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FINAL FOCUS SYSTEM FOR TLC*

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ABSTRACT

A limit of the chromaticity correction for the final focus system of a TeV Linear Collider (TLC) is investigated. As the result, it becomes possible to increase the aperture of the final doublet with a small increase of the horizontal β function. The new optics design uses a final doublet of 0.5 mm half-aperture and 1.4 T pole-tip field. The length of the system is reduced from 400 m to 200 m by several optics changes. Tolerances for various machine errors with this optics are also studied.

1. INTRODUCTION

One of the merits of the flat-beam scheme for a future linear collider is that it makes the final focus system very simple, because one can mainly concentrate on the chromaticity correction of one dimension. Actually, a consistent design of the final focus system for TLC with R. B. Palmer's parameters[1] has been given,[2] and the number of optical elements is much fewer than that for a round beam final focus system like SLC[3] owing to the single-family sextupole chromaticity-correction scheme. Table 1 and Fig. 1 show the main parameters and these optics.

Although this design proved the existence of a final focus system for the TLC, it still needs many improvements and further optimization. One major problem is the aperture of the final quadrupole. It requires 100 μm half-aperture and 1.4 T pole-tip field, but until today only 5 mm with 1.25 T has been built as a high-gradient quadrupole.[4] The 100 μm aperture corresponds to 6 σ of the vertical beam size of this design, however, it is proved in this workshop that it must be at least 10 σ to prevent the synchrotron radiation in the final doublet from hitting the surface of itself.[5] A large aperture quadrupole can only be achieved by extending its length, unless one can get higher surface field. This makes the chromatic effect of the quadrupole larger in general and, thus, we need to know the limit of the chromaticity correction. This will be discussed in the next chapter and a design with larger aperture quads will be given in Chap. 3.

Another problem with the final focus system is the tolerances to various machine errors. In Chap. 4 we will briefly estimate several of them.

Table 1. Parameters for the final focus system of Fig. 1.

Center-of-mass energy	E_{CM} = 1 TeV
Beta function at IP	β_x^* = 14 mm
	β_y^* = 43 μm
Normalized emittance	$\varepsilon_{Nx} = 2.5 \times 10^{-6}$ m
	$\varepsilon_{Ny} = 2.5 \times 10^{-8}$ m
Momentum bandwidth	$\lvert\Delta p/p\rvert \leq 0.30$ %
Pole-tip field	B_0 = 1.4 T
Length of the experimental area	ℓ^* = 0.4 m
Quadrupole half-aperture	a = 100 μm

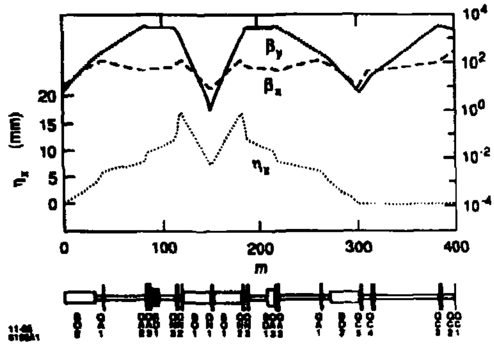

Fig. 1. A final focus optics for TLC with the single-family sextupole chromaticity correction scheme. The first character of each element specifies the type of the element as B:bend, Q:quadrupole, and S:sextupole.

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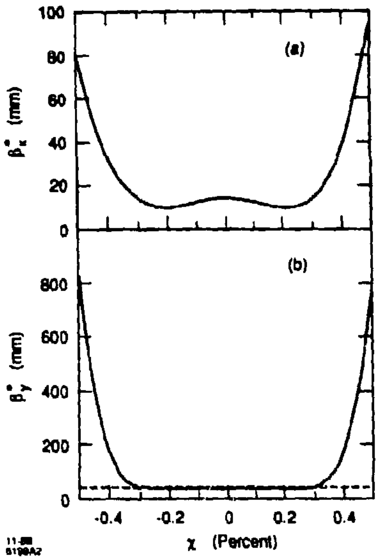

Fig. 2. The momentum dependence of the β functions at IP with the optics of Table 2. The horizontal axis is the parameter $\chi \equiv (p - p_0)/p$. The dashed line in β_y^* is the chromatic effect from the elements except the bad phase quadrupoles QC4 and QC5.

2. LIMIT OF THE CHROMATICITY CORRECTION

Figure 2 shows the momentum dependence of β functions at the interaction point with the previous optics. The behavior of the horizontal β function has been fully analyzed in Ref. 2 and the bandwidth for horizontal δ_x is determined by the horizontal chromaticity ξ_x

$$\delta_x = \frac{1}{\xi_x} \quad , \qquad \xi_x \equiv \int K \beta_x \, ds \quad , \tag{1}$$

where K is the focusing gradient of the final quadrupoles. When we use large aperture quadrupoles, we have to increase β_x^* to keep the desired bandwidth, as long as we use the single-family sextupole-correction scheme. Figure 3 shows how β_x^* depends on the aperture while keeping the bandwidth constant. We see in this figure that β_x^* is roughly proportional to $a^{\frac{1}{2}}$.

On the other hand, the behavior of the vertical β function has not been completely studied. We know that it is possible to cancel the momentum dependence up to fourth order by placing a sextupole at the phase difference $N\pi$ (N: integer) from the final doublet and setting the strength

$$k'\eta\beta_{S_y} = \xi_y \quad , \tag{2}$$

where η, β_{S_y} and ξ_y are the dispersion, vertical β function at the sextupole, and the vertical chromaticity of the final lenses. We see in Fig. 2 a large sixth-order term appears in β_y^* which gives the same bandwidth as β_x^*. We need to investigate this sixth-order term and determine the limit of the vertical chromaticity correction.

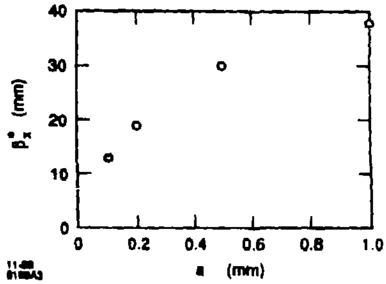

Fig. 3. The dependence of β_x^* on the aperture of the final doublet. The bandwidth is kept at $\pm$ 0.3 %. Here we fixed ℓ^*, β_y^*, and B_0 to 40 cm, 40 μm, and 1.4 T, respectively.

There are a lot of candidates for the sixth-order term. The doublet scheme, the finite thickness of quadrupoles and a higher order term in the dispersion at the sextupole give this effect, but estimations on these effects give a few percent bandwidth in this optics, far smaller than the actual strength of the sixth-order term. An analysis below will reveal the real source: the answer is the chromatic effect of quadrupoles between the sextupole and the final quadrupoles.

Consider a quadrupole with a strength k_1 which is placed at a position with a phase difference μ_1 from the collision point. The Twiss parameters are β_1 and α_1 at the quadrupole. We consider the system by a thin-lens approximation as shown in Fig. 4. Here we omit the suffix y, but the arguments below are only applied to the vertical dimension. We represent the effect of the final doublet by one thin lens as Ref. 2. Therefore, the chromaticity of the final doublet is written as $\xi_0 = k_0\ell^2/\beta^*$. After a simple thin-lens calculation, we find that it is not possible to cancel the chromatic terms completely even below the fourth order, but the main aberration appears in the sixth-order term

$$\frac{\Delta\beta^*}{\beta^*} = \xi_0^4\xi_1^2 \left(\cos\mu_1 - \frac{\beta^*}{\ell}\sin\mu_1\right)^4 \chi^6 \quad , \tag{3}$$

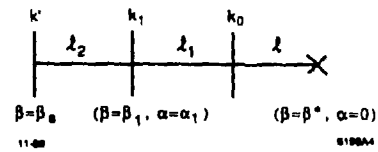

Fig. 4. A thin lens model of the final focus system. Here, ℓ is the length from the center of the final quadrupole to the collision point.

where $\xi_1 \equiv k_1\beta_1$ is the chromaticity of the intermediate lens and $\chi \equiv (p - p_0)/p$. Equation (2.3) tells us that a quadrupole gives a large sixth-order effect, unless the phase advance μ_1 is close to $(N + \frac{1}{2})\pi$. In our previous optics the quadrupoles QC4 and QC5 are at the bad positions $\mu_1 = 0.58\pi$ and $\mu_1 = 0.97\pi$, respectively. According to Eq. (2.3), the quadrupoles limit the bandwidth to ±0.27%, which is defined at the point where

$$\frac{\Delta\beta^*}{\beta^*} = 1 \quad . \tag{4}$$

This result agrees well with the behavior of β_y^* of Fig. 4. If both QC4 and QC5 were achromatic lenses, the behavior of the β function of this optics would become the dashed line of Fig. 4. It is a remarkable effect that despite the fact that the chromaticities of these lenses ($\xi_1 = 2.1$ and $\xi_1 = 0.4$ for QC4 and QC5, respectively) are much smaller than that of the final doublet ($\xi_0 = 14800$), they give the main contribution in the sixth-order term. For a lens which is at the phase advance $\mu_1 \approx (N + \frac{1}{2})\pi$, the sixth-order term given by Eq. (2.3) is smaller by the factor $(\beta^*/\ell)^4$ than those which are at the bad phase position.

What we have learned here is: "do not place a quadrupole at a position where the phase is not $(N + \frac{1}{2})\pi$ from the collision point." It is possible to remove these bad-phase quadrupoles, but at least one quadrupole is necessary to make the π phase advance between the sextupole and the final doublet.

We now consider the simplest system, which consists of one final lens, one sextupole and one intermediate lens which sets the phase advance to π. Let us denote the distances from the intermediate lens to the final lens and the sextupole as ℓ_1 and ℓ_2, respectively, as shown in Fig. 4. The π phase advance is achieved by setting the strength of the intermediate lens as

$$k_1 = \frac{\ell_1 + \ell_2}{\ell_1 \ell_2} \quad ; \tag{5}$$

therefore the residual sixth-order given by Eq. (3) becomes

$$\frac{\Delta\beta^*}{\beta^*} = \xi_0^4 \, \frac{\beta^* L^2}{\beta_S \ell^2} \, \chi^6 \quad , \tag{6}$$

where L is the distance between the sextupole and the final doublet. Equation (6) gives the final limit of chromaticity correction. The bandwidth for the vertical correction is written

$$\delta_y = \left(\xi_{y0}^2 \sqrt{\frac{\beta_y^*}{\beta_{yS}}} \, \frac{L}{\ell} \right)^{-\frac{1}{3}} \quad , \tag{7}$$

which corresponds to the condition of Eq. (4), and we have restored the y suffix. This bandwidth is proportional to $\beta_y^{*(1/2)}$ if the other parameters are fixed. The strength of the sextupole is still expressed as Eq. (2), but ξ_y at the right hand side of Eq. (2) is given not only by the final lenses but also by all quadrupoles of the system.

Figure 5 shows the band widths for both x and y achieved by actual designs, compared to the calculations from Eqs. (2.1) and (2.7). The agreement in vertical bandwidth is a little worse than the horizontal one, but Eq. (2.) still gives a rough estimation of the vertical bandwidth. The total bandwidth of the system is determined by the smaller of the horizontal and vertical band widths.

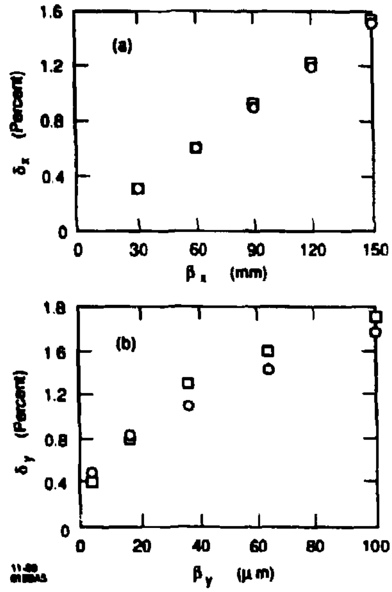

Fig. 5. The bandwidth δ_x and δ_y as functions of β_x^* and β_y^*. Here a final doublet with 0.5 mm half-aperture, 1.4 T pole-tip field, and $\ell^* = 40$ cm is used. The circles show the band widths achieved by actual designs, and squares the calculated values by Eqs. (2.1) and (2.7).

3. A LARGE APERTURE FINAL FOCUS SYSTEM

Although it is still not clear for us how small a quadrupole aperture is really available, here we use 0.5 mm half-aperture with 1.4 T pole-tip field for final doublet as an example. It is about one tenth of the aperture of quadrupole actually constructed.[4] According to the results of the last chapter, it is possible to design an optics with this aperture and a bandwidth of 0.3%. In this case, the bandwidth is only determined by the horizontal chromaticity, and we have to increase β_x^* from 14 mm to 30 mm to achieve this bandwidth, as indicated in Fig. 3. The vertical β function is 40 μm and almost the same as before. Although we have enough acceptance in β_y^*, it is worthless to decrease β_y^* any more because it has already hit the synchrotron-radiation limit of the final quadrupole.[6]

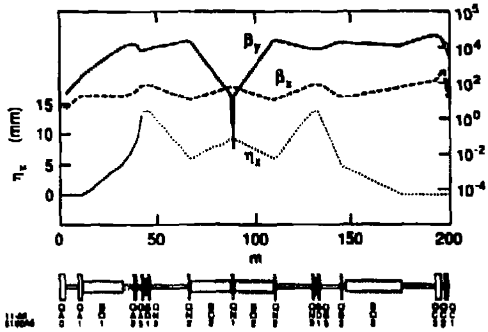

Fig. 6. A new design of the final focus optics with the 0.5 mm half-aperture final doublet.

Figure 6 shows a design of the final focus system with 0.5 mm half-aperture final doublet. This aperture is made by stretching the length of the final quadrupole QC1 from 40 cm to 120 cm and also QC2 from 40 cm to 68 cm. The pole-tip field and the length of the experimental area are the same as for the previous design. The system length is decreased to 200 m, which is just half of the previous one. In the previous design the mirror symmetry of the chromaticity correction section is kept from the first bend to the last bend, which is followed by a focusing section of 100 m length. The new design has kept the symmetry only between two sextupoles, and the dispersion suppressor and the telescope are merged into one complex. Another improvement is done to obtain a bigger dispersion/bending angle ratio. These two changes contribute to reducing the total length.

The vertical chromaticity is increased as the increase of the aperture and it needs strong sextupoles, which make the geometric aberrations large. One cure is to increase the dispersion at the sextupole, as in the paragraph above. Another cure is to shorten the length of the sextupoles. Although the shorter sextupole is the better in the geometric effects, owing to the $-I$ transformation between the two sextupoles, it is unclear how small an aperture sextupoles can be reduced to and still remain actually possible. Here we set the half-aperture to 0.4 mm, with a pole-tip field of 1.0 T, which is a modest value compared to those of the final quadrupoles.

Now the 200 m final focus system is short enough for the 500 GeV accelerator. This system has been checked by a multiparticle tracking simulation, and the total vertical aberration caused by synchrotron radiation and geometric nonlinearity is about 10% of the nominal beam size. The luminosity is decreased from the previous design due to the increase of β_x^*, but it can be recovered by changing other parameters of the collider.

Although a design with 1 mm half-aperture quadrupoles is also made, and it will be possible to increase the aperture more, a large aperture increases the chromaticity of the system and makes the tolerance of the system tighter, as shown in the next chapter.

Table 2. The optics parameters for the new design of the final focus system.

MARK

INPUT =	(ALPHAX = 0	ALPHAY = 0
	BETAX = 10.0 m	BETAY = 10.0 m
	EMIX = 2.5D-12 m	EMIY = 2.5D-14 m
		DP = 0.003)

DRIFT

LA0 = (L = 6.9938532)	LX0 = (L = 0.1000000)
LA1 = (L = 0.1000000)	LB2 = (L = 10.6758039)
LA2 = (L = 5.2890761)	LB1 = (L = 1.5095633)
LA3 = (L = 3.1396575)	LC4 = (L = 16.4694946)
LS2 = (L = 0.1000000)	LC3 = (L = 1.8851826)
LN2 = (L = 0.1000000)	LX2 = (L = 0.0400000)
LN1 = (L = 18.9086844)	LX1 = (L = 0.4000000)

BEND

B01 = (L = 21.0000000 ,	ANGLE = 0.000499346458)
B02 = (L = 21.0000000 ,	ANGLE = 0.000300000000)
B03 = (L = 29.0000000 ,	ANGLE = 0.000300000000)

QUAD

QA0 = (L = 3.0000000 ,	K1 = 0.2847124)
QA1 = (L = 2.0000000 ,	K1 = 0.2160445)
QA2 = (L = 1.0000000 ,	K1 = −0.1020459)
QA3 = (L = 1.0000000 ,	K1 = 0.0933806)
QN3 = (L = 1.0000000 ,	K1 = 0.0349031)
QN2 = (L = 1.0000000 ,	K1 = −0.0664416)
QN1 = (L = 1.0000000 ,	K1 = 0.0651954)
QB3 = (L = 1.0000000 ,	K1 = 0.0489054)
QB2 = (L = 1.0000000 ,	K1 = −0.0892923)
QC3 = (L = 3.0000000 ,	K1 = −0.2265658)
QC2 = (L = 0.6800000 ,	K1 = 1.1431554)
QC1 = (L = 1.2000000 ,	K1 = −2.0005762)

SEXT

SD1 = (L = 2.0000000 ,	K2 = −132.0000000)

LINE

FFS =	(INPUT	QA0	LA0	QA1	LA1
B01	LA2	QA2	LA3	QA3	LS2
SD1	LN2	QN3	LN1	QN2	LX0
B02	LX0	QN1	LX0	B02	LX0
QN2	LN1	QN3	LN2	SD1	LS2
QB3	LB2	QB2	LB1	B03	LC4
QC3	LC3	QC2	LX2	QC1	LX1)

Table 2 lists the parameters of these optics in the same format as Ref. 2.

4. TOLERANCES FOR MACHINE ERRORS

What we discuss in this chapter are the tolerances for various machine errors which reduce luminosity. In this section we discuss tolerances to abrupt changes of components from pulse to pulse. This is usually called jitter. For the flat beam collider, the tolerances are much tighter in the vertical dimension than the horizontal, because the final spot size is smaller and the chromaticity is higher in the vertical. We will show some simple expressions to estimate the tolerances for only the vertical, but these are easily applicable to the horizontal dimension. Figures in

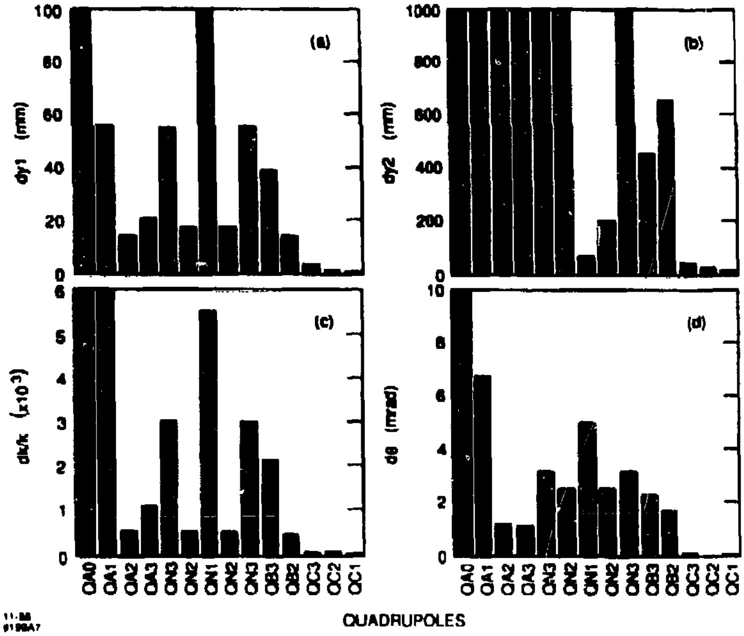

Fig. 7. Tolerances for vertical misalignments dy_1 and dy_2, strength error dk/k, and roll ang

this chapter show the values of machine errors for each quadrupole which reduce the luminosity to $1/\sqrt{2}$ of the nominal value. The new optics described in the last chapter is used in this calculation. We take into account only the first order optics and its first order momentum dependence.

The first kind of the error is the simplest one. The misalignment dy_1 of each quadrupole vertically shifts the beam spot and prevents the head-on collision. The amount which reduces the luminosity by $1/\sqrt{2}$ is

$$dy_{1i} = \frac{\sqrt{2\log 2}}{k_i \sin\mu_i}\sqrt{\frac{\varepsilon_y}{\beta_{yi}}} \quad , \tag{8}$$

where μ_i, β_{yi}, and k_i are the phase difference from the IP, the vertical β function, and the strength of the i-th quadrupole, respectively.

There is another effect of a misalignment of a quadrupole. A vertical displacement makes the vertical spot size larger due to the vertical dispersion created by the vertical displacement in the final doublet. The tolerance to this effect is written as

$$dy_{2i} = \frac{\sqrt{3}}{k_i\xi_y\cos\mu_i\delta}\sqrt{\frac{\varepsilon_y}{\beta_{yi}}} \quad , \tag{9}$$

where ξ_y is the chromaticity of the system, and we have assumed the beam has a uniform energy distribution of the full width 2δ. This effect becomes weaker for quadrupoles between two sextupoles, because about the half of the chromaticity is corrected, and ignorable for the quadrupoles before the chromaticity correction section.

Quadrupole strength error dk/k and roll $d\theta$ along its longitudinal axis also make the vertical spot size larger. The tolerances for them are written

$$\frac{dk_i}{k_i} = \frac{1}{k_i\beta_{yi}\sqrt{\sin^2\mu_i + \xi_y^2\delta^2\left[\frac{\sin^2 2\mu_i}{2} + \left(\frac{1}{3} + \frac{\xi_y^2\delta^2}{5}\right)\cos^4\mu_i\right]}} \tag{10}$$

and

$$d\theta_i = \frac{\sqrt{\frac{\varepsilon_y}{\varepsilon_x}}}{k_i\sqrt{\beta_{xi}\beta_{yi}\left(\sin^2\mu_i + \frac{\xi_y^2\delta^2\cos^2\mu_i}{3}\right)}} \quad . \tag{11}$$

Figure 7 shows above tolerances for each quadrupole used in this system. We see in this figure all tolerances are about one order more severe for the final three quadrupoles than other quadrupoles.

Tolerances for sextupoles can be estimated similarly. The tolerances for the horizontal displacement is calculated in the same expression as Eq. (4.3) by replacing dk

with $k'dx_g$. The vertical tolerances is also obtained from Eq. (11) by replacing $k_l d\theta$ with $k' dy_S$. These values are $dx_S = 0.82$ μm and $dy_S = 0.85$ μm. The tolerance for the sextupole strength dk'/k' is written

$$\frac{dk'}{k'} = \frac{\sqrt{3}}{k'\eta\beta_y s\delta} \quad , \tag{12}$$

which gives $dk'/k' = 3.4 \times 10^{-2}$.

5. DISCUSSIONS

In this paper we have a rough evaluation of the limit of the vertical chromaticity correction. This limit is still far from the present requirement of β_y^* and the actual bandwidth is determined only by β_x^*, due to the single-sextupole scheme. We have to abandon this scheme when we need smaller β_x^*, and use a two-family sextupole scheme instead. What limits the chromaticity correction with two-family sextupole scheme has not been studied, but another sixth-order terms from the coupling of these two families will appear, and the limit will be tighter than the single-family scheme.

We have achieved improvements of the final focus optics in the aperture of the final doublet and the total length. These will give more reality to TLC.

We have estimated the tolerances for several machine errors. The values estimated here give the maximum jitters of the components discussed. There are also other kinds of machine errors which have dc or very low frequency components. These are correctable by monitoring beam position and size in various points in principle, but there are some limits to the correction due to the finite errors of monitors and additional aberrations induced by correctors like synchrotron radiation. This problem also depends on the correction scheme with the specific optics.

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