

Production and Quality Control of the ITk Pixel Outer Endcap Local Supports for the High-Luminosity upgrade of the ATLAS detector

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VERTEX 2025, 33rd International Workshop on Vertex Detectors

25-29 August 2025, Knoxville (TN), USA



The University of Manchester



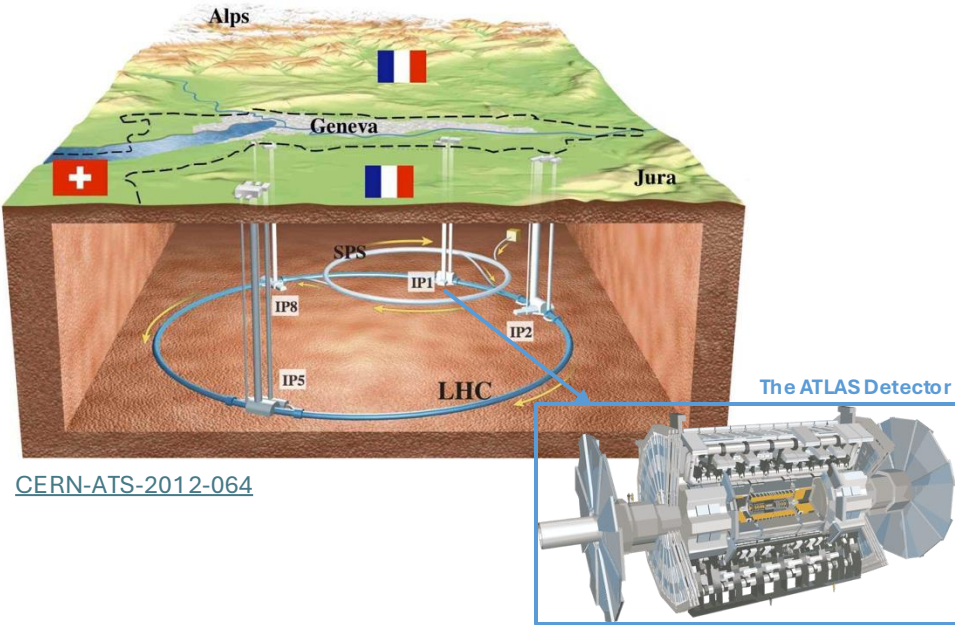
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Science and
Technology
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Particle Physics

The Large Hadron Collider (LHC) and its upgrade



CERN-ATS-2012-064

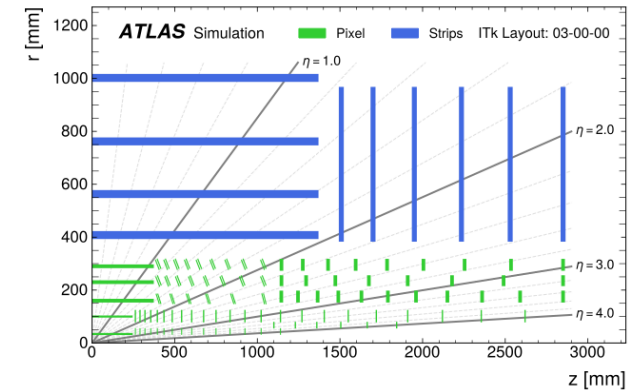
- Most powerful collider ever built
 - About 27 km of circumference
 - Centre of mass energy up to 13.6 TeV (pp collisions)
 - Four main experiments at the different interaction points
 - **ATLAS** : general-purpose detector
- The LHC will be upgraded for its High-Luminosity phase (**HL-LHC**)
 - pp collisions at $\sqrt{s} = 14$ TeV
 - Integrated luminosity up to 3000-4000 fb^{-1} by 2041
 - Peak luminosity increased up to $5-7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 - Average number of pp interaction per bunch crossing up to about 200



Schedule as of Jan 2025

The ATLAS Inner Tracker

- The ATLAS Inner Detector (ID) will be replaced by a new all-silicon Inner Tracker (ITk)
 - Dense tracking environment
 - Occupancy <1% and trigger rate up to 1 MHz
 - Large fluences
 - radiation hardness up to 10 MGy
 - Extended coverage from $|\eta| \leq 2.5$ to $|\eta| \leq 4$
 - Reduced material budget

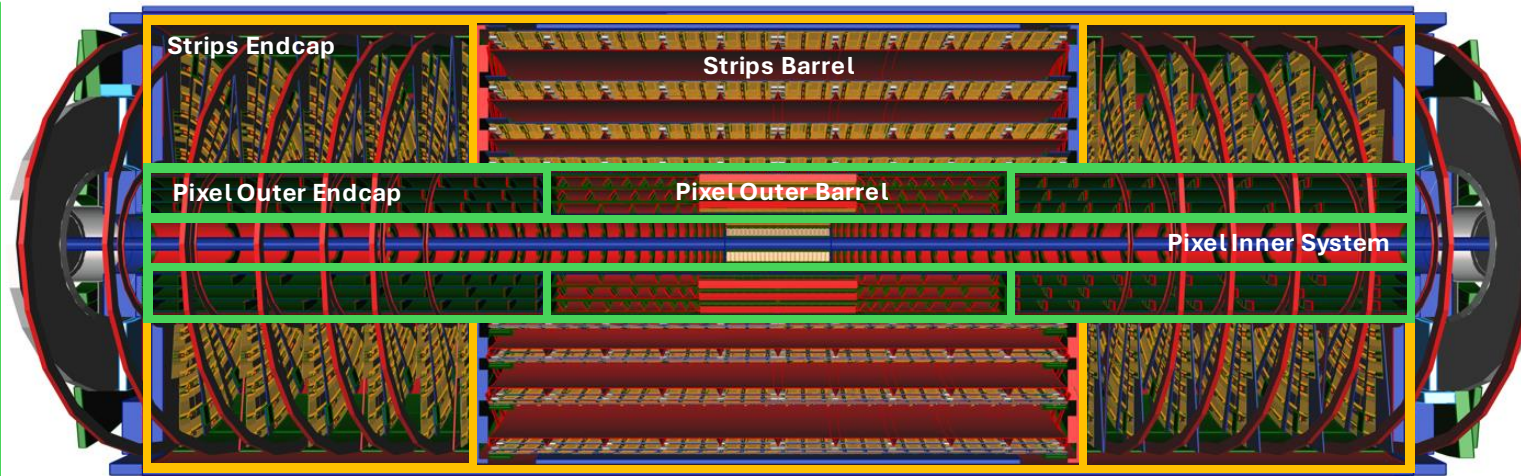


$$\eta = -\ln\left(\operatorname{tg}\left(\frac{\theta}{2}\right)\right)$$

ATL-PHYS-PUB-2021-024

Pixel detector

- 5 billion channels
- 2 (inner) + 3 (outer) barrel layers
- Multiple endcap rings



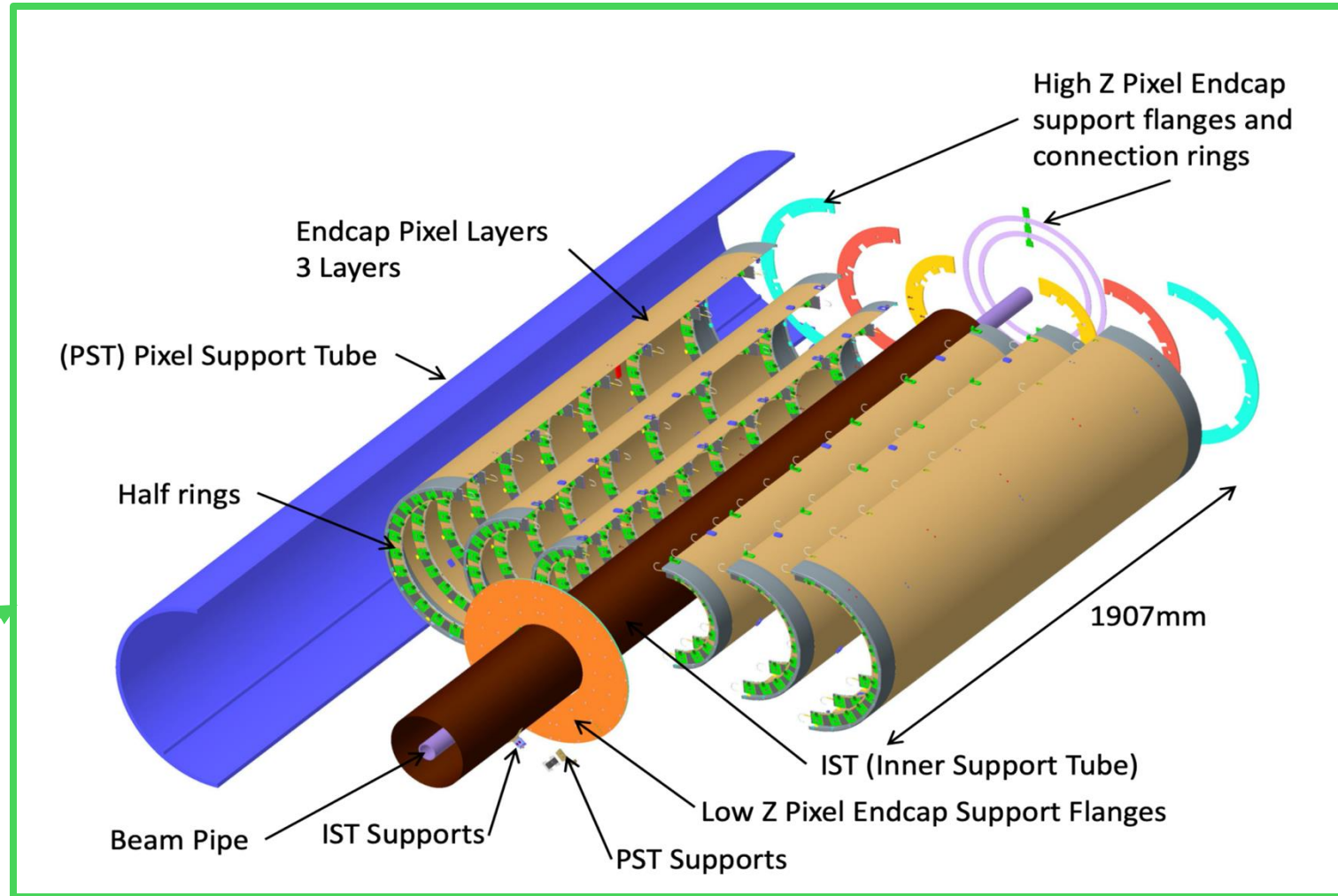
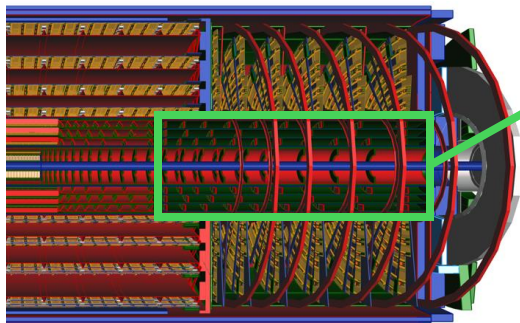
Strip detector

- 60 million channels
- 4 barrel layers
- 2 x 6 endcap rings

See [Caterina's talk](#) for more details on ITk

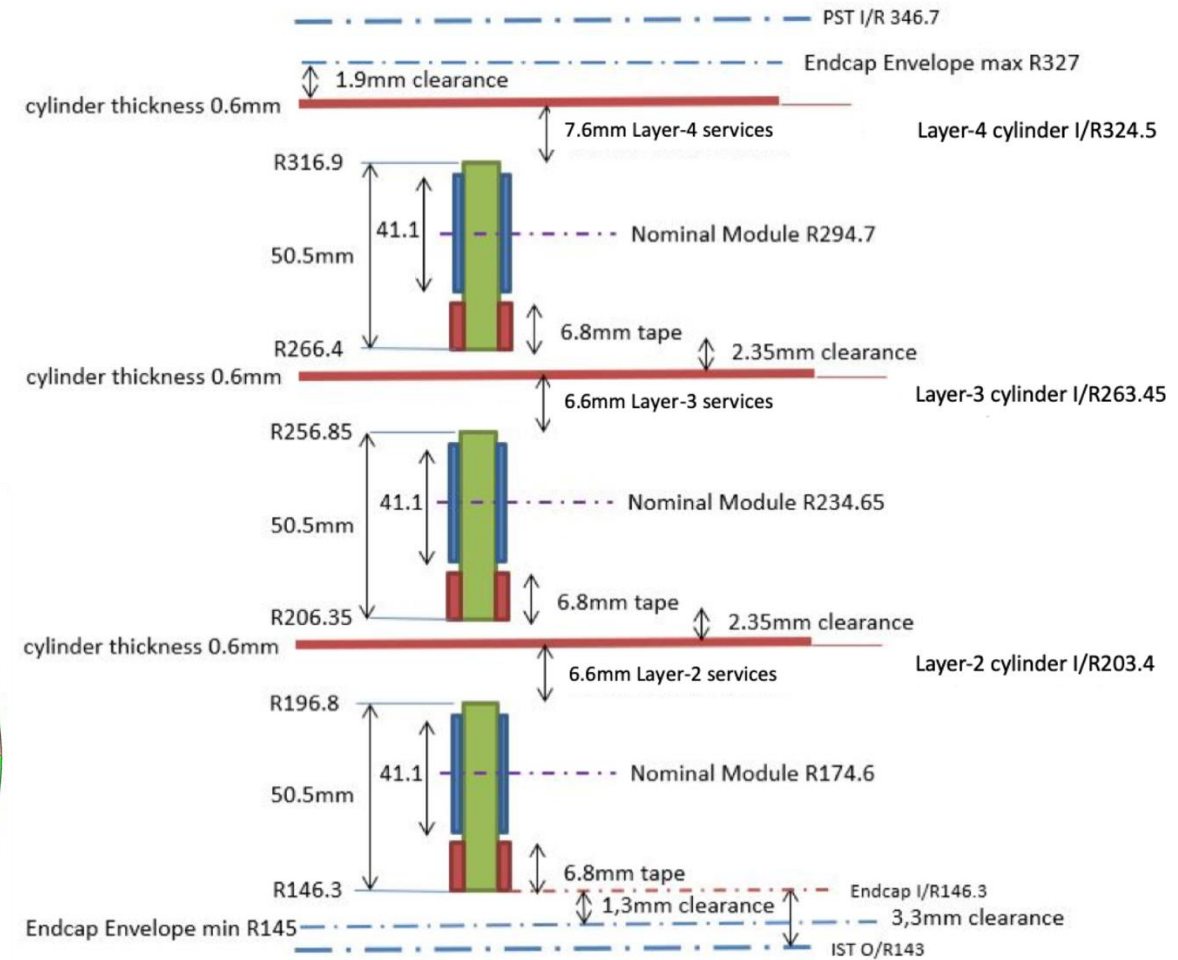
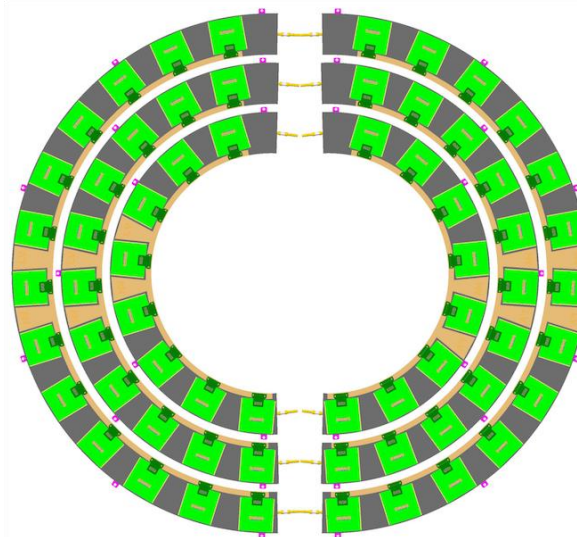
ITk Pixel Outer Endcaps (OEC)

- 3 concentric semi-cylindrical global support structures (half-shell) per endcap
- 3 layers of half-ring (HR) local supports per half-shell longitudinally distributed along the beam direction
 - 11 inner Layer 2 (L2) HRs
 - 8 middle Layer 3 (L3) HRs
 - 9 outer Layer 4 (L4) HRs
- The production of the Pixel OECs is a joint effort between Italy and the UK



ITk Pixel OEC Local Supports

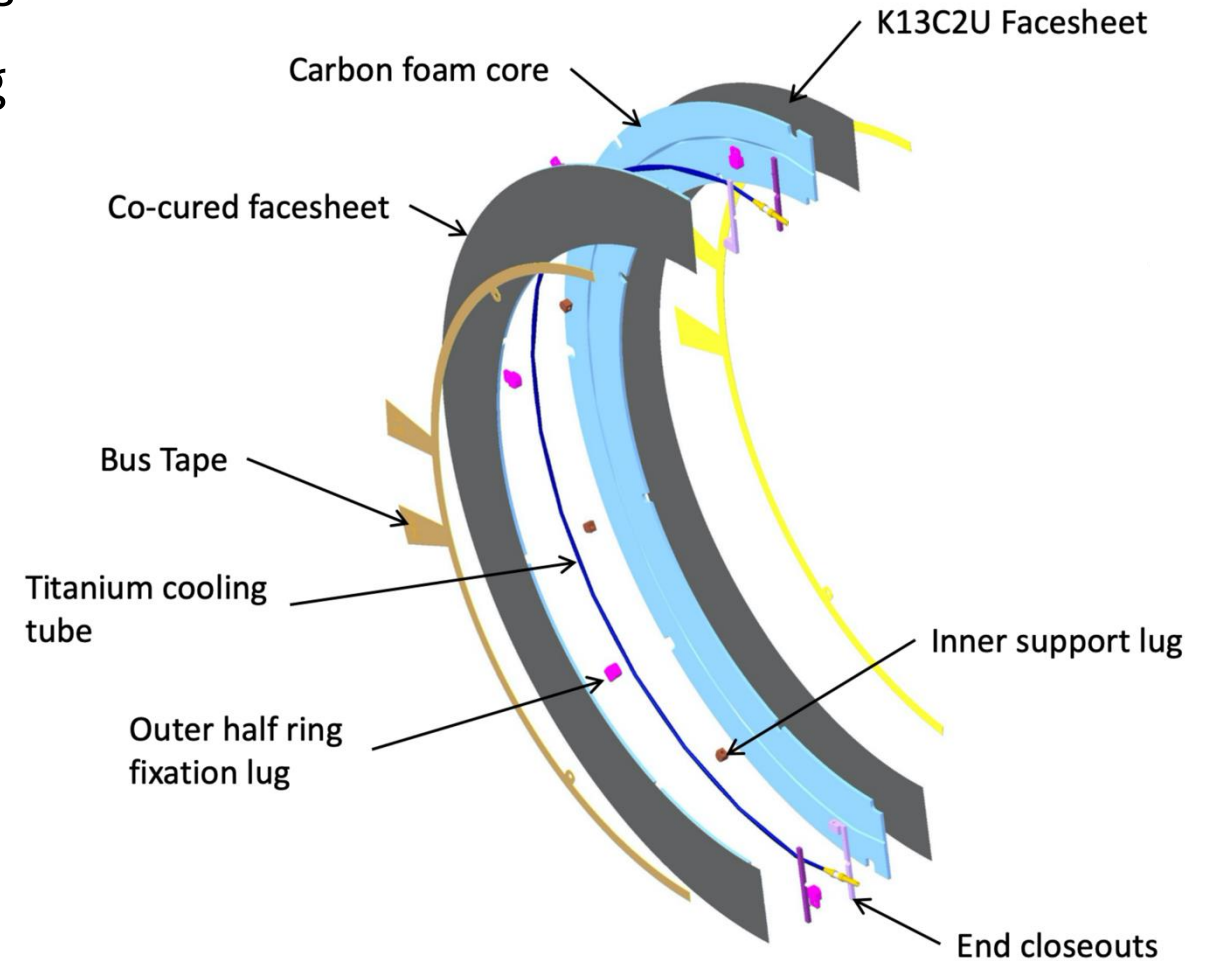
- The pixel modules will be glued to the local supports
- Quad modules with 4 FE chips
 - 8 modules per face in L2 HRs
 - 11 modules per face in L3 HRs
 - 13 modules per face in L4 HRs
- Modules staggered along the azimuthal angle and glued on both faces of the HRs to provide hermeticity
- Services allocated within layer gaps



Radial envelopes in the Outer Endcaps (not to scale)

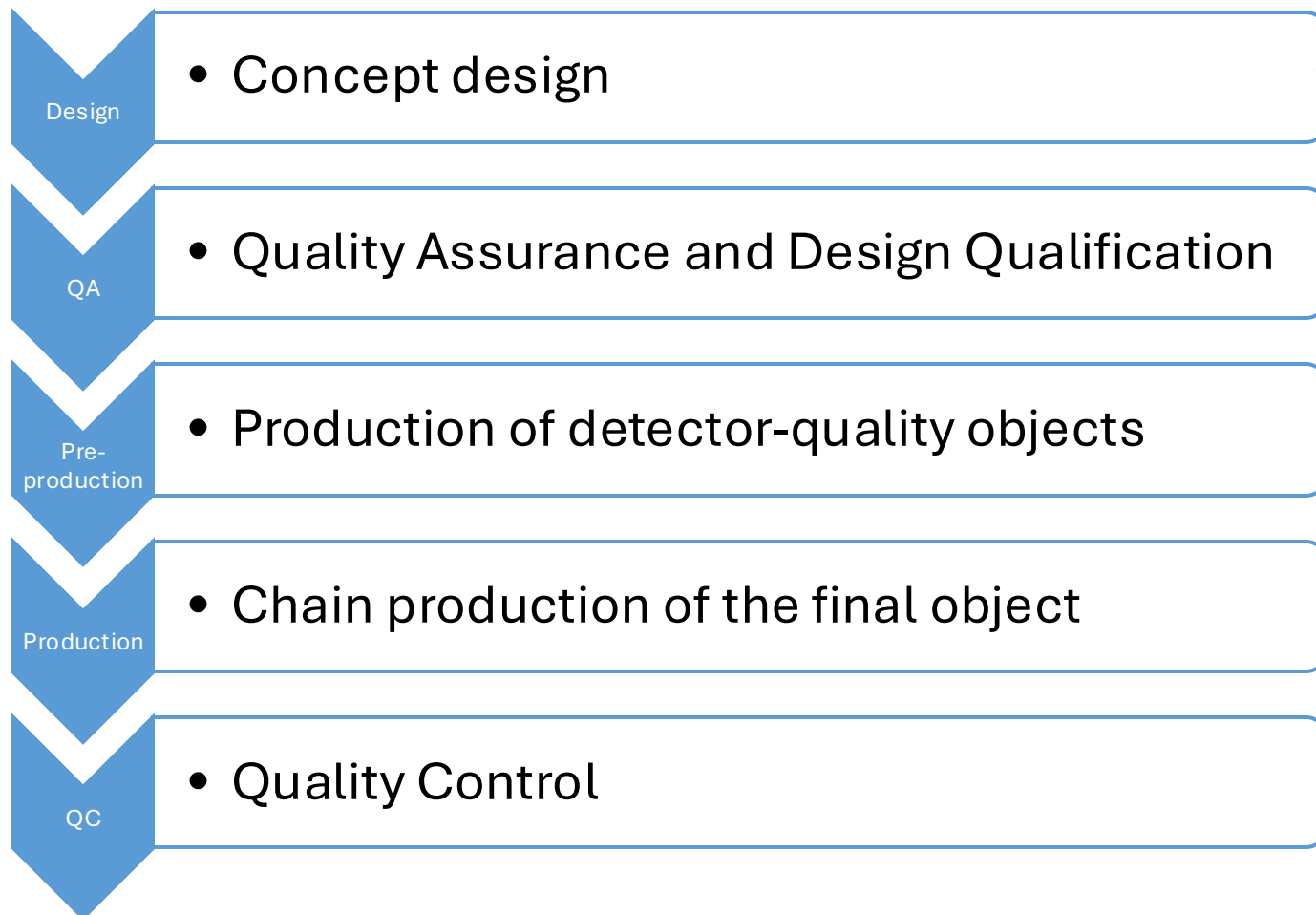
Half-Ring Design

- Provide mechanical support to the modules
- Provide a thermal interface with the cooling system
- Half-ring-shaped carbon assemblies (light material) presenting a sandwich structure
 - Carbon foam core
 - Carbon fibre laminate face-sheets
 - Embedded titanium pipe for cooling
- Copper-Kapton flex tape distributes power to the modules in a single serial power chain (one chain per face)
- ULTEM 1000 components (locators and closeouts) for alignment and integration



The journey so far

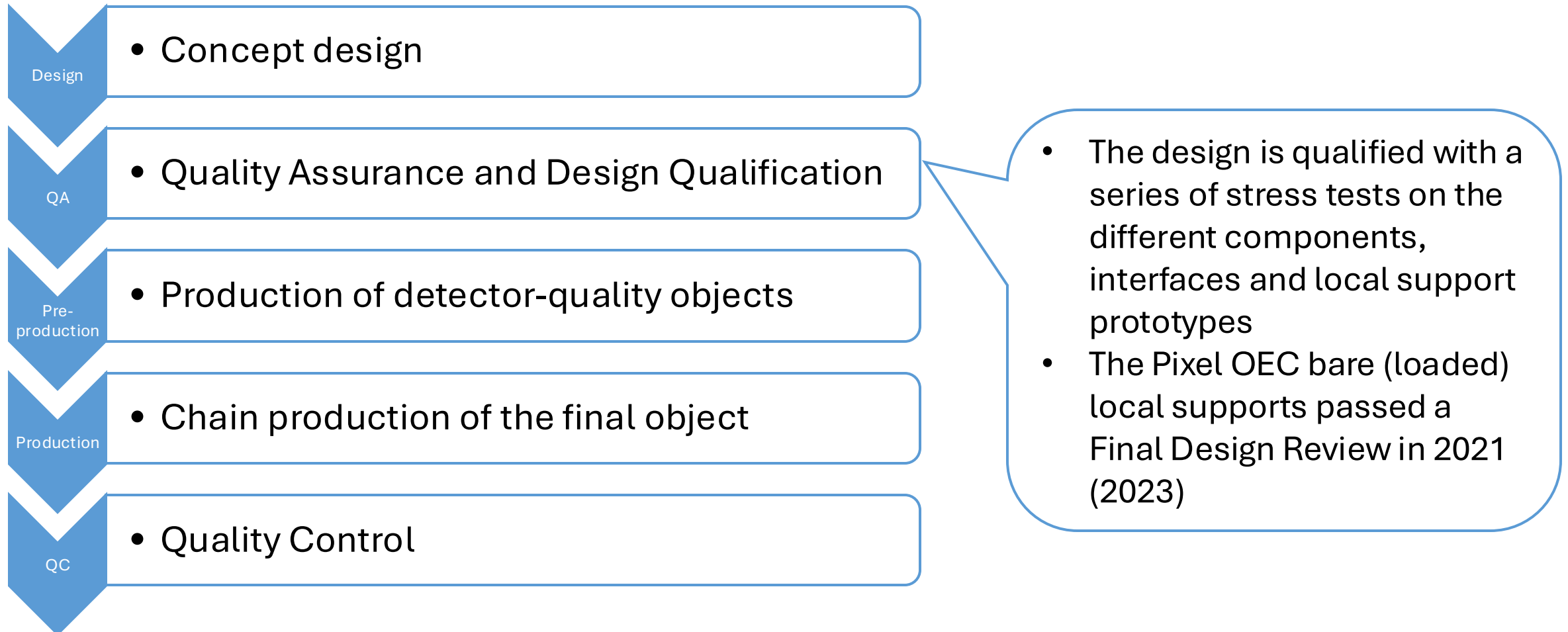
- How can we build a **good quality detector** and ensure it **will perform** as expected?



- Design requirements to achieve physics programme's goals
- ITk Pixel [technical design report](#)

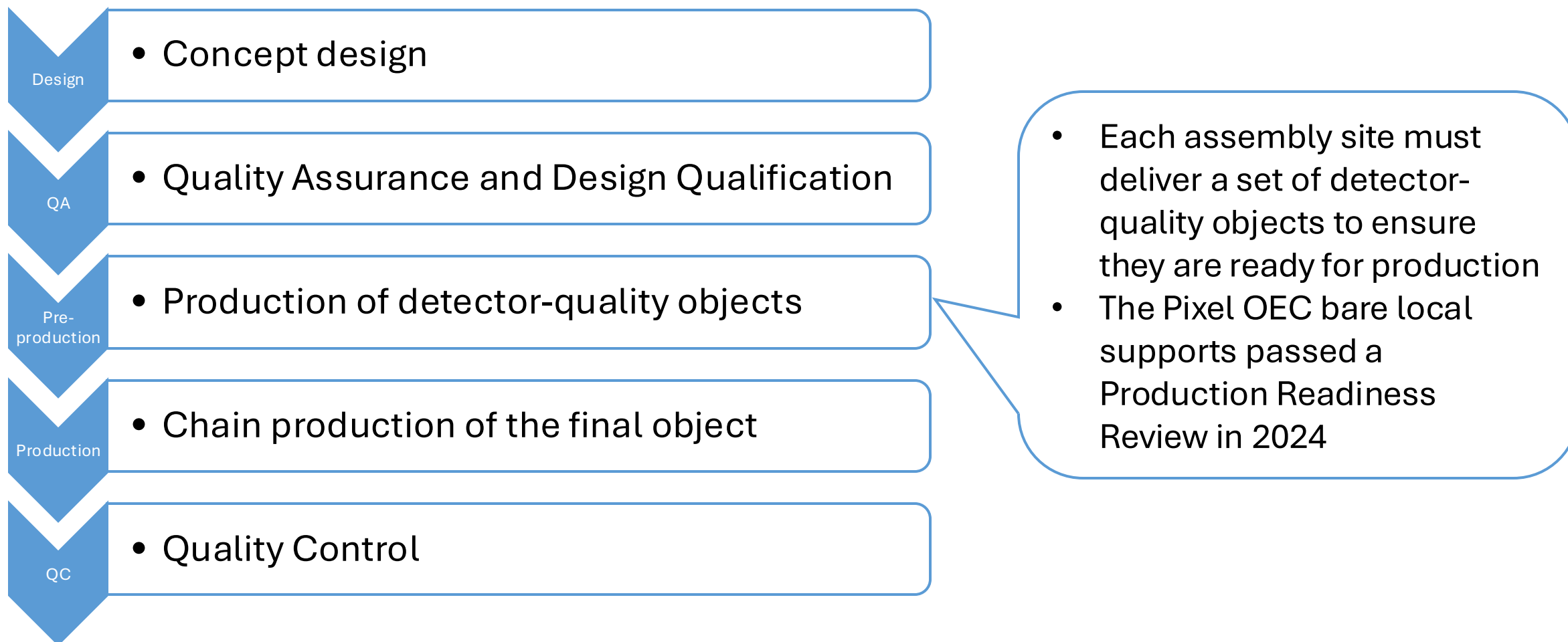
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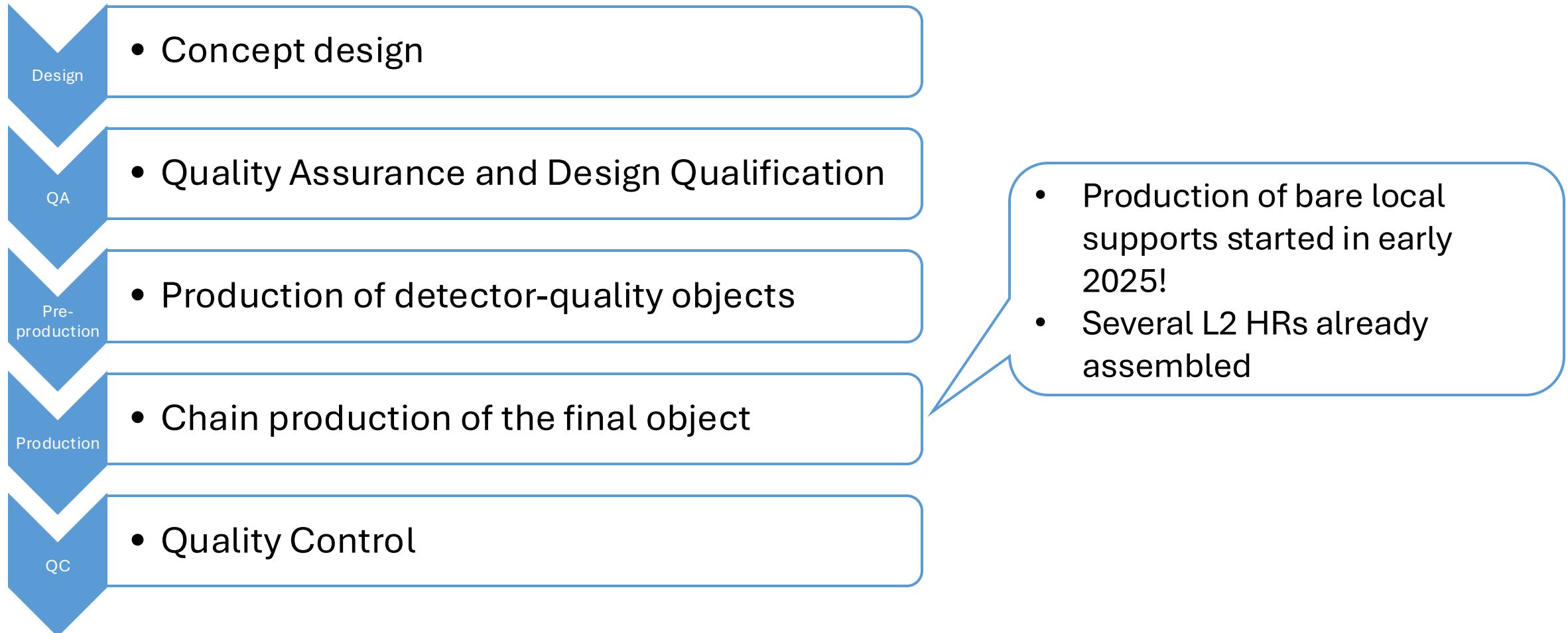
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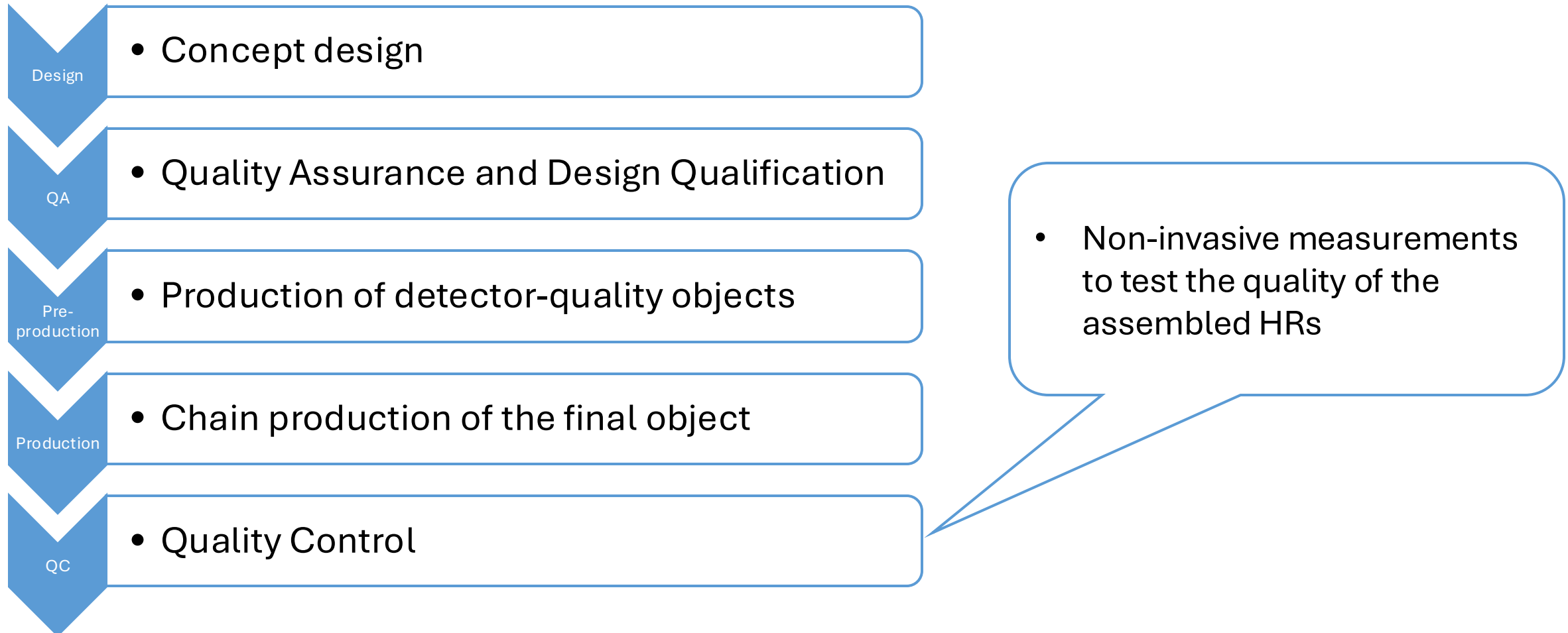
The journey so far

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The journey so far

- How can we build a **good quality detector** and ensure it **will perform** as expected?



Understanding the mechanical tolerances

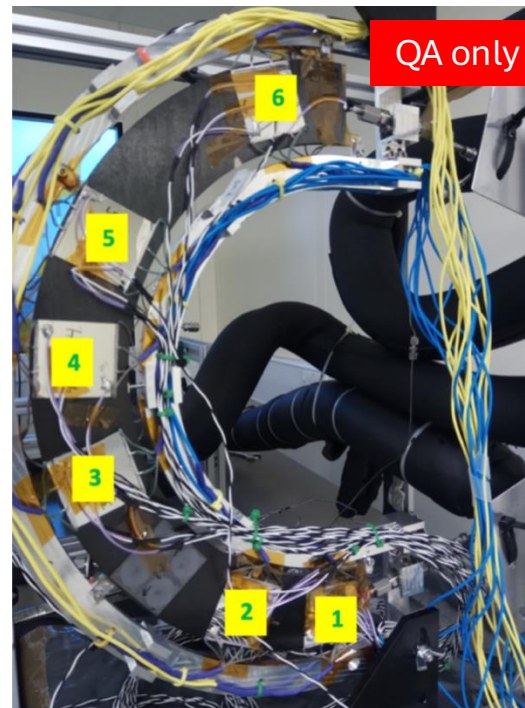
- Strict mechanical tolerances to ensure the correct integration of all the components
- More difficult to machine larger surfaces
 - Loosened planarity tolerances for L3 and L4 HRs
- Biggest challenges:
 - Accurate end-lug position needed for a precise locating and mounting of the HR
 - Asymmetric tolerance on the inner rim to respect the envelope and ensure the flex tape does not overhang
- We rely on high-precision CNC-machined tooling to achieve such a high level of precision

| Feature Tolerance | L2 | L3 | L4 |
|-------------------|---|-------------------|-------------------|
| Global Planarity | 200 μm | 250 μm | 300 μm |
| Lugs planarity | 100 μm | 150 μm | 200 μm |
| Lugs Positions | 50 (200) μm diametric for end (other) locators | | |
| Inner rim radius | +0/−100 μm | | |
| Outer rim radius | $\pm 150 \mu\text{m}$ | | |
| Thickness | 5.00 \pm 0.10 mm | | |

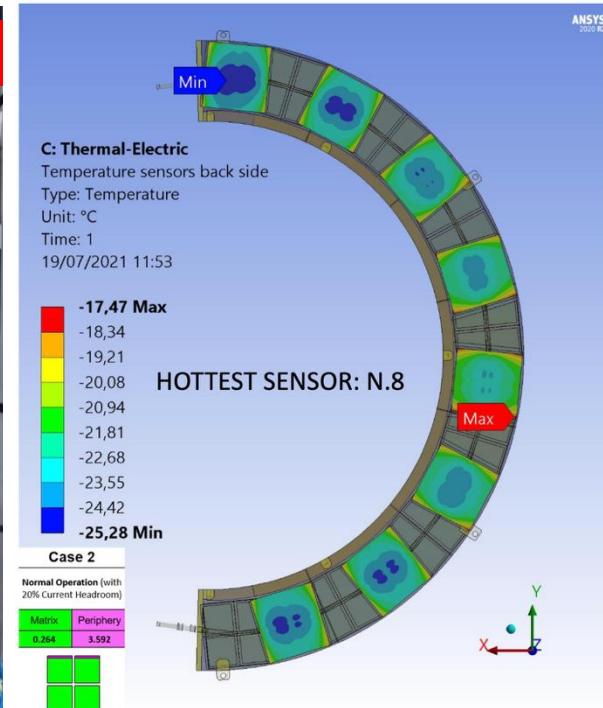
Thermal performance

- Leakage current increases with both radiation damage and temperature
- Efficient cooling is crucial to prevent thermal runaway of the modules
- Metric for the requirements given by the Thermal Figure of Merit (TFM)—the worst-case thermal resistance along the path between the pipe and the module
- Lower TFM values are preferred (lower sensor temperature for a given heat flux)
- Thermo-mechanical FEA simulations were used to validate the design
- TFM also measured with HR prototypes during QA

ATL-ITK-SLIDE-2022-671



TFM measurement with a HR prototype



FEA study

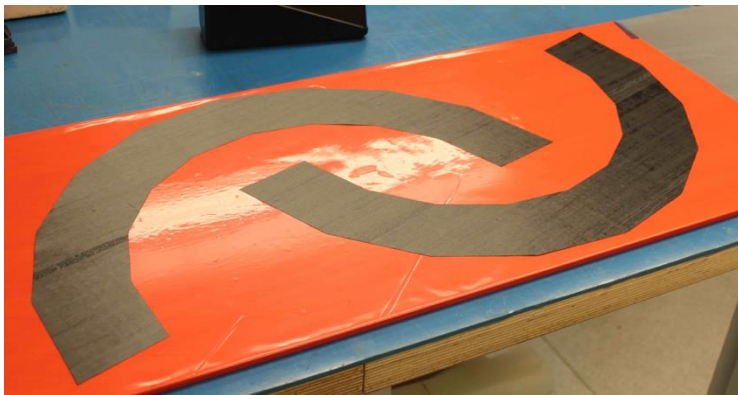
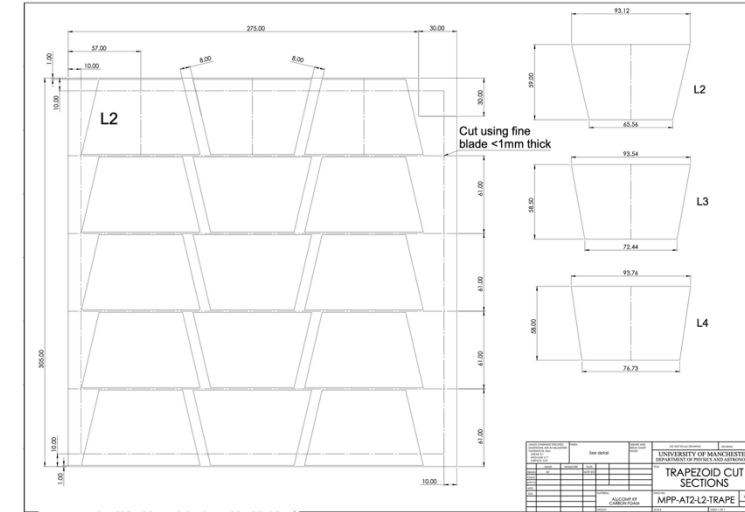
| Layer | TFM (nominal) [K cm ² / W] | TFM (design) [K cm ² / W] | Fluence [N _{eq} / cm ²] |
|-------|--|---|---|
| L2 | 28.85 | 38.75 | 3 · 10 ¹⁵ |
| L3 | 32.43 | 44.12 | 1.73 · 10 ¹⁵ |
| L4 | 34.76 | 47.62 | 1.84 · 10 ¹⁵ |

$$TFM = \frac{(T_{sensor}^{(max)} - T_{coolant})}{Power\ density}$$

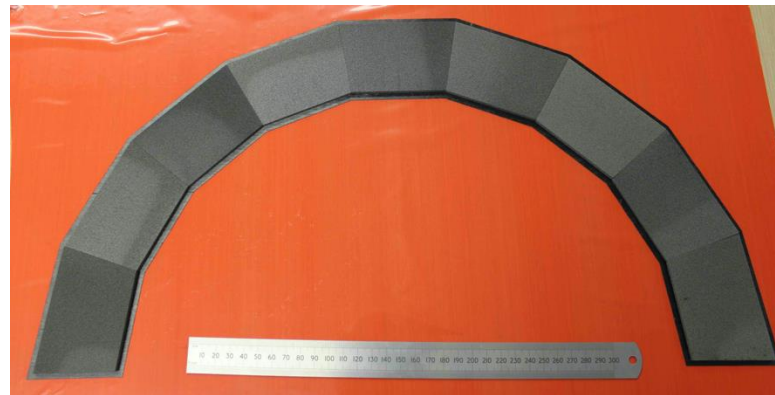
HR production: Trapezoids cutting and co-curing

- The HR production starts from blocks of carbon foam
 - Higher-density foam in L2 and L3 to increase the thermal conductivity
- Trapezoids are machined from the foam blocks
- Three layers of K13C2U/EX-1515 carbon fibre prepreg are cut into HR shapes and overlapped (0° - 90° - 0°)
- Trapezoids are placed on the prepreg and oriented to form a Half-Sandwich (HS)
- HSeS are placed in a vacuum bag and co-cured in an autoclave
- In-house HS fabrication in the UK and by an external company in Italy (Loson)

ATL-ITK-SLIDE-2025-355



Prepreg cut into shape (L3) at the UK co-curing site (Liverpool)



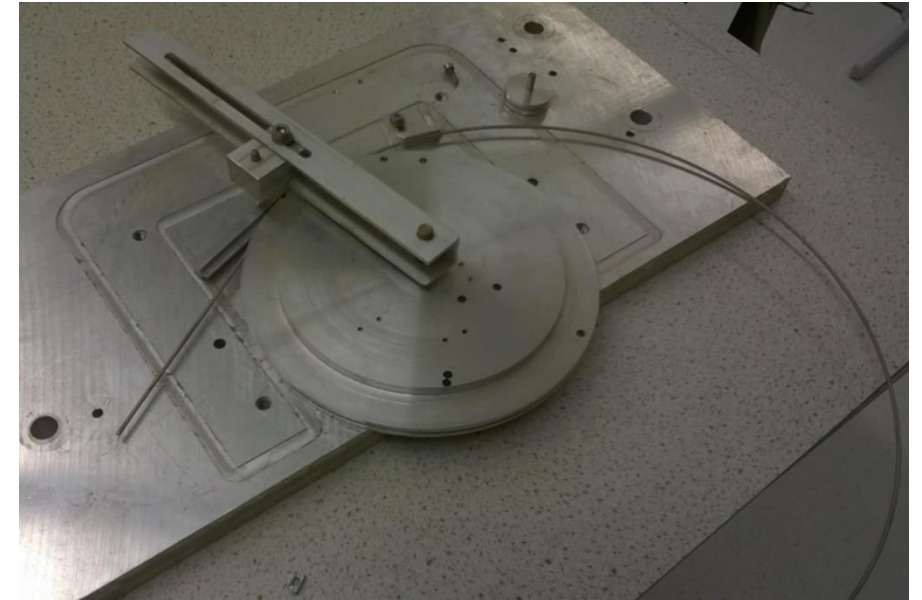
HS (L3) assembled from the prepreg and trapezoids



Vacuum-bagged co-cures (L3)

HR production: Evaporators

- Titanium pipes used as the main cooling loops
- Pipes delivered as straight tubes and later bent to shape
 - Go/no-go template used to check the final shape
- Ceramic electrical break (EB) originally used as a transition joint to the service pipes
 - During QC testing, one EB of a production HR cracked
 - It was not possible to identify the defect before assembly
 - One EB failure would compromise the functioning of a full layer
 - New titanium part designed as a replacement
 - No impact on the HR assembly process
- The design change caused a few months' delay in the production campaign



Evaporator bending jig



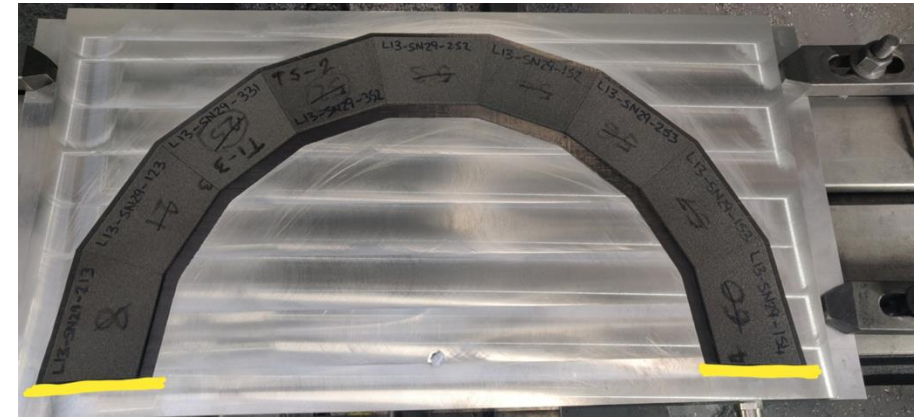
Evaporator with EB



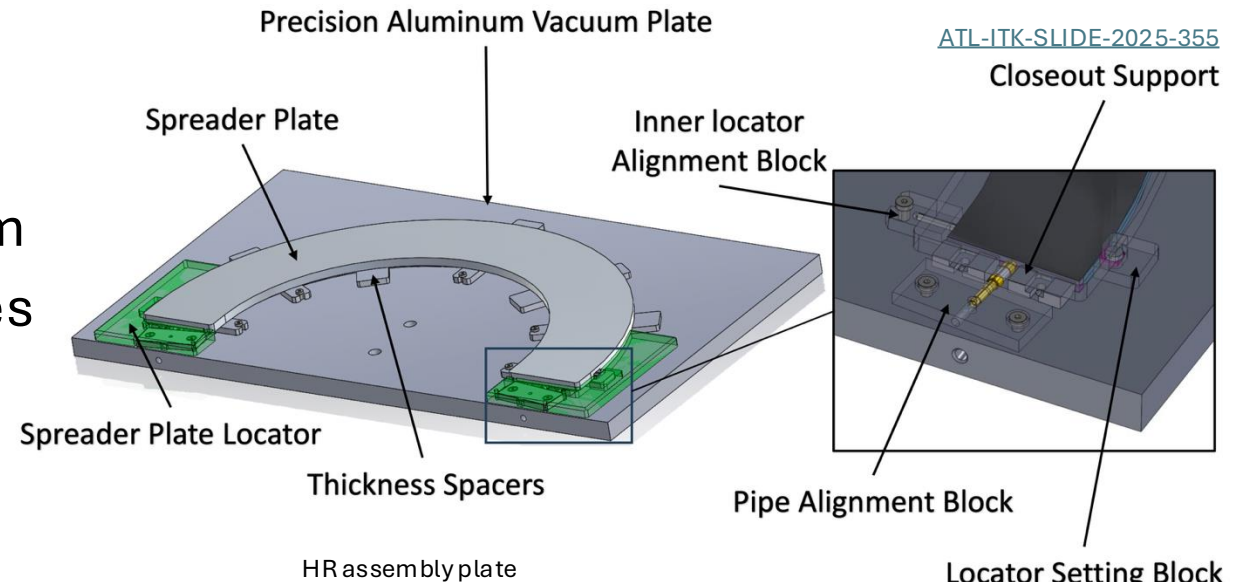
Evaporator without EB

HR production: HS machining and HR assembly

- HSeS are machined to their final shape using a CNC machine
 - Grooves for the pipe and the inserts are also added
- HR formed by two HSeS, the pipe and the inserts
- Precision alignment of the components is essential to meet the tight design specifications
 - Positional tolerances at the edge of CNC machining capabilities
 - Custom-made assembly plate and tooling
 - Room temperature controlled within ± 2 °C
- HR cured at room temperature under vacuum
- Edges are sealed with glue, and sticking fibres are carefully removed
- More details on the tooling available in [ATL-ITK-SLIDE-2025-355](#)

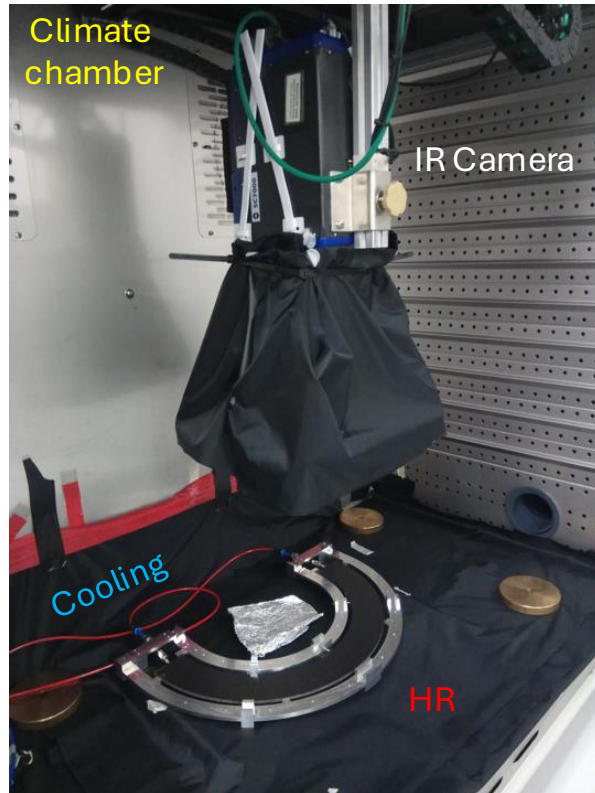


HS (L3) on the machining plate

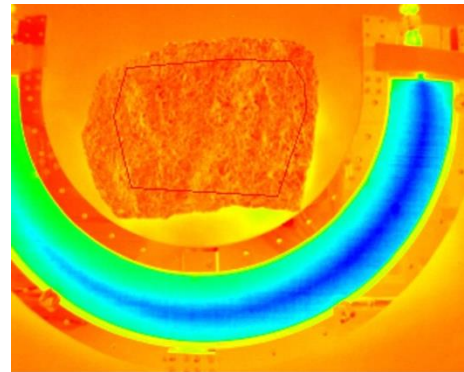


Thermal QC: Measurement

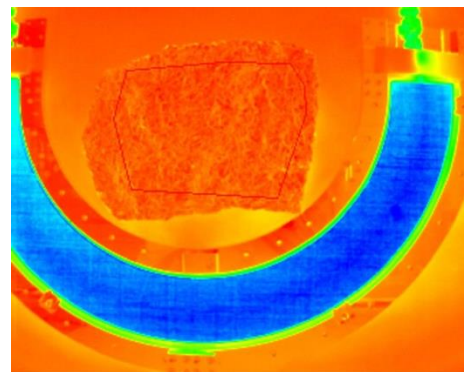
- The TFM measurement is invasive (requires heaters to be glued on the HR) and cannot be used for the QC during production
- An alternative procedure was developed to evaluate the thermal performance with infrared imaging (documented in [ATL-ITK-PUB-2021-001](#))



Experimental setup in Manchester



Recording at an early stage of the cooling

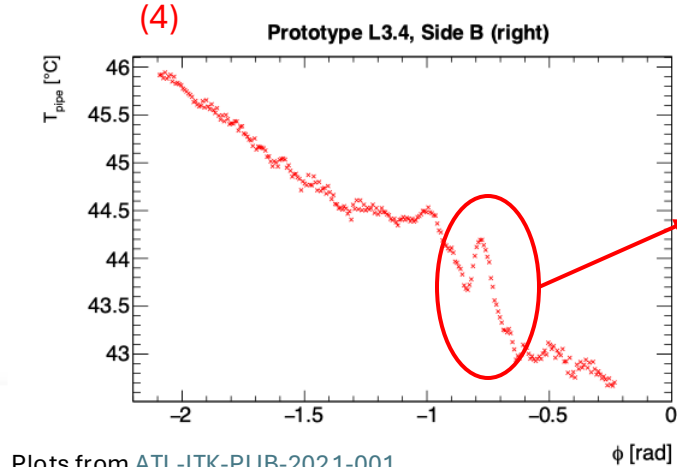
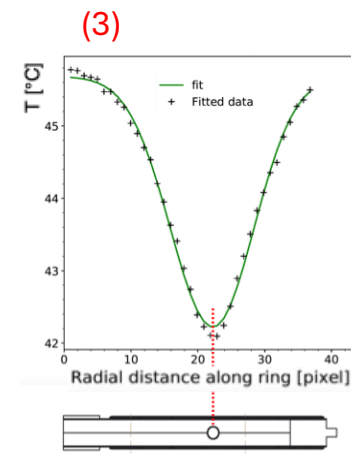
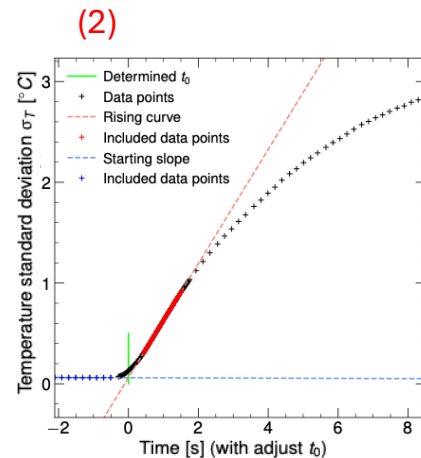
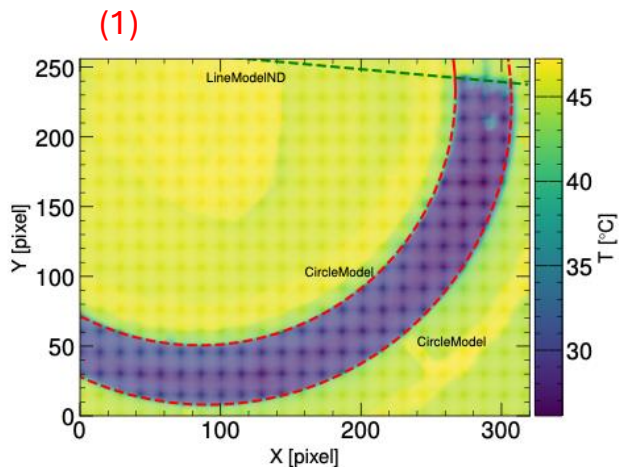
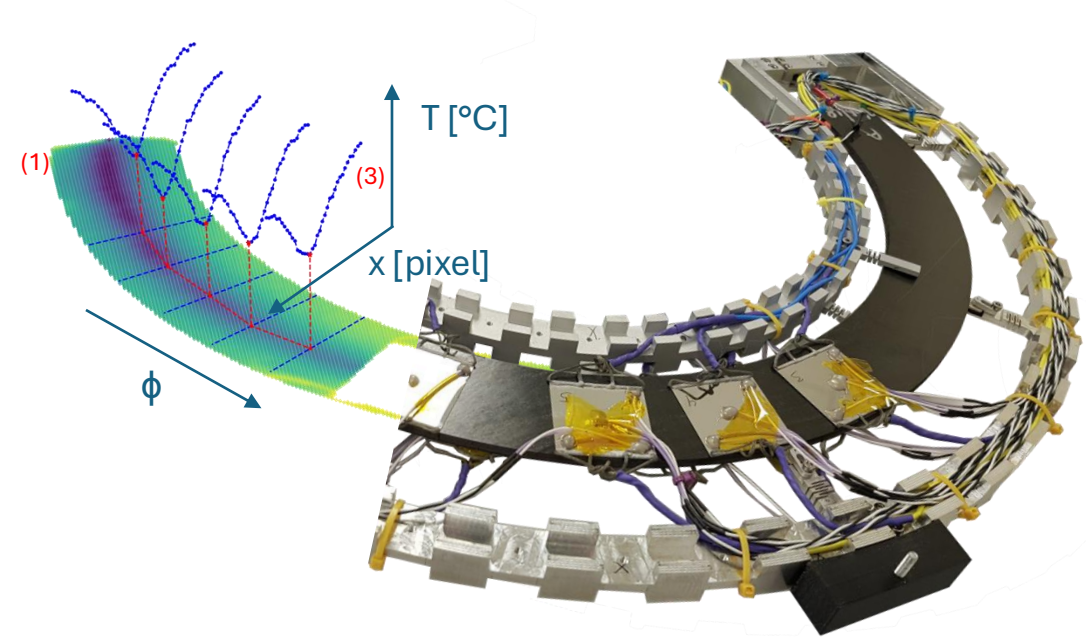


Recording at a later stage of the cooling

- The HR is placed in a climate chamber to control the environment temperature
- The chamber is heated up to 45°C to simulate the heating from the modules
- Liquid coolant is injected into the HR to initiate a cooling process
 - Typical coolant temperature of 5 °C
- An IR camera records the full cooling process
 - The recording is later analysed frame by frame to extract useful observables

Thermal QC: Analysis

- Python-based analysis framework
 1. Identify the HR surface from the background
 2. Identify the cooling start time (t_0)
 3. At a given time $t = t_0 + \Delta t$, extract radial temperature profiles and fit them to measure the temperature on top of the pipe (T_{pipe})
 4. T_{pipe} is expected to increase linearly from the inlet to the outlet. Peaks can be sign of defects

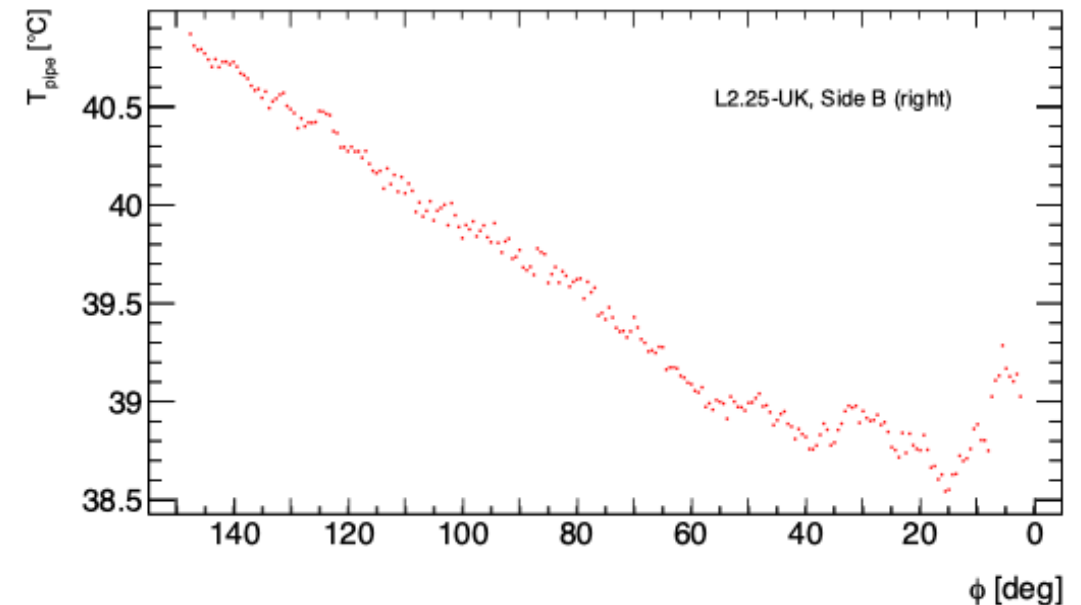
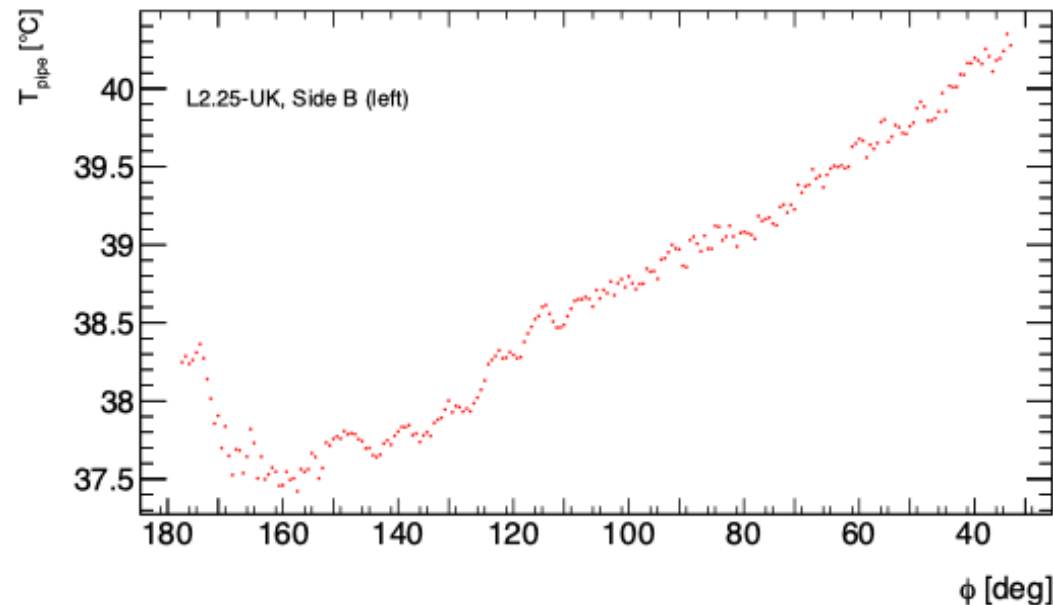
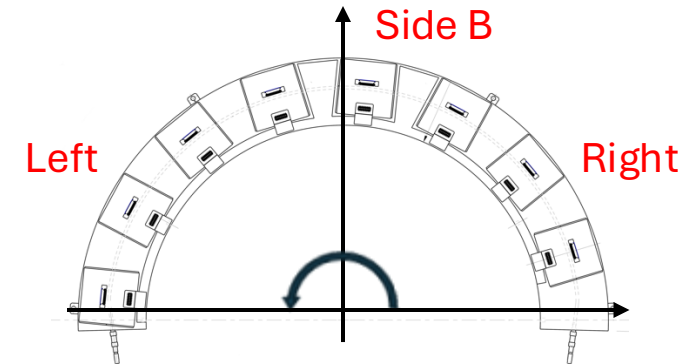


- Example of a defect
- Heaters were placed on its location to measure the TFM and correlate the results

Plots from [ATL-ITK-PUB-2021-001](#)

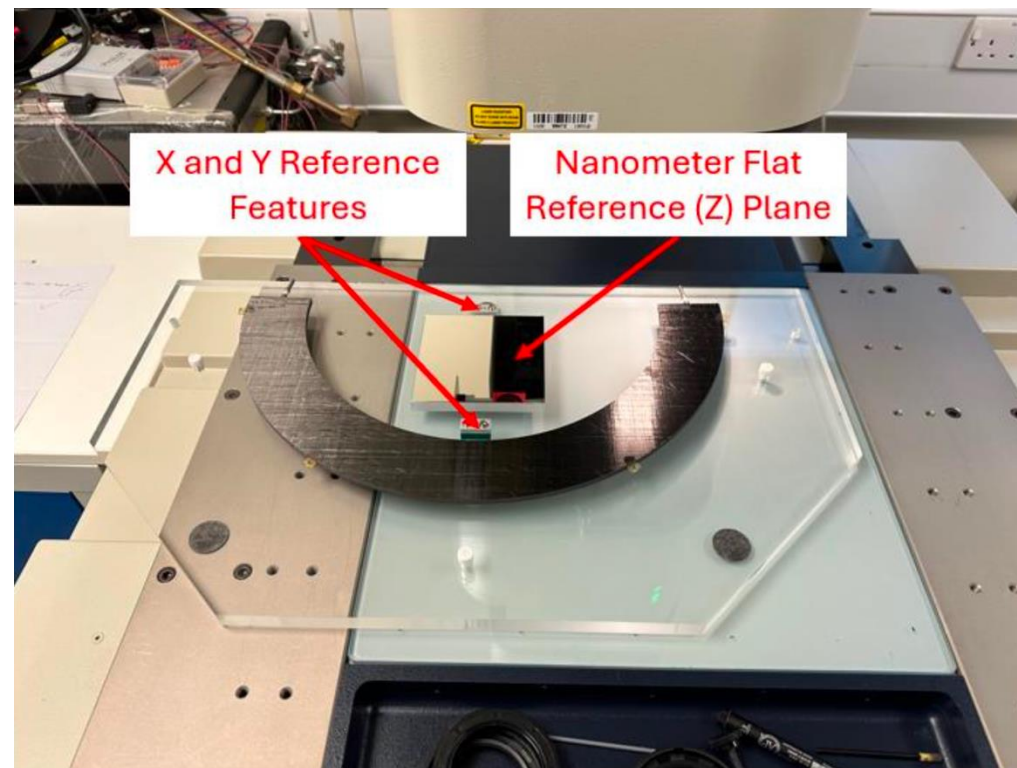
Thermal QC: Results from production

- Results from one production HR (L2.25-UK)
- Peaks with an amplitude $< 1^\circ\text{C}$ (evaluated from the underlying linear trend) are considered not problematic
- All the HRs produced so far show good thermal behaviour



Metrology measurement

- Metrology QC to measure the HRs dimensions
- Both production sites use optical systems for the measurement
- The smartscope in the UK assembly site has a smaller range
 - Only about half of the HR surface can be measured at a time
 - Using an alignment jig with the same reference system to combine the results for a complete HR reconstruction
- Procedures validated with measurements on the same objects done in both assembly sites, and other laboratories of the collaboration

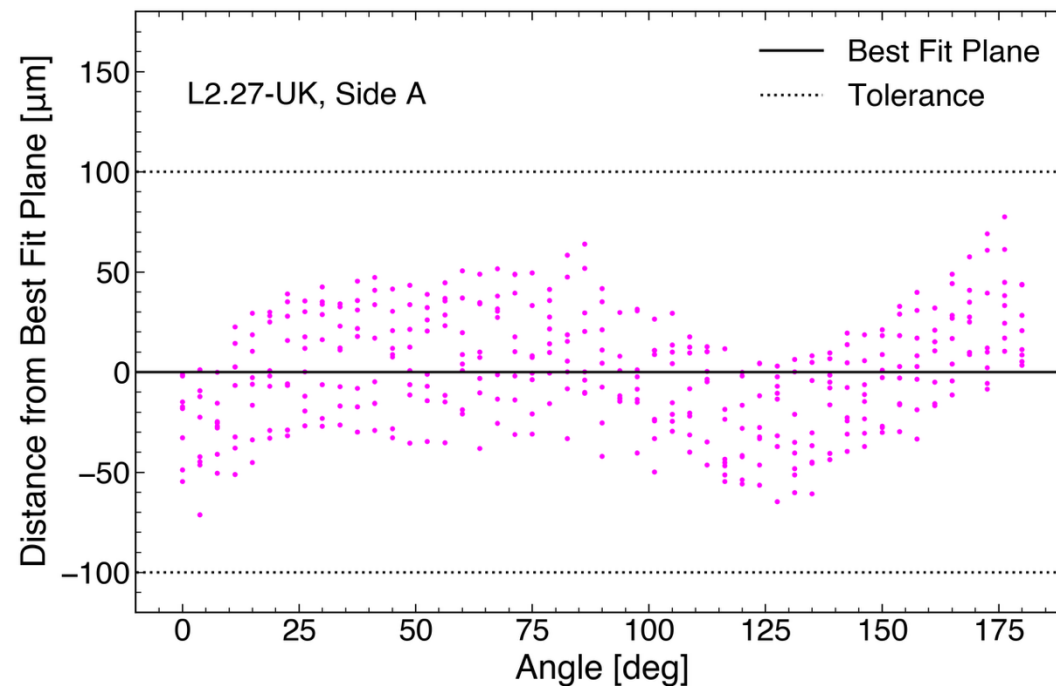
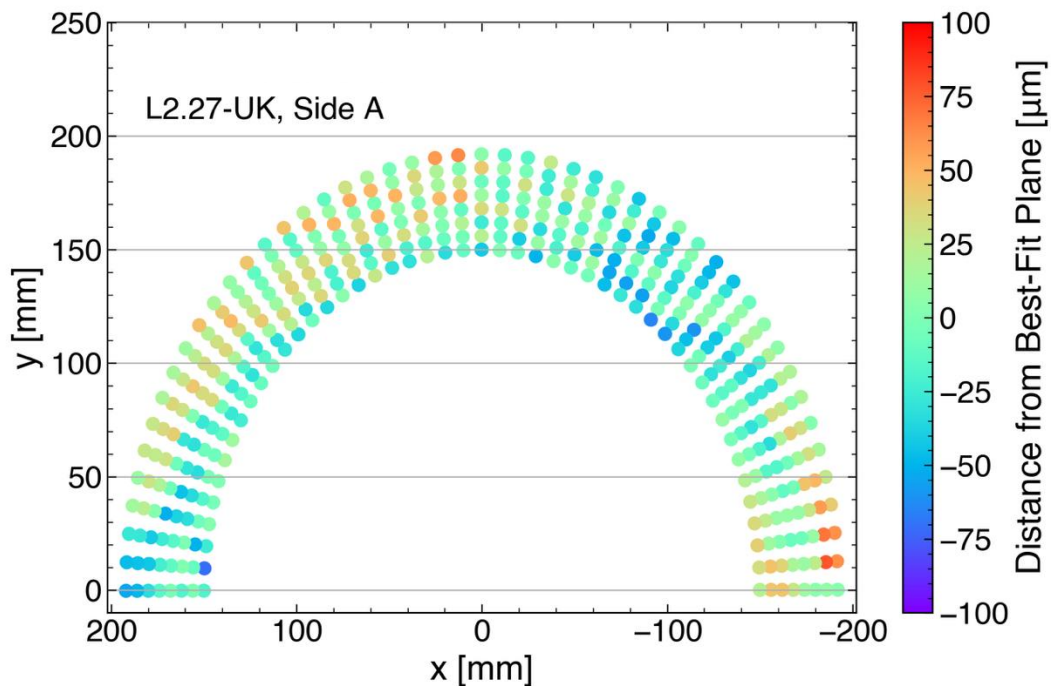
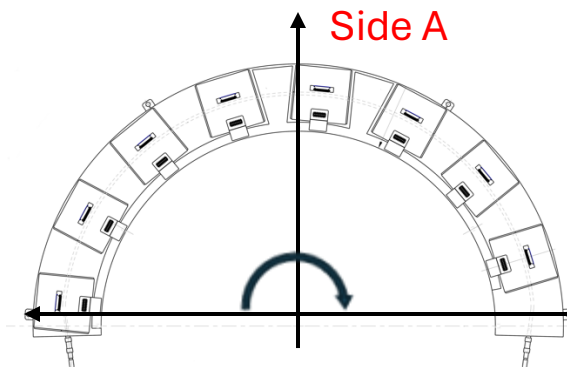


| Axis | Range | Accuracy |
|------|--------|------------------------------|
| x-y | 300 mm | $1.5 + 5 L/1000 \mu\text{m}$ |
| z | 250 mm | $3.0 + 6 L/1000 \mu\text{m}$ |

Experimental setup in Manchester

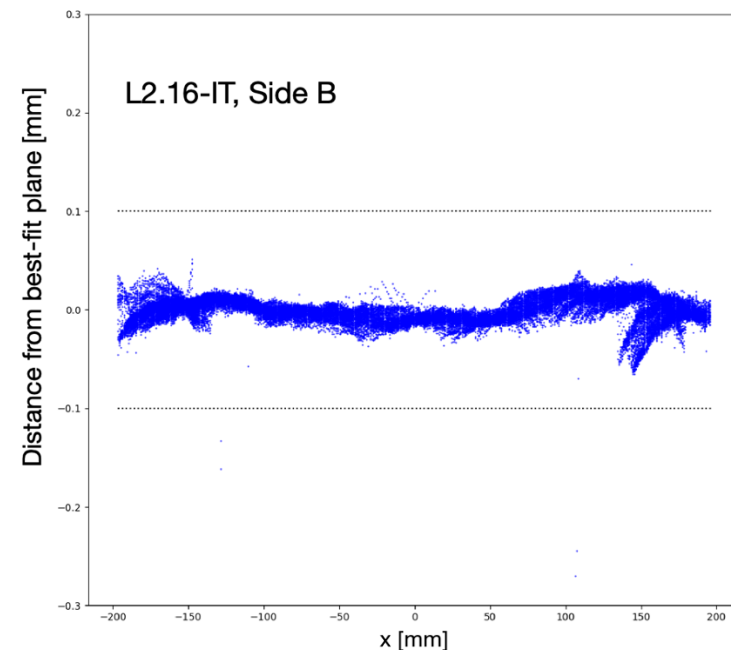
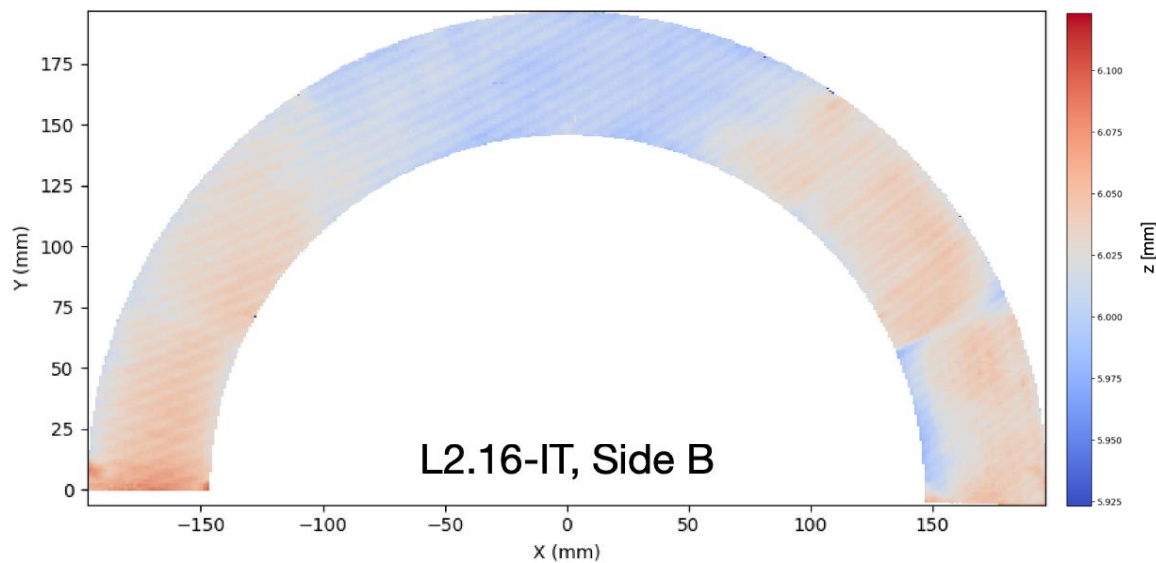
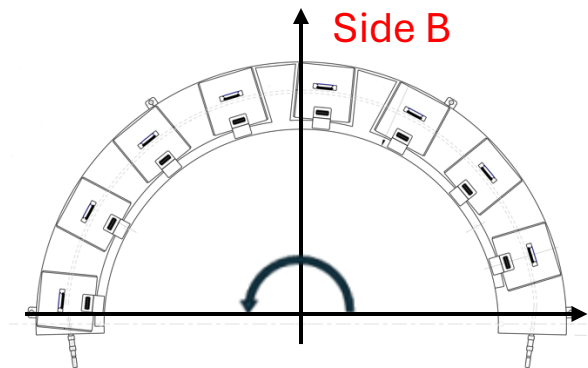
Metrology: Global Planarity (1)

- The HR is scanned to measure points on its surface
- Planarity assessed from the deviations from the best-fit plane
- The HR planarity is well controlled, with most of the points lying much below the limits
- Showcasing production HR L2.27-UK



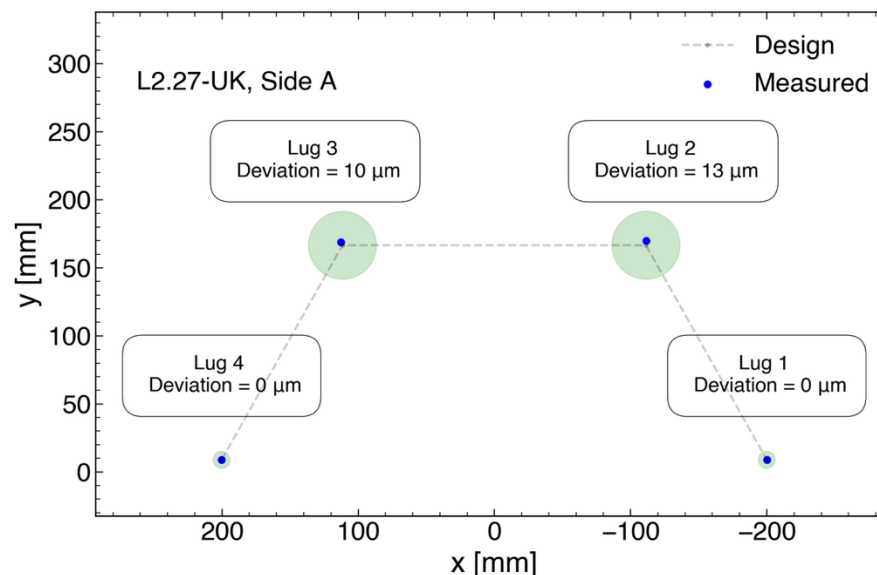
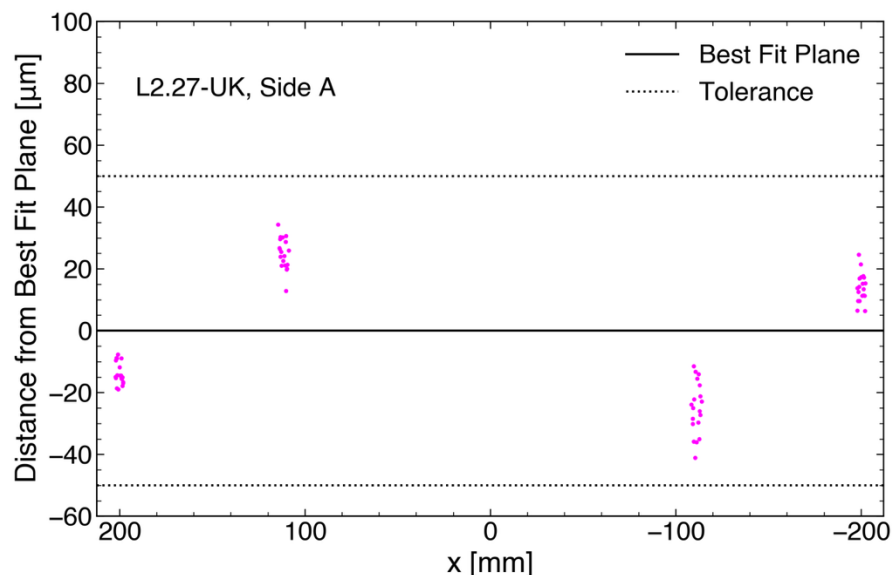
Metrology: Global Planarity (2)

- The HR is scanned to measure points on its surface
- Planarity assessed from the deviations from the best-fit plane
- The HR planarity is well controlled, with most of the points lying much below the limits
- Showcasing production HR L2.16-IT



Metrology: Lugs (1)

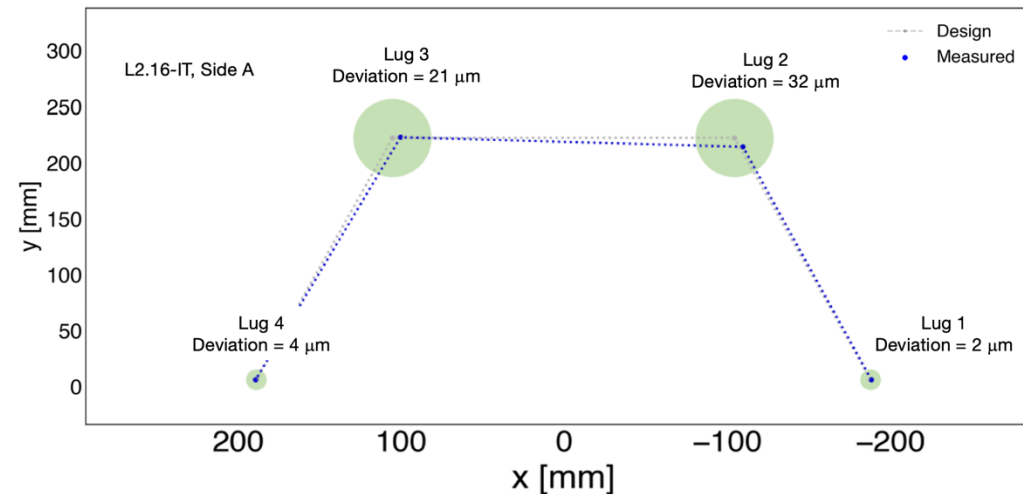
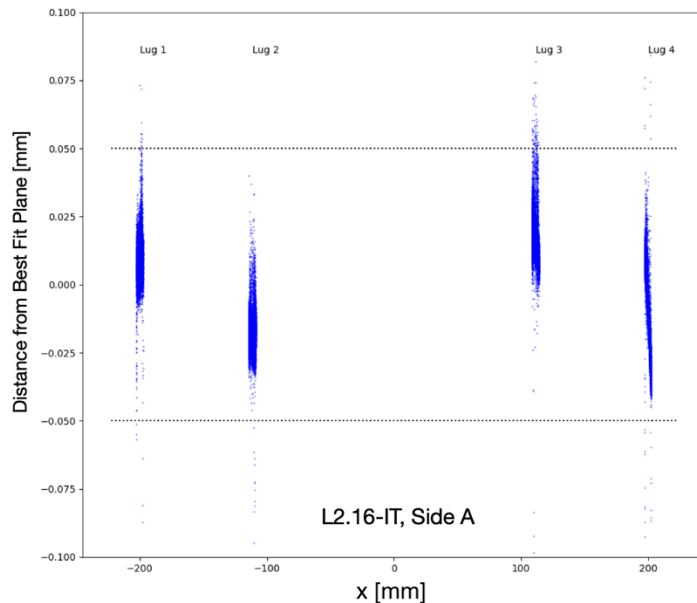
- The lugs' co-planarity is assessed in the same way as the global HR planarity
- Their position is identified from the lug hole centre
- Achieving such a level of precision for the end-lug placement was very challenging and required an extensive tuning of the assembly procedures to ensure correct alignment and prevent the components from moving or springing back when relaxed
- Showcasing production HR L2.27-UK



- The position deviation is computed as the distance from the nominal coordinates in the xy plane
- No uncertainties are included

Metrology: Lugs (2)

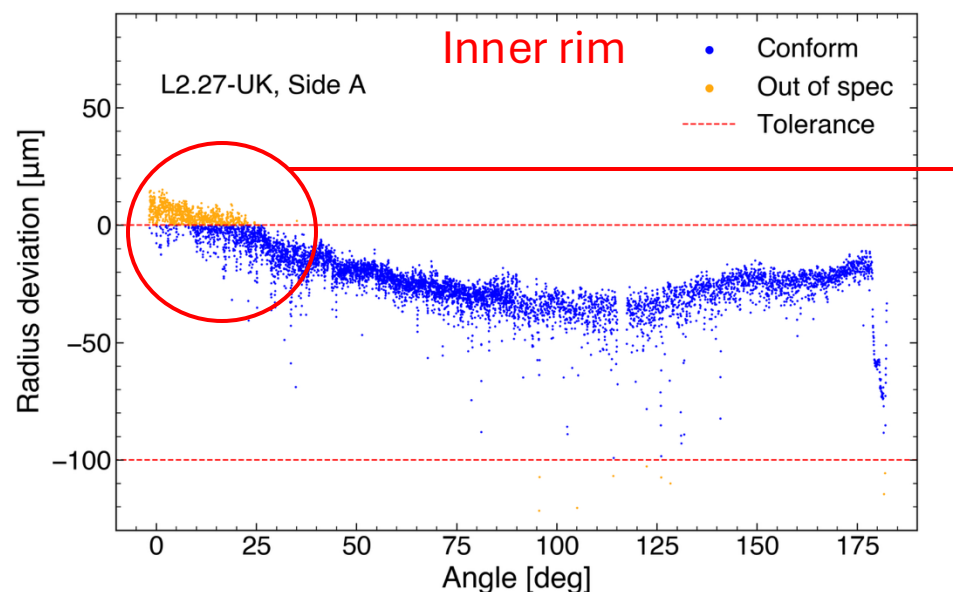
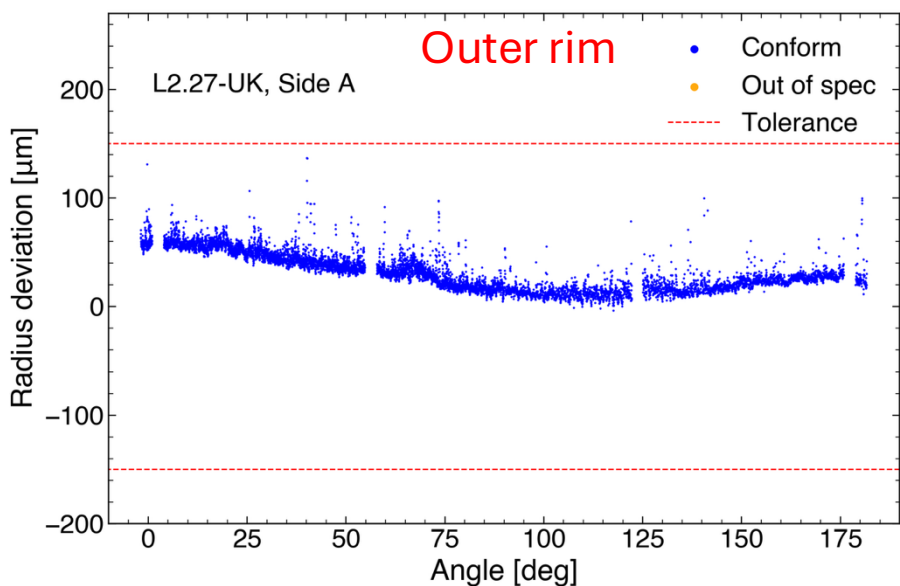
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Metrology: Radius (1)

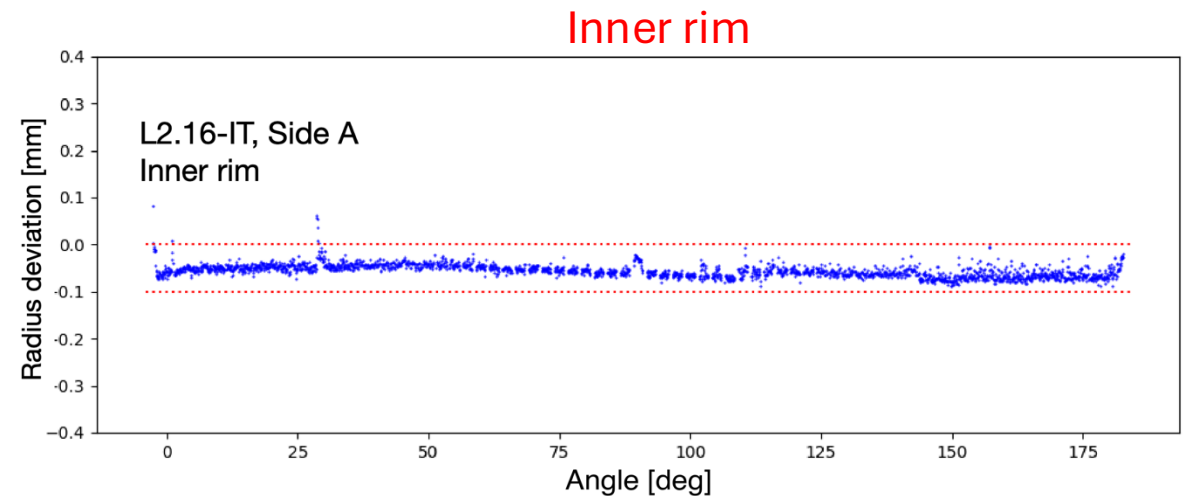
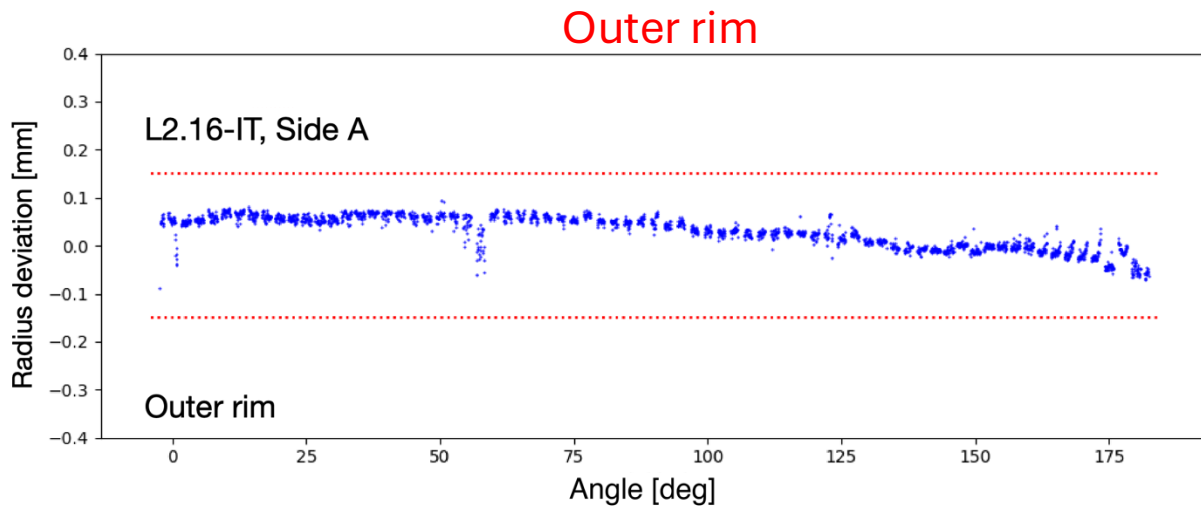
- Points are measured along the inner and outer rims to reconstruct the radii
- HR centre determined from the CAD design reference system (origin given by the end-lugs midpoint)
- The outer radius is always well controlled, while the inner radius is more challenging
- Showcasing production HR L2.27-UK



- Difficult to respect the $+0 \mu\text{m}$ tolerance
- Small non-conformal areas observed in some HRs (typically $< 20 \mu\text{m}$ off)
- We are considering if this can be accepted for assembly in the detector

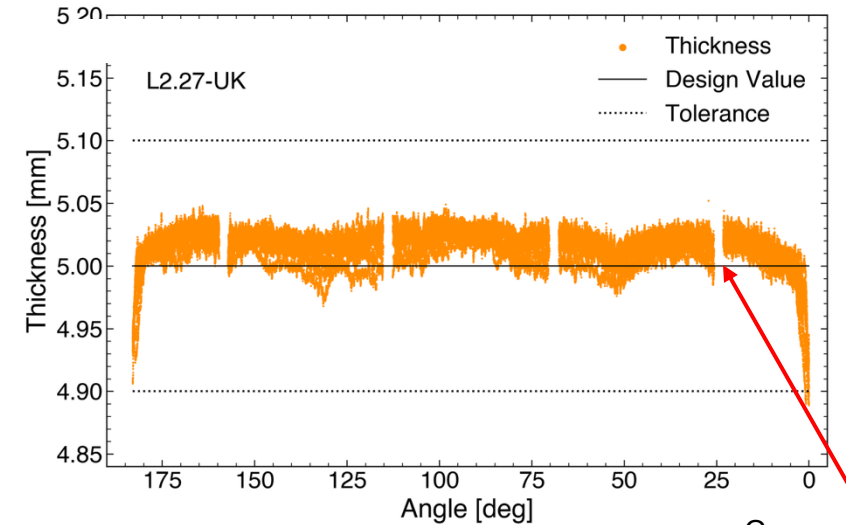
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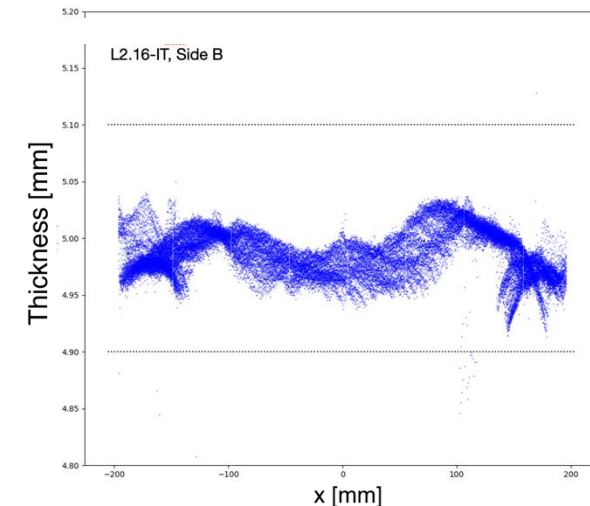


Thickness and other QC tests

- Two methods used to measure the thickness at the assembly sites
 - A pair of confocal displacement sensors used to measure the thickness directly
 - Optical profilometer used to scan the HR surface while the HR is forced to adhere to a vacuum plate
 - Typically well controlled
- Evaporators are pressure-cycled after HR assembly to ensure their integrity
- Electrical impedance measurement (DC) between the HR surface and the pipe to ensure grounding and shielding compliance
- Before assembly, the small parts are also QC-ed
 - Trapezoids' dimensions and integrity
 - Metrology of the inserts (also checked by the vendors)
 - Leak tests of the pipes (after welding and before/after HR assembly)



Gaps caused by the jig used in the measurement



Summary

- The ATLAS ITk detector will replace the current ATLAS ID in the Phase-II upgrade
 - More resilient to radiation damage and will boost the tracking performance
- Half-ring-shaped carbon local supports provide cooling and mechanical stability to the modules in the ITk Pixel OECs
- The Pixel OEC HRs are jointly assembled by Italy and the UK, with meticulous procedures and state-of-the-art technology to achieve the challenging design requirements
- Extensive testing campaigns have been carried out with prototypes to assess their performance and to improve the assembly procedures
- Quality Control protocols have been established to ensure that the production objects are good to use in the detector
 - These include infrared thermography measurements, metrology, leak tests, and grounding and shielding compliance
- Production of the local supports is currently ongoing
 - 24/44(+spares) L2 HRs have already been assembled and are being QC-ed
 - Production of L3 and L4 components has started and will ramp up in the upcoming months
- Stay tuned for more exciting news on ITk!

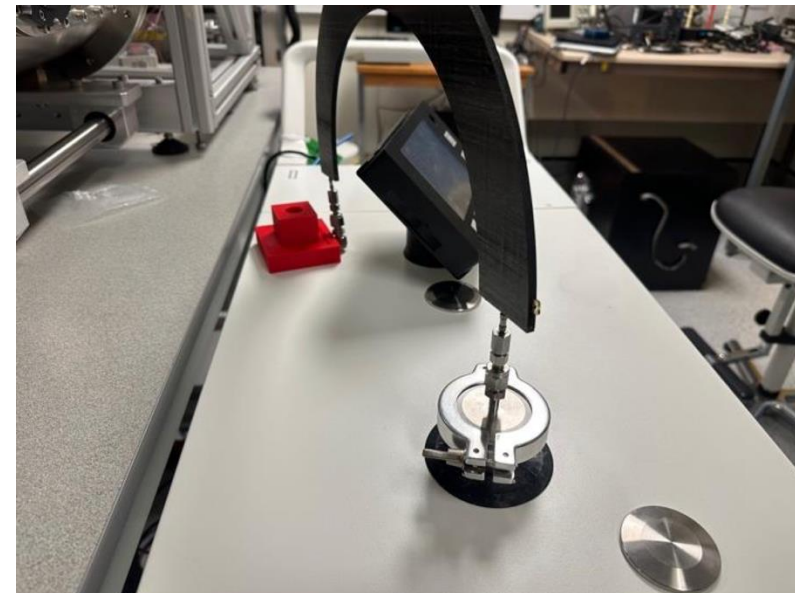
Thank you for the attention!

Questions?

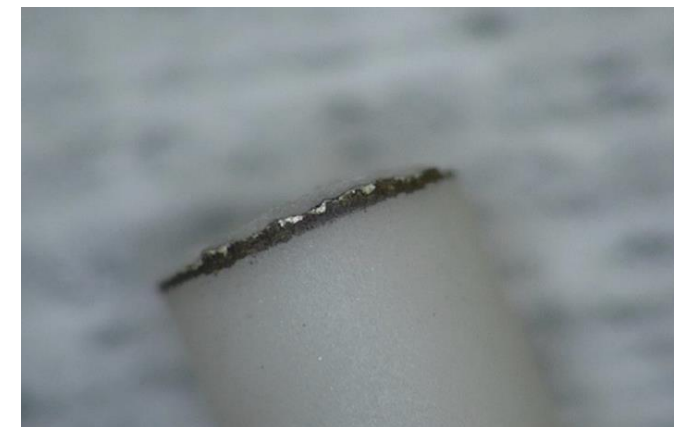
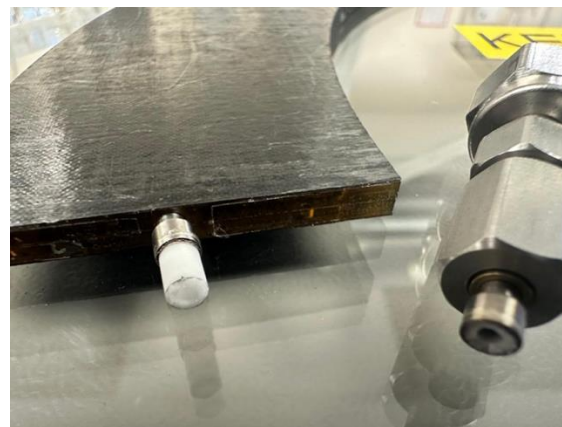
Backup

EB failure

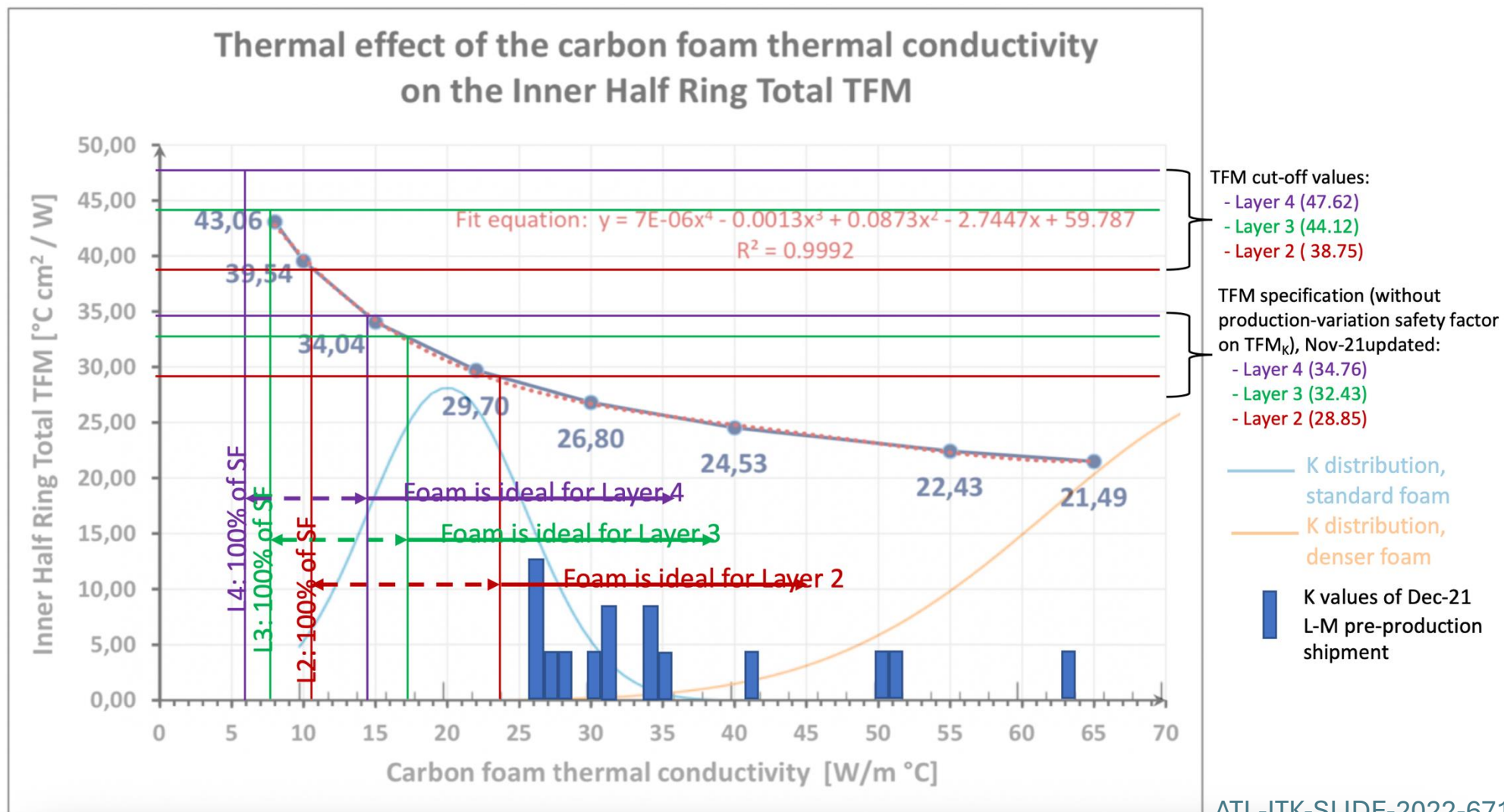
- Evaporators are tested before and after HR assembly, pressured up to 162 bar and leak tested under vacuum with helium
- One EB cracked while running the leak test after the HR assembly
 - No issues were spotted in the QC tests before assembly
 - The EB also survived the pressure test after assembly
 - It only broke when vacuuming for the leak test
- We believe it was caused by some (unidentified) mishandling or load stress in the setup
- No EB was ever damaged during the design qualification or pre-production



Leak test setup in Manchester



Foam density



ATL-ITK-SLIDE-2022-671