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Warm dense matter experiments with intense heavy ion beams†

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This talk will describe initial warm dense matter (WDM) experiments at neutralized drift compression experiment (NDCX) at Lawrence Berkeley National Laboratory (LBNL), with an emphasis on developed optical diagnostics.

WDM is characterized by near solid-state densities, temperatures up to 100,000 K and several Mbar pressure. These states are related to the field of plasma physics, astrophysics, geophysics and planetary sciences, and equation-of-states (EOS). The WDM field is relatively young and dynamically developing

An ideal driver for WDM experiment would be one which can deliver energy into the bulk of a sample homogeneously, at a time scale much shorter than the hydrodynamic response time of the target. The rate of energy deposition, as well as total energy deposited must be known precisely as well. In order to construct and verify various theoretical EOS models, a vast experimental data set is required. For this purpose, small quantities of WDM are generated in the laboratory and variables like, temperature, pressure, expansions velocity, conductivity, etc. are measured *in situ*.

In laser driven WDM experiments (nowadays the primary choice), very high temperatures in a short time can be reached relatively easily with a compact and inexpensive setup. However, homogeneity is achieved only within the skin depth of the laser light, leading to several-nm-size targets. Laser beam energy deposition depends strongly on initial surface quality (smoothness, contamination) and it changes significantly during phase transitions. Moreover, an inevitable laser pre-pulse creates a low density plasma plume which partially absorbs and refracts the main portion of the beam, thereby complicating the energy deposition mechanism. All this gives a higher degree of uncertainty to the energy deposition, resulting in reduced reproducibility and larger error bars.

Pulsed, intense, heavy ion beams, suffer from none of the above mentioned disadvantages and are a promising WDM driver. In contrast to photons, heavy ions penetrate deep into the bulk, allowing for rapid heating of up to cubic-mm volumes, and deposit their energy in a homogeneous fashion such that temperature gradients as well as density gradients are very low compared to other methods. More importantly one can achieve a fairly high degree of reproducibility, i.e. higher precision of data, due to the fact heavy ion deposition is practically immune to surface quality and pre-pulse gaseous plasma plumes. In the WDM regime, ion energy deposition is well understood and is known to have a weak dependence on phase, temperature, ionization degree, etc. These unique features of the ion-matter interaction allows for bulk heating of various types of materials, including, metals, semiconductors, liquids, minerals, powders, ceramics and bio cells, with a quantified total deposited energy. No laser experiments can yet make this claim.

LBNL, for some years has been involved in the design of (and construction of component prototypes for) compact heavy ion accelerators suitable for heavy-ion-driven ICF experiments [Bock, Logan 2]. Recently, the NDCX-I has been successfully commissioned and the first WDM experiments (2008) were carried out [Seidl, Bieniosek, Bieniosek2, Bieniosek3, Ni3]. Currently, this machine can heat various metallic samples up to 5000 K.

At present, NDCX-I delivers a 30-mA, 350-keV K^+ ion beam. Using the recently-developed technique of neutralized drift compression, the beam is simultaneously compressed longitudinally by a factor of 50, and focused transversely down to a 1 mm spot. This beam pulse heats Au targets (50-1500-nm thick) foils above 3000 K driving material into two-phase, liquid-vapor states. We have also performed experiments with Al, W, C, Pt and Si.

The NDCX-I beam current structure consists of the main, flat-top 1 μs pulse (variable up to 10 μs) with flux on target ~200 $mJ/cm^2/\mu s$ and the bunch-compressed 2-ns pulse with fluence ~10 mJ/cm^2. The compressed pulse can be delivered controllably at any time within the duration of the main pulse. The 2-ns compressed pulse width is at a comparable time scale to the hydrodynamic response of our targets.

Target diagnostics include a specially developed three-channel optical pyrometer which probes color temperatures of the target at 750 nm,1000 nm and 1500 nm, with 75 ps temporal resolution. Continuous target emission from 450 nm to 850 nm is recorded by a custom spectrometer, consisting of a high dynamic range Hamamatsu streak camera and a holographic grating. Both pyrometer and streak spectrometer are calibrated absolutely with a NIST traceable tungsten ribbon lamp. The spectrometer has a lower sensitivity than the pyrometer and applied in experiments with higher temperatures.

Hydrodynamic expansion velocity of a target's free surface is measured by a commercially available all- fiber Doppler shift laser interferometer (VISAR). The installed delay etalon allows for velocity detection with 2 m/s precision and 0.5 ns resolution.

Construction of the next generation machine NDCX-II, funded through the American Recovery and Reinvestment Initiative, has begun and is planned to be accomplished by 2012. NDCX-II will be capable of heating samples roughly up to 20,000 K within 1 ns. By the time it is commissioned, LBNL will be the only location capable of carrying out WDM experiments with heavy ions.

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