PA47

Refinement of Calibration Procedure for Beam Position Monitors

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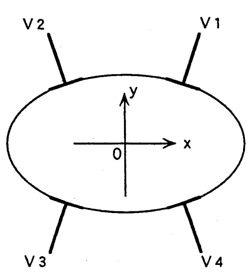
Abstract

Experimental studies to examine calibration accuracy of beam position monitors (BPM's) with an RF-antenna were conducted as an R & D for the BPM's of the SPring-8 storage ring. The antenna was optimized so as to generate the electric field similar to that carried by an electron beam. The accuracy was evaluated better than ± 1 % for the position sensitivity after correction of systematic error due to the effect of the finite diameter of the antenna, and within ± 56 μm for the offset of electrical center.

I. Introduction

To measure the position of an electron beam with a BPM, it is necessary to calibrate precisely the offset of electrical center, and the relation between imbalances of signals from pickup electrodes and the deviation of the electron beam from the electrical center. The imbalances are expressed by position sensitivities U and V (Fig. 1).



$$U=\frac{1}{2}\left(\frac{V_1-V_2}{V_1+V_2}+\frac{V_4-V_3}{V_4+V_3}\right)$$

$$V=\frac{1}{2}\left(\frac{V_1-V_4}{V_1+V_4}+\frac{V_2-V_3}{V_2+V_3}\right)$$

Fig. 1 Conceptual drawing of a BPM and definition of position sensitivities U and V.

We studied the calibration procedure with an RF-antenna as an R & D for the BPM's of the SPring-8 storage ring. Since the electric field around a relativistic electron beam is contracted into a thin disk perpendicular to the direction of motion, the electric field from the antenna has to be dominated by a transverse component at the position of a BPM. We optimized the antenna to generate a TEM field and examined the accuracy of position sensitivity and offset measurements with the antenna.

II. Equipment for BPM Calibration

A. RF-Antenna

The RF-antenna is made of a straight semi-rigid cable with an inner conductor bared at the tip (Fig. 2). The outer diameter of the cable is 3.6 mm and the length of the coaxial cable is chosen to be 295 mm which is a half wavelength of 508 MHz sinusoidal wave fed to the antenna. The frequency of 508 MHz is the RF frequency of the SPring-8 storage ring and the BPM electronics of the storage ring detects the 508 MHz component of the electric fields excited by an electron beam. The antenna is supported by a long rod which is fixed to a three-dimensional moving stage.

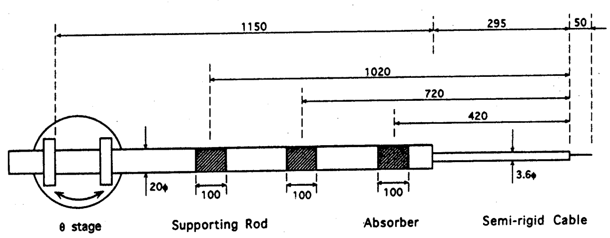


Fig. 2 Structure of the RF-antenna.

B. BPM Chamber

Two BPM chambers have been prepared for the present study.

One has a circular cross section of 30 mm in radius. The chamber has been made to have symmetry of rotation. Its dimensions have been measured with a precise coordinate measuring machine. This chamber was used to define the reference point for BPM calibration.

The other has an ideal elliptical cross section of the beam chamber of the SPring-8 storage ring. Since the electric field around a relativistic electron beam is transversal to the direction of motion, it can be modeled as two-dimensional electrostatic field from a line charge of infinite length located at the mass-center of the electron beam. We can calculate it numerically by the two-dimensional boundary element method (BEM) [1] imposing the boundary condition of the elliptical cross section of the chamber, and calculate the dependence of the output voltages of individual pickup signals upon the beam position. We measured the output voltages by moving the antenna in this chamber, and investigated its systematic difference from the calculation.

III. Experiments and Results

A. Distribution of Transverse Electric Field

Because uniformity of the coaxial structure, which is composed of the antenna and the elliptical BPM chamber, is broken at the tip of the antenna, many modes of electric field may exist there. However, only the TEM mode can propagate through the coaxial structure since the cutoff frequency is higher than 508 MHz.

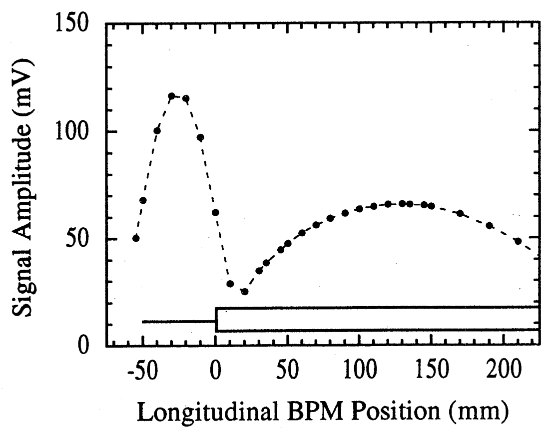


Fig. 3 Distribution of transverse electric field measured along the RF-antenna.

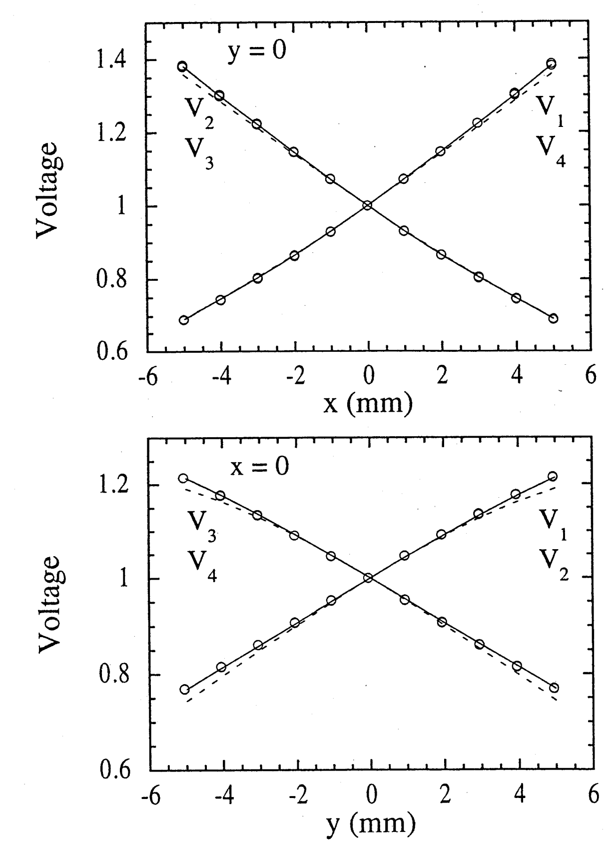


Fig. 4 Normalized voltages of individual pickup signals. Open circles show the measurement with the antenna. The broken curves and solid curves show the voltages by BEM calculated for an electron beam and the TEM mode, respectively.

To find the maximum point of the transverse electric field, we investigated the longitudinal distribution of transverse electric field along the antenna [2]. Changing the longitudinal position of the BPM with respect to the antenna, we measured the voltage of a pickup signal which is proportional to the transverse electric field. The transverse electric field reaches a minimum at the tip of the antenna and a maximum at about 130 mm (Fig. 3). We decided to use the maximum point at 130 mm for BPM calibration.

We measured the dependence of the output voltages of individual pickup signals upon the antenna position in the transverse plane in order to verify if the distribution of the electric field around the antenna is consistent with that of the TEM mode. The voltages measured with the antenna moving on the horizontal and vertical axes are shown as open circles in Fig. 4. They are normalized to be unity at the electrical center. We can calculate the expected voltages for the TEM mode by BEM, assuming an indefinitely long charged metal rod of 3.6 mm in diameter (solid curves). The position dependence of the measured voltages agrees with the calculation quite well. The theoretical voltages for an electron beam are calculated by assuming an infinitely long line charge (broken curves). Small systematic errors are found in measured voltages. We conclude that the electric field around the antenna is consistent with that of the TEM field, but is slightly different from that of an electron beam because of the finite diameter of the antenna.

B. Position Sensitivity

Moving the antenna by 1 mm step in a central square of 10 mm by 10 mm within the elliptical BPM chamber, we measured the position sensitivities U and V (open circles in Fig. 5).

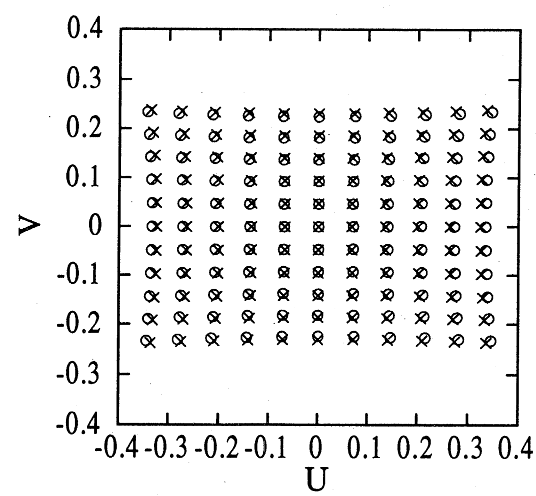


Fig. 5 The position sensitivities U and V measured with the antenna (open circles) and calculated theoretically (crosses).

Crosses represent the sensitivities calculated for the electron beam by BEM at the same points. We found small systematic errors in measured sensitivities. They are caused by the finite diameter of the antenna. In order to evaluate the systematic errors ΔU and ΔV quantitatively, they are plotted as a function of the theoretical sensitivity, respectively (Fig. 6). According to least squares fit to a straight line, the systematic errors are evaluated to be + 2.8 % in horizontal sensitivity U and - 2.2 % in vertical sensitivity V. After correction of the errors, residual systematic errors are ± 0.3 % for U and ± 0.6 % for V. Taking account of the random error of 0.2 % caused by the repeatability of measurement, we conclude that the total accuracy of position sensitivity measurement is ± 0.5 % for U and ± 0.8 % for V.

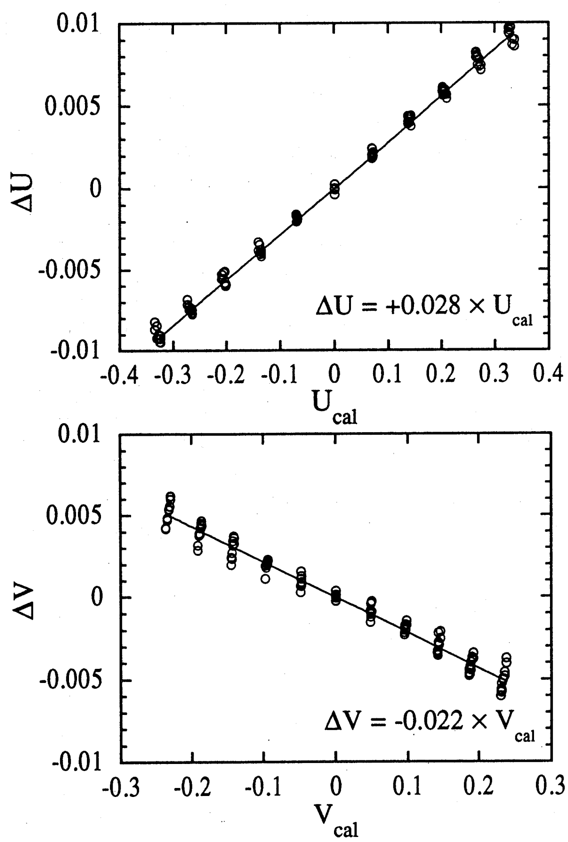


Fig. 6 Systematic errors of the position sensitivities measured with the RF-antenna.

C. Offset of Electrical Center

To measure the offset of the electrical center of a BPM, we have to locate the antenna at the reference point whose location is definitively identified. We defined it as the rotational center of the circular BPM chamber.

Owing to the measurement of its dimensions, location of the rotational center of the circular BPM chamber is known (crosses in Fig. 7). The position where we can set the antenna directly, however, is not the rotational center, but the electrical center (a solid circle in Fig. 7 (a)). If we know the distances between the rotational center and the electrical center, we can identify the location of the rotational center through the electrical center. In order to find out the distances, we rotated the chamber to the configuration shown in Fig. 7 (b), and measured the displacements of the electrical center (an open circle) from the position measured in case of the setup in Fig. 7 (a). Since the rotational center is at the midpoint of the electrical centers thus measured, we can identify the location of the rotational center, i.e., the reference point.

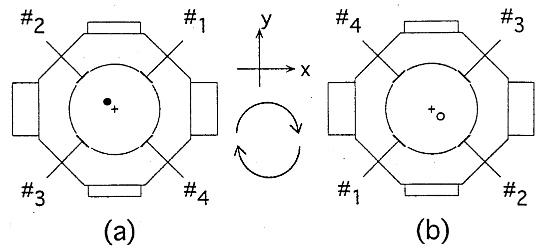


Fig. 7 Measurement of the distances between the rotational center and the electrical center of the circular BPM chamber. The midpoint between tow electrical centers in setups (a) and (b) corresponds to the rotational center.

After setting the antenna at the reference point with the circular BPM chamber, we slide the antenna away from the chamber and replace it with a BPM chamber which should be calibrated. Then the antenna is slid into the chamber, and the offset of the electrical center is measured.

The precision of the reference point and that of the electrical center of the elliptical BPM chamber were ± 24 μm (full error) and ± 15 μm (full error), respectively. The total accuracy of offset measurement is evaluated to be ± 54 μm (full error), which is the sum of the precision of the reference point, the precision of the electrical center and the residual errors of the characterization of the signal processing circuits.

IV. Conclusion

We studied the calibration procedure for BPM's and evaluated the calibration accuracy. An RF-antenna was optimized so that the distribution of electric field around it was consistent with that of TEM mode. The position sensitivities were calibrated with accuracy of within ± 1 % after correction of systematic errors due to the finite diameter of the antenna, and the total accuracy of offset measurement was evaluated to be within ± 54 μm.

References

[1] T. Shintake, M. Tejima, H. Ishii and J. Kishiro, Nucl. Instr. and Meth. A 254 (1987) 146.
[2] M. Tejima, H. Ishii, T. Shintake, J. Kishiro, A. Ogata, T. Ieiri and Y. Mizumachi, IEEE Trans. Nucl. Sci. 32 (1985) 1947.