DESIGN OF OPTICS FOR THE FINAL FOCUS TEST BEAM AT SLAC*

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INTRODUCTION

The goal of the Final Focus Test Beam experiment(FFTB) is to produce an electron beam spot of 1 μm by 60 nm in transverse dimensions. In the future linear collider of TeV region(TLC), a typical spot size of 100 nm by 1 nm at the interaction point is required to get luminosity of $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.[1] This spot size is about 1/1000 of that of the SLC in the vertical dimension, and is demanding for an optics design, alignments, beam diagnostics, and tuning procedures. The spot size of the FFTB will be an important next step from the SLC toward the TLC.

Beam Energy	E	50 GeV		
Horizontal Invariant Emittance	ε_{Nx}	3×10^{-5}m		
Horizontal Beta	β_x^*	2.5 mm		
Horizontal Spot Size	σ_x^*	1 μm		
Emittance Ratio	$\varepsilon_{Ny}/\varepsilon_{Nx}$	100 %	10 %	1 %
Vertical Beta	β_y^*	300 μm	100 μm	100 μm
Vertical Spot Size	σ_y^*	300 nm	60 nm	20 nm

Table 1. Parameters of the Final Focus Test Beam.

Table 1 shows several parameters of the FFTB. This beam line will be located at the end of the linac to use the 50 GeV electron beam. We show three cases of the vertical/horizontal emittance ratio: 100 %, 10 %, and 1 %. Although the TLC assumes 1 % emittance ratio, its realizability in the present machine is not clear yet, and further studies on the linac and the damping ring are necessary. Thus throughout the FFTB design, somewhat more conservative value, 10 %, is adopted as the design goal. We optimize the beam optics for this value. In fact, according to the recent simulation, 10 % emittance is realistic at the end of the linac with the design intensity, 1×10^{10} particles per bunch.[2]

Considering its future application to the TLC plan, we design the beam optics as follows; the beta functions and the pole-tip field of the final quadrupole are same as the TLC parameters. Previously a very flat beam, i.e., $\beta_x^*/\beta_y^* \geq 300$, was regarded as suitable for the TLC. Thus a method with single-family sextupole was sufficient to correct the chromaticity.[3] Recent studies, however, reveal that e^+e^- pair-productions during beam collision generate a huge amount of background.[4] In order to get out of the background, the 'crab-crossing' scheme is necessary. As a result, an optimum aspect ratio of the beta functions is reduced to less than 100,[5] and chromaticity corrections for both planes become inevitable. In this design we use a new chromaticity correction scheme with non-interlaced two-family sextupoles. The FFTB optics is an appropriate model for the final focus system of future colliders. The application of the results of the studies on beam diagnostics, alignments, and correction schemes to the TLC development is straightforward.

NON-INTERLACED SEXTUPOLE SCHEME

The chromaticity correction scheme adopted here uses two pairs of sextupoles, which cancel the chromatic effect of the final lens both in x and y planes. In general, when one makes the transformation $-I$ between two sextupoles in a family, the geometric aberration terms cancel up to the second order.[6] This remains true when two families of sextupoles are interlaced to each other as in the SLC final focus system.[7] While the interlaced scheme has an advantage to shorten the length of a system, it makes the third order geometric aberration larger.

Let us consider interlaced sextupoles, where each family S_1 and S_2 has $-I$ transformation between its two equivalent sextupoles. We consider that S_1 and S_2 are separated by a drift space of a length ℓ. For the time-being, we focus on a pure geometric effect without taking account of all chromatic effects and dispersions. The residual third order aberration consists of two parts; firstly, a particle passing the interlaced sextupole block receives a third order kick. According to a thin-lens calculation, the kick is written as

$$\begin{aligned}\Delta x_1' &= \frac{k_1'k_2'\ell}{2}\big[(x_1+x_2)(x_1x_2+y_1y_2)\\ &\qquad +(y_2-y_1)(x_1y_2-x_2y_1)\big]\\ \Delta y_1' &= \frac{k_1'k_2'\ell}{2}\big[(y_1+y_2)(x_1x_2+y_1y_2)\\ &\qquad -(x_2-x_1)(x_1y_2-x_2y_1)\big]\end{aligned}, \tag{1}$$

where k' is the strength of the sextupole, and the suffices 1 and 2 specify the sextupoles S_1 and S_2. Secondly, the finite thickness ℓ_S of the sextupoles also gives rise to a third order geometric term:[8]

$$\begin{aligned}\Delta x' &= \frac{k'^2\ell_S}{6}x(x^2+y^2)\\ \Delta y' &= \frac{k'^2\ell_S}{6}y(x^2+y^2)\end{aligned}. \tag{2}$$

In the interlaced scheme, (1) dominates (2), since $\ell \gg \ell_S$. Therefore this conventional scheme is very difficult to correct such a high chromaticity in this system. The non-interlaced scheme, in which the third order kick (1) is absent, is better for the present design.

There is an additional problem concerning the chromatic aberration; all chromatic elements in a final focus system must have the betatron phases from the final lens as close as possible to $N\pi$ (N: integer) to obtain a large momentum band width.[9] In interlaced schemes, it is impossible for both sextupoles to satisfy the condition simultaneously. In the non-interlaced scheme, on the contrary, all sextupoles can be arranged to meet the above requirement. This is another reason why the non-interlaced scheme is superior to the interlaced one.

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OPTIMIZATION OF THE SYSTEM

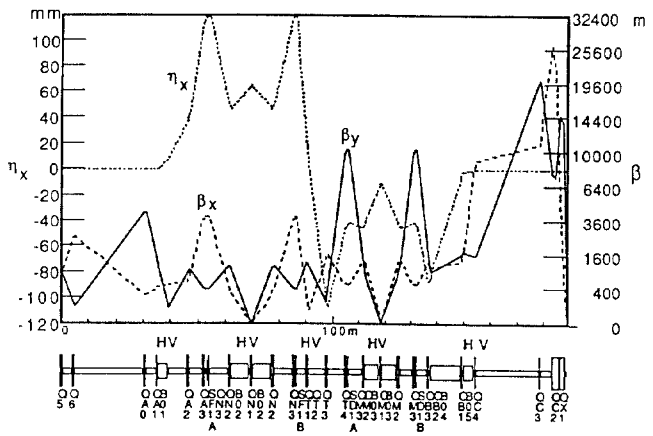

Fig. 1. The Optics of the Final Focus Test Beam. The initial of each element specifies the kind as B:bend, Q:quadrupole, and S:sextupole. The first four quadrupoles are used for a matching to the incoming beam. The beam line is bent +18 mrad by the first three bends, and bent back -27 mrad by the last four bends.

Figure 1 shows the present design of the FFTB. This system is optimized to focus a beam with 10 % emittance down to 1 μm by 60 nm in the given area of the SLAC experimental site. The FFTB project is not a collision experiment, so the bunch length can be larger than the vertical beta function. In order to reduce the chromaticity of the final lenses (therefore the total length of the system), the length of the experimental area ℓ^* should be as short as possible. Since the TLC may need $\ell^* \geq 1$ m, first we designed a system with $\ell^* = 1$ m. It turned out that the total length was longer than the available SLAC site. Therefore we set $\ell^* = 40$ cm for the present design, resulting in the length 40 m shorter. We note that the present result can be applied to the TLC, because the essential feature of the optics does not change.

The pole-tip field of the final quadrupole is chosen as 1.4 T, which is almost available with existing magnets.[10] The pole-tip field of other magnets are less than 1 T. We require that all magnets should have apertures 10 times larger than the transverse beam sizes. These conditions determine the geometry, the strength, and the chromaticity of the final doublet. In this design, the final quadrupole is 2 m long and has a half aperture of 12.7 mm. Then one can optimize the bending angle and the length of the bending magnets, which actually fix the total length of the system. In the present design the vertical chromaticity is dominant, thus the main characteristics of the system is determined by a minimization of the aberrations in the vertical focusing.

There are two major sources of the vertical aberration: geometric aberration from the thickness of the sextupoles and a blow-up of the final spot with the energy spread produced by the synchrotron radiation in the bends.[3] We assume that there are two bends between sextupoles and one before the final lens. These three bends have the same bending angle θ and the length ℓ_b, for simplicity. Note that the synchrotron radiation effect is important at the last bend after the sextupoles, and negligible for the bends before the sextupoles. Thus we obtain the relative increase of the final spot size as

$$\Delta^2 \equiv \frac{\Delta\sigma_y^{*2}}{\sigma_y^{*2}} = \frac{5}{12}\frac{k'^4\beta_y^4\varepsilon_{Ny}^2\ell_S^2}{\gamma^2} + \frac{55}{16\sqrt{3}} r_e\lambda_e\gamma^5\frac{\theta^3}{\ell_b^2}\xi_y^2, \qquad (3)$$

where the first term corresponds to the geometric one and the second the synchrotron radiation. In the first term, β_y is the vertical beta at the sextupole with a strength k'. On the derivation of the term from (2), we have neglected the contribution from the horizontal plane, because it is usually small at the vertical sextupole. In the second term of (3), r_e and λ_e are the classical electron radius and the Compton wavelength of electron, and ξ_y denotes the vertical chromaticity of the system. We require that the sextupole should have an aperture b times larger than the beam size, then its length is given by

$$\frac{B_0\ell_S}{B\rho} = \frac{k'\beta_y\varepsilon_{Ny}b^2}{2\gamma}, \qquad (4)$$

where B_0 is the pole-tip field of the sextupole. The strength of the sextupole and the chromaticity are related as

$$k'\beta_y = \xi_y/2\eta = \xi_y/2r\theta\ell_b, \qquad (5)$$

where η is the dispersion at the sextupole, which is proportional to $\theta\ell_b$ with a coefficient r (=0.92 in our design). Substitution of (4) and (5) into (3) gives

$$\Delta^2 = \frac{5}{3072}\left(\frac{\hbar}{eB_0}\right)^2 \frac{\varepsilon_{Ny}^4\xi_y^6 b^4}{\lambda_e^2\gamma^2 r^6\theta^6\ell_b^6} + \frac{55}{16\sqrt{3}} r_e\lambda_e\gamma^5\frac{\theta^3}{\ell_b^2}\xi_y^2. \qquad (6)$$

The aberration is minimized at the bending angle

$$\theta_0 = \left[\frac{1}{352\sqrt{3}}\left(\frac{\hbar}{eB_0}\right)^2 \frac{\varepsilon_{Ny}^4\xi_y^4 b^4}{r_e\lambda_e^3\gamma^7 r^6\ell_b^4}\right]^{1/9}. \qquad (7)$$

Therefore the minimum aberration is obtained by substituting (7) to (6):

$$\Delta_0^2 = \frac{165}{64}\left[\frac{1}{396}\left(\frac{\hbar}{eB_0}\right)^2 \frac{r_e^2\gamma^8\varepsilon_{Ny}^4\xi_y^{10}b^4}{r^6\ell_b^{10}}\right]^{1/3}. \qquad (8)$$

For a given value of Δ_0, ℓ_b is determined by (8)as

$$\ell_b = \frac{\xi_y}{4}\left[55\sqrt{15}\left(\frac{\hbar}{eB_0}\right)\frac{r_e\gamma^4\varepsilon_{Ny}^2 b^2}{\Delta_0^3 r^3}\right]^{1/5}. \qquad (9)$$

Using this ℓ_b, we obtain the bending angle from (7) as

$$\theta_0 = \left(\frac{8}{11\sqrt{3}}\right)^{1/9}\left[\left(\frac{1}{45375}\right)^{2/3}\left(\frac{\hbar}{eB_0}\right)^2\frac{\varepsilon_{Ny}^4\Delta_0^4 b^4}{r_e^3\lambda_e^5\gamma^{17}r^6}\right]^{1/15}. \qquad (10)$$

Note that the bending angle does not depend on the chromaticity, whereas the length of the bend is proportional to the chromaticity. The bending angle is almost proportional to $1/\gamma$.

The optimum values become $\ell_b = 5.5$ m and $\theta_0 = 7.8$ mrad for the FFTB parameters of the 10 % emittance case with $\xi_y = 20000$, $\Delta_0 = 0.45$, $B_0 = 1$ T, and $b = 18$. Actually our design has $\ell_b = 5.5$ m and $\theta_0 = 8.0$ mrad, which are very close to the optimum values. A similar optimization was done in the horizontal plane, where we included the emittance growth in the bends.

TOLERANCES AND TUNING METHODS

We examined tolerances for four kinds of jitters of the quadrupoles in this system. Firstly, a displacement of each quadrupole typically 0.5 μm in vertical or 5 μm in horizontal shifts the final spot by a amount enough to reduce the luminosity $1/\sqrt{2}$. A displacement of 5 μm in vertical or 10 μm in horizontal creates a dispersion at the final focus, and makes the spot size $\sqrt{2}$ times larger than the design. About 0.1 % of the strength error or 1 mrad of a skew angle error also increases the final spot size $\sqrt{2}$ times larger. These values assume that only one quadrupole has an error at one time, and all other components have the ideal values. The tolerances for the last three quadrupole are typically one order worse than the above values.

Another problem on the tolerance of the system is how large initial errors can be allowed and what is a suitable scheme of the compensation for these errors. Here we simulated a tuning process using a multi-particle tracking code. We assumed the errors shown in Table 2, where numbers are the r.m.s. values of Gaussian distributions.

Horizontal Displacement of Q and SX	100 μm
Vertical Displacement of Q and SX	30 μm
Strength Error of B, Q, and SX	0.1 %
Skew Rotation Angle of B, Q, and SX	0.5 mrad
Length Error of D, B, Q, and SX	100 μm
$\Delta\beta/\beta$ of the Incoming Beam	100 %
$\Delta\alpha/\alpha$ of the Incoming Beam	100 %

Table 2. Errors used in the simulation of the tuning. Here r.m.s. values of Gaussian distributions are given. D:drift space, B:bend, Q:quadrupole, SX: sextupole.

Our main method of the tuning is done by a bump orbit created by five correctors in each plane. We locate one corrector about $\pi/2$ before every sextupole and one before the final lens in each plane. The location of the correctors are shown in Fig. 1 by the marks H and V. The bump orbit are specified in terms of displacements at the sextupoles and a dispersion at the final spot. Although this orbit was calculated using the ideal optics, these parameters were almost orthogonal to each other during the minimization of the final spot. We controlled the linear optics with the skew term by the horizontal and the vertical displacements at the sextupoles. The dispersion at the final spot directly affects the beam size. Here we did not care about the displacement of the final spot and concentrated only on the spot size. Our procedures were done as the following:

1. Determine the Twiss parameters of the incoming beam by measuring the beam size at the beginning of the first bend as a function of the strength of the first quad Q5.
2. Change the strengths of the quads Q5, Q6, QA0, and QA1 to match the measured incoming beam parameters to the designed values at B01.
3. Adjust the orbit at the sextupoles to their center within the accuracy of the position monitor.
4. Search the minimum of the final spot by changing each parameter of the bump orbit. Iterate this step several times until a good spot near the design value is obtained

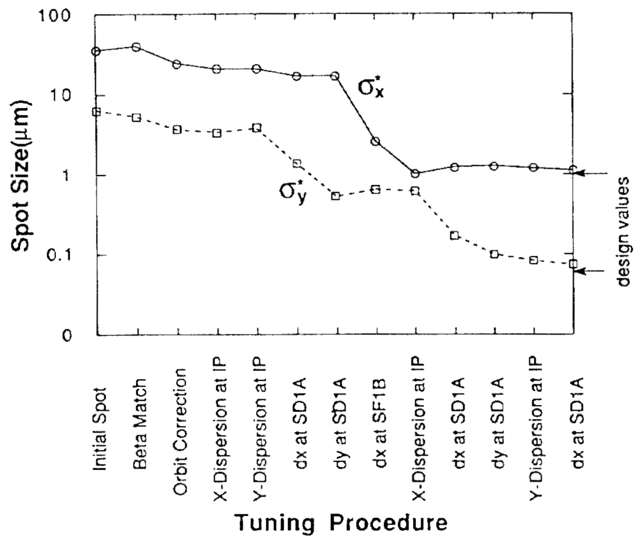

Fig. 2. A typical tuning process of the Final Focus Test Beam. This is a result a multi-particle tracking simulation. Each marker shows the minimum beam size after a search with varying the knob indicated at the bottom. The design beam sizes are shown by arrows on the right of this figure.

Figure 2 shows a typical example of this tuning procedure. We had roughly two orders larger initial spot than the design value and reduced it to 1 μm by 80 nm with this method. We tested four cases of the seed of the random number, and achieved the same results. These seed changed the most effective parameter, but the time for the whole tuning process were not much changed. We also assumed the accuracy of the position monitors 100 μm and the fluctuation of the final spot size 7 % during the tuning.

The magnitude of errors we assumed here are not far from those achieved by present alignment technologies.[11] This tuning method gives a good feasibility of the Final Focus Test Beam. We need further studies, especially on the stabilities of the components.

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REFERENCES

1. R. B. Palmer, SLAC-PUB-4295, 1987.
2. K. L. Bane, private communications.
3. K. Oide, SLAC-PUB-4660, 1988.
4. P. Chen, SLAC-PUB-4822, 1988.
5. R. B. Palmer, SLAC-PUB-4707, 1988.
6. K. L. Brown and R. V. Servranckx, SLAC-PUB-3381, 1984.
7. SLAC, *SLC Design Handbook*, 1984.
8. P. Chen and K. Oide, in preparation.
9. K. Oide, SLAC-PUB-4806, 1988.
10. W. O. Brunk and D. R. Walz. SLAC-PUB-3672, 1985.
11. G. E. Fischer and R. E. Ruland, private communications.