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Title: Parallel Simulation of Beam Dynamics in Particle Accelerators

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Final Report for Project t22_accelsim

Introduction

Particle accelerators are among the most versatile and important tools of scientific discovery. The Nation's accelerators are responsible for a wealth of advances in materials science, chemistry, the biosciences, particle physics, and nuclear physics. They also have important applications to national security, the environment, energy, medicine, and on the quality of people's lives. LANL has a long history of making pioneering contributions to Accelerator Science including key contributions to the field of Computational Accelerator Physics. These include the development of early beam dynamics codes with space charge (such as PARMILA and PARMELA), the development of rf cavity codes and magnet codes (including Poisson and Superfish), and the development and distribution of codes to the accelerator community through the Los Alamos Accelerator Code Group. LANL researchers also helped pioneer the development of massively parallel space-charge codes. In project t22_accelsim we have moved beyond electrostatic models of collective effects (i.e., solving the Poisson equation in the bunch frame) to fully electromagnetic models based on the Lienard-Wiechert formalism. This approach enables the large-scale simulation of radiation production and collective effects in high brightness electron beams. This is highly relevant to LANL given its future goal of developing an X-ray Free Electron Laser (XFEL). It also directly impacts a LANL LDRD project to develop an undulator-based non-invasive beam profile monitor for beams created in laser-plasma accelerator systems.

Accomplishments:

Simulations in support of a LANL LDRD project to develop a novel diagnostic for electron bunches: The goal of LANL LDRD 20190294ER, “A Non-Invasive Current Profile Diagnostic for Electron Bunches,” was to develop an undulator-based, non-invasive current profile diagnostic for electron bunches applicable to the types of bunches found in laser- and plasma-based accelerators. This project involved collaborative research between LANL, Lawrence Berkeley National Laboratory (LBNL), and SLAC National Accelerator Laboratory, to develop and test novel diagnostics for ultra-short bunches. The undulator was designed, fabricated, and then shipped to the BELLA facility at LBNL for experiments. LANL institutional computing resources were used, along with the LW3D code, during the design process. Since delivering the diagnostic system to BELLA, team at LBNL has been using one part of it, the pyrometer array, to measure coherent transition radiation, and has presented results that are based on these measurements.

Under this project we adapted and enhanced the parallel Lienard-Wiechert 3D code, LW3D, to model undulator radiation from an electron bunch using a first-principles approach. Among the code enhancements that were made, we developed a model for the 3D fields in the undulator, including fringe fields at the entrance and exit of the undulator. The code was modified to compute the radiation field off axis as is the case with the non-invasive profile monitor. We also developed a capability to visualize the radiation field. This work was presented at a LANL-organized workshop on High-Energy X-ray Free Electron Lasers.

3D Computation of radiative self-fields in chicanes: After using LW3D to predict far-field radiation produced by a bunch passing through an undulator, we next modified the code to compute the Lienard-Wiechert fields produced in transport lines found in beam delivery systems for FELs. One such type of beamline, known as a chicane, contains 4 dipole magnets and is used to compress an electron bunch.

Figure 1 shows the result of one such simulation. The upper curve shows a schematic of the magnetic field of each dipole. The dotted line in the middle of the figure shows the path of the electron bunch. The black frames show the magnitude of the Poynting vector of the radiation field when the bunch (shown as a blue dot) is at 6 positions along the beamline. The figure illustrates that, each time the bunch trajectory is bent by a dipole magnet, it creates a radiation field that propagates forward along the beamline. In the last frame there are 4 wavefronts visible. The earlier-produced wavefronts are ahead of the bunch because they travel a shorter distance than the bunch. The ability to predict radiation self-fields is important to the design of future beam delivery systems to optimize radiation production in future X-ray FELs.

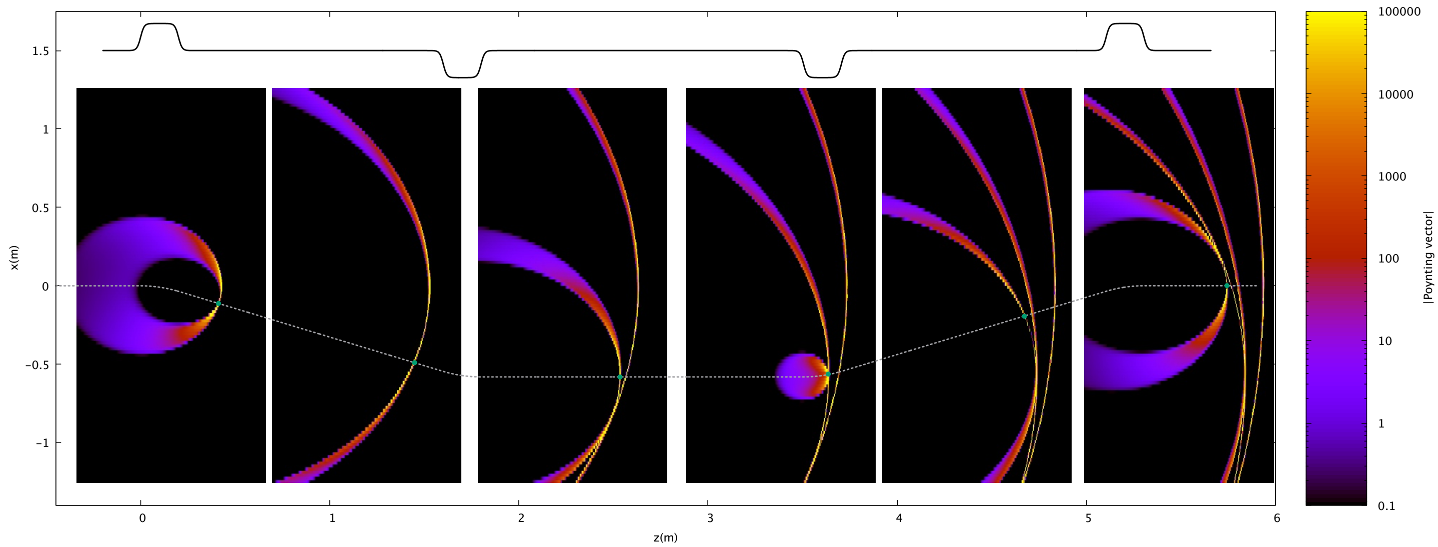

Figure 1: Radiation produced by an electron bunch propagating in a chicane, simulated using the LW3D code.

Parallel Simulation of Beam Dynamics in Particle Accelerators

LANL Institutional Computing Project t22_accelsim

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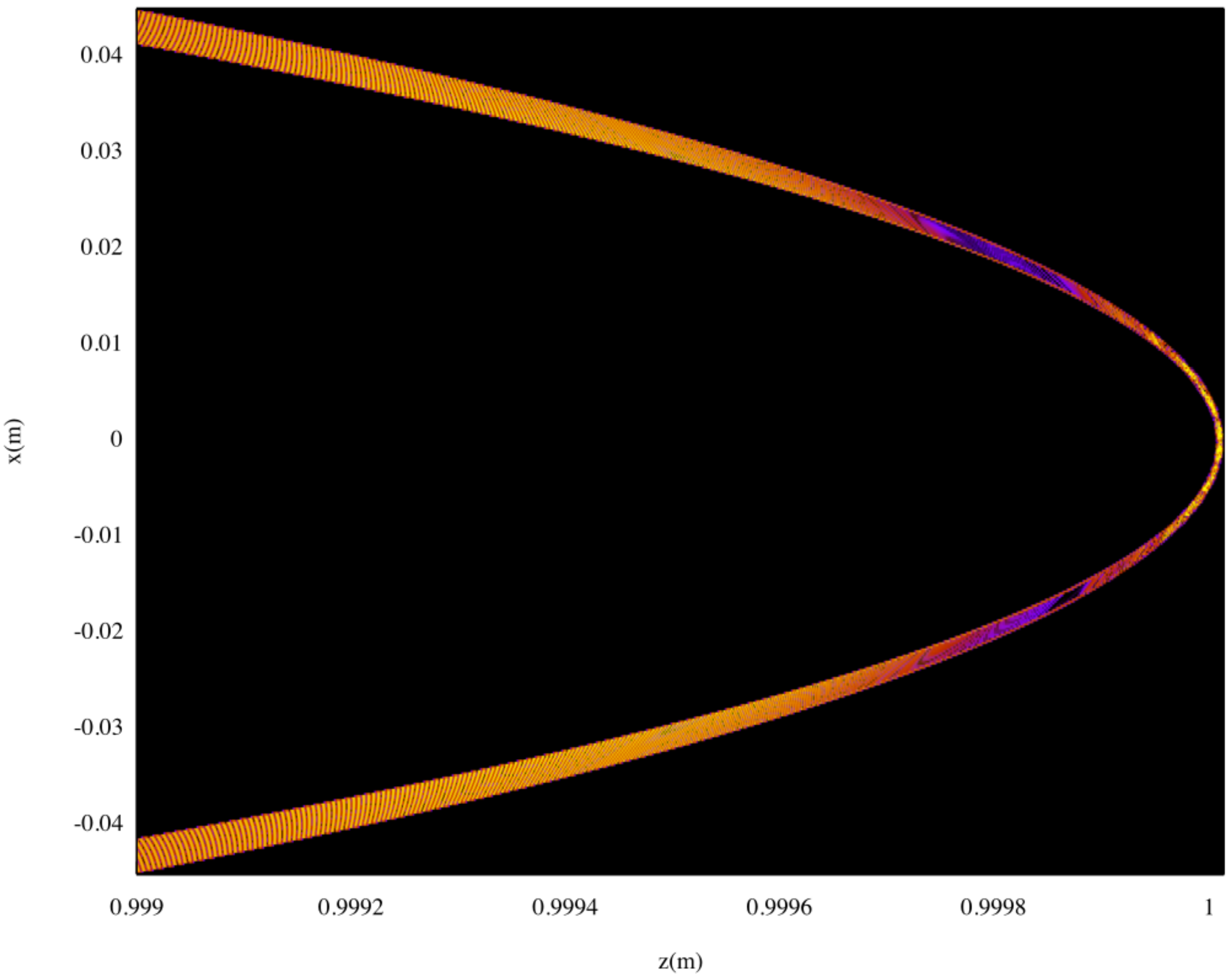
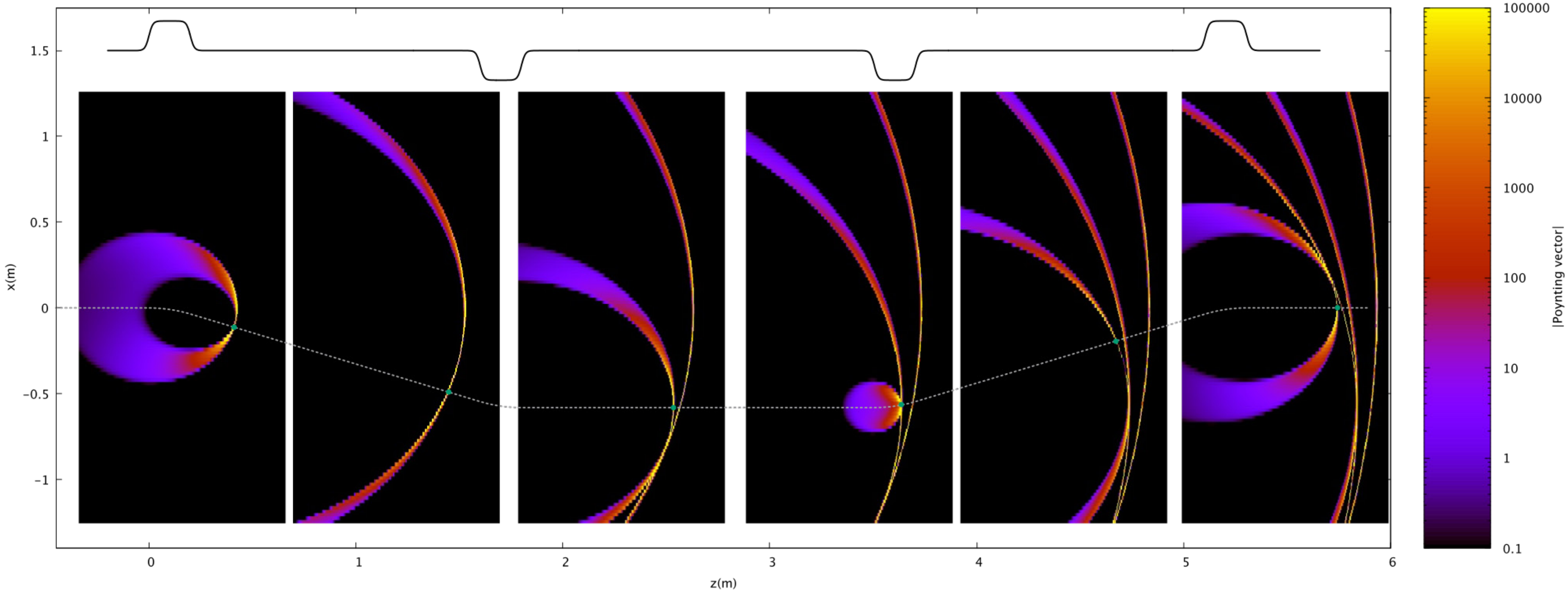
Project t22_accelsim highlights

- Goals:
  - Perform simulations to support LDRD project 20190294ER to develop an undulator-based, non-invasive beam diagnostic
  - Enhance the LW3D code so that it can be used to simulate coherent synchrotron radiation (CSR) effects in more complicated systems such as chicanes for bunch compression
- Accomplishments
  - LW3D was used to design an undulator-based, non-invasive beam profile monitor for LDRD project 20190294ER. Simulations were used to predict the downstream off-axis radiation.
  - LW3D was extended to model transport systems involving dipoles and quadrupoles. It was used to explore the radiation produced in a 4-dipole bunch compressor.
  - A self-consistent version LW3D was benchmarked using the 2-body problem with retarded self-fields.

LW3D simulation results showing the longitudinal radiation electric field in the x-z plane downstream from an undulator

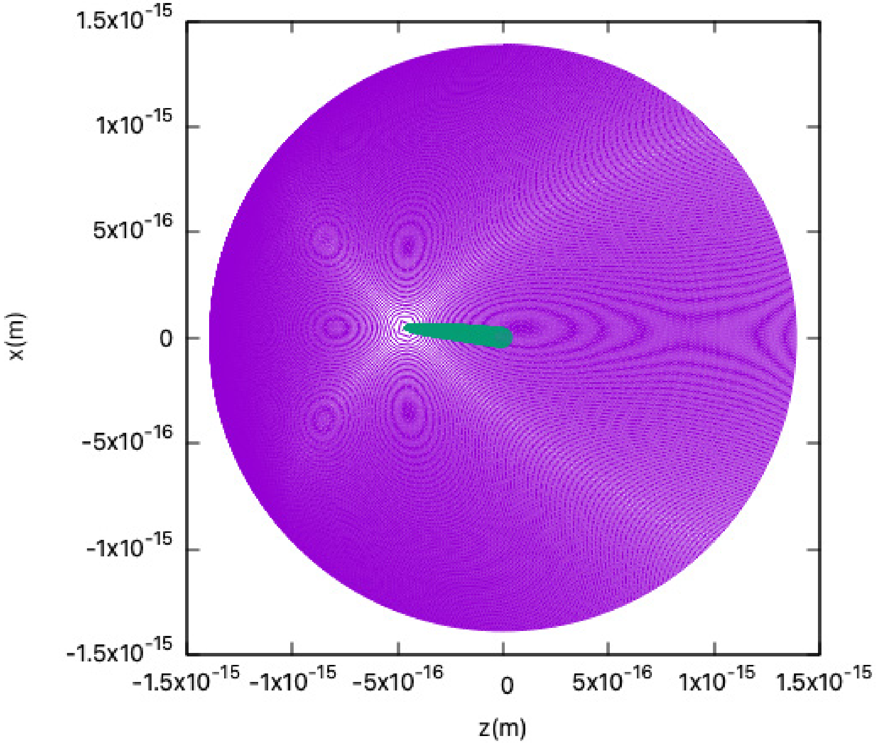


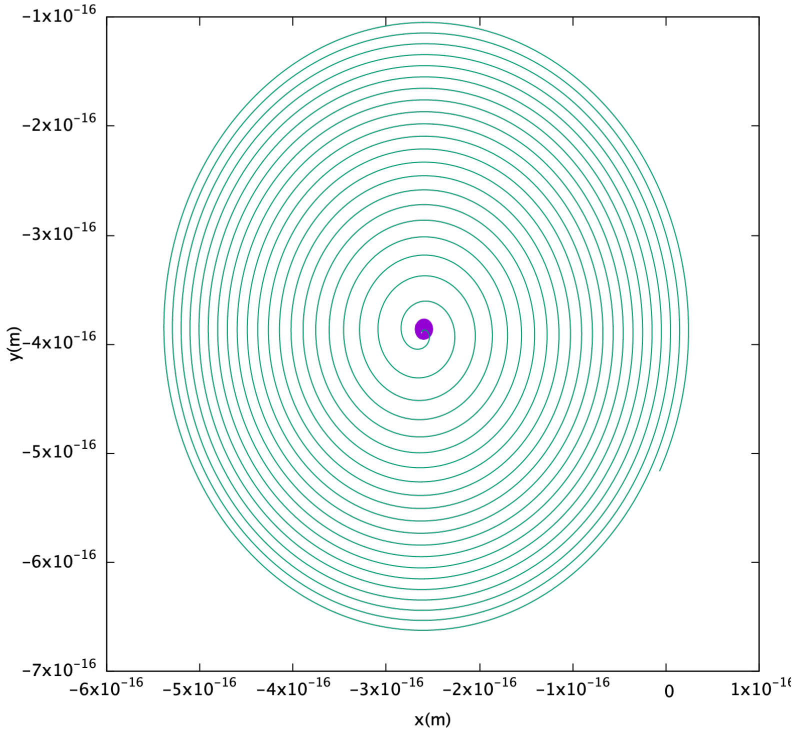
Simulation results of a bunch passing through a 4-dipole bunch compressor



Plot of the magnitude of the Poynting vector produced by an electron bunch passing through a bunch compressor. The simulation was performed using the parallel simulation code LW3D. Whenever the bunch passes through a dipole magnet (whose field is shown schematically along the top), a radiation wavefront is created. In the right hand panel, three narrow wavefronts are evident, having been produced by passage through the previous dipoles. A fourth (donut shaped) wavefront is seen emerging, having been produced by passage through the fourth dipole.

Benchmark of the LW3D code based on the 2-body problem with retarded Lienard-Wiechert fields





Trajectory of two oppositely charged particles interacting through self-consistent retarded self-fields. Left: complete trajectory. Right: final few turns before collision. (Note the change of axis scales in the two figures.) The collision time observed in simulation agrees with the analytical prediction of Synge (J.L. Synge, On the electromagnetic two-body problem, Proc. Royal Society A, 31 December 1940).