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Heavy-Ion-Fusion-Science: Summary of U.S. Progress*

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Over the past two years noteworthy experimental and theoretical progress has been made towards the top-level scientific question for the U.S. program in Heavy Ion Fusion Science and High Energy Density Physics: "*How can heavy ion beams be compressed to the high intensity required to create high energy density matter and fusion conditions?"* [1]. New results in transverse and longitudinal beam compression, beam-target interaction, high-brightness transport, beam production, as well as a new scheme in beam acceleration will be reported.

Longitudinal and Transverse Beam Compression: The Neutralized Transport Experiment (NTX) demonstrated transverse beam density enhancement by a factor greater than 100 when an otherwise space-charge dominated ion beam was neutralized by a plasma source [2]. This experiment was followed by the Neutralized Drift Compression Experiment (NDCX) in which an ion beam was longitudinally compressed by a factor of 50 [3]. This was accomplished by applying a linear head-to-tail velocity "tilt" to the beam, and then allowing the beam to drift through a meter-long neutralizing plasma. In both the transverse and longitudinal experiments, extensive 3-D simulations, using LSP, were carried out, and the agreement with experiments was excellent [4]. A three-dimensional kinetic model for longitudinal compression was developed, and it was shown that the Vlasov equation possesses a class of exact solutions for the problem [5].

Beam-Target Interaction: We have also made significant progress in identifying the unique role ion beams can play in heating material to warm dense matter (WDM) conditions. We have identified promising accelerator, beam, and target configurations, as well as new experiments on material properties. It is shown that the target temperature uniformity can be maximized if the ion energy at target corresponds to the maximum in the energy loss rate dE/dX [6]. Ions of moderate energy (~ a few to tens of MeV) may be used. The energy must be deposited in times much shorter than the hydrodynamic expansion time (~ns for metallic foams at 0.01 to 0.1 times solid density). Hydrodynamic simulations [7] have confirmed that uniform conditions with temperature variations of less than a few per cent can be achieved.

High-Brightness Transport: Unwanted electrons can lead to deleterious effects for high-brightness ion beam transport. We are studying electron accumulation in quadrupole and solenoid beam transport systems. Electrons can originate from background gas ionization, from beam-tubes struck by ions near grazing incidence, and from end-walls struck by ions near normal incidence [8]. In parallel with the experimental campaign, we have developed and implemented in WARP 3D a new approach to large time-step advancement of electron orbits, as well as a comprehensive suite of models for electrons, gas, and wall interactions [9]. If sufficient electrons are accumulated within the beam, severe distortion of the beam phase space can result. Simulations of this effect have reproduced the key features observed in the experiments.

Beam Production: The merging-beamlet injector experiment recently completed demonstrates the feasibility of a compact, high-current injector for heavy ion fusion drivers. In our experiment, 119 argon ion beamlets at 400 keV beam energy were merged into an electrostatic quadrupole channel to form a single beam of 70 mA. The measured unnormalized transverse emittance (phase space area) of 200-250 mm-mrad for the merged beam met fusion driver requirement. These measurements are in good agreement with our particle-in-cell simulations using WARP3D [10]. We have also completed the physics design of a short-pulse injector suitable for WDM studies.

Beam Acceleration: A new concept for acceleration, the Pulse Line Ion Accelerator PLIA [11], offers the potential of a very low cost accelerator for WDM studies. It is based on a traveling wave structure, using a simple geometry with a helical conductor. We have obtained experimental verification of the predicted PLIA beam dynamics. Measured energy gain, longitudinal phase space, and beam bunching are in good agreement with WARP3D simulations.

Computational Models and Simulator Experiments: The pioneering merger of Adaptive Mesh Refinement and particle-in-cell methods [12] underlies much of the recent success of WARP3D. BEST, the Beam Equilibrium Stability and Transport code was optimized for massively parallel computers and applied to studies of the collective effects of 3D bunched beams [13] and the temperature-anisotropy instability [14]. Space-charge-dominated beam physics experiments relevant to long-path accelerators were carried out on the recently completed University of Maryland Electron Ring, and on the Paul Trap Simulator Experiment at PPPL.

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