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Issues and Opportunities: Beam Simulations for Heavy Ion Fusion

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Issues and Opportunities: Beam Simulations for Heavy Ion Fusion*

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Issues

The physics of the beams in an HIF system is a complex interplay between the applied confining fields, the beams' intense space charge, and their environment. In the driver, key issues include emittance growth (phase space dilution); "halo" generation; instabilities; and stray electrons. In the fusion chamber, key issues include beam spreading due to emittance and space charge; beam stripping, neutralization, photoionization by x-rays from the target, and instabilities (all of which affect the spreading rate); inductively driven return currents; and multi-beam effects.

Status

Both "fluid" and "kinetic" models are in regular use. Codes based on truncated moment equations are key accelerator design tools due to their speed. One such code, CIRCE, solves the "envelope" moment equations for each of hundreds of transverse slices, and couples them longitudinally via Lagrangian fluid equations. CIRCE is used for setting error tolerances; studying beam sensing, steering, longitudinal control; and synthesizing accelerating waveforms. However, the model does not incorporate "nonlinear" (anharmonic) transverse fields, and so cannot capture emittance growth or phase-mixing of "mismatch" oscillations.

Most work has been done using particle-in-cell (PIC) simulations. WARP is an electrostatic code offering 3-D, axisymmetric, and "transverse slice" (steady flow) geometries, with a hierarchy of models for the "lattice" of focusing, bending, and accelerating elements. Interactive and script-driven code steering is afforded through an interpreter interface. The code runs with good parallel scaling on the T3E. Detailed simulations of machine segments and of complete small experiments, as well as simplified full-system runs, have been carried out, partially benchmarking the code. A magnetoinductive model, with module impedance and multi-beam effects, is under study.

In the chamber, explicit electromagnetic PIC codes BIC and BPIC in axisymmetric and 3-D geometry are in use. IPROP offers implicit PIC as well as a fluid/particle hybrid electron model, and will be more suitable for dense-background cases.

Newer methods under development and coming into use include the "delta-f" code BEST, which will be used for detailed physics studies (especially instabilities and electron effects) in both driver and chamber; the code is being parallelized. A 2-D semi-Lagrangian continuum Vlasov code which represents well the low-density regions of phase space has been developed and will be used as a check on the particle models.

Tasks to be done

Simulations must play a key role in the design and support of ongoing and near-term experiments, including an injector scalable to multi-beam arrays, a high-current beam transport and acceleration experiment, and a scaled final-focusing experiment. These "phase I" projects are laying the groundwork for the next major step in HIF development, the Integrated Research Experiment (IRE). Simulations aimed directly at the IRE must enable us to: design a facility with maximum power on target at minimal cost; set requirements for hardware tolerances, beam steering, etc.; and evaluate proposed chamber propagation modes. Finally, simulations must enable us to study all issues which arise in the context of a fusion driver, and must facilitate the assessment of driver options. In all of this, maximum advantage must be taken of emerging terascale computer architectures, requiring an aggressive code development effort. An organizing principle should be pursuit of the goal of integrated and detailed source-to-target simulation.

Suggestions for accomplishing goals

Source-to-target simulation of the beams in an HIF driver and fusion chamber is a key goal of the HIF program. Such a capability is also a major element of the Fusion Energy Strategic Simulation Initiative proposal, which is currently being developed; should funding through that source become available, highly detailed 3-D simulations will be available much sooner. Even on the new next-generation NERSC machine, source-to-target simulations with good fidelity will be possible, provided HIF receives a sufficiently increased share of the allocated computer time.

An effective source-to-target simulation effort must depend heavily on discrete-particle methods for analysis of the beam dynamics in the various machine concepts, using moment-based methods for purposes of design, waveform synthesis, steering algorithm synthesis, etc. Three classes of discrete-particle models should be coupled: (1) electrostatic/magnetoinductive PIC simulations should track the beams from the source through the final-focusing optics, passing details of the time-dependent distribution function to (2) electromagnetic or magnetoinductive PIC or hybrid PIC/fluid simulations in the fusion chamber (which would finally pass their particle trajectory information to the radiation-hydrodynamics codes used for target design); in parallel, (3) detailed PIC, delta-f, core/test-particle, and perhaps continuum Vlasov codes should be used to study individual sections of the driver and chamber very carefully; consistency may be assured by linking data from the PIC sequence, and knowledge gained may feed back into that sequence. The following table summarizes what is possible:

	Present day (0.5 TF)	At terascale (5 TF)
Driver, pulse compression, final focus	end-to-end 2-D "multi-slice" simulations of IRE beams; 3-D of parts of driver; run linking	integrated 3-D particle simulations of IRE and driver from source to fusion chamber
Chamber propagation	chamber propagation studies using axisymmetric (r,z) electromagnetic particle codes	chamber propagation in 3-D; linkage from driver simulation; multi-beam effects
Detailed studies	studies of halos and beam-plasma instabilities using idealized initial conditions	linking of end-to-end run data into halo and instability calculations to ensure fidelity

To make these advances, we must adapt existing codes to the emerging computer architectures, improve their physics, and link them to each other. Hierarchical memories will require multiple levels of parallelism. The physics demands improved and more complex models to describe self-magnetic fields, module impedances, and multi-beam effects. End-to-end simulation requires flexible model linkage, drawing upon scripting systems (*e.g.*, Python); workspace tools (*e.g.*, PAWS) for linking separate codes while they are actually running; and self-describing data files in standard formats (*e.g.*, NetCDF). Other advanced computational methods should be explored, *e.g.*, incorporating force-averaging methods into the PIC calculations to allow larger timesteps, evaluating higher-order methods, and perhaps incorporation of kinetic effects into moment models. This last is challenging because entrainment of empty phase space must be faithfully captured, but it merits study since the payoff might be quite significant.

Finally, benchmarking of codes (and theory) versus experiments will offer essential reality checks. The use of a hierarchy of models will be very helpful for cross-benchmarking, as well.

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