INTENSITY DEPENDENT BEAM DYNAMICS STUDIES IN THE FERMILAB BOOSTER*

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Abstract

The Fermilab Booster, part of the injection chain, is continually called on to provide increasing beam intensity to meet the goals of the experimental program. The Booster, now about forty years old, runs significantly above the original design intensity. It is a continuing effort to understand the sources of emittance growth and particle loss at the highest intensities. While both space charge and machine impedance effects are present, the intensity limitations are primarily due to impedance. The impedance effects are exacerbated by the Booster magnets, with laminated pole surfaces, which are used directly as vacuum tanks. The dipole-wakefield contribution from the resistive wall impedance has been shown in other work [1] to provoke the head-tail instability. Evidence given here shows that the quadrupole component of the wake also plays a role, generating intensity dependent tune shifts. Application of an analysis by Chao, Zotter, and Heifets of a cumulative quadrupole wake generated by the non-circular vacuum chambers provides quantitative agreement for observed increase in tune separation with intensity [2]. Measured positive and negative tune slopes, obtained from a study of the dependence of transverse coupling on beam intensity, are compared with analytic results. A comparison with simple particle-tracking simulations is also provided, demonstrating qualitatively the equal but opposite tune slopes in the transverse planes.

MOTIVATION

The Fermilab Booster is a rapid cycling, combined-function proton synchrotron with a bunch intensity of about 6×10^{10} protons; about twice that planned in the original design. At higher beam intensities, beam halo is a demonstrated problem in the Booster [4, 5], and particle loss impacts operations. The injection energy is 400 MeV, corresponding to a gamma factor of 1.4. While the beam energy at injection is still low enough for space charge forces to play a role in the Booster dynamics, in this paper, we study coherent effects; thus, the direct space charge effect may be neglected here. In studies of coherent motion, impedance effects dominate. A commonly studied phenomenon in the transverse plane is the resistive wall dipole impedance, and in fact, this has been shown to generate a head-tail instability in the FNAL Booster [1]. However, previous work [7, 2] has shown that lack of circular symmetry of the beam chamber can generate quadupolar wakes resulting in intensity-dependent tune shifts of opposite sign in the two transverse planes. An experimental study of the transverse coupling dependence on beam intensity shows mode frequency shifts consistent with a quadrupole wake contribution, which arises from the magnet chamber asymmetry.

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EXPERIMENT

An estimate for the quadrupole component of the machine resistive wall impedance is obtained using results of a study of the beam intensity versus strength of transverse mode coupling between planes. The tunes in the horizontal and vertical planes were set as close together as practically possible for the study. The current in the skew quadrupole correction circuits was then changed systematically in order to find the operating point for minimum coupling. The injected Booster beam intensity was then increased several times, and the skew quadrupole scan done again each time. All other machine parameters remained the same.

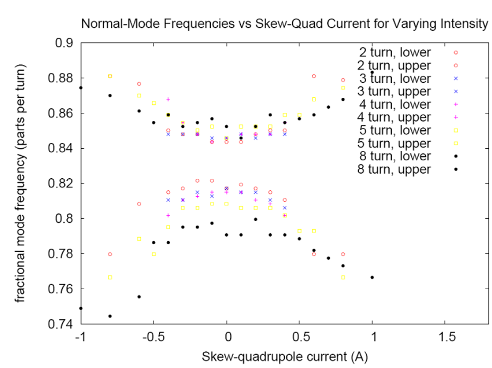

Figure 1: Measured mode frequencies vs. skew quadrupole circuit current at varying intensities. At each intensity there are two curves (plotted with the same symbol) which correspond to the dependence of upper and lower mode frequencies on the skew quadrupole current. The separation of the upper and lower curves is a measurement of the minimum coupling.

Figure 1 shows the raw data of the skew quadrupole scans at differing beam intensities overlaid. While the location of minimum mode separation remained consistent, the mode separation increased with intensity. A plot of mode separation versus intensity shows a linear dependence of mode separation on beam intensity. Figure 2 is comprised of two plots; the tune slope for the mode decreasing in frequency with intensity (top) and for the mode that increases in frequency with intensity (bottom). The mode frequencies were obtained from a signal analyzer Fourier transform of the signal from BPM plates. The analyzer was gated to the injection portion of the Booster cycle. The beam was kicked periodically to maintain a strong enough signal level on the BPMs. The result is that the one mode had a tune/intensity slope of -.01, while the other had a tune/intensity slope of +.004. Note while one mode is shifting downward in frequency, the other is shifting upward; this as is also clear in Figure 1. This is a clear signature of a quadrupole wake contribution. Note that, in general, we expect that the dipole wake is contributing to the measured intensity dependent tune shifts. However, unlike the quadrupole, the dipole effect has the same sign in both planes. This may be the cause of the difference in absolute value of the measured slopes. These results will be compared to an analytic impedance calculation for the tune change in the next section.

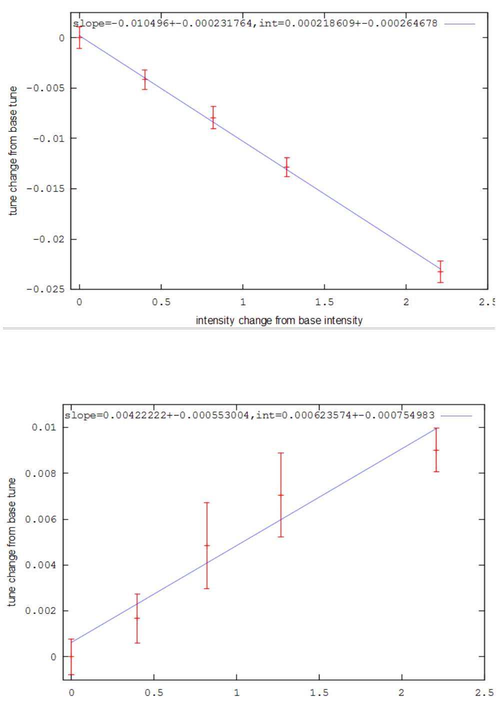

Figure 2: Mode frequency vs. beam intensity. The x-axis is the beam intensity in units of 10^{12} protons, and the y-axis is the change in tune (mode frequency) with respect to the tune (mode frequency) at the low intensity data point.

ANALYSIS

Heifets, Zotter, and Chao [2] have analyzed the tune shifts due to a resistive wake, treating the case of a beam aperture with a parallel plate geometry. They point out that while the quadrupole contribution vanishes for a structure with rotational symmetry, it is non-zero for the parallel plate geometry that the Booster magnets more closely resemble. They give the mode frequency shift as the following:

$$
\begin{aligned}
\Delta\nu_{x,y} &= \frac{rNr_0L}{48\gamma b^2\nu_{x,y}}\left(1+\frac{2t}{rb\pi}\right) \\
&= \frac{r\pi}{48\nu_{x,y}}\left(\frac{L}{C}\right)\left(\frac{R}{b}\right)^2\frac{2Nr_0}{R\gamma}\left(1+\frac{2t}{rb\pi}\right)
\end{aligned}
$$

where R is the machine radius, $2b$ is the average gap height of the Booster magnets, L/C is the fraction of the Booster ring containing magnets, r_0 is the classical proton radius, γ is the relativistic factor, and N is the number of particles in the beam. The parameter $r = 1 + \frac{b^2}{b^2+t^2} \approx 1.1$ is a geometric factor that accounts for the magnet geometry, and t is the thickness of the magnet. This thickness is the thickness of the beam chamber, since there is no pipe inside the magnet. The term in parenthesis, $1 + (2t/rb\pi)$, compensates for the fact that the chamber walls are not thin compared to the aperture size.

The values corresponding to the parameters given in Eq. 1 for the Fermilab Booster ring are given in Table **??**.

Table 1: Booster parameters

Booster parameter
Total beam energy at injection, E = 1.3 GeV
Packing fraction of magnets in ring, L/C = .60
Booster radius, R = 74 m
Average magnet half-aperture, b = 2.5 cm
Base tune, ν=6.7
Factor for magnet geometry r=1.1
Magnet (chamber) thickness, t=11.43 cm
Relativist gamma factor, γ=1.4

Our calculated values for the intensity dependent tune shift are $\pm.006$ for each plane, giving a total tune separation of .012. Using this tune separation, these preliminary results show agreement of about 15% between our experimental and calculated values. To finalize the analysis, we will do a detailed simulation of the beam dynamics in the Booster, including all effects discussed here.

A particle tracking simulation was done to visualize the intensity dependent tune shift using published expressions for the transverse wakefield kicks in a chamber with up-down symmetry [Equation two of reference [2]]. The kicks depend on the wake function, set to one for the purposes of this simulation, as well as the positions of the test charge and the driving charge. The beam was circulated through a FODO cell, and a comparison was done of the tunes for the cases of a wakefield present and no wakefield present. The tunes were obtained by taking an FFT of the horizontal and vertical beam position. The tunes in the horizontal and vertical planes were initially made equal. In the no-wakefield case, they don't change, and the frequency of the horizontal and vertical peaks is the same, as can be seen in Figure 3.

When kicks dependent on the wakefield and particle positions are applied, the tunes shift as shown in Figure 3. The mode frequency associated with the y-plane shifts upward from the original value, while the mode frequency associated with the x-plane shifts downward.

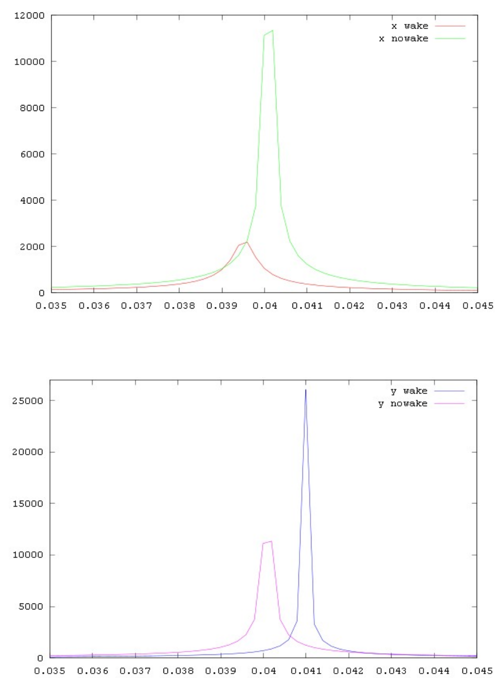

Figure 3: Results of simulation of wakefield effects in rectangular geometry. Top plot shows an FFT of the x position of the beam for the cases of a wakefield present, and no wakefield present. The bottom plot is similar, except it is y-plane data.

CONCLUSION

The results of a beam study in the Fermilab Booster demonstrates the presence of a quadrupole component of the resistive wall wake. Existence of a quadrupole component depends on lack of rotational symmetry in the shape of the beam chamber. The Booster magnets have a roughly rectangular aperture when averaged over the two magnet types, although there is only top-bottom symmetry within a given magnet, not left-right symmetry. Comparison of study results to analytic calculation gives agreement to about 15%. The qualitative agreement is excellent, as the behavior due to a quadrupole component of the wake should shift the tunes in opposite directions, as is seen both experimentally and in simulation. The asymmetry in the magnitude of the tune shifts in the two transverse planes is consistent with an additional dipole wake component acting with the same sign in both planes.

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