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ScienceDirect
Nuclear Instruments and Methods in Physics Research A 577 (2007) 284–288
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Diagnostics for near-term warm dense matter experiments

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Heavy Ion Fusion Science Virtual National Laboratory
Available online 22 February 2007

Abstract

We describe near-term ion beam-driven warm dense matter (WDM) experiments. Initial experiments are at low beam velocity, below the Bragg peak, increasing toward the Bragg peak in subsequent versions of the accelerator. The WDM conditions are envisioned to be achieved by 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. The range of the beams in solid matter targets is about 1 μm, which can be lengthened by using porous targets at reduced density.

Initial candidate experiments include an experiment to study transient darkening in the WDM regime; and a thin target dE/dx experiment to study beam energy and charge state distribution in a heated target. Further experiments will explore target temperature and other properties such as electrical conductivity to investigate phase transitions and the critical point.

Initial diagnostics will be relatively simple or extensions of existing capabilities. These include electrical resistivity and optical absorption measurements to provide information on target temperature and electronic phase transitions. Beam energy and charge state after passing through thin targets can be measured using time of flight and the existing electrostatic energy analyzer. Ion beam current and profile diagnostics will be improved to diagnose the small spot sizes to be achieved in these experiments. Other diagnostics of interest may monitor optical emission (e.g. fast optical pyrometer, streak cameras), and utilize laser reflectometry, polarimetry, or shadowgraphy.

PACS: 51.30.+i; 52.50.Gj; 52.59.Sa; 52.70.−m

Keywords: Inertial fusion energy; Ion beam; Diagnostics; Warm dense matter

1. 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]. There is growing interest in obtaining experimental data in WDM, a range which is difficult to model theoretically because of strong coupling and excited states.

Intense ion beams provide an excellent tool to generate homogeneous WDM in an easily accessible, open facility. We describe plans for near-term ion beam-driven WDM experiments. We consider the accessible range for these experiments to be $T\sim1000$–$100{,}000$ K, and density $\rho\sim1$–100% of solid density.

Several techniques exist for generating WDM, including shock waves, high power lasers, and electrical pulsed power such as exploding wires. However, intense ion beams have specific advantages that may be difficult to achieve by other techniques. These advantages include:

- local beam energy deposition dE/dx is generally well characterized, nearly uniform throughout a given volume, and not strongly affected by target temperature,
- capability for a high repetition rate, and
- the ability to heat any solid-phase target material independent of, for example, its electrical conductivity or optical properties.

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doi:10.1016/j.nima.2007.02.063

WDM experiments using high energy beams from large particle accelerators such as GSI operate at an energy much greater than the Bragg peak (where $\mathrm{d}E/\mathrm{d}x$ is maximum) to avoid regions where $\mathrm{d}E/\mathrm{d}x$ changes rapidly with ion energy [2]. In contrast, our approach maximizes both uniformity of target heating and efficiency of beam energy deposition by operating with the Bragg peak at the center of the target [3]. This approach allows operation with relatively low beam energy (e.g. $\sim$2 MeV for He^+; $\sim$50 MeV for Ar^+). Because the range of such beams is typically on the order of a few microns, it is necessary to compress beam pulses to roughly 1 ns to be consistent with the hydrodynamic expansion time of the target. Important progress to this level of beam pulse compression using space charge neutralized rotation in phase space has been achieved [4]. The range can be extended by heating low-density porous targets with density in the range of 1–10% of solid density, thus extending ion beam range by factors of 10–100 and increasing hydrodynamic expansion time. Initial experiments will be at low beam velocity, below the Bragg peak (NDCX-1), increasing toward the Bragg peak in subsequent versions of the accelerator (NDCX-2). The WDM conditions are envisioned to be achieved by 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.

Near-term experiments provide an opportunity to gain experience with diagnostics for WDM targets. Initial diagnostics will be simple or extensions of existing capabilities, including electrical resistivity and optical absorption to provide information on target temperature and phase transitions, beam stopping power, visible light emission, and laser probes.

2. WDM experiments

We plan a sequence of experiments designed to yield scientifically interesting results at progressively higher beam intensities, initially based on existing HIFS-VNL beam facilities (NDCX and HCX) and continuing with a higher energy beam facility, such as NDCX-2 [5].

2.1. Transient darkening of quartz

Transient darkening has been observed in initially transparent materials such as quartz when rapidly heated to high temperature (WDM) by a laser [6]. Transient darkening of scintillators and quartz fibers irradiated by a charged particle beam is a related phenomenon. Attenuation of an optical signal transmitted through a quartz fiber irradiated by an intense electron beam pulse has been observed and studied in detail [7]. In particular the decay rate of the transient optical attenuation is a strong function of the temperature of the fiber.

We have developed a simple model to describe the transient response of the material that should be applicable to both WDM and irradiation by a charged particle beam. In this model, in the case of SiO_2 (quartz), electrons from the ground state (2s, 2p states for the oxygen atoms) are excited to the 3s, 3p states leaving holes in the ground state. Both electrons and holes may absorb visible light. They recombine at a rate dependent on material properties and temperature. Optical attenuation is given by

$$f = \exp\left(-\sum_j N_j \sigma_j \,\mathrm{d}x\right) \quad (1)$$

where $N_\pm$ is the density of holes/electrons, σ is the cross-section for photon absorption, and x is path length in the material. An equation for the concentration of holes N_+ and excited electrons N_- is

$$\frac{\mathrm{d}N_\pm}{\mathrm{d}t} = S(t) - \alpha N_+ N_- - \beta_\pm N_\pm \quad (2)$$

where the source rate $S(t)$ is proportional to the beam flux; the loss rate coefficients α, β depend on the temperature. This model can be made to fit the data for transient optical attenuation in an irradiated fiber, but not all parameters are uniquely determined.

Model results can be used to design and interpret a new experiment using ion beams to excite the quartz. For example the experiment can study the dependence of attenuation on target temperature and optical probe wavelength. This experiment does not require WDM conditions; it can be done using low intensity beams and cold targets. Similar measurements of optical emission provide further information on the model parameters, including absolute source and decay rates, in a well characterized experiment. The result will be a model that has predictive power for the optical properties of WDM. One potential application that can be envisioned is fast optical switching of an initially transparent material. Since optical characteristics are generally correlated with electrical conductivity, fast electrical switching may also take place. Decay rate measurements of transient optical emission and attenuation are beginning using a ion beam pulse to excite the quartz target and a laser diagnostic probe.

2.2. Development of WDM experimental capability

Beam diagnostics that have already been developed [8] will continue to be useful in characterizing 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) and gas-cloud optical emission measurements.

A high-resolution EEA measures the beam energy distribution up to a maximum energy of 1 MeV for single-charged beam ions. The energy analyzer is a cylindrical 90° bend analyzer with a radius of curvature $r = 0.5$ m and first-order focus. It is designed to achieve an energy resolution of a few parts in 10^4, implying longitudinal beam temperature resolution of <1 eV. Applications include detailed measurement of beam energy spread for drift compression experiments, studying and correcting energy errors in the head and tail of the beam pulse, studying beam energy ripples and longitudinal space charge waves, providing an independent measure of gas production at the wall using multiple ionization states, and measuring beam energy loss and straggling in thin-target WDM experiments. An example of energy measurements using the EEA is in Ref. [9].

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. As the beam spreads out longitudinally downstream of the target its energy distribution is easily measured by TOF; comparisons between the energy distribution with and without the target provide information on beam energy loss in the target as a function of beam energy.

Gas desorption coefficients on the order of 10^4 are observed when a 1-MeV heavy ion beam strikes a vacuum wall [10]. In addition to the impact of the expanding gas cloud on beam transport in a particle accelerator, the optical emissions of the gas cloud may partially mask optical emissions from the target in WDM experiments. Fast beam–target interaction measurements to date have studied the development and expansion of the gas cloud, imaged by a gated intensified CCD camera [11]. These measurements indicate that the gas cloud emits light through excitation by the ion beam, and expands at a rate on the order 1 mm/μs, with an afterglow that persists for some microseconds after the beam pulse. In addition to its applicability as a diagnostic of target conditions, care must be taken to include gas cloud emission in interpreting optical emission data from the target. Also promising as a diagnostic is the use of the optical emission from the gas cloud generated at the intense beam focal spot (e.g. "optical Faraday cup" [12]). This is a self-healing alternative to other diagnostics such as an alumina scintillator or a fast Faraday cup [13] which may be limited in their lifetime, linearity or bandwidth.

Initial WDM experiments will be performed on thin foils using NDCX beam focused in both longitudinal and transverse directions to achieve significant target heating. Some of the measurements of transmitted beam that can be performed in thin-foil target experiments include

- collecting beam transmitted through the foil in a Faraday cup,
- measuring the transmitted beam energy distribution,
- 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 [14].

Target temperature is an important target parameter to measure. Examples of diagnostics include several ways to measure target temperature, include measuring the rate of hydrodynamic release such as lasers and optical imaging, electrical conductivity, and optical emission of the heated target using a fast optical pyrometer [15].

Because of the very 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; diagnostic equipment that we plan to obtain include 2.5 GHz oscilloscopes, an optical spectrometer, a fiber Doppler VISAR system, and a streak camera system.

As part of this effort we are designing a prototype target chamber and target capsule. A conceptual drawing of a target arrangement is shown in Fig. 1. Initially the target will be a thin self-supporting metallic foil, for example gold or aluminum, mounted on a glass substrate. Subsequently it could be any of a number of materials, such as a thin layer of halogen atoms deposited on the glass substrate. The ion beam passes through and heats the target foil, exiting through a hole in the glass substrate to be measured downstream with diagnostics as described above. A few diagnostics are indicated on the drawing including electrical voltage and current taps to measure the conductivity of the target, probe lasers for both transmission and reflection, and an optical imaging system for measuring self-emission such as with a fast optical pyrometer.

A mechanical design concept to realize this target geometry 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. Fig. 3 shows a prototype target chamber as it would be

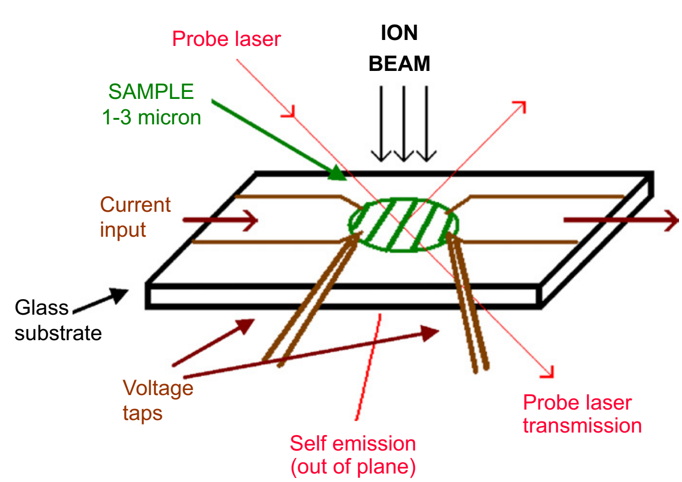

Fig. 1. Concept of target mounted on a glass substrate showing diagnostic access.

attached to an existing NDCX beamline. The beam enters from the left and is focused onto the target by the final focus solenoid (red). In addition to the solenoid 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 shown is the location of the target manipulator which 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.

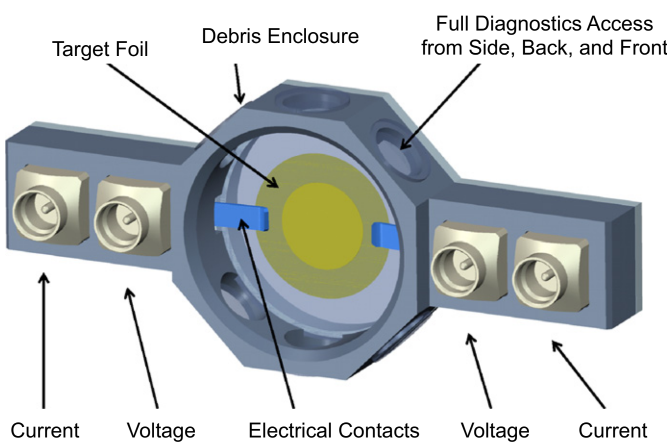

Fig. 2. HIFS-VNL prototype WDM target capsule. Capsule dimensions: 5.66 cm wide, 2.29 cm high.

2.3. Positive–negative halogen ion experiment

As target temperature reaches approximately 0.4 eV, other experimental options become available. This target temperature may be achievable on NDCX with a focusing solenoid or on a pulse compressed HCX. One proposed experiment studies the unique properties of a dense electron-free positive–negative ion halogen plasma [16]. Halogens (F, Cl, Br) are characterized by large electron affinity (3.35–3.6 eV). Heating the foil 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 ions 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 [17].

2.4. Increased target temperature

As temperature surpasses 1 eV using an existing accelerator or the proposed NDCX-2, further WDM regimes open up. These experiments may include liquid–vapor metal experiments and critical point measurements of refractory metals. The dynamics of the target material as it

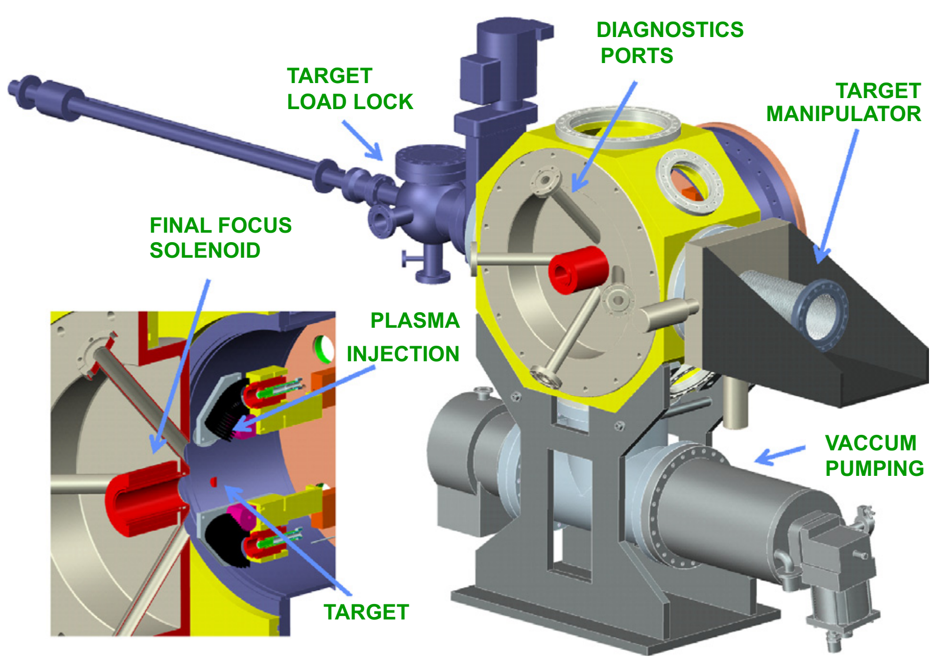

Fig. 3. WDM experiment prototype target chamber.

passes through the phase transition are of interest, and the critical points of many materials remain unknown.

2.5. Collaborative target heating experiment at GSI

Porous targets have 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. In order to gain experience with porous targets and determine the effect of the pore size and porosity on the response of the target material, we plan to perform collaborative experiments at the existing HHT target station at GSI [18]. Target parameters may depend on the porosity of the material. The experiment will study the effect of pore size on target behavior using existing diagnostics, for example to measure 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.

3. Conclusions

This paper describes plans to develop a WDM experimental capability. The accelerator requirements are relatively modest, thus making it possible to provide open facilities with dedicated beam time for experimental access. Initial experiments are planned to yield scientifically interesting results while developing experimental and diagnostic capability; subsequent experiments will be developed through collaboration with the WDM community.

Acknowledgment

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore and Lawrence Berkeley National Laboratories under contracts No. W-7405-Eng-48 and DE-AC03-76SF00098.

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