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X-ray-line plasma satellites of ions in a dense plasma produced by a picosecond laser pulse

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Abstract

X-ray spectral lines of multicharged ions in a solid target interacting with picosecond laser pulses of moderate intensity ($\sim 3 \times 10^{17}$ W cm^{-2}) were measured on the 'Neodim' laser facility. Strong modulations in x-ray Ly$_\alpha$ line profiles of hydrogen-like fluorine ions were observed, evidencing the presence of intense plasma oscillations with an amplitude of the electric field larger than 10^8 V cm^{-1} and a frequency of about 10^{15} s^{-1}.

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1. Introduction

The x-ray emission spectra of a high-temperature plasma are formed mainly due to such atomic processes as electron–ion collisions and radiative or autoionization ionic level decay. Slowly varying (quasistatic) electric fields produced by chaotically moving ions affect the radiative characteristics of a plasma, causing the modification of profiles of the emitted spectral lines through the Stark effect. In addition, strong oscillating electric fields (OEFs) can exist in a plasma, leading to the change of spectral line profiles. These fields can be either the fields associated with the development of plasma instabilities, or the fields of laser radiation penetrating into the plasma from the outside.

Observation of spectroscopic effects caused by OEFs is of considerable importance, since, first, it confirms the nature of plasma oscillations, and, second, it provides a way of determining the field parameters. At present, there are a number of publications reporting the observation of plasma (or laser) satellites in x-ray spectra of multicharged ions. These satellites are caused by

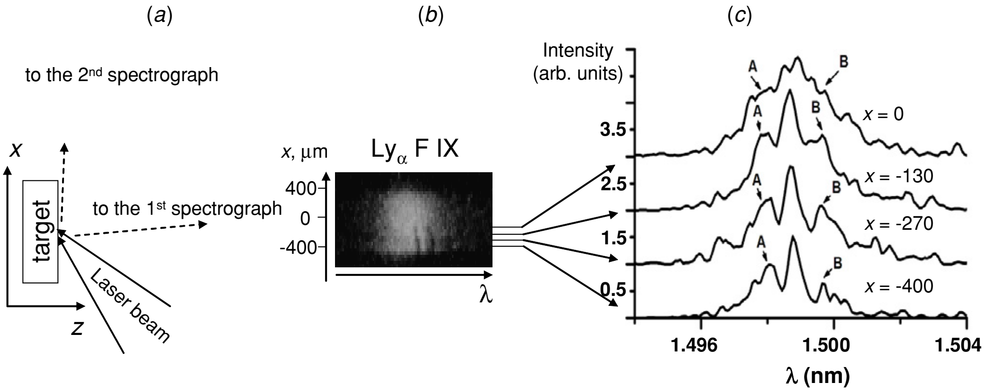

Figure 1. Experimental set-up (*a*), example of F IX Ly$_\alpha$ line spectrogram (*b*), and Ly$_\alpha$ line profiles emitted by various spatial plasma regions at $J_{\text{las}} = 3 \times 10^{17}$ W cm^{-2} (*c*). The letters A and B show the peaks in the experimental Ly$_\alpha$ line profiles.

the OEFs in laser plasmas [1–9]. In [9–16], theoretical approaches were developed to describe the modification of emission spectra of hydrogen-like radiators interacting with OEFs in a plasma.

2. Experimental set-up and results

The experiments were carried out with the 'Neodim' terawatt laser facility [17]. This laser facility provides the following laser pulse parameters: energy up to 1.7 J, a wavelength of 1.055 μm and duration of 1.5 ps. A laser beam 60 mm in diameter was focused on the target by a 14.5 mm thick aspherical lens with a focal length of 140 mm that concentrated 50% of the beam energy into a circle 15 μm in diameter. As a result, the intensity of the beam when focused on the target reached $J_{\text{las}} = 3 \times 10^{17}$ W cm^{-2}. Flat 200 μm thick fluoroplastic plates were used as the targets. The residual gas pressure in the vacuum chamber did not exceed 10^{-3} Torr. The x-ray radiation from the plasma produced by the interaction of a laser pulse with the target (see figure 1) was recorded by two focusing spectrometers with spatial resolution (FSSR-1D) [18], with spherically bent quartz or mica crystals (the radius of curvature of the crystal surface was 150 mm). In all experiments, the angle of observation was 5° and 85° to the normal to the target surface for spectrographs 1 and 2, respectively.

The plasma emission spectra were investigated in the spectral range 1.49–1.51 nm. Under experimental conditions, the spectrographs provided a spectral resolution $\lambda/\Delta\lambda$ of at least 5000. Figure 1(*b*) shows a typical space resolved F IX Ly$_\alpha$ line spectrogram recorded from the plasma in the direction almost along the normal to the target surface. Figure 1(*c*) shows the Ly$_\alpha$ line profiles of hydrogen-like fluorine ions observed from different spatial plasma regions for experiments where the laser flux density was $J_{\text{las}} = 3 \times 10^{17}$ W cm^{-2}. The spectra in our experiments were recorded without time resolution, i.e. the experimental spectra are integrals of the plasma emission over its lifetime. A characteristic feature of the profiles is the presence of strong modulations (a combination of peaks and dips in line profiles). As can be seen from figure 1(*b*), these strong modulations occur in the plasma region localized at $-400\ \mu\text{m} \leqslant x \leqslant 0\ \mu\text{m}$, the noise amplitude for most of the experimental profiles being considerably smaller than the modulation amplitude. The strong modulations in the F IX Ly$_\alpha$ line profiles were observed only for the first spectrograph. As for the second spectrograph, it collects radiation not only from the region where the F IX Ly_α line profiles are modulated, but also from a large plasma region where the F IX Ly_α line profiles are smooth (see figure 1(*b*)). Therefore, it was not possible to observe the modulations in the F IX Ly_α line profiles with the help of the second spectrograph. The modulation of the F IX Ly_α line profiles cannot be explained either by the Doppler effect or by the standard theory of Stark broadening of spectral lines developed for atoms (ions), subjected to electric microfields produced by electrons and ions. Also, it cannot be explained by the existence of the dielectronic satellites. For the Ly_α line of F IX ions, the spectral range where the most intense dielectronic satellites can be present (these satellites correspond to the $1\mathrm{s}2l'$–$2l2l'$ radiative transitions) is the following: $\lambda_1 \leqslant \lambda \leqslant \lambda_2$, where $\lambda_1 \approx 1.515$ nm and $\lambda_2 \approx 1.530$ nm. This spectral range lies beyond the range where spectral line profiles of the Ly_α line of F IX ions are localized (cf figure 1(*c*)). Moreover, as is evident from our spectroscopic measurements, under the experimental conditions the intensity of these dielectronic satellites is weak—it is close to the noise level. The other effect that in principle could cause the appearance of an additional peak in the spectral line profiles of ions is connected to the prepulse. The prepulse can induce a macroscopic plasma motion, which can lead to the Doppler shift of spectral lines. However, there are no physical reasons for the prepulse to be responsible for the simultaneous appearance of intense both red and blue peaks in the emission spectrum of the F IX Ly_α line. For our experiments, the intensity of the prepulse is about 10^{-5} of the pulse intensity. We would also like to note that in previous experiments, performed at a laser intensity of about 6×10^{12} W cm^{-2} [19] (this intensity is of the order of the intensity of the prepulse typical of the present experiment), no modulations were observed in the F IX Ly_α line profile. The Ly_α line profiles of hydrogen-like ions consist of two fine-structure components corresponding to the $1\mathrm{s}_{1/2}$–$2\mathrm{p}_{1/2}$ and $1\mathrm{s}_{1/2}$–$2\mathrm{p}_{3/2}$ radiative transitions. However, for ions with relatively small nuclear charges Z (typically, for ions with $Z \leqslant 11$, and, in particular, for the F IX ions), the fine structure of the Ly_α line is not observable due to the broadening of this line (Doppler broadening, Stark broadening under plasma electric microfields and instrumental broadening).

The Stark effect under the OEF $\mathbf{E}_0 \cos \omega t$ is the most universal mechanism for the appearance of strong modulations (sharp peaks and/or dips) in the smooth line profiles (see, e.g., [20, 21]).

3. Calculation of profiles of the Ly_α line of F IX ions

Let us consider the modification of the Ly_α line profiles of F IX ions under the combination of two electric fields in a plasma: (a) a quasistatic electric field $\mathbf{F}$ produced by randomly located perturbing ions and (b) an OEF $\mathbf{E}_0 \cos \omega t$. The field $\mathbf{F}$ forms smooth quasistatic Stark profiles of the Ly_α line of F IX ions, whereas the OEF generates peaks and dips in the quasistatic profiles. The angle θ between vectors $\mathbf{F}$ and $\mathbf{E}_0 \cos \omega t$ in general depends on the particular F IX ion.

For the calculation of profiles of the Ly_α line of F IX ions, we used our simulation code STARKPRO. This code calculates line profiles of hydrogen-like atoms and ions under the combined action of two electric fields in a plasma: a quasistatic field $\mathbf{F}$ and OEF $\mathbf{E}_0 \cos \omega t$. An essential point of the code is that it is based on the use of the Floquet theory [22] for finding the solutions of the time-dependent Schrödinger equation. Using the code STARKPRO, we calculated first the quasienergies and corresponding wave functions of the quasienergy states (QES) for the system of levels $2\mathrm{P}_{3/2}$, $2\mathrm{S}_{1/2}$ and $2\mathrm{P}_{1/2}$ interacting with the electric field $\varepsilon(t) = \mathbf{F} + \mathbf{E}_0 \cos \omega t$, by solving numerically the Schrödinger equation for the F IX ion. We took into account the fine-structure splitting of the $n = 2$ level. After calculating the quasienergies and QES, the code performs a calculation of the Ly_α line spectrum (for

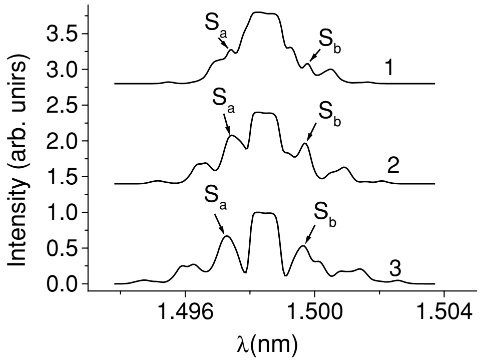

Figure 2. Theoretical profiles of the Ly$_\alpha$ line of F IX ions. For profiles 1, 2 and 3 the amplitude of the oscillating electric field (OEF) is $E_0 = 5 \times 10^8$ V cm^{-1}, $E_0 = 7 \times 10^8$ V cm^{-1} and $E_0 = 9 \times 10^8$ V cm^{-1}, respectively.

fixed values of **F** and θ), and finally the lineshape was averaged over a spherically symmetric distribution of the field **F**. This involves the averaging over both the absolute values of **F** and angle θ. We used a Holtsmark distribution function [23] as the distribution function of the magnitude F of the quasistatic electric field. The perturbing ions are assumed to be nuclei of fluorine ($Z = 9$). Along with the Stark effect, the Doppler effect was also taken into account. Finally, we took into account the optical thickness of the plasma by calculating the resulting line profile $S(\Delta\lambda)$ using the relation

$$S(\Delta\lambda) = 1 - \exp[-P(\Delta\lambda)x], \tag{1}$$

where $P(\Delta\lambda)$ is the normalized line profile ($P(\Delta\lambda)_{\max} = 1.0$) for an optically thin plasma, and the parameter x is the 'dimensionless' length (the parameter x was varied in our calculations).

The F IX Ly$_\alpha$ line profiles calculated for three OEF amplitudes are shown in figure 2. The calculations were carried out for the electron density $N_e = 2 \times 10^{20}$ cm^{-3} and the plasma temperature $T = 100$ eV. The frequency of the OEF was taken to be 10^{15} s^{-1}. The letters S_a and S_b show the features in the profiles corresponding to the following wavelengths counted from the line centre: $\delta\lambda = -\lambda_0^2\omega/(2\pi c)$ and $\delta\lambda = \lambda_0^2\omega/(2\pi c)$, respectively, where λ_0 is the unperturbed wavelength of the Ly$_\alpha$ line of F IX ions. Typically, these features have the form of a peak and two dips located on each side of the peak.

The appearance of modulations in the F IX Ly$_\alpha$ line profile can be understood as follows. The wave functions of the QESs belonging to the level of the principal quantum number $n = 2$ of a F IX ion interacting with the electric field $\varepsilon(t) = \mathbf{F} + \mathbf{E}_0 \cos\omega t$ have the following form:

$$\begin{gathered}\Psi_q(t) = \exp(-\mathrm{i}\mu_q t/\hbar) \sum_{j=1}^{N} \sum_{k} A_{jk}^{(q)} \exp(-\mathrm{i}k\omega t)\varphi_j, \\ k = 0, \pm 1, \ldots, \qquad q = 1, 2, \ldots, N, \qquad N = 8.\end{gathered} \tag{2}$$

In equation (2), μ_q is the quasienergy. The values of μ_q and $A_{jk}^{(q)}$ depend on F, E_0, ω and θ. If $E_0 = 0$, only the zeroth harmonic ($k = 0$) is present on the right-hand side of equation (2). If E_0 increases from zero, the contribution of the coefficients $A_{jk}^{(q)}$ with $k \neq 0$ to the wave function $\Psi_q(t)$ becomes larger. It follows from equation (2) that the F IX Ly$_\alpha$ line spectrum consists of a number of components at frequencies

$$\Delta\omega_{q,k} = \mu_q/\hbar + k\omega, \tag{3}$$

where $q = 1, 2, \ldots, 8$, and $k = 0, \pm 1, \ldots$ Due to the averaging over the distribution of the field $\mathbf{F}$, the components at frequencies $\Delta\omega_{q,k}$ in (3) smear out over the spectrum, and the smooth Ly_α profile is formed. There exist, however, regions of the field $\mathbf{F}$ where the quasienergies μ_q depend only slightly on $\mathbf{F}$. It is these regions that make a contribution to the features that occur in the smooth Stark profiles of the Ly_α line. In particular, as was studied in detail in [11, 12], such features can occur in the Stark profile of the Ly_α line of hydrogen atoms due to the resonance between the Stark splitting of the $n = 2$ level under the quasistatic electric field $\mathbf{F}$ and the frequency of the dynamic field $\mathbf{E}_0 \cos\omega t$.

Our calculations have shown that the F IX Ly_α line profiles strongly depend on the plasma temperature T and electron plasma density N_e, as well as on the parameters of the OEF $\mathbf{E}_0 \cos\omega t$. Our choice of the plasma parameters ($T \approx 100$ eV, $N_e \approx 2 \times 10^{20}$ cm^{-3}) and of the OEF parameters ($\omega \approx 10^{15}$ s^{-1}, $E_0 \approx$ (5–9) $\times$ 10^8 V cm^{-1}) provides the best match between theoretical and experimental profiles. Thus, the comparison of experimental profiles of the F IX Ly_α line with a set of theoretically calculated profiles of this line, enabled us to estimate not only the amplitude and frequency of the OEF, but also the plasma parameters.

We would like to note that the theoretical line profiles shown in figure 2 are slightly asymmetrical, due to the effect of the fine structure splitting of the $n = 2$ level of the F IX ions. As for the experimental profiles shown in figure 1(c), their asymmetry can be due to the fine structure splitting of the $n = 2$ level, as well as to several other spectroscopic effects characteristic of a dense plasma. Such effects are considered, e.g., in [23]. The central peak of theoretical line profiles presented in figure 2 is flatter than that of the experimental profiles. The main effect that is responsible for the appearance of such a rather flat central peak is self-absorption. We consider the self-absorption effect within a simple model of a homogeneous plasma, leading to expression (1). Under the experimental conditions, the central part of the Ly_α line profiles of F IX ions is formed due to emission from different plasma regions, each being of its own optical depth. The Ly_α line profiles of F IX ions emitted from plasma regions for which the effect of self-absorption is smaller, have sharper central peak. It can lead to the central peak of the resulting F IX Ly_α line profiles being sharper than the central peak of the theoretical profiles discussed above.

4. Discussion

Concerning the possible mechanisms of the generation of oscillating electric fields, we would like to note that these fields can be related to the existence of large spontaneous magnetic fields (MFs) that can be generated in laser-produced plasmas. Such MFs were detected in many experiments including, for instance, [24–26]. Strong MFs B can be generated due to several mechanisms including, e.g., Weibel-like instability in laser generated electron beams [27, 28]. The strength of such B fields depends on the laser intensity, and can be as high as a few hundred of megagauss for laser intensity exceeding 10^{19} W cm^{-2}. Existence of strong MFs in plasma can lead to the generation of oscillations of the Bernstein mode type [29]. The frequency of a Bernstein mode is a multiple of the electron cyclotron frequency $\omega_{ce} = eB/(m_e c)$. Assuming for the estimation that $\omega = \omega_{ce}$ for theoretical profiles shown in figure 1(b), we obtain an estimate for the MF that can be generated in the plasma: $B \approx$ 57 MGs. This value is in agreement with the estimate for the maximum value of the MF that can be generated in the laser-produced plasma $B \approx 10^{-1}(J_{\mathrm{las}})^{1/2}$, where B is expressed in G and J_{las} is expressed in W cm^{-2}. The latter relation can be derived by setting the energy density of the laser wave J_{las}/c to the energy density of the generated MF $B^2/(8\pi)$.

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