PROCEEDINGS OF SCIENCE

Automated Assembly of Petals for the ATLAS New Inner Tracker Strip Detector

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The ATLAS experiment is gearing up 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 4 barrel layers and 6 endcap disks. The strip tracker will consist of 11,000 silicon sensor modules in the central region and 7,000 modules in the end-cap region, which are mounted onto larger carbon-fibre support structures called 'petals' for the end-cap and 'staves' for the barrel. To facilitate the assembly of these larger detector structures, an automated system has been developed for mounting modules on petals and staves. The automated procedure streamlines and simplifies the production process and ensures uniformity across the international production clusters. This contribution presents the latest results from the assembly of the first ATLAS ITk pre-production petals and staves, alongside electrical test results and performance measures.

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1. Introduction

The ATLAS and CMS experiments at the LHC had spectacular success with the 2012 discovery of the Higgs boson. To enable precise Higgs measurements and searches for new phenomena beyond the Standard Model, the LHC will be upgraded to the High-Luminosity LHC (HL-LHC) [1]. After Run-3, the HL-LHC aims to deliver an integrated luminosity of up to 4000 fb^{-1} by 2042, with a peak instantaneous luminosity of $7.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ at a center-of-mass energy of 14 TeV. This will increase inelastic proton-proton collisions per bunch crossing up to 200, raising particle track densities and radiation levels by a factor of ten. The current ATLAS Inner Detector cannot operate under these conditions, so it will be replaced by a new all-silicon Inner Tracker (ITk) comprising pixel and strip systems [2]. The ITk will cover a surface area of about 180 m^2. The ITk detector is approximately six meters long and two meters in diameter, covering a pseudo-rapidity region out to ±4. A simulation of an HL-LHC collision in the planned ATLAS ITk is shown in Fig 1.

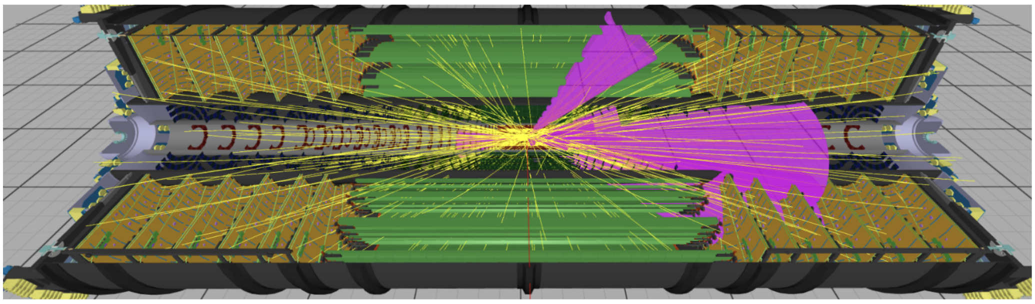

Figure 1: Simulation of HL-LHC collision in the ATLAS new Inner Tracker (ITk) [2].

2. The ITk Strip Detector

The ITk strip-detector consists of a barrel section (green region in Fig 1) and an endcap section on each side (yellow regions in Fig 1). The total number of readout channels (strips) is about 60 million with a pitch of 75.5 µm in the barrel and 69 µm to 85 µm in the endcap. The barrel section consists of four cylindrical layers composed of *staves* arranged in the r-phi direction. Each stave is equipped with 28 silicon sensor modules, 14 on each side. There is a total of 392 staves, resulting in 10,976 silicon sensor modules across the entire barrel. The modules are rotated by 26 mrad along the stave axis for stereo-hit reconstruction. Each endcap features 6 disks composed of larger structures called *petals*. The disks are arranged along the z-direction. Each disk contains 32 petals, with each petal holding 18 sensor modules, 9 on each side. A rotation angle of 20 mrad to the radial axis of the sensor is built into the strip sensor design for stereo-hit reconstruction. This configuration results in a total of 384 petals and 6,912 silicon sensor modules. The ITk modules serve as the fundamental components of the ITk strip detector [3]. To keep occupancy below 1%, the sensors of each module are sectioned into either 4 or 2 rows of strip segments. In the barrel, this corresponds to modules with a strip length of either 2.4 cm (used for staves in the first two barrel layers) or 4.8 cm (used in the outer two barrel layers). In the endcap, the strip lengths vary from 19.0 mm in the innermost radius to 60.1 mm in the outermost, with six different module geometries, labeled R0 - R5 (from inner to outer radius). Each module consists of silicon sensors, one or more hybrids with readout ASICs, and a power board. The readout and power electronics are directly glued onto the silicon sensors and connected to every individual readout channel through wire bonds. The modules are mounted to the local supports referred to as the stave and petal *cores*. The cores are made of carbon fibre honeycomb structure with embedded titanium cooling pipes [4]. The services associated with petals and staves provide optical readout, slow control, power and cooling. The local supports host the back-end electronics “End-of-Substructure” (EoS) boards, located at the edges of each stave and petal side [5]. The ATLAS ITk is designed to be more radiation tolerant with less passive material and to deliver a similar or better tracking performance compared to the current Inner Detector in the more challenging environment at the HL-LHC [6].

3. Automated Assembly of Petals

To facilitate the loading of ITk modules onto staves and petal cores, an automated system has been developed, which streamlines the production process and ensures uniformity across the international production sites. For the endcap system (which is the focus of this paper), the automated system consists of a programmable robotic gantry system, capable of dispensing adhesive and precisely picking up and placing modules with micron-level precision. Careful optimization of the adhesive pattern and its dispensed volume has been performed to ensure sufficient coverage under each module while avoiding seepage, which could adversely affect electrical performance. Electrical isolation of neighbouring strip modules on petals and staves requires placement accuracy of ±50µm [7] and the automated system has been designed to meet this specification.

3.1 Module Loading Algorithm

The module loading algorithm depends on the accurate determination of the module and petal locations and orientations within the robotic gantry's coordinate system, utilizing precision reference markers (fiducials) integrated into the ITk petal [4] and sensor designs [8].

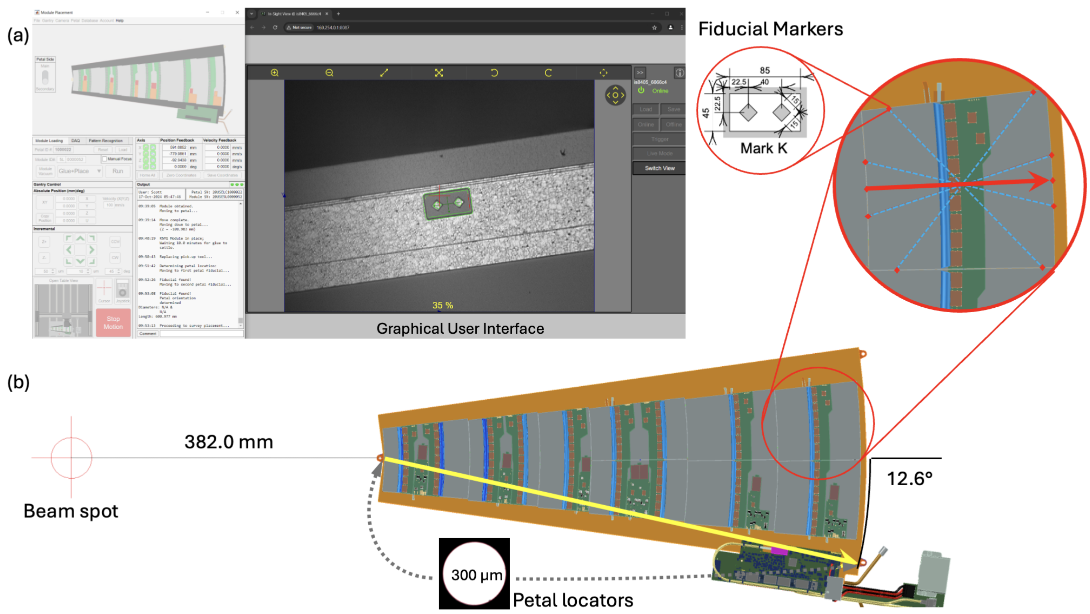

Figure 2: (a) Graphical User Interface (GUI) of petal assembly and module loading software. (b) ITk petal and sensor position vectors defined through petal locators and precision reference markers (fiducials).

To establish the petal location and orientation, two precision holes with a diameter of 300 µm serve as reference markers, known as *petal locators*. They are positioned at the inner and outer edges of the petal, near the kinematic mounts. The vector connecting these petal locators, starting from the inner marker, defines the *petal location and orientation* in the coordinate system of the gantry, as illustrated in Fig. 2 (yellow arrow). Each ITk sensor is equipped with fiducials along its perimeter. These markers establish the center of each module by connecting lines between pairs of fiducials and define the *module location and orientation*, as shown in Fig. 2 (red arrow).

Once the module and petal location and orientations are determined, the software can compute the target positions for all module types based on parameters derived from computer models of the ITk and the sensor design [8]. These parameters include: (1) the angle between the petal location vector and the module location vector, and (2) the length and orientation of the vector(s) pointing from the inner petal locator to the center of each module type, which ensures the center of each module is placed at the required fixed distance from the beam spot.

3.2 Module Loading Equipment

The robotic system is based on a four-axis gantry from *Aerotech*, featuring a freely movable x-y-z stage with an additional rotation stage mounted to the z-axis as shown in Fig. 3. To facilitate the loading procedure, a custom aluminium tool was added to the rotation stage, allowing a vacuum line to connect to customized 3D printed vacuum tools for picking up and placing modules. Furthermore, a precision displacement sensor, an optical system and a visual capture camera are mounted to the z-stage. The optical system is a *Cognex* pattern recognition camera used to determine the coordinates of fiducials on modules and petal cores. The other camera offers a much larger field of view and is utilized for visual capture for quality control (QC) and process control purposes. The displacement sensor is a *CL-3000* coaxial laser displacement system with a *CL-L070* sensor head from *Keyence*. It is employed to collect (petal) *out-of-plane* metrology information, both before and after modules are loaded. This provides information on both module shape and glue height as part of the QC and process control. Programmable glue dispensing is available through the robotic system using a high precision dispenser *Ultimus*^{TM} *V* from *Nordson* mounted to the z-stage.

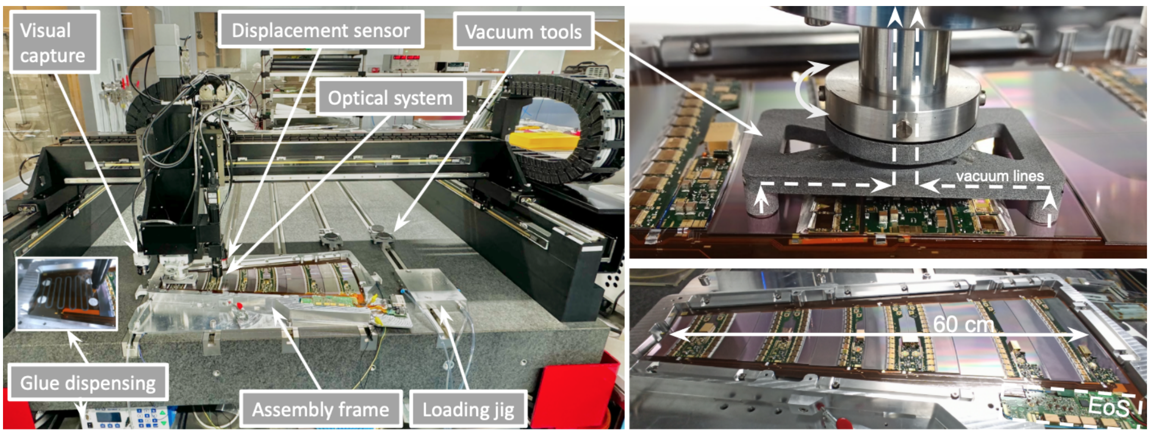

Figure 3: (Left:) Robotic gantry system of the ITk-Vancouver cluster at SFU. (Right top:) Vacuum tool holding a module before placing it on the petal core. The vacuum supply to the vacuum tool is controlled by the angular alignment of the rotation stage. (Right bottom:) Fully assembled and loaded petal.

3.3 Petal Assembly Procedure

The petal assembly and module loading sequence is summarized in Fig. 4. The automated loading of modules on the petal core is controlled by a graphical user interface (GUI) programmed in *MatLab*. To locate the petal within the gantry coordinate system, the (calibrated) gantry finds the two petal locators and fits circles to the observed (backlit) precision holes. To locate the module(s), the gantry moves to the module location (typically placed on a custom *loading jig* next to the petal core) and measures the fiducials along its perimeter to determine the module location and orientation. Auto-focus and pattern recognition algorithms are applied to precisely measure each fiducial. The module loading algorithm described above is then used to compute the target position of each module type on the petal core. An adhesive is used to permanently mount the modules (and the EoS card) to the petal core - the current default is the thermal gel (*DOWSIL™ SE 4445*). Once a module type is selected for loading, the gantry dispenses lines of adhesive at the module's target location on the core. Pre-placed kapton spacers are used to control the glue height. To enable

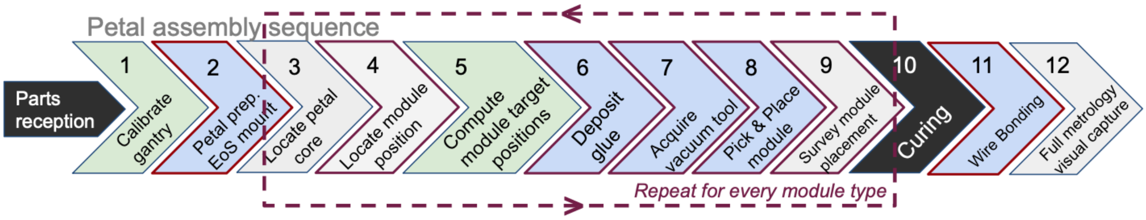

Figure 4: ITk petal assembly and module loading sequence.

the loading process, the gantry makes use of custom vacuum tools available on pre-programmed locations on the gantry table. The gantry autonomously obtains the required vacuum tool for the selected module before moving to its location on the loading jig. The gantry lifts the module by routing vacuum through the feet of the pick-up tool with (chemical-resistant, cleanroom grade) O-rings fitted in each foot to protect the sensor. The vacuum supply to the vacuum tool is controlled by the angular alignment of the rotation stage to the tool. The gantry rotates the module to match the petal's orientation and moves to the target location over the petal. The pre-calibrated tool thickness ensures consistent force application during both pick-up and placement. One advantage of the automated module loading setup is that the speed at which the module is pushed into the adhesive can be precisely controlled (currently 30 µm/s). After placement, the gantry remains stationary for 10 minutes to allow the adhesive to settle without disturbance. The robotic system then proceeds to conduct a survey by moving around the sensor's perimeter and automatically finding and recording the positions of the fiducials. If the placement error is less than the specified ±50µm, the system is ready for loading the next module type. If the placement error exceeds the specified tolerance, the user can choose to have the gantry adjust the position and resurvey before proceeding.

3.4 Results

The first ITk petals have been assembled during the pre-production phase of the ITk project with good mechanical and electrical performance. Fig. 5 shows examples of module placement accuracy (better than ±50µm) and petal out-of-plane metrology, well within specifications. Examples of the electrical noise performance before and after module loading is shown below, demonstrating that the loading procedure does not impact electrical noise performance of the ITk modules.

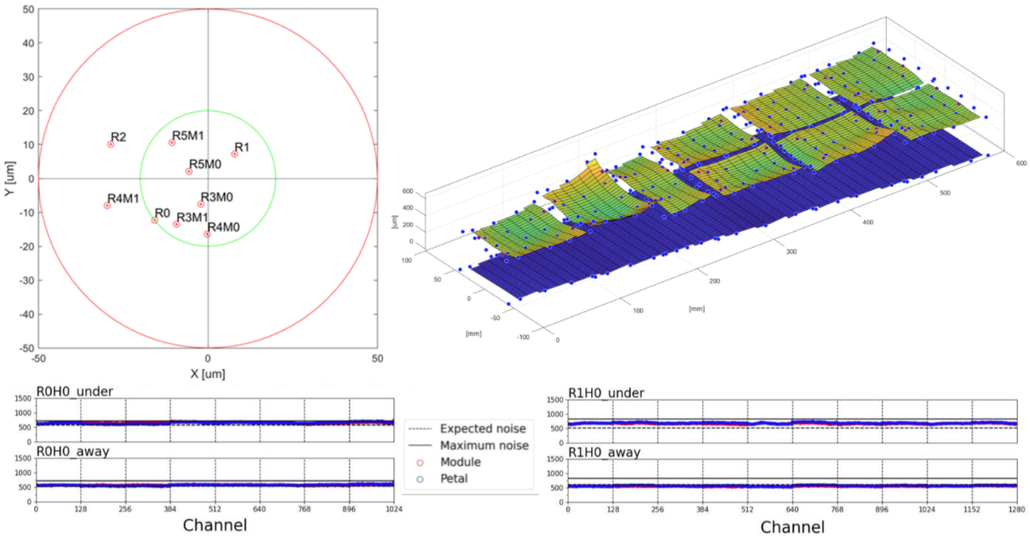

Figure 5: Example performance measures. (Top left:) Placement accuracy of modules loaded on to a petal core. The red circle indicates the required specification of ±50µm. (Top right:) Out-of-plane metrology showing module shapes (green/orange) offset by adhesive and sensor thickness (about 440µm) from the petal core surface (blue). (Bottom:) Noise performance of selected modules before and after module loading.

4. Conclusions and Outlook

A fully automated robotic gantry system was developed which enables precision placement of ITk modules on the petal local supports. The system allows for automated glue deposition, module mounting and realtime visual inspection of sensor and petal fiducials. Assembly of petals during the ITk pre-production phase have demonstrated module loading well within specifications. Electrical performance testing before and after loading show the loading process does not affect noise performance down to the coldest expected operating temperatures of −35°C.

When operating ITk petals at extremely cold temperatures ≤ −35°C (e.g. situations that may arise from cooling plant failure modes) "sensor cracking" has been observed due to coefficient of thermal expansion (CTE) mismatch between the electronics and sensors [9]. A comprehensive program is currently underway to study mitigation strategies to guide the experiment on which solution should be adopted for full production.

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