SIMULATING BATCH-ON-BATCH SLIP-STACKING IN THE FERMILAB RECYCLER USING A NEW MULTIPLE INTERACTING BUNCH CAPABILITY IN SYNERGIA

J. F. Amundson*, E. G. Stern, Q. Lu, R. Ainsworth, Fermilab, Batavia, Illinois

Abstract

The Recycler is an 8 GeV/c proton storage ring at Fermilab. To achieve the 700 MW beam power goals for the NOvA neutrino oscillation experiment, the Recycler accumulates 12 batches of 80 bunch trains from the Booster using slip-stacking. One set of bunch trains are injected into the ring and decelerated, then a second set is injected at the nominal momentum. The trains slip past each other longitudinally due to their momenta difference. We have recently extended the multi-bunch portion of the Synergia beam simulation program to allow co-propagation of bunch trains at different momenta. In doing so, we have expanded the applicability of the massively parallel multi-bunch physics portion of Synergia to include new categories of bunch-bunch interactions. We describe the new batch-batch capability in Synergia and present preliminary results from our first application of these capabilities to batch–on-batch slip stacking in the Recycler.

INTRODUCTION

The Fermilab accelerator complex is currently being reconfigured and upgraded to meet the needs of the U.S. high-energy physics research community as defined by the Particle Physics Project Prioritization Panel (P5) report of 2014 [1]. Several steps are being taken to to increase the delivered intensity from the complex. The step we study in this work is slip-stacking in the Fermilab Recycler.

THE FERMILAB RECYCLER AND SLIP-STACKING

The Recycler is a 3.3 km long permanent magnet storage ring. Being based on permanent magnets, it has only a limited energy acceptance, but it can be used to accumulate protons, through the slip-stacking procedure, during which the Recycler will receive six *batches* of 80 *bunches* each from the Fermilab Booster at its central momentum. These batches will be decelerated to a lower momentum by detuning one of two RF cavities in the Recycler. Because the batches are lower in momentum than the design momentum, their position in the ring will slip backwards relative to bunches at the design momentum. Six more batches will then be injected at the design momentum. As the batches at different momenta slip through each other, they will interact with their near neighbors through the space-charge effect. At the moment when the two sets of six batches slip into alignment they can be considered to be six double-strength batches instead of twelve single-strength batches. At that time, they will be extracted from the Recycler and injected into the Main Injector where higher voltage RF cavities will merge and combine the different momentum bunches. See Figure 1.

Since the slip-stacking in the Recycler involves low energies and high intensities, space charge effects are of particular concern. They are also quite complex – during slip-stacking the lead bunch in Batch A passes through/near each bunch in Batch B. The second bunch in Batch similarly interacts with all but one bunch from Batch B, and so forth. By the time the two batches are combined into a new, high-intensity batch, each bunch will have a history different from every other bunch. Simulating this procedure requires significant computing resources, particularly massively parallel computing resources.

SYNERGIA

The simulation package for this work is Synergia [2, 3], an accelerator simulation framework designed to scale from desktop computer to massively parallel supercomputers. Synergia supports fully symplectic particle tracking through linear and non-linear lattice elements with arbitrary apertures. It specializes in combining single-particle tracking with a variety of collective effects for the simulation of intensity-dependent physics.

The currently released version of Synergia supports the calculation of space charge and wakefield effects in both single bunches and a train of bunches (*i.e.,* a batch.) Collective effects are incorporated in Synergia simulations using the split-operator method [4]. In general, the Hamiltonian describing the beam dynamics can be separated into single-particle and collective pieces,

$$\mathcal{H} = \mathcal{H}_{single} + \mathcal{H}_{collective}.$$

The time evolution mapping for a time step τ can be approximated:

$$\mathcal{M}(\tau) = \mathcal{M}_{single}\left(\frac{\tau}{2}\right)\mathcal{M}_{collective}(\tau)\mathcal{M}_{single}\left(\frac{\tau}{2}\right)+O(\tau^3).$$

Thus the beam propagation is reduced to simulating a series of time steps. The step length τ should be chosen small enough to ensure the convergence of the results.

Single-bunch simulations

Single-bunch simulations are at the core of Synergia. A bunch of particles is evolved through the successive application of single-particle and collective operators. The single-particle operators are applied to each particle in the bunch individually, while the collective operators operate on the

---

[*] amundson@fnal.gov

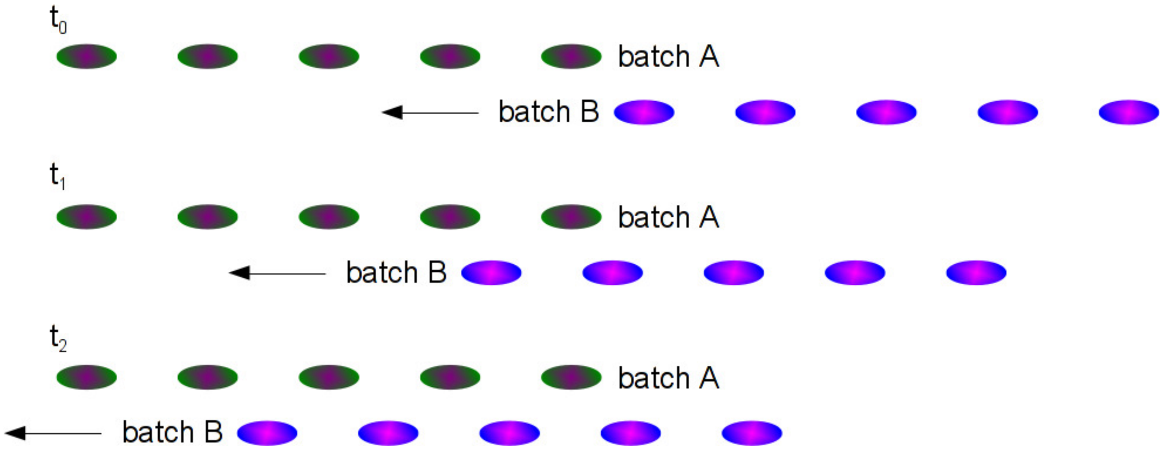

Figure 1: Slip stacking of two batches. Recycler batches consist of 80 bunches; only five bunches are shown for simplicity. Batch B is injected first, then decelerated. Batch A is then injected and kept at the design momentum. Batch B is allowed to slip relative to batch A until the two batches are aligned.

bunch as a whole. Synergia currently has single-bunch collective operators corresponding to space charge in a variety of approximations from simple analytical (Bassetti-Erskine) approximations to fully self-consistent three-dimensional approaches. Synergia also contains models for wakefields within the bunch for arbitrary external structures [5, 6].

Multiple-bunch Simulations

Synergia has the unique capability to perform multiple-bunch simulations. The multi-bunch model consists of potentially many bunches, each centered around its own reference particle. The bunches are assumed to stay at (nearly) steady separation, but the separations themselves do not have to be even, allowing for the incorporation of gaps. The single particle operators behave in the same way as for single bunches. The collective operators, however, can operate on individual bunches or one the entire set of bunches (batch) at once. The most common application of multiple-bunch simulations in Synergia involve space charge calculations for each individual bunch combined with wakefield calculations between bunches. We have demonstrated that Synergia simulations of multiple bunches can scale to use entire supercomputers. Figure 2 shows excellent scaling behavior of a multiple-bunch Synergia simulation up to 131,072 cores.

Two-batch Simulations

The single- and multiple-bunch capabilities of Synergia are sufficient to simulate a wide variety of accelerator scenarios. We have even found it possible to simulate a simplified version of slip-stacking using the single-bunch model with two sets of particles at different momenta combined with periodic longitudinal boundary conditions. See Figure 3.

In order to model the full bunch-to-bunch variation in the slip-stacking process, we have extended Synergia to include two-batch simulations. The single-particle portion of the two-batch model is a trivial extension of the single-particle portion of the other models in Synergia; each batch is treated as a separate multi-bunch simulation. The collective effects are more involved however. The two batches are not assumed to maintain constant separation. This makes space charge calculations much more involved. In our model, the primary batch determines the domain for the space calculation through the location of its bunches. The overlap of the secondary batch is then superimposed on the domain and the space charge effects are calculated. The overlap changed dynamically throughout the simulation. Care must be taken to avoid space charge models that assume a "typical" longitudinal profile because any such assumptions will certainly be violated during portions of the slip-stacking process.

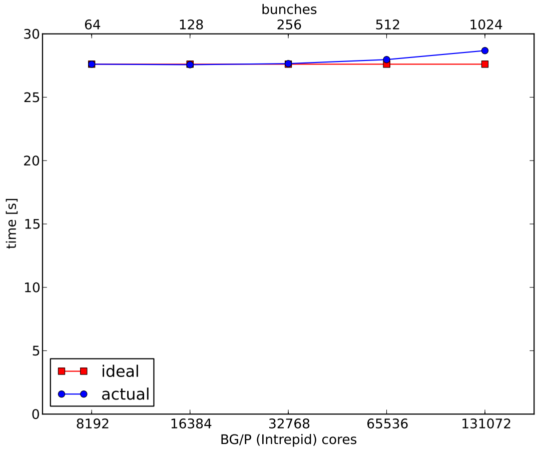

Figure 2: Weak scaling results for a multiple-bunch space charge problem on a BlueGene/P system (Intrepid).

PRELIMINARY RESULTS

We have implemented the two-batch model in Synergia and demonstrated its use in a simple two-on-two scenario. See Figure 4. Unfortunately, this simulation does not yet include space charge. We expect similar results with space charge to be available soon.

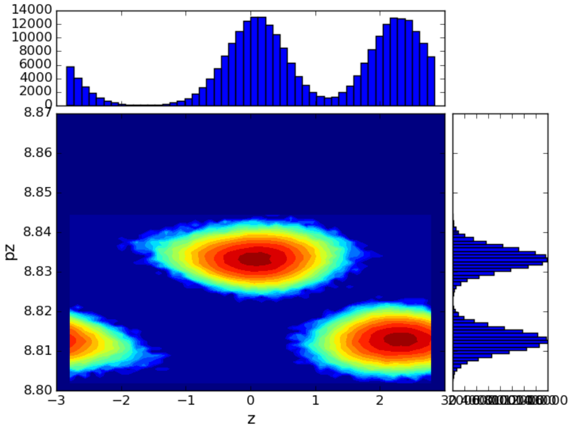

Figure 3: Longitudinal phase space of slipping bunches in a simplified model with two bunches and periodic boundary conditions.

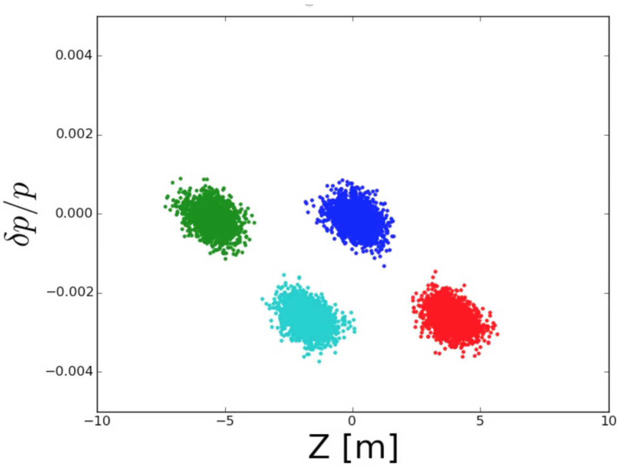

Figure 4: Two batches of two bunches each during slip-stacking.

FUTURE WORK

We have obtained a grant for 50 million core-hours on the Mira BlueGene/Q supercomputer at the Argonne Leadership Computing Facility to perform the full 80-bunch-on-80-bunch simulation slip-stacking in the Fermilab Recycler. We expect results within six months.

The addition of two-batch capabilities in Synergia opens up the several possibilities for modeling other collective effects. By treating one batch as a stationary set of electrons, we could incorporate electron cloud effects in Synergia. By treating the second batch as another beam, we could model beam-beam effects. Both types of simulations are part of the long-term goals for Synergia.

ACKNOWLEDGEMENTS

This work was performed at Fermilab, operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy. Synergia development is partially supported through the ComPASS project, funded through the Scientific Discovery through Advanced Computing program in the DOE Office of High Energy Physics. An award of computer time was provided by the ASCR Leadership Computing Challenge (ALCC) program [7]. 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.

REFERENCES

[1] “Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context,” report of the Particle Physics Project Prioritization Panel, `http://usparticlephysics.org/p5/`

[2] Amundson J, Spentzouris P, Qiang J and Ryne R 2006, *J. Comp. Phys.*, vol. 211, pp. 229–248.

[3] `https://cdcvs.fnal.gov/redmine/projects/synergia2`

[4] H. Yoshida, *Phys. Lett. A*, vol. 150, p. 262 1990.

[5] A. Macridin, P. Spentzouris, J. Amundson, L. Spentzouris and D. McCarron, *Phys. Rev. ST Accel. Beams*, vol. 14, p. 061003, 2011.

[6] A. Macridin, P. Spentzouris, and J. Amundson, *Phys. Rev. ST Accel. Beams*, vol. 16, p. 121001, 2013.

[7] `http://science.energy.gov/ascr/facilities/accessing-ascr-facilities/alcc/`