PROCEEDINGS OF SCIENCE

Overview on Current State of the Art Pixel Mechanics for the Upgrade Tracking Detectors at the ATLAS and CMS Experiments

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The pixel tracking detectors in the ATLAS and CMS experiments are scheduled to be replaced with upgraded versions during the next long shutdown period at the LHC. The upgraded detectors are designed to take advantage of the high-luminosity operation of the LHC which is due to begin in 2029. This means that the active sensor area must increase, and these additional sensors need mechanical support, cooling, and electrical and data transmission services. The mechanics must suitable for the increased radiation dose that will arise from the increase in luminosity. These requirements demand the use of novel mechanical solutions and materials.

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1. Introduction

Over a 36-month long shutdown period (LS3) of the Large Hadron Collider (LHC) at CERN, the ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid) detectors will be upgraded in preparation for high-luminosity operation of the LHC from 2029 onward (HL-LHC). In order to deal with higher levels of radiation and increased particle density during HL-LHC, the tracking detectors in both experiments will be fully replaced [1, 2].

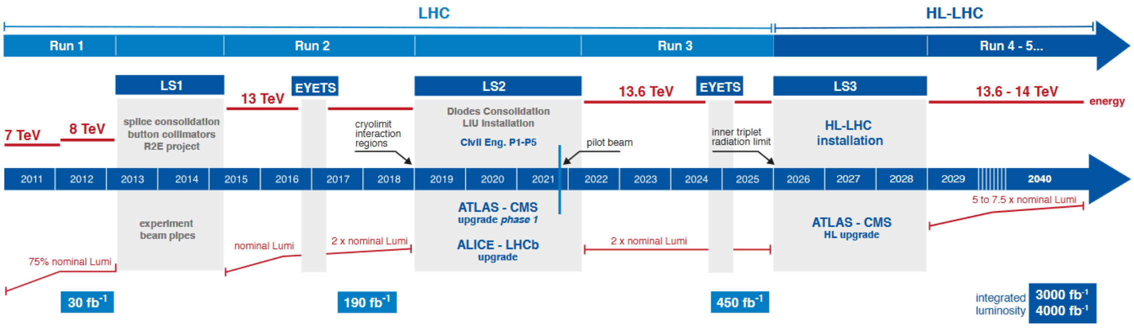

Figure 1: HL-LHC schedule timeline (adapted from [3])

1.1 CMS and ATLAS Pixel Sensor Modules

The pixel sensor modules which will be used in the upgraded tracking detectors of CMS and ATLAS share many similarities. Both have the same options for pixel size, either 50×50 μm^2 or 25×100 μm^2. The pixel size and silicon thickness varies depending on the position of the module in the detector. The readout chip, which is bonded to the sensor, has been developed jointly for ATLAS and CMS by the RD53 collaboration [4]. The production chips that will be used in two experiments are different flavours of this chip which evolved from the same prototype [5].

2. CMS Inner Tracker (IT) Upgrade

The tracking detector of CMS comprises an Inner Tracker (IT) and Outer Tracker (OT). The IT is a pixel-based system, while the OT is strip-based. The IT sits within the OT, at the heart of CMS. The IT has three sections, the Tracker Barrel Pixel (TBPX), the Tracker Forward Pixel (TFPX), and the Tracker Extended Pixel (TEPX), listed in order of increasing distance from the interaction point.

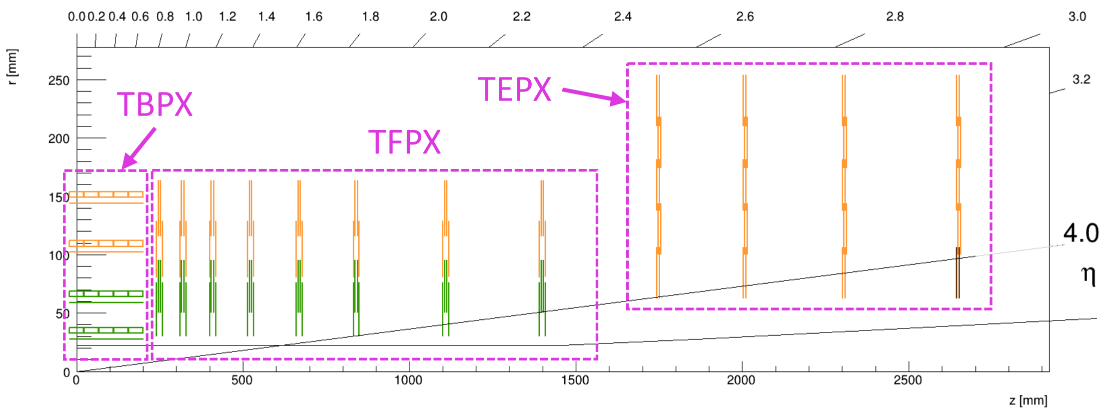

Figure 2: IT pixel sensor layout. Green represents modules with two readout chips (1x2), yellow represents those with four (2x2). This view is a slice through one quarter of the full detector. Adapted from [5]

2.1 TBPX Mechanics

In the TBPX, there are four layer of sensor modules arranged in barrel layout around the beamline. The basic mechanical structure of each layer is a four-ply carbon fibre ladder support, which provides a mounting surface for modules, as well as carbon foam ribs which provide an interface to cooling pipes. Because the TBPX is split at $z = 0$, the modules are staggered to avoid having a gap in coverage. This necessitates a long and short version of each ladder, so that each one matches up with its complement in the opposite half of the detector. Each quarter of the TBPX is built up separately from various flavours of ladder, cooling pipes, mounting pillars, and end flanges. Each layer is constructed then joined together, starting from the outermost layer, which is connected to an external carbon fibre shell. The services travel out of the barrel at its end flange, and are collected on the outer surface of the shell which supports the TFPX.

2.2 TFPX Mechanics

The orientation of modules in the TFPX is perpendicular to the beam axis. They are mounted on the front and rear surfaces of support discs. In order to allow construction of the detector in four pieces, these discs are split into semi-circular structures, called dees. In the TFPX, dees are made from a carbon foam core, with machined slots for cooling pipes,

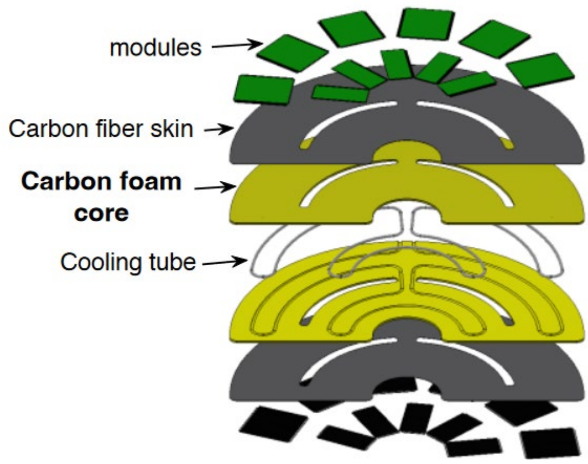

Figure 3: TFPX dee composition

sandwiched between carbon fibre skins. The dees are held by cartridges which are then attached to an external cylindrical support, made from carbon fibre. These shells support the services from the TBPX, which are joined by the TFPX services as the emerge through holes in the shell.

2.3 TEPX Mechanics

The TEPX layout is largely analogous to the TFPX. It also uses a carbon foam-carbon fibre sandwich to build up dees, although the TFPX dees also include a PCB in the sandwich. The TEPX dees are mounted to a carbon fibre support cylinder.

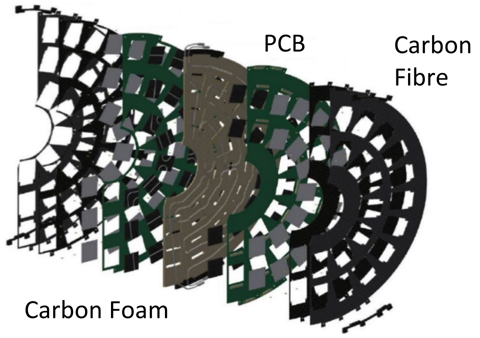

Figure 4: TEPX Dee Composition

2.4 CMS IT Assembly

The IT is built up in quarters. First, each quarter of the TBPX and TFPX are joined to one another. These quarters are then connected, closing around the beam pipe. Once these systems are in place, the TEPX quarters are similarly clam-shelled around the beam pipe,

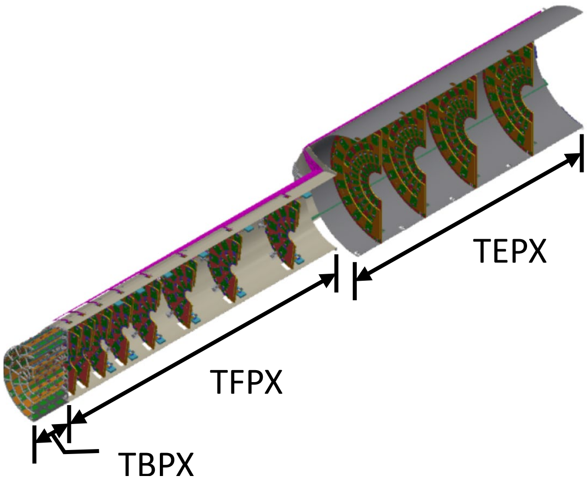

Figure 5: One-quarter of the IT showing the three sections

completing the IT. A view of one quarter of the IT is shown in figure 5. The services run on the external surfaces of the support cylinders. This method of assembly differs from that used in the ATLAS pixel detector. It has the advantage of not requiring the removal of a section of the beam pipe, but requires a more complex motion to complete the final installation.

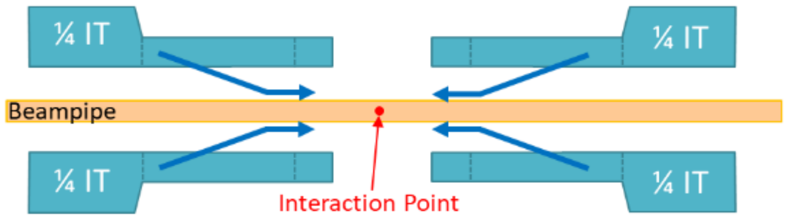

Figure 6: Schematic view of IT final installation

3. ATLAS Inner Tracker (ITk) Upgrade

3.1 Overview

The upgraded ITk is an all-silicon tracking detector comprising a Strip Detector and Pixel Detector [1, 6]. The Strip Detector surrounds the Pixel Detector, covering a pseudorapidity range up to $|\eta| = 2.7$, while the Pixel Detector covers up to $|\eta| = 4$. The total pixel sensor area in the existing Inner Detector is approximately 1.9m^2, which will increase to 13m^2 with this upgrade. The Pixel Detector is divided into three sections, the Inner System, the Outer Barrel, and the Outer End-caps. The pixel detectors consist of a silicon sensor bonded to an ASIC which reads out the sensor signal.

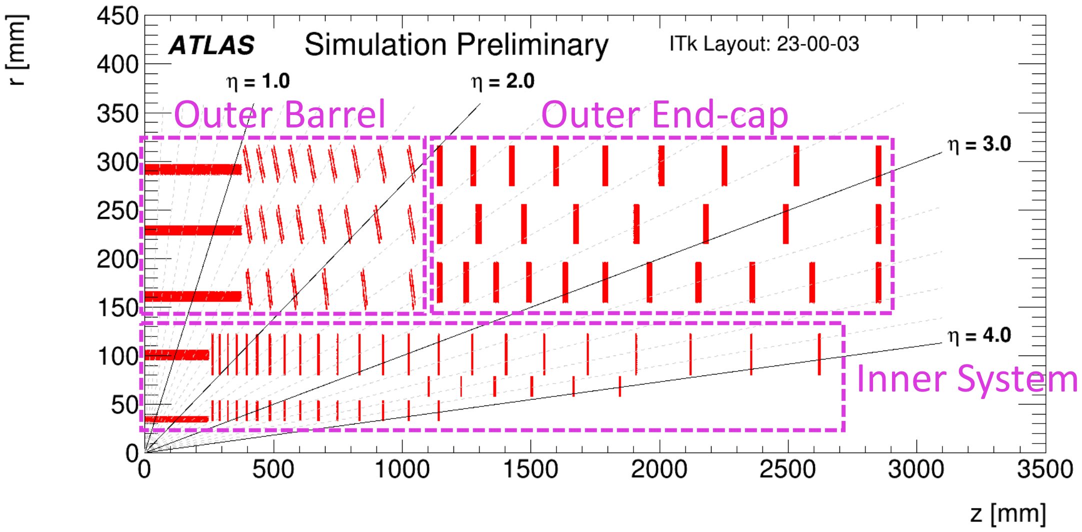

Figure 7: ITk Pixel Detector subdivisions (adapted from [7]). Red indicates the sensitive elements. This view is a slice through one quarter of the full detector.

3.2 Inner System Mechanics

In the Inner System, sensor modules are mounted flat on staves in the central barrel section (closest to the interaction point) or perpendicular to the beamline on rings in an endcap region (further from the interaction point). The barrel staves are staggered to provide full coverage around the interaction point with no gaps. There are two layers of staves in Inner System. There are three flavours of ring in the endcaps, depending on which layer they are supporting. In order to achieve full radial coverage on a circular ring with rectangular modules, they must be mounted on the front and rear faces of each ring, with some overlap required.

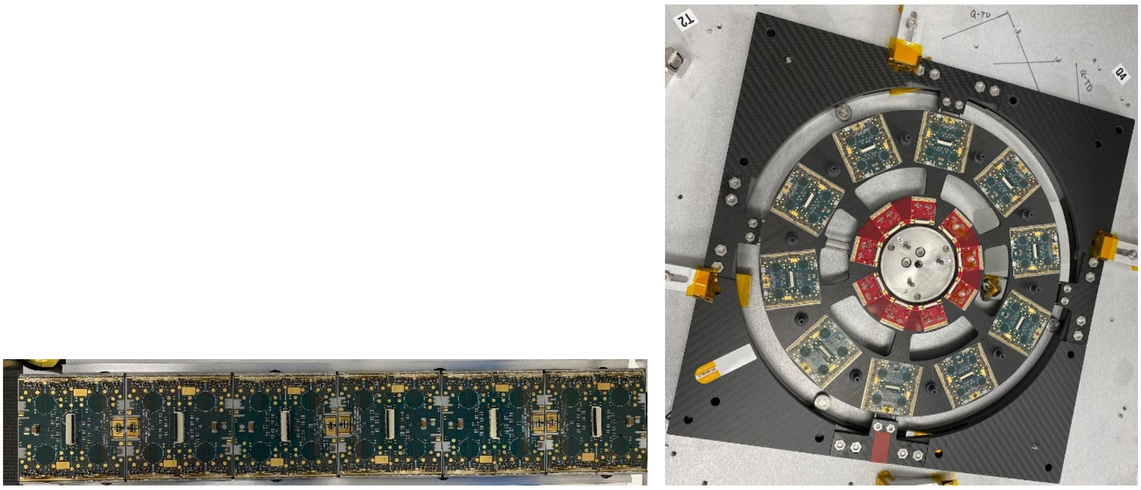

Figure 8: Prototype Inner System stave (left) and ring (right) with modules mounted

Although they have different form factors, the makeup of the local supports in both sections of the Inner System is similar. The staves and rings are made from carbon foam sandwiched between carbon fibre faces. The titanium cooling pipes are also sandwiched in the foam. Inserts to provide mounting points and mounting hardware are made from either radiation-hard plastic or aluminium.

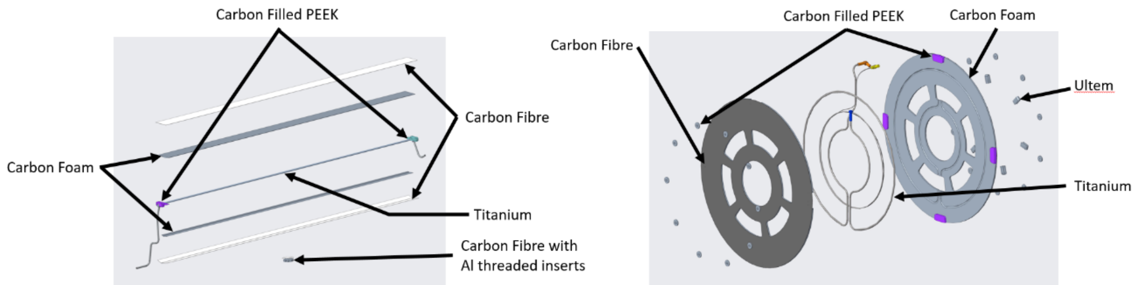

Figure 9: Materials used in the Inner System local supports

The Inner System is made up of two halves, split at $z = 0$ and each of these halves constructed from four quarter-cylinder shells, made from carbon fibre. Each quarter shell supports a portion of the endcap rings, so that the full complement of rings is present once the shells are combined. The shells also provide support for data transmission, module powering, and cooling services. Data and power cables are constrained in trays on the outer surface of the shells, and are connected to modules through holes in the shell.

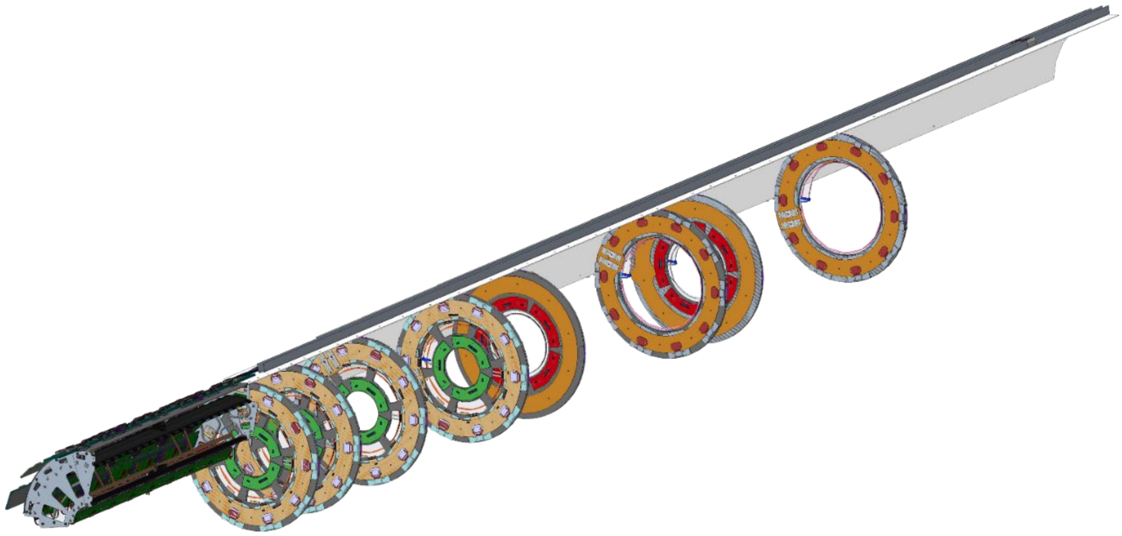

Figure 10: Inner System quarter shell with barrel region on the left and endcaps to the right

3.3 Outer Barrel Mechanics

The Outer Barrel also supports modules in two orientations, similar to the Inner System. In the range of $z = 0$ to $z = 400$mm, they are mounted flat on longerons which form a cylinder around the beamline. Beyond this, modules are mounted on inclined rings which are angled towards the interaction point. This provides better perpendicularity to the incoming particles. The spacing between inclined rings was selected to provide hermeticity in η [8]. In both regions of the Outer Barrel, modules are glued onto pyrolytic graphite tiles which are then placed on an aluminium-graphite mounting block which provides the interface to cooling pipes. This differs from the rest of the ITk pixel detector, where these cooling blocks and tiles are not used.

In the flat section, the basic mechanical support structure is the longeron. The longerons are made from a carbon fibre trusses, which provide excellent stiffness with low mass. The longerons are connected together at their ends with a carbon composite face. In the inclined region, modules are mounted on structures made from carbon fibre reinforced polymer (CFRP). Unlike the Inner System, the longerons span the interaction point from negative to positive z.

Figure 11: Prototype longeron (left) and inclined half ring (right)

The Outer Barrel is built in two halves, split at the horizontal plane through the beam axis. The longerons and inclined half rings are tied together by a carbon fibre shell. The services feed through holes in the shell and run on the outside surface. The left and right inclined regions are built separately, connected to the longerons to form a complete half cylinder.

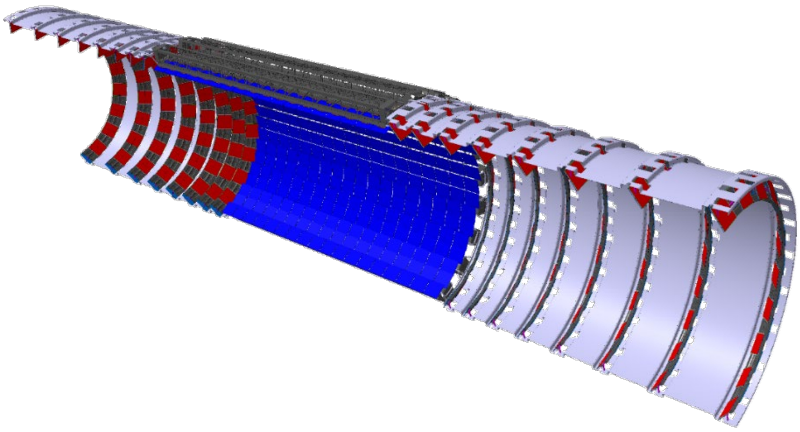

Figure 12: One half of the Outer Barrel

3.4 Outer End-caps

In the Outer End-caps, modules are mounted on the faces of rings which are perpendicular to the beam axis. As with the rings in the Inner System and Outer Barrel, both sides of the ring are used in order to provide full radial coverage. The rings are made from a carbon foam-carbon fibre sandwich, with titanium cooling pipes embedded in the foam. The rings also include mounting lugs made from PEEK.

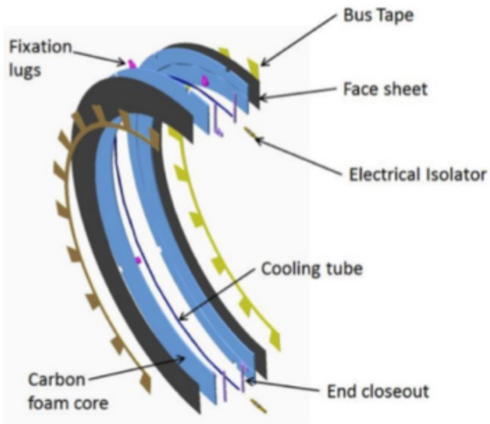

Figure 13: Outer End-cap ring composition

There are two Outer End-caps (left and right) which are built separately. Each of these is made up of three layers, which are constructed as half cylinders, split at the vertical plane through the beam axis. The half rings in each layer are supported by a carbon fibre shell, which also provides the guides and mounting points for services. Contrary to the Inner System and Outer Barrel, the services run on the inside surface of the shell and pass through the gap between the rings and shell. The three layers are held together by carbon fibre end flanges (one at each end).

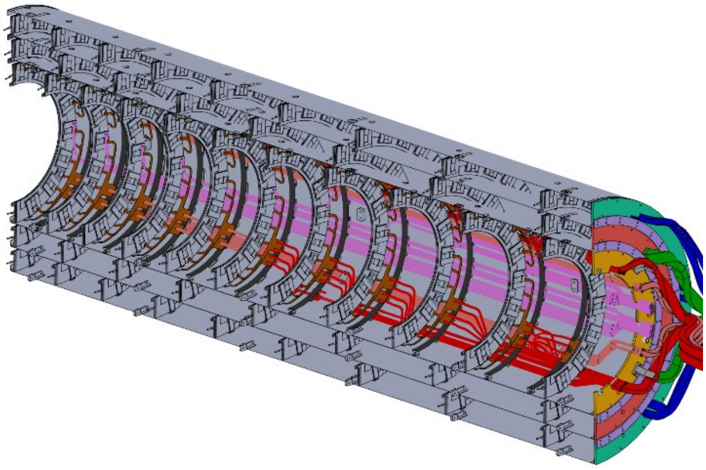

Figure 14: Half of one Outer End-cap, with the services of the innermost layer shown

3.5 ITk Pixel Detector Assembly

Once the three subsystems have been built, they need to be combined and eventually installed into ATLAS. The Outer Barrel and Outer End-caps are attached together, with one of the Outer End-caps sliding in from the left and one from the right. The sliding action is facilitated by rails which both subsystems sit on. The combined Outer Barrel-Outer End-cap system is referred to as the Outer System. A carbon fibre cylinder runs down the centre of the Outer System, supported at various points by the Outer Barrel and Outer End-cap into which the Inner System is inserted. This cylinder is the Inner Support Tube (IST), and it separates the Outer and Inner Systems. Rails on the inside of the IST allow the Inner System to slide in and out of the Outer System for installation and replacement. This replacement is foreseen to take place during the HL-LHC, and is required due to the higher levels of irradiation closer to the interaction point. The ITk Pixel Detector is inserted into the full ITk by sliding on rails mounted on the Pixel Support Tube (PST). The PST is another carbon fibre cylinder which surrounds the Pixel Detector and separates it from the Strips system. The final positioning of the detector is done by pulling it in a straight line, in contrast to the CMS IT which must be closed around the beam pipe.

4. Conclusion

The pixel detectors in ATLAS and CMS will be replaced with all new upgraded versions between 2026 and 2029, when the luminosity at the LHC will start increasing. In both the ATLAS ITk and CMS IT, the mechanics have been carefully designed to support an increased number of sensors (with smaller pixels), while minimising mass and withstanding the high radiation dose over the detectors' lifetime. Carbon fibre and foam, titanium, and radiation-hard plastics are widely used. The specific solutions adopted by ATLAS and CMS share many similarities (including their base sensor design), but the specific geometry and assembly techniques differ. The development of these detectors is subject to a stringent gated review process. Most systems have passed Final Design Review and many have begun production.

References

[1] ATLAS Collaboration; *Technical Design Report for the ATLAS Inner Tracker Pixel Detector*, CERN-LHCC-2017-021, 2017, URL: https://cds.cern.ch/record/2285585.

[2] CMS Collaboration; *The Phase-2 Upgrade of the CMS Tracker*, CERN-LHCC-2017-009, 2017, URL: https://cds.cern.ch/record/2272264.

[3] LS3 schedule change, 2022, URL: https://hilumilhc.web.cern.ch/article/ls3-schedule-change.

[4] RD53 Collaboration; *RD53B Design Requirements*, CERN-RD53-PUB-19-001, 2019, URL: https://cds.cern.ch/record/2663161.

[5] S. Orfanelli on behalf of the CMS Collaboration; *The Phase 2 upgrade of the CMS Inner Tracker*, CMS-CR-2020-063, 2020, URL: https://cds.cern.ch/record/2780125/.

[6] ATLAS Collaboration; *Technical Design Report for the ATLAS Inner Tracker Strip Detector*, CERN-LHCC-2017-005, URL: https://cds.cern.ch/record/2257755.

[7] ATLAS Collaboration; *Expected tracking and related performance with the updated ATLAS Inner Tracker layout at the High-Luminosity LHC*, ATL-PHYS-PUB-2021-024, 2021, URL: https://cds.cern.ch/record/2776651/.

[8] J. Pater, *The ATLAS Pixel Detector Upgrade at the HL-LHC*, ATL-ITK-PROC-2020-002, 2020, URL: https://cds.cern.ch/record/2709133/

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