

# Simulation of the Fermilab Booster using Synergia

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**Abstract.** High precision modeling of space-charge effects is essential for designing future accelerators as well as optimizing the performance of existing machines. Synergia is a high-fidelity parallel beam dynamics simulation package with fully three dimensional space-charge capabilities and a higher-order optics implementation. We describe the Synergia framework, developed under the auspices of the DOE SciDAC program, and present Synergia simulations of the Fermilab Booster accelerator and comparisons with experiment. Our studies include investigation of coherent and incoherent tune shifts and halo formation.

## 1. Introduction

### 1.1. The Synergia Framework

Synergia [1] 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. It is designed to be a general-purpose tool with an interface that is accessible to accelerator physicists who are not experts in simulation and computing techniques. Synergia was developed as part of the DOE SciDAC “Accelerator Science and Technology” project.

Space-charge calculations are computationally intensive, typically requiring the use of parallel computers. The implementation of Synergia utilizes Particle-In-Cell (PIC) techniques and is fully parallel, including the particle tracking and space-charge modules. The code itself is a hybrid system using components of the IMPACT [2] space-charge code and the *mxzptlk/beamline* linear optics libraries [3], which include a MAD parser. Synergia includes enhancements to these codes as well as new modules. The space-charge module uses the path length along the reference trajectory,  $s$ , as the independent variable and implements a variety of different boundary conditions. In addition to the FFT based Poisson solver from IMPACT, a prototype multi-grid solver which utilizes the PETSc [4] libraries is also available. Synergia has multi-turn injection capabilities and can follow multiple bunches longitudinally. The Synergia model has been benchmarked by comparing to other codes [5] and to semi-analytic calculations [1].

The user-level interface to Synergia consists of a set of Python classes that wrap the low-level interfaces to the various packages used. The Python interface generates an input file that is read by the simulation itself. The Python interpreter need not be present at run time. The Python interface can even generate a job to be automatically transferred and submitted to a remote machine where no Python interpreter is available. Synergia also includes a build system that allows it to be compiled and run on various platforms without requiring the user to modify the code and/or build system.

### 1.2. Performance

For high precision 3D simulations, large numbers of macroparticles, on the order of  $10^{6-7}$ , and fine space-charge grids, of typical size  $33 \times 33 \times 257$ , are required. In order to obtain the necessary computing power for such simulations, we have ported our code to different parallel machines, including commodity PC clusters, as well as specialized parallel computers. A detailed discussion of the performance of the Synergia code for FNAL Booster modeling can be found in [1]. The performance depends on an interplay of networking speed, latency, and processing speed. For our Booster simulations, peak performance of  $\sim 100$  Booster turns per hour is obtained running on 512 processors on the NERSC supercomputer.

## 2. Fermilab Booster Simulations

The Fermilab 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 6.9 and 6.7, respectively. The Booster accelerates protons from a kinetic energy of 400 MeV to 8 GeV, using 17 rf cavities with frequency that slews from 37.8 MHz at injection to 52.8 MHz at extraction. Typically, the injection process lasts for ten Booster turns, resulting in a total average current of 420 mA. The injected beam is a stream of bunches equally spaced at the linac RF frequency of 201.2 MHz.

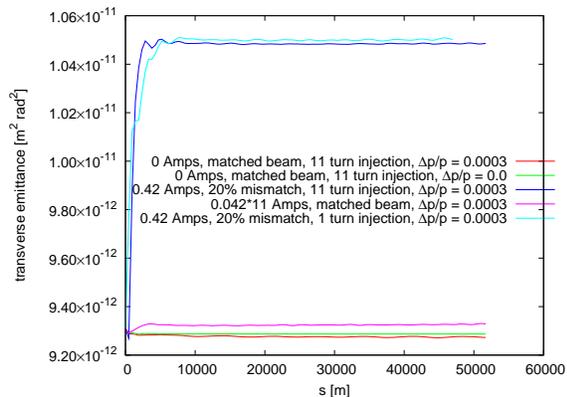
In this section we study how space-charge affects the Booster beam during the first 500 turns of the cycle (injection, capture, and bunching). For the simulations we use an idealized Booster lattice without any non-linear elements, but we do employ second order maps and a beam with realistic energy spread.

### 2.1. Emittance dilution

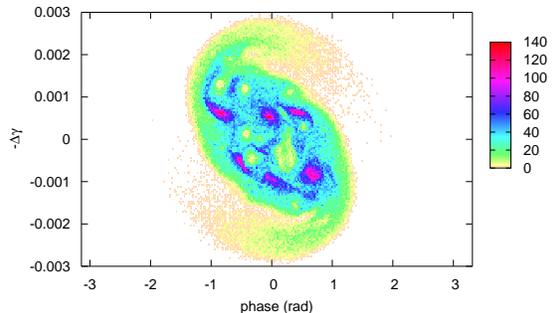
First we investigate how space-charge affects the emittance of the Booster without including rf. In Fig. 1 we plot the normalized 4-D transverse emittance<sup>1</sup> for five different initial beam conditions: matched beam without space-charge and with and without a momentum spread of 0.0003, beam of 0.420 Amps total current and momentum spread of 0.0003, matched and mismatched. Multi-turn injection of 11 turns was used in all cases, except one (see figure). As expected, in the cases where the beam was matched there is no emittance growth. (Our matching procedure takes into account space-charge effects on the second moments of the beam). In the mismatched cases, with a 20% mismatch, we observe a 12% increase of the beam emittance during the first 10 to 15 turns after injection. The effect is a combination of chromatic and space-charge effects and is very similar for both the single- and multi-turn injection cases. The total current is the same, 0.420 Amps, in both cases. The emittance growth can be related to the conversion of beam free energy from mismatch oscillations into thermal energy of the beam, due to the effect of the non-linear space-charge forces [7]. With a mismatch parameter of 1.2, as in the case of our simulation, the free energy model predicts a 4-D transverse emittance growth of 13%, in good agreement with the Synergia result.

Including rf in the simulation increases the space-charge effects through bunching and introduces a stronger coupling between the horizontal (bending) and the longitudinal planes. The simulation of a typical Booster cycle consists of 10 injection turns (linac beam with 200 MHz structure), followed by 20 turns of debunching (no rf), then 200 turns of capture. In the capture process, cavity pairs start paraphased and are brought linearly in phase. In Fig. 2 we show a longitudinal phase-space slice,  $2\pi$  wide in the 37.8 Mhz rf phase, after the capture process. The bunch is “s-shaped”, due to space charge and it maintains some structure (uneven density) due to the “folding” of the injected linac bunches. Fig. 3 shows the effects of the rf on the normalized 4-D transverse emittance: the emittance growth is  $\sim 2.5$  times larger (30% versus 12%) than in

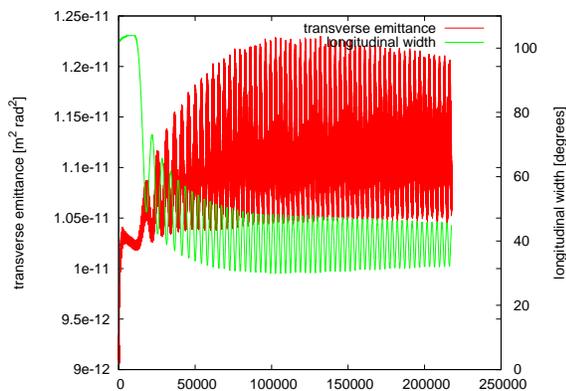
<sup>1</sup> Defined as the square root of the determinant of the covariance matrix of the transverse phase space.



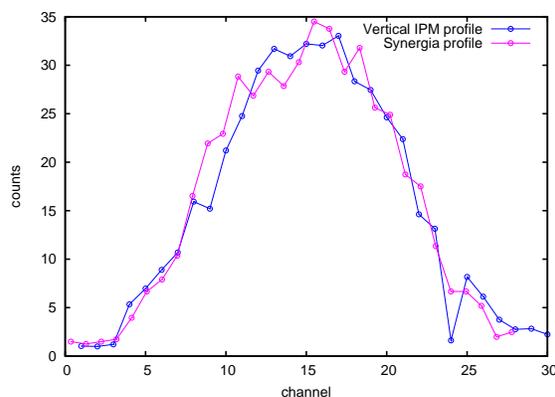
**Figure 1.** Normalized 4-D transverse emittance in  $m^2 rad^2$  for different initial conditions.



**Figure 2.** Longitudinal phase-space after 385 turns.



**Figure 3.** Normalized 4-D transverse emittance ( $m^2 rad^2$ ) and longitudinal beam width (degrees), versus  $s$ .



**Figure 4.** Horizontal IPM beam profile compared with Synergia simulation results passed through our IPM simulation.

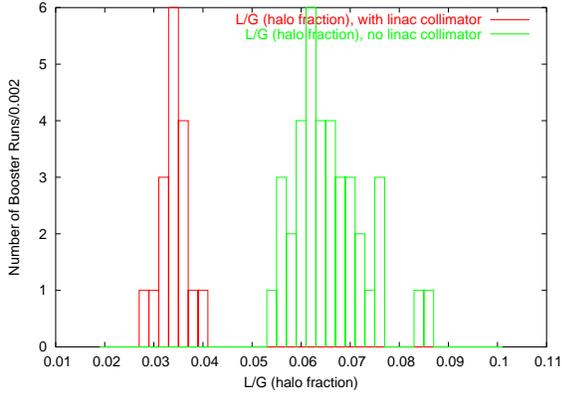
the case with no rf. In addition the emittance varies, following the variation of the longitudinal beam width, due to the correlation between longitudinal and horizontal phase-space planes.

## 2.2. Beam profile analysis

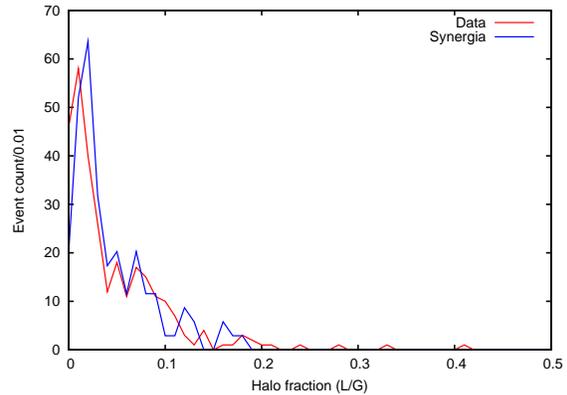
The Booster Ionization Profile Monitor[8] (IPM) is able to extract horizontal and vertical beam profiles on a turn-by-turn basis for an entire Booster cycle. The IPM utilizes an electric field to collect ions from ionization of the residual beam gas on micro-strip counters. Because the ions also see 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. [9], 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 apply our IPM simulation to results from Synergia to get (simulated) raw IPM profiles. The resulting profiles can be directly compared to raw IPM measurements. We show one such result of the procedure in Fig. 4; the agreement is very good.

In order to quantitatively describe overall beam shapes, we first fit the raw IPM data to the function  $f(x) = g(x) + \ell(x)$ , where  $g(x) \equiv N \exp\left[-\frac{(x-x_o)^2}{2\sigma^2}\right]$  and  $\ell(x) \equiv c_o + c_1x$ . 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  $L \equiv \int_{\text{detector}} \ell(x)dx$  and  $G \equiv \int_{\text{detector}} g(x)dx$ , 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 order to verify this technique, we examined the effects of collimating the injected beam on  $L/G$ . For this study we measured the average value of  $L/G$  for the first 500 turns in the booster cycle. We repeated the measurement for several cycles with and without collimating the injected (linac) beam. Fig. 5 displays the results. The overall distributions clearly show that  $L/G$  is lower when the collimators are in the linac (thus the injected beam is expected to have smaller tails). We conclude that  $L/G$  is a good measure of the size of beam halo.



**Figure 5.** Distribution of  $L/G$  values in the Booster with and without linac collimators.

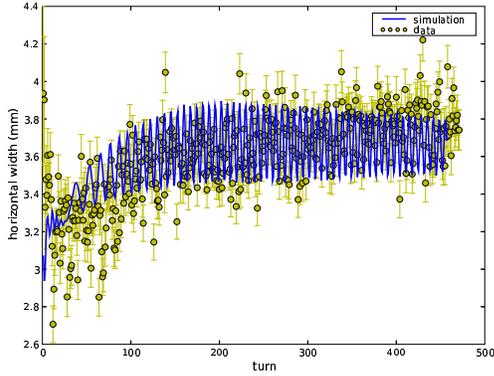


**Figure 6.** Distribution of  $L/G$  values near injection in a single Booster cycle, compared with the distribution of  $L/G$  values from a Synergia simulation

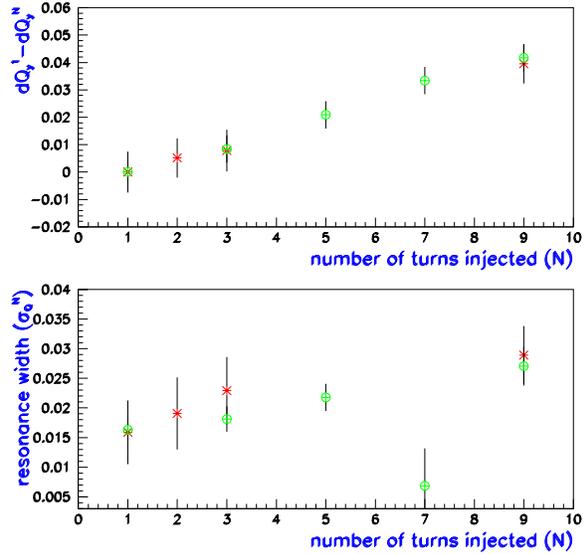
In Fig. 6 we compare the distribution of  $L/G$  values over the early turns of a Booster cycle in the data with the results of a Synergia run combined with our IPM simulation. In Fig. 7 we compare IPM measurements of the horizontal width with the results of the Synergia adiabatic capture simulation (see previous section). The IPM measurements have been adjusted using the calibration in Ref. [9]. We find that we are able to reproduce the data very well, both on the size of the non-Gaussian tails and the beam width as a function of turn.

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 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 dramatically near a resonance, the transmission measurement allowed us to locate resonances and 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 coherent space-charge tune shift as a function of current. In Fig. 8 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.

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**Figure 7.** Evolution of horizontal beam size (mm) versus turn number during injection and adiabatic capture in a Synergia simulation compared with IPM data.



**Figure 8.** 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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