Topic: IF

Simulation of Chamber Transport for Heavy-Ion Fusion*

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In a typical thick-liquid-wall scenario for heavy-ion fusion (HIF), between twenty and two hundred high-current beams enter the target chamber through ports and propagate about three meters to the target. They first heat the target for about 30 ns, then deposit a total of 3-7 MJ in the final 8-10 ns. Since crisscrossed molten-salt jets are planned to protect the chamber wall, the beams move through vapor from the jets, and collisions between beam ions and this background gas both strip the ions and ionize the gas molecules. Radiation from the preheated target causes further stripping and ionization. Due to this stripping and photoionization, beams for heavy-ion fusion are expected to require substantial neutralization in a target chamber. Simulations with no electron sources other than beam stripping and background-gas ionization show an acceptable focal spot only for beam currents far below the values assumed in recent HIF drver scenarios. Much recent research has, therefore, focused on beam neutralization by electron sources that were neglected in earlier simulations, including emission from walls and the target, photoionization by the target radiation, and pre-neutralization by a plasma generated along the beam path.

The principal computer code used for these chamber-transport simulations is LSP, a multi-region and multi-species electromagnetic simulation code with a large palette of particle models, boundary conditions, and physical interactions. The code employs a number of unconventional techniques that allow it to treat higher gas densities than typical particle-in-cell codes. An implicit integration step permits the use of a longer integration step than that prescribed by the Courant condition; particles are merged as needed to maintain a tractable particle count; the use of spatially extended particles can decrease statistical noise; and an optional hybrid particle/fluid electron model reduces artificial heating at higher densities. LSP results are cross-checked where possible using BICrz, an older axisymmetric code with an explicit integration step, and analytic calculations provide further code verification. Although most LSP chamber-transport simulations to date have treated only a single axisymmetric beam with an idealized initial particle distribution, the code is designed to model complicated three-dimensional geometries, and it can be initialized with realistic beam

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profiles from other codes. Some aspects of the chamber environment, such as the molten-salt jets and multiple ionization of the background gas, have not yet been incorporated into LSP simulations, but preliminary calculations indicate that these omissions do not seriously compromise the results.

Emission from surfaces is, by itself, an ineffective means of beam neutralization. Electrons pulled off the chamber walls and entry ports are attracted by the beam space-charge field, gaining an energy that can exceed 10^5 eV. Due to this thermal energy, many of these electrons escape the beam as it converges to the target. In simulations that allow Child-Langmuir emission from walls, we see some initial improvement in neutralization, but this difference disappears during chamber transport, so the final spot size is only slightly improved. Emission from the target is likewise ineffective at neutralizing an impinging beam because the target surface quickly develops a large positive potential that curtails the further escape of electrons. Simulations with target emission show that the focal spot is virtually unaffected by the process.

As an indirect-drive HIF target is heated, it begins emitting soft X rays that photoionize the surrounding background gas. For reasonable gas densities, the resulting plasma is predicted to provide effective neutralization near the target for later-arriving pulses. Preliminary single-beam simulations including this photionized plasma indicate that self-pinching occurs near the target for a sufficiently high current, producing a focal spot comparable with that of a fully neutralized beam.

Pre-neutralizing beams with highly ionized plasma near the chamber entry ports has been studied for a wide range of plasma, beam, and chamber parameters. When the background-gas density is low enough that the characteristic length for ionization is comparable to the chamber radius, pre-neutralization is found to reduce significantly the beam spot size and emittance growth in the chamber. This technique is particularly valuable for the reduced-current “foot” pulses that heat the target initially, since these beams must reach the target without additional neutralization from photoionization. For the 870 A, 3-GeV Pb^{+1} foot pulse shown in the figure, 90% of the beam falls within a 3-mm spot on the target, compared with about 60% without pre-neutralization.

Preliminary runs have also been made simulating multiple-beam effects and beam instabilities in a chamber. These areas are expected to be more fully explored in coming years as numerical models evolve.