Advances in U.S. Heavy Ion Fusion Science* IAEA-08 Topic 1F

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Abstract

During the past two years, the U.S. heavy ion fusion science program has made significant experimental and theoretical progress in simultaneous transverse and longitudinal beam compression, ion-beam-driven warm dense matter targets, high-brightness beam transport, advanced theory and numerical simulations, and heavy ion target physics for fusion. First experiments combining radial and longitudinal compressionπ of intense ion beams propagating through background plasma resulted in on-axis beam densities increased by 700X at the focal plane. With further improvements planned in 2008, these results enable initial ion beam target experiments in warm dense matter to begin next year. We are assessing how these new techniques apply to higher-gain direct-drive targets for inertial fusion energy.

1. Combined transverse and longitudinal compression of beams within neutralizing plasma:

In 2007, the Neutralized Drift Compression Experiment (NDCX) combined neutralized drift compression with the previous induction bunching module imparting a head-to-tail velocity ramp for compression [1], together with a new final focusing solenoid (FFS) and a new target chamber. The target focal plane beam diagnostics were a multiple-pinhole Faraday cup, and a scintillator (the light emission of which was detected using a gated CCD camera). Figure 1 shows the beam profile with and without the FFS energized. Full-width half-maximum (FWHM) spot sizes of 2 mm and 3 mm were measured when the FFS field was 5T and 0 T, respectively. The peak intensity corresponds to a beam density $\approx 2.6 \times 10^{11}$ cm^{-3}, about 700 times the upstream beam density before compression. The simulations [2, 3] suggest the background plasma density may not be sufficient for complete charge neutralization of the ion beam pulse. Repeating these experiments with increased plasma density, a new induction bunching module capable of compressing twice as much ion beam charge from the injector, and a higher field 8 T focusing magnet will be reported. These techniques in neutralized beam compression enable first warm dense matter target experiments in 2008, and high-gain direct-drive target concepts with low range ions.

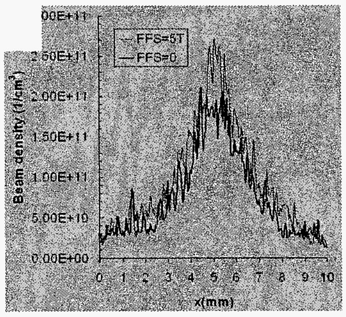

Figure 1: Beam density profiles at the target focal plane with the final focus solenoid on (FFS=5T) and off (FFS=0). The corresponding focal spot FWHM = 2 mm with FFS=5T and 3 mm with FFS=0.

2. Warm dense matter experiments: joint US German experiments at GSI: Joint HIFS-VNL and GSI warm dense matter experiments were performed in the HHT area of GSI (December, 2006) to develop target diagnostic instruments and methods for different beam-target configurations for equation-of-state (EOS) studies near the two-phase liquid-gas and the critical point regions. The effect of pore size on the behavior of porous and solid-density gold and copper targets was studied by measuring the target temperature as a function of pore size and comparing with model predictions of the physics of porous targets. The analysis of experimental results and hydrodynamic simulations will be reported.

3. Progress in e-cloud research Experiments were performed to study e-cloud effects on the transport of a space-charge dominated ion beam in the solenoid transport channel used in the Neutralized Drift Compression Experiment (NDCX). Cylindrical electrodes were placed in gaps between the magnets, and intercept the magnetic flux that expands between magnets and passes through the outer half of the beam radius in the center of the solenoids. These electrodes are biased positively to remove electrons. Short electrodes are provided in the center of each solenoid; these electrodes are biased negatively, in the clearing mode, to expel electrons from the solenoids. The biases can be reversed for a trapping mode: negatively-biased gap electrodes emit electrons due to ion or photon impact and repel trapped electrons, and positively-biased solenoid electrodes trap electrons in the center of each solenoid magnet. Images of the transverse beam structure taken about 5μs into a 10μs beam pulse with a 10-ns gate showed a clear difference between the clearing and trapping bias patterns. When the electron population is minimized in either the solenoids or the magnetic quadrupoles, we find that the measured beam envelope agrees well with simulations [4].

4. Advances in theory and integrated simulations Much progress in analytical and numerical studies of intense ion beams and their interaction with background plasma [5] has been made in the past two years. Selected advances include: (a) development and application of optimized analytical and particle-in-cell simulation models for intense ion beam charge and current neutralization in solenoidal and dipole magnetic field configurations; (b) development and application of advanced kinetic and macroscopic warm-fluid models to describe longitudinal drift compression and pulse shaping in intense heavy ion beams; (c) development of criteria to minimize halo particle production during the transverse compression of intense charged particle beams, including benchmarking of criteria with WARP simulations; (d) continued improvement and optimization of ionization cross-section models for ion–atom interactions for a wide range of ion and atomic species; (e) development of optimized input distribution functions for advanced particle-in-cell simulations of charged particle beams at high space-charge intensity; (f) advanced LSP numerical simulation studies aimed at optimizing the simultaneous longitudinal and transverse focusing of intense ion beam pulses and neutralizing plasma flows for warm dense matter applications; and (g) non-invariance of the range of space and time scales under a Lorentz transformation has been applied to gain an order of magnitude speedup for the calculation of the interaction of relativistic beams with plasma and/or electron clouds.

5. Applications to heavy ion fusion The success of strong transverse and longitudinal beam compression in neutralizing plasma enables the application of heavy ion beams to direct drive in the ablative rocket regime. A simple analytic implosion model with a heavy-ion dE/dx deposition model, together with hydrodynamic implosion calculations using both LASNEX and HYDRA [6], have been used to explore the characteristic beam requirements for heavy ion direct drive in the ablative regime, for small, 1 MJ-drive, DT targets as well as for larger, tritium-lean (> 90% DD) targets needing 5 MJ drive energy. Ion beams can couple 100 % of their incident energy into hydrogen or DT ablators (most electrons per unit mass), which also have the lowest specific ionization energy << $u^2_{ex}/2$. However, ion beams can also suffer greater parasitic energy loss when passing through ablation corona plasmas compared to laser or x-ray drive photons, despite the dE/dx Bragg peak near the end of the ion range. Increasing the ion energy during the drive pulse (synergistic with velocity ramps used to drift compress the neutralized beams) can reduce the parasitic beam losses on ablated plasma. Low adiabat implosions are found possible with an initial ion beam range selected to be 25 % of the initial ablator ρr. Overall beam-to-fuel coupling efficiencies exceeding 15% are found for small targets driven by 1 MJ of 50 MeV Argon ion beams. This is 4 to 8 times better coupling than that of any hohlraum target, and twice that of any laser direct-drive target, despite major parasitic beam losses (which can be further reduced by optimizing parameters in planned future work. Shock timing control with direct ion drive is sufficient for low adiabat implosions with $\alpha<1.5$ enabling gains of about 50 at 1MJ (adequate for accelerators of >20 % efficiency), with higher gains possible with more fuel mass.

6. References

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* This research was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC02-05CH11231 and W-7405-Eng-48, and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.