SIMULTANEOUS POSITION MEASUREMENTS OF PROTONS AND ANTI-PROTONS IN THE TEVATRON

R. K. Kutschke*, J. Steimel, R. Webber, S. Wolbers, Fermilab†, Batavia IL, USA

Abstract

Fermilab has embarked upon a program to upgrade the electronics of the Beam Position Monitor (BPM) system that measures the transverse position of the beams inside the Tevatron collider. The new system improves on the current system in precision, accuracy and reliability. A new feature in the upgraded system is the ability, when both protons and anti-protons are present in the Tevatron, make simultaneous measurements of the closed orbit position of both beam species. The method chosen for achieving the simultaneous measurement is an algorithm that deconvolutes the imperfect directionality of the BPM pickups from the raw measurements. This paper will discuss the algorithm, the calibration of the parameters used by the algorithm and the robustness of the algorithm. It will also present results from the upgraded system which demonstrate that the system meets the requirements set out at the start of the upgrade project.

INTRODUCTION

The stripline directional-coupler design of the Tevatron BPM pickups[1] would ideally offer perfect isolation between signals from particles traveling in opposite directions. In reality, little more than 26dB isolation is available at the 53 MHz processing frequency. With the now-typical 10:1 proton-to-antiproton bunch intensity ratio, this isolation alone is insuf£cient to support millimeter-accuracy antiproton ($\bar{p}$) position measurements in the presence of protons (p). An accurate and manageable solution to this interfering signal problem is required for $\bar{p}$ measurements now and, as $\bar{p}$ intensity increases, to facilitate elimination of $\bar{p}$ bias on p measurements in the future. Two avenues of approach are suggested: 1) separate the signals in the time domain, and 2) calibrate the cross-talk in the frequency domain and make compensation before computing beam position. This paper discusses the second approach; the £rst is discussed elsewhere [2]. An overview of the BPM upgrade project has has also been contributed to this conference [3].

METHODOLOGY

Each BPM station consists of two stripline pickups, referred to as the A and B pickups, each of which is read out at both ends, referred to as the p and $\bar{p}$ ends. If the pickups were perfectly direction-coupled, the signals from each beam species would pass 100% into the end named after it. The four signals from each BPM station are are passed through a band-pass £lter, centered at 53 MHz, and into a digital receiver board, which is programmed to measure the Fourier amplitude of each signal in a narrow frequency band around 53 MHz. A single raw measurement produced by this system is 4 complex numbers, referred to as A_p, B_p, $A_{\bar{p}}$ and $B_{\bar{p}}$. These numbers are expressed in Echotek Units (EU). Further details of the signal processing may be found elsewhere [3].

In Collider operation, the Tevatron beam consists of 36 bunches each of counter-circulating p's and $\bar{p}$'s within the common beam tube. Bunches are arranged in three groups of twelve with 396 ns bunch spacing within a group and 2636 ns between groups. For the $\bar{p}$ measurements discussed here, the the digital receiver board is programmed in closed orbit mode; that is, it integrates over approximately 50 turns of the Tevatron, which corresponds to a resolution bandwidth of about 1 kHz. This measurement is averaged over all of the bunches in the machine and over many turns of each bunch. The integration time is suf£ciently long to average out the betatron oscillations but not the synchrotron oscillations. Moreover, the long integration time ensures that the method requires timing only at the level of a few hundred ns and the narrow resolution bandwidth reduces the dependence of the position measurement on bunch shape.

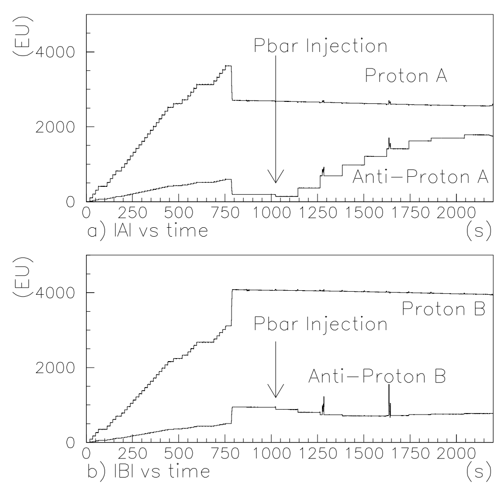

Figure 1: Magnitudes of the raw signals on the four channels from the BPM HB34. The time axis is in seconds from the start of the dataset.

Figure 1 shows the magnitudes of the signals from each of the four channels on one BPM for the £rst 36 minutes of a Tevatron shot. On the $|A_p|$ and $|B_p|$ traces, one can see the 36 steps corresponding to the injection of 36 p bunches.

* kutschke@fnal.gov

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These bunches are injected onto the central orbit. At about 800 s the separators are energized, moving the beam onto the p helix and giving rise to steps in $|A_p|$ and $|B_p|$. The vertical arrows mark the beginning of the $\bar{p}$ injection. The $|A_{\bar{p}}|$ and $|B_{\bar{p}}|$ traces to the left of the arrow show that the p contamination on the $\bar{p}$ channels is signi£cant. The two glitches in the traces occur when the $\bar{p}$ bunches are cogged relative to the p bunches.

In £gure 1 there is, as expected, no evidence for signi£cant $\bar{p}$ contamination on the p cables. Until the Tevatron $\bar{p}$ currents are increased signi£cantly the p raw measurements will be used without correction. The $\bar{p}$ raw measurements, on the other hand, need to be corrected and studies have shown that a linear model meets the speci£cations:

$$\begin{aligned} A'_{\bar{p}} &= A_{\bar{p}} - aA_p - bB_p \\ B'_{\bar{p}} &= B_{\bar{p}} - cB_p - dA_p, \end{aligned} \quad (1)$$

where the primed quantities are the corrected ones and where a, b, c, d are complex parameters referred to as cancellation coef£cients. To determine these coef£cients two sets of raw measurements are taken, one at a time, t_1, just before the helix opens and another at a time t_2, a few seconds later, just after the helix opens. Under normal operations there is insigni£cant loss of beam during the opening of the helix and one may make the approximations that, $A'_{\bar{p}}(t_1) = A'_{\bar{p}}(t_2)$ and $B'_{\bar{p}}(t_1) = B'_{\bar{p}}(t_2)$. Using the two raw measurements and this approximation, one can invert Equation 1 and solve for the cancellation coef£cients.

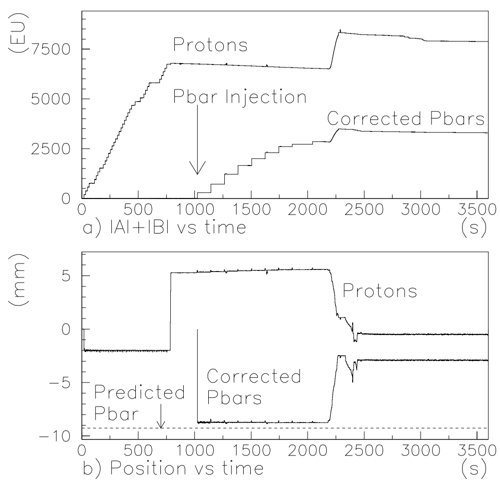

Figure 2: Intensities and positions for both p and $\bar{p}$s, after correction for the p contamination on the $\bar{p}$ channels.

Figure 2a) shows $|A|+|B|$, referred to as the sum signal, for both p's and for corrected $\bar{p}$'s, for the £rst hour of a shot.[1] For a constant beam energy, $|A|+|B|$ is proportional to the beam intensity.[2] The vertical arrow marks the ime of the £rst $\bar{p}$ injection. The $\bar{p}$ sum signal before this arrow provides a £rst check on the quality of the cancellation: it is typically 5 to 10 counts, well below the level from the true $\bar{p}$ signal, but above the noise of the system when no beam is in the machine, 1 to 3 counts.

The beam position for either species, in mm, is computed as,

$$P = 26\frac{|A| - |B|}{|A| + |B|} \quad (2)$$

where the constant 26 is determined by the spacing of the stripline pickups. While additional corrections are important for operation of the Tevatron, they would only confuse this discussion and have been ignored. Figure 2b) shows the p and $\bar{p}$ positions for the same time period as Figure 2a). The main features of the this £gure are the opening of the helix, seen in the p trace, and the energy ramp near 2200 s.

There are no intended changes to the central orbit during the opening of the helix and during the $\bar{p}$ injection. Therefore one can predict the expected position of the $\bar{p}$ orbit: it is the mirror image, about the central orbit, of the p orbit. In Figure 2b) a dashed horizontal line is drawn at the predicted $\bar{p}$ position, obtained using the p position immediately before and after the opening of the helix. The measured position disagrees with the prediction by about 400 μm, but that is within the accuracy speci£cation of 1 mm.

As the beam energy ramps up, near at time of 2200 s, the separator voltages are held constant so the separation of the helices decreases, with both beam species moving as mirror images towards the central orbit. This is qualitatively observed in the data. The comparison is not exact because the central orbit does change during the ramp . After the energy ramp the beams are squeezed and brought into collision. These two operations further change the position of the central orbit

I should remake this using the attenuation corrections - hopefully it goes in the right direction!

And Figure 3 shows a detail Figure 2b) during $\bar{p}$ injection. This provides a second check on the quality of the

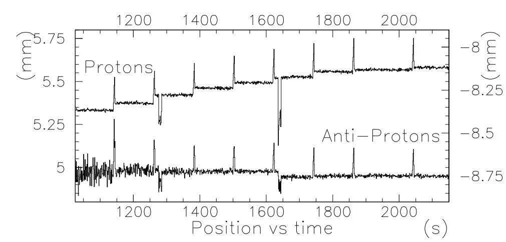

Figure 3: Detail of the p and $\bar{p}$ positions during $\bar{p}$ injection. The left hand scale is for the p position and the right for the $\bar{p}$ position.

cancellation of the proton contamination. When that cancellation is poor, the $\bar{p}$ position trace will show large steps, as large as 1 mm, at each $\bar{p}$ injection. In Figure 3, on the other hand, the $\bar{p}$ position is stable to better than 100 μm throughout the $\bar{p}$ injection. The conclusion is that the cancellation is excellent.

[1] The unadorned symbols A and B always refer to the raw p measurements and the corrected $\bar{p}$ measurements.

[2] Both traces show a rise in the sum signal at a time of about 2200 s. This is an artifact due to the ramping of the Tevatron energy from 150 GeV to 980 GeV.

Figure 3 £gure also provides evidence for $\bar{p}$ contamination on the proton position. The effect is about 300 μm, well below the accuracy speci£cation of 1 mm. It is understood in principle how to correct for this contamination but doing so would not result in signi£cant operational improvements at the current $\bar{p}$ intensities. Moreover calibrating the correction would $\bar{p}$ only stores, which $\bar{p}$ economics argues strongly against. The injection bumps and the cogging operations are also clearly seen in Figure 3.

One of the Tevatron tune up steps is to inject a proton bunch and then energize the helix with the opposite polarity, which places the proton bunches on the $\bar{p}$ orbit. Figure 4a) shows the measured proton position during one

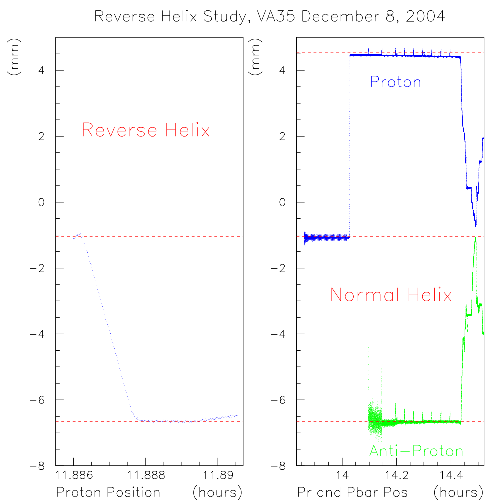

Figure 4: Reverse Proton tests.

of these reverse helix injections. Horizontal dashed lines are drawn at the positions of the central orbit and the $\bar{p}$ orbit. Figure 4b) shows the measured proton and $\bar{p}$ positions for a shot which followed soon after the reverse helix tune up. The two horizontal lines drawn on a) have been repeated in b). A third horizontal line has been drawn on b) at predicted position of the proton helix, using the mirror image model to make the prediction. Inspection of the £gure shows that the central orbit has moved by about 50 μm between shots. It also shows that the $\bar{p}$s are measured to be at the predicted position to better than 100 μm and that the protons are at the mirror image position with an accuracy of about 150 μm. Again these deviations are within the speci£ed tolerances.

In order to further test the self consistency of the upgraded BPM electronics, there is a plan for a proton only store with the separators off. During this store the measured proton position will trace out the central orbit from initial p injection to the initiation of collisions. Immediately following this study a normal physics shot will be done and the measured p and $\bar{p}$ positions will be compared to the central orbit determined in the proton only store. If there are signi£cant deviations from the expected mirror image model, a correction scheme will be developed.

The cancellation coef£cients vary from one BPM to the next, presumably due to material and construction tolerances. The coef£cients for a given BPM also change signi£cantly from store to store. The scale of the store to store variation is illustrated in Figure 5. The green points in show the $\bar{p}$ position for a particular shot using the cancellation coef£cients computed at the helix open of the same shot. The red points show the positions computed using the cancellations coef£cients from the previous shot, 2 days earlier, and the blue points show the positions computed using cancellations coef£cients from a shot 7 days earlier. The older

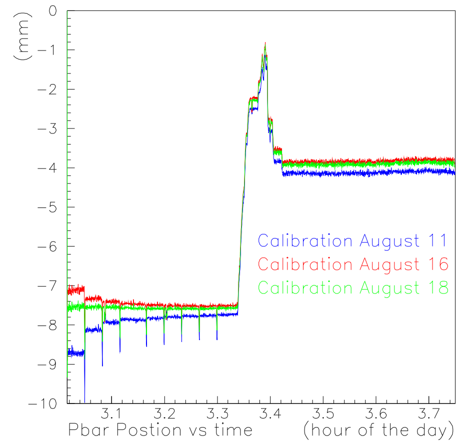

Figure 5: Variation store to store.

cancellation coef£cients do a poorer job. When the full $\bar{p}$ load has been injected, the error in the position is on the scale of 500 μm, which is within the 1 mm spec. However the error in the measurement of the £rst $\bar{p}$ injection is larger than spec. An automated procedure to recompute the cancellation coef£cients every shot is currently under development.

For a BPM that measures horizontal position, the cancellation coef£cients depend on the vertical beam position as it passes through the pickups. And vice versa for a BPM that measures vertical position. It is believed that correcting for this effect will remove most of the time dependence of the cancellation coef£cients. However such a correction requires knowledge of lattice functions and will only be done in of¤ine studies and will not be used operationally.

CONCLUSIONS

This note has described the so called "frequency domain" method for measuring the $\bar{p}$ postion using the upgraded Tevatron BPM system. Using data taken during the commissioning period, the method has been shown to meet the stability requirements. The method also passes self consistency tests for its accuracy but no absolute accuracy test have been performed.

REFERENCES

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