SLAC-PUB-95-6769

*BEAM-BASED MAGNETIC ALIGNMENT OF THE FINAL FOCUS TEST BEAM**

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In order to optimize tunability and backgrounds in linear collider final focus systems, it is necessary to align strong quadrupole and sextupole magnets with beam-based measurements. Algorithms for alignment have been used successfully on the Final Focus Test Beam (FFTB) beamline at SLAC. Quadrupole magnets were aligned using a shunt technique, with resolutions from 50 microns down to 700 nanometers. Sextupole magnets were aligned by moving the magnets transverse to the beam and observing the kick on downstream beam position monitors. This procedure resulted in sextupole misalignment resolutions of 5 to 20 microns. All magnets were then moved into aligned positions via remote-controlled stages capable of sub-micron resolution. Details of the fitting algorithms, results of the measurement, and potential improvements in the system are discussed.

I. INTRODUCTION

Linear colliders operating in the TeV CM energy range are expected to have extremely tight *a priori* alignment tolerances on their quadrupole and sextupole elements. Misaligned quadrupoles generate dispersion, which can dilute the nanometer-sized focused spot; they can also cause the two beams to be steered out of collision, to such an extent that re-steering with correctors introduces unacceptable dispersion. Misaligned sextupoles can generate normal and skew quadrupole effects, resulting in waist shifts, dispersion, and coupling (x'y) at the IP. Finally, any significantly misaligned magnet can create detector backgrounds through aperture limiting in the element itself, or downstream via steering.

The Final Focus Test Beam (FFTB) is a prototype linear collider final focus designed to focus the 46.6 GeV SLAC beam to a vertical size of 60 nanometers. Tuning studies [1] have indicated that the spot size goal can be achieved if the RMS misalignments for quadrupoles and sextupoles do not exceed 100 microns in the horizontal and 30 microns in the vertical. In order to achieve these tolerances, we have developed a beam-based algorithm for measuring the misalignments of all strong quadrupole and sextupole magnets upstream of the Focal Point (FP). The magnets are then moved into aligned positions by remote-controlled stages. This eliminates the need to shut off the beam and enter the tunnel to correct alignment, reducing the concomitant risks from changes in the tunnel environment during positioning.

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

II. THE FINAL FOCUS TEST BEAM

The optics of the FFTB have been discussed elsewhere[2]. There are 30 strong quadrupoles upstream of the FP which are subject to beam-based alignment, and 4 sextupoles arranged in 2 families. The beamline contains 40 beam position monitors (BPMs) of a stripline design which are used in the alignment procedure[3]. Each quadrupole and sextupole magnet subject to beam-based alignment is mounted on a remote-controlled stage capable of independent x and y motion, with positioning accuracy of under 1 micron[4].

III. PREPARATION FOR ALIGNMENT

Prior to the beginning of beam-based alignment, the strong sextupole magnets are reduced to a nominal zero value. The entire line is then standardized. The magnets from the first bend magnet to the end of the line are set to their design values for small-spot operation. The matching quadrupoles upstream of the first bend are set to produce a low-divergence beam at the FP. This setting reduces the beam size throughout most of the FFTB, which eases constraints on the shunt range of the quadrupoles, and minimizes beam jitter and BPM background considerations. The FFTB enclosure is locked, and allowed to warm up to thermal equilibrium for several days.

IV. QUADRUPOLE ALIGNMENT

The quadrupole alignment procedure uses a shunt technique to measure the offset of the beam centroid from the magnetic center of each quad. Each quadrupole upstream of the FP is powered by a separate power supply, eliminating the need for shunt or boost supplies to change the quadrupole strength. The strength range of each quadrupole has been determined for the low-divergence optics by a series of simulation studies which optimize resolution and downstream aperture clearances at each setting of every quadrupole.

A. Data Acquisition

The beamline is aligned in segments, each of which contains between 3 and 6 consecutive magnets. For each segment, the alignment acquisition procedure is as follows:

1. Read in all FFTB-region BPMs for 100 orbits, average the positions at each BPM over the 100 orbits. This average constitutes the "reference orbit," which is subtracted from all subsequent BPM data at the beginning of the fit. This reduces the data used in fitting to differences from the

reference orbit, which are correlated to quadrupole shunt values to extract the misalignments. Despite extensive averaging, the reference orbit may still differ systematically from the nominal trajectory due to injection or energy offsets. The reference orbit is compared to several subsequent orbits to ensure its conformity before continuing acquisition.

2. Scan each quadrupole in the segment sequentially through its range of strengths. Three settings are used for each magnet, typically the nominal strength and (nominal ± offset). At each setting, acquire readings from all FFTB BPMs for 8-10 pulses (not averaged). During this time, operators watch loss monitors, energy feedback signals, etc., to ensure that no errors occur which may contaminate the data. If so, the data for a quadrupole may be re-taken.
3. Once all data for a segment has been acquired successfully, the BPM and magnet strength data are submitted to a fitting routine, OPTFIT.

B. Fitting Algorithm -- OPTFIT

OPTFIT is an online program which combines first-order matrix formalism for centroid and/or beam matrix transport with MINUIT function minimization. It uses beamline data (magnet strengths, BPM readings, wire scanner measurements) to fit selected parameters of the line (magnet misalignments, strengths, incoming beam matrix).

The program takes as input the data acquired via the SLC data acquisition system; files describing the beamline devices and the transfer matrices between them; and a set of flags which indicate the parameters to be fit. Once this data has been passed to OPTFIT, the following steps are followed:

1. The reference orbit is subtracted from all other BPM data.
2. For each pulse, the energy variation from the reference orbit is determined. The FFTB extraction line contains BPMs on either side of a vertical permanent bend magnet, and these are used for this computation. The energy and energy uncertainty of each pulse are stored, and the BPM data used for this step are not used in the main fit.
3. For each pulse, the incoming jitter (x,x',y,y') relative to the reference orbit is determined. This is done using BPMs upstream of the first magnet whose alignment is to be fitted, i.e., in a region of non-varying transfer matrices. The fitted incoming coordinates and their error matrix are stored for each pulse, and the data used in this step are eliminated from the main fit. Because steps 2 and 3 are simple linear fits, matrix inversion (not MINUIT) is used.
4. The data between the last magnet to be fitted and the energy BPMs are subjected to quality tests. Because these BPMs are also in a region of invariant transport, the BPM readings can be fitted, pulse by pulse, to a "track" emanating from the downstream face of the last fitted magnet. The quality of fit to the "tracks" can indicate BPMs with excessive noise, individual bad readings, etc. These are eliminated from the fit.
5. The errors from fitting the incoming beam are propagated to each BPM used in the fit, and added in quadrature to the intrinsic BPM resolution.
6. MINUIT is called. The fit algorithm will then minimize χ^2 by changing the magnet positions and re-transporting each pulse (using the initial coordinates determined above), then comparing the results to the BPM data. The fitted misalignments are then returned, along with uncertainties, the normalized χ^2, and the contribution to χ^2 from each BPM.

C. Refinements to the Procedure

Early experiments indicated that naively implementing the corrections recommended by OPTFIT was not satisfactory in all cases: frequently the misalignment of an upstream quadrupole served to kick the beam onto the line of the remaining magnets. In this case, simply moving the magnets would have forced us to move the entire FFTB line onto the arbitrary line of the incoming beam. A fit option was added in which the last quadrupole of a segment is defined to be "aligned," and a kick angle is fitted at the upstream end of the segment. This dramatically improved our ability to converge, especially in the beam matching region upstream of the first bend.

Other experiments showed that the quality of the fit was deteriorating as the area of interest moved downstream, as indicated by monotonically increasing normalized χ^2 values. This was traced to upstream magnets losing hysteresis, usually at the end of a scan (when set back to their original values). The magnets were then required to "mini-standardize," i.e., when the magnets are changed in a direction opposite to their hysteresis curves, the power supplies automatically overshoot the new set point by 5%, so the set point is approached from the correct direction. The dilution of fit quality was nearly eliminated by this refinement.

D. Results

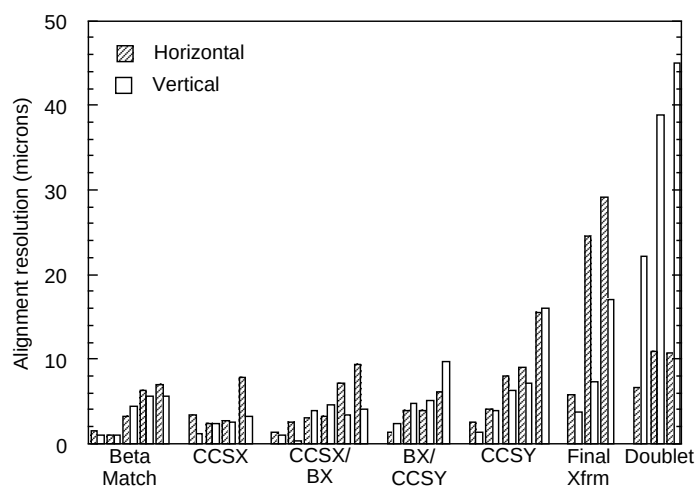

Figure 1. Resolution of quadrupole alignment technique for all FFTB magnets upstream of FP.

Figure 1 shows the achieved resolutions of the fitting procedure. These represent the resolution of the distance from the quadrupole center to the arbitrary line of the incoming beam. Each quadrupole in the segment introduces a kick to the nominal trajectory, whose magnitude is uncertain due to the uncertainty in the quadrupole's alignment. The propagation of this kick is included in the fit of the downstream quadrupoles. Consequently, the resolution of the method degrades from upstream quadrupoles to downstream within a given segment. The monotonic loss of resolution from upstream segments to downstream segments is due to the decreasing number of BPMs downstream of the fitted magnets.

V. SEXTUPOLE ALIGNMENT

The SLC Final Focus performs CCS sextupole alignment by varying their sextupole families in strength and observing changes in waist, dispersion and coupling at the IP[5]. This technique relies on IP single-beam size monitors, which can be difficult to use in a linear collider final focus. The FFTB alignment technique, by contrast, relies only on BPMs and magnet movers, and can be completed before small-spot tuning begins.

Once all the quadrupoles have been aligned, the CCS sextupoles are turned on to a strong value (integrated second derivative = 33,000 kG/m). The sextupole is then scanned *in position*, via its mover, over the full range of the mover in either x or y. The thin lens kick of a sextupole magnet is of the form:

$$B_y = K_S (x^2 - y^2).$$

Consequently, the position on a downstream BPM will vary quadratically in x as a function of the mover (x or y) position. The downstream BPM values can then be fit to a parabola:

$$X_{BPM} = A(X_{mover} - B)^2 + C.$$

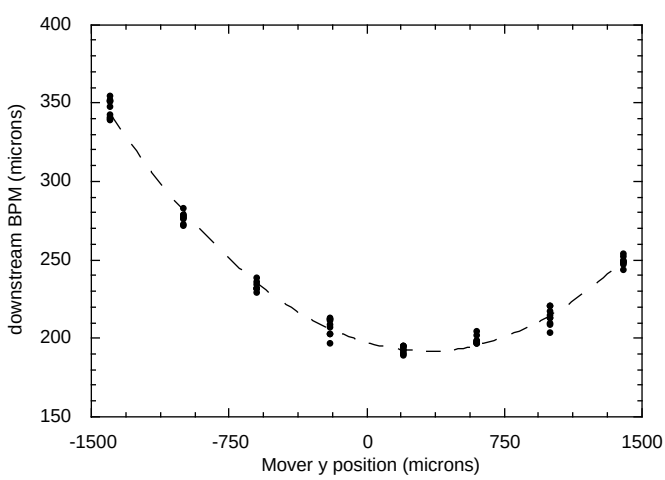

Figure 2. Reading of a downstream BPM vs sextupole mover position. Note that both x and y mover scans produce a quadratic horizontal kick at the downstream BPM.

The offset value, B, is the unambiguous center of the sextupole magnet, i.e., the point at which the magnetic gradient vanishes. The sextupole may then simply be set to this position. Figure 2 shows such a quadratic form for a BPM vs. sextupole mover scan, and Figure 3 shows the achieved resolution of this procedure for all 4 FFTB CCS sextupoles.

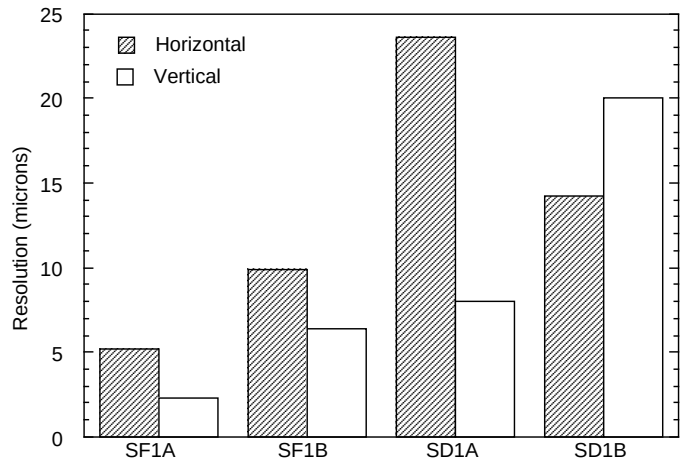

Figure 3. Resolution of sextupole alignment technique for all four CCS sextupoles.

VI. POSSIBLE IMPROVEMENTS

The incoming trajectories for the alignment of the upstream quadrupoles in the FFTB is determined by a pair of BPMs, separated by 85 meters. The first of these is a low-resolution device, rather than a high-resolution FFTB BPM. Replacing this BPM would improve convergence of these magnets. Since the upstream quadrupoles are used for beam matching and changing the IP divergence, this would be a significant improvement.

VII. ACKNOWLEDGMENTS

The authors would like to thank Lee Ann Yasukawa for writing the Quad Alignment interface software in the SLAC control system.

VIII. REFERENCES

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