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STABILITY CONSIDERATIONS FOR FINAL FOCUS SYSTEMS OF FUTURE LINEAR COLLIDERS.

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Abstract

The final focus systems for the future linear colliders need to focus beams to nm-range spot sizes at the collision point. The design spot size varies from several nm for 500 GeV to the one nm range for 3 TeV. In order to keep the beams in collision and to maintain the luminosity stringent stability optimization must be applied. We discuss different sources of beam perturbations and estimate the expected beamline stability based on previous experimental observations. Possible measures for beam stabilization are discussed and plans of further collaborative efforts are outlined.

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The Final Focus systems of future linear colliders need to focus beams to nm-range spot sizes at the collision point. The design spot size varies from several nm for 500 GeV to the one nm range for 3 TeV. In order to keep the beams in collision and to maintain the luminosity stringent stability optimization must be applied. We discuss different sources of beam perturbations and estimate the expected beamline stability based on previous experimental observations. Possible measures for beam stabilization are discussed and plans of further collaborative efforts are outlined.

1 INTRODUCTION

The three major proposals for future linear colliders, NCL/JLC [1], TESLA [2] and CLIC [3], differ in their design choices, especially for the main linac RF systems. This paper makes no attempt to review those choices nor to explain their rationale. In spite of their differences, the designs all require similar values for the vertical beam size at the interaction point. The design vertical spot size is 5 nm for TESLA [2] at 0.5 TeV, 2.7 nm for NLC/JLC at 1 TeV and 1 nm for CLIC [4] at 3 TeV center of mass energy. The nanometer size beams imply rigid stability requirements which are similar for all three proposals.

The most severe stability tolerance is for the final quadrupoles that focus the beams at the interaction point. A vertical displacement Δy of these quadrupoles causes roughly the same beam position offset at the interaction point. If the relative beam offsets at the IP are to be less than 10% of the vertical beam size, then the tolerance for vertical movements of the final magnets are roughly 0.5 nm for TESLA, 0.27 nm for NLC and 0.1 nm for CLIC. Typical tolerances for other elements in the final focus system are about 10 times looser.

Present experience with beam stabilization comes from the first prototype collider and the test facilities:

1. SLAC Linear Collider (SLC): 45 GeV beams with 500 nm vertical beam size were collided at 120 Hz for production of Z-bosons. The pulse-to-pulse jitter was estimated to about 30% of the vertical beam size.

2. Final Focus Test Beam (FFTB): For a 45 GeV beam at 30 Hz and an effective vertical spot size of 70 nm a pulse-to-pulse jitter of 40 nm was measured (dominated by vibrations of the beam size monitor) [5].

Many effects which contributed to this beam jitter have been understood and should be less important in future designs. These include poor design of quadrupole supports, large wakefields (which will be much smaller in all designs), absence of longitudinal beam collimation, etc. Nevertheless, the experience at the SLC and the FFTB shows that the requirements for future linear colliders are not easily achieved. New technical solutions and methods of beam stabilization are required. In this paper we discuss fundamental limits of beamline stability, given by ground motion, consider the various techniques proposed to overcome these limits, and outline plans for further collaboration.

2 GROUND MOTION

The natural stability of a beamline is limited by the motion of the supporting ground. Ground motion can be divided into "slow" ($f \lesssim 0.1$ Hz) and "fast" ($f \gtrsim 0.1$ Hz). Fast ground motion has been studied extensively and we summarize below its main qualitative features.

The power spectrum of natural ground motion is a steep function of frequency which falls off as $1/f^4$. Above 1 Hz, the amplitude is affected by "cultural" noise; the power spectrum can be several orders of magnitude higher than the natural one. The correlation of the ground motion shows what part of the total motion is actually dangerous for a collider. It depends on sound velocity in surrounding media and on distribution and nature of the noise sources. Sites on hard rock have high sound velocities and good correlation; sites on sediment tend to have poor correlation.

A major part of the on-surface produced cultural noise due to cities, traffic, etc. is localized within about one wavelength near the surface. Therefore shallow tunnels located in urbanized areas are usually noisy, like the HERA tunnel, regardless of the geology (rock/sediment). In contrast, deep tunnels, like LEP, are much quieter. Table.1 shows the typical rms amplitude of the ground motion in several frequency bands for a deep quiet tunnel with good correlation (LEP) compared with a shallow noisy tunnel with moderate correlation (HERA) [6, 15, 20]. The "quiet" amplitude is better than required for any of the currently proposed linear colliders. A "noisy" location would be unacceptable unless feedbacks were able to damp the motion.

Slow motion (f $\lesssim 0.1$ Hz) produces misalignments of the collider components which would cause emittance growth if not reduced/removed by beam-based feedback. In contrast with fast motion, it does not constitute an immediate limitation for a linear collider. The diffusive ATL model of slow ground motion [16] improved understanding and pre-

Table 1: Typical rms amplitude of ground vibrations in quiet (LEP deep tunnel) and noisy conditions (HERA shallow tunnel). Single point motion ("total") and the uncorrelated part for $\Delta L = 20$ m. Note that relative motion is $\sqrt{2} \times$ the uncorrelated part.

f	rms y "Quiet", nm		rms y "Noisy", nm	
Hz	total	uncorrelated	total	uncorrelated
3–∞	0.2	0.02	50	20
10–∞	0.05	0.015	5	5
30–∞	∼0.01	∼0.007	3	3

dicts that the misalignment of two points is proportional to their distance L and elapsed time T: $\langle \Delta y^2 \rangle = ATL$. A is a site/condition/geology specific parameter whose observed range is $10^{-9} - 10^{-4}$ μm^2/s/m. There is still controversy over the region of validity. The T dependence has been confirmed in the minute to month time scale. For years, the T dependence may change to T^2 due to systematic motion [17]. Careful investigation of the spatial dependence of slow motion is subject of further studies.

The noise generated in the tunnel is of particular concern. Accelerator equipment which is not carefully designed may produce unacceptably large noise. For example, the ventilation system located near point 5 of LEP increases the amplitude for $f \gtrsim 3$ Hz by more than a factor of ten [6]. Key factors to reduce the in-tunnel generated noise are careful design of accelerator equipment, avoidance of resonances with modes which propagate along the tunnel, use of passive/active vibration damping.

Special care must be taken with beam-induced vibration in the interaction region. Analytical studies of the beam-induced thermal shock waves suggest that significant vibration may be induced in the beam dump [8]. Proper measures must be taken to minimize those vibrations and to decouple them from the magnets. The noise in the experimental areas is another concern. Detector equipment may produce additional noise. Also, tunnel discontinuities (like large experimental halls) may alter/destroy the correlation of motion. The relative motion measured 17 meters left and right across a HERA IP was found to be about 100 nm above 1 Hz [7]. Further investigations of the contributing factors should be done in HERA and other colliders.

Three key approaches can be relied upon to ensure sufficient stability of the final focus: a naturally quiet site, proper design of accelerator equipment, development and use of correction methods that overcome vibration problems. For the three different designs of a linear collider, the balance between these three approaches is different, as described in the following sections.

3   PASSIVE AND ACTIVE SUPPORT

The magnets are carried by support structures that unavoidably transport the ground motion to the magnet. The driving ground motion is usually somewhat enhanced, leading to larger magnet motion. Measurements at LEP show an amplification of between 10 and 30 in the range of 0-100 Hz with peaks at the acoustical resonance frequency of the

quadrupole stand (33Hz) and the acoustical resonance frequency of the LEP tunnel (diameter 3.76 m). It has been shown at the FFTB that a well designed stand can significantly reduce this amplification. In the vertical plane, the difference between the motion of a magnet and the tunnel floor was measured to be 2 nm for $f > 3$ Hz while the accelerator was operating [9]. In contrast, the horizontal plane had a much greater difference between magnet and floor, likely because the magnet stands are rather narrow and high ~ 2 m. Alternately, passive damping can be used to damp the high frequency motion. For example, passive damping pads were placed between the supports and the floor at the Advanced Photon Source to reduce the high frequency motion which drove girder resonances [19]. Another example, is the multi-layered approach taken at LIGO to stabilize the interferometer mirrors [18].

Active magnet supports can also be used to damp the magnet motion. Here, the magnet motion is continually monitored with accelerometers. Piezo-actuators are incorporated into the design of the support and are used within a feedback circuit to compensate the measured motion. Such an active support system has been built and tested at DESY [10]. Damping was achieved in the frequency range from 5 Hz to 25 Hz. The magnet motion was measured to be 10 nm above 4 Hz, about a factor of three smaller than the motion of the supporting ground. It is believed that active stabilization schemes can stabilize magnets at the nm- or sub-nm level. Special schemes have been proposed for the stabilization of the final doublet that has the tightest tolerances. A so called optical anchor could measure the stability in the interaction region using laser interferometry [11]; experimental studies are ongoing.

4   BEAM-BASED FEEDBACK

All linear collider designs have tolerances on the alignment of beamline components which require continuous beam-based feedback to counteract performance deterioration. Misalignments can change the trajectories so that the beams no longer collide optimally. They can also cause emittance growth and introduce aberrations which increase the beam size. NLC plans to use a multi-layered approach on different time scales. A slow "feedback" will move quadrupoles and structures onto the beam trajectory every 30 minutes to compensate for slow ground motion. Inter-pulse feedback in a few locations will correct the accumulated trajectory error between beam-based alignments. Fast kickers may also be used to straighten out the bunch train. Finally, a very fast feedback capable of acting within the bunch train will be used to keep the beams in collision. Similar systems are proposed for the other collider designs. An important topic for further study is to simulate and understand the interaction of these different systems which must work together.

Inter-pulse feedback will be used to measure and correct the average properties of a bunch train throughout a linear collider. Such systems were used extensively at

the SLC but their performance was poorer than predicted. These problems are now understood from simulations and an improved algorithm has been developed [12]. The maximum rate of beam measurements used for inter-pulse feedback is set by the repetition frequency of the machine. The SLC feedback system was optimized to damp motion at frequencies below about $\frac{1}{20}$ of the sampling rate; a more aggressive algorithm might have a cross-over point as high as $\frac{1}{6}f_{rep}$. The response time of this type of feedback must be carefully optimized with respect to the position monitor resolution. This has been studied in detail for TESLA.

Intra-pulse feedback operates at high frequency and acts within a bunch train. The operational scenario of luminosity stabilization has been studied in detail for TESLA [13]. In total, three intra-bunch train feedback systems are envisioned: one at the end of each main linac (optional), one in each chromatic correction section (CCS) and one at the IP. At the end of the linac the feedback removes vertical position and angle jitter expected to be 0.5σ. In the CCS, it will correct the angles at the IP. At the IP, it removes the relative orbit jitter between the two beams by measuring the beam-beam deflection and steering the beams back into collision. The large bunch spacing of 337 ns in TESLA makes it possible to damp frequencies of up to 170 KHz, covering most sources of noise. In TESLA, a train-to-train jitter up to $35\sigma_y$ in beam separation and $5\sigma_{y'}$ in crossing angle is predicted (with 70 nm uncorrelated quadrupole vibration in linac and final focus). Simulations have shown that the beam-beam interaction can be successfully stabilized within $0.1\sigma_y$ and $0.1\sigma_y'$ except for the first 3% of each bunch train. An intra-pulse IP feedback option has been studied for NLC [14] and CLIC but the shorter bunch spacing makes its implementation more challenging.

5 BEAM SIMULATIONS

Simulation of beam stability in linear colliders is a demanding enterprise. The simulation must include realistic time-dependent models of initial beam conditions (position, angle, charge, longitudinal and transverse beam distributions), alignment changes (two dimensional ground motion model with correlations), magnetic field variations, and correction systems (orbit correction, slow and fast feedbacks). The proper design of the collimation system requires an accurate tracking of beam tails from the damping rings, through the bunch compressors, the linac, the collimation, into the Final Focus.

Some requirements have been implemented into tracking programs. LIAR [21] has been developed for linac simulations, verified during SLC operation, and includes detailed ground motion and feedback models. It can be run on parallel computing facilities, opening new possibilities for the study of beam tails and halos. It is planned to incorporate bunch compression and the Final Focus into this program. MERLIN [22] has been developed for the TESLA Final Focus system. It includes imperfections and feedback models. It is planned to incorporate a collimation model.

6 CONCLUSION AND FURTHER PLANS

The stability requirements for the Final Focus systems of future linear colliders have been reviewed. In most cases, the required stability is close to the limit due the natural ground motion, without added human-made noise. The cultural and technical noise levels found in existing accelerators are larger than tolerable, but well constructed technical equipment with good passive damping is expected to improve these levels significantly. Supports with active damping can further reduce vibrations although these techniques need further verification from planned experiments.

If the vibration of magnetic elements cannot be completely avoided, beam-based feedback can compensate for the effect on the beam. The TESLA design with a long bunch spacing supports a very efficient intra-bunch train feedback, which would make it possible to tolerate even the large magnet motion observed at DESY. The shorter bunch spacing for NLC and CLIC make it more difficult technically to implement intra-bunch feedback, especially for CLIC. An intra-bunch train feedback will, however, still relax the tolerances for NLC and to some extent for CLIC. Inter-pulse feedback is included in all designs to compensate for the deteriorating effects of slow alignment drifts. Further development of simulation programs is needed in order to verify the feasibility of the design choices.

Additional topics that require further studies and were not discussed in this paper include temporal stability of magnetic field centers in the nm-regime and the effects of time-varying stray fields.

7 REFERENCES

[1] T. Raubenheimer (ed.). SLAC Report 474.
[2] R. Brinkmann. Proc. EPAC 1998.
[3] J.P. Delahaye et al. Act.Phys.Polon.B30(2029-2039).
[4] F. Zimmermann et al. These proceedings.
[5] M. Woods et al. FFTB98-03.
[6] V.M. Juravlev et al. CERN-SL-93-53.
[7] C. Montag. These proceedings.
[8] B. Jeanneret, E. Wildner. CERN-SL-99-072-AP.
[9] R.J. Fenn, T. Slaton, M. Woods. LCC-0036 (2000).
[10] C. Montag, NIM A378(1996)369-375.
[11] T. Markiewicz, T. Maruyama. Proc. 1999 LCWS.
[12] L. Hendrickson et al. SLAC-PUB-8055 (PAC99).
[13] I. Reyzl. These proceedings.
[14] D. Schulte. CERN-OPEN-99-243.
[15] C.Montag, V. Shiltsev, in Proc. PAC95.
[16] B.Baklakov, et al. Tech. Phys. **38**, 894 (1993).
[17] R.Pitthan, SLAC-PUB-7043,8286, 1995,1999.
[18] J. Giaime et al., Rev. Sci. Instrum. **67**, 208-214 (1996).
[19] G. Decker et al. In Proc. PAC97.
[20] A. Seryi. These proceedings.
[21] R. Assmann et al. SLAC/AP-103.
[22] N. Walker. http://www.desy.de/~njwalker/merlin.htm