A Discussion of the NLC Linac Alignment and Tuning Procedures

T.O. Raubenheimer

1 Introduction

In this paper, we give a short introduction to the NLC linac alignment and tuning procedures. A more detailed description of the techniques, as well as the simulations verifying the techniques, can be found in Chapter 7 of Ref. [1] and in Refs. [2, 3]. In the next sections, we will describe the basic layout of the linac, the pre-alignment strategy, and the beam-based alignment techniques. Then, we will discuss the stability issues and possible methods of additional emittance control. Finally, it should be noted that the linac model described in this note is probably incorrect with the new (May 1997) parameters where the accelerator structures are naturally grouped in set of three and not pairs. However, the correction procedures described are still those thought to be utilized.

2 Layout

The main NLC linacs primarily consist of 1.8 meter X-band accelerator structures and quadrupole magnets. At the beginning of each linac, the quadrupoles are separated by a single accelerator structure 'girder' on which a pair of accelerator structures are mounted. The number of structure girders between quadrupoles increases very roughly as the square root of the beam energy along the length of the linac until there are six girders (twelve accelerator structures) between quadrupoles. Since the linac elements are not moved when the acceleration gradient is increased for the energy upgrade from 500 GeV to 1 TeV in the center-of-mass, this scaling of the quadrupole spacing, $L_{cell} \propto \gamma^{\alpha}$, is about $\alpha = 0.55$ in the 500 GeV design and $\alpha = 0.45$ in the 1 TeV upgrade.

The phase advance in each FODO cell is roughly 90 degrees but is varied reduce the variation of the energy spread required for autophasing. Specifically, in a sector where the cell length is constant, the phase advance typically starts at about 100 degrees per cell and then decreases to about 70 degrees per cell by the end of the sector. In addition, to reduce the sensitivity to betatron coupling from systematic quadrupole errors or ion and space charge effects, the horizontal phase advance per cell is about 5% smaller than the vertical. This leads to an autophasing energy spread that differs slightly in the X and Y planes but that is not thought to be a limitation.

To limit the emittance dilution, the system has to be aligned accurately and must rely upon beam-based alignment procedures to meet the required tolerances. The beam-based alignment is performed using Beam Position Monitors (BPMs) having 1 μm resolutions and which are located in the bores of the quadrupole magnets. To facilitate the alignment, all of the quadrupoles and every accelerator structure girder, which consists of a pair of accelerator structures, are mounted on remote movers. These movers are based on the FFTB magnet mover systems which move in 0.3 μm steps. The quadrupoles can be moved with three degrees of freedom: X, Y, and Θ (the azimuthal angle), while the accelerator structures can be moved with five degrees of freedom: X, Y, pitch, yaw, and Θ; the azimuthal degree of freedom is not thought to be necessary for the accelerator structures but arises from the mover design. In addition, each of the quadrupole magnets also has a trim winding which is powered as either an X or Y dipole corrector to make fine steering/alignment corrections.

Finally, there are five diagnostic stations spaced along the length of the linac. At each of these diagnostic stations, there are ten high-resolution BPMs, with resolutions of 0.1 μm, which are used by beam-based feedback systems to constrain the beam trajectory, five laser wire stations which can measure the fully coupled 4-D beam emittance, and a magnetic chicane that is used to monitor the beam energy and energy spread. All of these diagnostics have built in redundancy so that measurement errors can be estimated and, if a diagnostic element fails, measurements can still be made.

3 Pre-Alignment

The only elements that require significant pre-alignment are the accelerator structure pairs which are mounted on the structure girders. The NLC ZDR specifies that the centerlines of these structure pairs will be aligned with, respect to each other, to better than $15\,\mu$m rms and the cell-to-cell misalignments within the structures should be less than $15\,\mu$m rms; the cell-to-cell misalignment cause emittance growth through the long-range wakefields while the short-range wakefield dilutions primarily depend on the average offset, *ie.*, the centerline, of the structures.

The present belief is that the structures can be constructed with the required cell-to-cell alignment accuracy. A number of short 40 cell portions of a structure have been bonded with accuracies better than $10\,\mu$m rms. Furthermore, after the alignment has been determined on a Coordinate Measuring Machine (CMM), these structure pieces can be straightened. After straightening the structure segments, the alignment accuracy is roughly $5\,\mu$m rms.

The tolerance for smooth variations in the structure alignment, such as that due to bowing of a single structure, is much looser than the cell-to-cell and structure centerline alignment; bowing of a structure might arise from thermal gradients in the structure. For example, only a few percent emittance growth occurs if the structure pairs bow with a $100\,\mu$m sagita but the average displacement is corrected.

Although, it was stated that the only significant pre-alignment tolerance is that on the accelerator structure pairs, we still plan to pre-align the quadrupoles, BPMs, and accelerator girders accurately. In particular, we will strive to align the BPM electrical center to the quadrupole magnetic center at the level of $50\,\mu$m rms. In addition, the quadrupoles will be aligned with a short-range alignment resolution, *ie.*, lengths comparable with the betatron wavelength, of $100\,\mu$m rms and long-range alignment of better that 4 mm. The former will be implemented using the standard laser alignment practices while the latter will be determined using the satellite-based Global Positioning System (GPS). Finally, the accelerator structure girders will be aligned at the $100 \sim 200\,\mu$m level. Of course, the final beam-based alignment is very insensitive to these pre-alignment values and thus the tolerances have been based on what is thought to be readily attained; these tolerances can be loosened if desired.

4 Beam-Based Alignment

As stated, to attain the required level of alignment, beam-based techniques must be used. The rms alignment 'tolerances' that must be attained are roughly 2 μm BPM-to-quadrupole alignment, 4 μm quadrupole-to-beam alignment, and 15 μm accelerator structure-to-beam alignment. The three different techniques that have been proposed for these tasks are described below. It should be noted that in all cases, the goal has been to make the alignment system as robust as possible.

4.1 BPM-to-Quadrupole Alignment

The offset of the electrical centers of the BPMs with respect to the magnetic centers of the quadrupoles must be determined to an accuracy of roughly 2 μm rms; this is twice the single bunch BPM resolution of 1 μm which has been attained in the FFTB BPMs. Once determined, it is believed that this offset will be stable over periods in excess of 24 hours. The primary source of drift will be the BPM electronics which will be in the temperature stabilized klystron gallery. In this case, stability at the level of 1 in 1000 is not thought unreasonable; if necessary, we could include an in-situ calibration to remove the electronic drifts.

Given the long-term stability, we have proposed a straightforward, although time consuming, procedure to determine the alignment: each quadrupole will be individually varied and the BPM-to-quadrupole offset will be determined from the resulting betatron oscillation. In a 90° FODO lattice, the peak betatron oscillation from 100% variation of a focusing quadrupole is roughly 5 times the amplitude of misalignment while that from a defocusing quadrupole is roughly twice the misalignment. By averaging a number of measurements and by using roughly 10 upstream BPMs to fit the incoming jitter oscillation, as well as, 10 downstream BPMs to fit the resulting oscillation, this technique should be able to determine the BPM-to-quadrupole offset with a resolution equal to the BPM resolution when the quadrupole strengths are varied by 25%. Furthermore, to speed the measurement process, many quadrupoles, separated by 10 to 20 BPMs can be measured at the same time; this assumes that the alignment is already fairly accurate. In such a case, the magnets would be chosen to minimize the betatron mismatches that would arise.

Of course, there are other sources of systematic error such as differential saturation of the quadrupole poles or mechanical changes which will cause the magnetic center to vary as a function of excitation. Provided that the field levels in the iron are well below saturation, the former effect is expected to be a small contribution and with proper construction, the latter effect should also be insubstantial. Regardless, we have assumed that these systematic effects limit the effective resolution of the measurement to two times the single bunch BPM resolution.

There are roughly 700 quadrupole magnets in each of the main linacs. Assuming that 35 BPMs could be aligned simultaneously and that is would take five seconds for the quadrupoles to stabilize at the different set points, the alignment process would take ten to fifteen minutes. However, attaining such a rate will require extensive care when designing the control system.

4.2 Quadrupole-to-Beam Alignment

After the BPM-to-quadrupole offsets have been determined, the quadrupole alignment is straightforward. The concept is to use the BPM measurements to align the quadrupoles in a straight line between first and last quadrupole in a region as well as finding the initial conditions at the first quadrupole. Assuming that all the beam deflections are caused by misalignments of the quadrupoles, N BPMs are used to solve for $N-2$ quadrupole offsets as well as the initial position and angle; the positions of the first and last quadrupole are fixed and are not determined in the solution. Next, a corrector at the first quadrupole is used to launch the beam along the straightened trajectory; its setting is determined from the initial angle. In addition, weak dipole trim windings are used on the focusing quadrupoles to finish the correction because the mover resolution is $0.3\,\mu$m. Finally, as the trajectory is changed, the accelerator structures are moved to keep them aligned to the beam. Thus, the structure alignment is interleaved with the quadrupole alignment.

Because the linac model is not known perfectly, the alignment is performed over short segments that include roughly 40 quadrupoles or five betatron oscillations. Furthermore, because the BPM-to-quadrupole offsets are not known exactly, a weighting function is included in the fit to limit the quadrupole moves. This has the effect of causing the trajectory to slowly bow towards the axis but, provided that the wavelength of the bowing is long compared to the betatron wavelength, no significant emittance dilution arises. Finally, there can be significant dilution at the end points of the alignment where the dipole corrector or quadrupole is used to launch the beam along the aligned trajectory. This dilution can be reduced by interleaving the alignment regions.

We have verified that the technique is still robust when one or two BPMs or quadrupole movers are not operating in an alignment section. Presently, additional work is being performed to quantify the sensitivity to malfunctioning BPMs or movers.

4.3 Structure-to-Beam Alignment

The structure pairs will be aligned to the beam trajectory using a dipole mode monitor to measure the structure offsets and then the girder movers to center the structures appropriately. The dipole mode monitor will measure the induced dipole modes in the four damping manifolds on the Damped-Detuned accelerator Structures (DDS). The power and phase of the induced dipole modes will indicate the misalignment and the frequency will indicate the longitudinal position along the structure. Presently, it is thought to make four measurements in each plane, X and Y, on each accelerator girder, *ie.*, two measurements in each plane per accelerator structure, and to use the movers at either end of the girder to minimize the average offset. The accuracy of the dipole mode monitors is expected to be better than $10\,\mu$m in which case it adds a small contribution to the $15\,\mu$m rms misalignment of the accelerator structures.

This alignment system is relatively straightforward. Regardless, it is extremely important to remove any coherent betatron oscillation that might exist in the data from the measurements since this will align the structures to the same oscillation and cause a large emittance growth. The tolerance on the amplitude of an oscillation along the length of the linac is less $0.5\,\mu$m. To solve this problem, the girders will be aligned in groups covering roughly 40 quadrupoles or five betatron oscillations. Then, a betatron oscillation will be fit and subtracted from the measured data. The length of the fit, five oscillations, is limited due to practical limitations in the modelling of the linac.

4.4 Stability

One of the largest problems surrounding the alignment issue is that of stability. A linac is a pulsed device which is inherently unstable. Thus, the beam parameters will vary from pulse-to-pulse. This makes it extremely difficult for complicated alignment procedures to converge to their optimal solutions.

There are three time scales that are important when considering the stability: first, jitter, or pulse-to-pulse variations, that cannot be corrected for using beam-based feedback (in the NLC this is about 6 Hz), second, motion of the accelerator elements that change the steering though the linac with time-scales that are slow compared to the beam-based feedbacks, and, third, slow drifts of elements or settings that impact the beam emittance.

The primary sources of pulse-to-pulse jitter that are thought important are fast ground motion induced by 'cultural' activities and variation of the acceleration fields, pulsed kickers, and feedback systems. The primary source in the second category is the natural ground motion and the primary sources in the last category are thermal variations and diffusive ground motion.

The effect of the first category is obvious; the fast motion causes the beam centroid and emittance to jitter. Although the jitter usually has relatively little impact on the actual luminosity, the jitter will degrade the performance of the diagnostics and this may impact the ability of any complex tuning algorithms or beam-based alignment techniques to converge to the optimal solution; this is particularly true with techniques that rely on small differences between trajectories to infer a solution. At present, this is thought to be one of the largest source of luminosity loss in the SLC final focus [4] and is thought to be one of the reasons for the poor performance of the initial DF steering tests in the SLC [5].

There are partial solutions to this problem. For example, many of the emittance diagnostics in the SLC now use 'jitter correction' where BPMs are used to subtract the shift in the beam centroid on a pulse-by-pulse basis from the beam size measurements. Unfortunately, this does not correct for tilts of the beam or betatron mismatches due to fluctuations in the beam energy or energy spread. Furthermore, it is difficult to completely correct for the effect of even the centroid jitter which is relatively straightforward to measure.

In the NLC design, we want to limit the beam centroid jitter to be less than 0.25 sigma of the beam. From the recent ground motion measurements and measurements at the FFTB, this seems to be reasonable goal. Furthermore, wherever possible, we have chosen to use relatively simple tuning techniques which are relatively insensitive to changes that occur during the measurements. In particular, the quadrupole alignment is based on absolute BPM measurements and is insensitive to fluctuations in the incoming conditions; the initial conditions are automatically subtracted from the fit. Similarly, the structure alignment depends only on local dipole mode measurements and does not rely on the difference of two measurement although, as described above, it is still extremely important to remove any incoming betatron oscillation from the measurements since this will align the structures to the same oscillation.

The effect of the second category is not actually thought to be a limitation. In the low frequency regime ($f \lesssim 10\,\mathrm{Hz}$), the rms ground motion can be quite large but is highly correlated. Measurements at SLAC [6] and elsewhere have shown that this motion can be described as waves arriving from different directions. Thus, the motion is correlated over a distance comparable to the ground motion wavelength and this high degree of correlation reduces the effect on the beam. Furthermore, in this regime, the beam-based feedback systems can compensate most of the changes to the beam trajectory.

The effect of the last category is more difficult to estimate. On these time scales, changes to the beam trajectory are straightforward to correct using both discrete beam-based feedbacks and a slower 1-to-1 style correction loop using the dipole correction coils in the magnets. However, slow drifts of the elements can cause increases in the beam emittance as well as fluctuations in the energy and energy spread and drifts of the instrumentation can make re-tuning of the accelerator difficult.

To reduce the drifts, the electronics will be in the temperature controlled klystron gallery. As mentioned, it is believed that this should stabilize the BPM-to-quadrupole alignment of $2\,\mu$m as well as the klystron phases. Then, assuming diffusive ground motion described by the 'ATL' relation with a coefficient $A = 5 \times 10^{-7}\,\mu\mathrm{m}^2/\mathrm{m/s}$, the trajectory must be corrected using 1-to-1 correction every 30 minutes. At the same time, the accelerator structures must be re-aligned to the beam trajectory. Fortunately, both of these processes will require very small motions and could be performed without interrupting the delivery of luminosity. Additional beam-based alignment would probably be needed on a weekly or monthly time-scale.

Similarly, the beam energy and energy spread will be stabilized by locking the klystron phases to local measurements of the beam passage. Changes in the rf phases due to electronic drifts will be detected as changes to the energy and energy spread in the chicanes at the five diagnostic stations along the linac and can be corrected with local energy feedbacks. If necessary, additional klystron phasing can probably be performed non-invasively using dither techniques similar to those used presently in the SLC.

5 Additional Emittance Control

The NLC ZDR does not rely upon global forms of emittance control such as trajectory bumps like those used in the SLC. The primary reason for this is that the global 'bump' emittance corrections tend to be less stable than a local correction of the dilution sources since, in the former, one is using one large effect to cancel another large effect which is very sensitive to the phase advance between the source and the correction. Another reason is that, in the NLC, there are both dispersive and transverse wakefield dilutions are significant. In addition to having extra dilutions to minimize, this makes the trajectory bumps more difficult since one has to use both 'non-dispersive' and 'dispersive' bumps, neither of which is a simple betatron oscillation, for orthogonal control—orthogonal control is very important to allow the tuning to converge efficiently. One solution is to move accelerator structure girders to minimize the wakefield dilutions and use dispersive bumps to reduce the dispersion.

Regardless, the NLC design includes five emittance diagnostic stations along the linac where the emittance could be minimized using trajectory bumps, or other techniques, if desired. In particular, high-speed kickers have been specified that could be used to re-align the bunch trains if they are distorted by the long-range transverse wakefields. Similarly, the quadrupoles can be rotated with the magnet movers and thus the betatron coupling could also be minimized at these stations if the magnet roll tolerances are exceeded. In addition, the stability of the quadrupole power supplies have been specified to allow large (100 μm) trajectory offsets without introducing significant beam jitter so that trajectory bumps could also be introduced. Finally, all of the accelerator girders are on movers so that any set could be used to minimized the wakefield dilutions. However, as stated previously, none of these global reduction techniques are included in the emittance budget that is listed in the ZDR.

6 Summary

In this note, we have outlined the alignment and emittance control techniques planned for the NLC linac. Throughout the design, we have attempted to use robust procedures that should be insensitive to jitter and noise which frequently complicate the implementation of such tuning procedures. These basic procedures should be sufficient to produce a beam within the specified emittance and budgets. Regardless, we have also provided the capability to implement more complicated procedures, such as emittance bumps, to further reduce the dilution and thereby provide additional margin in the design.

References

[1] NLC Design Group, “A Zeroth-Order Design Report for the Next Linear Collider,” SLAC Report 474 (1996).

[2] R. Assmann, C. Adolphsen, K. Bane, T.O. Raubenheimer, K. Thompson, “Emittance and Trajectory Control in the Main Linacs of the NLC,” *Paper presented at 1996 Linac Conf.,* Geneva, Switzerland (1996).

[3] R. Assmann, C. Adolphsen, K. Bane, T.O. Raubenheimer, K. Thompson, “Simulation Results Concerning Stability Issues for the Main Linac of the NLC,” *Paper presented at 1996 Linac Conf.,* Geneva, Switzerland (1996).

[4] F. Zimmermann, *et. al.,* “Performance Issues, Downtime Recovery and Tuning in the Next Linear Collider,” SLAC–PUB–7455 (1997).

[5] R. Assmann, T. Chen, F.J. Decker, M. Minty, T. Raubenheimer, R. Siemann, “Quadrupole Alignment and Trajectory Correction for Future Linear Colliders: SLC Tests of a Dispersion-Free Steering Algorithm,” *Proc. of the Fourth Int. Work. on Acc. Alignment*, KEK Proceedings 95–12, Tsukuba, Japan (1995).

[6] Appendix C of Ref. [1].