The recent results of the ATF

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Abstract

This report describes the recent results of the beam commissioning of the ATF at KEK. Recent progress on the studies on production of low emittance beam, multi-bunch beam operation and development on beam instrumentation are discussed. So far, a horizontal emittance of 1.7 ± 0.3 nm was measured with wire-scanners in the extraction line and with the horizontal spatial coherence using an SR interferometer. In addition, a vertical emittance of 15 ± 7.5 pm was measured with a laser wire and the SR interferometer in the ring and 5 wire scanners.

1 INTRODUCTION

The ATF [1] has been designed to investigate the feasibility of the LC operation scheme and to develop beam-control techniques for the LC [2]. The purpose of the ATF is to develop accelerator technology that can stably supply to the main linear accelerator an extremely flat "multi-bunch beam". Presently, we are refining the beam-tuning techniques and are stabilizing the key machine components to supply the extremely small emittance beam stably into the extraction line (EXT). Table 1 summarizes the achieved accelerator performance of the ATF. Fig. 1 shows the normalized beam emittance which has been observed at ATF. The achievement of ATF is compared with the beam emittance at third-generation synchrotron light sources (ALS, SPring-8) as well as the past performance of the SLC damping rings, and the required performance for JLC/NLC, TESLA and CLIC.

In the following sections we describe the importance of small normalized vertical emittance for high luminosity and the recent results on the emittance measurements in Section 3, results of the damping ring (DR) study in Section 4, our goal and the experimental plans in Section 5.

2 LUMINOSITY

The beams to use at LCs have to be very high intensity. In addition, the beams at the interaction point needs to be tightly focussed to a very small spot (one several hundredth, or a few thousandth of the beam size in typical storage rings). To allow this, the beams to use at LCs will have to have an extremely small emittance, and sufficient measures need to be taken to avoid growth of emittance during acceleration through the linacs.

Another aspect that calls for special attention is Beamstrahlung. Beamstrahlung is a phenomenon, where the bunches of electrons and positrons, colliding at the interaction point, emit a large amount of synchrotron radiation.

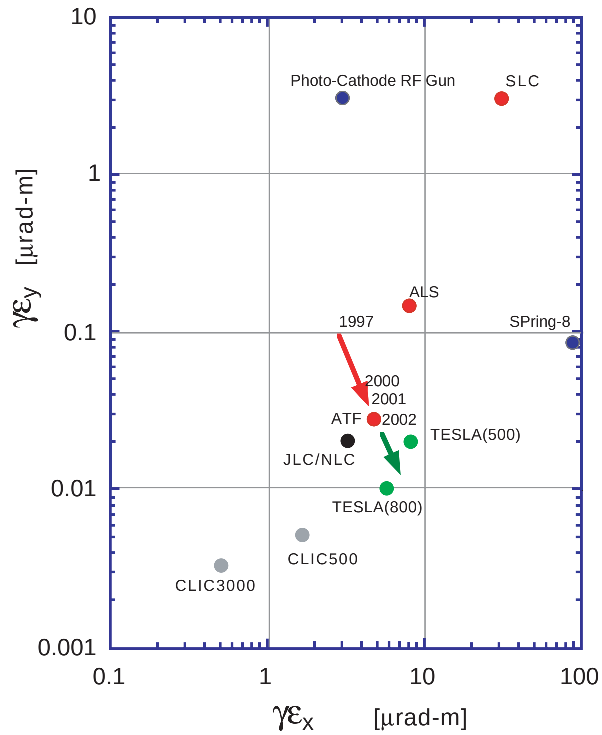

Figure 1: Comparison of the normalized emittance.

This is due to an extremely strong focusing electromagnetic fields that the bunches exert on each other. Beamstrahlung becomes stronger as the beam intensity becomes higher or the beam sizes is made smaller at the interaction point. Thus Beamstrahlung creates undesirable background signals for the detector facility. Consequently, the beam intensity or the beam sizes at the interaction point cannot be arbitrarily chosen just for maximizing the luminosity. The formula for luminosity is as follows.

$$L = \frac{N^2 f}{4\pi\sigma_x^*\sigma_y^*} H(D) \tag{1}$$

Following two equations on the total AC power consumption(P_{AC}) and the Beamstrahlung(δ_B) constrain the realistic constant.

$$P_{AC} = \frac{2EfN}{\eta_{AC\rightarrow beam}} \tag{2}$$

$$\delta_B = const\frac{N^2E^2}{{\sigma_x}^{*2}\sigma_z} \tag{3}$$

From above equations, the luminosity per the AC power is inversely proportional to the square root of the vertical

Item	Achieved Performance	Design
Linac		
Maximum Beam Energy [GeV]	1.42	1.54
Maximum Gradient with Beam [MV/m]	28.7	30
Single Bunch Population	1.7×10^{10}	2×10^{10}
20 Multibunch Population	7.6×10^{10}	20×10^{10}
Energy Spread (Full Width) [%]	< 2.0 (90% beam)	< 1.0 (90% beam)
Damping Ring		
Maximum Beam Energy [GeV]	1.28	1.54
Momentum Compaction	0.00214	0.00214
Single Bunch Population	1.2×10^{10}	2×10^{10}
COD (peak to peak) [mm]	$x \sim 2, y \sim 1$	1
Bunch Length [mm]	~ 6	5
Energy Spread [%]	0.08	0.08
Horizontal Emittance [m]	$(1.33 \pm 0.04) \times 10^{-9}$) (2×10^9) $(1.94 \pm 0.11) \times 10^{-9}$) (8×10^9)	1.4×10^{-9}
Vertical Emittance [m]	$(1.1 \pm 0.1) \times 10^{-11}$) (2×10^9) $(2.2 \pm 0.1) \times 10^{-11}$) (8×10^9)	1.0×10^{-11}
Multibunch Population	$19 \times (0.6 \times 10^{10})$	$20 \times (1 \times 10^{10})$
Multibunch Vertical Emittance [m]	$(2 \sim 3) \times 10^{-11}$	1.0×10^{-11}

Table 1: Achieved and design parameters characterizing the performance of the ATF. The achieved values of the single-bunch emittances are based on wire scanner measurements in the extraction line, when the ring was operated at 1.28 GeV. The numbers in parentheses indicate the number particles per bunch. The quoted errors are estimated based on the fitting analysis of the wire scanner data, together with the observed statistical fluctuations of the measurements.

normalized emittance($\gamma\epsilon_y^*$) as follows.

$$\frac{L}{P_{AC}} = \frac{C}{E^{1.5}}\eta_{AC\rightarrow beam}(\frac{\delta_B}{\gamma\epsilon_y^*})^{0.5}(\frac{\sigma_z}{\beta_y^*})^{0.5}H(D) \qquad (4)$$

3 EMITTANCE MEASUREMENTS

Extracted beam is prepared in a few hours without hardware trouble. After that, we check the beam quality and start the beam studies to develop the beam-tuning techniques for the LC.

Figure 2 shows the dependence of the measured emittance on the bunch intensity, which indicates the effects of intra-beam scattering. The error bar in the figure shows the statistical variation found in repeated measurements. The measurements have been done under following condition.

i) Vertical beam position jitter at the wire scanners is less than a few μm. ii) Horizontal beam position jitter at the wire scanners is less than several μm. iii) Beam energy drift is less than 0.01 % within 8 hours.

It appears that the following points play an important role.

1. Tuning with skew knobs in the arc sections of the DR for reducing the betatron coupling in the ring.

2. Careful corrections for residual dispersion in the EXT.

3. Additional cross-plane coupling correction using a skew quadrupole magnet in the EXT, upstream of the wire scanners.

4. Careful examination of dependence of beam emittance on the stored bunch intensity in the ring.

The emittance is found to grow up to $(2.2 \pm 0.1) \times 10^{-11}$m for a beam intensity of $(8.0 \pm 0.3) \times 10^9$ electrons per bunch. Here, an effect of intra-beam scattering is suspected. According to a simulation, the intra-beam effect can lead to an emittance growth of ~ 50 % at this bunch intensity. More careful theoretical and experimental studies are needed to fully understand the situation.

It is also noted the x-y beam profiles, which have been measured during emittance measurements with EXT wire scanners, show a tilting by a few degrees. Apparently, there exists a coupling source somewhere in the region between the beam extraction point and the wire scanners in EXT. A few skew quadrupole magnets have been introduced in the EXT to apply tilt corrections. The quoted vertical emittance might be further reduced by re-optimizing the setting of these skew magnets.

4 RESULTS OF DAMPING RING STUDY

4.1 Beam Tuning

The SAD modelling program [3] is used to calculate settings for steering magnets in orbit and dispersion corrections. A COD correction algorithm and local-orbit bumps are used to correct the stored-beam orbit. After correction, the typical peak-to-peak COD is less than 2 mm in the horizontal plane and 1 mm in the vertical plane. The dispersion functions at the BPMs in the ring and in the EXT are measured from the orbit shift induced by a change in the RF frequency. The measured vertical dispersion in the arc

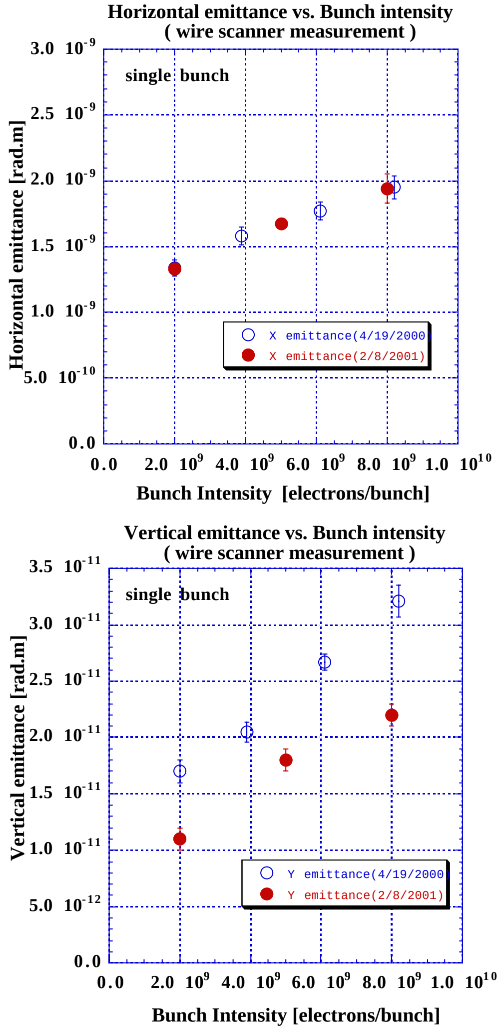

Figure 2: Recent results of emittance measurements using wire scanners at the EXT.

section was reduced from 40 mm to 5 mm by an additional correction using vertical steerings. We thus established correction techniques for the COD and the dispersion, as well as a beam-based technique for measuring the quadrupole-field errors.

A global correction of the coupling using skew quads was also developed. The orbit coupling is measured as COD change due to change of strength of horizontal streerings. A set skew of quads (trim coils of sextupoles) is adjusted to make the orbit coupling minimum. The orbit coupling was clearly reduced after the correction. Setting many bumps one-by-one the vertical beam size was monitored using the SR-interferometer.

4.2 Turn-by-Turn BPM (Tune Monitor)

DR stored orbit stability was analyzed using 4 sets of turn-by-turn BPMs. This system can be used to monitor injection orbit error, damping after injection, stored orbit oscillation, and stored orbit stability. It can also be used as a precise tune monitor in combination with a strip line exciter at the South straight section in the DR. The FFT software showed that we can determine betatron and synchrotron tunes with an accuracy of 100 Hz (corresponding to 0.00005 in units of revolution frequency). Also, with this system we detected a 100-Hz betatron tune oscillation of amplitude 0.001.

4.3 Laser Wire

A laser beam with a very thin waist is generated in an optical cavity formed by nearly concentric mirrors. The laser intensity is amplified by adjusting a cavity length to meet the Fabry-Perot resonance condition. We have already built the cavity which produced a beam waist of 12μm (2σ) and an effective power of 100 W, with good long-term stability. A laser wire has been installed in the ATF DR at a location with a transverse electron beam size of $\sim 10\mu$m. We will measure the vertical emittance of each bunch in the ring with sufficient accuracy in 2002[4].

4.4 Wire Scanner

The beam emittance can be measured independently in the EXT. The EXT is equipped with 5 wire scanners, an air Cerenkov γ detector, BPMs with single-pass signal processing and a current transformer (CT). We can measure a 5μm beam size with sufficient accuracy using a 10μm W(tungsten) wire scanner when the extracted beam is stable from pulse to pulse. Figure 3 shows wire scans in the EXT and illustrates the high degree of stability that has been achieved.

4.5 Intra-Beam Scattering and Touschek Effect

An indirect method of inferring the beam size in the ring is to take advantage of the Touschek effect, which causes the beam lifetime to be approximately proportional to the bunch volume at equilibrium. If the horizontal and vertical beam sizes are known, this allows one to evaluate the vertical emittance from the Touschek lifetime. A beam lifetime model which includes the effects of potential well distortion, intra-beam scattering, photo-desorption and the Touschek effect has been developed. The effect of intrabeam scattering (multiple Touschek scattering) can also be used to estimate the emittance in the ring via the increase of the energy spread. According to a recent analysis, the measured dependence of the lifetime and the energy spread on the beam intensity consistently indicate the emittance ratio to be $<\sim$ 1%, if the intra-beam scattering effect is assumed to be responsible for the growth of the beam size[5].

4.6 Performance

The horizontal beam emittance, measured by using wire scanners in the EXT, agrees well with the theoretical calculation [6]. The vertical emittance has been measured both in the DR using the SR interferometer and the laser wire and in the EXT using wire scanners. We have also

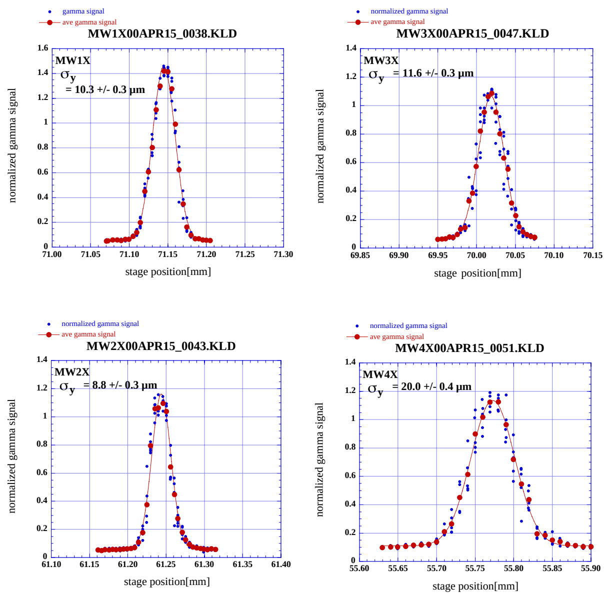

Figure 3: Vertical wire scans in the EXT, using W filaments with $10\mu m$ diameter.

estimated the vertical emittance from the dependence of the energy spread and the beam lifetime on the bunch charge, which gives an apparent vertical emittance of approximately 0.006 nm with zero current, or 0.6% of the horizontal emittance [7, 8].

5 OUR GOAL AND EXPERIMENTAL PLANS

The current short-range goal at ATF is to demonstrate a stable operation of the DR with three bunch trains stored, by the end of JFY 2003. Here, each train would consist of 20 bunches with a bunch spacing of 2.8 ns. The study items associated with multi-bunch, multi-train operations include the following: transient beam loading, multi-bunch instabilities, fast ion instability and emittance blow-up issues due to the multi-bunch beam, which should be overcome. The RF photocathode source provided twice the present stored beam intensity, allowing more precise studies of single bunch intensity dependent phenomena, such as intra-beam scattering and impedance effects[9]. Studies on numerous items are under way in collaboration with both Japanese and overseas research institutes and universities.

5.1 Photo-Cathode RF Gun

Since the beam injection efficiency of $\sim 100\%$ was dramatically demonstrated during RF gun tests in 2001, we manufactured a photo-cathode RF gun with a Cs_2Te Cathode. After completion and performance tests, a program is being pursued where the ATF thermionic gun and buncher system replaced by a photo-cathode RF gun in 2002[10, 11].

5.2 Beam Based Alignment

Using new, high-resolution ring BPMs, we will develop a quick, accurate beam based alignment procedure that will provide insight into the nature of the optics corrections that are presently used for emittance optimization. We will be able to identify the sources of instability and understand the physical limits on the minimum vertical emittance. This is one of the highest priority beam studies[12].

5.3 Stable Beam Extraction using Double-Kicker Scheme

We already demonstrated in a single bunch operation that the stability of the beam orbit at the EXT was less than a few μm with double-kicker system using a cavity BPM. Regarding multibunch operation, we need a precise bunch-by-bunch BPM with pulse-by-pulse to check the performance of the double-kicker system[13].

5.4 Optical Transition Radiation

The linear collider needs a profile monitor that provides images of a low emittance beam with a resolution well below typical beam sizes in order to accurately determine the x-y and y-z coupling and other phase space distortions. The required resolution (2μm) is well below the state of the art for such monitors (20μm), and we have a program to test and perfect such a monitor in beam extraction. To date, beam sizes of 5μm have been imaged, and tests of the transition radiation target durability have been performed[14].

5.5 Optical Diffraction Radiation Monitor

A "proof-of-principle" experiment on the use for optical diffraction radiation (ODR) as a single pulse beam profile monitor was conducted using the electron beam extracted from the DR. We are measuring the yield and the angular distributions of the optical diffraction radiation from a thin metal target at different wavelengths, impact parameters and beam characteristics. A new beam diagnostic tool was proposed for μm beam size measurements[15].

5.6 Polarized Positron Generation

We have proposed a new method for generating highly polarized positrons through the Compton scattering of polarized laser light off relativistic electron beams and successive pair creation. A preliminary experiment was performed in the ATF extraction line. A polarized γ-ray yield of 1.1×10^6 photons/pulse was measured[16].

Acknowledgements

The authors would like to thank Professors H.Sugawara, Y.Kimura, S.Yamada, S.Iwata, Y.Kamiya, K.Takata, S.Kurokawa, and A.Enomoto for their encouragement. All members of KEK-ATF group and international collaborators for this research program are acknowledged. We also thank Professor E.Paterson and Professor D.Burke of SLAC and K.Hubner of CERN for supporting the ATF project as an international collaboration.

6 REFERENCES

[1] Edited by F.Hinode, et al., KEK Internal 95-4, June 1995.

[2] Edited by H.Hayano et al., KEK Internal 2000-6 A (2000).

[3] SAD is a computer program complex for accelerator design. http://acc-physics.kek.jp/SAD/sad.html.

[4] Y.Honda et al., Proc. of this conference.

[5] T.Okugi, et al., NIM A455(2000)207-212.

[6] T.Okugi et al., Phys. Rev. ST Accel. Beams 2, (1999) 022801.

[7] K. Kubo et al., Phys. Rev. Lett. 88, 194801 (2002).

[8] I.Sakai et al., Phys. Rev. ST Accel. Beams (to be published).

[9] K. Bane et al., Phys. Rev. ST Accel. Beams 5, (2002) 084403.

[10] R.Kuroda et al.,NIM A455(2000)222-227.

[11] N. Terunuma et al., 8th ATF International Collaboration Meeting.

[12] M. Woodley et al., 8th ATF International Collaboration Meeting.

[13] T. Imai et al., Phys. Rev. ST Accel. Beams (to be published).

[14] M. Ross et al., 8th ATF International Collaboration Meeting.

[15] J. Urakawa et al., Nucl. Instr. Meth A**472**, 309 (2001).

[16] M.Fukuda et al., to be submitted to Phys. Rev. Lett..