Extremely Low Vertical-Emittance Beam in the Accelerator Test Facility at KEK

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Electron beams with the lowest, normalized transverse emittance recorded so far were produced and confirmed in single-bunch-mode operation of the Accelerator Test Facility at KEK. We established a tuning method of the damping ring which achieves a small vertical dispersion and small *x*-*y* orbit coupling. The vertical emittance was less than 1% of the horizontal emittance. At the zero-intensity limit, the vertical normalized emittance was less than 2.8×10^{-8} rad m at beam energy 1.3 GeV. At high intensity, strong effects of intrabeam scattering were observed, which had been expected in view of the extremely high particle density due to the small transverse emittance.

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Introduction.—The accelerator Test Facility (ATF) [1] at KEK consists of an *S*-band linac, a damping ring, and an extraction line [2]. The ring has been designed to produce a beam of extremely low emittance. The natural, normalized horizontal emittance is 2.8×10^{-6} rad m and the target value of the vertical emittance is 1% of that. These are comparable to the requirement of the linear collider designs (JLC/NLC [3]) and are the smallest transverse emittances recorded so far among electron accelerators [4]. The History and summary of past beam operations were reviewed in Refs. [2,5,6]. This paper reports on the production of the ultralow emittance electron beams in single-bunch-mode operation of ATF. The beam energy was 1.3 GeV, and the typical repetition rate was 1.56 Hz.

Low emittance tuning and measurement.—Our tuning method of the damping ring for low vertical emittance is a series of corrections: COD (closed orbit distortion) correction, vertical COD + dispersion correction and coupling correction. The strengths of a set of steering magnets are calculated to minimize $\sum_{\mathrm{BPM}} y_{\mathrm{meas}}^2 + r^2 \sum_{\mathrm{BPM}} \eta_{y,\mathrm{meas}}^2$ in the vertical COD + dispersion correction. Here, y_{meas} and $\eta_{y,\mathrm{meas}}$ are the beam vertical position and vertical dispersion, measured at each BPM (beam position monitor). The factor r is the relative weight of the dispersion and COD, and it is chosen to be 0.05 based on a simulation study. For the coupling correction, trim coils of all 68 sextupole magnets are wired so as to produce skew quadrupole fields. The strengths of these skew fields is calculated to minimize $\sum_{\mathrm{steer}} [\sum_{\mathrm{BPM}} (\Delta y_{\mathrm{steer}})^2 / \sum_{\mathrm{BPM}} (\Delta x_{\mathrm{steer}})^2]$, where $\Delta x_{\mathrm{steer}}$ and $\Delta y_{\mathrm{steer}}$ are measured horizontal and vertical position responses to each horizontal steering magnet. Usually, two horizontal steering magnets, which are apart by approximately $3/2\pi$ in horizontal and $1/2\pi$ in vertical phase advances, are chosen for this correction.

Because the vertical emittance in a damping ring is primarily determined by the vertical dispersion and the horizontal-vertical coupling, it is essential to make the vertical dispersion and the coupling small. After these corrections, the rms of $\eta_{y,\mathrm{meas}}$ becomes about 3 mm and the coupling, $[\sum_{\mathrm{BPM}} (\Delta y_{\mathrm{steer}})^2 / \sum_{\mathrm{BPM}} (\Delta x_{\mathrm{steer}})^2]$, becomes about 0.004.

Simulations were performed to study this tuning method, where realistic magnet misalignment and random errors of BPM are considered [7]. From 500 different seeds for the random errors, the average of the vertical emittance was 5.8×10^{-12} rad m, well below our target (1.1×10^{-11} rad m), and 91% of the random seeds gave the emittance less than the target value. This should be regarded as the emittance at the zero intensity limit because the simulation did not consider intrabeam scattering.

The beam size in the damping ring is measured using two types of monitors. One is an interferometer with two slits which allows us to observe interference patterns created by the synchrotron radiation (SR) monitor [8]. The other is a laser-wire (LW) monitor [9,10]. A thin horizontal "wire" of light is created in an optical cavity. When the electron beam hits the wire, gamma rays are produced via Compton scattering and detected by a scintillation detector. The whole optical system is placed on a table, which can be vertically moved, and the position of the table is measured with a resolution better than 1 μm. The vertical beam size is measured in a manner similar to conventional wire scanners. The apparent vertical emittance is evaluated as

$$\epsilon_{y,ap} \equiv \sigma_y^2/\beta_y \,, \tag{1}$$

where σ_y is the vertical rms beam size and β_y is the vertical beta function at the monitors.

In addition, the beam size is measured in the extraction line using tungsten wire scanners [11]. There are 5 wire scanners in the dispersion-free region of the extraction line, and the emittance is calculated from the measured beam sizes and the beam optics between the wire scanners.

For evaluation of the energy spread of the extracted beam, the horizontal beam size is measured using a screen monitor in a high dispersion region in the extraction line, and calculation is made as $\sigma_E/E = \sqrt{\sigma_x^2 - \epsilon_x\beta_x}/\eta_x \approx \sigma_x/\eta_x$, where σ_x is the horizontal beam size, ϵ_x is the emittance, β_x is the beta function, and η_x is the dispersion at the monitor. Since $\epsilon_x\beta_x$ is much smaller than $\eta_x\sigma_E/E$ at the monitor, the second term in the square root is ignored.

Horizontal emittance.—Figure 1 shows the horizontal emittance measured using wire scanners as a function of the beam intensity (number of electrons per bunch) on two different days.

The lines in the figure are from a calculation, assuming the emittance ratio ϵ_y/ϵ_x to be 0.004, 0.006, and 0.008. We used the computer program SAD [12] for the calculation. The calculation of intrabeam scattering was developed based on the Bjorken-Mtingwa formula [13,14].

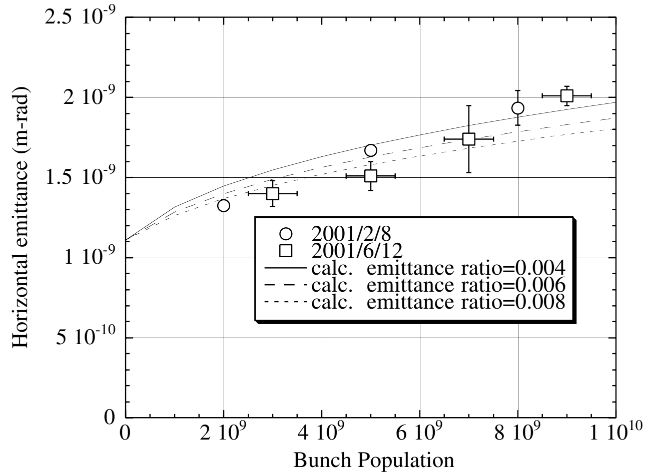

FIG. 1. Horizontal emittance vs bunch intensity measured in the extraction line. The lines are from a calculation with intrabeam scattering assuming the emittance ratios 0.004, 0.006, and 0.008.

Roughly speaking, the growth rate of emittance due to intrabeam scattering is proportional to the average of particle density. Measured intensity dependence of the horizontal emittance is consistent with the calculation of the intrabeam scattering. Extrapolating the data to the zero intensity, it agrees with the calculated natural emittance, 1.1×10^{-9} rad m or normalized 2.8×10^{-6} rad m.

Vertical emittance.—Figure 2 summarizes the estimated vertical emittance as a function of the beam intensity from measurements with SR (a circle symbol) and LW (square symbols) monitors. The beta function at the radiation source position of the SR monitor was evaluated to be 2.4 m. To calculate the beta function at the source position, we first measured the dependence of the beam tunes on the strength of the nearby quadrupoles to calculate the beta functions in these magnets. These beta functions were then fit to calculate the beta function at

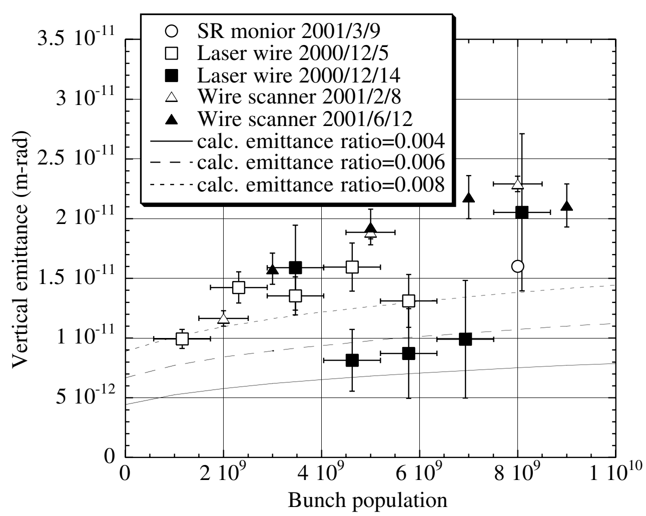

FIG. 2. Vertical emittance vs bunch intensity measured using three different types of beam size monitors. The lines are from a calculation with intrabeam scattering assuming the emittance ratios 0.004, 0.006, and 0.008.

the radiation source. The vertical dispersion was assumed to be zero at the source position. In the case of the LW monitor, data are shown for two conditions where slightly different ring tunes were used. The beta function at the laser-wire position was obtained, using the same method as for the SR monitor. It was 5.77 m on 5 December and 3.97 m on 14 December of the year 2000. The vertical dispersion at the LW monitor was measured to be less than 2 mm using BPMs in the neighborhood, and was thus ignored in the emittance calculation. The size of the laser wire was estimated to be 7.26 ± 0.22 μm [15]. The error bars reflect the statistical error as well as the uncertainty in both the laser-wire size and the beta function at the monitor. Figure 2 also shows the vertical emittance measured using wire scanners in the extraction line as a function of the beam intensity on two different days. The error bars were calculated only from fluctuations of the beam size measurement and from the uncertainty in the dispersion at each wire scanner. Other possible systematic errors were not estimated.

There was a large variation in the measured vertical emittance on different days and different monitors, suggesting different conditions in the damping ring or in the extraction line. For the laser wire and SR monitors, a possible beam oscillation would increase the apparent beam size. The gate width of a camera at the SR monitor was set to be 2 ms for sufficient light intensity. If the beam oscillates within this gate width, the apparent beam size can be affected. In the case of the laser wire, since position scanning takes a much longer time, slower oscillation or position drift of the beam can have a significant effect. Fluctuation of the temperature of the cooling water of the magnets is suspected to be the source of the slow drift. Defects on the first mirror of the SR monitor and mechanical vibration of the monitors were also possible error sources.

For wire scanners in the extraction line, pulse-to-pulse position jitter, which can be induced by possible beam oscillation in the ring and fluctuation of the extraction kicker field, would enlarge the apparent beam size. Residual dispersion in the extraction line is known to affect the accuracy of the measurement. Also the unknown nonlinear magnetic field at the beginning of the extraction line is suspected to be a source of small *x-y* coupling which makes the apparent vertical emittance large due to the small vertical-horizontal emittance ratio. Note that a possible fluctuation of the beam orbit in the damping ring causes fluctuations of the orbit, the residual dispersion, the *x-y* coupling in the extraction line, and then the measured vertical emittance.

The lines in the figure are from a calculation with intrabeam scattering, assuming the emittance ratios to be 0.004, 0.006, and 0.008. It should also be noted that calculated values of the emittance shown here refer to the normal mode emittance, which is defined as one of the independent modes of transverse oscillation. On the other hand, the apparent vertical emittance in the damping ring, $\epsilon_{y,ap}$, is evaluated as Eq. (1). If coupling components are absent in the extraction line, we measure the projected vertical emittance which is a constant in the line,

$$\epsilon_{y,pr} \equiv \sqrt{\langle y^2 \rangle \langle y'^2 \rangle + \langle yy' \rangle^2}\,, \tag{2}$$

where y is the vertical position, y' is the vertical angle of a particle, and $\langle \cdots \rangle$ denotes the average of all particles. Because of residual orbit coupling in the damping ring, $\epsilon_{y,ap}$ and $\epsilon_{y,pr}$ are not the same as the normal mode emittance. Further analysis of the simulation, which was mentioned earlier, showed that $\epsilon_{y,ap}$ in the damping ring and $\epsilon_{y,pr}$ in the extraction line are expected to be larger, respectively, by 1.3 and 1.6 times the normal mode emittance on average. The difference is important only for the vertical emittance because the horizontal emittance is too large to be affected by a small coupling.

Since these possible errors tend to make the apparent emittance larger, the real vertical emittance is likely to be smaller than the measured values. The obtained data strongly suggest that the vertical emittance was smaller than 1% of the horizontal emittance, i.e., 1.1×10^{-11} rad m, or 2.8×10^{-8} rad m normalized.

Energy spread.—The measured energy spread is shown in Fig. 3 as a function of the beam intensity. At zero intensity limit, the energy spread is calculated to be 5.5×10^{-4}, which is consistent with the measured data.

The lines show calculation results with intrabeam scattering using the SAD program, assuming the emittance ratio ϵ_y/ϵ_x to be 0.004, 0.006, and 0.008. Since the effect of intrabeam scattering is large when the bunch density is high, energy spread is expected to be large at high intensity with small vertical emittance. This intensity dependence of energy spread indicates that the vertical emittance is smaller than 1% of the horizontal emittance, which is our target.

Intrabeam scattering.—The effect of intrabeam scattering is clearly demonstrated by the intensity dependence of the energy spread and the horizontal emittance. At high intensity, strong effects of intrabeam scattering were

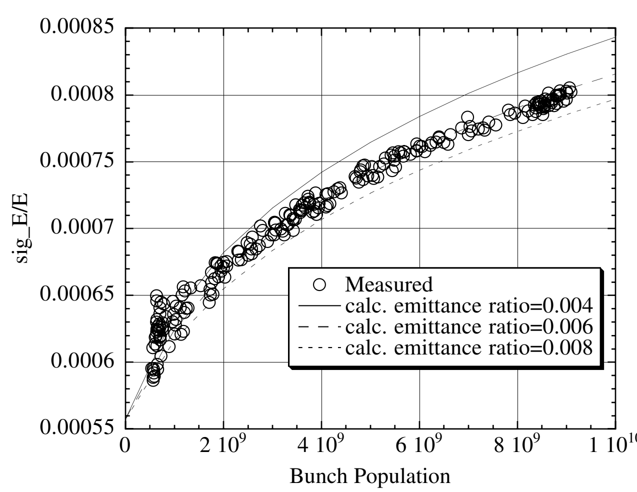

FIG. 3. Energy spread vs intensity measured in the extraction line. The lines are from a calculation of intrabeam scattering assuming the emittance ratios 0.004, 0.006, and 0.008.

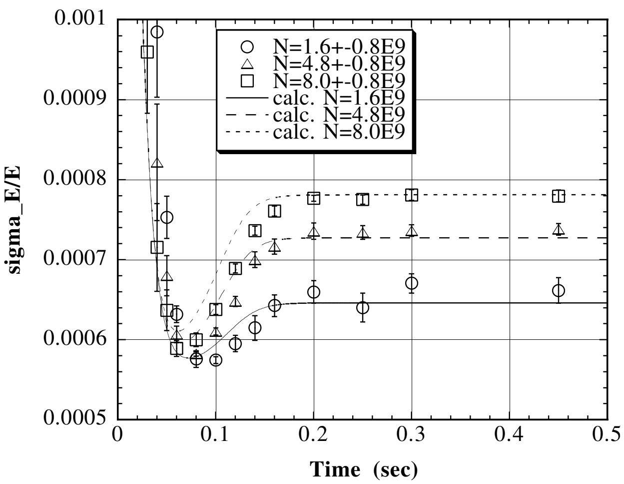

FIG. 4. Energy spread vs store time in the damping ring at different intensities. The lines are from a calculation assuming an emittance ratio of 0.006.

expected because of the extremely high particle density due to the small transverse emittance and the relatively low beam energy. To confirm the strong impact of intrabeam scattering, complementary measurements were performed.

Figure 4 shows the energy spread, measured in the extraction line, as a function of storage time in the damping ring at different intensities. The horizontal emittance was also measured as a function of the storage time. The results show that the beam energy spread and the horizontal emittance exhibit a minimum at the storage time of about 70 ms, before reaching stable equilibrium values. This behavior may be explained by the fact that the ratio of the vertical equilibrium emittance to the injected emittance is approximately 100 times smaller than the ratios for the longitudinal and the horizontal, so vertical damping continues for an additional two damping times. Also, the vertical damping time (calculated to be 27 ms) is longer than the longitudinal one (20 ms) and the horizontal one (17 ms). At first, the longitudinal and horizontal sizes are damped when the vertical size is still large. After a while the vertical beam size shrinks, enhancing the beam density. Then intrabeam scattering blows up the longitudinal and horizontal beam sizes. The lines in Fig. 4 are from simulations based on calculations of SAD, assuming ϵ_y/ϵ_x to be 0.006.

Considering that the theoretical calculation of the intrabeam scattering has some ambiguities, more accurate experimental data of the intrabeam scattering are desirable for a detailed comparison with calculations.

Conclusions.—We have confirmed that the horizontal emittance and beam momentum spread agree well with theoretical calculations. The vertical emittance was smaller than 1% of the horizontal emittance. At the zero intensity limit, the horizontal emittance and the vertical emittance were 1.1×10^{-9} rad m and less than 1.1×10^{-11} rad m, respectively, which corresponds to normalized emittances 2.8×10^{-6} rad m and less than 2.8×10^{-8} rad m at a beam energy of 1.3 GeV. These are the lowest normalized transverse emittances of electron beams ever measured.

At high intensity, strong effects of intrabeam scattering were observed. These effects were expected due to the extremely high particle density caused by the small transverse emittance and relatively low beam energy. The dramatic increase of energy spread and horizontal emittance with intensity also indicated that the vertical emittance was extremely small.

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