PROCEEDINGS OF SCIENCE

The ATLAS Pixel Detector Upgrade at the High-Luminosity LHC

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In 2025 the Large Hadron Collider will be shut down to allow upgrades to the accelerator and the experiments. After this "Phase-II" shutdown the LHC is expected to reach unprecedented values of instantaneous luminosity, with hundreds of interactions in each bunch crossing. This means much higher data rates and occupancies and increased radiation damage for the experiments. During the Phase-II shutdown the entire ATLAS Inner Detector will be replaced by an all-silicon system called the Inner Tracker (ITk). The innermost part of the ITk will be a state-of-the-art pixel detector with about 13 m^2 of active silicon, which will provide precision tracking capability up to $|\eta| = 4$. The outermost layers of the ITk pixel detector are being designed to last the lifetime of the HL-LHC, collecting up to 4000 fb^{-1} of integrated luminosity; the portion of the pixel detector with R<141mm will be replaced once, after collecting about 2000 fb^{-1} of data.

The ITk pixel detector will be instrumented with new sensors and readout electronics to provide improved tracking performance and radiation hardness compared to the current detector. The sensor type will be dependent upon location in the detector: most of the detector will be populated with thin planar silicon sensors, but 3D-silicon sensors will be used in the innermost layer, due to their higher radiation tolerance and lower power consumption (which eases demands on the support structures). The sensors will be read out by new ASICs, based on the one currently being developed by the RD53 Collaboration, which will be thinned to 150 μm or less to save material.

Support structures will be made of carbon-based materials, chosen for low mass, high stability and high thermal conductivity. They will be cooled by evaporative CO_2 flowing in thin-walled titanium pipes. Servicing the detector reliably within the limited space available, and without introducing excessive amounts of material, is a significant challenge. Data will be transported electrically inside the detector, on cables carrying 1.28 Gb/s; conversion to optical signals will take place at larger radii where the radiation background is less intense. Serial powering has been chosen as the baseline for the system as it minimises service cable mass.

The ITk pixel detector is currently in the final stages of R&D, with production scheduled to start in 2021.

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1. The LHC and the ATLAS Detector

The ATLAS detector [1] at the Large Hadron Collider (LHC) [2] is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle[1]. A 3D drawing of ATLAS in its present state can be seen in Figure 1.

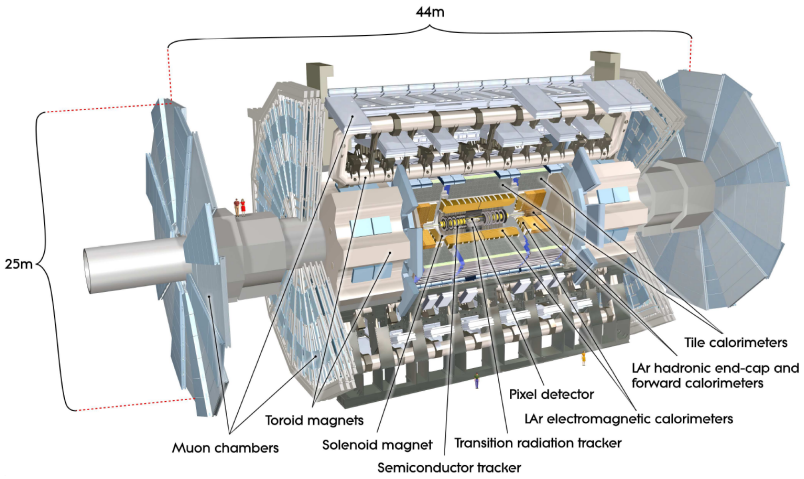

Figure 1: The ATLAS detector: a layered multi-purpose detector comprising tracking detectors at the center, surrounded by electromagnetic and hadronic calorimeters, which are surrounded in turn by muon detectors.

The LHC achieved its first collisions in 2009 at $\sqrt{s} = 900$ GeV, ramping up to $\sqrt{s} = 7$ TeV shortly thereafter. As shown in Figure 2, a number of upgrades since then have produced higher center-of-mass energies and higher luminosities, and the LHC will continue to be enhanced in coming years.

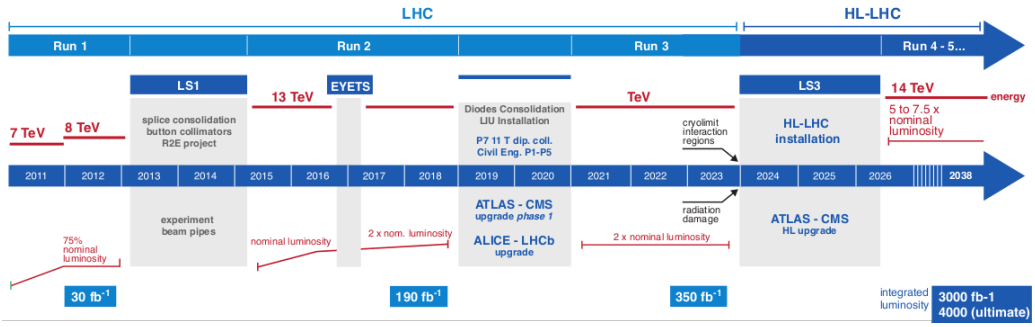

Figure 2: Timeline of past and future upgrades of LHC to HL-LHC.

All four LHC detectors (ALICE, ATLAS, CMS, and LHCb) must be upgraded also, to cope with the new conditions that will result from the LHC upgrades. For example, after LS3, the

[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. Cylindrical 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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

ATLAS tracker will have to cope with an average of 200 interactions per bunch crossing (compared to about 37 now) and a factor of five times more pileup, resulting in much higher data rates and occupancies. In addition, the ten-fold increase in integrated luminosity will result in a dramatic increase in background radiation, which the detector must be able to survive while remaining in good operational condition.

2. The New ATLAS Inner Tracker

The "Phase-II" upgrade of ATLAS, planned for LS3, will replace the current ATLAS tracking system with a new all-silicon Inner Tracker ("ITk") covering up to $|\eta| = 4$. The requirements for the ITk are

- at least thirteen hits per track in the central (or "barrel") region,
- at least nine hits per track in the forward ("endcap") region,
- radiation hardness up to 10 MGy (total ionising dose) and 2x10^{16} n_{eq}/cm^2,
- track reconstruction efficiency > 99% for high-p_T muons and > 85% for high-p_T electrons and pions,
- fake rate $< 10^{-5}$,
- occupancy $< 1\%$,
- robustness against loss of 15% of channels,
- readout rate 1-4 MHz,
- output bandwidth up to 5.12 Gb/s per front-end chip, and
- a material budget of about 1.5-2.0% per layer.

The proposed layout for the ITk is shown in Figure 3. The left-hand diagram shows the entire ITk (sensitive silicon only). The strip tracker [3] (shown in blue) has about 160 m^2 of sensitive silicon and 50 million readout channels; the pixel tracker [4] (shown in red) has 13 m^2 of silicon and is read out by about 5 billion channels. The innermost parts of the pixel detector (R<141mm) are designed to be replaced once in the lifetime of the detector, after the collection of about 2000 fb^{-1} of data.

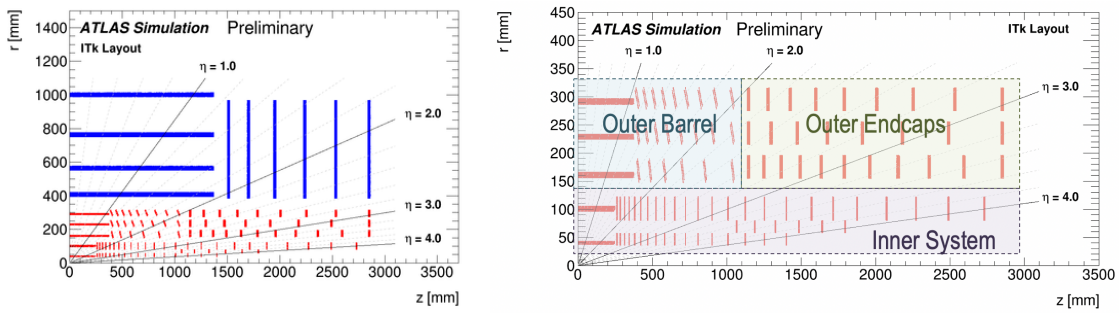

Figure 3: Left: the proposed layout of the ATLAS ITk, with the strip tracker [3] shown in blue and the pixel tracker [4] shown in red. Right: the layout of the ITk pixel detector, showing the three main subsystems.

3. The ITk Pixel Detector

3.1 Modules

The geometry of a pixel module is shown in Figure 4. A module consists of one or four front-end chips bump-bonded to a sensor, with single-chip assemblies in the innermost (3D-silicon) layer, and four-chip ("quad") assemblies elsewhere, and with a copper-kapton hybrid glued to the sensor and wire-bonded to the front-end chips, to provide connection to power, slow controls and data distribution systems.

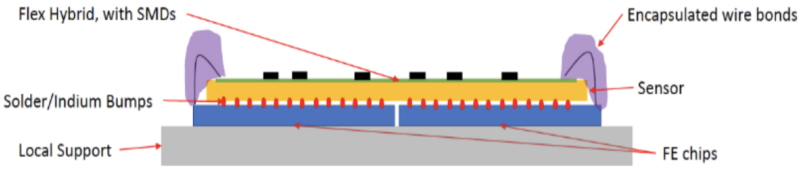

Figure 4: A sketch illustrating the parts of an ATLAS-ITk pixel module.

The ITk's pixel-sensor technology is region-dependent: the innermost layer will be instrumented with 3D-silicon sensors due to their higher radiation tolerance and lower power consumption, which leads to easier servicing; the next layer out will have 100-μm-thick planar silicon sensors; and the outer layers will have 150-μm-thick planar sensors. The pixel size may also be region-dependent: in the outer layers the pixels will be 50×50 μm^2 squares, but the pixels in the inner system will be either 50×50 μm^2 or 25×100 μm^2, with the choice due to be made at the end of 2019.

The sensors are to be read out with a front-end chip being developed by the RD53 Collaboration [5], a joint ATLAS-CMS effort to produce radiation-hard chips (including readout software and prototypes) in 65 nm technology. The final ATLAS chip will be 2.0×2.1 cm^2 and have 153,600 50×50 μm^2 pixels on a 400×384 grid. The chip will be able to operate at trigger frequencies up to 4 MHz and has a shunt-LDO (low-dropout) regulator to allow serial powering. "RD53A" half-size prototypes are currently being tested, which have most of the features required for the production chip; RD53A-based ATLAS-pixel system tests are planned for early 2020 on realistic local support structures, and will pave the way for first production chips shortly after.

The ATLAS pixel collaboration is striving for a common hybrid design at least for the outer system layers; a mechanical envelope has been defined that works for all subsystem geometries although the final connections, via subsystem-dependent "pigtails", are still being designed. The wirebonds are planned to be encapsulated as baseline, although further testing of the suitability of encapsulation is ongoing. The modules will be serially-powered in chains up to fourteen quad modules long, to reduce cable mass in the detector.

3.2 Support Structures and Cooling

All the support structures in the pixel detector are made of carbon-based materials, due to their low mass, high stability, and high thermal conductivity. Cooling is provided by evaporative CO_2 in thin-walled titanium tubes which are integrated into the carbon structures.

Due to differing geometrical and logistical requirements, the design of the support structures varies somewhat between the subsystems.

In the Outer Barrel, completed modules are glued to tiles made of thermal pyrolitic graphite (TPG) which are then attached to "longerons" (lightweight open structures made of carbon fibre) in the barrel region, or to novel inclined half-rings in the mid-η region (see Figure 5) to keep the modules approximately normal to high-p_T tracks from the interaction point. On the half-rings, adjacent modules are placed on alternating sides of the structure to achieve hermeticity in ϕ; the half-rings are strategically placed in z to achieve hermeticity in η. Cooling tubes make connection to the TPG tiles via a cooling block.

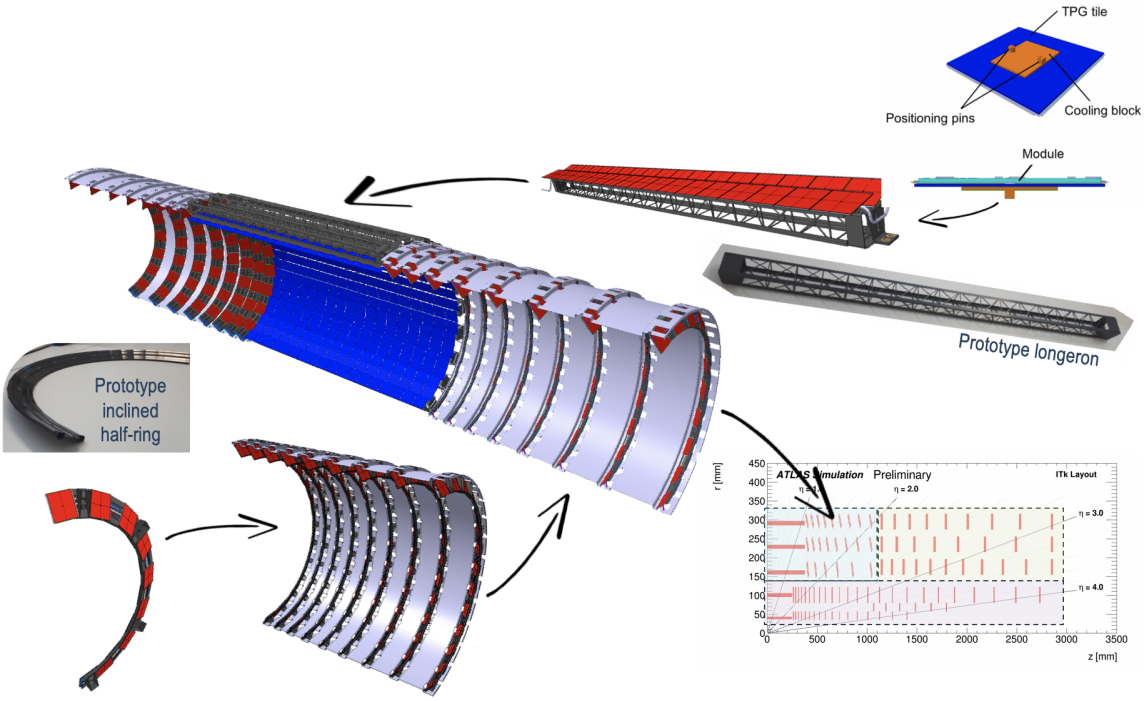

Figure 5: The supporting structures of the Outer Barrel.

In the Outer Endcaps (see Figure 6), modules are loaded directly onto narrow, flat, half-ring-shaped supports, which are carbon-foam / carbon-fibre "sandwiches" with embedded cooling tubes. Again, modules are loaded onto alternating sides of the half-ring to achieve ϕ-hermiticity and rings are placed into supporting half-cylinders strategically in z to achieve η-hermeticity. The finished half-layers are then "clam-shelled" together to form three concentric radial layers, which are all held together by flanges at the low-z and high-z ends.

The Inner System support structures (see Figure 7) are constructed similarly to those in the Outer Endcaps, in that the structures are carbon-foam / carbon-fibre sandwich assemblies with embedded cooling tubes, with the modules directly glued to the external carbon-fibre surfaces. The structures are stave-shaped in the barrel region, and ring-shaped in the endcaps, with three different ring geometries depending on the position in z, and therefore the required radial coverage to achieve η-hermeticity. The staves and rings are mounted on quarter-shell structures made of carbon fibre, which are then integrated to form the complete detector, which is contained inside an Inner Support Tube (IST) to facilitate its replacement after an integrated luminosity of about $\sim$2000 fb^{-1} has been delivered.

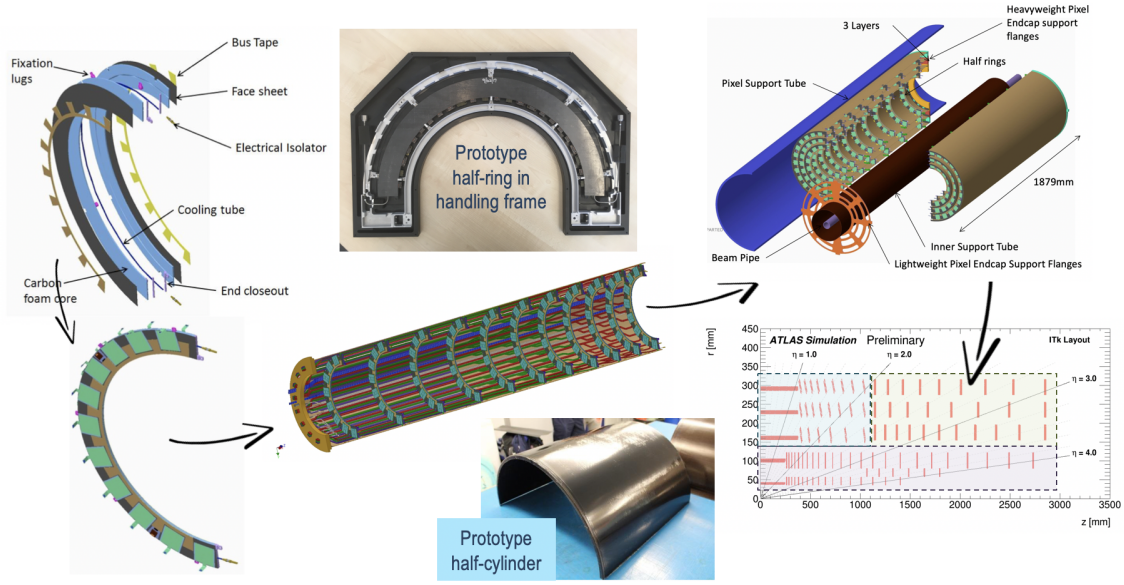

Figure 6: The supporting structures of the Outer Endcaps.

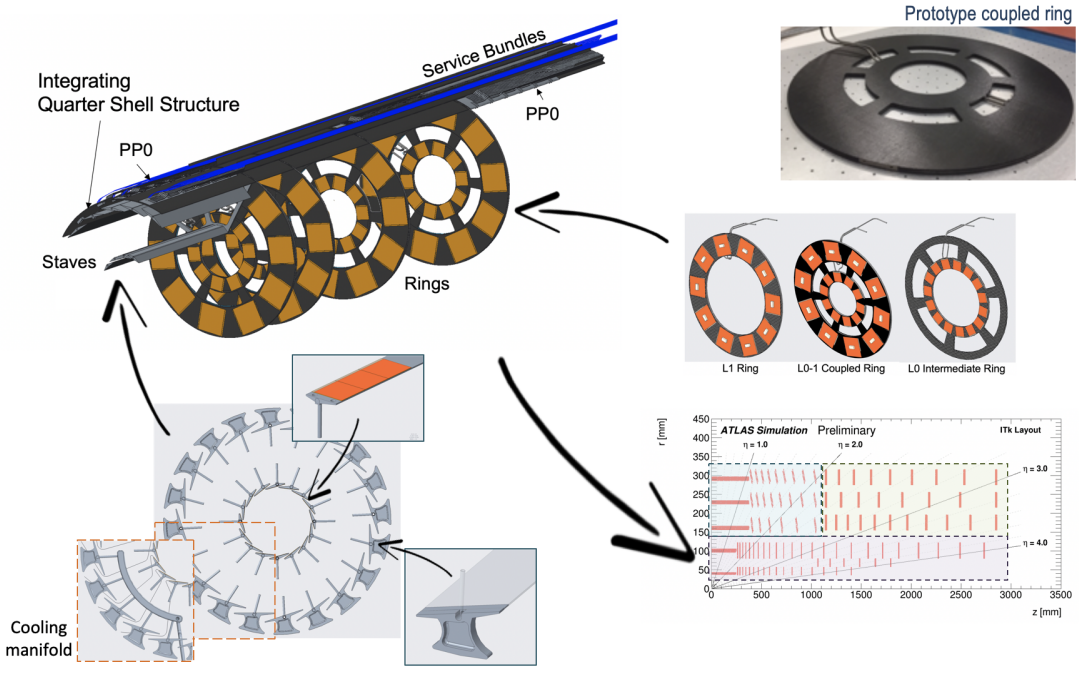

Figure 7: The supporting structures of the Inner System.

3.3 Electrical Services

A number of types of electrical services are required to power, control and read out the pixel detector.

- Twisted pairs are used for power, monitoring, and interlocks.
- Data is carried on very thin twinaxial cables inside the detector, with electrical-to-optical conversion done outside the tracker volume. This is due to the lower background radiation levels expected outside the detector (the conversion electronics can be quite sensitive to radiation) and also for accessibility, as the outer subsystems are not foreseen to be opened during the lifetime of the detector. Each front-end chip needs up to four 1.28GB/s output lines (the data rate is dependent upon location in the detector) as there is no on-module aggregation.

The services consist of successive steps of patch panels and cables of increasing thickness up to the electronics caverns. Electrical patch panels called PP0s are mounted on the support structures of the detector, to provide electrical connections to the modules. "Type-1" services connect the PP0s to the outside world, exiting the detector at the high-z ends.

In the Outer Barrel and the Inner System, PP0s run along z, supported by the longerons/staves and the ring-supporting cylinders (see Figure 8), and the Type-1 services carry on on the same trajectory to exit the subsystem at its highest z point. At the junction of the Outer Barrel and the Outer Endcaps, the Outer Barrel services dog-leg out in radius to run along the outside of the Outer Endcap.

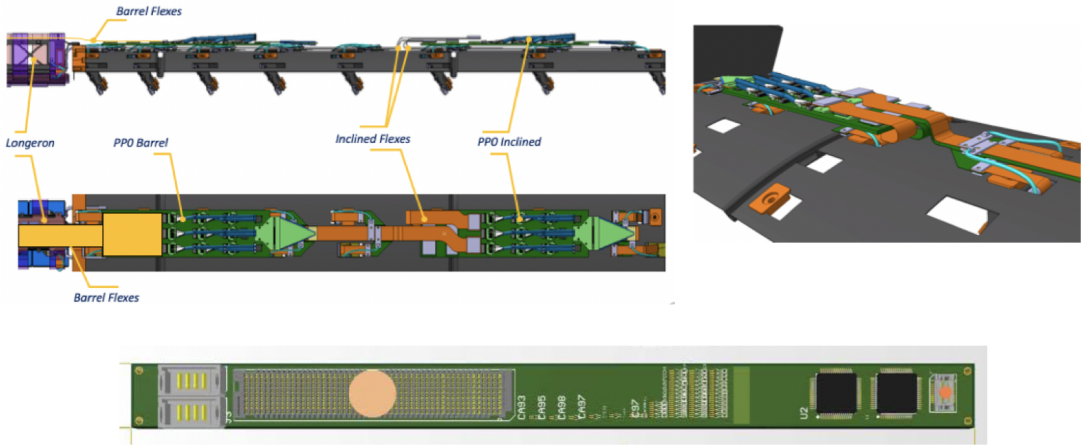

Figure 8: Top: PP0 for the Outer Barrel. Bottom: PP0 for the Inner System.

In the Outer Endcaps the PP0s are glued directly to the half-rings in two main components: "bus tapes" are glued to the inner rims of the half-rings and carry power, slow controls and monitoring to and from the modules; "EoS cards" are glued to the spaces between the modules and connect the bus tapes and modules to the Type-I services (see Figure 9). Type-I services are laid onto the inner surface of supporting half-cylinders before the half-rings are installed, and exit the detector through the high-z end flange.

Once the Type-I services have left the detector, they go through "PP1" which has connectors for the cooling and the power and monitoring cables; data cables pass through PP1 to "optoboxes"

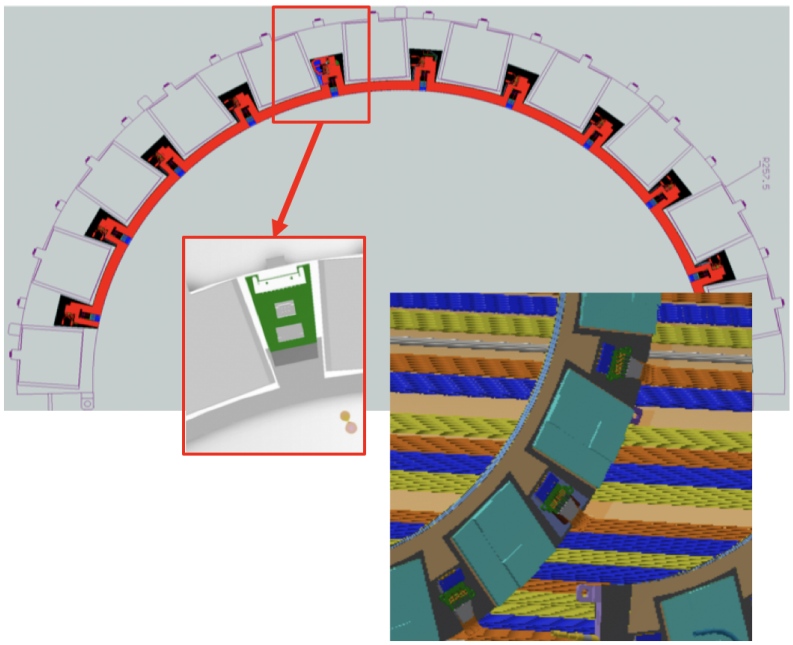

Figure 9: Outer Endcap services - top left: bus tape and EoS card on the surface of the half-ring; bottom right: Type-I services running between the half-rings and the inner surface of the support cylinder.

located further on. Thicker "Type-2" cables then continue to PP2, and Type-3 cables proceed to the electronics caverns - see Figure 10.

Servicing is a major challenge for the pixel detector as it is proving very difficult to fit everything, especially the large number of data cables, into the limited space. The collaboration is exploring ways to reduce the number of data cables – for example by using RD53 uplink sharing – and is also re-examining services engineering schemes to see if better use could be made of available space.

3.4 Status and Near-Future Plans

Most activities in the ITk pixel detector project are currently in the mid-to-late R&D phase, with a lot of work ongoing with prototypes, in testbeams, irradiation campaigns, and thermo-mechanical and electrical testing of support structures and services. In addition to design qualification, this will inform procurement procedures, and also production procedures including quality control.

The ITk pixel project is subject to a strict sequence of formal reviews. Modules, services and global supports efforts are currently preparing for Preliminary Design Reviews, while sensors, front-end chips, and local supports are preparing for their Final Design Reviews. Also a number of market surveys are underway to choose final vendors for the more costly items.

Pre-production will start upon completion of Final Design Reviews, with some aspects of the detector entering final production in 2021, and all others following within the next few years.

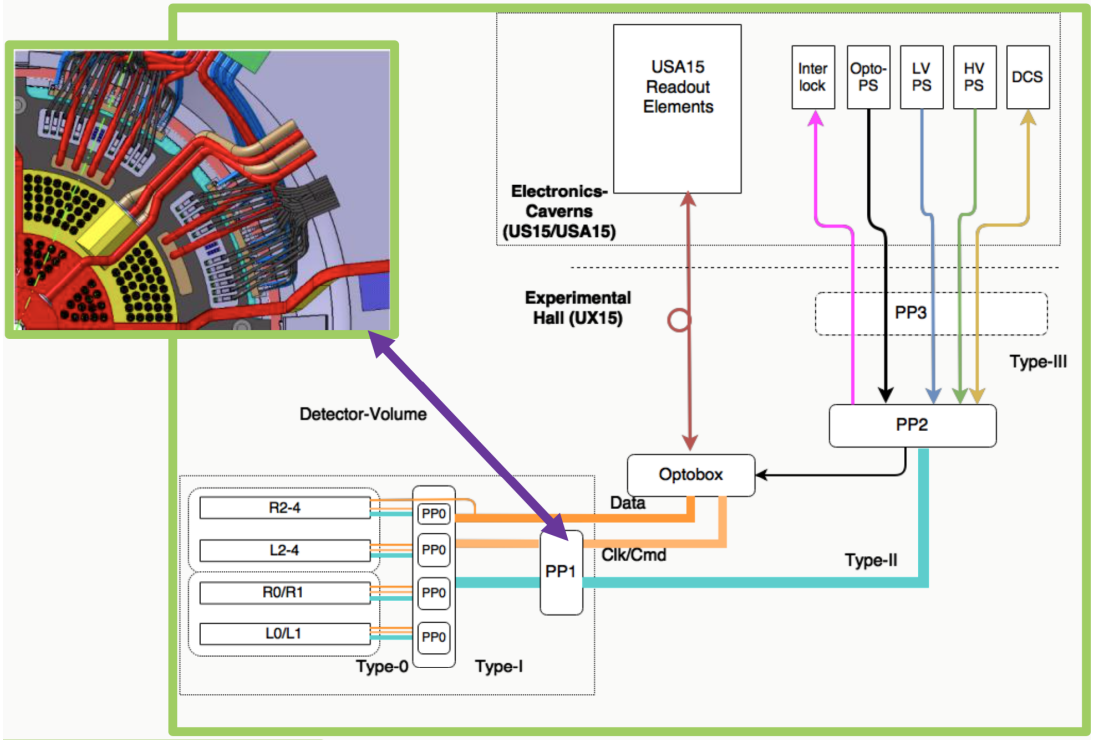

Figure 10: The pixel services external to the detector.

References

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

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