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3D Particle Simulation of Space-Charge-Dominated Ion Beams for Heavy-Ion Fusion*

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Heavy-ion induction accelerators are the principal driver approach in the U.S. Inertial Fusion Energy program.[1,2] Such accelerators, which pass multiple beams through a series of ferromagnetic induction cores, are expected to be capable of directly accelerating the high currents necessary to drive a fusion target. A related approach, being pursued in a multi-national European research effort, involves the use of a radiofrequency linac feeding a set of storage rings via multi-turn injection to develop the required ion current.[1,2]

A major challenge in the practical realization of Heavy-Ion Fusion (HIF) power production is the development of an accelerator of moderate cost capable of producing a set of beams with the power and quality dictated by target requirements. The intense, low emittance (small phase-space volume) beams in induction accelerators for HIF are non-neutral plasmas with transverse extents on the order of 10-100 Debye lengths. They are "space-charge-dominated," in the sense that the transverse force balance is primarily between the applied confining fields and the space-charge forces; thermal pressure plays a relatively minor role in a successful machine. If great care is not exercised in developing the beam manipulations, nonlinear self-fields associated with beam nonuniformities, as well as imperfections in applied fields, can lead to phase-space distortion and emittance growth. Fortunately, HIF beams reside in the accelerator for relatively few plasma periods, and can be simulated effectively using the techniques of plasma modeling.

Much of our work is carried out using the WARP code, which embodies both three-dimensional and axisymmetric models. The WARP3d package combines features of an accelerator code and a 3D particle-in-cell plasma simulation.[3,4] It can efficiently track a beam through hundreds of "lattice elements" of an accelerator. WARP also includes an axisymmetric PIC package, WARPrz, which is used to follow beams over very long times and models the efffects of accelerating module impedances.[5] WARP was built using the Basis system, which facilitates modular programming and provides a flexible, user-programmable interactive user interface.[6]

Simulations in WARP3d are done in the laboratory reference frame; the computational mesh fills a moving window and is laid down anew at each time step. This mesh can be "warped" (with curvature varying as necessary) to follow bends in the actual accelerator or transport lattice; each element of the lattice is described in a local Cartesian frame aligned with the element's principal axes.[7] The beam's self-field is obtained by a solution of Poisson's equation using an FFT sine-sine-periodic solver, FFTs with a capacity matrix (for a round pipe or for simple internal structures), or an SOR method (for detailed internal structures), the last optionally allowing subgrid-scale placement of internal conductor boundaries.[4] The accelerator lattice is a user-specified set of acceleration modules and electric or magnetic focusing and bending elements. For several of these elements, the user may choose among representations. For example, electric quadrupoles may be represented by idealized "hard-edged" fields, or by realistic fields (including fringe fields) calculated by solving Poisson's equation with the physically correct boundary conditions. Alternatively, the fields may be specified as a set of multipole moments with longitudinal dependence (perhaps obtained via a separate calculation using WARP3d itself).

Recent applications of WARP3d have included design studies of the novel "Electrostatic Quadrupole" injector developed at Lawrence Berkeley National Laboratory,[8] and multi-lap simulations of LLNL's planned small prototype recirculating induction accelerator.[9,10] Additional applications include studies of: pulse compression; the basic physics of beam equilibria; transverse-longitudinal temperature equilibration via a collective process; beam bending in achromatic transport lines; misalignment effects; and bent "matching" sections that couple the beams from a multi-beam injector into the main accelerator.

In this talk the context of this research is briefly reviewed. The main emphasis is on the numerical techniques employed, including: methods for bent systems; subgrid-scale placement of internal conductor boundaries; mesh motion to follow the beam; and force-averaging techniques which allow the use of timesteps so large that they do not resolve gradients in the applied fields. Some representative results are presented.

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1. An excellent reference on Heavy Ion Fusion is the *Proceedings of the International Symposium*, Frascati (Italy), May 25-8, 1993, S. Atzeni and R. A. Ricci, Eds., pub. as *Il Nuovo Cimento* **106 A** Nos. 11-12, November 1993.
2. The most recent International Symposium on Heavy Ion Inertial Fusion was held at Princeton Plasma Physics Laboratory, September 6-9, 1995. The Proceedings will be published in *Journal of Fusion Engineering Design* in 1996.
3. A. Friedman, D. P. Grote, and I. Haber, "Three-dimensional particle simulation of heavy-ion fusion beams," *Phys. Fluids B* **4**, 2203 (1992).; A. Friedman, D. A. Callahan, D. P. Grote, I. Haber, A. B. Langdon, and S. M. Lund, "What We've Learned from 3-D and r,z Intense-Beam Simulations using the WARP Code," ref. 1, pp 1649-55.
4. D. P. Grote, A. Friedman, I. Haber, and S. S. Yu, "Three-Dimensional Simulation of High-Current Beams in Induction Accelerators with WARP3d," in ref. 2.
5. D. A. Callahan, A. B. Langdon, A. Friedman, I. Haber, "Longitudinal Beam Dynamics for Heavy Ion Fusion," *Proc. 1993 IEEE/APS Part. Accel. Conf.*, Washington DC, May 17-20, 1993.
6. P. F. Dubois, "Making Applications Programmable," *Computers in Physics* **8** No. 1, 70 (1994).
7. A. Friedman, "Methods for PIC Simulation of Bent Particle Beams in 3d and 2d," *13th Int. Conf. on Num. Sim. of Plasmas*,, Santa Fe, NM, September 18, 1989; A. Friedman, D. P. Grote, and I. Haber, "Simulation of High-Current Ion Beams in General Accelerator Lattices," *14th Int. Conf. on Num. Sim. of Plasmas*, Annapolis, Sept. 3-6, 1991.
8. S. S. Yu, "Driver Scale Ion Injector Experiments," in ref. 2.
9. J. J. Barnard, F. Deadrick, A. Friedman, D. P. Grote, L. V. Griffith, H. C. Kirbie, V. K. Neil, M. A. Newton, A. C. Paul, W. M. Sharp, H. D. Shay, R. O. Bangerter, A. Faltens, C. G. Fong, D. L. Judd, E. P. Lee, L. L. Reginato, S. S. Yu, and T. F Godlove, "Recirculating Induction Accelerators as Drivers for Heavy-Ion Fusion," *Phys. Fluids B* **5**, 2698 (1993).
10. A. Friedman, J. J. Barnard, M. D. Cable, D. A. Callahan, F. J. Deadrick, S. Eylon, T. J. Fessenden, D. P. Grote, H. A. Hopkins, V. P. Karpenko, D. L. Judd, H. C. Kirbie, D. B. Longinotti, S. M. Lund, L. A. Nattrass, M. B. Nelson, M. A. Newton, T. C. Sangster, and W. M. Sharp, "Recirculating Induction Accelerators for Inertial Fusion: Prospects and Status," in ref. 2.