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THE OPTICS OF THE FINAL FOCUS TEST BEAM*

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I. INTRODUCTION

The Final Focus Test Beam (FFTB), currently under construction at the end of the SLAC Linac, is being built by an international collaboration[1] as a test bed for ideas and methods required in the design and construction of final focus systems for next generation e^+e^- linear colliders. The FFTB lattice shown in Fig. 1 is based on the previously developed principle of using sextupole pairs in a dispersive region to compensate chromaticity.[2] The linear lattice was optimized for length,[3] and implementation of diagnostic procedures. The transformations between sextupole pairs (CCX and CCY) are exactly -I, the matrix for the intermediate transformer (BX) is exactly diagonal, and the dispersion function has zero slope at the sextupoles and is thus zero at the minimum of the β_x function in the intermediate transformer.

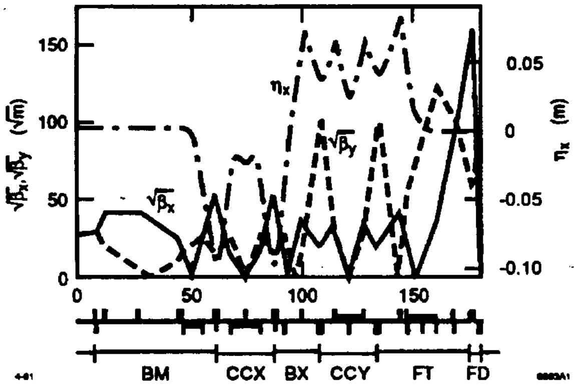

Figure 1.

The introduction of sextupoles in final focus systems leads to the presence of additional optical aberrations, and synchrotron radiation in the dipoles also enlarges the final spot size. The important fourth-order optical aberrations which determine the main features of the design[4] have been identified. Additional lower order aberrations arise in the implementation of these designs, since the real system is not the ideal design. We concentrate on these aberrations and describe strategies for their diagnosis and correction.

2. STABILITY TOLERANCES

In addition to steering correction at the focal point (FP) there are 14 important low-order aberrations that arise as the real machine departs slightly from the ideal system. Five of these affect only the horizontal motion and the other nine affect the vertical motion. These aberrations (Table 1) result from changes in quadrupole and sextupole alignment, changes in strength or tilt of any element, or changes in incoming-beam conditions. In Table 2 we present the most demanding of these stability tolerances, beginning at the FP and proceeding upstream. We have chosen 2% spot size increase as a criterion to specify the magnitude of the tolerances because the best aberration tuning at the SLC is accurate to about 2% and we would

Table 1. Low-order aberrations and global correctors

Time scale	Generator	Cause of luminosity loss	No of knobs	Knob name (corrector)
τ_0	x', y'	Horiz/vert. steering	2 at FQ	Dipole
τ_1	$x'\delta, y'\delta$	Dispersion	2	Dipole in FT
τ_2	x'^2, y'^2	Waist motion	2	FD trims
	$x'y'$	Coupling	1	Skew Q in FT
τ_3	$x'^2\delta, y'^2\delta$	Chromaticity	2	Main sext
	$x'^3, x'y'^2$	Sextupole	2	Sext in FT
	y'^3, x'^2y'	Skew sext.	2	Sk sext in FT
??	$xx', x'^2,$ $yy', y'^2,$ $x'\delta, y'\delta$	β and α mismatch	6	Quads in BM
		Incoming dispersion		
??	$xy', x'y'$	Incoming coupling	2	Skew Qs in BM

Table 2. Important FFTB stability tolerance

Sect	Elem	Tolerance	Attribute	Aberration	Time
FD	Quads	$0.2\,\mu$	Δx	Steering	τ_0
		12 nm	Δy	Steering	τ_0
		$50\,\mu$	Δx	Disp	τ_1
		$4.7\,\mu$	Δy	Disp	τ_1
		$16\,\mu$rad	Tilt	Skew Q	τ_2
		2×10^{-5}	$\Delta k_Q/k_Q$	Nor Q	τ_3
		1×10^{-4}	Bs/Bq at .7a	N/Sk sext	
FT	Mid Q	$1.5\,\mu$	Δx	Disp	τ_1
		$1.2\,\mu$	Δy	Disp	τ_1
CCY	Sext	$0.9\,\mu$	Δx	Nor Q	τ_2
		$1.4\,\mu$	Δy	Skew Q	τ_2
		3×10^{-3}	$\Delta k_S/k_S$	Sext	τ_3
		2 mrad	Tilt	Sk sext	
	End Q	2×10^{-4}	$\Delta k_Q/k_Q$	Nor Q	τ_3
		1 mrad	Tilt	Skew Q	τ_2
	Ctr Q	$1.0\,\mu$	Δx	Nor Q	τ_2
		$0.3\,\mu$	Δy	Skew Q	τ_2
	Dipole	1×10^{-5}	$\Delta k_B/k_B$	Nor Q	τ_2
BX	Mid Q	$4\,\mu$	Δy	Disp	τ_1
CCX	Sext	$3.5\,\mu$	Δx	Nor Q	τ_2
		$3.5\,\mu$	Δy	Skew quad	τ_2
	End Qs	$.6\times10^{-3}$	$\Delta k_Q/k_Q$	Nor Q	τ_3
		.3 mrad	Tilt	Skew quad	τ_2
	Ctr Q	$.7\,\mu$	Δx	Nor Q	τ_2
		$4.0\,\mu$	Δy	Skew Q	τ_2
	Dipole	2×10^{-5}	$\Delta k_B/k_B$	Nor Q	

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Table 3. Accuracy of beam-based quadrupole alignment procedure.◇

Segment	Section	Element	Horizontal		Vertical	
			Tol	Sen	Tol	Sen
1	BM	Q5	110	.74	4.5	.04
		QA1	60	.42	20	.30
2	CCX	QN2	2.9	1.7	2.0	.36
		QN1	.7	.57	4.0	.63
3	BX	QT2	10	2.5	4.4	.53
		QT3	1.3	.55	30	1.9
	CCY	QM1	.65	.75	1.2	2.1
		QM2	1.1	1.3	.31	.81
4		QM1	.65	.73	1.1	2.6
	FT	QM1	1.3	.53	2.0	2.1
		QC5	4.4	.9	1.2	1.0
5	FD	QC2	15	1.5	4.8	6.8
		QC1	44	3.6	5.5	4.9

◇Tolerances (Tol) and sensitivites (Sen) are in microns

be pleased to achieve the same. Since seven of the nine aberrations affecting beam height must ultimately be tuned by observation of the final spot height, a 2% increase from each would result in a spot size about 14% larger than the design. This lies within our objectives for the absolute accuracy of the final spot size measurement.

3. GLOBAL CORRECTORS

If the system is aligned and tuned within a set of tolerances which we refer to as "capture" tolerances, the aberrations of Table 1 are the only aberrations of significance, and each aberration can be corrected by compensation with a global corrector. There are global correctors in the FFTB line for all of these aberrations. In order to use them, we must (a) tune the system to within the capture tolerances, (b) measure the final spot size with sufficient accuracy to carry out the tuning, and (c) maintain the stability of the system during a complete tuning process.

4. BEAM-BASED TUNING AND ALIGNMENT STRATEGIES

4.1 Quadrupole alignment

Every quadrupole and sextupole in the FFTB is mounted on a remotely-controlled magnet mover capable of horizontal and vertical motion in steps of $1\,\mu$ and tilt about the beam line in steps of $50\,\mu rad$. Initially quadrupoles and sextupoles will be located horizontally and vertically to an accuracy of $30\,\mu$ using a laser tracker survey system. These survey specifications were chosen to be smaller than the "capture" tolerances. Wires mounted above the beamline along each straight line segment will be capable of detecting small horizontal or vertical displacements with resolution[5] $\leq 2\,\mu$ and will be used to monitor changes in magnet location.

It is also possible to align the quadrupoles by individually varying the strength of each quadrupole, starting at the input end of the line and attempting to detect any change in the downstream trajectory. Each quadrupole contains a beam position monitor (BPM) within its bore which will have, on a single beam pulse, a measurement precision of 2 to $4\,\mu$, depending on beam intensity. All BPM readings will be available on each pulse to reconstruct the trajectory of the bunch within the system. We are expecting that an average of ten beam trajectories will yield an accuracy of $1\,\mu$ in beam trajectory determination. Table 3 indicates the accuracy of alignment achievable for each quadrupole assuming $1\,\mu$ beam position determination.

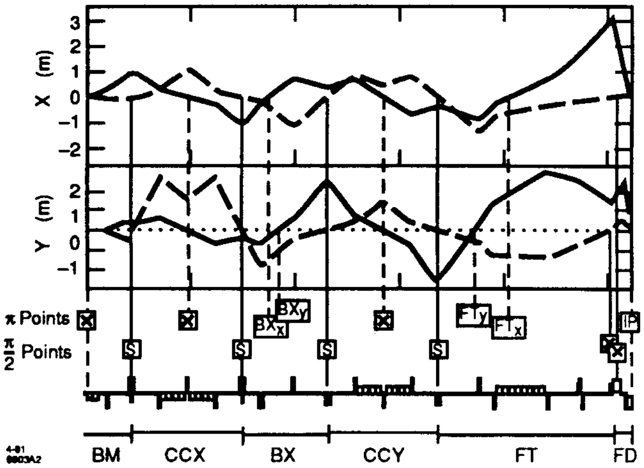

Figure 2.

Table 4. Beam-based quadrupole tuning procedure accuracy.

Section	Element	$\delta k/k \times 10^{-4}$	
		Tolerance	Sensitivity
CCX	End quads	3.3	2.5
	Mid quads	12	6.2
	Central quad	210	.6
BX	End quads	2	1.5
	QT2	15	.6
	QT3	5.1	1.5
CCY	End quads	0.9	.6
	Mid quads	6.7	2.9
	Central quad	270	2.7

4.2 Quadrupole tuning

Quadrupole strength settings may be checked by creating orbit bumps within the final focus system and studying the beam trajectory. The block structure of the system (-I for the CCX and CCY, magnifiers for BX and properly chosen sections of the FT) greatly enhances and simplifies this procedure. Six vertical and six horizontal dipoles are located within the system for the purpose of creating and terminating bumps to optimize the strength determination for each quadrupole, while maintaining a 8 σ clearance of the orbit from the beampipe. Unoptimized versions of these bumps are shown in Fig. 2. Table 4 shows the accuracy of quadrupole strength determination, assuming a beam position determination of 1 μ.

4.3 Sextupole pair alignment and tuning

If one of the sextupoles in a pair moves, or if a quadrupole in the -I between sextupoles moves, a normal quad, skew quad, or dispersion aberration may be created. To check the sextupole alignment a bump is created $\pi/2$ upstream of the first sextupole and beam position is

Table 5. Accuracy of sextupole alignment procedure.

Section	H or V	Tolerance	Sensitivity
CCX	H	3.5 μ	1.4 μ
	V	3.5 μ	2.9 μ
CCY	H	0.9 μ	0.9 μ
	V	1.4 μ	0.8 μ

studied $\pi/2$ downstream of the second sextupole, with and without the sextupoles turned on. For a horizontal bump in the CCX, a change in the horizontal position indicates a horizontal misalignment of the sextupoles. A change in the vertical position indicates a vertical misalignment of the sextupoles. A vertical bump is used for the study of the alignment of the CCY. See Table 5.

4.4 Stability of CCX, CCY, and final doublet

Although the normal quad, skew quad, and dispersion aberration must be tuned using the final spot size, the beam position can be monitored within the final focus system to assure that the system has not changed. If the relative position in the sextupole pairs, and the position in the final doublet relative to the last sextupole of the CCY remains stable to 1 μ, the normal and skew quadrupole aberration from the sextupoles, and the dispersion arising from the final doublet will remain acceptably constant. By introducing feedback to hold the beam constant at these locations the most sensitive aberrations can be stabilized for at least the stability time of the BPM readings, estimated to be many minutes. This stability time is referred to as τ_1 in Tables 1 and 2. Occasionally a series of pulses can be "bumped" through the CCX or CCY as described above, to actively monitor the alignment of those subsystems. Thus, the stability of the CCX and CCY should be assured for even longer times, τ_2. It is hoped these methods will insure the stability of the system for a sufficient time to tune the system—and to retune it, as necessary—with the global correctors. The τ_3 refers to the stability time characteristic of power supplies, and should be considerably longer than τ_1 and τ_2. The τ_0 refers to the typical time needed for steering correction. If the beam position can be determined on each pulse, this time will correspond to the passage of about 15 pulses.

5. TUNING THE INCOMING BEAM

5.1 Alpha and beta matching

The incoming beam is initially matched to the final focus system by using a special configuration of quadrupole strengths in the beta match (BM) section, and sweeping a quadrupole strength as the beam size is measured. In this way, the incoming beta and alpha are determined, . and the beta match section can be set accordingly.

These settings of the beta match can be confirmed by sweeping the quadrupoles at each end of the CCX section in unison, and observing the beam at the BXx and BXy beta minimum points noted in Figure 2. To study these points, listed in Table 6, the sextupoles must be set to eliminate the effect of chromaticity at these points.

Table 6. Beam sizes at minima within the FFTB.

Location	BXx	BXy	FTy
σ_x	3 μ	330 μ	780 μ
σ_y	95 μ	0.9 μ	0.44 μ

5.2 Incoming dispersion

If the CCX sextupoles are moved antisymmetrically ($\Delta x_1 = -\Delta x_2$), then they remain at -I with respect to one another, but dispersion is introduced. By minimizing spot sizes, while either moving the sextupoles or changing incoming dispersion knobs upstream of the final focus system, dispersion at the beta minimum points in BX can be eliminated. In the CCX, an antisymmetric horizontal (vertical) motion of ±6.5 μ corresponds to a change of spot width (height) of 2% at BXx (BXy). In the CCY, an antisymmetric vertical motion of ±2.7μ corresponds to a change of spot height of 2% at FTy.

5.3 Incoming coupling

Incoming coupling can be characterized by four parameters. Three independent parameters can effect the spot size at the FP; however, only two of these can effect the vertical spot size. Because vertical emittance is a factor of ten less than the horizontal emittance, the incoming coupling, known to be about 10% cannot alter the horizontal beam size. These two parameters can be chosen so that one of them rotates the spot, and the other increases the height without affecting the orientation.

If one observes the spot at the points in Figure 2 labeled FTy or BXy, these same two parameters come into play, but are reversed in role: the parameter that affects only beam height at the FP affects only spot orientation at FTy and BXy. Thus, one can use the intermediate spots at FTy and BXy to observe and correct incoming coupling, or identify any coupling that has been introduced before these spots.

6. CONCLUSIONS

We have presented strategies for tuning and correcting aberrations that arise as the real FFTB lattice departs from the design lattice. The situation is similar for next generation final focus systems, except that tolerances scale with the beam size and are much tighter. [6] The required precision of the BPMs will be in the range of tenths of microns. With such an instrument, it appears that the next generation colliders can be aligned and tuned, using the procedures we have described here.

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