Title
DIAGNOSTICS FOR ION BEAM DRIVEN HIGH ENERGY DENSITY PHYSICS EXPERIMENTS

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Diagnostics for ion beam driven high energy density physics experiments[a]

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Intense beams of heavy ions are capable of heating volumetric samples of matter to high energy density. Experiments are performed on the resulting warm dense matter (WDM) at the NDCX-I ion beam accelerator. The 0.3 MeV, 30-mA K^+ beam from NDCX-I heats foil targets by combined longitudinal and transverse neutralized drift compression of the ion beam. Both the compressed and uncompressed parts of the NDCX-I beam heat targets. The exotic state of matter (WDM) in these experiments requires specialized diagnostic techniques. We have developed a target chamber and fielded target diagnostics including a fast multi-channel optical pyrometer, optical streak camera, laser Doppler-shift interferometer (VISAR), beam transmission diagnostics, and high-speed gated cameras. We also present plans and opportunities for diagnostic development and a new target chamber for NDCX-II.

I. INTRODUCTION

As a technique for heating volumetric samples of matter to high energy density, intense beams of heavy ions are capable of delivering precise and uniform beam energy deposition dE/dx, in a relatively large sample size, and with the ability to heat any solid-phase target material. The US heavy ion fusion science program has made significant progress in techniques for heating and diagnosing warm dense matter (WDM) targets [1]. The WDM conditions are achieved by combined longitudinal and transverse space-charge neutralized drift compression of the ion beam to provide a hot spot on the target with a beam spot size of about 1 mm or less, 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-I beam contains an uncompressed pulse up to >10 μs of intensity ≥0.2 MW/cm^2, and a compressed pulse of fluence ~10 mJ/cm^2 [2]. Recent improvements in the NDCX-I beamline have provided increased beam intensity on target including a new induction bunching module which doubles the volt-seconds available to provide bunch compression [3]. The temporal profile of the beam current at the target plane is measured with a fast (~1 ns) Faraday cup and the spatial profile by an Al_2O_3 scintillator and a newly-developed tungsten foil calorimeter. The range of the beams in solid matter targets is about 0.1 - 1 micron, which can be lengthened by using porous targets at reduced density. The beam pulse heats solid foil targets (e.g. Au, Si, Pt, C) to temperatures approaching 0.5 eV (6000 K).

We have developed a WDM target chamber and fielded 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 gas-liquid equation of state. [4, 5]

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II. TARGET POSITIONER AND DIAGNOSTICS

The position system has motor drives to provide 6 degrees of freedom for remote positioning of the target and optical diagnostics. These include 3 axes on the target positioner and 3 axes on the light collection optics table. The precision target positioning equipment allows rapid re-positioning of the target assembly between shots without breaking vacuum. Fig. 1 shows a platinum target after a number of shots were taken on the foil. Up to 40 beam shots have been taken per day. The target assembly includes a focusing gold cone immediately upstream of the target. [6]

Fig. 1. Target holder containing a platinum target foil.

A number of target diagnostics are installed or under development (Fig. 2). The primary optical diagnostics are a fast pyrometer, streak camera-spectrometer, and gated optical cameras.

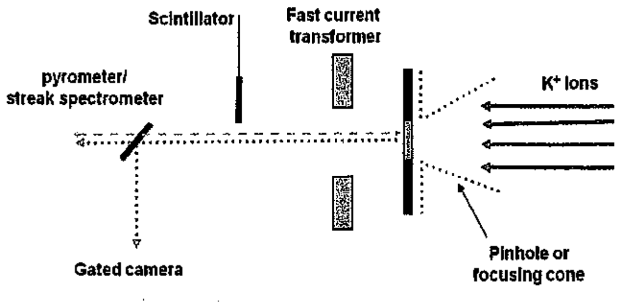

Fig. 2. Schematic layout of target diagnostics described in the text.

The light collection system (LCS) optics for pyrometer and spectrometer diagnostics is based on two achromatic lenses (relay lens system). It allows for direct 1:1 imaging of the target surface onto optical fibers (200-micron diameter) connected to the pyrometer and streak camera. The LCS has a capability for simultaneous usage of the streak-camera-spectrometer and the pyrometer. This is achieved by a custom, selective beam splitter placed after the primary collection lens. The beam splitter transmits near infrared (NIR: 950 to 2000 nm) and reflects the visible band (VIS: 430 to 950 nm). The NIR fiber is attached to the pyrometer and the VIS fiber to the streak camera. The LCS also contains an imaging leg for alignment and target snapshots during the experiment. This imaging leg consists of an imaging fiber guide, macro lens and intensified gated (PIMAX) camera.

A three-channel optical pyrometer probes color temperatures of the target at 750 nm, 1000 nm and 1500 nm, with 75 ps temporal resolution. The pyrometer is based on custom spectrally selective optical beam splitters and can be upgraded to up to seven channels. Each beam splitter reflects a spectral band 150 nm wide and transmits the rest. The spectrally discriminated light is coupled to an amplified photo-receiver. A Si PIN diode is used as a detector for the visible part of the spectrum and an InGaAs PIN diode for the near-infrared part. The distinctive feature of the detectors is that they have a flat gain curve from DC to 4 GHz with 75 ps rise time. The estimated detectable blackbody temperature range is roughly 2000 to 10,000 K.

Continuous target emission from 450 nm to 850 nm is provided by a streak camera combined with a spectrometer. The combination consists of a Horiba Jobin Yvon spectrometer grating (CP-140), and high dynamic range C7000 Hamamatsu streak camera, which records the spectrum as a function of time and wavelength. Fig. 3 shows a typical target emission spectrum, corrected in terms of absolute radiation intensity ($W/cm^2/sr/nm$). Both pyrometer and streak spectrometer are calibrated absolutely with a NIST traceable tungsten ribbon lamp.

Fast gated imaging of the targets and scintillators is provided by two Princeton Instruments PIMAX cameras.

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

Downstream of the target is a fast current monitor (Bergoz FCT-016-20:1-VAC). The purpose of the current monitor is to measure beam current transmitted through the target as a function of time. In a target thicker than the range of the beam, the beam current transmitted should be small even as the target vaporizes since the beam stopping for solid and vapor target material is very similar. This is the case if no droplets form in the target. However when the target bunches up into liquid droplets there is an increase in transmitted beam current. The current monitor can also be used as a diagnostic of beam transmission through an open cone or pinhole in the absence of the target for purposes of calibration and alignment.

A removable Al_2O_3 scintillator downstream of the target measures the transmission and scattering of beam ions downstream of the target. This measurement provides a diagnostic of the state of the target because the transmission and scattering of the beam is sensitive to the amount of matter that the beam ions pass through in the target region. The scattered beam profile on the scintillator is imaged using a PIMAX camera. One advantage of the scintillator is that it is mainly sensitive to high energy beam ions, and much less sensitive to electrons than the current transformer.

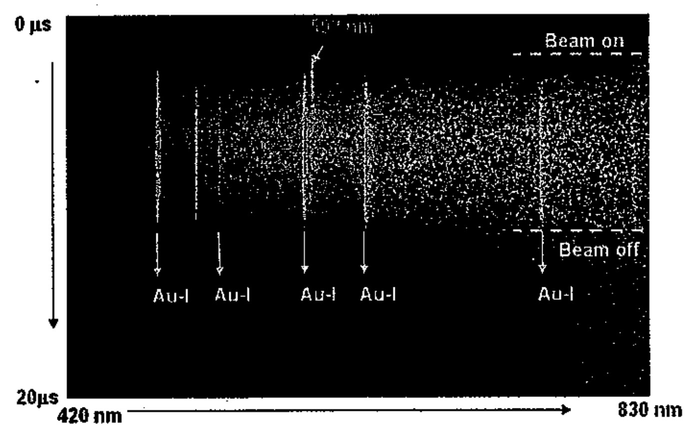

Fig. 3. Emission of a 60-nm Au foil as a function of time and wavelength. Beam turn-on and turn-off times are noted. Beam pumped Au I lines (from NIST tables) combined with continuum radiation emanating from liquid gold droplets indicate the presence of both liquid and vapor states.

We have developed a 3-micron tungsten foil calorimeter for absolute calibration of the incident beam energy flux using the pyrometer diagnostics. This calorimeter takes advantage of the fact that the melting point of tungsten (3422 C) is the highest among the refractory metals. The melting point is high enough that the target provides a sufficiently intense optical thermal emission to the multi-channel and streak pyrometer diagnostics while in solid form, thus ensuring that the target remains intact during the beam heating pulse during beam measurement. It thus provides a calibration of the beam flux for comparison with the target scintillator, and is invaluable for tuning of the NDCX-I beamline. Since the specific heat of tungsten is well known up to the melting point, the tungsten foil can be utilized as a calorimeter. In addition, the melting point provides an absolute temperature benchmark for the temperature measurements provided by the optical pyrometry diagnostics. Recent measurements indicate that the specific beam energy flux on a bare foil target is about 0.25 MW/cm^2 as described in Ref. [7]. Further refinements of the measurements are underway.

Other available diagnostics that have not been implemented include an electrostatic energy analyzer [8] for measuring the beam energy and energy distribution after passing through the target, and several lasers that are available as probes such as a laser backlighter.

III. EXPERIMENTAL BEAM-TARGET DATA

NDCX-I beam-target shots have been performed on foil targets including Au, Pt, C, Al, W and Si. Optical data was taken using the gated PIMAX cameras, the streak-camera spectrometer, and the fast optical pyrometer diagnostic. Since the thickness of the Au target is larger than the range of ions, most of the ions are stopped in the target. The moment the spectral lines in Fig. 3 appear is related to breaking of the foil into droplets, i.e. K^+ beam ions now can pass through the void and excite the Au atomic vapor downstream of the target. Optical imaging of self-emission from the expanding shower of hot debris after the target shot indicates the presence of hundreds of hot droplets, supporting the characterization of the target as forming droplets early in the beam pulse.

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, depending on the situation, can be modeled as having either a linear or square dependence on wavelength [5].

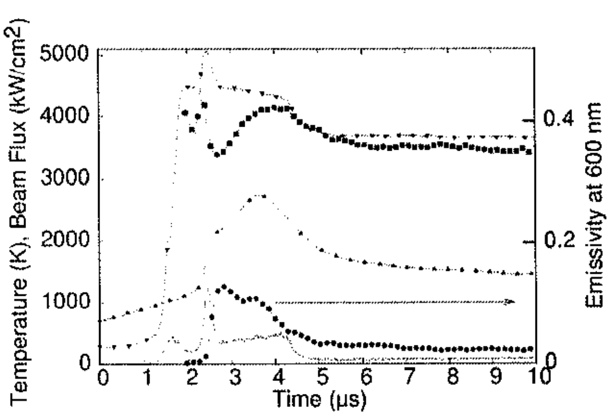

Fig. 4. Reconstructed target temperature (squares) using a fit to the measured emission spectrum, brightness temperature at 600 nm (triangles), emissivity at 600 nm (circles), and relative time history of beam intensity (no marker). The compressed pulse is timed at 1 μs after the head of the beam. Also shown is the predicted temperature behavior from the equilibrium model (inverted triangles) based on the beam current pulse shown.

Fig. 4 shows typical streak-spectrometer data for the platinum target temperature. Note that the measured target temperature, which reaches >4000 K, remains slightly lower than the predicted temperature. Rapid changes in target emissivity account for differences in the brightness temperature and reconstructed temperature.

IV. CONCLUSIONS

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. A number of diagnostics have been fielded on NDCX-I. 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 [9].

Future plans include target experiments using the next-step facility, NDCX-II, which is designed to heat targets at the Bragg peak using a 2-3 MeV lithium ion beam. It is estimated that a 1-μm thick foil will be heated volumetrically to 1-3 eV in <1 ns. NDCX II is under construction and will offer greatly improved beam-target heating capability, with a projected completion date of April 2012 [10]. A new target chamber will provide improved diagnostic access and capabilities. Several diagnostics are planned to be developed, including laser backlighting, laser polarimeter, and x-ray backlighting.

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