Systematic Ground Motion and Macro-Alignment for Linear Colliders

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Future colliders with their μm-range operational tolerances still need to be classically aligned to the 50 - 100 μm range, and kept there, over the km range. This requirement will not be a show-stopper, but not be trivial either. 50 μm movements over a betatron wavelength is a the range where systematic long term motions can prevent efficient operation.

1. Ground Motions and Alignment

Ground Motions and their impact on Accelerators have first, as a separate scientific topic in its own right, been brought into the conscience of Accelerator Physicists by G.E. Fischer. Summaries of his work, which covered the frequency range from the very fast to the very slow, can be found in [1] and references therein.

He was the first to point out that compared to the sub-micron vibration stability requirements of future accelerators any ground would be like butter and nothing would be rigid, pointing to problems in operating the machines.

He also noticed that there were areas in accelerator tunnels which moved unidirectional with many microns a day, up to 10 μm, at SLAC [2].

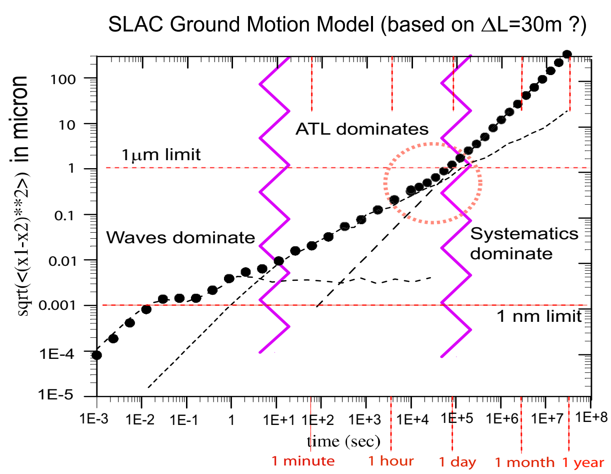

Figure 1: The SLAC ground motion model of A. Seryi. Measurements of the rms ground motions at high frequencies (waves, many Hz) and at low frequencies (systematic, months to years) have been the foundation of this model. The intermediate region, indicated by the dotted circle, is not so well measured.

Fischer was very aware of the need for specific concepts and methods in Alignment for Linear Colliders [3]. The general optical methods of old were clearly no longer sufficient.

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2. Ground Motion Models

Figure 1 shows the measured, or sometimes just deduced, order of magnitude of SLAC ground motions as a function of time scale [4]. Other sites, like TESLA, have different magnitudes of motion to cope with. While the yearly (systematic) [5],[6] and sub-Hz (waves) [7] movements have been measured at several places with great accuracy (and very different techniques), it is the intermediate regime which is of concern here.

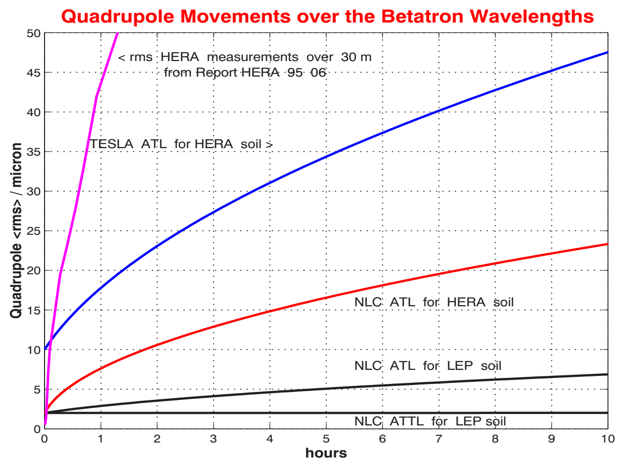

Figure 2: The left steep curve are data from Report HERA-95-06 replotted vs. time instead of the customary Hz. The next curves are combination of what random models predict for combinations of TESLA and NLC lattices with the soil conditions at HERA and SLAC/LEP. The bottom curve is a prediction of rms movement with a systematic model, assuming the rms movements of the worst region (Region 1) of LEP.

What is still questionable is the magnitude of the (difficult to measure) hour to day movements, approximately indicated with the dotted circle in Figure 1. Those movements have to be corrected with frequent beam-based alignment [8]. If the dynamic misalignments are big and fast enough they will impact the efficiency of operation.

Unfortunately, because of technical difficulties there are very few measurements in the hourly range. Data deduced from the variation of the beam orbits in HERA have such a large variation for this time span as to be not very decisive [9]. A plot from HERA in Figure 2 from Reference [10] shows directly measured rms movements of the Quadrupoles, which are 2 orders of magnitude larger than any reasonable ATL predictions. These data should be verified by other means. In view of the time-scale (hour) it must be explored if these large excursions are systematic, but cyclic, diurnal motions.

3. Random vs. Systematic Motions

It is also of great importance for operation of linear colliders to ascertain where the random regime ends and the systematic regime starts. This importance is due to the very different time development of mis-alignment immediately after a (beam based operational) alignment, as indicated in Figure 2.

Figure 3 shows in a systematic way that under nearly **any** circumstances or assumptions the random movements by their very nature lead to a faster initial misalignment ($\propto \sqrt{t}$, A_1TL) than systematic motions ($\propto$ t, A_2TTL) .

4. Tolerances and Placement Accuracy

The problems of the accelerator **ab initio** (installation) alignment, in the betatron wavelength range, can be deduced from Figure 4.

For NLC the typical Linac betatron wavelength is 180 m. Up to this distance the Figure shows that the distance tolerances to be met vs. distance (misalignment wavelength) are tight, about 3 μm, a tolerance which at present only can be reached with beam based alignment during operation. Beyond this betatron wavelength the distance tolerances rapidly increase to the mm range at a distance of $\approx$ 500 m for NLC. The next-neighbor tolerances and tolerances up to 180 m, naturally, stay at the 3 μm level throughout the linac at each point. CLIC, the planned CERN collider, has to meet even tighter tolerances, but only over $\approx$ 30 m, while TESLA with its looser tolerances, has to meet them over a longer distance, 600 m. Consequence: since on the other hand the accuracies achievable decline with distance, the tighter tolerances for CLIC (or NLC) are not necessarily more difficult to reach than the looser TESLA numbers.

Also, Figure 4 shows that there are cross-overs between several ab initio alignment methods. E.g., while the hydro-static levels are less accurate over short distances than stretched wire systems, they are more accurate beyond 200 m.

But again there is a caveat. While hydrostatic levels work well for accelerators following the curvature of the earth (= are level), laser straight tunnel and linac alignment is planned for those colliders which want to keep a Multi-TeV option open. Reasons are: (1) beam based alignment is easier with straight trajectories, (2) time stability is better if no dipole correctors but only mechanical magnetic movers are being used [11], (3) the spurious dispersion introduced in a curved linac limits the energy which can eventually be achieved.

What has not been addressed sofar is the problem of the linac overall straightness, and defining this overall straightness requirement as a tolerance. Beam-based alignment had to be developed at the SLC [8] for determining and smoothing the historic quadrupole misalignment to make the SLC work. It was then successfully used at the FFTB [12] to demonstrate NLC requirements could be met. But in both cases an independent laser alignment system kept the beam lines within better than 100 μm straight over 3 km and 500 m, respectively.

All modern alignment methods are based on the realization that to align the quadrupoles relative to a reference line is more important than the actual absolute choice of this line. But this is only true if this line is close to the average alignment line determined by the rms positions in the pre-alignment step. How close is close enough as a function of distance still has to be quantitatively defined for the linear collider proposals under consideration.

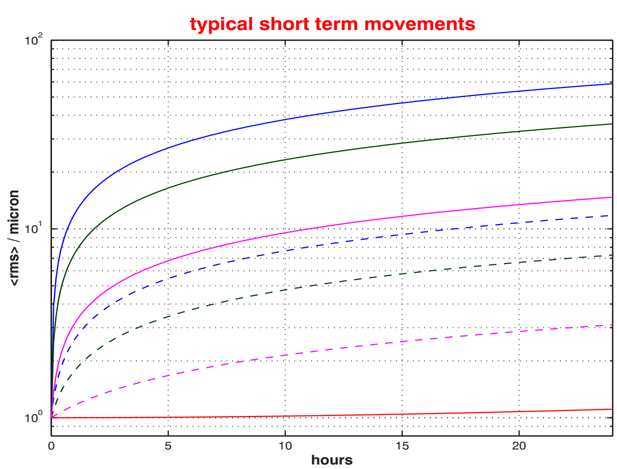

Figure 3: Rms values expected from extrapolation of ground motion alone, accrued to a machine aligned to 1 μm at T=0. The solid curves starting with an infinite slope are rms-values calculated from a random ATL model with A equal to A_{LEP}, A_{PS} and A_{ZDR}, from top to bottom, respectively with L=5 km, half the length of NLC. The dashed curves are ATL calculations with the length of one betatron oscillation $\approx$ 200 m chosen instead for L. The line on the bottom represents the development of rms defined in a systematic ATTL model, with A from the analysis of the worst region of LEP.

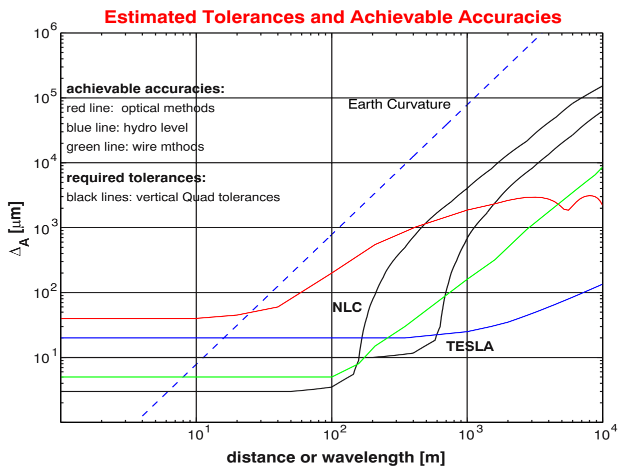

Figure 4: For NLC the typical Linac betatron wavelength is 150 m. Up to this distance the Figure shows that the tolerances versus distance to be met are tight, about 2 μm. Beyond this point the tolerances rapidly increase to the mm range (Figure after R. Ruland, using the data of Figure 7-24 of Reference [13]).

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