



ATF2 for Final Focus Test Beam for Future Linear Colliders

S.Kuroda^{a,b}, ATF2 Collaboration

^aKEK, Tsukuba, Ibaraki, Japan

^bSOKENDAI, Tsukuba, Ibaraki, Japan

Abstract

In future linear colliders, extremely small beam size is required at collision point for high luminosity. For example, it is of order of nanometer in ILC(International Linear Collider). ATF2 is a project at ATF(Accelerator Test Facility) in KEK which demonstrates performance of final focus system experimentally. ATF2 beam line is a prototype of ILC final focus system where the local chromaticity correction scheme is adopted. The optics is basically the same and the natural chromaticity, too. Thus the tolerance of magnet alignment and field error is similar for both of the beam lines. We report here observation of small beam size of about 45nm there. We also report plan for smaller beam size with higher beam intensity.

Keywords:

1. Introduction

It is very important to produce very small beam size at the interaction point in linear colliders for high luminosity. For example in ILC(International Linear Collider) [1], the vertical beam size is designed to be 5.8nm at the interaction point(IP). In such beam line, the chromatic effect to the IP beta function should be seriously taken care of. Furthermore the beam position jitter must be well controlled to the order of nm, which is done by fast intra-train feedback.

ATF(Accelerator test facility) is an accelerator in KEK for accelerator R&D. Figure 1 shows the ATF accelerator layout. It consists of a photo-cathode RF gun, a 1.3GeV linac with S-band normal conducting accelerating structures, a damping ring and an extraction line followed by a final focus test line. The damping ring can produce very low emittance beam[2, 3], which can be used to test the final focus system. This final focus system was designed to study the ILC one. The project of this study is called ATF2[4] and carried out by international collaboration in all phases; design, construction and operation.

There are two major goals for the ATF2 project;

Goal1; Demonstration of the final focus method called Local Chromaticity Correction.

Goal2; Demonstration of the beam position stabilization using intra-pulse (bunch-by-bunch) feedback system.

For the Goal1, target beam size at the focal point is 37 nm. Study has been done for years, and the beam size less than 70nm was measured in 2012[5]. In the following sections, the result of the recent experiment is reported. This report is slightly updated from IPAC14[6].

For the Goal2, intra-train feedback test has been successfully done in the middle of the ATF2 beam line. The jitter of the second bunch is suppressed well. In order to stabilize the beam at the focal point, high resolution BPMs were installed at the IP in 2013. Study has started with these BPMs.

2. ATF2 Final Focus Test Beam Line

In order to produce such small beam size as order of nm, the chromatic effect should be carefully treated. Chromaticity creates beam size growth through momen-

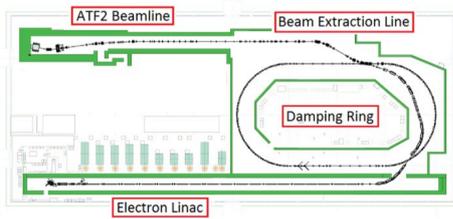


Figure 1: ATF accelerator layout

tum dependence of beta function;

$$\beta\left(\frac{\Delta p}{p}\right) \approx \beta(0)\left(1 + \left(\xi\frac{\Delta p}{p}\right)^2\right)$$

, where Δp is momentum deviation and ξ is chromaticity. The contribution to the chromaticity by the final quadrupole magnet is $\frac{L^*K}{\beta^*}$, where L^* is the distance between the quadrupole magnet and IP, K is normalized integrated strength of the magnets and β^* is the beta function at IP. If L^* and β^* are of order of m and 0.1mm, the contribution will be order of 10000 assuming KL^* is of order of 1. For momentum spread of 0.1%, the beam size $\sigma^2 = \beta\epsilon$ becomes so huge, where ϵ is emittance. Of course, there might be other contribution by quadrupole magnets at high beta section. This chromaticity can be corrected by introducing sextupole magnets in dispersion section. However, the sextupole magnets introduce additional aberration, which also must be corrected. There are two method to correct the whole effect; one is called 'global correction' and the other 'local correction' [7].

In the global correction method, there are two dedicated regions upstream to correct chromaticities in horizontal and vertical planes respectively. In each region, there are two sextupole magnets, and the transfer matrix between them is set to -I to cancel out the additional aberration(geometrical aberration). Final focus system based on this method was tested by the project FFTB at SLAC[8].

In the local correction method, two sextupole magnets are placed next to the final quadrupole magnets which produce much chromaticity. So there must be dispersion here. Dispersion crosses zero exactly at IP, but the dispersion slope remains finite. The geometric aberration is cancelled by other sextupole magnets upstream. In this case, all the aberration is not cancelled, but some important ones are corrected to produce small

beam size. This method has been shown to have larger momentum acceptance and less beam halo[7] and ILC adopted this scheme. ATF2 is a project to test this method experimentally.

Thus the optics design of ATF2 is scaled down from the ILC one. Magnet configuration is almost the same as ILC one. Figure 2 shows the optics of ILC and ATF2 final focus system. Some important parameters are listed in Table 1. The natural chromaticity to be corrected is almost the same both for ILC and ATF2. Therefore the tolerance for alignment and magnetic field error is similar in both of the accelerators[4].

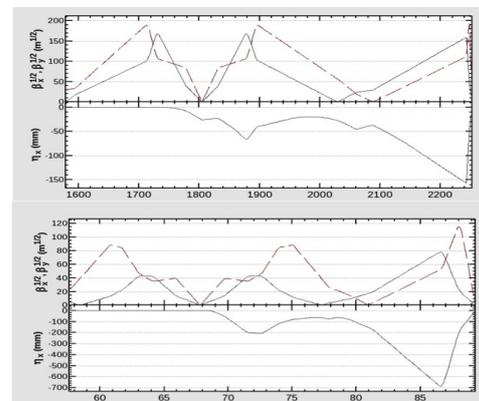


Figure 2: Optics of ILC(up) and ATF2(down) final focus line. Electron goes from left to right. In each figure, horizontal(line) and vertical(dashed) beta function are shown in upper half and the dispersion in lower half.

Parameter	ILC	ATF2
Beam Energy[GeV]	250	1.3
Energy Spread (e^+/e^-)[%]	0.07/0.12	0.06 0.08
$L^*(\text{SiD/ILD detector})[\text{m}]$	3.5/4.5	1.0
$\beta_x^*[\text{mm}]$	11	4
$\beta_y^*[\mu\text{m}]$	0.48	0.1
$\epsilon_x[\text{nm}]/\gamma\epsilon_x[\mu\text{m}]$	0.02/10	1.1/2.8
$\epsilon_y[\text{pm}]/\gamma\epsilon_y[\text{nm}]$	0.07/35	12/31
$\xi_y(\text{SiD/ILD detector})[\text{m}]$	7300/9400	10000

Table 1: Comparison of parameters of ILC and ATF2. L^* is a distance between final quadrupole magnet and IP. β^* is a beta function at IP. $\epsilon/\gamma\epsilon$ stand for physical and normalized emittance, respectively. ξ is chromaticity.

Finally, the normalized vertical emittance is quite similar in both machines, though the energy is so much different. In this point of view, ATF is a good place to test the ILC final focus system. Physical emittance in the ATF damping ring is measured to be around 10pm in the ATF2 experiment described in this paper.

3. IP beam size monitor

For the Goal1, design vertical beam size of 37nm should be measured. The beam size monitor used at FFTB experiment was modified for this purpose. The monitor was originally developed by T.Shintake[9].

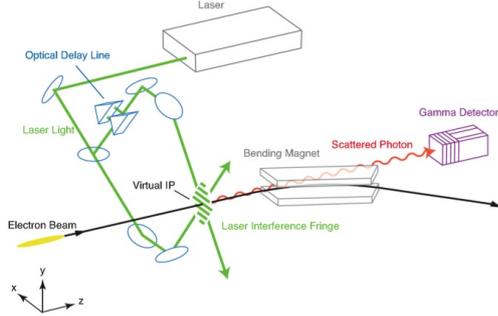


Figure 3: Schematic view of IP beam size monitor[10]

Figure 3 shows the monitor (IPBSM; IP Beam Size Monitor) schematically. A laser light is divided in two and they cross at the IP with angle θ to produce interference pattern with pitch $h = \frac{\lambda}{2\sin(\theta/2)}$, where λ is laser wavelength. Electron beam collides this laser interference pattern at IP. In case that the electron beam size is much smaller than this fringe pitch, intensity of the gamma ray produced by this scattering depends much on where of the pattern electrons hit. The fringe phase ϕ can be changed by changing path difference of the two laser beam. On the other hand, when the electron beam size is huge, larger than the fringe pitch, for example, the gamma ray intensity is almost constant wherever electrons hit. Thus the electron beam size can be measured.

When scanned with phase ϕ , gamma intensity shows sinusoidal pattern. An example of this pattern is shown in Figure 4. When fitted this pattern by sinusoidal function, modulation M can be define as;

$$M = \frac{\text{peak} - \text{bottom}}{\text{peak} + \text{bottom}}$$

If the electron beam distribution is Gaussian with beam size σ_y , this modulation M can be expressed as;

$$M = |\cos\theta| \exp(-2\pi^2 \sigma_y^2 / h)$$

and this equation can be solved for σ_y as;

$$\sigma_y = (h/2\pi) \sqrt{2\ln(|\cos\theta|/M)} \quad (1)$$

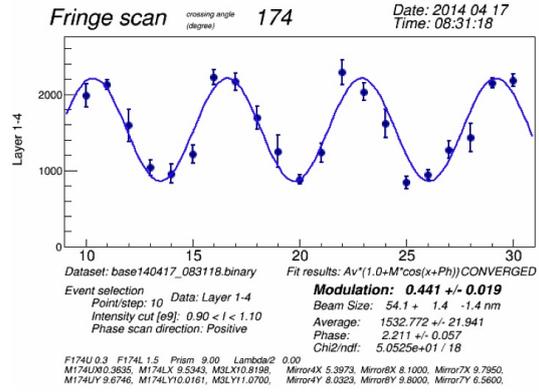


Figure 4: An example of fringe scan measurement. Gamma ray intensity is plotted as a function of the fringe phase.

Using this equation, vertical beam size can be calculated from modulation M . It is obviously understood that large M corresponds small beam size.

The laser wavelength of the monitor is 532nm. Laser crossing angle θ can be changed 2-8, 30 and 174 degree. Here the angle can be changed continuously from 2 to 8 degree. In Figure 5, modulation is plotted as a function of beam size. Beam size larger than $1\mu\text{m}$ can be measured in 2-8 degree mode. When the beam size goes smaller by beam tuning, it is changed to 30 or 174 degree mode. Thus the monitor can be used in the range from a few μm down to 20nm.

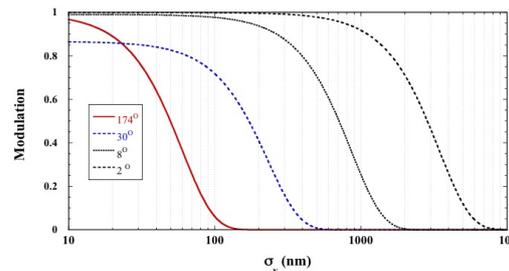


Figure 5: Modulation vs beam size. Black, blue and red line correspond to the crossing angle of 2-8, 30 and 174 degree, respectively.

4. Beam tuning

After orbit correction, beam tuning starts upstream extraction line. There are multi-OTR system[11] in non

dispersion section. The system measures beam profile using OTR(Optical Transition Radiation) at four points with adequate phase advance. Twiss parameter and emittance can be measure with this monitor and optics mismatch can be corrected. For precise measurement, dispersion and coupling should be corrected before. Vertical dispersion can be corrected by two skew quadrupole magnets in horizontal dispersion section, and coupling by other four skew quadrupole magnets upstream.

In the final focus line, scan of the final quadrupole magnets strength makes the beam size down to a few μm . Then fine tuning of the beam size starts. In the final focus line, all magnets sit on movers, which can change horizontal and vertical position and roll remotely. Horizontal movement of sextupole magnets can change waist position or $\alpha_{x,y}$, while vertical one can change vertical dispersion and x-y coupling. The combination of sextupole magnets for the above knob can be orthogonalized, i.e. chosen independent for each other, and called 'linear knob'. First the beam size is minimized by scanning these 'linear knobs'. There are another knobs. They are combinations of sextupole and skew sextupole magnet strength, and called 'non-linear knob'. They correct higher order aberrations. Fine tuning of chromaticity is actually done by the 'non-linear knob'. Iteration of these 'linear' and 'non-linear' knob tuning makes the beam size smaller and smaller[12, 13]. Now about 1 day(24 hours) tuning squeezes the beam size down into the range of IPBSM 174 degree mode(below 70nm) even after long shutdown.

5. Results of small beam size measurements

Figure 6 shows history of minimum beam size. Minimum beam size has been going down and now it is below 50nm. Plotted are the beam sizes directly calculated from equation (1) and no correction is applied. The electron beam intensity in this period is about 1×10^9 per bunch, and emittance measured in the damping ring is around 10pm. Improvement of IPBSM is one of the important contribution to the progress, including laser stabilization.

There were also works in beam line in this period. Higher multi-pole field of horizontally focussing final quadrupole(QF1) magnet affect the beam size significantly. Here the beta function is as huge as of order of 10000m and the beam size is big, so the beam is very sensitive to the non-linear multi-pole magnetic field. Actually, the multi-pole field measured was beyond the tolerance. One countermeasure is to change optics so that the horizontal beta function at IP is 10

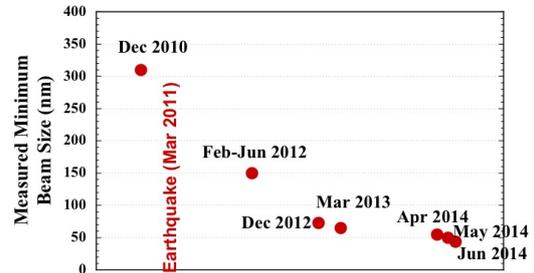


Figure 6: History of measured minimum beam size.

times bigger than original design[14]. With this optics, the beam size at QF1 can be smaller. The other thing is to replace the QF1 magnet itself with larger aperture one which improves field quality. It was done in November 2012.

One of the sextupole magnet coils was turned out to be shorted. Since 2013, this magnet had been used as one with the weakest strength setting. In April 2014, a new sextupole magnet setting was calculated so that the magnet was turned off.

There have been vacuum work to improve impedance which will be discussed later. Suspicious components to have high impedance were removed or replaced, such as reference cavity for cavity BPM(Beam Position Monitor), vacuum port, and so on. This work was successively done in shutdown period.

Finally, stabilization of the electron beam was found to be very important. This is not meant for Goal2, but for slow orbit drift in beam tuning or measurement. So orbit feedback system by corrector magnets was introduced, which contributed much for the results.

Figure 7 shows the recent results of the beam size of about 44nm measured by IPBSM 174 degree mode. Histograms are the results of 10 times measurement and the numbers upper right are average and standard deviation. The beam size is directly calculated from equation (1) and no correction is adopted. The results are tabulated in Table2.

	Average	Standard deviation
Modulation	0.58	0.05
Beam size(nm)	44	3

Table 2: Recent results shown in Figure 7. Measurement was done by IPBSM 174 degree mode.

The measurement is affected by many errors such as drift of electron beam and/or laser beam. Such error analysis should be done and some results are reported in reference[15]. However these errors generally reduce the measured modulation and the resulted beam size is bigger. So the measured beam size is expected to be smaller than 44nm.

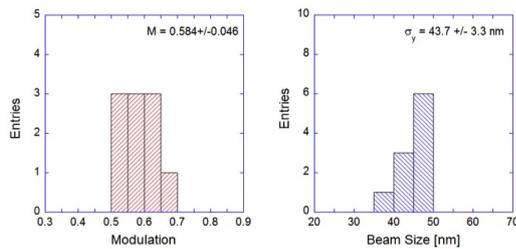


Figure 7: Recent results of beam size measurement by IPBSM 174 degree mode. The left histogram shows modulation distribution of 10 times measurement and the right one is beam size directly calculated from equation (1).

6. Remaining issues for Goal1

Beam size of 44nm is close to the design 37nm, but not yet reached. In order to make smaller beam, precise measurement should be necessary. The IPBSM are thought to have some systematic errors[15] and this analysis is an important issue. Stabilization of electron beam is another important issue. Orbit change in measurement gives wrong signal corresponding to different phase ϕ . Furthermore orbit change in sextupole magnets spoils correction of aberration. High resolution BPMs were installed in IP region recently, and these will be used to study the electron beam stability.

Apart from pursuit of minimum beam size, intensity dependence of the beam size is another thing to be improved. Figure 8 shows the measured modulation as a function of electron beam intensity. With higher intensity, modulation rapidly decreases which means that beam size blows up. That is why the beam tuning and measurement was done in low intensity region such as 1×10^9 per bunch. This is thought to be wakefield effect. As is mentioned before, much effort has been done to remove possible wake source. The dependence is becoming weaker, however, still remaining. In future linear colliders, the wakefield effect can be neglected because

the energy is much higher and better vacuum chamber material such as Cu or Al is used (in ATF2, stainless steel is used for that). So this might be a problem intrinsic to ATF2. But weakening this effect is now important issue for ATF2. The OTR monitor position was found to have some effect to the intensity dependence these days. The impedance of the monitor will be calculated and will be improved in next operation.

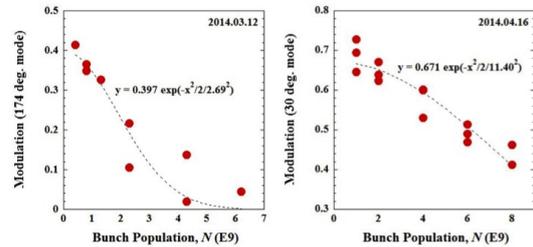


Figure 8: Intensity dependence of modulation. The left figure is measured in IPBSM 174 degree mode, and the right one is in 30 degree mode.

7. Electron beam stabilization(Goal2)

Bunch by bunch stabilization of the electron beam is another goal of ATF2. In ATF, 2 or 3 bunch operation is possible with bunch spacing 150 to 250ns. Position of these bunches are well correlated. When there is pulse by pulse jitter, looking at the first bunch position, next bunch can be corrected. Here the key point is the latency of the feedback system, which must be shorter than the bunch spacing.

The feedback system has been tested at the upstream of ATF2 line. The feedback system worked well and made jitter of the second bunch significantly smaller[16]. Further study of stabilization of nm level has been started already in 2013. High resolution BPMs are installed at IP, and now their basic performance is tested. Feedback study using these BPMs will be done in the future.

8. Conclusion

ATF2 project has been operated for years. Beam tuning method to squeeze the beam is almost established. So far beam size of 44nm has been measured in low intensity. Study will continue to make the beam size

smaller and with high intensity. Fast feedback system upstream has been demonstrated to suppress beam jitter. Next step is to stabilize beam to nm order level at IP.

9. Acknowledgment

The authors would like to thank all members of ATF collaborations and managements of KEK and all other collaborating institutes.

References

- [1] ILC Technical Design Report, <https://www.linearcollider.org/ILC/Publications/Technical-Design-Report>
- [2] K. Kubo et al., Phys. Rev. Lett. 88, 194801 (2002)
- [3] Y. Honda et al., Phys. Rev. Lett. 92, 054802 (2004)
- [4] B. I. Grishanov et al. (ATF2 Collaboration), ATF2 Proposal, (2005)
- [5] G. White et al., Phys. Rev. Lett. 112, 034802 (2014)
- [6] K. Kubo Proc. IPAC14, WEZA01 Dresden, Germany (2014)
- [7] P. Raimondi and A. Seryi, Phys. Rev. Lett. 86, 3779 (2001)
- [8] V. Balakin et al., Phys. Rev. Lett. 74, 2479 (1995)
- [9] T. Shintake, NIM A 311, 455 (1992)
- [10] Y. Yamaguchi, Master thesis at Graduate School of Science, The University of Tokyo, 2010
- [11] J. Alabau-Gonzalvo et al., Proc. IPAC12, MOPPR044, 879, New Orleans, USA (2012); <http://jacow.org>
- [12] G. R. White, S. Molloy, M. Woodley, Proc. EPAC08, MOPP039, Genoa, Italy (2008); <http://jacow.org>
- [13] T. Okugi et al., PRST-AB 17, 023501 (2014)
- [14] E. Marin et al., PRST-AB 17, 021002 (2014)
- [15] J. Yan et al., NIM A 740, 131 (2014)
- [16] P. Burrows et al., these proceedings, Proc. ICHEP14 (2014)