BEAM DYNAMICS STUDIES FOR HEAVY ION FUSION DRIVERS*

A. Friedman#, J. J. Barnard, C. M. Celata, G. D. Craig, M. J. L. de Hoon, A. Faltens, D. P. Grote, E. P. Lee, W. M. Sharp, and E. Sonnendrucker+, LBNL/LLNL VNL for Heavy Ion Fusion
I. Haber, NRL
R. A. Kishek, University of Maryland

Abstract

A quantitative understanding of space-charge-dominated beam dynamics issues is essential to the development of a cost-effective driver for heavy-ion beam-driven inertial fusion energy (Heavy Ion Fusion, or HIF). A multi-laboratory "working group" is collaborating to develop such an understanding via detailed computer simulations, benchmarked versus experiments where possible. This work is motivated by the need to plan for an "Integrated Research Experiment" (IRE) facility to be proposed for construction, and for magnetic quadrupole beam transport experiments planned for the very near term. We began by identifying the issues which must be addressed; developing a model IRE design; and conducting "baseline" transverse WARPxy-code simulation studies of the central nominal-energy portion of the beam, for an ideal error-free version of that design. Current work is examining the effects of a wide spectrum of mismatches (including head-to-tail effects), errors, and imperfections, which establish the allowable tolerances and ultimately constrain the design. We are beginning to employ WARP3d to perform integrated time-dependent 3-D simulations from the source through the end of the machine.

1 INTRODUCTION

A successful HIF driver must produce a set of beams with the intensity, brightness, and pulse shape dictated by target requirements. This implies constraints on the ultimate transverse and longitudinal beam emittance. The beam phase space evolves as the beam moves down the accelerator, under the influence of applied-field, space-charge, and image nonlinearities, and of collective modes. Furthermore, it is necessary to minimize beam loss. This translates into limits on the allowable beam halo. Finally, the cost of the accelerator must be minimized, and so the beam must fill as much of the channel as possible. Thus a quantitative understanding of the dynamic aperture and its scaling with beam and accelerator parameters is essential.

Available experimental data is limited, so this effort must make heavy use of simulations and analytic theory, while planning for near-term full-scale magnetic transport experiments. The dynamics issues in a full-scale driver and a next-step IRE are very similar, except that issues associated with the highest beam kinetic energy arise only in the former. Detailed design is more urgently needed for IRE than it is for a driver, and simulations for a shorter system are more readily performed. Thus we are following a balanced approach whereby most calculations are being carried out in the IRE context.

Aspects of this work are presented in more detail in other papers at this conference; please see [1,2,3,4,5].

2 PRELIMINARY ACTIVITIES

As preliminary activities, we first identified a list of issues that must be addressed . These include mismatches and nonlinearities, machine errors, low-energy issues, collective modes, multi-beam and high-energy effects, and required diagnostics. We then developed "an" IRE design to use as the initial object of our studies. This is a "straw person" and is not "the" IRE design; however, a fairly complete "physics design" was needed. Finally, we began simulating a baseline "perfect IRE" accurately and efficiently, at first using a set of 2-D "slice" simulations of the center, head, and tail of the pulse, and most recently in full 3-D. It was deemed important to validate these simulations via convergence studies.

We sought a representative IRE design that would be credible, straightforward, and relatively easy to simulate. The design we developed is similar to an earlier "HTE Update" concept [6], but does not employ beam merging, since a detailed design for a magnetic merging section is not yet available. Relative to the earlier design, the initial pulse is twice as long, and the final kinetic energy is twice as great, so that the same total energy is achieved. This design is embodied in stand-alone scripts (versions using Basis and Python exist), which produce input that can be read by various codes, in particular the WARPxy and WARP3d PIC models, and SLV, a semi-Lagrangian Vlasov model. Some parameters are: initial line charge density $\lambda_1 = 0.25$ μC/m, pulse duration $\tau_1 = 7.33$μs, 32 beams, 30 kJ total, phase advance $\sigma_0 = 70°$, tune depression $\sigma/\sigma_0 = 0.1$, beam radius a = 1.5 cm. Other features of this design are summarized in Table I.

These parameters set requirements on numerical resolution; the sheath at the edge of the beam falls off over 2-3 mm, so the maximum usable cell size is about 1 mm. With four-fold symmetry, we typically employ

---

*Work performed under the auspices of the U.S. DoE by LLNL, LBNL, NRL, and U. Md. under contracts W-7405-ENG-48, DE-AC03-76SF00098, DE-AI02-93ER40799 / DE-AI02-94ER54232 and DEFG0292ER54178.
#Email af@llnl.gov
+On leave from C.N.R.S., IECN – Projet Numath, Université Nancy 1, France.

	l_{beam} (m)	L_{hlp} (m)	I (A)	quad occ.	accel grad.	foc gradient
V_0 = 1.6 MeV	20.6	0.23	0.7	0.6	31	1.5×10^8 V/m^2
elec focusing accelerator: load-and-fire	const	$\propto V^{1/2}$	$\propto V^{1/2}$	0.6	$\propto V$	1.5×10^8 V/m^2
V_1 = 8.3 MeV	20.6	0.5	1.54	jump	148	jump
mag focusing accelerator 1: compression	$\propto V^{-1/2}$	$\propto V^{1/4}$	$\propto V$	0.33	$\propto V$	40 T/m
V_2 = 52 MeV	7.9	0.81	10.4	0.33	1000	40 T/m
mag focusing accelerator 2: const. accel	const	$\propto V^{1/2}$	$\propto V^{1/2}$	$\propto V^{-1/2}$	const	slow variation
V_3 = 200 MeV	7.9	1.59	20.4	0.17	1000	37 T/m

Table I. Parameters of reference IRE design

128 zones along each coordinate axis, then apply spatial filtering to minimize grid "aliasing" (this is important only for beams colder than those studied here); use of 32 zones unfiltered gives roughly similar results. Crude runs in (x,y) geometry require 5000-20,000 particles. Simulations of the baseline case also aided our learning to run WARPxy efficiently; we use the FFT Poisson solver, obtaining a round pipe via the capacity matrix method. We take the same number of steps across each half-lattice period. (HLP). HLP's start and stop at zero-length accelerating gaps, and the step size is changed at those points. We began by using sharp-edged elements and the code's "residence correction" capability which preserves second-order accuracy when the applied fields are so non-smooth. Numerical convergence tests show that with 80,000 particles and 128 cells there is emittance growth only in the second section; with 5000 particles, numerical collisionality causes some spurious growth of about 20%, but even this much is tolerable in the design, and less than that caused by undesirable physical effects, *e.g.*, mismatching of the off-nominal-energy parts of the beam.

3 ISSUES AND PROJECTS

Mismatch effects are associated with: transitions in the lattice period and element dimensions (does use of a small number of element designs lead to more emittance growth than a continuous variation, which may be harder to manufacture?); head-to-tail variations arising from acceleration and compression; and dispersion in bends, primarily in the injector, drift compression, and final focus sections. Nonlinearities of concern are associated with electric-quadrupole applied fields and images; magnetic quadrupole fields, including higher multipoles, and fringe fields (is it sufficient to design magnets that have zero integrated unwanted multipoles, or must cancellation be more local?); accelerating gap fields; and space charge, associated with nonuniform charge density.

We are beginning to examine (or re-examine) all of these areas; for example we employ both capacity-matrix methods (crude) and subgrid-scale boundary conditions (precise, but more expensive) to obtain electrostatic quadrupole fields and image effects. We also are comparing runs using axially-integrated fringe fields (lumped into an element one moderate Δs step long) against runs which resolve the fringing using small steps.

A key goal is the development of tolerance requirements with respect to errors in: beam alignment; magnet strength; magnet position and angle; accelerating waveforms (systematic, ripple and jitter); "ear" waveforms; and sensing / steering. The simulations in Figure 1 show the effect of various magnet errors on the normalized x emittance. Each color is an overlay of five runs with differing errors (obtained by varying the random number "seed"). Table II lists the RMS errors included in each set of runs (and notes whether the pseudo-octupole term is included in the magnet description); from top to bottom the rows in the table correspond to the shaded areas of the plot. The large fluctuations in the upper two plots with rotated quads appear because ε_{Nx}, rather than a generalized emittance, is shown.

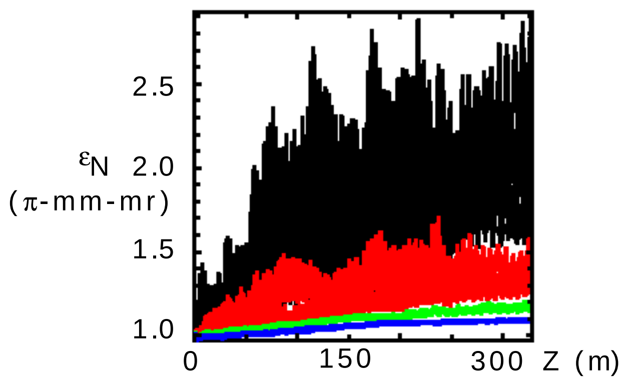

Figure 1. Effects of errors (see text and Table II).

Pseudo-octupole	Offset RMS	Strength RMS	Angle RMS
yes	25 μ	0.1%	0.2°
yes	25 μ	0.1%	0.1°
yes	25 μ	0	0
no	25 μ	0	0

Table II. Errors included in runs in Figure 1.

Low energy issues include: the initial longitudinal capture of the injected beam, using shaped accelerating pulses, and the initial acceleration program (a variant of "load and fire" is currently assumed, but may not be optimal); the competition between longitudinal "accelerative cooling" and collective modes which couple transverse thermal energy into longitudinal thermal energy when the former exceeds the latter; and the relaxation of initial inhomogeneities via the phase-mixing of transverse oscillations. We are learning how to use a fixed computational grid in WARP3d to simulate the injection process, and then when the beam has been fully injected, setting the grid to act as a moving window so that it continually overlays the beam (zones are discarded from the "rear" of the mesh and inserted at the front; the alignment of the computational grid lines with the accelerator remains fixed). It is most rigorous to begin with an injected beam for all runs. However, for convenience it is desirable to learn how to begin simulations at downstream stations, and we are studying how best to do this; for example, we may be able to inject a Maxwell-Boltzmann beam at a "waist" (with correction for envelope convergence/divergence).

Collective mode issues include interactions of the beam with the walls and accelerating modules, especially: proper treatment of effects of voltage-divider shielding plates; longitudinal instability driven by module impedance (there has been much past work on this); and effects of the "beam break-up" mode (BBU). Transverse-longitudinal thermal energy coupling in the main accelerator needs to be better understood; does the seed amplitude matter, or is the beam always "marginally stable" with respect to this mode? If the seed amplitude matters, where does it come from, how big is it, and what are the implications with respect to machine design?

Multi-beam and high-energy issues include assessing the degree to which the separate beams must be kept "identical," understanding the deflections induced by neighboring beams, and the effects of the beam-induced magnetic field. This field can be important in a driver even when $v/c \leq 0.3$ because the self-electric field from neighboring beams may be well-shielded while the self-B is not; thus the "g-factor" which relates E_z to $\partial\lambda/\partial z$ can be driven negative, and space-charge waves may behave in an unfamiliar manner. The implications for longitudinal stability need to be understood. Furthermore, it is likely to be important to treat inductive effects with enough fidelity; to this end we are investigating magnetoinductive (Darwin) models, as well as simplified models motivated by the fact that (to a good approximation) the beam produces only a longitudinal current.

An early assessment of the required diagnostics will be important to the upcoming experiments; we must determine how often to measure the beam, in both the IRE (a research tool which must afford detailed knowledge of beam behavior through extensive diagnostics) and a driver (which needs just those diagnostics required for machine operation). Techniques for diagnosing beams at high kinetic energy must be developed.

4 DISCUSSION

We must refine the model IRE design. At the electric-to-magnetic transition, there is a jump in focusing strength experienced by the "off-energy" head and tail of beam, so we may take out the velocity "tilt" in advance, and then reintroduce a larger tilt to initiate longitudinal bunch compression; alternatively, we can perhaps achieve "matching" via time-varying quadrupoles. Our near-term goal is to simulate the IRE in full 3D, including detailed accelerating waveforms and a realistic beam.

To properly model a fusion system it will be essential to perform integrated calculations. We must carry the particle distribution coming out of each accelerator section into the subsequent section, because the beam already has internal structure as it emerges from the injector, and disturbances can propagate long distances. Furthermore, the beam must have a particular pulse shape on target; hence it has a time-varying energy distribution and transverse distribution function, and the optical aberrations will be time-varying. Time-varying currents in the chamber affect the focusing, and must be modeled consistently with partial neutralization and other effects. Links have been made between WARP runs; linkages to the chamber code BIC, and thence to the target code LASNEX, exist, but have yet to be employed. It will also be desirable to establish links between the long-time beam transport calculations and detailed simulations studying instabilities, halo formation, and other effects. We believe that source-to-target simulation of a driver is within reach on upcoming "terascale" computers. A schematic for such simulations is depicted in Figure 2.

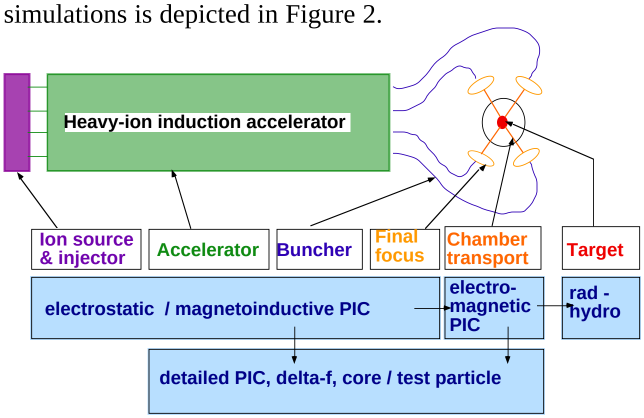

Figure 2. Schematic of driver and computational models.

5 REFERENCES

[1] C. M. Celata, J. J. Barnard, and M. J. L de Hoon,, "Effects of Misalignments on Space-Charge-Dominated Heavy Ion Beams in an IRE," paper TUP133, this conference.
[2] R. A. Kishek, J. J. Barnard, and D. P. Grote, "Effects of Quadrupole Rotations on the Transport of Space-Charge-Dominated Beams: Theory and simulations Comparing Linacs with Circular Machines," paper TUP119, this conference.
[3] W. M. Sharp, D. P. Grote, and D. L. Judd, "Shaping and Focusing of High-Current Pulses for Heavy-Ion Fusion," paper TUP145, this conference.
[4] D. P. Grote, et. al., "3-D Simulations Studies of IRE designs," paper THA61, this conference.
[5] E. Sonnendrucker, A. Friedman, and D. P. Grote, "Progress toward simulations of heavy ion beams for Inertial Fusion Energy based on a Darwin model field solver," paper THA64, this conference.
[6] A. Faltens, "HTE Update," LBNL note HIFAR 468, May 3, 1996.