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BEAM STEERING IN THE SLC LINAC*

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ABSTRACT

In order to control emittance growth due to transverse wakefields it will be necessary to transport electrons and positrons through the Stanford Linear Collider (SLC) linac to within a hundred μm of the centers of the linac irises. Beam centering will be accomplished using computer routines to read stripline beam position monitors and in turn correct the orbits with dipole magnets. Several different steering algorithms have been investigated using electrons in the first third of the SLC linac lattice. The most promising scheme is a cascade of modified "three-bumps" in conjunction with long spanning harmonic corrections. General features of the orbit correcting software are discussed along with the mathematical recipes for correction. Experimental results and a discussion of future plans are presented.

INTRODUCTION

Transverse wakefields are generated in the Stanford Linear Collider (SLC) linac when the intense SLC bunches travel off the axis of the accelerator. Wakefields act within a single bunch to further displace the tail of that bunch with respect to its head. This displacement within a bunch causes an effective beam emittance growth which subsequently reduces the luminosity at the Interaction Point. To keep the wakefield induced emittance growth below 10% it is necessary that beam trajectories remain within 100 μm of the linac irises.[1]

Trajectory distortions in the accelerator arise from launching errors, RF steering, quadrupole misalignment, position monitor (BPM) misalignment, and from extraneous magnetic fields. Magnetic errors will deflect positrons and electrons in opposite directions and can be compensated directly with dipole magnetic fields. RF errors will deflect both e^+ and e^- in the same directions so that magnetic magic bumps[2,3] are required for correction.

The SLC linac is being instrumented to permit the detection and correction of trajectory errors. Downstream of beam reinjection from the damping rings, a beam position monitor and a pair of steering dipole magnets (horizontal and vertical) have been installed for each quadrupole of the linac lattice. BPMs are clamped by the quadrupoles to within 50 μm of the magnetic centers of the focusing elements. The quadrupoles are manually aligned and lie within 100 μm of the linac axis. The corrector magnets straddle the accelerator structure, typically within 0.5 m of its associated quadrupole-BPM assembly. The distance between a corrector pair and monitor is typically a small fraction of the spacing between adjacent monitors. When the lattice is adjusted for SLC operation, there is 45° of betatron phase advance between monitors through the first half of the linac; this phase advance decreases adiabatically to about 26° between monitors by the end of the linac.

Automated beam steering is being developed for the SLC linac. Several of the algorithms have been tested in the first third of the accelerator, which for the last year and a half has been instrumented with the SLC equipment.

GENERAL FEATURES

All autosteering programs will be required to simultaneously center both positron and electron beams to within 100 μm RMS of the BPM centers. Programs must have the facility to ignore broken monitors and correctors. In addition it will be necessary that the routines accommodate hardware offsets. The region within the linac over which correction occurs should be variable according to the desires of the operator. From the software development point of view, it is preferrable that programs are modular so as to facilitate changes. Once the system is working, however, streamlined software should be implemented.

Online mathematical models of the SLC linac have been developed for use with the steering software. Principally, models were developed to generate elements of the beam transfer matrices necessary for orbit correction software. Originally, a TRANSPORT deck of the linac was updated to reflect current magnet values and best estimates of the beam energy gain. The output from running the deck was digested to extract the necessary matrix elements. Magnet strengths (quadrupoles and dipoles) have been available in engineering units from the control database since the earliest versions of the SLC control program. Estimates of the beam energy gain must be made offline and manually entered into a file via the touch panel system. At present, COMFORT[4] is used to model the linac. As in the case of TRANSPORT, a COMFORT deck is updated online to reflect the current status of the machine. The chief reason for switching to COMFORT is the speed at which the VAX implementation runs. It is planned in the future that COMFORT will be used in conjuction with GIANT[5] to perform orbit correction not only in the linac but in the various transport lines of the SLC.

The beam steering algorithms which are being considered can be broadly classified into two groups: those which correct a single beam, and those which can handle both beams at once. Ultimately, the latter is required and can be trivially made to handle single beams as well. At the present time only e^- beams are available in the SLC portion of the SLAC linac and efforts have gone into developing single beam correcting software. This was done so that working experience could be gathered with the existing (and developing) hardware and control software. Orbit correction software has been used to diagnose problems associated with both the model developments and the installed equipment.

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The remainder of this paper is used to describe those algorithms which have been developed or are being planned. In the following: Δ_i represents the measured beam offset at the i^{th} monitor, ϕ_j is the betatron phase at the j^{th} location along the linac, and θ_k is the calculated kick which must be added to the k^{th} corrector for compensation ($\Delta B_k = 33.356E\theta_k$ where ΔB_k is the required change in the k^{th} corrector in kG-m when E, the beam energy, is in GeV and θ_k is specified in radians). Throughout the text below, only the horizontal plane is considered explicitly; formulation of the vertical problem is made through changes of the appropriate subscripts and superscripts.

A SINGLE BEAM BUMP

For a beam displacement at the ith monitor, Δ_i, the corrector kicks, θ_j with $j = i-1, i$, and $i+1$, required to center the orbit are given by

$$\begin{pmatrix} \theta_{i-1} \\ \theta_i \\ \theta_{i+1} \end{pmatrix} = -\begin{pmatrix} R^{12}_{i,i-1} & 0 & 0 \\ R^{12}_{i+1,i-1} & R^{12}_{i+1,i} & 0 \\ R^{12}_{i+2,i-1} & R^{12}_{i+2,i} & R^{12}_{i+2,i+1} \end{pmatrix}^{-1} \begin{pmatrix} \Delta_i \\ 0 \\ 0 \end{pmatrix}$$

with the R^{12}_{nm} being the (1,2) elements of the TRANSPORT matrix between the mth corrector and the nth monitor. R^{12}_{nm} is defined as

$$R^{12}_{nm} = \left(\frac{E_m}{E_n}\beta_n\beta_m\right)^{\frac{1}{2}} \sin[2\pi(\phi_n - \phi_m)] \quad for \quad z_n > z_m$$

where $\frac{E_m}{E_n}$ is the ratio of beam energies at locations m and n; β_m and β_n are the lattice βs at locations m and n; and $\phi_n - \phi_m$ is the betatron phase advance between the corrector and monitor.

The correction may be expressed in matrix notation as

$$\theta_j = -C^i_{jk}\Delta_k$$

wherein C^i is the correction matrix associated with the ith monitor.

CASCADED BEAM BUMPS

To correct orbit distortions in a series of monitors, single beam bump corrections are cascaded to yield

$$\theta_j = T_{jk}\Delta_k$$

wherein $\theta_j \equiv$ correction at the jth corrector, $\Delta_k \equiv$ reading at the kth monitor, and $T_{jk} \equiv$ correction matrix. For readings at k=i-1,i,i+1 and j=i, it is seen that

$$\theta_i = -(C^{i-1}_{31}\Delta_{i-1} + C^i_{21}\Delta_i + C^{i+1}_{11}\Delta_{i+1}).$$

For N monitors and correctors, the above leads to

$$T_{jk} = 0 \quad if \quad |j-k| > 2$$

or

$$T_{jk} = -C^k_{j-k+2,1} \quad if \quad |j-k| \le 2.$$

and

$$T_{11} = T_{NN} = 0.$$

The matrices look like

$$\begin{pmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_{N-1} \\ \theta_N \end{pmatrix} = \begin{pmatrix} 0 & T_{12} & T_{13} & 0 & 0 & \dots & 0 & 0 & 0 & 0 \\ 0 & T_{22} & T_{23} & T_{24} & 0 & \dots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \dots & T_{N-1,N-3} & T_{N-1,N-2} & T_{N-1,N-1} & 0 \\ 0 & 0 & 0 & 0 & 0 & \dots & 0 & T_{N,N-2} & T_{N,N-1} & 0 \end{pmatrix} \begin{pmatrix} \Delta_1 \\ \Delta_2 \\ \vdots \\ \Delta_{N-1} \\ \Delta_N \end{pmatrix}.$$

HARMONIC CORRECTION

Beam launching errors can be handled by correcting the component of free betatron oscillation in the downstream orbit. A typical beam trajectory through the linac may be expressed in terms of either position, z, or betatron phase advance, ϕ_β,

$$X(z) = \sum_{j=1}^{J} \Delta(z)\delta(z - z_j) \quad \Longleftrightarrow \quad X(\phi) = \sum_{j=1}^{J} \Delta(\phi)\delta(\phi - \phi_j).$$

A new function $\chi(\phi)$ is defined as:

$$\chi(\phi) = X(\phi) \times (\beta_0 \beta \frac{E_0}{E})^{-\frac{1}{2}}.$$

Fourier analysis of $\chi(\phi)$ results in

$$\chi(\phi) = \sum_j \sum_k [a_k \sin(k\phi) + b_k \cos(k\phi)]\delta(\phi - \phi_j)$$

with $a_k = Im\{A \int \chi(\phi) e^{+jk\phi} d\phi\}$ and $b_k = Re\{A \int \chi(\phi) e^{+jk\phi} d\phi\}$. A is a normalization factor. Corrector kicks θ_m^k and θ_n^k at locations m and n are selected to remove the kth harmonic of betatron oscillation from the beam trajectory:

$$\begin{pmatrix} \theta_m^k \\ \theta_n^k \end{pmatrix} = -\begin{pmatrix} \cos(k\phi_m) & (\frac{\beta_n E_n}{\beta_m E_m})^{\frac{1}{2}} \cos(k\phi_n) \\ \sin(k\phi_m) & (\frac{\beta_n E_n}{\beta_m E_m})^{\frac{1}{2}} \sin(k\phi_n) \end{pmatrix}^{-1} \begin{pmatrix} a_k \\ b_k \end{pmatrix}.$$

In practice, only the first harmonic, $k = 1$ is useful in centering the beam. Harmonic correction has been used successfully in conjunction with cascaded beam bumps to center beam trajectories in the linac.

RMS TRAJECTORY CORRECTION[6]

For simultaneous correction of the positron and electron orbits we define $\Delta_i^+ \equiv$ positron position at the ith monitor; $\Delta_i^- \equiv$ electron position at the ith monitor; $A_{ij}^+\theta_j \equiv$ the positron deflection at the ith monitor due to a kick at the jth corrector; $-A_{ij}^-\theta_j \equiv$ the electron deflection at the ith monitor due to the same kick at the jth corrector. In the horizontal plane $A_{ij}^+ =$ electron TRANSPORT R_{ij}^{34}, $A_{ij}^- =$ electron TRANSPORT R_{ij}^{12}, and $A_{ij}^{+,-} = 0$ if $z_j > z_i$.

In the case of M monitors and N correctors the orbit is flattened by minimizing the rms value of S:

$$S = \sum_{i=1}^{M} \{(\Delta_i^+ + \sum_{j=1}^{N} A_{ij}^+\theta_j)^2 + (\Delta_i^- - \sum_{j=1}^{N} A_{ij}^-\theta_j)^2\}.$$

The solution to this problem is given in matrix notation as

$$\theta_j = -(A^{+T}A^+ + A^{-T}A^-)_{jk}^{-1}(A^{+T}\Delta^+ - A^{-T}\Delta^-)_k$$

wherein A^{+T} and A^{-T} are the transposes of the positron and electron correction matrices, A^+ and A^-.

When only electron beams (or positron beams as in the case of the positron returnline or south collider arc) are transported through a region, the proper orbit correction solution is still given by the above expression with Δ^+ (or Δ^-) set to zero.

STATUS AND FUTURE PLANS

Single beam bumps, cascaded beam bumps, and harmonic correction software has been written and successfully tested using the ten sectors of SLC linac installation. These steering programs have been used to check the hardware and to test the linac model. Automated steering was used to generate the corrector lattice which was used in the Ten Sector Tests of January, 1984.[7] The handling of over-ranged correctors has been problematic. A partial solution is afforded through the removal of launching errors with first harmonic correction before cascading beam bumps. Because of the fluidity of the main SLC control software, these programs have not been released for everyday operations.

At present, the primary programming effort with regard to orbit correction is being directed toward the development of GIANT. GIANT is a general program which will be used for trajectory correction in the beam transport lines, collider arcs, and damping rings, as well as in the linac. For the linac, it is expected that RMS correction will be the principal algorithm used. Harmonic correction will be called upon for launching error compensation while local bumps are reserved for hardware checkout. Point to point steering is being considered as a solution to the problem of transporting the first beam through a line. Magic bumps will be useful during kylstron replacement for rapid compensation of RF steering. The COMFORT model must be extended to cover the full thirty sectors as well as the increased focusing which will be installed in the first three sectors of the linac after beam reinjection from the damping rings.[8]

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