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Offset Calibration of the Beam Position Monitor Using External Means*

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ABSTRACT

Determination of the offset of the electrical center of the beam position monitor (BPM) relative to the mechanical center is required for the absolute beam position measurement in the injector synchrotron and the storage ring of the APS. Conventionally, RF signal is sent to an antenna or through a wire carefully aligned in the vacuum chamber and the signal is measured at each electrode. A new method using only external means which does not involve mechanical alignment inside the vacuum chamber was applied to the injector synchrotron BPM unit in this work. The result shows a good agreement with the wire method within 15 µm error. A similar measurement on the storage ring BPM will also be discussed.

INTRODUCTION

The Advanced Photon Source consists of an electron linac, a positron linac, a positron accumulator ring, an injector synchrotron, and a storage ring. The storage ring has a circumference of 1104 meters, along which will be placed 360 beam position monitoring stations, each composed of four button-type capacitive pickup electrodes. The injector synchrotron, which is exactly one third the circumference of the storage ring, has BPM's that are of the same type of button electrodes as the storage ring. A total of 80 stations are planned. Shown in Table 1 are accelerator parameters relevant to diagnostic instrumentation design.

A measurement accuracy of ±200 µm for the storage ring is required relative to the magnetic centerline of adjacent sextupole magnets, with a required resolution of better than 25 µm. The APS storage ring BPM specifications are listed in Table 2. The reason for the tight accuracy specification is that, at commissioning, the dynamic aperture of the machine approaches the physical aperture when the rms placement error of the sextupole magnets is equal to 200 µm. After commissioning, the insertion device vacuum chambers (1.2 cm vertical full aperture) will be installed and become the limiting aperture.

The storage ring vacuum chamber is an aluminum extrusion with a roughly elliptical inner bore near the positron beam, a photon exit slot, and an antechamber containing NeG pumping strips. The pickup electrodes will be

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Parameter	Storage Ring	Injector Synch.
Energy (GeV)	7	.45 – 7
RF Frequency (MHz)	351.93	351.93
Harmonic No.	1296	432
Minimum Bunch Spacing (ns)	20	1228
Revolution Period (μs)	3.68	1.228
Number of Bunches	1 – 60	1
Maximum Single Bunch Current (mA)	5	4.7
Bunch Length (2σ, ps)	35 – 100	61 – 122
Damping Times $\tau_{h,v}$ (ms)	9.46	2.7 @7GeV
Tunes $\nu_{h,v}$	35.22, 14.30	11.76, 9.80
Damping Time τ_s (ms)	4.73	1.35 @7GeV
Synchrotron Frequency f_s (kHz)	1.96	21.2

Table 1: Accelerator Parameters for Diagnostic Instrumentation

First Turn, 1 mA Resolution / Accuracy	200 μm / 500 μm
Stored Beam, Single or Multiple Bunches @ 5mA Total Resolution / Accuracy	25 μm / 200 μm
Stability, Long Term	±30 μm
Dynamic Range, Intensity	≥ 40 dB
Dynamic Range, Position	±20 mm

Table 2: APS Storage Ring Beam Position Monitor Specifications.

mounted on machined flats surrounding the positron side of the chamber. They will be located with a tolerance of ±0.004" (±100 μm) relative to the positron chamber center.

In case of the injector synchrotron, each BPM unit is machined out of stainless steel and welded between two vacuum chamber segments. The required accuracy of 1 mm is not so stringent, and therefore, a prototype unit will be calibrated on the test stand and the result will be applied to all others.

For the storage ring BPM, the tight accuracy requirement calls for calibrating each and every monitor for the mechanical offset and sensitivity in both the horizontal and the vertical directions. Since the BPM is an integral part of the vacuum chamber (≈ 5 m long), it will be very difficult to calibrate the BPM's using wire suspended inside the vacuum chamber. Therefore, a new method involving only external measurements is desired.

This paper describes the application of the external calibration method developed by G. Lambertson[1,2] to the offset calibration of the injector synchrotron BPM. It also serves as a feasibility study of the method for calibrating the storage ring BPM with an accuracy of less than 30 μm.

THEORY

Consider the schematic of the button configuration in Fig. 1. The position of the beam (x_0, y_0) is determined from

$$\begin{aligned}
\Delta_x &= V_1 - V_2 - V_3 + V_4 , \\
\Delta_y &= V_1 + V_2 - V_3 - V_4 , \\
\Sigma &= V_1 + V_2 + V_3 + V_4 , \\
Q &= V_1 - V_2 + V_3 - V_4 , \\
X_0 &= \frac{\Delta_x}{\Sigma} \approx S_x x_0 + R_x , \\
Y_0 &= \frac{\Delta_y}{\Sigma} \approx S_y y_0 + R_y , \\
Q_0 &= \frac{Q}{\Sigma} .
\end{aligned} \tag{1}$$

S_x, S_y, R_x, and R_y are sensitivity and offset functions. Associated with each button is a gain factor g which causes the difference between the mechanical and the electrical centers. The electrical center is the wire or beam position where Δ_x and Δ_y vanishes. The larger the gain factor of a button, the farther the electrical center from that button. With these gain factors, we can obtain the electrical center (x^e, y^e) relative to the mechanical center, which is the coordinate origin. That is,

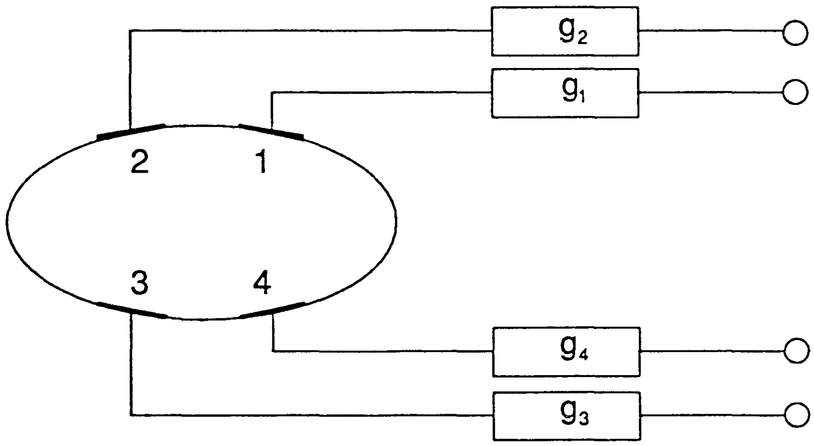

Fig. 1: The schematic of the button configuration. g's represent the gain associated with the buttons.

$$x^e = -\frac{1}{S_x}\frac{g_1 - g_2 - g_3 + g_4}{g_1 + g_2 + g_3 + g_4},$$
$$y^e = -\frac{1}{S_y}\frac{g_1 + g_2 - g_3 - g_4}{g_1 + g_2 + g_3 + g_4}. \qquad (2)$$

The external measurement method described in Ref. 1 uses the coupling between the buttons to determine the gain factors. Here, we will briefly summarize the result. As shown in Fig. 2, the RF signal V_j is applied to the button j and then the signal V_i is detected at button i. The voltage on the button j is twice the applied signal times g_j, that is, $V_j^b = 2g_jV_j$. With the capacitive coupling coefficient G_{ij} (= G_{ji}), there appears current on the button i equal to $I_i = 2G_{ij}g_jV_j$. If the transmission line has characteristic impedance of 50Ω and if terminated with 50Ω, the detected signal will be $V_i = 2{\cdot}50{\cdot}G_{ij}g_ig_jV_j$. Therefore, the normalized voltage V_{ij} is equal to

$$V_{ij} = \frac{V_i}{V_j} = 2{\cdot}50{\cdot}G_{ij}g_ig_j. \qquad (3)$$

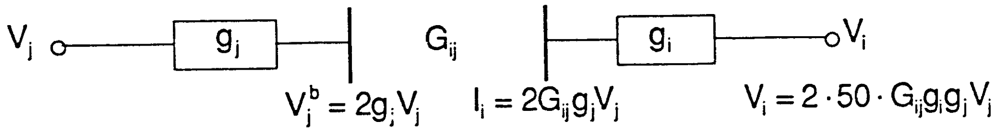

Fig. 2: The coupling between the buttons i and j.

If we assume 2-D symmetry of the button configuration, that is, $G_{12} = G_{34}$, $G_{14} = G_{23}$, and $G_{13} = G_{24}$, the gain factors g_i then can be obtained from three alternative combinations of the measured V_{ij} as shown in Eq. (4). Since we are interested in the ratios of the gain factors, the values of G's need not be known.

$$2\cdot 50\cdot g_1^2 = \frac{V_{21}V_{14}}{V_{42}}\frac{G_{13}}{G_{12}G_{23}} = \frac{V_{12}V_{31}}{V_{32}}\frac{G_{23}}{G_{12}G_{13}} = \frac{V_{41}V_{31}}{V_{43}}\frac{G_{12}}{G_{23}G_{13}},$$

$$2\cdot 50\cdot g_2^2 = \frac{V_{21}V_{32}}{V_{31}}\frac{G_{13}}{G_{12}G_{23}} = \frac{V_{21}V_{42}}{V_{14}}\frac{G_{23}}{G_{12}G_{13}} = \frac{V_{32}V_{42}}{V_{43}}\frac{G_{12}}{G_{23}G_{13}},$$

$$2\cdot 50\cdot g_3^2 = \frac{V_{32}V_{43}}{V_{42}}\frac{G_{13}}{G_{12}G_{23}} = \frac{V_{43}V_{31}}{V_{14}}\frac{G_{23}}{G_{12}G_{13}} = \frac{V_{32}V_{31}}{V_{21}}\frac{G_{12}}{G_{23}G_{13}}, \qquad (4)$$

$$2\cdot 50\cdot g_4^2 = \frac{V_{43}V_{14}}{V_{31}}\frac{G_{13}}{G_{12}G_{23}} = \frac{V_{43}V_{42}}{V_{32}}\frac{G_{23}}{G_{12}G_{13}} = \frac{V_{14}V_{42}}{V_{21}}\frac{G_{12}}{G_{23}G_{13}}.$$

MEASUREMENT SETUP

In Fig. 3 is shown the measurement setup for the external calibration of the injector synchrotron BPM. Measurement of the RF characteristic of buttons is described in Ref. 3. The network analyzer was Hewlett-Packard Model 8753C with an S-parameter test set. To compensate for the weak button-to-button coupling, an RF amplifier with 45 dB gain (1.7 – 500 MHz) was used at port 1 of the S-parameter test set. A computer-controlled SP4T switch was used at the port 2 for multiplexing through the buttons. Its insertion loss was measured and corrections were made to the data. This helped minimize the number of times needed to disconnect and connect the cables and buttons.

The measurement was made at a fixed frequency of 351.93 MHz. In Eqs. (3) and (4), the normalized voltage V_{ij} is equal to the transmission coefficient s_{21} between buttons i and j. The network analyzer was put in CW mode and an IF bandwidth of 10 Hz was used to reduce the noise-to-signal ratio to a minimum. The data was transferred to a desktop PC for storage and analysis.

The buttons were selected from eight available buttons such that the measured capacitances were the closest to each other. Eqs. (3) and (4) can be applied to the offset measurement only when the characteristic impedances of buttons, cables, and connectors are carefully matched. Otherwise, the matrix V_{ij} will not be symmetric and the measurement error will be significant.

RESULTS

Table 3 shows data from a single measurement on the injector synchrotron BPM using the external calibration method. With the sensitivity functions $S_x = 0.070\ mm^{-1}$ and $S_y = 0.057\ mm^{-1}$, we obtain $x_L{}^e = 155\ \mu m$ and

Frequency = 351.93 MHz (in dB)

Out(i)↓ In(j)→	1	2	3	4
1		-39.3776	-45.4625	-36.1599
2	-39.4058		-35.7875	-45.8526
3	-45.4953	-35.7799		-39.6083
4	-36.1638	-45.8309	-39.5856	

g factors	1.0000	1.0009	1.0100	0.9678
X_0, Y_0, Q_0, S	-0.0108	0.0058	0.0104	3.9787

Table 3: The result of external calibration measurement on the injector synchrotron BPM. The upper table is the normalized voltage matrix V_{ij} while the lower one lists the gain factors, X_0, Y_0, Q_0 and S.

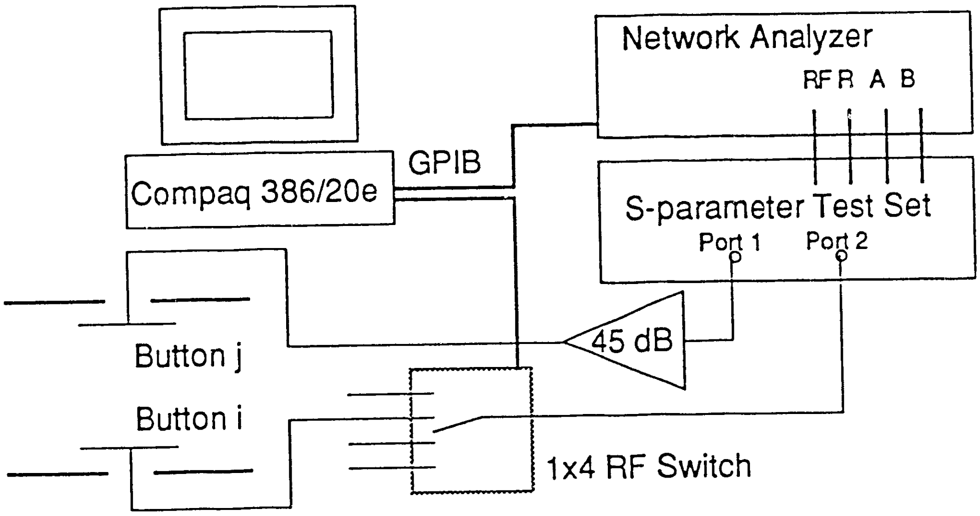

Fig. 3: Application of Lambertson's external calibration method to the offset calibration of the injector synchrotron BPM.

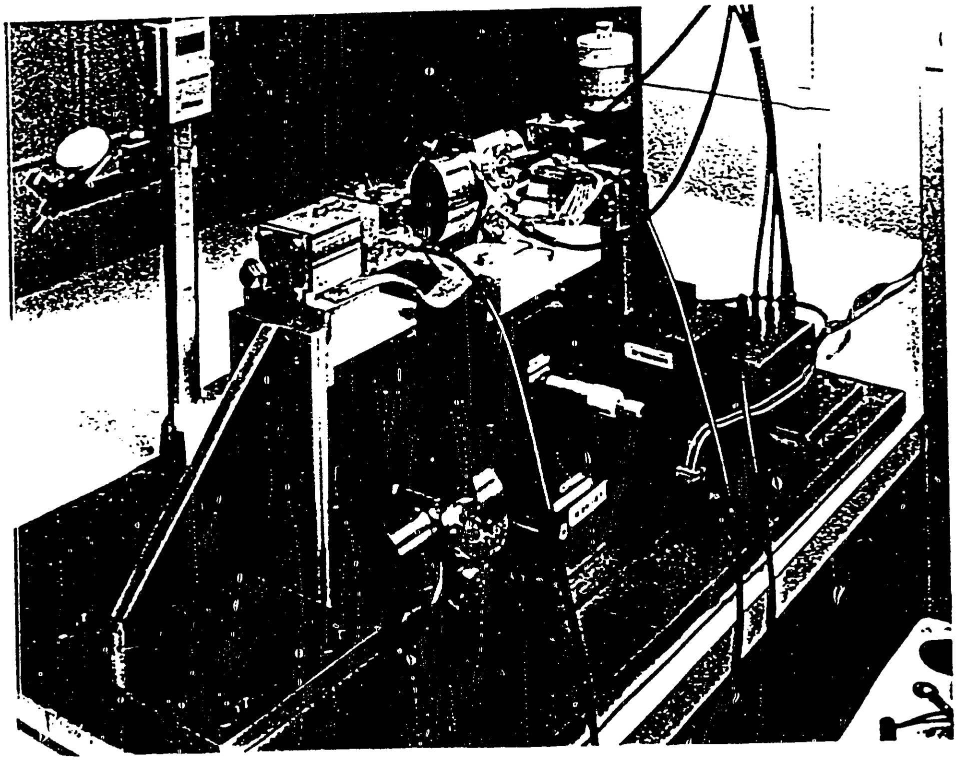

Fig. 4: Injector synchrotron BPM test stand.

y_L^e = -100 μm. A separate measurement using the wire method[3] gave x_w^e = 150 ± 6 μm and y_w^e = -103 ± 13 μm. The two results agree very well. It is to be noted that the asymmetry in the normalized voltage matrix V_{ij} is quite small. The largest error was 0.033 dB between buttons 1 and 3.

In Table 4 are listed results from measurements with different button configurations. In case 2, the buttons in case 1 were swapped about the x-plane (y = 0), and in case 3, the buttons in case 2 were swapped again about the y-plane (x = 0). The comparison of the results with those obtained using the wire method shows good agreement within a typical error of 15 μm.

(in μm)

	Wire Measurement		External Measurement†	
Case*	x_w^e	y_w^e	x_L^e	y_L^e
1	150 ± 6	-103 ± 13	159	-100
2	167 ± 4	-185 ± 4	152	-194
3	-81 ± 4	-189 ± 6	-73	-189

Table 4: Result of the offset measurement using the wire and the external methods on the injector synchrotron BPM. "w" denotes the wire method and "L" denotes the Lambertson method.

* Buttons were swapped symmetrically about the x- and y- planes for different configurations.

† Typical measurement error was ≤ 3 μm.

DISCUSSION ON THE STORAGE RING BPM CALIBRATION

A storage ring BPM calibration test stand is being built for measurements similar to those described in previous sections. In contrast to the injector synchrotron BPM, which is a separate machined unit to be welded to the vacuum chamber, the storage ring BPM has buttons directly mounted at an angle of 15.11° on the vacuum chamber.

The vacuum chamber has asymmetry about the y-plane due to the photon exit slot height of 0.426". Therefore, the wire alignment method used on the injector synchrotron BPM[3] is not applicable to the storage ring BPM. We plan to use tiny alignment holes approximately 500 μm in diameter with a laser beam passing through them. This will enable us to position the wire at the mechanical center within an error of 10 μm or better, excluding the machining error.

It is expected that the vacuum chamber will be deformed by as much as 500 μm at the photon exit slot once it is put under vacuum. The significance of the effect on the beam position measurement will be studied.

Details of the measurement setup and the results obtained from the wire and the external methods will be published separately in the near future.

REFERENCES

1. G. R. Lambertson, "Calibration of Position Electrodes Using External Measurements", LSAP Note-5, Lawrence Berkeley Laboratory, May 6, 1987
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3. G. Decker, Y. Chung and E. Kahana, "Progress on the Development of APS Beam Position Monitoring System", Proceedings of 1991 IEEE Particle Accelerator Conference.

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