

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 $\mathcal{L}_{ins} = 75\text{nb}^{-1}.\text{s}^{-1}$ [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 a complete overhaul of the current ID. 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.

There are currently two designs for the ITk; the extended layout and the inclined layout, where the extended layout can be seen in Fig. ???. 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 the inclined will have less silicon for the particles traverse and will get more hits in the forward region[6].

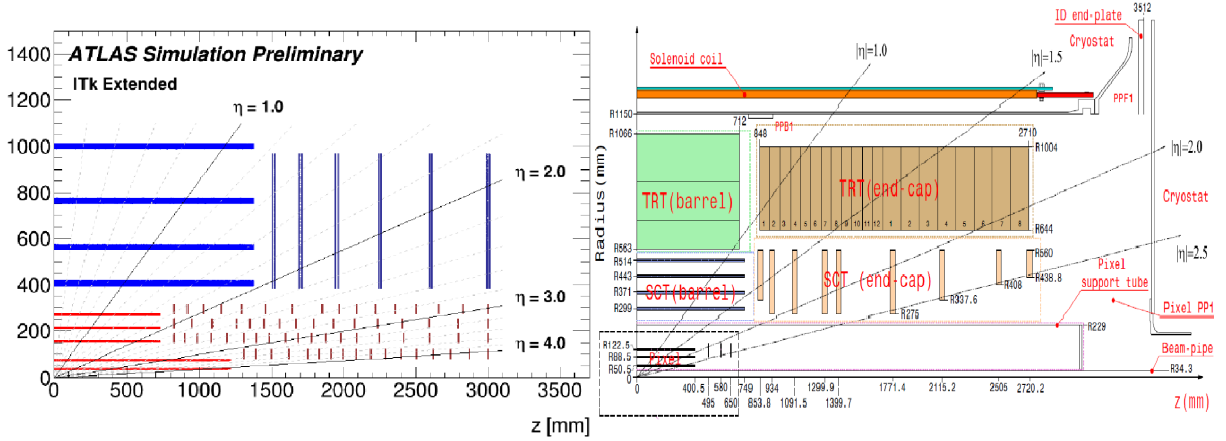


Figure 1. Diagram comparing the new Inner Tracker (left) to the current Inner Detector (right)[3][5]. On the left, the blue and the red are respectively the strip and pixel semiconductor detectors with the horizontal lines being the barrels and the vertical lines being the endcaps. As can be seen, there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

2. R0 module

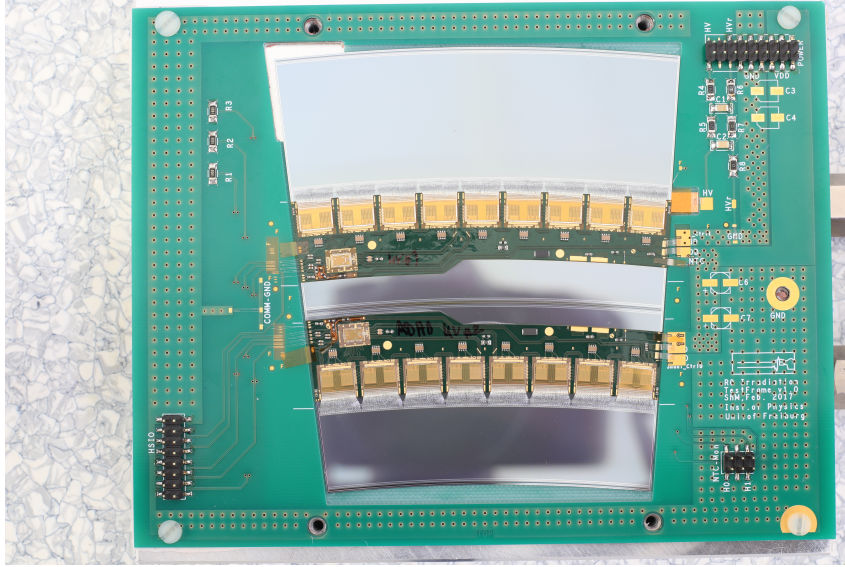
The R0 module will be located in the strip endcap, where it will be the closest strip endcap module to the beam pipe. The shape of the R0 sensor is known as a stereo annulus and a simple definition of this geometry is shown in Fig. ???. The inner and outer curved edges will be rings concentric to the 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

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		

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. An image of a R0 module can be seen in Fig. ?? . 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 $310\mu\text{m}$ with an allowed error of up to $25\mu\text{m}$ and more R0 specifics are given in Table ??[7].

**Figure 2.** Image of the R0 module tested at the testbeam at DESY.

3. Experiment

The testbeam telescope is a EUDET-type telescope[8] located at DESY in Hamburg, Germany and is where the R0 module underwent testing. The telescope comprises of Mimosa26 high granularity pixel detectors[9], as shown in Fig. ??, that are used for track fitting. The Device Under Test (DUT) is placed between the third and fourth Mimosa planes. The beam tracking can be performed to precisions of up to $2\mu\text{m}$ [10], 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[10] 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.

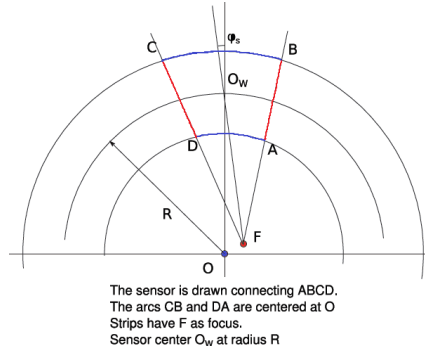


Figure 3. Diagram illustrating how the R0 module is defined[7]. The strips will be parallel to the sides in red, providing a stereo angle $\phi_s = 20\text{mrad}$. The radius of the sensor center O_w will be at $R=438.6\text{mm}$.

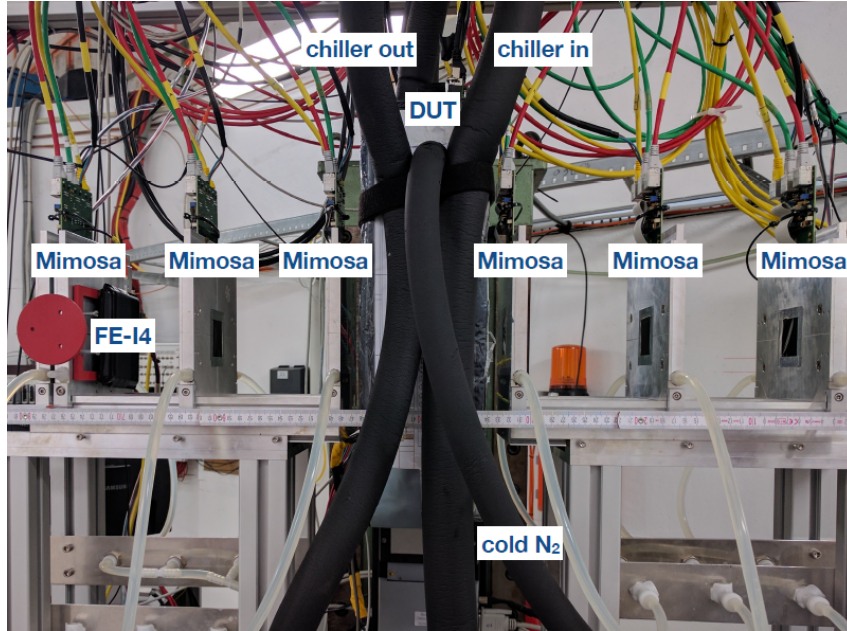


Figure 4. Image of the EUDET testbeam telescope at DESY with the R0 placed as a Device under test (DUT)[13]. Shown are the six mimosa pixel detectors used for beam tracking, The DUT within an insulated box, an FEI4 detector for timing and the various cooling pipes. The electron beam comes in from the right.

4. Simulation

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 the desired number of detectors 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 is then analysed as if coming from the telescope itself.

EUTelescope[14] 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 in the analysis of data from both the testbeam telescope as well as AllPix simulations. 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. The detector geometries may be defined using the geometry class TGeo of CERN's data analysis framework, ROOT[15].

5. Progress

The simulation of the R0 sensor in AllPix has been completed, which includes the Geant4 description of the sensor and the digitiser for that specific sensor. The R0 sensor placed as a DUT in the testbeam has been simulated and can be seen in Fig. ?? . A rectangular strip digitiser was created by one of the members of the ATLAS ITk strip community using the FEI4 digitiser as the basis. The R0 digitiser was in turn based on this rectangular strip digitiser, where charge sharing over the boundary at which the strip row pitches differ was the more challenging and significant change. Due to the EUTelescope code having been originally written to analyse rectangular sensors, some of the output from the testbeam experiment was analysed as if the R0 sensor had simple rectangular ordered strips, not radially ordered strips. Therefore, a simulation of simple rectangular strips with the same pitch as the R0 sensor at the point of the testing has been done in AllPix as well.

The TGeo description of the R0 sensor for EUTelescope has also been completed. However, the alterations of the EUTelescope code to analyse a radially ordered strip sensor has not been fully completed. This change to the EUTelescope code is being done by another member of the ATLAS ITk strip community and is very near to being finished. The TGeo description only involves the strips of the sensor and does not require all the extra material. The output of the AllPix simulation consists of the channel numbers of the hits on the sensor after the particles have interacted with all the different materials. EUTelescope, however, only needs to map the channel numbers to the position of the strip corresponding to that channel number.

All that is left for this specific project will be to look at the EUTelescope code once it has been updated for the R0 sensor and make any reasonable changes. The changes will be due to the EUDAQ software of the Testbeam telescope having slightly different output as that of AllPix.

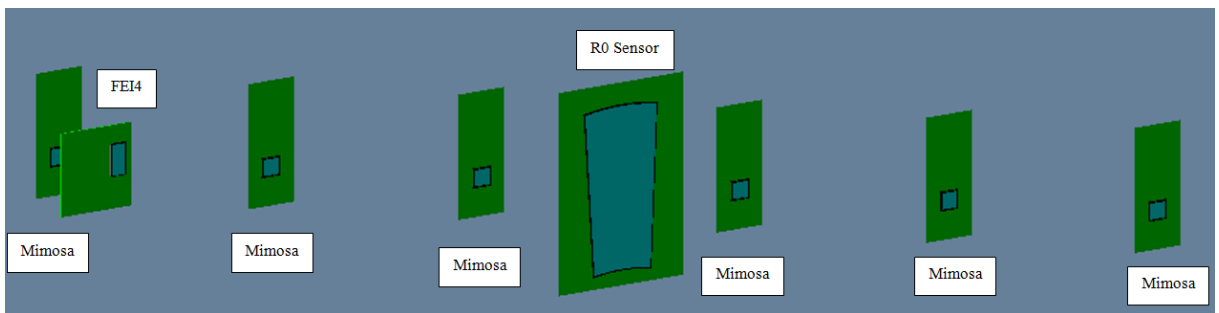


Figure 5. Image of the simulated EUDET telescope with the R0 module as the Device Under Test and an FEI4 detector for timing. The green rectangles are the PCB's, the light blue areas are the sensitive areas of the detectors and the black lines around these sensitive areas are the inactive silicon guard rings.

6. 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 is well developed, with the AllPix simulations complete. Some slight adjustments need to be made to EU Telescope and the output from AllPix can be analysed and compared to testbeam data.

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