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Diagnostics for near-term warm dense matter experiments

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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.

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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 $T \sim 1000$–100,000 K, and density $\rho \sim 1$–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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WDM experiments using high energy beams from large particle accelerators such as GSI operate at an energy much greater than the Bragg peak (where dE/dx is maximum) to avoid regions where dE/dx 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

$$f = \exp\left(-\sum_j N_j \sigma_j \, dx\right) \quad (1)$$

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

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

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