LOW EMITTANCE BEAM GENERATION IN ATF

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Abstract

The smallest vertical emittance achieved in single bunch mode operation of the Accelerator Test Facility (ATF) was confirmed by the laser-wire monitor [1]. The achievement was done by the BPM electronics improvement and the laser-wire monitor development. The measured vertical emittance at low intensity was 4 [pm rad] at beam energy of 1.3 GeV, which corresponds to the normalized emittance of 1.1×10^{-8} m. The value satisfies the requirement of the present design of a linear collider.

INTRODUCTION

Accelerator Test Facility at KEK consists of an S-band linac, a damping ring and an extraction line is a test accelerator complex for the study of GLC (Global Linear Collider accelerator). The damping ring has been designed to produce a beam of extremely low emittance. The natural, normalized horizontal design emittance is 2.8×10^{-6} [m rad] and the target value of the vertical emittance is 1% of that. The corresponding physical emittance is 1.1 nm and 11 pm. These are comparable to the requirement of the linear collider designs (GLC/NLC) [2]. This paper reports on the production of the ultra low 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.

Recently, several essential improvements were implemented which permitted us to further reduce the beam emittance: (1) The detection circuits for the beam position monitors (BPMs) in the damping ring were replaced by a new type. The maximum position resolution of the BPMs was, thereby, improved to 2μm for a single shot measurement. (2) The position offset of the BPMs with respect to the field center of the nearest magnet were measured by a beam-based method [3]. (3) In January 2003 the positions of the magnets in the damping ring were re-aligned. (4) In parallel, the optics diagnostics and correction were further refined. They are based on measuring the beam-orbit response to corrector-magnet excitations. For an accurate and reliable measurement of the beam emittance, the laser-wire beam-profile monitor was upgraded [4-5]. The emittance was measured with this laser-wire beam-profile monitor installed in the damping ring.

TOOLS OF LOW EMITTANCE GENERATION

BPM Electronics Improvement

Since the damping ring is operated with short storage time and high repetition cycle, BPMs of the damping ring are required to have an ability of single shot acquisition. The signal processing electronics of BPM should have wide band width. The signal peak of the damping ring button BPM is around 1GHz. Therefore, a good S/N is expected in that region, however the existing module has been selected at below 50MHz band considering available inexpensive electronics and circuit technology. Recently, microwave components become inexpensive at around 1GHz frequency region by the growth of industry of mobile telecommunications. The replacement of the existing circuits to 1GHz wide-band circuit has been done inexpensively together with the development of the calibration pulse module, which can be used for an online BPM electronics offset calibration.

The simplest design for 1 GHz electronics was adopted for the cost reduction. The charge ADC accepts only negative swing pulse, therefore, diodes will be used to cut positive swing signal. Using identical components for 4 channels, non-linearity of each channel coming from diodes will be similar and can be corrected by using calibration pulse signal into 4 channels. The detected response by the calibration pulse are fitted to 4-th order of polynomials, and the response is linearized. The electronics diagram is shown in Fig.1. The cables, the charge ADC and the gate circuits have not been changed. The replacement has been done for the detection module and calibration system.

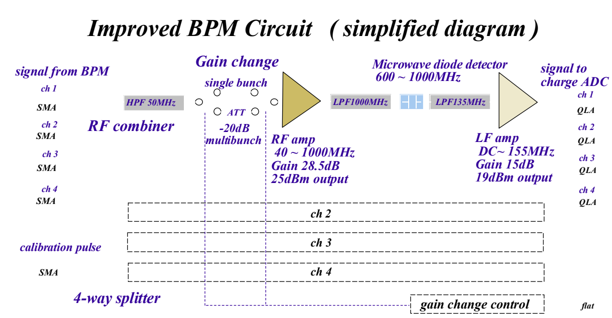

Figure 1: Improved BPM circuit diagram

Comparison of resolution between the new detection circuit by the calibration pulser and the existing detection circuit by beam are shown in Fig.2. The estimated resolution data by the calibration pulse (red solid circle & square) are consistent to 2.2μm resolution at 1×10^{10} intensity line. On the other hand, the existing detection circuit (blue solid circle & square) lies on 15μm resolution at 1×10^{10} intensity line. The resolution improvement is factor 7.

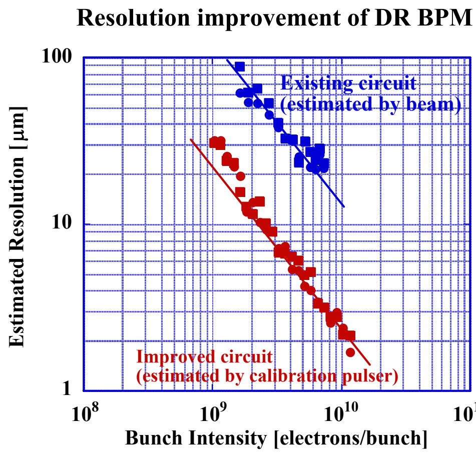

Figure 2: Estimated resolution of the new circuit, together with the one of existing detection circuit.

BPM Offset by Beam-based method

ATF arc optics is FOBO cell consisting of two focusing quadrupoles, two sextupoles and a defocusing gradient dipole. All the quadrupoles and the sextupoles have the trim windings connected to the independent power supplies. The two BPMs in a cell are located near the one of focusing quadrupoles and near the one of sextupoles. BPM offsets from the center of the nearest magnet have been estimated by a beam-based method [3]. 6 x 5 matrix of difference orbit sets is taken as both a local bump at the magnet under test and the magnet trim excitation. In order to extract the beam kick by the small trim excitations together with a local bump, BPM data averaging and fitting of beam kick using knowledge of the ring optics were applied. For each bump setting, the fitted kick is linear as a function of the trim excitation. The fitted kicks can be interpreted as an offset in the magnet. The reading of BPM nearby the test magnet with giving the minimum kick is the BPM offset. Data collection was automated, and the orbit analysis was done in offline. The procedure was developed with the existing BPM electronics, the offset data have been updated by using the improved BPM electronics.

Low Emittance Tuning

Our tuning method of the damping ring for low vertical emittance consists of a series of corrections [6–8]: COD (closed-orbit distortion) correction, followed, first, by a combined correction of vertical COD and dispersion and, finally, by a coupling correction. Because the vertical emittance in the damping ring is primarily determined by the vertical dispersion and by the horizontal-vertical coupling, it is essential to make the vertical dispersion and the coupling small. After the above corrections, the rms value of $\eta_{y,\mathrm{meas}}$ is about 1.5 mm and the coupling, $[\Sigma_{\mathrm{BPM}}(\Delta y_{\mathrm{steer}})^2/\Sigma_{\mathrm{BPM}}\ (\Delta x_{\mathrm{steer}})^2\ ]$, about 0.004, where $\Delta x_{\mathrm{steer}}$ and $\Delta y_{\mathrm{steer}}$ are the measured horizontal and vertical position responses to a set of horizontal steering magnets.

We observed that the residual COD, vertical dispersion, and *x-y* coupling have been significantly reduced after the improvement of BPM readout circuits, by performing a beam-based offset correction of the vertical BPM readings, and with frequent beam-based updates of the optics model. The dispersion correction and the coupling correction are iterated, until no further enlargement of the momentum spread is seen.

MEASUREMENT OF EMITTANCE

Laser Wire profile monitor

The transverse beam sizes in the damping ring were measured with a laser-wire monitor (see Fig.3). Both electron beam and laser beam have a nearly Gaussian intensity distribution (with rms widths σ_e and σ_{lw}, respectively) in the transverse direction. The measured size (σ_{meas}) is a convolution of the two. The electron-beam size was extracted by unfolding the laser size as $\sigma_e^2 = \sigma_{\mathrm{meas}}^2 - \sigma_{lw}^2$. The size σ_{lw} are 5.65µm and 14.7 µm for h wire and v wire.

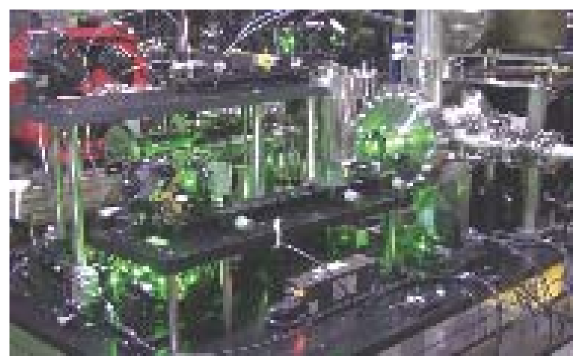

Figure 3: Picture of the laser wire monitor installed in the damping ring.

The procedure of the beam-size measurements was as follows. An electron beam with a target intensity was stored in the damping ring. The position of the laser wire (the whole optical system on the table) was scanned in steps of 10µm, and data were taken over 10sec per point for the vertical measurement, and every 50µm over 30sec for the horizontal. One profile measurement corresponds to a complete scan back and forth across the beam (round-trip). It took about 6min to obtain one profile for the vertical beam-size measurement, and 15min for the horizontal. It should be noted that the obtained profile includes the amplitude of the beam-orbit jitter faster than ~0.1 Hz. The real size might be a little smaller especially in the vertical beam-size measurements for the small emittance cases. The beam emittances were evaluated from $\varepsilon\beta = \sigma_e^2 - [\eta(\Delta p/p)]^2$, where β is the beta function, η is the dispersion, and Δp/p is the momentum spread of the beam. To estimate the beta function at the laser-wire positions, the beta functions at the quadrupole position in the neighborhood were measured by taking the dependence of the betatron tunes on the strength of the quadrupoles. The beta functions at the laser-wire position were inferred by interpolation. The dispersion function at the laser-wire position was estimated and found to be less than 2mm (20mm) in the vertical (horizontal) plane. The dispersion term was found to be negligible and was ignored in the calculation.

Measurement Results

The current dependence of the horizontal and vertical emittances were measured by the laser-wire monitor. Typically, β_y at the horizontal laser wire was 4.51 m, and β_x at the vertical laser wire was 7.45 m. These values were stable within 10% in this series of experiments. Data of runs *B* and *D* (normal condition, just after tuning) are shown in Fig. 4. The source of the intensity dependence of the transverse emittance is considered to be intrabeam scattering. The higher the particle density (smaller vertical emittance), the stronger is the effect of intrabeam scattering. The intensity dependence was compared with calculations using the SAD program [9]. The results of these calculations are shown as lines in Fig. 4, where the vertical-horizontal emittance ratio was set, based on the measured data, as 0.4% for the case of normal coupling correction (runs *B* and *D*). The measured data agreed to the calculation of intensity dependences from intrabeam scattering within much better than a factor of 2. The smallest vertical rms emittance measured at low intensity was 4 [pm rad] at beam energy of 1.3GeV, which corresponds to the normalized emittance of 1.1×10^{-8} m. The vertical and horizontal emittances were 1.5 times bigger at 10^{10} [electrons/bunch] intensity than at zero current. No clear differences are seen between the strengths of the current dependence in the horizontal and the vertical plane. The simulation study shows that the expected ratio $[\Delta\varepsilon_y/\varepsilon_{0y}]/[\Delta\varepsilon_x/\varepsilon_{0x}]$ is about 1.6 if η_y is dominant, and about 1 if the coupling is dominant [10]. The strength of the current dependence seems to be weaker in the cases with larger zero-current emittance. This is easily understood as the lower electron density reduces the rate of intrabeam scattering. It was found that our model calculation [11] reproduces well the overall characteristics of the data such as the current dependence of emittances, bunch length, and momentum spread.

We would like to note that the achieved vertical emittance in the single-bunch-mode operation satisfies the requirement of the present design of a linear collider. The emittance in multibunch-mode operation also has been measured [12] though a definite conclusion is yet to be reached.

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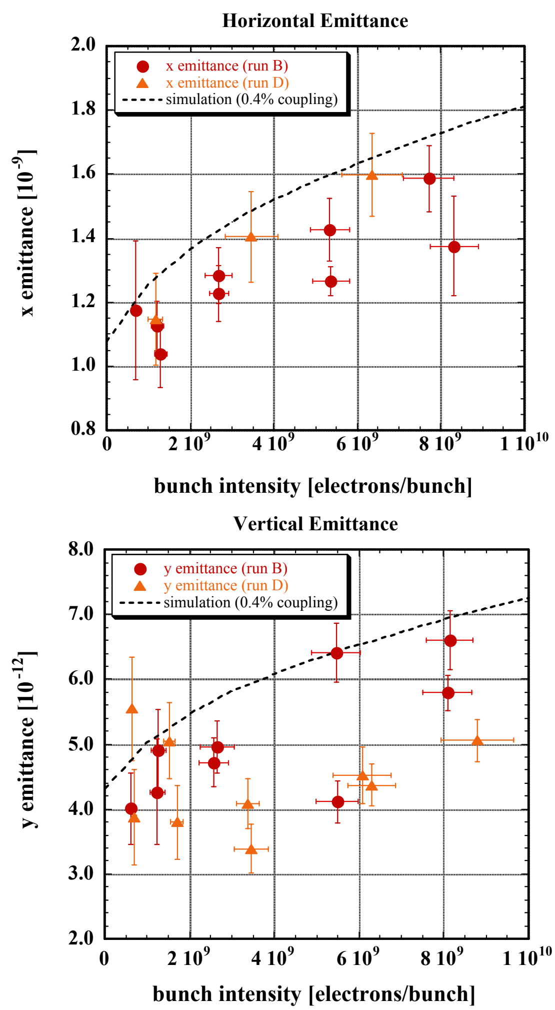

Figure 4: Intensity dependence of the horizontal and the vertical emittances measured by the laser-wire monitor.

REFERENCES

[1] Y. Honda *et al.*, Phys. Rev. Lett. **92**, 054802 (2004).
[2] GLC Project Report, 2003, http://lcdev.kek.jp/ProjReport/.
[3] M. Ross, J. Nelson, M. Woodley, and A. Wolski, SLACPUB-9239, 2002.
[4] H. Sakai *et al.*, Jpn. J. Appl. Phys. **41**, 6398 (2002).
[5] H. Sakai *et al.*, Phys. Rev. ST Accel. Beams **5**, 122801 (2002).
[6] K. Kubo *et al.*, Phys. Rev. Lett. **88**, 194801 (2002).
[7] K. Kubo *et al.*, in Proceedings of the Seventh European Particle Accelerator Conference,Vienna, 2000 (Ref. [8], pp. 483– 484).
[8] K. Kubo, Phys. Rev. ST Accel. Beams **6**, 092801 (2003).
[9] SAD is a computer program for accelerator design. http:// acc-physics.kek.jp/SAD/sad.html
[10] K. L. F. Bane *et al.*, Phys. Rev. ST Accel. Beams **5**, 084403 (2002).
[11] K. Kubo and K. Oide, Phys. Rev. ST Accel. Beams **4**, 124401 (2001).
[12] Y. Honda *et al.*, Phys. Rev. ST Accel. Beams **6**, 092801 (2003).