A plan of KEK-ATF Final Focus Test Beam Line (ATF2)*

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Abstract

This report describes one of the possible programs which is being investigated as the near-future extension of Accelerator Test Facility (ATF) at KEK. In this program, a $36.6m$ long final focus test beam line, which we call ATF-2, adopts the new final focus optics proposed by P. Raimondi and A. Seryi. The goal of ATF-2 will be to test experimentally this new optics and to realize the beam size of 50nm or less for the $E = 1.5GeV$ beam extracted from ATF. We present in this short report the basic design of ATF-2, results of tracking simulation and a simulation study of a possible beam tuning procedure.

1 INTRODUCTION

ATF [1] was built to investigate the feasibility of future Linear Collider (LC), in particular, the feasibility to provide an extremely-flat multi-bunch beam to the LC main linac [2]. Recently we focus on the development of beam-tuning techniques and the stabilization of key machine components to extract the small emittance beam from the ATF damping ring. Table 1 summarizes the accelerator parameters so far achieved at ATF.

With the successful demonstration of the production of ultra-low emittance beams, the ATF group has initiated investigations on its next-stage research programs, which are collectively called ATF-II. One possibility is called ATF-1, where a bunch compressor will be added in the beam extraction line of ATF, followed by a short X-band linac unit. This allows ATF-II to serve as a complete test injector for an LC. Another possibility is called ATF-2, where the issues associated with the final focus system at linear colliders will be studied. The ATF-2 takes advantage of the ultra-low emittance beam at ATF, which offers a unique opportunity to experimentally study the LC final focus system. Fig. 1 shows a proposed plan view for ATF-II.

In the following we present the basis of the LC final focus system, the new final focus optics recently proposed, the current design of ATF-2 and finally a short summary.

2 BASIS OF LC FINAL FOCUS SYSTEM

The LC final focus system is to squeeze electron and positron beams from the main linacs to obtain maximum luminosity. The vertical size of the beams at the interaction point (IP) must be a few nm. One of the critical issues in designing the final focus optics is how to suppress the beam size growth due to the energy deviation $\delta = (E - E_0)/E_0$.

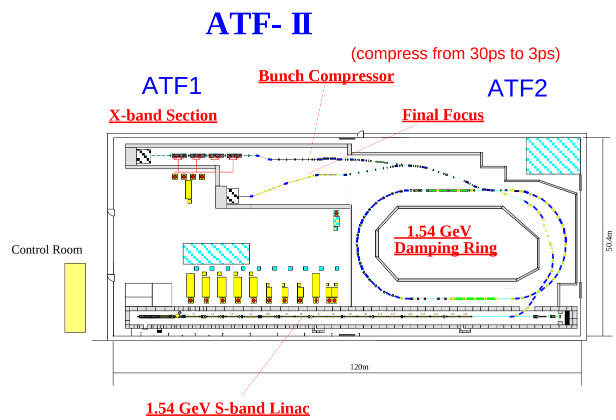

Figure 1: Layout of ATF-II

The growth is approximately expressed as;

$$\Delta\sigma^* = \xi\delta\sigma_0^* \qquad (1)$$

where ξ and σ_0^* are the chromaticity and the linear-optics beam size, respectively. For the standard final focus optics the chromaticity ξ is in the order of $10^3 \sim 10^4$. Thus, even with the small energy spread δ of $\sim 10^{-3}$, the beam size easily grows by a factor of 10. The chromaticity can be corrected by introducing sextupole magnets (sextupoles) in the dispersive regions. The sextupoles, however, have nonlinear magnetic field that also causes the beam size growth. This nonlinear effect, the geometric aberration, can be cancelled by the magnet configuration shown in Fig. 2. Only

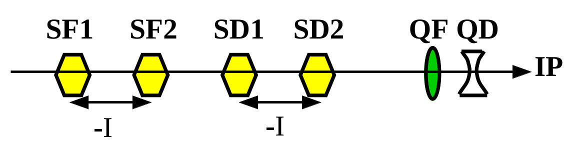

Figure 2: Cancellation of the Geometric Aberration

sextupoles and final quadrupole magnets (quadrupoles) are shown in the figure. Between them there are many other quadrupoles that are not shown. The two pairs of sextupoles are required for the correction of horizontal and vertical chromaticity. The transfer matrix between the two sextupoles of each pair is set to be $-I$ so that the nonlinear kick by the first sextupole may be cancelled by the second. This scheme of the geometric aberration cancellation

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Table 1: Achieved and design parameters of ATF.

Items	Achieved Values	Design
Maximum Beam Energy	1.28GeV	1.54GeV
Circumference	138.6 ± 0.003m	138.6m
Momentum Compaction	0.00214	0.00214
Single Bunch Population	1.2×10^{10}	2×10^{10}
COD(peak to peak)	$x \sim 2$ mm, $y \sim 1$ mm	1 mm
Bunch Length	~ 9 mm	5 mm
Energy Spread	0.08 %	0.08 %
Horizontal Emittance	$(1.7 \pm 0.3) \times 10^{-9}$ m	1.4×10^{-9} m
Vertical Emittance	$(1.5 \pm 0.75) \times 10^{-11}$ m	1.0×10^{-11} m
Multibunch(M.B.) Population	12×10^{10} m	20×10^{10} m
M.B. Vertical Emittance	$(1 \sim 3) \times 10^{-11}$ m	1.0×10^{-11} m

has been applied, with some modifications, to the JLC final focus system [3] and also in the JLC Design Study [4]. The scheme was verified experimentally at the Final Focus Test Beam (FFTB) at SLAC, where beam was successfully squeezed to $\sigma_y \sim 60nm$ [5]. A simple extrapolation from FFTB, which takes only the physical emittance into account, predicts the beam size of $36nm$ for ATF-2.

Recently P.Raimondi and A.Seryi has proposed a new final focus optics [6]. With this optics that squeezes beam as small as the standard optics does, the final focus beam line for JLC or NLC can be as short as 500 m, much shorter than those by the conventional design [7]. Therefore it is very important to verify this new optics experimentally and here ATF-2 will provide a unique opportunity.

3 NEW FINAL FOCUS SYSTEM

The new final focus system is shown schematically in Fig. 3. In Fig. 3 some quadrupoles upstream of SF2 are

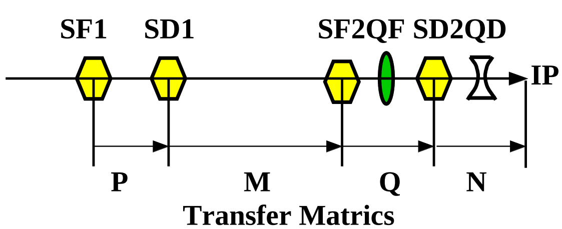

Figure 3: New Final Focus Optics

not shown. P, M, Q and N represent the transfer matrices as shown in the figure. The chromaticity is corrected by the sextupoles. Two of them are placed close to the final quadrupoles that are major chromaticity sources because of large beta-function there. The second order geometric aberration is cancelled by other two sextupoles with the transfer matrix given below;

$$MP = \begin{pmatrix} F & 0 & 0 & 0 \\ F_{21} & \frac{1}{F} & 0 & 0 \\ 0 & 0 & F & 0 \\ 0 & 0 & F_{43} & \frac{1}{F} \end{pmatrix} \tag{2}$$

$$QM = \begin{pmatrix} D & 0 & 0 & 0 \\ D_{21} & \frac{1}{D} & 0 & 0 \\ 0 & 0 & D & 0 \\ 0 & 0 & D_{43} & \frac{1}{D} \end{pmatrix} \tag{3}$$

Here the strength of the sextupoles must be chosen as $k2_{SF1} = -F^3 k2_{SF2}$ and $k2_{SD1} = -D^3 k2_{SD2}$. With this conditions, however, still remains the 3rd order geometric aberration that can be given by the coefficients of polynomial expansion of the nonlinear map including the sextupole actions. In the thin lens approximation, it is expressed as;

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

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

The indices $1, 2, 3$ and 4 represent x, p_x, y and p_y, respectively. Thus the 3rd order geometric aberration is determined only by the two transfer matrices Q and N. With adequate choice of the strength of the final quaduapoles, $U_{1244} = U_{3224}$ becomes zero and thus U_{3444} becomes small.

4 DESIGN OF ATF-2

As we have discussed above, it is important to test experimentally the new final focus optics at ATF-2. We here propose a design of ATF-2. All the calculation in this section was done by the computer program SAD developed at KEK [8].

Before we discuss the design, we summarize in Table 2 the parameters of the extracted beam from ATF. The beam emittance is same with that of the JLC design. The energy

Table 2: Design beam parameters.

Maximum Beam Energy	$1.54GeV$
Normalized Equilibrium Emittance	3×10^{-6} m
Emittance Ratio	1.0 %
Energy Spread	0.1 % (Gaussian Distribution)

is, of course, lower by two orders, resulting in the physical emittance ϵ that is larger by a factor of few hundreds. Therefore, by assuming the same β-function, we expect the beam size that is larger by a factor of few tens. Since the nonlinear effect becomes strong for larger beam size, large geometric aberration is foreseen at ATF-2. Fortunately, the momentum spread is smaller than that of JLC. The sextupole strength may be smaller and therefore the nonlinear effect might be reduced.

We choose the length of the final drift space L^* of ATF-2 to be $2m$ so that the whole beam line may be contained in the existing ATF building. The distance between QF and SD2 is also taken to be $2m$. Two sextupoles are placed at $0.3m$ from the quadrupoles. Then only two free variables of the downstream section QN, the strength of QF and QD, remain. Solving the equation for the 3rd order geometric aberration $U_{1244} = 0$ the strength of one final quadrupole is expressed by the other. We then choose the strength of QD to be $k = -0.67/m$ and the strenght of QF $k(QF) = 0.31/m$. Although $U_{3444} = 9.57$ is not at its minimum, our choise may be optimum because for smaller $k(QD)$ the QF strength rapidly increases and would introduce larger chromaticity.

Next is the section between the sextupole pairs. Quadrupoles between SF1 and SF2 are adjusted so that the equations (2) and (3) hold. Doing so we set the lattice P to be identical to Q. We then obtain $F = -1.12$ and $D = -0.893$. Here we note that the β-function can be very large in this region and thus the quadrupole fields must be very weak. Otherwise the quadrupoles would produce large chromaticity. We choose the strength of the quadrupoles to be $k < 0.2/m$.

Finally the matching section is designed. Optimizing the upstream quadrupoles and the sextupoles, the following condition is posed at the interaction point;
$\alpha_x = \alpha_y = 0$
$\beta_x = 0.01m$
$\beta_y = 100\mu m$
$\eta_x = 0m$
for $\delta = -0.2\%, -0.1\%, 0\%, 0.1\%$, and 0.2%. To cancel the 2nd order geometric aberration, we keep for the sextupole pairs the relations; $k2_{SF1} = -F^3 k2_{SF2}$ and $k2_{SD1} = -D^3 k2_{SD2}$. The beam size given in the equation (1) grows because the β-function varies with the momentum deviation. Therefore the above relations are actually almost equivalent with the chromaticity correction. The α-function, which is proportional to the derivative of the β-function, is set to be zero so that the beam size is less sensitive to the position at the interaction point.

The result of the optimization is shown in Table 3. The table shows that our optimization is successful. The strength of the two sextupoles are sufficiently weak; $K2[1/m^2] = -1.2$ and 3.5 for SF2 and SD2, respectively.

The designed optics is shown in Fig. 4. Here the beam travels to the right from the end of the present ATF extraction line. The total length of the final focus beam line is $36.6m$, which is short enough to install the whole beam line in the ATF building. As seen in the figure the dispersion at the downstream sextupoles happens to be almost zero. It means that the upstream sextupole pairs do most of the chromatic correction and the downstream ones cancel the geometric aberration. This condition provides the interaction point that is completely dispersion free. This is not a problem in testing the new final focus optics. We tested the

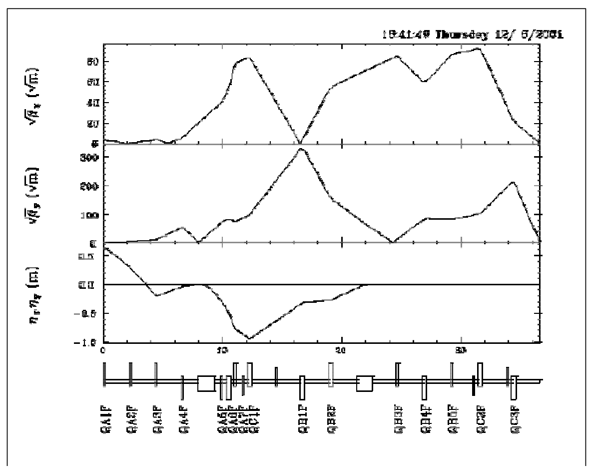

Figure 4: Final Focus Optics for ATF-2

performance of the ATF-2 optics by tracking simulation. The number of particles in the simulation was 1000 and the initial condition was assumed to be $\epsilon_x = 1nm, \epsilon_y = 10pm$ and $\delta = 0.1\%$. The horizontal and the vertical beam size at the interaction point was found to be $3.42\mu m$ and $36.8nm$, respectively. They are very close to our design goals for ATF-2 [9].

5 BEAM TUNING METHOD

We also performed tracking simulation to study the procedure of beam tuning at ATF-2. First, we did the orbit correction by steering magnets monitoring ideal BPM's at 15

Table 3: Results of Matching

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

quadrupoles. Then the longitudinal movement of the two final quadrupoles and the four sextupoles are tuned by monitoring the beam size at IP. Moving the final quadrupoles and the sextupoles, squared sum of the beam orbit error, the dispersions at the two sextupoles near IP and the dispersion at IP was minimized. This tuning process was repeated four times. Finally we obtained the beam size of $47nm$ at IP with the confidence level of 90% as shown in Fig. 5.

The dispersion correction should not be made at the beginning because the correction for rolling error of the quadrupoles requires strong steering fields. From Fig. 5, one can see that the rotational alignment of the quadrupoles is essential to achieve the final beam size. We have known at ATF that the initial alignment for the magnet rotation can be done to the accuracy of $\pm 0.02mrad$ (peak-to-peak). We expect that the $37nm$ beam size at IP will be possible at ATF-2 if the following alignment accuracies can be acheived: the horizontal alignment within $50\mu m(rms)$, the vertical $30\mu m(rms)$, the longitudinal $100\mu m(rms)$ and the rotational alignment $20\mu rad(rms)$. We need, however, further studies on the long term diffusion of the alignment errors. We have found at ATF the big diffusion in the rotational error $0.15mrad$ (peak-to-peak) after two years of operation.

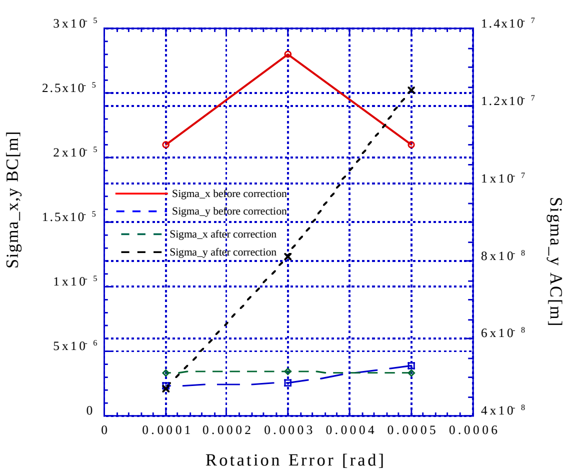

Figure 5: Tuning of the ATF-2 Final Focus Beam Line

6 SUMMARY

To test experimentally the principle of the new final focus system proposed in Ref.[6], we plan to add the final-focus test beam line ATF-2 in the next phase of ATF, ATF-II. The optics of ATF-2 has been designed adopting the new optics and tested by tracking simulation. The beam size at IP is expected to be $\sigma_x = 3.4\mu m$ and $\sigma_y = 37nm$. Further studies such as the tolerance of the beam line and some hardware R& D are necessary.

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