Offline Alignment & Calibration of the Inner Detector

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Abstract

In this note, we examine the possibility of understanding the ID alignment and calibration sufficiently well to allow a 20 MeV measurement of M_W. In particular, this requires understanding the momentum scale to the 0.02% level and potentially controlling the alignment to ~1 μm.

The requirements for the alignment, magnetic field and material of the ID are considered. Questions are posed and work-plans with time-scales related to the Physics TDR are set out. Even if the goal of improving M_W should prove impossible, the methods discussed will be necessary to achieve the best possible understanding of the ID performance.

This is a **working document**: as information becomes available and methods are developed, the document should be updated. *Corrections, improvements and updates are very welcome.* It is clear that there are very many questions which can be asked. What is set out here is intended to be a starting point.

The latest version of this document can be found from the Web by following the links:

ATLAS → ID → Performance → Alignment

Revision History

1. v0.0 Summer 98 First draft for discussion.
2. v0.1 Spring 99 Precision in R-z. Stability.

To Do

1. Update corresponding to work for Physics TDR [9-3].
1. Write-up *Dilution Factors*.
2. Think about requirements in R-z plane.

1 Introduction

At the end of 1997, it was believed that the precision which was required for p_T resolution would be ~0.1% [9-1] - this was considered ambitious! However, at the Grenoble 98 ATLAS Physics Workshop, Fabiola Gianotti proposed that we could make a useful measurement of the W mass if we could **control the p and E scales measured in the ID and EM Calo respectively at the 0.02% level** [9-2]. You can think of your own description of such a determination! The requirements were based on an extrapolation of what might be possible and appropriate from measurements of the W mass from CDF [9-3].

A more complete set of requirements is:

1. Control alignment of ID to ~1 μm in x-y plane.
2. Understand the B-field to better than 0.02%.
3. Understand the material in the ID (in particular the Pixels and SCT) to ~1% of its value.
4. Understand the p_T resolution to 1%.

There are many questions associated with these requirements - they will be addressed in the subsequent sections. Further, the list should not be considered to be complete, but rather indicative.

To some extent, all uncertainties can be 'mopped up' in an overall calibration using the Z mass. However, it is usually the case that to really understand and control systematics, it is necessary to understand the individual components of the systematics with the highest possible accuracy and only at the end mop up any remaining uncertainties.

The requirements listed above will be difficult enough to meet on their own. However, undoubtedly things will be made significantly more complicated because of couplings between the different measurements. In order to make progress with the studies, such complications will be ignored.

CDF has been used as a comparison for ATLAS. ATLAS is better than CDF in so far as:

- It has far higher statistics with which to understand systematics, e.g. 6M $Z \rightarrow ll$ and 60M $W \rightarrow l\nu$ after cuts per year at 10^{33} $cm^{-2}s^{-1}$, compared with 3.5K and 35K respectively from CDF Run I.

  In comparison with CDF, it might be hoped that many of the systematics may be understood by a factor of $\sqrt{10^3}$ better at ATLAS. This includes all physics systematics (such as the W p_T spectrum) which are controlled by studying real data.
- Better resolutions, e.g. $\sigma(1/p_T) \sim 0.4\times10^{-3}$ GeV^{-1} compared to 0.8×10^{-3} GeV^{-1} at CDF.
- Somewhat higher energy particles.

- A large fraction of the tracking will be provided by solid-state devices (although the TRT is very important for the p_T measurement).
- ATLAS has pixels, which have 3D readout.

ATLAS suffers from:

- A significantly more complicated tracker. The SVX is much more compact than the Pixels and SCT.
- Pile-up of minimum bias events (although for an M_W measurement at low luminosity, the number of superimposed events will be 2 or 3).
- More material in the tracking volume and hence in front of the calorimeter causes increased dE/dx, multiple scattering and brem - all of which degrade resolution, while the brem can introduce systematic shifts.
- A significantly non-uniform B-field.
- The SCT has binary readout rather than analogue.

While CDF have achieved an impressive understanding of their detector, it has taken ~10 years ... ATLAS should be trying to achieve a much better understanding on the time-scale of the low-luminosity running.

The requirements advocated in [9-2] are five times more than 'ambitious'. Nevertheless, the approach which will be adopted for this programme of work is:

1. Check the assumptions and omissions.
2. Understand the requirements.
3. Identify any 'killer' arguments.
4. Study parts of the problem with an attitude of trying to succeed.

   It is all too easy to see difficulties with meeting the requirements - but in many cases there are ways around the problems.

To achieve the desired understanding will take many man-years. We should not invest that effort now, since as we start to build detectors, we will develop a far better picture of what systematics we can expect. It would be all too easy to set up programmes of work to prepare code to align the detector, but this would be less useful when we are a long way off having the final software. Further, there is a danger that one simulates expected systematics and then tries to determine the distortions using fitted tracks. This is somewhat academic, since one will inevitably recover the original distortions, yet in real life it is unexpected systematics which tend to limit understanding.

To achieve the ultimate precision will require the use of all possible 'handles' and while the use of real tracks will supersede any measurements made by hardware, the hardware measurements will provide very useful starting points to enable the alignment to converge rapidly and they will provide valuable constraints, especially for parameters which are difficult to measure with tracks.

2 Alignment

2.1 Introduction

2.1.1 General Considerations

In this note, a distinction is made between **local** effects which in principle should be corrected at the level of individual components, such as modules or straws, and **global** effects which are extended in space and can be corrected at the level of complete units, such as barrels, subdetectors or even the complete ID.

Ideally, one would like to have straight line tracks passing through the ID for alignment purposes. Unfortunately there is no source of sufficiently many really high-p_T tracks. Since a priori, the p_T of a given track is not known, alignment by shifting modules so as to reduce the means of residuals can only correct certain distortions. Tracks can be used to produce continuity through out the detector, but cannot remove global **translations**, **rotations** or, most importantly, **sagitta** or **scale corrections**.

Global translations and rotations can only be corrected by reference to external systems - in fact, such distortions are only of relevance to measurements with external systems, i.e. the calorimeters and muon chambers. Sagitta distortions cause shifts in Q/p_T and can be corrected by reference to particles of opposite charge - this is discussed more in Section 2.5.

The handle on alignment comes from the **residual distributions**. The residual of a track in a detector is the difference between the measured hit position and the extrapolated track fit. Unfortunately, one cannot use the true position where the track crosses the detector, since in real life, this is not known. Undoubtedly, the most important effects which need to be corrected are in the x-y projection.

In what follows, greater emphasis is placed on alignment with the Precision Tracker, consisting of the SCT and Pixels, rather than the TRT. This is not very satisfactory since it is well known that the TRT contributes very significantly (more so than the Pixels or SCT) to the p_T determination - see Figure 4.9 of the ID TDR. Clearly more thought must go into the TRT alignment. Nevertheless, a well aligned Precision Tracker will be a valuable tool for understanding the TRT.

In general, if a module of the Precision Tracker can be considered to be a well understood unit, then it is a rigid body with 6 Degrees of Freedom (DoF). Each module makes 2D measurements. The measurements provided by many tracks in principle give many constraints, however, it is necessary to group these measurements from separate track residuals into a reduced number of characteristic quantities - the most obvious being the mean. It is impossible to determine 6 DoF from two means, and so additional quantities (such as the means in different regions of the module or moments of the residuals over the spatial extent of the module) must be formed. When complete equations are written to solve for all DoF of the module, there is a tendency for the naive precisions which can be achieved (for example simply determining $R\phi$ shifts from means of $R\phi$ residuals) to suffer from **dilution** - these occurs when there are other correlated degrees of freedom. I define the dilution factor D as the increase in the variance on a fitted parameter (in particular, the $R\phi$ shift) arising from allowing for all DoF compared to the naive assumptions. This factor corresponds to the increase in statistics required to achieve a given precision. These dilution factors turn out to be quite delicate to estimate and cannot be guessed naively (my first guess was to divide the number of DoF by the number of measurements). These factors are typically between 1 and 2 and are discussed in more detail in Appendix 10.1. However, what really matters is the errors on reconstructed measurements and fitted track parameters, and any dilution of precision of the alignment constants due to correlations will tend to cancel when correcting measured coordinates.

2.1.2 Requirements

2.1.2.1 In the Bending Plane

After all residual effects have been 'mopped up' using global calibration, in particular the Z mass constraint, the effect of alignment systematics will be to smear W transverse mass distributions, but the mean position of the peak should be correct. Hence it is not obvious that superb alignment is necessary. However, unless all possible contributions to systematics are well understood, then differences between W's and Z's (number of leptons, p_T and angular distributions) could lead to systematics which are hard to reduce.

The current specs are 7 and 12 µm for the Pixels and SCT respectively, and they come from the desire that the momentum resolution (and other track parameter resolutions) should not be degraded by more than 20% (see Table 9-5 of [9-4]).

If the alignment were sufficiently good that the local systematics on $1/p_T$ were less than 0.02%, then it would require that the alignment was good to O(0.1) µm. This seems completely implausible.

If some of the mis-alignment is to be mopped up by global corrections, then one might argue that statistically one could reduce the alignment uncertainties by an order of magnitude by looking at means of a system with several hundred components. To get to an effective 0.1 µm, would necessitate having an alignment of the order of 1 µm.

In some trivial sense, any resolution (for example 1 µm) can be achieved by the averaging of residual distributions containing very many tracks: the means are determined to $\sigma/\sqrt{N}$ (where σ is the width of the residual distribution). However, what type of *average* is satisfactory is far from clear. Since one ought to try to understand systematics as a function of many variables, for example

- time: fill-to-fill or within a fill
- p_T, η, ϕ
- local position within module

N will not be infinite. Further, there will be many complicated effects which will come in at the ~1 µm level. While some of these may be capable of being parametrised separately, it will be difficult to understand the alignment better than a factor of ten below these effects.

Lastly, it goes without saying that 1 µm really is very small on the scale of the ID. 1 µm is a hundredth of the width of a human hair!

2.1.2.2 In the R-z Plane

The ultimate calibration will come from the use of the Z resonance. Effectively, this will be used to understand the measurement of p_T since it is p_T which enters the formula for the transverse mass, used to estimate M_W. But since $M^2 = 2\, p^+p^-\, (1-\cos\Delta\omega)$, to understand $p_T = p \sin\theta$ will require that the polar angle is measured sufficiently well. The statistical error on θ is of the order of 1 mrad (see [9-7]) and is dominated by the Pixels - this will lead to statistical error O(0.1)% on the p_T scale. To obtain a systematic error which is a factor of 10 less would require an understanding of the position of the pixel modules to a 10% of their intrinsic resolution. Since the Pixels provide $\sigma_z \sim 70\ \mu m$ (see [9-10]), this would necessitate understanding the position of the pixel modules to ~7 µm in z. This seems quite tough and maybe the effects of averaging random displacements would soften this requirement so that it does not have to be met for all positions and times. Further, since this requirement comes from the Z mass calibration, which will necessitate data accumulated over a period of the order of a month or more, it may be sufficient to obtain this precision after averaging over the same time-scale.

Some of the systematics associated with the difference between using the mass for calibration with the Z, and using the transverse mass for the W mass measurement would be reduced by the use if the transverse mass for both [9-8].

This would benefit from more thought and care with the terms containing θ.

2.1.3 Summary

Plausible estimates of the requirements for the alignment are:

- O(1) µm in Rϕ - a factor of ~10 better than indicated in [9-4];
- O(10) µm in z or R - a factor of ~2 better than indicated in [9-4].

While the need for high precision alignment in Rϕ is difficult to motivate because it can be taken out by the calibration with the Z mass, the requirement in the R-z plane is different in nature since it will not be removed by the calibration.

2.2 Practical Issues

There are many practical issues which will make alignment very difficult. Nevertheless, by taking care to understand all issues in some detail, it ought to be possible to allow for most of these effects by **parametrising** the effects and **factorising** the alignment problem so that the effects of some features can be 'deconvoluted'. This process will necessitate the use of all available information, including that from hardware alignment (FSI), surveying and lab measurements of individual components. For example, if there are global expansions of the detector due to thermal effects, these could be scaled to determine the motion at a given place of the ID, and such effects could be considered separately from local displacements of individual components.

The list which follows is undoubtedly not exhaustive, but should be illustrative. The emphasis is on the SCT, but some of the considerations will also apply to the TRT. A crucial issue is that of **stability** - see Section 3.

Global Distortions of Structures

During running, the effects due to thermal expansion are expected to be small due to the low CTE of the support structures and the goal of isothermal running. Nevertheless, some expansions cannot be ruled out. If sufficiently large, these maybe detected by the FSI system, otherwise they should be relatively easy to determine as a function of time during a fill using tracks which can be averaged over larger regions of the ID. It may be possible to parametrise such effects as a function of measured temperatures or luminosity.

There will also be gravitational effects whereby complete assemblies will be distorted. In addition, in the case of the TRT, individual wires will sag in the barrel by as much as 15 μm (see Section 12.4.3.2 of [9-5]).

Module Assembly Errors

It would be nice to be able to treat SCT modules as perfect, well-aligned components which can be used as basic building blocks. Each module consists of four silicon wafers. Clearly it would be nice not to have to align the individual wafers separately. Further, there will be a finite number of jigs and should these have systematic effects, the imperfections can be parametrised for sets of modules. The silicon wafers will be aligned correctly to 2-3 μm in Rϕ. Each module will be measured with a precision of < 1 μm on each side; the relative alignment of one side to another should be good to 4 μm. With the possibility of using these measurements, it seems feasible to use the SCT modules as well defined sub-units.

Thermal Effects in Modules

As for the support structures, the thermal effects for the modules should be minimised. However there may be effects whereby modules will distort: expand, twist and go banana-shaped. By measuring detectors in the lab as a function of heat-load, for example with ESPI, it should be possible to understand possible distortions and parametrise as a function of measured temperature or luminosity. Recent (Spring 99) tests of cooling a module by 30°C from room temperature caused distortions at the ends of ~16 μm. This module did not have a base-board - it is not clear whether a real module will be more or less rigid.

Vibrations

Significant effort is going in to reducing vibrations. Nevertheless, other experiments have seen vibrations at the level of a few microns. The most likely consequence of vibrations is a small degradation of the resolution, but they should not lead to systematic effects.

Silicon Wafer Construction

The features on the silicon wafers will be positioned to precisions generally better than 1 μm. In particular the active width of the SCT detectors will be correctly described by 768×80 μm. In practice, care should be taken to avoid edge effects from the outer strips when reconstructing hits. There may be small relative misalignments at the micron level between the implants in the silicon and the metal layers which include the readout strips.

Location of Charge Deposition in Silicon

While mechanical surveys of detectors may indicate that they are at some location, the actual location of charge deposition and the subsequent location of reconstructed coordinates is a separate issue. It is the latter which is of greatest significance to track reconstruction. Reconstructed coordinates will depend on

- Microscopic details of charge transportation in silicon wafers - can be understood at some level by careful modelling. Angular effects can be investigated in test-beam.
- Lorentz effects - will necessitate a modest knowledge of the local B-field.

- Depth of charge deposition - this is important for the reasons discussed in Section 2.5.1. It also induces Rϕ displacements by projection due to non-normal angles of incidence.

  It has been observed (for example in Delphi) that the effective charge deposition is not located at the mid-plane of the detector because of the details of charge transportation.

  - The SCT strip detectors are p-on-n, and ought to be operated fully depleted. However, after irradiation, the detectors undergo inversion. Should radiation damage prevent the fully-depleted operation of the detectors, the effective depth will not be in the centre of the wafer.
  - The pixel detectors are n-on-n and can be operated partially depleted.

Beam-spot Variations
It is anticipated that the beam-spot size will be $\sigma_x = \sigma_y = 15$ µm. This is compatible with the resolutions of the silicon detectors. However, from fill-to-fill, it is likely that the beam-spot will move around by ~100 µm (in LEP, comparable jumps were observed typically a few times per fill corresponding to the loss of RF power-units). It should be no problem to monitor this motion: for example, for a single B-physics event, the beam spot can be determined to ~30 µm and hence the mean position can readily be followed at the 1 µm level.

2.3 Local Alignment with Overlaps

Overlaps will enable local alignment of modules within units (barrels or wheels). Currently (Spring 99) there is some debate as to how large these overlaps should be in the SCT. The size of the overlaps must allow for edge-effects when reconstructing measurements (which may necessitate ignoring edge strips) as well as placement tolerances. The tolerances (half-width of a square distribution) on the overlaps are guessed as being 100-200 µm in the SCT Barrel and 40 µm in the SCT Wheels. Overlaps are also planned in the Pixels. The Rϕ overlaps will enable alignment of *rings* of modules in ϕ; the R/z overlaps will correct the relative alignment of rings in ϕ and in the Pixels provide the R/z alignment shifts.

The advantage of the overlaps is that there is very little extrapolation error and hence the effects of multiple scattering are small. The appropriate quantity to consider is the **difference of the residuals** between the two overlapping detectors. The uncertainty due to extrapolation from other layers cancels to first order. The width of the distribution should be close to $\sqrt{2}$ times the intrinsic resolution (22 µm, for SCT). The measurement of the residuals around a barrel effectively 'pins' the modules at the edges. The method is unable to identify which module is displaced (i.e. global ϕ-rotations of the complete barrels/wheels) and is insensitive to most global distortions (e.g. elliptical or 'pear-shaped' deformations) in x-y in the barrel. The corresponding algebra is considered in Appendix 10.2. Despite the fact that there will be global distortions to be removed and some DoF of single modules will not be well constrained, locally ϕ measurements will probably be correct to the level of the naive expectations without the need for dilution factors. If the SCT modules are considered to be well understood, there is the possibility of a factor of 2 improvement in the variances coming from the use of the stereo measurements.

A valuable constraint in using the overlaps comes from the ability to 'complete the circle' in each ring. If this constraint is lost then it will be analogous to performing the alignment of a simple line of detectors. Problems will occur from dead modules or inefficiencies which may be more likely for edge diodes. There is the possibility to lose complete columns ('staves') of modules in the barrels which would certainly weaken this approach.

2.4 Local Alignment using the Complete Detector

Using tracks crossing several barrels/wheels, the complete ID can be internally aligned. The advantage is that the acceptance is the complete detector rather than just the overlaps. The disadvantage is that extrapolation between layers is more uncertain and will be sensitive to multiple-scattering.

Because nearby tracks will cross different modules, since the modules in different SCT barrels are not arranged in 'towers', constraints can be obtained between adjacent modules by connection to those in different layers. The tracks can be considered to loosely 'pin' the modules with a 'web' of connecting measurements - just like the FSI networks. The statement about 'towers' is not completely true: due to the periodicity of 8 in the SCT, the connections made by stiff tracks will be limited to sectors of 45°.

This approach is *local* in so far as corrections are made by aligning individual modules. Nevertheless, it should be able to remove many of the larger scale *global* distortions. While radial distortions (e.g. elliptical distortions) would seem hard to remove, the finite width of modules should provide some handle on this.

Similar remarks as for the overlaps can be made about dilution factors and stereo strips in the SCT. If there are dead modules, then the constraints which may have been lost then looking at the overlaps for a given ring of modules may be partially recovered by 'hopping around' dead modules in the R/z direction on the same barrel/disk or by reference to modules in neighbouring barrels/disks.

2.4.1 Obtaining a Solution

The standard way to solve problems of alignment is by minimising a χ^2 describing the measurements. Here, 'measurements' correspond to the means (or higher moments) of residual distributions (averaged over many tracks) with errors corresponding to *width/√tracks*. Since the residuals are with respect to the fitted tracks, and the fitted tracks are formed using the same set of hits, there is some bias in the residuals which will tend to reduce residuals.

If we consider for example N = 2112 barrel SCT modules which are considered to have perfect internal alignment, then there are 6N parameters to be found. Therefore for each module, at least 6 measurements will have to be derived to allow a determination of all the parameters. Just for the SCT barrel, this would lead to solutions involving the inversion of $6N\times6N$ matrices.

This may seem unthinkable, however this is precisely what ALEPH [9-9] and SLD have done with 1000×1000 matrices. Surprisingly, the solutions are well defined and stable and the matrices inverted in time-scales ~1 hour. Because the approach is rigorously correct (although only as good as the assumptions) and democratic (does not give any part of the detector preferential treatment), it is worth considering - at least as a tool for parts of the bigger problem. Further, different types of measurements could be used corresponding to regions where overlaps could or could not be used.

2.5 Sagitta Corrections

Sagitta distortions can occur even when the detector elements seem to be perfectly aligned using particle tracks. They can arise from differential twists of structures and have the form $R\Delta\phi \propto R^2$. Ideally these should be corrected in a more global way by rotating complete SCT barrels or rings. However, inevitably corrections are made not in the alignment but to reconstructed tracks in the form: $Q/p_T \rightarrow Q/p_T + \Delta$.

To avoid sagitta distortions, it is necessary to ensure that tracks of opposite charge have the same behaviour. In principle, one could compare the measured spectra of oppositely charged particles - in practice this is not so precise. If one looks at the means of $1/p_T$ for oppositely charged particles, the uncertainties on the correction to Q/p_T will be $\sim 1/(\bar{p}_T\sqrt{N})$. If the p_T spectra can be normalised by an estimate of p_T, then the uncertainties on the correction will be $\sim\sigma/(\bar{p}_T\sqrt{N})$, where σ is the width of the normalised distribution and may be much less than unity. The estimate of p_T need not be unbiassed, the only condition is that it should not be correlated to the track charge.

One approach, followed by CDF, is to use electrons and the energy determination from the calorimeter, i.e. one studies E/p for e^+ and e^- separately. Another possibility would be to normalise muons by the momentum measured in the muon system (the uncertainty on the energy loss correction is around 0.5 GeV). The drawback with this is that the momentum measured in the Muon System is also charge dependent and could suffer even worse from sagitta corrections. Estimates of the numbers of events required are given in Appendix 10.3.

2.5.1 Radial Distortions

Radial distortions stretch tracks and cause scale errors in $1/p_T$. Since $1/p_T \propto 1/R^2$, $\delta p_T/p_T = 2\delta R/R$ so if we want $\delta p_T/p_T$ better than 0.02%, need δR better than 100 μm at R = 1 m. It is not clear to what extent it is appropriate to apply this directly to the SCT, since the TRT is essential in measuring p_T, however it would suggest we need to know the outer barrel radius to ~50 μm.

The radii may depart from their nominal value due to:

- Imperfections in the construction of support cylinders.
- Gravitational sagging causing elliptical or pear shaped distortions.
- What actually is required is the location of reconstructed coordinates and this will be affected by the location of charge deposition in the silicon.

Handles on the radial distortions should come from:

- FSI alignment.
- Overlaps: The circumference determined from the sum of the wafer widths can be compared with $2\pi R$. This can only constrain the circumference and not detect deviations from cylindricity. See Appendix 10.2.
- General alignment: If relative shifts of residuals within a module can be understood to O(1) μm, then since the module subtends ~0.1 rad, it should be possible to obtain some 10's of microns precision.

2.6 Questions and Work Programme

This section includes questions and proposals for studies. It is undoubtedly far from complete.

Simon Peeters is studying the Precision Tracker and **no-one** is studying the TRT.

2.6.1 Specifications

- Is ~1 μm the appropriate scale for the alignment in the x-y plane?
- What does it mean? With what frequency in time does it need to be determined?

These are difficult questions to consider and answers will probably only become clear after a lot more work.

2.6.2 Hardware Alignment

- How precisely can the FSI system determine the barrel radii and cylindricity?

2.6.3 Local Alignment with Overlaps

- What is the width of the distribution of the difference of the residuals?

  Should be ~30 (14) μm for SCT (Pixels).
- How quickly can we align within barrels (or rings in the end-cap)?

  In Section 9.3.6.1 of the ID TDR, it was estimated 1 day[1] was needed to fix the overlaps with low-p_T (6 GeV) muons. This gives ~100 muons/overlap giving ~3 μm. To get ~1 μm relative alignment would require ~10 days.

  Need to ensure overlaps are enough. Should have ≥ 10 strips overlap - outer strips may be less useful due to edge effects.
- How does alignment (residual distribution) vary with p_T and η?

  Could we use all tracks with p_T > X GeV?

  The overlaps should be OK down to p_T ~ 1 GeV, but will appear greater for one particle charge compared to other. Does this matter? Probably not.
- How easy would it be to break each of the 12 cm sets of strips into the two 6 cm wafers, and what can be deduced about their relative orientations in the plane of the module?

The above studies can probably be done by effectively studying a single example of the overlap in each barrel (or ring). Since the datasets which are available tend to have tracks (e.g. single muons) produced uniformly in azimuth, the statistics can be multiplied by adding the residuals for all overlaps in a given barrel (ring). This works, since the alignment in `DICE` is perfect.

1. I tried to repeat the calculation: 100 Hz of μ6, flat in η, hitting barrel modules at $|\eta| = 0$ at R = 52 cm with 10 strips overlapping with a 100% duty cycle gives 100 hits/day/overlap.

2.6.4 Local Alignment using the Complete Detector

Similar questions to those for the overlaps could be foreseen.

- What is the width of the distribution of the residuals?
- How quickly can we align within barrels (or rings in the end-cap)?

  Start with 6 GeV muons and consider firstly azimuthal shifts. As one gets more involved with this work, so the extent of the study can develop and become more sophisticated.
- To what extent can one use the variation of residuals across the width of a detector to constrain the radial location?
- How does alignment (residual distribution) vary with p_T and η?

  Could we use all tracks with $p_T > X$ GeV?
- The 6 GeV muons from the B-physics triggers could be significantly contaminated with π/K decays in the ID. Is this a problem? Certainly seems undesirable.

  If quality cuts are applied to muon candidates, such as χ^2 cuts, then they will appear to be continuous helices - however, then this is biassed. The muons could be cleaned by demanding that they come from displaced vertices, consistent with the B-lifetime.

  Is it better to avoid using muons with the above problems. In triggered events, are there enough tracks (pions) of modest p_T and sufficiently clean (isolated) which can be used?

In principle, the questions of 'How long will it take to attain a certain precision?' do not depend on the quality of the initial alignment - irrespective of the size of corrections, a χ^2 method gives the corrections without iteration - the only considerations are to collect sufficient statistics. In practice, alignment is inevitably far from straightforward since there can be many different types of information to combine, the procedure may need to broken up into sub-problems and there inevitably will be discrepancies to resolve - the latter often limit the extent to which systematics can be reduced by increased statistics, and hence lead to limits determining the final systematics. It is probably true that the initial alignment does not affect the ultimate precision which can be achieved, but in real terms it tends to increase the time to converge on the final alignment. Hence it is very difficult to answer the question 'How long will it take, given that one starts from an initial alignment of X μm?', but it is possible to estimate the integrated luminosity and hence running time needed to collect the required statistics.

With the above questions, it is probably inappropriate to try to write an 'all singing, all dancing' program to solve for all parameters. Rather, it is best to start simply, trying to understand how to do alignment in a small range of $\Delta\eta\times\Delta\phi$.

What about the TRT?

- What are the degrees of freedom?

  Probably need to consider straws within modules and modules within the TRT.

3 Stability

3.1 Introduction

This chapter deals with the mechanical stability and is manifestly correlated to the previous chapter on alignment. To a large extent, the alignment and the understanding of the imperfections of the detector would be relatively straightforward in the absence of time-dependent changes. The other stability issue relates to the Magnetic Field. Presumably the field strength stability will be determined by measuring the current in the coil as well as directly using NMR probes at the centre of the ID. These probes will also be sensitive to shifts of the coil within the cryostat.

This chapter sets out some of the requirements associated with the stability of the ID. In many ways, it should precede the discussion as to how the alignment will be performed. However, it is perhaps more helpful to put it in the context provided by the more general discussion of alignment and an understanding of what tools will be available.

The specifications on the stability must take into account:

- The requirements for Physics and the need to be able to understand other sources of systematic uncertainty.
- The frequency and nature with which in situ alignment measurements can be made.

The specifications should not be set in isolation from the alignment strategy, since if movements can be followed, they are not a problem. In situ alignment constraints will come from

1. Hardware alignment, i.e. FSI which will provide a limited number of measurements at particular times and with fixed precision.
2. Track based measurements which will have statistical precisions which decrease roughly like $\sqrt{time}$.

3.1.1 Requirements

There will be different types of movement (see following sections), but firstly, envisage movements in which displacements increase with time at a rate ρ over periods of time which are not too long and such that the motion is reasonably smooth. If the intrinsic resolution of a module is σ_i, then after a time T in which N measurements have been collected, the precision which can be obtained will be approximately $\sigma_i/\sqrt{N} \oplus \rho T$. If this is to be less than some target precision σ_T, then the time T required will be such that $N > (\sigma_i/\sigma_T)^2$ and the stability must be $\rho < \sigma_T/T$. If the rate at which measurements are made is R = N/T, then $\rho < R\sigma_T^3/\sigma_i^2$.

The goal for the alignment set out in this note is 1 µm in Rϕ and 10 µm in z/R (see Section 2.1). It would appear that the statistical precision for the alignment with track measurements can be met on a time-scale of the order of 1 day [9-7][1], hence the stability requirements for the Precision Tracker are:

- Stable in Rϕ to 1 μm/day.
- Stable in z (barrels) and R (disks) to 10 μm/day.

Having made these statements, there are a number of qualifications which need to be made (see Section 3.2).

In what follows, emphasis will be put on Rϕ displacements, but in many cases, the corresponding estimates for R-z quantities can be obtained by multiplying by 10.

Finally, as with many of the sources of systematics, one should not be too generous with the requirements. Although it may appear that an understanding of various effects can be obtained at the required precision, the combination of many different systematics will lead to huge difficulties in trying to identify the separate components. Further, in the case of Rϕ measurements, the effective precision required to have an absolute understanding of the momentum scale to 0.02% is actually O(0.1) μm. To obtain this precision statistically would require most of one year and to require a stability of 0.1 μm/year is not sensible. The assumption has been made that by understanding the alignment locally to a precision O(1) μm and assuming the underlying systematics are fairly random, then by averaging in time and space, the precision can be improved by the required factor of 10. It is far from obvious that this will be true.

3.2 Different Types of Time-dependent Distortions

This section overlaps to some extent with Section 2.2. The types of movement which will be easiest to deal with are those which are small and smoothly varying in space and time; however not all motions will be like this.

3.2.1 Vibrations

As stated earlier, vibrations should not lead to systematic effects. The principle requirement is that they should not spoil the track parameter resolutions and therefore should have amplitudes less than the specifications set out in Table 9.5 in the ID TDR: 7 μm (12 μm) in the Pixels (SCT).

Since it will be necessary to understand the momentum resolution to O(1)%, it will be important for any vibrations to have a stable amplitude.

3.2.2 Local Distortions

These correspond to changes at teh level of individual modules.

1. The alignment was considered in Rϕ only - however, since the resolutions are approximately an order of magnitude worse in the R-z plane, it seems plausible that if the goals can be met in Rϕ, they can also be met in R-z.

Jumps
Random jumps where modules move in a discrete way (for example, they suddenly overcome the friction provided by a grease joint associated with a cooling pipe) are highly undesirable and should be less than 1 μm in total in Rϕ in a day.

Thermal distortions
These should be minimised as much as possible by a) isothermal running (all modules of the same type should run at the same temperature which is constant during a fill) and b) designing modules to reduce thermal distortions. These conditions may be difficult to fulfil and it may prove necessary to parametrise the effects as a function of measured temperature or luminosity. This could be done by superimposing data as a function of temperature from different runs or modules. For this to work, it is important that from run to run, the modules should operate at the same temperature and that there should not be hysteresis effects as the electronics is powered up and that any distortions are reporoducible. Changes due to powering up electronics should occur rapidly to avoid large changes at the start of running.

3.2.3 Global Distortions

These correspond to larger scale distortions associated with the structure.

Gravity
There will be some sagging of the ID. Due to differences between the loading and supports used at the time of the external survey, the distortions will inevitably be somewhat different from those measured in the survey. This is not likely to be a significant problem; what is less desirable is the time dependence of this: after any installation/access, the ID will relax. It is important that when data-taking resumes a few (?) days later, that the rate of change is small: less than a few microns per day.

Humidity
Should be reduced by keeping ID in dry nitrogen (or $C0_2$). Again, after interventions, damp air may enter and there will be a relaxation time. Similar requirements to Gravitational effects.

Thermal distortions
Similar remarks to those in Section 3.2.2 can be made.

3.3 Measuring Time-dependent Distortions

3.3.1 Local Distortions

Local distortions will need to be followed using charged tracks.

3.3.2 Global Distortions

Global distortions should be monitored by charged tracks, although this will be difficult for some modes.

Global translations
These will not affect mass measurements within the ID, but will affect:

- Matching to the EM Calorimeter. The η-strips have a resolution of ~300 mm [9-6].
- Matching to the Muon System tracks. If the ID is to be able to contribute to the combined momentum estimate, it is essential that translations should be controlled to better than $\sigma(z_0)$ ~50 µm.

In the absence (?) of some in situ measurements of the position of the ID with respect to external reference frames, the Muon System itself may provide the best measurements of global longitudinal translations.

Global Longitudinal Expansions
If the complete ID expands uniformly in z, then straight tracks will continue to look like straight tracks and it will not be possible to deduce distortions from charged track residuals. However such effects should be readily observed with the FSI which will have a longitudinal resolution O(1) µm. Although the FSI will probably only be on the SCT, the connection to the Pixels with charged tracks will enable the Pixels to be understood. Of course it is unlikely that with its different subdetectors, the complete Precision Tracker will have a uniform expansion, but nevertheless, a uniform expansion is the lowest order component of a more general distortion.

The FSI will be associated with the SCT and so it should be possible to understand the overall longitudinal expansion of the SCT. However, since the z resolution of the SCT (~500 µm) will be much worse than the alignment precision in z required for the Pixels (~10 µm), it may prove difficult to transfer this information to the Pixels. Therefore, if the Pixels are not equipped with FSI, they need to be stable in z over the complete length of the barrels to 10 µm.

Global Radial Expansions
Radial expansions will affect the mesurement of the polar angle and the curvature measurement. These require that the radius be known to ~10 µm (Section 2.1.2.2) and ~50 µm (Section 2.5.1) repsectively. These uncertainties should be well constrained by the use of the overlaps (see Section 2.5.1).

4 B-field and Momentum Scale

The momentum scale depends critically and directly on the B-field. In addition, there will be some residual effects arising from imperfections in the alignment and some of these will be mopped up with the scale corrections.

4.1 Magnetic Field

The original goal was to understand the B-field to the 0.1% level [9-1] - now we need to know it at least a factor of five better. One of the limitations for CDF was the knowledge of inhomogeneities in the field - of course our field is much worse. It is not clear what the spatial scale is over which the field must be known locally. Further, it should not be assumed that the field is axially symmetric.

Since the field is a continuous spatial function (unlike some of the displacements of individual detector modules), knowledge of the field at one point will constrain the field at a neighbouring point. More explicitly, it is probably very valuable to express the field in terms of solutions of **Maxwell's Equations**. This expression should be limited to a reasonable number of higher order terms and the result of calibrations will be to determine the coefficients of the various terms.

4.2 Direct Measurements of the Field

The field will be mapped with ~10^3 measurements each of 0.1% precision (both statistical and systematic). This mapping will be made inside ATLAS before the ID is inserted. The assumption is that there will be no magnetic materials which will perturb the field. There is the possibility that nickel will be needed to coat the aluminium power cables where they enter the ZIF connectors - rough estimates suggest that this could total O(100) gm. There will be stainless steel pipes, but their permeability is believed to be negligible.

During data-taking, the field will be monitored with an NMR probe to 0.01%. This should control the overall normalisation of the field. The NMR probe has to be in a region of fairly uniform field. It would be nice to include some Hall probes, however there do not appear to be sufficiently radiation hard.

Finally, there is some optimism that the technology for measuring magnetic fields will improve and allow significantly better measurements than those currently planned.

4.3 Calibration with Z Mass

CDF used $J/\psi \rightarrow \mu\mu$ to understand their tracker calibration. This suffers from the fact that there are systematic uncertainties in extrapolating from the J/ψ mass scale to the W mass. ATLAS will benefit from the plentiful statistics available in $Z \rightarrow ll$. Using $Z \rightarrow ll$ has the distinct advantage that the leptons have similar (but not identical) distributions to those from $W \rightarrow l\nu$. If the B-field can be directly measured with sufficient precision, this will enable the Z mass constraint to 'mop up' any residual problems. It should be noted that the reconstructed Z mass is not very sensitive to sagitta distortions because they tend to cancel when multiplying the momenta of +ve and –ve leptons.

The EM Calorimeter plan to use $Z \rightarrow ee$ (in conjunction with E/p) to determine the absolute energy scale locally [9-6]. With 100 pb^{-1}, they can achieve a local calibration of 400 separate regions to 0.4%. Things are conceptually straightforward for the Calorimeter: electrons of given η–ϕ, calibrate cells on the 2D surface of a cylinder. For the ID, it is less obvious how to proceed since the magnetic field extends through the 3D volume of the ID and the effect on charged particles is via an integral of the field along the trajectory. Nevertheless, if all remaining uncertainties are absorbed into the finite number of coefficients in the field expansion, then perhaps 'measurements' could be made in a small number of bins, say 10×4 in η–ϕ. Subsequently, these 'measurements' would need to be used to constrain the field coefficients. With 10^4 pb^{-1}, this would lead to a precision of 0.01%.

It is not clear how to proceed with studies of this. The momentum which will be reconstructed for a given track depends in a complicated way on the B-field at all points along the trajectory and the precision of measurements at detector planes. The effect of perturbations, other than those to the overall scale, cannot be trivially estimated. Work has started recently (Winter 98/99) [9-11]to study track fitting with an inhomogeneous field. In principle, to formulate a χ^2 which could be used to determine coefficients of the field components would require an understanding of how the reconstructed track momenta depend on the coefficients. This would seem very difficult. Instead, it might be necessary to consider tracks in η–ϕ bins and determine a 'measurement' of the average field - what this 'average' would mean is unclear. Then, as indicated above, these 'measurements' would be used to constrain the field coefficients. One would need to know how the average field depends on the coefficients - and again this would be equivalent to understanding the reconstructed momentum dependence. The trouble is that since the tracks effectively provide 2D information (as a function of η–ϕ), there may not be the ability to constrain the 3D field. However, since the situation is exactly the same for leptons from W's, this probably does not matter too much. Maybe we should simply derive corrections to the $1/p_T$ scale as a function of η–ϕ.

While it would be nice to fit solutions of Maxwell's equations, this would only be possible if the alignment was sufficiently well controlled. This would imply understanding it to the level of 0.1 μm (see Section 2.1.2). While this would seem completely hopeless, when averaged over the coarse η–ϕ bins, this may be achievable.

4.4 Calibration with J/ψ Mass

CDF used the $J/\psi \rightarrow \mu\mu$. This has the feature (advantage or disadvantage?) that the muons are close together in space and will see similar global effects. The problem with J/ψ is that CDF found they were limited by understanding the energy losses experienced by the muons. Muons at ATLAS will tend to be of higher energy, but then there is much more material to traverse. Nevertheless, at some time, the resonance should be studied. Generally, every piece of information will be valuable.

4.5 Questions and Work Programme

Steve Snow has given some thought to the B-field. **Igor Gavrilenko** has coded track-fitting in the non-uniform field.

4.5.1 Magnetic Field

- How confident are we that the mapped field will not be modified by the insertion of the ID into ATLAS?
- What are the systematics of the field measurements? Is there a chance that they could constrain the field sufficiently well?
- How could a parametrisation of the field be constructed?

  Solutions could be obtained using cylindrical solutions of Laplace's equation $\nabla^2 B = 0$ - leads to Bessel functions (see Section 3.7 of [9-12]). However the actual solution, allowing for the boundary conditions of the current in the coil, should correspond to a good approximation to that of a perfect solenoid[1] of finite length. To describe the latter well may require many terms in the expansion as Bessel functions. The situation will be further complicated by the magnetisation of the iron in the calorimeter. Ideally, one should seek parametrisations which are close to that of a perfect solenoid but with suitable perturbation terms.

- With a suitable parametrisation, is it plausible that a set of probe measurements could constrain the field sufficiently well?

4.5.2 Calibration with Z Mass

- Is it plausible that the alignment can be understood sufficiently well to allow the Z mass constraint to allow the B-field components to be determined in he final calibration step?
- Given a parametrisation of the B-field, think of a strategy to understand the B-field with $Z \rightarrow \mu\mu$.
- It might be possible/worthwhile to design some studies at the `KINE` level - although I cannot think what.

5 Material

Knowledge of the ID material is important to understand the energy loss suffered by electrons. Unless corrected, this reduces the reconstructed p_T and leads to a bias in the energy scale derived from E/p. What is important is the shift of the peak in E/p - this is determined by small but continuous energy losses as an electron traverses the ID material. Although there is no clear distinction between the two, the tail on the E/p distribution tends to be caused by one or more hard bremsstrahlung radiations. The reconstruction of p_T in the ID is not well defined but depends intimately on the assumption of the fitting procedure. The observed shift in the peak of E/p depends in a complicated manner on the integral of the material. Most of the weight will come from the Precision Tracker.

CDF understood their material by considering the E/p distribution and confirmed it by the use of conversions. They had ~10% X_0 in front of their main tracking volume. By contrast, ATLAS has an average of ~40% within the volume of the active tracking. By having so much material, we will be liable to second order complications, i.e. electrons undergo multiple brem, converted electrons brem and brem photons convert. Further, CDF estimated from first principles that they had 6.4% X_0, whereas they measured 8.1 ± 0.4% with conversions - a discrepancy of a factor of 1.3. Although we are going to great lengths to understand the material contents of the ID, there will be significant uncertainties on the numbers - things like hybrids can be notoriously tricky to understand. Various cross-checks must be made of the material:

- Detector elements should be weighed.
- They should be placed in test-beams to measure the material.
- In particular, reference planes (see comments on conversion) should be placed in test-beam.

1. By which, I mean uniform current flowing round a cylinder - not a helix.

5.1 X_0 Determination with E/p Tails

The size of the tail in E/p distributions should be a measure of the amount of hard brem which electrons undergo. This is in contrast to the smaller energy losses suffered by electrons in the peak. It is not obvious that the dependence of the tails and peak on the material is the same, and it may depend on the cuts.

Let the E/p distribution for electrons whose hardest brem is at a radius R be F(E/p,R) (normalised to unity) - this can be determined from the `KINE` information for a reference sample. The complete E/p distribution is

$$\Sigma\, C(R)\, F(E/p,R) + C(\infty)\, F(E/p,\infty)$$

where the sum is over the radii of the hardest brem, and R=∞ allows for cases where there is no brem above a certain threshold. To first order, the coefficients C(R) are proportional to the amount of material. Hence by fitting real E/p distributions by a sum of terms, it ought to be possible to estimate the corresponding coefficients and the relative amounts of material.

5.2 X_0 Determination with Conversions

Conversions provide an obvious way to determine the amount of material. However, for this to work, it is necessary to understand the efficiency very accurately up to some radius (probably around 80 cm). This is easier if efficiencies can be made very high, but currently, these efficiencies are typically 85%. Ideally, a dedicated conversion finding program should be developed with very high (or well understood) efficiency. Further, it is necessary to normalise the rate

a. either absolutely using a known flux of photons

b. or relative to some component whose material can be accurately estimated from first principles.

A known flux of photons could be determined from taking all EM clusters above some thresholds and subtracting all prompt electrons. This would then leave conversion photons and photons which are unconverted in the ID. However, it is probably difficult to avoid miscounting photons arising from π^0 decays. Alternatively, it may prove possible to extract a well defined rate of photons using FSR in the decay $Z \rightarrow ee\gamma$ where the presence of the photon is deduced by reconstruction. It seems plausible that reasonable rates of a few percent could be obtained after cuts to define reasonable energies and isolation for the photon. This could yield ~10^5 photons/year at low luminosity, but whether this would be enough remains to be seen.

CDF normalised their conversion rate to the rate from a wall in the tracker volume. It is necessary to find a component whose material is well understood and which can be clearly identified as a peak in the conversion distribution. The CDF conversion radial position resolution was ~4 mm, whereas in ATLAS it is somewhat larger with large tails due to electron brem. This may make it difficult to resolve clearly components in the tracker and generally, many composite components will have radiation lengths which are difficult to estimate. Alternatively, one could try normalising to the beryllium beam pipe. This is well defined, however it may be difficult to resolve due to its proximity to thermal shields and the B-layer and the conversion rate may be buried under the Dalitz decays at the primary vertex.

5.3 Questions and Work Programme

To facilitate studies, datasets with several geometries could be generated to compare with the standard geometry corresponding to 98_2. It turns out to be easy to increase SCT material in a fairly uniform way by increasing the density of the supporting cylinders and wheels. However, it is not so easy to increase Pixel material uniformly (it is dangerous to increase the silicon density, since this will modify the ionisation deposited, affecting hit resolution due to the effects of charge sharing). So far, data corresponding to an additional ~5% X_0 in the SCT has been generated. Data with increased Pixel material will only be generated if there are people who are prepared to study it. Information about these datasets can be found by going to the 'Material' page linked to the 'ID Performance' Web page:

http://atlasinfo.cern.ch/Atlas/GROUPS/INNER_DETECTOR/PERFORMANCE/X0/x0.html

The datasets which have been generated contain changes which are much greater than the required sensitivity in order to study the issues with much fewer number of events than will be available as real data.

Matevz Tadel is studying E/p in the ID; **Monika Wielers** had a quick look at conversions.

5.3.1 General

- Do we believe GEANT describes electron energy loss sufficiently accurately?
- How does the shift of E/p peak depend on the integrated material?

  Presumably it is associated with an integral of X_0 along the track weighted by some function of the radius.
- At what level do we need to know X_0 to control p and hence E at the 0.02% level?

  Can be seen from the difference in the peak position of E/p using the different datasets. Is it really at the 1% level?

  I have had a quick look at p^{KINE}/p and to understand this to 0.02% would require that the material of the SCT is understood at the 0.2% X_0 level, i.e. ~1% of the material present.
- At what level can we calculate material budgets from first principle?

  Richard Apsimon believes that the module material will be known to <1% (relative, not percent of X_0) and away from the ends, the complete SCT barrels will be known to <5%.
- Can we measure material, at least for a reference, using an X-ray source?

5.3.2 X_0 Determination with E/p Tails

- Is the dependence on X_0 the same for peak and tails?

  To ensure a direct relationship, it may be necessary to avoid some cuts. Further, it will probably be desirable to avoid the fits which try to account for brem.
- Is it possible to understand the E/p tails for the modified layouts in terms of the components of the distribution characterised by different radii for the hardest brem?
- It would be nice to use the electrons from $W \rightarrow e\nu$ for this - but is this biassed?

5.3.3 X_0 Determination with Conversions

- What does the radial distribution of conversion points in the ID look like?

  We have some experience with this following from the work of Section 6.3.2 of [9-4]. This is not totally trivial, since layers have an apparent thickness due to the tilt of modules.

- Is there some well defined component of the ID which could be used for normalising the rate?

  The need for a single simple component would be reduced if complete subdetector planes could be measured with an X-ray source.

- Is it plausible that we could understand the conversion finding efficiency sufficiently accurately?

  Also, one needs to understand the photon flux as a function of radius: it is reduced by conversions, but is regenerated by electron brem from primary electrons (not many) and from conversion electrons.

- Could $Z \rightarrow ee\gamma$ be useful?

6 Resolutions

It is claimed that we need to understand the actual p_T resolution at the percent level. It is not clear over what distributions this is allowed to be averaged, in particular is it averaged over pseudorapidity? Inevitably, the resolutions will be obtained from understanding the convolution of the resolution functions with the Z lineshape.

6.1 Questions and Work Programme

- At what level is it necessary to know the p_T and E resolutions and in what intervals?
- How many events are required to understand the resolutions to the required (1%?) precision?

7 Strategy

In principle, if a super-dooper calibration procedure can be developed, including all survey information, all alignment information from FSI etc. and all track residual measurements, then all corrections can be derived in a single process. However this is implausible and such a procedure may fail to identify some problems. Instead, it seems likely that calibration will be broken down into certain sub-problems. Undoubtedly, to derive a complete (or best) understanding will involve iteration.

The obvious strategy is as follows. With time it can be refined.

- Local alignment of ID starting from survey, FSI and previous alignment data.

- If necessary, a fast global alignment of barrels and wheels relative to each other using high-p_T tracks (muons from W and Z) to ensure efficient track finding.
- Local alignment using track data.
    - Alignment with respect to overlaps in Precision Tracker sublayers (barrels and disks).
    - Local alignment using all modules in Pixels, SCT and combined Pixels and SCT.
    - Alignment of TRT straws and modules with respect to Precision Tracker.
- Estimation of sagitta corrections using E/p.
- Estimation of scale corrections using $Z \rightarrow \mu\mu$. Cross check with J/ψ.

On a longer time-scale, the fo.llowing can be done:

- Estimation of ID material using E/p and conversions.
- Determination of ID resolution using $Z \rightarrow \mu\mu$.

8 Conclusions

The conclusions should indicate whether it is possible to control systematics on the p_T scale to better than 0.02%. At the time of the current draft, it is not possible to say anything. However, only by making a start on the studies discussed in this note will it be possible to gain understanding. As the work progresses, how to proceed should become clearer and the relevant questions will come to light.

I would like to thank Todd Huffman, Armin Reichold, Steve Snow, Daniel Froidevaux, Fred Wickens, Bill Murray, Richard Apsimon and Fabioa Gianotti who have contributed to thinking in this document.

9 References

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10 Appendix

10.1 Dilution Factors

See discussion in Section 2.1.

Just because errors on alignment constants are diluted, does not necessarily mean that the errors on reconstructed coordinates and hence track parameters are significantly diluted.

I need to write up my rough notes.

10.1.1 In SCT Strips

Current guess for simple ϕ-strips, ignoring stereo layers is 9/4.

10.1.2 In Pixel Modules

Current guess is ~1.5

10.2 Using Overlaps

Consider N silicon detectors {i=1,N} arranged in a ring around a barrel. There are N overlaps between the pairs (1,2), (2,3), ..., (N-1,N), (N,1). For a track crossing an overlap i, the residual between the measured hit and the extrapolated track can be found in the detectors i and i+1. By taking the difference of the residuals, the uncertainty in the extrapolation cancels to first order. (Care may be needed to allow for the small tilt angles between detectors.) The mean μ_i of the differences in overlap i has an rms $\sigma = \sqrt{2}\sigma_0/\sqrt{n}$, where σ_0 is the intrinsic resolution of the detectors and n is the number of tracks entering the distribution for each overlap.

The simplest assumption is that the alignment needs to be corrected by Rϕ shifts to each detector by Δ_i - these are relative shifts (because one cannot determine an absolute rotation of a barrel, only N-1 are independent). Further, there is a correction to the circumference Γ. This can arise from either the effective width of the detectors not being correctly understood (should be good to 1 μm) or due to a radial uncertainty. This leads to N independent parameters to be determined from N measurements.

If the circumferential change is shared evenly by all detectors, then

$$\mu_i = \Delta_i + \Gamma/N$$

Since the sum of the relative shifts ($\Delta_i = \text{shift}_{i+1} - \text{shift}_i$) must be zero: $\Sigma\Delta_i = 0$, it follows that

$$\Gamma = \Sigma\, \mu_i$$

and

$$\Delta_i = \mu_i - \Sigma\, \mu_i/N$$

The variance of Δ_i is $(1-1/N)\sigma^2$, while the relative shift of the (m+1)th detector relative to the 1st is $\Sigma\Delta_i$ and this has a variance $m(1-m/N)\sigma^2$. The variance on the change to the circumference is $N\sigma^2$, hence the error on a correction to the radius is $\sqrt{N\sigma^2}/2\pi$.

10.3 Estimating Sagitta Corrections

The sagitta correction is of the form: $Q/p_T \rightarrow Q/p_T + \Delta$. Δ can be estimated from the comparison of the normalised signed distribution: $Q\rho/p$ where ρ is an estimate of p from another detector, such as E measured in the EM Calorimeter:

$$\Delta = (Q\rho/p\,|_{+ve} + Q\rho/p\,|_{-ve})\ /\ 2$$

With the assumption that the statistical error on p is negligible compared to that on ρ (not necessarily true, but probably OK within uncertainties), the uncertainty on Δ is $\sigma(\rho)/p^2/\sqrt{N}$ where N is the total number of tracks used for correction. The uncertainty on the momentum scale for M_w measurements is $p_w\delta\Delta$, where $p_w \sim M_w/2$. So the requirement is that

$$p_w/p\ \sigma(\rho)/\rho/\sqrt{N} < 2\times10^{-4}$$

- For electrons from $Z\rightarrow ee$ measured by the EM Calorimeter, $p \sim p_w$ and $\sigma(\rho)/\rho = 10\%/\sqrt{\rho} \sim 2\%$. This implies N must be greater than $\sim10^4 \ll 3\times10^6$ Z's per year.
- For muons from the μ_6 trigger measured by the Muon Spectrometer, $\sigma(\rho)$ is dominated by correction to energy loss ~0.5 GeV, so $\sigma(\rho)/\rho \sim 10\%$. Since p ~ 6 GeV, N must be greater than $\sim10^7 \ll 10^9$ muons per year.
- For muons from $Z\rightarrow\mu\mu$ measured by the muon chambers, $p \sim p_w$ and $\sigma(\rho)/\rho = 1\%$. This implies N must be greater than $\sim10^5 \ll 3\times10^6$ Z's per year.

The above calculations are fairly hand-waving, but clearly there are sufficient statistics within one year to measure the sagitta corrections globally. Further, the statistics would allow the corrections to be determined with coarse bins in $\eta-\phi$ or time.

For this method to work, it is not necessary that ρ is accurate, but it must be insensitive to charge. To a good approximation, this will be the case for energies measured by the EM Calorimeter, but may not be the case for the Muon Spectrometer.

10.4 Test-beam Measurements

It would be useful to have data taken with the following conditions:

- Different incident angles.
- With irradiated detectors, partially depleted.
- Fixed orientation of detectors with angled tracks provided by nearby target.
- Combined Pixel/SCT/TRT runs, including non-uniform B-fields.
- Determination of number of radiation lengths using a photon beam.