Simulation of the strip sub-detectors in the Inner Tracker of the ATLAS detector

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Abstract. In the beginning of 2025, the Large Hadron Collider (LHC) will be shutdown in order for the final upgrades to the High Luminosity LHC (HL-LHC) to commence. This will almost quadruple the amount of collisions in the LHC, increasing the amount of data the detectors will have to deal with. Since the detectors were not designed to operate at these levels, they will also need an upgrade to deal with the increased radiation, data rates and amount of particles travelling through the detectors. One of the most extensive upgrades to the ATLAS detector will be the replacement of the current Inner Detector (ID) with an all silicon semiconductor based Inner Tracker (ITk). However, not only will the actual detector be upgraded, but the simulation of the detector will also need to be updated to match this new version. An accurate simulation of the detector is important since this is what is used to convert the outputs of the theoretical calculations (be it Standard Model (SM) or Beyond the Standard Model (BSM)) into a format that can be directly compared with the data coming from the experiment. Presented is some of the work behind updating the simulation of the strip detector in the ITk, from the sensors to the support structures and shielding components.

1. Introduction

With new physics searches pushing the limits of the current Large Hadron Collider (LHC) [1] and its detectors, an upgrade of the LHC to the High Luminosity LHC (HL-LHC) [2] has been planned. The principal upgrade will occur during the third Long Shutdown (LS3) starting at the beginning of 2025 and ending in 2027 [3]. The upgrade will increase the instantaneous luminosity to an ultimate value of $\mathscr{L}_{ins} = 75\ \text{nb}^{-1}.\text{s}^{-1}$ [3], around 7.5 times the design luminosity. This will result in a total integrated luminosity of around $\mathscr{L} = 4000\ \text{fb}^{-1}$ after the 10 years of operation and up to an average of $\mu = 200$ collisions per bunch crossing. These improvements will greatly increase the statistics available for analysis while at the same time exceeding the current detectors' design capabilities with respect to pile-up management and radiation tolerance. Therefore the detectors will require an upgrade themselves. In particular, the ATLAS detector's main upgrades (phase-2 upgrades as laid out in the Letter of Intent (LoI) [4]) will occur during LS3. The focus will be on upgrading the current tracking Inner Detector (ID) to the full silicon semiconductor Inner Tracker (ITk) [3]. The purpose of the ID upgrade is to improve the tracking resolution as well as to cope with the higher occupancy environment and radiation doses.

SAIP2021 Proceedings

Table 1. Some specifications of the ITk strip detector.

	no. Sensors	**no. Chips**	**Channels** [$\times 10^6$]	**Radial coverage [mm]**	**$\|z\|$ coverage [mm]**
Barrel	10976	162624	$\sim$38	399→1000	0→1375
Endcap	6912	96768	$\sim$22	385→968	1512→2850
Total	17888	259392	$\sim$60	385→1000	0→2850

1.1. ITk

The current ID was designed to deal with an average of 23 proton-proton collisions per bunch crossing, not the expected 200 during the HL-LHC phase [3]. The current resolution of the ID would make pattern recognition difficult and provide a poor track finding efficiency in the higher occupancy environment. The ITk will be a full silicon semiconductor tracker divided into the strip detector (elongated read-outs capable of measuring 1 spatial co-ordinate) and the pixel detector (small read-outs capable of measuring 2 spatial co-ordinates). Both of these detectors are further split into the barrel (central region, $|\eta| < 1.8$[1]) and endcap (forward region, $|\eta| > 1.8$) detectors. The tracking pseudorapidity range will be increased from $|\eta| < 2.5$ to $|\eta| < 4$, which will be important for electro-weak and new physics searches, as well as improving missing transverse momentum resolution and pile-up jet rejection [3].

The strip barrel has 4 layers of sensors, with the inner two layers being the short strip modules and the outer two layers the long strip modules. The strip endcap has 6 disks each side of the barrel, with the modules arranged in 6 rings. Some extra specifications of the strip detector are shown in Table 1, and a diagram comparing the current ID to the ITk is shown in Figure 1.

2. ITk strip modules

The strip sensors will be planar, n-in-p type silicon semiconductors with elongated readout strips (ranging from 19 mm to 60.2 mm in length) [3]. A module is a composite device composed of a power board and one or two hybrids (kapton board with read-out chips) glued to a sensor. An image of a barrel short strip module and an endcap module showing the sensor and hybrids is given in Figure 2. In the barrel the strips are placed parallel to the beam axis and in the endcaps the strips are placed radially pointing towards the beam axis. As the strips are only capable of measuring 1 spatial co-ordinate, the combination of strip sensors on either side of a stave or petal (the local support structures that hold the modules in the barrel and endcap respectively) allows for the measurement of the second spatial co-ordinate. The sensors on either side are placed at slight angles to each other (40 mrad in the endcap and 52 mrad in the barrel), allowing the strips to cross over at points which are used to get the 2D measurement [3]. Each readout chip reads 128 strips from two rows of strips, totalling 256 channels per chip. The chips provide a 1-bit digital output that only stores a yes or no if the charge collected in a strip is over a predefined threshold charge, hence the name ATLAS Binary Chips (ABCs).

3. Simulation

Apart from having the physical detector, a simulation of the ITk is also very important. Before the detector is running, the simulation is required to estimate its performance and test its viability. The simulation can also be used to check if the engineering designs work, making sure everything fits and that the amount of material is not too much. The simulations are created using a software that interfaces with the Geant4 package [5]. Geant4 is a C++ based program

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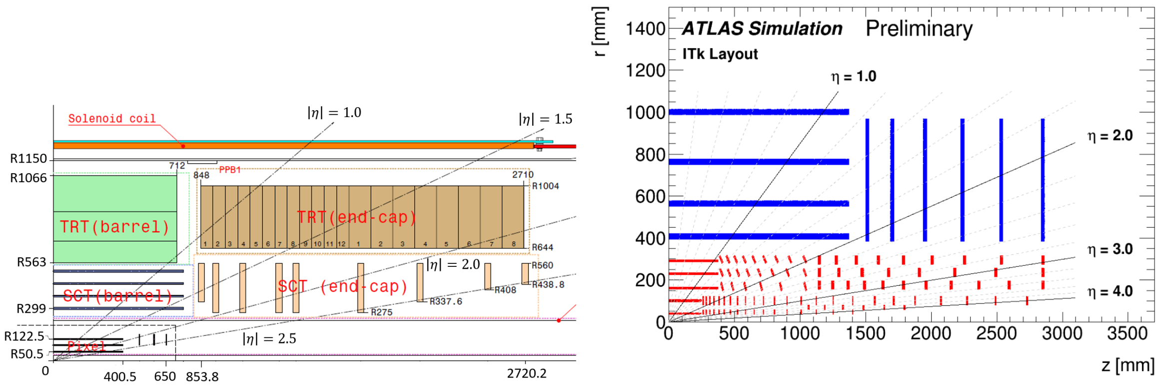
[1] The ATLAS detector uses cylindrical coordinates (r, ϕ) in the transverse plane, with ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined as $\eta = -\ln(\tan(\frac{\theta}{2}))$, where θ is the polar angle.



(a) (b)

Figure 1. A diagram of the current ATLAS Inner Detector (a)[6] and the future ATLAS Inner Tracker (b)[7]. The Transition Radiation Tracker (TRT) is not present in the ITk as this type of detector would become saturated in the high luminosity environment. In (b), the blue shows the positions of the strip sensors while the red shows the position of the Pixel sensors. The increase in the pseudorapidity range (η) is also noticeable.

that simulates how particles interact with matter and is used by the ATLAS collaboration to model the full ATLAS detector. Once the detector is running, the simulation is important for producing the Monte Carlo simulated samples that are used to compare our theories to the data collected from the detector. Since our theories are all mathematically based, and our data from the detector is essentially just electronic signals, we need a way to convert our theories into a format that matches what we get from the detector. A simulation of the detector estimates how the theoretically produced particles would interact with the material in the detector and emulates how the data acquisition systems would convert those interactions into electronic signals.
As the ITk is still being built, there are often changes and finalisations to the original design laid out in the Letter of Intent [4]. One of the more recent updates was in the strip module Final Design Report in 2019, which finalised the strip module designs. From this, the dimensions and shapes of the strip module components were improved in the simulation, as well as an update to the material descriptions. The result of these can be seen in Figure 3. The main updates were to the hybrids and powerboard. One thing that is obvious is the lack of chips in the simulation, but this is explained in Section 5. Some simplifications in terms of the shapes can also be seen, particularly for the endcap module. This is because the gain from a more accurate description is not worth the increased computational cost.

4. Support Structures

Apart from updating the modules, there are also the support structures that need to be updated in the simulation. These are basically the skeleton of the ITk that either provide the structure that houses the modules and electronics, or provide protection from excessive radiation damage. A major update to the ITk outer cylinder was performed, which is the outer most structural support. It went from a uniform carbon fibre cylinder to a thinner carbon fibre cylinder, with flanges and titanium mount pads. The effect of this change can be seen in the X_0 measurements in Figure 4. Looking at the outer cylinder component, overall it has reduced, except for a few peaks that are located where the new flanges and mount pads are.
Another update was to the polymoderators. These are polyethylene cylinders around the ITk

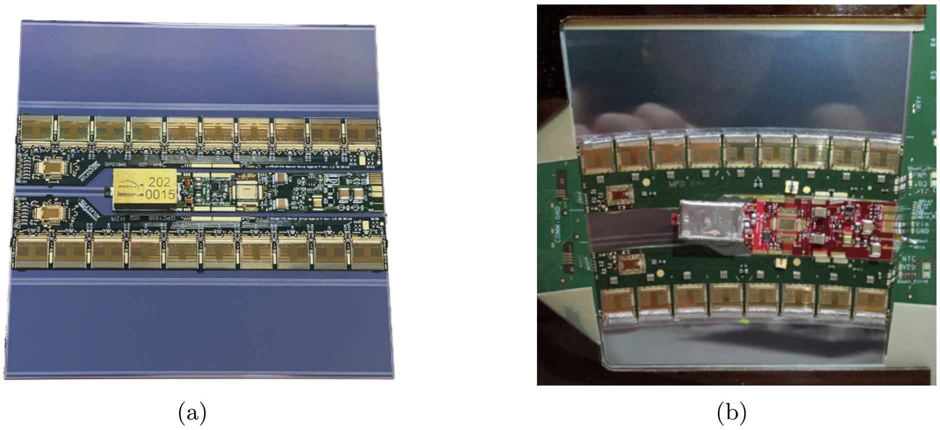

(a) (b)

Figure 2. An image of a barrel short strip module (a) and an endcap module (b). The metallic is the silicon sensor, with the middle PCB and box object being the powerboard and DCDC converter respectively. The PCBs on either side of the powerboard are the hybrids housing the ABC readout chips and the hybrid controller chips (the smaller chip on the left of the hybrids). Both sensors have four rows of strips, hence two hybrids, and in both pictures the strips essentially run vertically.

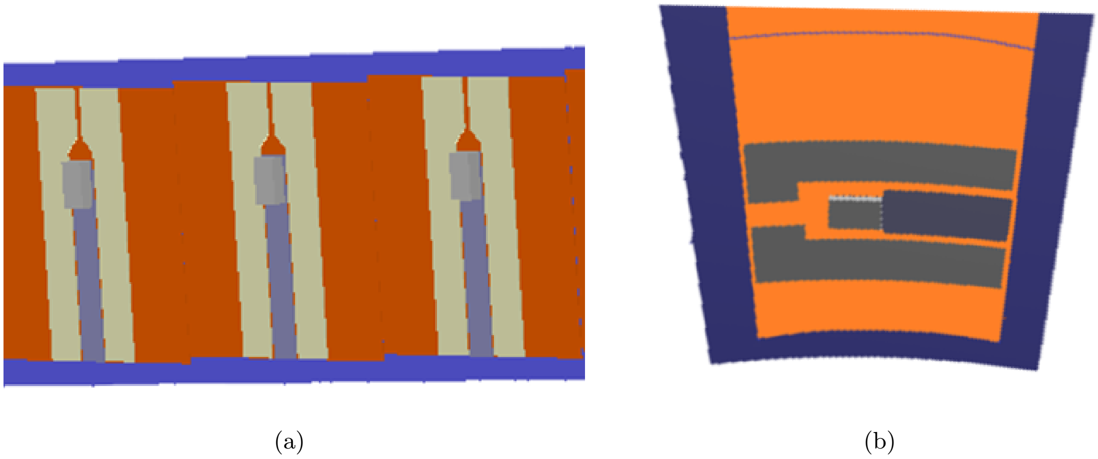
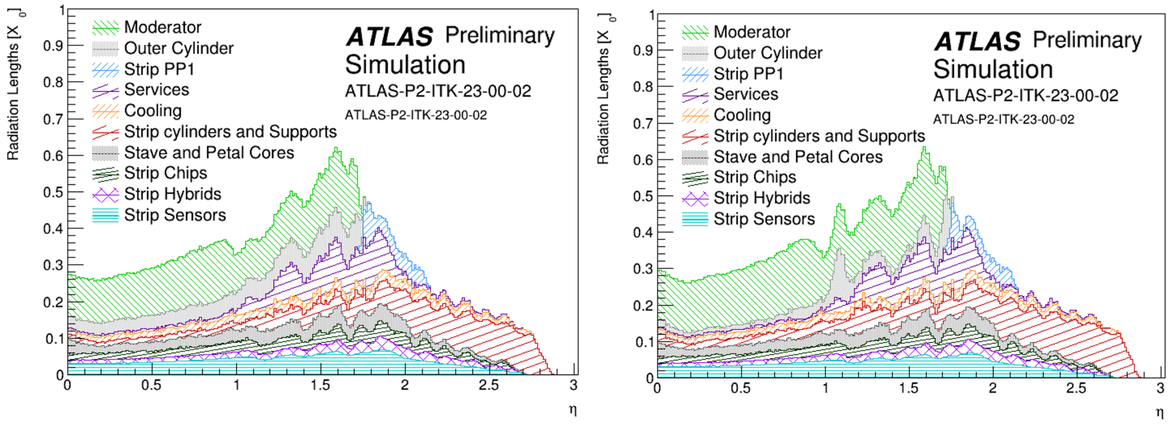

(a) (b)

Figure 3. A visualisation of a barrel short strip module (a) and an endcap module (b) from the simulation. The orange is the sensor, on which are the hybrids and powerboards. The blue is the stave (a) and petal (b). Noticeably absent are the chips which is discussed in Section 5.

that help protect against neutrons that back-scatter from the calorimeters which could cause excessive damage to the sensors. The moderators' widths were slightly increased and they got an extra structural layer. This increase in material is shown in Figure 4 where the moderator component has slightly increased uniformly across pseudorapidity.



(a) (b)

Figure 4. Plots of the Radiation Lengths of each of the components in the strip detector before the updates (a) and after the updates (b) as a function of the pseudorapidity (η). Radiation length X_0 is the mean distance a high-energy electron will travel before it is left with e^{-1} of its energy due to bremsstrahlung radiation.

5. Computational Improvements in Simulation

In simulations, it is not only important to have an accurate description of what is being tested, but for them to also be computationally efficient. There's no point in having a simulation that is a few percent more accurate but uses far more memory and CPU time to complete its calculations.

5.1. Simulation of readout chips

One of the first things we checked to improve computational cost was the simulation of the strip module chips. As can be seen in Table 1, there are almost 260000 chips that need to be created in the strip detector alone. We decided to try remove the chip objects from the simulation, but still included their material in the hybrids. This reduced the number of objects but kept the amount of material the same. While this had negligible impact on the radiation lengths, it did reduce the memory usage quite a bit and the CPU time a little bit, as is shown in Table 2.

5.2. Redefining compound volumes

The next test was more on the side of the simulation structure than the detector. When defining a composite object comprised of multiple objects, e.g., the strip module, this can be done with either an assembly volume or a logvol object. In the assembly volume, one of the objects is chosen as a reference and the other objects are placed in reference to it, resulting in a grouping of objects whose reference point is defined by the reference object. In the logvol, the different components are placed within a "mother" volume, and the reference point becomes that of the mother volume. Due to how the simulation tracks the particles and how it determines what object the particle is in, the logvol has a better memory and CPU time usage. We tried looking at changing the module descriptions from the assembly volumes to logvols. This resulted in a large reduction in memory usage and CPU time, which can be seen in Table 2. After both the chip and volume change, there is a reduction of almost 76% in the memory usage and 71% in the CPU time for the entire ITk.

Table 2. Summary of the computational cost for the strip detector. Shown is the memory and CPU time required for the voxelisation of the detector components.

Location	**Memory [MB]**			**CPU time [s]**		
	Original	**Chip update**	**Chip+volume update**	**Original**	**Chip update**	**Chip+volume update**
Barrel 3	314	212 (-32%)	67 (-79%)	25.96	21.71 (-16%)	6.64 (-74%)
Barrel 2	280	199 (-29%)	54 (-81%)	17.96	16.02 (-11%)	4.69 (-74%)
Barrel 1	239	145 (-39%)	48 (-80%)	14.75	11.25 (-24%)	3.95 (-73%)
Barrel 0	181	82 (-55%)	21 (-88%)	10.67	6.17 (-42%)	1.62 (-85%)
Endcaps	131	66 (-50%)	20 (-85%)	5.9	4.10 (-31%)	1.82 (-69%)
ITk Total	1184	743 (-37%)	279 (-76%)	79	63.00 (-20%)	23.00 (-71%)

6. Conclusion

Due to the HL-LHC upgrade, the ATLAS detector will require an upgrade to cope with the new high pile-up environment. But apart from the physical detector, an accurate simulation is also required for predictions of performance, and for the correct modelling of the Monte Carlo generated samples used to compare theory to data.

The simulation requires constant updates as the latest designs and new engineering specifications come out. Some of the updates to the strip detector of the ITk were to the descriptions of the modules and support structures. This has brought those objects closer to their true descriptions. Also the computational cost of the simulation was improved by removing some volumes and changing how the modules are defined in the code. There are still parts of the ITk that need to be updated in the simulation, e.g., the inner support structures and the electronics and cooling, but these will only be done when the latest engineering specifications are available.

Some studies were performed with these updates, but the results have not been made public yet so could not be shown in this paper. However, the ITk simulation is performing as good, and in some cases, better than the current ATLAS Inner Detector despite the more complicated reconstruction environment.

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