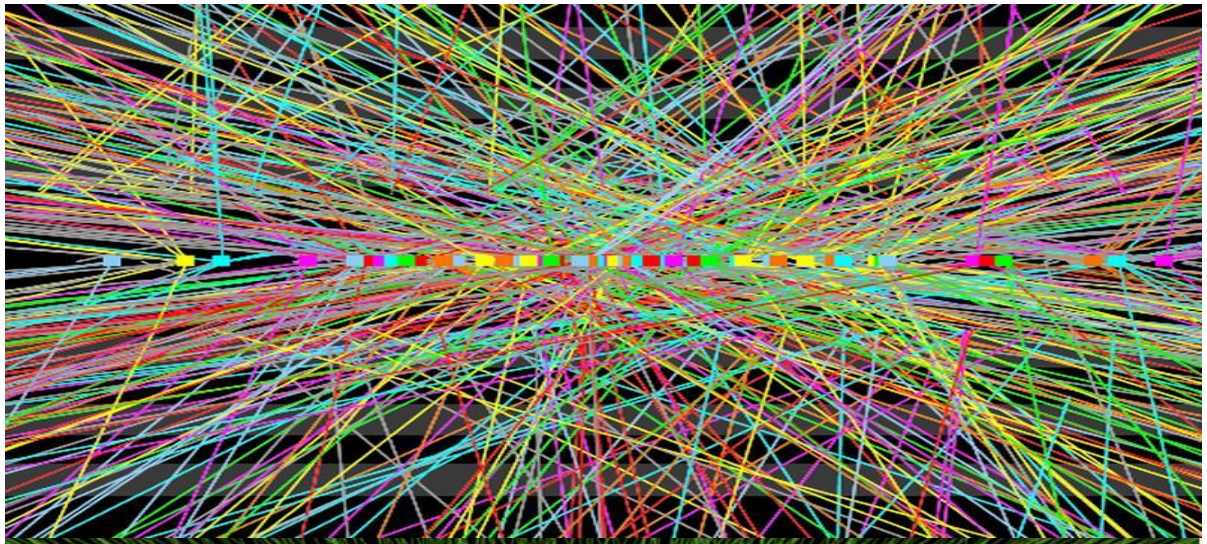
26th International Workshop on Radiation Imaging Detectors

# Outline

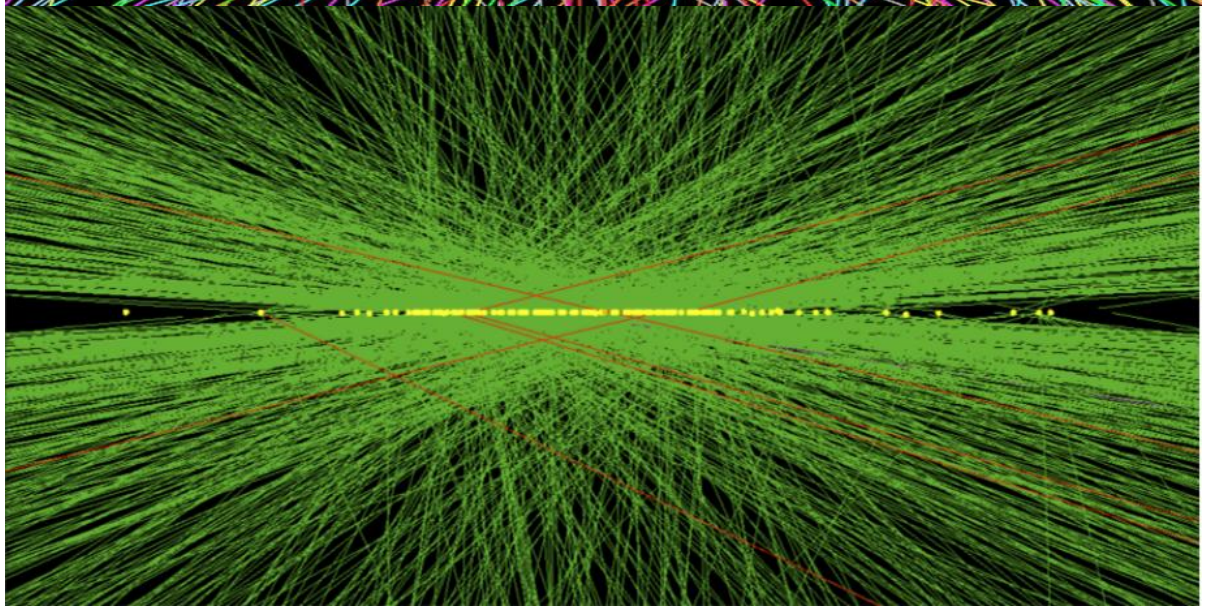
- High Luminosity LHC (HL-LHC)
- The New ATLAS Inner Tracker
- Global Mechanics
- Loading Progress
- Silicon Sensors
- Pixel Modules
- Module Quality Control
- Conclusion

# High Luminosity LHC

- Proton-proton collisions at 13.6TeV centre of mass energy
- Currently, 64 proton-proton interactions in a typical bunch crossing



- High Luminosity LHC will begin operation in around 2030 and increase the integrated luminosity from 300fb$^{-1}$ to 3000fb$^{-1}$with centre of mass energy up to 14 TeV
  - Luminosity is the proportionality factor between the number of events per second and the cross section
- Around 200 proton-proton interactions in a typical bunch crossing
- This will increase both the radiation damage the detectors are subject to which calls for an increase in resolution and bandwidth



# ATLAS Inner Tracker (ITk)

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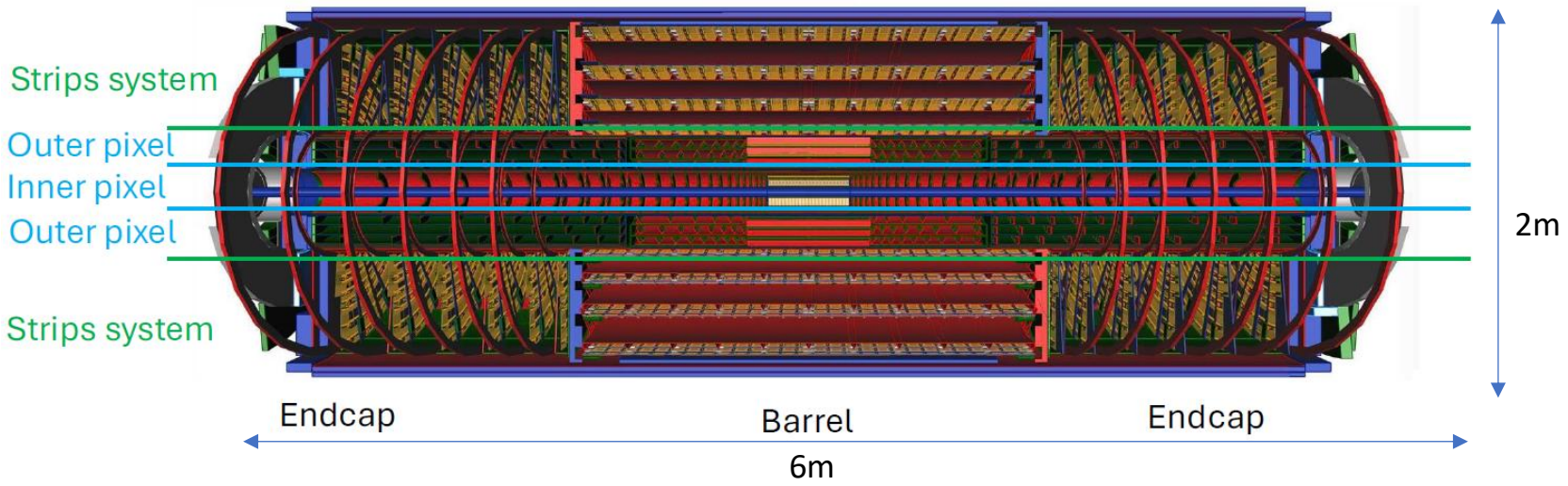


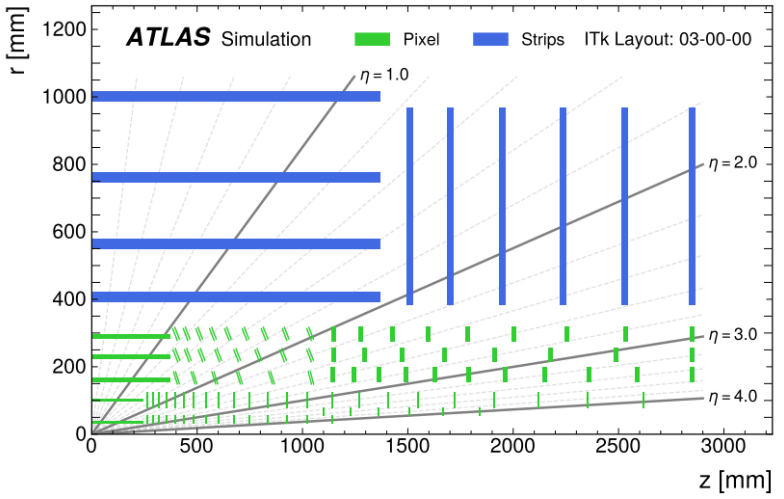


- Current inner detector will not be usable for HL-LHC, needs to be replaced by **full-silicon Inner Tracker** (ITk)
- New silicon inner tracker with **increased acceptance** from $|\eta|$<2.5 to $|\eta|$<4 and increased pile-up rejection
- **Radiation hardness increased tenfold** up to 2 x $10^{16}$ n/cm$^2$
- Inner section composed of Pixels while outer of Strips
- **Increased bandwidth** up to 5 TB/s
- Tracking **performance comparable or better than before HL-LHC** in conditions of higher pile-up



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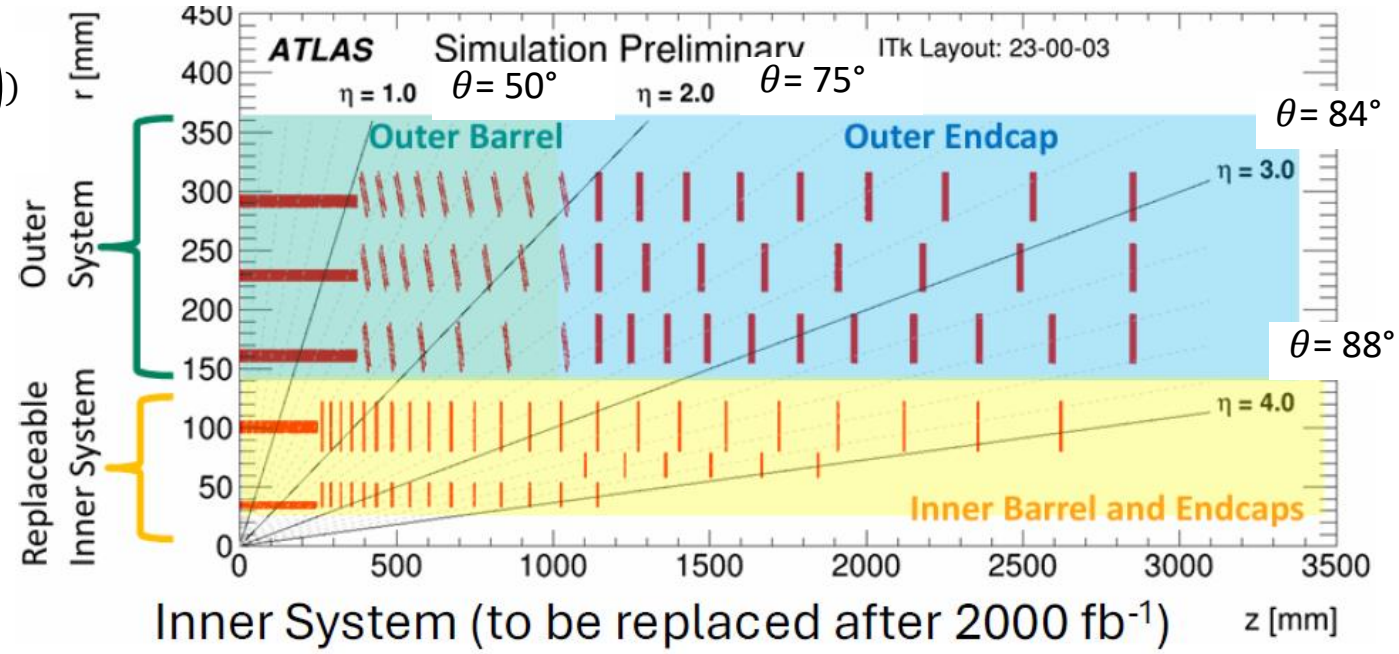
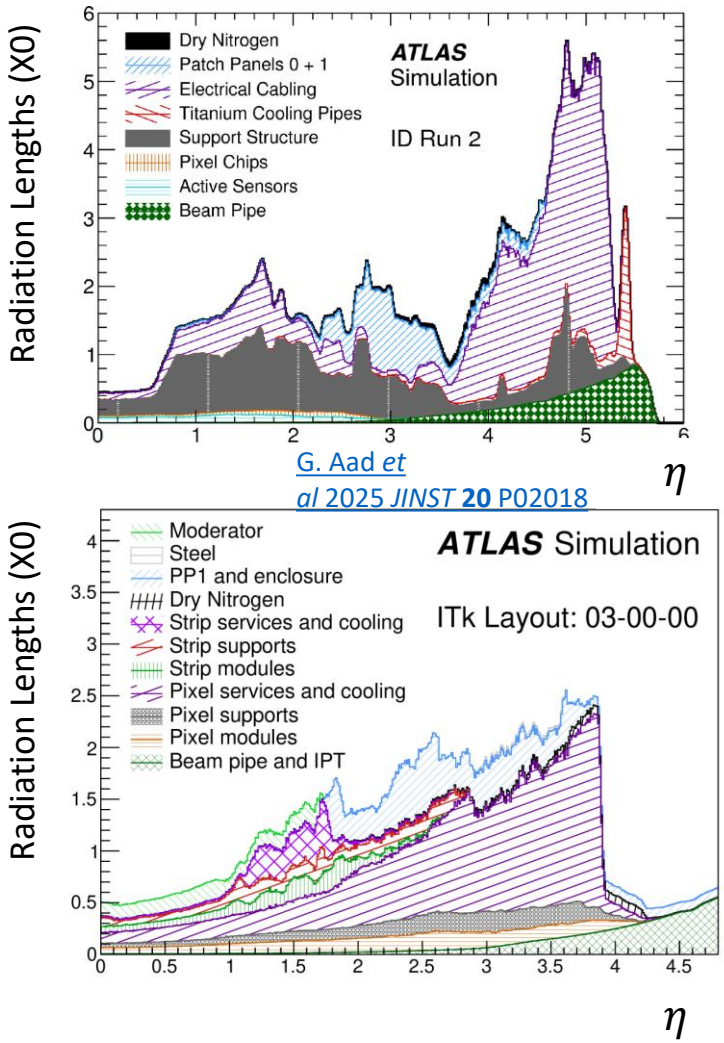
# ATLAS Pixel Detector

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$



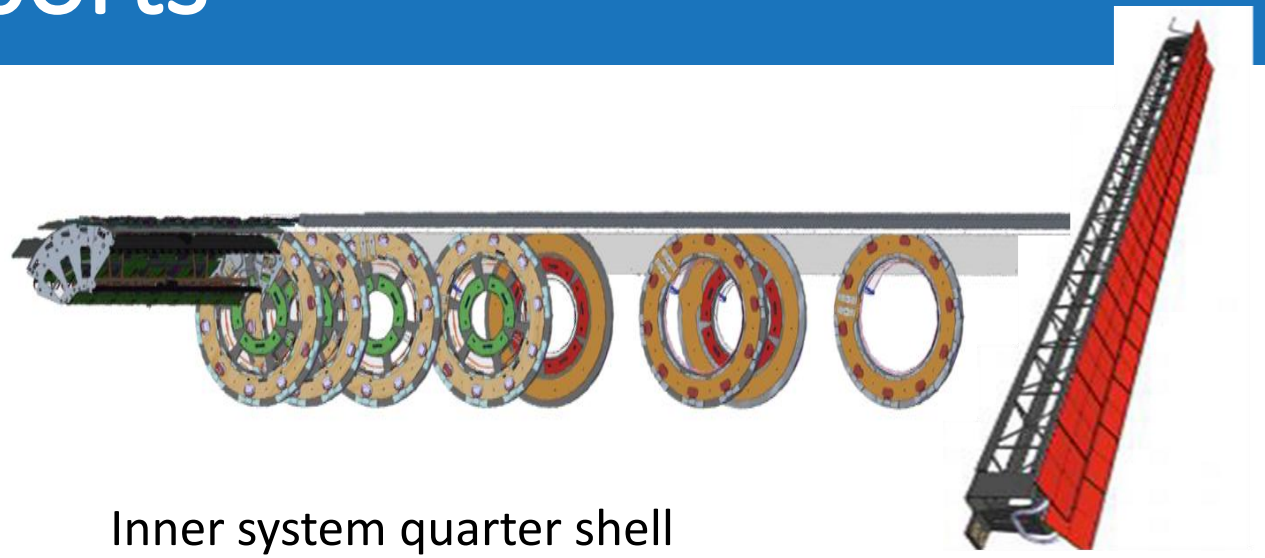

G. Aad *et al* 2025 *JINST* **20** P02018

- **Largest pixel detector ever constructed**, 8372 modules for 13m$^2$ of area, 15kW of power consumed
- Increase in pixels from 92 million to 5 billion
- 3D sensors in the innermost layer of the inner system, planar sensors in the outer side of the tracker
- Serial powering used to power the modules, reducing number of cables and material budget
- Biphase $CO_2$ cooling throughout the tracker

Current ATLAS material budget (top) versus upgraded version (bottom)

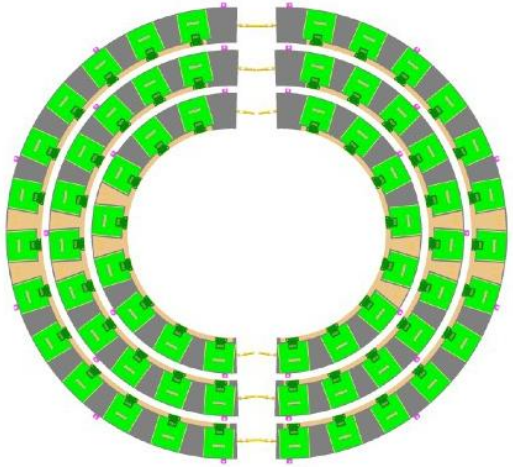
# Local Supports

- Assembled modules then glued to carbon fibre and carbon foam local supports
- Material chosen to minimize mass while maximising thermal performance and providing mechanical rigidity
- Many different geometries used but with a common quad module design to ensure maximum scalability
- Modules serially powered to reduce cabling
- Number of readout cables reduced by module data link sharing
- Supports cooled with $CO_2$ through thin titanium pipes



Inner system quarter shell

Outer barrel longeron



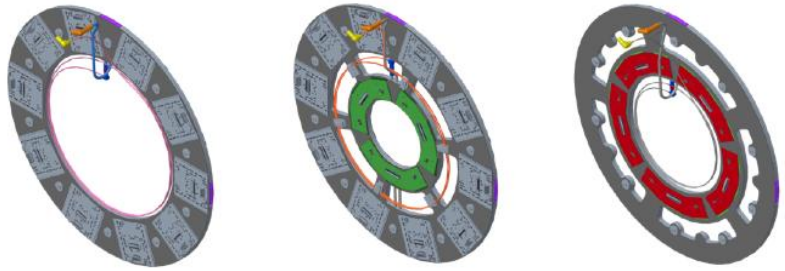
Outer endcap rings

Outer barrel inclined half-ring

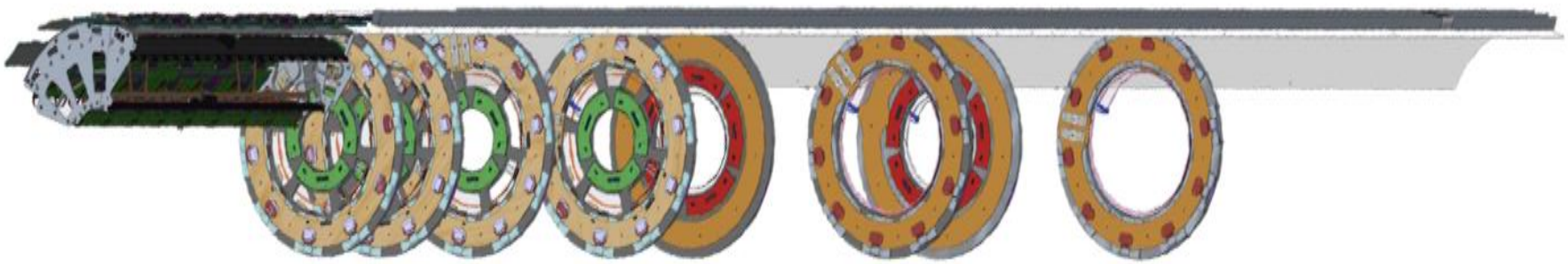
# Inner Tracker Global Mechanics

Inner system coupled rings:

- Whole inner-system is independent of the outer system, will be replaced at around half of the detector's lifetime due to radiation damage
- Two innermost layers share support structures to reduce material budget
- Three types of rings all perpendicular to beamline

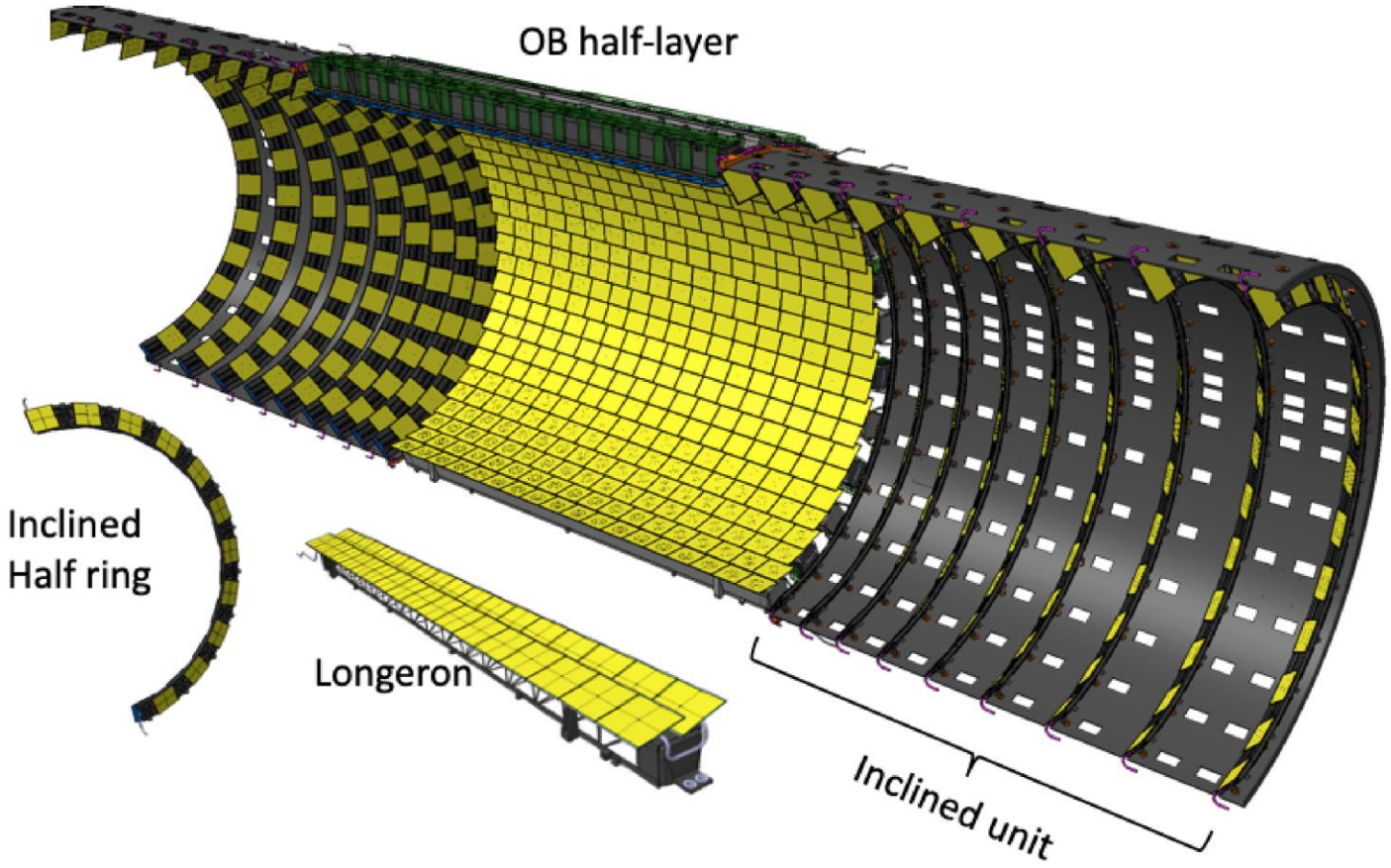


L1 Ring | L0-1 Coupled Ring | L0.5 Intermediate Ring



# Outer Barrel Global Mechanics

- Modules mounted onto pyrolytic graphite tiles
  - Increases material budget but permits reworkability
- This holds modules in place and provides contact to the cooling pipes
- Modules mounted on longerons in the central section, on inclined half rings further out
  - Angle between 55° and 67° to the beam pipe
- Half rings inclined to be perpendicular to tracks
  - Reduced material interaction
  - Reduce cluster size and data rate
  - More complex to build





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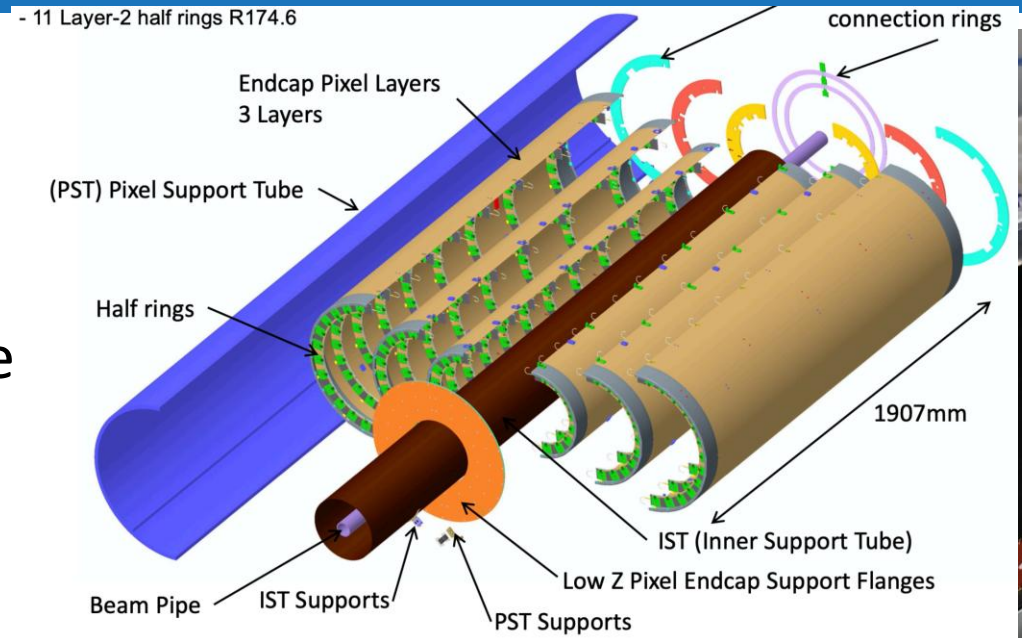
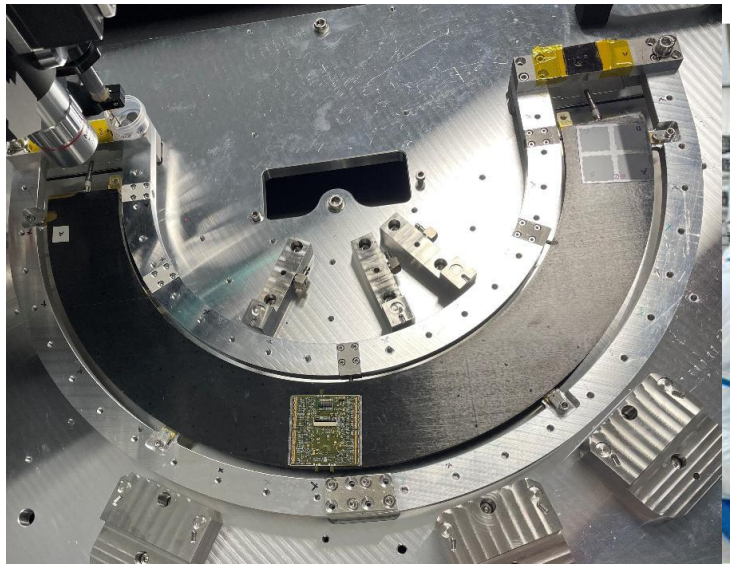
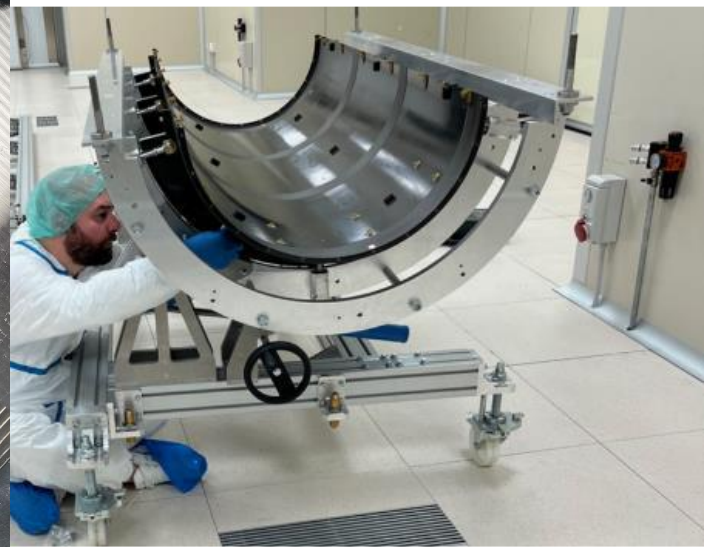
# Outer Endcap Global Mechanics

- Modules glued onto endcap half rings
  - Glue soft enough to allow reworking
- Allow increased flexibility in module placement for optimal coverage
- Three concentric sizes of half rings
- Rings separated by carbon fibre half-cylinders
- Cooling and electrical services supported by these half-cylinders



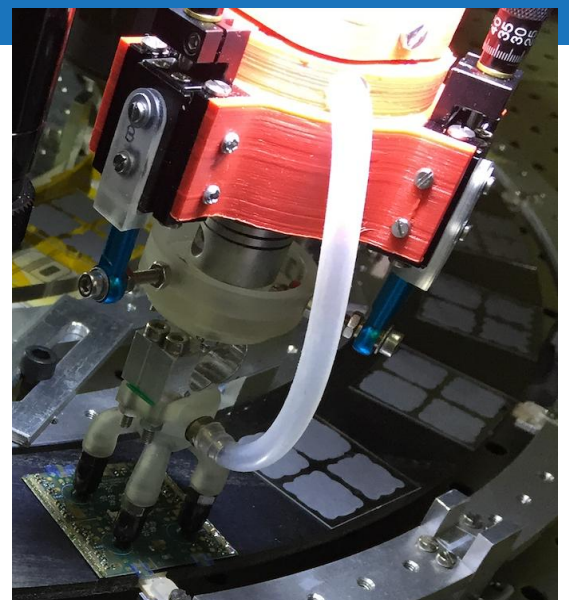





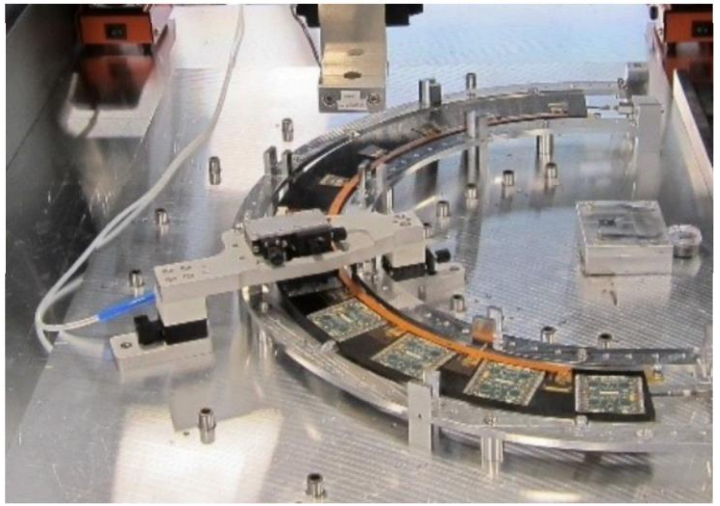
# Local Support Loading

- Ring loading performed differently based on site
  - Makes best use of expertise and experience of different sites
- Genova, Lecce, and Oxford use a gantry robot with pick and place head
- Setup reused for module assembly provides repeatability and reliability
- STFC-RAL uses manual bridges with micrometric adjustments
- Modules placed within specified precision of 150 µm
- Assembly in preproduction, aiming for production in autumn
- Currently building 4 loaded rings for a tracker-wide review

Gantry robot system



Alternate gantry robot system



Manual bridge system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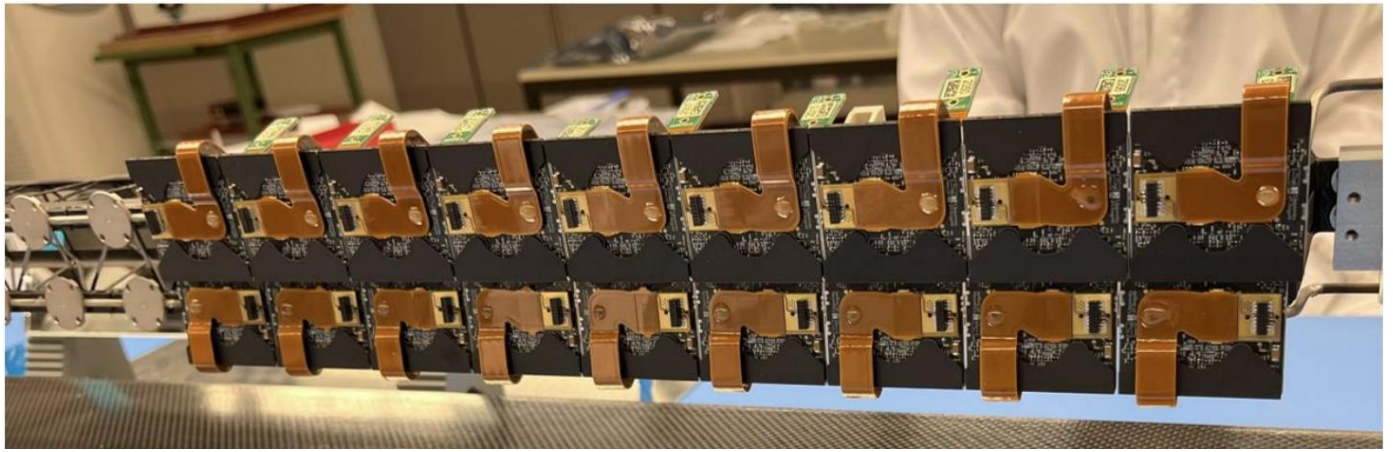
# Local Support Loading

- First Outer Barrel pre-production loaded local support
  - 18 modules in two serial powering chains
  - Assembled and first tested at CERN



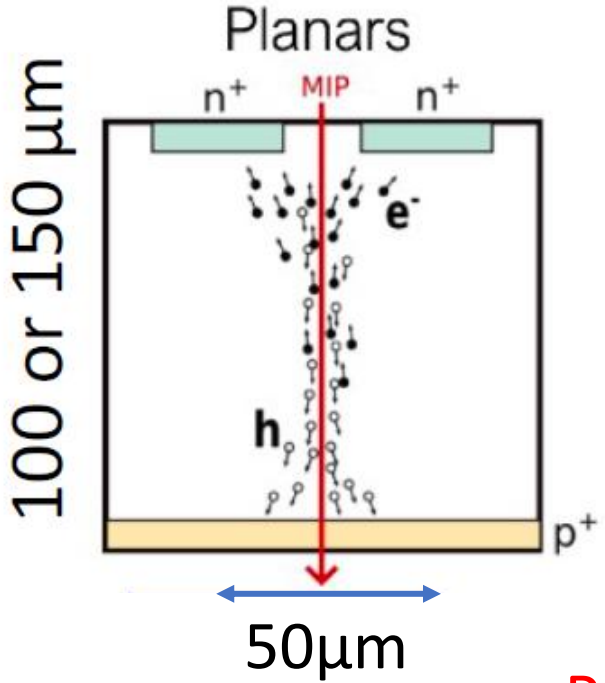
- Three chains assembled for Inner System loaded local support


- Working on optimization for quality control
- Performance testing in progress for production

# Silicon Sensors

Planar sensors:

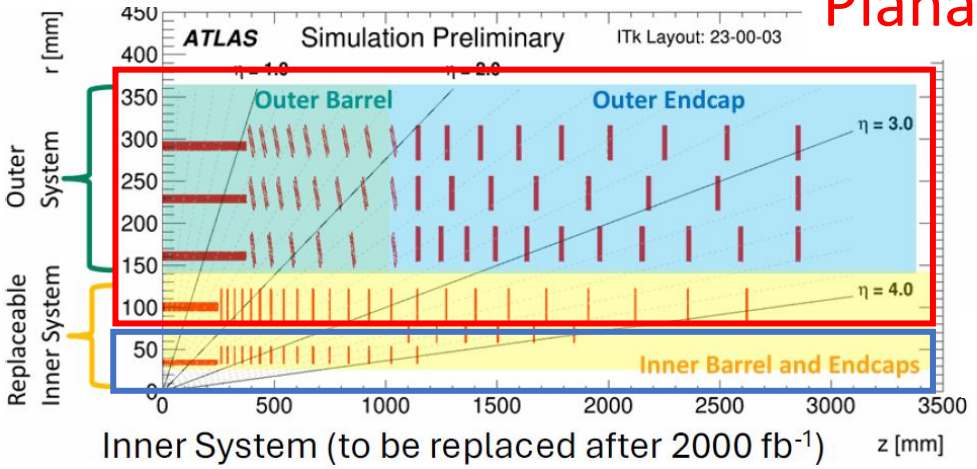
- Layers 1-4
- More than 10,000 modules to be assembled (compared to 396 3D sensors)
- Bias voltage up to 600V
- Simpler production process than 3D sensors
- 100µm and 150µm thickness variants based on radiation hardness requirements




Differences between vendors (HPK,FBK,Micron) following review of market survey:

- Guard ring geometry
- Method of biasing
- p-stop or p-spray insulation

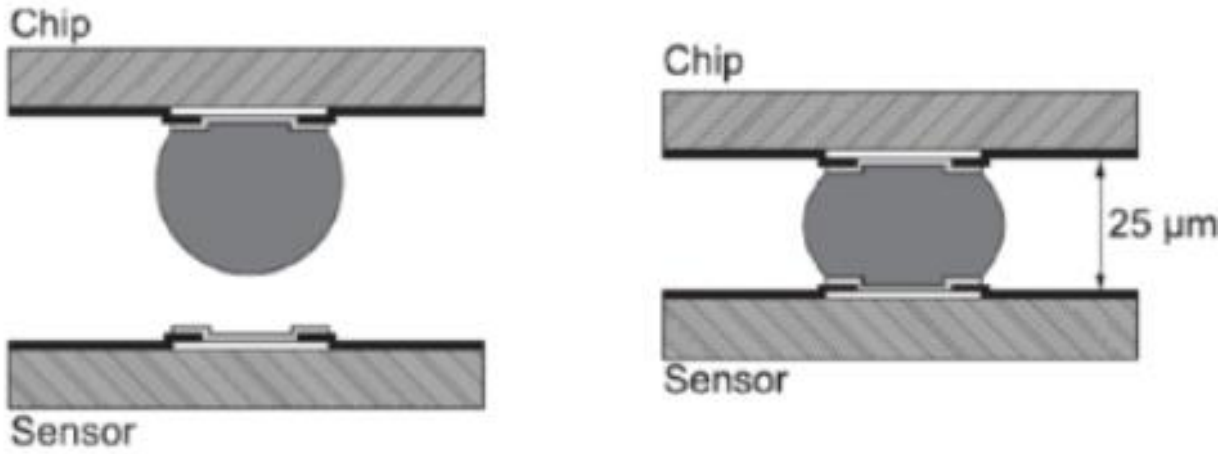
Planar

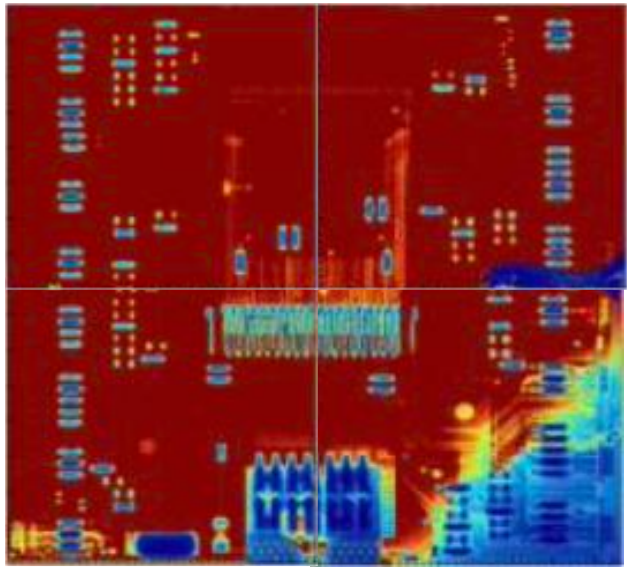



3D

# Bump Bonding

- Hybridisation performed by Leonardo, IZM, Advacam, HPK
- Solder and indium bump bonding to ASIC completes bare module assembly
- Thermal cycling (100x from -45°C to 40°C for QA) and connectivity tests are performed to ensure bumps do not disconnect due to material expansion
- Known difficulties:
  - Debris from dicing of FE-chips
  - Difficulties in handling large area sensors for some vendors

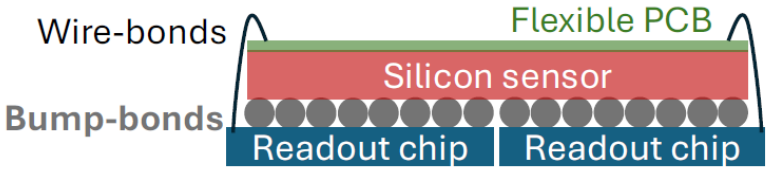


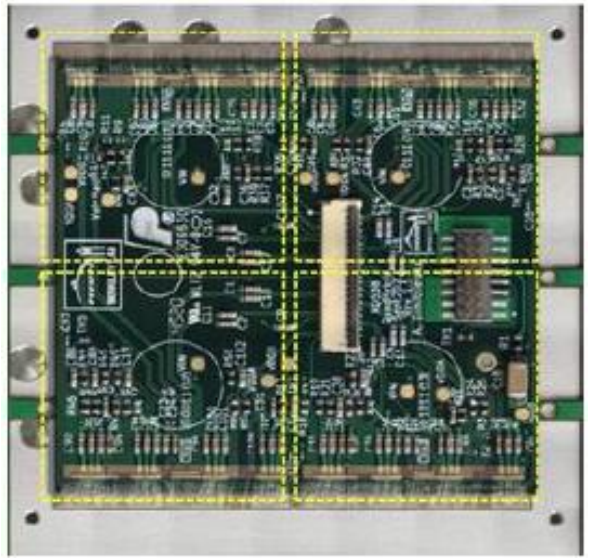



Example of disconnected bumps at the edge of a chip

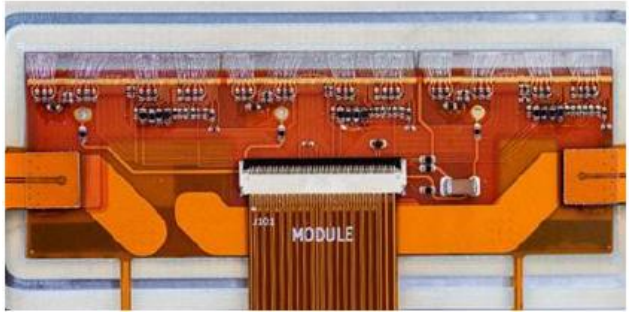
# Pixel Modules

- Two types of modules:
  - Quad modules with four FE chips attached to a single sensor
    - Used for all other layers
    - 7976 modules
  - Triplet module with three sensors, each with an FE chip
    - Used for innermost layer
    - 396 modules
- PCB glued onto bare modules for data and power connections
- Common flex design leads to increased modularity in production
  - Differences between quads and triplets due to detector geometry



Quad module




Triplet module-barrel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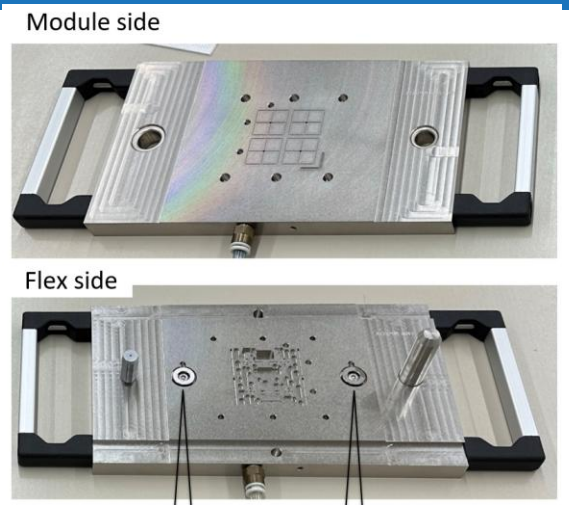
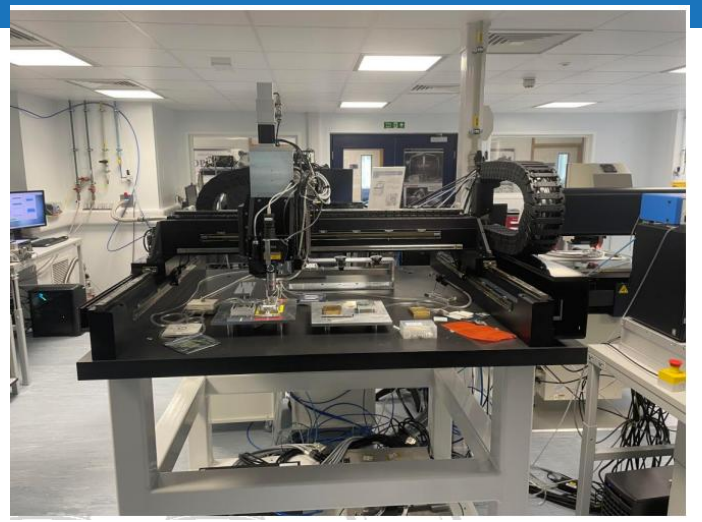
# Quad Module Assembly

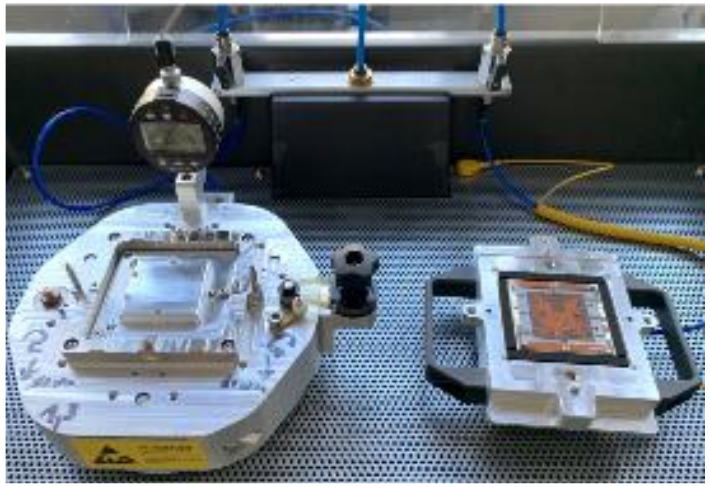
- Module assembly progressing well and process has been streamlined
- 1111 modules built so far including prototypes
- Modules built and tested in 25 different sites
- Assembly process mostly based on common tooling, though alternatives (Japan, Oxford) exist
  - Common tool has vacuum to hold components in place and precision screws for positioning
  - Oxford using automated gantry system which allows for module assembly and loading in one system
  - Japan uses microscope-assisted assembly tuning
- Main limitations are availability of parts, bump disconnect, and core column issues (next slide)




Japan assembly tool



Oxford gantry tool



Common assembly tool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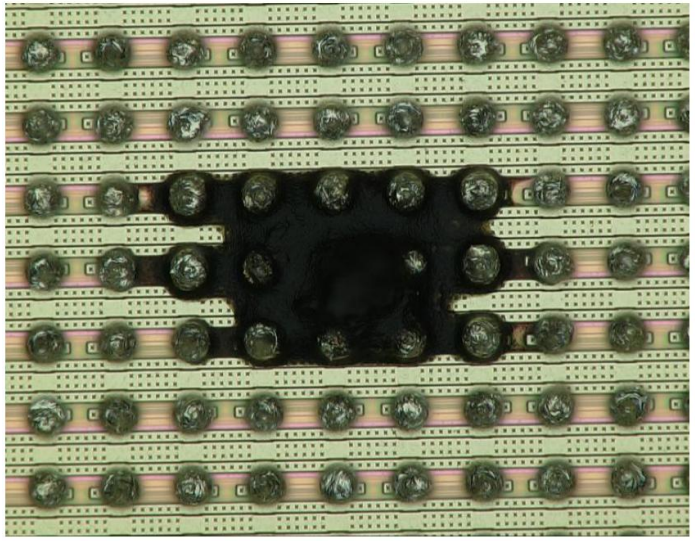
# Module Quality Control

- Assembled 1064 quad modules and 47 triplets, 86% module assembly yield

- Complicated testing organization due to collaboration between 25 different sites
  - Some sites assemble but not test and vice versa
  - **Need to test 9400 modules!!**

- "Core column" issues present during electrical QC
  - Core column is a connected set of 8 columns
  - Column on chip sends out illegible data that the overwhelms the system
  - Chips will recurrently malfunction but return to regular operation by disabling certain core columns on the chip
  - Column to disable is usually on the chip edge
  - Software tool available to find and mask the required core columns

- Core column issues present due to dicing process leaving debris on ASIC, countermeasures fed back to the relevant companies



- Module with core column issues disassembled
- Found Si debris jammed between bumps in core column position

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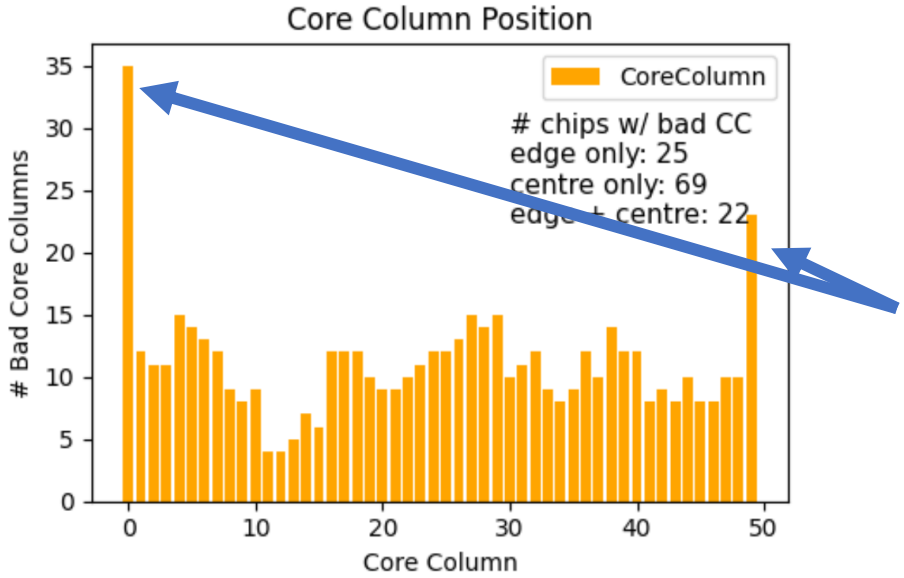
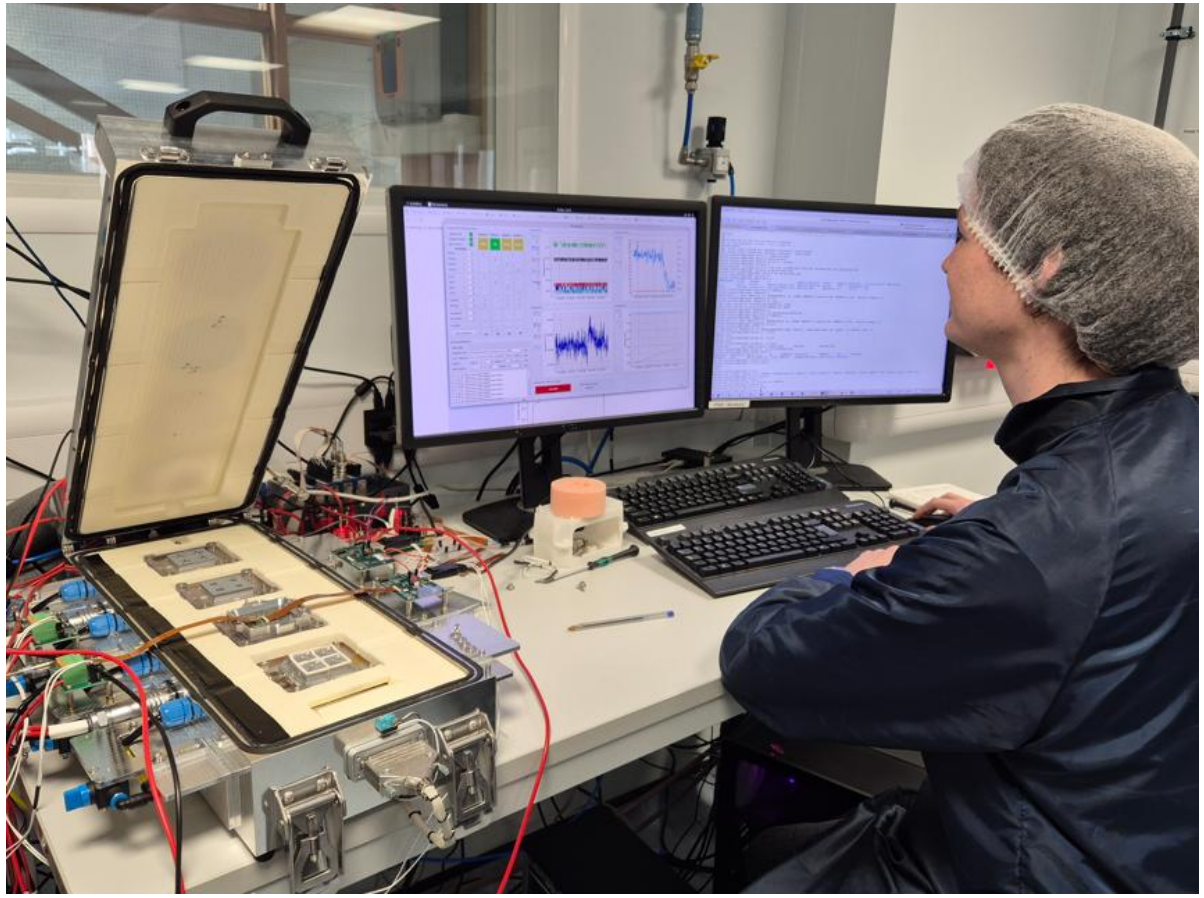



More core column issues at chip edges

# Conclusion


- ATLAS ITk is a vast project combining over 50 sites from across the world
- An experiment of this size needs careful optimization of all production steps to coordinate between sites
- Significant effort went into uniforming procedures: common module design, common tooling, common testing software
- Ordering five time more bumps than any previous experiment: important to have prompt communication with vendors

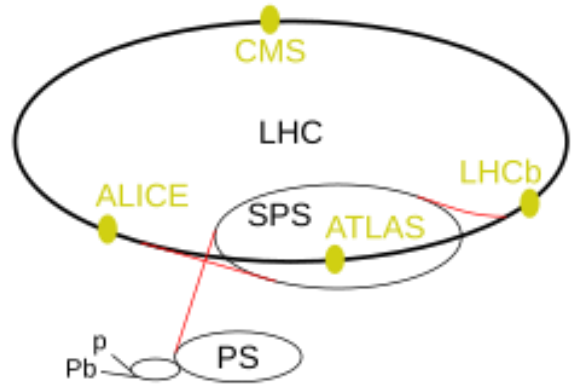


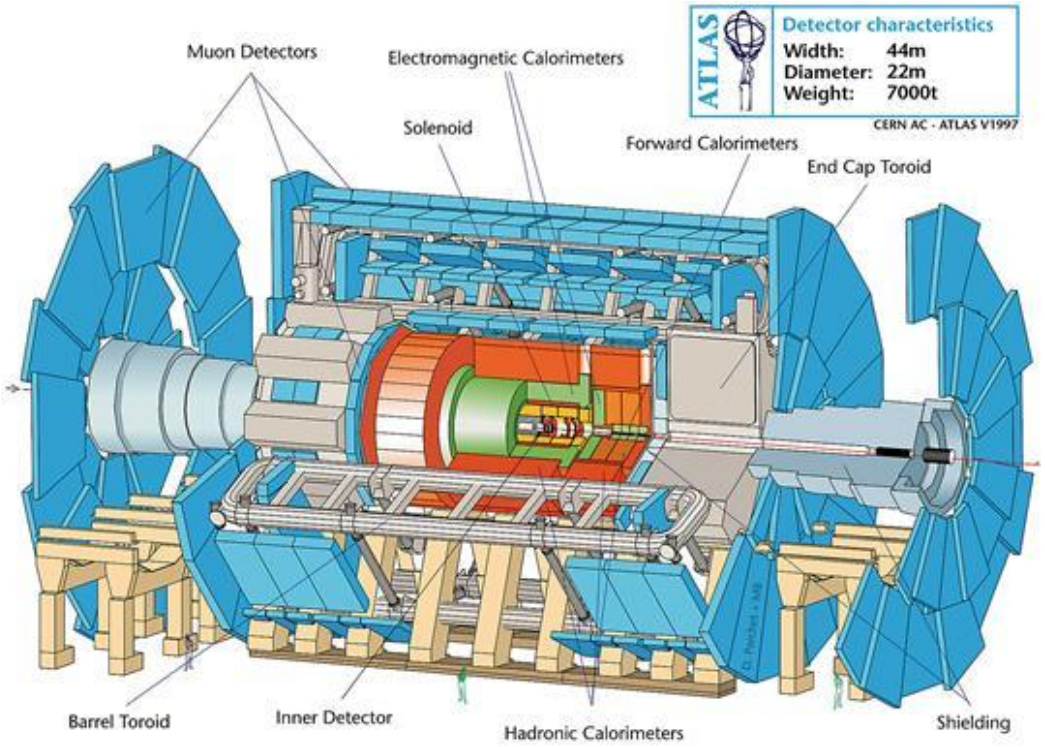
# Additional Material

# LHC and the ATLAS Experiment

- Large Hadron Collider:
  - Proton-proton collisions at 14TeV centre of mass energy
  - Largest accelerator at CERN with a 27km circumference
  - Four main experiments: ATLAS, CMS, ALICE, LHCb
  - Started up in September 2008

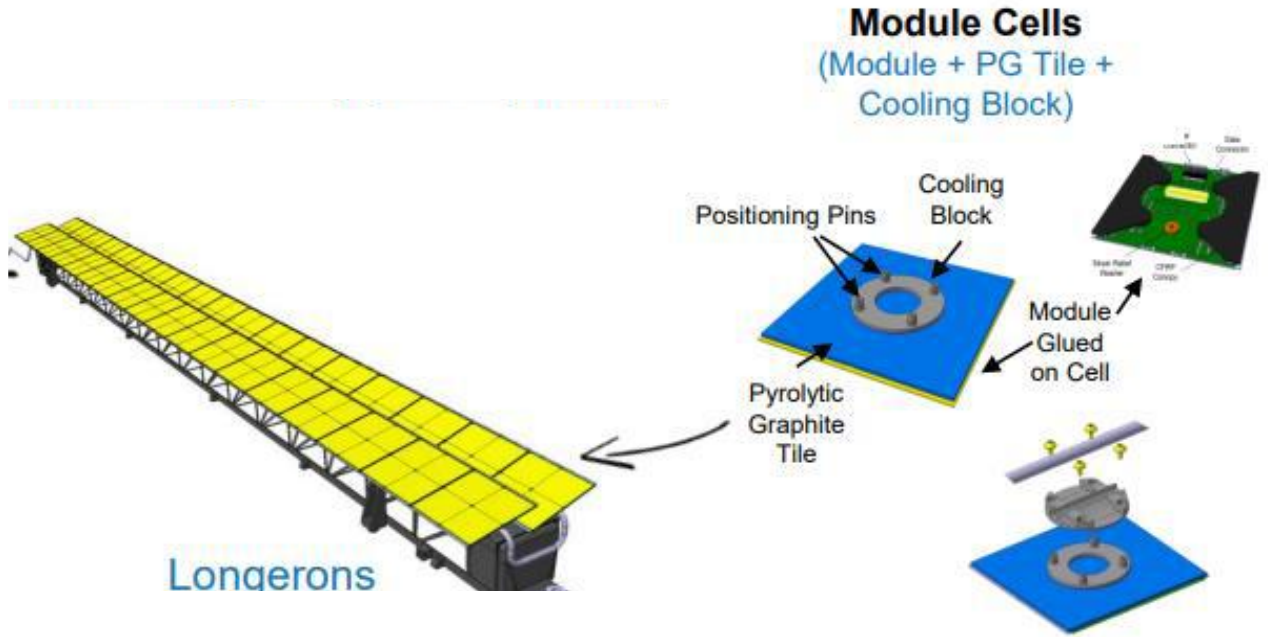
- ATLAS:
  - Largest multi-purpose detector at the LHC
  - Layered with dedicated concentric sections
    - Inner tracker
    - Electromagnetic and Hadronic calorimeters
    - Muon chambers



# Pyrolitic Graphite Tiles

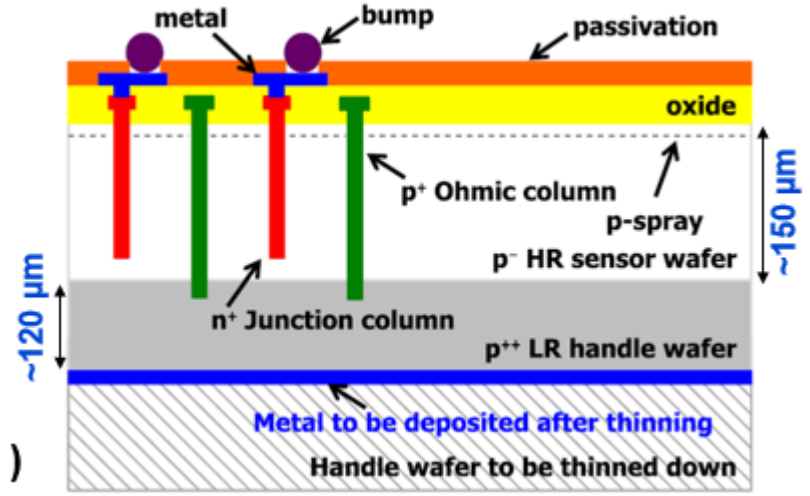
- Modules loaded onto pyrolytic graphite tiles
- This holds modules in place and provides contact to the cooling pipes
- Tiles are screwed into the supports
- Increases material budget but permits reworkability

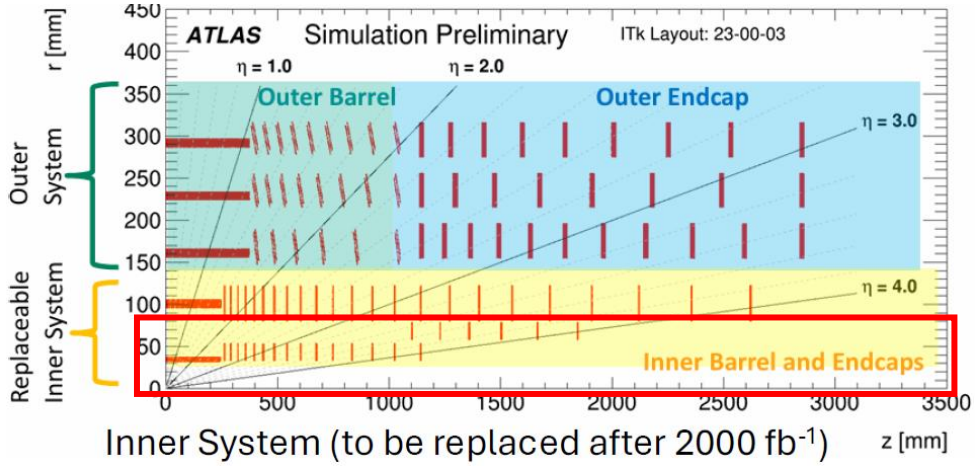


# Silicon Sensors

3D sensors:

- Found in Layer 0, closest to the beam
- 396 to be assembled
- n+ columns used for readout kept at 25µm from the low resistive substrate
- Improved resistance to radiation damage due to smaller electron-hole path length
- 250µm thickness; 50x50 $\mu m^2$ area
- Manufacturers are FBK and Sintef





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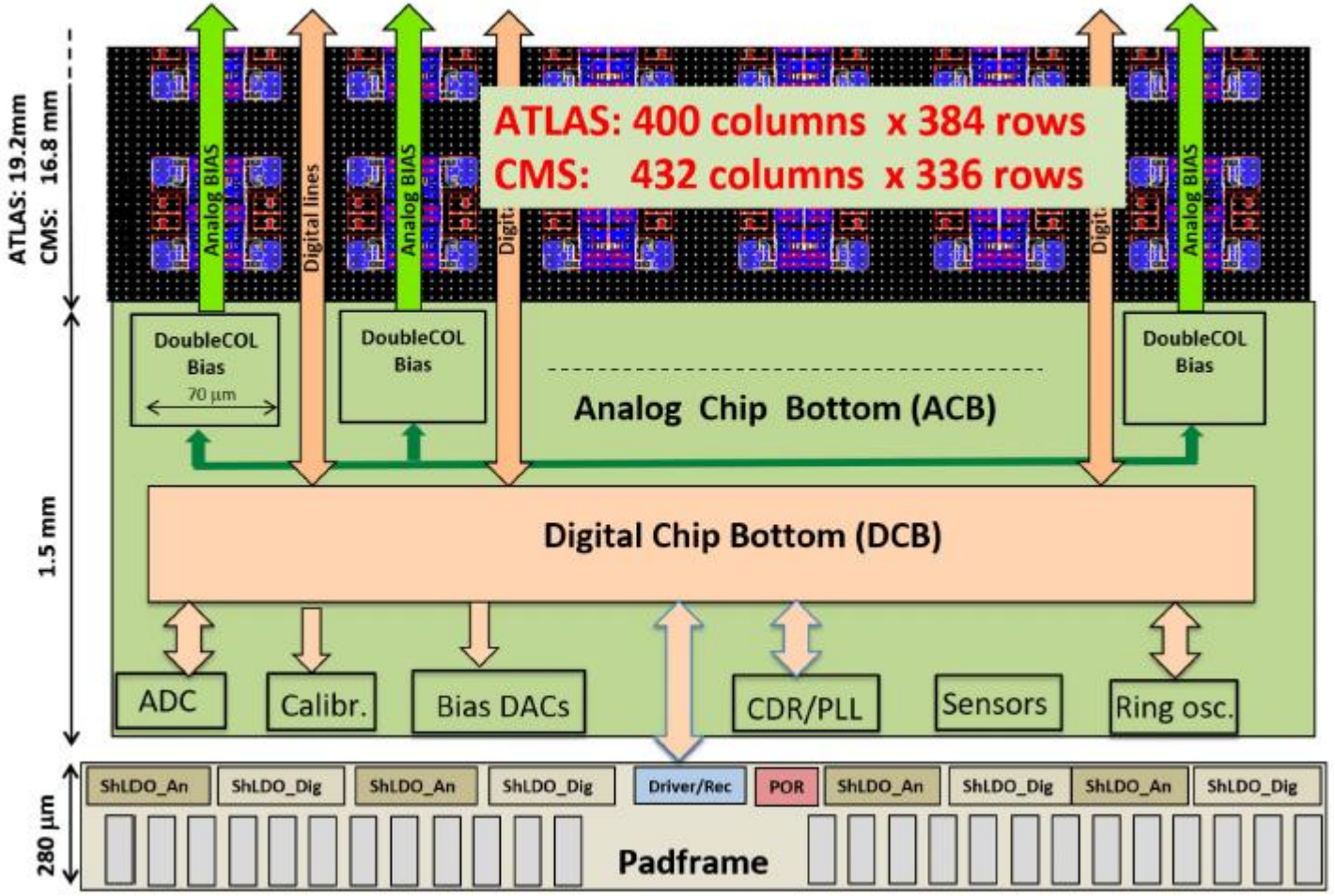
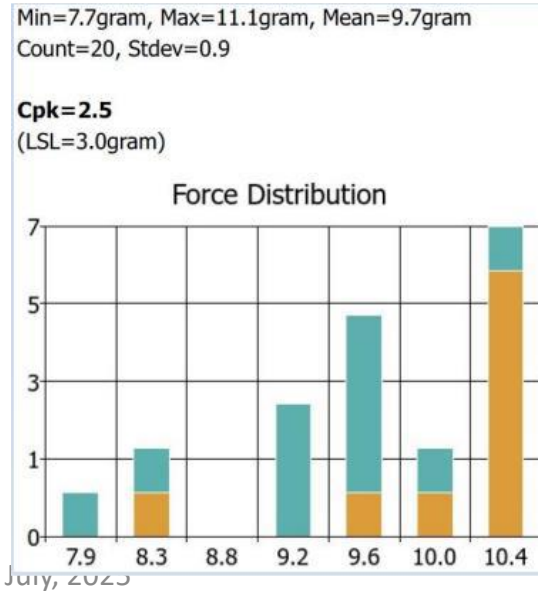
# ITkPix v2 FE-Chip

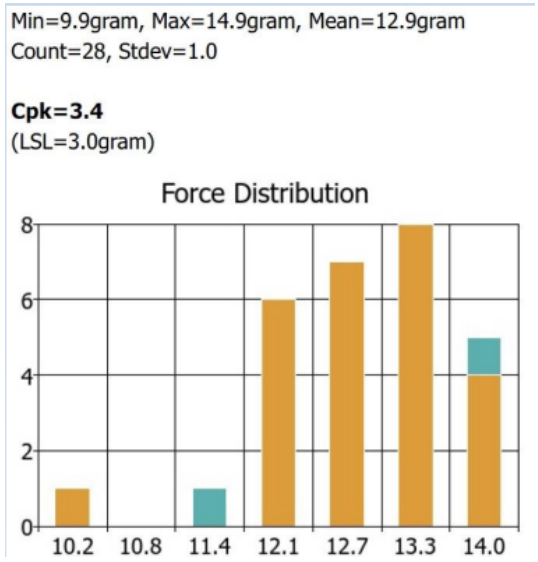
- FE-chip developed by the RD53 collaboration in common between ATLAS and CMS
- 65nm CMOS technology, radiation hard up to 1Grad
- 384 rows and 400 columns for a total 152.800 pixels
- Potential technical issues due to debris from dicing
- ITkPix V2 submitted in March 2023, first wafer delivered in September 2023
- Production modules being assembled across different sites

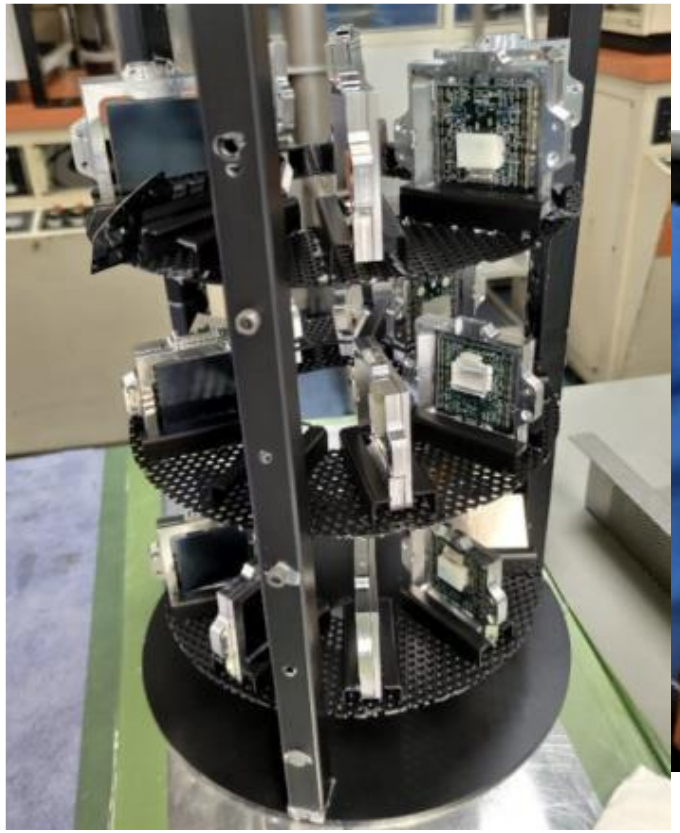


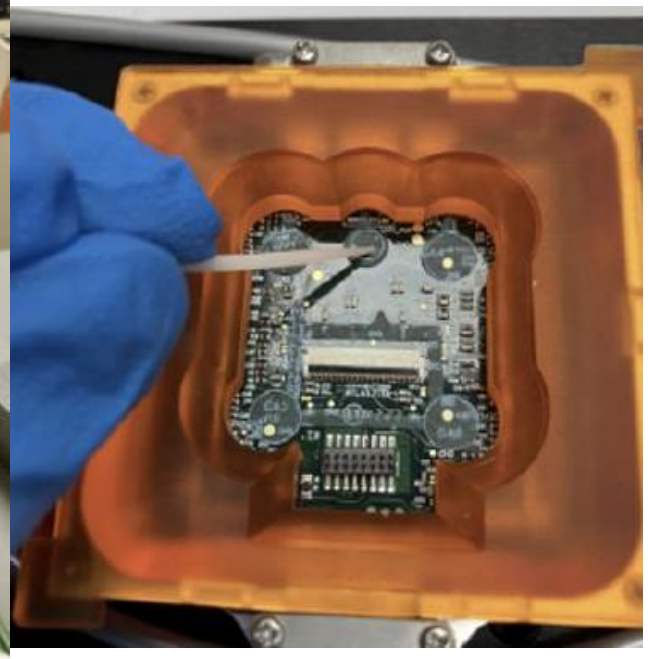
# Parylene Coating

- Coating required to prevent infiltration of humidity
- Incapsulation investigated but no material could handle thermal range and irradiation
- Modules coated 7-8 $\mu$m of parylene with vapor deposition process
- Prevents electical discharge
- Provides mechanical protection
- Increases wirebond strength by about 2g



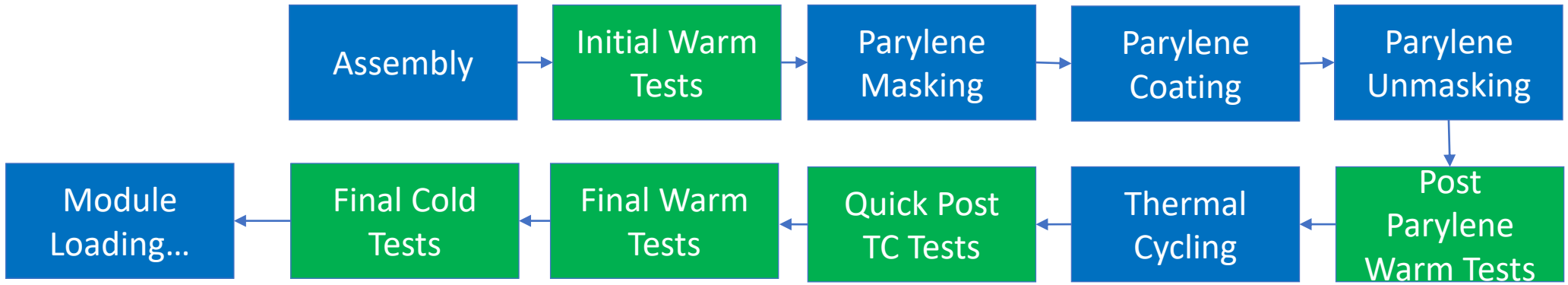





# Qualification Electrical Tests

- Extensive testing procedures performed after module assembly
- Serve to test electrical performance of modules after assembly and key steps such as parylene coating and thermal cycling
- Information uploaded and commonly consultable on database



# Qualification Electrical Tests

- Extensive testing procedures performed after module assembly
- Status of different modules in testing is kept into account via common database and production tracker
- Large effort went into facilitating assembly and testing through:
  - Availability of parts
  - Optimization and finalization of procedures
  - Completion of supporting software tools

| | | | | | |
|---|---|---|---|---|---|
| PASSED | Electrical Test (e-test) Module Summary | 683dc2bfed63ab215dd43e3e | Initial Warm | 6/2/2025 4:26 pm | 6/2/2025 4:28 pm |
| PASSED | Electrical Test (e-test) Module Summary | 683dc2bfed63ab215dd43e3e | Initial Warm | 6/2/2025 4:26 pm | 6/2/2025 4:28 pm |
| PASSED | IV measurement | 683d9c0fed63ab215dd439cd | Initial Warm | 6/2/2025 1:41 pm | 6/2/2025 4:28 pm |
| PASSED | IV measurement | 683d9c0fed63ab215dd439cd | Initial Warm | 6/2/2025 1:41 pm | 6/2/2025 4:28 pm |
| PASSED | Wirebonding Information | 1A | Wire Bonding | 5/28/2025 4:45 pm | 5/28/2025 4:25 pm |
| PASSED WITH PROBLEMS | Visual Inspection | 1A | Bare module to module PCB assembly | 5/27/2025 10:19 am | 5/27/2025 11:20 am |
| PASSED | Quad Module Metrology | 1A | Bare module to module PCB assembly | 5/27/2025 10:18 am | 5/27/2025 11:19 am |
| PASSED | Mass Measurement | 1A | Bare module to module PCB assembly | 5/27/2025 10:17 am | 5/27/2025 11:18 am |