INTERNATIONAL LARGE DETECTOR

LETTER OF INTENT

Aligning the ILD Tracker: Status Report and Answers to IDAG

The ILD concept group

The ILD tracker alignment task force:
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CHAPTER 1

Introduction

1.1 INTRODUCTION

The ILD tracking system is a sophisticated precision instrument. It consists of a high precision vertex detector, surrounding the interaction point, followed by a silicon-based tracking system of a few layers in the barrel, and up to seven layers in the forward direction, and a large volume time projection chamber. Precision detectors outside of the TPC just inside of the calorimeters both in the barrel and in the endcap provide additional precise space points at large radii and in the forward direction.

The ambitious physics requirements of the ILD program require that the resolution in momentum and impact parameter of the combined tracking system are significantly better than in existing facilities. Special attention therefore has to be given to the question of calibration and alignment of the overall detector and the different sub detectors.

For the purpose of the this note we consider calibration all tasks which deal with the internal description of the detectors. Alignment is the relative positioning of parts of the subdetectors or of sub-detectors relative to each other. Subdetectors relevant for this note are the ILD tracking detectors: VTX, SIT, FTD, EDT, SET and TPC. All with the exception of the TPC are based on Silicon sensors. For a detailed description of the system the reader is referred to the ILD LOI.

The situation is complicated by the requiremnet that the ILD detector can operate within the push-pull concept at the ILC, where within a short time of approxmiately two days the ILD detector has to be able to move in or out of the interaction region. This requirement implies that after a push - pull operation, to be able to re-start data taking, the ILD detector must be re-calibrated quickly to a point that data taking can commence, and that refinements of the calibration are possible based on physics data recorded.

Another complication is the intended power cycling of sub-detectors, to reduce the overall power consumption. This might introduce significant forces on parts of the detector, making precision alignment more difficult. The consequences of power pulsing will be an important focus of future R&D work.

Calibrating the ILD detector therefore will happen in a number of distinct steps.

During construction tolerances must be carefully controlled, during commissioning careful metrology of the different detector parts is needed. This will provide an initial alignment of the modules internally, and of the different systems relative to each other. The need for a high precision metrology has consequences for the mechanical design of the different subsystems, which from the beginning need tolerances determined to allow the necessary level of mechanical precision.

After installation, and throughout the lifetime of the detector, constants measurements will be taken using dedicated hardware to monitor the position of the different detector components. Currently a laser based system is foreseen, which will be used to locate the position of the ladders in the silicon tracking system, possibility also the location of the other tracking systems - VTX and TPC - relative to the silicon tracking system.

The final calibration of the system will be done using data. Tracks from the decay of the Z - boson will play a central role here, as they are of well known high momentum. The best source of such tracks are from short and dedicated runs of the collider on the peak of the Z resonance. For the discussions in the following sections we assume that we can collect around $1pb^{-1}$ of data within a few hours of running at 91 GeV. This will result in some 30000 Z bosons, of which around 1000 will decay as $a \rightarrow \mu^{+}\mu^{-}$. While this sample is not enough to calibrate the detector from scratch, it should be sufficient to re-establish a calibration after a push-pull operation. Longer runs, with maybe 10 times the statistics, might be needed after longer shutdowns, to re-establish the overall calibration.

The final high precision calibration will be derived from tracks in the data sample taken at high energies. Stiff tracks e.g. from W decays or from $q\bar{q}$ pair events will provide a large sample of tracks. The design of the detector has been optimised in a way to allow a calibration heavily relying on data.

In this note we present concepts for the calibration and alignment of the different tracking detectors, and of the combined system. These are concepts which will need much more in-depth study to be fully evaluated. However we feel that based on the work done, and based on experience gained with the LEP detectors, and more recently with the LHC detectors, the goals given are realistic and can be achieved.

CHAPTER 2

Vertex Detector

2.1 INTRODUCTORY REMARKS

The alignment of the ILD vertex detector (VTX) will consist in aligning about 70 double-sided ladders or 120 single-sided ones to a micron accuracy (needed to exploit the 2.5-3 μm single point resolution). Besides the required high-precision mechanical alignment of the different detector elements, a high-performance software alignment needs to be performed. For this purpose, within each detector layer, neighbouring ladders will feature an overlapping active band which is expected to be typically 500 μm wide. This means that each individual overlapping band would intercept 0.5% of all tracks crossing the innermost layer of the VTX, and about 0.1% of those traversing the outer layer.

The process which was successfuly used for the alignment of LEP experiments, i.e. muon-pair production, will exhibit a cross-section of about 350 fb at 500 GeV. This translates into 60,000 muon-pairs produced per annum (assuming an intrinsic luminosity of $2{\cdot}10^{34}\mathrm{cm}^{-2}/\mathrm{s}$), a number which is likely to be too small for the ambitionned accuracy. Two complementary solutions to this problem are considered hereafter: using high-momentum tracks of hadronic final states produced at 500 GeV for the ladder alignment inside each layer and muon-pairs for the rest of the alignment.

The approach consists in splitting the off-line alignment procedure in two separate steps: one restricted to each layer (based on high momentum - mainly hadronic - tracks at 500 GeV collision energy), and one achieving the inter-layer alignment as well as the VTX alignment w.r.t. the rest of the detector (using muon-pairs). This approach may however only work with the double-sided layer geometry and assumes that the sensors belonging to the same ladder do not need to be aligned with each other with this procedure.

2.2 RUNNING AT 500 GEV FOR THE LADDER-TO-LADDER ALIGNMENT

High-momentum tracks composing final states resulting from quark-pair or W-pair production may be considered for mutual alignment of two neighbouring ladders. Double-sided ladders would provide 4 hits per track, which should allow using the value of the transverse momentum obtained from the central tracking procedure, i.e. handling the trajectory curvature efficiently.

One may, for instance, consider tracks with transverse momentum above 30 GeV/c crossing the overlapping zone of two ladders in the innermost layer. The average distance between the two ladders being 1 mm, and their thickness amounting to 2 mm, a 30 GeV/c particle will be shifted by about 100 μm over a distance of 5 mm due to the curvature in the 3.5 T solenoidal field of the experiment. Knowing the particle momentum with 1% accuracy from the TPC (+ SIT) should be enough to combine the 4 hits left by the track in two neighbouring ladders into a single reconstructed (curved) trajectory.

Multiple scattering in the ladder material will introduce distortions well below 1 μm, thus not affecting the alignment. It is therefore likely that the 2.5-3 μm single point resolution of each hit will be fully usable for the alignment.

The statistics available with such tracks has been evaluated from Monte-Carlo simulations (courtesy of Mikael Berggren). The results are shown in Figure 2.1. The processes accounted for in the figure, starting from below, are:

- red: $\gamma\gamma \rightarrow$ anything
- blue: ee $\rightarrow$ 2 leptons
- green: ee $\rightarrow$ 2 quarks
- yellow: Compton scattering
- magenta: ee $\rightarrow$ 4 fermions (WW compatible)
- red: ee $\rightarrow$ 4 fermions (compatible with both WW and ZZ)
- blue: (hardly visible) ee $\rightarrow$ 4 fermions (ZZ compatible)
- green: ee $\rightarrow$ 6 fermions

The other processes considered (nγ, 8 fermions) do not leave any track with $p_T > 30$ GeV/c in the VTX.

By using the 2-, 4-, and 6-fermions final states, a relevant track would occur every 10 s in average, meaning about 10^6 tracks per year. This is to be compared to the 60,000 muon-pairs mentioned earlier. Each overlapping band would intercept about 5,000 tracks in the innermost layer and about 1,000 tracks in the outer layer. The statistics would, of course, be inbetween these two extremes in the intermediate layers.

The alignment accuracy one can extract from these samples is still to be assessed, but simple calculations indicate that the approach is likely to work. A crucial condition is however that the sensors remain aligned on their ladder, even in case of power cycling. This is still to be proven.

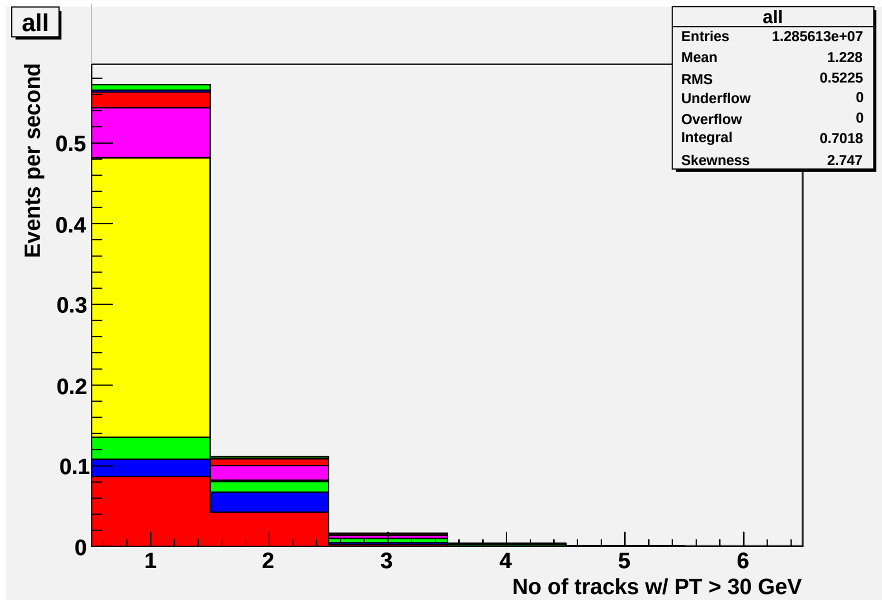

FIGURE 2.1. Number of events/second with n tracks with $p_T > 30$ GeV/c and at least one hit in the VTX (based on the full SM mass production of ILD). Nominal beam-parameters are assumed (ie. $L = 20$ nb^{-1}/s, polarisation -0.8/0.3). The colour code is provided in the text. (Courtesy of Mikael Berggren.)

2.3 USING MUON-PAIRS FOR THE OVERALL ALIGNMENT

The procedure exposed in the previous section is unlikely to allow aligning the VTX layers, nor to achieve its alignment with respect to the rest of ILD. Muon-pairs could be used for this part of the alignment task. Besides using the 60,000 muons-pairs collected at 500 GeV, one may think of running at the Z-pole, which would allow using muon-pairs produced with a cross-section in excess of 1 nb.

Considering a conservative value of the intrinsic luminosity (10^{32} cm^{-2}/s), the number of events would be in the ordre of 10^4 pairs produced in one day. Such a sample, though not larger than the one produced at 500 GeV, offers the advantage of being free from slow, continuous, drifts of the detector element position accross a one year long data taking campaign. The Z sample is expected to be large enough for such an overall, snap-shot like, alignment after one day of data taking.

CHAPTER 3

Silicon Tracking System

3.1 INTRODUCTION

The scope of alignment reaches the complete life cycle of the detector, from construction and assembly to operation. It starts with the metrology of the Si modules on the support structures, where dimensional control techniques like Coordinate Measuring Machines (CMM) will be used. The knowledge of relative positions within these structures will be of few tens of microns. During the assembly of the sub-detectors the former techniques will be complemented with high precision survey methods like short range photogrametry. At this stage, the information from optical survey can be compared with data from hardware alignment. The hardware alignment system will provide the first dimensional information once the detector commissioning has started. Eventually, the transform between local measurements and space points in the global reference frame is to be determined using a combination of track-based methods, engineering constraints and the hardware position monitoring system. The precision to be achieved is given in the answer to section 3.4.

The ILD tracking system is a hybrid system where the Silicon components entirely surround the TPC. This makes it a powerful tracking system but also quite challenging to integrate and to align. Therefore the positioning/ alignment of the various Silicon components between them and with the TPC and the Vertex detector are since the beginning, an important part of the ongoing R&D programme for the Silicon detectors. The Silicon component alignment comprises the following steps: i) the manufacturing of each element of these devices (sensors, modules, super-modules and support structures) with the requested quality constraints, ii) the integration of the Silicon devices into the overall ILD detector; iii) inclusion of a hardware system for monitoring their geometry positioning as well as the changes in alignment and taking into account the push pull operation and all the possible perturbations; iv) once the detector is installed refining the alignment with tracks.

The precision to be achieved is given in section 3.4.

To reach the required precision reliably the track-based alignment must furthermore be supported by very tight engineering constraints (see section 3.7). The system that is most sensitive to the alignment, the vertex detector, is quite small and can be precisely measured. Similarly, the positions of the silicon wafers on the ladders and rings can be measured routinely to a precision of a few μm.. These constraints will be inserted into the global alignment procedure. Experience gained in previous experiments has shown that these are particularly powerful means to avoid local minima that minimize χ^2, but yields the wrong momentum

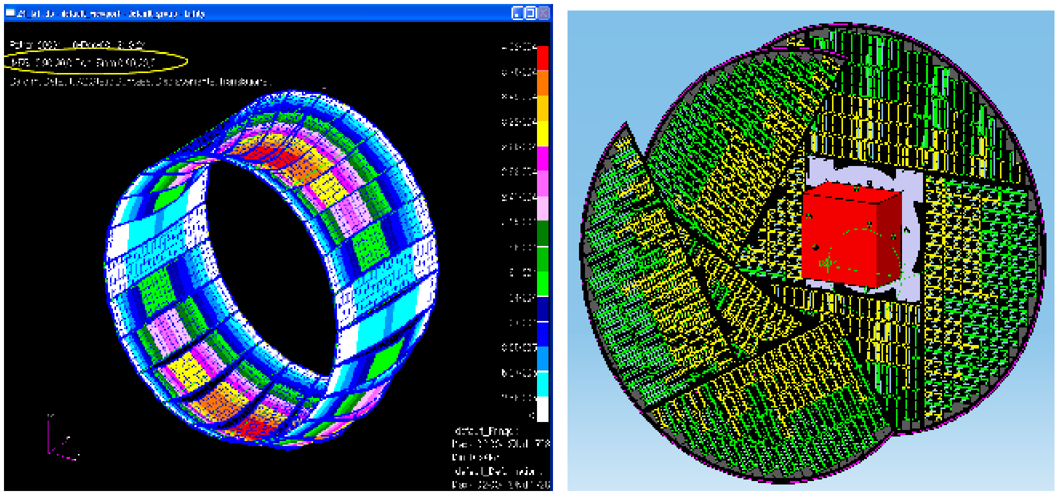

FIGURE 3.1. (left)View of the SET (one half of the detector), showing the results of a finite element calculation to estimate the mechanical stability. (right) The ETD XUV planes made each of 4 quadrants, tilted by 60^o with the modules distribution, yellow 2 sensor-modules and green 3-sensor modules.

measurement

3.1.1 Manufacturing and assembly of the Silicon components

The parameters of the Silicon tracking system is summarized in Section 3.5, with Table 3.1 describing the details of each components.

All the components, apart from the FTD, that is the SIT, SET and ETD, are made with the same sensor type and will be built following the same strategy. Thus manufacturing simplicity is a major asset in the detector design and manufacturing.

Each Silicon component is an assembly of super-modules. The SET will be made of 24×2 rectangular shape super-modules (Fig. 3.1.1 (left)), and the SIT layers will be made in the same way. The ETD super-modules are arranged in quadrants (Fig. 3.1.1 (right)). The modules are positioned on the super-modules fixed to the overall support structure of the Silicon component.

An active R&D is ongoing within the SiLC R&D collaboration on sensors and related FE and readout electronics that will be directly connected onto the detector. This will drastically modify the current design of the modules and of their assembly and positioning in the super-modules and the overall support structure design.

Tools and expertise are developed for the manufacturing of the modules and super-modules, in order to achieve the rigidity and position/alignment precision requested by the high detector performances. It will be part of the manufacturing quality control of these elements.

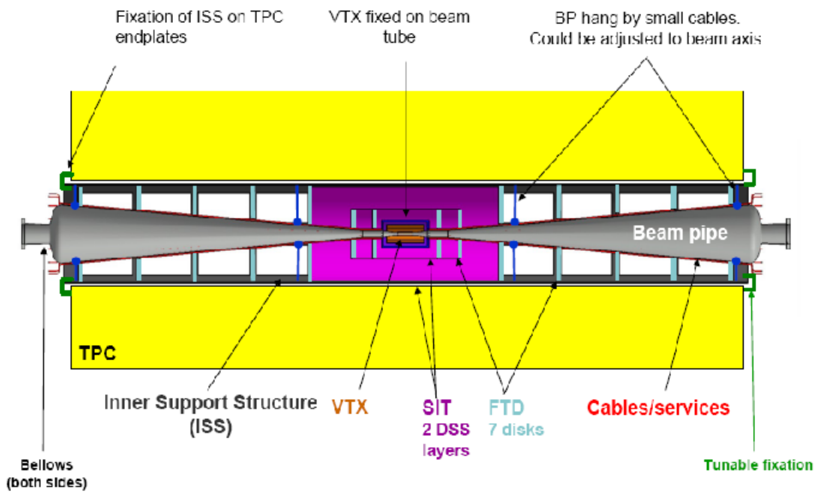

FIGURE 3.2. Integration of the innermost detectors

3.1.2 Integration of the Silicon components in the overall ILD tracking system

The SIT and FTD are included into a Carbon Fibre envelope (Fig. 3.2) and directly attached to it. This envelope (ISS) is itself fixed to the end plates of the TPC inner wall. The SET structure will be fixed in the same way on the outer wall of the TPC (see Fig2, left) The ETD is fixed on the end cap e. m. calorimeters through a thin but rigid Carbon Fiber plan. The integration work of the Silicon devices will be pursued both on the mechanical and on the simulation sides over the next years as well as with the related Lab test bench and test beams.

An alternative solution for fixing the Silicon barrel components (SIT, FTD and SET) independently of the TPC is under study. The Carbon Fibre Envelope (to which the SIT and the FTD are suspended) and the SET structure are fixed to support structures located on each side of the TPC (Fig. 3.3 left). These structures will host part of the hardware system for monitoring the relative variations on the alignment/positioning of each components and of each one relative to each other including also the TPC (Fig. 3.3 right).

3.2 HARDWARE SYSTEMS FOR MONITORING THE POSITION AND ALIGNMENT OF THE SILICON COMPONENTS

A hardware position monitor system based on infra-red laser beams mimicking straight tracks will be installed in the ILD detector. Currently it is planned to use this system for the inner silicon detectors, SIT and FTD. The use of this system for aligning the outer Silicon detectors is problematic because of their position far away from the rest of the detector. Here

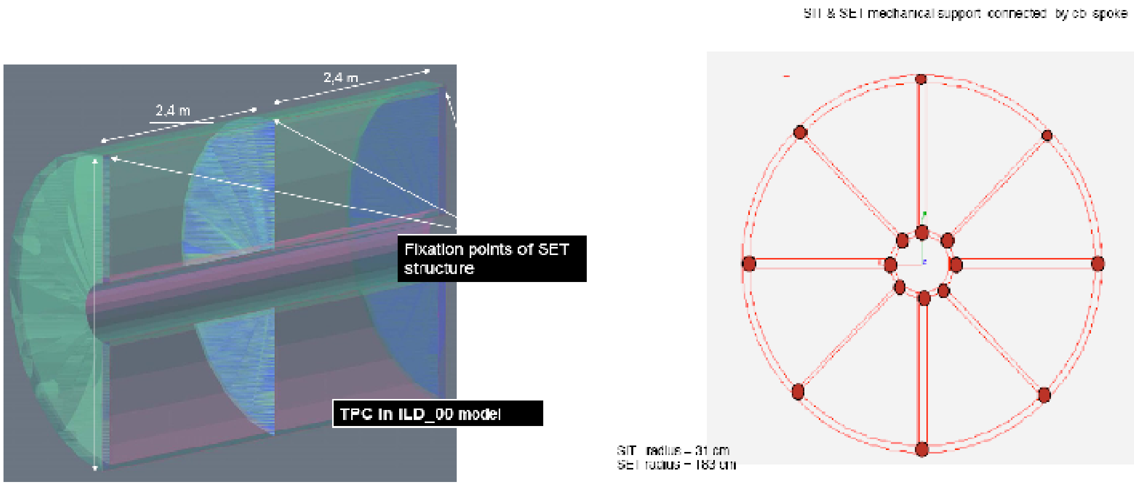

FIGURE 3.3. Support structure of the SET

a pixel based monitoring system (PMD), excited by IR laser through optical fibres is under consideration. In this system special pixel detectors are attached to the sensors to be aligned. The pixel devices will be installed in a several strategic places of the tracking system (see Sections 3.5 to 3.7).

The laser beams traverse several sensors optimized for IR laser transmittance (see Fig.3.4). The laser alignment system (LAS) is readout using the module sensor and front end electronics. Therefore, there is no added contribution to the error budget associated to the mechanical transfer between monitored fiducial marks and strips. The resolution expected on sensor transversal movements will depend on the number of strips illuminated by the beam and the sensor pitch. For a pitch value of 50 m with a gaussian sigma of 300 m, resolutions below $1\mu m$ are achievable. The system accuracy will be strongly dependent on the layout of the system. For the laser alignment system of the AMS-01 silicon tracker with a geometry similar to the FTD (comparable tracking volume, number of layers and cylindrical symmetry) an accuracy of 2 m has been quoted [?] Importantly, the laser alignment system provides the possibility to precisely monitor fast movements (see section 3.7 and 3.8). Beam tests of a prototype system are foreseen for the next years. The current design of the Forward Tracking Disks incorporates this system. The system is able to constrain several degrees of freedom of a large fraction of the installed micro-strip sensors in the FTD and the other strip detector, and of the third tracking disk based on pixel technology. The extension to other sub-detectors is being investigated.

The LAS will be complemented by a network of fiber optic sensors (Fiber Bragg System or FBS) that will monitor structural changes like deformations or relative displacements among structures and environmental parameters as humidity and temperature. These sensors are based on Bragg gratings built into mono-mode optical fibers. In this technology, the carrier fiber is as well the readout line. Compared to other traditional sensing techniques they are immune to electromagnetic interference and temperature effects. The optical fibers will be embedded in the carbon fiber structures already during the fabrication process. This technology will reduce the total amount of material by replacing the copper lines from the

DCS system and will contribute to the reduction of conductive EM noise. In the past, the DCS copper lines induced EM noise on other sensible components of the module front-end electronics.

The impact of the hardware systems (LAS and FBS) on the detector performance and engineering is negligible. Laser beams will be produced at the end of optical fiber collimators placed outside the silicon inner tracker volume (VXD, SIT, FTD).

3.3 TRACK BASED ALIGNMENT

Previous experiments have developed a sophisticated machinery and have shown that the alignment transform can be determined to a precision well below the intrinsic resolution of their detectors. The ultimate precision of this approach is limited by:

- the available statistics of alignment-quality tracks.
- distortions/movements of the detector
- loosely constrained alignment parameters

The most important consideration in selecting the track sample is to tightly constrain all degrees of freedom of the detector geometry, including those that leave the track residual distributions (nearly) unchanged. Typically, the alignment sample is composed of a mixture of collision data and tracks from other sources. High pT tracks are particularly valuable as they minimize the influence of multiple scattering. A strong constraint on the detector geometry derives from tracks that traverse overlapping detector modules (in the vertex detector and silicon tracking systems). Tracks from cosmics and beam halo are useful as they allow to relate different parts of the detector (upper and lower half, both end-caps). Tracks with known momentum are extremely valuable, both as a means to determine some of the weakly constrained alignment parameters and as a monitoring tool to validate the alignment. This role has traditionally been played by tracks from resonances with a well-known mass (the Z-resonance is the most popular as it provides stiff tracks, but J/psi and Upsilon have been used as well).

Clearly, distortions of the detector on a time scale smaller than the time required to accumulate sufficient statistics cannot be corrected for by the track-based approach. Given the rather small production rate for $Z- > \mu\mu$ events in the ILC at 500 GeV the typical time constant to align all degrees of freedom of the detector is likely to be of the order of months . However, reduced sets of degrees of freedom, corresponding to higher-level mechanical units like ladders and rings, or even complete cylinders and disks, can be aligned with much less statistics and, hence, at a much greater frequency.

To reach the required precision reliably the track-based alignment must furthermore be supported by very tight engineering constraints (see section 3.7). The system that is most sensitive to the alignment, the vertex detector, is quite small and can be precisely measured. Similarly, the positions of the silicon wafers on the ladders and rings can be measured. Infrastructure to precisely (O(5 um)) measure small structures O(20 cm) is available in most laboratories. These constraints will be inserted in the global alignment procedure. The experience in previous experiments has shown that these are particularly powerful means to avoid local minima that minimize c2, but yield the wrong momentum measurement.

The alignment of the ILD detector is definitely a challenge, due to the complexity of the detector and due to the precision required. However, provided fast distortions of all degrees of freedom are avoided, it is a well-understood problem. The sophisticated track-based alignment methods developed by the high-energy physics community, in conjunction with engineering and hardware alignment system constraints, provide a robust and reliable solution.

3.4 PRECISION REQUIREMENTS

Studies of the ILD detector physics performance have been done with the following assumptions for the spatial resolution of the various detector subsystems:

- Vertex Detector (VXD): $2.8\mu m \times 2.8\mu m$
- Inner Silicon Tracking (SIT/FTD): $5\mu m$
- Time Projection Chamber (TPC): $50 - 100\mu m$
- Outer Silicon Tracking (SET/ETD): $10\mu m$

This overall resolution for the space point measurements is the (quadratic, in case of Gaussian distributions) sum of two terms. The first contribution, the resolution term, is due to finite resolution of the devices in the measurement of the local spatial coordinate. A second contribution, the alignment term, is due to the finite precision of the transformation from the local coordinate to the global detector reference frame.

The ILD concept requires that the alignment should not lead to a significant deterioration of the performance; the overall resolution should be dominated by the intrinsic resolution of the measurement devices. Quantitatively, we require that the alignment precision should be such that the effect on the momentum resolution of the tracker is less than 5 % (this requirement goes back to the Snowmass workshop). Introducing mis-alignments to one subsystem at a time, this requirement leads to a required alignment precision (RMS) that ranges between 50 % and 100 % of the intrinsic resolution. The innermost and outermost silicon systems should be aligned to 3.5 mm and 6 mm, respectively. TPC distortions should be known to the level of 20 mm. The momentum resolution criterion is not adequate for the vertex detector. A stronger constraint is derived from the requirement of small distortion of the impact parameter that requires a precision of 1.5 mm.

The detector R&D program has given rise to detector prototypes with unprecedented resolution. This leads to a substantial gain in physics output, provided the alignment precision matches the improved resolution. The requirements on the alignment precision are therefore quite challenging.

3.5 ALIGNMENT PROCEDURES AND PUSH-PULL

The push-pull operation includes the adjustment of the beam pipe position. The complete inner tracker is rigidly connected to the beam pipe and follows its movements. The mechanical coupling with the beam pipe is particularly tight for the vertex detector. The position of the main tracking sytem (TPC, FTD, SIT, SET and ETD) and calorimeters is not affected by these movements. The movements and deformations of the tracker system during the push-pull operation will be monitored using the optical fiber sensor system. As long as the tracker sensors are operative it will also be possible to use the LAS system. Both systems will provide a real time response during the process.

The ILD detector starts taking "physics-quality" data as soon as this adjustment is finished. The alignment of inner tracking system and the remainder of the detector is determined by a track-based alignment of a limited number of degrees of freedom.

3.6 ALIGNING THE SILICON TRACKING SYSTEM

The total number of degrees of freedom of the ILD tracker is of the order of 100.000 (calculated as six times the number of sensors). If the relative sensor positions in the module are known to the required precision (from CMM data) the number of degrees of freedom is reduced by a large factor (a factor five in SET that dominates the NDOF count, a factor two or three in ETD). The contribution of the outer tracking system is larger than that of the inner tracker by a factor 10.

As discussed in Section 3.1, the time required to accumulate sufficient statistics to determine all degrees of freedom is likely to be of the order of months, comparable in magnitude to the push-pull interval. It is, therefore, important that the internal degrees of freedom of subsystems (ladders and rings, cylinders and disks) are stable over the same time scale. After each push-pull operation the number of alignment parameters to be determined, and the required statistics, is then greatly reduced.

Those structures that are considered as rigid bodies, but that can undergo relative movements during push-pull operation should be monitored using a real-time hardware system. The LAS system and the optical Fiber Bragg system will contribute to this task, but dedicated metrology/survey techniques may be used to monitor the movements of these rigid bodies with respect to external fixed points (for instance references in the cavern walls).

If we can assume that the different support structures are basically rigid, and do not change dimensions internally, we only need to worry about the overall alignement of the different sub-detectors relative to the rest of the detector. The goal of ILD is that this situation is reached for a re-alignment after a push-pull operation. In this case the number of degrees of freedom is greatly reduced:

- The outer Silicon tracker, SET, is fixed to the TPC. It is supported by a rigid carbon fibre structure. It probably needs to be split in the middle. In this case 12 degrees of freedom are needed to determine the position of the overall SET.
- The ETD is attached to the endcap calorimeter in one piece. In total 8 degrees of freedom need to be considered.
- The SIT and the FTD are connected to a common support structure. The movement of this structure has 6 degrees of freedom.

In total 26 degrees of freedom are present if only the subdetectors need to be realigned.

Details about the module and channel count in the Silicon system are given in Table 3.1.

Component	number of		# of sensors/	# of channels	area
	layers	modules	module		m^2
SIT1	layer 1	33	3	66000	0.9
	layer 2	99	1	198000	0.9
SIT2	layer 1	90	3	180000	2.7
	layer 2	270	1	540000	2.7
SET	layer 1	1260	5	2520000	55.2
	layer 2	1260	5	2520000	55.2
ETD_F	X,U,V	984		2000000	30
ETD_B	X,U,V	984		2000000	30
FTD	7	350		5000000	

TABLE 3.1
Number of modules, channel count, and sensitive area for the different Silicon based detectors.

3.7 ALIGNMENT AND DETECTOR DESIGN

The alignment has been considered an integral part of the design since the earliest stages of the ILD detector:

Metrology during assembly and constant quality control is an extremely valuable asset in track-based alignment. This is particularly relevant for the most weakly constrained alignment parameters, where constraints from metrology may allow to "choose" the real detector geometry among the possible solutions to the c2 minimization. Therefore, the precision with which the position of the different detectors is known should be tightly specified . The detector element with the strongest requirements on the alignment precision, the vertex detector, is a small device and a precise metrology (with a precision of a few microns) can be performed. For the silicon tracker systems, a metrology with a precision of 5 micron is possible on intermediate-level structures like ladders and disks.

A hardware alignment system based on infra-red laser beams provides a tight constraint on a number of degrees of freedom of the silicon tracker. Importantly, the response of the system is on a time scale of seconds. Thus, the laser alignment allows to monitor (and correct for) collective movements that are too fast for the track-based alignment. Periodic movements of the detector on an even shorter time scale may be monitored by this system as well (see Section 3.8).

The impossibility to correct for fast distortions of all degrees of freedom implies that the internal alignment of each subsystem is required to be stable over long periods of time. Processes like the magnet ramp-up, temperature changes, ground movement, etc. may affect the alignment of SIT with respect to the TPC, or even of one Forward Tracking Disk to the next. However, the internal alignment of the disk, i.e. the relative positions of all petals in the disk, must remain stable to the level specified above. This requires an extremely careful design of the mechanical support of the detector. To assess this effect the optical Fiber Bragg System (FBS) will be extremely useful, as it is able to monitor deformations of the disks of 1 part in a million.

A potential threat is the proposed pulsed powering scheme, where the power consumption closely follows the duty cycle of the ILC. The resulting temperature excursions on a time

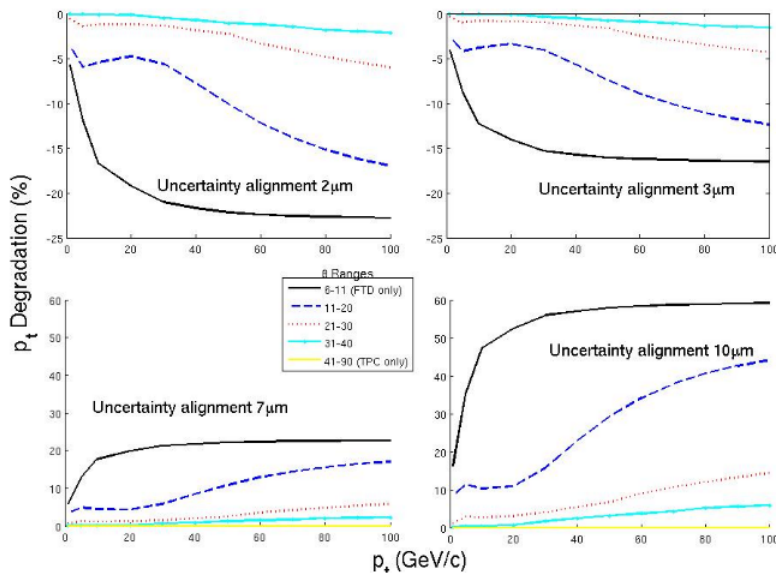

FIGURE 3.4. Effect of different misalignment scenarios in the forward tracking disks (referred to the situation where there is a 5 micron alignment uncertainty)

scale of a millisecond that may lead to mechanical distortions. The small thermal expansion coefficient of silicon and the relatively small wafer size mitigate the mechanical effects in the most sensitive systems (VXD, inner silicon), but more work is needed to fully understand the implications of this powering scheme. Real-time evaluation of these temperature effects can be carried out using the FBS where temperature and deformations are simultaneously measured.

The sensor overlaps should be made sufficiently large that a high-statistics sample can be collected in a limited time.

3.8 REAL-TIME MONITORING OF THE TRACKER ALIGNMENT

The position of sub-detectors and large detector structures can be determined using a relatively small sample of tracks, that can be accumulated in a matter of hours. Distortions of the detector geometry on a shorter time-scale cannot be monitored using tracks. The hardware system based on infra-red laser beams (LAS and PMD) is able to monitor detector distortions on the time-scale of seconds. Of the systems and tools explored so far only the FBS is able to provide real-time information for very fast distortions (FBS can monitor at 1 MHz).

It is, however, possible to use slower tools like the LAS and PMD or track-based methods to reconstruct periodic movements of the detector by sampling at different phases of the bunch train over a longer period of time. The hardware alignment system can be triggered on demand and is therefore especially suited to this task.

The pulsed powering scheme could lead to mechanical distortions over a 1 ms interval. Effects due to thermal excursions as a result of the increase in power during the spill are

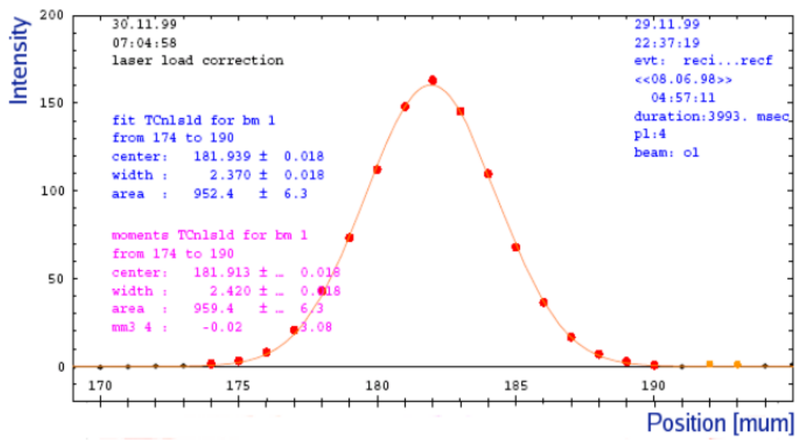

FIGURE 3.5. AMS results on the reconstruction of the laser signal on the third sensors in the stack. The data points are the result of averaging 480 readings. The position of the laser pulse can be reconstructed with a resolution of 1 micron.

mitigated by the small thermal expansion coefficient of silicon and the relatively small wafer in the most sensitive systems (VXD, inner silicon). At the same time Lorentz forces on the (varying) current in the supply cables could distort the overall tracker geometry in an unpredictable way. A detailed study of these effects in simulation and on real-life prototypes are expected by 201X.

The best way to avoid a deterioration of the alignment precision is by making sure that the effects are small compared to the required resolution. ILD has to draw up tight specifications of the allowed distortion of the detector geometry (and thus on thermal excursions, on the maximum force exerted by the power cables, etc.). At the moment, a detailed prediction of such effects is not possible and much more work is needed to fully understand the implications of this powering scheme.

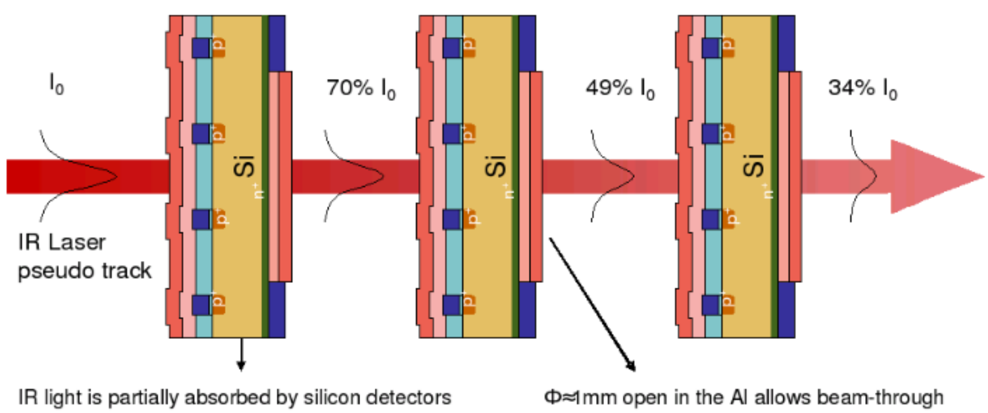

FIGURE 3.6. Schematic view of the infra-red laser beam traversing several micro-strip sensors.

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CHAPTER 4

Time Projection Chamber and Global Alignment

4.1 INTRODUCTION

The large volume time projection chamber is the central piece of the ILD tracking system. The TPC will provide more than 200 space points along a track. The longest drift distance possible is around 2.5 m. THe anticipated spatial resolution in the device is around 60-100 μm.

In addition to the calibration issues discussed in the previous chapters, the TPC is sensitive to the magnetic field in the detector. The survey and calibration of the magnetic field will be a major part of the TPC calibration.

Mechanically the Silicon tracking detectors will all be mounted relative to the TPC. Most probably - though a detailed engineering design has not yet been done - the inner Silicon tracking system will be suspended from the end - plate of the TPC on either side. The external Silicon tracking int he barrel will be supported by the field cage, the external Silicon tracking behind the TPC endplate will be supported by the endplate itself. The TPC as a whole will be mounted to the coil of the ILD detector.

4.2 INTERNAL TPC ALIGNMENT

The internal alignment of the TPC will be based on a well understood and measured field cage of the system. A construction of the field cage at the 0.1 mm level seems possible, and a survey of the finished field cage at the level of 30μm might be not unrealistic.

The B-field, which is as important to the ultimate measurement precision as the mechanical components, will be mapped using probes to a level of dB/B¡10-4 as described in the note: LC-DET-2008-002. At this point, unambiguous preliminary tracks can be defined using TPC alone. These tracks, with only preliminary fits, are sufficient to improve the internal TPC calibration iterativly, and to serve as starting tracks for an overall tracking based alignment of the TPC with the rest of the tracking system.

In the TPC, the internal components, i.e. the detector modules, will be manufactured to tolerances of 20μm while tolerances for placing the modules on the endplate will be about 60μm. The internal TPC alignment process must provide the final required precision for both the mechanical alignment and the magnetic field measurement. Achieving these goals will require iteration. As mechanical distortions and magnetic field distortions can lead to similar track distortions, supplementary alignment systems will be used to resolve the ambiguities.

The internal alignment in the TPC will be helped by laser systems installed on the TPC in two ways: using a system of mirrors straight tracks created by a laser are created inside the drift volume, and can be used to determine many calibration constants. In addition diffuse light will be shone on the cathode surface, on which an appropriate coating creates a pattern of charge, which can e.g. be used to calibrate field distortions and the drift velocity.

4.2.1 Maintaining the alignment

Probes mounted on the fieldcage of the TPC will be used to monitor the B-field during running. Pressure and temperature will be measured continuously and will be corrected for on the fly. Cosmic-ray tracks and laser systems will be used to check for changes of the internal alignment in the TPC. Tracks from Z running will be used to extend coverage to the whole detector because lasers can only monitor a limited number of reference points, and cosmic rays give reasonable coverage of the vertical direction only.

4.3 GLOBAL ALIGNMENT

A preliminary global alignment of the subdetectors, using a survey-reference network, can achieve a precision of 0.2 mm, similar to that achieved at CMS.

For the track-based global alignment, hits will be selected as in the internal alignment. Fits of the tracks using all available detectors provide the momentum and hit residuals. In the global alignment stage, parameters that define the overall position in space of the subdetectors will be varied to produce correct momentum of $Z \to \mu^+\mu^-$ events and minimize the hit residuals sensitive to misalignment of the subdetectors. Recognition of patterns of residuals that are sensitive to the subdetector internal alignments will require iteration between the internal and global alignments.

4.3.1 Time scale for the alignment

At LEP, after experience was gained, it required a few days to produce and cross-check all of the alignment constants for all of the tracking subdetectors after Z-peak running (for example). After that, fresh data was continuously monitored to check for changes. If needed, alignment constants were adjusted and the fresh data was reprocessed. This continuous monitoring can detect changes in the detector or machine that happen on a time scale of an hour or more. Changes to the detector on the time scale of seconds (for example due to power pulsing) must be engineered away in the design of the detector or at least measured/ understood well enough to allow relevant corrections to the data. How rapidly the machine will change is not known at the moment, and if these happen on the level of seconds, they will have to be investigated and remedied during the commissioning phase of the collider.

4.4 REQUIRED PRECISION

We use a criterion that misalignments should not increase the momentum uncertainty by more that 5% over that due to measurement errors. Subtracting in quadrature, the contribution from any misalignments must be less than 32% of the contribution from measurement errors.

We have used a simple simulation (without digitization) of track measurements in the ILD detector. We have considered several examples of misalignments of the subdetectors and determined, using the criterion above, limits for each:

- coherent displacement of the VTX, 2.8 μm;
- coherent displacement of the SIT, 3.5 μ;
- coherent displacement of the SET, 6 μm; and
- coherent displacement of the TPC, 3.6 μm.

We have also considered an internal distortion of the TPC that would result in a sagitta when the track is fit to TPC space points only. The distortion could result from either misalignments of the readout modules mounted to the endplate, or an uncorrected distortion of the magnetic field. The limit to internal distortions of the TPC is

- distortions that result in a sagitta in the TPC of 20 μm.

The above distortion limit defines the alignment precision required for the TPC endplate. It also defines the precision required for the magnetic field calibration. In a TPC, the drifting electrons follow the magnetic field lines; field components perpendicular to Bz result in deflections of the track as measured at the readout plane. The magnet is designed to have a field uniformity of ?dB?,r(constructed)/Bz dz=2mm-10mm. These deflections are largely corrected with the application of the magnetic field map. However, residual misunderstanding of the magnetic field will result in track distortions with magnitude: ?dB?,r(uncorrected)/Bz dz. Thus, the mapping of the magnetic field must be significantly improved beyond the initial probe precision stated above, dB/B¡10-4. Based on the limit of the internal fit sagitta above, the magnetic field map must have a precision of ?dB?(uncorrected)/Bz dz ¡ 20 m. For the case that magnetic field distortions that are coherent along the drift length of about 2 meters, the integral is equivalent to the requirement that dB/B¡10-5.

4.5 PUSH PULL AND ALIGNMENT

The push-pull operation is expected to result in changes in the global alignment of the subdetectors, while changes in the internal alignments will be smaller. Data-taking will not necessarily be delayed because track-finding in ILD is based largely on identifying tracks internally in the TPC and does not depend on the precision alignment of the subdetectors. However, we anticipate using 1/pb of Z-peak running to check the global alignment.

Deriving from experience at LEP, the internal alignments of the silicon detectors and TPC can also be performed with using tracks from $1pb^{-1}$ of Z-peak events. If such an operation is prohibitive for the machine, tracks from high energy running can also be used but the integration time for collecting enough statistics will be longer (this method was used at LEP as a cross-check between Z-peak and high energy conditions).

4.6 ALIGNMENT AND DETECTOR DESIGN

For none of the systems discussed a detailed engineering has been done. Nevertheless already at this conceptual stage the needs of alignments have been considered, and have entered into the current level of design. Nevertheless developing the conceptual designs into real engineering designs will be an important next step. For instance, the TPC endplate and fieldcage mechanical requirements must be well understood. For the silicon, the support structures for the ladders demand a minimum of material and a maximum of stiffness.

As the precision alignment of the TPC endplates and calibration of the magnetic field will both rely on tracks, it is important to start with the best measurement precision possible, from non-track-based methods as described above. The anti-DID magnet presents additional challenges to the alignment because the dipole components will create curvature of the tracks. It will be useful to design an anti-DID-clear zone in the longitudinal center of the magnet to provide a more straightforward anchor for the global alignment.

Finally, last not least, R&D and design of the power pulsing will be a top-priority task, and this is planned in the present R&D programs for all subdetectors.

4.7 SUMMARY

In this note we have discussed the current state of thinking about aligning the different tracking detectors in ILD. We propose to base the alignment on a mixture of harware alignment systems, e.g. a powerful laser system for the Silicon tracking system, and a sophisticated use of tracks taken from data. We consider the abvility of the collider to deliver some luminsity on the peak of the Z resonance to be important and very beneficial for a fast calibration, and in particular a fast re-calibration after a push pull operation.