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Time-resolved soft x-ray spectra from laser-produced Cu plasma[a)]

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The volumetric heating of a thin copper target has been studied with time resolved x-ray spectroscopy. The copper target was heated from a plasma produced using the Lawrence Livermore National Laboratory's Compact Multipulse Terrawatt (COMET) laser. A variable spaced grating spectrometer coupled to an x-ray streak camera measured soft x-ray emission (800 – 1550 eV) from the back of the copper target to characterize the bulk heating of the target. Radiation hydrodynamic simulations were modeled in 2-dimensions using the HYDRA code. The target conditions calculated by HYDRA were post-processed with the atomic kinetics code CRETIN to generate synthetic emission spectra. A comparison between the experimental and simulated spectra indicates the presence of specific ionization states of copper and the corresponding electron temperatures and ion densities throughout the laser-heated copper target.

I. INTRODUCTION

Time-resolved x-ray spectroscopy is interpreted with numerical simulations to diagnose plasma conditions in thin copper targets heated by a short-pulse laser. A variable spaced grating (VSG) spectrometer was coupled to an x-ray streak camera to measure the soft x-ray emission from the back surface of a laser-heated copper target. Radiation hydrodynamic simulations were performed using HYDRA to calculate the temporal evolution of the electron temperature and ion density profiles in 2-dimensions (2D) across the target. The HYDRA target conditions were used as an input for the atomic kinetics code Cretin to produce synthetic emission spectra. The HYDRA and Cretin calculations served to characterize the laser-heating of materials. We discuss the utility of using the HYDRA and Cretin simulations to interpret recorded spectra.

II. INSTRUMENT DESCRIPTION

The instrument used in these experiments has been described in the literature.[1-2] Figure 1 provides a schematic of the variable-spaced grating (VSG) spectrometer used to measure soft x-ray spectra. The VSG spectrometer is coupled to a commercially available x-ray streak camera (XRSC) manufactured by Kentech Instruments. A vertical slit of width 0.4375 mm is positioned at the entrance of the streak camera, along the detector plane of the VSG. The streak camera was outfitted with an aluminum and Lexan ($C_{16}H_{14}O_3$) photocathode coated with cesium iodide. The Kentech XRSC was mated to a Photek microchannel plate image intensifier and a Spectral Instruments CCD camera. The VSG spectrometer coupled to the Kentech x-ray streak camera demonstrated an overall time resolution of 31 ps.

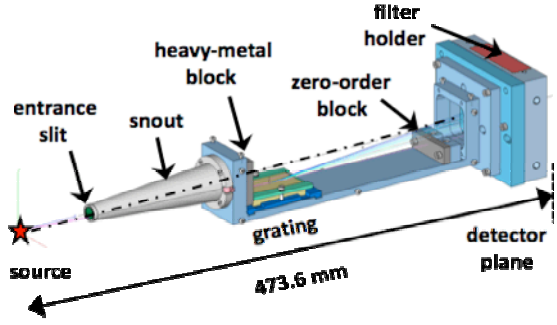

FIG. 1. VSG soft x-ray grating spectrometer

III. EXPERIMENT

The plasma-heating experiments were performed at Lawrence Livermore National Laboratory's (LLNL) Jupiter Laser Facility using the COMET laser. COMET is a hybrid chirped-pulse amplification laser consisting of a Ti:sapphire oscillator and a regenerative amplifier tuned to 1053 nm with a four-stage Nd:phosphate glass amplifier.[3] In an effort to minimize the pre-pulse and reduce the potential for the interaction of the laser with a preformed plasma, the COMET laser was frequency doubled to a wavelength of 527 nm. An ultrafast photodiode manufactured by Electron Optics Technology measured the temporal pulse shape of the laser. Figure 2 shows a top view of the experimental setup. The VSG spectrometer was mounted inside the COMET target chamber at 40° from the back of the target normal surface. The Kentech streak camera was mounted in a custom reentrant shroud behind the VSG spectrometer.

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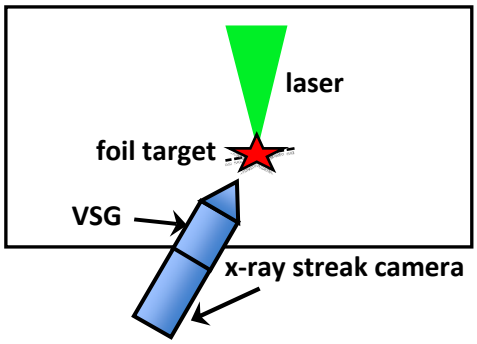

FIG. 2. Top view of the experimental setup. The VSG was looking at the back of the target.

IV. TARGETS

A thin Mylar foil was used to calibrate the dispersion and resolution of the spectrometer. The Mylar foil was heated with the COMET laser to produce line emission from highly charged oxygen ions. The energy resolution (E/ΔE) of the VSG spectrometer coupled to the x-ray streak camera was measured to be 205 at 653.69 eV and 135 at 816.88 eV, respectively. This is described in reference 1 and the dispersion curve is given in reference 2.

The targets were composed of 9000 Å of copper coated onto 0.5 µm of plastic. The target fabrication lab within the Jupiter Laser Facility at LLNL manufactured the targets used in these experiments. Figure 3 shows the streaked spectrum measured

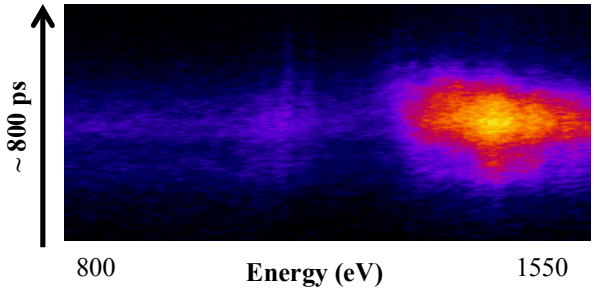

FIG. 3. Raw streaked spectrum from the rear surface of a Cu foil heated by a 2.1 X 10^{15} Wcm^{-2} laser pulse delivered in 480 ps.

with the VSG spectrometer from the rear surface of a copper foil heated by a 2.1 X 10^{15} Wcm^{-2} laser pulse focused to 25 µm diameter at full width at half maximum (FWHM) delivered in 480 ps.

V. SIMULATION

The state of the copper disk target for two specific laser-plasma experiments was calculated with the radiation hydrodynamics code HYDRA.[4] HYDRA is a multiphysics single fluid hydrodynamics code used to perform numerical simulations for 2 and 3-dimensional geometries. HYDRA divides the target into a mesh of several thousand nodes to model the flow of energy between the laser deposition region and the back layer of the target. Ultimately, HYDRA provides details of the evolving target conditions while calculating the electron temperature and ion density conditions across the target versus time.

The HYDRA simulations utilized an Arbitrary Lagrange Eulerian (ALE) mesh to control grid motion. A 2° wedge geometry was chosen to model the copper disk target, assuming cylindrical symmetry of the laser and target. The laser deposition was modeled as inverse bremsstrahlung absorption. The Livermore Equation of State (LEOS) was used throughout the calculations. The HYDRA calculations were performed assuming Local Thermodynamic Equilibrium[5] and utilized the temporal measurements of the laser profile, the measured beam diameter, and the laser energy on the target to simulate the energy deposition into the target over time. HYDRA calculations were performed for two specific laser experiments corresponding to 10^{14} and 10^{16} Wcm^{-2} intensities. The peak intensity on target for shot "O15s18" (shown in Figure 3) was 10^{15} Wcm^{-2}, which is between the conditions used in the HYDRA simulations.

The Cretin code is used to post-process the hydrodynamic calculations performed by HYDRA. Cretin is a radiation transfer code capable of simulating physical processes relevant to laboratory plasmas.[6] Cretin calculates the atomic kinetics and level populations within the target for the electron temperatures and ion densities provided by HYDRA. It then calculates the radiation transfer through the target to generate synthetic spectra.

The measured data was at an intensity between the two simulations, so the emission coefficients for the different ionization states of copper calculated by Cretin were used compare to the data. Figure 4 shows a comparison of emission from various charge states of copper calculated with the Cretin code and the measured time-integrated soft x-ray spectrum. The spectra has been corrected for the filter transmission and grating reflectivity. The time-integrated copper spectrum shown in Figure 4 is a lineout over the ~ 800 ps spectrum shown in Figure 3.

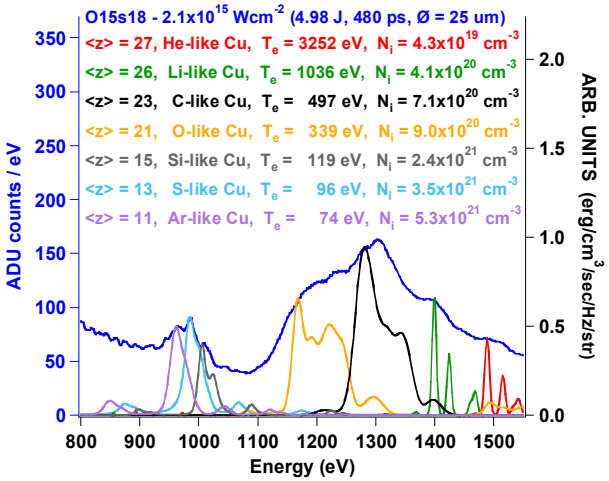

FIG. 4. Comparison of Cretin line emission from different ionization states of copper to a time-integrated spectrum measured from the rear surface of a copper target heated by a 480ps laser pulse at 2.1 X 10^{15} Wcm^{-2}.

VI. DISCUSSION

The time-integrated spectrum measured from the rear surface of the copper disk target heated by a laser pulse with a peak intensity of 2.1 X 10^{15} Wcm^{-2} has two prominent emission features in the regions of 900-1000 eV and 1200-1300 eV. The calculated emission coefficients for the different species of ionized copper show that soft x-ray emission above 1200 eV is generated by O-like to He-like copper with electron temperatures

and ion densities in the ranges 300 eV - 3250 eV and 5.9 X 10^{20} cm^{-3} to 4.3 X 10^{19} cm^{-3}, respectively. Similarly, the calculated line emission for the different species of ionized copper indicate that the soft x-ray emission in the region 940-1000 eV is produced from V-like to Mg-like copper ions with electron temperatures and ion densities in the range 25 eV – 155 eV and 1.6 X 10^{21} cm^{-3} to 2.3 X 10^{22} cm^{-3}, respectively. Futhermore, the absence of the cold copper L-edge absorption feature at ~ 933 eV suggests that the back copper layer of the target was 'warm' from the laser-heating of the target.

Figure 5 shows the temporal evolution of soft x-ray emission measured from the copper target heated by a 2.1 X 10^{15} Wcm^{-2} laser pulse focused to 25 μm diameter (FWHM) delivered in 480 ps. The blue curve indicates the emission measured 100 ps before the peak x-ray emission, the red curve indicates the peak emission measured (t_0), and the green curve indicates the emission measured 100 ps after the peak emission. Line emission from different ionization states of copper were identified using the transition energies for each isosequence calculated by the Cretin code.

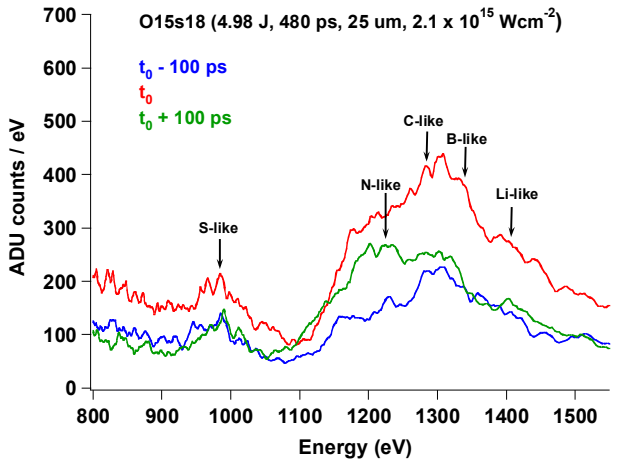

FIG. 5. Measured temporal evolution of emission from the rear surface of a copper foil heated by a 480 ps laser pulse at 2.1 X 10^{15} Wcm^{-2}.

The ionization states of copper identified in the time-resolved spectra are indicated in Figure 5. The peak soft x-ray emission measured (t_0 - the red curve in Figure 5) indicates the presence of highly ionized C-like and B-like copper ions. Comparison of the calculated line emission to experimental spectra indicate the strongest emission from C-like and B-like copper originates from some region within the target with electron temperatures between 500 – 600 eV and ion densities in the range 5.5 – 7 X 10^{20} cm^{-3}.

The temporal evolution of soft x-ray emission suggests that some of the target was heated to electron temperatures of ~ 1000 eV, producing Li-like copper at the peak of the x-ray emission (t_0, the red curve shown in Figure 5). Later in time, the target cools (t_0 + 100 ps, the green curve in Figure 5) and the emission spectrum indicates a greater presence of lower ionization states including N-like copper with an electron temperature of 395 eV with ion densities on the order of 8.3 X 10^{20} cm^{-3}. The apparent dip in the emission spectra between 1000 – 1130 eV is produced as colder ionization states absorb radiation from the hottest volume of the target, closer to the laser interaction region. The simulation indicates significant absorption of radiation between 955 – 1050 eV is caused by the presence of Cl-like to Na-like copper ions with electron temperatures and ion densities between 85 – 180 eV and 4.3 X 10^{20} cm^{-3} to 1.3 X 10^{21} cm^{-3}.

The heating of a thin copper target has been characterized using time-resolved x-ray spectroscopy with numerical simulations. Radiation hydrodynamic calculations performed with HYDRA were processed with the atomic kinetics code Cretin, providing a robust method to diagnose the electron temperature and ion density conditions within a laser-plasma heated target. Time-resolved x-ray spectra combined with sophisticated calculations in the manner presented provide a crucial tool for characterizing the bulk heating and cooling of laser-heated targets.

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