SciDAC advances in beam dynamics simulation: from light sources to colliders

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Abstract. In this paper, we report on progress that has been made in beam dynamics simulation, from light sources to colliders, during the first year of SciDAC-II accelerator project, “Community Petascale Project for Accelerator Science and Simulation (ComPASS)”. Several parallel computational tools for beam dynamics simulation will be described. A number of applications in current and future accelerator facilities, e.g. LCLS, RHIC, Tevatron, LHC, ELIC, are presented.

1. Introduction

Particle accelerators are some of most important tools of scientific discovery. They have been widely used in high energy physics, nuclear physics, other basic sciences to study the interaction of elementary particles, to probe the internal structure of matter, and to generate high brightness radiation. The design and operation of accelerators, which may be hundred or thousands of meters long and may involve thousands of components, present not only great technological challenges but also significantly economic cost. Large-scale beam dynamics simulations on massively parallel computers will help to minimize design cost and to optimize the machine operation. In this paper, we report on beam dynamics simulations of next generation light sources and of high-energy ring colliders during the first year of SciDAC-II accelerator project.

2. Beam dynamics simulations in light sources

The next generation of accelerator based light sources will offer unprecedented photon flux, brightness, and temporal resolution. They also present significant technological challenges. These challenges include producing and transporting high brightness, low emittance electron beams through

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the accelerator while maintaining good beam quality in the presence of collective effects such as space charge, wakefields, and coherent synchrotron radiation. At LBNL, two parallel particle tracking codes, IMPACT-Z [1] and IMPACT-T [2], have been developed and used to study the electron beam generation from photoinjectors and to simulate beam transport through RF linacs. Both parallel particle tracking codes assume a quasi-static model of the beam and calculate space-charge effects self-consistently at each time step together with the external acceleration and focusing fields. There are six Poisson solvers in the IMPACT code corresponding to different boundary conditions. These solvers use either a spectral method for closed transverse boundary conditions, or a convolution-based (FFT-based) Green function method for open transverse boundary conditions. The parallel implementation is based on a two-dimensional domain decomposition approach for the three-dimensional computational domain. New features such as a short-range wakefield, CSR wakefield, integrated Green function solver, and particle-field decomposition were added to the code. Figure 1 shows strong scaling studies of the IMPACT-T and the IMPACT-Z codes on a Cray-XT 4 computer at NERSC. It is seen that both codes shows more than 50% parallel efficiency on one thousand processors.

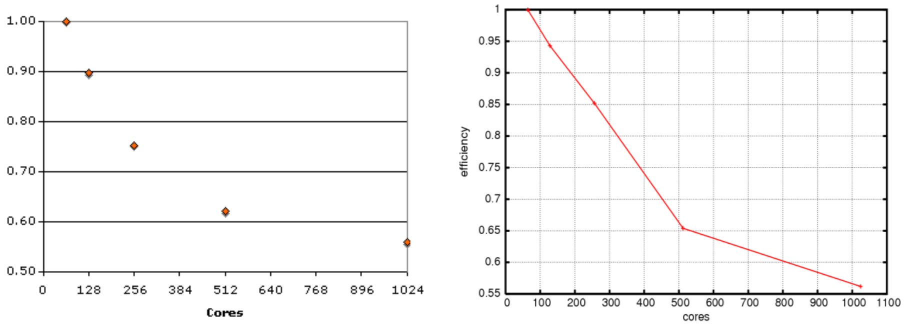


Figure 1. Parallel efficiency of IMPACT-T (left) and IMPACT-Z (right) on Cray-XT 4.

The IMPACT-T code has been used to help commissioning of the electron generation and transport in the LCLS photoinjector. Figure 2 shows the evolution of rms emittance of the beam with an initial 0.5 mm horizontal and vertical offsets through the LCLS photoinjector. With such a big offset, the simulation shows the separation of horizontal and vertical emittance and significantly larger final emittance compared with the nominal design value of 1.2 mm-mrad. The IMPACT-Z code has been used to simulate the beam transport through a designed RF linac for a next generation FEL light source at LBNL. A large number of macropartices is needed in order to accurately predict the final uncorrelated energy spread of the electron beam due to the presence of the microbunching instability. Figure 3 shows the final energy spread as a function of number of macroparticles for the FEL linac studied at LBNL. It is seen that final energy spread starts to saturate with an initial macroparticle number beyond one billion particles.

At ANL, the ELEGANT code has been used for design, simulation, and optimisation of FEL driver linacs, energy recovery linacs, and storage rings. It has been used to support for LCLS design and commissioning [3]. The ELEGANT code has been completely parallelized recently. The new version has demonstrated the ability to utilize 400 million macroparticles on 100 nodes after implementation of parallelized SDDS I/O and elimination role of the master node in particle management. Figure 4 shows growth of microbunching instability through a number of dipoles in the designed Fermi/Elettra FEL linac.

3. Beam dynamics simulations in colliders

Beam-beam interaction limits the luminosity that can be achieved in high-energy colliders. We have developed a parallel three-dimensional particle-in-cell code, BeamBeam3D, to model beam-beam effect in high-energy ring colliders [4]. This code includes a self-consistent calculation of the electromagnetic forces (beam-beam forces) from two colliding beams (i.e. strong-strong modeling), a linear transfer map model for beam transport between collision points, a stochastic map to treat radiation damping, quantum excitation, an arbitrary orbit separation model, and a single map to account for chromaticity effects. Here, the beam-beam forces are calculated by solving the Poisson equation using an FFT-based algorithm. It can handle multiple bunches from each beam collision at multiple interaction points (IPs). New features such as wakefield, wire compensator, crab cavity compenator were added to the code. The parallel implementation is done using a particle-field decomposition method to achieve a good load balance. Parallel performance of the code was measured on a variety of high performance computers and showed reasonably scalability up to thousand processors [5].

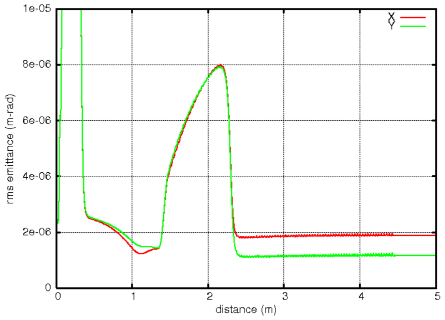


Figure 2. Transverse emittance evolution at LCLS photoinjector with initial 0.5 mm offset from IMPACT-T simulation.

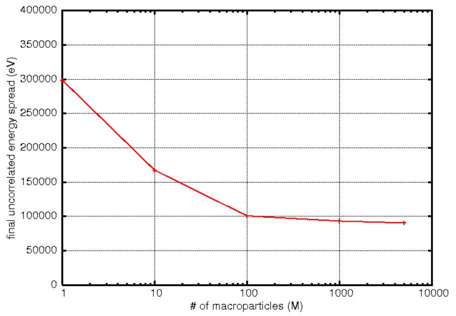


Figure 3. Final energy spread as a function of number of macroparticles from IMPACT-Z simulation.

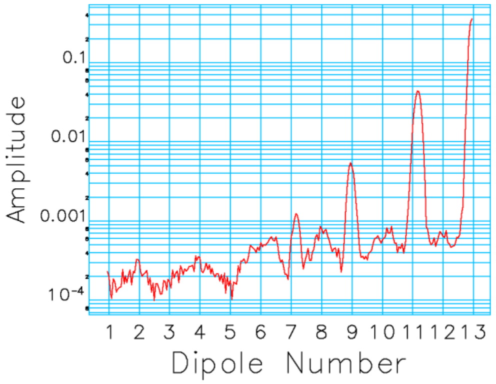


Figure 4. Growth of microbunching instability in the designed Fermi/Elettra FEL linac from ELEGANT simulation.

The BeamBeam3D code has been applied to the study of multi-bunch coherent beam-beam effects at RHIC. Each beam in the simulation has three bunches that are coupled to three bunches in the opposite beam at four interaction points. Figure 5 shows the emittance growth in the tune space for the nominal working point near half integer and for a new working point near integer. The new working point appears to have a better performance than the nominal one.

The BeamBeam3D code has also been extended and been used to study coherent beam-beam effects at Tevatron. With the commissioning of electron cooling in the Recycler, the head-on beam-beam tune shifts of the two beams become essentially equal. Under these circumstances the coherent beam-beam effects may become an issue. Figure 6 shows the emittance variation among 36 bunches from 50000 turn strong-strong simulations at Tevatron. Here, each beam contains 36 bunches subject to both head-on and long-range beam-beam effects. A three-fold symmetry of emittance growth is observed from the fill pattern of bunches in the ring.

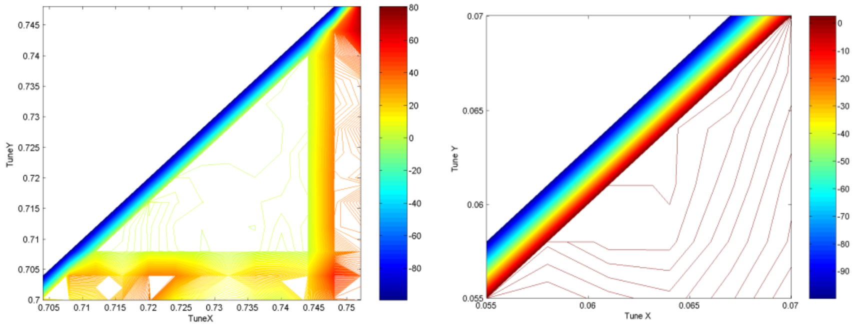


Figure 5. Emittance growth in tune space scan for nominal working point (left) and for a new working point (right) at RHIC from BeamBeam3D simulation.

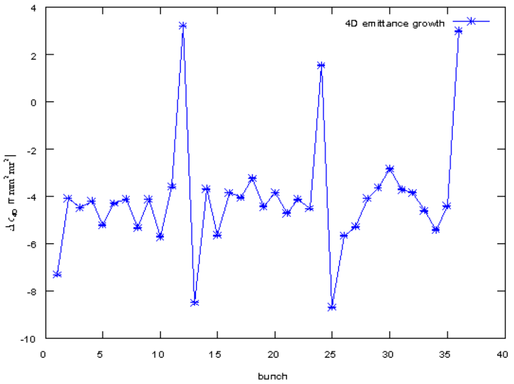
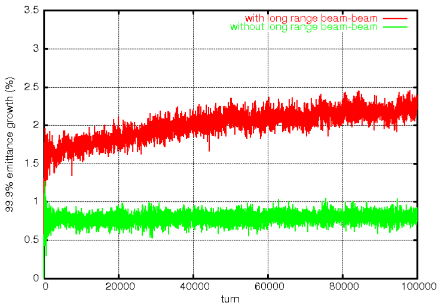


Figure 6. Emittance as a function of bunch number at Tevatron from BeamBeam3D simulation.

The BeamBeam3D has also been applied to studying long-range beam-beam effects at the LHC and to studying crab cavity compensation of crossing angle collision at the LHC upgrade. Figure 7 shows the 99.9% emittance growth with and without long-range beam-beam interactions. The simulation includes two head-on collision points (IP 1 and IP5) with 0.3 mrad crossing angle and 64 distributed long-range beam-beam interactions on both side of the interaction region. The long-range beam-beam interaction has significantly increased the 99.9% emittance growth of the beam, which characterizes the tail of the beam. Figure 8 shows the luminosity evolution with and without crab cavities for two beams colliding with 0.3 mrad crossing angle. It is seen that using a crab cavity significantly improves the luminosity at the LHC.



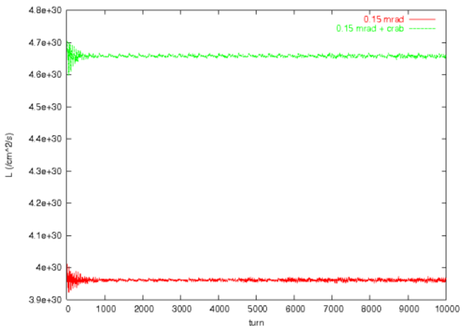


Figure 7. Emittance growth at LHC with /without long-range beam-beam interactions from BeamBeam3D simulation.

Figure 8. Luminosity evolution at LHC with /without crab cavity compensation from BeamBeam3D simulation.

The BeamBeam3D code has also been used to study the electron light ion collider (ELIC) proposed at JLab. Understanding beam-beam effects at ELIC is crucial for achieving high luminosity. Figure 9 shows the luminosity as a function of electron and proton current using an old working point near the integer and a new working point near the half integer. The new working point has significantly improved luminosity for all currents.

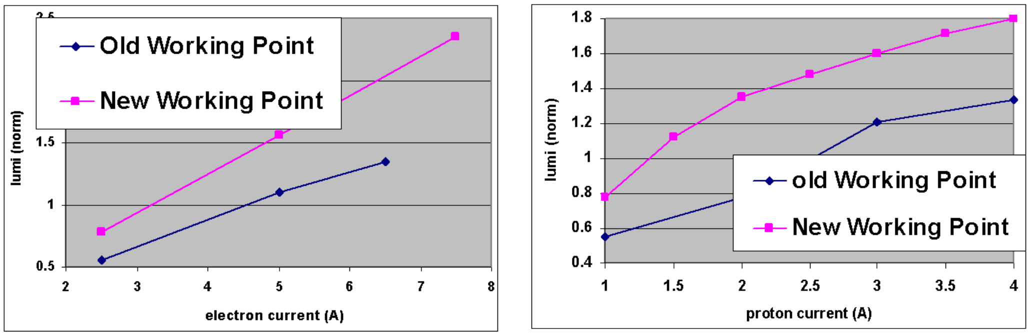


Figure 9. Luminosity as a function of electron (left) and proton (right) current at JLab ELIC collider from BeamBeam3D simulation.

At SLAC, a particle-tracking framework PLIBB has been developed and used to study beam-beam effects at the Tevatron, RHIC and LHC with emphasis in beam lifetime calculation using a weak-strong model [6]. The physics of the code includes intrabeam scattering, noise sources, common magnetic elements, weak-strong and strong-strong beam-beam interactions as well as wire and electron lens compensators. Figure 10 shows tune space footprint with/without electron lens compensation at LHC. Using an electron lens significantly reduces the size of the tune spread.

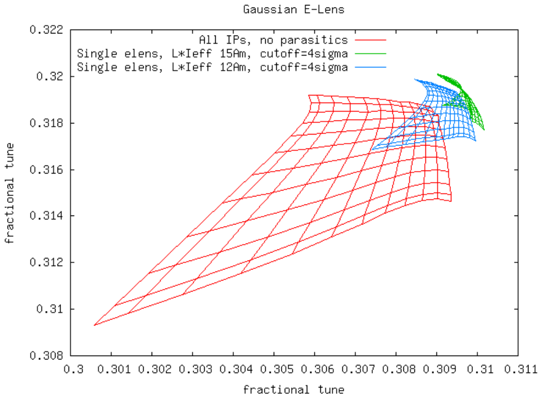


Figure 10. Tune footprint at LHC with/without electron lens from PLIBB simulation.

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