

CHARACTERIZATION OF BEAM POSITION MONITORS IN TWO-DIMENSIONS*

J. Power, D. Gilpatrick, F. Neri and B. Shurter
 Los Alamos National Laboratory
 Los Alamos, NM 87545

Abstract

We describe characterization of a beam position measuring system. We used an automatic test fixture to map the response in two dimensions of dual-axis beam position monitors (BPMs) and their associated ratio-signal processing electronics and applied signals to a thin wire whose position is controlled by way of stepper motor actuators on x-y stages. The wire may be moved within a circular area of up to 50 mm in diameter with 5- μ m accuracy. The resulting signals picked up by a BPM are recorded for each point on a grid within the mapping area. We present a comparison of the theoretical with the actual response, as well as techniques employed to calculate suitable correction functions that accurately predict the beam position over at least 80% of the probe's inner aperture.

Introduction

The Ground Test Accelerator (GTA) is a 50-ma, H-linac used to produce high-brightness, low-emittance neutral particle beams. GTA uses a 425-MHz RFQ feeding 850-MHz DTL structures to accelerate the beam. The beam position measurements described here are used after the beam exits the DTL and is bunched at 425 MHz. They are mounted on a "diagnostics plate" used to characterize the output beam.

A typical beam position measurement system includes a beam-line-mounted pickup, electronics for signal processing, and a data acquisition and display. The electronics and the pickup's responses are programmed into the data acquisition system to display the measured beam position.

Accurate measurements of charged particle beam positions require an in-depth knowledge of the response of the beamline pickup assembly and the signal processing. Theoretical analysis makes it possible to design beam position measurement systems with the desirable characteristics. This analysis is generally carried out with the aid of certain assumptions and approximations that lead to discrepancies in the measured position of particle beams in the true environment. After fabrication, these BPMs must be tested to verify their actual responses.

The responses of our microstrip BPMs are mapped over their entire aperture with the aid of a mapping test system that is controlled with a LabVIEW® program. We then fit equations to the two-dimensional map data to determine the best functions to use with a given probe.

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These equations are then programmed into the accelerator's data acquisition system. The response of each signal processing electronics module is also measured and is adjusted so that the correct transfer function is realized.

Beam Position Monitor Pick-Up

The GTA beam position monitor pickups are of the directional coupler type design.[1] Four lobes are symmetrically placed around the circumference of the probe. Each lobe is a 2.25-mm-long section of a microstrip transmission line, with each end connected to a printed circuit stripline (Fig. 1).

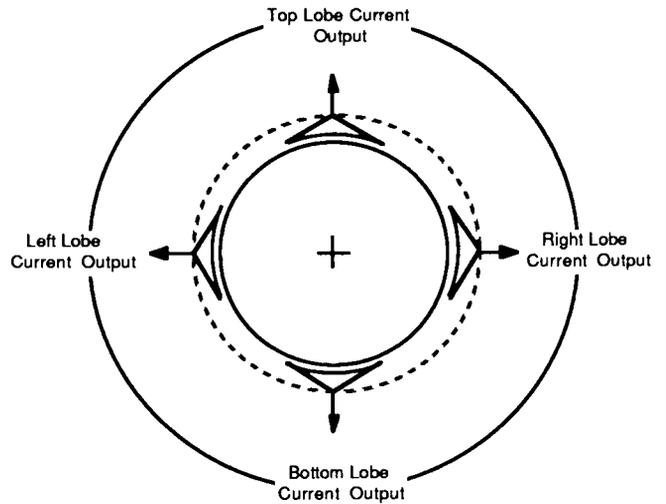


Fig. 1 A simplified cross section of a microstrip beam position probe. The current outputs exit by way of a printed circuit stripline through the vacuum vessel wall. The dotted inner circle is to indicate that the BPM lobes are inset into the beam line wall.

The downstream (relative to beam direction) lobe end is terminated with 50 Ω and the clear aperture is 45 mm. In fact, all GTA BPMs are of this style, with various lengths and apertures. For centered beams, a 425-MHz signal with an equal power level is available at the lobe outputs. As the beam moves away from the center position, the lobe signal levels vary, with more power available on the lobes closest to the beam. A useful model for a single-axis BPM is shown in Fig. 2. [2] Two lobes located at 0° and 180° are shown with subtended angle, ϕ . The time-dependent output current of each lobe is

$$I_R(t) = \frac{-I_b(t)\phi}{2\pi} \left\{ 1 + \frac{4}{\phi} \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{r}{b}\right)^n \cos(n\theta) \sin\left(\frac{n\phi}{2}\right) \right\} \quad (1)$$

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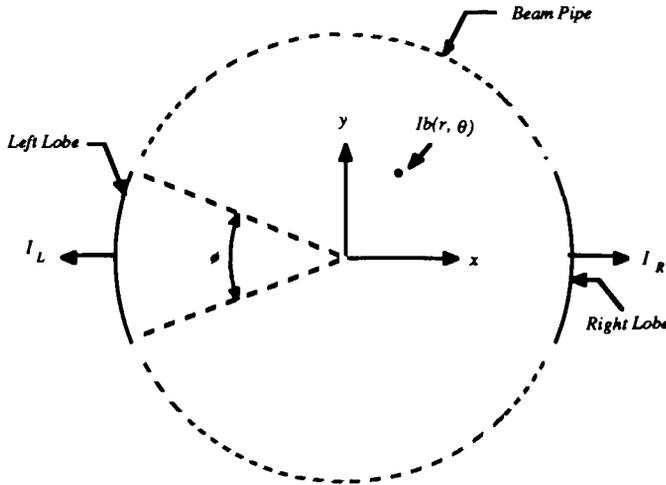


Fig. 2 Cross section of a single-axis beam position monitor model for calculating position response.

and

$$I_L(t) = \frac{-I_b(t)\phi}{2\pi} \left\{ 1 + \frac{4}{\phi} \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{r}{b}\right)^n \cos(n\theta) \sin\left[n\left(\pi + \frac{\phi}{2}\right)\right] \right\} \quad (2)$$

where b is the pipe radius and I_b is the beam current at position r, θ . Position data is acquired by measuring the logarithmic ratio (in dB) of two opposing lobes' signals such that

$$R_{x(dB)} = 20 \log \left\{ \frac{1 + \frac{4}{\phi} \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{r}{b}\right)^n \cos(n\theta) \sin\left(\frac{n\phi}{2}\right)}{1 + \frac{4}{\phi} \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{r}{b}\right)^n \cos(n\theta) \sin\left[n\left(\pi + \frac{\phi}{2}\right)\right]} \right\} \quad (3)$$

where $R_{x(dB)}$ is the ratio of the powers of the right and left lobe. The same equation is used for the vertical axis when the top and bottom lobes are included and θ is shifted 90° . These equations are not readily solved for beam positions as a function of the power ratios. They can be numerically solved to predict the two axis power ratios as a function of beam position. Mapping the response of an actual BPM allows comparison of the theoretical and actual responses.

Mapping the Response of BPM Pick-Ups

A test fixture was constructed for mapping the response of the BPM pickup. The BPM is mounted in a fixed position with a thin wire running through the aperture. A 425-MHz signal is applied to the wire to simulate the beam current. The wire can be positioned anywhere within the circular BPM aperture using a two-axis translation stage. The absolute accuracy of the wire position with respect to the mechanical center of the BPM is repeatable to about 5

μm . The BPM is mounted between two sections of pipe which present the correct boundary conditions to the BPM, i.e., minimal discontinuities to the beam image current. Each section of pipe is twice as long as the pickup inside diameter. A dual-channel rf power meter is used to measure the power ratio for each axis of the BPM as the wire is moved over the aperture. The entire process of probe mapping is controlled by a Macintosh running LabVIEW®, a symbolic instrument control program.

Two data sets are produced, one for each axis. This data is the measured power ratio in decibels. Figure 3 shows a typical map for one axis. In the region near the center of the BPM, the response is essentially linear, as indicated by the flat surface in the middle of the probe map. If the operation of the accelerator were such that the beam was always within the central 30% or so of the BPM aperture, the position equation for the x direction would simply be

$$x = x_o + S_x R_x \quad (4)$$

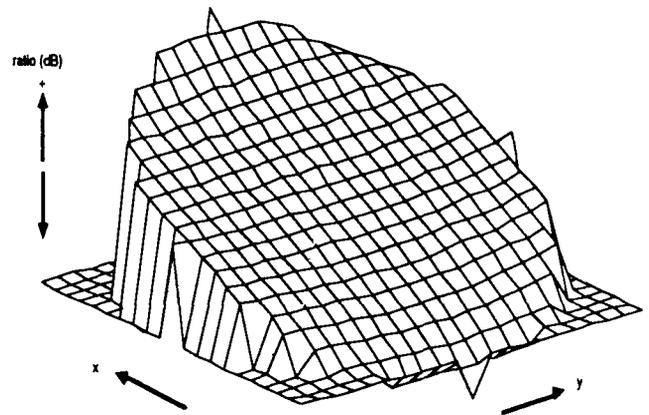


Fig. 3 A typical single-axis data map. The center of the matrix corresponds to the probe center. The data is in dB of power ratio with 0 dB in the center. A flat base has been artificially created at a level of -25 dB.

where S_x is the gain coefficient for the x direction, R_x is the measured power ratio, and x_o is the offset (ideally zero). The y -axis equation would be similar. In our accelerator we need to know the beam position accurately over as much of the aperture as possible. At beam positions far from the center, we observe a nonlinear response with significant coupling between axes. The probe response map graphically shows this, as does Eq. (3). Fortunately the surface of the response map is "well behaved," so that only a few terms need to be added to Eq. (4) to get good beam-position measurement over a large portion of the BPM aperture. These equations become

$$x = x_o + S_x R_x + S_{x^2} R_x^2 + S_{xy} R_x R_y \quad (5)$$

and

$$y = y_o + S_y R_y + S_{y^3} R_y^3 + S_{yx^2} R_y R_x^2 \quad (6)$$

where the S or "sensitivity" terms are the most significant coefficients of a least-squares fit to a two-dimensional, third-order polynomial fitted to the measured BPM map data. There are a total of 10 terms to each of the third-order equations. The ones not shown being of negligible magnitude. We have computed the various coefficients for fifth-order polynomials and have found the third-order equations to be sufficient. We do not include other terms, as their addition would require a higher degree of accuracy (than we can achieve) in the acquisition of our map data. Typical values of the coefficients are $S_x = S_y = 0.80$, $S_{x^3} = S_{y^3} = -0.00023$ and $S_{xy^2} = S_{yx^2} = 0.00098$. Probes manufactured to specification show very good symmetry between axes.

The previous equations are suitable for position measurements when the beam is within the inner 80% of the probe aperture. If accurate measurements of position are required in the outer 20% of the aperture, more terms must be added to the calculation of position. Noise in the electronics becomes a dominant source of error for measurements near the pipe walls.

Electronics Processing

For the GTA position measurement systems, we convert the BPM lobe signals from 425 MHz to 20 MHz.[3],[4] All signal processing is done at 20 MHz. Precision wide-dynamic-range circuits are much simpler to design and less expensive at 20 MHz. The position processor consists of an amplitude-to-phase converter followed by a phase-measuring circuit (Fig. 4).

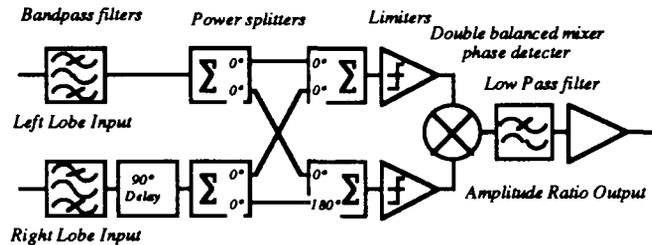


Fig. 4 Block diagram of the amplitude-ratio-measuring circuit consisting of the amplitude-to-phase converter and phase detector. The left and right lobe signals must be in phase at the inputs. The top and bottom axis channels are identical.

In this circuit the inputs are split and vectorially recombined so that two signals of varying amplitude are created whose phase difference is a function of the amplitude ratio of the inputs.[3] Limiters remove the amplitude dependence before the phase-detection circuit, which results in a final output voltage that is solely dependent on the ratio of the input amplitudes. The dynamic range of our present limiters has been measured at more than 50 dB in input amplitude (beam current range).

The transfer function of this circuit is

$$V_o = \frac{4GA_f}{\pi} \left[\tan^{-1} \left(10^{\frac{R_x}{20}} \right) - \frac{\pi}{4} \right] \quad (7)$$

where V_o is the output voltage, G is the amplifier gain, A_f is the peak voltage driving the double balanced mixer, and R_x is the amplitude ratio in dB of the inputs.[5] From Eq. (7) we solve for the amplitude ratio,

$$R_x = 20 \log \left[\tan \left(\frac{V_o \pi}{4GA_f} + \frac{\pi}{4} \right) \right] \quad (8)$$

Equations (7) and (8) refer to the horizontal axis and are essentially identical for the vertical axis.

We now have all equations necessary for the calculation of the beam position. Starting with the output voltages of position circuit, we calculate R_x and R_y from Eq. (8). Substituting the values of R_x and R_y into Eqs. (5) and (6), we calculate the true beam position.

Conclusion

We have developed a mapping test fixture that is used to characterize beam position monitors as they are used on an accelerator beamline. From this data we have derived a simple set of equations, which when coupled to the transfer function of our position-processing electronics, measure the true beam position. These measurements are accurate to within $\pm 2\%$ for beams within the inner 80% of the BPM's aperture.

References

- [1] J. D. Gilpatrick, et al., "Overview of the Microstrip Beam Diagnostics," Los Alamos National Laboratory document LA-CP-89-460, (1989).
- [2] R. E. Shafer, "Characteristics of Directional Coupler Beam Position Monitors," IEEE Trans. Nucl. Sci. 32, 1933 (1985).
- [3] J. D. Gilpatrick, J. Power, F. D. Wells and R. B. Shurter, "Microstrip Probe Electronics," Los Alamos National Laboratory document LA-CP-89-488 (1989).
- [4] S. P. Jachim, R.C. Webber and R.E. Shafer, "RF Beam Position Measurements for Fermilab Tevatron," IEEE Trans. Nucl. Sci. 28, 2323 (1981).
- [5] J. D. Gilpatrick and F. D. Wells, "Double Balanced Mixer Operation Used as Phase and Synchronous Detector as Applied to Beam Position and Intensity Measure," Los Alamos National Laboratory document AT-3 Technical Note 92-8, (1992).