FINAL FOCUS SYSTEMS FOR LINEAR COLLIDERS*

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Abstract

Final focus systems for linear colliders present many exacting challenges in beam optics, component design, and beam quality. Efforts to resolve these problems as they relate to a new generation of linear colliders are under way at several laboratories around the world. We will outline criteria for final focus systems and discuss the current state of understanding and resolution of the outstanding problems. We will discuss tolerances on alignment, field quality and stability for optical elements, and the implications for beam parameters such as emittance, energy spread, bunch length, and stability in position and energy. Beam-based correction procedures, which in principle can alleviate many of the tolerances, will be desribed. Preliminary results from the Final Focus Test Beam (FFTB) under construction at SLAC will be given. Finally, we mention conclusions from operating experience at the Stanford Linear Collider (SLC).

Introduction

Some laboratories which host major research and development efforts on the next generation of linear colliders are listed in Table 1. Innovative work on Final Focus systems has come especially from DESY and KEK.

TABLE 1
Centers of Linear Collider Activity

Location	Projects
CERN	CLIC
DESY/Darmstadt	DLC
KEK	JLC, ATF
Novosibirsk	Theory, R & D
Protovino	VLEPP
SLAC	SLC, FFTB, NLC, NLCTA

The function of the Final Focus system is to match the incoming beam, with β functions of a few meters, to the Interaction Point where betas will be in the millimeter or submillimeter range. Table 2 lists IP and beam parameters for several FF designs. To attain the required small beam sizes, the system must suppress beam size growth from effects such as optical aberrations, synchrotron excitation and wakefields. We must also consider factors such as the severity of tolerances and the need for workable tuning procedures in the presence of errors.

Optics Problems in Final Focus Design

Chromaticity

Source and Remedy. Second order chromatic aberrations arise predominantly from the final quadrupoles.

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TABLE 2
Typical Beam and Interaction Point Parameters

Parameter (Units)	FFTB	NLC	VLEPP	DLC	JLC
Energy/beam (GeV)	50	250	250	250	250
Luminosity ($10^{33}\,cm^{-2}\,s^{-1}$)	n/a	9	12	4	9.7
$e^{\pm}$/bunch (10^{10})	≤ 1	0.65	20	2.1	1.1
Bunches/pulse	1	90	1	172	72
Repetition rate (Hz)	10	180	300	50	150
Rf frequency (GHz)	2.856	11.4	14	3.0	5.7
Bunch length (mm)	2	0.10	0.75	0.5	0.08
Emittance					
$\gamma\epsilon_x$ (μm)	30	5.0	20	5.0	3.6
$\gamma\epsilon_y$ (μm)	3	0.05	0.075	0.5	0.05
β_x^* (mm)	3.0	10	100.0	16	10.0
β_y^* (mm)	0.1	0.1	0.1	1	0.1
σ_x^* (nm)	1000	300	2000	400	280
σ_y^* (nm)	60	3	4	32	3.5
l^* (m)	0.4	1.5			2.2
Passband (%)	±0.4	±0.4	±1.8	±1.8	±1.2
Crossing angle (mr)	n/a	7.2	0	2	8

In thin-lens approximation, focal length is proportional to energy, which spreads the beam by $\Delta y^* \simeq f y'^* \delta$. We then find that $\frac{\Delta\sigma_y^*}{\sigma_y^*} = \frac{f}{\beta_y^*}\delta = \xi_y \delta$, where ξ is the **chromaticity**. If $f \simeq l^* \simeq 2m$ and $\beta_y^* \simeq 10^{-4}m$, the passband would be $|\delta| \ll \beta_y^*/l^* \simeq 0.5 \times 10^{-4}$. Clearly this is an unreasonable demand on energy spectrum and stability from the linac.

The well-known fix for chromaticity is to place sextupoles at locations where there is dispersion and a large β, and which is in phase (modulo π) with the final quadrupoles. This introduces a nonlinear kick which transforms to the IP as $\Delta y^* \propto K_2 \eta_x \beta_y \beta_y^* y'^* \delta$. Appropriate choice of sextupole strength K_2 then cancels the chromatic effect of the high-β quadrupoles. Geometric sextupole aberrations are cancelled by using pairs of sextupoles separated by $-\mathbf{I}$ transformations [1].

"Generic" FF System. Figure 1 illustrates the essential elements of a Final Focus. The horizontal and vertical chromatic corrections are in separate modules which are matched together by the "β-exchange" transformer. Early designs (such as SLC) combined the horizontal and vertical functions in a single module with the two sextupole families *interleaved.* In this case, the the nonlinear kick from a given sextupole excites higher order aberrations cumulatively in succeeding sextupoles which do not have the $-\mathbf{I}$ relation. The *non-interleaved* design avoids this problem.

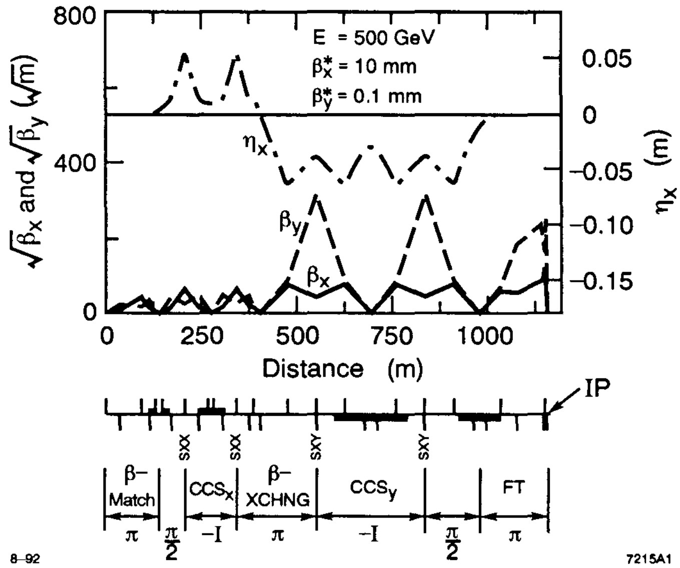

Fig. 1. Optics of a "Generic" Final Focus System.

Higher Order Aberrations

After the second-order chromatics are corrected as described above, the energy passband is still limited by higher order chromatic terms; also several geometric aberrations remain.

Dispersion. The second- and third-order dispersion coefficients can be minimized by employing certain cancellations among the driving terms [2] (*i.e.*, the dipole magnets). Other approaches involving more complicated optics will be discussed later.

Third-Order Chromatics. K. Brown [3] has shown that the dominant third-order chromatic terms may be corrected by detuning the lattice to introduce non-zero values of the R_{22} and R_{44} in the $(n+\frac{1}{2})\pi$ transformation from the sextupoles to the IP. (In first order these matrix elements affect only the divergence, not the beam size, at the IP.) These terms couple with the second-order chromaticity of the Final Transformer to affect the third-order aberrations and allow them to be nulled.

Long Sextupole Effect. In a sextupole of finite length the second order kick cumulatively drives higher order terms over the length of the sextupole. The perturbation is given by [4,5] $\Delta\sigma_y^{*2}/\sigma_y^{*2} \propto K_2^4 l_S^2 \epsilon_y^2 \beta_y^4$. If the length is minimized by using maximum pole-tip field and minimum aperture, we can write $\Delta\sigma_y^{*2}/\sigma_y^{*2} \propto \Delta^4 \xi_y^6 (\gamma\epsilon_y)^2 (\eta\beta_y)^{-2}$ where Δ is bandwidth. That is, suppression of the effect requires large dispersion or β_y at the sextupoles.

Breakdown of the −I Transformation. Because of chromaticity within the CCS the cancellation of the sextupole nonlinearity is not perfect for off-energy particles. This excites the so-called *chromo-geometric* aberration which has been roughly estimated [6] to be of the form $\frac{\Delta\sigma_y^{*2}}{\sigma_y^{*2}} \propto \frac{\xi_x \xi_y^2 \epsilon_x \delta^4}{\gamma\theta^2 l_b}$ ($\xi_{x,y}$ = chromaticities; θ = bend angle; l_b = length of bend).

Quadrupoles at "Wrong" Phase. Chromaticity generated by quadrupoles which are not $n\pi$ from the sextupoles is not cancelled. The out-of-phase chromaticity does not affect the spot size directly, but can generate higher order cross terms with other nonlinearities. For example, Oide [8] has estimated that the effect of the quadrupoles near the beginning of the final telescope is $\frac{\Delta\sigma_y^{*2}}{\sigma_y^{*2}} \simeq \xi_y \frac{\beta_y^* L^2}{\beta_S l^{*2}} \delta^6$ (L = distance from sextupole to final doublet).

Synchrotron Radiation Effects.

Energy Excitation by Dipoles. If a particle suffers a random energy shift within or after the CCS it is no longer chromatically corrected. The excitation by the dipoles is [9] $\sigma_\delta^2 = \sum 4.13 \times 10^{-11} E^5 |\theta_B|^3 / l_B^2$. ($\theta_B$ =bend angle per dipole; l_B =dipole length; E is in GeV). This energy spread must be small compared to the passband set by uncorrected chromaticity, which we have seen to be on the order of 10^{-4}. The bending angle θ_B is needed to generate the dispersion required for chromatic correction; thus the dipoles must be made longer at higher energies. Above about 500 GeV the dipoles begin to set the length scale of the CCS.

Energy Excitation by Quadupoles. This effect is rather small except in the final quadrupoles. In this case the energy spread induced in the quadrupoles increases the spot size because of the chromatic effect of the quadrupoles themselves [10] (the "Oide effect"). It depends most strongly on the normalized emittance of the beam, and also limits the use of extremely high gradients in the final quadrupoles.

Orbit errors in quadrupoles also cause synchrotron radiation. This somewhat limits the size of orbit offset which can be used to control dispersion (see **Dispersion Control**, below).

Excitation of Transverse Emittance. Transverse excitation depends on integrals over the bend magnets involving the term $H(s)E^2|B|^3$, where Sands' "curly H" function [9] is $H(s) = \left(\eta^2 + (\beta_x\eta' + \alpha_x\eta)^2\right)/\beta_x$. This effect becomes small once the dipole fields have been reduced as required by the energy excitation (see above).

Resistive Wall Wakefields

Reactive wakefields can be reduced by using smoothly tapered transitions in the vacuum chamber radius. However, transverse resistive wall wakefields may be serious in the final quadrupoles. A result by Yokoya [11] may be written $\frac{\Delta\sigma_y^*}{\sigma_y^*} \propto \frac{NL}{\gamma\epsilon_y}\left(\frac{\lambda}{\sigma_z}\right)^{\frac{1}{2}}\frac{\Delta\hat{y}}{\hat{\sigma}_y}\frac{1}{an^2}$. ($N$ = particles/bunch, L = quad length, $\lambda = 1/(Z_0\sigma)$ = penetration depth, $\Delta\hat{y}$ = beam offset at quad, $\hat{\sigma}_y$ = beam size at quad, a = radial aperture, and $n = a/\hat{\sigma}_y$.) If we allow $\Delta\hat{y}$ to be equal to $\hat{\sigma}_y$, this sets a lower limit on aperture requirement, which turns out to be 20 to 40 $\hat{\sigma}_y$ in typical designs–somewhat larger than the 10σ or so needed for beam clearance. The increased aperture penalizes the chromaticity (and passband) but eases IP masking problems and the collimation requirements. Gold plating the quadrupole surfaces reduces the effect by about a factor of two (compared to steel).

Wakefields generally are unimportant in all the quadrupoles except the final doublet. They do need to be considered in the sextupoles which as we have seen should be short, and therefore of small aperture.

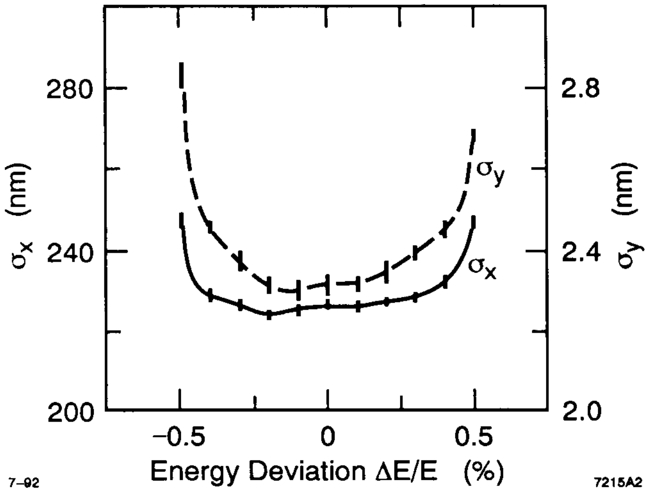

Fig. 2. Energy passband of the "Generic" Final Focus System.

Typical Optics Designs

Generic Final Focus System.

This design (Fig. 1) is used here for illustrative purposes. The various functions are separated into telescopic modules. Chromatic correction to third order has been effected as described above, and the β-exchange telescope is configured to minimize second- and third-order dispersion. Spot size growth has been held to $< 1\%$ from long sextupole effect and $\sim 3\%$ from synchrotron excitation. The apertures of the final quadrupoles have been chosen such that a one-σ jitter in vertical beam position enlarges σ_y^* by no more than 2%. The energy passband (Fig. 2), limited by uncorrected high order aberrations, is $\sim\pm0.4\%$.

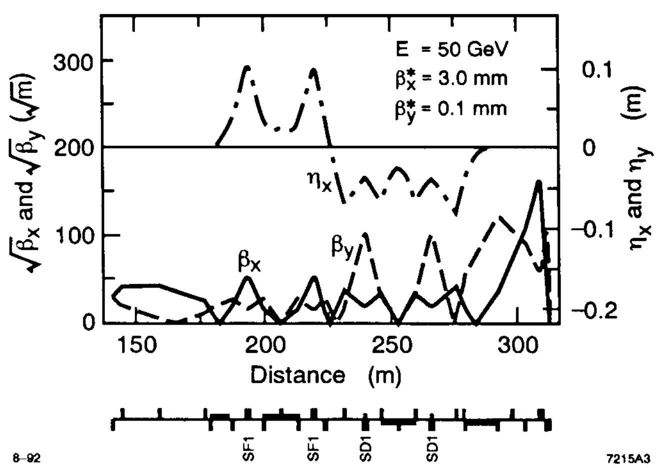

Fig. 3. Optics of the Final Focus Test Beam.

Final Focus Test Beam.

The FFTB [4,12] (Fig. 3) is being built by a collaboration between SLAC, KEK, Novosibirsk, and Orsay, to study problems related to the next generation of colliders, such as instrumention, operation, and tuning procedures. Note in Table 2 that the invariant emittances available at SLAC are considerably larger than the design values for future systems; however the β^*s and l^* are comparable.

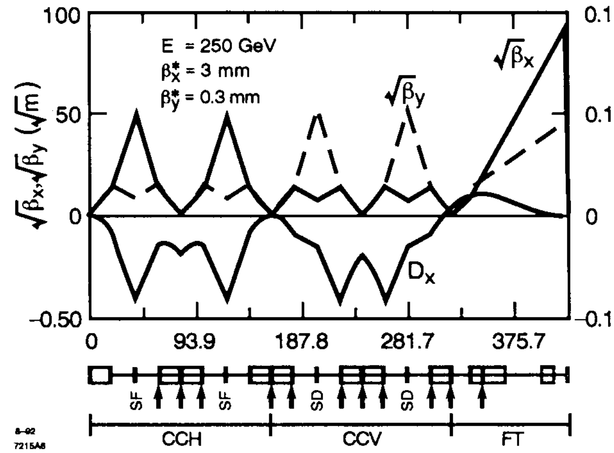

Fig. 4. Optics of the DLC Final Focus. The arrows show location of the added sextupoles.

In the FFTB design the functions of β- and η-matching have been combined in the β-match and in the final telescope, which saves considerable length. Chromatic correction is to third order. The passband is $\sim\pm0.4\%$.

DLC (DESY) Final Focus.

R. Brinkmann [13] has developed a wide passband lattice by using numerous additional sextupoles (Fig. 4). The sextupole srengths are found by a variational method based on computer tracking of selected rays. High order chromatic and dispersion terms are suppressed and also the geometric terms from the interleaved sextupoles are controlled. The passband (Fig. 5) is $\sim\pm1.8\%$.

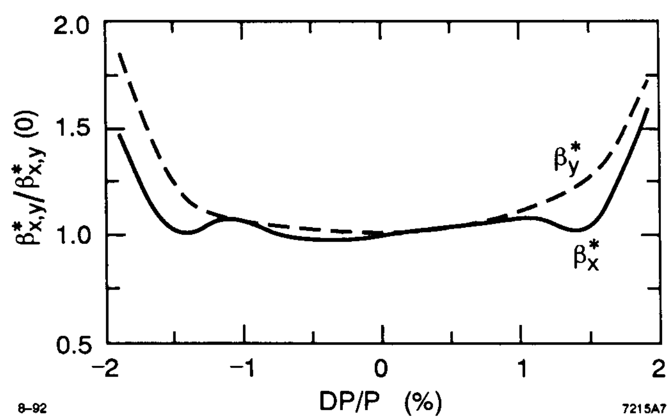

Fig. 5. Energy passband of the DLC Final Focus.

JLC (KEK) Final Focus.

K. Oide [7] has produced a design (Fig. 6) which uses carefully tailored unsymmetrical dispersion and β functions to effectively cancel the chromo-geometric aberration. A passband of $\sim\pm1.2\%$ was obtained without need for additional nonlinear elements.

The Traveling Focus Idea (VLEPP)

The VLEPP group [14] has proposed a novel scheme in which the focal points of the e^+ and e^- beams are moved back from the nominal IP during the course of the collision, in a way which keeps the incoming beam

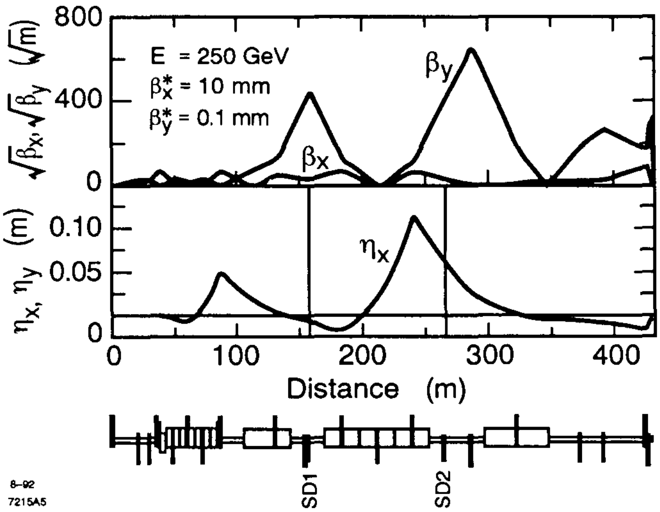

Fig. 6. Optics of the JLC Final Focus.

TABLE 3
Error Aberrations to Third Order in Hamiltonian

Error Type	Source	Hamiltonian Generator	Cause of Luminosity Loss
Dipole	Incoming beam Quad misalign Dipole errors	x', y'	$\Delta x^*, \Delta y^*$
Dispersion	Incoming beam Orbit in quads η-match quad err Dipole roll	$x'\delta, y'\delta$	$\eta^*\delta$
Normal quad	Incoming α Quad errors H orbit in sexts	x'^2, y'^2	Waist motion Δl^*
Normal quad	Incoming β Multiquad err	xx', yy'	Linear σ^*
Skew quad	Incoming beam Quad roll V orbit in sexts	$x'y'$	$x'^* \to \sigma_y^*$
Skew quad	Incoming beam Multiquad roll	xy'	Beam tilt
Sextupole	Sext err in FD Uneq CCS sexts Err in CCS $-$I	$x'^3, x'y'^2$	Nonlin $\sigma^*_{x,y}$
Skew sextupole	Sext err in FD Sext roll in CCS	$x'y'^2, y'^3$	Nonlin $\sigma^*_{x,y}$

envelopes matched to the pinched interacting beams. Simulations predict that disruption is suppressed and instabilities do not set in until the bunches have nearly passed. Luminosity enhancement factors of 5 or so are predicted, allowing more conservative machine design.

TABLE 4
Worst Case Tolerances in FFTB Lattice

	Final Quads		Other Quads		Sextupoles	
Quantity	Gen.	Tol.	Gen.	Tol.	Gen.	Tol.
Δx [μm] Δy [μm]	$x'\delta$ y'	0.2 0.06	x' y'	.75 .18	x'^2, y'^2 $x'y'$	0.9 1.4
$\Delta k/k$ [10^{-5}]	x'^2, y'^2	2.0	x'^2, y'^2	7.3	$x'y'^2$	52
$\Delta\theta$ [μr]	$x'y'$	33	$x'y'$	40	x'^3, x'^2y'	700

The traveling focus is obtained by introducing corelation between energy and position within the bunch, and providing appropriate chromaticity in the FF system. The energy spread (and passband) needs to be $\sim 1\%$, which is provided *e.g.* by the DESY FF design.

The Imperfect Machine

Errors and Tolerances

Summary of Effects. In a real machine performance is degraded by errors and imperfections. Table 3 summarizes effects of the dominant errors [12]. Table 4 gives some of the worst-case tolerances for the FFTB [15].

Uncorrectable Errors. Absolute tolerances are imposed on errors which are not amenable to on-line correction or are on too short a time scale to be stablized by feedback: (1) Pulse-to-pulse jitter in position and energy and intra-pulse wakefield distortion of the incoming beam. Here we rely on the skills of Linac builders. (2) Short-term noise and drift in power supplies. The stated tolerance of $\sim 10^{-5}$ needs to be maintained on a time scale of hours. This should be possible with standard technology. (3) Position jitter in the quadrupoles and sextupoles. Seismic monitoring at SLAC and KEK indicate that ground motion is generally within tolerance if stable support structures and efficient mechanical isolation are used. Active stabilization of the final doublet may be required. (4) Noise and resolution of Beam Position Monitors (BPM)s. The requirement for FFTB is about $1\mu m$ and will be about an order of magnitude smaller for the next generation.

Correction Procedure

Tolerances (Table 4) which are too small to be achieved by conventional construction and alignment techniques require a correction strategy which relies on beam-derived information. Several tuning schemes are described in the literature [15]. The basic steps of such a procedure, after initial beam launch and β-matching, include first a series of local trajectory and lattice corrections, then a series of local corrections of beam parameters, and finally a series of global corrections based on optimizition of the final spot (or luminosity).

Preliminary. The system is first aligned mechanically with laser-based surveying techniques. The precision is expected to be on the order of 100 μm.

Launch. Initial beam steering is stablized by means of feedback. Tolerance on position and angle is $< 1\sigma$ on a time scale of hours and $< 0.2\sigma$ on a time scale of minutes.

Matching the Incoming Beam. The betas, alphas and emittance of the beam will be measured by the method of varying a quadrupole to scan a beam waist across a profile monitor (*e.g.*, a wire scanner). A model-driven correction of the β-matching telescope can then be made.

Beam Based Quadrupole Alignment. Varying the strength of a quadrupole drives an orbit shift at downbeam BPMs proportional to the offset between the beam and the quadrupole magnetic center. One can then use magnet movers and steering correctors to align the quadrupoles and beam along a prescribed trajectory. Analysis shows that the precision of this method (limited by BPM sensitivity) is within tolerance for most of the elements in FFTB.

Quadrupole Tuning, Coupling, and Sextupole Alignment. Orbit shifts produced by selected steering correctors can be analyzed to localize quadrupole errors. Phase and magnification errors in the CCS $-\mathbf{I}$ and other π telescopes are corrected by trimming quadrupoles within the telescope. Coupling from quadrupole rotation error (*e.g.*, vertical orbit from horizontal kick) is corrected by skew quadrupole correctors. Sextupole misalignments in the horizontal or vertical produce normal or skew quadrupole errors which may be corrected either by sextupole movers or by appropriate beam bumps through the sextupole pair.

Dispersion Control. Dispersion comes from the incoming beam, from beam offsets in strong chromatic sources such as quadrupoles, and from roll in dipoles. It can be measured by analyzing orbit shifts induced by an energy change in the linac and corrected by using closed-orbit bumps at appropriate quadrupoles. In first order we only need correct dispersion in the IP phase.

Incoming Coupling. Skew quadrupole correctors in the β-match telescope are used to cancel incoming coupling, by minimizing σ_y and beam tilt at profile monitors in IP phase.

Local β Matching. The beam envelopes may be checked at intermediate profile monitors such as in the β-exchange or at the beginning of the final telescope, in order to confirm that the initial matching and lattice corrections are satisfactory.

Global Corrections. Global corrections are provided by controls ("multiknobs") which vary several correcting elements simultaneously to provide nearly orthogonal control over individual aberrations. Use of these controls is directed by monitoring position, spot size, and/or luminosity at the IP. Some examples of global corrections are: beam position, dispersion, normal and skew quadrupole and sextupole effects, and initial beam matching. These corrections not only provide the final step in optimizing the IP beam spot, but also should greatly extend the time scale for major retuning.

Experience with Existing FF Systems

Preliminary Experience with FFTB

Installation of the FFTB is on schedule and commissioning is expected to begin in April, 1993. Preliminary beam tests and hardware checkout have been done with the first few installed magnets. Magnet movers are found to operate over the design range of $\pm 1mm$ with a precision of $\sim 0.3\mu m$. Resolution of the standard BPMs is found to be $< 6\mu m$ (specification: $5\mu m$). Beam jitter is measured to be $\sim 0.2\sigma$ which is about tolerance and is consistant with results from SLC.

Lessons from SLC [16]

As the only existing linear collider, the SLC has proven to be an invaluable source of guidance–and encouragement. Some of the lessons for the next generation which have been learned at SLC: (1) The system should be readily tunable and the correctors should be highly orthogonal. (2) Diagnostics must be completely adequate in accuracy, type, and number. (3) Beam-based alignment will be necessary. (4) As many systems and corrections as possible should be stabilized by feedback. (5) Every subsystem from the detector back to the gun (including the FF) is dependent on every preceding subsystem. Therefore the overall machine design should be global.

Summary and Conclusions

Satisfactory optical designs for Final Focus systems exist; further optimization is possible. The tolerances are difficult but seem to be possible. Correction procedures are reasonably well understood in theory and by extrapolation from SLC, and are expected to be enhanced by experience with FFTB.

Acknowledgments

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