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OPERATIONAL EXPERIENCE WITH MODEL-BASED STEERING IN THE SLC LINAC*

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ABSTRACT

Operational experience with model-driven steering in the linac of the Stanford Linear Collider is discussed. Important issues include two-beam steering, sensitivity of algorithms to faulty components, sources of disagreement with the model, and the effects of the finite resolution of beam position monitors. Methods developed to make the steering algorithms more robust in the presence of such complications are also presented.

1. INTRODUCTION

In the 3 km linac of the Stanford Linear Collider, it is necessary to keep the beam within about 100 μm of the axis of the accelerating structure in order to avoid emittance growth due to the transverse wake field. In this paper, we discuss the steering algorithms that have been found most useful in the linac, with emphasis on operational experience in the normal mode of SLC operation in which e^+ and e^- bunches of high intensity (at present up to about 3×10^{10} particles per bunch) must be steered simultaneously. More general discussions of the SLC steering algorithms and software implementation appear elsewhere.[1,2] The linac consists of 100 m sectors, each containing eight girders; at the end of each girder of a typical sector is one quadrupole magnet of the FODO lattice. The first sector after the damping rings has four times as many quads, and the next two sectors each have twice as many, in order to provide proportionately smaller beta functions where the low-energy beams from the damping rings are more sensitive to wakefields. The phase advance per cell is 90° in about the first half of the linac, then tapers to about 45° at the end of the linac as the quads saturate. Installed in the bore of each quad is a stripline beam position monitor (BPM). Each BPM is gated so that it can measure the position of either an e^+ or e^- bunch on a given machine pulse. A short distance after each quad is a pair of dipole corrector magnets, for steering in the horizontal (X) and vertical (Y) directions.

2. STEERING ALGORITHMS

2.1 The Basic 1-to-1 Steering Algorithm

The basic steering algorithm in the SLC linac utilizes a one-to-one matching between correctors and downstream BPMs, for each direction (X or Y) and beam (e^+ or e^-). For each beam and transverse direction, the one-to-one steering algorithm uses a corrector just after a focusing quadrupole to zero the BPM reading in the next downstream focusing quadrupole. Thus each beam is being corrected at the BPMs where its beta function is largest, and is left to fend for itself at the BPMs in the defocusing quads, where its beta function is smallest. In this way e^+ and e^- beams are simultaneously steered.

The general setup is shown in Fig. 1 for the case of one of the beams. The correctors not used for this beam are used for the other beam in a complementary manner (see the discussion of two-beam steering in Sec. 2.3, below).

One may correct the orbit in either or both of the X and Y directions at a time. The kick(s) are calculated to "zero," the reading on the matched BPM in the desired direction(s), then the effect at all downstream BPMs is calculated. (Note that one may actually steer to specified desired offsets in BPMs rather than literally zero, but in our discussion we shall simply refer to this as zeroing the BPMs.) In steering a given region of the linac, the algorithm proceeds downstream through the matched corrector/BPM sets in the region. In general, one ends up with smallest offsets of the beam at the matched BPMs, and larger (but still acceptable) offsets at the unmatched ones.

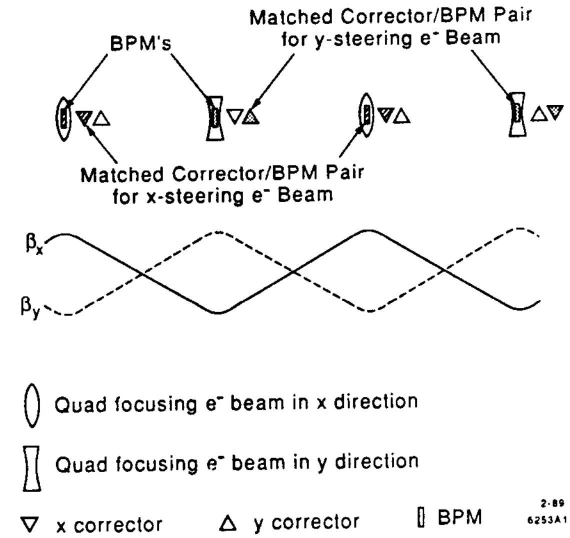

Fig. 1. The matching between correctors for one of the two beams, say the electron beam. Note that the matched corrector/BPM pairs are nearest the focusing quads for the direction (X or Y) being steered. The remaining correctors are used to steer the other beam.

2.2 The Robust, 1-to-1 Steering Algorithm

It is often the case that one or more BPMs or correctors in a region are broken. Note that the simple 1-to-1 algorithm makes no change to a corrector whose matched BPM is broken, and makes no attempt to zero a BPM whose matched corrector is broken. A new "robust" algorithm was developed that steers on a slightly more global level when something is broken, in order to overcome these limitations. The basic idea is to work with a group of BPMs and correctors in a region containing one or more broken components. If there are more BPMs than correctors in the group, the RMS of the BPM readings is minimized, and if there are more correctors than BPMs, the RMS of the corrector strengths is minimized. Details of the algorithm are given in the Appendix.

2.3 Two-Beam Steering

For a given beam, β_x and β_y are out of phase, and for a given direction (X or Y) the beta function is out of phase between the two beams. The beta functions reach their maxima and minima at alternate quads, with the ratio $\beta_{max}/\beta_{min} \approx 4$. Thus, as noted above, one may steer one of the two beams without having a large effect on the other one. There is some residual effect however, so what is done is to iterate back and forth

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between the two beams. Typically, the orbit of the positron beam has somewhat larger RMS offsets than the orbit of the electron beam, so the best results are obtained by starting with the positron beam. Indeed, if one starts by steering the electron beam when the positron orbit is relatively bad, one can end up losing the positron beam completely.

The overall two-beam steering algorithm is as follows:

1. Calculate the settings of the correctors for the positron beam that should zero its orbit at the matched positron BPMs.
2. Predict the change in the orbit of the electron beam due to these new positron corrector settings.
3. Calculate the settings of the correctors for the electron beam that should zero its orbit at the matched electron BPMs.
4. Predict the resulting change in the orbit of the positron beam.
5. Continue iterating steps 1 through 4, correcting the predicted orbit of one beam and calculating the effect on the other beam. Simulations and experience with the actual machine have led to an implementation having a total of three such iterations.
6. Trim the correctors in the linac to the final calculated settings.

Note that we are in effect inverting a matrix by iteration. This is much faster than a direct inversion since the matrix may be quite large (300×300).

3. PHASE ADVANCE IN MODEL AND ACTUAL MACHINE

As noted above, an essential part of the steering algorithms is being able to predict the downstream effects of a change in corrector setting. In particular, the betatron phase advance predicted by the machine model needs to agree with the actual phase advance over the region of the linac being steered. There are about 30 betatron oscillations in the length of the linac, and one would like to have the actual and predicted phase advance agree over the entire length, since any significant discrepancy makes it necessary to steer in shorter segments over which the model and machine phase advance remain fairly coherent. For this and other reasons, methods have been developed to characterize the phase advance, diagnose and fix the causes of discrepancies where possible, and compensate for the effects of any discrepancies whose origins remain uncertain.[3] The basic idea of this "lattice diagnostic" program is to introduce a betatron oscillation in the actual machine, compare the phase advance with that predicted by the model, then vary the model energy profile to obtain the best possible agreement between the predicted and actual phase advance. The program outputs the apparent energy errors required to obtain the fit. Obviously, large phase advance errors should be fixed at their source where possible. However, to take account of any remaining model/machine disagreement, "fudge factors" can be computed from the apparent energy errors, to enable more efficient steering.

4. BEAM POSITION MEASUREMENT EFFECTS

The beam position monitors measure the transverse position of bunch centroids. The bunches have a transverse extent comparable to the offsets one is interested in (of order 100 μ), and a length of approximately 1 mm. Wakefield-induced tails are a potential problem for steering, since they enlarge and distort the bunch. By using BNS damping,[4] such tails have been successfully controlled in the SLC linac at intensities up to about 3×10^{10} particles per bunch,[5] and the steering algorithms have continued to work under these conditions. We have yet to obtain experience with higher currents, but it is expected that use of BNS damping will allow sufficient control of wake field effects in this regime as well.

Ideally, after enough iterations of the robust, one-to-one steering algorithm to eliminate residual coupling effects, one would end up with all good, matched BPMs zeroed. There are, of course, limits in reality, due to the finite resolution of the BPMs and to beam jitter. It is possible, at present, to successfully steer both beams to about the desired 100 μ RMS offsets in both transverse directions. There is still room for improvement in the speed with which this can done, which will come about as it becomes possible to predict the orbits more accurately over longer regions.

5. OTHER PLANNED IMPROVEMENTS AND EXTENSIONS

The present steering software is based on the Twiss parameter representation of the machine model for the horizontal and vertical directions, and thus is not suited for handling regions where there is X/Y coupling. Steering in the linac is essentially uncoupled in X and Y, but this is not the case in some other parts of the SLC, for instance the arcs from the end of the linac to the final focus. Thus, there has been a tendency to handle steering in different parts of the SLC in a rather disjoint manner. Work is currently in progress to base the steering software throughout the SLC on the fully-coupled transfer matrices rather than Twiss parameters. It is hoped that this will allow more general algorithms and more continuity in steering the beam through larger regions of the SLC.

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APPENDIX

For simplicity, we describe the robust one-to-one steering algorithm for the case of steering one of the two beams in one direction, say electrons in the X direction. Denote the transfer matrix element from an angle at a corrector to the resulting offset at a BPM by T_{12}. Thus, we initially have matched pairs of X correctors and BPMs, and associated with each corrector in a pair there is a transfer matrix element T_{12}^{match} to its matched BPM. However, some of the correctors or BPMs may be bad, so we do the following, proceeding downstream from the first matched pair:

1. If the BPM/corrector pair is to be used for positrons only, go to the next matched pair.
2. Else if both the BPM and corrector are bad, then go on to the next pair.
3. Else if both the BPM and corrector are good, see if there is a bad corrector in either of the next two downstream matched pairs for electrons.
   (a) If there is such a bad corrector, and T_{12} from the present corrector to the BPM matched to the bad corrector is at least 0.3 of the T_{12}^{match} of the bad corrector, then all the electron correctors from the present corrector, up to but not including the bad one, will be used to minimize the RMS of the BPMs matched to those correctors plus the one matched to the bad corrector.

(b) Otherwise, the present good corrector will be used to zero the present good BPM as in the simple one-to-one algorithm.

4. Else if the corrector is bad and the BPM is good, go on to the next matched pair. Note that according to the previous step, we used a previous corrector to minimize the reading of the BPM matched to this bad corrector, if it was possible.

5. Else if the corrector is good but the BPM is bad, then look for other BPMs to help determine the setting of this corrector, as follows:

(a) First see whether all of the following hold:

(i) The matched BPMs immediately before and after the present BPM are intended for use only on the other beam, namely positrons.

(ii) These two BPMs are both good, and they have T_{12}'s to the present corrector of at least $0.2T_{12}^{match}$.

(iii) The next BPM designated for electrons only is good. Then these three good BPMs, the present corrector, and the corrector matched to the third BPM are grouped together. We then zero the reading of the third BPM and minimize the RMS of the other two.

(b) Otherwise, look downstream for a good electron BPM with a T_{12} from the present corrector of at least $0.3T_{12}^{match}$. If we come to a bad electron BPM or a bad electron corrector before finding such a BPM, or if we don't find such a BPM within the next six BPMs, or if we find such a BPM but its matched corrector is bad, then give up and go on to the next BPM/corrector pair. If we do find such a BPM, then all electron BPMs and correctors between the present pair and that BPM are grouped together. Since there should be one more corrector than BPM in the group, we zero the BPMs and minimize the RMS of the corrector kicks.

REFERENCES

1. J. Sheppard *et al.*, "Beam Steering in the SLC Linac, "IEEE Particle Accelerator Conf., Vancouver (1985).
2. I. Almog, H. Shoaee *et al.*, in preparation.
3. T. Himel and K. Thompson, "Energy Measurements from Betatron Oscillations," these Proceedings.
4. V. Balakin, A. Novakhatsky and V. Smirnov, *Proc. of the 12th Int. Conf. on High Energy Accelerators,* Fermilab (1983).
5. J. T. Seeman *et al.*, "Transverse Wakefield Damping (BNS–Landau Damping) in the SLC Linac," these Proceedings.