

MEASUREMENTS AND SYNERGIA SIMULATIONS OF EMITTANCE DILUTION AT THE FERMILAB BOOSTER*

P. Spentzouris[†], J. Amundson, B. Pellico, Fermilab, PO Box 500, IL 60510, USA
D. McCarron, Illinois Institute of Technology, Chicago, IL 60616, USA

Abstract

We present a study of the beam evolution in the Fermilab Booster operating both under nominal conditions and in the vicinity of the half-integer, sum and difference resonances, for different beam currents. We simultaneously recorded the horizontal and vertical beam profiles using the Ion Profile Monitor (IPM) and beam current monitor. Our analysis extracted 2-D emittances and beam shape information from the IPM data. We compare the results with Synergia simulations including 3-D space charge and higher-order optics to analyze and interpret the experimental results.

THE SYNERGIA FRAMEWORK

Synergia [1, 2, 3] is a framework for state-of-the-art simulation of linear and circular accelerators with a fully three-dimensional (3D) treatment of space charge, and the capability to use arbitrary order maps for the single-particle optics modeling. The space-charge module utilizes parallel Particle In Cell (PIC) techniques, and has the choice of 2 Poisson solvers, one FFT and one multi-grid based. The FFT solver has its origins in the IMPACT FFT solver (see Ref. [1]) and is the one used in the simulations presented in this paper. Synergia has been ported both to commodity PC clusters (linux) with fast networking, and supercomputers. Depending on the system, space-charge simulations could utilize effectively up to 512 processors (see Ref. [1, 4]). The space-charge module has been benchmarked both against theory [1] and other codes and experiment [5].

Synergia2, the second version of the Synergia framework, was released in the beginning of 2006. Synergia2 is a fully Python-steered accelerator physics framework. Whereas Synergia used Python only for the user interface, Synergia2 creates actual Python programs, calling modules written in Fortran and C++ for the computationally intensive calculations. The use of Python greatly simplifies the process of adding new physical models to Synergia2. At the same time, the main loop has become almost arbitrarily flexible, allowing the user to create simulation logic with little effort. Some of the features of Synergia2 simulations relevant to this discussion are the ability to simulate multiple bunches and multi-turn injection, ramping magnets and rf, and modeling of active feedback. Synergia2 implements a variety of boundary conditions to the Poisson solver: open, closed (perfect conductor), periodic.

Synergia2 also takes advantage of the wide variety of existing physical and numerical software. In Fig. 1, we

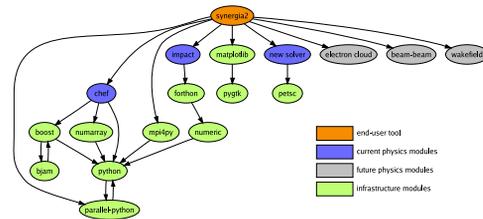


Figure 1: Synergia2 and its relationship to dependent software modules.

show the variety of modules incorporated in Synergia2.

EMITTANCE DILUTION AT THE FERMILAB BOOSTER

The Booster [6] is a rapid-cycling, 15 Hz, alternating gradient synchrotron with a radius of 75.47 meters. The lattice consists of 96 combined function magnets in 24 periods, with nominal horizontal and vertical tunes of 6.7 and 6.8 respectively. The Booster accelerates protons from a kinetic energy of 400 MeV to 8 GeV, at harmonic number $h = 84$, using 17 RF cavities with frequency slewing from 37.7 MHz at injection to 52.8 MHz at extraction. The nominal average current at injection is $\sim 30 - 35$ mA per injected turn. Typically, the injection process lasts for ten to fifteen Booster turns. The injected beam is a stream of bunches equally spaced at the linac RF frequency of 201.2 MHz. The Booster instrumentation consists of an Ionization Profile Monitor (IPM), a Beam Position Monitor (BPM) system, a Resistive Wall Monitor (RWM), beam current monitors, and loss monitors.

There are many factors affecting the behavior of the Booster beam, including the energy spread and emittance of the injected beam, nonlinear field errors and space-charge effects. The space-charge effects have long been believed to contribute significantly to the observed losses in the Booster during the first 2 ms of the cycle (the injection, capture, and bunching phases). The authors of a recent study [7], proposed that the observed losses and vertical emittance increase at high current are due to a combination to proximity to the $\nu_x + \nu_y = N$ sum resonance, skewed quadrupole errors, and space-charge. In this section we study how these affect the beam (beam size and beam losses) using experimental data and Synergia. Synergia has been used successfully to model the Booster at normal operating conditions, especially the emittance growth as measured by the IPM (Ref. [1, 4]).

* Work partially supported by SciDAC under DOE/SC HEP and ASCR

[†] spentz@fnal.gov

Experimental Data

The purpose of our experiment was to study the properties of the Booster beam (beam size and losses) close to the $\nu_x + \nu_y = N$ sum resonance. For this purpose, we changed the tune of the machine to $\nu_x = 6.24$, $\nu_y = 6.75$ using the corrector quadrupoles. We then collected IPM and beam current versus turn data for five and ten turns injected in the machine, and different settings of the skewed quadrupoles. The skewed quadrupole settings were at the nominal operation values, skewed quadrupole setting 1 which corresponded to an increase of ~ 0.3 Amps for all circuits, and skewed quadrupole setting 2, which was a decrease of ~ 0.3 Amps for all circuits (corresponding to a difference in field of $\sim 2 \times 10^{-3} m^{-1}$). The tunes were measured using the BPMs (Fig. 2) with only one turn injected in the machine, to avoid space-charge effects.

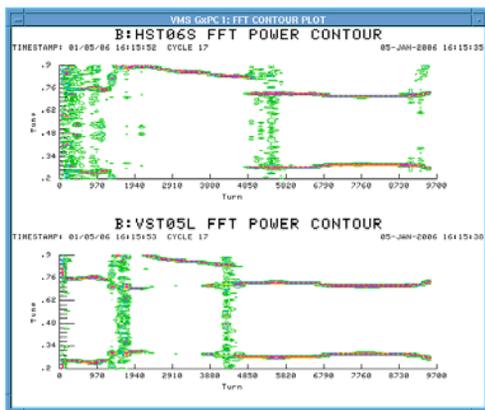


Figure 2: Horizontal and vertical Booster tunes versus turn, extracted using a BPM signal. The tunes are kept constant to the desired values for the first 2000 turns in the machine.

The Booster performance under nominal operational conditions (tunes at 6.7 and 6.8) is shown in Fig. 3. The data was collected just before the tunes were changed to the resonant condition, to avoid systematic effects in our comparisons. There is a small emittance (beam size) blow-up close to injection; Losses are on the order of few percent. The data shown are for ten injected turns, the five turn injection data are not shown for space considerations, but show the same general characteristics, with a few percent higher injection efficiency.

The beam characteristics are very different when the tunes are at 6.24 and 6.75. The vertical beam width grows very fast between turn 500 and 1000, accompanied by high losses. After that, the remaining beam reaches equilibrium and the size and current remain constant. In Fig. 4 we show the measurements for 10 turns of injection and in Fig. 5 for 5 injected turns, both for skewed quad setting 1. It is clear that the amount of beam current affects the beam characteristics: with higher current the resonant behavior appears earlier (at turn 500 versus turn 650), the vertical size grows faster and to a larger size (30% larger), and the losses are proportionally higher (25% of the beam survives with 10

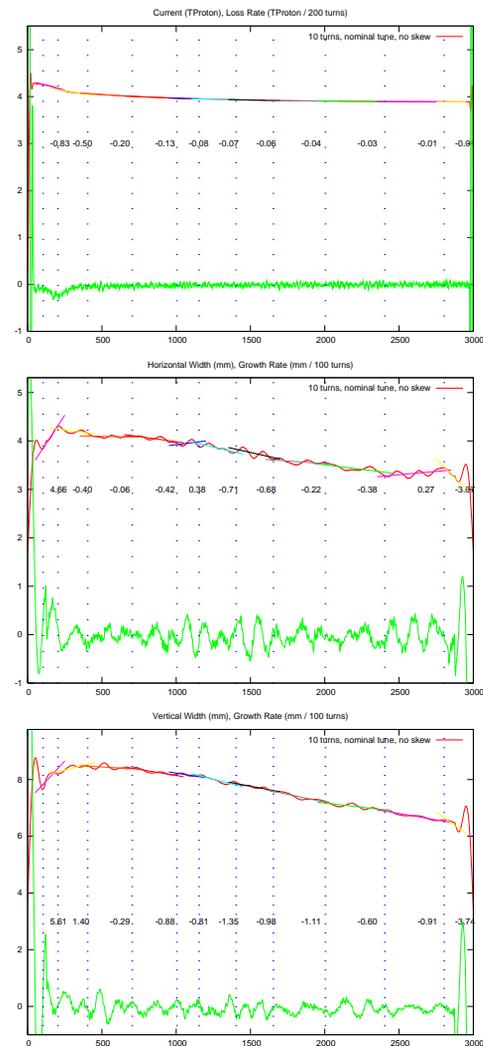


Figure 3: 10 turn injection. Beam charge (top) in units of $1E12$ protons, horizontal width (middle) in mm, and vertical width (bottom) in mm, versus turn number. The data were taken with nominal tune. Each plot shows 2 curves, the data (smoothed with a low pass filter), and the first derivative.

turns injected, 50% with 5 turns injected). The different skewed quad settings affected how early the resonance appeared, and the difference between low and high current data. Skewed quad setting 1 showed the most difference between 5 and 10 turn injection: 30% in size increase, versus 15% for skewed quad setting 2. (The difference in increase is calculated from the maximum size of the vertical beam width for 5 and 10 turns injection. The 30% number for skewed quad setting 1 can be extracted from the values in Fig. 4 and 5). In all cases, the vertical beam width and the surviving beam current converge to the same value: ~ 5 mm width and ~ 100 mA current. In addition, the horizontal beam width is monotonically decreasing between turns 300 and 1000, much faster than the adiabatic damping due to acceleration, indicating possible emittance exchange be-

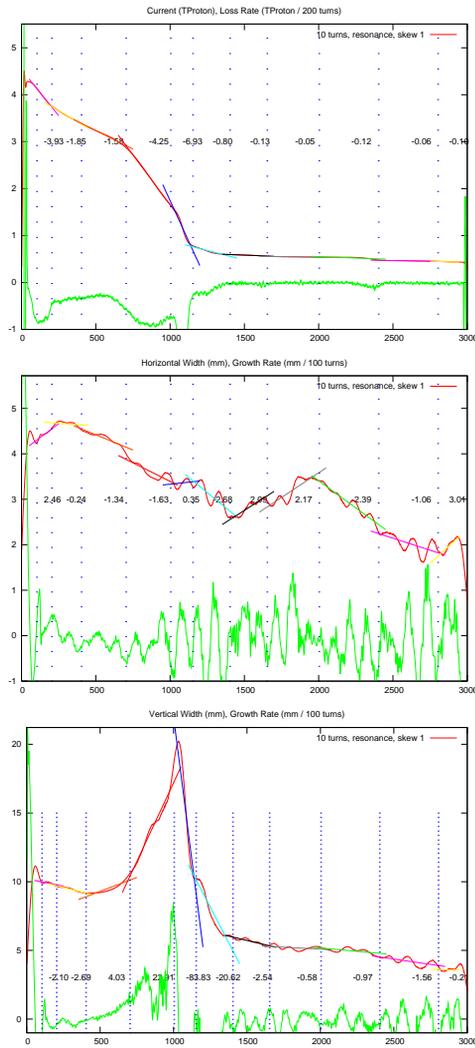


Figure 4: 10 turn injection. Beam current (top) in units of $1E12$ protons, horizontal width (middle) in mm, and vertical width (bottom) in mm, versus turn number. The data were taken with tunes at 6.24 and 6.75, for skewed quad setting 1. Each plot shows 2 curves, the data (smoothed with a low pass filter), and the first derivative.

tween the two planes (the slope of the horizontal width versus turn curve in Fig. 4 is two times steeper than the same slope for nominal running, shown in Fig. 3).

The beam widths shown in Fig. 3-5 are all obtained by fitting calibrated IPM data according to the procedure in Ref. [8].

Synergia simulations

We performed Synergia simulations using a lattice tuned at 6.24 and 6.75 and a mismatched beam, similar to the experimental conditions (the input beam was matched to the nominal lattice, and the input transverse and horizontal widths set to the widths measured by the IPM in a Gaussian distribution). We assumed that the nominal skewed

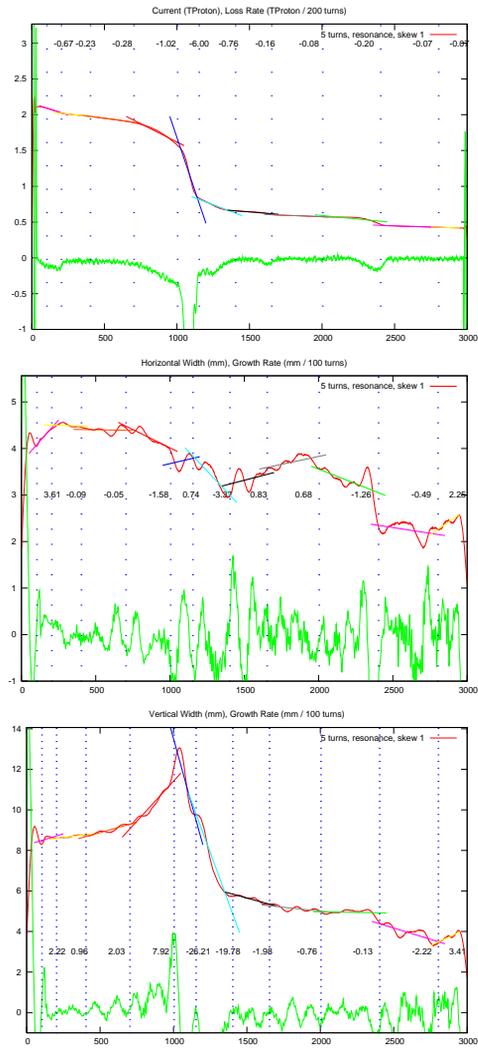


Figure 5: 5 turn injection. Beam current (top) in units of $1E12$ protons, horizontal width (middle) in mm, and vertical width (bottom) in mm, versus turn number. The data were taken with tunes at 6.24 and 6.75, for skewed quad setting 1. Each plot shows 2 curves, the data (smoothed with a low pass filter), and the first derivative.

quadrupole settings cancel existing coupling due to rolls in the real machine, thus in our simulations the skewed quad settings were ± 0.3 Amps for settings 1 and 2. The simulations used 5M macroparticles distributed on a $33 \times 33 \times 257$ grid.

The simulated beam characteristics show qualitative agreement with the experimental results in the vertical width blow up and the losses. Fig. 6 shows that the vertical beam width grows to a maximum value at about 1000 turns, faster for 10 turn injection than for 5 turn injection. This maximum value is smaller than in the data, and the difference in the maximum value for 10 and 5 turns of injection is 15% versus 30% in the data, for the “same” skewed quad setting (“same” means the value for the skewed quad current in the simulation is set to the difference of the skewed

quad setting from the nominal in the data, as discussed above). We tried both systematic and random skewed quadrupole errors; the qualitative picture remains the same in either case. The oscillatory behavior shown in the simulated vertical width (“thick” lines in Fig. 6) is anticorrelated with the exact behavior in the horizontal width, indicating emittance exchange. Fig. 7 shows the beam transmission in

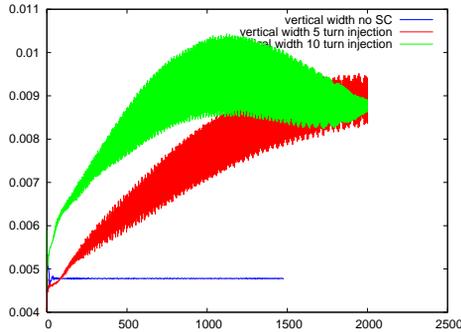


Figure 6: Synergia simulation vertical width versus turn for 5 (red curve) and 10 (green curve) injected turns, with skewed quad error corresponding to setting 1, and with no error and space charge effects turned off (blue curve).

the simulation: although the losses are not the same in magnitude as in the data (30% compared to 70%), the losses occur faster in the 10 turn injection case. It will be very hard to match the exact loss magnitude since in the simulation we use a nominal average aperture for the accelerator, while in the actual machine, location dependent restrictions due to misalignments, etc, make the aperture position dependent.

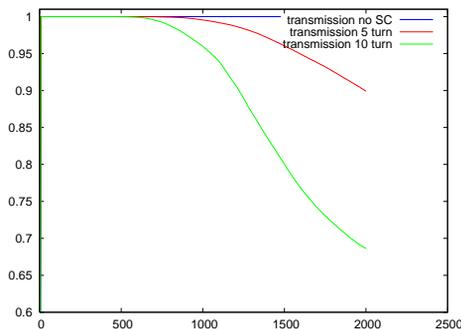


Figure 7: Synergia simulation transmission versus turn number for 5 (red curve) and 10 (green curve) injected turns, with skewed quad error corresponding to setting 1, and with no error and space charge effects turned off (blue curve).

Interpretation of data and simulation results

Both the data and the simulation show that increased beam current in the machine maximizes the observed effect of high beam loss and beam blow-up. This trend could be interpreted as evidence that the sum resonance is not the

culprit of the beam behavior. Since we are approaching the resonance from below, the space charge tune depression is moving us away from the resonance, thus we should see a reduced effect. We used the simulation to study the phase

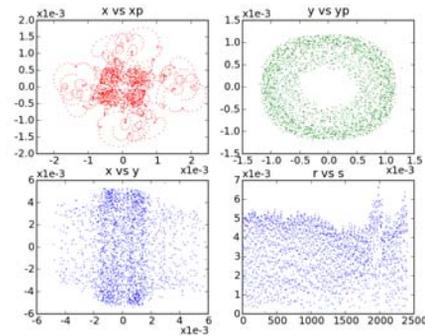


Figure 8: Horizontal (top left) and vertical (top right) phase space trajectories of a typical particle which starts at the beam core (within 1σ of the initial phase space distribution) and is lost due to large amplitude. The vertical versus horizontal position and radius versus turn number plots are shown at the bottom left and bottom right respectively.

space trajectories of particles that were lost in about 1000 turns and were generated at the core of the beam. Such a typical trajectory is shown in Fig. 8. The coupling between the two planes is evident, as is the 4th order resonance characteristics of the trajectory. In Fig. 9 we plot the sum of the vertical and horizontal particle tunes for an ensemble of the simulated particles together with the difference of two times the vertical minus two times the horizontal tune. This is done for the case of 10 turn injection. It is clear that with the space charge tune depression, our data sits on the $2\nu_y - 2\nu_x = 1$ resonance. To conclude our preliminary in-

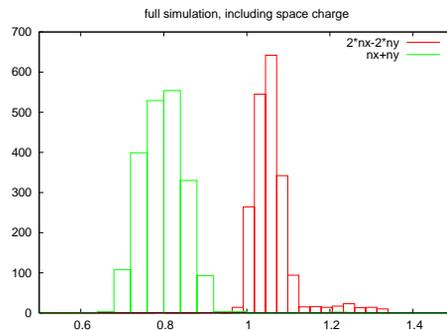


Figure 9: Histogram of individual particle tunes: sum of horizontal and vertical (green) and two times the horizontal minus two times the vertical (red).

vestigation, we consider the possibility of overlapping the half integer stop band. In previous studies with coasting beam we measured both the tune depression versus charge and the half integer stop band width, by scanning the vertical and horizontal tune space for different injected number

of turns [4]. The results of these studies are summarized in Fig. 10, where both the measurements, and Synergia simulations of the experiment are shown. The simulation matches the experiment very well. In Fig. 11 we show a

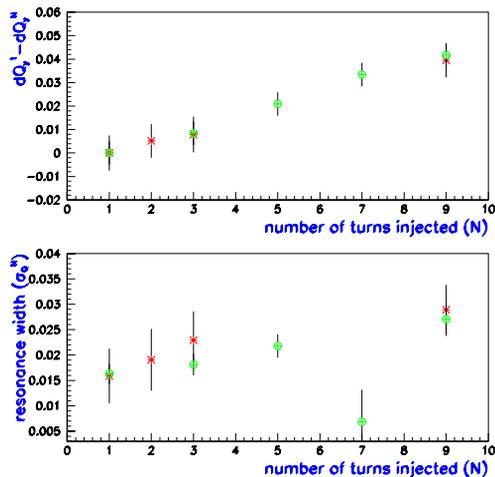


Figure 10: Measured (red) and simulated (green) space charge tune depression using the vertical plane half integer resonance (top), and resonance width (bottom) versus number of injected turns.

normalized histogram (the area is equal to 1) of the particle tunes from the 10 turn injection simulation run, and a plot of the half integer stop band extracted from the data shown at the bottom plot of Fig. 10. The resonance width for a current of 10 injected turns was found by linear extrapolation of the data, and the stop band was represented as a normalized Gaussian with σ equal to that width. There is a significant amount of overlap between the the particle tune distribution and the stop band. The data shown in Fig. 10

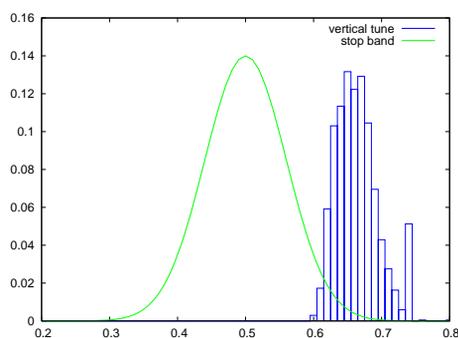


Figure 11: Vertical plane half integer resonance measured stop band (green curve) and individual particle vertical tunes from the Synergia simulation (blue curve).

clearly shows that the half integer stop band increases as a function of beam current. A similar behavior could be possible for the resonance stop band. If the potential stop band increase is of the same order of magnitude as the space charge tune shift, then the observed beam behavior could be still due mostly to the sum resonance.

Summary and outlook

Both data and simulation show that running the FNAL Booster with vertical and horizontal tunes of 6.24 and 6.75 results in high beam loss and vertical beam width blow-up. Increasing the beam current in the machine maximizes the observed effect. Different settings of the skewed quadrupoles change the rate of the observed effect. Both data and simulation show evidence for emittance exchange, and the simulation clearly indicates that the fourth order difference resonance $2\nu_y - 2\nu_x = 1$ is important, as is the half integer resonance. This last result also uses earlier measurements of the half integer stop band width as a function of beam current. If the sum resonance stop band width is less than ~ 0.2 (the space charge tune shift) then our results cannot be described by the sum resonance. On the other hand, if we postulate a strong dependence of the sum resonance width to beam current this could still be possible. This is a result of the experimental observation that the effect is greater when there is more beam current. If the stop band of the sum resonance is narrower than the space charge tune depression then the sum resonance cannot be the dominant effect. We are in the process of performing more simulation studies and re-analyzing the coasting beam experimental data to clarify the dominant effect.

REFERENCES

- [1] J. Amundson, P. Spentzouris, R. Ryne and J. Qiang, Journal of Computational Physics, Volume 211, Issue 1, 1 January 2006, Pages 229-248.
- [2] "Overview of the synergia 3-D multi-particle dynamics modeling framework." P. Spentzouris, J.F. Amundson, D.R. Dechow. FERMILAB-CONF-05-163-CD, PAC-2005-TPAT060, May 2005. 3pp. Published in *Knoxville 2005, Particle Accelerator Conference* 3490
- [3] "Synergia: An advanced object-oriented framework for beam dynamics simulation. D.R. Dechow, P. Stoltz, J.F. Amundson, P. Spentzouris. PAC-2005-TPAT026, May 2005. 3pp. Published in *Knoxville 2005, Particle Accelerator Conference* 1925
- [4] "EMITTANCE DILUTION AND HALO CREATION DURING THE FIRST MILLISECONDS AFTER INJECTION AT THE FERMILAB BOOSTER." Panagiotis Spentzouris, J. Amundson. FERMILAB-CONF-05-407-CD, 2005. 5pp. Published in AIP Conf.Proc.773:127-131,2005.
- [5] "Benchmarking of simulation codes based on the Montague resonance in the CERN proton synchrotron." I. Hofmann et al. PAC-2005-MOPC003, May 2005. 3pp. Published in *Knoxville 2005, Particle Accelerator Conference* 330
- [6] "Booster Synchrotron." ed E L Hubbard Fermi National Accelerator Laboratory Technical Memo TM-405, 1973.
- [7] X.Huang, et al. Phys.Rev.ST Accel.Beams 9, 014202 (2006).
- [8] J. Amundson et al, Phys.Rev.ST Accel.Beams 6, 102801 (2003).