PROCEEDINGS OF SCIENCE

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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PoS(VERTEX2025)024

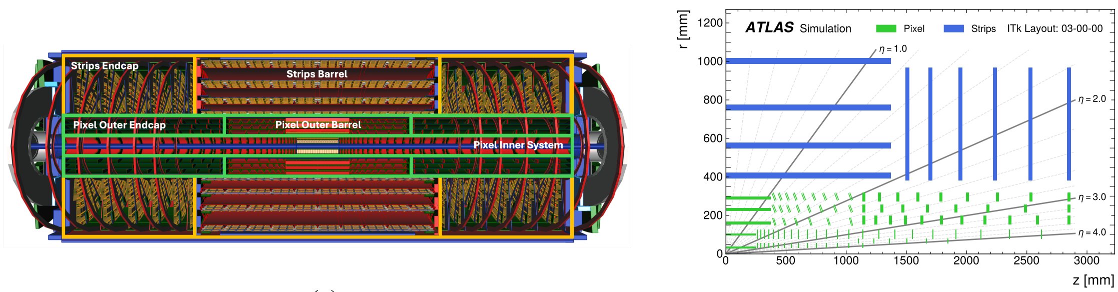
The ATLAS experiment will be upgraded with a new Inner Tracker (ITk) detector for the High-Luminosity phase of the Large Hadron Collider. The ITk, a fully silicon-based detector, will replace the current Inner Detector, enhancing its tracking performance through increased acceptance and improved spatial and time resolution. The ITk will operate in a very harsh radiation environment, requiring an optimal cooling system to deliver effective performance and protect the components from damage. In the ITk pixel outer endcaps, the cooling is provided by bi-phase CO_2 that flows through the local supports, carbon-based structures that secure the pixel sensors in place. The design and construction of these local supports present several challenges, which have led to an extensive R&D campaign over the past few years that included testing numerous prototypes. The local support assembly demands meticulous procedures and state-of-the-art technology to achieve the high level of precision necessary to meet the design specifications and prevent operational failures. A series of Quality Control tests, including metrology and infrared thermography measurements, have been implemented to assess the thermo-mechanical properties of the local supports and identify defective objects. This document will cover the techniques used, the major challenges encountered during the R&D phase, and the solutions developed. Additionally, highlights from the ongoing production campaign will also be shown.

33rd International Workshop on Vertex Detectors (VERTEX2025)
25-29 August 2025
University of Tennessee, Knoxville, USA

1. Introduction

1.1 The ATLAS ITk upgrade

The High-Luminosity Large Hadron Collider (HL-LHC) upgrade will increase the capabilities of the LHC to deliver collisions at higher instantaneous luminosities, up to a factor 7.5 larger than the current operational values. The corresponding increment of the interaction rate is expected to yield about 200 simultaneous interactions per bunch crossing, demanding high granularity for the particles' tracks reconstruction. Large radiation fluences up to $1 \times 10^{16}\ \mathrm{n_{eq}/cm^2}$ also pose a risk to the survivability of the detector. The current ATLAS Inner Detector (ID) was not designed to operate in such conditions, and will be replaced by a new all-silicon Inner Tracker (ITk) detector. The ITk comprises a pixel detector [1], close to the interaction point, surrounded by a strip detector [2], as illustrated in fig. 1. The pixel detector is further segmented into an Inner System (IS), surrounded by an Outer Barrel (OB) in the central region, and two Outer Endcaps (OECs) in the forward directions. The ITk detector will have a larger geometrical acceptance and an increased number of readout channels, thus improving the tracking performance.



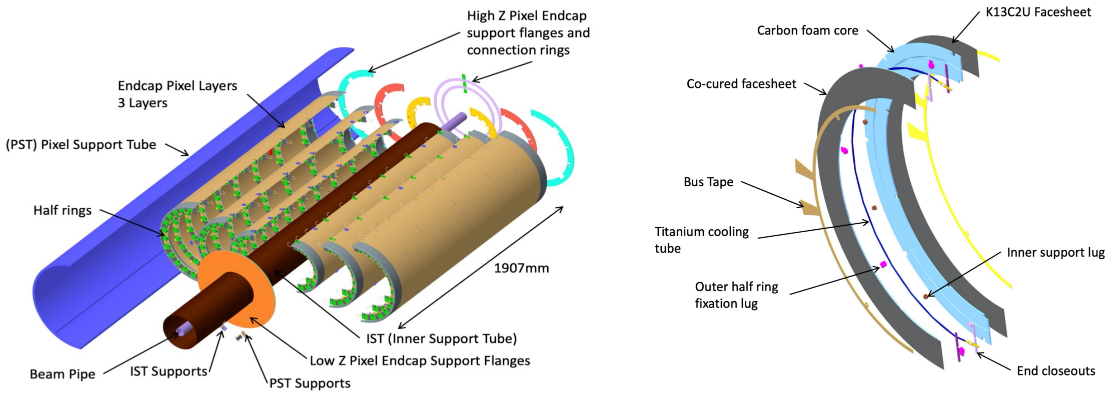
(a) **(b)**

Figure 1: (a) Modified layout of the ATLAS ITk detector: the pixel and strip sub-systems are highlighted in green and yellow, respectively. Figure adapted from [3]. (b) Zoomed-in view of the pixel (green) and strip (blue) layers in one quadrant of the detector. Figure sourced from [4].

This work relates to the Pixel OECs sub-systems, covering the region $1145.5 \leq |z| \leq 2858$ mm (fig. 1b) and consisting of three layers of concentric cylindrical structures of different radii, called layer 2 (L2), 3 (L3), and 4 (L4) from the innermost to the outermost. These global supports host arrays of half-ring-shaped local supports, onto which the pixel modules are glued. Figure 2a shows an exploded view of one of the OECs. The half-rings (HRs) are distributed along the beam direction, with modules arranged on both sides and at different angles to provide hermeticity. The modules will be cooled using bi-phase CO_2 at −35 °C delivered through the local supports.

2. Pixel OEC local supports

The HRs are primarily made out of carbon, to reduce the amount of active material budget in the detector and provide a thermally conductive interface for the cooling of the modules. The HRs present a sandwich structure, with a carbon foam core encapsulated within two carbon fibre face-sheets. A titanium pipe is embedded in the foam core to deliver the coolant to the modules.



(a) **(b)**

Figure 2: Exploded view of the ITk pixel outer endcaps (a) and of one HR local support (b).

Several small ULTEM™ lugs are inserted along the HR rims for handling and support purposes. Two closeouts, also made of ULTEM™, stabilize the pipe at the HR ends. All the modules mounted on one HR face will be powered by a single serial powering chain distributed by a copper-Kapton bus tape, which is glued along the HR inner rim. A schematic of the HR structure can be seen in fig. 2b.

The HR assemblies must satisfy a series of design requirements to ensure they can maintain good performance throughout the lifespan of the detector. The main requirements are summarized in table 1. Very strict mechanical tolerances are necessary for the correct integration of all the components. The planarity tolerances of the lugs and HR surface are loosened for L3 and L4 to account for the higher difficulty when assembling larger objects. The position of the end-lugs and the inner diameter requirements have proven to be very challenging to achieve. Particularly, the inner diameter has a +0 µm tolerance to prevent potential delamination issues due to an overhanging bus tape. The HR assembly procedure required the development of meticulous techniques and custom-made jigs to successfully comply with the specifications. Efficient cooling is also essential to prevent thermal runaway of the silicon sensors and ensure their correct functioning. The thermal requirements are expressed in terms of the Thermal Figure of Merit (TFM), defined as the difference between the temperatures of the hottest point on the sensor's surface and the coolant, divided by the power density. The TFM can be interpreted as the thermal resistance along the path between the pipe and the module, for which lower values are preferred. The HR design was validated with thermo-mechanical simulations and TFM measurements carried out with HR prototypes [5].

The production of the HRs is a joint effort by institutes in Italy and the UK. L2 HRs are currently being assembled in both sites, while L3 and L4 HRs will only be made in the UK and in Italy, respectively. Before starting production, each site was qualified to ensure it can deliver conformal HRs.

2.1 Assembly procedure

The HR assembly begins from blocks of carbon foam which are machined into several trapezoid-shaped slices that constitute the core of the HRs. A denser foam is utilized for L2 and L3 to provide

Mechanical			
Feature Tolerance	L2	L3	L4
Global planarity	200 µm	250 µm	300 µm
Lugs planarity	100 µm	150 µm	200 µm
Lugs position	50(200) µm diametric for end (other) lugs		
Inner rim radius	+0/−100 µm		
Outer rim radius	±150 µm		
Thickness	5.00 ± 0.10 mm		
Thermal			
Feature Tolerance	L2	L3	L4
TFM	$38.75\,\mathrm{K\,cm^2\,W^{-1}}$	$44.12\,\mathrm{K\,cm^2\,W^{-1}}$	$47.62\,\mathrm{K\,cm^2\,W^{-1}}$

Table 1: Summary of the main mechanical and thermal design requirements of the HR assemblies.

higher thermal conductivity in the innermost regions of the detector, where larger fluences are expected. Three layers of carbon fibre pre-preg (K13C2U/EX-1515) are overlapped in a $0° - 90° - 0°$ pattern and cut into HR shapes. Multiple trapezoids are carefully placed on top of the cut-out pre-preg to form a half-sandwich (HS). The assembly is then inserted in a vacuum bag, sealed, and cured in an autoclave at high pressure and temperature. The HS co-curing is carried out in-house in the UK (Advanced Materials Lab, Department of Physics, Liverpool), and by an external company (Loson) in Italy. The HSs are later machined to a uniform thickness and cut to their final shape using a CNC machine. Grooves for the pipe and the inserts are also added at this stage. The evaporators are constructed from straight titanium tubes, which are shaped with a bending jig and cut to the desired length. Titanium sleeves are orbital-welded at both ends, acting as transition joints to the service pipes. An HR is finally formed by two HSs, the pipe, and the inserts, which are glued together and cured at room temperature under vacuum. The temperature must be controlled within ±2 °C throughout the process, to prevent the thermal expansion of the different components. Custom-made assembly plate and tooling were developed to achieve the high level of precision in the alignment of the components needed to meet the specifications [6]. As a final step, the HR edges are sealed with glue, and eventual sticking fibres are carefully removed.

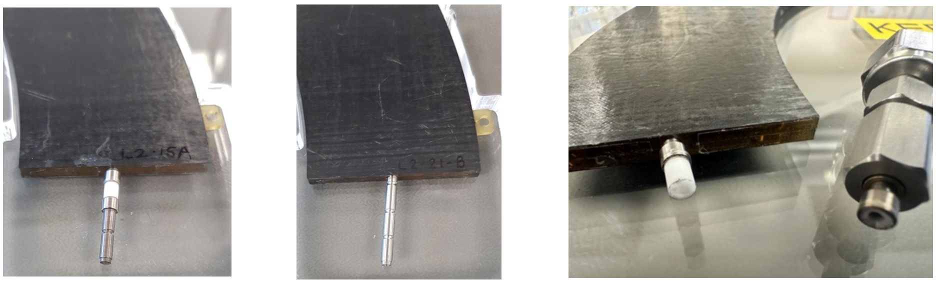
2.2 Quality Control

The quality control (QC) of the components and the assembled objects is a crucial part of the production chain to assure they are of good enough quality to achieve the physics performance. A set of QC tests is carried out on the components before and after assembly to measure key properties such as dimensions and thermal performance.

QC of the HR components

The QC of the smaller parts, like the locators and closeouts, primarily consists in checking their dimensions. This is done both by the vendors, and again at the production sites by sample-checking them. The trapezoids must pass a visual inspection and a geometry check, including height, thickness, and angles measurements. The pipes' shapes are checked with a go/no-go gauge, and leak tests are carried out before the final HR assembly. The evaporators are also pressure-cycled to ensure their integrity.

The original HR design included a ceramic electrical break (EB) at the pipe's ends, to isolate the HR from the services. However, one EB cracked during a QC test of an assembled HR, without any prior identification of structural defects that may have foreseen the breaking. Despite being an isolated case, the risk of a catastrophic failure in the detector was considered too high, since even a single failure would compromise an entire layer. The design was then updated to replace the EBs with titanium sleeves in all production HRs, with no changes to the overall assembly procedures. A comparison of the original and modified design can be seen in figs. 3a and 3b respectively, while fig. 3c shows the EB that broke during QC.



(a) **(b)** **(c)**

Figure 3: Example of HRs with an electrical break (a) and with a titanium replacement sleeve (b). Picture of the EB which broke during a QC test (c).

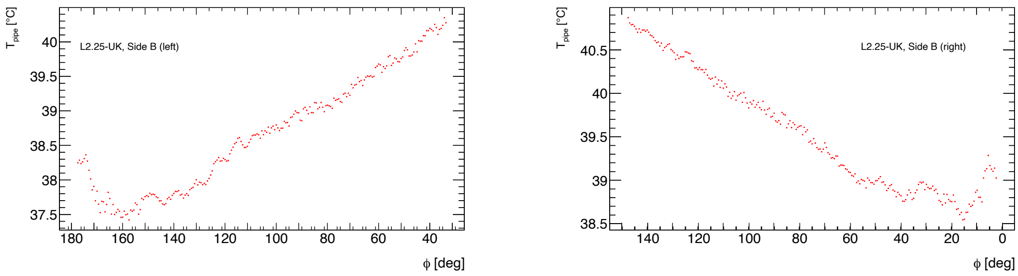
QC of assembled HRs

While it is not possible to directly measure the TFM of production HRs[1], infrared thermography offers a non-invasive way of assessing their thermal performance. A procedure was developed to measure observables that are sensitive to structural defects in the thermal exchange path between the pipe and the HR surface. The technique is described in [7] and consists in emulating the heat load of the modules in a controlled environment (climate chamber), while recording a cooling process with an infrared camera. The video is then analysed frame by frame to extract useful information, particularly the temperature value of the points on the HR surface along the pipe's position (T_{pipe}). These values are expected to increase linearly from the inlet to the outlet, and (large) peaks in the T_{pipe} distribution can be a sign of defects. An example of a measurement performed with production HR L2.25-UK[2] is reported in fig. 4. No significant deviations from the expected behaviour are observed, and all the other production HRs measured until now have not shown problematic thermal performance.

Metrology measurements are carried out to check the HRs pass the mechanical requirements listed in table 1. Both production sites rely on optical measurements, with the Italian site employing a CMM machine integrated with a confocal sensor and the UK site using a smartscope. Measurements of the global HR and lugs planarity are performed with a scan of points measured across the respective surfaces. The tolerances are checked against the distances from the measured best-fit

[1]The TFM measurement requires loading heaters on the HR surface, making them unusable in the detector.

[2]The naming of half-rings follows the convention L<layer>.<HR ID>-<production site: {IT, UK}>.



(a) **(b)**

Figure 4: Example of a thermal QC measurement carried out with production HR L2.25-UK. Due to limitations of the camera's field of view, the measurement is repeated for the left (a) and right (b) portion of the HR, with inverted cooling directions. No evident signs of defects are visible.

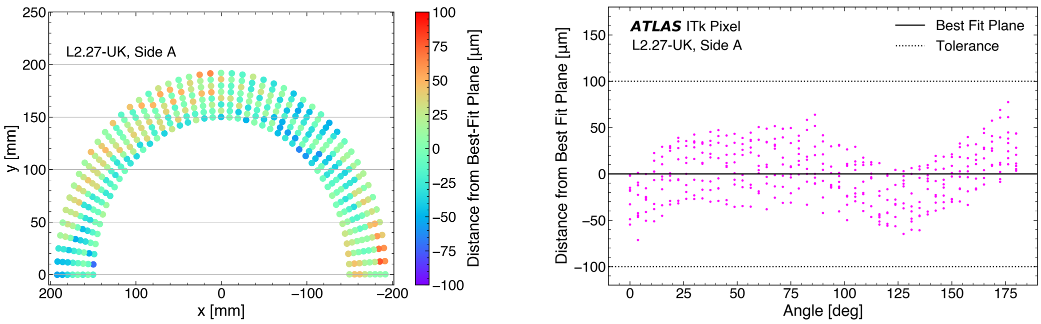
planes. Examples of planarity measurements are shown in figs. 5 and 6a, for the HR surface of L2.27-UK and the lugs co-planarity of L2.26-IT respectively. The lugs' positions are estimated by measuring a set of points along the lug holes and finding their centre with a circle fit. The results for the Italian L2.16-IT HR are reported in fig. 6b. These prove the outstanding accuracy reached in the assembly procedure, which is able to locate the two end-lugs within a few microns from their design location in an HR object of nearly 400 mm diameter. Several points are measured along the inner and outer rim profiles to evaluate the deviations from the nominal values of the radii[3]. Examples of measurements for L2.17-UK are given in fig. 7. The requirements for the inner radius are very tight and difficult to achieve. Some HRs present areas that slightly exceed the tolerance, similarly to the case shown in fig. 7a. Such small non-conformities are not considered problematic, and the HRs can still be used in the detector. The HR thickness measurement slightly differs between the production sites in Italy and the UK. The first relies on the same apparatus used in the metrology, measuring points on the HR surface while it adheres to a vacuum plate. The second uses a pair of confocal displacement sensors to directly measure the thickness. The thickness value was found to be well controlled in the assembled objects.

Similarly to the evaporators, the HRs are pressure-cycled up to 162 bar to assess their integrity. Measurements of the electrical impedance between the HR surface and the pipe are also conducted to ensure compliance with the grounding and shielding requirements. So far, no faulty HRs have been observed.

3. Conclusions

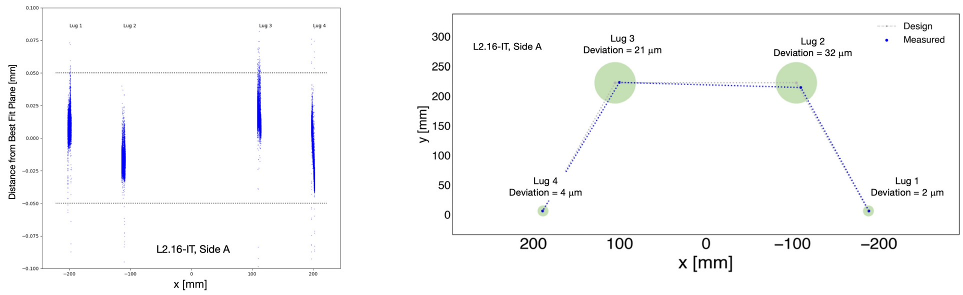
This contribution described the design and assembly procedures of the ATLAS ITk Pixel OEC local support, along with the QC tests carried out at the production sites to ensure the good quality of the objects. At the time of writing this document (Oct. 2025), the production of L2 HRs is well underway, with several assemblies already completed and tested. Highlights of the thermal and metrology QC results were shown for some Italian and UK HRs. The production effort for the outer layers HRs is starting and is expected to ramp up over the coming months.

[3]The HR centre is derived from the end-lugs mid-point, using the same reference system used in the drawings.



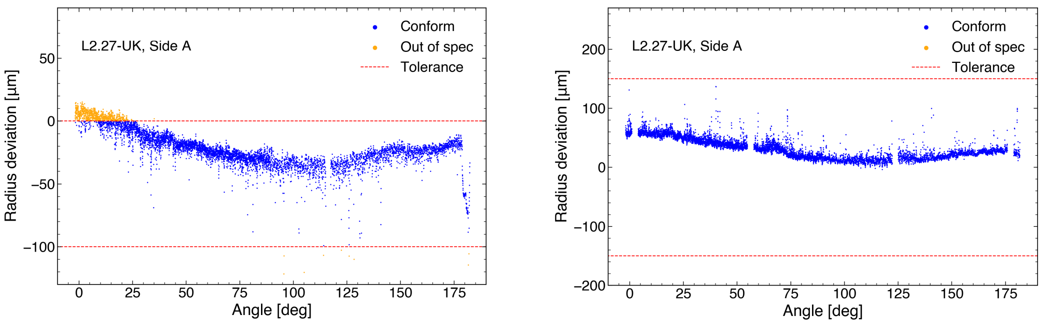
(a) **(b)**

Figure 5: Example of a global planarity measurement of the production HR L2.27-UK, showing a scan of points across the HR surface (a) and their distance from the measured best best-fit plane (b).



(a) **(b)**

Figure 6: Examples of lugs planarity (a) and positions (b) measurements with production HR L2.16-IT.



(a) **(b)**

Figure 7: Examples of inner (a) and outer (b) radius measurements of the production HR L2.27-UK. The plots show the deviations of points measured along the HR rims from the nominal radii values, with (non-)conformal points displayed in (orange) blue.

Acknowledgments

This work could have never been presented without the essential effort of the ATLAS ITk Pixel Outer Endcaps community.

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