Compensation of Beam Roll Due to HP3US Regulation Errors in Switchyard

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ABSTRACT

Power supply regulation issues with a bending magnet string in Switchyard have led to horizontal beam movement of greater than 10mm during the beam spill. This paper shows a method for improving the current regulation of the bend string's power supply, and that two horizontal corrector magnets can be used to compensate for small remaining deviations. Finally, results of a beam study to show the feasibility corrector magnet compensation are shown.

Introduction

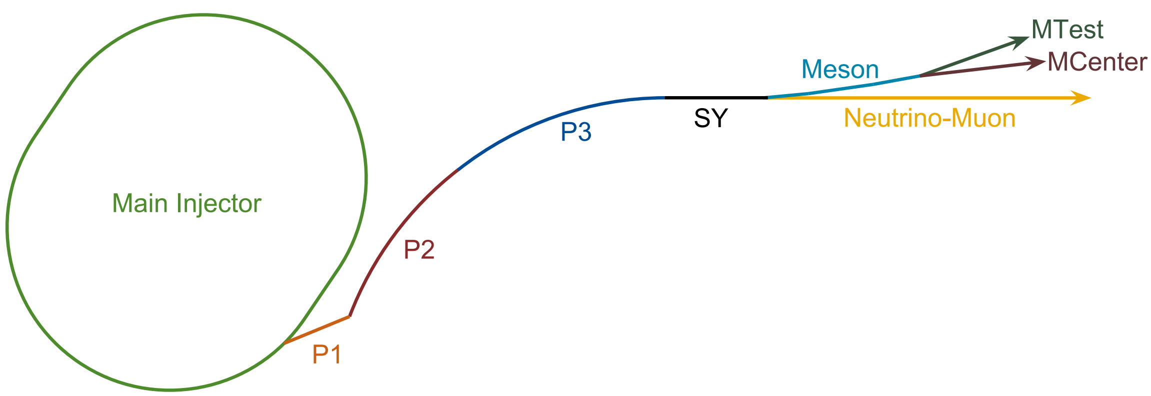

Figure 1. The Fermilab Switchyard and Fixed Target experimental beamlines.

The Fermilab Switchyard beamlines provide 120 GeV protons to several experimental fixed-target areas via resonant slow-extraction from the Main Injector synchrotron. A significant portion of the transfer beamline to the experimental areas consists of remnants of the Main Ring synchrotron, labeled in **Figure 1** as "P2" and "P3". The dipole bending magnet string for the upstream half of the P3 beamline is powered by a single power supply named "HP3US". Regulation of this power supply's output current is crucial to maintaining stable horizontal beam position over the four-second-long beam spill. Known as "beam roll", this position movement throughout the spill creates difficulties for experiments and increases beam loss at aperture restrictions.

The main transformer for HP3US is slightly undersized for the tight current regulation the beam requires. When the 13.8 kV line voltage from the substation sags due to changing load (for example, in the summer when home air conditioners start turning on), the regulation of HP3US suffers noticeably at the 1-2 Amp level, and horizontal beam roll increases. AD EE Support engineers have adjusted the regulation of the supply to provide a more consistent "flat-top" current during the spill, but there is an apparent trade-off; HP3US is more consistent, but comes up to full current after the beam has already started to extract. This means that although the majority of the spill has noticeably-reduced beam roll, the first half-second of spill is far worse. **Figure 2** shows the current of HP3US (and its downstream counterpart HP3DS for comparison) during the spill, along with two downstream horizontal beam position monitors ("BPMs") to show the position change. Notice in the left image of **Figure 2** that the HP3US current (green trace) comes up noticeably later than the downstream supply HP3US (red trace). This creates significant beam roll in the horizontal BPMs downstream of the magnet string, shown in the blue and yellow traces.

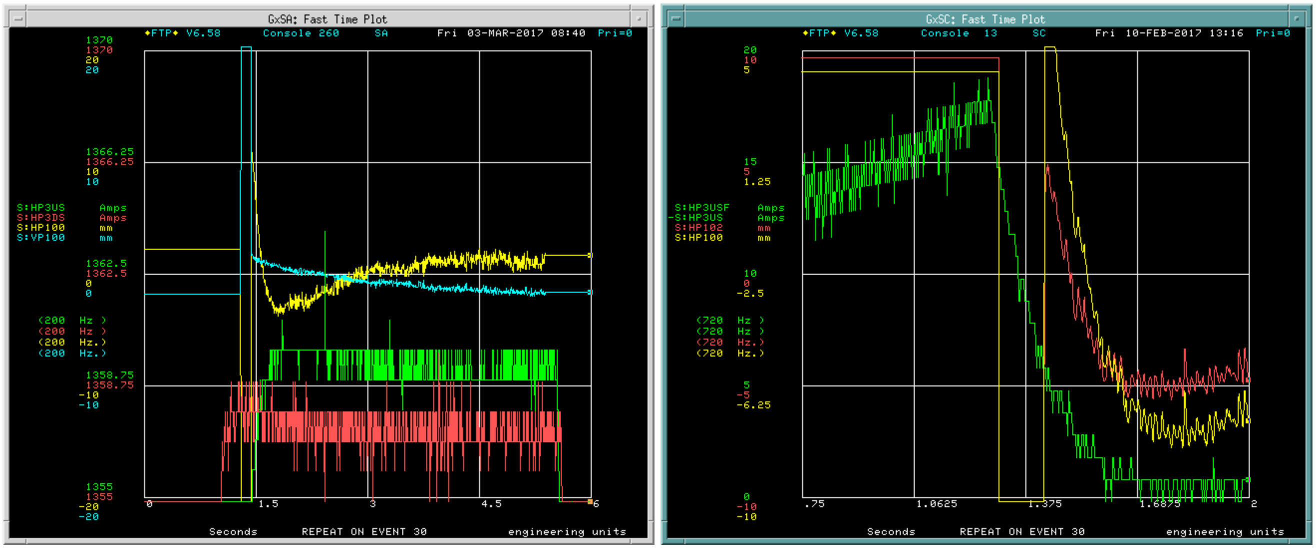

Figure 2. Horizontal position movement throughout the beam spill as caused by HP3US coming up to full current too late.[1,2]

HP3US Reference Adjustment

The largest alleviation of the beam roll has been achieved by building a custom ramp that over-shoots the current reference so the actual power supply output current is much closer to nominal by the time beam begins to spill. This alleviates the more than 10mm spike in horizontal position in the first half-second of the spill. It remains to be seen how consistent this behavior will be when the seasons and line voltage change.

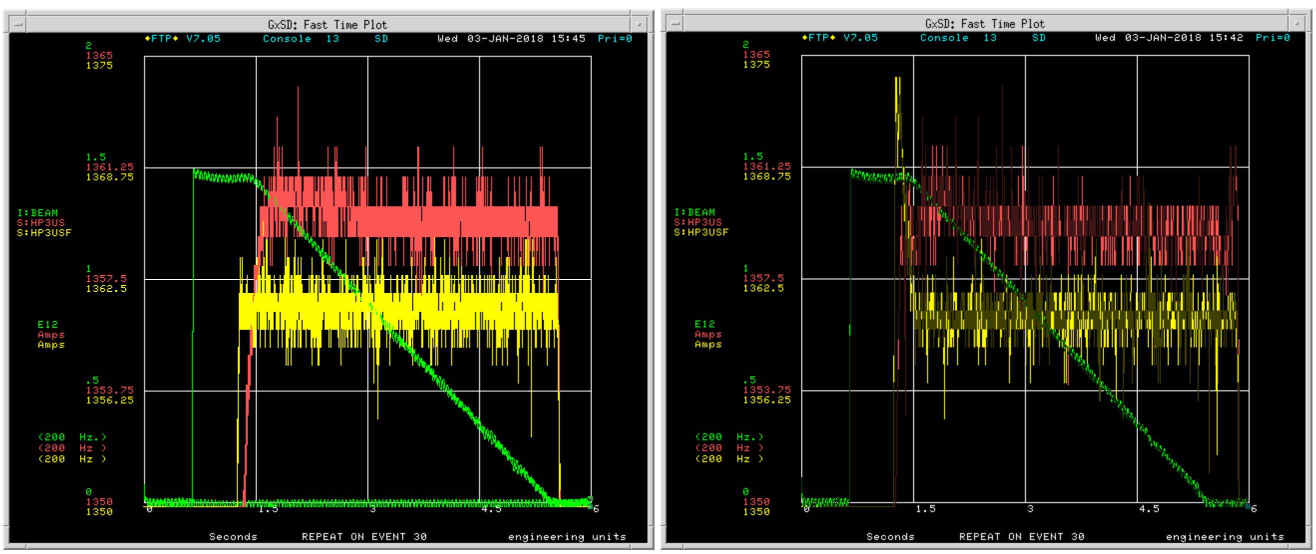

Figure 3. HP3US power supply current reference (yellow) and output current (red) as-found (left) and with the intentional over-shoot reference (right).[3]

Figure 3 shows the original HP3US reference signal (yellow) and output current (red) on the left, and the same signals after creating a reference over-shoot on the right. **Figure 4** shows the resulting improvement in the horizontal beam roll as measured by BPMs downstream of the magnet string. The improvement is significant, though there may be more room for improvement given dedicated tuning time to further adjust the reference over-shoot.

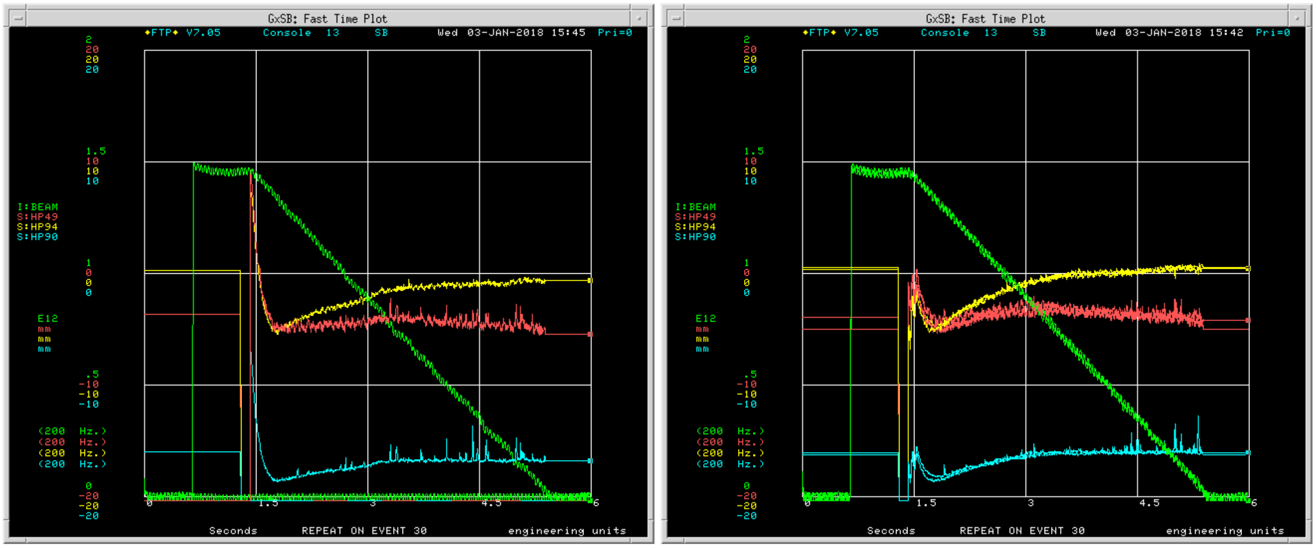

Figure 4. Horizontal BPM readings during the spill without any change to HP3US (left), and with the over-shoot reference ramp (right).[3]

Beam Trajectory Compensation

While the reference over-shoot has greatly improved the horizontal beam roll, it would be prudent to have adaptive compensation that can adjust for small deviations in HP3US current so the beam position remains steady. This could take the form of a traditional auto-tune program, albeit one that makes multiple corrections throughout the long spill to maintain consistent beam positions. This section investigates how much the available corrector dipole magnets downstream of HP3US are able to compensate to maintain stable trajectory. The two relevant correctors are HTF26 and HTF36, though a fully-operational auto-tune system will use more than just these two magnets.

To compute the necessary corrector current to adjust for HP3US offset errors, it is necessary to scan the HP3US DC flat-top current and observe the offset in average horizontal position as measured by the downstream BPMs. These data are pictured in **Figure 5** along with the fitted linear relationship for each BPM as a function of HP3US current.

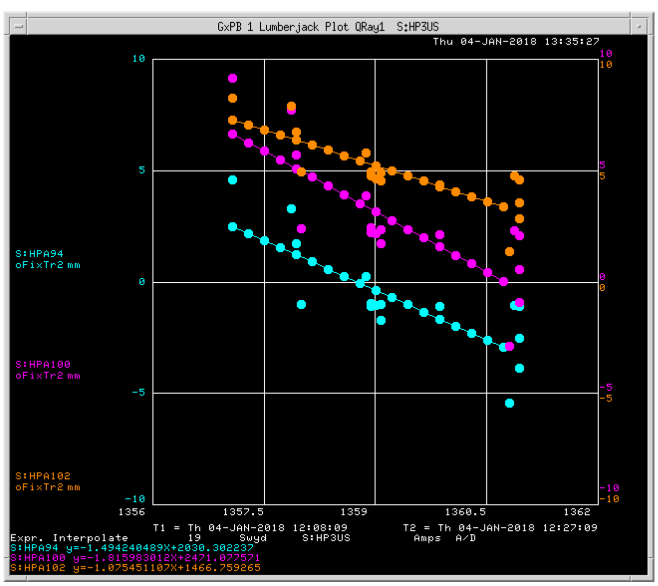

Figure 5. Scan of HP3US DC flat-top current to compute the linear response of downstream BPMs.[4]

Similarly, both HTF26 and HTF36 DC flat-top currents are scanned, and the linear relationship between current and downstream horizontal BPM average is computed. These fits and data are shown in **Figure 6**. To reiterate, the BPM readings for these plots are the average position over the entire spill.

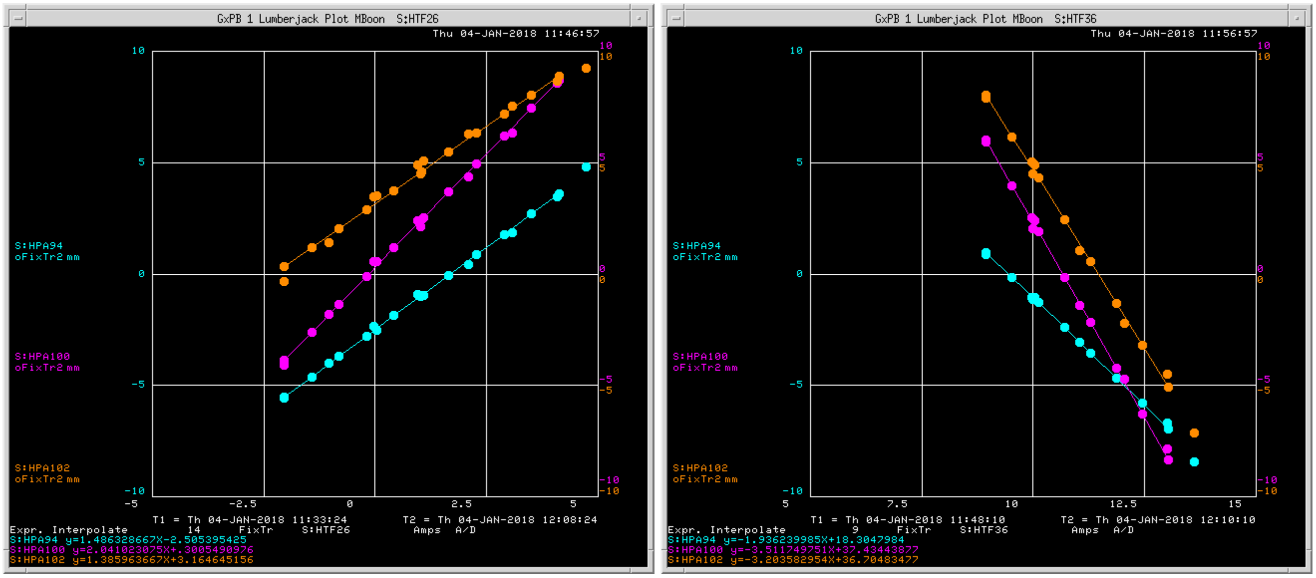

Figure 6. Scan of HTF26 (left) and HTF36 (right) DC flat-top current to compute the linear response of downstream BPMs.[4]

To work out the correct current changes needed to compensate for HP3US changes, we first consider the linear system described by the scan data for **Figure 6**, which shows how changes corrector current correspond to downstream BPM reading changes.

$$\begin{pmatrix} \Delta HP94 \\ \Delta HP100 \end{pmatrix} = \mathbf{C} \begin{pmatrix} \Delta HTF26 \\ \Delta HTF36 \end{pmatrix} = \begin{pmatrix} 1.486 & -1.936 \\ 2.041 & -3.512 \end{pmatrix} \begin{pmatrix} \Delta HTF26 \\ \Delta HTF36 \end{pmatrix} \tag{1}$$

Similarly, the scan of HP3US DC flat-top current in **Figure 5** provides the following relationship:

$$\begin{pmatrix} \Delta HP94 \\ \Delta HP100 \end{pmatrix} = \Delta HP3US \begin{pmatrix} -1.494 \\ -1.816 \end{pmatrix}. \tag{2}$$

Now setting **Eq. 1** equal to **Eq. 2**, and solving for the corrector currents, we can determine the correlation between changes in HP3US and the correctors. To determine how to *correct* for the HP3US changes, we simply multiply the resulting expression by -1 so the correctors counteract the HP3US change. To summarize:

$$\begin{pmatrix} \Delta HTF26 \\ \Delta HTF36 \end{pmatrix} = -1 * \Delta HP3US \left[\mathbf{C}^{-1} \begin{pmatrix} -1.494 \\ -1.816 \end{pmatrix} \right] = \Delta HP3US \begin{pmatrix} 1.366 \\ 0.277 \end{pmatrix} \tag{3}$$

Using this relationship, a simple ”two-mult bump” has been created that one can ”knob” to adjust for offsets in HP3US current, shown in **Figure 7**. The ”two-mult bump” from **Figure 7** was tested in the beamline by making small changes to the HP3US

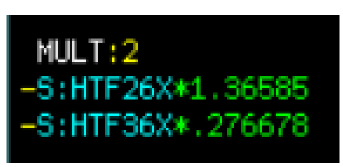

Figure 7. Computed bump to correct for HP3US offsets.

current, then compensating with the bump until downstream beam position monitors return to nominal values. The results of the beam study are shown in **Figure 8**, and show successful proof-of-principle operation of the HTF26 and HTF36 corrector magnets to correct for small deviations in HP3US output current.

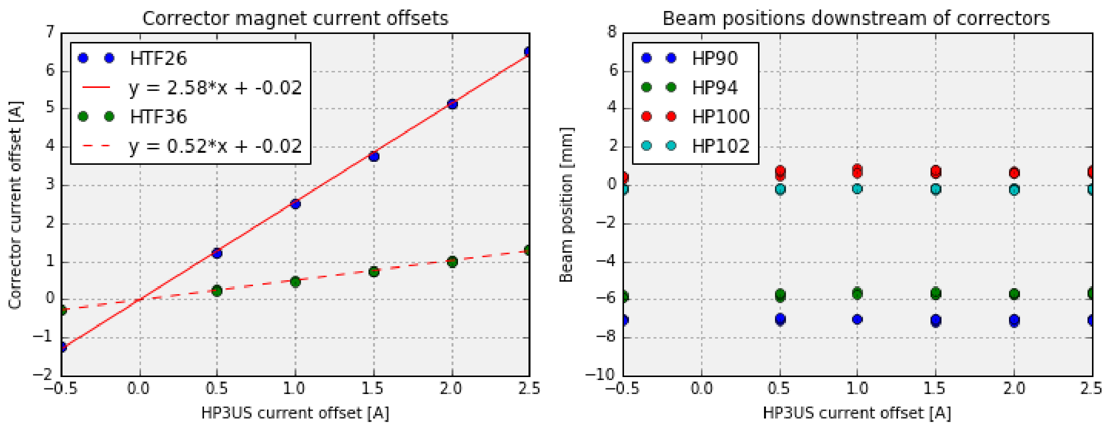

Figure 8. Corrector current changes (left) to compensate for small HP3US output current offsets. Beam positions remain unchanged when correctors are used to compensate (right).

Summary

The current regulation errors in HP3US have been compensated using two methods, both of which significantly improve the horizontal position stability of the beam during the spill. The current reference for the HP3US power supply was corrected manually to include an intentional over-shoot in the first half-second of the spill, forcing the output current to come up to its nominal level in time for the beam arrival. For small deviations in HP3US flat-top current during the rest of the spill, a two-bump using downstream corrector magnets has been developed that provides a proof-of-principle correction to the beam trajectory. This result shows that a future auto-tune program that makes multiple corrections throughout the beam spill will be capable of correcting for small errors in HP3US current.

References

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