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Emily Duden

Special Issue
Selected Papers from the 13th International Conference on New Frontiers in Physics (ICNFP 2024)

Edited by
Prof. Dr. Larissa Bravina, Prof. Dr. Sonia Kabana and Prof. Dr. Armen Sedrakian

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https://doi.org/10.3390/particles8010016 *particles*

Article

The ATLAS Inner Tracker Strip Detector System for the Phase-II Large Hadron Collider Upgrade †

Emily Duden on behalf of the ATLAS-ITk Strips Collaboration

Department of Physics, Brandeis University, Waltham, MA 02453, USA; emily.rose.duden@cern.ch

† This Paper is Based on the Talk at the 13th International Conference on New Frontiers in Physics (ICNFP 2024), Crete, Greece, 26 August–4 September 2024.

Abstract: ATLAS is currently preparing for the HL-LHC upgrade, with an all-silicon Inner Tracker (ITk) that will replace the current Inner Detector. The ITk will feature a pixel detector surrounded by a strip detector, with the strip system consisting of four barrel layers and 12 endcap disks. After successful completion of a large-scale prototyping program, final design reviews have been completed in key areas, such as sensors, modules, front-end electronics, and ASICs. We present an overview of the strip system and highlight the final design choices of sensors, modules, and ASICs. We summarize the results achieved during prototyping and the current status of production and pre-production on various detector components, with an emphasis on QA and QC procedures.

Keywords: HL-LHC; ATLAS; ITk; detector upgrades; silicon detectors

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Academic Editors: Larissa Bravina, Sonia Kabana and Armen Sedrakian

Received: 29 December 2024
Revised: 24 January 2025
Accepted: 9 February 2025
Published: 12 February 2025

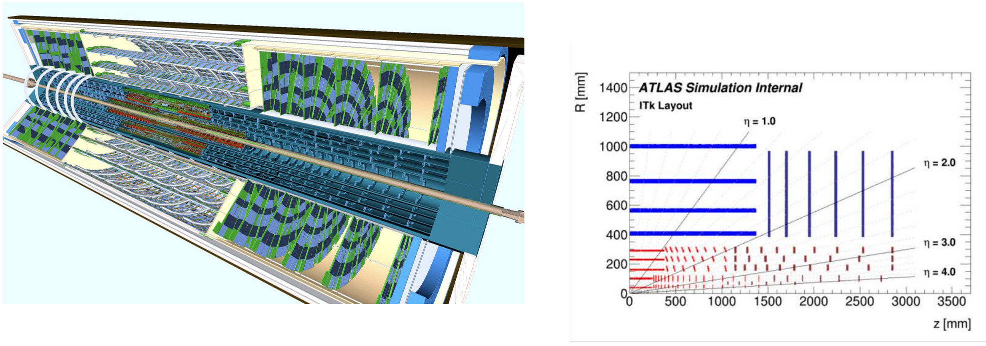
Citation: Duden, E., on behalf of the ATLAS-ITk Strips Collaboration. The ATLAS Inner Tracker Strip Detector System for the Phase-II Large Hadron Collider Upgrade. *Particles* **2025**, *8*, 16. https://doi.org/10.3390/particles8010016

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

The Large Hadron Collider (LHC) is the most advanced facility in the world for investigating matter at its smallest scale. With a record-holding collision energy of 13.6 TeV, the LHC possesses a unique opportunity to explore questions from the nature of dark matter to the origin of neutrino mass. To observe low-probability phenomena that address these questions and increase the precision of current measurements, the LHC will be upgraded to the High-Luminosity LHC (HL-LHC). The HL-LHC will achieve a peak luminosity of 7.5×10^{34} cm^{-2} s^{-1}, corresponding to approximately 200 proton–proton collisions per bunch crossing. This is more than three times the current pileup. Ultimately, the ATLAS detector [1] expects to collect 3000 fb^{-1} of data during the HL-LHC, an order of magnitude higher than that previously collected.

Radiation damage, limitations from detector occupancy, and bandwidth saturation associated with this luminosity increase will render the current ATLAS Inner Detector inoperable in the HL-LHC. As a result, it will be replaced with the new ATLAS Inner Tracker (ITk) [2]. ITk is an all-silicon detector that consists of a pixel detector close to the beamline surrounded by a strip detector. It will have better radiation tolerance, increased granularity, a higher (1 MHz) trigger rate, and extended η coverage ($|\eta| < 4.0$).

Figure 1 shows a rendering of ITk and the layout of detector elements in one quadrant of ITk. The strip detector consists of four barrel layers and six endcap disks per forward region. In total, more than 15,000 modules consisting of over 65 million channels and 165 m^2 of silicon will make up the strip detector.



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

Figure 1. (**a**) A complete simulation of ITk. (**b**) The layout of ITk detector elements. The pixel detector is shown in red and the strip detector is shown in blue. The horizontal axis is distance along the beamline and the vertical axis is the radial distance from the beamline [2].

2. ITk System

The ITk is composed of silicon detector units called modules glued on carbon fiber local support structures. To create a module, electronics are mounted on silicon sensors. There are two types of local support structures: staves for the barrel region and petals for the endcap regions. An overview of ITk components is given below.

2.1. Sensors

ITk silicon strip sensors are AC-coupled strip sensors with n^+ implants in a p-type bulk. A bias voltage depletes the sensor and creates a potential difference. Charged particles then pass through the sensor and create electron–hole pairs that travel according to the potential difference and are collected as signals. ITk strip sensors are radiation-tolerant up to fluences of 1.6×10^{16} neq/cm^2 and will experience an expected maximum fluence of 5.4×10^{14} neq/cm^2 [2].

There are six types of strip sensors in the strip detector [3]. The inner two layers of the barrel region consist of short-strip sensors with a 2.4 cm strip length, while the outer two layers consist of long-strip sensors with a 4.8 cm strip length. Both of these sensor types have an active area of 9.7×9.7 cm^2 and a 75.5 μm strip pitch. The endcap region requires six sensor geometries to create the disk shape of the endcaps, with strip lengths varying from 1.5 to 6 cm and strip pitches from 70 to 80 μm. These lengths are decreased from 12.8 cm in the current ATLAS Semiconductor Tracker, giving the improved resolution necessary in the high-occupancy environment of the HL-LHC. All eight sensor geometries are shown in Figure 2.

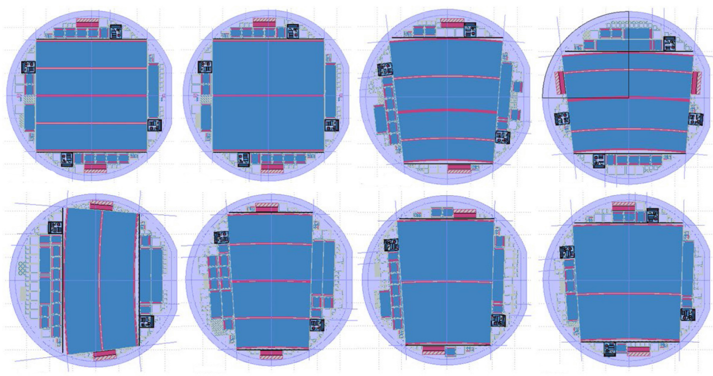


Figure 2. The eight types of sensors in the ITk strip detector. The two rectangular sensors in the upper-left side make up the barrel region. The remaining six curved geometries are used in the endcap regions [4].

2.2. Power Boards

Power for front-end electronics and various monitoring and control functionalities is provided by power boards. Power boards receive 11 V and output 1.5 V to front-end Application Specific Integrated Circuits (ASICs) via an aluminum shielded buck converter called the DC-DC. Then, 11V is also received by the LinPOL, a linear regulator on the power board that steps down this voltage for power board components.

The LinPOL is necessary to immediately supply 1.4 V to the Autonomous Monitor and Control Chip, a custom ASIC that monitors the module environment (via measurements of voltage, current, and temperature) and controls module electronics. The AMAC is responsible for enabling and disabling the DC-DC and, thus, controls the powering of front-end ASICs. The LinPOL also supplies 3.3 V to the Gallium Nitride FET (GanFET), a transistor that acts as a switch for isolating failed sensors connected to the same high-voltage line. Figure 3 shows a barrel module power board.

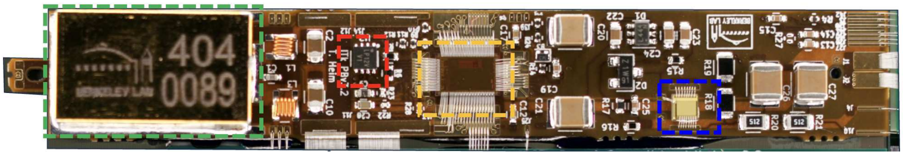


Figure 3. A barrel module power board. The DC-DC buck converter (covered by aluminum shield), LinPOL linear regulator, Autonomous Monitor and Control chip, and Gallium Nitride Field Effective Transistor are outlined in green, red, yellow, and blue, respectively.

2.3. Hybrids

Front-end electronics are hosted by low-mass PCBs called hybrids. Each hybrid contains 7–12 ATLAS Binary Chips (ABCs), front-end chips with 256 channels that read analog signals from the sensor and provide a binary per strip readout. The amplified, shaped, and discriminated signal is then sent to a Hybrid Controller Chip (HCC) for packaging and shipping out of the module. The HCCs also distribute bunch crossing clock and control signals to ABCs. Each hybrid has 0–2 HCCs—ABCs on hybrids without HCCs send data to connected hybrids with two HCCs. Figure 4 shows a barrel module hybrid.

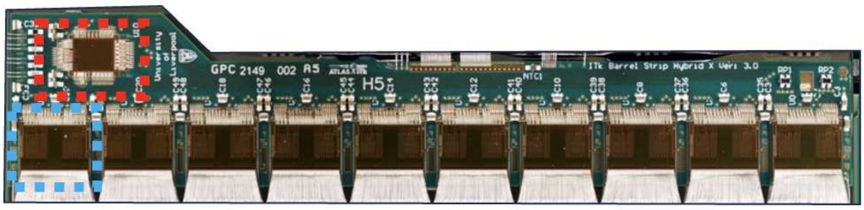
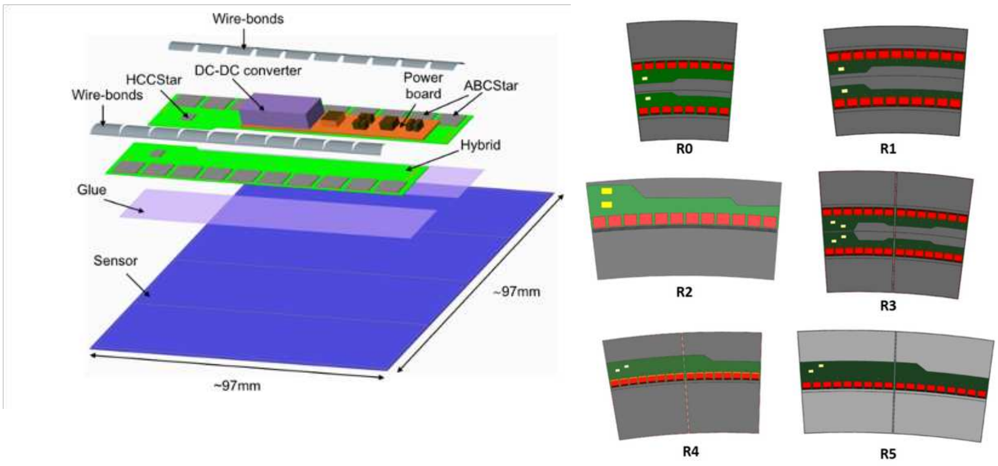


Figure 4. A barrel module hybrid. The HCC is outlined in red, and one of the ABCs is outlined in blue. Note that each ABC has 256 wire bonds connecting the front-end channels to the sensor's silicon strips.

2.4. Modules

Power boards and hybrids are glued directly onto sensors to form silicon detector units called modules [5]. Barrel region modules have one power board and either one long-strip sensor and one hybrid or one short-strip sensor and two hybrids (to allow for readout of twice as many strips). Endcap region modules also have one power board but can be "split" into two sensors with connected hybrids. The different types of modules are shown in Figure 5. Modules are biased up to −500 V during detector operation to ensure appropriate end-of-life signal-to-noise ratios.



(a) (b)

Figure 5. (a) An exploded view of a barrel region short-strip module. (b) The six types of endcap region modules. Power boards are not pictured. HCCs are shown in yellow and ABCs are shown in red [2].

2.5. Local Support Structures

Modules are glued onto lightweight carbon fiber support "cores" to form the units for insertion into the ITk detector, which are called staves in the barrel and petals in the endcaps (Figure 6). These cores provide mechanical support to modules and are thermally conductive to facilitate cooling via fluid routed through the cores with titanium pipes. In ATLAS, liquid CO_2 will be used for cooling. Electrical services are provided to the modules through bus tape made of copper and kapton, which form the top layer of the cores.

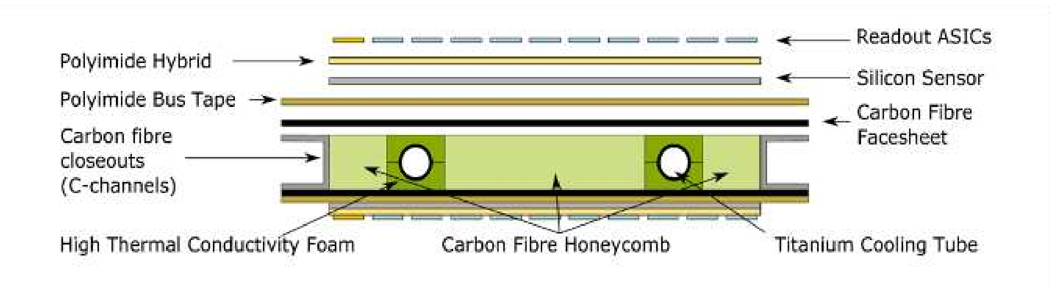


Figure 6. An exploded view of a stave core with a module glued on top. Note the titanium cooling tubes passing through the core and the bus tape at the top of the core [2].

The simple geometry of the barrel region permits rectangular staves, each consisting of 14 modules per side. A total of 392 staves will make up the barrel region. Petals, on the other hand, have a wedge shape, so that 32 petals with six modules per side can be combined to form the endcap disks. Petal modules have a ± 20 mrad stero angle implemented in the sensor geometry. In contrast, modules must be loaded onto staves with a ± 26 mrad angle with respect to the beamline. ITk will consist of a total of 776 petals and staves.

Each local support structure has and End of Substructure (EoS) card for data transfer and communication outside of the stave or petal. Notably, the EoS card hosts the VTRx, a fiber-optic driver/receiver package that transmits optical data, and the lpGBT, a radiation tolerant ASIC that houses the associated electrical tranceivers. The lpGBT performs serialization, error correction, and synchronous signal distribution for communication with off-detector electronics. An overview of a stave and petal is shown in Figure 7.

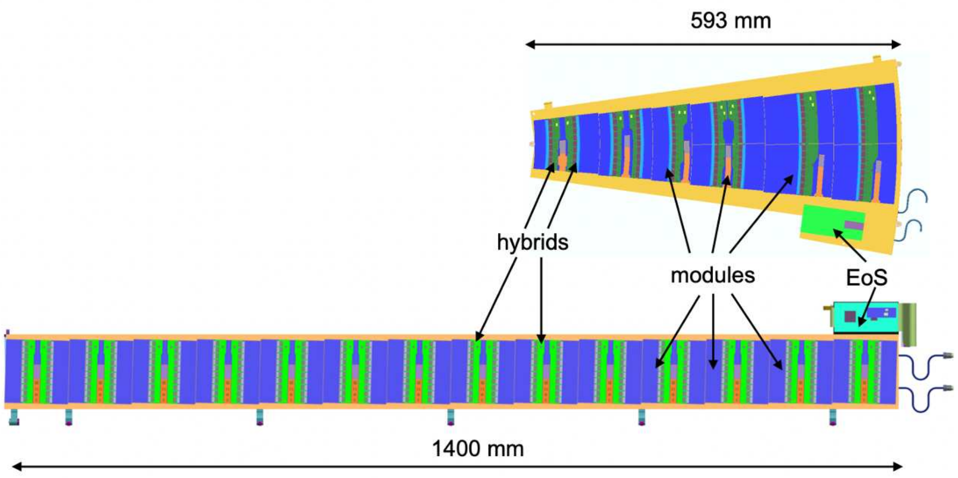


Figure 7. Local support structures for the ITk Strips subdetector. Petals (**top**) make up the endcap regions while staves (**bottom**) make up the barrel regions [2].

3. Assembly and Testing

3.1. Stave and Petal Loading

Staves and petals are loaded with modules at various international sites. Staves are loaded at Brookhaven National Laboratory and Rutherford Appleton Laboratory. Petal loading occurs at DESY, Vancouver, Freiburg, and IFIC. During the loading procedure, a glue-dispensing robot deposits glue onto the stave in a particular pattern. Modules are then placed within a 50 μm accuracy. An XYZ metrology scan is performed after the loading. The loading procedure is relatively uniform across sites, with only slight differences in glue patterns, setups, and metrology procedures.

3.2. Quality Control

ITk components must be extensively tested at every stage of assembly. Hybrids, modules, and staves/petals undergo electrical testing, in which the front-end timing is calibrated, channels are made to have a uniform response, and noise in each channel is characterized [6]. Modules and staves also undergo IV scans, in which varying bias voltages are applied to the sensor and the leakage current through the sensor is measured, ensuring modules do not exhibit exponentially increasing current (electrical breakdown) before the −500 V necessary for detector operation. These electrical tests are performed at least 10 times each at room temperature and at −35 °C on modules and staves as part of the thermal cycling procedure. In addition to electrical testing, visual inspections and metrology tests are performed on components throughout assembly.

3.3. Systems Tests

To test the full ITk Strips production chain with final parts and CO_2 cooling, barrel and endcap Systems Tests are in development. These tests include the full powering chain, cooling infrastructure, electrical services, safety interlocks, and DAQ systems that will be used in the ATLAS detector. The barrel Systems Test (Figure 8) is located at CERN and will house up to eight staves, four of which are already installed. The endcap Systems Test is located at DESY and hosts up to 12 petals, with 1 currently installed.

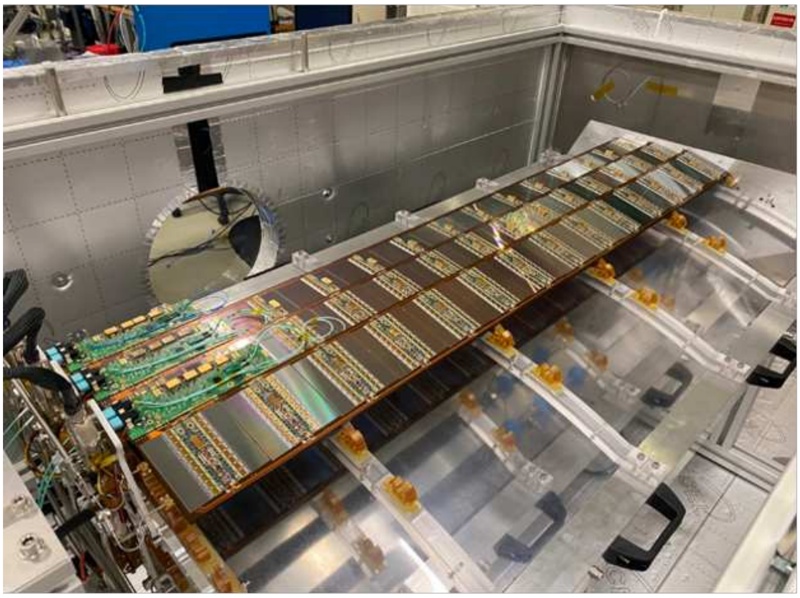


Figure 8. The barrel systems test located at CERN. In this image, three short-strip staves and one long-strip stave have been installed.

3.4. Challenges and Mitigation

ITk Strips encountered two major technical challenges during pre-production. The first, dubbed "Cold noise", is excessive noise observed below 0 °C on modules [7]. Cold noise for ten modules measured in equivalent noise charge by sensor channel is shown in Figure 9. The source of this noise was determined to be mechanical capacitor vibrations on the power board near the DC-DC. It is believed that a piezoelectric effect induces electrical signals from these vibrations, but this mechanism is still under investigation. Short-strip modules (characterized by high power consumption) are primarily affected, leaving half of the barrel region susceptible to cold noise. Using different glues between module electronics and the sensor has been shown to effectively reduce cold noise, especially for long-strip barrel and endcap modules. Kapton sheets placed as an intermediary layer between the sensor and module electronics, called interposers, are another promising solution to cold noise, particularly on short-strip barrel modules.

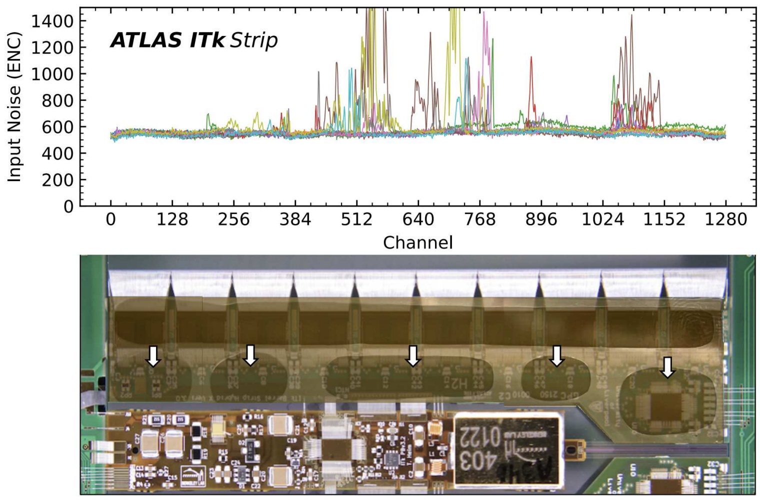


Figure 9. Noise measurements in equivalent noise charge as a function of front-end channel at −35 °C for ten modules [7]. Note that strips exhibiting cold noise tend to coincide with the glue lines underneath the hybrid that are close to the power board.

During thermal cycling of staves, another issue was identified in which cracks form on the silicon sensor, primarily between the hybrid and power board [8]. This cracking occurs due to a mismatch of the coefficient of thermal expansion between module electronics, glue, and sensors. During cooling, the hybrids and power board contract more than the sensor, causing curling. Sensors are more constrained when glued to the local support structure, resulting in a maximum stress between the hybrid(s) and power board. This is a major concern, especially in the barrel region. Rigorous testing of several cracking remediation strategies is ongoing, and some of them have proven to be effective in solving the issue.

4. Conclusions and Outlook

ATLAS ITk will deliver similar or better tracking performance than the current ATLAS Inner Detector in the harsh HL-LHC environment. The Strip Detector has undergone extensive prototyping, and pre-production and rigorous quality control procedures have been established. The Strip Detector is almost fully in production, with several critical areas having passed the Production Readiness Reviews. Notably, the three ASICs (AMACs, ABCs, and HCCs) and the majority of sensors are already manufactured. Modules have entered production contingent upon resolution of the cracking problem. All remaining components are expected to enter production in 2025.

Funding: This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists, and Office of Science Graduate Student Research (SCGSR) program. The SCGSR program is administered by the Oak Ridge Institute for Science and Education (ORISE) for the DOE. ORISE is managed by ORAU under contract number DE-SC0014664. All opinions expressed in this paper are the author's and do not necessarily reflect the policies and views of DOE, ORAU, or ORISE.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. The ATLAS Collaboration; Aad, G.; Abat, E.; Abdallah, J.; Abdelalim, A.A.; Abdesselam, A.; Abdinov, O.; Abi, B.A.; Abolins, M.; Abramowicz, H.; et al. The ATLAS Experiment at the CERN Large Hadron Collider. *J. Instrum.* **2008**, *3*, S08003. [CrossRef]
2. ATLAS Collaboration. *Technical Design Report for the ATLAS Inner Tracker Strip Detector*; Technical report; CERN: Geneva, Switzerland, 2017.
3. Unno, Y.; Abidi, H.; Affolder, A.; Affolder, K.; Allport, P.P.; Beaupre, S.; Beck, G.A.; Bernabeu, J.; Bevan, A.J.; Chisholm, A.; et al. Specifications and pre-production of n+-in-p large-format strip sensors fabricated in 6-inch silicon wafers, ATLAS18, for the Inner Tracker of the ATLAS Detector for High-Luminosity Large Hadron Collider. *J. Instrum.* **2023**, *18*, T03008. [CrossRef]
4. Miyagawa, P.S.; Affolder, A.; Affolder, K.; Beaupre, S.; Beck, G.A.; Bernabeu, P.; Bevan, A.J.; Chen, Z.; Dawson, I.; Deshmukh, A.; et al. Analysis of the results from Quality Control tests performed on ATLAS18 Strip Sensors during on-going production. *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **2024**, *1064*, 169457. [CrossRef]
5. Poley, L.; Sawyer, C.; Addepalli, S.; Affolder, A.A.; Allongue, B.; Allport, P.; Anderssen, E.; Anghinolfi, F.; Arguin, J.F.; Arling, J.H.; et al. The ABC130 barrel module prototyping programme for the ATLAS strip tracker. *J. Instrum.* **2020**, *15*, P09004. [CrossRef]
6. Tishelman-Charny, A. The quality control programme for ITk strip tracker module assembly. *J. Instrum.* **2024**, *19*, C03015.

[CrossRef]

7. Dyckes, G.; Kurth M.K.; on behalf of the ITk Strip collaboration. How the discovery of Cold Noise delayed the production of ATLAS ITk strip tracker modules by a year. *J. Instrum.* **2024**, *19*, C04058. [CrossRef]
8. Iakovidis, G. The ATLAS ITk Strip detector system for the Phase-II LHC upgrade. *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **2024**, *1062*, 169241. [CrossRef]