Intense Ion Beams for High Energy Density Physics and Inertial Fusion Energy:

The U.S. Heavy Ion Fusion program is developing intense beams of heavy ions as drivers that can heat matter to the regime of High Energy Density Physics (HEDP), that is, 10^{11} J/m^3 or greater. Near-term beam applications will center on fundamental physics studies of the Warm Dense Matter (WDM) regime, enabled by the unique energy deposition properties of heavy ions in matter whereby the heating can be both volumetric and shockless. Indeed, ion drivers promise a means for the thorough exploration of the entire HEDP region of the temperature-density parameter space. In the longer term, because ion beams can be created efficiently and focused by electromagnetic lenses that can be robust to the effects of target explosions, a number of studies and reviews have concluded that intense beams of heavy ions represent an attractive approach to Inertial Fusion Energy: Heavy Ion Fusion, or HIF.

The WDM regime corresponds to densities of ~.01 to 10 times solid density and temperatures ~0.1 to 10 eV. Here, the space charge potential energy of neighboring ions is of the same order as, or somewhat greater than, the ion thermal energy; the traditional "weak-coupling" assumption of ordinary plasmas breaks down and theoretical descriptions become more complex. Exploring this regime experimentally is thus critical to assessment of the various theoretical models. Establishing the equation of state and transport properties in this regime is of considerable importance not only for its intrinsic scientific value and its relevance to inertial fusion target physics, but also because understanding these quantities is crucial to the quantitative understanding of the structure of planets and stars. The HIF program in the U.S. plans to use ion beams to heat thin foils uniformly, with beam energy deposition occurring as the ions slow down through their Bragg peak energy. Complementary programs in Germany, Japan, and Russia are centered on the use of higher-energy ions depositing a small fraction of their energy in long cylindrical targets.

Both the beams themselves, and their interactions with the targets they heat, require extensive simulations for a full understanding. The target interaction studies are similar in many regards to those carried out in the larger Inertial Confinement Fusion program, and indeed rely to a large degree on the same computational tools. The key question in Heavy Ion Fusion beam science is: "*How do intense ion beams behave as they are accelerated and compressed into a small volume in space and time?*" Here, the challenges and opportunities associated with simulating these beams are described briefly.

Intense ion beams are non-neutral plasmas and exhibit collective, nonlinear dynamics that must be understood using the kinetic models of plasma physics. This physics is rich and subtle: a wide range in spatial and temporal scales is involved, and effects associated with instabilities and non-ideal processes must be understood. Ion beams have a long memory, and initialization of a simulation at mid-system with an idealized particle distribution is often unsatisfactory; thus, a key goal is to develop and extensively exploit an integrated and detailed source-to-target beam simulation capability. Major issues include:

Long-term evolution of space-charge-dominated beams: The beams are accelerated by inductive electric fields, and confined by applied "focusing" fields. The dynamics are mainly governed by a balance between applied fields and space charge forces, and are

Liouvillean (collisionless): the phase space density remains constant along particle orbits. As a result, emittance growth (dilution of the phase space) takes place through complicated distortions driven by collective processes, imperfect applied fields, image fields from nearby conductors and inter-beam forces. Such dilution must be minimized, because of the need to focus the beams onto small (1 to a few mm) focal spots on the targets. This area is challenging because of the need for an efficient but detailed description of the applied fields, and the needs for good statistics and mesh resolution.

Beam halo generation and multispecies effects in driver: Oscillations of the beam core can parametrically pump particles into an outlying, or halo, population. To avoid the adverse effects of ions impinging on walls, beam halo must be kept minimal. Here, PIC methods have been used, but emerging nonlinear-perturbative and continuum-Vlasov methods may offer advantages. A new and comprehensive set of models of the physics of stray electron "clouds" and gas in positive-particle accelerators is well along in development. These models account for the complex set of interactions among the various species, with the walls, and with the applied and self-fields. This area is computationally challenging because of the ratio between the time scales for electron motion and those for electron build-up. To this effect we have developed a new large-timestep electron "mover" that smoothly interpolates between direct-orbit and drift formulations as the magnetization of the electrons varies.

Beam interactions with target chamber environment: 3-D simulations of the propagation of beams through the final focusing optics, and onward through the target chamber's environment of gas and plasma, are required in order to provide a realistically complete model of the target illumination. The beam and background plasma dynamics include: multibeam effects; return current formation and dynamics (streaming instabilities); imperfect neutralization; beam stripping; emittance growth; and photo-ionization of the beam ions and background gas. Multiple-beam interactions near the target will be one focus of research efforts; collective instabilities, such as resistive hose, filamentation and two-stream modes, will be another. Here, the challenges include the needs for complex physics models, outgoing-wave boundary conditions, and an implicit hybrid model (*i.e.*, a blend of fluid and discrete-particle electrons). An implicit electromagnetic (EM) field model (which can stably under-resolve fast time scales not essential to the physics) or a magneto-inductive (Darwin) model that eliminates light waves, is also needed.

Representative images from simulations of a variety of problems are shown in Figure X.. The principal computer codes have been adapted to NERSC's parallel computers, and achieve good scaling. However, since simulation needs are progressing toward self-consistent full-system studies, and multi-species effects must be understood, the research effort stands to benefit greatly from a qualitative increase in available computational resources. A detailed end-to-end particle-in-cell simulation of a single full-scale beam, in a full-scale general HEDP facility or inertial fusion driver, will require 10^8-10^9 particles, 10^5-10^6 time steps, and a (moving and adaptive) 3D computational grid of order 10^9 mesh points or more. This estimate assumes success in the development of an improved large-timestep electron mover, and the use of optimized parallel Adaptive Mesh Refinement with Particle-In-Cell dynamics (AMR-PIC, a technique pioneered by the HIF program). Thus, simulations to date have covered only sections of a system, and in most cases have used approximate models, e.g., neglecting stray electrons.

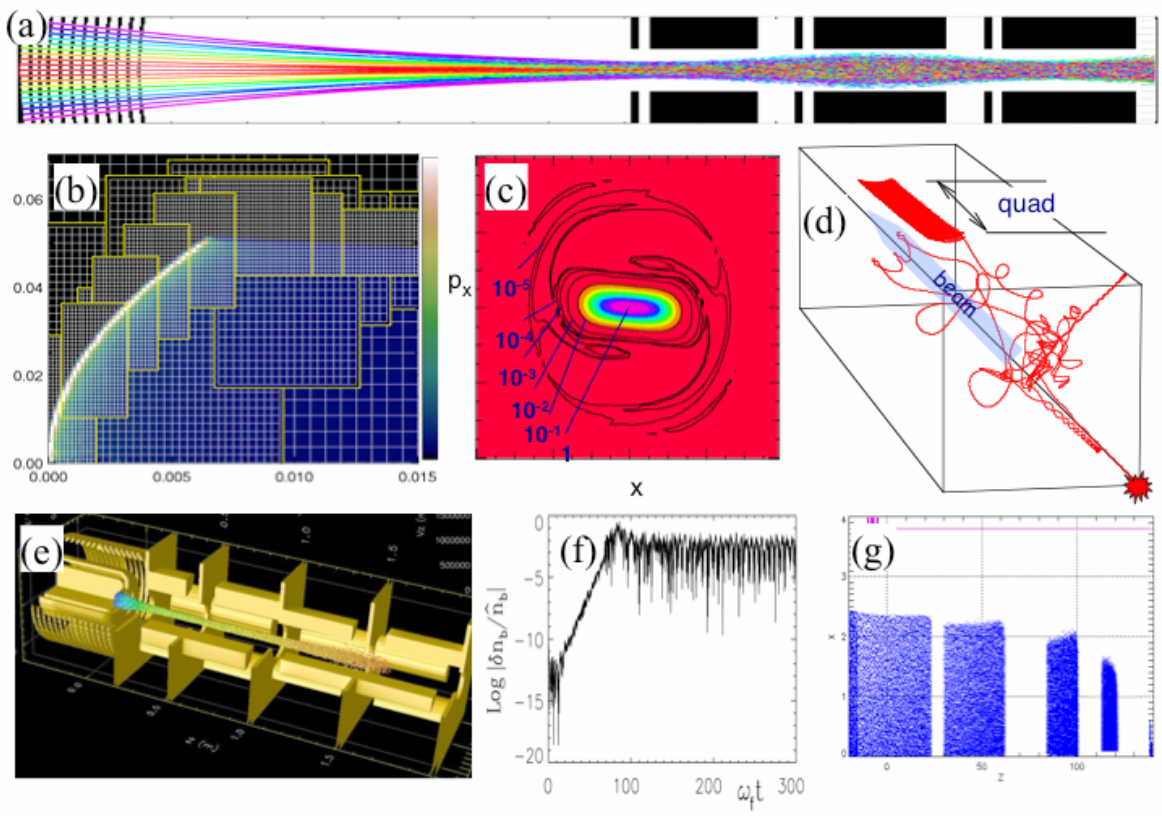

Figure X. Representative output from beam simulations carried out in Heavy Ion Fusion program: (a) Simulation of merging-beamlet intense-beam ion injector experiment at LLNL; (b) expanded view of a WARP3d simulation of the injector diode in the HCX experiment at LBNL, showing mesh-refinement patches; (c) semi-Lagrangian Vlasov simulation of beam halo generation due to anharmonic applied fields, using prototype model in WARP-SLV; (d) WARP3d simulation of a stray-electron orbit in a quadrupole magnet and adjacent regions; (e) WARP3d particle-in-cell simulation of space-charge-limited emission off a curved surface, and acceleration in the 3-D structure of the HCX injector, including sub grid-scale placement of conductor boundaries (cut-cell method); (f) BEST nonlinear-perturbative simulation of electrostatic anisotropy-driven beam mode, showing linear growth and saturation; and (g) LSP simulation of neutralized pulse-compression and focusing in support of upcomind NDCX experiments at LBNL. (A. Friedman, Heavy Ion Fusion Virtual National Laboratory, a partnership among LBNL, LLNL, and PPPL)