For the JPS 2023 spring meeting
Talk 10049 room 23aT2-7

Performance study of the alignment algorithm on the HL-LHC ATLAS ITk geometry.

Speaker: Isaí Roberto Sotarriva Álvarez

Dept. of Phys., Tokyo Inst. of Tech., The High Energy Accelerator Res. Org. (KEK)[A], The ATLAS collaboration[B]

Isai Roberto Sotarriva Alvarez, Osamu Jinnouchi, Hideyuki Oide[A], Nicholas Styles[B], Shaun Roe[B], Noemi Calace[B]

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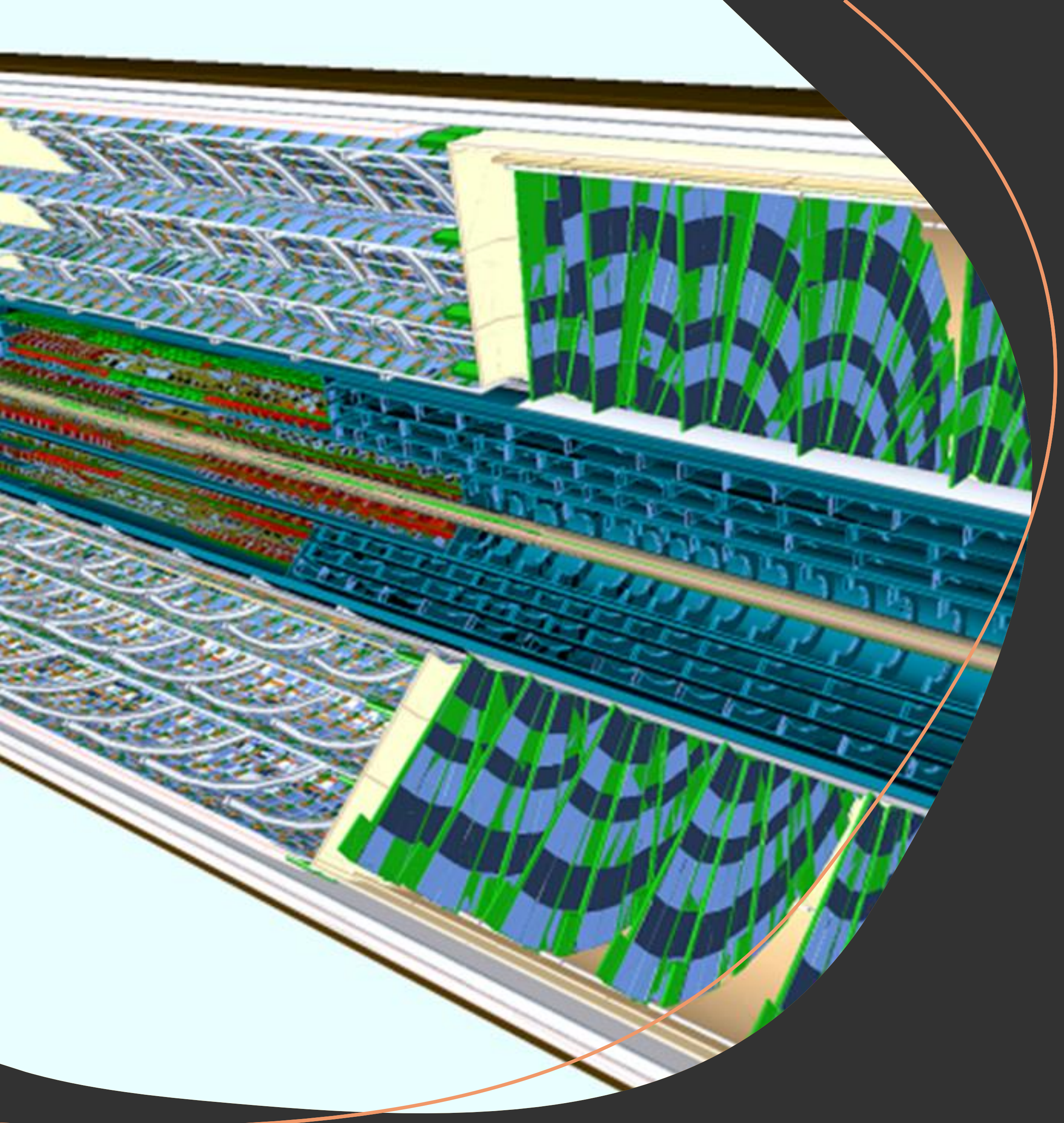


Source: The ATLAS Collaboration, "Technical Design Report for the ATLAS Inner Tracker Strip," Geneva, 2017

Overview

- The HL-LHC upgrade
- Importance of the alignment
- Validating the model
- Simulating the misalignments
- Testing the Alignment
- Summary

The high luminosity LHC (HL-LHC)

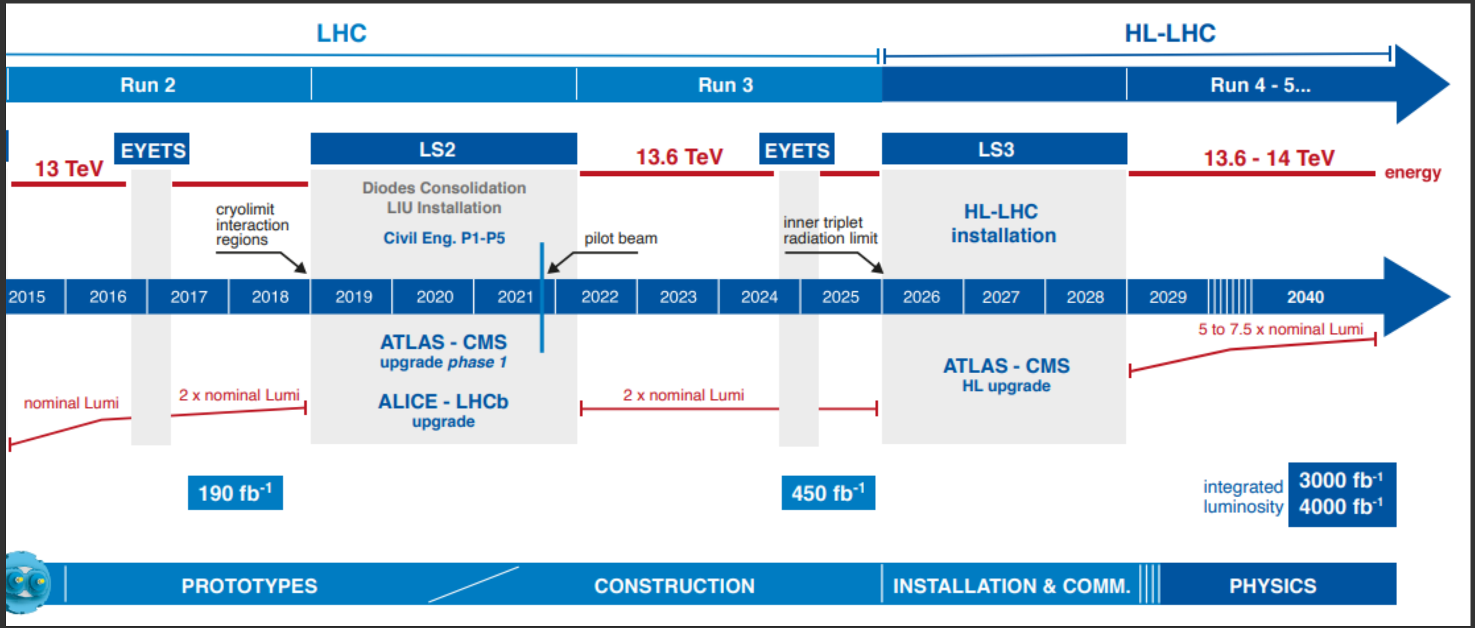
The instantaneous luminosity (L) of an accelerator is defined as

$$L = \frac{1}{\sigma}\frac{dN}{dt}$$

Where σ is the cross-section, and dN is the number of events detected over a time frame dt

The luminosity of the accelerator presents a limit to the amount of data that can be obtained from the experiment.

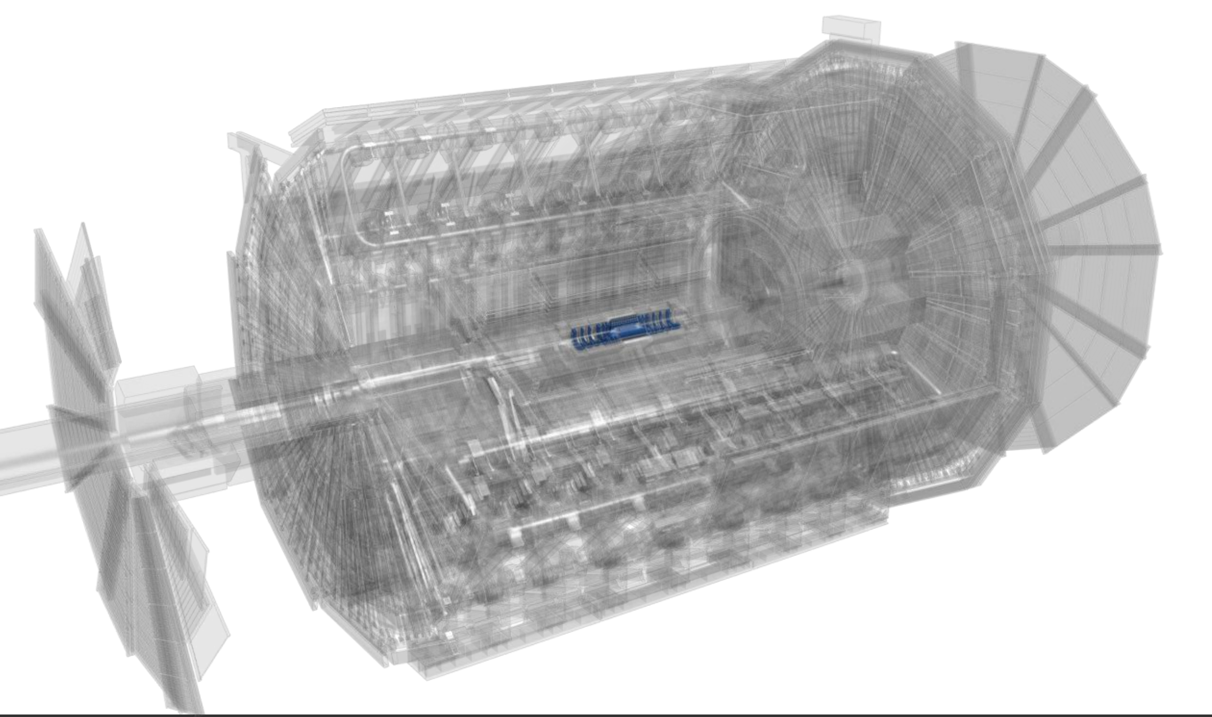
The high luminosity LHC (HL-LHC) is the upgrade plan to increase the luminosity of the LHC from the current $2 \times 10^{34} cm^{-2}s^{-1}$ in run 3 to $5 \times 10^{34} cm^{-2}s^{-1}$.



Source: https://hilumilhc.web.cern.ch/sites/default/files/HL-LHC_Janvier2022.pdf (accessed on 2023/02/23)

Inner detector upgrade

Current ATLAS detector



Highlighted in blue is the current inner detector

Source: Dominguez, Daniel and Moles, Kevin Patrice and Mehlhase, Sascha, “ATLAS detector schematics" ATLAS, Geneva, 2021 https://cds.cern.ch/record/2777214

The current Inner detector will need to be replaced during the HL-LHC upgrade since:

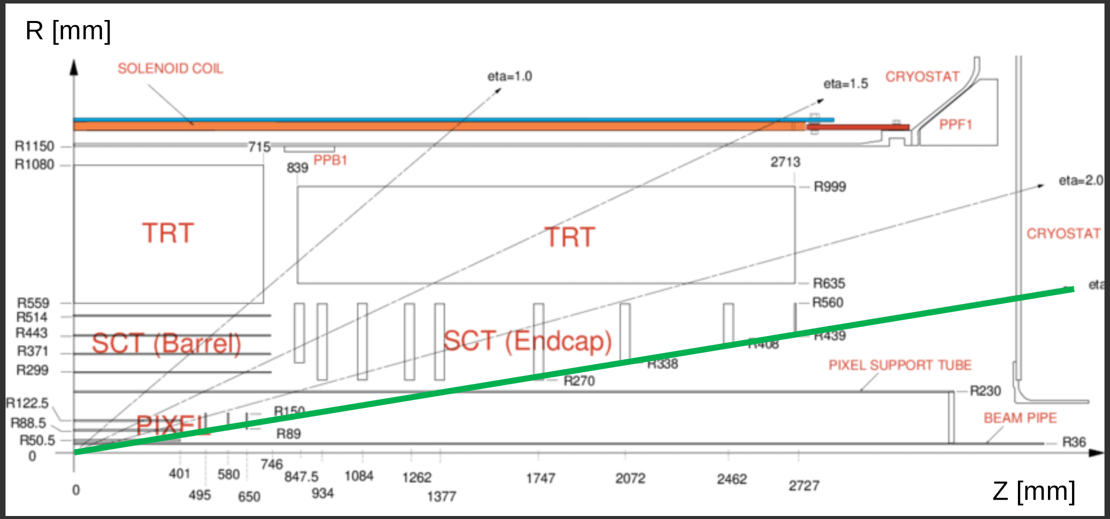
- It accumulated a lot of radiation damage over the years leading to increased power consumption and lower hit efficiency.
- It doesn’t have enough bandwidth.
- It doesn’t have enough spatial resolution to provide accurate tracking with the pile-up levels expected at the HL-LHC

The inner detector upgrade will take place during the long shutdown 3 (2025-2029).

Comparison of the Inner detectors

Current Inner detector (2010-2025)

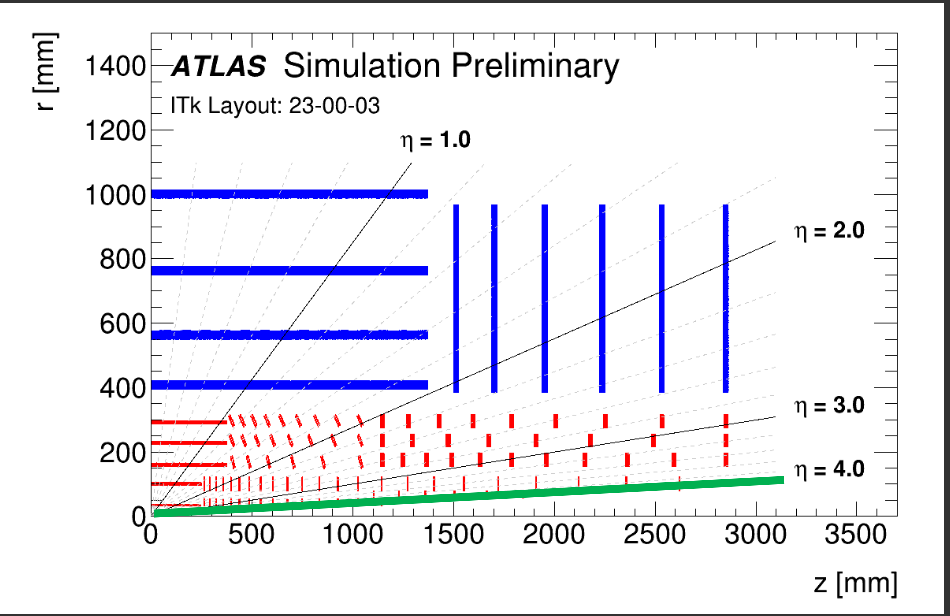
Composed of: Pixel modules, Silicon strips (SCT), and the transition radiation trackers (TRT)
Pseudo rapidity coverage $|\eta|<2.7$ (green)



Source: Ahmad, Mohammad et al. "The silicon microstrip sensors of the ATLAS semiconductor tracker". Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment,2017.
DOI 578. 98-118. 10.1016/j.nima.2007.04.157.

New Inner detector (ITk) (2029-2039)

Composed of: Pixel modules (red) and Silicon strips (blue)
Pseudo rapidity coverage $|\eta|<4.0$ (green)

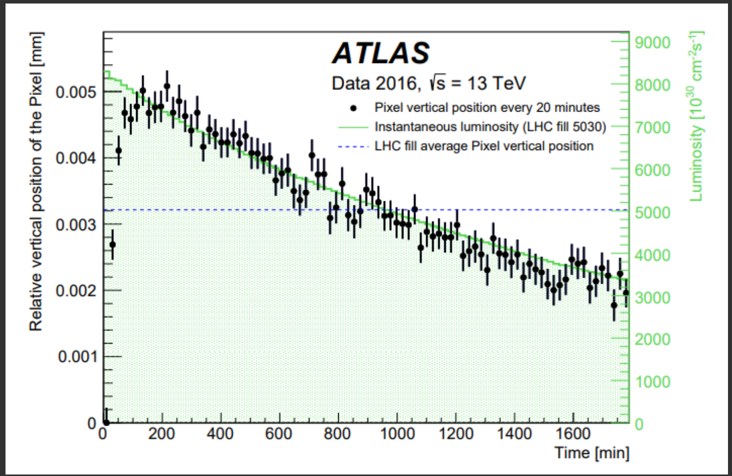


Source: The ATLAS Collaboration, "Expected tracking and related performance with the updated ATLAS Inner Tracker layout at the High-Luminosity LHC" Geneva, 2021

Importance of the alignment

The track reconstruction is limited by how well we can record the position of the hits in space.
It is the job of the alignment algorithm to keep track of and correct for the shifts in position and rotation over time.

Example from the current detector Run-2 alignment.



- On the left is the correction on the y-axis applied by the alignment algorithm over time.
- Time starts at the beginning of an LHC fill.
- The alignment algorithm was run once every 20 minutes for the first hour, and once every 100 minutes then after.

Source: The ATLAS Collaboration, "Alignment of the ATLAS Inner Detector in Run-2," *The European Physical Journal C,* vol. 80, 2020

Motivation

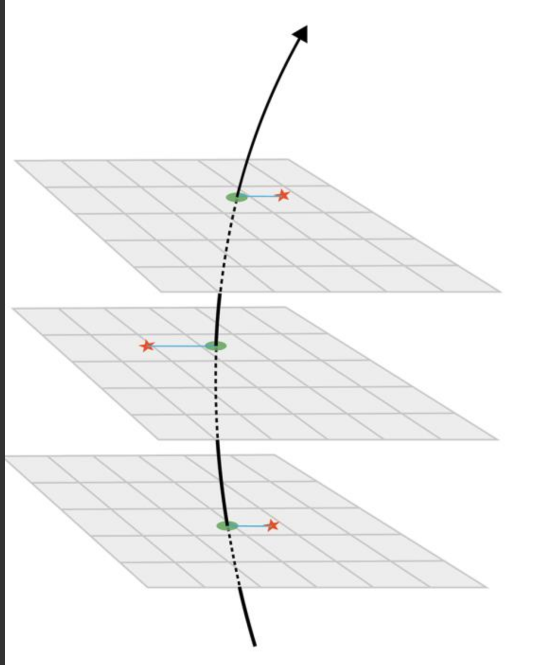
- It is necessary to migrate the tools and algorithms used for the detector alignment to work with the new ITk.

- We need to validate the alignment tools before the ITk is commissioned, for this we will use a software model of the ITk.

The alignment algorithm

A hit-residual (green) is the distance between the hit (red) and the intersection of the track.

The alignment algorithm minimizes the global residual $\chi^2_{Global} = \sum_i \chi^2_{Track\ i}$ by Newton-Raphson over all the degrees of freedom (3 translations and 3 rotations per object).



The residual of a single track is defined as:

$$\chi^2_{Track} = r^T \Omega^{-1} r + \theta^T \Theta^{-1} \theta$$

Where r is the vector containing all the hit-residuals in the track and Ω it the covariance matrix of the hit-residuals.

The second term $\theta^T \Theta^{-1} \theta$ is a correction to account for the multiple Coulomb scattering inside the detector.

Source: The ATLAS Collaboration, "Alignment of the ATLAS Inner Detector in Run-2," *The European Physical Journal C,* vol. 80, 2020

The alignment algorithm

The algorithm must optimize 6 degrees of freedom per module for around 27,000 individual components (~18,000 strips and ~9,000 pixels)

Due to the cost of optimizing so many parameters, the algorithm starts by doing a rough optimization using groups of modules. Then the groups are subdivided into smaller groups and optimized further, this is repeated until we reach individual modules.

Workflow

Modeling

- The ITk detector had to be modeled from scratch in Athena.
- The model will be updated frequently to represent the latest state of the detector.
  - BASE MODEL
- The model represents the detector in perfect conditions (no misalignment).

Mostly done

Validating the model for the alignment

- Try applying translations and rotations to individual modules or groups of modules and corroborate there are appearing on the simulation.

Mostly done

Creating the misalignments

- In order to test the alignment algorithm, it is necessary to simulate the bending and random shifts on the module positions
  - MISALIGNED MODEL
- The model represents a detector with some misalignment to be corrected.

Work in progress

Alignment

- After running the Alignment algorithm on the misaligned model, an aligned model is obtained.
  - ALIGNED MODEL
- The aligned model represents the best guess of the alignment algorithm on the correct position of the modules.
- The difference between the aligned model and the base model is called the residual.

Work in progress

My work has been mostly here

My contributions

My work in the alignment group has consisted in updating the code to generate the misalignments in the latest version of Athena (the analytical framework used by the ATLAS collaboration) using the new geometry.
There are 2 kinds of misalignments:

Global distortions (simple misalignments):

- The global distortions are a group of translations in which the modules are shifted along the $\hat{\boldsymbol{x}}_{\mathbf{1}}$ axis by an amount $\boldsymbol{\Delta x_1}$ proportional to their location along another axis $\hat{\boldsymbol{x}}_{\mathbf{2}}$
- Used to validate the model and groupings to be used by the complex misalignments and the alignment algorithm

The complex misalignments:

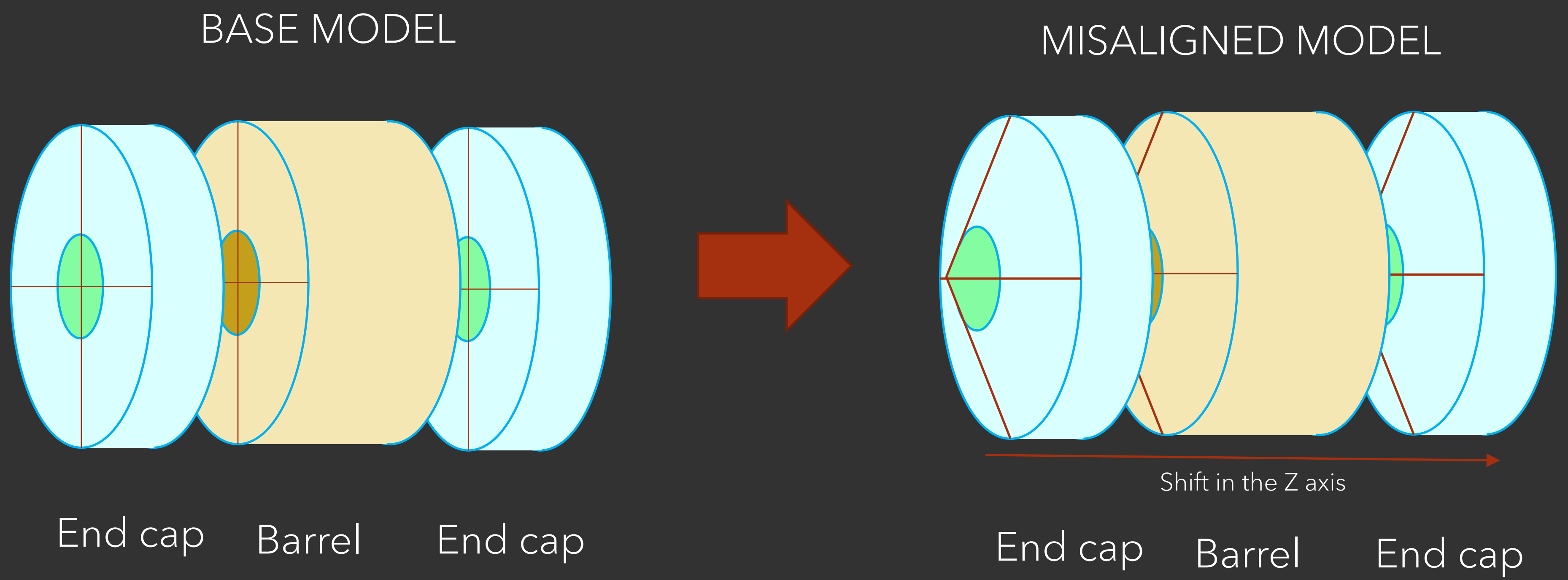
- Simulate more realistic misalignments, closer to what we expect to see on the detector.
- These misalignments will be used as the input of the alignment algorithm for the performance test.

Validating the model

*Not to scale

Let's follow the example of the global distortion

$$Z_{Misaligned} - Z_{base} = a * R_{base}$$

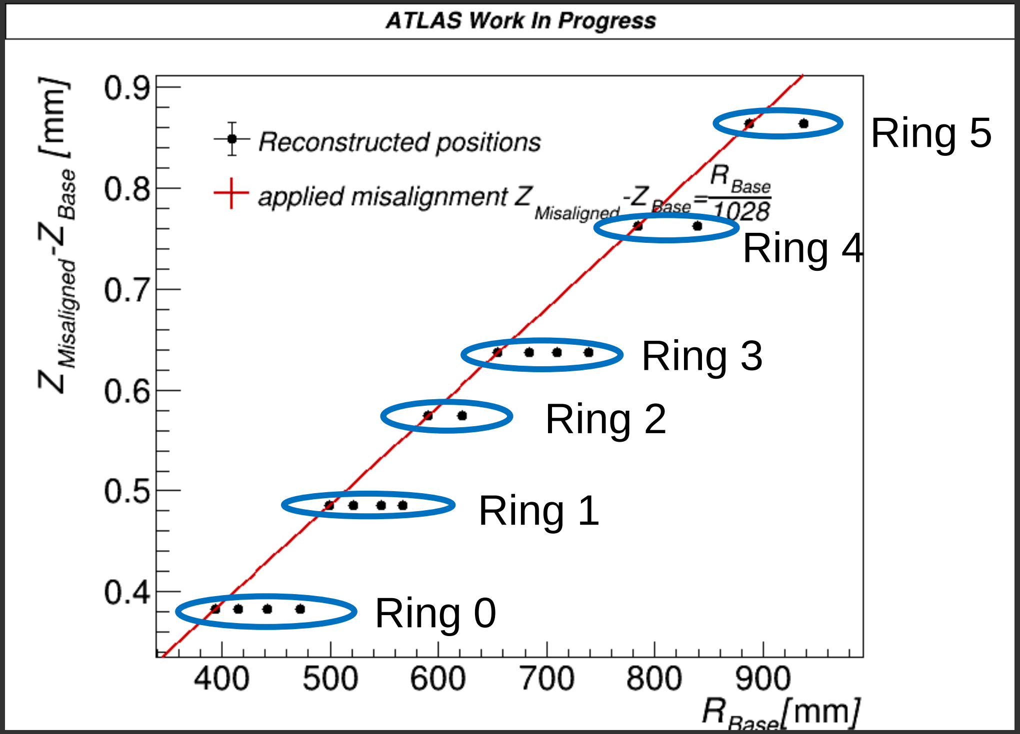


Testing the model with misalignments

On the plot on the right, we have the strip modules following the global distortion $Z_{Misaligned} - Z_{base} = a * R_{base}$, we can see:

- The applied misalignment matches the observed translations generated based on the coordinates of the first module of each group.
- The groups observed on the plot to the right correspond to the strips end-cap regions as shown bellow.

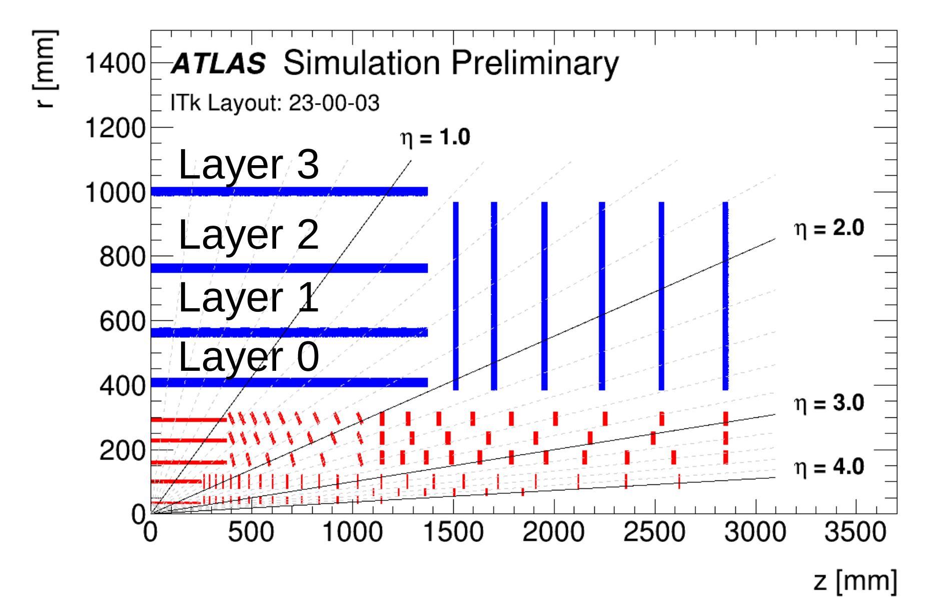
Source: The ATLAS Collaboration, "Technical Design Report for the ATLAS Inner Tracker Strip," Geneva, 2017



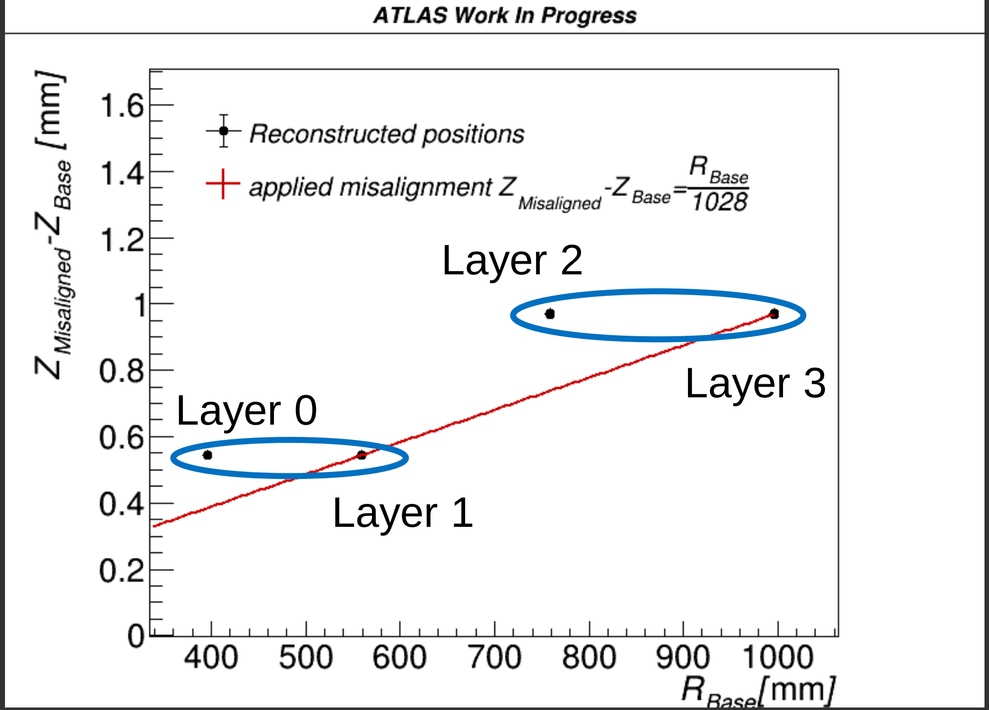
End-cap strips with misalignment $\Delta Z = a * R_{base}$

Testing the model with misalignments

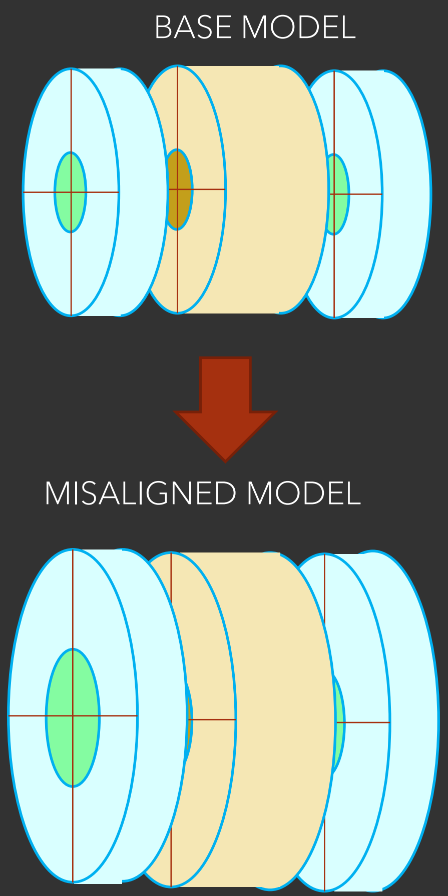
Similarly, to the strips on the end-caps, the ones in the barrel are also grouped for the alignment.



Source: The ATLAS Collaboration, "Expected tracking and related performance with the updated ATLAS Inner Tracker layout at the High-Luminosity LHC" Geneva, 2021

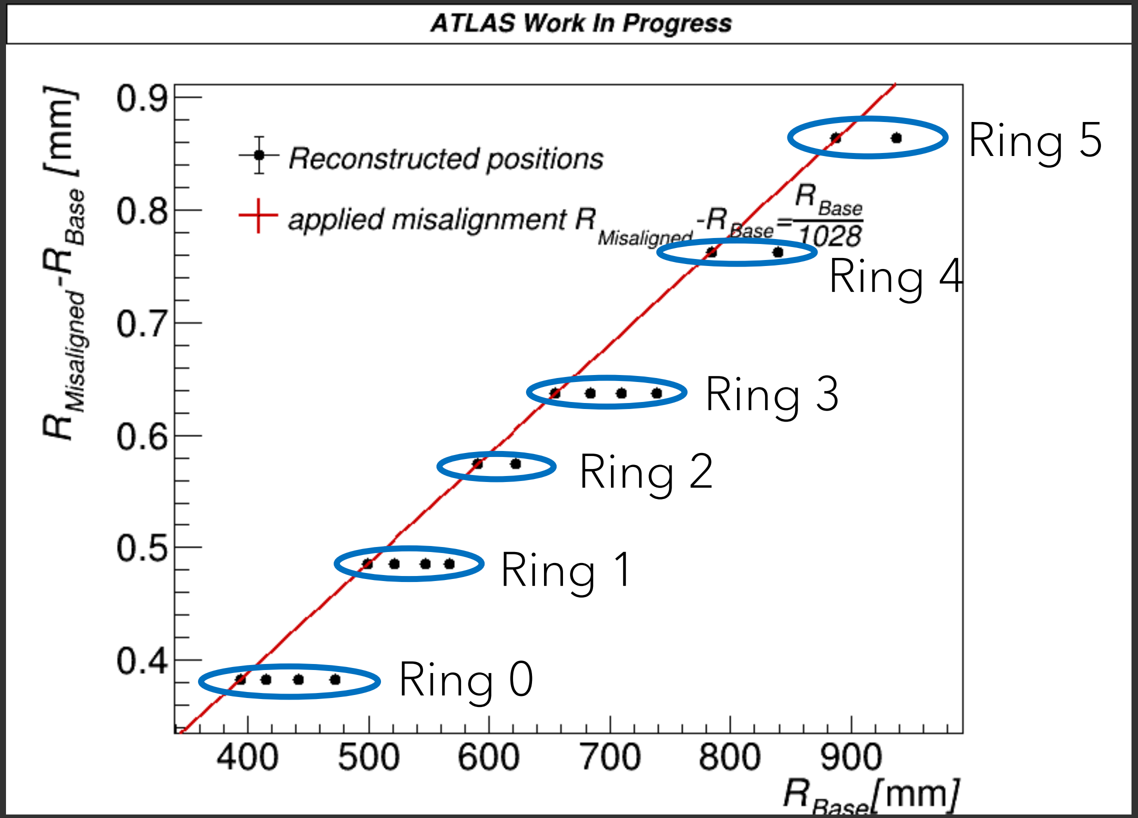


Other global distortions



The results are similar to the other global distortions.

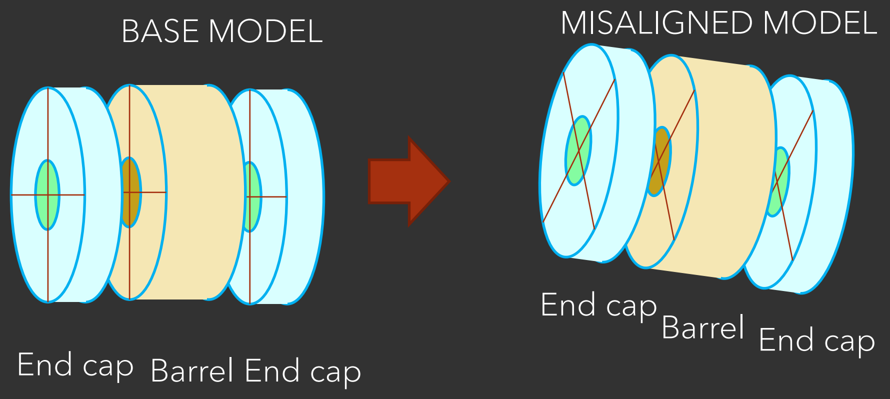
We have corroborated that the model is responding correctly to translations by using global distortions.



Complex misalignments

Used to simulate the kind of misalignments we expect to see in the detector.
These are still in progress and will be needed to test the alignment algorithm

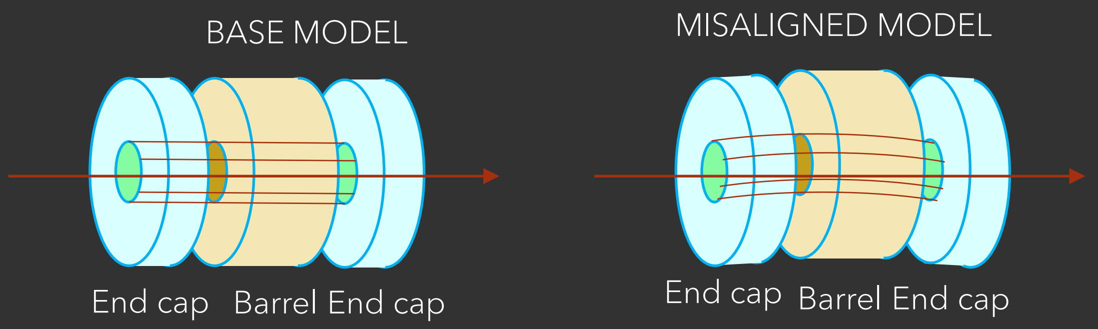
Shifts and rotations



The rotations and or translations can be applied to individual modules or groups of modules.
If the translation and rotation values for each object are different and follow a gaussian distribution, they can simulate random misalignments.

* Rotations haven't been validated yet.

Temperature-dependent bowing



This kind of deformation has been observed on the current detector and is mostly a result of the convective currents of the cooling fluid.

*Work in progress, the misalignment isn't working yet on the latest version of Athena.

Summary

- The LHC will undergo a significant upgrade with the aim of increasing the Luminosity of the accelerator.
- As part of the upgrade the Inner detector will be replaced by the new ITk, for this reason, a new model of the detector had to be developed.
- I have been working on the migration of the misalignment algorithm which can be used for testing the translations, rotations, and grouping needed by the alignment algorithm
- I have tested the module translations and confirmed that the modules shown in the plots are being translated correctly.
- The complex misalignments are still in progress.