Understanding and Improving the High Field Orbit in the Fermilab Booster

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Abstract

With the implementation of the BPM system in the Fermilab Booster, complete survey data of the main magnets have been employed to determine magnet moving schemes to correct the high field orbit at 8 GeV kinetic energy and to understand the global pattern of the high field orbit in both planes. Considerable success has been achieved in the former task. We also obtained reasonable understanding in the latter effort, given the multitude of factors that have to be dealt with. In this paper an account is given of the survey record, the orbit correction exercise, and the effort to reconstruct the high field orbit based on the survey records.

1. Introduction

This note is an account of the effort to both understand the Booster high field orbit and to control it through displacements of the main combined function magnets. This work was initiated in Spring 1987 with orbit control via magnet moves the chief purpose. A series of magnet moves in 1987 and 1988 resulting from this study demonstrated its reliability. The understanding of the Booster orbit is an ongoing process in which we keep modifying our model with the hope of eventually having a quantitative grasp of the closed orbit.

In section 2 we give a brief account of the Booster and background information concerning the magnet moves. The method used is discussed in section 3. The result of the moves is documented in section 4. In section 5 our effort to understand the Booster high field orbit is discussed.

2. Background information

The Fermilab Booster is an alternating gradient proton synchrotron with an extraction kinetic energy of 8 GeV. Bending and focusing of the beam are done through the 96 combined function magnets grouped into 24 identical DOFOFODO periods. The low field orbit (up to ~ 2 GeV/C in momentum) can be effectively controlled by the correction dipole packages installed around the ring. Near extraction energy, the correction dipoles are too weak to have any noticeable effect. In principle the major sources of high field orbit distortion are the transverse displacement of the main (quadrupole) magnet center from the design orbit, to be called the **offset** in the following, and the rotation around the beam axis of the main (dipole) magnet with respect to the nominal orientation, to be called the **roll** in the following. In the Booster the main dipole and quadrupole magnets are integrated into one piece as combined function magnets. A constantly updated survey record by the Fermilab survey staff keeps track of the offsets and rolls of all 96 of these magnets.

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Figures 1 and 2 show the horizontal and vertical offsets of these magnets before (April 1987) and after (April 1988) the magnet moves. Figure 3 shows the roll values. The data in figure 1 were obtained by fitting the raw measurement to a theoretical model of the Booster geometry (see reference 1).

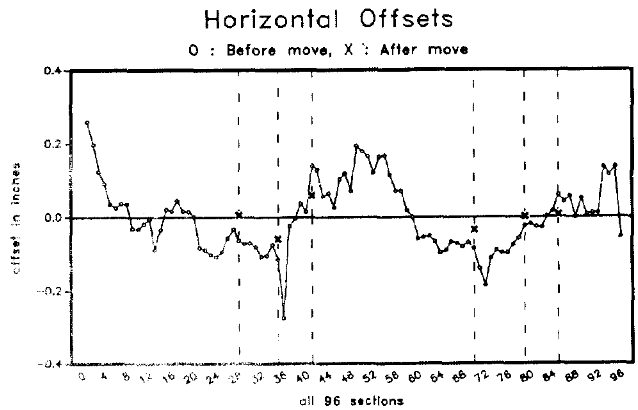

Figure 1. Horizontal offsets before and after moves

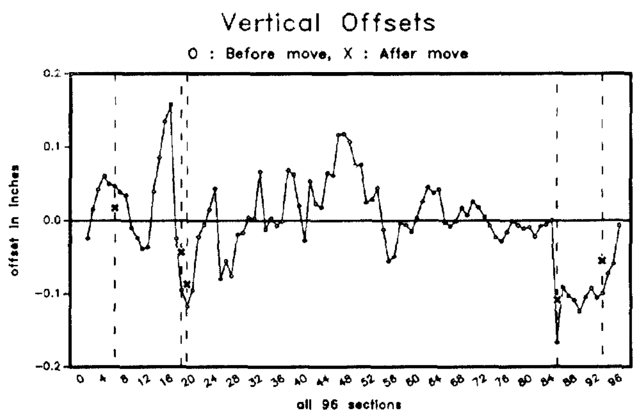

Figure 2. Vertical offsets before and after moves

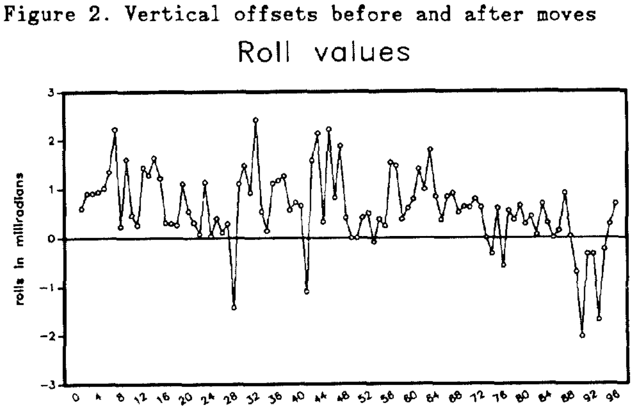

Figure 3. Roll values as of April 1987

Besides affecting the vertical orbit, the rolls of the main magnets also contribute to the linear coupling. An independent study[2] of the Booster beam dynamics shows that the amount of linear coupling

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agrees very well with that predicted by the roll data.

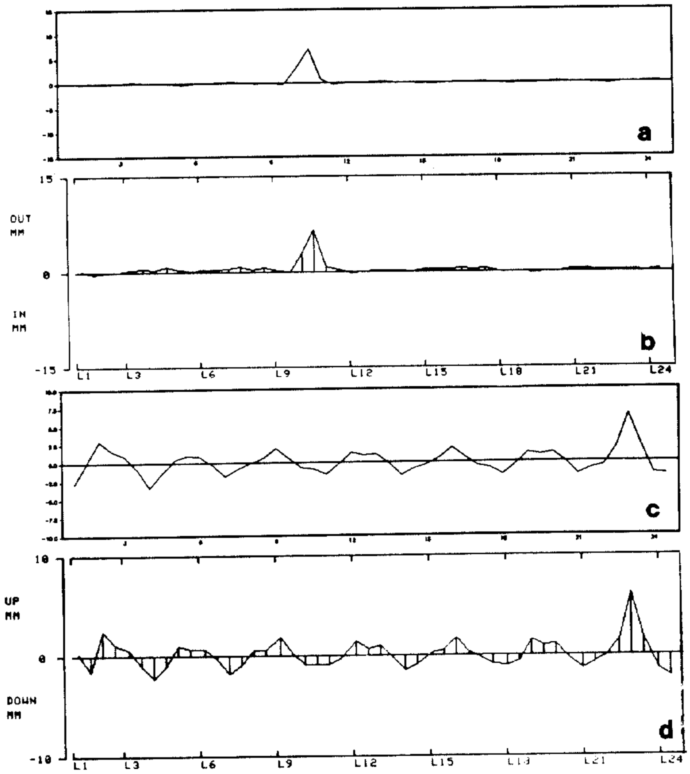

Figure 4. Orbit changes in the 1987 move:
(a) horizontal predicted, (b) horizontal observed,
(c) vertical predicted, (d) vertical observed.

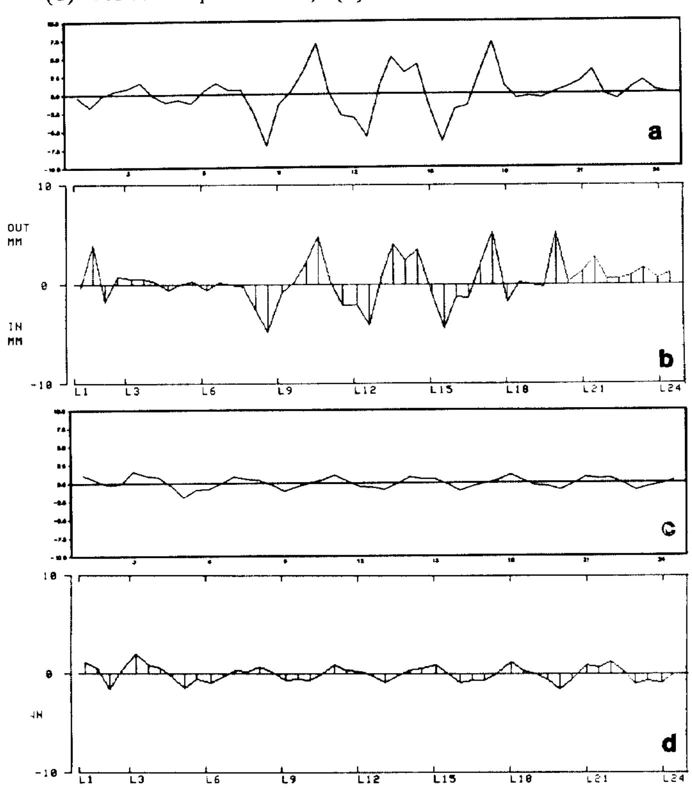

Figure 5. Orbit changes in the 1988 move:
(a) horizontal predicted, (b) horizontal observed,
(c) vertical predicted, (d) vertical observed.
The horizontal BPM's at S1 and L20 were not working.

3. Method and criteria used in determining the moves

(a). Evaluating the closed orbit

The known Booster lattice is used in a one-turn closure program to calculate its closed orbit for given sets of main magnet offsets, rolls, and correction dipole settings. This program is used iteratively leading to the optimal moving scenario that reduces a given orbit distortion.

(b). Additional considerations

The moving scenario mentioned above is further subject to considerations due to economics or physical limitation of the Booster. These are:

1. Minimum number of moves
2. Minimum magnitude of moves
3. Avoiding injection and extraction areas
4. Moves should reduce the specific offsets of the magnets in question
5. Moves should reduce the tension induced on the beam pipe between magnets caused by initial offsets or previous moves.

With these considerations, our choice is greatly limited and it will become more and more stringent as we perform more and more moves. We have managed to plan all of our moves so far (6 horizontal and 5 vertical in two moving plans one year apart) so that none of the above criteria were violated. Further moves would certainly demand more caution.

(c). Special moving combinations

A useful combination of moves is the so called **2-bump**, consisting of two moves $N\cdot\pi$ apart in betatron phase, which induces an orbit change spanning several periods of the Booster. Using this technique it is possible to correct the orbit at many locations at the same time, and in March 1988 the horizontal orbit was corrected across 11 periods (or almost halfway around the ring) with a 2-bump. The move was quite successful.

In order to correct very localized orbit excursions, local 3-bumps are used. These are moves in 3 consecutive main magnets so that the orbit at only one straight section is significantly affected. Table 1 lists the typical moving ratios for these bumps.

The usual approach adopted is to first try to fix the orbit at as many points as possible through a 2-bump, even if the overall effect is not quite localized. We then try to find a strategic moving point in the ring by phase counting or simple trial and error to neutralize the nonlocal effect. Of course all this is still subject to the constraints 3,4,and 5 in (b), which complicates the picture considerably.

4. Results

Figures 4 and 5 give the calculated and actual change of the orbit after the magnet moves in 1987 and 1988, showing the high accuracy of the method. As a result of the moves, the scatter in the magnet offset data was also reduced, conforming to criteria 4 and 5 in section 3(b).

5. Predicting the global high field orbit

Considerable effort has been devoted to reconstructing the measured high field orbit using lattice parameters, the magnet survey data, the correction element settings, the radial feedback effects, and other BPM-independent measurements. It is clear that such an understanding would help us control the Booster orbit much more accurately and reliably.

(a) Horizontal

Figure 6 shows the comparison between the predicted horizontal orbit and the observed orbit. Both are obtained at t=32.6 msec in the cycle. The former is calculated using the surveyed offset values. A complication arises due to the radial position feedback (**ROFF**) loop, which controls the orbit at a pickup point not near any BPM. For both the predicted and measured orbits, a root finding algorithm is employed to solve for the slope of the orbit at the nearest BPM, using the orbit values at 2 BPM's and all intervening kicks. The orbit value at the ROFF pickup is then interpolated and proper adjustment made to match the predicted and measured orbits at this point.

The predicted orbit possesses the basically correct phase information. The discrepancy in magnitude at several points cannot be attributed to a clearcut origin at this point.

(b) Vertical

Besides the main magnet offsets, the magnet rolls also affect the vertical orbit. Figure 7 shows the comparison between the predicted and the measured vertical closed orbits taken at t=33.0 msec. We are largely able to explain the observation with our model except near L11, where a large discrepancy is observed. The BPM at L11 has been rechecked and no malfunction was detected. Apart from the unrealistic amplitude, the deviation displays a valid betatron half period covering about 1.13π of the vertical betatron phase, suggesting a possibly unaccounted 2-bump in the vicinity. This will be investigated further.

To avoid perturbation artifacts in the orbit prediction due to the choice of the absolute horizontal plane as the unperturbed orbit plane, we identified the natural unperturbed orbit plane by least square fitting a "tilted" orbit plane to the surveyed offset data. The orbit distortion caused by the difference between this tilted plane and the absolute horizontal plane is then subtracted from the predicted orbit. In practice this effect turns out to be very small. More detail is given in reference 1.

Conclusion

The effort devoted in understanding and improving the Booster closed orbit has been presented in this note. We have achieved considerable success in moving individual magnets (instead of the girder which supports 2 magnets) to correct the high field orbit. This practice also helped to bring all of the magnets back toward the overall average according to the survey data. The well defined procedure can be applied to future moves, although the criteria will be more stringent with more moves.

Our current understanding of the global high field orbit based on the survey offsets gives us a generally correct picture. Room for refinements definitely exists. This will depend on more accurate input of the field survey and magnet measurements. Further improvements in both the survey technique and analysis tools are expected in this ongoing process.

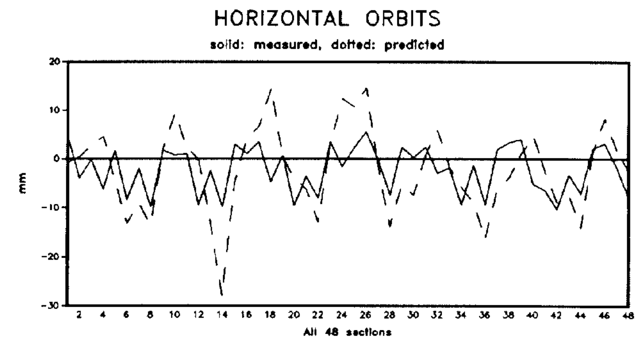

Figure 6. Calculated (dotted) and observed (solid) horizontal high field orbit.

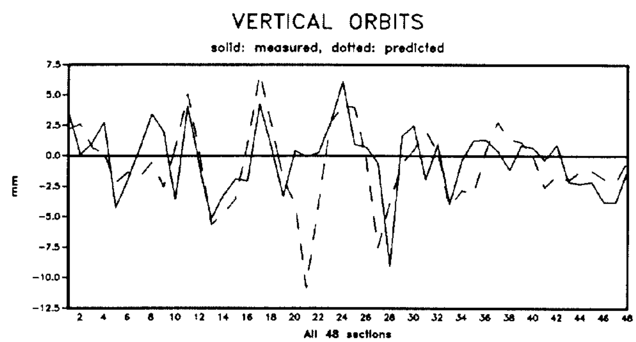

Figure 7. Calculated (dotted) and observed (solid) vertical high field orbit.

Magnets moved	Inches moved	Orbit change
1.1(D)	+0.0141	L2 +1 mm
4.3(F)	+0.0149	L4 -1 mm
(N-1).4(D)	+0.0383	LN +1 mm
N.1(D)	-0.0852	N=1,23
N.2(F)	-0.0884	
24.3(F)	0.0894	L1 +1 mm
24.4(D)	-0.0835	
1.1(D)	+0.0363	
N.1(D)	+0.1230	SN +1 mm
N.2(F)	+0.2788	N=1,24
N.3(F)	-0.0978	

Table 1: 2-bump and 3-bump moving combinations. L and S are the long and short sections

References

1. Y.Chao, L. Ketcham and C. D. Moore, Fermilab Technical memo TM-1571 (1989)

2. Y.Chao, Fermilab experimental note # 159 (1988)