Soft x rays from high-intensity laser interactions with solids

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High-density plasmas are produced by illuminating solids with ultrashort laser pulses of 120 fs at 800-nm light, focused down to an intensity of approximately 8×10^{16} W/cm^2. Soft x rays are thus generated from the subsequent cooling of the plasma. Spectral data are presented for aluminum, Pyrex, and quartz targets. Emission from up to the lithiumlike species of all targets was observed. [S1063-651X(97)08807-7]

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I. INTRODUCTION

Advances in the technology of short-pulsed lasers have made it possible to routinely achieve intensities greater than 10^{17} W/cm^2 [1–3]. At such high intensities, both high-order harmonic generation (HOHG) [4,5] and high-density laser-produced plasmas (LPP's) [3,6,7] are viable methods for producing various wavelengths of short-duration light pulses. In particular, there has been a great deal of interest in the table-top production of ultrashort pulsed soft x rays [8–11]. In the x-ray regime, the energy of the light is on the same order as the binding energy of inner-shell electrons. If ultrashort pulses (in the 5–20 fs range) of x rays could be created, the inner-shell transitions of these electrons could actually be time resolved; slightly longer pulses (in the 20–200 fs range) of x rays would allow time-resolved studies of outer-shell transitions. This is a fundamental area of interest that has widespread application from medical imaging and treatment to understanding chemical and biochemical mechanisms by tagging specific atoms in complex molecules during reactions.

One method for producing these x rays that has received much attention over the last decade is to capture the photons emitted from high-density plasmas. A short-pulsed laser is focused down to greater than 10^{14} W/cm^2 onto a target material, producing the plasma. As this plasma cools, much of the energy is reemitted as photons. Depending on the material irradiated, discrete or continuous emission can occur at various wavelengths and pulse widths. An advantage of this process is that soft x-ray pulses on the order of a few picoseconds are presently attainable [12,13], with the hope of improvement in the future. Another benefit is that in whichever way the plasma is generated, an abundance of photons is generated, though often times collection of the light is a problem [14].

Certain obstacles exist, no matter what method is chosen to obtain these x rays. First, soft x rays are difficult to study; optics do not work well in this energy range [15], and so the light is difficult to either observe or deflect out for use. Also, most spectral data that exist come from traditional low-density plasma experiments [16]; hence, the ratios of the intensities of lines in these reports are of limited use.

In this paper, we report the soft x-ray spectral data for light emitted from high-density plasmas generated from high-intensity light interacting with solid target materials. While we do not attempt to assess relative intensities of peaks, all of those shown are within a factor of 5 of the most prominent peaks as opposed to much of the published data, in which some of these lines are listed as 100 times smaller than the most prominent peaks.

II. EXPERIMENT

Figure 1 shows the experimental setup. Four types of targets were used: aluminum, quartz, Pyrex, and brass. A rod of each target material was irradiated with p-polarized pulses of titanium-doped sapphire-generated 800-nm light. Each pulse was approximately 120 fs in duration and delivered 10 mJ of energy. The pulses were focused with an $f/25$ plano-convex lens such that the intensity at the target was approximately 8×10^{16} W/cm^2. The repetition rate of the laser was 10 Hz, and the target rod rotated such that each pulse irradiated a fresh portion of the target. Much of the light was emitted normal to the target, but to keep the amount of plasma debris entering the monochromator to a minimum, the beam trajectory was set perpendicular to the slits of the 1.5-m grazing-incidence Rowland circle monochromator. Thus the angle between the incident light and the normal to the target surface was adjusted to get as much light as possible at one particularly strong wavelength from the plasma; this angle fell between 45° and 55°. To eliminate noise and further protect the monochromator grating, a (1000-Å carbon) filter was placed just in front the entrance slit; hence, light with wavelengths smaller than 44 Å does not appear in

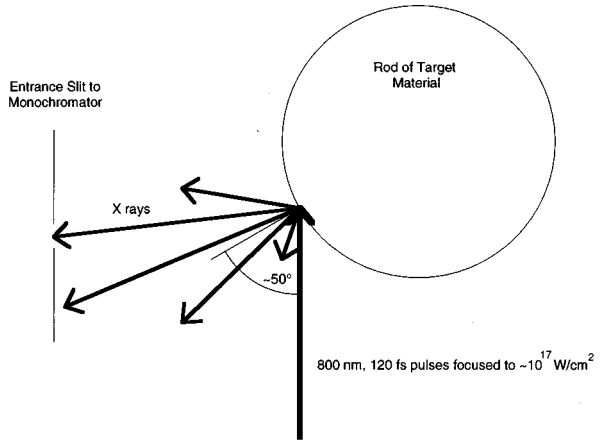

FIG. 1. Experimental setup.

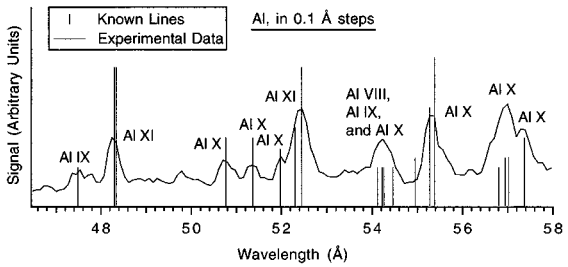

FIG. 2. Aluminum spectrum from plasma generated with 8×10^{16} W/cm^2 light. Laser parameters are listed in Sec. II. This is an expanded region of Fig. 3. Vertical lines are data taken from Kelly and Palumbo [16].

this study due to the carbon K-edge absorption. The primary range of light observed was in the soft x-ray range, and so a crossed pair of microchannel plates, the top plate being coated with CsI, was placed directly behind the exit slit of the monochromator. The entire system was evacuated to approximately 10^{-7} torr.

The monochromator held a Au-coated grating ruled with 1200 grooves/mm, and the slit widths were closed to smaller than 5 μm, yielding a resolution on the order of 0.3 Å. For this reason, the step size between wavelength data points was chosen to be either 0.05 or 0.1 Å. However, despite this excellent relative resolution between points, the scaling of our monochromator varied by approximately 1.0 Å over its entire 400-Å range.

For each wavelength position of the spectrometer, the signal from the microchannel plates was averaged over 20 shots, with point-to-point fluctuations of approximately 10%. In this way, spectra were collected with a computer and had excellent reproducibility.

III. RESULTS

Figure 2 shows a portion of the spectrum from the irradiated aluminum target ($Z=13$), as well as some lines and their relative strengths as found by the Naval Research Laboratory [16]. Our data were taken in 0.1-Å intervals. Note that these line strengths do not always correspond to the relative intensities of our data, since we did not use the same methods; however, they are a fairly good indication of which lines should appear and (usually) what their relative strengths could approximately be. The resolution is more than sufficient to easily distinguish even 10-times ionized aluminum (Al XI) lines. The average spectral full width at half maximum (FWHM) of these lines is approximately 0.5 Å.

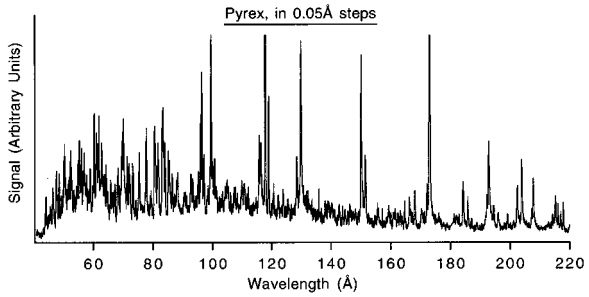

FIG. 4. Pyrex spectrum from plasma generated with 8×10^{16} W/cm^2 light. Laser parameters are listed in Sec. II.

Figures 3, 4, and 5 show the ''full'' spectra (from 40 to 220 Å) for aluminum, Pyrex, and quartz, respectively. The data for the Pyrex and quartz were taken in 0.05-Å steps. The composition of both of the glasses is quite similar [17]. The quartz is nearly 100% SiO_2 (Si, $Z=14$; O, $Z=8$), with at most trace amounts of impurities. The Pyrex is approximately 80% SiO_2 and 13% B_2O_3 (B, $Z=5$) by weight. The other substances Na_2O and Al each comprise less than 5% of the Pyrex by weight; however, in the regions shown, the predominant Pyrex lines are mainly silicon and oxygen, with just two boron peaks near 60 Å. The average FWHM for the glasses is approximately 0.6 Å. Note that even though the placement of lines in Figs. 4 and 5 is nearly identical, the intensity pattern is distinctly different; this is likely due to the different chemical structures and molecular bond strengths in the Pyrex and quartz. For a comparison of line strengths between the two glasses, the tallest peak in the quartz (near 118 Å) shone with approximately the same intensity as the series of tall peaks in the Pyrex.

For a contrast to these three low-Z materials which yield sharply peaked spectra, brass (Cu, $Z=29$: Zn, $Z=30$) was also examined. Figure 6 shows this spectrum, which is largely continuous due to the multitude of transitions that can take place in these heavier metals.

There is one main difference between the spectral character of the plasmas we have observed here and that which has been seen elsewhere. In studies by Teubner *et al.* [18] and Workman *et al.* [3], nearly the same range of x rays from aluminum plasmas is studied. In both of these cases, no such narrow peaks were observed; the features were much more continuumlike: similar to the brass spectrum in Fig. 6. This most likely indicates that the plasma we generated had a lower density than those produced in these previous works.

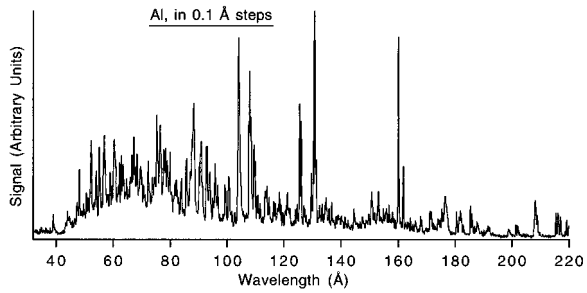

FIG. 3. Aluminum spectrum from plasma generated with 8×10^{16} W/cm^2 light. Laser parameters are listed in Sec. II.

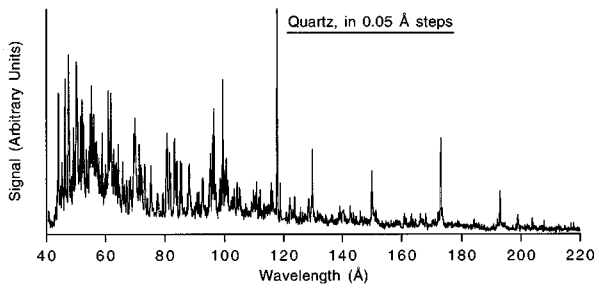

FIG. 5. Quartz spectrum from plasma generated with 8×10^{16} W/cm^2 light. Laser parameters are listed in Sec. II.

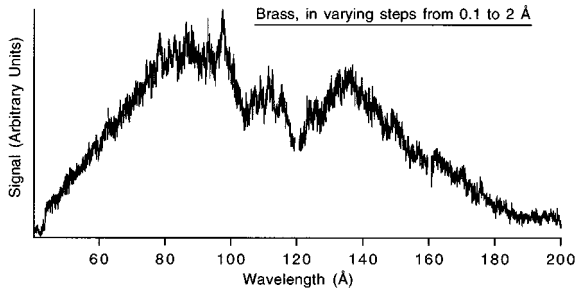

FIG. 6. Brass spectrum from plasma generated with 8×10^{16} W/cm^2 light. Laser parameters are listed in Sec. II.

A lower-density plasma could result from many factors, but there are two that are most likely the cause. First, we are using Ti:sapphire 800-nm light, whereas some others use KrF* 248-nm light. The higher-frequency light penetrates to higher-density regions, and since the density is proportional to the square of the plasma frequency, our pulses are only able to couple to plasmas with an order of magnitude lower density than the light from these other experiments. Of course, this does not explain the difference between our results and those of groups who use Nd:glass 1.06-μm light.

A second reason we may be observing a lower-density plasma could be that the leading edge of our pulses are prematurely generating a plasma, while the main peak of the pulse merely heats the preformed plasma. For a peak intensity of 8×10^{16} W/cm^2, the plasma begins forming a few hundred femtoseconds prior to the peak. Thus the highest intensities interact with a longer-scale-length plasma. For *p* polarization this leads to enhanced heating at a lower density.

IV. CONCLUSION

We have presented high-resolution soft x-ray spectra for the region of wavelengths between 40 and 220 Å. The research was performed by producing high-density plasmas through the interaction of *p*-polarized light at an intensity of 8×10^{16} W/cm^2 with various target materials. Many of the strong peaks which appear in this study are either considered weak or do exist in data previously collected with methods other than those which use high-density plasmas.

ACKNOWLEDGMENT

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