EXPERIMENTS IN WARM DENSE MATTER USING AN ION BEAM DRIVER*

F.M. Bieniosek#, M. Leitner, B.G. Logan, R.M. More, P.K. Roy, P. Ni, LBNL, Berkeley CA,
J.J. Barnard, M. Kireeff Covo, A. Molvik, LLNL, Livermore CA,
L.R. Grisham, PPPL, Princeton NJ, and HIFS-VNL, USA,
H. Yoneda, U. of Electro-communications, Tokyo, Japan.

Abstract

Warm dense matter (WDM) conditions are to be achieved by combined longitudinal and transverse neutralized drift compression of an intense ion beam pulse to provide a hot spot on a target with a beam spot size of about 1 mm, and pulse length about 1-2 ns. The range of the beams in solid matter targets is about 1 micron, which can be lengthened by using reduced density porous targets. Initial experiments in ion-beam-driven WDM will be at low beam velocity, below the Bragg peak, increasing toward the Bragg peak in subsequent higher-energy accelerators.
Initial experiments include a transient darkening experiment and a experiment in porous targets at GSI. Further experiments will explore target temperature and other properties such as electrical conductivity to investigate phase transitions and the critical point.

INTRODUCTION

Warm dense matter (WDM) is a form of strongly coupled high energy density matter at the intersection between condensed matter and plasma physics [1]. Intense ion beams provide an excellent tool to generate homogeneous WDM in an easily accessible, open facility [2]. We consider the accessible range for these experiments to be T ~ 1000 to 100,000 K, and density ρ ~ 1% to 100% of solid density. Intense ion beams have several advantages as a technique for generating WDM. These advantages 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),
- the ability to heat any solid-phase target material, for example, foams, powders, conductors, insulators, etc.

Both uniformity of target heating and efficiency of beam energy deposition are maximized by heating with the Bragg peak at the center of the target [3]. This approach allows operation with relatively low beam energy (e.g. ~2 MeV for He^+; ~50 MeV for Ar^+). Because the short range of such beams, it is necessary to compress beam pulses to roughly 1 ns to be consistent with the hydrodynamic expansion time of the target. The range can be extended by heating low-density porous targets, for example density in the range of 1-10% of solid density, extends ion beam range and hydrodynamic expansion time by factors of 10-100. Initial experiments will be at low beam velocity, below the Bragg peak using an existing accelerator (NDCX-1), increasing toward the Bragg peak in subsequent versions of the accelerator (NDCX-2). The ion beam will undergo combined longitudinal and transverse neutralized drift compression to provide a hot spot on the target with a beam spot size of about 1 mm, and pulse length about 1-2 ns [4, 5].

* Work performed under the auspices of the U.S. Dept. of Energy by LBNL, LLNL, and PPPL under Contracts No. W-7405-Eng-48, DE-AC02-05CH11231, and DE-AC02-76CH3073.
# fmbieniosek@lbl.gov

WDM EXPERIMENTS

Development of WDM experimental capability

Existing beam diagnostics will characterize the parameters of the incident heating ion beam, such as its energy, and its transverse and longitudinal distributions incident on the target. Recently developed diagnostics include a high-resolution electrostatic energy analyzer (EEA) [6] and optical diagnostics [7]. An alternative measurement of beam energy distribution that can provide some of the same information as the EEA is time of flight (TOF). A beam that is focused longitudinally by phase space rotation has a large energy spread (up to ~30%) at the target but is localized in time, providing a well-defined time marker for the TOF measurement.

When an ion beam strikes a vacuum wall, a cloud of gas is desorbed [8]. Care must be taken to include gas cloud emission in interpreting optical emission data from the target. In addition a promising diagnostic is the use of the optical emission from the gas cloud generated at the intense beam focal spot (e.g. “optical Faraday cup” [9]). This is a self-healing alternative to other beam diagnostics such as a scintillator or a fast Faraday cup which may be limited in their lifetime, linearity or bandwidth.

Some measurements of transmitted beam can be performed in thin-foil target experiments including collecting beam transmitted through the foil in a Faraday cup, measuring the transmitted beam energy distribution , and using a downstream scintillator to image beam scattering in the foil. Ion scattering, energy distribution and charge state near the Bragg peak are of theoretical interest for both cold and heated targets [10].

Because of the short time scales of these experiments, high speed diagnostic capability is essential. We will make use of existing fast gated cameras in conjunction with other diagnostics. These include an optical spectrometer, a fiber Doppler VISAR system, and a streak camera system.

For measurement of target temperature, we are developing a fiber-coupled multi-channel optical pyrometer with sub-ns response, and temperature sensitivity to as low as 1000 C. Position resolution is 400 micron or less, depending on the diameter of the coupling fiber to be used. The required positioning accuracy of the beam and target is much less than the position resolution of the diagnostic. Fig. 1 shows a schematic layout of the light collection optics for the pyrometer (thermal light) and other diagnostics such as the VISAR and laser probes such as a polarimeter.

A prototype target chamber and target capsule are under development. Initially the target will be a thin self-supporting metallic foil, for example gold or aluminum, mounted on a glass or sapphire substrate. Subsequently it could be any of a number of materials, such as a thin layer of halogen atoms deposited on the substrate. The ion beam passes through and heats the target foil, exiting through a hole in the substrate to be measured downstream with diagnostics as described above.

A mechanical design concept of a target in a prototype target capsule is shown in Fig. 2. The design includes provision for electrical voltage and current contacts and taps that can be remotely connected and disconnected, a debris enclosure, and extensive diagnostic access from front, side and back. In the target chamber the NDCX-1 beam is focused onto the target by the final focus solenoid. In addition the target chamber has a plasma injection system to provide the space charge neutralization for the beam final focus. A number of diagnostic ports are provided for viewing from the front, side and rear. Also a target manipulator will be used to remotely place the target at the beam focus. A target load lock arrangement provides the capability to load several target capsules at a time for handling by the target manipulator.

Issues to be explored with the prototype target chamber include making and breaking electrical connections to the target capsule, precision positioning of the target capsule, interface with beam and target diagnostics, and the influence of pulsed final focus magnet and plasma source on the target and diagnostics.

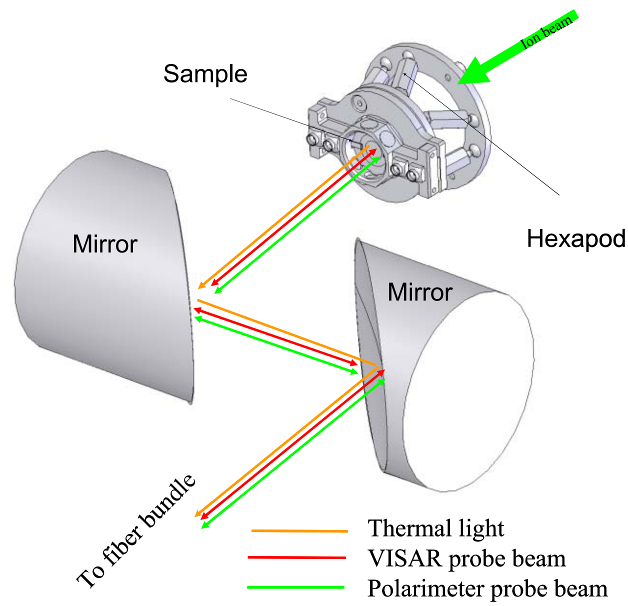

Figure 1: Concept of light collection optics for target diagnostics.

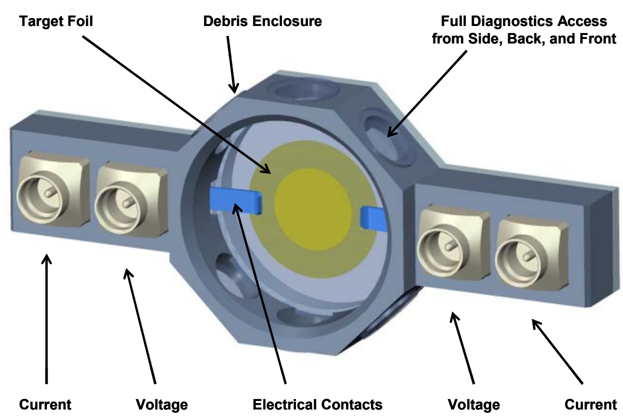

Figure 2. Prototype target capsule.

As WDM regimes become accessible, experiments will explore the thermodynamic properties of matter heated by the ion beam pulse. These experiments may include liquid-vapor boundary experiments in metals to study the differences between solid and porous targets, the liquid-vapor phase diagram, the equation of state, and droplet formation. Another topic of interest is critical point measurements of refractory metals. The dynamics of the target material as it passes through the phase transition are of interest, and the critical points of many materials remain unknown.

Transient darkening of quartz

In this low-temperature experiment, the ion beam impacts a cold quartz target, and transient effects on optical transmission, optical emission and electrical conductivity are observed. This experiment does not require WDM conditions; it can be done using low

1-4244-0917-9/07/$25.00

intensity beams and cold targets. Transient darkening has been observed in initially transparent materials such as quartz when rapidly heated to high temperature (WDM) by a laser [11] and in a cold quartz fiber irradiated by an intense electron beam pulse [12]. In particular the decay rate of the transient optical attenuation is a strong function of the temperature of the fiber. Similar measurements of optical emission provide further information on the model parameters. Optical decay rate measurements of transient emission and attenuation have used an ion beam pulse to excite the quartz target, and a flash-lamp diagnostic probe. Results indicate a small effect of the ion beam on the optical transmission in a quartz fiber. Further work to explore these results as well as conductivity effects are planned. A simple model describes the transient response of the material that should be applicable to both WDM and irradiation by a charged particle beam [2].

Positive-negative halogen ion experiment

A proposed experiment studies the unique properties of a dense electron-free positive-negative ion halogen plasma [13]. Halogens (F, Cl, Br) are characterized by large electron affinity (3.35-3.6 eV). Heating the foil to approximately 0.4 eV with a compressed ion beam pulse produces the halogen WDM. Because of the large electron affinity, a novel state of matter may be obtained, characterized by the presence of a plasma with positive ion balanced predominantly by negative ions with the relative absence of free electrons. This state may exhibit unusual conductivity properties because conduction is ionic. Target parameters and diagnostics of interest include electrical conductivity, beam energy loss, target temperature, etc. Initial operation may utilize gold foils which are expected to be easier to work with than a layer of deposited halogen material. Gold has a relatively large electron affinity (2.3 eV) and the formation of a plasma with positive and negative ions is expected [14].

Target heating experiment at GSI

Porous targets have the advantage that the ion beam range is longer than in a solid-density target, thus slowing down the hydrodynamic expansion time of the heated target. We have conducted a series of experiments at the existing HHT target station at GSI [15]. The experiment studied the effect of pore size on target behavior using existing diagnostics, for example by measuring the target temperature as a function of pore size and compare with model predictions of the physics of porous targets. A matter of particular interest is the isotropization of the pore walls as they are heated by the beam, which is expected to scale with the pore size. For example, target dynamics may be affected if the hydrodynamic expansion time to fill in the cells is longer than the beam pulse length. Initial results of these experiments are presented elsewhere [15].

REFERENCES

[1] R.C. Davidson, Chair, Frontiers in High Energy Density Physics, National Research Council of the National Academies, National Academies Press, Washington, DC, USA 2003.

[2] F.M. Bieniosek, et. al. Nucl. Instrum. Methods Phys. Res. A544 (2005) 268-276.

[3] L. R. Grisham, Phys. Plasmas 11 (2004) 5727.

[4] B. G. Logan, et.al., Nucl. Instrum. Meth. A 577 (2007) 1-7.

[5] J. Coleman, et. al., Bunching and focusing of an intense ion beam for target heating experiments, Paper THPAS004, these proceedings.

[6] F.M. Bieniosek and M. Leitner, 1-MeV electrostatic energy analyzer, Paper FRPMS018, these proceedings.

[7] F. M. Bieniosek, L. Prost, W. Ghiorso, Beam Imaging Diagnostics for Heavy Ion Beam Fusion Experiments, Proc. 2003 Particle Accelerator Conference, PAC03, Portland, OR, p. 2524.

[8] F. M. Bieniosek, et.al., Time resolved measurements of desorbed gas during 1-MeV K+ pulsed beam deposition in a stainless steel target, submitted for publication in Phys. Rev. ST Accel. Beams.

[9] F. M. Bieniosek, et.al., Optical Faraday cup for heavy ion beams, Proc. 2005 Particle Accelerator Conference, PAC05, Knoxville, TN, p. 1805.

[10] C. Deutsch and R. Popoff, Laser and Particle Beams, 24 (2006) 421-425.

[11] D.F. Price, et.al., Phys. Rev. Lett. 75 (1995) 252.

[12] P. Lyons, Fiber optics in transient radiation fields, SPIE, vol. 541; Radiation Effects in Optical Measurements, 1985, pp. 89-95.

[13] LR Grisham, JW Kwan, and G Westenskow, Nucl. Instrum. Meth. A 577 (2007) 267-274.

[14] R. More, H. Yoneda, and H. Morikami, JQSRT 99 (2006) 409-424.

[15] P. Ni, et.al., Recent HEDP Experiments with Intense Heavy Ion Beams at GSI-Darmstadt, Paper WEOCC02, these proceedings, and references therein.

 1-4244-0917-9/07/$25.00