Effect of the satellite lines and opacity on the extreme ultraviolet emission from high-density Xe plasmas

Akira Sasaki
Advanced Photon Research Center, Kansai Research Establishment, Japan Atomic Energy Research Institute, 8-1 Umemidai Kizu-cho, Soraku-gun, Kyoto 619-0215, Japan

Katsunobu Nishihara and Masakatsu Murakami
Institute of Laser Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

Fumihiro Koike
Physics Laboratory, School of Medicine, Kitasato University, 1-15-1 Kitasato, Sagamihara, Kanagawa 228-8555, Japan

Takashi Kagawa
Faculty of Science, Nara Women’s University, Nara 630-8506, Japan

Takashi Nishikawa
Department of Electrical and Electronic Engineering, Okayama University, 1-1 Naka 1-chome, Tsushima, Okayama 700-8530, Japan

Kazumi Fujima
Faculty of Engineering, Yamashita University, 4-4-37, Takeda, Kofu, Yamanashi 400-8510, Japan

Tohru Kawamura and Hiroyuki Furukawa
Institute for Laser Technology, 1-8-4 Utsubohomachi, Nishi-ku, Osaka 550-0004, Japan

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Extreme ultraviolet (EUV) emission from Xe plasma in the \( \lambda = 13.5 \) nm band is theoretically investigated for lithographic application. It appears that a large number of satellite lines due to the \( 4d - 4f \), \( 4d - 5p \), and \( 4p - 4d \) transitions significantly contribute to the emission over the spectral range from 10 to 17 nm. At electron densities above \( 10^{20} / \text{cm}^3 \), laser-produced Xe plasmas attain quasilocal thermodynamic equilibrium (LTE) in order to make the emission intensity in the 13.5 nm band comparable to that in the 11 nm band. © 2004 American Institute of Physics.

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Development of the high power (>100 W) and efficient extreme ultraviolet (EUV) light source is a challenging subject in microolithography, for manufacturing next-generation semiconductors.\(^1\) Theoretical simulations are expected to direct guide source developers to optimize target material and pumping conditions.\(^2\) In this study, we find that the effect of satellite lines and opacity is essential for reproducing the experimental EUV spectrum of the laser-pumped Xe source. The results obtained facilitate quantitative analysis of the conversion efficiency from pumping laser energy to EUV emission through the coupled atomic processes and radiation hydrodynamics simulation.\(^3\)

Figure 1(a) shows a typical EUV spectrum from a laser-pumped Xe plasma.\(^4\) The spectrum shows a predominant peak near 11 nm, which is attributed to the \( 4d - 4f \) resonance lines of \( \text{Xe}^{7+} - \text{Xe}^{11+} \). Weak peaks arising from the \( 4d - 5p \) transitions near 13.5 nm (\( \text{Xe}^{10+} \)),\(^5\) 14.8 nm (\( \text{Xe}^{9+} \)),\(^6\) and 16.0 and 16.4 nm (\( \text{Xe}^{8+} \))\(^7\) are also observed; however, in contrast to those observed in the low-density discharge-pumped plasmas,\(^8,9\) the emission in the 13.5 nm band is dominated by an unidentified broad spectral structure. Existing theoretical models fail to explain the experimental spectrum between 12 and 17 nm (Ref. 10) on the sole basis of resonance lines, as shown in Fig. 1(b).

Figure 2 shows the atomic structure of \( \text{Xe}^{9+} \) calculated by the HULLAC code,\(^11\) which suggests the possibility of having a variety of satellite lines along with the \( 4d - 4f \), \( 4d - 5p \), and \( 4p - 4d \) resonance lines of \( \text{Xe}^{8–11+} \) ions. For instance, transitions from the doubly excited configurations, \( 4d^24fnl \) to \( 4d^4nl \), correspond to the satellite lines of the \( 4d - 4f \) transition of \( \text{Xe}^{8+} \). Similarly, the \( 4d - 5p \) resonance lines may have satellite lines, which originate from the \( 4d^5pnl \) configurations. Each satellite line consists of a large number of fine structure transitions, which produces unresolved transition array (UTA).\(^12\) Furthermore, emission may occur from doubly excited configurations with the spectator electron in different \( nl \) orbit, resulting in a huge number of satellite lines distributed over 10 eV (≈1 nm) on the longer wavelength side of the resonance lines.

In high-density laser-produced plasmas, where the population approaches local thermodynamic equilibrium (LTE), the upper level of the satellite lines may have a significant population due to the large statistical weight of multiply excited configurations. In particular, as the opacity of the resonance lines becomes large in high-density plasmas, the relative intensity of the satellite lines increases until the emission spectrum has a quasicontinuum structure.

In the present study, using the numerical simulation, the theoretically expected Xe spectrum features are being investigated. First, we calculate the atomic energy levels and radiative rates of Xe ions using the HULLAC and GRASP codes.\(^13\) We investigate the effect of configuration interaction (CI) between the \( 4d^n \), \( 4d^{n-1}4f \), \( 4d^{n-1}5p \), \( 4d^{n-1}5f \), and \( 4p^54d^5 \) configurations, since CI changes considerably the...
the WHIAM collisional–radiative model. 15 We use the

FIG. 2. Grotrian diagram of Xe 9+ showing the energy of the configurations.

classical–ab initio model. The atomic model used here is the HULLAC code.

The height of the box corresponds to the standard deviation of the energy of

configuration-averaged atomic model with charge states ranging from neutral Xe to Xe 18+. We include the excited configurations with principal quantum number up to n=8 and orbital quantum number up to l=3 of the excited electron. All the states with the same n are averaged for levels of n > 5. The radiative rates and autoionization rates are calculated using the HULLAC code. The rates of electron collisional excitation, ionization, and radiative recombination are calculated using empirical formulas. 16 The dielectronic processes are taken into account under explicit consideration of the autoionizing levels. It is found that at electron densities n_e > 10^{20}/cm^3, which are typical of the emission region in laser-produced plasma, the population of all the excited states can be approximated to be in LTE as a result of fast collisions. The details of the analysis of atomic kinetics will be published elsewhere. 17

Finally, we investigate the radiation intensity from the Xe plasma as shown in Figs. 1(b)–1(d). The calculation is carried out with n_e = 10^{11}/cm^3, T_e = 25 eV, and plasma size of 10 μm. Using the atomic model shown in Table I, the calculated abundances of Xe 7+–Xe 11+ are 0.015, 0.072, 0.32, 0.41, 0.16, 0.019, and 0.007, respectively, which correspond to the average charge of z^* = 8.7.

The radiation intensity at the surface of a uniform sphere with optical radius τ is analytically evaluated in the form: 18

\[ I_\nu = I_{\nu p} \left( 1 - \frac{1}{2\tau} + \frac{1}{\tau} + \frac{1}{2\tau^2} \right) \exp(-2\tau), \]

where \( I_{\nu p} \) is the intensity of Planck radiation. It is to be noted that generally, \( I_\nu \) is obtained by solving the radiative transfer equations. In deriving Eq. (1), it is assumed that the LTE population can be applied.

We take into account the fine structure of resonance lines in order to calculate the optical depth. We average the absorption coefficient for a width of 0.01 nm. This appears to be a reasonable approximation because although the line width of the 4d–4f and 4d–5p transitions is estimated to be tens of milli-angstroms, 19 the calculated intensity for λ = 13–14 nm is found to be rather insensitive to the width. In the case of satellite lines we consider UTA to have the averaged transition energy and width defined from the statistical weight of the upper level \( g_i \) and radiative rate \( A_{ij} \) as: 20

\[ \bar{E}_{\text{UTA}} = \frac{\sum (g_i A_{ij}) E_{ij}}{\sum (g_i A_{ij})}, \]

and

![Image](https://via.placeholder.com/150)

FIG. 2. Grotrian diagram of Xe\(^{9+}\) showing the energy of the configurations. The height of the box corresponds to the standard deviation of the energy of the fine structure levels.

| Configuration | Xe\(^{6+}\) | Xe\(^{7+}\) | Xe\(^{8+}\) | Xe\(^{9+}\)| Xe\(^{10+}\) |
|---------------|----------|----------|----------|----------|
| 4d\(^{10}\) 5s5nl | 4d\(^{10}\) 5s5nl | 4d\(^{10}\) 5s5nl | 4d\(^{10}\) 5s5nl | 4d\(^{10}\) 5s5nl |
| 4d\(^{12}\) 5p | 4d\(^{12}\) 5p | 4d\(^{12}\) 5p | 4d\(^{12}\) 5p | 4d\(^{12}\) 5p |
| 4d\(^{14}\) 5d | 4d\(^{14}\) 5d | 4d\(^{14}\) 5d | 4d\(^{14}\) 5d | 4d\(^{14}\) 5d |
| 4d\(^{16}\) 6s | 4d\(^{16}\) 6s | 4d\(^{16}\) 6s | 4d\(^{16}\) 6s | 4d\(^{16}\) 6s |
| 4d\(^{18}\) 7s | 4d\(^{18}\) 7s | 4d\(^{18}\) 7s | 4d\(^{18}\) 7s | 4d\(^{18}\) 7s |
| 4d\(^{20}\) 8s | 4d\(^{20}\) 8s | 4d\(^{20}\) 8s | 4d\(^{20}\) 8s | 4d\(^{20}\) 8s |
| 4d\(^{22}\) 9s | 4d\(^{22}\) 9s | 4d\(^{22}\) 9s | 4d\(^{22}\) 9s | 4d\(^{22}\) 9s |
| 4d\(^{24}\) 10s | 4d\(^{24}\) 10s | 4d\(^{24}\) 10s | 4d\(^{24}\) 10s | 4d\(^{24}\) 10s |
| 4d\(^{26}\) 11s | 4d\(^{26}\) 11s | 4d\(^{26}\) 11s | 4d\(^{26}\) 11s | 4d\(^{26}\) 11s |
\[ \Delta E_{\text{UTA}} = \sqrt{\sum (g_i A_{ij} (E_{ij} - \bar{E}_{\text{UTA}})^2) / \sum (g_i A_{ij})}, \]  

Each UTA consists of a large number of fine structure transitions for which we can assume that the separation between each line becomes smaller than the line width. Therefore, the spectrum is determined by the statistical distribution of the fine structure lines rather than by the profiles of individual lines.

From the comparison between Figs. 1(b) and 1(c) it is apparent that the intensity between 11 and 13 nm significantly increases when the satellite line emission is included, which results in an agreement between the calculated and experimental spectrum in Fig. 1(a). It is found that the emission of 4d–4f satellite lines occurs from 11 to 13 nm. The 4d–5p satellite lines appear at the longer wavelength side of the resonance line; thus, the 4d–5p satellite lines from Xe\(^{9+}\) and Xe\(^{10+}\) mainly contribute to the absorption in the 13.5 nm band. On the other hand, the 4p–4d transitions form a broad background, as shown in Fig. 1(d). Eventually, a broad “red wing” structure, which is similar to that theoretically investigated by Busquet\(^1\) for the 3d–4f resonance line from a hot dense gold plasma, is formed in the longer wavelength side of the 4d–4f transitions.

Figure 1(d) also shows a peak absorption coefficient of 10\(^3\) cm\(^{-1}\) in the 13.5 nm band, while it is 10\(^4\) cm\(^{-1}\) in the 11 nm band. The relative intensity at 13.5 nm increases with increasing plasma size because the resonance lines saturate due to the opacity. As a result, the emission spectrum shows the broad red wing structure from 10 to 17 nm.

In summary, the significant contribution of the satellite lines and opacity to the broad EUV spectrum of laser-produced Xe plasmas is identified and the experimental spectrum is reproduced. As part of an integrated simulation, the present model can be applied to the estimation of the spectral efficiency, which is defined as the ratio between the total and the in-band intensity in the 2% bandwidth of the 13.5 nm band, as well as to the optimization of the EUV source.

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\(^3\)A. Sasaki et al., JSTQE (to be published).


