A Characterisation of the ATLAS ITk High Rapidity Modules in AllPix and EUTelescope

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Abstract. The upgrade of the LHC to the high luminosity LHC (HL-LHC) will result in far more collisions occurring per bunch crossing, in turn producing more particles per second. Consequently, the current detectors will need to be upgraded to accommodate the large increase in radiation and data acquisition as well as a need to improve the tracking efficiency for the high pile-up environment. One of the main upgrades to the ATLAS detector is the complete overhaul of the inner detector (ID) by replacing it with an all silicon Inner Tracker (ITk). A simulation of the ITk will be required for performance predictions as well as for testing sample sensors in testbeams. The current testbeam software of Allpix and EUTelescope are written completely using Cartesian definitions, however some of the geometries in the ITk have radial definitions. In particular, the R0 geometry of the strip end-cap is in need of a radial description. Presented is the work behind creating a radial geometry for the R0 module in Allpix (using Geant4 descriptions) and EUTelescope (using TGeo descriptions).

1. Introduction
With the discovery of the Higgs boson in 2012[1][2] at the Large Hadron Collider (LHC) and with new searches pushing the limits of the current LHC and its detectors, an upgrade of the LHC to the High Luminosity LHC (HL-LHC) has been planned. This upgrade will occur during the third long shutdown (LS3) for 30 months from the beginning of 2024 till half way through 2026[3]. The upgrade will increase the instantaneous Luminosity to an ultimate value of $\mathcal{L}_{\text{ins}} = 75\text{nb}^{-1}\text{s}^{-1}[3]$, around 7.5 times the current instantaneous Luminosity. This will result in a total integrated luminosity of over $\mathcal{L} = 3000\text{fb}^{-1}$ during 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) will occur during LS3 as laid out in the Letter of Intent (LoI)[4]. The focus will be on upgrading the current inner detector (ID) to the inner tracker (ITk) as well as the upgrade of the Trigger and Data AcQuisition systems (TDAQ). Other areas include the forward calorimeters, muon spectrometer and computing and software. The purpose of the ATLAS detector during the HL-LHC will be on precision Higgs measurements, Vector Boson Fusion (VBF) and Scattering (VBS), as well as searches for new physics.
1.1. ITk

The largest contribution to the ATLAS phase-2 upgrade will be the complete overhauling of the current ID, coming in at around 50% of the total upgrade cost. A comparison of the current ID to the future ITk is shown in Fig. 1. The Transition Radiation Tracker (TRT) will not be present in the ITk as this type of detector will become saturated in the high pile-up environment of the HL-LHC and thus make it incapable of precision tracking. This removal will make the ITk a full silicon semiconductor tracker divided into the strip detector, elongated sensors capable of 1D space point detection, and the pixel detector, square sensors capable of 2D space point detection. The pseudorapidity range will also be increased to $|\eta| < 4$ while having less inactive material in the tracking volume. The higher rapidity range will be important for the VBF, VBS and new physics searches, as well as improving $E_T^{miss}$ resolution and pile-up jet rejection [3].

There are currently two designs for the ITk; the extended layout and the inclined layout, where the extended layout can be seen in Fig. 1. The inclined layout will be exactly the same as the extended except that the pixel barrel in the range $|\eta| \gtrsim 1$ will be inclined towards the interaction point. The extended will be less challenging to build and will allow for long pixel clusters while the inclined will have less silicon for the particles traverse and will get more hits in the forward region [6].

The main reason for a completely new inner tracker is that the luminosity during HL-LHC will be over 7 times the design value of the current ID. The ID was designed to deal with an average of 23 p-p collisions per bunch crossing [3], not the proposed 200 during HL-LHC and the current pixel detectors were only intended to deal with radiation from 400 fb$^{-1}$ of data [3]. The current granularity of the the ID as well would fail at pattern recognition and have a poor track finding efficiency and so needs to be improved.

Figure 1. Diagram comparing the new Inner Tracker (left) to the current Inner Detector (right) [3][5]. On the left, the blue and the red are respectively the strip and pixel semiconductor detectors with the horizontal lines being the barrels and the vertical lines being the endcaps. As can be seen, there will be no transition radiation based detector in the ITk and the pseudorapidity, $\eta$, range will be increased to 4. The layout for the ITk is that of the extended layout.

2. R0 module

The strip endcap local support structure, known as a petal, will be installed castellated with 32 petals per endcap disk [3]. The petal will have 6 rings of modules on both faces, one in each of the first 3 rings and two in each of the outer 3 rings. They will be arranged from the R0
Table 1. R0 specifics

| Row number | nStrips | nChips | Inner Radius [mm] | Length [mm] | Min/Max pitch [µm] | Angular Pitch [µrad] |
|------------|---------|--------|-------------------|-------------|---------------------|----------------------|
| 0          | 1026    | 8      | 384.5             | 19          | 73.5/84             | 193.3                |
| 1          | 403.5   | 24     |                   |             |                     |                      |
| 2          | 1154    | 9      | 427.5             | 28.9        |                     | 171.8                |
| 3          | 456.4   | 32     |                   |             |                     |                      |

Figure 2. Diagram illustrating how the R0 module is defined[7]. The strips will be parallel to the sides in red, providing a stereo angle $\phi_s = 20\text{mrad}$. The radius of the sensor center $O_W$ will be at $R=438.6\text{mm}$.

module closest to the beam pipe to the R5 modules furthest from the beam pipe. A module is a compound device comprising of a power board and one or two hybrids glued to a silicon semiconductor sensor, where the hybrid has ABC130 readout chips (ATLAS Binary Chip at 130nm thick) and hybrid control chips glued to a kapton board.

The shape of the R0 sensor is known as a stereo annulus and a simple definition of this geometry is shown in Fig. 2. The inner and outer curved edges will be rings concentric to the center of the pipe while the straight sides will converge to a point offset from the beam centre. The strips will be placed parallel to these offset sides and focus on the same offset point, providing a stereo angle of 20mrad built into the sensor and a total of 40mrad[3] when combined in conjunction with the sensor on the other side of the petal. The stereo angle was chosen to be built into the sensor as rotating the sensor during installation to obtain the stereo angle would have complicated the installation process. As the strips are only capable of 1D space point measurements, the strips are placed at a stereo angle which when combined with the strips on the other side of the petal will allow for the measurement of the second space point co-ordinate.

The R0 module will have two hybrids each reading out two rows of strips. Each row will have an extra strip at each end that will not be readout strips but will rather be used to shape the electric field for the outer readout strips. The two inner rows will have a different angular pitch to the two outer rows, where the pitch is the distance from the center of one strip to the center of the next strip. The thickness of the sensor will be 310µm with an allowed error of up 25µm and more R0 specifics are given in Table 1[7].

3. Testbeam

The testbeam telescope is a EUDET-type telescope[8] operated by the EUDAQ framework and analysed with the EUTelescope software[9]. EUDET was the detector R&D towards the
Figure 3. Image of the EUDET testbeam telescope at DESY[9]. Shown are the six mimosa pixel detectors used for beam tracking when a device is being tested, which would be placed in the gap in the middle of the telescope. The beams would come in from the right where the large red object is part of the magnet system which focuses the beam.

International Linear Collider (ILC) which ended in 2010. The telescope is located at DESY in Hamburg, Germany and is where the R0 module will undergo testing. The telescope comprises of Mimosa26 high granularity pixel detectors[10], as shown in Fig. 3, that are used for track fitting. The sensor that is being tested is known as a DUT (Device Under Test) and is placed between the third and fourth mimosa detectors. The beam tracking can be performed to precisions of up to 2 \( \mu \)m[9], usually much smaller than the DUT resolution, with the telescope utilising electron beams which are produced through the conversion of bremsstrahlung beams originating from carbon fibre targets in the DESY II accelerator. The energy of the electrons range from 1 GeV to 6 GeV[9] and are used to test whether a hit in the DUT corresponds to a track calculated from hits in the mimosa planes passing through the sensor at that point.

4. AllPix
AllPix[11] is a Geant4[12] based simulator dedicated to the study of solid state detectors where it is possible to create an experimental set-up of how ever many detectors one would like and in any configuration, so long as it’s within the limits of Geant4. Geant4 is a C++ toolkit used for the simulation of particles through matter based on the particles energy and the radiation length of the material. It is in this software that the geometries are defined, as well as where the physics processes and particles used are chosen. The AllPix software is used to simulate the EUDET telescope and the digitisers that are used to digitise the hits from Geant4. This simulated data obtained from AllPix will then be analysed as if coming from the telescope itself. The individual detector specifications are defined in a separate file using eXtensible Markup Language which is called by a macro file within which the experimental set-up is defined and the simulation is run from.

5. EUTelescope
EUTelescope[13] is a generic pixel telescope data analysis framework comprising of a group of Marlin processors and is embedded in the ILCsoft framework. The software is used to extract tracks from LCIO data (Linear Collider I/O) and it is used in the analysis of data from both the testbeam telescope as well as AllPix simulation. The raw data from either the experiment or simulation is converted into LCIO format using a suitable converter. For the experimental data, a converter in the EUTelescope package is available, whereas a converter that comes as
part of the AllPix package is used for converting the AllPix data. Clustering, alignment and track fitting is performed on the LCIO data to obtain the tracks of particles through the telescope to compare with a DUT hit. During these steps a GEAR file (GEometry API for Reconstruction) is called within which the geometry and orientation of the detectors is defined. These geometries may be defined using the geometry class TGeo of CERN’s data analysis framework, ROOT[14], in a separate file and called by the GEAR file as well. Once the tracks have been extracted from the data, they are analysed to check whether a registered hit in the DUT corresponds to a particle passing through the DUT at that point.

6. Current Status of R0 Module Simulation
The current designs of the simulated geometries for the software packages AllPix and EUTelescope are shown in Fig. 4 while Fig. 5 shows the design within the telescope as a DUT. The EUTelescope design is simpler than the AllPix design as AllPix will actually simulate how the particles interact with the sensor and digitise the hits obtained from that, whereas EUTelescope will perform more of a mapping from the hits in the LCIO data to the geometry defined using the TGeo class. The main characteristic these designs do not share with the R0 module is the stereo annulus shape as these designs are basic segments of a cylinder. The reason for this is that work is still being done on how to implement the stereo annulus shape in these software packages.

![AllPix simulation](image1)

![EUTelescope simulation](image2)

(a) AllPix simulation  
(b) EUTelescope simulation

**Figure 4.** Current progress of the simulated R0 module. Both images do not have the correct amount of strips for visualisation purposes as the strips would not be observable if the correct number of strips were used.

![Image of the simulated EUDET telescope with the R0 module placed as a DUT](image3)

**Figure 5.** Image of the simulated EUDET telescope with the R0 module placed as a DUT. Placement of the planes along the z-axis is 0, 59, 119.5, 250, 404, 534 and 604 mm.
7. Conclusion
Due to the HL-LHC upgrade, the ATLAS detector will require an upgrade to cope with the new high pile-up environment. However before the actual upgrade can commence, research and development has to occur. Part of this R&D is the characterisation of the detector and the sensors that will be used in simulations. Progress on the R0 module of the strip endcap in the ITk so far has provided a radial geometry with specifications of the R0 module. However the stereo annulus shape has not yet been simulated due to its complicated geometry. Once a decision on the final shape has been made, a simulation of the geometry in AllPix is required from which data will be obtained that will be analysed in EUTelescope.

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