A Frequency-domain Directivity Enhancement of Beam Position Stripline Detectors

Edward L. Barsotti
Fermi National Accelerator Laboratory*
P.O. Box 500, Batavia, IL 60510 USA

Abstract

Stripline detectors are commonly used in beam position monitoring (BPM) systems and can be used as dual directional couplers for beams passing in opposite directions. Directivity between 21-26 dB is typical near the Tevatron operating frequency of 53.1 MHz, and these values are limited by mismatches on the upstream ports. Improvements to the directivity can be made with external corrections to these mismatches, but in the Tevatron the four ports (two striplines, proton upstream and downstream) are available only after a series of discontinuities (tapers, feedthroughs, cables) forming unknown frequency-dependent networks. A method has been developed to characterize the networks and compensate the mismatches, at a single frequency. No beam is needed, so this simplifies implementation. The technique can be applied to a narrowband BPM system operating in an approximately steady-state condition. Conditions for directivity, development of the method, and a large-scale implementation procedure are described with applicable results, including an explanation of shortcomings in a transient beam situation.

I. INTRODUCTION

The Tevatron BPM stripline detector [1]-[3] is designed to form a 50Ω transmission line with the beam pipe. At each end of each stripline plate, a taper and feedthrough bring signals to 50Ω cables and the rest of the system. This arrangement turns each stripline into a directional coupler, and its directivity is the ratio of upstream and downstream signal. Ideally, the upstream port has a doublet signal while the downstream port has none. The directivity is primarily determined by how well matched the upstream system is to the stripline. The signal is reflected by various discontinuities as it travels in time from the stripline towards the processing electronics upstairs: the taper, the feedthrough, cables, adapters, and finally the RF Module itself. In the frequency domain, all of these reflections combine as a function of frequency to form the impedance $Z_{upstream}(f)$. The mismatch between $Z_{upstream}$ and the characteristic impedance of the stripline, Z_{plate}, forms a frequency-dependent directivity. At 53.1 MHz, this directivity has been measured for the TeV BPM system to range between 21-26 dB, representing a mismatch of 5-10 Ω. To obtain a directivity of 40 dB, a match within 1Ω would be required.

Directivity is important in the collider mode of the Tevatron, when protons and antiprotons coexist in counterrotating, separated helical orbits. Directivity should be as high as possible to prevent interference of one beam signal upon another, especially when trying to read the antiproton beam in the presence of the more intense proton beam. Any external correction to increase directivity must take place outside the vacuum enclosure, and in the Tevatron, there is a half meter of cable and various discontinuities between the stripline and a vacuum flange.

In order to determine the correction, a method [4] was devised to characterize the discontinuities between the stripline detector plate and the vacuum flange ports. This process is now described.

II. CORRECTION DEVELOPMENT

In this case, 220 BPM detectors and vacuum enclosures were already in place, and only a single cable per stripline existed between the tunnel and the upstairs processing electronics. Thus, a relay per stripline is needed to switch between the two ports, and the directivity correction algorithm is performed in the tunnel (with no beam) and implemented with the relay circuitry. In summary, the external correction is derived by exciting one of the proton upstream flange ports and tuning a variable load until a minimum in forward coupling to the proton downstream port of the other stripline is obtained. This provides enough information about the unknowns inside the vacuum enclosure to compensate for them. The first step requires electrostatic knowledge of the coupled line system formed by the two stripline plates.

A. Even and Odd Mode Impedances

In a symmetric system with two coupled signal conductors, such as the BPM striplines, "self-capacitances" between each conductor and ground, C_a and C_b (C_a=C_b) exist along with mutual capacitance C_{ab}. For these coupled lines, three characteristic impedances can be defined: Z_{even}, for the even mode between the lines (both conductors at same potential); Z_{odd}, for the odd mode (conductors at opposite potentials); and Z_{plate}, the equivalent transmission line impedance for a single conductor in the presence of the second. The characteristic impedances are defined by

$$Z_{even} = \frac{1}{C_a v_p},\ Z_{odd} = \frac{1}{(C_a + 2C_{ab})v_p},\ Z_{plate} = \frac{1}{(C_a + C_{ab})v_p}. \quad (1)$$

where v_p is the velocity of propagation. Two programs, "Matrix Parameters for Multiconductor Transmission Lines" from Artech House and POISSON (with the author's post-processing program), were used to find the required capacitances. From the results, the assumed impedances were Z_{plate} =45Ω and Z_{even} =50Ω.

B. Excitation of a Plate

Directivity as a function of terminating impedance was simulated for the coupled lines, using EEsof's Touchstone program. When one of the striplines is excited at its proton upstream port and directivity of the coupling to the other stripline is desired, the optimum termination at the ports is Z_{plate}. Backward-wave coupling is predominant for the coupled lines, just like the beam coupling to the striplines. The coupling from the upstream port of A to upstream B was -35 dB, highly independent of terminations. The amount of coupling from upstream A to downstream B is a combination

* Operated by the Universities Research Association under contract with the U.S. Department of Energy.

of two factors: 1) the upstream B signal, down 35 dB from upstream A, partially reflects back from upstream B due to its mismatch from Z_{plate}, and 2) the excitation signal from upstream A is partially reflected from downstream A, due to its mismatch from Z_{plate}, and then couples down 35 dB to downstream B.

C. Excitation by Beam, Systematic Directivity Decreases

When the striplines are excited by the centered beam, modeled by an ideal current source, only the even mode is present and the correct upstream terminating impedances for maximum directivity is Z_{even}. The amount of odd mode excitation, or the difference in the stripline currents for beam closer to one of the striplines, determines downstream magnitude when all ports are terminated in Z_{even}. Thus, directivity will change for beam displacement towards one stripline, but displacement in the orthogonal plane has negligible effect. For perfect Z_{even} terminations and a stripline current ratio of 1.25:1, corresponding to 3 mm off-center in the Tevatron detector, directivity is decreased from infinity to 40 dB. Another possibility for a systematic decrease in directivity is a difference between the beam propagation velocity and the plate transmission line propagation velocity. Directivity will decrease to 35 dB for a 3.5% mismatch and 27.7 dB for an 8% difference. As discovered in stochastic cooling work, these differences can be caused by the longitudinal gaps between beam pipe and pickup, as well as the finite width of the pickup plates.

D. Requirement for Solution

To best solve the directivity problem, given the systematic errors, the impedance Z_{even} needs to be applied at all frequencies to the correct "termination points" at the ends of the striplines. Since the nearest access point for each of the four ports is the N-type elbow connector on the flange, everything between the two points must be characterized at all frequencies. Broadband implementation becomes impossible, so here the characterization is restricted to the frequency of interest, 53.1 MHz. Finally, the desired mode for tuning, beam on and centered, prohibits tunnel access. The only measurement mode to "view" the striplines is the *Excitation of a Plate* case described above.

E. Attempt at a Broadband Solution

At first, an attempt was made to characterize the line between plate and flange over a broad frequency band. A flange-to-flange two-port S-parameter matrix measurement was taken over a wide frequency range. A model consisting of three transmission lines (two vacuum cables and the stripline) and four electrically "thin" lumped element models (two flange discontinuities and two vacuum cable-to-stripline transitions) was entered into EEsof's Touchstone program. The model could not be optimized to the data, due to the large number of variables and model breakdown over the large frequency range. Even artificially created [S] data from a known model solution would not converge. Because of the problems with a broadband solution, the need for a single frequency solution was more apparent.

F. Equivalent Transmission Line for Discontinuities

The complexity of the above problem was reduced by converting everything between the flange ports into two equivalent "uniform" transmission lines (consisting of the four sets of discontinuities and two vacuum cables) and the stripline transmission line. This model works because 1) none of the discontinuities are too large at 53.1 MHz, and 2) the system is nearly 50Ω throughout. The goal of using this equivalent transmission line concept is the ability to use the formula for input impedance Z_{in} of a load Z_{load} propagated along a uniform transmission line,

$$Z_{in} = Z_o \frac{Z_{load} + Z_o \tanh(\gamma d)}{Z_o + Z_{load} \tanh(\gamma d)}, \tag{2}$$

where Z_O is the complex transmission line characteristic impedance, d is its length, and $\gamma=\alpha+j\beta$ is its propagation coefficient. Because of the different phasings of the discontinuities, there is a different Z_O at each frequency. Also, under the above restrictions, S_{21} of a transmission line is approximately equal to $exp(-\gamma d)$ and is cascaded with other lines by simply multiplying the S_{21} parameters together.

G. Applying Correct Terminating Impedance to Plates

If the equivalent uniform transmission line between flange and plate can be found, then the impedance Z_{load} can be selected and applied to the flange port to produce the terminating impedance $Z_{in}=Z_{even}=50\ \Omega$ at the "termination point" at the stripline end. The variables Z, γ, and d can be defined for ports 1 (proton upstream for stripline A), 2 (downstream A), 3 (upstream B), and 4 (downstream B). As described above, the amount of coupling S_{41} from excitation of port 1 depends on the sum of the mismatches of ports 2 and 3 as

$$|S_{41}|_{dB} = |\rho_2 + \rho_3|_{dB} - 35, \quad \rho_{2,3} = \frac{Z_{in2,3} - Z_{plate}}{Z_{in2,3} + Z_{plate}}. \tag{3}$$

If the reflections from ports 2 and 3 cancel, or $\rho_2= -\rho_3$, then S_{41} will be a minimum and (3) simplifies to

$$Z_{in2} Z_{in3} = Z_{plate}^2. \tag{4}$$

If a known load Z_{load2} is applied to flange port 2 and a variable load Z_{load3} on flange port 3 is tuned for a minimum in S_{41}, then (4) is true and can be expressed from (2) as

$$Z_{plate}^2 = Z_2 Z_3 \frac{Z_{load2} + Z_2 \tanh(\gamma_2 d_2)}{Z_2 + Z_{load2} \tanh(\gamma_2 d_2)} \frac{Z_{load3} + Z_3 \tanh(\gamma_3 d_3)}{Z_3 + Z_{load3} \tanh(\gamma_3 d_3)}. \tag{5}$$

From a measurement of S_{21} and S_{43}, the variables $\gamma_2 d_2$ and $\gamma_3 d_3$ can be estimated. The path of the S-parameter S_{21} consists of a cascade of three transmission lines, and so,

$$S_{21} = \exp\left(-\gamma_1 d_1 - \gamma_{plate} d_{plate} - \gamma_2 d_2\right). \tag{6}$$

From the plate dimensions, $\gamma_{plate} d_{plate}$ is known, and if the approximation $\gamma_1 d_1 = \gamma_2 d_2$ is taken, then for the various ports,

$$\gamma_1 d_1 = \gamma_2 d_2 = \tfrac{1}{2}\left(-\ln|S_{21}| - \gamma_{plate} d_{plate}\right), \tag{7}$$

and similarly for ports 3 and 4. This leaves two unknowns in (5), the characteristic impedances Z_2 and Z_3. A second equation with a different Z_{load2} and Z_{load3} pair would be needed, but a lack of resolution prevents reasonable results from the root finder. The further approximation $Z_2=Z_3$ must be taken for satisfactory results. Then, from (2),

$$Z_{load2,3} = Z_{2,3} \frac{Z_{in2,3} - Z_{2,3} \tanh(\gamma_{2,3} d_{2,3})}{Z_{2,3} - Z_{in2,3} \tanh(\gamma_{2,3} d_{2,3})}. \tag{8}$$

The method can be done for S_{23} to find Z_{load1} and Z_{load4}.

III. IMPLEMENTATION AND RESULTS

A. Circuitry

The tuning circuitry to implement the desired Z_{load} at the flange is housed in the tunnel along with a relay to select which of the two beams has its upstream port sent upstairs. The undesired beam's upstream port (the desired beam's downstream) has a tuned termination which presents Z_{load} at the flange, taking into account the cable between the module and the flange. The reflection off the tuned circuitry actually cancels, at the selected frequency, the signal created by the non-directive reflections between the stripline and flange. It trails the non-directional signal in time. The circuitry consists of discrete inductors, resistors, and capacitors, the latter two are adjustable for orthogonal tuning. Good beam impedance is ensured in two ways. First, a diplexer filter is included before the relay and the tune circuit, transmitting a 35 MHz bandwidth centered at 53.1 MHz while terminating the stopband in an external 50Ω for higher power dissipation. Also, the tuning section includes a shunt resistor to provide a return loss of at least 13 dB at all the bandpass frequencies.

B. In-tunnel Tuning Procedure

To find the correct tunes for all of the in-place detectors, an automated procedure of the above algorithm was devised. A two-channel variable-load module was developed for this purpose. It consisted of two varactor diodes separated by a quarter-wavelength at 53.1 MHz for orthogonal tuning, plus the DACs to bias them. A Macintosh computer and a program using LabVIEW software controlled the tuner and an HP8753B vector network analyzer. The operator changed connections between the analyzer, the tuner, and the flange. First, S_{21} and S_{43} were measured. Then S_{41} was minimized for two different Z_{load3} settings, and the solutions were averaged. The procedure was repeated for S_{32}. A Mathematica program was used to find the roots to (5). The operator then performed the correction tune, using the network analyzer. With this procedure, the in-tunnel work was greatly reduced and a database of the detectors was created.

C. Measuring Directivity

The directivity with beam present was measured in two ways. First, a spectrum analyzer was used for fixed target operation, during which the vast majority of the ring's 53.1 MHz buckets are filled with beam bunches, resulting in most of the spectral content at 53.1 MHz and its harmonics. Second, the "intensity" output of the RF Module front-end electronics was viewed with an oscilloscope for both a beam structure of 20 consecutive bunches and also normal collider mode single-bunch operation. The signal, used to self-trigger the position signal digitizer, is down-converted to baseband from a 5 MHz bandwidth, 53.1 MHz bandpass filter.

D. Interpretation of Results

The directivity from the full ring case was measured for two detectors and four striplines, ranging from 31 to 38 dB. These results, especially the higher directivities, were considered good, considering the number of approximations and systematic errors. In the single-bunch case, however, the unwanted signal appeared in time as two large peaks, barely separated. Going to 20 bunches, the peaks remained at the signal's beginning and end, but between the peaks the unwanted signal decreased to a level consistent with the full ring result.

It was concluded that the peaks were caused by the tune having a bandwidth less than the RF Module's 5 MHz bandwidth. Outside the tune bandwidth, directivity is actually worse than the original 21-26 dB. At the edges of a signal, when the RF Module's filters are charging, other frequencies are present. However, for a long train of 53.1 MHz buckets filled with beam, the filters are in a steady-state, and only the fundamental frequency is present.

During single-bunch collider operation, the results are unacceptable, for two reasons. First, when a proton and antiproton bunch are coincident at a detector, their signals interfere too much with each other and affect the position reading. Second, when reading antiprotons, the more intense proton bunches cause peaks comparable in amplitude to the desired antiproton intensity signal. Thus the digitizer can trigger on the unwanted proton signals. The latter problem is eliminated by a fast switch gated by the control system, currently being added to the system, removing the unwanted triggers as well as providing other improvements.

VI. CONCLUSION

A method to increase the directivity of beam stripline detectors has been devised and implemented for the Fermilab Tevatron. The technique enables external circuitry to correct for an unknown series of discontinuities causing the non-directivity. An in-tunnel (no beam) tuning algorithm has been developed. The correction method works best for narrowband signal processing approximating steady-state. This occurs from either a long sequence of RF buckets filled with beam, resulting in narrow spectral peaks at the RF harmonics, or a filter with a bandwidth smaller than the implemented tune.

IV. ACKNOWLEDGEMENTS

The author wants to recognize the many contributions of Rodolfo Gonzalez (now with SSC) and others in the Fermilab Accelerator Instrumentation Department.

V. REFERENCES

[1] R. Shafer, "Characteristics of Directional Coupler Beam Position Monitors," *IEEE Trans. Nucl. Sci.* NS-32, No. 5, 1933 (1985).

[2] R. Shafer, R. Webber, and T. Nicol, "Fermilab Energy Doubler Beam Position Detector," *IEEE Trans. Nucl. Sci.* NS-28, No. 3, 2323 (1981).

[3] R. Shafer, R. Gerig, A. Baumbaugh, and C. Wegner, "The Tevatron Beam Position and Beam Loss Monitoring Systems," *Proc. XIIth Internat.Conf. on High-Energy Accelerators*, Fermi National Laboratory, 609 (1983).

[4] E. Barsotti and R. Gonzalez, "Tev BPM PSD Module Description," Beam Position Monitor Design Note #27, internal Fermilab document (1992).