Time-resolved density measurements of x-ray heated Teflon foils using absorption spectroscopy

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We report on time-resolved absorption line shape measurements of lithiumlike fluorine produced from x-ray heated Teflon foil targets. X-ray emission created by a separate gold target was used as a backlighter. The width of the F VII $2p$-$3d$ line, which is Stark broadened, is observed to vary in time. This linewidth is used to infer the time-dependent electron density of the plasma when the density falls below 10^{21} cm^{-3}. These measurements agree well with hydrodynamic code calculations of the plasma density.

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INTRODUCTION

High power lasers irradiating a solid can efficiently convert their energy into thermal x rays. X rays produced in this manner have been used to heat matter to very high densities and temperatures. The study of these x-ray heated plasmas has important applications to indirectly driven inertial confinement fusion [1]. Opacities of these plasmas have been shown to be relevant to astrophysical studies [2].

Several different approaches have been utilized in the study of high density plasmas. On the one hand, measurements of Stark broadening of line emission from plasmas have been used extensively to infer the electron density of a wide range of plasmas from x-ray laser sources to inertial confinement fusion (ICF) plasmas [3,4]. Densities above 10^{24} cm^{-3} have been measured in indirectly driven ICF capsules from the Stark broadening analysis of Ar He-β line profiles [5]. Similar densities were also observed in direct drive implosion experiments also using Stark broadening measurements of highly ionized Ar emission lines [6]. On the other hand, absorption spectroscopy of radiatively heated foils has been used increasingly as a tool for understanding opacity and radiation transport in warm matter [2,7–9]. However, in the search for an ideal plasma testing ground for high energy density matter we pursue the characterization of an appropriate plasma with controllable gradients using absorption spectroscopy of Stark broadened spectral lines. In this experiment we observed time-dependent spectra of ionized fluorine in absorption from a radiatively heated tamped Teflon foil. We measured Stark broadened line profiles of Li-like F in absorption. The electron density was determined from these profile measurements and compared to hydrodynamic simulations.

EXPERIMENT

For our experiments we used two beams of the Nova laser typically with pulse lengths of 1 ns and energy of 3200 J. The experimental setup is shown in Fig. 1. One beam of the laser, which has been smoothed using random phase plates and wedges, is focused to a spot size of approximately 1 mm^2 on a thin (2000 Å) Au burnthrough foil. X rays produced from the backside of the Au foil then radiatively heat a thin (1400 Å) Teflon (C_2F_4) foil tamped on both sides with 1000 Å of parylene (CH). The parylene layers on each side of the Teflon constrain the expansion of the heated Teflon and therefore produce a more uniform density plasma in the central region. The second laser beam heats a separate Au foil that backlights the observed sample. The backlighter target was either a 2000 Å Au foil, in which case x rays from the backside were used, or a thick Au foil, in which case x rays from the frontside were used for the backlighter. The timing of the backlighter with respect to the heater varied from 0 to 1 ns after the heater pulse in order to optimize the temporal coverage of the absorption spectra.

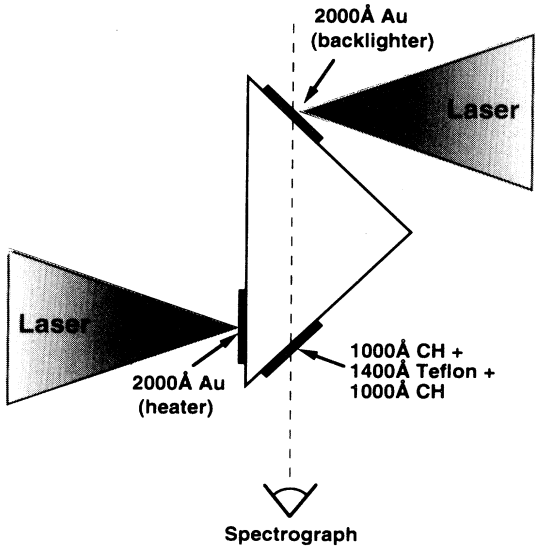

FIG. 1. Experimental setup showing triangular shaped target with tamped Teflon sample, Au heater foil, Au backlighter foil, and spectrograph view.

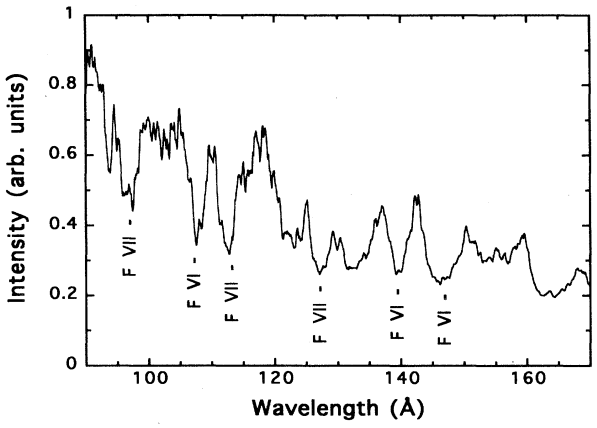

FIG. 2. Absorption spectrum from low resolution time-resolving spectrograph. The dominant emission in this wavelength region is from Li-like and Be-like charge states.

Two spectrographs were used. First a low resolution streaked flat field spectrograph was used to obtain survey spectra. This spectrograph employs a varied line space grating to achieve a flat focal plane [10]. A streak camera attached to the spectrograph gave time resolved spectra in the wavelength range from 90 Å to 200 Å. A typical spectrum obtained with this instrument is shown in Fig. 2. Strong absorption features are observed from Li-like and Be-like transitions as indicated in the figure. However, the spectral resolution of this instrument ($\lambda/\Delta\lambda \sim 200$) was too low to measure accurate line profiles. Note that these lines are too weak to be observed directly in emission.

We then used a high resolution spectrograph to obtain detailed time-resolved line shapes [11,12]. This spectrograph, of total length 8.5 m, is capable of a resolution of 35,000 at $\lambda = 160$ Å but had a resolution in these experiments of ~ 8000 due to the wide (28 μm) entrance slit employed. The instrument consists of cylindrical and spherical mirrors for focusing and pointing, as well as a varied line space grating. Its useful total spectral range is 100 – 220 Å; however, with a streak camera detector it has a wavelength coverage of ~ 4 Å at 128 Å. The much higher resolution of this spectrograph comes at a cost of reduced sensitivity due to its length and number of optical components and a more limited wavelength range. The Li-like F 2p-3d line, which is Stark effect dominated over the density range of interest, was selected to use as a Stark broadening density diagnostic. The width of this line in absorption is observed to decrease in time. This is shown in Fig. 3, where the measured line shape (crosses) is shown at three different times with respect to the start of the heater pulse. The solid curves are the best fit using numerically calculated Stark profiles. We only observe absorption spectra late in time and therefore have a limited range over which we can accurately measure the line profiles.

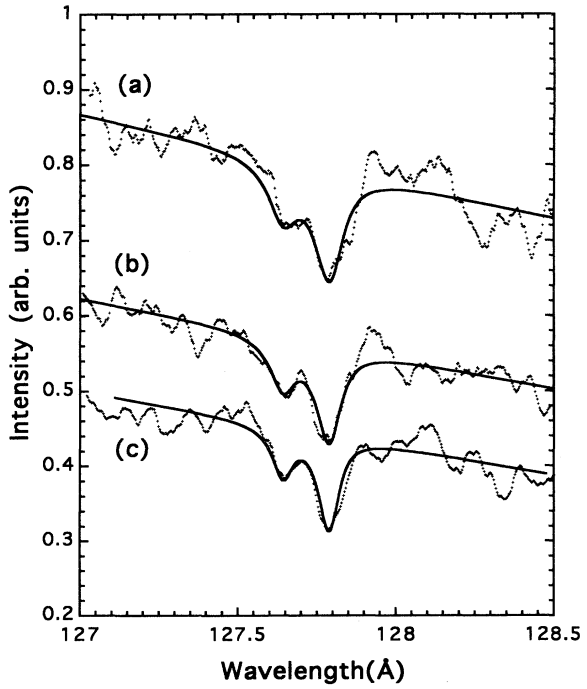

FIG. 3. Measured absorption spectra (crosses) from high resolution time-resolving spectrograph at different times: (a) 1600 ps (b) 1750 ps, and (c) 1900 ps. The solid curves are the best fit of numerical modeling of the Stark broadened profile of the Li-like F $2p$-$3d$ line.

DISCUSSION

We are interested in measuring the density of a sample that is volumetrically heated by a uniform x-ray source. The x-ray source used here has been characterized previously by Kania *et al.* [13]. In those experiments, the x-ray flux of a laser irradiated Au sample was absolutely measured for various thicknesses of Au using primarily a ten-channel time-resolving filtered x-ray diode system. Based on those earlier measurements we selected a Au foil thickness of 2000 Å because this thickness gave a relatively good x-ray conversion efficiency while being thick enough not to allow the laser to burn through, thus heating the sample directly. There will also be some additional heating from the backlighter, particularly for the cases when the front surface x-ray emission from a Au slab was used.

The method employed here is to measure the linewidth of a Stark broadened line in absorption. In this case we chose the Li-like F $2p$-$3d$ line, which is bright enough to be observed with the high resolution spectrograph and also sufficiently sensitive to Stark broadening. The linewidth and shape of the $2p$-$3d$ line has a density dependence due to the Stark effect while it is relatively insensitive to the electron temperature [14]. Our numerical calculations of this line shape used the standard approximation of quasi-static ions and impact electrons [15]. The inclusion of ion dynamics, which was checked using the frequency fluctuation model [17], has a negligible effect on the shape of this line. One must also consider other line broadening mechanisms in the analysis. Doppler

broadening and instrumental broadening contribute little ($\Delta\lambda < 0.02$ Å) to the linewidth due to the relatively low temperature of the plasma and the high resolution of the instrument. Opacity effects can also play a role in the line shape. However, detailed line transfer calculations, discussed in more detail below, show very little effect on the $2p$-$3d$ line profile due to the low opacity of the plasma.

The spectra has been modeled using CRETIN (a subset of the code GLF), which is a two-dimensional non-local thermodynamic equilibrium atomic kinetics and radiation transfer code [16]. The electron density and the temperature is first calculated using a Lagrangian hydrodynamics simulation. The experimentally measured x-ray source is input into the simulation. Output from the simulation is then used in CRETIN to model self-consistently the time evolution of atomic populations and photon distributions as radiation interacts with the plasma. Our experimental measurements, which show absorption spectra only for times greater than $\sim$ 1 ns after the start of the heater pulse, agree qualitatively with code calculations in that early in time the temperature is too low to produce much Be-like and Li-like charge state emission. At early time the observation is compromised by two additional factors. First, the high electron density early in time produces a large Stark broadening of the brightest lines, which in turn reduces the peak intensity of the lines. Second, the background level is also much higher earlier in time, as is evident in Fig. 3. Our simulation also predicts a maximum optical depth of the F VII $2p$-$3d$ line of approximately 1, which is again consistent with our absorption measurements.

We have compared the measured electron density to one-dimensional hydrodynamic simulations. In Fig. 4 the solid and the dotted lines are results from the simulation for the electron density and the temperature respectively, while the open triangles are the experimental measurements using the density inferred from the best fit of numerically calculated Stark broadened profiles to the measured profiles. The agreement is generally good over the experimental range for which our method is applicable. The accuracy of our density measurement is limited mainly by our choice of best fit of a Stark profile to the data. We computed a nonlinear least-squares fit to our data using a double Lorentzian profile. Since the simulated Stark profile of the $2p$-$3d$ line is well approximated by a double Lorentzian, we could then use this fitted profile to determine the electron density. Our best fit resulted in an uncertainty of $\pm$ 20% for the measured electron density. The uncertainty in the time relative to the heater pulse is relatively small ($\pm$ 50 ps), since there is a sharp increase in extreme ultraviolet and x-ray emission when the backlighter turns on, giving a good reference.

The other possible source of error is the accuracy of the numerical simulation, which is determined to a large degree by the x-ray source input. For our high resolution measurements we used as a backlighter x rays emitted from the front surface of a thick Au foil irradiated by a Nova laser beam focused to a small $\sim$ 150 μm diameter spot. This x-ray source is sufficient to produce additional heating of the sample. However, a comparison of the electron density for the cases with and without the backlighter heating, which increases the x-ray flux by $\sim$ 20%, shows less than 5% change in the average electron density indicating that the calculated electron density is not very sensitive to the x-ray source for the range of conditions we are considering. The calculated electron temperature, on the other hand, depends more strongly on the intensity of the x-ray source.

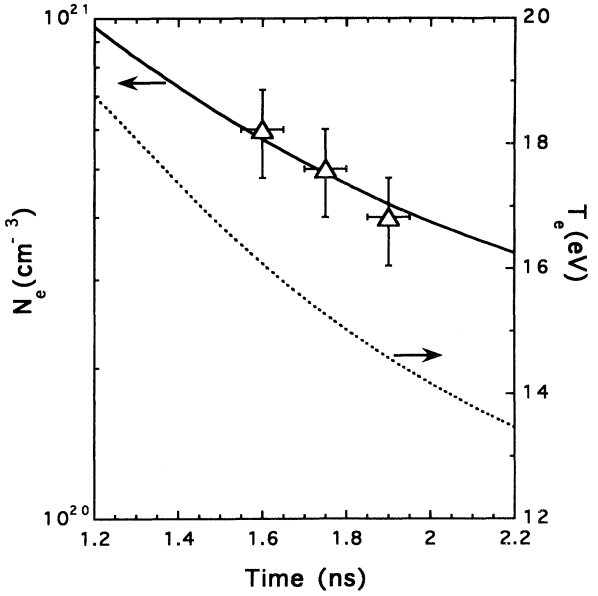

FIG. 4. The solid curve is a simulation result for the average electron density while the dashed curve is the electron temperature. The experimentally measured densities are the open triangles.

CONCLUSION

We have shown that Stark broadening in highly ionized absorption spectra can be successfully used to measure the electron density of x-ray heated foils for a window of time when the plasma conditions are appropriate. There are limitations to this method due to the difficulty of achieving sufficient contrast above the background emission early in time. Late in time the line intensity and the Stark width decrease due to the rapid decrease of electron density. In addition, care must be taken to limit the amount of broadening due to other mechanisms. With improved sensitivity of the spectrograph and careful selection of spectral lines to be observed, this density diagnostic can be more widely applicable to high density plasmas.

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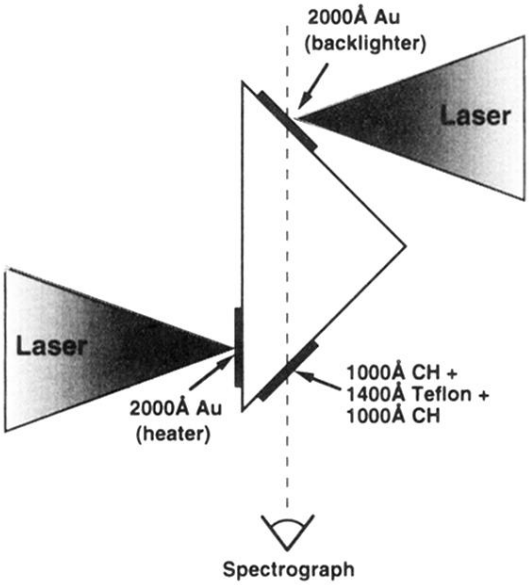

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