ALIGNMENT AND VIBRATION ISSUES IN TeV LINEAR COLLIDER DESIGN

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Abstract The next generation of linear colliders will require alignment accuracies and stabilities of component placement at least one, perhaps two, orders of magnitude better than can be achieved by the conventional methods and procedures in practice today. The magnitudes of these component-placement tolerances for current designs of various linear collider subsystems are tabulated. In the micron range, long-term ground motion is sufficiently rapid that on-line reference and mechanical correction systems are called for. Some recent experiences with the upgraded SLAC laser alignment systems and examples of some conceivable solutions for the future are described. The so called "girder" problem is discussed in the light of ambient and vibratory disturbances. The importance of the quality of the underlying geology is stressed. The necessity and limitations of particle-beam-derived placement information are mentioned.

INTRODUCTION

The surface of Mother Earth, on which we wish to build well aligned accelerators, is not Terra Firma but is constantly in motion. The purpose of this talk is to review some facets of this motion, to examine whether they present fundamental limitations and to estimate whether the problems encountered can be solved by sound engineering in the foreseeable future. I submit that, in the case of the next linear collider, the answer to this question is "Yes," but it will take a good deal of effort and money.

The earth is a glob of material held together by its own gravitation and subject to a variety of internal and external forces. Portions of its interior are thought to be liquid (will not support shear waves), and its relatively thin, elastic, wrinkled and, in places, broken crust swims around on an outer mantle that can hardly be called an engineering material. Peoples who live along the Pacific rim have become quite used to this concept, but I nevertheless thought you might be interested to know that Japan and California, separated by almost one billion centimeters, are approaching each other at the rate of between 2 and 5 cm/year depending on where and how this measurement is made[1]. I might add that California is drifting away from Europe at a similar rate.

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About ten years ago, when we first began to think about the bizarre world of ground motion in relation to the construction of linear colliders, we became alarmed about motion in the frequency band ~ 0.1 to 50 Hz. The reasons for concern in specifically this domain were (a) that high frequency jitter appeared to present difficult engineering problems and (b) that disturbances at slower rates. that is with wavelengths greater than site dimensions, would move the machine monolithically causing no relative motions between focussing elements and hence produce no deleberious orbit distortions. In the intervening years we have learned to live with microseismic disturbances. For example: The magnitudes and signatures of natural and man-made sources were identified[2]. From such considerations project site tolerance recommendations could be made[3]. Common sense solutions to local groundnoise abatement followed. Great strides were made in the understanding of how circular machines react to random plane wave excitation through the extension of the pioneering work of Aniel and Laclare[4] and by Rossbach[5]. The importance of resonances in magnet supports was quantified by Chou[6] and more recently by Rossbach[7]. Vibration isolation of final focus elements by means similar to those used by workers in Gravitational Wave detection was discussed by Ash[8], and recently we have heard of the Active Alignment System at KEK[9] and of the commercial vibration isolation system "TACMI"[10]. For such reasons and the fact that the general level of consciousness regarding vibration problems has been raised, I wish to turn to another region of the motion spectrum: — namely *slow drift*. We will see that in the world of micron-level alignment, these problems can become pernicious.

COMPONENT PLACEMENT TOLERANCES

In this section we will attempt to define the general level of alignment tolerances likely to be found in various linear collider concepts, designs and subsystems. I say it this way because tolerance setting is an unpopular and odious task — very often an ongoing debate between the desired and the achievable that may still be carried on even after the collider is in operation when effects, not dreamed of at conception, rear their ugly heads. All values listed in the table below were kindly provided with this caveat in mind and are meant, at this time, to be only *guidelines* to workers developing alignment techniques.

I should now try to explain what I mean when one says "alignment tolerance". There has been some confusion about this term. I hope you will bear with me for the following, somewhat pedantic, definitions,

Quite often simple calculations or computer simulations are performed in which the effects of offsetting any single element from its correct "on-axis" position are measured in terms of, say, a 10% loss of luminosity. Since making luminosity is the purpose of a collider, this seems like a not unreasonable way to proceed and immediately gives the relative sensitivities of element placement. For reasons that will become clearer later, let me call such displacements *incoherent jitter tolerances*. There are, however, at least two serious conceptual flaws with this method. No account is taken of the facts that in a real machine (a) all elements (not just one at a time) are out of place simultaneously, and (b)elaborate orbit and tune correction systems are applied to recover the lost luminosity. Permissible alignment errors (either systematic or random) 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. Let us define survey and alignment tolerances to be those values of placement error which, if exceeded, lead to a machine that is *uncorrectable* - with its unacceptable loss of luminosity. In recent years, 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 those derived for one component at a time. The reason for choosing the name jitter is now more apparent. Jitter tolerances are the magnitudes of errors that are NOT amenable to compensation by either static or dynamic (including BNS) methods. To recapitulate: It is the loosest survey errors that we are now looking for, not those tolerances associated with keeping an already operating machine running at peak luminosity.

TABLE I. Estimated Transverse Component Survey and Alignment Tolerance (μm) *

System\ Project	CLIC$^{\diamond}$(CERN)	VLEPP† (USSR)	JLC‡(KEK)	TLC$^{\heartsuit}$(SLAC)
Injector Accelerator:			200	standard
Damping Rings:				
Quads (Horiz.)			100	100
Quads (Vert.)			50	30
Compressor #1:			50	?
Intermediate Linac:				
R.F.Structure			50	
Magnetic Foc.(H)			50	
Magnetic Foc.(V)			50	
Compressor #2:			50	?
Main Linac:				
R.F.Structure	10	.3*	50	10 - 50
Magnetic Foe.(H)	1.7	.03*	10	100
Magnetic Foe.(V)	1.0	.03*	10	20
Final Focus Elements (V)			5	10
Final Focus Elements (H)			5	30
Final Lenses (V)			5	2nm*
Final Lenses (H)			5	200nm*
Beam Analysis before dump			5	?

⋆ 1 σ value of the population unless otherwise indicated, jitter values are denoted with an *. ◊ Provided by H.Henke. † Provided by V.Balakin, for a bunch population of 2×10^{11}. ‡ Provided by K.Takata, Values are tentative and are meant to be maximum deviation from central orbit. ♡ Provided by R.Ruth.

In the above table, distinction is drawn between the linac's RF structure and its Magnetic lattice elements; both of which may focus and steer. Further, for those groups who engage in asymmetric beams, vertical and horizontal tolerances may be substantially different. This is of import for those wishing to align, since techniques in these planes may be quite different. Finally, there is clearly something very special about the final lenses.

REFERENCE SYSTEMS

An examination of periodic realignment records of several large accelerators [Linac, PEP (SLAC), PS, SPS (CERN) and others] shows that, on the average, tunnel floor motion is at least about 50μ per 6 month interval. Much higher rates are seen in certain well known locations which are associated with the trauma inflicted on the ground by construction activity resulting in rebound, recompaction etc.. Ground water levels, varying with rainfall, have been shown to cause both vertical and horizontal tunnel displacements[11,12]. We see therefore that in the micron world, the rate of drift, albeit slow compared to conventional vibratory motion, is faster than can be corrected by conventional survey and realignment. We need servo-realignment, and for this we need reference systems more or less independent of the earth! Four such systems are listed below.

The Large Rectangular Fresnel Lens System [13] The principle of this system is shown in Figure 1. Divergent laser light is made to impinge on lenses which are inserted into an optical path one by one, and the relative displacements of their images is measured at the far end. The resolution of such a system depends on three terms: (1) the size of the diffraction limited images, $w \approx \lambda s/D$, in which D is the effective width of a lens, (2) the ability of a scanner to locate the centroid of an image, and (3) the optical lever arm $(r+s)/r$. A 3 km long system of this kind has been used to keep the SLAC linac aligned for 20 years. With λ = 628 nm, $D \approx 30cm$ and centroid discrimination $w/100$, the resolution at midspan (the most difficult region) is about 25 microns. Systematic errors can creep into the results from (a) constructional asymmetries in lens etching, (b) nonuniform illumination or improper masking and (c) most seriously in the transfer of lens coordinates to those of the accelerating guide. Overdesigned for its originally intended use, it can nevertheless be improved in the future. Already the scanner has been replaced with a CCD-based camera whose output is digitized and can be processed with all the mathematical armament of image enhancement. One can imagine also shortening the wavelength and/or increasing the diameter of the lenses. The chief conceptual advantage is the following: A perfectly straight line (neglecting general relativity) is established by the classical method of path differences (interfering wavefronts in this case) without resorting to extreme laser pointing requirements. The chief disadvantage is having to insert targets mechanically, a process which is time consuming and prone to mechanica. problems.

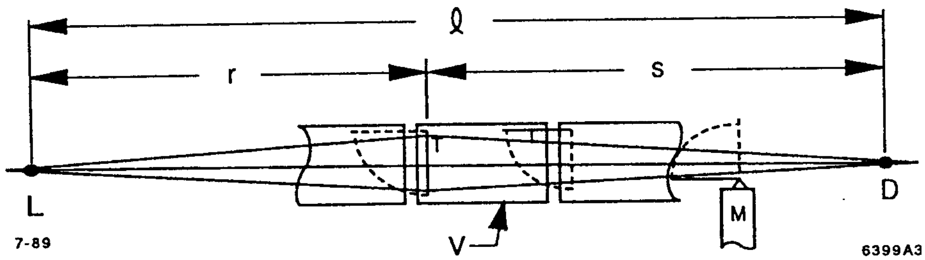

Fig. 1. Schematic illustration of the SLAC alignment system. T is one of 294 rectangular Fresnel lenses which focus laser light L to an image at the detector D. V is one of 60-cm diam. vacuum pipes, each 12 meters long which also serve to support the accelerator

We propose to exploit the optical lever arm of the SLAC Beam Switchyard laser alignment system[14] to align the Final Focus Test Beam[15,16] with resolutions in the 1 to 10 micron range. One nice thing about linear colliders is that they are linear, or very nearly so.

The Poisson Alignment Reference System[17] This novel system, which was conceived to align a free electron laser, illuminates spheres with plane waves whose diffraction- limited shadows are cast onto the observation plane as shown in Figure 2. The location of the "Poisson spots" ie. the bright center of the diffraction patterns, is determined by four-sectored detectors. Since the incident beam of collimated light has a large diameter, many spheres can be illuminated and detected simultaneously, provided they are sufficiently far apart so that the resulting patterns are still interpretable. Based on results from a 26.5 meter long prototype exhibiting submicron resolution, simulations indicate that $\approx 2\mu$ should be possible at 300 meters. Its chief advantage is readout of many sheres at kHz rates. Its disadvantages are that only a limited number of spheres may be used in a given pipe diameter and that since pointing accuracies of order 20 nrad are required, it is sensitive to ground vibration. That such pointing accuracies have been achieved today attests to the skill of the proponents and miracles of modern piezoelectric technology and opens the way for other schemes that depend on highly accurate laser steering.

The Egyptian Method Drawing a straight line by means of a stretched string must predate Pythagoras, but I haven't been able to find the reference. This method has been used with success at CERN[18] and other laboratories[19] but was limited to about the 50 μ level due to air currents. Its length is ultimately limited by the strength of

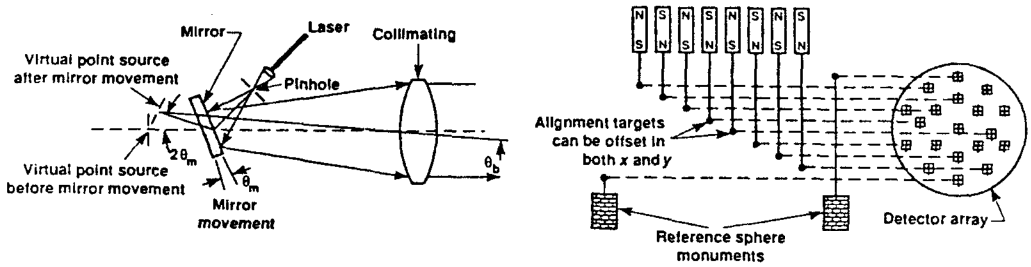

Fig. 2. Schematic of the Poisson Alignment Reference System

the string (kevlar), although proposals years ago[20] suggested this limitation could be overcome by intermediate supports floating on liquids. Updating this method with modern proximity sensors and with the wire inside a vacuum tube seems like an opportunity that should not go unexplored for intermediate length linac straightness testing.

The Archimedes Method (Hydrostatic Levels) The history of "height difference" measurement is also long and continues to be an exciting one in the fields of precision alignment and in crustal deformation[21,22] Water levels have been used to align the PEP storage ring[23] (100 µ rms), and are proposed for use at the European Synchrotron Light Source with about one order of magnitude better performance [24]. At SLAC we are trying to develop a mercury liquid transfer level in connection with the Final Focus Test Beam that we hope will have micron accuracy over limited distances. Limited distances because, not only is the world not flat, its geoid (local equipotential surface) is not smooth; rather it is distorted by static gravity anomalies such as mountains and oil deposits. Worse yet, it is time dependent!

THE EFFECTS OF EARTH TIDES [25]

It was pointed out by Lord Kelvin in 1876 that the varying gravitational potential exerted by the moon and sun on the earth should cause radial excursions of a non-rigid earth. By comparing long-period ocean tides (monthly and semimonthly) with theory, G.H.Darwin concluded in 1883 that the earth's crust is rising and falling with amplitudes approximately 1/3 that of the oceans that cover it. One can see that semidiurnal and diurnal effects can occur because the declinational plane of the moon is not earth equatorial. Nor are orbits circular. A hundred years of observation by scientists in every country have yielded a very rich spectroscopy of planetary motions (at least 10 dominant and 19 periods of lesser amplitude). Although 'table top' experiments exploiting this effect can yield interesting information regarding the constituency of our globe, what concerns us here is that all aspects of geodesy and precision alignment are affected.

Leveling The concept "*horizontal*" begins to loose its meaning. Theoretically the direction of gravity may swing up to $1/4\mu$radian and in practice many times this amount due to ocean or atmospheric loading (Fig.3)[26]. One need not add that one micron displacement at one meter — the kind of dimensions we are concerned about here — is one microradian. Moreover the NS and EW tilts are not likely to be the same in either magnitude or phase.

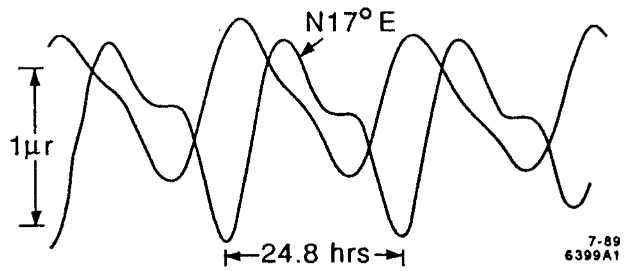

Fig. 3. A 100 hour record segment of two orthogonal tilt components showing their amplitude and phase. (Taken in a gun gallery at the San Francisco Presidio in 1969, Ref.25)

Strain[27] It is not hard to imagine that if the earth undergoes radial strain, the other five components of the strain *tensor* will manifest themselves as well. Typical values are $\Delta L/L \approx 10^{-8}$. Such variations, usually measured interferometrically or by means of stretched wire extensometers, are somewhat beyond our current interest. But one day, data from the 55 km baseline between Tsukuba and Kashima will have to be corrected for this effect!

Variations in the magnitude of "g" All devices that are affected by gravity will experience periodic change. On the rising and falling surface of the earth the fractional variations of "g" are of order 2.5×10^{-7} Probably the most important effect is on the orbits of satellites with which precision laser ranging is carried out in establishing baselines. Very sophisticated programs are employed to take care of this effect but the concept of mean height above sea level might have to be replaced by mean height above the center of mass of the earth.

What does all this have to do with the practical aspects of aligning a large future accelerator? Quite simply, precision measurements require reference systems independent of mother earth. Further, since mother earth is used to support the accelerator, we should not be surprised that measurements and correction contain less noise if they are carried out by a data acquisition system on time scales small compared to the shortest period of the moon. Since planetary motion is after all a rather predictable sport, should not all this be calculable? Yes, if it were not for the weather. We note that another time scale, that of the rising of the sun, turns out to be just as, if not more, important. In California, the onset of light brings on rapid air temperature rises.

THE GIRDER PROBLEM

It is now time to get down to earth regarding accelerator supports. The issue that needs to be addressed is: "What style of fabrication and installation are the proponents of the next linear collider going to adopt?" I will assume that the issue of the need for a reference system and mechanical movers to bring the machine back into alignment will be further debated and then settled[28]. Investigations on kinematic mounts, computer controlled movers and readbacks having micron accuracies are currently underway at CERN[29]. The question can be rephrased: "What is the function of a linac support *girder* and what is its optimum length?" Let us examine two cases.

1. No girder at all: In this case all the accelerating waveguide sections and their associated fittings lie directly on a shelf which is part of the tunnel structure. The consequences of such a style are (a) each section must have its own expensive mover and connection to the reference, (b) since the whole machine is assembled in the field, testing it for mechanical and electrical integrity becomes more difficult and (c) testing it with beam becomes a logistical horror.

2. A very long-, perfectly rigid and aligned support member: This object provides for assembly, alignment and pretesting (even with beam) of long accelerator modules in the controlled environment the factory-laboratory. Position correction movers are provided only at its ends because the object maintains its perfect shape even when transported to and installed in the tunnel. Somehow, it has no resonant vibratory modes. I believe the strength of materials prevents the existence of such a member.

Perhaps we should separate the alignment and transportation requirements by suggesting that a light flexible girder, whose sole purpose is to hold the ends of components relative to each other, be placed on beds that permit fast realignment. This light girder is transported with the aid of a removable strongback. Fast sectional realignment is carried out in the lab with very long precision coordinate measurement machines and in the tunnel with portable secondary reference gadgets such as automated strung wires and levels. But what should the mattress beds be made of? Steel rails are probably wrong because they are terribly prone to distortion through thermal gradients. Traditional optical benches are made of massive granite for thermal and mechanical stability, but their internal ability to absorb vibration is poor. More modern tables are made using a honeycomb structure[30]. The high precision machine tool industry has resorted to polymer composites[31] which have good strength, vibration absorption, thermal mass, dimensional stability and can be relatively inexpensively cast with high order flatness and surface finish. To stimulate innovative engineering solutions, let me make a somewhat outrageous suggestion. Amateur holographers, who cannot afford expensive apparatus, successfully mount the optical components of their artistic creations on stakes stuck in large boxes filled with sand which are in turn supported by under-inflated automobile tire inner tubes. Should science imitate art? Surely nature and man have provided enough of these materials to construct 20 km of collider.

THE IMPORTANCE OF THE UNDERLYING SITE GEOLOGY

It has been pointed out before that the geology of the chosen site will have great bearing on the cost of tunneling. Good ground properties[32] probably also result in more economic solutions than having to mitigate the drift and vibration effects of a bad site. The ideal site would be well removed from man-made disturbances, have a water table well below the tunnel, have a uniform, homogeneous, competent material that can nevertheless be easily mined with boring machinery. It is a pleasure to note that the Austin Chalk of Waxahachie, Texas appears to come close to fulfilling such a description. The unweathered material near the surface is said to have [33] compressional sound velocity of between 2.6 to 3 km/set. The shear wave velocities range between 1.1 and 1.8 km/set. Ng and Peterson[34] have calculated, among other things, the detailed response of the two colliding beams at the interaction point of the SSC due to noise sources on the surface. These calculations, when applied to estimating the effects of trains passing through the site, show that the results depend sensitively on the absorptive properties of the medium. While the chalk bedrock appears to have attenuation lengths, (in the sensitive betatron wavelength region), in the many tens of kilometers, train noise may be sufficiently absorbed in the unconsolidated overburden and reflected at the dirt/bedrock interface.

Deep (depth >15m) underground tunnels have some of the properties of a wine cellar, namely remarkable constancy of tunnel wall temperature. Surface-temperature-driven thermoelastic strains are therefore likely to remain sma11[35]. But since temperature changes, worse yet temperature gradients, are probably the single most important cause of misalignment[36], early consideration should be given to the thermal engineering of the tunnel and its contents if we do not wish to pollute the naturally occurring stable conditions. Two problems arise. Accelerating waveguide cooling water temperature stabilization systems generally run at temperatures higher than the highest cooling tower temperature which is likely much higher than that of the tunnel wall. Permitting warm moist summer air to enter a cool tunnel will cause not only misalignments, but fog and rain as well!

One object guaranteed to cause distortions of the final focus is a massive detector. Figure 4. depicts the time dependence of the motion of the final lenses of the SLC when the weight of the 1800 ton Mark II detector was rolled on line and the east shielding wall reconstructed[37]. The floor of the experimental hall pit (61 cm of heavily reinforced concrete) rests directly on the very stable grey, unweathered, well-cemented, tertiary miocene sandstone that permeates the SLAC site. The time constant of the total (plastic and elastic) rather small deformation (2mm) was of order 30 days.

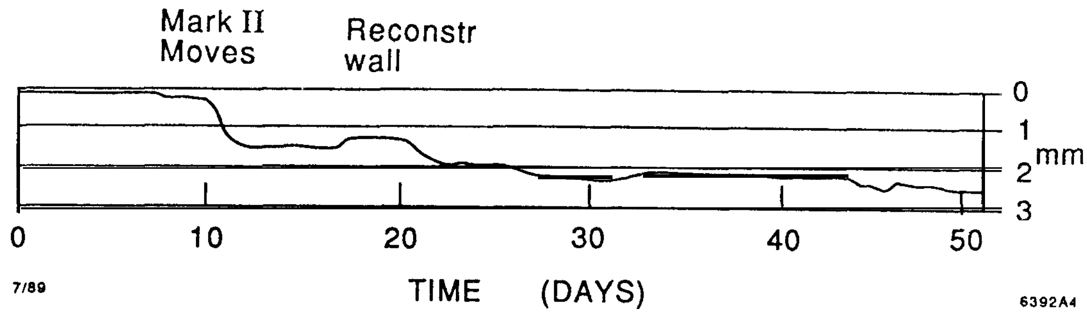

Fig. 4. Amplitude of Mark II dector settling on floor of SLC experimental pit. (Outboard levels are mounted in tunnels, inboard on piers in the pit supporting the final lenses.)

IMPORTANCE AND LIMITATIONS OF 'BEAM DERIVED' ALIGNMENT

At the very outset we have stipulated that we will allow relaxation of survey tolerances by about one order of magnitude over operational (ie. jitter) tolerances, provided that systems can be *tuned*, both on paper and in practice. This should help with the problem of systematic offsets in that, being under the influence of elements whose effective electric and magnetic centers do not a *priori* coincide with their surveyable mechanical centers, the final arbiter of where the beam wants to ride is, of course, the beam itself. In accelerating structures there have been the notorious effects of RF input couplers and the 'bookshelf' constructional errors; although for center finding of magnetic elements at the micron level there have fortunately been some recent advances using the singing wire technique[38]. In short we have always relied on the time honored fall back: — Feedback. Be it manual or automatic, fast or slow, we depend on the application of beam-derived intelligence to extricate us from the dilemma of not meeting tolerances.

But there are several traps we can fall into. The first of these is that the initial alignment must be good enough to get enough beam through to permit measurements to be made. Secondly, beam-position sensors too must have a certain modicum of electronic stability and immunity to beam spray to permit a meaningful analysis. (Under certain circumstances the absolute position of quads and BPM's is not required for a linac[39], provided the mathematical model of the machine[40] is adequate.) Thirdly, the proliferation of feedback systems will, if not held in check, lead to increasing inoperability since each system adds another layer of complexity. Sometimes, for example, downstream systems cannot begin to function if upstream systems are not tuned. To help in diagnosis, instrument and feedback stations should be located between sections of a collider that are functionally distinct. It is my unsubstantiated judgment that we should strive to do the very best, we can, in both arenas, to make the future linear collider live up to its potential.

CONCLUSIONS

The Micron World, in which steel acts like butter and in which temperature excursions are like Gulliver's Travels, has been tamed and industrialized on the laboratory scale. I do not believe the problems that we are going to encounter in the design of future linear colliders on a kilometer scale will turn out to be *fundamental*. Rather, the challenge will be to be innovative enough to find sound engineering solutions that we can *afford*. Further, we should involve the alignment community in all aspects of the design decision making process at the earliest moment.

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