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New developments in WARP: Progress toward end-to-end simulation[1]

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Abstract

The development of a high current, heavy-ion beam driver for inertial confinement fusion requires a detailed understanding of the behavior of the beam, including effects of the strong self-fields. The necessity of including the self-fields of the beam makes particle-in-cell (PIC) simulation techniques ideal, and for this reason, the multi-dimensional PIC/accelerator code WARP has been developed. WARP [1] has been used extensively to study the creation and propagation of ion beams both in experiments and for the understanding of basic beam physics. An overview of the structure of the code will be presented along with a discussion of features that make the code an effective tool in the understanding of space-charge dominated beam behavior. Much development has been done on WARP increasing its flexibility and generality. Major additions include a generalized field description, an efficient steady-state modeling technique, a transverse slice model with a bending algorithm, further improvement of the parallel processing version, and capabilities for linking to chamber transport codes. With these additions, the capability of modeling a large scale accelerator from end-to-end comes closer to reality. Published by Elsevier Science B.V.

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1. Introduction

For the design of a driver for heavy ion driven inertial fusion energy, a thorough understanding of the beam behavior throughout the system is required. The analysis must be integrated, with beam distributions generated early in the accelerator included in the analysis of later sections. One tool which can be used is particle-in-cell (PIC)

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simulation. The WARP code, a multi-dimensional PIC/accelerator code, has been developed to study the propagation of the high-current, space charge dominated beams in induction accelerators for the U.S. heavy-ion inertial fusion energy program. Though the code has been used extensively to study independent sections of accelerators, a number of advancements have given the code the power and flexibility so that it can be used to study accelerators and driver designs from the source to the target.

This paper discusses some of the computational aspects of WARP as well as a number of representative applications. In Section 2 of this paper an overview of the WARP code is presented. More complete details can be found in Refs. [1,2]. In Section 3 several applications along the length of the accelerator are described, illustrating the flexibility of WARP to cover all parts of a driver. In Section 4 future plans for end-to-end simulation are presented.

2. WARP overview

The WARP code combines the particle-in-cell plasma simulation technique with a realistic description of the elements which make up an accelerator. The particle-in-cell model is used to self-consistently follow the beam particle distribution, specifically including the space-charge effects. The self-fields are assumed to be electrostatic and are calculated on a Cartesian grid which moves with the beam. The beam can be two dimensional, either axisymmetric (WARPrz) or transverse slice (WARPxy) or it can be fully three-dimensional (WARP3d). The code's accelerator 'lattice' consists of a fully general set of accelerating, focusing and bending elements as well as elements with arbitrary applied fields. Different types of elements are allowed to overlap. The self-consistently calculated self electric field and the electric and magnetic fields from the lattice elements are used in the Lorentz force law to advance the beam particles.

The code derives its name, WARP, from its capability of following beams through bent, or warped, systems. In a bend, cylindrical coordinates are used, with the axial position, *s*, being equal to the bend radius times the angle. Both WARP3d and WARPxy have this capability. (In a bend, axisymmetry is lost so WARPrz cannot have this capability.)

The features and capabilities of WARP allow it to be used to model all sections of the driver. Some of these, listed in order of use along an accelerator are: space charge limited injection, iterative steady-state mode, subgrid scale resolution of conducting boundary locations in the solution of Poisson's equation, detailed lattice elements, bending, parallel processing, and links to other codes such as BPIC3D and BIC for chamber propagation studies. Links between WARP runs can also be made, connecting runs of accelerator sections with different symmetries or boundary conditions, for example. Fig. 1 shows the layout of a typical driver

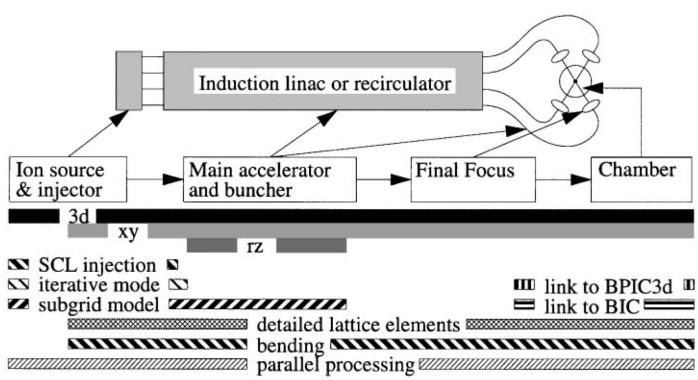

Fig. 1. The layout of an induction driver for IFE is shown. Using WARP, the beam can be followed through the whole system using the packages of different dimensionality, WARP3d, WARPxy, and WARPrz. Some of the code features which are important for each of the driver sections are listed.

and what parts of WARP are used in simulations of each section.

WARP is built on top of the Basis system which allows interactive (run time) control of the code and access to its internal database [3]. Much flexibility is gained by use of the interpreter to select and control those parts of the code used in a simulation.

3. Applications

WARP has been used to simulate experiments and accelerator designs which are representative of nearly all parts of current induction accelerator driver designs, from injection through the main acceleration section to the target. A number of these simulations are described in this section.

3.1. Injection

The electrostatic quadrupole (ESQ) injector experiment at LBNL [4] has been developed to study physics and engineering issues of injection. The injector produces 0.8 A of 2 MeV singly charged potassium ions at low normalized transverse emittance, less than 1π mm mrad. The injector uses ESQ's arranged to give a net acceleration along the axis while maintaining alternating gradient focusing. A major issue is emittance growth from both the nonlinear multipole components of the focusing fields and the so-called 'energy effect'.

Simulations of this system have been discussed in detail in Refs. [5,6]. Both WARP3d and WARPxy have been used to study this injector (with the diode modeled by WARP3d only). Three major features of WARP are space charge limited injection, iterative steady-state model, and the subgrid conductor model. The latter allowed a detailed model of the conductors of the ESQ's. Links have been made to simulations of the subsequent matching section. The simulations have played a major role in the understanding and design of the injector.

3.2. Main accelerator and buncher

This section comprises of the bulk of the driver, where most of the beam acceleration is done. Some driver scenarios split this into two sections, one using electric quadrupoles, the other using magnetic quadrupoles. The two major designs of the magnetic quadrupole section use either an induction linac or an induction recirculator. In the buncher, the beam is compressed axially to increase the current and to shorten the bunch length.

Extensive simulations have been done examining transport, acceleration, and bunching. See, for example, Ref. [7] which discusses simulation with WARP3d of the LBNL MBE-4 bunch compression experiment. Many simulations of induction recirculators have also been done. For example, simulation studies with WARP3d have been done of designs for the LLNL small recirculator experiments [5]. These simulations have examined both acceleration and bunch compression in a ring. Recently, a series of simulations using WARPxy was begun in order to examine in greater detail the effects of resonances with field errors on high current beams [8].

3.3. Final focusing and chamber propagation

In order to study axial bunch compression in the presence of axial thermal spread and focusing aberrations during final focusing, a study was begun with both WARPxy and WARP3d. Most of the important physics of final focusing can be studied with WARP. The exceptions are self-magnetic/inductive effects in the high-energy parts of the driver and the chamber. Since the self-magnetic and relativistic effects in the driver are in general small, approximations can be made and included in WARP.

Though the beam can be propagated to the target using WARP, WARP does not easily deal with important chamber propagation issues, including ionization and interaction with background plasma. For this reason, links are being made to other codes which were designed to include all of the physics of chamber propagation. These include the three-dimensional, electromagnetic chamber propagation code BPIC3D [9] and the axisymmetric code BIC [10,11]. At present, the beam data is transfered to BPIC3D several meters before the target, after the last lens. Vacuum propagation to the target with BPIC3D has shown good agreement with WARP3d.

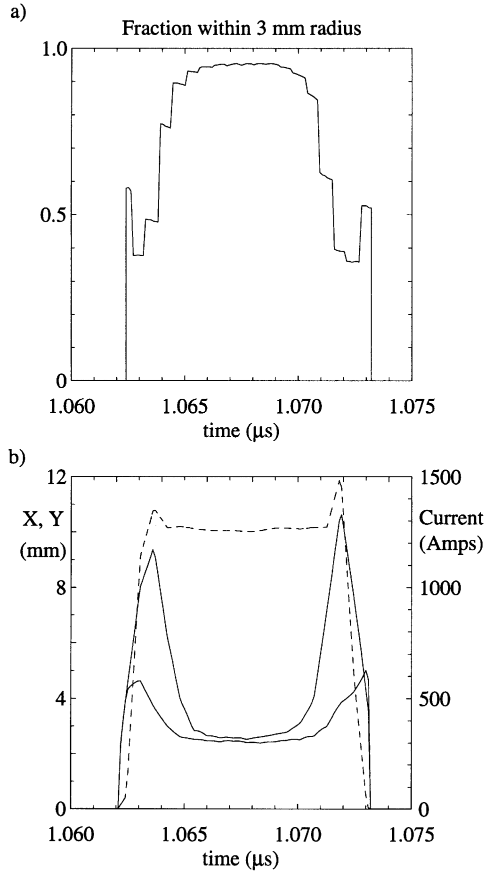

Fig. 2. Results from initial simulations of final focusing. (a) The fraction of the beam which hits the 3 mm spot size of the target. (b) The transverse beam size, twice the x and y RMS value (solid curve), and current (dashed curve) at the target. The time is relative to the time the beam enters the final focusing system. The ends of the beam are not focused well because the current differs from the design current at the beam center.

Preliminary simulations have been carried out of the HIBALL II final focus lattice [12], which consists of two quadrupole triplets. The dipoles in the design have not yet been included in the simulation. In the initial simulations, as much as 80% of the total beam was focused onto a 3 mm spot with vacuum propagation. Fig. 2 shows results from the initial simulations; a smaller fraction of the ends of the beam hits the target. That result is expected since the current is different in the beam ends due to the fall-off of the line-charge density and the velocity tilt which gives the axial compression. We believe that this can be greatly improved with optimization. This work will be described in a forthcoming publication.

4. Conclusions and future plans

We believe that the WARP code will be able to simulate all sections of a driver, from the source to target. Much development has been done toward improved physics models and toward optimization, making such source-to-target simulations realizable. Much support is still needed from other codes, though, for the quick scoping of designs and for examining areas that require physics not yet included in WARP.

Future plans include both continued code development and application. Two major areas of code development required are further optimization and generalization of the mechanisms linking WARP simulations together and to other codes. The primary optimization needed is further development of the massively parallel version of WARP. Much applications work needs to be done, including continuation of existing applications and examination of other sections of various driver scenarios, such as beam combining. We expect that in the near future a much larger fraction of our simulations will employ linkage between the various sections of the driver.

References

[1] A. Friedman, D.P. Grote, I. Haber, Phys. Fluids B 4 (1992) 2203.

[2] D.P. Grote, Methods Used in WARP3d, a Three Dimensional PIC/Accelerator Code. Proc. of the Computational Accelerator Physics Conf., 1996, AIP Conf. Proc. 391, pp. 51–58.

[3] P.F. Dubois, The Basis System, LLNL Document M-225, 1988.

[4] S. Yu, S. Eylon, E. Henestroza, C. Peters, L. Reginato, A. Tauschwitz, D.P. Grote, F. Deadrick, Fus. Eng. Des. 32 (1996) 309.

[5] D.P. Grote, A. Friedman, I. Haber, S. Yu, Fus. Eng. Des. 32 (1996) 193.

[6] S. Lund et al., Nucl. Instr. and Meth. A 415 (1998) 345.

[7] D.P. Grote, Three Dimensional Simulations of Space Charge Dominated Heavy Ion Beams with Applications to Inertial Fusion Energy, University of California, Davis, February, 1994, Doctoral thesis, LLNL Rep., UCRL-LR-119363.
[8] A. Friedman et al., Nucl. Instr. and Meth. A 415 (1998) 455.
[9] J.-L. Vay, C. Deutsch, Fus. Eng. Des. 32–33 (1996) 467.
[10] A.B. Langdon, Comput. Phys. Commun. 70 (1992) 447.
[11] D.A. Callahan, Fus. Eng. Des. 32–33 (1996) 441.
[12] Hiball II, An improved conceptual heavy ion beam driven fusion reactor study, Kernforschungzentrum, Karlsruhe, Rep., KfK3840 1985, p. 58.