# Final Focus Test Optics for the ATF

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## 1. Introduction

ATF(Accelerator Test Facility)[1) ] is the facility at KEK for R&D of the injector part of future Linear Colliders Fig.1 shows the overview of the ATF. It consists of 70 m S-Band linac, Beam transport line, damping ring and extraction line. It has been operated since 1995. In single bunch operation, very low vertical emittance $\gamma\varepsilon_y \sim 0.03\mu\text{m}$ was successfully produced, which matched with the JLC requirement. Experiment for multibunch beam production is on going, and the beam quality is getting better. Especially, improvement of the vacuum system in 2001 reduced the multibunch emittance very much. Many other experiments are also on going there which are very important for the future linear collider technology such as RF gun, double kicker system, laser wire scanner, polarized positron production, cavity BPM, ODR&OTR monitor and so on.

Now the next phase of the ATF can be thought. The project called ATF2 proposes mainly two things. One is to add bunch compressor downstream the extraction line, which makes the ATF complete injector system of a linear collider. The other is to make a final focus line also downstream the extraction line. This provides us a place to study experimentally the final focus system, which is the subject of this report.

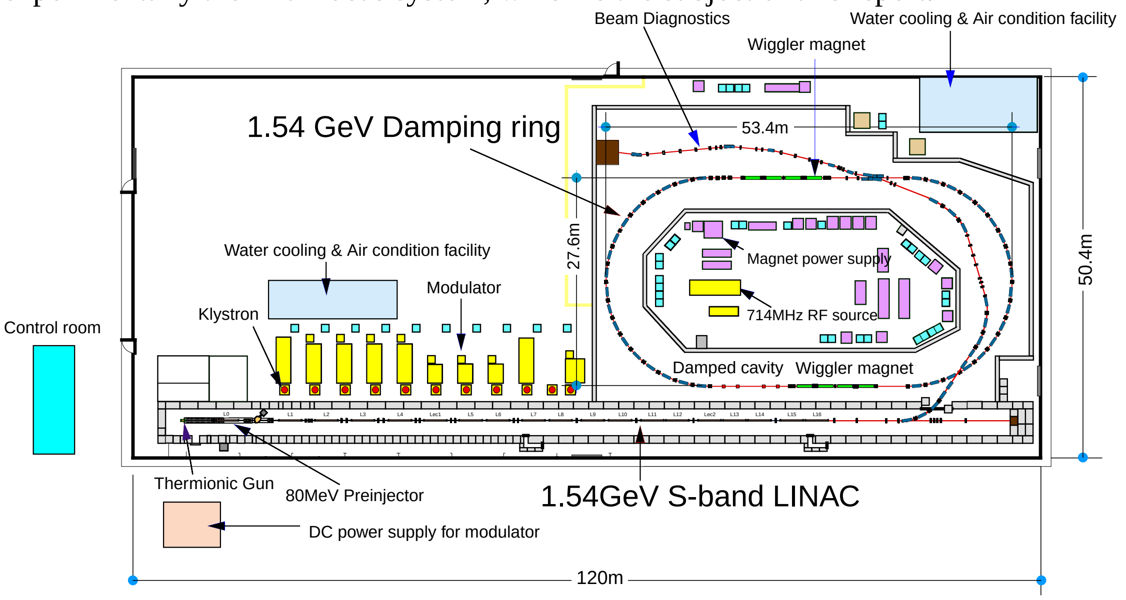



Fig.1 ATF Layout

## 2. Basics of Final Focus System

Final focus system is the most downstream part of linear collider, which squeezes beam to very small spot size. The vertical beam size of the JLC is a few nm at the interaction point. One of the most important thing in the final focus design is to take care about the beam size growth due to the energy deviation $\delta=(E-E_0)/E_0$. The growth is approximately expressed as follows;

$$\Delta\sigma^* = \xi\delta\sigma^*_0 \qquad (1)$$

where $\xi$ and $\sigma^*_0$ are the chromaticity and the linear optics beam size, respectively. For usual final focus system the chromaticity $\xi$ is of order of $10^3 \sim 10^4$. Thus even assuming the small energy spread $\delta$ of $\sim 10^{-3}$, the beam size easily becomes about ten times larger. The chromaticity can be corrected by introducing sextupole magnets to dispersive region. The sextupole magnets, however, have nonlinear magnetic field which also causes the beam size growth. This nonlinear effect, geometric aberration, is cancelled by the magnet configuration shown in fig.2.

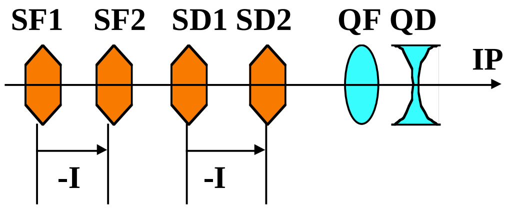



Fig.2 Cancellation of Geometric Aberration

In the figure, only the sextupole magnets and the final quadrupole magnet pair are shown. Not shown in the figure, however, many quadrupole magnets are assumed to exist among them. Two families of sextupole magnets are required for correction of both of the horizontal and vertical chromaticity. Each family forms a pair of magnets and the transfer matrix in between is set to be –I so that the nonlinear kick produced by the first magnet is cancelled by the other one.

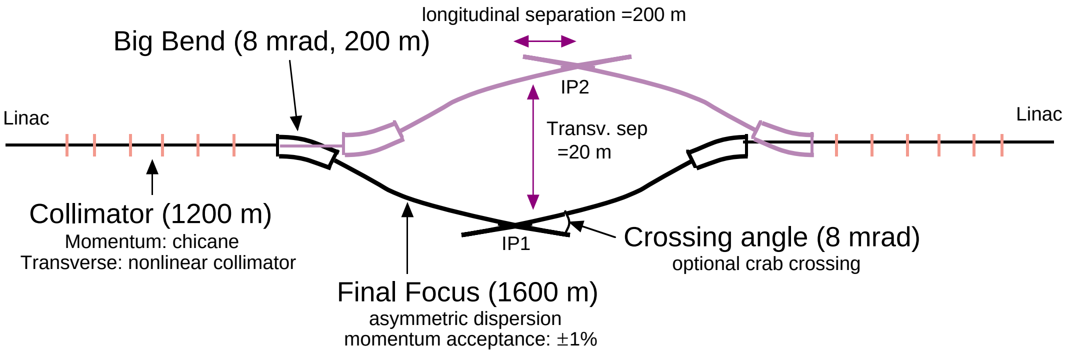



Fig.3 Schematic view of the interaction region of linear collider

The scheme of the geometric aberration cancellation, though slightly modified, is applied in the final focus system of JLC-I[2)]. It is also adopted in 'JLC Design Study'[3)]. Furthermore, at FFTB(Final Focus Test Beam) in SLAC, the cancellation scheme was experimentally confirmed to work. They had successfully produced so small beam size of $\sigma_y \sim 60$nm which was almost the design value[4)].

Fig.3 shows the schematic view of the interaction region of linear collider, that is from ref.3). The whole length of the final focus system is $\sim$1600m. That in NLC ZDR[5)] has similar long length of $\sim$1800m. Recently a new final focus optics[6)] was proposed by P.Raimondi and A.Seryi, which had the equivalent performance in squeezing the beam, however, the total length was so short, $\sim$500m. It is so preferable if it really works. Thus it is very important to test the new final focus system experimentally. The ATF is one of the best place to check principle of the new final focus system.

## 3. New Final Focus System

The new final focus system is schematically shown in fig.4.

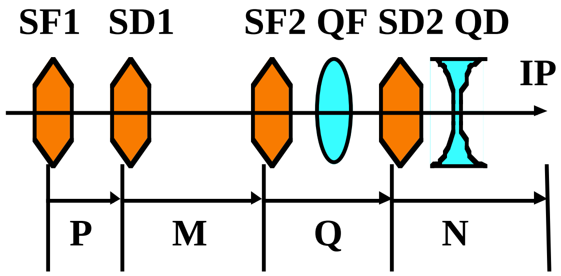



Fig.4 New Final Focus System

In the figure, some quadrutic magnets upstream of SF2 are not shown and P,M.Q and N represent the transfer matrices there. The chromatic effect is corrected by sextupole magnets. The two of them are placed just next to the final quadrupole magnets, which are major chromaticity sources because of large beta-function there. The 2nd order geometric aberration is cancelled by the other sextupole magnets with the transfer matrix as follows;

$$MP = \begin{pmatrix} F & 0 & 0 & 0 \\ F_{21} & 1/F & 0 & 0 \\ 0 & 0 & F & 0 \\ 0 & 0 & F_{43} & 1/F \end{pmatrix} \quad (2)$$

$$QM = \begin{pmatrix} D & 0 & 0 & 0 \\ D_{21} & 1/D & 0 & 0 \\ 0 & 0 & D & 0 \\ 0 & 0 & D_{43} & 1/D \end{pmatrix} \quad (3)$$

Here the strength of the setupole magnets must also be chosen as $k2_{SF1}=-F^3k2_{SF2}$ and $k2_{SD1}=-D^3k2_{SD2}$. In this case, however, remains the 3rd order geometric aberration. The 3rd order geometric aberration is expressed by the coefficients when the nonlinear map including the sextupole magnets action is expanded as polynomials. In thin lens approximation,

$$U_{3444} \propto N_{34}{}^2 Q_{12} \left( N_{33} Q_{34} + N_{34} Q_{44} \right)^2 \quad (4)$$

$$U_{1244} = U_{3224}$$
$$\propto Q_{12} N_{34}{}^2 (NQ)_{12}{}^2 + Q_{12} N_{12}{}^2 (NQ)_{34}{}^2 - 4 Q_{34} N_{12} N_{34} (NQ)_{12} (NQ)_{34} \quad (5)$$

where the indices 1,2 3 and 4 represent for x, $p_x$, y and $p_y$, respectively. Thus the 3rd order geometric aberration can be expressed with only the transfer matrices Q and N. With adequate choice of the final quad strength, $U_{1244}=U_{3224}$ can be zero. And $U_{3444}$ also can be made small at the same time.

## 4. Design of Final Focus Test Optics for ATF

As mentioned before, it is very important to test the new final focus system experimentally. So here the test optics designed for ATF is reported. The calculation in this section was done by the computer program SAD[7)] which was developed for accelerator design at KEK.

Before the final focus design, the beam parameters from the ATF damping ring is summarized as follows;

| | |
|---|---|
| Beam Energy | 1.54 GeV |
| Equilibrium Emittance $\gamma\varepsilon_x$ | $3\times10^{-6}$m |
| Emittance Ratio $\varepsilon_x$:$\varepsilon_y$ | 100:1 |
| Energy Spread | 0.1% ( Gaussian Distribution ) |

The emittance specification is the same as the JLC one. The energy, however, is lower by order of two. That results the physical emittance $\varepsilon$ is larger by factor of a few hundred. So the beam size becomes a few ten times larger , assuming the same beta –function. Since the nonlinear effect becomes rapidly strong for larger spot size beam, large geometric aberration is expected in ATF final focus system. Fortunately, the momentum spread is a little bit smaller than that of JLC case. So the sextupole strength might become smaller and help to reduce the nonlinear effect.

Firstly for the ATF final focus system, the final drift space length L* was chosen to be 2m. It is because the whole beam line must be contained in the already existing building, Assembly Hall. The distance between QF and SD2 was also taken to be 2m and quadrupole and its correction sextupole magnets were placed with 0.3m distance. Then only two variables, strength of QF and QD, remain in the downstream section QN. The equation for the 3rd order geometric aberration $U_{1244}$=0 is solved and one of the strength of the final quadrupole magnets is expressed by the other. The results is shown in Fig.5. The $U_{3444}$ value is also plotted in fig.5. Strength of QD was chosen to be k=-0.67/m. Then k(QF)=0.31/m and $U_{3444}$ =9.57. $U_{3444}$ is not minimum here. The QF strength, however, shows rapid rise for less k(QD). Larger k(QF) produces larger chromaticity. So the chosen value may be the optimum point.

Next is the section between the sextupole pairs. The quadrupole magnets between SF1 and SF2 are adjusted so that the equations (2) and (3) hold. For that the lattice P was set to be identical to Q, which matches the necessary condition for equations (2) and (3). As the results F=-1.12 and D=-0.893 were obtained. Here one should notice that the beta-function in this region could be very large. So the quadrupole field should be very small there, otherwise the quadrupole magnets would produce much chromaticity. Thus the quadrupole strength was chosen as $|k|<0.2$/m.

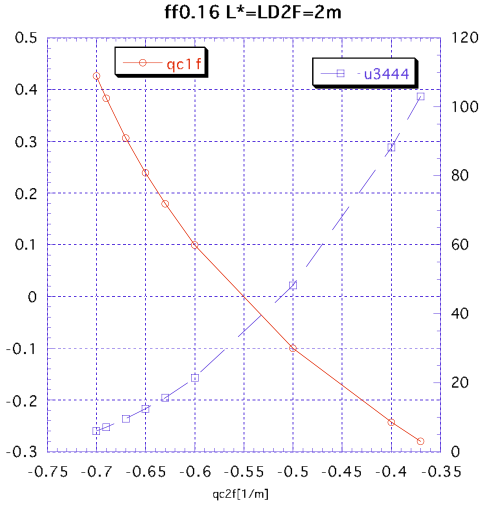



Fig.5 Solution for $U_{1244}$=0 and $U_{3444}$ value

By $U_{1244}$=0, k of QD is plotted as a function of k(QF).

For $U_{3444}$ value, the r.h.s of eq.(4) is plotted.

Finally, the matching section was designed. Using the quadrupole magnets upstream and sextupole magnets, the following condition at the 'interaction point' was 'matched';

For $\delta$=-0.2%, -0.1%, 0%, 0.1%, and 0.2%,

$$\alpha_x=\alpha_y=0$$
$$\beta_x=0.01\text{m}$$
$$\beta_y=100\mu\text{m}$$
$$\eta_x=0$$

For the cancellation of the 2nd order geometric aberration, the sextupole magnet pair keeps the relationship, $k2_{SF1}=-F^3k2_{SF2}$ and $k2_{SD1}=-D^3k2_{SD2}$ , in this calculation. The equation (1) for the beam size growth is derived from the fact that the beta-function varies with the momentum deviation. Therefore the above condition is almost equivalent with the chromaticity correction. Alpha-function which is proportional to the derivative of the beta-function, is set to be zero for less sensitive beam size to the deviation of the 'interaction point' position.

The results of the 'matching' is shown in Table 1. From the table, it is seen that the matching was successfully done. The sextupole strength is so weak as K2[1/m$^2$]=-1.2 and 3.5 for SF2 and SD2 respectively.

| DP | -0.2% | -0.1% | 0% | 0.1% | 0.2% |
|---|---|---|---|---|---|
| $\alpha_x$ | -0.089 | -0.019 | 0.008 | -0.010 | -0.074 |
| $\beta_x$ [cm] | 1.01 | 1.01 | 1.01 | 1.02 | 1.03 |
| $\alpha_y$ | -0.063 | 0.003 | 0.007 | -0.024 | -0.058 |
| $\beta_y$ [$\mu$m] | 102 | 102 | 101 | 101 | 101 |
| $\eta_y$ [$\mu$m] | -110 | -20 | 12 | -28 | -153 |

Table 1. Results of Matching

The final optics is shown in Fig.6. Beam travels from the left to the right. The initial point is supposed to be the end of the present extraction line. Accidentally, the dispersion at the final sextupole magnets is almost zero. This means the chromatic correction is done by the sextupole pair upstream and the down stream one plays the role of the geometric aberration cancellation. It does not prevent the experimental test of the new final focus optics. And it provides completely dispersion free interaction point; $\eta = \eta' = 0$. The total length of the beam line is about 36.6 m that is so short as can be contained in the Assembly Hall.

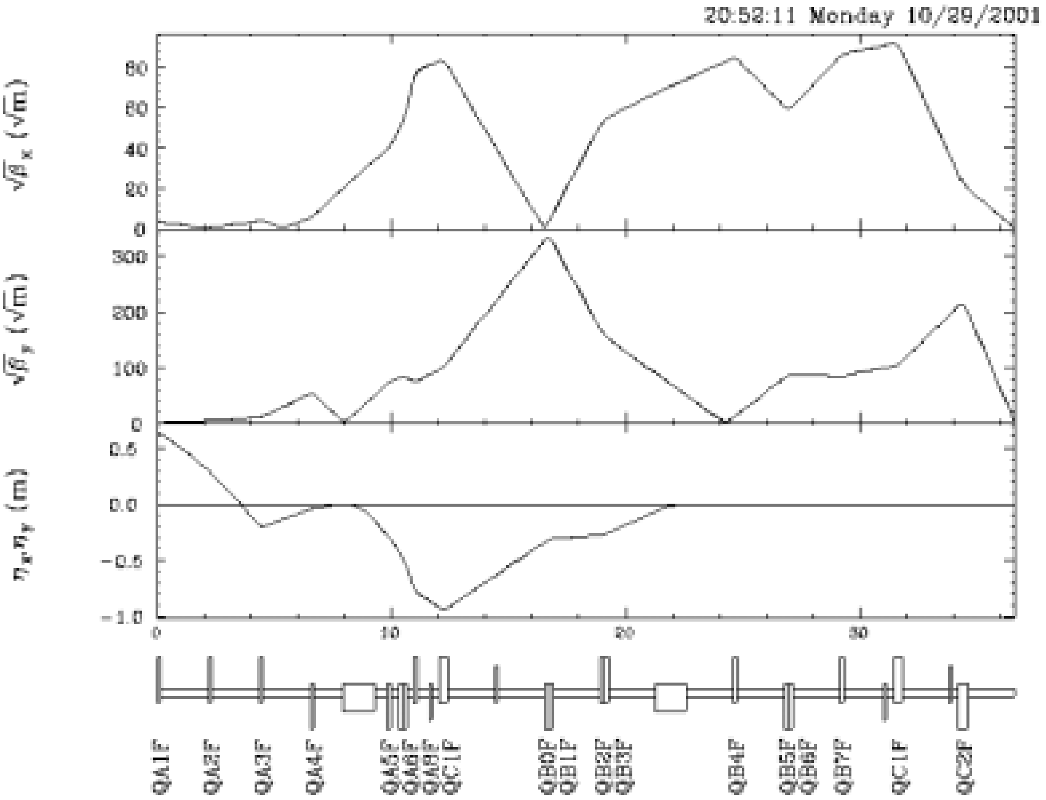
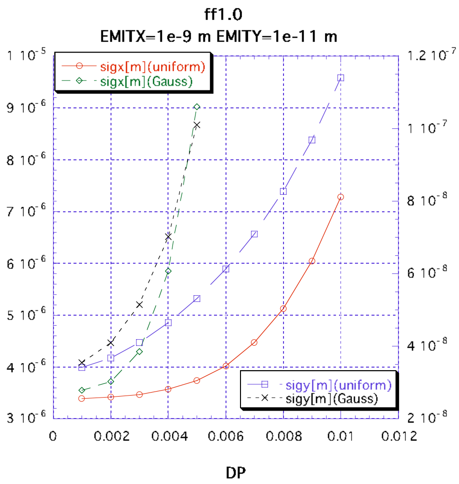



Fig.6  ATF Final Focus Optics

The performance of the final focus system was checked by tracking simulation. Number of particles was 1000, and the initial condition that $\varepsilon_x$=1nm, $\varepsilon_y$=10pm and $\delta$=0.1% was assumed. The horizontal and vertical beam size at the interaction point was 3.42μm and 36.8nm, respectively. These are almost the goal values.

The beam size dependence on the initial condition was studied and shown in Fig.7 and Fig.8. In the Fig.7, the beam size at the interaction point is shown with the various initial momentum spread DP. Case of uniform distribution is also shown in the figure, however, DP of which is the full width. So some scaling procedure might be required when the Gaussian and uniform distributions are compared. For the Gaussian beam, the beam size grows with the momentum spread and reaches $\sigma_x$=6μm and $\sigma_y$=70nm at DP=0.4%. Measured momentum spread at the ATF extraction line is always less than 0.1% up to the beam intensity of $10^{10}e^-$/bunch. Thus this dependence would not be a problem.



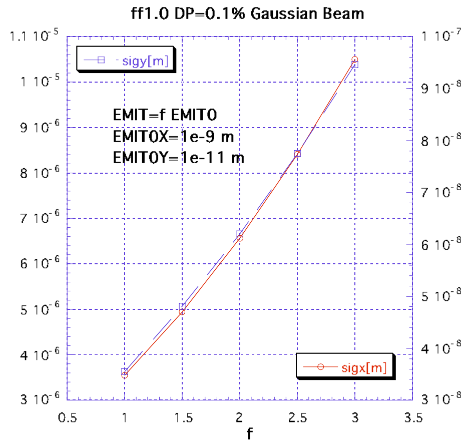




Fig.7 δ-Dependence of σ

Fig.8 ε-Dependence of σ

In the Fig.9, shown the initial emittance dependence of the beam size. The beam size becomes almost twice larger for the twice larger initial emittance. The twice larger vertical emittance is sometimes observed in the ATF extraction line. So the ATF damping ring and the extraction line must be well tuned to achieve the beam size of 30nm.

## 5. Summary

It is very important to test experimentally the principle of the new final focus system proposed in Ref.[6]. So the new final focus optics for the ATF was designed. The beam size is expected as $\sigma_x$=3.4µm and $\sigma_y$=37nm.

Tolerance of the beam line is needed to be studied. And also R&D for some hardware might be required.

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