# A Beam-Based Alignment Technique for Correction of Accelerator Structure Misalignments*

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## Abstract

This paper describes a method of reducing the transverse emittance dilution in linear colliders due to transverse wakefields arising from misaligned accelerator structures. The technique is a generalization of the Wake-Free [5] correction algorithm. The structure alignment errors are measured locally by varying the bunch charge and/or bunch length and measuring the change in the beam trajectory. The misalignments can then be corrected by varying the beam trajectory or moving structures. The results of simulations are presented demonstrating the viability of the technique.


## Introduction

A number of $e^+/e^-$ linear colliders are being designed with center-of-mass energies from 0.5 to 1.5 TeV. One of the major problems facing these designs is the preservation of the transverse emittance through the multi-kilometer linear accelerators. [1] In the linacs, the magnets, accelerating structures, and beam position monitors (BPMs) are all misaligned with respect to the ideal centerline and thus the beam is offset in the magnets and the structures. This can lead to both dispersive errors and transverse wakefields which dilute the projected transverse emittance and thereby reduce the collider's luminosity. In this paper, we will discuss a new approach to aligning the accelerator structures.

In most designs, the magnets and structures must be aligned with an accuracy the order of microns. [2] This would be extremely difficult to achieve and maintain with a mechanical alignment system [3] and thus a number of beam-based alignment procedures have been proposed to align the BPMs and the quadrupole magnets. [4-8] These beam-based procedures utilize information from the response of the beam to changes in the strength of the quadrupole magnets; the resulting alignment accuracy depends upon the BPM resolution (reading-to-reading measurement jitter) and is insensitive to the initial alignment. [9]

Unfortunately, these techniques cannot be used to align the accelerating structures. At this time, there are four approaches to the structure alignment: (1) extremely accurate mechanical alignment, (2) direct measurement of the dipole mode (transverse wakefield) excited by the beam in the structure, (3) alignment by mechanically attaching a very accurate BPM to the structure, and (4) trajectory bumps, tuned by emittance measurements, which correct the effect of the emittance dilutions.

Although all of these techniques will work at some level, it may be difficult to achieve the required accuracy and emittance preservation. In this paper, we present an alternate method, first suggested in Ref. 5, which is similar to the beam-based alignment techniques for the quadrupoles. Although this technique will also be difficult to implement, it is an alternate approach that is worthy of consideration.

## Theory

When a beam travels off-axis through an accelerating structure, the transverse wakefield deflects the tail of the beam. This has two effects: it increases the projected emittance of the beam and it deflects the beam centroid. The centroid deflections can be used to determine the offsets of the structures relative to the beam.

We can estimate the magnitude of the centroid deflections due to rigid structure misalignments. Because the BNS damping will reduce the growth of the induced oscillation, we only need to consider the first order contribution. Thus, the deflection of the bunch centroid is approximately:

$$\theta_a \approx x_a L_a \frac{N r_e}{\gamma} \int_{-\infty}^{\infty} dz \rho(z) \int_{z}^{\infty} dz' \rho(z') W_\perp(z - z') \quad , \quad (1)$$

where $x_a$ is the structure offset and $L_a$ is the length of the accelerating structure. For a gaussian beam and linear wakefields: $W(z) = zW'$, this is deflection equal to

$$\theta_a \approx -x_a L_a \frac{\sigma_z N r_e W'}{\sqrt{\pi}\gamma} \quad (2)$$

As mentioned, the deflections are typically small. For example, in the SLAC 500 GeV c.o.m. NLC design, a 25 $\mu$m misalignment of a single 1.8 m structure at the beginning of the linac, where the beam energy is 10 GeV, will lead to a 0.15 $\mu$m oscillation. Of course, a single misaligned structure does not generate significant emittance dilution. Again, we can use the first order approximation to estimate the emittance dilution that would arise from the structure misalignments. For a gaussian bunch and linear wakefields, the emittance dilution, before filamentation, is roughly

$$\Delta\epsilon \approx 0.91 \frac{\beta}{2} \theta_a^2 \quad (3)$$

where $\theta_a$ is given by Eq. (2) and we assumed that $\Delta\epsilon \ll \epsilon$.

This equation is useful in that it relates the emittance dilution to the deflection of the beam centroid. For example, if we want to keep the emittance dilution to less than 6%, Eq. (3) suggests that we need to limit the centroid deflections due to the wakefields to the level of $\sigma/3$; in the SLAC NLC design, this is roughly 0.5 $\mu$m.

Because the wakefield deflections are so small, their effect on the trajectory will be masked by the misalignments of the BPMs and deflections due to the misaligned quadrupoles and dipole correctors. Thus, to measure the wakefield deflections, we measure the *change* in trajectory while

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changing the bunch length and/or the bunch population. This measurement is then limited by the BPM resolution, the reading-to-reading measurement jitter, which is usually much smaller than the absolute alignment error. Furthermore, because numerous BPMs are located through the linac, this measurement provides local information about the structure misalignments. Of course, this difference trajectory will still be very small. We magnify the effects by comparing the trajectories of a short low current bunch with that of a bunch having a charge and/or length much larger than nominal.

Ideally, we would like to make these changes without varying any other parameters of the bunch or the machine. Unfortunately, the beam energy and energy spread and the autophasing condition all change when the either the bunch charge or the bunch length are varied. This has two principal effects: first, when the beam energy varies, dispersive errors will cause centroid fluctuations that would mask the effect of the wakefields. Second, if the autophasing condition and BNS damping are lost, the beam would become more sensitive to jitter, making it difficult to measure the change in trajectory due to the wakefields.

Finally, we correct for the structure alignment errors by either steering the trajectory or moving the structures. If we correct for the structure misalignments by steering the trajectory, we must be careful not to generate dispersive errors. This could be avoided by using non-dispersive bumps [10] or by combining the steering with dispersive error correction. Directly moving the structure avoids these problems; this was noted in Ref. 11 where the author proposed a global emittance correction scheme.

### Simulations

Tracking simulations [12] were performed to test the correction technique on the SLAC 500 GeV c.o.m. NLC linac [13]. In the simulations, the bunch was divided into ten slices longitudinally and each slice was further subdivided into five macro-particles with different initial energies. The RF phase was chosen to optimize the autophasing condition and the tracking included both the longitudinal and transverse wakefields for the NLC structure. [14]

Although the bunch charge and bunch length are varied in the simulations, the amplitude and phase of the accelerating voltage and the magnetic fields of the quadrupoles and dipole correctors were kept constant. Thus, beam energy and energy spread would vary because of the sinusoidal RF and longitudinal wakefields and the transverse focusing would vary because of the variation in beam energy. Although this is not optimal for the correction procedure, it should make the operational implementation simpler.

At first, to separate the wakefield effects from the dispersive effects, only accelerating structures were misaligned; the quadrupoles and BPMs were aligned perfectly. For these simulations, the accelerating structures were misaligned with errors having a gaussian distribution with $\sigma = 50\,\mu$m and truncated at $\pm 3\sigma$, and the BPMs were assumed to have a resolution (reading-to-reading jitter) of $\sigma_{res} = 1\,\mu$m.

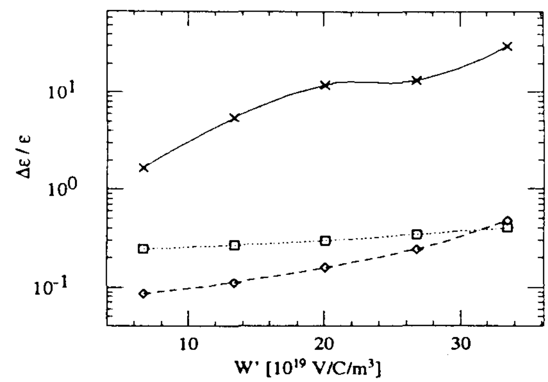


Fig. 1 Emittance dilution versus wakefield strength for 3 cases: (solid) no correction, (dashes) correction varying charge and bunch length, and (dots) correction varying only charge; in the SLAC NLC design, $W' = 7 \times 10^{19}$ V/C/m$^3$.

We considered two methods of correction:

(*a*) Adjust the beam trajectory using dipole correctors,

(*b*) Move some of the accelerating structures.

In method (*a*), four trajectories with different bunch charge, bunch length, and quadrupole strengths were measured by BPMs located at the quadrupoles. In this case, the relative emittance growth was estimated as 14% from 100 different seeds. For comparison, before correcting the structures, the relative emittance growth was 170%, as found from 100 different distributions of errors.

In method (*b*), we moved accelerating structures instead of steering the trajectory. We moved one structure every three FODO cells, or every six quads; thus, there were 103 moving structures out of a total of 3622 structures. Three different trajectories with different bunch charges and lengths were measured by BPMs located at the quadrupoles and the moving structures; other parameters were as same as for case (a). Here, we found an average relative emittance growth of 8% from 100 different distributions of random errors; again, the emittance dilution before correction was 170%.

Next, we studied the effectiveness of the technique versus the strength of the wakefield. The effective strength of the transverse wakefield can be characterized by the centroid deflection Eq. (2). Thus, the effective strength of the wakefield depends upon the magnitude of the wakefield, the bunch length and charge, the beam energy, and the transverse focusing. When the effective strength of the wakefield is larger, the deflections are more easily measured and we can make smaller changes of the charge and/or bunch length. Figure 1 is a plot of the emittance dilution versus the slope of transverse wake field $W'_\perp$ in the SLAC NLC linac for three cases: (1) corrections changing both charge and length, (2) corrections changing only charge and (3) no correction; the apparent kink at $W' = 20 \times 10^{19}$ occurs because we reoptimized the RF phase for autophasing, changing it from $-6°$ to $-4°$. In all cases, the results were averaged from 100 different sets of random structure misalignments with $\sigma = 50\,\mu$m and the BPM $\sigma_{res} = 1\,\mu$m.

Table 1. 500 GeV SLAC NLC Simulation Results.

| Method | Quad. | BPM | Acc. | $\Delta\epsilon$ [%] |
|---|---|---|---|---|
| No Correction | 0 | 0 | 50 $\mu$m | 170 |
| (a) | 0 | 0 | 50 $\mu$m | 14 |
| (b) | 0 | 0 | 50 $\mu$m | 8 |
| 1-to-1 | 50 $\mu$m | 50 $\mu$m | 50 $\mu$m | 1660 |
| (c) | 50 $\mu$m | 50 $\mu$m | 50 $\mu$m | 14 |
| (d) | 50 $\mu$m | 50 $\mu$m | 50 $\mu$m | 20 |

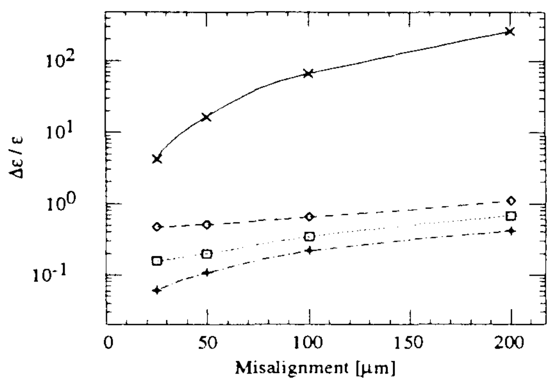


Fig. 2 Emittance dilution versus BPM resolution and misalignment magnitude for 4 cases: (solid) 1-to-1 correction only, (dashes) method (d) with $\sigma_{res} = 2.0\,\mu$m, (dots) method (d) with $\sigma_{res} = 1.0\,\mu$m, and (dash-dot) method (d) with $\sigma_{res} = 0.5\,\mu$m.

Finally, we included alignment errors of the BPMs and quadrupoles, as well as alignment errors of the structures, in the simulations. Again, two methods were studied:

(*c*) Adjust the dipole correctors as in method (*a*) to minimize both wakefield and dispersive effects simultaneously.

(*d*) First adjust the dipole correctors to minimize dispersive effect using low current beams (DF correction [6]). Then, move the accelerating structures to minimize the wakefield effects as in method (*b*).

In the simulation for method (*c*), five trajectories were measured and the dipole correctors were used in the same manner as method (*a*). The accelerating structures, quadrupole magnets, and BPMs were all independently misaligned with $\sigma = 50\,\mu m$ (truncated $\pm 3\sigma$) and the resolution of the BPMs was $\sigma_{res} = 1\,\mu m$. The relative emittance growth was estimated as 14% from the average of 100 different sets of random errors; for comparison, the emittance growth was 1660% after using 1-to-1 trajectory correction.

In method (*d*), we first corrected the dispersive errors and then corrected the wakefield effects. In the first step, bunch charge was set to be 0.1 of nominal charge ($6.5 \times 10^8$) and then DF trajectory correction [6] was used to minimize the dispersive errors. In the second step, we corrected for wake field effect using the the same procedure as method (*b*). Three trajectories were measured and the accelerating structures were moved to minimize the difference of the trajectories. In this case, the relative emittance growth was estimated to be 20% from the average of 100 different sets of random errors.

Finally, Fig. 2 illustrates the effectiveness of the correction technique versus the BPM resolution and the magnitude of the misalignments; the simulations with $\geq 100\,\mu m$ misalignments were performed using 3 times as many moving structures as nominal, *i.e.* 309 out of 3622.

## Discussion

In this paper, we have described a new technique for correcting the effects of misaligned accelerator structures. This is a beam-based technique where the effectiveness primarily depends upon the BPM resolution (reading-to-reading jitter) and not the initial alignment. We have performed initial simulations to verify the technique for the 500 GeV c.o.m. SLAC NLC linear collider design with results summarized in Table 1. We have also simulated the correction with stronger wakefields and found that the correction was more effective at reducing the emittance dilution.

## Acknowledgements

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## References


[1] T. O. Raubenheimer, "The Preservation of Low Emittance Flat Beams," *1993 IEEE Part. Acc. Conf.*, Washington D.C. (1993).

[2] R. Siemann, "Overview of Linear Collider Designs," *1993 IEEE Part. Acc. Conf.*, Washington D.C. (1993).

[3] G. E. Fischer, "Ground Motion: An Introduction for Accelerator Builders," *1992 CERN Accelerator School*, Montreux, Switzerland (1992).

[4] C. Adolphsen, *et. al.*, "Beam Based Alignment Technique for the SLC Linac," *1989 IEEE Part. Acc. Conf.*, Chicago, IL. (1989).

[5] T. O. Raubenheimer, "A New Technique of Correcting Emittance Dilutions in Linear Colliders," *Nucl. Instr. Meth.*, **A306**:61-64 (1991).

[6] T. O. Raubenheimer and R. D. Ruth, "A Dispersion-Free Trajectory Correction Technique for Linear Colliders," *Nucl. Instr. Meth.*, **A302**:191-208 (1991).

[7] G. Guignard, "Treatment of Nonlinearities in Achromatic Trajectory Correction for Future Linacs," *1992 European Part. Acc. Conf.*, Berlin, Germany (1992).

[8] V. Balakin, *Third Int. Workshop on Linear Colliders*, BINP, Protvino, USSR (1991), p. 302.

[9] C. Adolphsen and T. O. Raubenheimer, "Method to Evaluate Steering and Alignment Algorithms for Controlling Emittance Growth," *1993 IEEE Part. Acc. Conf.*, Washington D.C. (1993).

[10] T. O. Raubenheimer, "Generation and Acceleration of Low Emittance Flat Beams for Future Linear Colliders," Ph.D. Thesis, Stanford University, (1991).

[11] J. T. Seeman, "New Compensation of Transverse Wakefield Effects in a Linac by Displacing Accelerator Structures," *1990 Linear Acc. Conf.*, Albuquerque, NM (1990).

[12] K. Kubo, *et. al.*, "A Simulation Program for Phase Space Dynamics in Future Linear Colliders," in progress.

[13] The SLAC NLC is a future linear collider being designed at SLAC. Parameters can be found in: "*5th Int. Workshop on Next-Generation Linear Colliders*," SLAC–Report–436 (1993).

[14] K. Bane, private communication.