FERMILAB-CONF-03-162-CD MAY 2003

SPACE CHARGE EXPERIMENTS AND SIMULATION IN THE FERMILAB BOOSTER *

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Abstract

We have studied space charge effects in the Fermilab Booster. Our studies include investigation of coherent and incoherent tune shifts and halo formation. We compare experimental results with simulations using the 3-D space charge package Synergia.

INTRODUCTION

The Fermilab Booster is an alternating gradient synchotron of radius 75.47 meters. It accelerates protons from 400 MeV to 8 GeV over the course of 20,000 turns. The optical lattice consists of 24 cells with four combined function magnets each, with horizontal and vertical tunes of 6.9 and 6.7, respectively. The injected beam from the Fermilab Linac has a typical peak current of 42 mA and an RF structure of 200 MHz. The beam is typically injected for ten Booster turns, for a total average current of 420 mA. Immediately after injection, the beam is allowed to debunch longitudinally, then is adiabatically captured at the initial Booster RF frequency of 37.8 MHz (harmonic number $h = 84$.) After capture, acceleration begins and the RF frequency ramps, reaching 52.8 MHz at extraction. The Booster cycles at 15 Hz. A detailed technical description of the Booster can be found in Ref. [1].

Since the Booster operates at high intensities and relatively low energies, space charge has a significant effect. In fact, space charge has long been considered responsible for the observed losses early in the Booster cycle[2]. In order to simulate the effects of space charge in the Booster, we have employed Synergia[3], an accelerator simulation package including fully three-dimensional space charge calculations.

Below, we describe three experimental studies of effects related to space charge performed in the Booster and compare with the results of Synergia simulations. In the first section, we describe a new technique for charactarizing beam shapes. In the second, we study the evolution of the horizontal beam width during the adiabatic capture phase. In the third and final section, we investigate the Booster beam space-charge tune shift.

* Work supported by the Scientific Discovery through Advanced Computing project, "Advanced Computing for 21st Century Accelerator Science and Technology," which is supported by the US DOE/SC Office of High Energy Physics and the Office of Advanced Scientific Computing Research.

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BEAM PROFILE ANALYSIS

The Booster Ion Profile Monitor[4] (IPM) is able to extract horizontal and vertical beam profiles on a turn-by-turn basis for an entire Booster cycle. The IPM utilizes an electric field to collect ions from ionization of the residual beam gas on micro-strip counters. Because the ions also see the electric field of the beam itself, a non-trivial calibration is required to relate the output of the IPM to the true beam shape. We performed such a calibration in Ref. [5], where, we developed a simulation of the IPM and compared the simulation results with independent measurements of the beam size. The end result is a tested, semi-phenomenological formula to extract the beam widths from IPM measurements. We use this formula in the following section on beam width evolution.

We can also use our simulation of the IPM to directly compare IPM measurements with simulated beam profiles. To do so, we model the Booster beam with Synergia and apply our IPM simulation to get the (simulated) raw IPM profiles. The resulting profiles can be directly compared to raw IPM measurements. We show one such result of the procecdure in Fig. 1.

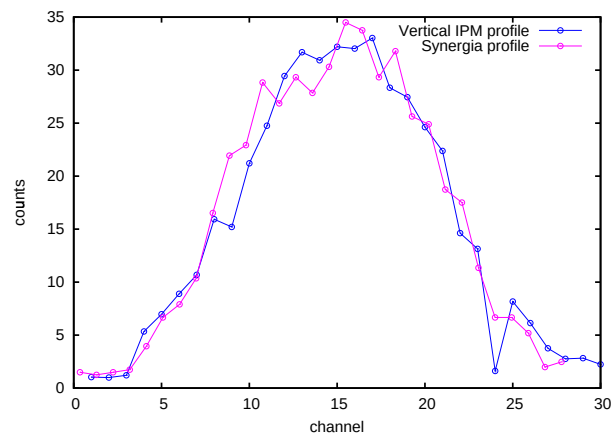

Figure 1: Horizontal IPM beam profile compared with Synergia simulation results passed through our IPM simulation.

In order to quantitatively describe overall beam shapes, we first fit the raw IPM data to the function

$$f(x) = g(x) + \ell(x), \tag{1}$$

where

$$g(x) \equiv N \exp\left[-\frac{(x - x_o)^2}{2\sigma^2}\right] \tag{2}$$

and

$$\ell(x) \equiv c_o + c_1 x. \tag{3}$$

The two components of $f(x)$ can be thought of as the Gaussian core $[g(x)]$ and non-Gaussian tails $[\ell(x)]$ of the beam distribution. Defining

$$L \equiv \int_{\text{detector}} \ell(x)dx \tag{4}$$

and

$$G \equiv \int_{\text{detector}} g(x)dx, \tag{5}$$

we can now characterize the beam shape by the ratio L/G. A perfectly Gaussian beam will have $L/G = 0$, whereas a beam with halo will have $L/G > 0$. In Fig. 2 we show a typical beam profile with the Gaussian and non-Gaussian portions highlighted.

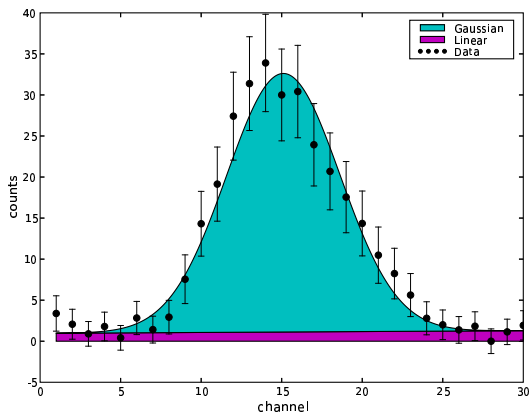

Figure 2: Fitted IPM profile showing Gaussian and linear (non-Gaussian) contributions in cyan and magenta, respectively.

In Fig. 3 we compare the distribution of L/G values over the early turns of a Booster cycle in the data with the results of a Synergia run combined with our IPM simulation. We find that we are able to reproduce the data very well.

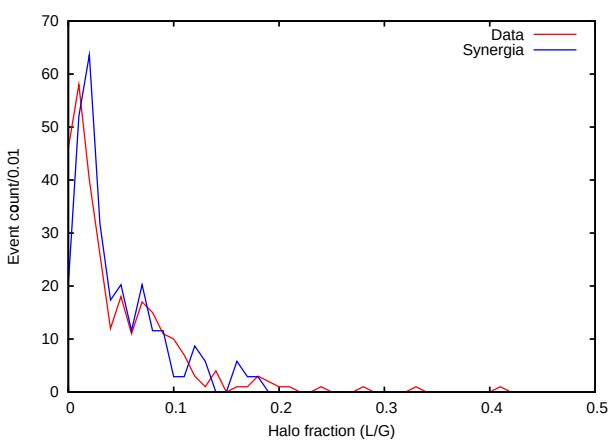

Figure 3: Distribution of L/G values near injection in a single Booster cycle, compared with the distribution of L/G values from a Synergia simulation.

As an application of the L/G technique, we have studied the effects of the Booster collimators on the beam shape. For this study we measured the average value of L/G for 500 turns early in the booster cycle. We repeated the measurement for several cycles and formed distributions from the results. Fig. 4 displays the results. Even though there is a great deal of spread in the data, the overall distributions clearly show that L/G is lower when the collimators are in the Booster. We conclude that the Booster collimators are effective in reducing beam halo and that L/G is a "good" quantitity to use to characterize beam shapes.

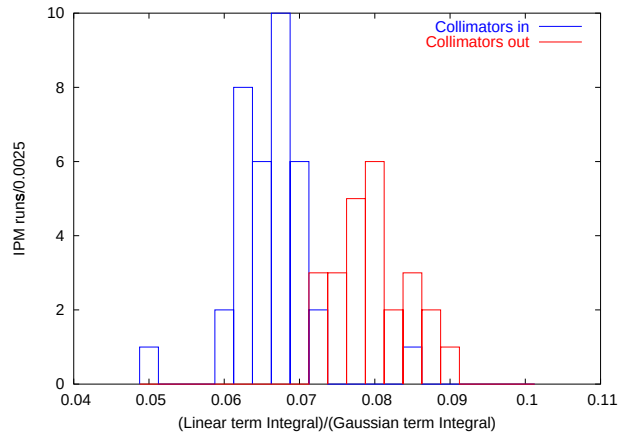

Figure 4: Distribution of L/G values in the Booster with and without collimators.

BEAM WIDTH EVOLUTION

We have designed and run a Synergia simulation of the injection and capture phases in the Booster. In the simulation, ten turns of beam are injected for a total average current of 420 mA. The beam is allowed to coast for 20 turns, during which time it debunches longitudinally. We then adiabatically capture the beam by ramping the relative phase of the RF cavities from paraphased mode to fully-bunching mode over the course of 200 turns. During the capture phase, there is tumbling in the longitudinal phase space. This tumbling can lead to horizontal emittance growth because of the longitudinal-horizontal coupling induced by dispersion.

In Fig. 5 we compare IPM measurements of the horizontal width with the results of the Synergia adiabatic capture simulation. The IPM measurements have been adjusted using the calibration in Ref. [5]. We find good agreement between the growth trend seen in the data and the grow seen in the simulation.

TUNE STUDY

Our final study extracts the coherent tune shift due to space charge. For this study we ran the Booster in coasting mode, i.e., without acceleration. We varied the horizontal

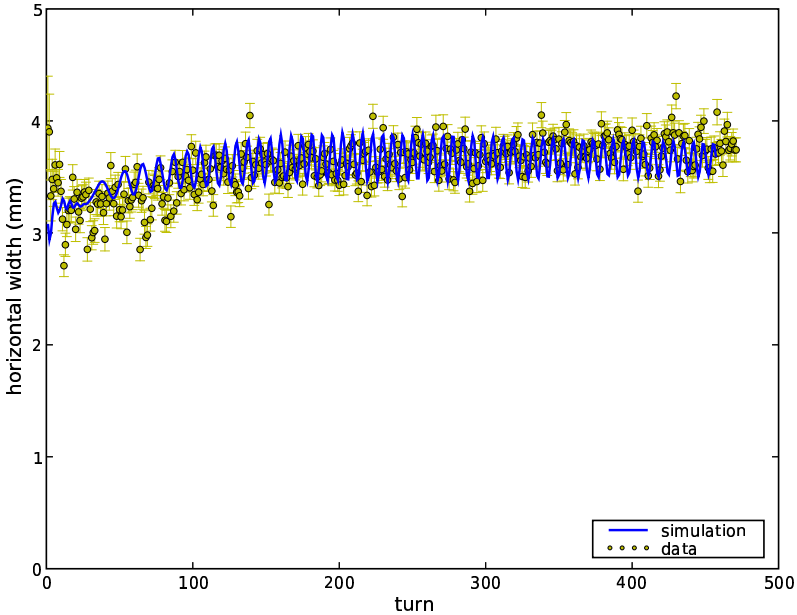

Figure 5: Evolution of horizontal beam size during injection and adiabatic capture in a Synergia simulation compared with IPM data.

and vertical tunes Q_x and Q_y by tuning the quadrupole correction magnets. We systematically covered half-integer tune differences in both directions in the Q_x, Q_y-plane. At the same time, we measured beam transmission over the course of roughly 1000 turns. Because transmission falls dramaticaly near a resonance, the transmission measurement allowed us to locate resonances and measure their widths in tune space. By following this procedure for several different beam currents and measuring the resulting shifts in resonance locations, we were able to extract the space-charge tune shift as a function of current.

In Fig. 6 we compare the results of our study with the results of a Synergia simulations. The comparison includes both the observed space-charge tune shifts and the widths of the resonances as measured by the transmission study. We find excellent agreement between the data and the simulation.

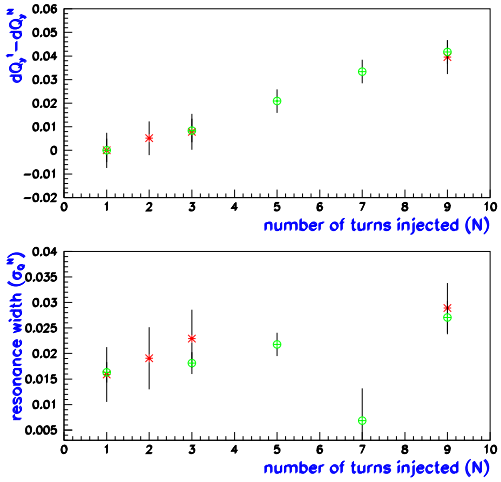

Figure 6: Extracted tune shifts and resonance widths as a function of current, measured in injection turns of 42 mA. The red crosses are experimental data and the green circles are the results of Synergia simulations.

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