The Calibration of BEPC Beam Position Monitors

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Abstract. The basic requirement for the BEPC beam position monitor is the measurement of the beam orbit with 0.1 mm precision near the collision point. To improve the measurement accuracy, the response of the beam position monitor pickups was mapped in the laboratory before they were installed in the BEPC ring. The microcomputer-controlled test set consists of high frequency coaxial switches to select each pickup electrode, a movable antenna to simulate the beam, a signal source, a spectrum analyzer to measure the pickup signals, and analysis software. The signal source operates well below the –3 dB cutoff frequency of the pickups (buttons). We believe that the low-frequency measurement yields the same information as the real beam. The button signals were clear. This calibration technique is satisfactory for BEPC operation.

INTRODUCTION

Four-button type beam position monitors (BPM) are used in the BEPC 2.2 GeV storage ring. The BPM assembly is an electrostatic type with four disk electrodes and BNC vacuum feedthrough connectors. The beam pipe is a cylinder. The buttons are rotated 45 degrees off vertical and horizontal axes to avoid the fan of synchrotron radiation. A tooling ball located on the top of the vacuum chamber is used as the fiducial mark for survey and alignment of the BPM assembly, relative to an adjacent quadrupole magnet. Electrical differences in the buttons and the mechanical installation tolerances cause the BPM to report beam offsets that are not real. We measured these offsets in our test set.

The button disk is made of stainless steel. The disks are welded to the center conductor of the BNC feedthroughs. The feedthroughs themselves are welded into the vacuum pipe. The disks are flush with the vacuum pipe wall. Button signals can reach a few GHz. A spectrum analyzer was used to measure button response.

The BPM quality was measured with three different tests. First, we measured the button response to a fast pulse on an antenna in the center of the chamber. This measurement gave the button sensitivity to beam current. In the second test, we excited the antenna with a low-frequency field with the antenna centered. This gave us the BPM offset due to electrical and mechanical errors. If the buttons had equal capacitance and were perfectly installed relative to the center of the beam pipe, there would be no offset error and all buttons would produce identical signals. The third test we performed was an evaluation of the BPM sensitivity to antenna position. Figure 1 shows button signals from a typical antenna scan.

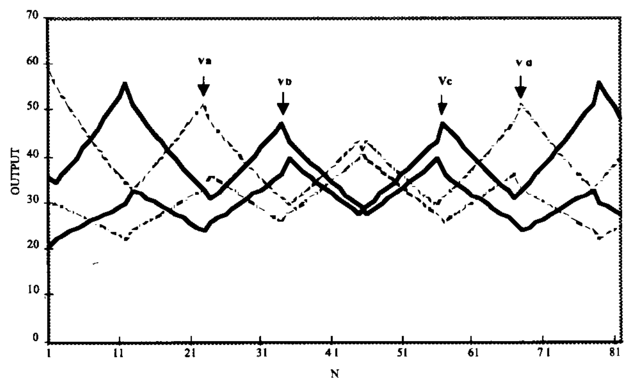

FIGURE 1. Button outputs over 10 × 10 mm scan.

The measuring setup is shown schematically in Figure 2. The antenna may be moved transversely inside the monitor along the X- and Y-axes. A SP6T rf switch is used to select signals from each button. The insertion loss of the switch was tested and corrections were made to the data. The attenuation of all button cables were measured. The mechanical error of the stepping motor was considered while the antenna moved. A personal computer (PC) controls the equipment via a PC I/O board, the RS232 port, and a GPIB board. The measurement is completely automatic.

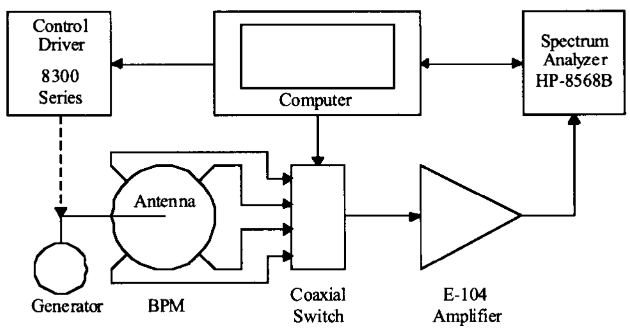

FIGURE 2. BPM calibration method schematic.

The button electrode faces a beam, and the button senses an image current Ib:

$$I_b = \frac{dQ}{dt} \propto \frac{a^2}{b}\frac{d\rho}{dt} \qquad (1)$$

where ρ is the linear charge density, a is the radius of the button, and b is the radius of the duct (beam pipe).

The self-capacitance of the button to the wall of the beam duct is C_b. A load resistor R, in shunt with C_b, will produce a frequency-dependent coupling impedance to the beam that acts like a high-pass filter:

$$Z = \frac{R}{1 + i\omega R C_b} \tag{2}$$

The button output signal is as follows:

$$V = I_b Z = I_b \frac{R}{1 + i\omega R C_b} \tag{3}$$

$$V \propto \frac{a^2}{b}\left(\frac{i\omega}{\beta C}\right)\left(\frac{R}{1 + i\omega R C_b}\right) I(\omega) \approx \frac{a^2}{b}\left(\frac{i\omega}{\beta C}\right) R I(\omega) \tag{4}$$

where β is the beam velocity relative to light. Here C_b is very small, only 10 pF. With R equaling 50 ohms the –3 dB high-pass cutoff frequency is 318 MHz, given by

$$f_{3dB} = \frac{1}{2\pi R C_b}. \tag{5}$$

In our case, the antenna radiates a 4 MHz signal to simulate the beam in the beam duct. In this case, we believe that the low-frequency measurement yields the same information as the real beam using the usual difference/sum algorithm.

The antenna is moved by the stepper motors over a 20 by 20 mm area in 2 mm steps. The PC gives a conversion mapping of the normalized electrical position (H, V) to the mechanical position (X, Y) at the experimental spots. At the center of the BPM the response is linear. At a large antenna displacement the data show pincushion distortion. Fourth order polynomials are used to determine actual antenna position from the measured data:

$$\begin{aligned} X &= \sum_{i=0}^{4} \sum_{j=0}^{i} A_{i-j,j} H^{i-j} V^{j} \\ Y &= \sum_{i=0}^{4} \sum_{j=0}^{i} B_{i-j,j} H^{i-j} V^{j} \end{aligned} \tag{6}$$

The $A_{0,0}$ $B_{0,0}$ terms show the offset of the electrical signal center from the geometric center.

Curve-fitting in Mathcad was used to extract polynomial coefficients from the experimental data using the least square method. The monitor has $X-Y$ symmetry, so major distortion contributions come from the terms of $A_{1,0}$, $A_{1,2}$, $A_{3,0}$ for X, and $B_{0,1}$, $B_{2,1}$, $B_{0,3}$ for Y. The other terms are negligible.

CALIBRATION

Each BPM is calibrated before it is installed into the accelerator. Two kinds of calibration are necessary to convert the four button signals into beam position. One is obtaining the mapping diagram from the antenna position. The other calibration involves the antenna-setting error which we know from mechanical measurements. From its original position the antenna is moved step-by-step over the desired area in the center of the BPM assembly. At 4 MHz, the coupling impedance of the buttons to the antenna is low, so pre-amplifiers are used to boost the signals and to improve the measurement noise figure. The bipolar signal from these amplifiers is not easily measured on an oscilloscope to the required accuracy, so an HP8568B spectrum analyzer is used to measure the button signal amplitude. The signal from the analyzer screen is clear with a good signal-to-noise ratio.

Conversion between the signals from four buttons to the actual beam position is done by using polynomial expressions fitted to the BPM mapping. X and Y are nonlinear functions of H and V. Given the signal amplitudes at the four buttons, H and V are found by the usual difference over sum algorithm

$$
\begin{aligned}
H &= \frac{V_A + V_D - V_B - V_C}{V_A + V_B + V_C + V_D} \\
V &= \frac{V_A + V_B - V_C - V_D}{V_A + V_B + V_C + V_D}
\end{aligned}
\qquad (7)
$$

where V_A, V_B, V_C, V_D are the output signals from corresponding button electrodes. Figure 3 shows the H and V values plotted on a rectangular grid.

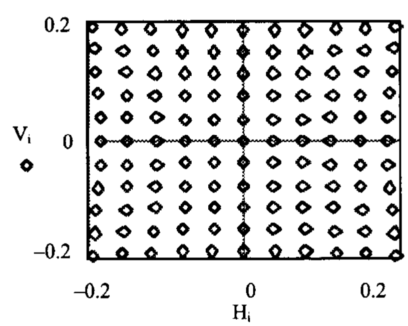

FIGURE 3. The *H* and *V* distribution from four buttons.

In Figure 3 pin cushion distortion is seen at large antenna offset from center. From these data the BPM sensitivity in %/mm may be found at any location in the measurement area. X' and Y' are found from

$$
\begin{aligned}
X' &= X + \Delta X \\
Y' &= Y + \Delta Y
\end{aligned}
\qquad (8)
$$

where X and Y are geometrical coefficients and chamber electrical offsets, and ΔX and ΔY are offsets of the chamber mechanical center referred to the magnetic center of an upstream quadrupole magnet which is used as the primary reference point for beam position measurement. Figure 4 shows the calculated X and Y position found from above. Note that the pin cushion distortion has been eliminated.

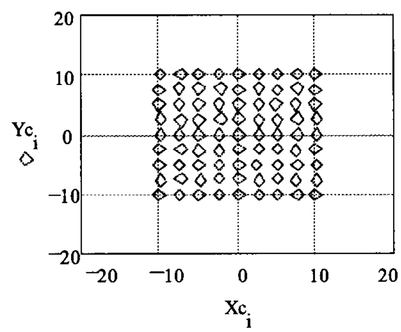

FIGURE 4. Using the fourth order polynomials to reconstruct X,Y from H,V.

During actual closed-orbit measurements we have obtained false position data from some BPMs mainly due to poor contact in switches. We have determined that we can obtain beam position from only three buttons. Below we show how to obtain beam position from buttons B, C, and D. Figure 5 shows the highly distorted H and V.

$$H = \frac{V_D - V_C}{V_C + V_D} \qquad V = \frac{V_B - V_C}{V_B + V_C} \tag{9}$$

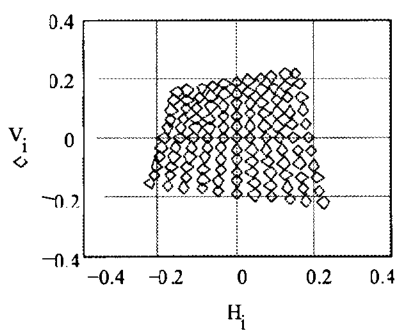

FIGURE 5. H and V calculated from buttons B, C, and D.

When all button signal paths function correctly we find the same beam position calculated in five ways. We compare signals from (a,b,c,d), (a,b,c), (b,c,d), (c,d,a), and (d,a,b). These calculations agree to 0.02 mm in the laboratory calibration. In cases where a large error is found the bad data are rejected. If the difference from five calibrations is larger than 0.4 mm, the data are considered bad. This is a good way for us to determine if we have a defective channel. Figure 6 shows X and Y for signals obtained from buttons B, C, and D.

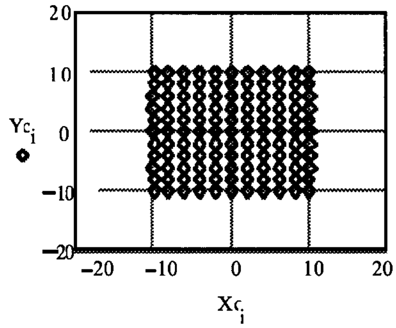

FIGURE 6. *X* and *Y* calculated from 3 buttons. It is essentially the same as Figure 4.

ERROR ANALYSIS

In the BPM calibration the maximum fitting error and rms errors are found as follows:

$$\sigma_{X_P} = \sqrt{\frac{\sum_{n=1}^{N}(\overline{X}_P - X_P(i))^2}{N}} \tag{10}$$

$$\sigma_{Y_P} = \sqrt{\frac{\sum_{n=1}^{N}(\overline{Y}_P - Y_P(i))^2}{N}} \tag{11}$$

where N is the number of measurements taken at each point, $\overline{X}_P$ is the X coordinate average value of p^{th} point, and $\overline{Y}_P$ is the Y coordinate average value of the p^{th} point. If we measure 25 points, the steps are 5 mm, and the fitting error is 0.05 mm. If we measure 81 points, the steps are 2.5 mm, and the error is about 0.03 mm.

The relative accuracy for a selected button signal measurement is

$$\frac{\Delta V}{V} = \sqrt{\frac{1}{4}\sum_{j=1}^{4}\frac{1}{P}\sum_{k=1}^{P}\frac{1}{N-1}\sum_{i=1}^{N}\frac{\left(\frac{V_{ijk}}{\sum_{j=1}^{4}V_{ijk}} - \frac{1}{N}\sum_{i=1}^{N}\frac{V_{ijk}}{\sum_{j=1}^{4}V_{ijk}}\right)^2}{\frac{1}{N}\left(\sum_{i=1}^{N}\frac{V_{ijk}}{\sum_{j=1}^{4}V_{ijk}}\right)}} \tag{12}$$

where in $1 \leq k \leq P$, P is the number of measured points; $1 \leq j \leq 4$ is a sum over the four buttons; and in $1 \leq i \leq N$, N is the number of measurements at every point.

In this case we tested every point 100 times. The relative error is less than 0.1%.

CONCLUSION

We have shown a method to test the BEPC BPM pickups in the laboratory. All error terms are compensated. We have demonstrated a technique for eliminating the geometric distortion inherent in all BPM pickups of this type. In addition we have shown how we can obtain good beam position readings even if one of four signal channels has become defective.

In the future, the antenna will be improved. We are considering working at a higher frequency to determine whether our assumption that low-frequency measurements are adequate is correct.

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