ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-WEZA01

TOWARDS INTERNATIONAL LINEAR COLLIDER: EXPERIMENTS AT ATF2

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Abstract

For linear colliders, realizing extremely small and stable beam is essentially important. At ILC (International Linear Collider), designed vertical beam size and required position stability at the interaction point is nanometer level. In ATF (Accelerator Test Facility) at KEK, study of the final focus system has been performed using small emittance beams extracted from the damping ring. The project is called ATF2. The ATF2 beam line is designed as a prototype of the final focus system of ILC, with basically the same optics, similar beam energy spread, natural chromaticity and tolerances of magnetic field errors. Its design, construction and operation have been performed as an international collaboration. We have demonstrated the local chromatic correction method, which will be used for ILC, and observed the vertical beam size about 55 nm. Test and demonstration of intra-pulse orbit feedback has been successfully performed in the middle of the ATF2 beam line. For demonstration of nm level stable beam, high resolution beam position monitors were installed around the focal point. Here, we report our achievement, status and future plans.

INTRODUCTION

For linear colliders, realizing extremely small and stable beam at the collision point is essentially important for high luminosity. At ILC (International Linear Collider), vertical beam size at the interaction point (IP) is designed as 5.8 nm (in sigma of a Gaussian-like beam profile). For colliding the two beams, the relative vertical beam position is to be stabilized using intra-pulse orbit feedback. The jitters are required to be as small as 2 nm (rms) [1].

In ATF (Accelerator Test Facility) at KEK, using the small emittance beam extracted from the damping ring [2,3], study of the final focus system has been performed. The project is called "ATF2", since a part of ATF beam line was modified and extended for this project [4]. The ATF2 beam line optics is designed as same as the final focus system of ILC, with the similar beam energy spread (about 0.1%) and natural chromaticity (about 10000), tolerances of magnetic field errors for achieving the designed beam size are also similar. This project has been performed as an international collaboration in all phases, design, construction and operation.

There are two goals of the project as follow.

- Goal-1: Demonstration of the final focus method called "Local Chromaticity Correction".
- Goal-2: Demonstration of the beam position stabilization using intra-pulse (bunch-by-bunch) feedback system.

For the Goal-1, we had confirmed the vertical beam size smaller than 70 nm with low intensity by December 2012 [5]. During following experiments, tuning procedure for small beam size has been established, and minimum beam size is gradually decreased to smaller than 60 nm. In recent operation, such small beam size has been routinely observed.

However, the observed beam size was still larger than that expected ideal size from the designed optics and the beam emittance, which is 37 nm. We have observed several effects which can explain the discrepancy, such as the fact that the beam size strongly depends on the beam bunch intensity, which had not been expected. Investigations of reasons of these problems are ongoing.

For the Goal-2, test and demonstration of intra-pulse orbit feedback has been successfully performed in the middle of the ATF2 beam line. The performance of the feedback was limited by the resolution of the beam position monitors (BPM) and bunch-by-bunch uncorrelated orbit jitter. For demonstration of stabilization in nm-level, high resolution BPM were installed around the focal point in the summer of 2013 and commissioning and basic performance studies of the BPM system has been started.

ATF2 BEAM LINE AND OPTICS

Figure 1 shows layout of ATF, which consists of a photo-cathode RF gun, a linac using S-band normal conducting accelerating structures, a damping ring and an extraction beam line followed by a final focus system.

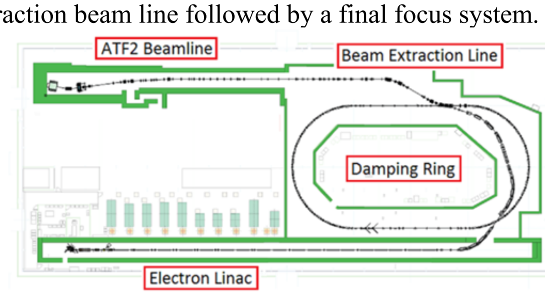

Figure 1: ATF layout.

Three essential conditions for achieving small beam size at the focal point are (1) small emittance of the beam, (2) small aberration in the final focus beam line and (3) small contributions of other effects such as wakefields, etc.

As for the condition (1), we had confirmed production of extremely low emittance beam in the damping ring [2,3]. In recent operations, usual vertical emittance measured in the damping ring is about 8 pm (beam energy 1.3 GeV), which corresponds to the same normalized emittance designed in the ILC damping rings (physical

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emittance 2 pm for the beam energy 5 GeV) [1]. Assuming the vertical emittance of the extracted beam is 12 pm including some emittance growth, vertical beam size at the focal point is calculated as 37 nm for the designed vertical beta-function at the point, 0.1 mm.

ATF2 was designed as a prototype of the ILC final focus system with almost the same magnet configuration. They have also similar natural chromaticity (see later discussion) and similar tolerances for field errors [4]. Table 1 compares important design parameters of the final focus system of ILC and ATF2.

Table 1: Design Parameters of ILC and ATF2 Final Focus

Parameter	ILC	ATF2
Beam Energy [GeV]	250	1.3
Energy Spread (e^+/e^-) [%]	0.07/0.12	~0.07
Final quad – IP distance (L^*) (SiD/ILD detector) [m]	3.5/4.5	1.0
Vertical beta function at IP (β^*_y) [mm]	0.48	0.1
Vertical emittance [pm]	0.07	12
Vertical beam size at IP (σ^*_y) [nm]	5.9	37
L^*/β^*_y (~natural vertical chromaticity, SiD/ILD detector)	7300/9400	10000

As for the condition (2), one of the most important issues in designing the final focus of linear colliders is the chromatic aberration which is induced by chromaticity, the focal position dependence on the particle energy. Without correcting the chromatic aberration, beam energy spread causes beam size blow up at the interaction point because particles with different energies are focused at different positions.

Since the vertical beam size is much smaller than the horizontal beam size at ILC and ATF2, the vertical chromaticity is critically important. It is mostly contributed from the final vertically focusing quadrupole magnet, which is roughly expressed as $\xi_y \approx L^* / \beta^*_y$, where L^* is the distance between the final focusing magnet and the interaction point, and β^*_y the beta-function at the interaction point.

Chromaticity makes the beam size at IP large. Roughly, for small residual chromaticity, the size at IP for a beam with energy spread σ_δ is expressed as $\sigma(\sigma_\delta) \sim \sigma(0)\sqrt{1+(\xi\sigma_\delta)^2}$. In ATF2, the vertical natural chromaticity is about 10^4, which is approximately the same as ILC. The beam energy spread in ATF2 is also similar to that in ILC, about 0.1%.

Other second order aberrations and higher order aberrations can be also significant sources of beam size growth. Some of the aberrations can be induced by sextupole magnets (see the following section) and some are from field errors of magnets in the beam line. The beam optics should be designed with good cancellations of the aberrations and ability of correction of the errors. The recipe of designing the final focus beam line optics used for ILC and ATF2 was described in [6] and a systematic optimisation method was proposed in [7].

CHROMATIC CORRECTION

Chromaticity created in quadrupole fields can be compensated by introducing sextupole fields at locations where horizontal dispersions (η_x) are not zero.

There are two different methods of chromatic correction, the "global correction" and the "local correction" [8]. In the global correction method, two regions are inserted in the beam line, which are dedicated for producing chromaticities differently in horizontal and vertical planes. Each region consists of two sextupole magnets, and the beam optics is designed to make their locations highly symmetric. This symmetry makes most of undesired higher order aberrations be cancelled out within each region. Final focus system based on this method was tested as the project FFTB at SLAC [9].

In the local correction method, a pair of sextupole magnets is interleaved with the final quadrupole doublet. Geometrical aberrations and the second order dispersion are compensated by adding at least two other sextupole magnets upstream. The local correction method is chosen for ILC, mainly because this method requires much shorter beam line for the final focus system. This method is also expected to have a better energy acceptance and a less beam halo [8]. On the other hand, the optics of the local correction method is more complicated compared with the global method because the optics for the chromatic correction has no obvious symmetries and no clear horizontal-vertical separation [6,7]. These complications had been expected to make both designing the beam line and the beam tuning process more difficult and need to master the design and tuning procedures has been one of the motivations for creating the ATF2. The new design and tuning methods have been successfully developed and tested at the ATF2 project at KEK.

BEAM SIZE MONITOR AT FOCAL POINT

The designed vertical beam size at the final focal point of ATF2 is 37 nm. Measuring such small beam size is a major challenge of the project. We reconstructed the beam size monitor used at FFTB using laser interference and inverse Compton scattering for measuring small beam size (called IPBSM, Interaction Point Beam Size Monitor, or Shintake Monitor, invented by T. Shintake [10]).

Figure 2 shows IPBSM schematically. Laser light (wavelength λ) is divided into two by a half mirror and crossed at IP with a certain angle (θ). Interference fringes with contrast $|\cos\theta|$ and pitch $d = \lambda/(2\sin(\theta/2))$ are created. The electron beam is collided with the light and gamma-rays are created as the results of inverse Compton scattering and detected by a gamma-ray detector located downstream. The fringe phase (ϕ) is scanned by changing the length of one of the light paths, and the gamma-ray intensity is recorded as a function of the fringe phase.

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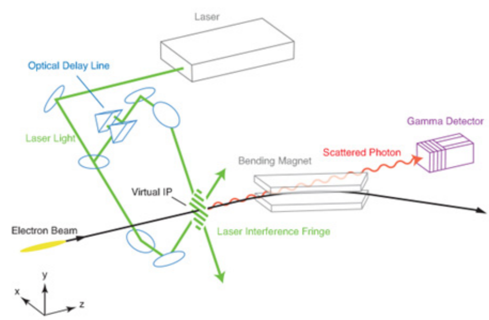

Figure 2: Beam size monitor at the focal point, called IPBSM, or Shintake Monitor [11].

The intensities measured scanning the phase ϕ are fitted with a function of ϕ as:

$$G(\phi) = G_0\left(1 + M\cos(\phi + \phi_0)\right) , \quad (1)$$

with three free parameters (G_0, ϕ_0, M) .

The modulation, M , is a product of the contrast of the interference and the relative amplitude of Fourier component at $2\pi/d$ of the electron profile. For a Gaussian electron beam with its rms size σ_y , the modulation can be expressed as

$$M = \left|\cos\theta\right|\exp\left(-2\pi^2\sigma_y^2/d^2\right) . \quad (2)$$

In a realistic case, there are various possible sources to reduce the apparent modulation [12]. These sources can be taken into account by a correction factor (C_M). The beam size is expressed as

$$\sigma_y = (d/2\pi)\sqrt{2\ln\left(C_M\left|\cos\theta\right|/M\right)} . \quad (3)$$

C_M is expected to be slightly smaller than 1, but in the following, we assume C_M =1 since it is not accurately known yet and evaluated beam size from the modulation can be slightly over estimated.

At ATF2, the wavelength of the laser is reduced from 1064 nm, used in FFTB, to 532nm for better sensitivity for small beam sizes. We also have three different modes of crossing angles, 174, 30, and 2-8 degree. In the last mode, the crossing angle can be changed continuously between 2 and 8 degrees. As the result, the beam size monitor can cover a wide range of the beam sizes, from about 25 nm to 6 μm [13].

BEAM TUNING METHOD

Small emittance beam extracted from the damping ring is used for our experiment. The beam property from the damping ring is measured in the extraction line, upstream of the final focus beam line. Dispersion, emittance, Twiss parameters and x-y coupling are measured and corrected. The vertical dispersion (including in the final focus line) is corrected using a pair of skew quadrupole magnets and setting a closed orbit bump. The skew quadrupole magnets are located at designed horizontal dispersion. The horizontal and vertical emittances and Twiss parameters are evaluated from measured beam sizes at 4 locations using a multi-OTR system [14] which consists of 4 OTR (Optical Transition Radiation) beam profile monitors. Optics mismatch is corrected based on these measurements adjusting strengths of some quadrupole magnets. The x-y coupling is corrected by using a pair of skew quadrupole magnets upstream and additional 4 skew quadrupole magnets located upstream of the OTR monitors. The correction is performed based on the beam profile measurements using the OTR monitors.

In the final focus line, all quadrupole magnets and sextupole magnets are set on remotely controlled movers of three degrees of freedom (vertical and horizontal offset and rotation around the beam axis). The beam orbit is flattened by using some of the dipole corrector magnets and moves of a few quadrupole magnets. Minimization of the beam size at IP is performed using moves of sextupole magnets which are for adjusting the linear optics, such as focal position, dispersion and x-y coupling ("linear knobs"). Then, strength change of sextupole magnets and skew sextupole magnets are used for correction of the second order optics, such as chromaticity, second order dispersion and higher order geometric aberrations ("non-linear knobs") [15,16].

Figure 3 shows examples of recent knob scans. Each graph shows modulation of IPBSM signal as function of strength of each knob.

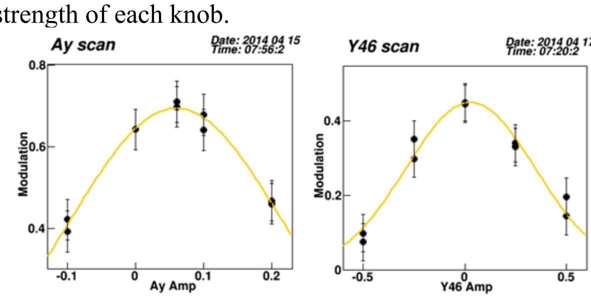

Figure 3: Examples online figures of knob scans. IPBSM modulations as functions of strengths of tuning knobs (a.u.). Left: A linear knob scan with IPBSM crossing angle 30 degrees. Right: A non-linear knob scan with IPBSM crossing angle 174 degrees. After each scan, "knob" was set at the peak of the fitted curve.

ACHIEVEMENT OF SMALL BEAM SIZE

Figure 4 roughly shows the history of measured minimum beam size. While improvement of IPBSM is one of the most important factors of this progress, some beam tuning efforts also have contributed as follow.

It was found that multi-pole fields of quadrupole magnets affected the beam size. Especially, the magnetic field quality of the final horizontally focused magnet (QF1), where the horizontal beam size is the largest and x-y coupling strongly affects the vertical beam size at IP, was not acceptable. In November 2012, this magnet was replaced by a new one with larger aperture and much better field quality. We also increase horizontal beta-function at IP by factor 10 compared with the nominal design, which reduces horizontal beam sizes at almost all the quadrupole magnets and reduces effect of x-y coupling [17].

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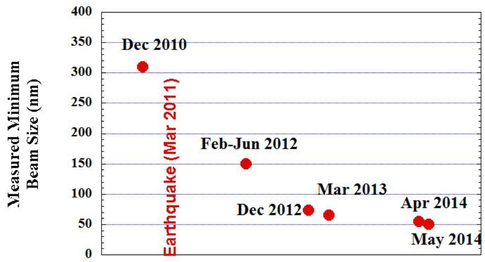

Figure 4: History of measured minimum beam size.

We had observed strong skew-quadrupole corrector setting was necessary for minimize the beam size, which suggested unexpected multi-pole field error. From analysis of the corrector settings, the locations of the field error were estimated and we found a coil of the strongest sextupole magnet (SD4) was shorted. In January 2013, this magnet had been swapped with the weakest sextupole magnet (SF5). After that, the strong skew-sextupole correction has not been necessary. In recent operation, from April 2014, we have used a setting of the second order optics with this magnet turned off, for avoiding remained possible field error.

It is also important to make the beam orbit stable during the beam tuning and measurement. We introduced an orbit feedback in the final focus line and efforts for its optimisation have contributed to the improvement of the beam tuning results.

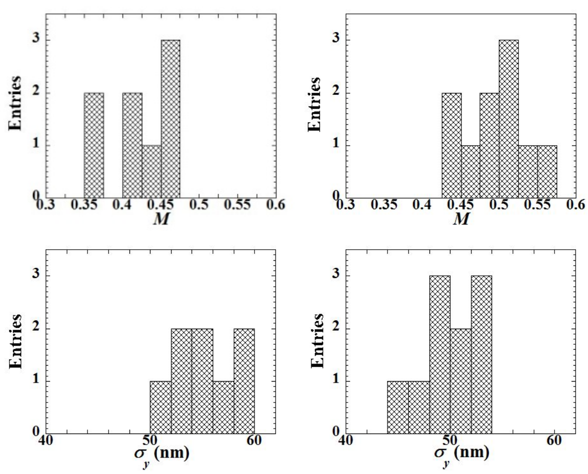

Figure 5: Two sets of consecutive beam size measurements. Top: Distributions of the IPBSM modulations with 174 degree mode. Bottom: Beam size distributions evaluated from the modulations, without systematic error correction (These represent upper limits of the beam sizes.). The bunch charges during the measurements were about 160 pC (left) and 90 pC (right). Data were taken on April 17 (left) and May 22 (right), 2014.

Figure 5 shows examples of consecutive beam size measurements after beam tuning, distributions of IPBSM modulations with 174 degree mode and beam size distributions evaluated from the measured modulations assuming no modulation correction (C_M=1). Their means and standard deviations are summarized in Table 2. No beam tuning was performed during each set of measurements, which took about 30 minutes. Similar histograms in the reference [5] showed beam size was about 73 nm in December 2012 and 65 nm in March 2013. Careful analysis suggested that the data were affected by some systematic errors, probably due to drifts of beam orbit and unstable condition of IPBSM. However, the error is not expected to increase the apparent modulations, and the evaluated beam sizes will give upper limits of the real sizes.

Table 2: Means and Standard Deviations (SD) of M and σ_y, for the Consecutive Measurements shown in Figure 5

	mean M	SD M	mean σ_y	SD σ_y
April 17	0.43	0.04	55 nm	3 nm
May 22	0.50	0.04	50 nm	3 nm

The results demonstrate the performance of the local chromaticity correction method. The observed beam size, about 50 nm, can be compared with the calculated beam size for the present linear optics without the chromatic correction using the sextupole magnets, about 450 nm.
In recent operations, about 60 nm or smaller beam size is routinely observed. After a week or more period of shutdown, we could observe such small beam sizes in about 24 hours of tuning. It shows the tuning procedure to this beam size level has been well established.

REMAINED ISSUES FOR GOAL-1

Intensity Dependence

We observed the beam size strongly depends on the bunch intensity. Figure 6 shows examples of the intensity dependence measurement, IPBSM modulation as a function of the bunch population, with the IPBSM 174 degree mode and the 30 degree mode. The data is fitted assuming the beam size ($\sigma_y(q)$) is expressed as

$$\sigma_y^2(q) = \sigma_y^2(0) + w^2 q^2 , \quad (4)$$

where q is the bunch charge, and a free parameter w was estimated to be about 100 nm/nC.

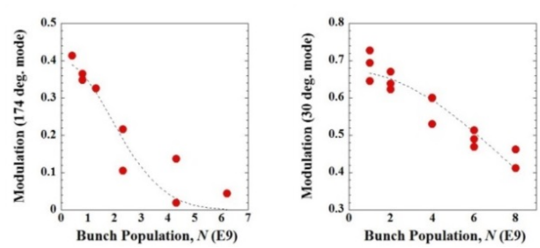

Figure 6: IPBSM modulation as function of bunch population. Measured with a crossing angle 174 degrees (left) and 30 degrees (right).

The most probable cause of the dependence is wakefield in the final focus line, where the beta-function is large. Such strong dependence had not been expected in the design stage. Recently, studies of the wakefield effects have been performed, both theoretical calculations and experiments. More detailed discussions and results of

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studies are in the reference [18], though there has not been clear conclusion yet and the studies are still ongoing.

Because of the intensity dependence, low bunch charge beam (population about 10^9) is used in usual operation for the small beam size. According to Eq. (4), the measured beam sizes described in the previous section may be larger than the zero-intensity beam sizes by 2 or 3 nm.

Beam Size at Low Intensity

Even at low beam intensity, the measured minimum beam size is larger than the expected beam size from the design optics and the vertical emittance, 37 nm. Measurements of the beam optics and the emittance have some ambiguities and can be sources of the discrepancy.

One possible reason of the discrepancy is systematic error of IPBSM [12]. The errors can be caused by, for example, deformed or unstable laser light of the monitor and increase the apparent beam size.

Beam orbit jitter and orbit drift are probable sources of the beam size increase. Position jitters at IP affect the beam size measurement. Orbit drift will change the beam positions at sextupole magnets and affect the higher order aberrations. Recently installed high resolution BPMs at the IP area (see next section) will be useful for measuring the beam orbit jitters and drifts.

Presently, study of these errors is one of the most important tasks of ATF2.

Experimental Simulation of ILC tuning

So far, most efforts have been for observing the smallest beam size using all available tools and choosing the optimum condition at ATF2. However, we should eventually simulate beam tuning procedure of the ILC final focus system in a condition as similar as possible to that at ILC.

Beam tuning with the nominal horizontal beta-function at IP is one of the most important tasks. For such nominal optics, the chromatic corrections in both in horizontal and vertical are important. It also requires better cures of higher order magnetic field errors.

Testing beam tuning procedure which can be used in ILC is another task. It is desirable to establish and demonstrate a semi-automated tuning algorism.

STABLE BEAM (GOAL-2)

For high luminosity of colliders, beam positions at IP must be stable and controlled. In ATF2, we are trying to stabilize the vertical beam position in accuracy of a few nm.

The ATF damping ring can produce small emittance multi-bunch beam. In experiments for the goal-2, two or three bunch beam, with bunch spacing 150 to 250 ns, is extracted from the damping ring. While there are pulse to pulse orbit jitters, the orbits of bunches in one pulse are expected to be well correlated. The orbit of the first bunch is measured and the orbits of the following bunches in the same pulse are corrected. The latency of the feedback should be shorter than the bunch spacing. This system is a prototype of the intra-pulse feedback to be used at ILC collision point.

The feedback system has been successfully demonstrated in the extraction beam line. The residual position jitter was dominantly determined by the BPM resolution and bunch to bunch uncorrelated orbit jitter. Details of the feedback study are reported in [19].

For test and demonstration of nm-level beam stabilization, high resolution BPM system was installed at the IP area and commissioning of the BPM system started in autumn 2013. The BPM system consists of three C-band cavity type BPMs. Presently, studies for basic performance of the system, such as resolution and dynamic range of each BPM, are ongoing. Orbit feedback using this high resolution BPM system is under preparation.

ACKNOWLEDGMENT

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

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