HORIZONTAL EMITTANCE MEASUREMENT IN ATF EXTRACTION LINE

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Abstract

The beam operation of the damping ring of the KEK accelerator test facility (ATF) has been started since January 1997 for the development of the technologies to achieve a low emittance beam, which is required in future linear colliders. The ATF consists of a injector linac, the damping ring and a beam extraction line for a beam diagnosis. An operation of the extraction line has been started since November 1997. However, the beam position at the extraction line was not stable for the reason why extraction kickers did not work stable and the longitudinal beam oscillation is still remained in the damping ring at extraction timing and so on. Therefore, we established the method to correct measured beam size and evaluated the horizontal emittance. In this paper, we report the performance of jitter subtraction method for the horizontal beam size. The amount of the evaluated horizontal emittance was 1.37 ± 0.03nm.

1 INTRODUCTION

It was reported that a small beam emittance was measured by synchrotron radiation at several synchrotron radiation storage rings. In ESRF, extremely small horizontal and vertical emittances, 3.5nm and 0.04nm, were evaluated with X-ray pinhole camera[1]. It is difficult to measure the horizontal emittance with small systematic error by utilizing the synchrotron radiation in the ATF damping ring, because a fraction of horizontal beam size due to horizontal dispersion and energy spread was comparable or greater than that from horizontal emittance. However, ATF has a beam extraction line, which contains a beam diagnosis section of the extracted beam. Operation of the ATF extraction line has been started since November 1997.

2 ATF EXTRACTION LINE

In the ATF extraction line, there is a beam diagnostic section, which is designed to be horizontal dispersion free and the quadrupole magnets are designed to form FODO cells.

There are an integrating current transformer (ICT) and 14 single path strip-line type beam position monitors (BPMs) at the extraction line. And four wire scanners are located to measure a beam size and to evaluate a beam emittance[2]. Wires of each wire scanner are mounted to wire mounts. And the wire mounts are rotated by $45°$ to horizontal plane as shown in Figure 1. The wire positions are read out by measuring the wire mount positions with digital position gauges. And scattered γ-rays by wire scanners are detected by an air Čerenkov detector with photomultiplier (PMT). All of these beam monitors at the ATF extraction line are read out in the single beam passage simultaneously. Thereby, we can examine a correlation between all monitors in the ATF extraction line.

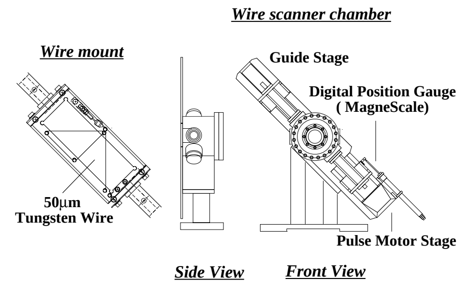

Figure 1: Schematic figure of wire scanner used in ATF.

3 DISPERSION CORRECTION

The magnet setting, especially steering magnets, is often changed for various beam studies, because ATF damping ring is a test accelerator. It changes dispersion in the damping ring and as consequence in the extraction line. Residual horizontal dispersion at the beam diagnostic section produces an additional beam size and a longitudinal beam oscillation make additional horizontal position jitter as proportional to the dispersion. Thereby, we must make dispersion correction every time at the beginning of beam diagnosis on the extraction line. The dispersion function at the extraction line is evaluated by measuring orbit difference with different rf frequency in the damping ring (rf ramp method). At a beam injection timing, the damping ring rf must be synchronized with a linac rf. However, the damping ring rf frequency can be changed between a beam injection and the next beam injection in order to measure the dispersion function.

Dispersion correction was carried out as following procedures. At first, beam positions were measured by BPMs for five rf frequency offsets, +2kHz, +1kHz, 0kHz, -1kHz and -2kHz. Slopes $\Delta x_{\rm ramp}/\Delta f_{\rm RF}$ were evaluated with linear fitting using MINUIT[3] software package and horizontal dispersions were evaluated as

$$\frac{\eta_x}{\alpha_{\rm M}} = -f_{\rm RF}\frac{\Delta x_{\rm ramp}}{\Delta f_{\rm RF}} \tag{1}$$

for each BPM locations in the extraction line. Horizontal dispersions at locations of wire scanners were evaluated using a fitting with two parameters of η_x, η'_x at the entrance of extraction line on restricted condition of design momentum compaction factor $\alpha_{\rm M}$. Linear optics model for the extraction line was used for the fitting. Finally, a calculation of magnet settings to suppress horizontal dispersion at beam diagnostic section were carried out based on the dispersion measurement. Consequently, strength of some quadrupole magnets were changed to suppress horizontal dispersion.

4 JITTER SUBTRACTION

Horizontal beam position of the extracted beam was not stable for the reason why one of extraction kickers[4] discharged, which was located at the extraction line. An amount of horizontal beam position fluctuation was 50-200μm at the beam diagnostic section and the beam fluctuation affected to horizontal beam size measurement, because a typical horizontal beam size of 30-100μm at the beam diagnostic section was comparable to the beam fluctuation. We applied a position jitter subtraction to a beam size measurement.

Horizontal beam offset at arbitrary position x_3 is calculated from offsets at other two locations x_1, x_2 as follows

$$x_3 = \frac{R_{12}(s_3, s_1)}{R_{12}(s_2, s_1)} x_2 - \frac{R_{12}(s_3, s_2)}{R_{12}(s_2, s_1)} x_1 \qquad (2)$$

at the dispersion free section. Where $R_{12}(s_j, s_i)$ is a transfer matrix component from s_i to s_j. As more than two horizontal positions are possible to be measured by BPMs, we can estimate a horizontal beam offset at arbitrary position. An expected position resolutions for the position estimation depends upon a BPM readout resolution as follows

$$\begin{aligned} \sigma_{x_3} &= \sqrt{\left(\frac{R_{12}(s_3, s_1)}{R_{12}(s_2, s_1)}\right)^2 + \left(\frac{R_{12}(s_3, s_2)}{R_{12}(s_2, s_1)}\right)^2}\ \sigma_{x,\mathrm{BPM}} \\ &= f(s_1, s_2, s_3)\ \sigma_{x,\mathrm{BPM}} \end{aligned} \qquad (3)$$

with $\sigma_{x,\mathrm{BPM}}$ the BPM readout resolution. As any set of BPM readout positions can be applied to x_1, x_2 in Eq. (2), the set of BPMs should be chosen to make the resolution factor $f(s_1, s_2, s_3)$ minimize for each noticeable locations s_3.

We applied the position estimation method to beam size measurement using wire scanners. The set of BPMs used for position estimation and corresponding resolution factor $f(s_1, s_2, s_3)$ are listed in Table 1. As mentioned above, horizontal beam positions at the wire scanners were fluctuated pulse by pulse. However, we can expect a beam position with respect to wires by using the position estimation of Eq. (2). And the beam position with respect to a wire can be expressed as

$$x_{\mathrm{WS}} = \frac{x_{\mathrm{DG}}}{\sqrt{2}} - \left(\frac{R_{12}(s_{\mathrm{WS}}, s_1)}{R_{12}(s_2, s_1)} x_2 - \frac{R_{12}(s_{\mathrm{WS}}, s_2)}{R_{12}(s_2, s_1)} x_1\right) \qquad (4)$$

with s_{WS} the wire scanner location, x_{WS} the beam position with respect to the wire and x_{DG} the digital position gauge readout on the wire scanner, which was divided by $\sqrt{2}$ to convert the horizontal position by its 45° tilt. A typical readout of PMT signals for wire scanner MW1X is shown in Figure 2(a) as a function of wire positions. It was found that PMT signals were scattered over wide range. On the other hand, Figure 2(b) shows PMT signals as a function of the x_{WS} in Eq. (4) and horizontal position jitter was well corrected.

Wire Scanner Name	BPM1	BPM2	$f(s_1, s_2, s_3)$
MW1X	ML11X	ML10X	0.758
MW2X	ML12X	ML10X	0.432
MW3X	ML12X	ML9X	0.868
MW4X	ML10X	ML11X	0.370

Table 1: The list of resolution factor for each monitors located at beam diagnostic section. BPM1, BPM2 are the set of BPMs for the minimum resolution factor.

5 EMITTANCE EVALUATION

Two different methods are used for horizontal emittance evaluation. One is a waist scan method, and the other is a four wire method. The waist scan method is the method to evaluate a beam emittance by measuring a beam size with single wire scanner while changing strength of a quadrupole magnet located upstream of the wire scanner. The beam size square changes as quadratic as shown in Figure 3. We evaluated a horizontal emittance by the waist scan method with MW1X, MW2X and MW3X. Waist scan method with MW4X was not carried out, because a horizontal beam size at MW4X was insensitive to a strength change of quadrupole magnets located upstream of the monitor. The results are listed in Table 2.

The four wire method is the method to evaluate a beam emittance by measuring beam sizes with four wire scanners. In this method, Twiss parameters α_x, β_x and horizontal emittance are evaluated from a fitting for the beam sizes at the four wire scanner locations, knowing the optics information between them. The result of the fitting are shown in Figure 3(d). The ellipse shows the evaluated beam distribution in phase space (x, x') at the entrance of the extraction line. And four lines show the measured beam size boundaries converted to the same phase space. Result is also listed in Table 2. All evaluated horizontal emittances with both of waist scan and four wire methods agreed within 2σ and the averaged horizontal emittance was obtained as

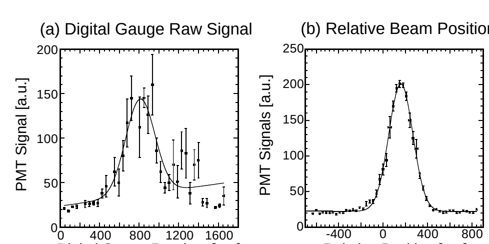

Figure 2: Result of a position jitter subtraction to magniscale readout position of wire scanner. (a) PMT signals as a function of wire readout position, (b) PMT signals as a function of evaluated relative beam position to wire.

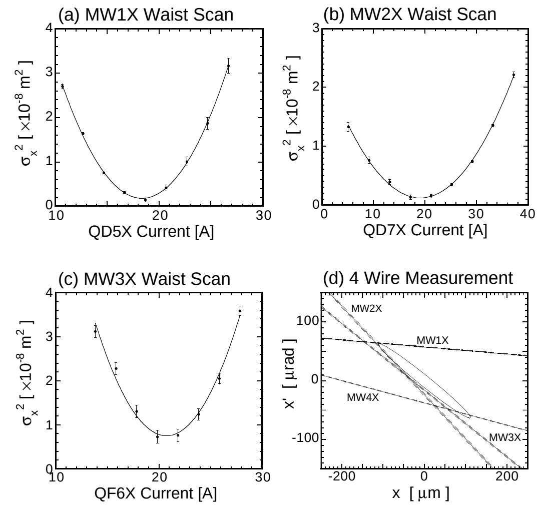

Figure 3: Beam size measurement result. (a),(b),(c) are results of waist scan method for each monitors, and (d) shows a result of four wire method.

1.37 ± 0.03nm.

The fitted Twiss parameters were compared for a verification of consistency of the horizontal emittance evaluations. Factor $B_{\rm mag}$ is defined as

$$B_{\rm mag} = \frac{1}{2}\left[\frac{\beta_2}{\beta_1} + \frac{\beta_1}{\beta_2} + \beta_1\beta_2\left(\frac{\alpha_1}{\beta_1} - \frac{\alpha_2}{\beta_2}\right)^2\right] \quad (5)$$

for two different set of Twiss parameters α, β. The evaluated $B_{\rm mag}$'s are also shown in Table 2. In the calculation of $B_{\rm mag}$, each measurement was used as one set of Twiss parameter and an averaged Twiss parameter of the other three measurement weighted by their errors was used as the other. It was found that all $B_{\rm mag}$ were close to unity. Thereby, evaluated horizontal emittance had the consistency each other.

6 CONSIDERATION

The evaluated horizontal emittance was a little bit larger than design natural emittance of 1.12nm. A momentum spread was evaluated by measuring a beam size with screen monitor at about 1.7m of huge horizontal dispersion region of the extraction line and the evaluated momentum spread was increased with increasing a bunch current as shown in

Method	Emittance [nm]	$B_{\rm mag}$
MW1X Waist Scan	1.47 ± 0.06	1.05 ± 0.09
MW2X Waist Scan	1.27 ± 0.06	1.00 ± 0.03
MW3X Waist Scan	1.38 ± 0.05	1.07 ± 0.11
Four Wire	1.29 ± 0.11	1.07 ± 0.34
Average	1.37 ± 0.03	α_x:3.83 β_x:6.77

Table 2: The results of horizontal emittance. "Average" is an averaged data weighted by their errors.

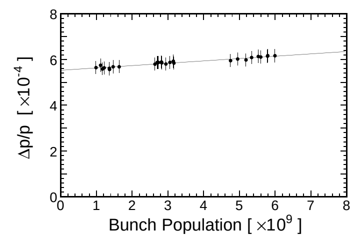

Figure 4: Result of momentum spread measurement. There was clearly intensity dependence.

Figure 4. A horizontal emittance is expected to increase with the momentum spread as

$$\epsilon_x = \frac{J_\epsilon}{J_x}\left\langle \frac{1}{\beta_x}\left[\eta_x^2 + (\beta_x\eta_x' + \alpha_x\eta_x)^2\right]\right\rangle_{\rm arc}\left(\frac{\sigma_p}{p}\right)^2, \quad (6)$$

where J_x and J_ϵ are the damping partition number for horizontal and longitudinal direction and the angular bracket means average over the arc section. As momentum spread was enhanced by about 8-12% at the bunch population of 3-5$\times10^9$ in Figure 4, the horizontal emittance should be 1.31-1.41nm for the beam intensity. This horizontal emittance agreed with the evaluated horizontal emittance of 1.37 ± 0.03nm.

7 SUMMARY

The horizontal emittance was evaluated by the horizontal beam size measurement at the ATF extraction line with position jitter subtraction method. The horizontal emittance was 1.37 ± 0.03nm and this was a little bit larger than the design natural emittance. However, this difference can be explained by intensity dependence of the emittance. Measured horizontal emittance well agreed with the designed one.

8 ACKNOWLEDGEMENT

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9 REFERENCES

[1] P. Elleaume et al., Jour. of Synchr. Rad. **2** (1995) 209.

[2] S. Kashiwagi et al., "DIAGNOSIS OF THE LOW EMITTANCE BEAM IN ATF DR EXTRACTION LINE", Proc. of the 6th EPAC, Stockholm (1998).

[3] MINUIT Reference Manual, edited by F. James, CERN Program Library Long Writeup D506.

[4] H. Nakayama, KEK Proceedings 92-6 (1992) 326.