The Preservation of Low Emittance Flat Beams*

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Abstract

Many future linear collider designs require beams with very small transverse emittances and large emittance ratios $\epsilon_x \gg \epsilon_y$. In this paper, we will discuss issues associated with the preservation of these small emittances during the acceleration of the beams. The primary sources of transverse emittance dilution in a high energy linear accelerator are the transverse wakefields, the dispersive errors, RF deflections, and betatron coupling. We will discuss the estimation of these effects and the calculation of tolerances that will limit the emittance dilution with a high degree of confidence. Since the six-dimensional emittance is conserved and only the projected emittances are increased, these dilutions can be corrected if the beam has not filamented (phase mixed). We discuss methods of correcting the dilutions and easing the tolerances with beam-based alignment and steering techniques, and non-local trajectory bumps. Finally, we discuss another important source of luminosity degradation, namely, pulse-to-pulse jitter.

Introduction

In this paper, we will discuss emittance preservation in the linear accelerators of future linear colliders. Currently, many groups around the world are designing the "next generation" of e^-/e^+ linear collider which would have center-of-mass energies ranging from $\frac{1}{2}$ to 2 TeV [1]. Although some designs are more extreme than others, they all specify beams with low emittances and a large aspect ratio ϵ_x/ϵ_y, *i.e.* flat beams. Parameters for the various designs are listed in Table 1 and a discussion of the differences can be found in Ref. 2.

There are three principal reasons for using low emittance flat beams: first, the small emittances allow for small spot sizes at the IP which is needed to achieve the required luminosity. Second, flat beams take advantage of the natural asymmetry of the damping ring based sources and of the final focus; quadrupole focusing is asymmetric and a flat beam final focus is easier to design than a round beam final focus. Third, for a given cross sectional area and charge, flat beams generate less beamstrahlung than round beams; the beamstrahlung increases the energy spread and causes detector backgrounds. In fact, a simple scaling suggests that very large aspect ratios are needed at the higher energies of 1 to 2 TeV to keep reasonable detector backgrounds [3].

Although low emittance flat beams are desirable from the standpoint of the luminosity and the IP physics, there is the obvious disadvantage that the low emittance beams need to be generated and then the emittances must be preserved during the subsequent acceleration and manipulation. In this paper, we will discuss issues pertinent to emittance preservation during the acceleration; these issues, as well as issues relevant in the damping rings, are described in more detail in Ref. 4.

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Sources of Dilution

In a high energy linear accelerator, the principal sources of emittance dilution or luminosity reduction are conservative dilutions and pulse-to-pulse jitter. A conservative emittance dilution arises when the transverse or longitudinal degrees of freedom become coupled. In this case, the six-dimensional emittance is conserved but the projected emittances, which are the values relevant at the IP, are increased. It can easily be shown that coupling of two planes always increases the smaller of the two projected emittances from the uncoupled value.

Thus, the primary sources of dilution in the linacs of a future linear collider are:

- Dispersive errors: $\delta \to (y, y')$
- Transverse wakefields: $z \to (y, y')$
- RF deflections: $z \to (y, y')$
- Betatron coupling: $(x, x') \to (y, y')$
- Multi-bunch effects: $z \to (y, y')$
- Pulse-to-pulse jitter: $t \to (y, y')$

Because the emittance dilutions are conservative, they can be corrected, *i.e.*, the emittance can be uncoupled, provided that the dilution has not filamented (phase mixed). The filamentation occurs because the beam has a spread in betatron oscillation frequency due to an energy spread in the beam, space charge forces, ions trapped in long bunch trains, *etc.*

Bare Machine Tolerances

It is straightforward to calculate alignment tolerances assuming only simple 1-to-1 trajectory correction, *i.e.*, the trajectory is corrected to zero the beam position monitors (BPMs) located at the focusing quadrupoles; we refer to these tolerances as "bare machine tolerances." Approximate tolerances to limit the principal single bunch dilutions to 25% of the design emittance with a 95% confidence are listed in Table 2. Brief descriptions of the formula used in these calculations can be found in Refs. 5 and 6 and more detailed derivations can be found in Ref. 4.

The first tolerance is on the amplitude of a betatron oscillation injected into the linac which will filament and increase the projected emittance; this tolerance is simply related to the injected beam size specifies the minimum BPM precision (reading-to-reading measurement jitter) since the trajectory needs to be resolved at this level. The second tolerance is that on random misalignments of the quadrupoles and BPMs. With standard trajectory correction, the trajectory is deflected to follow these random misalignments. This leads to anomalous dispersion and wakefield errors since the beam is off-axis in the cavities. The third tolerance is on the random misalignments of the cavities which leads to wakefield dilutions and the last tolerance is on the rotational alignment of the quadrupoles which leads to betatron coupling.

In all designs, these bare machine tolerances are very tight and thus we must consider methods of correcting the emittance dilutions. There are essentially two approaches: non-local correction where the beam emittance is mini-

Table 1. Parameters of future linear collider designs for 500 GeV c.o.m.

	CLIC	VLEPP	JLC	NLC	DLC	TESLA
$\gamma\epsilon_x$ [mm-mrad]	1.8	20	5.5	5	10	20
$\gamma\epsilon_y$ [mm-mrad]	0.2	0.08	0.08	0.05	1	1
Part./bunch [10^{10}]	0.6	20	1.3	0.7	2.2	2.5
Bunches/pulse	4	1	20	90	172	1600
Rep. rate [Hz]	1700	300	150	180	50	12

Table 2. Bare machine tolerances for 25% ϵ dilution

Source	CLIC	VLEPP	JLC	NLC	DLC	TESLA
Injected betatron osc. with BNS damping	3.5 μm	1.5 μm	0.7 μm	0.7 μm	7 μm	15 μm
BPM and quad. misalignments	0.5 μm	0.2 μm	5 μm	4 μm	20 μm	50 μm
Accel. section misalignments	0.4 μm	0.4 μm	1.4 μm	5 μm	15 μm	300 μm
Quadrupole rotations	1 mrad	0.2 mrad	0.3 mrad	0.3 mrad	1 mrad	1 mrad

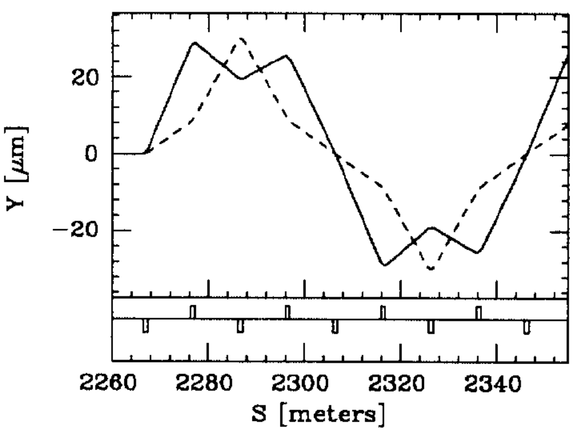

Fig. 1 A non-dispersive bump (solid) compared with a betatron oscillation (dashes); from Ref. 4.

Table 3. Non-dispersive bumps in the NLC with 70 μm RF structure misalignments

Uncorrected dilution	$11.7\pm2\ \epsilon_{y0}$
Initial conditions (y_0, y_0')	$9.8\pm1\ \epsilon_{y0}$
2 Non-disp. bumps (near front)	$2.6\pm.2\epsilon_{y0}$
4 Non-disp. bumps	$1.4\pm.1\epsilon_{y0}$
6 Non-disp. bumps	$1.1\pm.02\ \epsilon_{y0}$

mized at diagnostic stations and local correction where one effectively attempts to re-align the linac.

Non-local ϵ Correction

To perform non-local emittance correction, the linac is interspersed with diagnostic stations where the beam emittance is measured. Then, the emittance couplings are removed using trajectory bumps to compensate the dispersive errors, transverse wakefields, and RF deflections, using kickers or special structures to re-align bunch trains, and using skew quadrupoles to cancel the betatron coupling. Because the dilutions cannot be corrected after they filament, the spacing between diagnostic stations must be small compared to the filamentation length; in the NLC design, the linacs need to be divided into four sections.

In the SLC, simple betatron oscillations are used to reduce the effects of the wakefield dilutions [7], but, in most future linear collider designs, both dispersive and wakefield errors are important. Thus, one needs to have orthogonal correction for the two effects. This is possible using non-dispersive bumps to correct the wakefield tails and non-wakefield bumps for the dispersive errors; a non-dispersive bump is illustrated in Fig. 1.

Table 3 lists the average of twenty simulations of the NLC where non-dispersive bumps were used to correct for 70 μm rms random accelerator section misalignments. The average uncorrected dilution is over 1000%. As additional pairs of non-dispersive bumps are added, pairs of bumps separated by 90° in betatron phase are needed for orthogonal control, the emittance dilution is corrected to 10% on average. Thus, the bare machine tolerance of 5 μm on the accelerator section alignment could be eased to a more reasonable 70 μm with this non-local correction.

The difficulties with this approach are: (1) the beam emittance and tails need to be measured accurately to correct the dilution, (2) multiple stations are needed to prevent filamentation of the dilutions, and (3) the technique is sensitive to changes in the linac energy profile and quadrupole settings since it depends upon the phase advance between the dilutions and the corrections.

Local ϵ Correction

Local emittance correction involves correcting the emittance dilutions at their source, typically using information from the BPMs and not from emittance measurements. There are a few techniques that have been proposed. To align the quadrupoles one can: (1) vary independent power quadrupole power supplies as suggested in

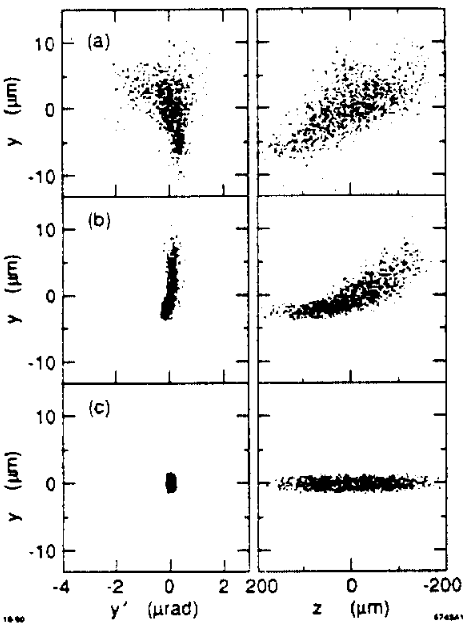

Fig. 2 The beam distribution after (a) 1-to-1, (b) DF, and (c) WF correction at the end of the 250 GeV NLC linac. The left-hand plots are the y-y' phase space while the right-hand plots are the beam in y-z space; from Ref. 10.

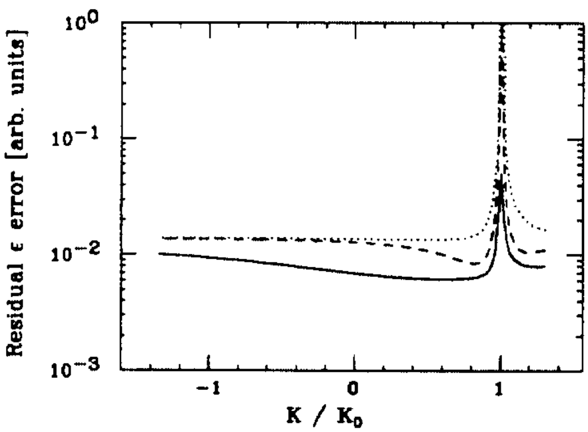

Fig. 3 Effectiveness of DF type correction versus the energy deviation or quadrupole scaling (K/K_0) used. The curves correspond to cases where the rms alignment of the BPMs relative to the quadrupoles is $2\sigma_{prec}$ (solid), $10\sigma_{prec}$ (dashes), and $100\sigma_{prec}$ (dots).

the VLEPP design, (2) use the beam-based alignment like that used in the SLC [8], or (3) use specialized trajectory correction techniques such as the Dispersion-Free (DF) or Wake-Free (WF) techniques [9,10]. To align the accelerating structures, BPMs could be build into the structures with a very high accuracy as suggested in the CLIC design, or, the dipole wakefield, induced by the beam, might be measured directly and then minimized.

In all cases, the best alignment that can be attained is limited by the BPM precision (the reading-to-reading jitter of the BPM measurement) and is roughly *independent* of the magnitude of the misalignments. To limit the emittance dilution to 6% using these techniques, the BPM precision in the VLEPP and CLIC designs must be roughly $\sigma_{prec} \sim 100\,\text{nm}$, while the JLC and NLC designs require a precision of $\sigma_{prec} \sim 1\,\mu\text{m}$ and the DLC and TESLA designs need $\sigma_{prec} \sim 10\,\mu\text{m}$.

The SLC beam-based alignment technique has been demonstrated experimentally [8] and there has been extensive simulation of the other approaches. Simulations results using the VLEPP approach can be found in Ref. 1 while simulations using the DF and WF correction techniques are described in Refs. 9–12. Results from one simulation in the NLC are plotted in Fig. 2 where the quadrupoles and BPMs were randomly misaligned with a $70\,\mu\text{m}$ rms and the BPM precision was assumed to be $2\,\mu\text{m}$. Using just the standard 1-to-1 trajectory correction, the emittance is increased by a factor of 2400%. Using the DF technique, the dilution is reduced to roughly 1000%, but wakefield tails, due to the non-zero trajectory in the structures, are still apparent. Then, using the WF technique, the emittance dilution is reduced to less than 10%.

Finally, the various correction approaches can be studied using analytic techniques [13]. The effectiveness of the DF technique is illustrated in Fig. 3. Here, the residual emittance dilution is plotted versus the magnitude of the quadrupole scaling (K/K_0); the BPMs were assumed to be aligned to the quadrupole magnets with rms errors of $2\sigma_{prec}$ (solid), $10\sigma_{prec}$ (dashes), and $100\sigma_{prec}$ (dots). The large peak at a quadrupole scaling of $K/K_0 = 1.0$ is roughly equivalent to the 1-to-1 steering technique, while the values near 0.8 corresponds to the DF technique and the values near -1.0 approximate the SLC beam-based alignment approach. Notice that, using the DF or beam-based alignment techniques, the residual is roughly *independent* of the initial alignment and instead only depends upon the BPM precision.

The primary difficulty with these approaches is that the beam emittance is not actually measured, instead, the alignment information is inferred from the BPM measurements. Thus, one would not want to use these techniques alone without also having non-local diagnostic stations to correct for residual dilutions.

Pulse-to-Pulse Jitter

Another source of luminosity degradation is pulse-to-pulse jitter. The jitter can arise from motion of the quadrupole magnets, dipole power supply fluctuations, pulsed kickers, or noise from the klystrons in concert with the RF deflections. The induced oscillation will then either filament, increasing the projected emittance, or shift the beam centroid so the beams do not fully overlap at collision; this later effect is partially ameliorated by the beam-beam pinch.

Usually, the most severe effect is due to the motion of the quadrupole magnets. This motion arises from motion of the ground and the support structures in addition to turbulence in the cooling flows and vibrations transmitted through the RF feeds. Extensive measurements of the ground motion relevant to linear colliders have been made around the world. Some examples can be found in Refs. 14–17.

Assuming that the motion is uncorrelated from magnet to magnet, tolerances on the linac quadrupoles are typically a few nanometers in the small emittance designs and tens of nanometers to a 100 nanometers in the DLC and TESLA designs. At low frequencies, $f \sim 0.15\,\mathrm{Hz}$, the amplitude of the ground motion tends to be very large, the order of microns, while at higher frequencies, $f \gtrsim 1\,\mathrm{Hz}$, the motion is at the level of a few nanometers. Fortunately, the motion is highly correlated at low frequencies where the amplitude of the motion is large. When the quadrupole motion is correlated, the beam response is small at frequencies below the first resonance where the wavelength of the motion is equal to the betatron wavelength. An example of the beam response y_{beam}/y_{quad} to correlated motion in the NLC design is plotted in Fig. 4 versus the frequency multiplied by the cosine of the angle of incidence; the first resonance occurs at 2.5 Hz, assuming a wave parallel to the linac.

Of course, the higher frequency motion, which is dominated by cultural (man made) noise, is not correlated over long distances. In an attempt to model recent measurements [18] we have calculated the response with a frequency dependent random phase such that the correlation length is given by $l_c \approx 100/(f + 0.03)$. The average of 16 seeds is plotted in Fig. 5. Notice that the response to the low frequency motion is significantly larger than that calculated for purely correlated motion.

To reduce the effect of the ground motion, one can use feedbacks, based on either the beam position or the actual motion of the quadrupoles. In addition, one needs to have well designed support structures with resonances where the feedback systems can reduce the response or where the ground motion is not significant. Typically, active feedbacks are needed on the IP quadrupoles, where the tolerances are much tighter. But, installing such a system on each of the hundreds of quadrupoles in the linacs becomes expensive and complex. Thus, it is desirable to use a few beam-based feedback systems to stabilize the trajectory. Unfortunately, the frequency response of the beam-based system depends upon the linear collider repetition rate. Simple analysis of the broadband feedbacks suggest that they can begin damping at frequencies below $f_{rep}/6$. More realistic feedback designs have much lower crossover frequencies. For example, the SLC fast feedbacks begin damping at frequencies below $f_{rep}/30$ [19].

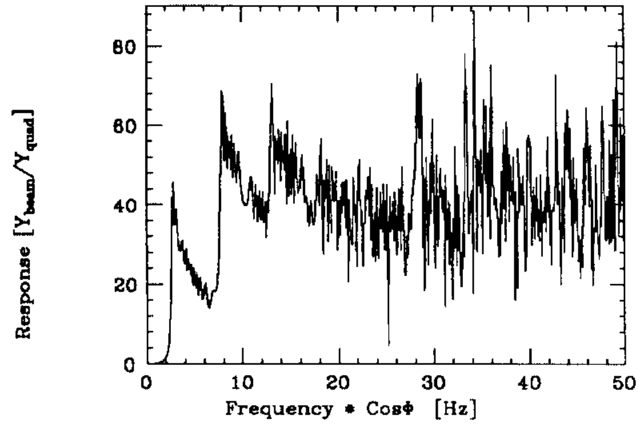

Fig. 4 Beam response to correlated motion of the linac quadrupoles in the 1 TeV c.o.m. NLC design.

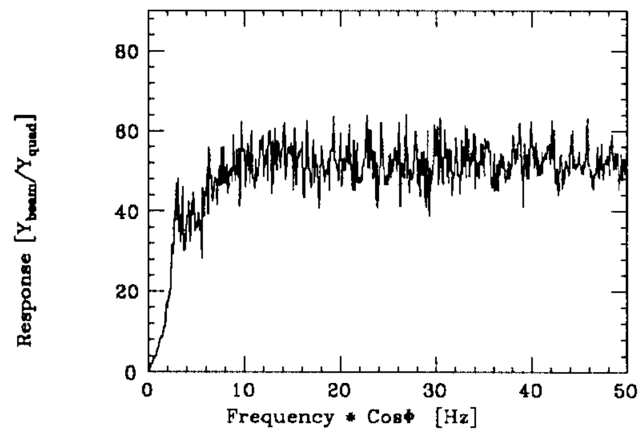

Fig. 5 Beam response to motion having a correlation length given by $l_c = 100/(f + 0.03)$ in the 1 TeV c.o.m. NLC design.

Results from the SLC

Three elements crucial for a future linear collider have been demonstrated at the SLC; these, as well as other recent SLC results, are described in Refs. 20–22. First, beam-based alignment techniques [8] have been used to reduce the rms alignment of the quadrupoles to roughly $60\,\mu$m; this is four times the BPM precision of $15\,\mu$m. Second, fast feedback systems are used to stabilize the beam trajectory and energy [19]; currently, there are over 28 fast feedbacks operating in the SLC. Third, trajectory bumps have been used to decrease the emittance dilutions in the linac.

The SLC has been running with "flat" beams since March 1993 [21,22]. In normal operation, bunches of over 3×10^{10} particles are accelerated from 1.2 GeV to 47 GeV. At the beginning of the linac, the rms beam emittances are roughly $\gamma\epsilon_x = 30$ mm-mrad and $\gamma\epsilon_y = 3$ mm-mrad. Without trajectory bumps to correct the emittance dilution, the emittances measured at the end of the linac are roughly $\gamma\epsilon_x = 60 \sim 80$ mm-mrad and $\gamma\epsilon_y = 20 \sim 50$ mm-mrad. With trajectory bumps, the emittances are reduced to roughly $\gamma\epsilon_x = 40 \sim 50$ mm-mrad and $\gamma\epsilon_y = 5 \sim 10$ mm-mrad; at lower currents, vertical emittances of $\gamma\epsilon_y = 2$ mm-mrad have been attained. The electron beam trajectory, with the emittance bumps, is shown in Fig. 6. The reduction in the emittance achieved with the bumps is equivalent to reducing the alignment errors by roughly a factor of three.

Figure 7 is a history of the emittances measured at the end of the linac during a week in April 1993. The fast fluctuations are thought to be due to changes in the linac energy profile which changes the phase relation between the emittance correction bumps and the sources of the dilution; this is one problem with non-local correction techniques and a feedback system is planned to compensate the phase errors.

Summary

We have discussed the principal sources of emittance dilution in future linear colliders and have listed some

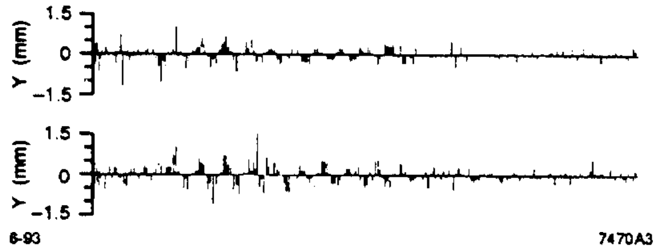

Fig. 6 e^- x and y trajectories in the SLC with emittances of roughly $\gamma\epsilon_x \approx 40$ mm-mrad and $\gamma\epsilon_y \approx 6$ mm-mrad. Notice the large betatron oscillations used to control the emittance dilutions.

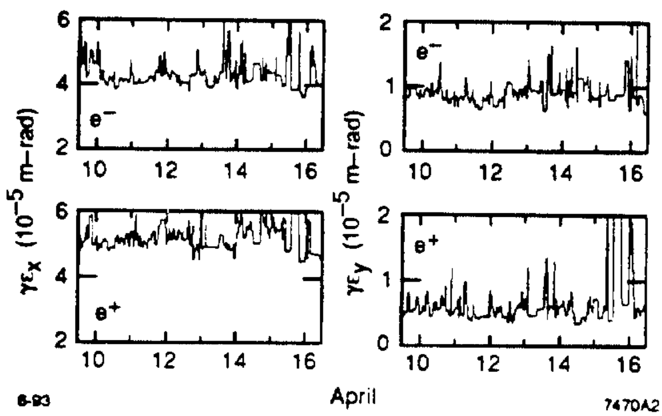

Fig. 7 e^- and e^+ emittances at the end of the SLC linac recorded over roughly one week in time.

"bare machine" alignment tolerances. In all designs, these alignment tolerances are extremely tight. Thus, detailed correction, tuning, and recovery procedures must be an integral part of a future linear collider design. In a linear collider the bare machine tolerances cannot be considered alone — emittance correction is needed just as orbit correction is needed in a storage ring. The emittance correction can be performed with a combination of local and non-local techniques. The local techniques are limited by the BPM precision while the non-local techniques are limited by the beam size measurement and by filamentation (phase mixing). Finally, jitter is another important source of luminosity reduction and feedback systems are essential.

A number of experiments have been performed or are being planned to fully verify the feasibility of preserving the necessary emittances. Foremost, of course, is the SLC which has demonstrated very impressive results. In addition, there is the FFTB project at SLAC, the ATF project at KEK, the ASSET project at SLAC, and multi-bunch and RF studies are planned for all of the linear collider designs.

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