ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPMA019

SIMULATION OF THE FERMILAB RECYCLER FOR LOSSES AND COLLIMATION*

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Abstract

Fermilab has recently completed an upgrade to the complex with the goal of delivering 700 kW of beam power as 120 GeV protons to the NuMI target. A major part of boosting beam power is to shorten the beam cycle by accumulating up to 12 bunches of 0.5×10^{11} protons in the Recycler ring through slip-stacking during the Main Injector ramp. This introduces much higher intensities into the Recycler than it has had before. Meeting radiation safety requirements with high intensity operations requires understanding the effects of space charge induced tune spreads and resulting halo formation, and aperture restrictions in the real machine to develop a collimation strategy. We report on initial simulations of slip-stacking in the Recycler performed with Synergia.

INTRODUCTION

Fermilab has recently completed an upgrade to the complex [1] with the goal of delivering 700 kW of beam power as 120 GeV protons to the NuMI target. Possible methods for increasing beam power are increasing the intensity of individual bunches and move beam bunches through the accelerator chain at a faster rate. Since we are already producing bunches close to the intensity limit that we can transport, we will be reducing the cycle time from 2.2 s to 1.33 s. Previously, the Main Injector combined one set of six booster batches each containing 80 beam bunches were combined with an additional set of six batches using the slip-stacking [2] procedure at 8 GeV. The resulting set of batches were then accelerated to 120 GeV for extraction to the NuMI target. Both the accumulation/slip-stacking and the ramping are time consuming operations. We will instead perform the accumulation and slip-stacking in the Recycler ring while the Main Injector performs its ramp.

The Recycler [3] is a permanent magnet based proton storage ring originally constructed to accumulate antiprotons during the Tevatron Run II era. As such it was not anticipated that it would have experience significant space charge problems. Injecting high intensity proton bunches now introduces space charge tune shifts causing possible resonance excitation, halo production and resulting particle loss. The slip-stacking procedure is inherently messy as it involves the transport of bunches at different mimatched momenta in the ring while at the same time the chromaticity has to be kept at large negative values to suppress a head-tail instability. To understand the dynamics of the machine and develop a plan for collimation and halo reduction we have initiated a campaign of simulation of the Recycler dynamics including the slip-stacking and true locations and sizes of machine apertures with the Fermilab developed beam dynamics code Synergia [4, 5].

* Work supported by U.S. Department of Energy contract DE-AC02-07CH11359

SYNERGIA

Synergia is developed and maintained at Fermilab by the Accelerator Simulations group within the Scientific Computing Division to provide detailed high fidelity simulations of particle accelerators or storage rings specializing in space charge and wakefield collective effects. Synergia is a Particle-in-Cell (PIC) based code that tracks macro-particles through the lumped elements of the accelerator. Synergia simulates the usual single particle optics from produced by magnetic elements as well as RF cavities. Space charge and impedance kicks are applied at locations around the ring using the split-operator method. So that realistic particle losses can be simulated, apertures may be associated with each element. The Synergia aperture model includes rectangular and elliptical apertures of arbitrary size and transverse offset as well as arbitrary user defined polygonal apertures. To achieve statistically meaningful results in a reasonable time, Synergia has been designed from the beginning to take advantage of multiprocessing systems such as Linux clusters and supercomputers.

RECYCLER SIMULATION MACHINE MODEL

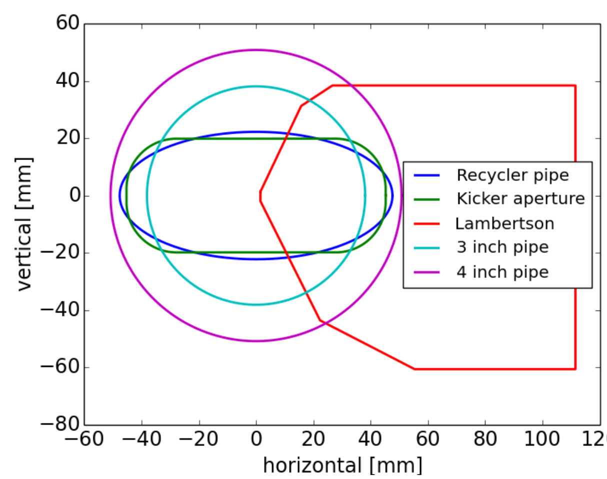

Figure 1: Apertures in the Recycler.

The Recycler machine lattice is described by a MAD file [6, 7] incorporating the measured multipoles for the magnet body and shim correctors. Synergia reads and interprets the same MAD description. The lattice functions for the Recycler calculated by Synergia are identical to those calculated by MAD. The apertures in the recycler are: 3" diameter pipe,

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4" diameter pipe, Recycler elliptical pipe (3.75×1.75 in full width), a rounded rectangular kicker (90.5×79.4 mm) and an irregular Lambertson magnet as shown in Fig. 1. The important parameters for the Recycler slip-stacking simulation are shown in Table 1.

Table 1: Recycler Machine Parameters for the Slip-Stacking Simulation

Parameter	Value
Length	3319.418 m
Momentum	8.835 GeV/c
Charge/bunch	0.5×10^{11} e
Bunch σ_h	1.0 mm
Bunch σ_v	2.0 mm
Normalized 95% transverse emittance	15 mm-mrad
Longitudinal emittance	0.8 eVs
Q_h	0.4205
Q_v	0.4318
RF voltage/cavity	90 kV
Harmonic number	588
Central RF frequency	52.8 MHz
Slip factor	-0.00871
Slip bunch momentum difference	24 MeV

The main feature that allows slip-stacking is two RF cavities tuned to different frequencies. One RF cavity is tuned to the main frequency of the ring and one cavity is tuned to a frequency 1260 Hz lower corresponding to a momentum reduced by 24 GeV/c. A bunch at the lower momentum will slip longitudinally with respect to a bunch at the design momentum. The particular momentum difference is set so that the bunch will slip longitudinally exactly 1/7 of the Recycler circumference during one booster cycle. To mimic the slippage of 80 bunch booster batches through each other, a single RF bucket length was simulated with periodic longitudinal boundary conditions. Particles in the lower momentum bunch that slip out of the bucket on one end of the bucket re-enter on the opposite side as if they were part of a neighboring bucket.

The space charge calculation was performed with 131072 macro-particles per bunch. The slip-stacking simulation followed two bunches with charges of 0.5×10^{11} e for 215 turns in the Recycler, corresponding to three bunch crossings. The longitudinal phase space of the bunches appears to be essentially the same after the first bunch crossing. For instance, the tail develops on the gaussian bunch during the first turn and remains for the subsequent turns. At each turn, the state of all the particles in both bunches was saved. The turn-by-turn tune for each macro-particle was determined using the average phase advance method [8] and used to plot a tune footprint. The longitudinal phase space tune footprint when the bunches are near maximum separation is shown in Fig. 2. The same plots when the bunches areclose to total overlap is shown in Fig. 3.

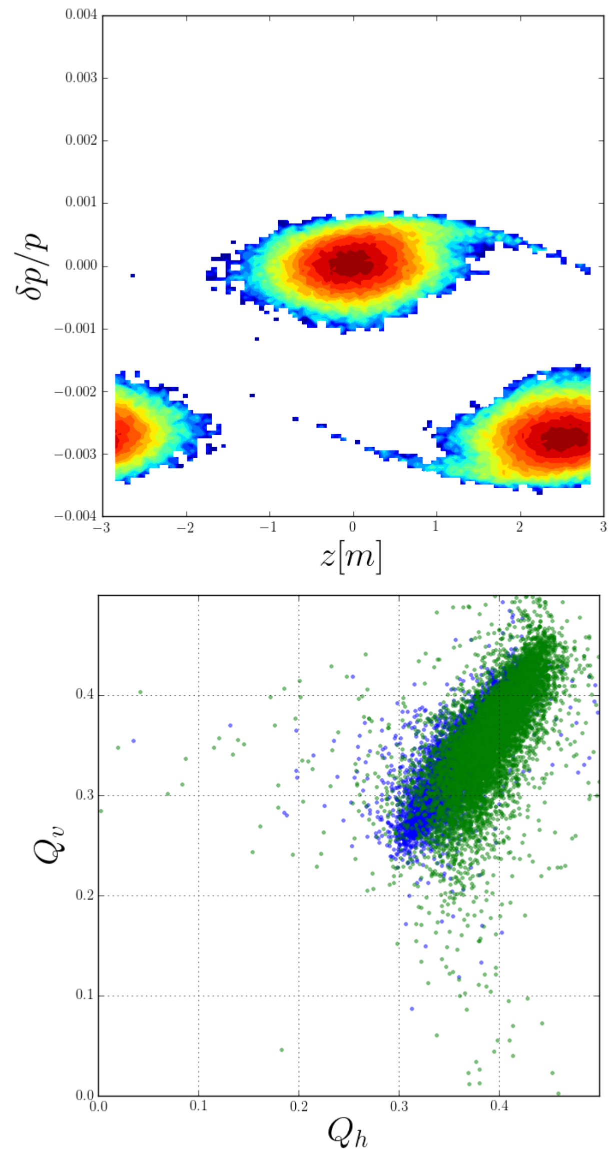

Figure 2: Upper: longitudinal phase space of two bunches close to maximum separation. Lower: tune footprint of the upper momentum (blue) and lower momentum (green) bunches. The lower momentum bunch is slipping to the right.

As expected, the tune spread during full overlap is larger than when the bunches are separated.

INITIAL COLLIMATION

The Recycler operating with high intensity protons will require the design and implementation a collimation system to localize beam losses from halo. Unfortunately there is limited space in the tunnel for equipment. As a first step in collimation studies, we simulated a vertical edge restriction located 3.5σ from the beam center in a candidate location implemented in Synergia as a displaced rectangular hole. The fraction of particles remaining as a function of turn with the restriction is shown in Fig. 4. After 1000 turns,

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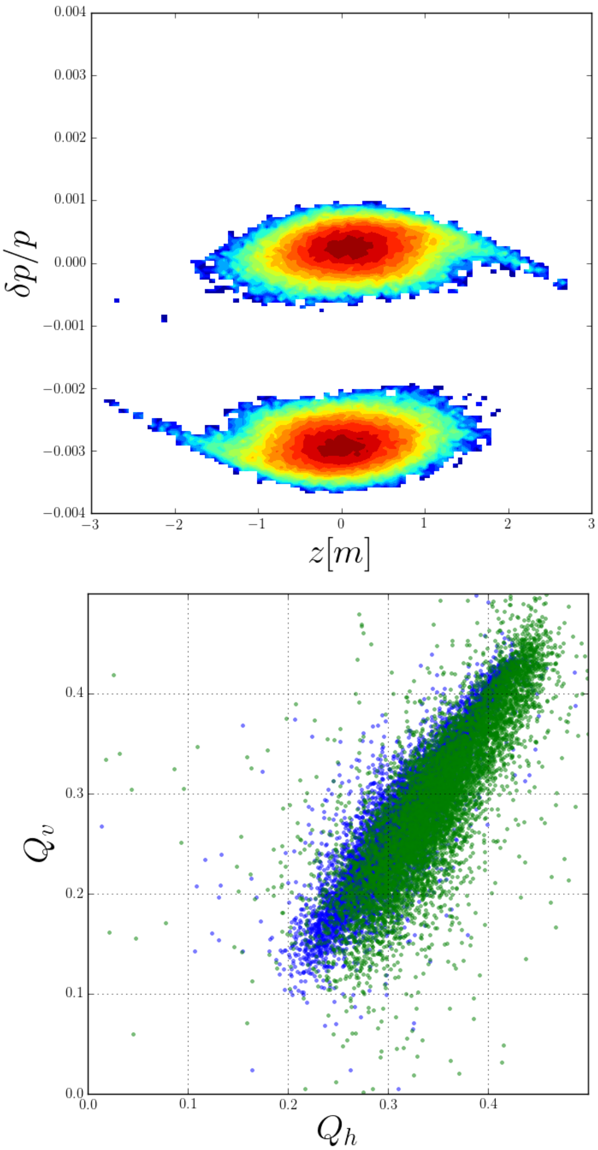

Figure 3: Upper: longitudinal phase space of two bunches close to full spatial overlap. Lower: tune footprint of the upper momentum (blue) and lower momentum (green) bunches.

0.6% of the particles are lost In Fig. 5, we show the initial horizontal distribution (red) and the distribution after 1000 turns. We see that the vertical restriction results in sufficient limits in the horizontal direction to make the single vertical restriction a viable option for the first collimation step.

CONCLUSION

We have demonstrated the simulation of slip-stacking in the Fermilab Recycler with space charge and a viable option for a primary collimator.

ACKNOWLEDGMENT

We thank the staff in the Fermilab Main Injector Department for many helpful discussions and the Fermilab HPC department. Synergia development is partially supported through the ComPASS project funded by the SciDAC program of the U.S. Department of Energy. An award of computer time was provided by the Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program. This research used resources of the Argonne Leadership Computing Facility, which is a DOE Office of Science User Facility supported under Contract DE-AC02-06CH11357.

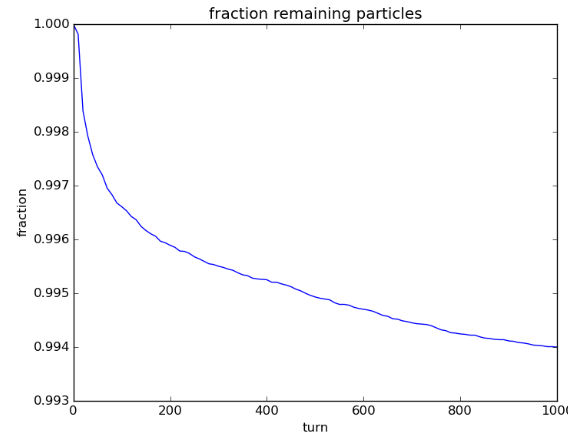

Figure 4: Fraction of particles remaining as a function of turn with vertical edge restriction.

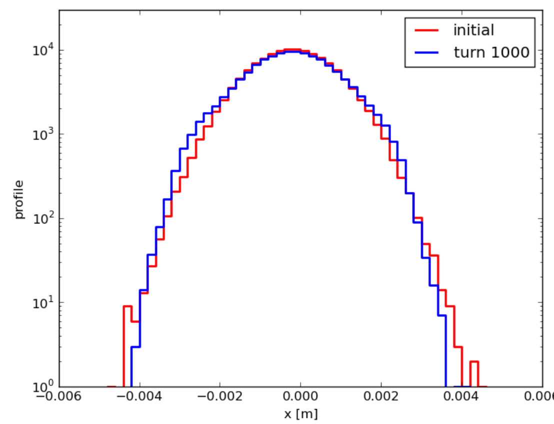

Figure 5: Effect of the vertical restriction on the horizontal particle distribution. The initial horizontal particle distribution is shown in red, and after 1000 turns is shown in blue.

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