Development and validation of self-consistent 3D beam-beam modeling code within SciDAC

J Amundson¹, J Qiang², R Ryne², P Spentzouris¹, E Stern¹ and A Valishev¹

¹ Fermilab, PO Box 500, Batavia, IL 60510, USA
² Accelerator and Fusion Research Division, Lawrence Berkeley National Laboratory, Berkeley, California, 94720, USA
E-mail: egstern@fnal.gov

Abstract.
The calculation of beam-beam effects has been an ongoing activity within SciDAC. We report the first validation of a detailed beam-beam simulation with data measured at the VEPP-2M collider in Novosibirsk. The validation of the simulation gives us confidence to apply it to understanding and improving the operation of existing colliders such as the Tevatron, RHIC and LHC, and the design of the International Linear Collider.

1. Introduction
The calculation of beam-beam effects has been an ongoing activity within SciDAC[1]. We report the first validation of a beam-beam simulation with data measured at an operating accelerator. The VEPP-2M accelerator in Novosibirsk which ended operations in 2000 was an $e^+e^-$ collider at modest energies that provided an environment for the measurement of beam physics effects.

Coherent synchrobetatron beam-beam oscillations[4] are a specific and unambiguous manifestation of beam-beam interactions. In a colliding beam accelerator bunches are subject to a beam-beam force from the electromagnetic fields generated by particles in the opposing beam. In a beam bunch with extended longitudinal length, particles in the head of the bunch couple indirectly with particles at the tail of the bunch through their mutual beam-beam interactions with an opposing beam bunch. The coupled system has oscillation modes at frequencies specific to the mode which can be observed experimentally. Normally, the longitudinal and transverse (synchrotron and betatron) oscillations are only weakly coupled, but the detection and measurement of synchrobetatron modes gives a detailed view into the operation of beam-beam interactions.

The BeamBeam3d[2] program has been developed to simulate beam-beam interactions with large statistics on parallel clusters. A particle-in-cell approach[3] divides the total charge from about $10^{10}$ real charged particles into roughly $10^5$–$10^6$ macroparticles which are simulated in detail. The macroparticles propagate through the accelerator and are subject to forces produced by electromagnetic fields generated by the opposing beam bunches. For the purposes of this simulation, the accelerator optics was simulated by applying a one-turn linear map to the phase space coordinates of each macroparticle. The BeamBeam3d program has the capability of applying...
more effects to the particles such as higher order maps, radiation damping, etc., but they were not employed for this simulation.

The simulation of the physical part of the beam-beam interaction involves solving Maxwell’s field equations for the electromagnetic fields produced by one beam bunch and applying the forces produced by those fields to the opposing bunch. The longitudinal progression of the bunch collision is modeled by dividing a bunch along its length into slices containing equal numbers of macroparticles. In a bunch-on-bunch collision, the slices are overlapped in turn. An impulse produced by the electromagnetic fields of the opposing slice is applied to each particle in the slice, as illustrated in figure 1. The bunches are moved to overlap the next group of slices allowing each particle to drift to its next position. The process is repeated until all the slices have interacted.

Because the particles are ultrarelativistic, electromagnetic fields and forces act only transversely to the beam direction reducing the calculation to the solution of a two-dimensional Poisson equation. The fields are evaluated numerically on a 128 × 128 grid encompassing the transverse space dimensions. The Poisson equation is solved with a discrete Fourier transform solver.

The code is parallelized by dividing the number of macroparticles evenly among processors. Each of the two beams has a set of compute processors. Within the processors for a beam, each slice uses a set of processors. Each processor calculates a local charge density for its own particles. A global sum produces the total charge density that includes all particles. Each processor evaluates the field and applies an impulse to all the particles that are local to it as illustrated in figure 2.

2. Experimental method
The measurement of synchrobetatron modes was performed at the VEPP-2M collider in Novosibirsk[5]. The VEPP-2M collider which ended operation in 2000 was an e⁺e⁻ collider operating between 200–690 MeV. While having too low an energy to contribute to particle physics research, it did provide a capability for investigating accelerator physics techniques and effects.

The strength of the beam-beam force is characterized by the beam-beam parameter

\[ \xi = \frac{N_e r_p \beta^*}{2 \pi \gamma \sigma_y (\sigma_x + \sigma_y)} \]  

where \( N_e \) is the number of electrons in the machine, \( r_p \) is the classical radius of the electron \( e^2/4\pi\varepsilon_0 mc^2 \), \( \beta^* \) is the beta function at the interaction location, \( \gamma \) is the Lorentz factor, and \( \sigma_x, \sigma_y \) are the RMS beam sizes at the interaction point. Since beam-beam effects vary with \( \xi \),
the experimental technique was to vary the beam current \( N_e \) to control \( \xi \), use a kicker magnet on one beam to excite oscillations, and observe the mean beam position with a synchrotron light detector over 8000 turns of the beam, of which 4000 turns give useful data. The Fourier transform of the beam position gives the oscillation mode spectrum of the beam.

Table 1. Beam parameters used for synchrobetatron mode simulations.

| Parameter                  | Value                     |
|----------------------------|---------------------------|
| beam current               | \( 5.55 \cdot 10^8 \text{–} 8.32 \cdot 10^9 \) |
| \( \beta^* \) \((x,y)\)    | 0.4, 0.06                 |
| betatron tunes \((x,y)\)   | 3.065, 3.101              |
| synchrotron tune           | 0.007                     |
| RMS beam size \((x,y)\)    | \(4.47 \cdot 10^{-4} \text{,} 1.643 \cdot 10^{-5} \) [m] |
| bunch length               | 0.04 [m]                  |

Figure 3. Fractional tune spectrum for the simulation of \( \xi = 0.008 \) showing the \( \sigma \) mode at the nominal tune, the first synchrobetatron mode one synchrotron tune higher and the betatron \( \pi \) mode.
Figure 4. Tunes for different modes as function of $\xi$ from measured data and simulation. The diamonds are the simulation points, the small circles are data. The horizontal line labeled $\nu_0$ is the fundamental mode tune frequency with $\nu_0 \pm \nu_s$ showing the upper and lower sidebands from synchrobetatron modes.

3. Simulation
To mirror the conditions of the beam experiment, 15 runs of the BeamBeam3d code varying the charge of the beams to give a $\xi$ between 0.002–0.030. The full list of beam parameters is shown in table 1. The beam is run through the simulation for 4000 turns, recording the mean beam position for each turn. The Fourier transform of these positions gives the tune spectrum as is done for the data. A sample spectrum of the beam position for $\xi = 0.008$ is shown in figure 3 with the position of the $\sigma$ mode, the first synchrobetatron mode, and the first betatron $\pi$ mode indicated.

The locations of the different modes are read from the spectra and plotted as a function of $\xi$ in figure 4. The simulation points are shown by diamonds over the data which are small circles. The simulation points fit the measured data quite well.

4. Plans
The validation of the beam-beam simulation now allows us to incorporate this code into a comprehensive accelerator simulation framework including multiple physics effects. We will add beam-beam interactions to our existing Synergia[6] framework that already includes non-linear optics and space charge solvers. We will also add other processes including transverse impedance, electron cloud and quantum effects to produce a tool that will be useful for modeling and understanding existing accelerators such as RHIC and the LHC, as well as designing new accelerators such as the International Linear Collider.

Acknowledgments
This work was performed under the auspices of a Scientific Computing for Advanced Computing project, “Advanced Computing for 21st Century Accelerator Science and Technology,” which is
supported by the U.S. DOE/SC Office of High Energy and Nuclear Physics and the Office of Advanced Scientific Computing Research.

References
[1] Qiang J, Furman M A and Ryne R D 2002 Phys. Rev. ST Accel. Beams 5 104402
Qiang J, Ryne R D, Habib S and Decyk V 2001 J. Comp. Phys. 163 pp 234–451
[2] Qiang J, Furman M A and Ryne R D 2004 J. Comp. Phys. 198 pp 278–294
[3] Hockney R W and Eastwood J E 1985 Computer Simulation Using Particles McGraw-Hill Book Company, New York
[4] Perevedentsev E A 1999 Proceedings of the 1999 Particle Accelerator Conference ed. Luccio A and MacKay W (IEEE, Piscataway, NJ) vol 3 p 1521
Perevedentsev E A 1999 Proceedings of the International Workshop on Performance Improvement of Electron-Positron Collider Particle Factories ed. Acai K and Kikutani E (KEK, Tsukuba) p 171
[5] Nesterenko I N, Perevedentsev E A and Valishev A A 2002 Phys. Rev. E 65 056502
[6] Amundson J, Spentzouris P, Qiang J and Ryne R 2006 J. Comp. Phys. 211 pp 229–248