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ATLAS ITk strip detector for the Phase-II Upgrade

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Abstract: The inner detector of the present ATLAS experiment has been designed and developed to function in the environment of the present Large Hadron Collider (LHC). At the ATLAS Phase-II Upgrade, the particle densities and radiation levels will exceed current levels by a factor of ten. The instantaneous luminosity is expected to reach unprecedented values, resulting in up to 200 proton-proton interactions in a typical bunch crossing. The new detectors must be faster and they need to be more highly segmented. The sensors used also need to be far more resistant to radiation, and they require much greater power delivery to the front-end systems. At the same time, they cannot introduce excess material which could undermine tracking performance. For those reasons, the inner tracker of the ATLAS detector was redesigned and will be rebuilt completely.

The ATLAS Upgrade Inner Tracker (ITk) consists of several layers of silicon particle detectors. The innermost layers will be composed of silicon pixel sensors, and the outer layers will consist of silicon microstrip sensors. This contribution focuses on the strip region of the ITk. The central part of the strip tracker (barrel) will be composed of rectangular short (~2.5 cm) and long (~5 cm) strip sensors. The forward regions of the strip tracker (end-caps) consist of six disks per side, with trapezoidal shaped sensors of various lengths and strip pitches. After the completion of final design reviews in key areas, such as Sensors, Modules, Front-End electronics, and ASICs, a large scale prototyping program has been completed in all areas successfully. We present an overview of the Strip System and highlight the final design choices of sensors, module designs and ASICs. We will summarise results achieved during prototyping and the current status of pre-production and production on various detector components, with an emphasis on QA and QC procedures.

Keywords: Si microstrip and pad detectors; Particle tracking detectors (Solid-state detectors); Large detector systems for particle and astroparticle physics; Radiation-hard detectors

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Contents

1 High-Luminosity Large Hadron Collider (HL-LHC) and the ATLAS Inner Tracker (ITk) Upgrade

The Large Hadron Collider (LHC) and its detectors, including ATLAS, explore the Universe's structure at its smallest scales, investigating fundamental mysteries including the origin of mass, the nature of dark matter, and the essence of the quark-gluon plasma. Many of the processes related to these questions are quite rare, requiring an extensive collision dataset for study. Producing that dataset requires increasing the LHC's instantaneous luminosity dramatically. The High-Luminosity LHC (HL-LHC) will achieve instantaneous luminosities of $5\text{–}7.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at a centre-of-mass energy of 14 TeV, corresponding to an average of 140–200 inelastic proton-proton collisions per bunch crossing. Ultimately, the ATLAS detector expects to collect more than $3000\,\mathrm{fb}^{-1}$ of proton-proton collisions by the end of the HL-LHC era.

The much harsher radiation environment and significantly higher track density pose a particular challenge to the current ATLAS detector. The ATLAS experiment [1, 2] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2-T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer immersed in a toroidal magnetic field. ATLAS features a two-level trigger system to select events. The first-level trigger is implemented in hardware, using a subset of the detector information to accept events at a rate below 100 kHz. Then, a software-based trigger that reduces

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

the accepted event rate to 3 kHz on average, depending on the data-taking conditions. An extensive software suite [3] handles data simulation, reconstruction and analysis of real and simulated data, detector operations, and the trigger and data acquisition systems of the experiment.

The current inner tracking detector (ID) is particularly vulnerable to the harsh HL-LHC conditions given its proximity to the beamline. It provides charged-particle tracking in the range $|\eta| < 2.5$. Four layers of silicon pixel detectors (the Pixel system) cover the vertex region. Tracks typically produce their first hit in the Insertable B-Layer (IBL) [4, 5]. The silicon microstrip tracker (SCT) surrounds the Pixel system, providing eight measurements per track. The gas-based Transition Radiation Tracker (TRT) radially extends track reconstruction up to $|\eta| = 2.0$.

By the end of LHC Run 3, the Pixel system and SCT are expected to have suffered severe radiation damage to their electronics. Predicted detector occupancies in HL-LHC conditions also exceed the design specifications of the TRT. The ATLAS Inner Tracker (ITk) is a full silicon solution replacing the current Pixel, SCT, and TRT sub-detectors with similar or better performance. ITk must provide higher granularity to cope with increased detector occupancies and feature an improved material budget. Its sensors and readout components must also be more radiation-resistant. Reference [6] provides maps of the radiation conditions throughout ATLAS in HL-LHC conditions. The ATLAS first-level trigger rate at HL-LHC will also increase ten-fold to 1 MHz, placing further demands on the ITk readout electronics.

ITk will employ five layers of hybrid silicon pixels (the ITk Pixels system [7]) at smaller radii and four layers of silicon micro-strip detectors (the ITk Strips system [8]) at larger radii. Figure 1 renders the ITk system on the left and displays the layout of one quadrant's active detector elements on the right. The barrel is the most central region, $|\eta| < 1.2$, sandwiched between two endcaps. Table 1 provides a comparison of the current ID installed in ATLAS and the future ITk. Notably, the ITk system contains almost three times the silicon area of the current ID. Figure 2 illustrates the ITk's reduced material budget (right) with respect to the ID (left). This paper focuses on the Strips subsystem specifically. After a brief review of the expected ITk performance (section 2), this paper provides an executive summary of the basic ITk Strips components and their integration.

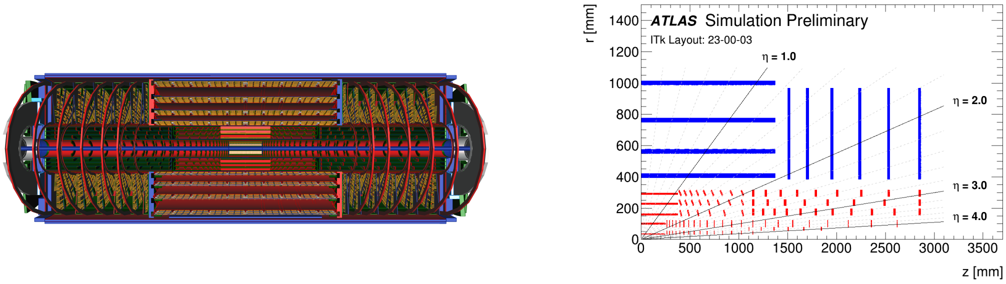

Figure 1. Left: rendering of the complete ITk system showcasing its cylindrical symmetry around the beamline. Right: layout of one quadrant of ITk active detector elements. The active elements of the strip detector are shown in blue, and those of the pixel detector are shown in red. The horizontal axis is along the beam line with zero being the nominal interaction point. The vertical axis is the radius measured from the interaction point. Reproduced from [9]. CC BY 4.0.

Table 1. Comparison of ATLAS' current Inner Detector and the future ITk for HL-LHC.

	Inner Detector (ID)	**Inner Tracker (ITk)**
Detector layers	Si (pixels, strips) and gas trackers	Si trackers (pixels, strips)
Coverage, $\vert\eta\vert$	< 2.5 (Pixel, SCT), < 2.0 (TRT)	< 4.0 (Pixels), < 2.7 (Strips)
Trigger rate	100 kHz	1 MHz
	Pixel System	ITk Pixels
Number of Pixels	92 million (80M Pixel + 12M IBL)	5 billion
Pixel silicon area	1.9 m^2	12.98 m^2
Pixel size	50×200 µm (IBL), 50×400 µm, 50×600 µm	50×50 µm, 25×100 µm
	SCT	ITk Strips
Number of Strips	6.2 million	59.9 million
Strip silicon area	61 m^2	165 m^2
Pitch	80 µm	75.5 µm
Strip length	12.8 cm	1.4–6.0 cm

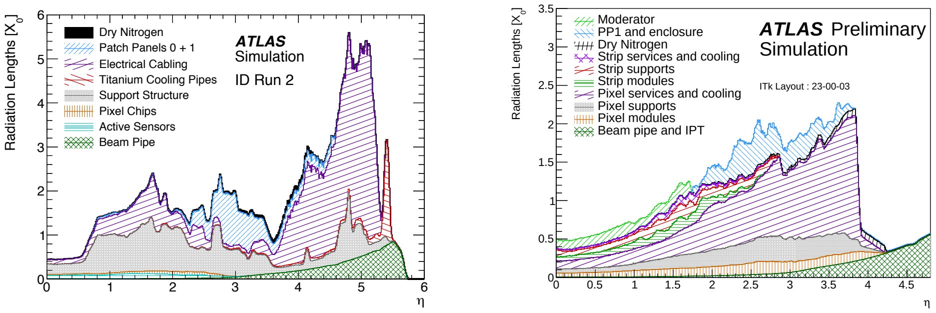

Figure 2. Radiation lengths, X_0, of material in the ID (left, reproduced from [8], CC BY 4.0) and the ITk (right, reproduced from [9]). Note that the y-axis maximum for the ID is six radiation lengths — compared with only 3.5 radiation lengths for the ITk. Services, rather than active components, constitute the bulk of the material in both systems.

2 Anticipated performance of the ITk

ATLAS' necessity for a new tracker compatible with HL-LHC conditions is also an opportunity to improve the detector's performance. Figure 3 shows two example performance metrics. The left plot illustrates the number of ITk silicon hits (strip and pixel measurements) as a function of pseudorapidity, η, simulated using an 1-GeV single muon gun. Tracks with the most hits occur in the transition regions between the barrel and endcaps ($1.2 < |\eta| < -2$). ITk Strips extends over $|\eta| < 2.7$, matching the coverage of the muon spectrometer. ITk Pixels is responsible for all hits in $|\eta| > 2.7$, with the two innermost layers providing all the hits at the edges of the ITk Pixels acceptance around $|\eta| \sim 4.0$. Particles leave at least nine hits throughout the full detector acceptance, except at the extremes of the ITk Pixels coverage. The colour gradient indicates the number of tracks reconstructed in each hits-η grid space. The right plot displays the relative transverse momentum resolution for 100-GeV single muons as a function of η. The ITk's resolution improves with respect to the ID by 20–60%. Further metrics, including efficiencies and resolutions at different energies,

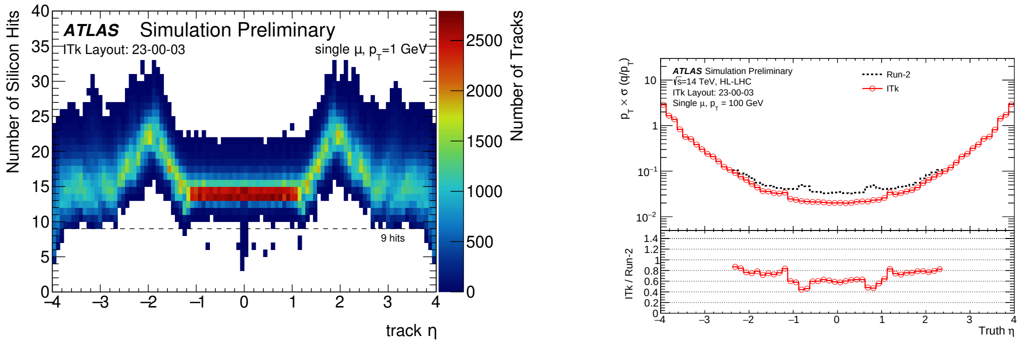

Figure 3. Left: number of strip plus pixel measurements on a track as a function of η. A sample of single muon events with p_T = 1 GeV is used. The muons are produced with a flat distribution between 0 to 2 mm in transverse distance to the beam line and at fixed values z = −15 cm, 0 cm, 15 cm, in equal amounts. Right: relative transverse momentum resolution as a function of η for 100-GeV muons without pileup, comparing the Run 2 detector and the ITk layout. Reproduced from [9]. CC BY 4.0.

impact parameters, flavour tagging performance, and vertexing, are available in reference [9]. The conclusion is the same: ITk maintains the ID's performance and often exceeds it.

3 ITk Strip system

The ITk Strips system is a composite construction. Sensors (section 3.1) mounted with electronics form fundamental detector units called modules (section 3.2). Modules, in turn, are glued to carbon fibre local support structures (section 3.3). Local supports come in two flavors — staves and petals. Four layers of staves are inserted into a global support to form the ITk barrel, while petals populate six rings in either endcap global support. This integration is described in section 3.4.

3.1 Sensors

The ITk Strips sensors are composed of float zone n$^+$ strips implanted in a p-type silicon bulk (FZ n$^+$-in-p). Each sensor is 300 microns thick, manufactured in 6-inch wafer technology. The 6-inch wafer technology drives the size of an individual sensor. Populating staves and petals requires different sensor geometries. The barrel permits a rectangular geometry, so "short strip (SS)" and "long strip (LS)" sensors have the same rectangular footprint. The endcap, on the other hand, is composed of rings, each divided into wedge-like petals. Each petal starts from the edge of ITk Pixels, widening out as it stretches to the ATLAS solenoid. Covering a petal therefore requires six sensor geometries with varying strip lengths, areas, and gradually widening footprints. Figure 4 illustrates the different sensor geometries on the left. The right image depicts a detail image of a barrel sensor corner. The strips and their bonding pads are clearly visible. The fiducial marks for positioning detectors during local support loading are also indicated.

The SS sensors of the first two stave layers in the barrel have four rows of strips, each 24.1-mm long, while the last two layers have LS sensors with two rows of 48.3-mm strips. Changing the strip length realizes resolution requirements given the particle flux as a function of distance to the interaction point while managing costs.

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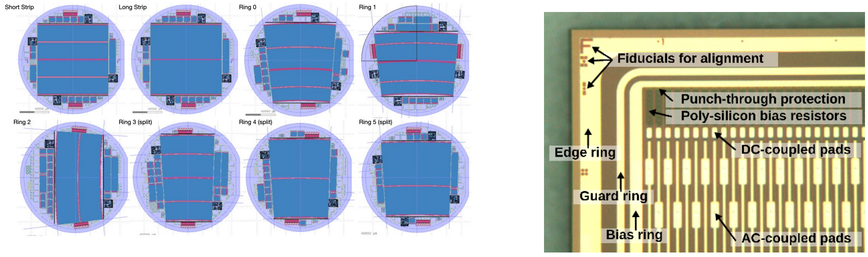

Figure 4. Left: sensors are manufactured in 6-inch wafer technology. The pattern for each sensor flavour and its test structures is shown. Three patterns are marked “split,” indicating that the two copies of a “split” pattern will be stitched together later to form a complete module. Reproduced with permission from [10]. Right: detail image of a barrel module sensor. Reproduced from [11]. © 2020 CERN for the benefit of the ATLAS collaboration. CC BY 4.0.

The first three “ring” sensors, called Ring 0 (R0), Ring 1 (R1), and Ring 2 (R2), are small enough to fit on single wafers. The last three — Ring 3 (R3), Ring 4 (R4), and Ring 5 (R5) — are instead produced as two separate sensors. The two halves are stitched together into a single module later. Endcap strips are between 16 mm and 60 mm long. Like the barrel, the sensors closer to ITk Pixels (and therefore the interaction point) have shorter strips.

3.2 Modules

Sensors fitted with their control and readout electronics form the ITk Strips’ fundamental detector units, called modules. ITk Strips uses a custom application-specific integrated circuit (ASIC) chipset based on 130-nm CMOS technology for module control and readout. Figure 5 illustrates the anatomy

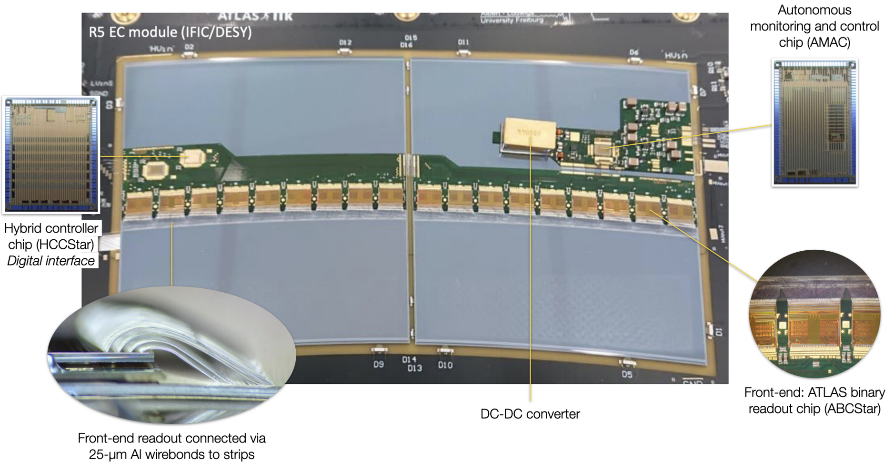

Figure 5. The control and readout circuits for modules are mounted directly on the sensor surface using a UV-cured glue. Key features of an R5 module assembled at IFIC and DESY using the production chipset are labeled. The Hybrid Controller Chip (HCC) is the interface between the ATLAS Binary Chips (ABCs), the front-end chips that readout individual strips, and the off-module electrical systems. The Autonomous Monitoring and Control Chip (AMAC) mounted on the powerboard handles the module’s slow control. 25-micron aluminium wire bonds make all electrical connections throughout the module, including the “stitching” between the two sensors in an R5.

of an R5 module constructed at IFIC and DESY, labeling key elements in the module's control and readout circuitry.

Each module has one powerboard. It is responsible for distributing high and low voltages throughout the module. It features a low-voltage power converter (the DC-DC converter marked in figure 5) and a high-voltage switching circuit. The main control workhorse on a powerboard is the Autonomous Monitor and Control Chip, AMAC. The AMAC provides monitoring and interrupt functionality. It can estimate the temperature of the module, for example, via an onboard NTC and activate an interlock of the module.

The ATLAS Binary Chip (ABC) converts incoming charge signals from the strips into binary hit information. The Hybrid Controller Chip (HCC) is the digital interface between the ABCs and the local support's bus tape. An HCC has a control path, interpreting clock and control signals for the ABCs. It also hosts 11 input channels, one per ABC, accepting data packets. The fundamental readout board, or hybrid printed circuit board (PCB), consists of one HCC and its set of ABCs surface mounted on flex PCB material. Modules may have between 10 and 28 ABCs depending on the number of strips they contain. As each ABC can read out 256 strips, and each HCC can only handle up to 11 ABCs, a module may require more than one hybrid to be read out fully.

Module assembly is distributed worldwide. First, hybrids and powerboards are populated with their surface-mounted electronics at different sites, both at academic institutes as well as with some industry partners. Completed hybrids and powerboards go through a rigorous quality control program, including electrical testing and burn-in. During module assembly, hybrids and powerboards are glued to the sensor surface with bespoke pick-up and mounting tools. Module assemblers apply the UV glue either with stencils or using a glue robot. Once the glue has cured, module assemblers wirebond all electrical connections between the powerboard, hybrid(s), and sensor using 25-micron aluminium wire. The two halves of split modules (R3, R4, and R5) are also stitched together at this time. The stitch bonds between the two halves of the R5 module are also visible, connecting the two hybrids, in figure 5.

The quality control procedures for modules include visual inspections and metrology before and after wire bonding. The electrical performance and front-end characterisation is also measured for each module, confirming successful bonding and acceptable noise levels. Modules are also thermal cycled ten times between −35 C and +40 C in dedicated environmental chambers.[2]

Ref. [11] gives a complete description of the 130-nm CMOS prototyping series of modules and their testing. The production chipset modifies the 130-nm series to directly connect each ABC to its HCC readout pin, giving the chips a star design, to meet the ATLAS upgrade trigger requirement on L0/L1 rates. Section 5.4.1 of ref. [8] describes this change in more detail.

3.3 Local support structures

The stave and petal local support structures, as shown in figure 6, provide the mechanical support, liquid CO_2 cooling, and electrical bus lines for modules. Staves host 14 modules per side, mounted so that there is a 52-mrad stereo angle between the strips on either side. Half of the 392 staves are loaded with modules at Brookhaven National Laboratory, while the other half are loaded at Rutherford Appleton Laboratory. Petals host six modules per side, half of which are the split modules

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[2] The maximum temperature of thermal cycles changed to +20 C shortly after the conference.

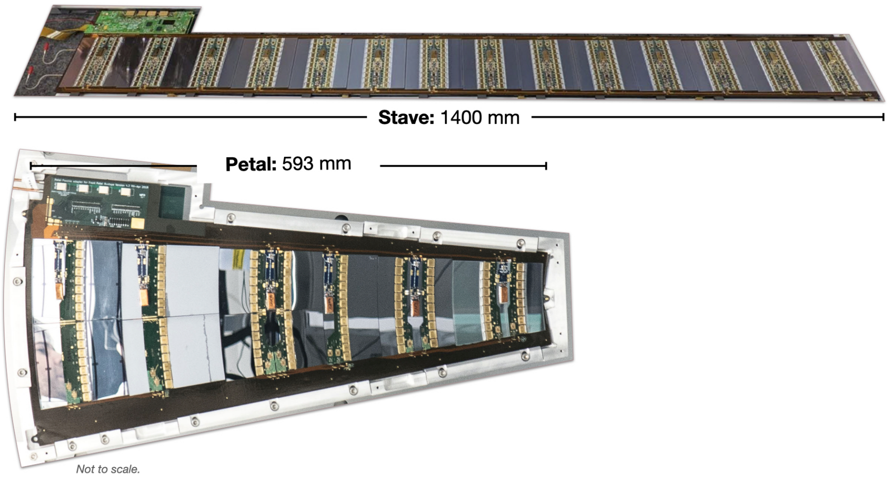

Figure 6. A fully loaded stave (top) and petal (bottom), including their lengths. The End-of-Substructure cards are visible sticking out from the sides of the local supports, like ears. The titanium cooling pipes are also visible at one end of the stave.

(R3, R4, and R5). The modules are arranged on either side to achieve a 40-mrad stereo angle. Petals are loaded at TRIUMF, DESY, Freiburg, and IFIC. End-of-Substructure cards handle control and readout for staves and petals. Staves and petals also have a series of locking points along their sides to connect them to their global support structures.

3.4 Integration

ITk Strips resembles a cylinder divided into three super-structures, inside an outer cylinder: the barrel and two endcaps. The outer cylinder has already arrived at CERN. The barrel and endcap super-structures, or global supports, are primarily carbon fiber-reinforced plastic layers.

The barrel will be 2.8-m long — the length of two staves — and constructed directly inside the outer cylinder at CERN. It consists of four low-mass layers, which will be filled with staves. The staves attach to a layer at a 10° tilt, permitting an azimuthal overlap between neighbouring staves, secured in-place with “locking points” at discrete intervals. Staves arrive for integration in transport frames to keep them protected and supported during travel. Transferring a stave to the structure requires adding an insertion frame to the barrel end of the transport frame at the designated azimuthal position. The insertion frame supports and aligns the transport frame — and by extension, the stave itself. Rails slide the 1.4-m length of the stave, through its locking points and their corresponding fixtures on the structure, forming a continuous guide. Integration personnel can then slide the stave into position along the rail, then lock the stave into the barrel.

Petals will be integrated into two endcap global support structures, one at NIKHEF and the other at DESY. Within ITk, the six disks of each endcap will be supported by an inner tube, enclosing ITk Pixels, and the rods and service trays. 32 petals will populate each endcap. Like a stave, the petal is also designed for end-insertion into its wheel of the endcap global support. A similar system of precision locking points and petal locators will guide the petal into place, where they will be locked into their kinematic mounts.

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In either the barrel or endcap case, secured local supports will then be welded to the cooling manifold. Finally, the End-of-Substructure card's tape will be connected.

4 Project status and outlook

The full ITk silicon-based tracking system must be delivered in time for the HL-LHC start at the end of this decade. It is the critical ingredient in ATLAS' plan to successfully collect physics data in the harsh HL-LHC environment. As the ITk Pixels system will slide into the ITk Strips system, ITk Strips must be complete first. A set of CERN-administrated reviews monitors the project's technical quality and progress. ITk Strips has passed CERN's Final Design Reviews, initiating the pre-production project stage where sites use production-level parts, in all areas except electrical services, systems, and integration. These areas rely on the stabilisation of the smaller components, like modules. Several critical areas have advanced into production, having passed the Production Readiness Reviews, including sensors, ASICs, DC-DC converters, and certain types of modules. Other module flavours and local supports are expected to enter production by the end of the year.

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