Ion-beam-driven warm dense matter experiments

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Abstract. As a technique for heating matter to high energy density, intense beams of heavy ions are capable of delivering precise and uniform beam energy deposition to a relatively large sample. The US heavy ion fusion science program has developed techniques for heating and diagnosing warm dense matter (WDM) targets. We have developed a WDM target chamber and a suite of target diagnostics including a fast multi-channel optical pyrometer, optical streak camera, VISAR, and high-speed gated cameras. Initial WDM experiments heat targets by both the compressed and uncompressed parts of the NDCX-I beam, and explore measurement of temperature, droplet formation and other target parameters. Continued improvements in beam tuning, bunch compression, and other upgrades are expected to yield higher temperature and pressure in the WDM targets. Future experiments are planned in areas such as dense electronegative targets, porous target homogenization and two-phase equation of state.

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1. Introduction
The US heavy ion fusion science program is developing techniques for studying ion-beam-driven warm dense matter (WDM) targets [1-3]. Intense ion beams have several attractive features as a technique for generating WDM. These features include: precise control of local beam energy deposition $dE/dx$, nearly uniform throughout a given volume, and not strongly affected by target temperature, large sample sizes (about 1 micron thick by 1 mm diameter), and the ability to heat any target material, for example, foams, powders, conductors, insulators, solid, gas, etc. The WDM conditions are achieved by space-charge neutralized longitudinal drift compression and transverse focusing of the ion beam to provide a hot spot on the target with a beam spot size of about 1 mm, and compressed pulse length about 2 ns. Initial experiments use a 0.3 MeV, 30-mA K$^+$ beam (below the Bragg peak) from the NDCX-I accelerator to heat foil targets. The NDCX-1 beam contains an uncompressed pulse up to $>10$ μs of fluence $\geq 200$ kW/cm$^2$, and a compressed pulse of fluence $\sim 10$ mJ/cm$^2$. We have recently improved the NDCX beamline and its capabilities for WDM studies. The improvements derive from the replacement of the original Induction Bunching Module (IBM) with a new one that can generate nearly twice the volt-seconds, and from a longer neutralized drift section that allows the longer duration energy modulated pulses to fully compress at the target plane. The IBM waveform has been optimized for several operating beam energies. The waveform fidelity is such that the relative error in energy is less than 1% over $\sim 400$-500 ns pulse duration.

2. Target positioner and diagnostics
The target holder has two axes of motor drives to provide two degrees of freedom of remote positioning of the target. These include 2 axes on the target positioner and 2 axes on the light collection optics table. This configuration allows us to remotely position the target and target assembly without breaking vacuum to move the target to a fresh spot. Precision target positioning equipment allows rapid re-positioning of the target foil between shots. Improvements to the target assembly include the installation of a simple final focus cone. The cone enhances beam intensity on target by reflecting additional beam ions that are initially radially outside the target area. Target diagnostics [4] include a fast optical pyrometer, an optical streak-spectrometer, VISAR, and two high-speed gated image intensified cameras. We have installed a new current monitor downstream of the target to measure beam current transmitted through the target as a function of time. The beam current transmitted should be sensitive to the formation of droplets in the target foil.

3. Model of target dynamical response
As the ion beam deposits its energy volumetrically on the solid target, the target goes through a series of phase changes depending on the total beam energy fluence and power. For the beam power density levels available in NDCX-1, in the 100 kW/cm$^2$ range for the longitudinally uncompressed beam (several μs), and in the $>> 1$ MW/cm$^2$ range for the longitudinally compressed beam (2 ns) the target will go through a melting process and vaporize a fraction of its mass reaching temperatures near 0.5 eV ($\sim 6000$ K).

The diameter of the beam spot on target is 1 mm. The thermal diffusivity of the thin-foil targets is of order 1 cm$^2$/s or less, which means that even on a 10-μs time scale the heat diffuses transversely on a 30 micron scale. Therefore we can model the target dynamics using only time and the spatial dimension along the beam direction. In the model, beam heating is balanced by energy flux from the surface of the foil due to evaporation, radiation, and thermionic (Richardson) emission. Using this model we calculate the temperature at which the cooling mechanisms equilibrate the energy flux from the ion beam (Fig. 1). The thickness of target foils referred to in Fig. 1 are: Au: 150 nm, Al: 350 nm, Pt: 120 nm, Si: 400 nm, and C: 400 nm.
One of the key areas of investigation in warm dense matter is the dynamic transition between liquid and vapor of superheated metals. In particular, as the solid is heated above the melting temperature, expansion will occur, and droplets form due to surface tension effects. A complete theory of precisely how these droplets form is under development. Experimental evidence for droplet formation is available from optical and current transformer data. We are beginning to compare detailed theory that describes the emission spectrum from droplets. The calculation is done by extending the textbook Mie scattering theory to a general dielectric function and adapting it to calculate absorption and emission coefficients for the droplets. This work is in progress.

4. Experimental beam-target data

The optical target emission spectrum is measured by a high dynamic range Hamamatsu streak camera coupled with a spectrometer. Reconstructed temperature, $T$, is obtained from non-linear least square fit of experimental spectra, $I(\lambda,T)$ to a radiation model. The model is the Planck formula multiplied by emissivity, $\varepsilon(\lambda,T)$, which is depending on situation, has either linear or square dependence on wavelength [4]. The streak-spectrometer data indicates that the target temperature in platinum reaches 4500 K, in approximate agreement with model predictions. Optical self-emission from the expanding shower of hot debris (liquid droplets) 500 µs after a platinum target shot shows the presence of hundreds of hot droplets, supporting the characterization of the target as forming droplets early in the beam pulse.

The evolution of the Au target during and after the ion-beam-heating can be characterized by 3 distinct phases. The thermal radiation reaches a maximum after about 1.5 µs relative to the head of the beam (Fig. 2, Phase 1).

Phase 2: Au I (atomic vapour) lines appear in spectral records slightly after the radiation peak. Simultaneously the total thermal radiation signal drops. We attribute the early peak in radiation pattern to the disassembly of the foil into droplets. Note that, while overall radiation decreases, the reconstructed temperature gives either a constant temperature or a slight increase (beam still deposits energy into the target).

Phase 3: The atomic lines turn off with the end of the beam pulse and the total radiated signal continues to fall. Since the atomic lines are ion-beam pumped, the moment the lines appear is related to droplet formation, i.e. ions pass through the vacated regions between droplets and excite the Au vapor downstream of the target.
5. Conclusions
Rapid bulk heating of target foils to temperatures up to ~4500 K (0.4 eV) has been achieved using NDCX-I beams. 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 mechanisms such as vaporization of the target material. Development of techniques for heating and diagnosing targets allows bulk heating of WDM targets in the laboratory using ion beam heating. The NDCX-I environment is conducive to multiple repetitive target experiments for detailed study of target behavior under various conditions and using multiple diagnostics.

Evidence for the formation of liquid metal droplets on the μs time scale is presented, and compared with predictions. Our experiments are expected to shed light on droplet formation in metal targets under WDM conditions and on the properties of the subsequent debris shower. These results could find wide application in areas such as simulating volumetric neutron heating in inertial confinement fusion facilities, and other applications of liquid metal droplets.

Other future areas of study include the equation of state near the solid-liquid and liquid-vapor phase boundaries, and material properties such as the evaporation rate, surface tension, electrical conductivity; identification of critical points and phase boundaries; porous targets; positive ion/negative ion experiments in high electron affinity targets; etc.

The next-step facility, NDCX II, is under construction and will offer additional capabilities [5]. The NDCX I work is essential to benchmarking our beam manipulation, targetry, and diagnostic techniques for NDCX II, which will be able to probe the WDM regime at higher temperatures and pressures. Improvements to the beamline, targetry and diagnostic components will continue to be made, and will improve the facility for a variety of WDM experiments.

6. References
1. B.G. Logan, et al., IFSA 2007, Journal of Physics, Conference Series 112 (2008) 032029.
2. P.A. Seidl, et al., Instrum. Meth. A 606 (2009) 75-82.
3. F.M. Bieniosek, et al., Nucl. Instrum. Meth. A 606 (2009) 146-151.
4. P.A. Ni, et al., Laser and Particle Beams, 27, December 2008.
5. Friedman, A; et al., Nucl. Instrum. Meth. A, 606, 6-10, (2009).