Advanced Computations of Multi-physics, Multi-scale Effects in Beam Dynamics

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Abstract. Current state-of-the-art beam dynamics simulations include multiple physical effects and multiple physical length and/or time scales. We present recent developments in Synergia2, an accelerator modeling framework designed for multi-physics, multi-scale simulations. We summarize recent several recent results in multi-physics beam dynamics, including simulations of three Fermilab accelerators: the Tevatron, the Main Injector and the Debuncher.

1. Introduction

Early accelerator simulations focused on single-particle dynamics. To a first approximation, the forces on the particles in an accelerator beam are dominated by the external fields due to magnets, RF cavities, etc., so the single-particle dynamics are the leading physical effects. Detailed simulations of accelerators must include collective effects such as the space-charge repulsion of the beam particles, the effects of wake fields in the beam pipe walls and beam-beam interactions in colliders. These simulations require the sort of massively parallel computers that have only become available in recent times.

We give an overview of the accelerator framework Synergia2[1], which was designed to take advantage of the capabilities of modern computational resources and enable simulations of multiple physical effects. We also summarize some recent results utilizing Synergia2 and BeamBeam3d[2], a tool specialized for beam-beam simulations.

2. Overview of Synergia2

Synergia2 is a framework for combining modules for the simulation of individual physical effects into a unified system capable of multi-physics simulations. Figure 1 shows an overview of Synergia2, including current components (non-linear dynamics, space charge, resistive wall) as well as components that are currently under development (electron-cloud) and planned to be integrated (beam-beam). It is a ultimate goal of the Synergia project to include multiple implementations of each component, so that optimal choices may be tailored for each individual simulation.

Synergia2 is also designed for computations on massively parallel machines. Figure 2 shows strong-scaling results for space charge calculation of a single bunch utilizing a $64 \times 64 \times 1024$ grid and 200M particles. Scaling for multiple-bunch problems is expected to extend to another two orders of magnitude in number of cores; multiple-bunch work is underway.

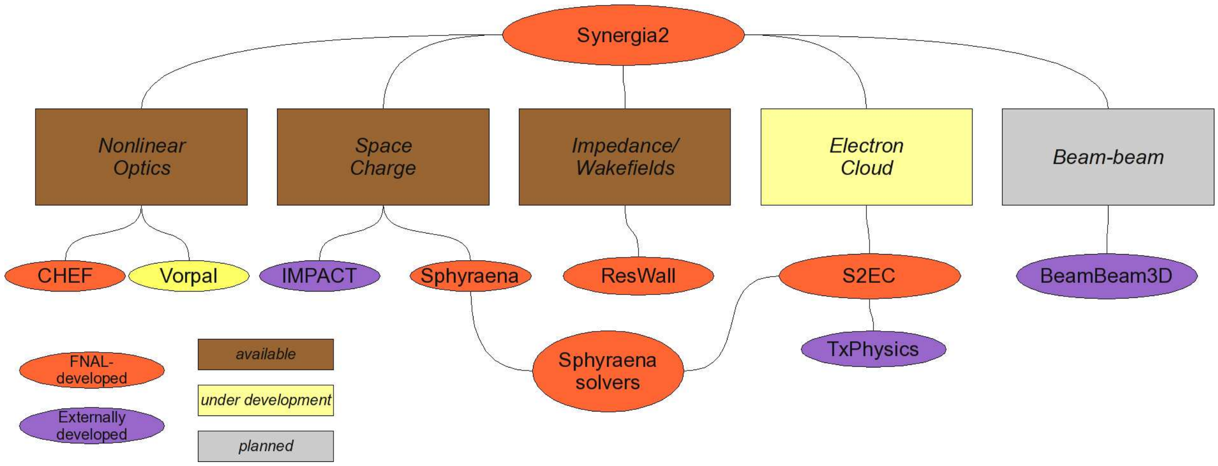

Figure 1. Overview of Synergia2.

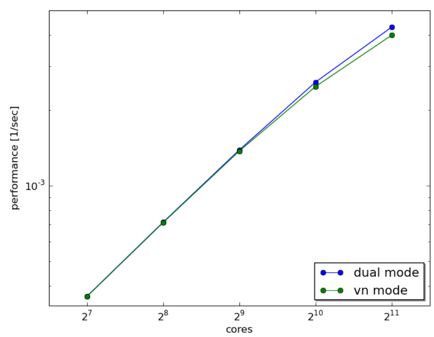

Figure 2. Parallel scaling results on ALCF's Surveyor BlueGene/P machine. The two curves were produced using two computational cores per processor (dual mode) and four computational cores per processor (vn mode), respectively.

3. Resistive wall module

The newest addition to Synergia2 is the resistive wall module. It simulates the effect of the current induced by the beam in the surrounding pipe. The current implementation contains a simple dipole approximation for resistive-wall wakefields in the thick wall limit [3]

$$\frac{\Delta\vec{p}_\perp}{p} = \frac{2}{\pi b^3}\sqrt{\frac{c}{\sigma}}\frac{N_i<\vec{r}_i>}{\beta\gamma}\frac{L}{\sqrt{z_i}} = W_0 L <\vec{r}> . \qquad (1)$$

Extensions to higher-order multipoles and thin walls are straightforward and underway. The module was originally developed as an extension to BeamBeam3d, where it was extensively benchmarked against analytical models of resistive wall effects[4]. The module as included in Synergia2 is capable of modeling resistive wall effects within a single bunch as well as bunch-to-bunch effects.

4. Poisson solver development

Poisson solvers are used in multiple contexts in beam simulations. They are required for the calculation of space charge effects, electron cloud effects and beam-beam interactions. The most recent extension of the Poisson solver suite in Synergia2 is the inclusion of a solver for elliptical boundary conditions. Elliptical boundary conditions are required for detailed simulations of accelerators with elliptical pipes; the Fermilab Main Injector is one such machine. Figure 3

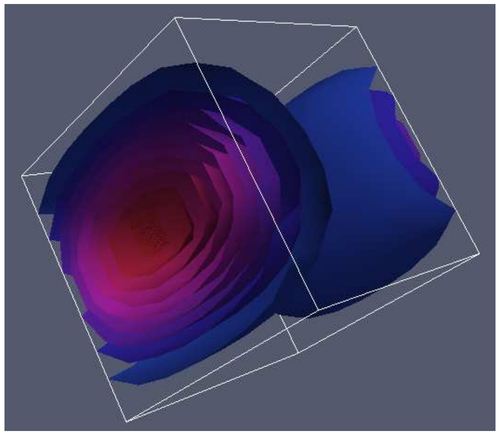

Figure 3. Test field solution using the Sphyraena elliptical solver.

shows the output of the Synergia2 elliptical solver for a test problem.

5. Beam-beam and resistive wall effects in the Fermilab Tevatron

Our first recent beam dynamics application is simulation of the Fermilab Tevatron. A detailed understanding of the behavior of the Tevatron requires the simulation of the interaction of the beams with each other (beam-beam) as well as the interaction between the beams and the currents they induce in the beam pipe (resistive wall.) These simulations are described in detail in Ref. [4].

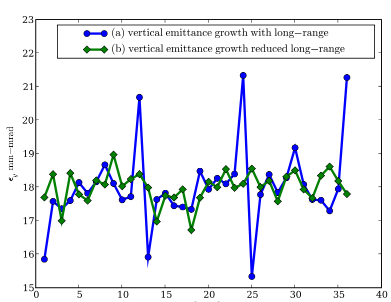

Figure 4. Simulations of beam-beam and resistive wall interactions in the Tevatron.

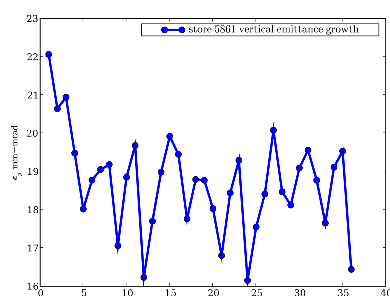

Figure 5. Experimental measurements in the Tevatron showing the same pattern as the simulations.

One of the main successes of Ref. [4] is the correlation between the simulation results shown in Figure 4 and the experimental results shown in Figure 5.

6. Space charge and resistive wall effects in the Fermilab Main Injector

The first application of the new resistive wall module in Synergia2 has been for simulations of the the Fermilab Main Injector[5]. The resistive wall instability in the Main Injector was discovered many years ago; an active damping system is required to keep the machine stable.

Future Synergia2 simulations will include a model of the full damping system. The injection energy of the Main Injector is 8 GeV. This low energy, coupled with the high intensity, makes space charge an important effect in addition to the resistive wall effect. Synergia2 is able to effectively combine simulations of these effects.

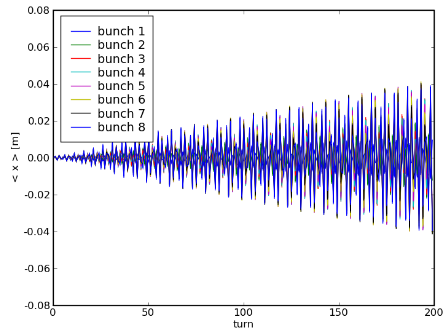

Figure 6. Resistive wall instability and space charge modeled with eight coupled bunches in Fermilab's Main Injector.

7. Space charge and non-linear optics in the Fermilab Debuncher

A current topic of simulation for Synergia2 is the beam for the proposed Mu2e experiment at Fermilab. The Mu2e project will require running the Fermilab debuncher at intensities 10^5 times higher than it has previously handled. At the same time, a highly-nonlinear resonant extraction system is planned to send the beam to the experiment. Synergia2 is uniquely qualified to simulate the ramped non-linear optics of the extraction system in the presence of a significant space charge effect.

The simulations start with a completely linear lattice. The linear lattice is both used as a benchmark to compare against non-linear effects and as a starting point for a smooth transition to the nonlinear lattice. Figure 7 shows the horizontal phase space distribution for the linear case, in contrast to the nonlinear case in Figure 8.

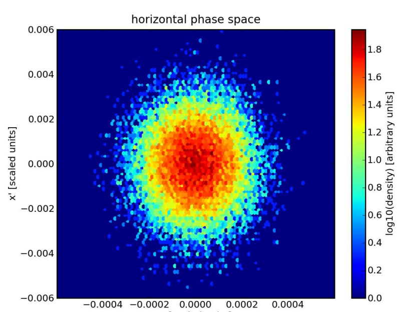

Figure 7. Horizontal phase space distribution for the linear Debuncher lattice.

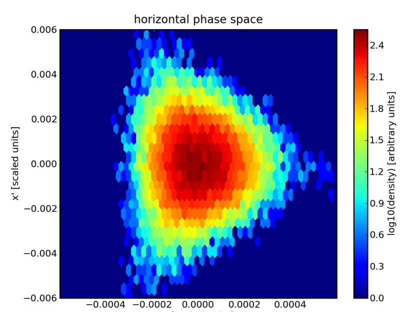

Figure 8. Horizontal phase space distribution for the nonlinear Debuncher lattice.

The most important result of the simulation is the identification of resonant behavior in the nonlinear lattice. Figures 9 and 10 show the transition from smoothly distributed tunes

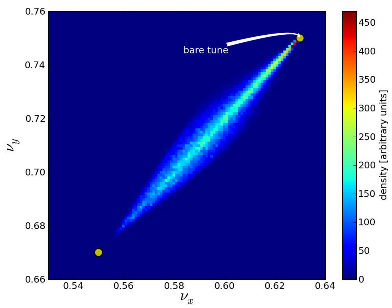

Figure 9. Transverse tune distribution for the linear Debuncher lattice.

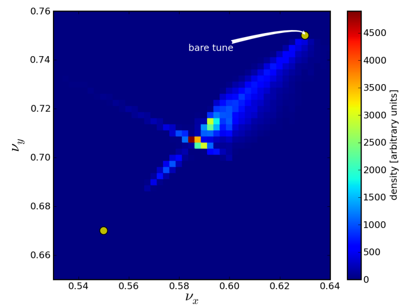

Figure 10. Transverse tune distribution for the nonlinear Debuncher lattice.

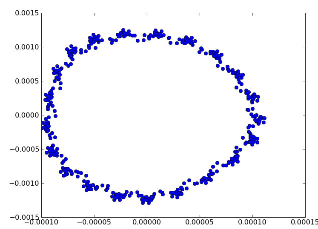

Figure 11. Individual particle phase space trajectory trapped on an 13/21 resonance.

in the linear case to particles bunched along resonant areas in the nonlinear case. The effect on individual particle trajectories can be seen in the phase space portrait of a single particle shown in Figure 11. The particle exhibits the quasi-periodic behavior consistent with a 13/21 resonance.

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8. References

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