BEAM-BASED ALIGNMENT TECHNIQUE FOR THE SLC LINAC*

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ABSTRACT

Misalignments of quadrupole magnets and beam position monitors (BPMs) in the linac of the SLAC Linear Collider (SLC) cause the electron and positron beams to be steered off-center in the disk-loaded waveguide accelerator structures. Off-center beams produce wakefields which limit the SLC performance at high beam intensities by causing emittance growth. Here, we present a general method for simultaneously determining quadrupole magnet and BPM offsets using beam trajectory measurements. Results from the application of the method to the SLC linac are described. The alignment precision achieved is approximately 100 μm, which is significantly better than that obtained using optical surveying techniques.

1. INTRODUCTION

The lattice of the SLC linac consists of 275 sets of elements, each consisting of a quadrupole magnet for focusing, a pair of dipole magnets for steering correction in the vertical and horizontal planes, and a stripline BPM for measuring beam position in each plane.[1] In each set the BPM is mounted in the bore of the quadrupole and the dipole magnets are located within a meter of these elements. The sets are separated from one another by spaces of between 3 and 12 m that contain accelerator sections.

The corrector magnets associated with electron focusing (defocusing) quadrupoles in each plane are used to steer the electron (positron) beam. The degree to which all BPM readings for both beams can be zeroed reflects, in part, the misalignments of the quadrupole magnets from a straight line. Offsets of the electronic centers of the BPMs relative to the magnetic centers of the quadrupoles also contribute to orbit distortion. Such offsets can be produced by mechanical displacements of the BPMs, although most are suspected of originating from biases in the readout electronics. An illustration of both a misaligned quadrupole and a misaligned BPM is shown in Fig. 1. The automated steering program for the SLC linac generally achieves a 200–300 μm rms orbit in each plane. The resulting corrector magnet strengths correspond to quadrupole or BPM offsets of comparable size.

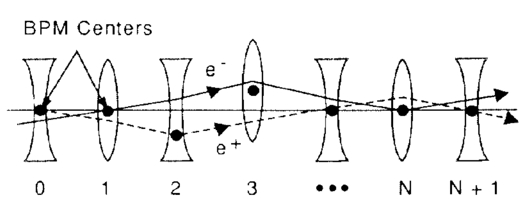

Fig. 1. Linac lattice containing a misaligned BPM (#2) and quadrupole (#3). The electron and positron beams are steered using corrector magnets near each quadrupole to minimize the orbit excursions as measured by the BPMs.

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A linac alignment task force was created with the objective of correcting both quadrupole and BPM offsets so the beams can be steered as close to the quadrupole axis as possible. The concern is that off-axis orbits in the intervening disk-loaded waveguide accelerator structures produce wakefields which lead to emittance growth. For the alignment procedure to help then, the waveguides must be centered on the quadrupole axis. The alignment method described here cannot verify this condition, so it remains an assumption in this program.

2. THEORY

In formulating the beam transport equations in the case of quadrupole and BPM misalignments, we denote by $0, \ldots N+1$ the sets of BPMs, quadrupoles and corrector dipoles in a given linac lattice segment. The linac reference axis is defined as the line connecting the centers of the endpoint BPMs (0 and $N+1$). Defining the axis relative to the BPM coordinate frame is necessary because no absolute reference from the BPMs to any physical structure in the linac exists. For either transverse coordinate (labeled x) let

d_k = offset of the k^{th} quadrupole relative to the reference axis.

b_k = offset of the k^{th} BPM relative to the center of the k^{th} quadrupole.

m_k = beam displacement measured by the k^{th} BPM.

x_k = displacement of the beam trajectory off axis at the k^{th} quadrupole.

x'_k = slope of the trajectory relative to the axis at the k^{th} quadrupole.

The displacement variables are illustrated in Fig. 2. Note that with our definition of the reference axis, b and d are zero at the endpoints.

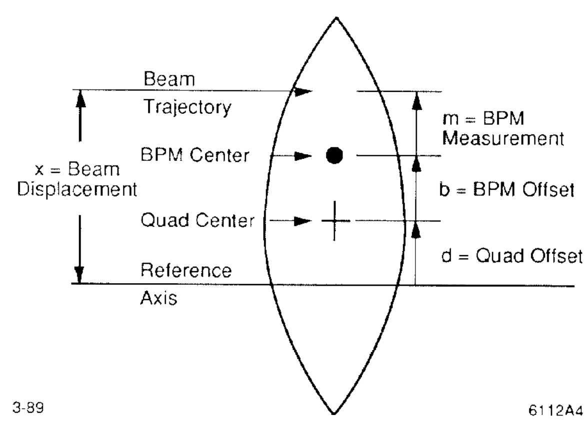

Fig. 2. Illustration of a quadrupole offset d, BPM offset b and BPM measurement m. The displacement of the beam from the reference axis x is thus d + b + m.

The beam displacement can be expressed as a function of the initial beam trajectory and intervening quadrupole offsets as

$$\begin{pmatrix} x_k \\ x'_k \\ 1 \end{pmatrix} = R_{0,k} \begin{pmatrix} x_0 \\ x'_0 \\ 1 \end{pmatrix} + \sum_{j=1}^{k-1} (R_{j+1,k} - R_{j,k}) \begin{pmatrix} d_j \\ 0 \\ 0 \end{pmatrix} \quad ,$$

where $R_{j,k}$ is the 3×3 beam transport matrix from quadrupole j to k. The matrix elements depend on beam energy, corrector magnet kicks, quadrupole strengths and drift lengths (note that corrector kicks are incorporated by adding the kick angle to the 2,3 element of the transport matrix at the locations of the dipole magnets). The measured beam positions are related to the beam displacements relative to the reference axis by

$$m_k = x_k - d_k - b_k \quad .$$

The unknowns in the above equations are the $2N$ quadrupole and BPM offsets, and the initial position and slope of the trajectory. With trajectory data from two independent lattice configurations, the number of unknowns, $2N + 4$, equals the number of BPM measurements so the equations can be solved uniquely. The most convenient source of such data is the nominal electron and positron orbits in the SLC where the opposite charges of the particles yield effectively independent lattices for the two beams. In this analysis, the offset computed for a BPM depends on its measurement and on the measurements of its two nearest neighbors. The quadrupole offsets, however, are a function of all BPM measurements because of the manner in which the reference axis is defined. Other aspects of the alignment analysis using two beams can be found in Ref. 2.

Extending the analysis to more than two independent lattices yields an overconstrained set of equations for the alignment offsets. Estimates of the offsets can then be obtained from a least squares fit. The advantages of the additional constraints are that trajectory data containing missing BPM information can be included, and that the goodness of fit provides a measure of the systematic errors on the quantities that enter the alignment equations. We construct the additional lattices in the SLC linac by scaling all quadrupoles and corrector magnet strengths from the nominal configuration while maintaining the same beam energy profile. An online program that is normally used to correct the SLC lattice for changes in the beam energy profile is used to make the magnet strength adjustments. The energy scale factors used range from 0.3 to 1.0. Because of misalignments, the orbit must be steered after each lattice rescaling. The positron beam, which is produced by an additional electron bunch, is thus hard to maintain and so is turned off for such data taking. For each lattice, BPM measurements are recorded to disk together with all magnet and klystron data needed to model beam transport in the linac.

In fitting for the misalignments, the function minimized is

$$\sum_{k=0}^{N+1} \left(\frac{x_k - m_k - d_k - b_k}{\sigma_k} \right)^2 \quad ,$$

where σ_k is the BPM measurement error. For a single measurement, the BPM error used is 25 μm (bad BPMs are assigned an error of 1.5 mm). We normally average four or five orbit measurements when taking data, so the statistical error on the measurement is reduced. Systematic errors, however, dominate this contribution to the error in the computed offsets, as will be discussed below.

3. RESULTS

Before fitting for misalignments, an analysis using difference orbit data is done as a check of the computed transport matrices for a given lattice. The data are obtained by changing the setting of a corrector magnet in the upstream end of linac and recording the change in the orbit over the entire linac. In computing the change in orbit, the effects of quadrupole and BPM offsets subtract out as do the effects of the corrector magnets. Therefore, the orbit difference depends only on the strengths of the quadrupoles, the accelerator section energy gains, and the initial kick given to the beam. Figure 3 shows an example of a difference orbit measurement taken for this purpose. In this case the corrector kick was in the horizontal plane at a location upstream of the region displayed. The solid line in the figure is a fit to the data which uses the transport matrices computed from the initial BPM in the region displayed to each downstream BPM (note that the effects of the corrector magnets are ignored when computing the R matrices in this analysis). The position and slope of the difference trajectory at the initial BPM location are varied in the fit, as is an overall energy scale factor to account for any calibration error in the energy gains of the accelerator sections. For the data shown, the scale factor corresponds to a $2.0 \pm 0.3\%$ increase in energy. The residuals from the fit, excluding the few BPMs known to be bad, have a 33 μm rms variation. Thus, local errors in energy and quadrupole strength are not significant. Although the goodness of fit does not provide a check of corrector magnet strengths, the method itself demonstrates that each fit can be used to calibrate the corrector magnet producing the kick; that is, the magnitude of the fitted beam kick at the position of the corrector magnet is compared with the value expected from the change of the magnet setting. Tests similar to this which measure just the local deflection of the beam have been done for most magnets, but only to a precision that would reveal large (> 20%) calibration errors.

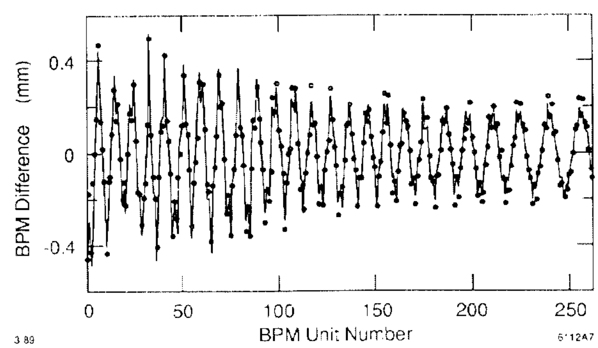

Fig. 3. Difference orbit in the horizontal plane of the SLC linac. The circles are measurements by nearly all the BPMs in the linac. The solid line is a fit to the data in which the launch condition and overall energy scale were allowed to vary.

With the checks of the transport matrices complete, alignment fits for the entire linac are done, usually 16 units at a time in regions overlapping by 8 units. So far, two complete data sets with trajectories from four and five independent lattices have been examined. The results have been compared both between data sets and within each data set for different choices of endpoints. One general observation from this analysis is that the fitted quadrupole offsets are subject to global systematic shifts because of their sensitivity to the definition of the reference axis. In fact, if the endpoint units are misaligned, one expects to see differences in the computed offsets that depend linearly on quadrupole position when comparing values determined with different endpoints. The quantities that are more accurately determined are the quadrupole-to-quadrupole (or "local") changes in the misalignments because these depend much less on the reference axis definition. The "core" distribution of local quadrupole offsets for the entire linac has an approximately 250 μm rms variation in each plane. The values are reproduced to 100 μm for different data sets and different choices of endpoints. The BPM offsets, which are independent of endpoint choice, have a 150 μm rms variation and are reproducible to about the same level as the quadrupole offsets. The residuals from the fits are generally less than 100 μm, and thus are smaller than the systematic errors "absorbed" into the fitted offsets. Some of the systematic effects suspected or known to contribute to the errors are transverse kicks imparted to the beam by the accelerator sections, differences in BPM offsets for electron and positron beams, drifts in BPM pedestals, and errors in corrector magnet calibrations. Global scale errors in energy or BPM measurements are less of a problem; deviations as large as 10% yield less than 100 μm rms change in the results.

The immediate goal of the alignment task force is to correct the large (> 500 μm) quadrupole offsets. Figure 4 illustrates a case where a 1 mm quadrupole offset in the vertical plane near the middle of the linac was found and corrected. The BPM data used to find the misalignment are shown in Fig. 4(a). Two of the orbits are the nominal electron and positron beams, and two are electron orbits for the lattice scaled by 0.5 and 0.7. The circles in Figs. 4(b) and (c) show the quadrupole and BPM offsets, respectively, that were computed for these data. The errors on the offsets from the BPM measurement uncertainty are smaller than the circle size. The quadrupole with the −1 mm offset was subsequently moved and alignment measurements were repeated. In this case, three scaled lattices were used (0.3, 0.5 and 0.75) in addition to the nominal configuration. The resulting offsets, which are shown by triangles in the figure, verify that the large quadrupole misalignment was corrected. The offsets of the other units, which in principle should have remained unchanged, show changes consistent with the 100 μm level of reproducibility observed for this method.

So far, we have realigned quadrupoles at 15 locations in the linac and verified the corrections. In most cases, it was either an individual or adjacent pair of quadrupoles that were misaligned. However, in one region where sets of four quadrupoles are supported on individual girders, the girders were found to be misaligned in a zigzag pattern. There are still more than 20 quadrupoles with misalignments greater than 500 μm to be fixed before we will consider correcting smaller local misalignments and small shifts in groups of units. We have not found any large BPM offsets, and no BPM corrections have been made.

4. CONCLUSION

A beam-based surveying technique has proven useful in finding and correcting misalignments of the SLC linac, making it possible to achieve a local quadrupole alignment tolerance of about 100 μm. This precision is significantly better than that previously attained using optical surveying techniques.

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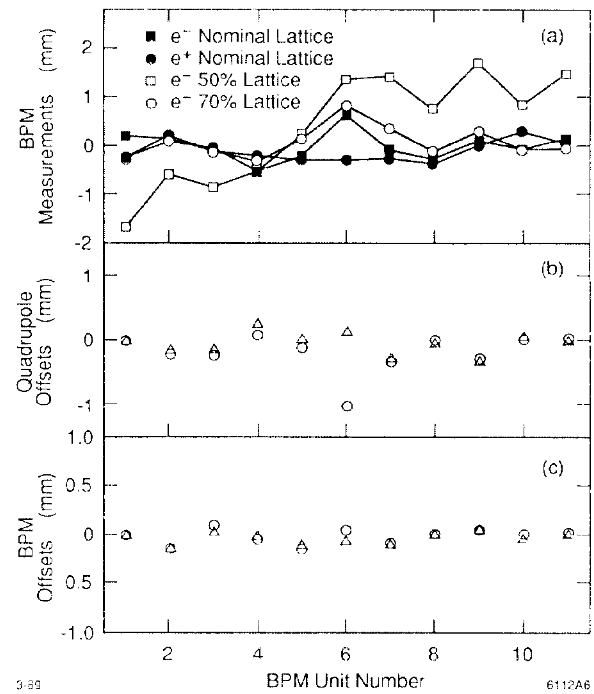

Fig. 4. Example of a quadrupole misalignment in the vertical plane that was found and corrected; (a) Trajectories used to find the misalignment, (b) quadrupole, and (c) BPM offsets computed from the orbit data shown (circles), and from data taken after a +1 mm move of the sixth quadrupole (triangles).

REFERENCES

1. *The SLAC Linac as used in the SLC Collider*, by J. T. Seeman *et al.*, SLAC-PUB-4890 (February 1989), published in these proceedings; J. T. Seeman and J. C. Sheppard, *Special SLC Linac Developments*, (SLAC-PUB-3944, April 1986), published in Proceedings of the Linear Accelerator Conference, Stanford, California, June 2-6, 1986 (SLAC Report 303, September 1986), p. 214.

2. *Beam Determination of Quadrupole Misalignments and Beam Position Monitor Biases in the SLC Linac*, by T. L. Lavine, J. T. Seeman, W. B. Atwood, T. M. Himel, A. Petersen, and C. E. Adolphsen, SLAC-PUB-4720 (September 1988), to be published in Proceedings of the Linear Accelerator Conference, Williamsburg, Virginia, October 3-7, 1988.