Large-Scale Simulation of the FNAL Booster and Comparison with Experiment

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Abstract

The Fermilab Booster is an important testing ground for our understanding of space-charge effects in accelerators. We present results of beam studies and simulations of the Booster. We start with an investigation of recent attempts to reduce beam halo through the use of collimators. We also use Synergia to predict halo formation and particle tune spreads. Finally, we compare a coherent tune study with predictions from Synergia.

Key words:
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1 Introduction

The Fermilab Booster [1] is crucial to the lab's particle physics program. It supplies protons for the Fermilab neutrino program as well as the Tevatron complex. It is an interesting machine for studying multi-particle effects because it operates in a regime where space charge is significant.

The Booster is a rapid cycling (15 Hz) machine. It accelerates protons from 400 MeV to 8 GeV. The 474.2 m machine consists of 24 FOFDOOD cells. The RF system ramps from 37.7 to 52.1 MHz during the cycle. The beam is injected over multiple turns, typically 10 turns for a total of 420 mA. Injection, capture and bunching occur during the first roughly two ms.

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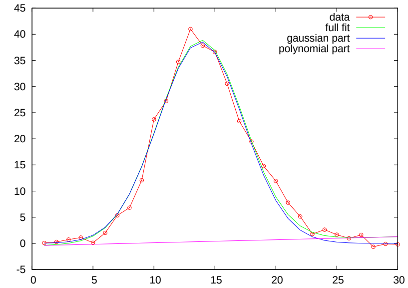

Fig. 1. Beam profile observed in the IPM. The plot shows the fitted Gaussian plus linear function as well as the contributions of the individual Gaussian and linear pieces.

2 Experiment

A new collimation system has recently been added to the Booster [2]. The system is designed to safely remove halo particles and localize proton losses, lowering losses around the rest of the machine. The design consists of primary collimators designed to scatter halo particles and secondary collimators designed to intercept the scattered particles. The beam is bumped, affecting the the beam in the region 2.5–4.5 ms into the cycle, so that the primary collimators may excite halo particles, which are then to be removed by the secondary collimators.

We studied the actual effect of the new collimation system with the Booster Ion Profile Monitor (IPM). The IPM is capable of measuring beam profiles on a turn-by-turn basis. A sample beam profile is shown in Figure 1. We fit each profile to a function that consists of a Gaussian sitting on top of a linear background.

For a simple model of halo, we ascribe

$$G \equiv \int (\text{Gaussian part}) \tag{1}$$

to the core and

$$L \equiv \int (\text{linear part}) \tag{2}$$

to the halo. We typically saw $L/G \simeq (10-20)\%$ in this study. Our expectation is then that the collimation system should reduce L. The quantity

$$\Delta \equiv L_{\text{no collimator}} - L_{\text{with collimator}} \tag{3}$$

is our measure of the collimators' effect. For each Δ measurement we averaged over 100 turns within a cycle and five cycles overall. Measuring over multiple cycles allowed us to smooth out the cycle-to-cycle variations, which are not small on the scale of the effect we are measuring. We measured Δ both before the bump (turns 100–200), where the collimation system was designed to have no effect, and after the bump (turns 5100–5200), where the halo is supposed to be reduced.

In the horizontal plane we find $\Delta = 0.267 \pm 0.041$ before the bump and $\Delta = 0.451 \pm 0.040$ after the bump. Typical values of Δ/L were in the range 5 to 10 percent. In the vertical plane we find $\Delta = 0.627 \pm 0.210$ before the bump and $\Delta = 0.398 \pm 0.099$ after the bump. Typical values of Δ/L were in the range 8 to 12 percent. The beam is much wider in the vertical than the horizontal in the region where the IPM performs its measurement. As a result, the IPM has less lever arm in the vertical direction with which to measure the region outside the beam core, leading to larger errors on the measurement of Δ in the vertical plane. We conclude that the collimators reduce halo, but that a significant fraction of the effect must be due to scraping, since the effect before the bump is roughly half the size of the effect after the bump.

3 Simulation

We have developed Synergia, an accelerator modeling tool [3]. Synergia is a hybrid of IMPACT [4], which provides parallel computing and a fully three-dimensional space charge module, and mxyzptlk/beamline [5], which provides single-particle optics including higher-order maps. Synergia has passed several cross-checks, including comparison with analytic or semi-analytic equations and other simulations.

We have run simulations of the Booster using approximately one million particles. We used second-order maps for the single-particle optics and a $33 \times 33 \times 257$ grid for the space-charge calculations. In the simulation we follow a longitudinal slice corresponding to one period of the 400 MHz input beam. We use periodic boundary conditions to account for the effects of the rest of the beam. We use Synergia's capability to model multiple-turn injection where it is relevant.

We start by investigating halo formation. We use the kurtosis k,

$$k \equiv \frac{\left\langle (x - \langle x \rangle)^4 \right\rangle}{\left\langle (x - \langle x \rangle)^2 \right\rangle^2} - 3, \tag{4}$$

as a quantitative measure of halo formation. A Gaussian beam has $k = 0$.

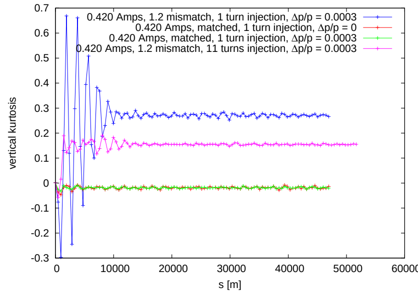

Fig. 2. Kurtosis in the vertical direction for four different simulation parameters.

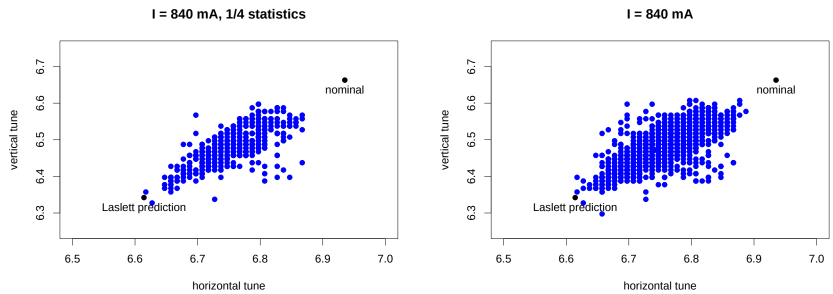

Fig. 3. Tune footprints using scatter plots. The plot on the right has four times the statistics of the plot on the left.

The beam we inject is Gaussian, so any deviation from $k = 0$ comes from the growth of halo. In Figure 2 we show the evolution of kurtosis in four different simulations. We find that a matched beam maintains zero kurtosis. A mismatched beam, however, quickly develops a positive kurtosis. In the case where we include multiple-turn injection, the effect is substantially reduced compared with the case where we inject the entire beam at the beginning of the simulation. Injecting in multiple turn results in an effective painting of the beam, reducing the space-charge effect.

We have also calculated the tune footprint for a beam of typical emittance of 3.05×10^{-6} m rad as a function of injected current for a Gaussian beam. We compare the simulated tunes with the nominal tune, i.e., neglecting space charge, and the tune shift predicted by the Laslett formula for the tune shift of a Gaussian beam [6],

$$\Delta\nu = \frac{-Nr_0}{4\pi\beta^2\gamma^3\epsilon_{\mathrm{rms}}}. \tag{5}$$

We find that the extent of the tune footprint is at least roughly linear in the current, as indicated by Equation 5. For simplicity, we present results for only for a current of 840 mA, which is twice the typical operating current in the Booster. In Figure 3, we display the tune footprint using a simple scatter plot, as tune footprints are frequently shown in the literature. The scatter plot is a poor representation of the spread of the distribution of tunes; two

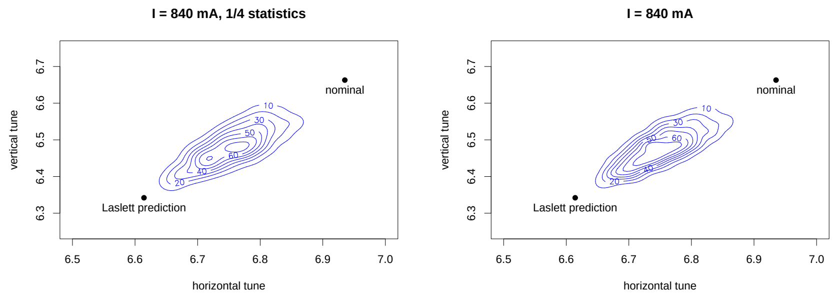

Fig. 4. Tune footprints using contour plots. The plot on the right has four times the statistics of the plot on the left.

plots differing only in statistics look quite different. In Figure 4, we show the same result, only this time we have used a contour plot to represent the tune distribution. The contour plot changes little when we vary the statistics, making it a much more accurate representation of the distribution. From this figure, we can see that the majority of the tune spread is confined to a region much smaller than suggested by the Laslett formula, which is really an upper bound.

4 Experiment and Simulation

We conclude by comparing an experiment directly with our simulation. We performed a study of the coherent tune in the Booster by measuring absorption versus beam intensity versus machine tune. We varied the tune by changing the current in some of the machine quadrupoles. By tracking the change in the position of the resonance and subtracting for the known tune shift due to the change in the quadrupoles, we can extract the tune shift due to space charge. In the simulation, we performed an FFT of the beam envelope to extract the coherent tune. Figure 5 displays our preliminary results. The simulation agrees quite well with the overall tune shift. More work will be required to compare the resonance widths with the simulation.

Acknowledgments

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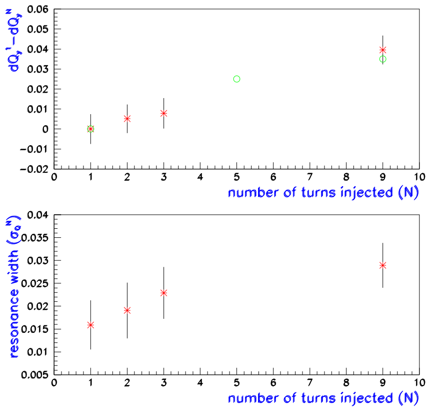

Fig. 5. Coherent tune shifts as a function of number of turns of beam injected. The red crosses with error bars are the measurement. The green circles are the results of the simulation.

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