EXPERIMENTAL RESULTS AND TECHNICAL RESEARCH AND DEVELOPMENT AT ATF (KEK)*

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Abstract

The ATF at KEK is a prototype for LC(Linear Collider) R&D. The ATF consists of an S-band high gradient linac (Linac), a beam transport line (BT), the damping ring (DR) and an extraction line (EXT). 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" that can be squeezed down to a few nanometers at the collision point of LC. 1.37nm horizontal emittance was confirmed by emittance measurements at 1.28GeV using wire scanners in the extraction line and measurement of the horizontal spacial coherence using a SR interferometer. I report the experimental results with emphasis on the main initial challenges of the project, the progress already obtained, and the remaining questions to be solved together with an estimate of the time needed to achieve these goals.The ATF is a international Facility for the LC R&D and you can get the information from KEK-ATF Home Page.[1]

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, 3, 4]. The pre-injector was completed in Aug. '93, when the development of multi-bunch beam-diagnostics started. In Nov. '95, we completed the high-gradient linac so that experiments on the acceleration of a multi-bunch beam and on the compensation of multi-bunch beam loading could be performed. After installation of the main hardware components, in Jan. '97 we started beam commissioning in the damping ring. In November, 1997, we completed the extraction line for precise beam diagnostics. 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. In this report we describe the results of the ATF beam commissioning.

Since many beam instrumentation devices in the ATF turned out not to be sufficient for precise beam tuning and measurements, we are also upgrading each of the systems and are developing new diagnostics. For example, a laser wire and skew quadrupole magnets were installed near the end of JFY '99 to measure the tiny beam size in the ring and to control the tilt of the beam at the extraction line. Table 1 summarizes the achieved accelerator performance of the ATF. A schematic drawing of the ATF and the design concept were presented in Ref.1 except for the EXT. The layout of the EXT for precise beam diagnostics is shown in Figure 1.

In the following sections I describe the recent results on the emittance measurements using the wire scanners at the EXT in Section 2, the results of the linac study in Section 3, results of the damping ring study in Section 4, problems to be solved soon in Section 5 and our goal in Section 6. Finally, I present conclusions.

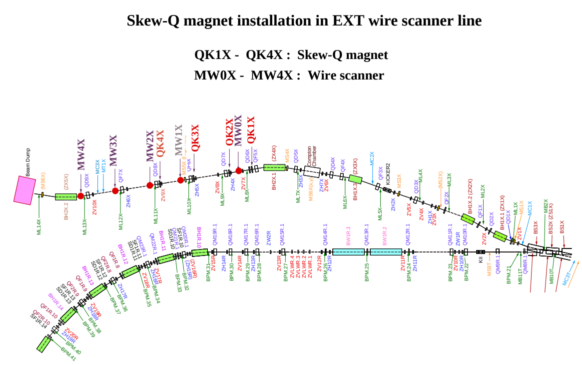

Figure 1: The layout of the extraction line.

2 EMITTANCE MEASUREMENTS AT THE EXT

The center picture of Figure 2 shows the observed dependence of the measured vertical emittance on the bunch intensity, which indicates the effects of intra-beam scattering. The error bar in the figure shows the statistical variation on repeated measurements. Intensive studies on the vertical emittance with the wire scanners in the ATF-EXT have been ongoing since March this year (2000). An important observation we made during this time is that there appears to be a source of x-y cross plane coupling somewhere between the extraction point of the DR and the wire scanner region in the EXT. Part of the cross-plane coupling effects can be reduced by using a skew quadrupole magnet (QK2X) in the EXT. The QK2X magnet is located upstream of wire scanners MW1X through MW4X. For instance, with QK2X excited at -0.2 A the vertical beam size at MW3X and MW4X is minimized, and the measured vertical emittance is approximately $(1.5 \pm 0.25) \times 10^{-11}$m

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[1] http://lcdev.kek.jp/ATF/

Table 1: Achieved and design parameters at ATF.

Items	Achieved Values	Design
ATF Linac Status		
Maximum Beam Energy	1.42GeV	1.54GeV
Maximum Gradient with Beam	28.7MeV/m	30MeV/m
Single Bunch Population	1.7×10^{10}	2×10^{10}
20 Multi-bunch Population	7.6×10^{10}	40×10^{10}
Bunch Spacing	2.8 ns	2.8 ns
Repetition Rate	12.5 Hz	25 Hz
Energy Spread (Full Width)	< 2.0 % (90 % beam)	< 1.0 % (90 % beam)
Damping Ring Status		
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	~ 6 mm	5 mm
Energy Spread	0.06 %	0.08 %
Horizontal Emittance	$(1.4 \pm 0.3) \times 10^{-9}$ m	1.4×10^{-9} m
Vertical Emittance	$(1.5 \pm 0.25) \times 10^{-11}$ m	1.0×10^{-11} m

for the beam intensity of $(1.6 \pm 0.2) \times 10^9$ electrons per bunch. This represents the best result so far obtained at the ATF-EXT in a single-bunch mode operation. The emittance is found to grow to $(3.15 \pm 0.33) \times 10^{-11}$m at the beam intensity of $(8.7 \pm 0.3) \times 10^9$ electrons per bunch, however. This could be due to effects of the intra-beam scattering, which according to a simulation 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. In the same operation week, the horizontal emittance was also remeasured. Combining the measured vertical and horizontal emittance values the emittance ratio was found to be approximately 1.3 %. The design emittance ratio is 1%. The plots in the Figure 2 summarize the results obtained with QK2X excited at 0.8 A. In these measurements, the x-y beam profile showed a tilting of a few degrees, as observed by using 10 degree wires. The quoted emittance and emittance ratios in these plots might be further reduced by re-optimizing the setting of QK2X. Obviously, repeated measurements and careful studies are needed, and the results shown here should be considered preliminary. It appears that the following points play an important role.

1. Tuning with skew knobs in the ARC sections of the damping ring for reducing the betatron coupling in the ring.

2. Careful corrections for residual dispersion in the extraction line.

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

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

Also, we should mention the following achievements on the stabilization of the beam position jitters at the EXT and of the beam energy drift in the DR.

1. Vertical beam position jitter at the wire scanners is less than a few μm.

2. Horizontal beam position jitter at the wire scanners is less than 20μm.

3. Beam energy drift is less than 0.01 % within 8 hours.

3 RESULTS OF LINAC STUDY

3.1 Linac Energy Spread in Single- and Multi-bunch Operations

A large single bunch energy spread and tail arise from the long bunch length which is created in the buncher section and propagated through the linac. This is one of the most important issues at ATF. In order to solve this problem, the injector buncher section was redesigned using the simulation code PARMELA [5]. An RF bunch length monitor was also installed [6], and has been utilized for buncher tuning and real-time bunch length monitoring.

Insufficient bunching creates a significant longitudinal tail which is converted to an energy spread tail at the end of the linac. PARMELA simulations showed the long tail at the injector 80 MeV output point. To increase the bunching with only small changes in the existing hardware, we rearranged the sub-harmonic cavity and the helmholtz focusing coil positions and set the helmholtz coil current according to PARMELA results. The bunch length after the upgrade, of around $10 \sim 12$ ps FWHM, was similar to the simulation result. The simulation predicted 80% of the charge would be focused into a 20 ps range. We therefore predicted 80% of the charge would be transmitted into the BT line. However, the current transmission was still ~60% even though

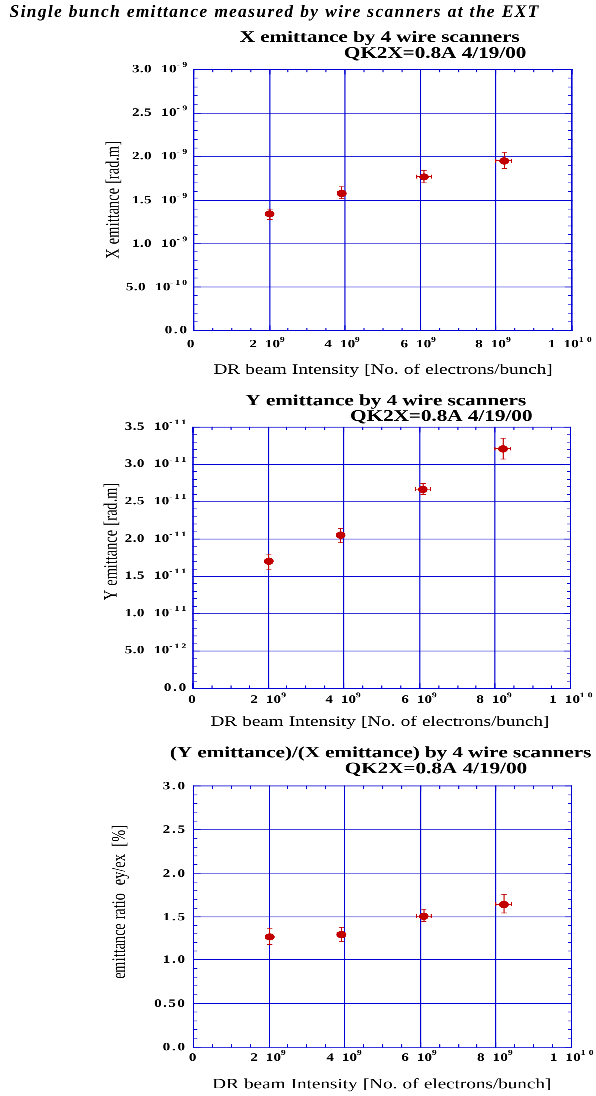
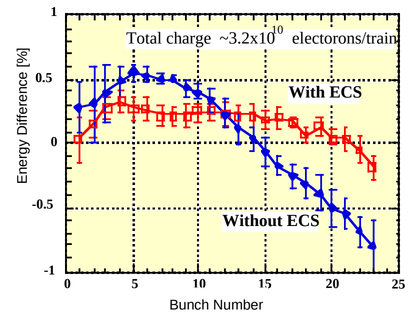
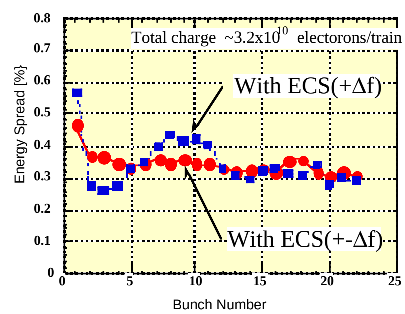


Figure 2: Recent results of emittance measurements using wire scanners at the EXT.



After the adjustments of the ECS RF phase, the RF power of the Klystrons were set to get a flat energy distribution for all bunches with 1.9MW for + Δf and 1.5MW for -Δf. The a BPM miss-reading by the beam loss of the collimator in front of the BPM.



The single-bunch energy spread was less than 0.5% expect for first bunch at the case of total charge/pulse=3.2x10^{10}. The single-bunch energy spread was generated by a RF slope in ECS structures was not observed in these intensity.

Figure 3: The results of multi-bunch beam loading compensation experiment.

the spot size after the first bend of the BT was significantly reduced. We are still investigating possible sources of the poor transmission of the BT collimator section.

Multi-bunch energy spread, defined as the bunch-by-bunch energy centroid difference, is caused by transient beam loading of the accelerator structures. The spread is calculated to be ±4.2% at 2×10^{10} electrons/bunch and 20 bunches/multi-bunch train. Since the energy acceptance of BT is not larger than 1%, an energy compensation system using ΔF accelerator structures was proposed and commissioned. In order to synchronize with DR injection, an offset frequency of 2856 ±4.327 MHz was chosen for the ΔF structures (4.327 MHz is twice the DR revolution frequency). The slight difference in accelerating field frequency causes a phase shift in the acceleration of each bunch so that it compensates by decelerating the head bunches and accelerating the tail bunches. The ± frequency for multi-bunch compensation corrects for the slope of the accelerating field within a single bunch. The experiment demonstrating this scheme was conducted with 6×10^9 electrons/bunch and 20 bunches/train. The original multi-bunch energy spread of 5% from head to tail was corrected to within 0.6 % using 25 MW klystron output fed into 3 m ΔF structures without any problem [7]. Figure 3 shows the results of the above beam loading compensation experiment.

3.2 Beam Stability

The gun HV station was modified to eliminate corona discharge on August 1998, and to reduce the timing jitter in the grid pulser trigger to less than 4 ps rms. As for input AC line fluctuation, an AC line stabilizer was introduced for both the gun HV (0.5% stability) and the gun thyratron system (1% stability). The klystron thyratron system was similarly stabilized at the level of 1%. Since the klystron modulator system is driven by a large, centralized DC power supply, voltage stabilization of this system is difficult. Instead, we introduced a feed-forward deQing system which reduced klystron voltage fluctuation by half. The AC line fluctuation of $2 \sim 3$% comes mainly from cyclic operation of the KEK proton synchrotron. With these upgrades, beam intensity fluctuation in the BT line was reduced from $4 \sim 5$% to $1 \sim 2$%. Nevertheless, the DR stored current still shows a $2 \sim 3$% fluctuation. Efforts to reduce the DR intensity jitter to less than 1% are still underway.

4 RESULTS OF DAMPING RING STUDY

In the following subsections I describe the status of the ring beam tuning. I report on the transverse emittance ratio and discuss the extreme intra-beam scattering effect.

4.1 Beam Tuning

A COD (Closed Orbit Distortion) correction algorithm and local-orbit bumps are used to correct the stored-beam orbit at many ($\sim 10^6$) turns after injection. After correction, the typical peak-to-peak COD is less than 2 mm in the horizontal plane and 1 mm in the vertical plane. We measured the R_{12} single-pass response matrix of each BPM to excitations of the different dipole correctors, with sextupole magnets turned off. From these data we calculated typical quadrupole field-strength errors of about 1% and upgraded the optics model so as to account for these errors, which arise from an interference effect between adjacent magnets. The magnetic-field difference between the upgraded model and new beam-based measurements are less than 0.01%.

The dispersion functions at the BPMs in the ring and in the extraction line are measured from the orbit shift induced by a change in the RF frequency. The RF frequency is ramped quickly (rise and fall times of 50 ms) after injection, since the beam stored time is less than 640 ms. The measured vertical dispersion in the arc section was reduced from 40 mm to 5 mm by an additional correction using vertical steering coils after the COD correction. The transverse and longitudinal oscillations are measured and the tunes under the typical operation condition agreed well with the model values. We thus established correction techniques for the COD and the dispersion, as well as a beam-based technique for measuring the quadrupole-field errors [8].

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[9]. 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. Local orbit bumps were also used for low vertical emittance. Setting many bumps one-by-one the vertical beam size was monitored using SR-interferometer. Probably, the resolution (or stability) of the monitor was not enough for this tuning technique.

4.2 Transverse Emittance Ratio

A comparison of the measured machine parameters and the model prediction shows that the first-order optics agrees with the design after appling corrections as outlined in 4.1. Of great interest is the emittance ratio (ϵ_x/ϵ_y) obtained in the $90°$ optics and the $135°$ optics. Until recently, the change in the ring circumference, and associated variations of the beam orbit and tune made it difficult to establish stable operating conditions, and disturbed the precision measurements in the extraction line. We can roughly estimate the emittance ratio in the ring from the results of the SR interferometer and the effect of intra-beam scattering. A $\sim 1\%$ emittance ratio for the design $135°$ optics was inferred in other report [10]. Employing the Bjorken-Mtingwa theory of intrabeam scattering [11], the measured dependence of the energy spread on the beam intensity indicates the emittance ratio less than 1%, if we assume that intra-beam scattering is the source of the beam-size variation.

4.3 Intra-Beam Scattering and Touschek Effect

Given the extremely low emittance of the ATF damping ring beam, it is difficult to directly and accurately measure the vertical beam size in the ring. In addition, the Touscheck effect is expected to be the dominant particle loss mechanism, making the beam lifetime much shorter than in many ordinary storage rings. These are challenges that we must also face at LC.

On the other hand, the Touschek effect causes the beam lifetime to be approximately proportional to the bunch volume at equilibrium. We can take advantage of this fact to infer the beam size in the ring. Since the bunch volume, or equivalently the vertical emittance when horizontal and longitudinal beam sizes are known, can be evaluated from the measurement of the Touschek lifetime, a novel beam diagnostic technique was developed. A beam lifetime model which includes the effects of potential well distortion, intra-beam scattering, photo-desorption and Touschek effect was proposed [12]. The effect of intrabeam scattering (multiple Touschek scattering) can also be used directly to infer the emittance in the ring via the increase of the energy spread. The measured dependence of the lifetime and the energy spread on the beam intensity recently both indicate an emittance ratio less than $\sim$ 1%, assuming that the intra-beam scattering effect is the source of the beam-size variation. In the analysis, we used the actual measured dynamic aperture of the DR rather than the predicted value. The emittance number obtained is consistent with the vertical emittance of $(1.5 \pm 0.25) \times 10^{-11}$ m measured by the wire scanner beam profile monitors in the extraction line. It was found that this method of emittance evaluation is effective in the lower emittance region, and that it can achieve a high resolution [13]. The evaluation of the vertical emittance due to the measurement of the energy spread and the Touschek lifetime has a ambiguity of $\sim\ 2$ which comes from the model dependence. In this subsection, we quoted the conservative values.

5 PROBLEMS

During commissioning, a number of problems were encountered. We measured the physical aperture by detecting the beam loss over the first few turns for different injection orbits, and estimated the dynamic acceptance from a beam-lifetime measurement. The physical aperture is consistent with the design. It corresponds to an acceptance of about 2×10^{-6}m. However, the measured dynamic acceptance for the stored beam is only 1×10^{-7}m, which is 20-times smaller than the physical aperture. This problem will be addressed in the next beam-commissioning period [14, 15, 16].

There are beam loss issues at the Linac, BT and at the injection area. Other problem was large variations in the ring circumference. We observed a change in the ring circumference by up to 6mm, correlated with the outside temperature and humidity. Over a period of one year, rf frequency changes of about 20 kHz were required in order to maintain a centered beam orbit under these conditions.

6 OUR GOAL

There is a big energy tail of the beam at the end of the linac which mainly comes from insufficient power of the linac buncher section. Improvement of the buncher section is under consideration to reduce the beam loss at the BT. We will also add more appropriate shielding in order to be able to perform single bunch beam operation with a repetition rate higher than 6.25Hz. Then multi-bunch operation can start at a repetition rate of 0.78Hz. This work should be pursued as soon as possible. We will try to confirm the vertical emittance value of 10 pm at 8×10^9 electrons/bunch within 9 months in JFY 2000. In the rest of JFY 2000 and onwards, we will concentrate on the study of the multi-bunch beam. Our goal is to confirm the stable operation with 3 trains in the DR towards the end of JFY2001. Each train should consist of 20 bunches with bunch spacing of 2.8 nsec. There are many study items on the multi-bunch beam physics. For example, transient beam loading, muti-bunch instabilities, fast ion instability and emittance blow-up isuues due to the multi-bunch beam which should be overcome.

7 CONCLUSIONS

The $\pm\Delta F$ beam loading compensation experiment in the ATF linac was successfully performed at 1.16GeV with 23 bunches/pulse in 1996[7]. The complementary ΔT beam loading compensation study has been with us as a remaining issue due to the DR commissioning. Instead, single bunch studies have been performed in the ring aimed at achieving the design emittances, and several novel instrumentation techniques were developed. At a beam energy of 1.28 GeV, we confirmed a 1.37 nm horizontal emittance by wire-scanner measurements in the extraction line[17] and by measuring the spatial coherence using an SR interferometer. Also, a vertical emittance of (15 ± 2.5) pm was measured by 4 wire scanners in the extraction line. However, the change in the ring circumference, and associated variations of the beam orbit and tune made it difficult to establish stable operating conditions and disturbed precise measurements in the extraction line. To accurately measure the vertical emittance over extended periods of time, it will be necessary to better stabilize the beam. A study of the beam sensitivity to changes in the ring circumference is very important for the LC in order to determine the optimum momentum compaction factor of the ring and to develop countermeasures. Still much effort is needed to produce a stable 10-pm beam at 1.3 GeV.

Regarding the multi-bunch study, we will add more appropriate radiation shielding and reduce the beam loss so that we can perform single bunch beam operation at a repetition rate above 6.25 Hz. Then multi-bunch operation as outlined in previous section will become possible at 0.78 Hz repetition rate. The multi-bunch beam study should be started as soon as possible. As illustrated by the necessary development of various advanced instrumentation, the many lessons being learnt at the ATF provide indispensable experience for the successful design and operation of future LCs.

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