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Abstract: New and unpublished results are reported on ion-beam-driven warm dense matter (WDM target physics on the Neutralized Drift Compression Experiment (NDCX-I) using polarization-sensitive fast optical pyrometry, on intense beam neutralization in strong magnetic fields, on simulations with novel pulse compression to a few-hundred picoseconds in a new, 100 X more powerful facility (NDCX-II) now under construction, and on first 2-D implosion calculations of fuel assembly and fast ignition using heavy ion beams.

Ion-beam-driven warm dense matter target physics and diagnostics. Intense beams of focused, neutralized 300 keV K+ ions in the present NDCX-I facility have induced rapid bulk heating of 100 nm thick target foils to temperatures up to ~4500 K (0.4 eV). The mechanism of target heating is described by a simple model of the equilibrium between energy input from the beam and energy loss from the surface of the target due to processes such as vaporization of the target material. Our warm dense matter (WDM) target chamber (Fig. 1) supports a suite of target diagnostics, including a fast multi-channel optical pyrometer, an optical streak camera, VISAR, and high-speed gated cameras, which we have applied to diagnose volumetrically heated WDM targets driven by ion beams.

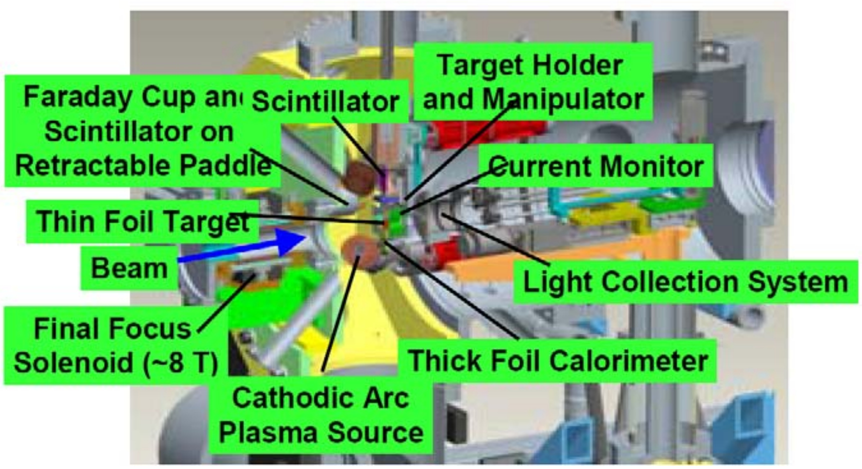

Figure 1: The current target chamber and beam diagnostic station for the NDCX-I beamline will be used during commissioning of NDCX-II in 2012

The NDCX-I environment is conducive to repetitive target experiments for detailed study of target behavior under various conditions and using multiple diagnostics. Figure 2 shows spectroscopic evidence for the formation of liquid metal droplets on the microsecond time scale. These experiments are expected to clarify the process of droplet formation in metal targets under WDM conditions, and the properties of the subsequent debris shower. These results may find wide application in areas such as simulating volumetric neutron heating in inertial confinement fusion facilities, and applications of liquid metal droplets.

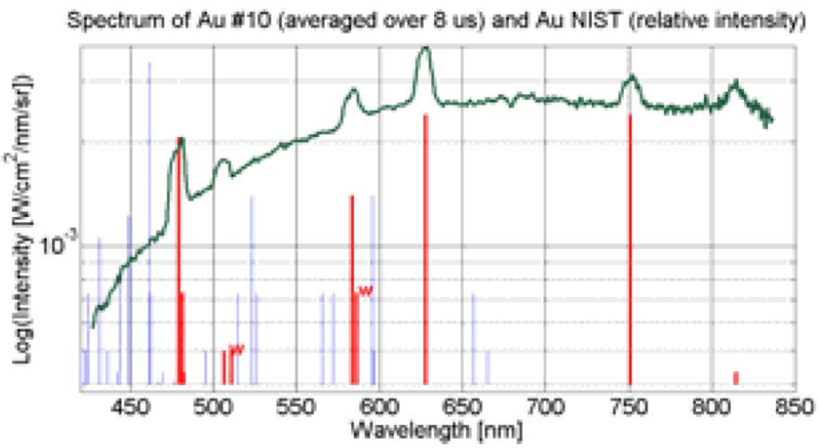

Figure 2: Au I lines (from NIST tables) atop the continuous radiation emanating from liquid gold droplets indicate the presence of both liquid and vapor states in NDCX-II heated 100nm-thick gold foils.

We are developing multi-wavelength and polarization-sensitive pyrometry to observe frequencies below the critical frequency, predominantly emitted from regions where the density and ion charge state correspond to a plasma frequency equal to the frequency of the observed radiation. By comparing the pyrometer data for the evolution of the critical density surface versus time for each of several wavelengths, and comparing results of hydrodynamic simulations using different equations of state, material properties can be inferred.

Advanced heavy ion beam theory and numerical simulations. Significant theoretical progress has been made since the 2008 IAEA meeting in support of present and planned experiments on NDCX-I and NDCX-II. These studies have included: (a) advanced particle-in-cell simulation studies aimed at optimizing the simultaneous longitudinal and transverse focusing of intense ion beam pulses for warm dense matter applications [1, 2], and advanced plasma flow simulations of cathodic-arc and ferroelectric plasma sources for neutralized drift compression [3]; (b) detailed theoretical investigations of the dynamic stabilization of the two-stream instability during longitudinal compression of intense charged particle beam propagation through background plasma [4, 5]; (c) development and application of optimized analytical and simulation models for intense ion beam charge and current neutralization in solenoidal and dipole magnetic field configurations [6, 7], and identification of regimes of enhanced self-focusing of an intense ion beam propagating through a background plasma along a solenoidal magnetic field [8, 9]; (d) development of improved analytical and advanced nonlinear perturbative simulation models using the BEST code, including detailed 3D investigations of collective effects and the Harris and Weibel instabilities in intense anisotropic ion beams, and the effects of finite-length charge bunches [10]; (e) detailed theoretical investigations of the collective instabilities for intense beam propagation through background neutralizing plasma [11], such as the multi-species two-stream and electromagnetic Weibel instabilities, including a determination of conditions to minimize the deleterious effects of the instabilities and the preparation of a formulary of instability growth rates [12]; (f) continued improvement and optimization of ionization cross-section models for ion–atom interactions for a wide range of ion and atomic species [13, 14]; (g) development of a self-consistent theoretical model describing the envelope and centroid dynamics of an intense ion beam in an transverse focusing lattice and oscillating wobbler field [15, 16] to be used for beam smoothing and instability suppression; and (h) development of optimized input distribution functions for advanced particle-in-cell simulations of charged particle beams at high space-charge intensity [17].

We have developed the physics design of the new NDCX-II facility using discrete-particle simulation models (1-D, 2-D, and 3-D) to faithfully capture the space-charge-dominated beam dynamics including realistic acceleration waveforms and such effects as magnet misalignments [18]. A novel approach to rapid beam compression and acceleration has been developed by using an initial non-neutralized compression to render the beam short enough that existing high-voltage pulsed power can be employed. This compression is first halted and then reversed by the beam's space-charge field. Downstream induction cells provide further acceleration and impose a head-to-tail velocity gradient that enables final neutralized compression to a full-width half-maximum duration of less than 1 ns on the target. The energy deposition rate in NDCX-II is projected to rise quickly enough to generate shocks in aluminum. Figure 3 shows WARP PIC simulations of minimum compressed beam pulse durations on target in NDCX-II as a function of the number of acceleration cells that will be added to the accelerator in stages- minimum pulses below 400 ps are predicted, decreasing with increasing ion energy as acceleration modules are added.

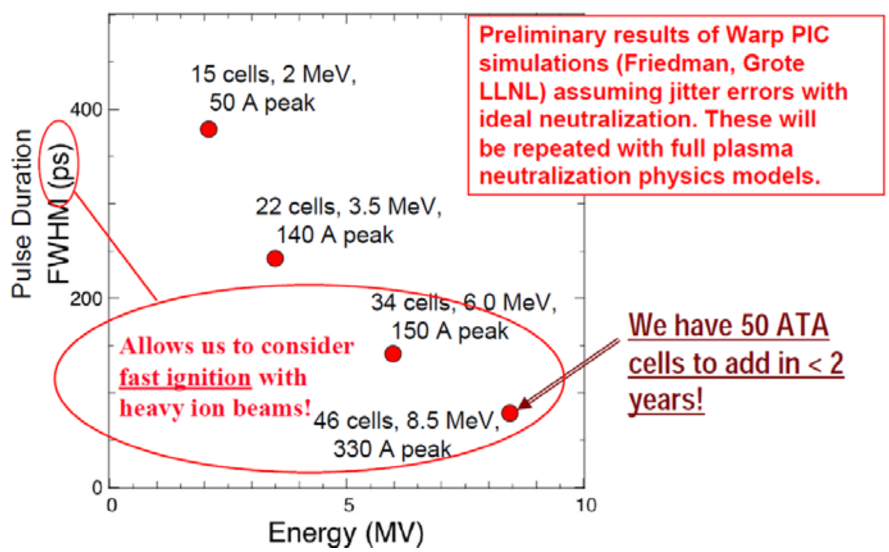

Figure 3: Sub-nanosecond ion pulses are simulated for NDCX-II as the beam ion energy is increased by adding ATA acceleration cells.

<u>Heavy ion target physics for high gain inertial fusion.</u> The success of strong transverse and longitudinal beam compression in neutralizing plasma in NDCX-I, and the greater capabilities projected for sub-ns pulses in NDCX-II (Fig.3), motivate exploration of the application of heavy ion beams to shock ignited and or fast-ignited [19] heavy ion fusion targets. Multi-GeV heavy ions beams, with sharp Bragg deposition peaks near the end of their range, can be particularly efficient at generating Gbar-scale pressures for shock ignition, or for fast ignition of pre-compressed fuel assemblies. Figure 4 shows a recent example of a fast ignited target illuminated by heavy ion beams from a single side. Experiments to test ion-driven shocks at sub-nanosecond pulse times are planned for NDCX-II.

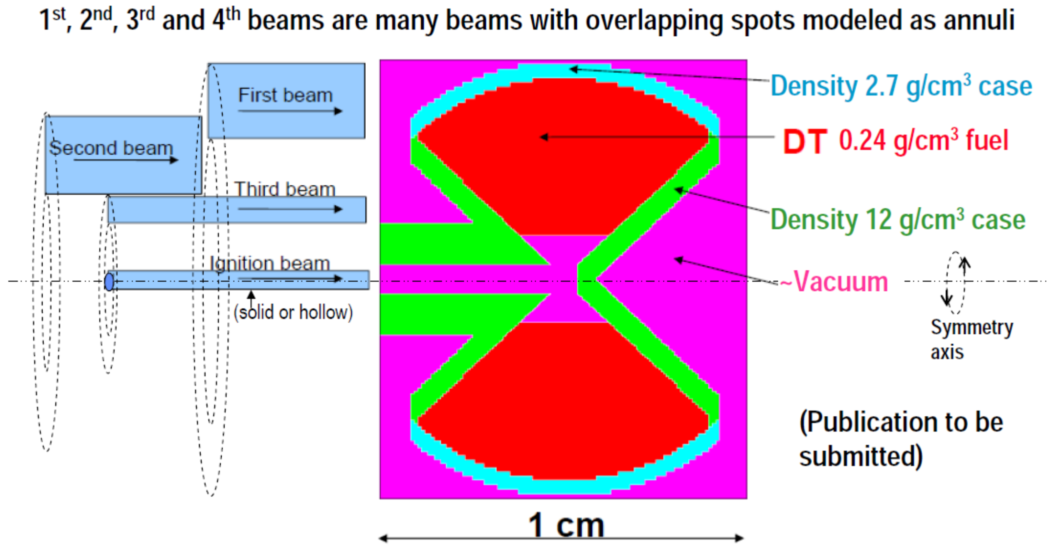

Figure 4: The X-target: First full-physics rad-hydro implosion calculations using HYDRA in 2-D give target energy gains equivalent to indirect drive: 3 MJ compression + 3 MJ fast ignition→300 MJ yield, all 60 GeV U beams, for one-sided beam illumination, robust RT stability. (E. Henestroza, August 2010)

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