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Spectroscopic characterization of post-cluster argon plasmas during the blast wave expansion

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Abstract. In this work we present temperature diagnostics of an expanding laser-produced argon plasma. A short-pulse (35fs) laser with an intensity of $I = 10^{17}$W/cm^2 deposits $\sim$ 100 mJ of energy into argon clusters. This generates a hot plasma filament that develops into a cylindrically expanding shock. We develop spectral diagnostics for the temperatures of the argon plasma in the shock region and the preionized region ahead of the shock.

A collisional-radiative model is applied to explore line intensity ratios derived from Ar II - Ar IV spectra that are sensitive to temperatures in a few eV range. The results of hydrodynamic simulations are employed to derive a time dependent radiative transport calculation that generates the theoretical emission spectra from the expanding plasma.

INTRODUCTION

Laser interaction with gas clusters of atoms provides a unique opportunity for studies of high temperature plasmas. This is due to the high absorption efficiency of laser light, in the range of 50%$\sim$100% [1] and the efficient transfer of absorbed laser energy into the kinetic energies of ions as well as electrons [2]. The strong absorption of 10-100 fs laser light by clusters shows great promise in the development of soft X-ray sources [3] and in the production of fast ions and electrons [4]. Moreover, an interesting application of the cluster-laser interaction arises in the study of laser-driven blast waves in rare gases that have parameters relevant to the evolution of astrophysical shocks [5, 6].

In the present laser-generated blast wave experiments, clusters are produced by discharging argon from a high-pressure gas jet with a backing pressure of 1000 psi and letting it expand adiabatically. A 35 fs laser pulse of 100 mJ is focused to irradiate a column 4mm (FWHM) in length with a 25 μm radius, and leads to $\sim$ 50% absorption, i.e., $\sim$ 12.5 mJ/mm energy deposition. The cylindrical shock formed in the gas by laser absorption is observed from the radial and temporal distributions of electron densities measured by interferometry [5, 6]. The peak electron densities in the compressed region are found to decrease from $\sim$ 10^{19} cm^{-3} at the time of shock formation, 6-7 ns after the laser shot, to 10^{18} cm^{-3} at the end of blast wave expansion, $\sim$ 200 ns later. Electron temperatures of the expanding plasmas also evolve spatially and temporally and are expected to decrease sharply from an initial value of $\geq$ 100 eV to $\sim$ 2 eV as the shock dissipates. In the present work, temporal and spatial spectra from the expanding plasmas are recorded in the ultraviolet spectral range between 230 nm - 360 nm with 2 ns resolution.

We develop temperature diagnostics of the argon plasma from the UV spectra. As the plasma evolves in space and time atoms and ions experience distinct phases with respect to kinetic processes: 1) during the shock compression level populations are predominatly governed by collisions and 2) during the preheating, ahead of the shock, radiative processes are also important. A collisional-radiative model is applied to explore line intensity ratios in the Ar II - Ar IV spectra that are sensitive to temperatures in a few eV range. We present theoretical predictions of population ratios as a function of temperature relevant to the blast-wave plasmas employing the results of hydrodynamic simulations.

COLLISIONAL-RADIATIVE MODEL

We use a collisional-radiative model (CRM) to develop an electron temperature diagnostic [7]. Time-dependent level population distributions are obtained by solving rate equations incorporating collisional and radiative rates. The rate equations and radiative transport equation are solved self-consistently with the radiative transport code CRETIN [8]. For collisional processes, we include thermal electron excitation and de-excitation, ionization and three-body recombination processes, while for radiative processes we included spontaneous emission, as well as stimulated emission and absorption, photoionization, radiative recombination and dielectronic recombination processes. Since the plasma expands cylindrically, level population distributions are solved as a function of radius as well as time. As an input parameter, electron temperatures as a function of time and radius are taken from hydrodynamic simulations (HYADES) [9] and corresponding charge states and electron densities are computed from CRETIN's population densities. We use data from an atomic model that was generated at the University of Wisconsin at Madison for ion beam transport experiments [10, 11].

TEMPERATURE DIAGNOSTICS OF EXPANDING ARGON PLASMAS

Laser-produced argon plasmas during blast wave expansion experience distinct time histories of temperature and density. This is depicted in Figure 1 by plotting electron temperature and density as a function of radius at a given time obtained from a hydrodyanmic simulation with HYADES [9]. Before the cylindrical shock wave arrives, atoms are preionized by radiation emitted from the shock, this is the preionized region. Once compressed, the region is heated rapidly, this is the shock region. As the shock wave passes by, the ion mass density decreases rapidly and the temperature decreases slowly to form the cavity region.

Robust temperature diagnostics using UV spectra can be developed by exploiting level population distributions as a function of temperature. We plot emission spectra from the expanding argon plasma at 6 ns and 20 ns in Figure 2. It shows that there are many Ar II

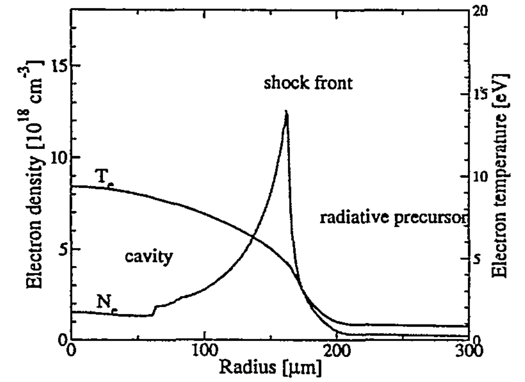

FIGURE 1. Spatial electron density and temperature distributions of plasma experiencing preionization, shock, cavity phases at a given time, 10 ns after the pulse in this case

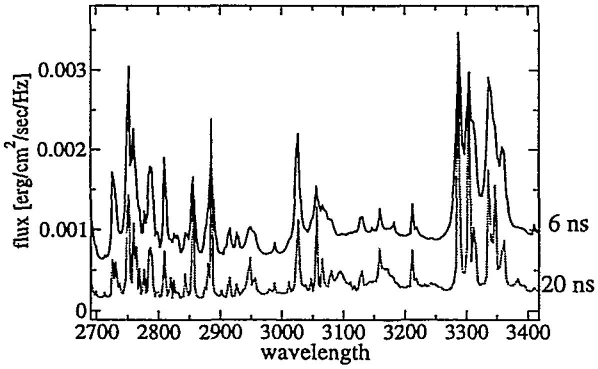

FIGURE 2. Emission flux calculations at 6 ns and 20 ns calculated at 500 μm away from the center

and Ar III lines present and potentially they can be used for temperature diagnostics. Emission spectra can be categorized based on relative temperatures of the radiating regions: hotter shock and post-shock regions and the colder preionized region. The level population distribution is dominated by collisional processes in the hot regions, where ion and electron densities are of the order of 10^{19} cm^{-3} and the electron temperature is $\geq$ 2 eV. On the other hand, in the cold preionized region, radiation from the existing hot region plays an important role in the charge state distribution and detailed level populations. Here we present T_e diagnostics for these two different regions.

Shock and post-shock region

As temperatures are greater than 2 eV in the shock and post-shock regions, emission from Ar II to Ar IV lines is observed in the spectral range of 230 nm - 360 nm. In this case, the mean charge state moves to more than singly ionized and the electron density is sufficiently high for collision processes to be predominant. We find that Ar II and III

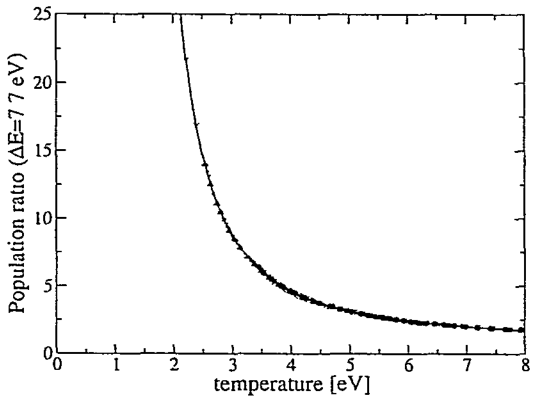

FIGURE 3. Ratio of population densities as a function of temperature between Ar II $3p^44p$ ^2P and $3p^45d$ ^2D levels.

spectra from the shock and post-shock region arise predominantly from line radiation of transitions of $3p^44p$–$3p^43d$, $3p^44p$–$3p^44s$, $3p^44d$–$3p^44p$ and $3p^45d$–$3p^45p$ levels. The energy spread of upper levels in strong transitions is 7.7 eV for Ar II and 8.1 eV for Ar III. Therefore, using Ar II and Ar III line intensities one can expect to have a good T_e diagnostic up to $T_e \sim 8$ eV. An example of a population ratio of two upper levels is shown as a function of temperature in Figure 3. Combining several populations ratios with different energy spacings, one can have a robust T_e diagnostic of plasmas in the shock and post-shock region.

Preionized region

A layer ahead of the shock front is photoionized by radiation from the hot inner region before the shock wave arrives. The average charge state in the preionized region closely follows that of the shock due to photoionization by radiation from the shock region even though the electron temperature is much lower. Emission from this region will be affected by non-local plasma conditions, that is, T_e of the hot region. We tested time-dependent and steady-state models and found that the two results are in agreement after the first nanosecond. During the first nanosecond, the cold gas at the ambient temperature is being ionized and its level population is yet to evolve to steady-state.

Since the strong photoexcitation dominates the level population distributions within the same spin system, relative population densities of levels with the same spin represent non-local properties of radiation flux. Relative population distributions of those levels with different spins, however, represent collisional properties as each spin system couples to the thermal bath of local temperature.

A sample of a population ratio of Ar II upper levels, one belonging to quartet system and the other to doublet system is shown as a function of temperature in Figure 4. In the figure, we plot time-dependent (symbols) and steady-state (lines) population density ratios from different radial positions in the plasma. The few below the dominant

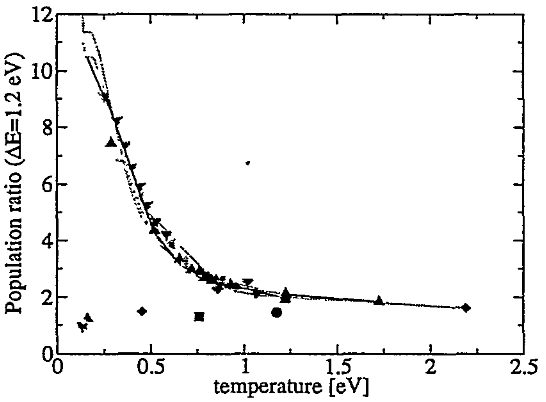

FIGURE 4. Ratio of population densities in Ar II $3p^44d\ ^4D$ and $3p^44d\ ^2D$ levels as a function temperature in comparison between time-dependent(symbols) and steady-state (lines) results.

curve represent the ratios in the first nanosecond in the time-dependent case before level populations reach a steady-state. Since temperature information of the radiating hot region is readily available from line diagnostics discussed in the previous section, local T_e diagnostics of preionized region will be also possible from steady-state results incorporating non-local radiative processes.

SUMMARY AND FUTURE WORK

We have shown that line intensity ratios can be used as a local temperature diagnostic for this expanding argon plasma. While collisional processes are dominant in shock and post-shock region, radiative processes play a critical role in preionized region. Accounting for the difference in dominant atomic processes, a collisional-radiative model can be applied for T_e diagnotics of both regions. We will apply the developed T_e diagnostics for analysis of measured argon spectra in the spectral range of 230 -360 nm.

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