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Tevatron Beam Position Monitor Calibration Specifications

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Abstract

This document describes the method for converting the raw I & Q outputs from the Tevatron BPM system into corrected beam positions. It includes the justification for inclusion and omission of certain corrections. It also describes the techniques used to realize the values of the correction parameters.

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History of this Document

Version 1

Version 1 of the Tevatron BPM calibration specifications includes the main correction formula, and the beam studies needed to derive the correction parameters. There is a rough discussion of the justification for which terms can be calibrated and how. There is also a rough discussion on the organization of the calibration applications and data. It is used as a first level communication to other sub-project leaders about the scale of the correction calculation and the beam studies required.

Introduction

The hardware specifications for the Tevatron BPM upgrade have the signals from each end of each plate of the BPM detector band-pass filtered and digitized directly. The digitized data is then digitally down-converted and filtered to produce data values that represent the baseband, band-limited values of the raw signal from each plate. These values are collected by the frontend processor of the system and converted into real position and intensity data for applications making data requests. The conversion from raw data to real position involves proper linear scaling of the difference of the signal between two plates, non-linear corrections due to detector geometry, compensation of amplitude differences between the two plates, compensation of mechanical offset of the detector from the center of the quadrupole magnet field region, and compensation of error due to oppositely charged particles circulating simultaneously. We need the complete formula for the correction as well as a means for deriving the parameters used for correcting the raw data. The process of deriving the parameters for the correction formula is referred to as the calibration.

Correction Formula

The formula for converting raw BPM signals to corrected positions is given below.

$$P_{final}(mm) = g\,\frac{\left|\mathbf{A}'_{HP}\right| - \left|\mathbf{B}'_{HP}\right|}{P_{Intensity}} + E_{offset} + Q_{offset} \qquad (1)$$

g – scale factor dictated by spacing between BPM plates. Nominally 26mm.
E_{offset} – electrical offset of measured zero displacement to actual center of BPM.
Q_{offset} – offset of center of BPM to center of quadrupole correction element.
$P_{Intensity}$ – corrected intensity of beam fundamental frequency.
$\mathbf{A'}_{HP}$ – corrected complex value of fundamental signal from the 'A' plate. Subscripts H & P refer to the BPM orientation (H for horizontal, V for vertical) and species (P for proton, A for pbar).
$\mathbf{B'}_{HP}$ – corrected complex value of fundamental signal from the 'B' plate.

$$P_{Intensity} = \left|\mathbf{A}'_{HP}\right| + \left|\mathbf{B}'_{HP}\right| - k * P^2{}_{posraw} \qquad (2)$$

P_{posraw} – raw position signal.
k – quadratic correction parameter.

$$P_{posraw}(mm) = g\,\frac{\left|\mathbf{A}'_{HP}\right| - \left|\mathbf{B}'_{HP}\right|}{\left|\mathbf{A}'_{HP}\right| + \left|\mathbf{B}'_{HP}\right|} + E_{offset} \qquad (3)$$

$$\mathbf{A}'_{HP} = \mathbf{A}_{HP} + \mathbf{a} * \mathbf{A}_{HA} + \mathbf{b} * \mathbf{B}_{HA} \qquad (4)$$

$$\mathbf{B}'_{HP} = \mathbf{B}_{HP} + \mathbf{c} * \mathbf{A}_{HA} + \mathbf{d} * \mathbf{B}_{HA} \tag{5}$$

$\mathbf{A}_{\mathrm{HP}}$ – raw complex value of fundamental signal form ‘A’ plate.
$\mathbf{B}_{\mathrm{HP}}$ – raw complex value of fundamental signal from ‘B’ plate.
a,b,c,d – complex BPM directivity correction parameters.

The equations for the antiproton signals are the same, except the species subscripts are interchanged. Also, the correction parameters have different values for each BPM and each species.

Solving Parameters

The correction parameters that can be derived with beam studies are: the directivity parameters, the quadratic correction parameter, and the electrical offset. The scale factor cannot be calibrated by beam any better than we know the scale factor between beam position at a BPM and some magnet settings. The quadrupole offset parameter can be calibrated at a few locations in the Tevatron where a quadrupole corrector supply powers only one quadrupole. In most locations, one power supply powers multiple quadrupole correctors. This makes solving for the center of the quadrupoles very difficult.

The formula for the quadratic effect of the sum signal is based on the formula for a static line charge coupled to cylindrical plates.

$$\frac{I_A}{I_{beam}} = \frac{\phi}{2\pi}\{1 + \sum_{n=1}^{\infty} \frac{4}{n\phi}(\frac{r}{b})^n \cos(n\theta)\sin(n\frac{\phi}{2})\} \tag{6}$$

$$\frac{I_B}{I_{beam}} = \frac{\phi}{2\pi}\{1 + \sum_{n=1}^{\infty} \frac{4}{n\phi}(\frac{r}{b})^n \cos(n\theta)\sin(n(\pi + \frac{\phi}{2}))\}$$

Reducing the equation to only the fixed and quadratic term reveals:

$$\frac{I_A + I_B}{I_{beam}} = \frac{\phi}{\pi} + \frac{2}{\pi}((\frac{x}{b})^2 - (\frac{y}{b})^2)\sin\phi \tag{7}$$

From this formula, we see that the minimum value of the quadratic offset corresponds to the electrical center of the BPM (assuming constant orthogonal position). Both the quadratic correction parameter and electrical offset can be solved by measuring the sum signal coming from the BPM for multiple positions. A difference between the attenuation of the A & B signal paths will cause the electrical offset to be displaced from the center of the BPM. This will also produce an error in the sum mode signal. If we assume a relative attenuation error of n between the signal paths, the new formula for the sum mode (ignoring high order terms and assuming n small) is:

$$\frac{I_A + (1+n)I_B}{I_{beam}} = \frac{\phi}{\pi} + \frac{4n}{\pi}\frac{x}{b}\sin\frac{\phi}{2} + \frac{2}{\pi}((\frac{x}{b})^2 - (\frac{y}{b})^2)\sin\phi \quad (8)$$

The values can be plotted as a function of measured beam position and fitted to a quadratic. If we assume that the electrical offset is due to amplitude errors, then the electrical offset is just $b*n\phi/\pi$.

The method of solving for the directivity parameters involves knowledge of how the directivity changes as a function of beam position. The directivity parameters defined earlier are really functions of transverse position and can be described by[1]:

$$\mathbf{a}(y) = \mathbf{m_a}y + \mathbf{a}_i \quad (9)$$

The calibration routine gathers many different values of the pbar(proton) signals for different proton(pbar) positions in a proton(pbar) only store. It then solves the linear parameters for zero pbar(proton) signal levels.

Unfortunately, the BPMs are only sensitive (to first order) to beam motion in a single plane. Trying to determine the effect of the orthogonal position, real time, would be impractical. Calculating the lattice over the subset of BPMs available to a single house would be relatively inaccurate and require excessive processing. Therefore, the real time correction equation does not include a term that is a function of orthogonal position. Calibration of the directivity will be performed when all BPM systems have been commissioned, and the orthogonal positions in each BPM can be estimated with considerable accuracy. Once the linear parameters are defined, the orthogonal positions at each BPM can be estimated for the operating helix. The off-line program that calculates the correction parameters can download the real time correction parameters to each of the house processors as a function of estimated beam position on the helix.

Justification

Wire measurements were conducted on a Tevatron BPM. BPM wire measurements involve inserting a suspended wire into the center of the BPM, terminating the end of the wire, stimulating the wire with an RF signal, and measuring the response of the pickup plates. The wire is carefully surveyed for each measurement, and response measurements are made for multiple wire positions. Figure 1 shows the wire position pattern used in the study. As the wire gets close to the plates, the impedance of the transmission line formed between the wire and plate changes significantly. This throws off the results because of reflections from the wire that the beam will not see because it basically has infinite impedance. Only readings from -15mm to 15mm are analyzed.

The primary purpose of this study is to analyze non-linear components of the plate response as a function of position. The first analysis looks at the quadratic term of the non-linearity. Figure 2 shows the sum of the response of the two plates as a function of the wire position. The plots were normalized to the sum signal down the center of the pickup. Notice that all the plots are quadratic and their minima are located in the center of the pickup for all off-axis position values. By finding the parameters of the quadratic response as a function of beam position, one can determine the electrical offset of the BPM.

The second analysis looks at the effect of the higher order odd term non-linearities on position. Figure 3 shows the error in position for different wire positions. The reference for the error is the best linear fit to the measured position vs. wire position data with the wire centered orthogonally. Notice that the position error is very small when the wire is centered orthogonally. However, the error becomes significantly larger when the wire is moved off center orthogonally, more that four times the error for the centered wire. Since we do not have real time orthogonal position information from the actual BPMs, there isn't much point in trying to correct the higher order errors. For 10mm excursions in both planes, the linearity error is about 5%.

The viability of the directivity calibration was tested by steering the beam with a pattern similar to Figure 1 (although not diagonally symmetric) through two BPMs. Analysis of the data revealed that without taking the orthogonal motion into account, worst case measurement errors on the order of 1mm could be expected when measuring pbars at their current intensity levels. With the orthogonal motion adjustment, the worst case error is reduced to about 300μm.

Not all of the correction parameters will be derived through calibration. The scale factor and quadrupole offset will be determined from the records of the calibration for the old system.

Calibration Study Plan

As mentioned above, the general study plan for deriving all of the calibration parameters involves the 7x7 grid of beam position. A set of dipole corrector magnets will be varied to create a pattern of displacements around the ring. The variation in beta functions around the ring will dictate the relative amplitude of the total excursions for each BPM. Also, because of different phase advances, it will be necessary to have at least two sets of dipole correctors to have a reasonable excursion of position at every BPM. These measurements would be performed by the BPM system in the normal narrowband closed orbit configuration without corrections.

Measurement of the quadratic parameter and electrical offset can be performed on a BPM by BPM basis. It is not necessary to have the full ring commissioned and taking data to have an effective calibration. It is still possible to calibrate more than one detector at a time, but it is not necessary. Because the directivity parameters are a function of orthogonal position, it is very important to have a good idea what the orthogonal position of the beam is going through the detector being calibrated. Extrapolating this position requires information from other BPMs around the ring to get an accurate idea of the orthogonal positions and angles. Calibration of the directivity will involve a ring-wide measurement of positions.

Calibration Control and Data

The application program that runs the BPM calibration routine should be the program that controls the correctors. That allows for the best correlation between settings and measurements, and it insures that the application can accurately store the machine conditions used for the calibration. When the application is called up, the user selects which correctors to use and the maximum excursion for each corrector. The user also selects the specific parameters to calibrate. The program then runs a pattern of corrector values and retrieves the uncorrected narrowband information from all relevant BPMs for each different corrector value. Once all of the relevant information is collected, the application calculates all of the requested calibration parameters. The application then stores the measurements in a special BPM calibration, non-volatile memory location. Information sent with the data should include, date of the calibration, corrector settings, and calibration parameters.

A separate application downloads and monitors which calibration parameters are used with each BPM. The application should download the value, date of the calibration, and calibration memory file descriptor for each parameter. Since the directivity parameters are functions of orthogonal position, the application should calculate the directivity correction based on an assumed orthogonal position through the BPM. There may be another calibration file that gives the nominal position of the beam for the directivity correction. The parameters and the assumed orthogonal position should be downloaded to the frontend.

Table 1: Correction parameters descriptions and calibration requirements.

Parameter	Description	No. of scalar values per position	Calibration
g	Position Scalar	1	No
k	Quadratic Scalar	1	Yes
M	Directivity Matrix	8	Yes
Eoffset	Electrical Offset	1	Yes
Qoffset	Quadrupole Offset	1	No

Table 2: Correction parameters data and metadata.

	Meta-data			Data
Parameter	Date of Calibration	Date of Creation	Orthognal Position	Calibration Data
g	N/A	Yes	N/A	N/A
k	Yes	Yes	N/A	Yes
M	Yes	Yes	Yes	Yes
Eoffset	Yes	Yes	N/A	Yes
Qoffset	N/A	Yes	N/A	N/A

Figures

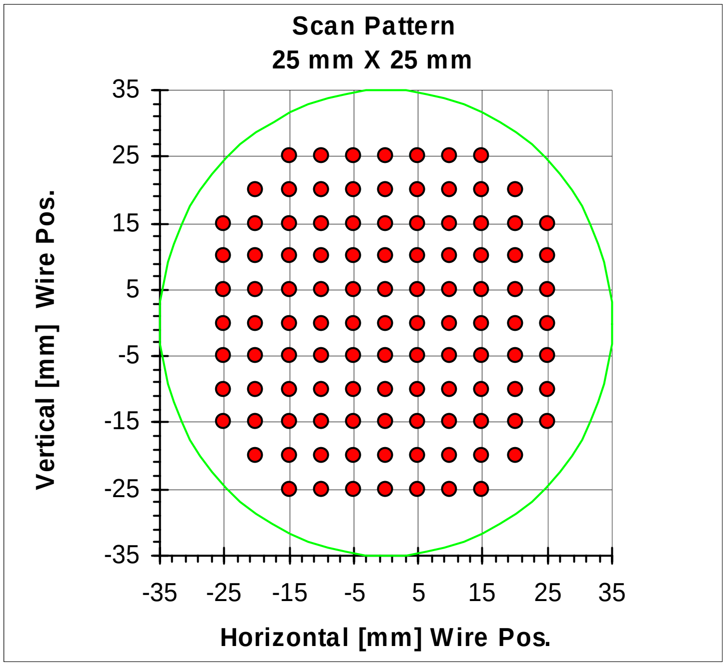

Figure 1: Wire scan pattern.

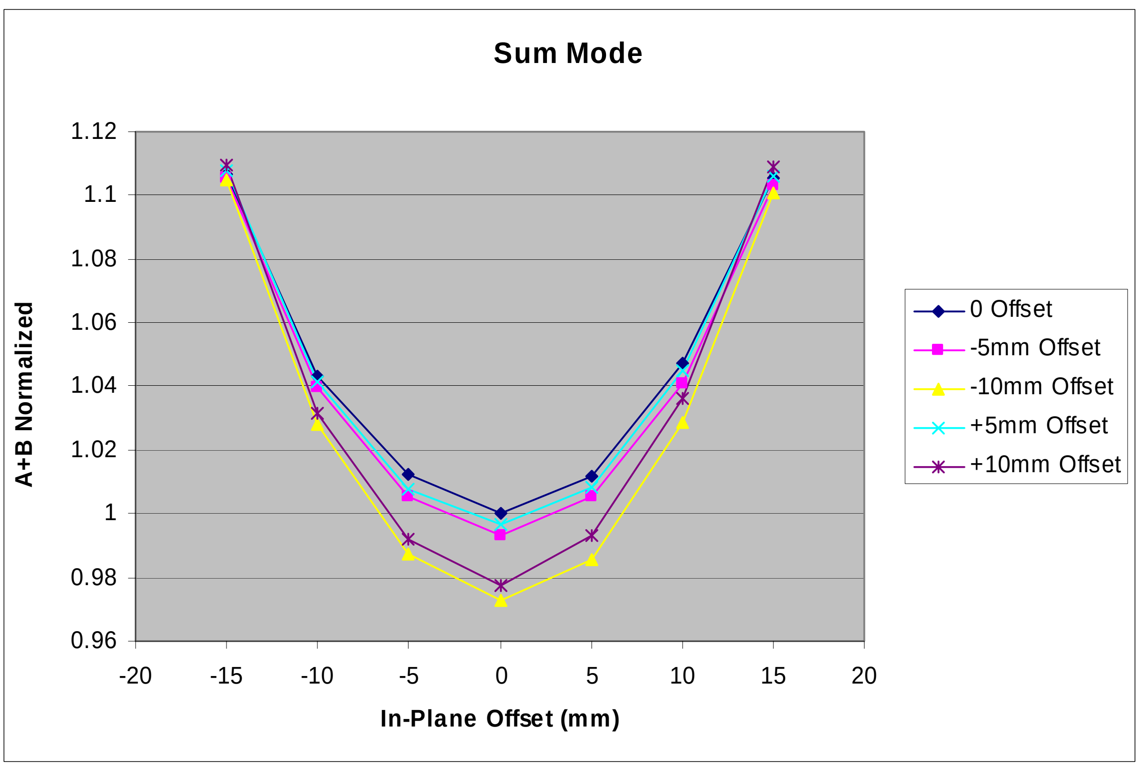

Figure 2: Plot of the normalized sum signal as a function of wire position.

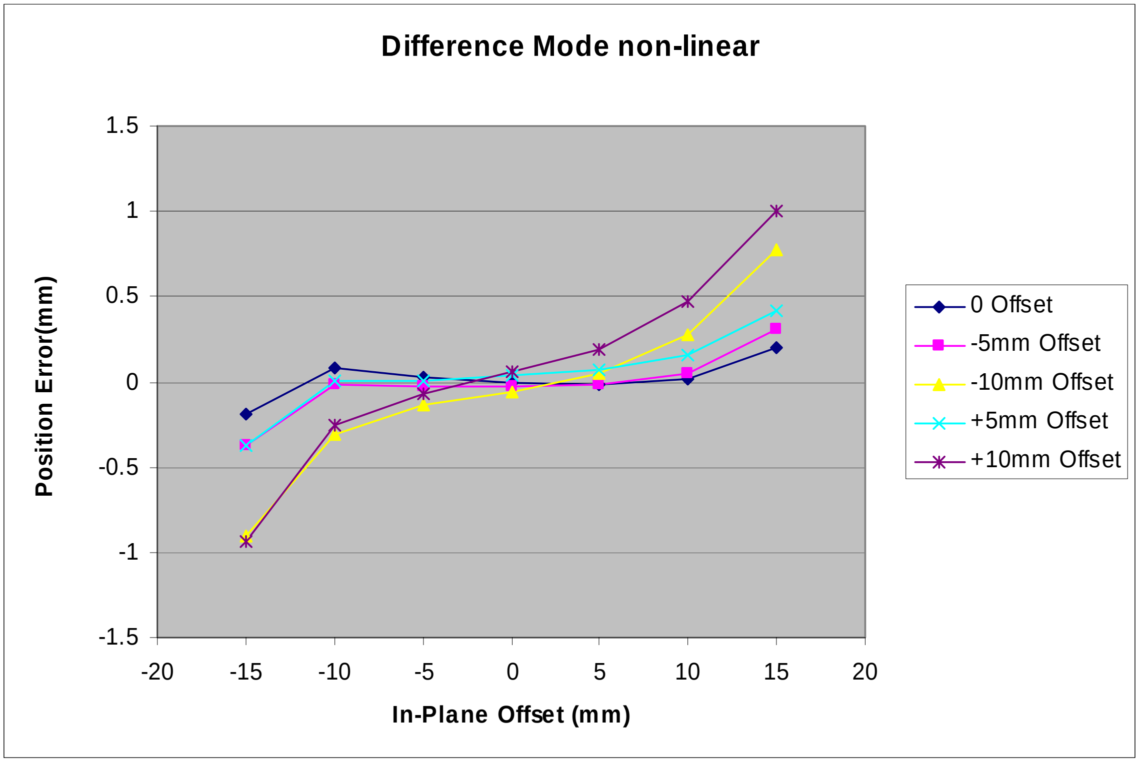

Figure 3: Odd-mode non-linear position error as a function of wire position.

References

1. Kutschke, Robert "Cancellation of the Proton Signal on the Antiproton Cable: A Status Report", Beams-doc-988, March 2004, http://beamdocs.fnal.gov/DocDB/0009/000988/002/cancel.pdf.