Alignment Considerations for the Next Linear Collider

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ABSTRACT

Conventional alignment techniques and special straight line alignment techniques are reviewed for their accuracy potential. It is shown that, whereas conventional alignment methods will be sufficient to achieve start-up conditions, only special straight line alignment methods can compete with beam based alignment techniques.

I. INTRODUCTION

Next Linear Collider type accelerators require a new level of alignment quality. The relative alignment of certain parts of these machines is to be maintained in an error envelope dimensioned in nanometers. Since conventional optical alignment methods cannot approach this level of accuracy, special alignment techniques must be pursued.

II. COMPONENT PLACEMENT TOLERANCES

Component placement tolerance specifications define the alignment operation. The definition of these tolerances has changed over recent years, resulting in significantly looser specifications. At the same time, the alignment requirements of NLC type machines are intrinsically more demanding, effectively offsetting these reductions.

The available space here does not allow a detailed discussion of all parts of an NLC design. While the following discussion will focus on the main linac alignment, most of it is nontheless directly applicable to the other machine parts.

A. Definitions

Originally, alignment tolerances were calculated as the offset of a single component resulting in an intolerable loss of luminosity. This seemed a reasonable way to proceed and immediately gave relative sensitivities of component placement. However, this method had two flaws: it failed to take into account that, firstly, not just one but all elements are out of alignment simultaneously, and secondly, that sophisticated orbit and tune correction systems are applied to recover the lost luminosity. Permissible alignment errors, random or systematic, under these more realistic assumptions are much harder to estimate because they require an understanding of all conceivable interactive effects that go into a simulation and a detailed scenario of tuning and correcting. The continued increase in available computing power has made it possible to calculate the simultaneous offsets of all components. Operating experience from the present generation of colliders has yielded significant advances in orbit tuning and correcting. On this basis, alignment tolerances can be defined as the value of placement errors which, if exceeded, make the machine uncorrectable. Experience with higher order optical systems has shown that alignment tolerances derived in this manner tend to be about an order of magnitude looser than before.[1]

B. NLC Linac Tolerances

Alignment tolerances according to the first and the most recent definitions have been computed[2] and are plotted in Fig. 1. The first curve shows the placement tolerances

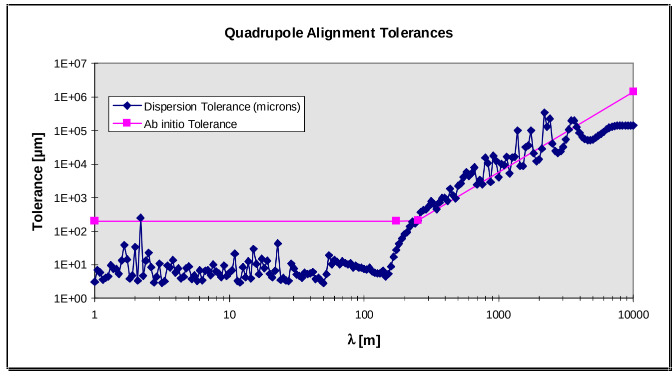


Fig. 1. Quadrupole alignment tolerances—running conditions

required to keep dispersion losses under a tolerable 3%, i.e. the machine would operate to design specifications. The placement requirements for adjacent components are a very tight 3 µm. Fortunately, the tolerances are scale dependent. The most stringent placement is required only for components within about 160 m of the point of investigation; further downstream the tolerances quickly drop off. The second curve shows the tolerance which, if exceeded, would make the machine uncorrectable. Here, we see the same scale dependency.

III. DATUM DEFINITION

Since the earth is spherical, a slice through an equipotential surface, i.e. a surface where water is at rest, shows an ellipse. For a project the size of an NLC, this has significant consequences.

A. Tangential Plane or Equipotential Surface

Traditionally, accelerators were built in a tangential plane, sometimes slightly tilted to accommodate geological formations. All points around an untilted circular machine lie at the same height (Fig. 2), but a linear machine such as the NLC cuts right through the equipotential iso-lines. The center of a 30 km linear accelerator is 17 m below the end

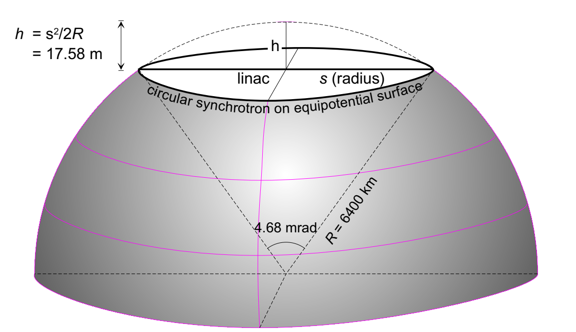


Fig. 2. Effect of earth curvature on linear and circular accelerators

points. To alleviate the problems one could build the accelerator on more than one plane, e.g. building the linacs and the final focus/detector section on three separate planes reduces the sagitta to 1.9 m (Fig. 3). To avoid the “height” difference completely, one would need to build the machine along an equipotential surface.

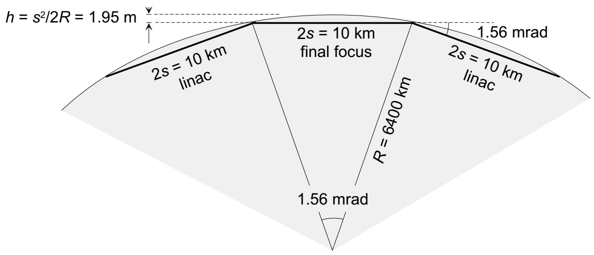


Fig. 3. Three plane lay-out

B. Lay-out Discussion

Since most surveying instruments work relative to gravity, the “natural” solution is a lay-out which follows the surface generated by equal gravity, the equipotential surface, although, for conventional alignment methods, the choice of a tangential surface adds just one additional correction. The choice of lay-out surface does have a major impact upon which special alignment methods can be used: a diffraction optics Fresnel plate alignment system requires a straight line of sight, but a hydrostatic level system can not accommodate height differences of more than a few centimeters.

IV. CONVENTIONAL SURVEY AND ALIGNMENT TECHNIQUES

Conventional alignment techniques are well understood and have been successfully applied in the alignment of accelerators such as HERA, LEP and SLC.

A. Procedure

A conventional alignment is usually a 6 step process:

1. Surface Survey Network A survey coordinate system is established on the surface and represented by control monuments to control scale and global positioning.

2. Transfer of Reference into Tunnel Scale and datum are transfered into the tunnel by sighting through vertical shafts (penetrations).

3. Tunnel Network A tunnel survey reference network is established integrating the transfer points (Fig. 4). It is usually represented by floor or wall monuments.

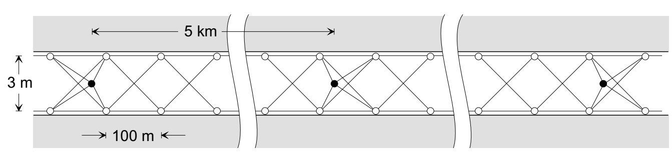


Fig. 4. Tunnel network lay-out with 3 surface connection points

4. Absolute Alignment All components are laid out and aligned in respect to the tunnel reference points.

5. *Relative Alignment* A smooting procedure is carried out to improve the relative positioning of adjacent components.

6. Quality Control Mapping A final mapping survey verifies the achieved alignment quality.

B. Equipment

The conventional survey and alignment equipment has greatly advanced over the last 10 years: electronic theodolites with a resolution of 2 µrad have become standard; gyro-theodolites can rapidly determine an azimuth with a resolution of 5 µrad; Electronic Distance Meters have increased in resolution (100 µm/100 m) and significantly shrunk in size, allowing their integration into the telescope of a theodolite to form a tacheometer; levels have at long last become digital; GPS (± 4 mm/30 km) has revolutionized surface net measurements; laser trackers allow on-line monitoring of an alignment process with a resolution of 15 µm over 10 m.

C. Measurement Quality Estimate

To estimate what alignment accuracy could be achieved in a conventional alignment procedure, the process as outlined in A. using equipment with the resolutions specified in B. has been simulated. Fig. 5 shows the resulting tolerance curve. As one can see here, conventional alignment can support the *ab initio* alignment requirements but not the running tolerance requirements.

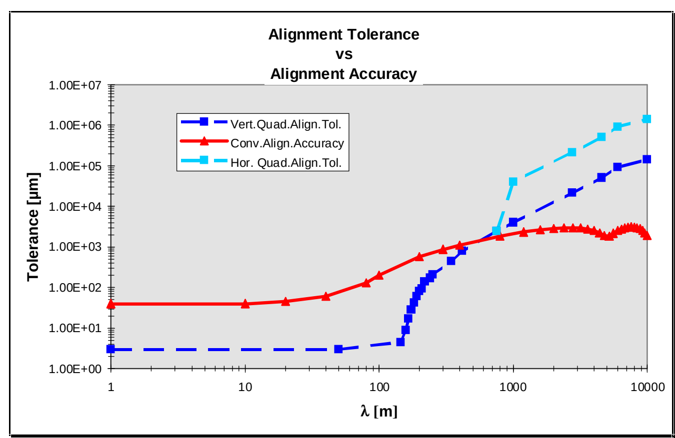


Fig. 5. Quadrupole alignment tolerances vs. alignment accuracy

V. SPECIAL ALIGNMENT SYSTEMS

The conventional alignment accuracy can be improved by adding alignment systems to the measurement plan which are optimized for the measurement of the critical dimension. The key element of any of these alignment shemes is to generate a straight line reference. Fig. 6 gives an overview of straight line reference systems categorized by working principle.[3]

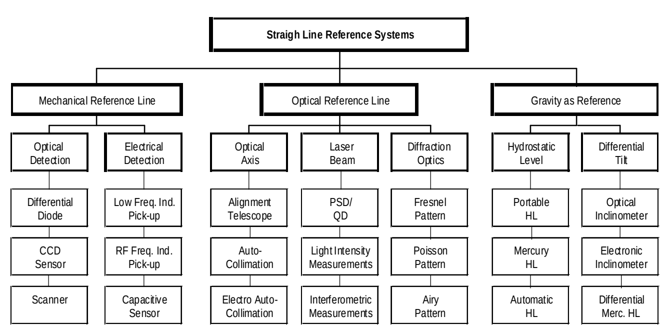
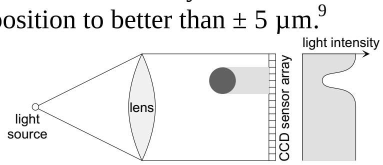


Fig. 6. Straight line reference systems

A. *Mechanical Reference Line*

A stretched wire is used to represent a straight line. While in the horizontal plane a wire projects to a first order a straight line, in the vertical plane it follows a hyperbolic shape due to gravitational forces. The deviation from a straight line in the vertical is a function of the wire's weight per unit length, wire length and tension. A 45 m spring steel wire with 0.5 mm diameter under a maximum tension has a sagitta of about 6 mm. A comparable wire made of a silicon-carbide material[4] which has the same tensile strength but at only one tenth of the spring steel's weight per unit length, creates a sagitta of only 0.6 mm. For very accurate measurements, deviations of a wire from a straight line in the horizonatal plane must also be considered. These deviations are created by internal bending moments caused by molecular stress of the material. The bending moments can be reduced to negligible size by heat-treating the wire or by stretching it into the yield range.

1. Optical Detection At LLNL, a GaAs infrared emitting diode illuminating a silicon phototransistor across a 2.5 mm gap combination was used to measure the deflection of a wire in an electro-magnetic field.[5] This set up was part of a system to align the solenoid focus magnets on the ETA-II linear induction accelerator. To stabilize drift problems, the phototransistor was replaced with CdS photoconductors.[6] The resolution proved better than 1 µm. A portable offset measurement device developed at CERN, the Ecartometer,[7] uses a differential diode to center a carriage under the wire. The centering accuracy is better than 20 µm. The SLAC LANI (**L**inac **A**lig**N**ment **I**nstrument) is also a portable device designed to measure offsets in reference to a Kevlar wire applying the CCD based light shadow technique (Fig. 7).[8] Offests within 2 mm range can be measured to ± 10 µm. The LPG 10 G sensor uses the same principle of operation; it can simultaneously measure the diameter of the wire and its position to better than ± 5 µm.[9]



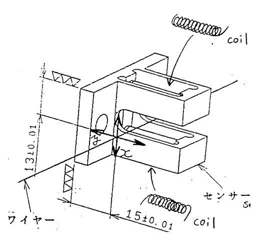


Fig. 7. (above) Light shadow technique

Fig. 8. (right) KEK inductive wire sensor

2. Electrical Detection Electrical pick-ups use inductive or capacitive techniques to measure the wire position. A very simple inductive system was developed at KEK to support the alignment of the ATF linac. The reference wire carries a 60 kHz signal which is picked up by two coils on either side of the wire (Fig. 8).[10] The differential signal is a measure for the relative wire position. The accuracy over the measurement range of 5 mm is better than ± 30 µm. The system developed by DESY for SLAC (Fig. 9) transmits a 140 MHz signal over the wire which is received by the wire position monitor antenna strips. The relative signal from diametrically opossing antennas is a measure of the wire position. The system is bi-axial, has a range of 2 mm, and at 8 mm object distance provides long term position accuracies

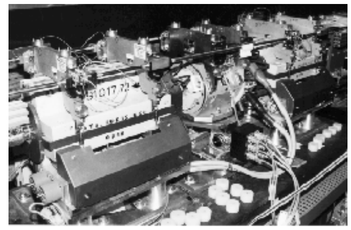


Fig. 9. FFTB magnets with wire system and magnet mover

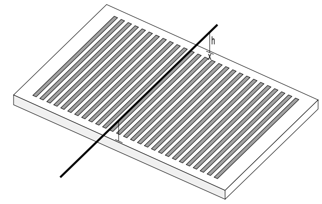


Fig. 10. MIT mini strip board

of better than ± 1 µm.[11] Another inductive sensor was developed for the position monitoring of detector components (Fig.10),[12] but could be used also for wire alignment systems. The wire carries pulsed signals which induce charges on the board strips. The strips are 50 mm long and 1 mm wide. The centroid of the distribution gives the horizontal position with respect to the strip board while the width of the distribution provides information on the vertical coordinate. An accuracy of better than ± 3 µm over 8 mm has been demonstrated. ESRF and CERN, in collaboration with the French company Fogale Nanotech, have developed capacitive sensors. The CERN sensor is bi-axial and resolves the wire position over a range of 2.5 mm to ± 1 µm.

B. *Optical Reference Line*

1. Optical Axis Reference The optical axis is the reference line to which components are positioned using traditional alignment instruments. Alignment telescopes can support the manual alignment of components to about ± 50 µm. If higher accuracies are required, like for the relative positioning of two accelerator structures on a single strong-back to ± 3 µm, electro-autocollimation is very well suited. The principle observable of this method is the differential tilt of a section of test object in respect to the optical axis (Fig. 11). An integration over the differential tilts yields the deviations from straightness. These measurements are usually bi-axial.

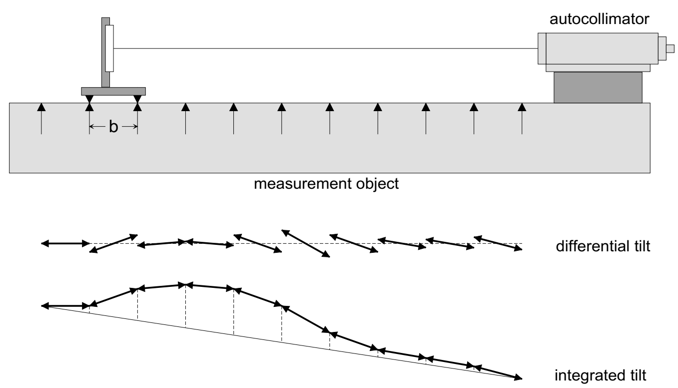


Fig. 11. Principle of autocollimation

2. Laser Beam Reference In its simplest form, a laser beam images a spot on a PSD, QD or CCD array, allowing a direct position read-out to few µm. The relative motion of adjacent girders in the KEK ATF is monitored by a laser/PSD combination. A diode laser beam is split into two arms, each creating a signal on a PSD. A relative girder motion results in two displacement vectors. Their analysis yields three translations and roll.[13] To compensate for instabilities of the laser, reference position detectors allow

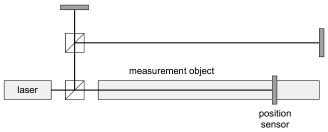


Fig. 12. System with compensation

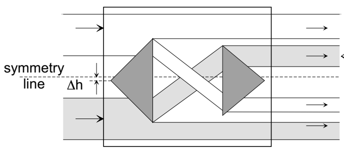


Fig. 14. Intensity system optics

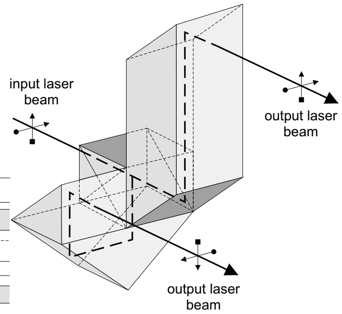


Fig. 13. Dual arm compensator

differential measurements (Fig. 12). In a different approach, the laser beam is split in a special optical component (Fig. 13) into two beams such that direction changes of the original beam affect the two beams in opposite ways, thereby compensating the instability.[14] This method yields a resolution of 200 nm over 10 m if refraction is controlled. Slightly less accurate are measurements relying on the comparison of light intensities. In this method, a reference laser beam is split into two beams of equal intensity. These two beams are split again in the straightness sensor into 4 beams (Fig. 14). The split ratio is a function of the position of the straightness sensor in respect to the reference line which is the symmetry axis of the initial two beams. A receiver measures and compares the intensity of the beams on both sides of the symmetry axis and converts the intensity difference into a metric offset. The offset accuracy is within ± 15 µm over 10 m. Total range is up to 40 m. Interferometric straightness measurements are inherently more accurate and are in the same accuracy domain as autocollimation measurements.

3. Diffraction Optics Reference While the above methods are well suited for short to medium ranges, diffraction optics methods can provide a straight reference line over kilometers, e.g. the SLAC Linac/FFTB Alignment System.[15,16] The reference line of a Fresnel system is defined by the pin hole

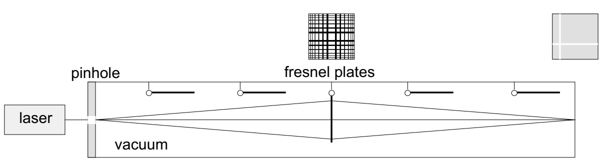


Fig. 15. Fresnel alignment system

and the center of the detector plane (Fig. 15). The Fresnel zone plate (Fig. 16) focuses the diffuse light onto the detector, forming an interference pattern (Fig. 17). The design parameters of the zone plates, size, width of strips, and gaps, are a function of the wavelength of the light source, image and object distances, and resolution. Only one Fresnel lens can be in the light path at any time. To incorporate more monitor stations into the system, the zone plates must be mounted on hinges so that actuators can flip the plates in and out of the light path. Since refraction would distort the fringe images to noise, the light path must be in a vacuum vessel. The FFTB alignment system's Fresnel zone plates, which, as an extension to the linac alignment system, are about 3.2 - 3.4 km from the detector, can resolve the motion of a zone plate to 5 µm.

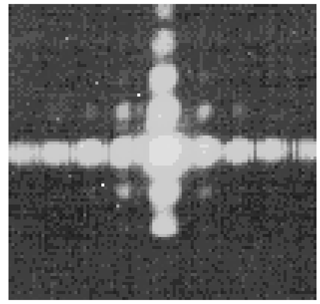


Fig. 16. Fresnel zone plate image

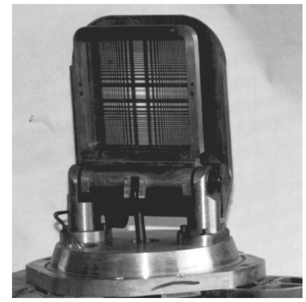


Fig. 17. Hinged fresnel zone plate

Another method of generating the straight line reference by diffraction is the Poisson line.[17] An opaque sphere illuminated by a plane wave generates a diffraction pattern behind the sphere. This pattern can be observed by placing an observation screen or camera in any plane behind the sphere. The Poisson reference line passes through one fixed point, the center of a sphere. The second point is formed by centering the Poisson spot on a quadcell in the detection plane, using a feedback circuit between the quadcell and the mirror that actively steers the incident plane wave. An advantage of the Poisson sheme is the possiblility to place several spheres simultaneously into a very large diameter beam. More spheres can be incorporated by mounting individual spheres to hinged frames similar to the Fresnel system, so as to measure different sets of spheres.

C. Gravity as Reference

A surface of equal "gravity" on which every point is the same height is called an equipotential surface. A hydrostatic level, in which an enclosed body of fluid conforms to an equipotential surface, is a very accurate tool to transfer a height from one point to another or to monitor height changes. Systems are available in different flavors: with optical, mechanical or electrical sensors; manual or computerized; with different fluids—water, oil, or mercury; portable or stationary. ESRF has developed a hydrostatic level system for on-line monitoring of magnet height changes (Fig. 18). To monitor the water level the system uses capacitive proximity gages interfaced to a control system. If significant height changes have been determined, the control computer activates motorized jacks to compensate for the changes. Measurement accuracies of ± 5 µm over 1 km have been reported.[18]

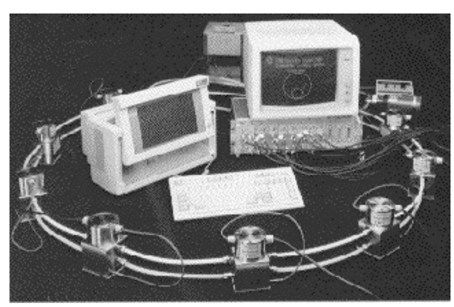


Fig. 18. ESRF Hydrostatic Level System

D. Error Propagations with Additional Systems

1. Stretched Wire For the purpose of estimating the error propagation of a wire system over the length of a possible

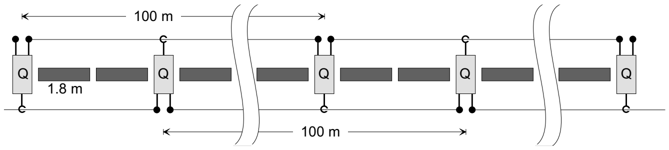


Fig. 19. Double-wire lay-out

NLC linac the lay-out as sketched in Fig. 19 was assumed. A double overlapping wire arrangement is necessary since it was found that in order to preserve a position survey accuracy of ± 5 µm the wire length must not exceed 100 m. Fig. 20 shows the resulting error estimates. The present wire curve is based on propagating linearly the FFTB wire accuracy to a length of 100 m. It is encouraging to see that an existing technology is almost able to support the operations tolerance. The improved wire curve assumes that it will be possible to achieve the present FFTB wire accuracy for a 100 m long wire. This system would be able to fully support the alignment needs.

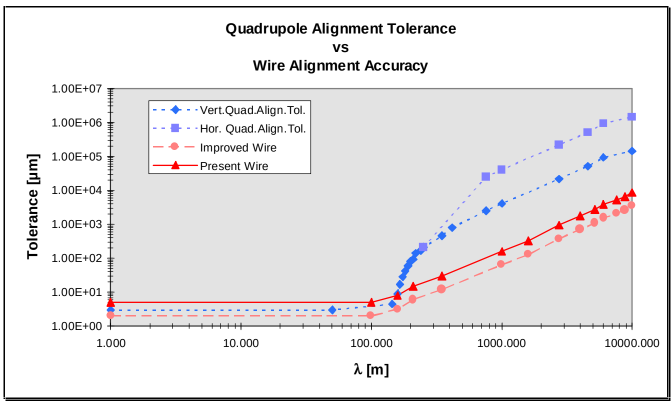


Fig. 20. Wire alignment accuracies

2. Hydrostatic Level System To simulate the effect of supporting the alignment with a hydrostatic level system, two cases need to be considered. If the machine would be built on a tangential plane, one hydrostatic level system cannot accomodate the heightdifference. Therefore, the simulation assumes individual 500 m long sections set up like a stair. The second case assumes an equipotential surface as reference plane allowing one continous system. Fig. 21 shows the simulation results.

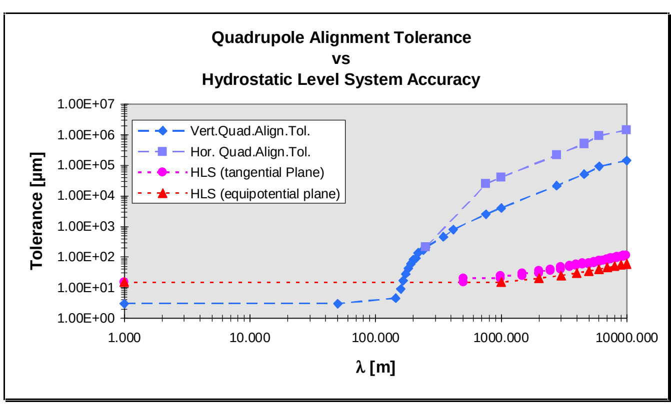


Fig. 21. Hydrostatic alignment accuracies

SUMMARY

Although the NLC requires alignment tolerances an order of magnitude tighter than required for existing machines, results from a conventional alignment will be sufficient to make the NLC correctable. It was shown also that more sophisticated alignment systems can very likely accomodate the operational requirements. While the beam itself is the ultimate judge of alignment, beam based alignment requires costly beam time. To maximize luminosity, the investment in more sophisticated alignment tools may well pay off.

[1]Fischer, G., Alignment and Vibration Issues in TeV Linear Collider Design, *Proc. International Conference on High Energy Accelerators*, Tsukuba, 1989, SLAC-PUB 5024.

[2]Adolphsen, C., A Linac Design for the NLC, *Proc. 1995 PAC*, Dallas, 1995, in print.

[3]Schwarz, W. ed., *Vermessungsverfahren im Maschinen- und Anlagenbau*, Schriftenreihe DVW, Wittwer Verlag, 13/1995, p. 128.

[4]Made by TEXTRON Specialty Materials.

[5]Griffith, L., Progress in ETA-II Magnetic Field Alignment using Stretched Wire and Low Energy Electron Beam Techniques, *Proc. Linac Conference*, Albuquerque, 1990.

[6]Griffith, L., private communication.

[7]Gervaise, J. & E. Wilson, High Precision Geodesy Applied to CERN Accelerators, *Applied Geodesy for Particle Accelerators*, CERN 87-01, Geneva, 1987, p. 162.

[8]Schwarz, W., Wire Measurements for the Control of the FFTB Magnets, *Proc. Second International Workshop on Accelerator Alignment* (IWAA), Hamburg, 1990, p.470.

[9] Ibid, p 475.

[10]Hayano, H., private communication.

[11]Ruland, R., et al., A Dynamic Alignment System for the Final Focus Test Beam, *Proc. Third IWAA*, Annecy, 1993, pp. 243-4.

[12]Korytov, K., Multi-Point Wide-Range Precision Alignment Based on a Stretched Wire Technique, *Proc. Third IWAA*, Annecy, 1993, p. 121.

[13]Takeuchi, Y., ATF Alignment, *Proc. KEK/SLAC X-Band Collider Design Mini-workshop*, SLAC, 1994, SLAC-R-95-456.

[14]Miyashita, K. et al., Transverse Displacement Measurement Using Split Laser Beam, *Proc. XV International Conference on High Energy Accelerators*, Hamburg, 1992, pp. 307-309.

[15]Hermannsfeldt, W., Precision Alignment Using a System of Large Rectangular Fresnel Lenses, *Applied Optics*, **7**, 1968, pp. 995-1005, SLAC-PUB 496.

[16]Ruland, R., op.cit., pp. 246-251.

[17]Griffith, L., et al., Magnetic Alignment and the Poisson alignment reference system, *Rev. Sci. Instrum.*, **61** (8), 1990, pp. 2138-2154.

[18]Roux, D., A historical First on Accelerator Alignment, *Proc. Third IWAA*, Annecy, 1993, pp. 88-91.