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Track based alignment of the ATLAS Silicon Tracker

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The ATLAS Experiment is one of the four detectors located at the Large Hadron Collider at CERN in Geneva, Switzerland. It is a multi-purpose detector that will study high-energy particle collisions and which main aim is the Higgs boson discovery. The reconstruction of charged particle tracks and their decay vertices is performed by a sohisticated tracking system based on silicon sensors and drift tubes called Inner Detector. In order not to degenerate the track measurements, the position of the silicon detector elements has to be known to a precision better than about 10 μm. This precision can be achieved thanks to track-based alignment algorithms combined with measurements from hardware based alignment techniques. The proposed alignment algorithms for the ATLAS Inner Detector and their implementation into the common ATLAS software framework are presented as well as the alignment strategy. Moreover, alignment results from testbeams, MonteCarlo simulations and real cosmic rays data are shown and discussed. Finally this note will also emphasize the importance of global distortions, so-called weak modes.

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1. Introduction

The Large Hadron Collider (LHC) at CERN will extend the frontiers of high energy particle physics with its unprecedented 14 TeV proton-proton collisions with 40 MHz rate at the design luminosity of 10^{34} cm^{-2} s^{-1} [1]. The ATLAS (A Toroidal LHC ApparatuS) detector is one of the four LHC experiments and it is a multi-purpose detector with the main aim of the Higgs boson discovery [2]. Its Inner Detector (ID), which operates embedded in a 2 T magnetic field, consists of silicon-based subdetectors, Pixels and SemiConductor Tracker (SCT), and a Transition Radiation Tracker (TRT) with drift tubes [2].

Due to the experimental conditions at the LHC, around 1500 charged particles will cross the ATLAS ID every 25 ns. Because of this, the ID electronics and all the sensor elements must be fast enough and of course radiation hard. In addition, a very fine granularity is needed to handle the particle fluxes and to reduce the influence of overlapping events, this is why the ID has 5832 individual silicon modules (with millions of readout channels). Each of those modules determine the position of incident particles with a precision of about 20 μm, depending on the silicon technology.

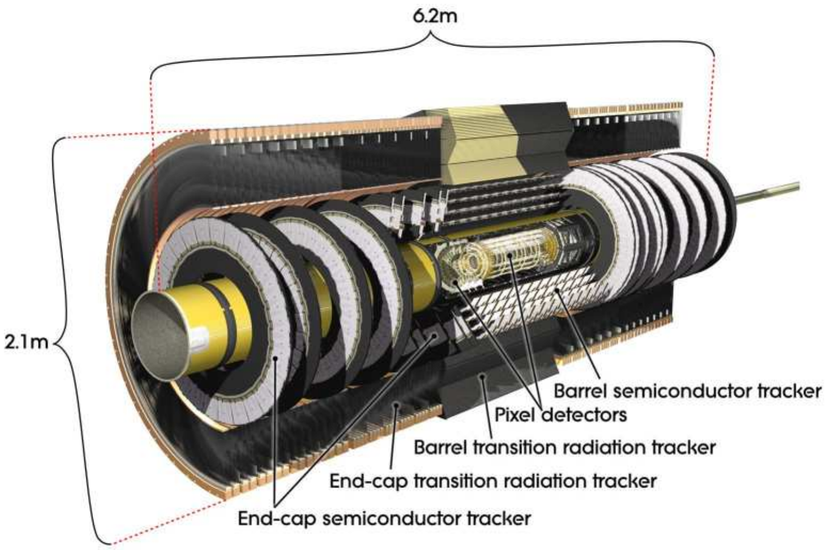

Figure 1: A sketch of the ATLAS inner detector. The pixel detector has three barrel layers and three endcap discs on each side. The SCT has four barrel layers and nine endcap discs each. The TRT has three barrel layers and two endcap wheels on each side.

Pixel modules are based on silicon pixel technology and they are arranged in three cylindrical barrels and three discs on each side of the central barrel. The pixel elements are 50x400 μm^2 resulting in an intrinsic resolution of 10 μm in the $r\phi$ (transversal) direction and 115 μm in the z (longitudinal) direction with a direct 2D readout. SCT elements are silicon microstrip detectors and consist on four barrel layers and nine endcap discs. With an average 80 μm strip pitch they ensure a 17 μm precision in $r\phi$ for each module and a stereo angle of 40 mrad allows 580 μm in z. Finally, the TRT consists of straw tubes arranged in a barrel and two endcap wheels on each side

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of the barrel with an intrinsic resolution of 130 μm per straw. Eventually, ID has been design to provide, in the barrel region and on average, 3 hits in the pixels, 8 SCT hits and 36 TRT hits for tracks coming from the interaction point.

1.1 The Challenge

To achieve the physics goals and therefore to exploit the excellent intrinsic resolution of our precision tracking devices, ATLAS tracking requires to know the position of the silicon modules with a precision better than 10 μm [2]. However, the position of the devices is only known to about O(100 μm) thanks to the assembly survey measurements [16]. Because of this fact, a track based alignment procedure has to be applied to determine the absolute position of the sensitive devices to reach the ultimate precision.

The ATLAS ID is a large and complicated system with 5832 individual silicon modules with about 87 million readout channels. If each module is assumed to be a rigid body, i.e. no bows nor bends, at least three translational and three rotational degrees of freedom (DoF) should be considered. This means that alignment algorithms have to deal with 34992 DoF just for the silicon system. Table 1 reports the number of modules of each subdetector as well as their design resolutions.

Subdetector	Pixels		SCT		TRT	
Structure	Barrel	EndCap	Barrel	EndCap	Barrel	EndCap
Type	silicon pixels		silicon microstrips		gaseous drift tubes	
Layers/Discs	3	2x3	4	2x9	3	2x40
Modules	1456	2x144	2112	2x988	96	2x398
Total per subdetector	1744		4088		992	
Total per topology	3568 (Barrel), 2264 (EndCap)				96 (Barrel), 796 (EndCap)	
Total per technology	5832				992	
Readout channels	80.4M		6.3M		351k	
Resolutions	10 μm ($r\phi$) 115 μm (z)		17 μm ($r\phi$) 580 μm (z)		130 μm	

Table 1: Inner Detector elements per subdetector together with their intrinsic resolution.

Up to now, the full ID has been described but as the aim of this note is to describe the silicon tracker alignment, we will now focus on the silicon alignment approaches and their results.

2. Track-based Alignment Algorithms

Currently, three alignment approaches are being developed, tested and commissioned with MonteCarlo and real data. All of these algorithms are implemented within the ATLAS software framework: Athena [10], and use common framework tools, such as tracking, databases, etc. The algorithms align the system using track residuals and are iterated until convergence. Then, final alignment constants are produced and stored. A brief description, pointing out the main advantages and disadvantages of each algorithm, is given:

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1. **Global** χ^2 approach: Minimizes a χ^2 with respect the alignment parameters using a nested minimization with respect the track parameters [3] [7]:

$$\chi^2 = \sum_{evt} \sum_{trks} \mathbf{r}^T V^{-1} \mathbf{r} \quad \rightarrow \quad \frac{d\chi^2}{d\mathbf{a}} = 0 \tag{2.1}$$

   where $\mathbf{r} = \mathbf{r}(\pi, \mathbf{a})$ and it means a residual vector [1], being π a track parameter vector and $\mathbf{a}$ a alignment parameter vector. This method uses 6 DoF per module and it takes into account module correlations and also Multiple Coulomb Scattering (MCS) effects through its covariance matrix V^{-1} (see appendix B in [7]). The solution comes from a set of coupled linear equations:

$$\mathbf{a} = \mathbf{a}_0 + \delta\mathbf{a} = \mathbf{a}_0 - M^{-1}\nu = \mathbf{a}_0 - \left[\sum_t \left(\frac{d\mathbf{r}}{d\mathbf{a}}\right)^T V^{-1} \left(\frac{d\mathbf{r}}{d\mathbf{a}}\right)\right]^{-1} \sum_t \left(\frac{d\mathbf{r}}{d\mathbf{a}}\right)^T V^{-1}\mathbf{r} \tag{2.2}$$

   where the module correlations are introduced thanks to this dependence:

$$\frac{d\mathbf{r}}{d\mathbf{a}} = \frac{\partial \mathbf{r}}{\partial \pi}\frac{d\pi}{d\mathbf{a}} + \frac{\partial \mathbf{r}}{\partial \mathbf{a}} \tag{2.3}$$

   It converges after a small number of iterations because the use of a simultaneous fit for π and $\mathbf{a}$ is very powerful. On the other hand, the main disadvantage is that it involves handling and solving large matrices (i.e. inverting M^{-1}), i.e. a large system of linear equations (35k x 35k). Furthermore, special care needs to be taken since the matrix is inherently singular. This poses inherent computing challenges with an extremely intensive CPU consumption. In the solving a matrix inversion is done via ScaLAPACK software on parallel dedicated clusters [18], although, in practice various preconditioning and fast solving techniques (MA27 [8], etc...) can be use to make the problem tenable.

2. **Local** χ^2 approach: Based also on a principle of χ^2 minimization (equation 2.1), but simplifies the problem by assuming that the track parameters are constant and just minimizing with respect to the alignment parameters [4] [5]. Therefore, although equation 2.3 holds, the matrix M is diagonal in 6x6 blocks. This advantage allows to consider little 6x6 matrices (one per module), thus avoiding the computer solving challenge but losing the module correlations. Because of that, this algorithm requires a large number of iterations to converge.

3. **Robust**: Does not use a χ^2 minimization approach, but calculates alignment corrections in the local module plane from centering track residual and overlap residual distributions in an iterative way, with focus on simplicity and robustness [6]. It can handle 2 or 3 DoF (normally the translational DoFs) per module and needs many iterations to converge and to produce good alignment parameters.

[1] A residual is normally defined as the distance between the measurement point and the extrapolated point (which has to follow a tracking model) of the track to the measurement sensor plane.

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To help with the determination of the alignment constants, functionalities exist to add constraints from tracking, physics and external data. For example, common vertex fit, which is already implemented in Global χ^2 and Robust, or assembly survey constraint, which is implemented in Global and Local χ^2 algorithms. Moreover, the algorithms can handle different alignment levels, which means that structures consisting of several elements (modules) can be aligned. Three basic levels were defined by general consent: Level 1 which considers entire subdetectors (whole Pixel, SCT barrel and EndCaps), Level 2 which treats barrel layers and discs of each subdetector and finally a Level 3 which considers individual modules. Many more levels have been defined within the Global χ^2, adding the possibility to align staves/ladders, the pixel half-shells, etc... [9]. Figure 2 shows how the three basic levels are defined.

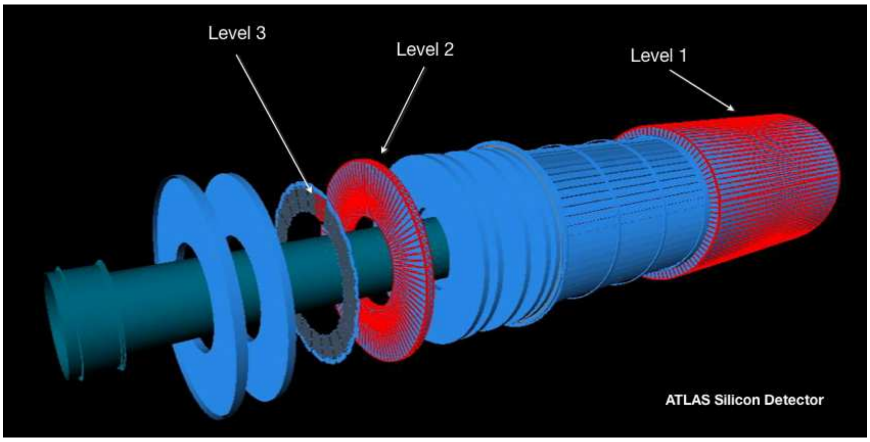

Figure 2: Alignment Level definition where Level 1 means entire subdetectors (whole Pixel, SCT barrel and EndCaps), Level 2 treats barrel layers and discs of each subdetector and finally a Level 3 considers individual modules.

3. Performance

Track-based alignment algorithms have been tested, commissioned and validated using MonteCarlo simulations and Cosmic ray data during the past few years. The following sections will report on the different challenges where these approaches have been tested.

3.1 Testbeam Commissioning

The first real data from the ID came from the Combined TestBeam (CTB) 2004 data. All the alignment algorithms were used to align the ID setup with this data [11]. Different sets of beams of e+/e-, μ+/μ-, γ and pions with energies varying from 2 to 180 GeV and with/without magnetic field runs gave abundant statistics (O(10^5) tracks per module and per energy run). The silicon tracker setup consists of 6 Pixel and 8 SCT endcap modules configured such that the beam would cross radially as in the actual configuration (simulating an ATLAS slice) [17]. Although the layout presented some systematic effects due to its limitations, the CTB proved to be a good start to test algorithms for upcoming data and allowed to test the software reconstruction chain and to tune

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the alignment algorithms. The alignment results from each approach were found to be consistent with slight differences likely to be attributed to global transformations of the layout. Before the alignment, the residual widths were 50-100 μm and after alignment, the overall Pixel $r\phi$ residual widths were 10-15 μm and SCT residuals were 20-25 μm, depending on the algorithm [19].

3.2 MonteCarlo Commissioning

Alignment algorithms must be extensively validated using MonteCarlo simulation of the ATLAS detector. Indeed, as truth information is available and one can debug the code. For this purpose, ATLAS simulations have a nominal detector description and several descriptions where misalignments were introduced either at reconstruction or at simulation level.

Within the CSC (Computer System Commissioning) exercise, a realistic simulation of the ATLAS detector accounting for the assembly imperfections and material description was performed. ID misalignments were introduced (at simulation level) at the three basic levels of detector structure hierarchy (described in section 2), according to the building precision: O(mm), O(100 μm) and O(100 μm) for translations and for Level 1, 2 and 3, respectively and O(mrad) rotations for all levels (see appendix A from [13]). A multimuon sample (100k tracks) plus a cosmic ray sample ($\tilde{4}$.5k and $\tilde{3}$0k tracks with and without magnetic field, respectively) were used in sequence to produce one set of alignment constants which was validated using Z$\rightarrow \mu\mu$ samples [13]. Figure 3 shows that the Z mass peak was successfully recovered with current algorithms, however, residual biases in track parameters were observed, due to global deformations. In addition to constraints imposed by using cosmic data, other constraints are needed to reach ultimate precision.

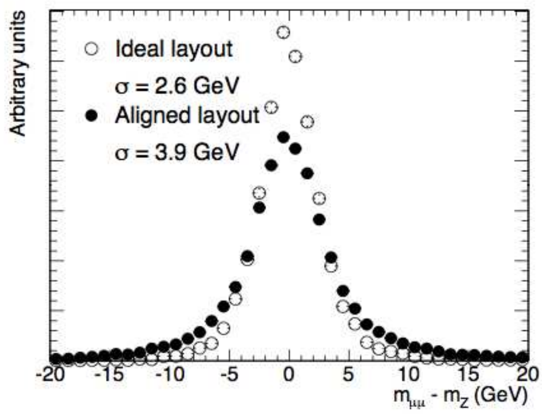

Figure 3: Invariant mass of dimuon pairs of Z boson in the CSC exercise as measured by the ID (not the muon spectrometer).

The latest challenge has been the Full Dress Rehearsal (FDR), where the readiness of the alignment algorithms was tested in order to be prepared for the upcoming data. Several sub-exercises (FDR1, FDR2, etc...) took place since February 2008 until June 2008. The alignment model and all its infrastructure were validated where a beam spot calculation, a center of gravity determination and the ID alignment were performed in almost automatic mode. This was possible using a special set of scripts to steer jobs running in parallel on 80 dedicated computer queues located in the

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CERN Analysis Facility (CAF) and delivering constants within a 24-hour loop. The alignment was performed level by level (as mentioned above) using the Global χ^2. Simulated event triggers and filters were used to produce an ID alignment stream. The introduced misalignments (at simulation level) where the same as for the CSC samples. The number of tracks used to align detector were incremented day per day as the data taking period was emulated. As in the CSC exercise cosmic events were added and a fix number of tracks was used ($\tilde{1}$2k tracks). Figure 4 shows the transverse momentum as a function of η for the nominal (up-left plot) and the aligned (up-right plot) case. The bottom plot shows the same distribution using the perfect geometry in order to be compared with previous distributions. Simulated particles for these exercises had a flat transverse momentum distribution within a range [10,50] GeV/c. Alignment improved the residuals and as figure shows also the momentum reconstruction after the 24 hours alignment loop.

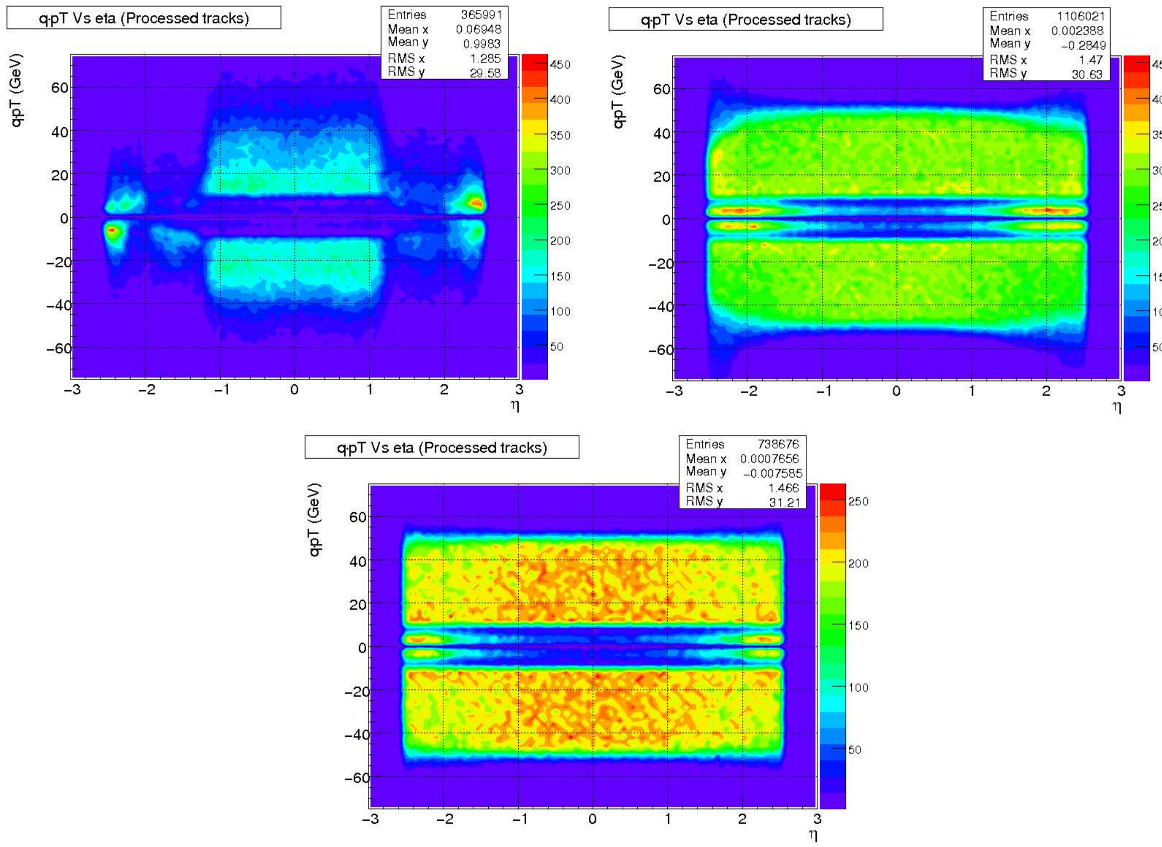

Figure 4: Reconstructed transverse momentum as a function of η for the same FDR sample. Three cases, using nominal geometry (up-left plot), aligned geometry (up-right plot) and perfect geometry (bottom plot). As it can be observed, a better momentum resolution is obtained in the barrel part.

3.3 Cosmic Ray Commissioning

In spring 2006, the first large scale test of the barrel SCT+TRT took place on the surface in the so-called SR1 cosmic run [14]. One of the goals of these tests was to confirm the alignment

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measurement provided by the optical survey. About 400k events were recorded during this period using a partially instrumented region of the fully integrated detector. 467 SCT barrel modules (22% of the barrel) and 13% of the TRT were read out, in a conical section of a 20 degrees tilted geometry covering about 30 degrees of the azimuthal ϕ slice. Two scintillators, with 0.5 ns of time resolution, were used for triggering and together with the roof material provided an intrinsic 0.4 GeV momentum cut-off. As there was no magnetic field, no track momentum measurements were possible and as most of the triggered events were below 10 GeV, where multiple scattering is important, the residuals were larger and the algorithms were adjusted to take this into account. A third scintillator was installed under the floor in order to use the Time of Flight (TOF) for momentum selection [12]. A preliminary SCT and TRT internal alignment and a TRT-SCT global alignment in the absence of magnetic field was performed. The residual widths before alignment were about 50 μm (better than the ones specified by the SCT assembly tolerances, thus indicating a very good assembly precision) and after alignment, 30 μm residual widths were obtained [19].

The first SCT+TRT alignment in the ATLAS cavern (without the pixel detector) came from the cosmic runs, so-called M6 milestone run, in March 2008, where about 12k useful events were collected (5k tracks for SCT and 4k tracks for TRT) and used to align the parts of the detectors covered by the trigger acceptance. Given the low number of tracks only barrel/endcaps and layers/discs (Level 1 and Level 2) alignment was possible. Module level alignment was not attempted for the SCT. Nevertheless, alignment based on M6 data improved the knowledge of the module positions.

Since September 2008 the full ID has been collecting cosmic data in the ATLAS cavern in combined mode, therefore a full silicon tracker alignment based on cosmic rays has been possible. By the time of writing, an accurate alignment has been performed using cosmic ray data with and without magnetic field together. This is the so-called M8 milestone run. Thus, more than 1 million tracks have been used to align the detector, starting from the Pixel survey measurements (SCT in nominal positions), and the residuals have been improved. Figure 5 shows the residuals for the Pixels (local x or $r\phi$ residuals upper-left and local y or z residuals upper-right) with about 35 μm and 158 μm in the widths for the Pixel $r\phi$ and z residuals, respectively, and SCT residuals (bottom-left) with less than 34 μm in the width for the SCT. The bottom right plot shows the impact parameter (d0) difference between the two cosmic muon segments (Up and Low) with a resolution of 63 μm.

Due to the low statistics in the endcaps, because of the poor horizontal illumination (cosmic rays arrive mostly vertically), the alignment of forward detectors is not ready yet.

4. Weak Modes

All the track-based alignment techniques suffer from a similar problem, there are some global distortions, so-called weak modes, which leave the χ^2 unchanged and therefore track-based residual minimisation cannot be resolved. It is not question of maths or statistics, all the samples (collisions, cosmics, etc...) have intrinsic and different weak modes and the only option is the use of "extra" information, generally called "external constraints". If one thinks of collision data (tracks coming from the interaction point) as the default data, then, these extra constraints can be a different data topology such as cosmic rays (muon tracks coming from the top of ATLAS) and beam

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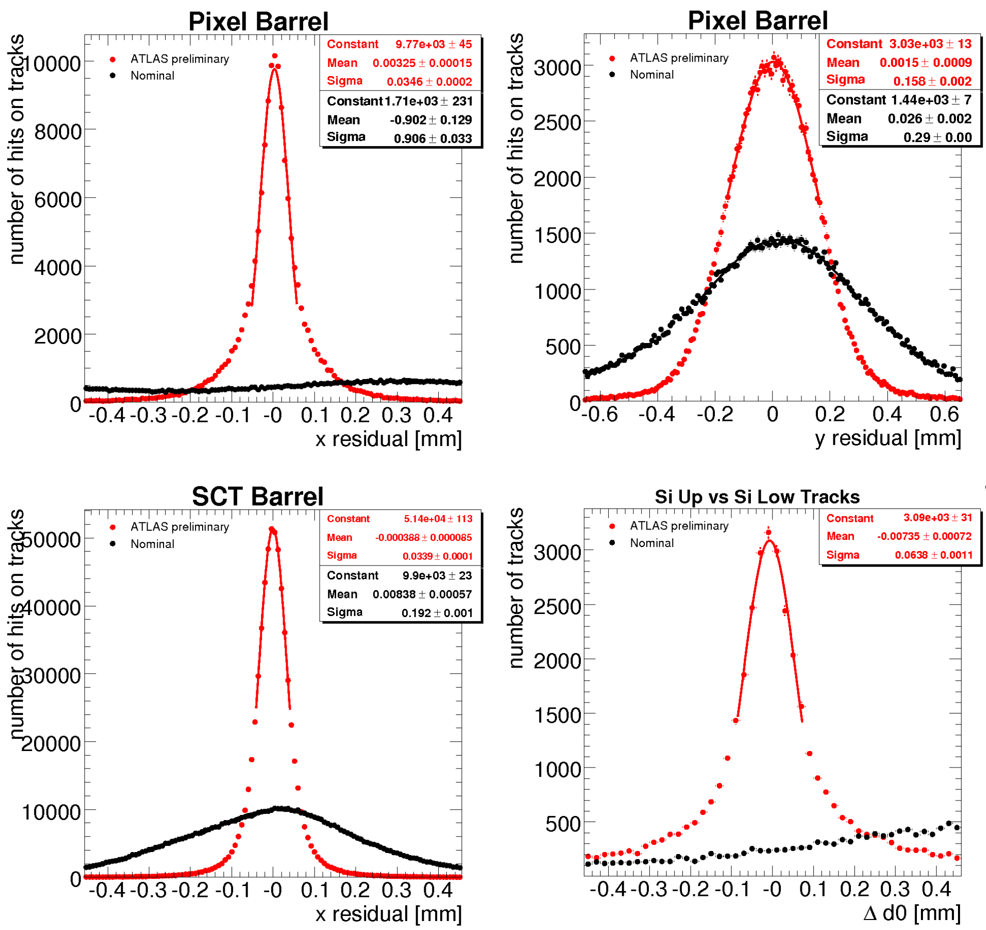

Figure 5: M8 cosmic run residuals for the Pixels (local x or $r\phi$ residuals in the upper-left and local y or z residuals in the upper-right) and SCT residuals (bottom-left). The bottom right plot shows the impact parameter (d0) difference between the two cosmic muon segments (Up and Low).

halo/beam gas events (tracks coming with a little angle with respect the beam line). Every kind of events will fix some weak modes, so adding all these events will cure most of the existing weak modes. Other sources of "external constraints" are fitting a group of tracks coming from the same vertex, or track parameters constrained thanks to an external tracking (using the muon spectrometer tracks to constrain the ID tracks), or using resonant masses, or the survey data, E/p constraints, etc...

Figure 6 shows the different track directions for cosmic rays and for beam halo events. Cosmics are very useful to fix clocking and telescope effects especially in the barrel region. Beam halo tracks have a similar role for the EndCaps, as the barrel modules and the endcap modules are perpendicular. The study of simulated beam halo and beam gas events for alignment optimisation is ongoing.

The ATLAS ID alignment group has developed an strategy to study systematically the weak modes. Figure 7 shows a table with all the lowest order identified global distortions. In that

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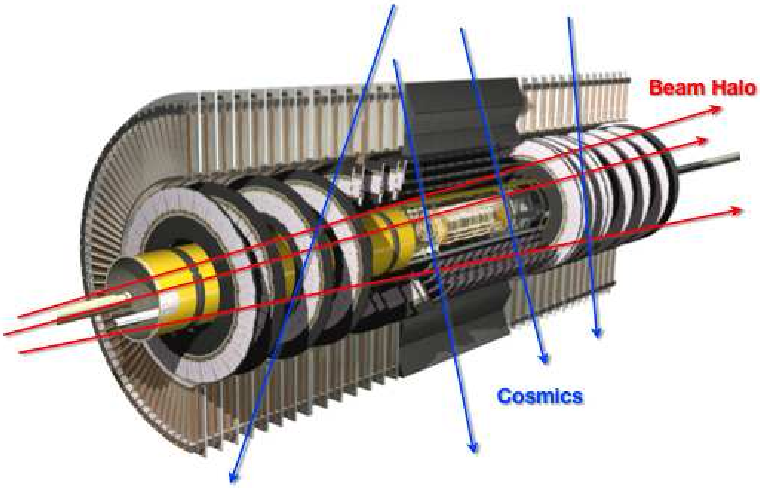

Figure 6: Track directions for cosmic rays and for beam halo events.

sense, MonteCarlo simulations are being prepared with global distortions on top of them. These simulations are allowing us to study how we can deal efficiently with this inherent problem. Some of the distortions, those believed to have the largest impact on physics, from the figure have been already produced and propagated to physics and performance groups. These are Curl, Telescope, Elliptical and Twist distortions (latest studies in [20]). As it has been emphasized, the physics performance community must evaluate the systematic uncertainty on measurements originating from these systematic deformations.

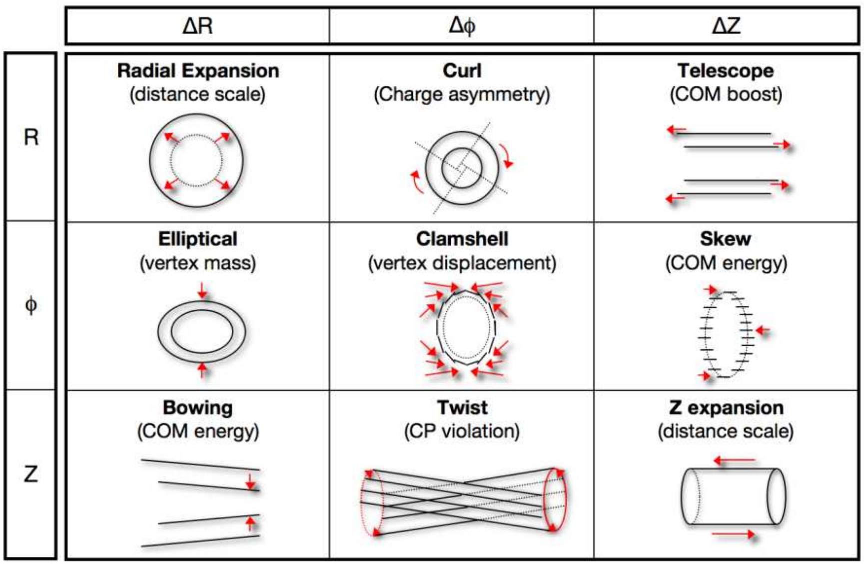

Figure 7: Summary table of the possible systematic deformations, the so-called Weak Modes.

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5. Hardware-based Alignment

There is a hardware-based alignment system available in the SCT subdetector. It is based on a Frequency Scanning Interferometry (FSI) [21] technology which performs 842 simultaneous real-time length measurements in-between nodes forming a geodetic grid on the SCT support structure. Figure 8 shows a sketch of the FSI grid where the 512 measurements lines in the barrel and 165 in both endcaps can be seen. Distance measurements between grid nodes can reach a precision of about 150 nm and a 3D grid geometry can be reconstructed to a precision of less than 5 μm in the grid line directions.

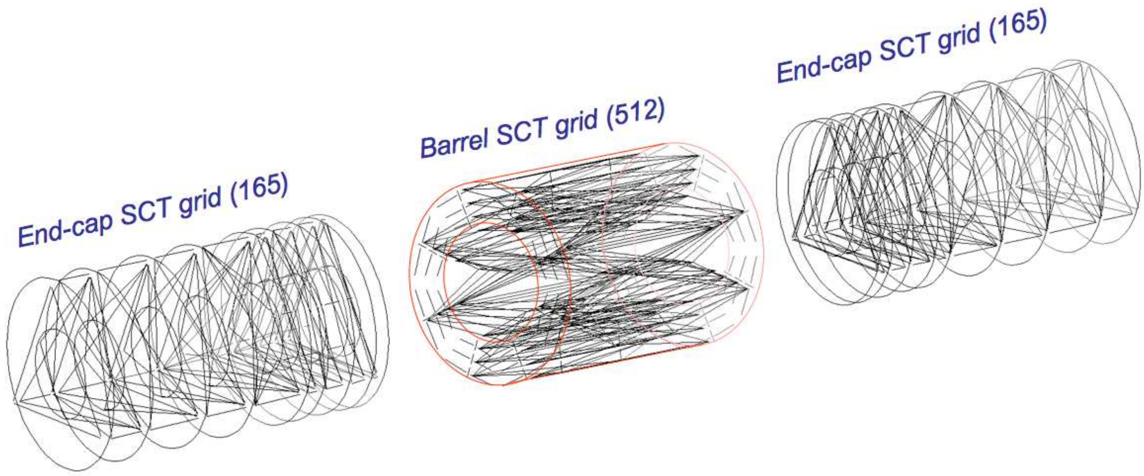

Figure 8: A sketch of the FSI grid lines with its 512 measurements in the barrel and 165 in both endcaps, i.e. 842 in total.

FSI is already installed in the ATLAS cavern and all grid lines have been successfully illuminated and read out. This system will operate in conjunction with the track-based software algorithms and it will help to constraint some weak modes. At the moment the software integration is underway. As it offers access to low spatial frequency detector deformations, i.e. as it has been designed to tackle the global deformations of the SCT, it would be a good complement to reduce the weak modes impact.

6. Conclusion

Three track based alignment algorithms have been developed to align the ATLAS Silicon Detector within the ATLAS software framework. All methods have been commissioned and tested with simulated or real data and extensive validations are being performed. Although algorithms use different approaches in extracting the alignment constants (χ^2 minimization, various DoF, etc...) all of them improve residuals and the quality of the track parameters significantly. The alignment team have been looking at real data since 2004 in the testbeams and then with cosmic rays. The infrastructure for full scale tests using nominal and misaligned detector simulation is in place and

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tests have been performed also using simulation data. Latest cosmic runs have allowed to have an accurate preliminary silicon alignment. It represents a fair starting point for the first LHC data reconstruction which should be available next year.

Deep studies are on going to tackle the intrinsic problems the track based algorithms have with the global distortions. Simulations with misaligned geometries are ready and alignment methods are being tested. Moreover, additional constraints are considered, like cosmic rays, beam halo events, track pairs originating from resonance decays, common vertex fits, etc. in order to add extra information to the alignment systems. Finally, information from a hardware based alignment system called FSI will be used in the SCT to help with the determination of the silicon alignment constants.

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