Tuning of Final Focus System for Future Linear Colliders

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I. INTRODUCTION

Development of a tuning method of a final focus system is one of the most important issues to realize the tiny spot size at the interaction point(IP) of a future linear collider. Here we examine a procedure to correct various initial machine errors, using the JLC final focus system as an example.

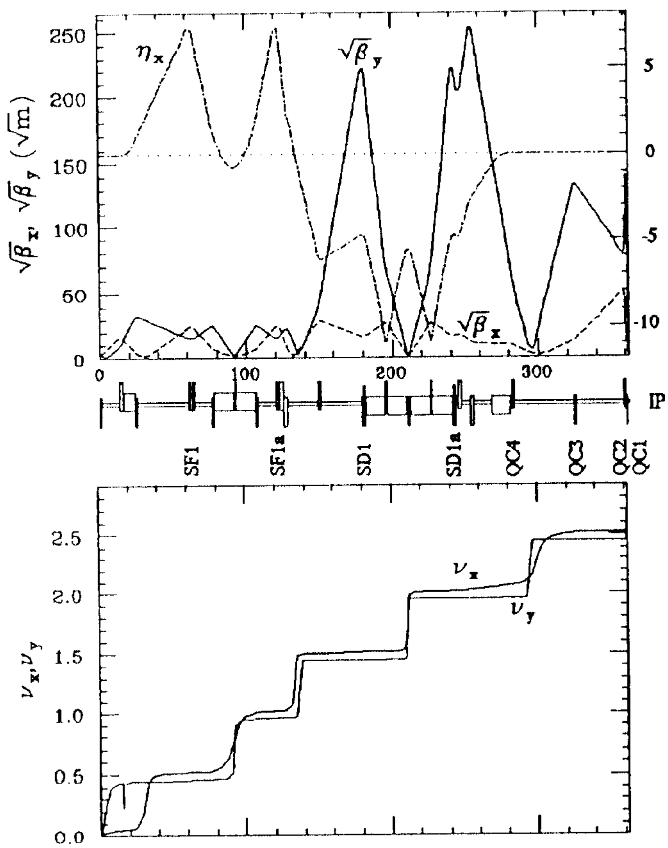

Fig. 1. Final focus system of JLC. The upper graph shows $\sqrt{\beta_x}$, $\sqrt{\beta_y}$, and η in dashed, solid, and dot-dashed lines, respectively. The IP is located at the right end. The lower graph is the phase advance normalized by 2π.

Figure 1 shows the optical functions of JLC final focus system,[1] whose the machine parameters are listed in Table 1. This system has two chromaticity correction sections(CCS). Each of the CCS consists of a pair of identical sextupoles separated by a $-I$ transformer, whose principle is based on the K. L. Brown's idea.[2] The parameters of the bending angle, the length of the bending magnets, strengths of the sextupoles, and β functions at the sextupoles are determined by an optimization which takes into account the chromo-geometric aberrations of the CCS and the optical disturbance by the synchrotron radiation in the bending magnets. The CCS for the vertical chromaticity correction is located closer to the IP and has SD1 and SD1a sextupole.

Table 1
Parameters of the JLC final focus system

Beam energy	E_0	500	GeV
Invariant emittances	$\varepsilon_x/\varepsilon_y$	$3\times10^{-6}/3\times10^{-8}$	m
Beta at the IP	β_x^*/β_y^*	14/0.08	mm
Spot sizes at the IP	σ_x^*/σ_y^*	210/1.7	nm
Free area length	ℓ^*	1	m
Half aperture of the final quad	a	0.5	mm
Pole-tip field	B_0	1.4	T
Length/beam	L_0	365	m
Momentum bandwidth	χ_m	±0.6	%

II. LINEAR KNOBS

As a beginning, we examine the effect of "linear knobs" in the tuning of the system. Here we use the word "linear knobs" for primitive knobs like the normal and skew correction quadrupoles at the sextupoles, and dipoles to correct the horizontal and vertical dispersions at the IP. These knobs are the always necessary to tune the system. Since almost all magnets are located at $N\pi$ apart from the final quadrupoles QC1 and QC2 as shown in Fig. 1, all errors in the linear optics can be corrected by these knobs if they are small enough. We can find the minimum of the final spot at the IP by changing these knobs by an appropriate spot size monitor at the IP. Figure 2 shows the effects of the linear knobs on the correction of the strength and the skew rotation errors of the quadrupoles and the sextupoles.

In this simulation we changed the horizontal and vertical position of the sextupoles to have the normal and the skew quadrupole components. The pair of sextupoles in a family moves same amount in the same direction. The same correction can be done also by correction quadrupoles. The horizontal and the vertical dispersions at the IP are controlled by changing the position of quadrupoles QC4 and QC3 which are located between the CCS and the final quadrupoles. One cycle of the minimization consists of five processes: 1) Minimize the horizontal spot size by changing the horizontal position of QC4, 2) Minimize the horizontal spot by the horizontal position of SF sextupoles, 3) Minimize the vertical spot by the vertical position of QC3,

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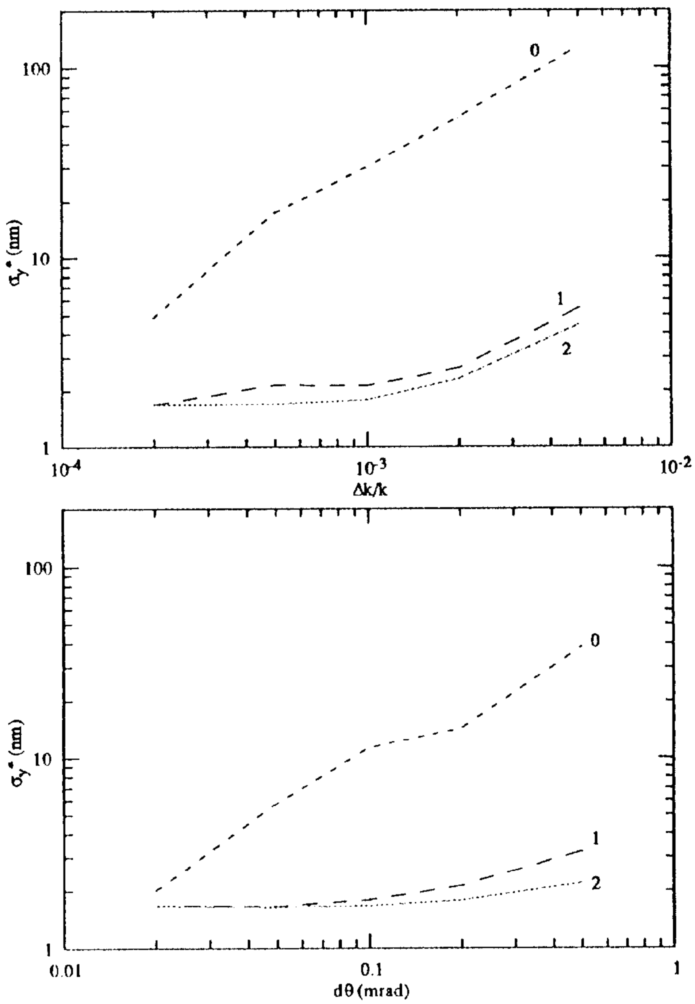

Fig. 2. The improvement of the vertical spot size at the IP by the "linear knobs" for the strength error (upper) and the skew rotation error (lower). The trace 0 is the spot size without the correction. The traces 1 and 2 show the results after one and two cycles of the minimization with the linear knobs are applied.

4) Minimize the vertical spot by the horizontal position of SD sextupoles, 5) Minimize the vertical spot by the vertical position of SD sextupoles. Gaussian errors with 3σ cutoff are applied on all the quadrupoles and sextupoles of this system. This result shows that a relative strength error of about 10^{-3}, or a skew rotation error of about 0.2 mrad can be corrected after 2 cycles of minimization process with the linear knobs. For the time being we concentrate on the effects to the vertical spot size, which require the most severe tuning because it has a small emittance, small β^*, and a large chromaticity. This simulation of Fig. 2 used 400 test particles. The effects of synchrotron radiation are ignored. We tested 12 cases of different random number seeds. These magnitudes of errors correctable by the linear knobs are not small compared those in existing machines built with conventional technologies.

Although the linear knobs have enough power to correct the strength and the skew rotation errors, they are less effective to transverse alignment errors of the magnets. Figure 3 shows results of the simulation for the horizontal and the vertical misalignment of quadrupoles and the sextupoles. Even though the minimization by the linear knobs can improve the vertical spot size at the IP by more than factor 10, it is not sufficient for the alignment errors more than horizontal 5 μm and vertical 0.5 μm. These numbers look much far from the alignment errors of existing machines. One reason of this difficulty is the horizontal and the vertical dispersions at the sextupoles created by these misalignments. These dispersions disturb the chromaticity correction and generates chromatic terms in the x-y coupling.

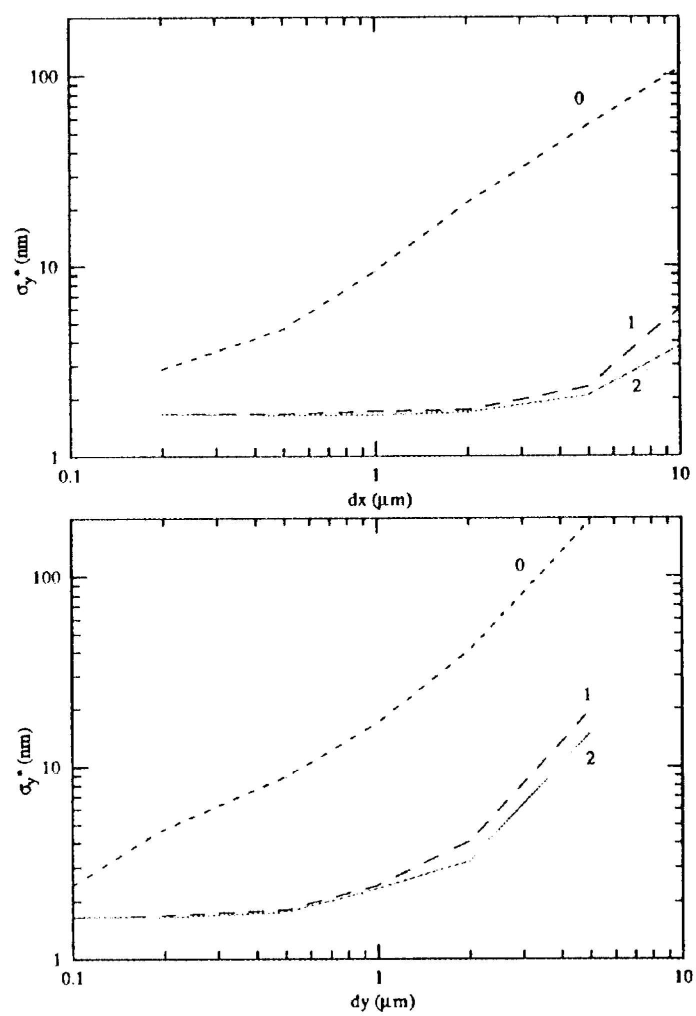

Fig. 3. The improvement of the vertical spot size at the IP by the "linear knobs" for the horizontal (upper) and the vertical (lower) misalignments of the quadrupoles and the sextupoles. The trace 0 is the spot size without the correction. The traces 1 and 2 show the results after one and two cycles of the minimization with the linear knobs are applied.

III. Alignment by Beam

It may be possible to use more sophisticated knobs to cure the effects from the misalignments, but generally speaking, a minimum search process with large number of parameters has a tendency to fall into local minima. Therefore a method which works differently from the minimization is more desirable. The next method we examine is the so-called "alignment by beam" method, which plays the roll of a bridge from the conventional level of misalignments, about 100 μm, to the region of a few μm, which is tunable by the linear knobs. It is a well-known method to determine the transverse displacement of a quadrupole by measuring the response of the beam angle to the change of the strength. We apply this method to the final focus system as follows. In this simulation we put position monitors at all 25 quadrupoles and 4 sextupoles in the beam line. Four extra position monitors are also placed in the damp line after the IP. All quadrupoles and sextupoles in the downstream of the quadrupole which is to be aligned are turned off during the alignment. We change the strength of the quadrupole from the design strength to zero and measure the change of the orbit at all position monitors downstream. The change of the orbit angle is obtained by a fitting of these data to a straight line. Thus we determine the coefficient between the change of the orbit angle and the strength $\Delta y'/\Delta k$, *i.e.*, the displacement of the quadrupole. Each magnet is realigned by a mover after the measurement. The merit of this method is that the accuracy of the alignment of the quadrupole does not depend on the alignment errors of the monitors.

One may expect that the same method can be applied to the alignment of sextupoles. The response of the beam angle to the strength of the sextupole is written as $\Delta x' = -(x^2 - y^2)\Delta k'/2$ and $\Delta y' = xy\Delta k'$. Is it possible to determine the misalignment of the sextupoles from these relations? The answer is no, because a position monitor senses the average $< x^2 > - < y^2 >$ and $< xy >$, those contains the terms from the beam size at the sextupole $\sigma_x^2 - \sigma_y^2$ and σ_{xy}. Those terms have comparable contributions to the beam response as the misalignment terms. We should not use the design values for these beam distributions, especially in the mode where the magnet is turned on after the alignment, because the beam size at the sextupole may be deformed by the upstream magnets.

An alternative method to align a sextupole uses a horizontal mover of the sextupole. We turn on the sextupole and move it horizontally, then measure the change of the orbit angle by the monitors downstream. The angle behaves as $\Delta x' = -(x_0\Delta x + \Delta x^2/2)k'$ and $\Delta y' = y_0\Delta xk'$, where x_0 and y_0 are the misalignments, and Δx is the amount of the horizontal motion of the sextupole. The horizontal misalignment is determined from the location of the extremum of $\Delta x'$. The vertical misalignment is determined directly from above relation. This method does not depend on the beam size at the sextupole.

There are two modes to apply this alignment-by-beam method to the final focus system. One is to turn on one magnet at a time. All quadrupoles and the sextupoles are turned off including the upstream magnets. Another is to turn off only the downstream magnets, setting the design strengths to the upstream magnets after the realignment. The bending magnets should be always turned on in both modes. While the former mode aligns the magnets around an ideal orbit with the accuracy of the method, the later aligns around the actual orbit which is distorted by the residual errors of the upstream magnets. The later mode has the merit to suppress the source of the dispersions, but also the demerit that the alignment error accumulates to the IP. Therefore here we used the combination of both modes. We apply the all-off mode first, then apply the upstream-on mode.

In this simulation we assume that each monitor has a jitter error of 5 μm and a calibration error of 1 %. The later means that each monitor cannot tell the amount of the change of the orbit with an accuracy better than 1 %. We used 9 pulses for every magnet to determine the misalignment. Each pulse contains 400 particles, which imply that the orbit always fluctuates in 5 % of the beam size. We also added 0.1 % strength errors and 0.2 mrad skew rotation errors for all quadrupoles and sextupoles. The initial alignment errors of the magnets were 100 μm both in horizontal and vertical directions. As the result of the alignment-by-beam method for quadrupoles, we obtained the horizontal and the vertical residual alignment errors of 9.3 ± 1.7 μm and 6.2 ± 2.7 μm, respectively. The horizontal and the vertical residual errors for the sextupoles were 23 μm and 15 μm. Because of the upstream-on mode, this error corresponds to the misalignment of each magnet measured from the actual orbit. We applied the linear knobs

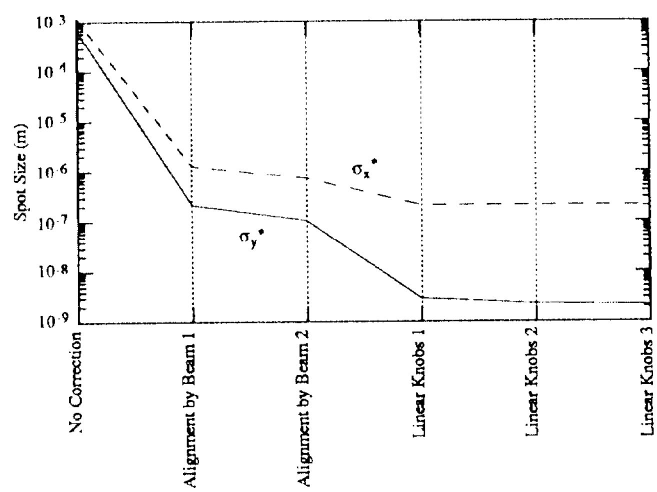

Fig. 4. The improvement of the horizontal and the vertical spot size at the IP. The curves show the spot sizes after the corresponding method was applied.

after the alignment-by-beam method, then achieved 2.2 nm × 0.20 μm spot size at the IP, which is enough close to the design value. We tested 12 cases with different random number seeds. These results does not depend on neither the jitter error nor the calibration error of the monitors. For example, the result does not change when both errors are made half simultaneously.

In the above simulations we did not include the effects of the synchrotron radiation. An off-centered orbit in a quadrupole generates synchrotron radiation which disturbs the chromaticity correction of the system and increase the spot size at the IP. This effect is most severe in the final quadrupole QC1. When the misalignment of QC1 is larger than 50 μm, which is much larger than the accuracy of the alignment-by-beam method, the increase of the vertical spot size becomes significant.

IV. Conclusion

The above simulation shows that the combination of the alignment by beam method and the linear knobs is a possible tuning method for the start-up of the final focus system of a future linear collider. It allows a conventional level of initial alignment of the magnets, setting errors and sensitivity of position monitors. On the other hand, it has rely on the spot size monitor at the IP and the accuracy and the stability of the magnet movers. It is not necessary for the magnet movers to have an ability to set the position in the sub-micron accuracy, because we can use a correction dipole instead of such a small displacement of a quadrupole. In this simulation we used about 400 pulses to tune up entire beam line. Since the linear collider has a few hundred Hz repetition rate, the actual speed of the tuning is limited by the response of the movers and the monitors. This means that in the actual situation, we can use more pulses to determine the displacement of the magnets and the minimum search than in the simulation. Therefore the accuracy of the method may become even better than the simulation.

V. References

1. K. Oide, Proc. 1st JLC Workshop, KEK, 1989, KEK-Prep.-89-190(1990).
2. See, e.g., K .L. Brown, IEEE Trans. NS-26(1979)3490 and also SLAC-PUB-2257(1979).