ArFIT: A Detailed Model of Ar K-Shell Emission from High Energy Density Plasmas

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Abstract

ArFIT, a detailed model of Ar K-shell emission from high energy density plasmas, is used to provide density and temperature dependent spectra for use in the inference of core conditions in laser-driven microballoon implosions. In order to make this process of inference independent of radiative hydrodynamic simulation, a uniform core approximation is used in the calculation of radiative transfer effects on line shapes and relative intensities. The impact of this core approximation is explored herein, and is found to have small effect on the accuracy of inferred emissivity average core electron temperatures and densities for implosions where the Ar K-shell lines used in the inference process are optically thin.

1. Introduction

Ar K-shell spectroscopy has proven to be a useful time-resolved diagnostic of core conditions in ICF-relevant implosions [1-3]. Recently, scientists at the Laboratory for Laser Energetics at the University of Rochester have reduced the required Ar dopant amounts so that the Ar serves as an almost non-interfering probe of these implosions, while still retaining sufficient Ar to provide useful spectroscopic data [4]. Here, we examine the application Ar K-shell spectroscopy to the inference of plasma core conditions. In particular, we explore the impact of the uniform core approximation on the accuracy of inferred temperatures and densities for plasmas where the lines used in the inference are optically thin. The uniform core approximation is made to account for the effects on radiative transfer on line shapes (opacity broadening) and relative intensities. The optically thick ($\tau_0 \sim 10$) α lines are not used for the inference of core conditions. However, the effect of their transfer is to drive the overall ionization balance of the Ar dopant to more stripped ionization stages, and this effect on relative intensities of lines emitted from different ionization stages must be included in an accurate model. The advantages of the uniform core approximation are that the inference of plasma conditions from Ar K-shell lines is independent of radiative hydrodynamics modeling, and that the analysis does not depend on the interpretation of monochromatic images [5]. After this brief introduction, details of ArFIT, a detailed model of Ar K-shell emission from high energy density plasmas will be presented, and its use to infer plasma conditions demonstrated. Then, the impact of the uniform core approximation is explored by the analysis of spectra produced by post-processing a one dimensional radiative hydrodynamic simulation.

2. ArFIT and the Uniform Core Approximation

ArFIT combines Stark broadened line profiles [6,7] with relative intensities derived from a detailed non-local thermodynamic equilibrium optically thin collisional-radiative equilibrium model [8]. To account for the effects of radiative transfer on the line shapes, the line shapes are modified according to a uniform plasma opacity model [9]. To account for the effects of radiative transfer on the distribution of population among the Ar energy levels, a less detailed Ar atomic model is used in conjunction with escape factors derived from the detailed Stark broadened line profiles [10]. The resulting Ar K-shell spectrum is both density and temperature sensitive for conditions relevant to the cores of current laser-driven ICF microballoon implosions. Inferences of emissivity averaged core temperatures and densities are produced by comparing time-resolved Ar K-shell spectra recorded during an experiment to the output of ArFIT and performing a least squares minimization on temperature and density.

Figure 1 demonstrates the density dependence of the Stark broadened Ar Ly-β line for conditions relevant to the core of imploded microballoons. Increased density results in a broader line shifted to lower energy. This plasma-induced line shift has been observed in many recent experiments and has been modeled adequately for densities below 2.5e24/cc [11]. The Stark broadened Ar K-shell line shapes vary only mildly with temperature between 1 keV and 2.5 keV.

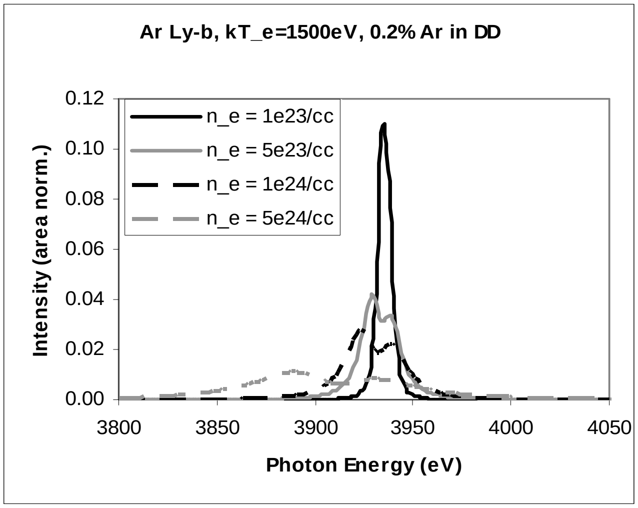

Figure 1. The density dependent Stark broadened Ly-β line (2l→1s) of Ar, calculated for several densities and an electron temperature of 1500 eV, for a plasma composed of deuterium plasma doped with 0.2% Ar.

The Ar K-shell spectra in the photon energy range 3.5 keV to 4.5 keV consists of the helium ($1snl \rightarrow 1s^2$) and Lyman ($nl \rightarrow 1s$) Rydberg series and satellites arising from associated doubly excited upper states ($1snln'l' \rightarrow 1s^2n'l'$, $nln'l' \rightarrow 1sn'l'$). A detailed collisional-radiative equilibrium model including 1380 energy levels is solved using CRETIN [8] in the optically thin approximation to determine the distribution of population among the levels relevant to Ar K-shell spectroscopy. To produce a model of emission from an optically thin plasma, one would combine the Stark broadened line profiles with the relative intensities resulting from the distribution of population and the oscillator strengths of the transitions.

Practical considerations dictate the amount of Ar used as a spectroscopic dopant in recent directly-driven microballoon implosions [2]. There must be enough Ar so that the diagnostic lines are distinguishable from the free-free continuum emitted by the fuel and the plastic ablator. The amount of Ar has to be small enough, though, so that the diagnostic lines are optically thin, and thus the whole core can be probed, and not just a thin outer shell. Also, Ar K-shell line emission can perturb the hydrodynamics of interest through radiative cooling. The Ar concentrations from these considerations lead to plasmas where the He- and Ly-α lines are optically thick ($\tau_0 \sim 10$). To account for the effect of the transfer of these lines on the population distribution, a less detailed Ar K-shell CRE model is solved using escape factors calculated using detailed Stark broadened line shapes. This smaller model is used in the uniform core approximation to generate corrections to optically thin intensity ratios. These corrections are then applied to the results from the detailed model. Figure 2 illustrates the temperature dependence of one such correction for a fixed density. The extremum in the correction factor arises for the temperature where the He-α opacity most strongly drives the ionization balance towards H-like Ar.

Even though the concentration of Ar is chosen so that the lines used for diagnosis are optically thin, the opacity broadening is not entirely negligible. Photons emitted from the center of the core at the peak of the line profile are more likely to be absorbed in the plasma than those emitted on the wings of the profile. This leads to a re-distribution of observed intensity from the peak to the wings of the line as the energy of the photon is re-emitted. The resulting line broadening must be accounted for, or else the density inference will be too high. The importance of this effect, and thus the importance of modeling it scrupulously, diminishes as the concentration of Ar and thus the optical depth of the line decreases. Figure 3, when considered alongside Figure 1, demonstrates the fact that for optical depths of less than 1, the opacity broadening of the lines is considerably less than the Stark broadening of the lines. Indeed, its effect on density inferences is less than 10% for the plasma conditions and optical depths of recent experiments [4].

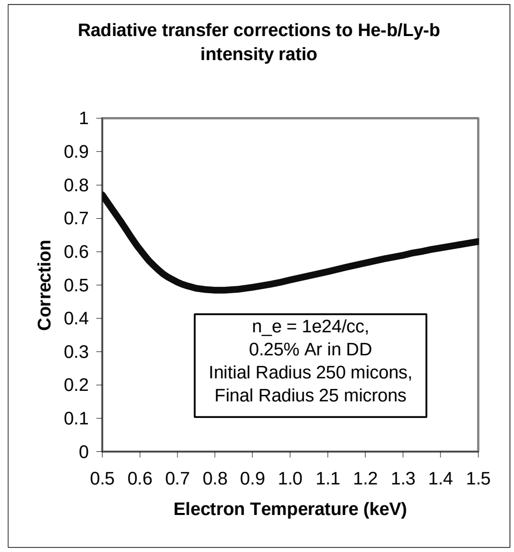

Figure 2. Radiative transfer corrections to the ratio of the integrated intensity of the He-β line to that of the Ly-β line.

To explore the impact of the uniform core approximation on inferences of emissivity-averaged core temperatures and densities, radiative hydrodynamics simulations of laser ICF relevant directly-driven implosions have been conducted using BUCKY, a flexible, one dimensional Lagrangian radiation-hydrodynamics simulation code [12]. Recently, a ray-tracing laser deposition package has been added to BUCKY, allowing more accurate simulation of directly-driven laser implosion experiments. Simulated electron temperature and density profiles were extracted for times of peak electron temperature and density. These profiles were then post-processed to produce Ar K-shell spectra by self-consistently solving a set of atomic kinetic rate equations and the radiation transport equation using a combination of linearization and Λ operator techniques [5]. The resulting Ar K-shell spectra, which include the effects of core gradients with 10% white noise added, were analyzed using the uniform core approximation, where the effects of radiative transfer are calculated using slab opacity models and escape factors. The simulated core structure and the fits to the post-processed spectra are shown in Figures 4 and 5. For these times, the inferred values for the emissivity-averaged core conditions differ by less than 10% from emissivity averaged calculated directly from the simulated core structure.

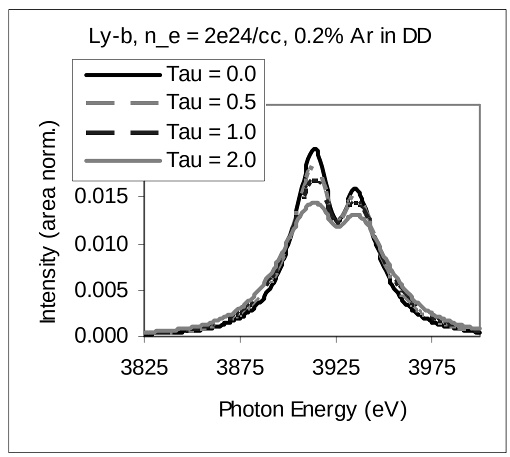

Figure 3. The effect of opacity broadening on the Ar Ly-β line for several peak optical depths.

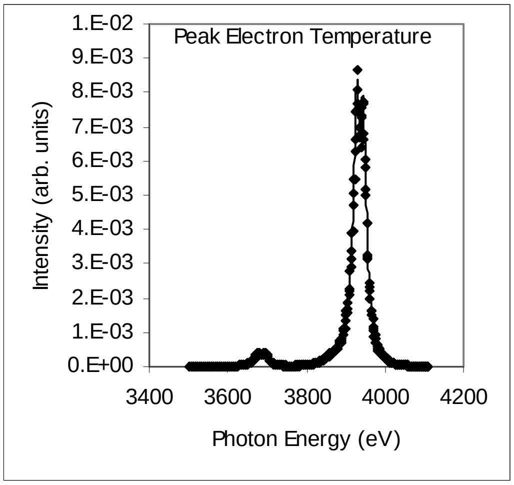

Figure 4. Post-processed spectra from the BUCKY simulation at the time of peak core electron temperature, and the results of using the uniform core approximation for its analysis. The simulated emissivity averaged core density and temperature were 1.51e24/cc and 2.61 keV. The corresponding inferences from the uniform model are, respectively, 1.4e24/cc and 2.8 keV.

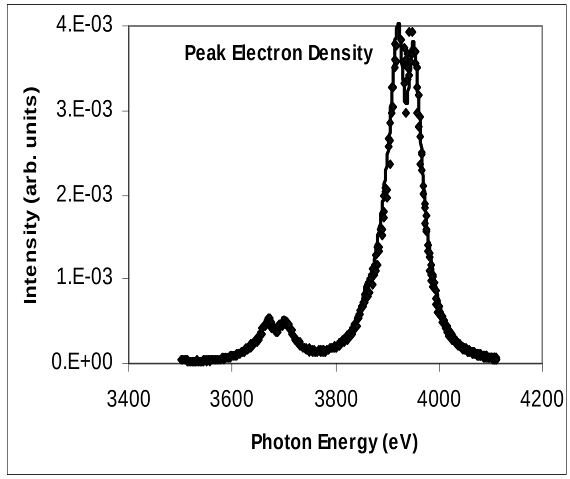

Figure 5. Post-processed spectra from the BUCKY simulation at the time of peak core electron density, and the results of using the uniform core approximation for its analysis. The simulated emissivity averaged core density and temperature were 3.55e24/cc and 2.03 keV. The corresponding inferences from the uniform model are, respectively, 3.5e24/cc and 2.1 keV.

4. Conclusion

The uniform core approximation in ArFIT is appropriate when ArFIT is applied to plasma conditions where the Ar concentration is sufficiently low such that the diagnostic Ar K-shell β lines are optically thin ($\tau_0 < 1$).

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