SLAC–PUB–5091
September 1989
(A)

BEAM DYNAMICS IN LINEAR COLLIDERS*

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INTRODUCTION

In this paper, we discuss some basic beam dynamics issues related to obtaining and preserving the luminosity of a next generation linear collider. In Figure 1 you see a diagram illustrating the main subsystems of one-half of the collider. The beams are extracted from a damping ring and compressed in length by the first bunch compressor. They are then accelerated in a preaccelerator linac up to an energy appropriate for injection into a high gradient linac. In many designs this pre-acceleration is followed by another bunch compression to reach a short bunch. After acceleration in the linac, the bunches are finally focused transversely to a small spot.

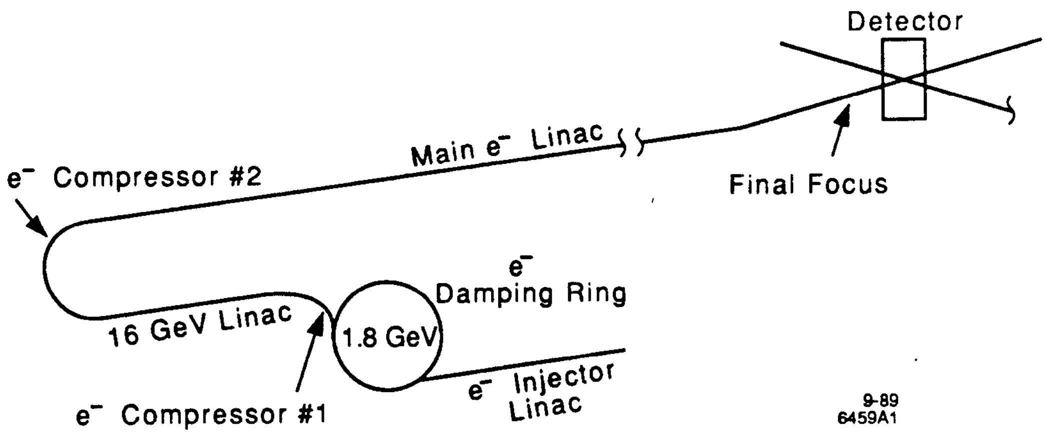

Fig. 1 Schematic of a Next Linear Collider

Before discussing each subsystem, it is useful to discuss the overall philosophy and parameters of this paper.[1,2] The energy range presently considered in various

*Work supported by the Department of Energy, contract number DE-AC03-76SF005515

Presented at the XIV International Conference on High Energy Accelerators, Tsukuba, Japan, August 22–26, 1989 designs throughout the world varies from 1/2 TeV to 2 TeV in the center of mass while the desired luminosity varies from $10^{33} - 10^{34}\text{cm}^{-2}\text{sec}^{-1}$. The energy will be achieved by RF acceleration at acceleration gradient $\mathcal{E}_z$ for a certain length L. The acceleration gradients currently under consideration range from 100–200 MV/m while the RF frequencies range from 10–30 GHz. In this paper we only discuss the RF in so far as it affects the luminosity. Although obtaining the energy of a linear collider may be very expensive and require technical development, it is, in a sense, the easy part of the problem. The hard part is to obtain the luminosity.

The increase in luminosity over the SLC is obtained primarily in two ways. First, the spot cross-sectional area is decreased. Second, the energy extraction is improved by the use of multiple bunches per RF fill which effectively increases the repetition rate of the collider. Both of these techniques lead to many beam dynamics questions.

The proposed vertical beam sizes at interaction point are the order of a few nanometers while the horizontal sizes are about a factor of 100 larger. This cross-sectional area is about a factor of 10^4 smaller than the SLC. However, the main question is: what are the tolerances to achieve such a small size, and how do they compare to present techniques for alignment and stability?

These tolerances are very design dependent. Alignment tolerances in the linac can vary from 1 μm to 100μm depending upon the basic approach. It is the premise of this paper that in order to achieve a next linear collider in this century, we must make design and correction choices which move most alignment tolerances into the 100 μm range. We begin the discussion with the damping rings.

DAMPING RINGS

The SLC damping ring has achieved normalized emittances of $\gamma\epsilon_x = 3 \times 10^{-5}$ and $\gamma\epsilon_y = 5 \times 10^{-7}$. A next generation linear collider will need an emittance at least an order of magnitude smaller horizontally. In addition, most designs use $\epsilon_x/\epsilon_y \simeq 100$. This type of emittance ratio is naturally produced in an electron storage provided that vertical dispersion and coupling are controlled. It does, however, set tolerances for vertical alignment in the 50–100μm range although these might be loosened by the addition of skew quadrupoles for compensation.

The designs typically include wigglers to decrease the radiation damping time.

As mentioned earlier, most plans include the use of multiple bunches per RF fill. In order to efficiently use the circumference it is possible to damp several "batches" of the order of 10 bunches each. These are separated by a distance which allows a kicker rise and fall time so that a batch can be extracted while allowing the remaining batches to continue damping.

Due to the small dispersion of the ring, the broad band impedance must be quite low ($Z/n \lesssim 0.5\Omega$) in order to avoid bunch lengthening. The long-range wakefield must also be controlled to avoid coupled-bunch instabilities. Because of the very close spacing of the bunches with a batch ($\sim$ 30 cm), it is thought that inter-batch feedback would be quite difficult.

Example designs for a damping ring are given in Ref. 3. Aside from higher energy ($\sim$ 1.8 GeV) and larger circumference (155 m), this design uses combined function bends to enhance the horizontal damping at the expense of the longitudinal. Similar designs have been done also at KEK, CERN and INP, and it seems that damping rings which produces flat beams of the desired emittance are relatively straightforward.

BUNCH COMPRESSION AND PREACCELERATION

In order to prepare the bunches for injection into a high-gradient structure, it is necessary to reduce their length by bunch compression. Actually, there are two primary reasons for bunch compression. First, the bunch length must be less than the β^* at the interaction point. Since in many designs $\beta^* \sim 100\mu$m, we must have $\sigma_z \lesssim 100\mu$m. In addition, we should reduce the bunch length to reduce transverse wakefields.

If the bunch length and relative energy spread in the damping ring are 5 mm and 10^{-3} respectively, then two bunch compressions are needed to reach 50 μm bunch length. Each compression is by a factor of 10, and they are separated by preacceleration so as to reduce the initial relative energy spread at the second compression back to 10^{-3}.

The energy spread is kept to $\sim$ 1% during each compression in order to avoid emittance dilution due to chromatic and dispersive effects in the compressors. After compression the bunch must be matched into the linac lattice. Studies of bunch compressors have been completed and tolerances are presently under study.[4]

LINAC[5]

Injection Errors

As the beam enters the linac, it is necessary to match the lattice functions to those of the linac. In particular the dispersion must vanish. For typical flat beam parameters, the beam size is about $2 \times 20\mu\text{m}$ which yields a tolerance on dispersion D given by

$$\begin{aligned} D_y &< 0.2 \text{ mm} \\ D_x &< 2 \text{ mm} \quad . \end{aligned} \tag{1}$$

This is an additive effect. There are also multiplicative effects due to the mismatch of the lattice functions. If the beam were monoenergetic, these mismatches would not filament; however, since this is not the case, there will be some filamentation. Allowing for complete filamentation, the emittance dilution is given by[6]

$$\frac{\epsilon}{\epsilon_o} = \frac{1}{2}\left[\frac{\beta_o}{\beta}(1+\alpha^2) + \frac{\beta}{\beta_o}(1+\alpha_o^2) - 2\alpha\alpha_o\right] \quad , \tag{2}$$

where α_o and β_o are the matched values, and α and β are the mismatched values. For $\alpha = \alpha_o$ and $\beta = \beta_o + \Delta\beta$

$$\frac{\Delta\epsilon}{\epsilon_o} \simeq \frac{1}{2}\left(\frac{\Delta\beta}{\beta}\right)^2 \quad . \tag{3}$$

For incomplete filamentation, the emittance dilution will be somewhat less.

Wakefields and BNS Damping

Wakefields are a key problem not only for linear colliders, but for all accelerators and storage rings. The standard solution to this problem is to first reduce the wakefield forces until they are small compared to the applied external fields. Then compensation can be used in the form of feedback, or we can simply live within the limits by keeping the number of particles in the bunch sufficiently small.

For linear colliders the reduction is accomplished first by keeping the RF frequency sufficiently small or by increasing the iris size for short wakes. Secondly, the β-function in the linac must be kept sufficiently small. Then compensation can be applied by using BNS damping—the use of a correlated energy spread to cancel wakefield effects. The BNS correlated energy spread is given by[7]

$$\left(\frac{\Delta E}{E}\right)_{\text{BNS}} = \frac{e^2 N W_\perp(\sigma_z)\beta_o^2}{4E_o} \quad , \tag{4}$$

where N is the number of particles, $W_\perp$ is the wakefield, and β_o is the β-function at energy E_o. For this paper I define a small wakefield by the condition

$$\left(\frac{\Delta E}{E}\right)_{\mathrm{BNS}} \lesssim \frac{1}{\psi_{\mathrm{tot}}} \lesssim 1\% \quad , \tag{5}$$

where ψ_{tot} is the total phase advance in the linac. If the wakefield is small in this sense, then tolerances are set by standard linear optics plus chromatic effects. If the wakefield is large, then one can still satisfy Eq. (4) with a variation of focusing strength along the bunch rather than energy variation. In this case, however, coherent oscillations filament rapidly. To avoid emittance dilution with strong wakes, the alignment and trajectory tolerances are less than the beam size. This leads to 1 μm alignment tolerances[8] and is rejected here as being unrealistic.

In the weak wakefield regime, BNS damping has been tested at the SLC linac.[9] In this case it was shown that tail growth due to a coherent oscillation was reduced by an order of magnitude. BNS damping has since been adopted as the normal running configuration for SLC.

Chromatic Effects

Upon injection into the linac, the compressed bunch has about a 1% energy spread. As the beam is accelerated, this relative spread decreases inversely with energy. At the same time an energy and bunch-position correlation is introduced due to the longitudinal wake and the curvature of the RF. Thus, the distribution in phase space becomes a wavy line which, when projected on the energy axis, yields an effective energy spread. At any location along the accelerator, the overall energy spread is a combination of the damping injected energy spread and the variation of energy along the bunch. After the bunch emittance is sufficiently damped, the relative energy spread remains constant unless deliberately increased by phase changes. For this reason it is useful to consider two models; one with constant energy spread and one with damping energy spread.

The first chromatic effect to consider is that of a coherent betatron oscillation. If the variation of the phase advance with momentum (chromatic phase advance) is much greater than unity, the oscillation filaments. In this case the oscillation amplitude must be less than the beam size to avoid emittance dilution. If the chromatic phase advance is small ($\delta\psi_{\mathrm{tot}} < 1$), then the tolerance on a coherent oscillation of size $\hat{x}_o$ is

$$\begin{aligned} \hat{x}_o &< \frac{\sigma_\beta}{\delta_o \psi_{\text{tot}}} = \frac{\sigma_\beta}{\delta_o \psi_{\text{cell}}} \frac{2}{N_q} \quad , \\ &< 4\sigma_\beta \quad \text{(ILC)} \end{aligned} \tag{6}$$

where δ_o is the constant relative momentum, ψ_{cell} and ψ_{tot} are the phase advance per cell and total phase advance respectively and N_q is the number of quadrupoles. In all cases we give not only the formula but also the value for an example design of an Intermediate Linear Collider (ILC) of energy 0.5 GeV in the center of mass. For the case of a damping energy spread with initial value δ_i, the tolerance is

$$\begin{aligned} \hat{x}_o &< \frac{\sigma_\beta}{\delta_i \psi_{\text{cell}}} \frac{2}{N_q} \left(\frac{\gamma_f}{\gamma_i}\right)^{1/2} \\ &< 2\sigma_\beta \quad \text{(ILC)} \quad . \end{aligned} \tag{7}$$

For the case of a corrected orbit let us consider the model of a sequence of random bumps. In this case the tolerance on the trajectory or alignment is

$$\begin{aligned} (\Delta x)_{\text{rms}} &< \frac{\sigma_\beta}{\delta_o \psi_{\text{cell}}} \left(\frac{3}{N_q}\right)^{1/2} \\ &< 50\mu\text{m} \quad \text{(ILC)} \quad , \end{aligned} \tag{8}$$

for a constant energy spread δ_o. For an initial damped energy spread δ_i, we have

$$\begin{aligned} (\Delta x)_{\text{rms}} &< \frac{\sigma_\beta}{\delta_i \psi_{\text{cell}}} \left(\frac{1}{N_q}\right)^{1/2} \left(\frac{\gamma_f}{\gamma_i}\right)^{3/4} \\ &< 30\mu\text{m} \quad \text{(ILC)} \quad . \end{aligned} \tag{9}$$

All the chromatic effects mentioned above create linear and higher order dispersion. The linear effects have been used to calculate the tolerances shown. However, it is possible to compensate these effects by correcting the linear part at the end of the linac (or perhaps within the linac). The second order chromatic effects, $x_2(\delta)$ are smaller than the first order, $x_1(\delta)$, provided the chromatic phase advance is sufficiently small. In this case

$$x_2(\delta) \sim x_1(\delta)\delta\psi_{\text{tot}} \quad . \tag{10}$$

This means that 2nd order tolerances will be enhanced by $(\delta\psi_{\text{tot}})^{-1}$.

For a single correction this leads to a factor of 4 improvement for ILC, while two compensations lead to a factor of 8 improvement. The limits on this technique are the diagnostic of the beam size. In the linac the range of beam sizes are $\sigma_y \simeq 1-2\mu$m and $\sigma_x \simeq 10-20\mu$m. This means that wire scanners can be used as they are in the SLC final focus. The point of this discussion of compensation is that this technique allows us to write down alignment tolerances in the 100 μm range.

<u>Beam Tilt</u>

If there are RF kicks due to construction errors of accelerator sections, the tail of the beam receives a different kick than the head. This can give a tilt to the beam. If we assume a random uncorrelated sequence of RF kicks, and compensate the center of the bunch with dipole correctors, the tilt tolerance is given by

$$(\Theta_{\rm rms})\left\{\beta_o < \sin\phi_o >_{\rm rms} \frac{2\pi}{\lambda_{\rm rf}} \sqrt{N} \left(\frac{\gamma_o}{\gamma_f}\right)^{1/2}\right\} < \frac{\sigma_y}{\sigma_z} \qquad (11)$$

where $\Theta_{\rm rms}$ is the rms RF kick angle if the beam is at energy γ_o, N is the number of accelerator sections and σ_z is the bunch length. For the ILC we have

$$\Theta_{\rm rms} < 2\mu{\rm rad} \quad . \qquad (12)$$

If such a kick is caused entirely by the systematic tilting of irises in a section (the bookshelf effect), then the tilt angle of the iris must be restricted by

$$\Theta_{\rm iris} < 0.3 \text{ mrad} \quad . \qquad (13)$$

<u>Jitter and Vibration: Motion Pulse to Pulse</u>

Feedback is essential to handle the "slow" drift of x, x', y, y', E. In practical cases it is possible to feedback at $f \lesssim \frac{f_{rep}}{5}$. This sets the scale for what we consider slow. Time variation has many sources in linear colliders, for example: damping ring kicker jitter, power supply variations and ground motion. The jitter of the kicker in the damping ring must be kept small compared to the natural divergence of the beam at the kicker. Tolerances in power supply variations are also set in many cases by the beam divergence. The effects of ground motion depend upon the design and assumptions for the motion. If the wakes are weak and chromatic effects are kept small, there is no filamentation, and the beam moves coherently from pulse to pulse. If wakes are strong, and there is a large spread of betatron wave number, there is filamentation so that the beam size varies from pulse to pulse with a smaller centroid motion.

In the first case if we assume random magnet-to-magnet jitter the tolerance is

$$\begin{aligned}(\Delta x)_{\rm rms} &< \frac{\sigma_\beta F}{\beta}\left(\frac{3}{N_q}\right)^{1/2} \\ &< (0.04)\sigma_\beta \quad \text{(ILC)} \quad ,\end{aligned} \tag{14}$$

where F is the focal length of a lens. If, on the other hand, there is correlated motion, then the dominant effect occurs when the wavelength is equal to the betatron wavelength. However, since the betatron wavelength changes $\propto \gamma^{1/2}$, the resonance is only temporary. If $2\pi\beta_i < \lambda < 2\pi\beta_f$, then the tolerance is given by

$$\begin{aligned}\Delta x_\lambda &< \sigma_\beta \frac{2}{(\pi\psi_{\rm cell})^{1/2}}\left(\frac{\gamma_f}{\gamma}\right)^{1/2}\left(\frac{2}{N_q}\right)^{1/2} \\ &< (.1 \text{ to } .4)\sigma_\beta \quad \text{(ILC)} \quad ,\end{aligned} \tag{15}$$

where γ is the energy at which $2\pi\beta = \lambda$.

Multibunch Effects

In order to efficiently extract energy from the RF, it is possible to accelerate many bunches per RF fill. This can increase the luminosity by an order of magnitude. Ideally we should put the maximum charge in a single bunch subject to restrictions on single bunch effects and beam-beam effects, then we should increase the number of bunches to extract as much energy from the RF as possible. This is not trivial in that the use of multiple bunches impacts every system.[10]

The most difficult problem, however, is the main linac, the primary problems being bunch-to-bunch energy spread and transverse beam breakup. The basic tolerance for bunch-to-bunch energy spread is that it be less than the single bunch energy spread. This assures that the bunch-to-bunch chromatic effects will be no worse than single bunch ones.

Transverse beam breakup in the linac is a very difficult effect to control. For a normal traveling wave structure at 17 GHz, the 10th bunch blows up by a factor of 10^5. Fortunately, there are solutions to this problem. The most useful approach seems to be the damping of the transverse modes in the structure to Q's $\sim$ 20–40 using external waveguides.[11] This is not completely sufficient; however, if the frequency of the first higher mode is also adjusted with a tolerance $\sim$ 0.5%, the 2nd bunch can be placed near the zero crossing of the wake and the blowup vanishes.[12]

This technique of damping high modes has also been shown to be useful for damping ring instability control.[13]

FINAL FOCUS

Much progress has been made on the design of final focus systems.[14] As mentioned earlier, the spot size desired is in the range 2–5 nm $\times$ 100-300 nm. The limiting effect seems to be the radiation of the particles in the final quadrupoles which yields a minimum vertical spot size in the nanometer range.[15]

Once the design is specified, one is led to the question of the sensitivity of the design to different types of errors. Clearly the most serious tolerance for vibration is the final doublet although there seem to be solutions to provide the vibration isolation.[16] Alignment tolerances in the absence of any correction are quite tight; however, it has recently been shown that one can recover from misalignments in the range 10–30 μm.[17] There is much more work to be done here, but the initial results indicate that tuning will be possible in the presence of errors.

Towards the experimental side, there is a collaboration developing between SLAC, INP, KEK, Orsay, and possibly CERN to construct a Final Focus Test Beam at SLAC. The purpose is to test a scaled next-generation final focus system which has about 10 times the demagnification of the SLC system.

OUTLOOK

Before completing a realistic design of a next-generation linear collider, we must first learn the lessons taught by the first generation, the SLC. Given that, we must make designs fault tolerant by including correction and compensation in the basic design. We must also try to eliminate these faults by improved alignment and stability of components. When these two efforts cross, we have a realistic design. I believe this will not occur at 1 μm alignment range. However, from the results presented here, I do believe that with compensaton designs exist which move us into the 100 μm range and closer to a realistic design.

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