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XUV Spectroscopy of Subpicosecond Laser Produced Plasmas

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The keV and XUV spectra of plasmas produced by the interaction of a laser pulse of various duration and wavelengths with a solid Al target are compared and discussed. Drastic decrease of the XUV emission from the high ionization states was observed with the shortest pulses (500 fs) and the shortest wavelength (0.5 μm), which may be due to rapid cooling and quenching of ultrashort-lived and initially ultra-dense plasmas.

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The development of high intensity subpicosecond laser has opened new horizons for the study of laser-plasma interactions.[1] The plasma heating and cooling occur on a time scale that is short compared to the characteristics excitation and ionization times of the observed states. The resulting plasma is far away from equilibrium[2] and the characteristics are very different from long pulses (0.1–1 ns) laser produced plasmas in which steady state model may be applied. Ultrashort-lived plasmas have bright future for the generation of ultra-short x-ray source[3,4] and for optical-field-induced ionization which may be a promising scheme to obtain table-top soft x-ray laser.[5]

The dynamics of the ultrashort plasmas depends tightly on the pulse shape and contrast ratio of irradiating laser.[3,4,6,7] With prepulse-free subpicosecond laser, near-solid density plasma can be obtained[8] and the gradient scale-length of such plasma is much less than laser wavelength. The life-time of x-ray emission from some ionization can be very short.[4] However, the prepulse of a short laser pulse, if its intensity is high enough, could produce low density preformed plasma before the main short pulse which decreases the plasma density at which the emission takes place and increases lifetime of x-ray and XUV emission.[3,4] The time-integrated XUV emission of Al plasma produced by a subpicosecond laser with prepulse was recently studied in Ref. 7 and time-resolved but spectrally integrated XUV emission was discussed in Ref. 3. These previous work showed that XUV emission, especially the one from high ionization states, increases significantly when the prepulse intensity is high or when the separation between two pulses is long, and thus the plasma gradient scale-length is increased.[7] On the other hand, time-resolved XUV emission indicated the emission duration becomes shorter when the prepulse intensity of a short pulse is low or absent.[3]

In the present work we have compared XUV emission spectra obtained with subpicosecond laser pulses with and without prepulse at similar laser intensity (around 10^{17} W/cm^2), and compared 1 μm short pulse results (500 fs) to the results obtained with longer pulse duration at the constant laser energy (1J). We observed a drastic decrease of the XUV emission from the high ionization states with the shortest pulses (500 fs) and the shortest wavelength (0.5 μm), which may be due to rapid cooling and quenching of ultrashort-lived and initially ultra-dense plasmas.

The experiments were carried out with the table-top terawatt (T^3) laser system at Institut National de la Recherchè Scientifique (INRS), Canada. The INRS T^3 glass laser system (1.053 μm) which employs the chirped pulse amplification (CPA) technique can provide 1J in

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a 500 fs (FWHM) with a repetition rate or 1 shot every 45 seconds. The prepulse (several nanoseconds long) intensity measured with a third order autocorrelator was about 10^{-6} of the main pulse intensity. The laser pulse was focused on a planar target by a f/6 lens. The focal spot was about 50 μm in diameter, measured by an x-ray pinhole camera equipped with 25 μm Be filter. The maximum intensity available with 500 fs pulse on target was about 10^{17} W/cm^2, with a prepulse intensity about 10^{11} W/cm^2. Furthermore, laser pulses of various duration can be obtained by changing the conditions of the final compression grating pair of the laser system. In our experiments we have compared results obtained at constant laser energy with 500 fs (at 10^{17} W/cm^2), 1 ps (at 5×10^{16} W/cm^2), 5 ps (at 2×10^{16} W/cm^2) and 1 ns (at 10^{13} W/cm^2) laser pulses. Higher contrast 500 fs laser pulse (prepulse-free) was obtained by frequency doubling the 1.053 μm laser pulse which gave us the possibility to produce near solid density plasma at 10^{17} W/cm^2. To obtain high laser intensity, it is worth noting that in these ultrashort laser plasma experiments, a vacuum tube has been installed between the target chamber and the final compressing grating to avoid nonlinear wavefront distortion which could arise from excessive B integral in the air and lead to a larger focal spot due to defocusing effect.

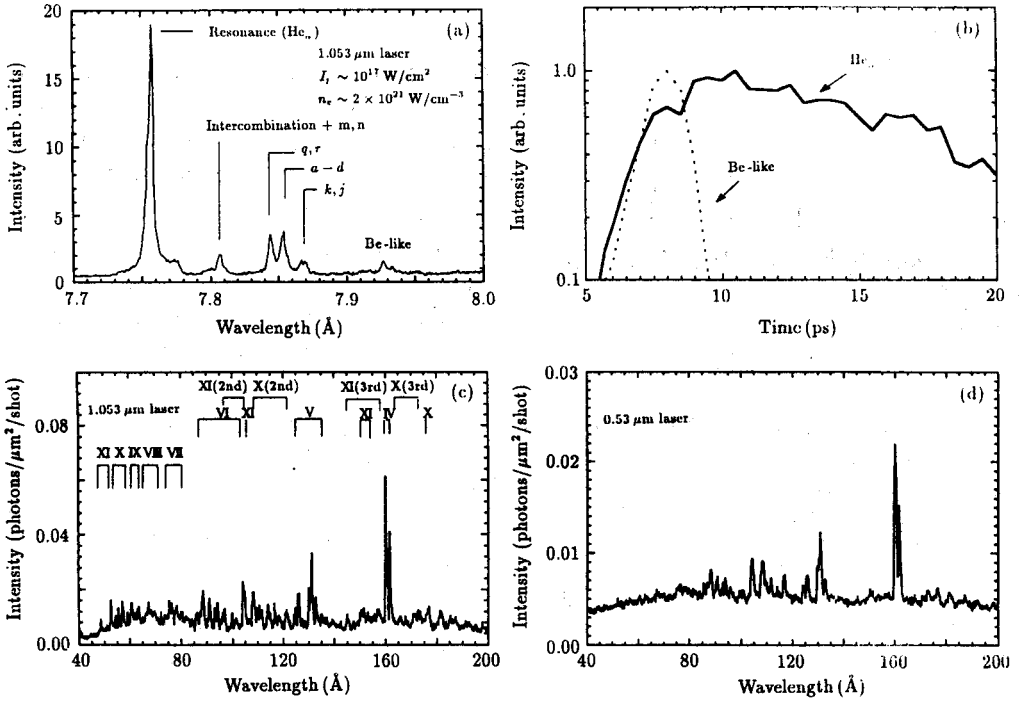
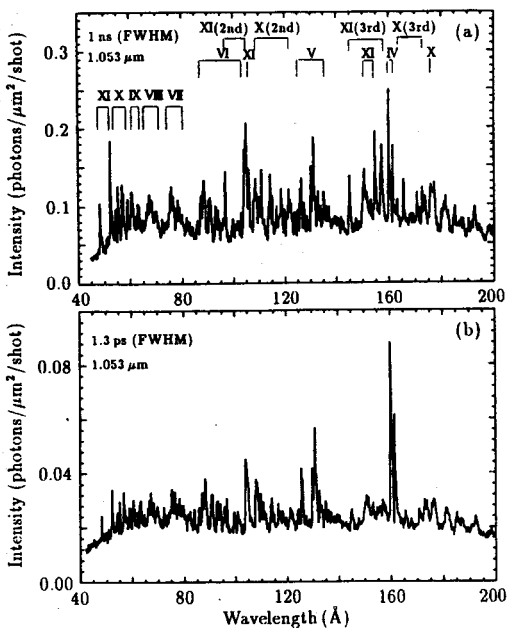


Fig. 1. Time-resolved and time-integrated keV and XUV spectra of Al plasmas produced by 500 fs, 1.05 μm and 0.53 μm laser pulses: (a) Time-integrated spectrum around He$_\alpha$ (0.776 nm), (1.05 μm laser intensity at 10^{17} W/cm^2); (b) Time histories of He$_\alpha$ and Be-like lines (1.05 μm laser). The time-resolution was 2 ps; (c) Time-integrated XUV spectrum in 4 to 20 nm region (1.05 μm laser intensity at 10^{17} W/cm^2); and (d) Time-integrated XUV spectrum (0.53 μm laser at 10^{17} W/cm^2).

The main XUV diagnostic used in the experiments was a grazing incidence flat-field grating spectrometer.[9] A variable-spacing concave grating was used to diffract XUV emission and focus the different spectral line on a flat field. The nominal spacing of the grating was 12001/mm and it gave us a spectrum ranging from 4 to 20 nm with spectral resolution from 0.43 to 0.67 nm per mm. In the experiments, Kodak 101-07, Kodak DEF and Shanghai 5FW film[10] were used, calibrated and compared.[11] In the experiments we used mainly Kodak 101-07 film.[12] Spectra

were recorded by accumulating different laser shots in order to get similar optical density at 16 nm (strongest line emission). Furthermore time-resolved keV spectra[4] (with a 2 ps temporal resolution) were simultaneously recorded with a modified Kentech streak camera coupled to a Von Hamos spectrometer. Time-integrated keV spectra were obtained with Von Hamos and Johann spectrometers. A set of x-ray diodes was also used to monitor the x-ray emission and control the focusing condition.



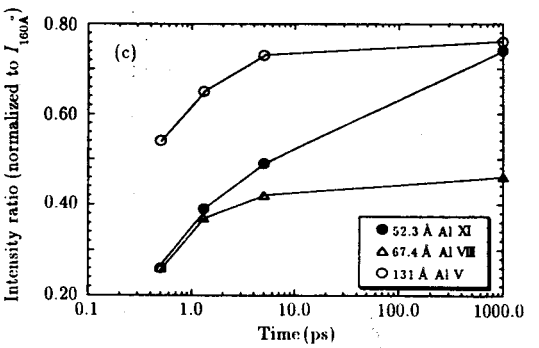


Fig.2 Time-integrated XUV emission of 1.05 μm laser plasmas produced by various pulse duration at constant laser energy: (a) XUV spectrum for 1.3 ps pulse at $I = 5 \times 10^{16}$ W/cm^2; (b) XUV spectrum for 1 ns laser pulse at $I = 5 \times 10^{13}$ W/cm^2; and (c) Emission intensity of several lines as a function of the 1.05 μm irradiation pulse duration. The emission intensity is normalized to the intensity of Al IV (16.007 nm) line, which is always the strongest line in both conditions.

Figure 1 shows keV and XUV spectra of Al plasmas produced by 500 fs, 1.053 μm and 0.53 μm laser pulses. The time-integrated spectrum around He$_\alpha$ (0.776 nm, $1s^2 - 1s2p\ ^1P_1$) recorded at the intensity of 10^{17} W/cm^2 with 1 μm laser is shown in Fig. 1(a). The intercombination line is relatively low while the Li-like inner-shell $a - d, q, r$, satellites are greater than the dielectronic k, j satellites. These features indicate the strong non-Maxwellian and non-stationary effects[8] and the comparison to calculation suggests the emission is produced at 2 times the critical density region. The time behaviors of He$_\alpha$ and Be-like lines for 1.053 μm irradiation are shown in Fig. 1(b) with a 2 ps temporal resolution. The duration of Be-like line emission is much shorter than He$_\alpha$ resonance line, which indicates the very different dynamics of various ionization states in plasmas produced by subpicosecond pulses, being contrary to what was observed with longer laser pulses. Figure 1(c) shows a time-integrated XUV spectrum of Al (1.053 μm–500 fs pulse) in 4 to 20 nm region at an irradiating laser intensity of 10^{17} W/cm^2. The ionization states are indicated along with high order diffraction. It is very interesting to compare this spectrum to the XUV spectrum obtained with 0.53 μm, 500 fs laser pulse at the same irradiating intensity, which is shown in Fig. 1(d). In the latter case the relative intensity of XUV line emission from high ionization states, e. g., Al XI, Al X, is drastically decreased, if we normalize the line intensities to the intensity of the Al IV line (16.007 nm), which is the strongest line emission in both conditions.

The influence of pulse duration on XUV emission have been further investigated with 1.053 μm laser at the constant laser energy. Figure 2 shows the XUV spectra obtained with 1.3 ps (Fig. 2(a)) and 1 ns (Fig. 2(b)) laser pulses. Compared to Fig. 1(c), more intense XUV emission in the short wavelength is observed with longer pulses, though the laser intensities are significantly lower. Figure 2(c) shows the intensity normalized to the Al IV line intensity

(16.007 nm) of several lines as a function of the pulse duration. This shows that the line emission from high ionization states (Al XI, for example) decreases strongly when the laser pulse duration decreases, at the constant laser energy. The line intensity decrease is less pronounced to the low ionization states (e. g., Al V).

This observation seems to be contrary to what is expected since the plasma temperature should be higher with the higher intensity giving more emission from high ionization states. However the rapid cooling of initial ultradense plasma produced by a subpicosecond laser pulse may be the reason for such a decreases of XUV emission. The target heating by a clean ultrashort laser pulse occurs only in an optical skin depth.[13] The plasma density in this layer could be near solid and the gradient scale length is only a part of laser wavelength. This high density plasma is extremely hot with plentiful hot electrons. This hot plasma will be cooled via rapid thermal conduction and plasma expansion. The rapid cooling and plasma density fall will subsequently quench some ionization states which reduce the duration of the line emission from corresponding excited states, as shown in time-resolved spectrum (Fig. 1(b)). Thus in time-integrated spectroscopy, the intensities of corresponding line emission would appear as "decreased"due to time average effect. Since the initial plasma density could be near solid by using prepulse-free 0.53 μm laser,[4] the quenching effect would be more pronounced with the shorter wavelength as observed in Figs. 1(c) and 1(d).

In subpicosecond laser plasma experiments the XUV emission is expected to be shorter with the shortest pulse and the highest contrast ratio as already observed with keV spectroscopy.[4] Picosecond time-resolved XUV spectroscopy will be investigated in a further study. All the characteristics observed in the present work are very interesting for the control and the optimization of an ultrafast XUV sources. Eventually we may change the brightness and pulse duration of XUV line emission by controlling the initial plasma density and gradient scale-length, as we already did for keV emission.[14]

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