EUV Spectra from Laser-Produced Tungsten Plasmas*)

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We observed the EUV emission spectra from laser-produced tungsten plasmas. The spectral structures were compared by optical thickness due to the critical density difference of 1×10^{21} and 4×10^{21} cm^{-3} with laser wavelengths of 1064 nm and 532 nm, respectively. We found some spectral structure changes, an increase of emission in 1 - 3 nm region under an optically thick condition while a decrease of a peak near 5 nm for unresolved transition array of 4d - 4f transitions. Some 1.3 - 2.5 nm peaks were attributed to charge states higher than W^{30+}. We showed some dependence of the spectral behavior for the EUV emission.

Keywords: tungsten (W), extreme ultraviolet (EUV), laser-produced plasma, highly charged ion (HCI)

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1. Introduction

Tungsten ($_{74}$W) is a promising material for plasma-facing components in future fusion reactors such as ITER due to its desirable properties, e.g., high melting point and low sputtering rate. However, such high atomic number ions tend to accumulate in the fusion plasma, and intense line radiations in the extreme ultraviolet (EUV) region from the multiply charged W ions reduce the plasma temperature [1]. Atomic data of W ions for each charge state contained in the fusion plasma is important to estimate and diagnose the plasma condition.

The EUV spectrum depends on the balance between the emissivity and absorption coefficient in the plasma. The EUV spectral structure is determined by the charge state of highly charged ions and the optical thickness. In the discharge-produced plasmas [2, 3], the plasma is optically thin at the electron density range of 10^{13} - 10^{14} cm^{-3}. Then, the self-absorption effect in the plasma is almost neglected. There are many reports about the EUV spectra in the discharge-produced plasmas [4–8]. The laser-produced plasmas, however, are generally optically thick. The EUV spectra are expected to be much different. Thus, it is interesting to investigate the spectral change in the optically thick condition. In the previous study for EUV emissions from a 1064-nm laser-produced tungsten plasma, the shortest identified emission peak, around 1.74 nm, was attributed to 4d - 5f transitions for W^{34+} and W^{35+} ions [9]. Note that the critical electron densities of 1×10^{21} cm^{-3} and 4×10^{21} cm^{-3} for the laser wavelengths of 1064 and 532 nm, respectively. Therefore, due to optically thick conditions, the EUV spectra showed strong absorption in a high electron density region. There, however, is no report of the EUV spectrum under the optically thicker condition at a higher critical electron density of 4×10^{21} cm^{-3} at a laser wavelength of 532 nm. Therefore, it is important to study the EUV spectral shape. We study the optical thickness effect of the EUV spectra in the W plasmas by changing the critical electron density and active control of the plasma conditions by the double laser pulse irradiation scheme.

The optical thickness is determined by plasma parameters, such as the ion density, the electron temperature, and the absorption length. Note that the optical thickness is solved by the radiative transfer equation. The plasma parameters depend on the initial density of the target, the thickness of the target, the pulse duration and wavelength of the laser pulse, and the irradiation scheme, i.e., whether single or double laser pulse irradiation is used. Double laser pulses are indirect self-absorption spectroscopy to control plasma dynamics. We demonstrate the self-absorption (opacity) caused by the change of the optical thickness using the double laser pulse irradiation [10, 11]. The scheme would effectively utilize the main laser pulse energy to heat a preformed plasma (pre-plasma), which would otherwise be wasted to ionize the target. The choice of an appropriate delay time of double pulses controls the electron density of the plasma and its scale length of the density gradient, where the main laser pulse heats the plasma. As the main laser pulse irradiates with a low-density pre-plasma, the electron temperature would be lower than that of a single laser pulse to the solid-density

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target [12, 13].

In this paper, we describe the EUV emission spectra from the laser-produced tungsten plasmas and identify some emission peaks compared with theoretical calculations.

2. Experimental Condition

Figure 1 shows a schematic diagram of the experimental setup. In the case of the single pulse irradiation experiments, two *Q*-switched Nd:yttrium-aluminum-garnet (Nd:YAG) lasers were used as the main operating at a wavelength of 1064 and 532 nm, respectively. The pulse durations were 150 ps at 1064 nm and 110 ps at 532 nm, respectively. The maximum laser intensity was 1×10^{14} W/cm^2 with a focal spot diameter of about 30 µm. In the case of double-pulse laser irradiation experiments to investigate the spectral behavior of W plasma emission, the condition was described previously in Refs. [10, 11].

The plasma emissions on the optical axis of a flat-field grazing-incidence spectrometer with a variable-line-spaced 2400 grooves/mm grating, which was positioned at 30° with respect to the incident main laser axis, were recorded by a thermoelectrically cooled back-illuminated X-ray CCD camera. The spectra were obtained over the spectral range from 1 to 7 nm. The uncertainty of the present wavelength calibration is estimated to be 0.01 nm [14]. We also detect the fast ions by use of a Faraday cup as a reference to confirm the hot, dense plasma production [15]. We set similar laser parameters in the present W and previous Bi plasma productions as heavy element plasma. We detected the 100-keV fast W ions (not shown).

Laser-produced plasmas of heavy element solid targets, such as W, irradiated by solid-state 1-µm lasers are optically thick. Therefore, it is critical to evaluate the plasma emissivity (radiation coefficient) and the absorption coefficient to control the spectra, which are determined by the ionic charge states in the hot, dense plasmas. The optical thickness, related to ion density, the electron temperature, and the absorption length through the EUV emission region, should be controlled to observe the absorption effects. The double laser pulse irradiation technique provides a controlled way to tune the electron density and density gradient of the pre-plasma. The length of the expanding plasma is expected to be controlled by changing the pre-pulse duration and the pulse delay, which alters the absorption length and the opacity in the EUV spectral region.

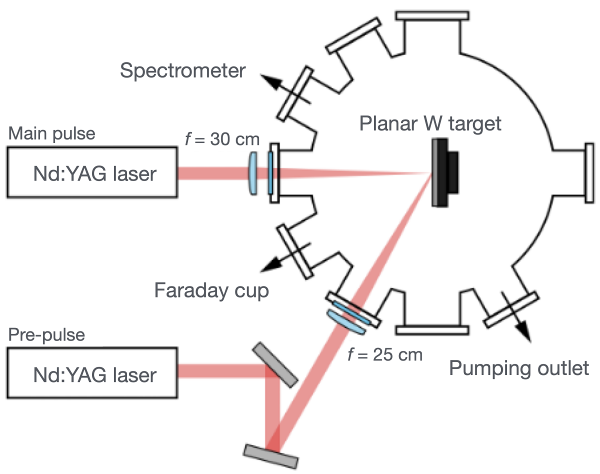

Fig. 1 Schematic diagram of the experimental setup.

3. Results and Discussion

Figure 2 shows the spectral comparison by optical thickness due to the critical density difference of 1×10^{21} and 4×10^{21} cm^{-3} with laser wavelengths of 1064 and 532 nm, respectively. The spectra show some spectral structure changes, an increase of emission in 1 - 3 nm under an optically thick condition, while a decrease of a peak near 5 nm for unresolved transition array of 4d - 4f transitions. We observe some peaks in 1.33 - 1.74 nm for the 532-nm irradiation. Some 1.3 - 2.5 nm emission peaks are attributed to charge states higher than W^{30+} as noted later. Therefore, the spectral shape consists of the UTA peaks from highly charged W ions with the continuum emission due to bremsstrahlung from the dense plasma of 10^{20} - 10^{21} cm^{-3}.

Figure 3 shows the comparison of shorter EUV emissions from a 532-nm laser-produced W plasma with normalized *gA* values calculated using the flexible atomic code (FAC) [16] for each transition: 4p - 5d, 4p - 6d, 4s4p^{M} - 4s4p$^{M\text{-}1}$4d, 4p$^{M\text{-}1}$4d - 4p$^{M\text{-}2}$4d5d, 4p$^{M\text{-}1}$4f - 4p$^{M\text{-}2}$4f5d, 4d - 5f, 4d - 6f, 4d^{N}5s - 4d$^{N\text{-}1}$5s5f, and 4d^{N}5s - 4d$^{N\text{-}1}$5s6f transitions. Note that the vertical axis on the right side of Fig. 3 is the charge states, ranging from q = 28 to 43 of W^{q+} calculated by the FAC code, the corresponding range of the variable M = 2 - 6 for q = 39 - 43 for 4p and N = 1 - 9 for q = 28 - 36 for 4d in the energy levels. Labeled

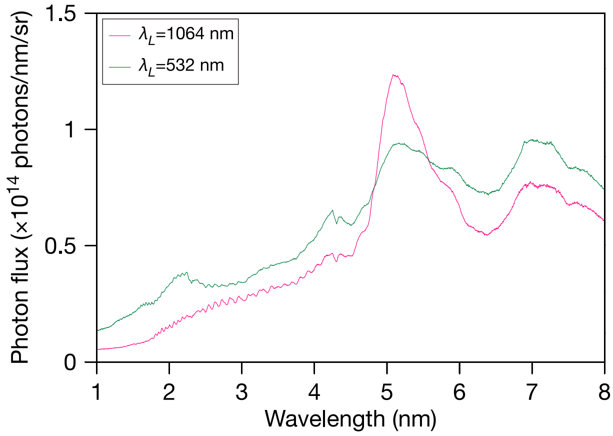

Fig. 2 Spectral comparison for the optically thick (green) and optically thin (magenta) conditions.

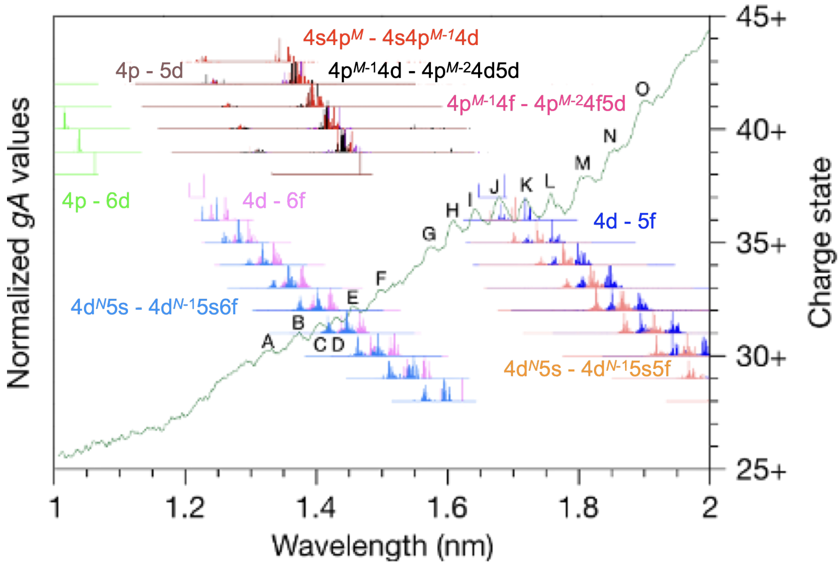

Fig. 3 Comparison of shorter EUV emissions from a 532-nm laser-produced W plasma with normalized *gA* values calculated using the flexible atomic code for each transition; (brown) 4p - 5d, (light green) 4p - 6d, (red) $4s4p^{M}$ - $4s4p^{M\text{-}1}4d$, (black) $4p^{M\text{-}1}4d$ - $4p^{M\text{-}2}4d5d$, (purple) $4p^{M\text{-}1}4f$ - $4p^{M\text{-}2}4f5d$, (blue) 4d - 5f, (pink) 4d - 6f, (orange) $4d^{N}5s$ - $4d^{N\text{-}1}5s5f$, and (light blue) $4d^{N}5s$ - $4d^{N\text{-}1}5s6f$ transitions.

peaks as L to O are also observed in the previous study and are assigned as contributions of the 4d - 5f transitions in $W^{31+}$to W^{35+} ions [9]. The same transitions in the higher charge states, in W^{36+} and W^{37+} ions, are observed in this work labeled as I to K. There are some possibilities of the contributions of 4d - 6f and its satellite $4d^{N}5s$ - $4d^{N\text{-}1}5s6f$ transitions in W^{28+} to W^{34+} ions, and 4p - 5d and their satellites of $4p^{M\text{-}1}4d$ - $4p^{M\text{-}2}4d5d$, $4p^{M\text{-}1}4f$ - $4p^{M\text{-}2}4f5d$ and core excited $4s4p^{M}$ - $4s4p^{M\text{-}1}4d$ transitions, whose wavelength regions are overlapped, in W^{38+} to W^{43+} ions. Considering the plasma condition using the 532-nm laser, the contribution from the $n = 4 - n = 6$ transitions is expected to be small as collisional de-excitation rates at such high density are usually higher than the radiative rates for transitions from high n-states which have a large atomic radius. The peaks, especially in shorter than 1.5 nm regions, thus seem to be attributed to the series of 4d - 5p transitions in the higher charge states as discussed later.

To elucidate opacity effects on EUV emissions, we determined the relative spectral intensity enhancement of $(I - I_0)/I_0 = \Delta I/I_0$, where I and I_0 were the spectral intensities with and without the pre-pulses. The spectral changes obtained by changing the delay time between the pre-pulse and the main pulse are shown in Fig. 4. In Fig. 4 (a), the ratio is shown for the 10-ns pre-pulse case. The emission spectrum from the W plasma without the pre-pulse (single-pulse irradiation) is shown in Fig. 2. In the 2.3 - 7.0 nm region in Fig. 4 (a), there is an intensity enhancement of over 10% for pulse separation times of 1 - 40 ns, while that of over 30% in the 4.8 - 7.0 nm region for 1 - 6 ns. The latter enormous, enhanced emissions, which were not observed in the case of 150-ps pre-pulse as shown in Fig. 4 (b), are attributed to 4d - 4f and 4d - 5p transitions for W^{37+} and lower charged W ions [9].

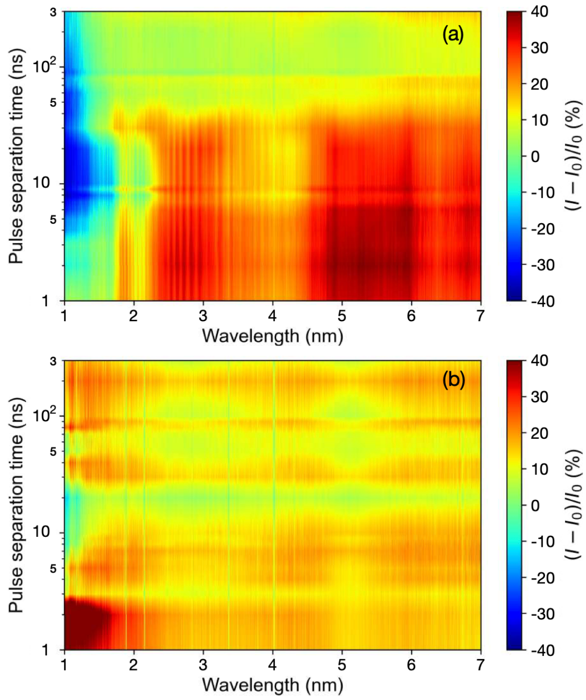

Fig. 4 Pulse separation time dependence of the relative spectral intensity enhancement of $(I - I_0)/I_0 = \Delta I/I_0$ of pre-pulses of (a) 10 ns duration and (b) 150 ps duration.

On the other hand, an enhancement of over 30% in the 1.0 - 1.8 nm region for the pulse separation time of 1 - 3 ns is observed only for the 150-ps pre-pulse case as shown in Fig. 4 (b). There is on the contrary a reduction of 10% for the same wavelength region for the pulse separation time of 7 - 20 ns for the 10-ns pre-pulse case. The enhancement occurs in terms of increasing the coupling of the reheating laser to the expanding plasma leading to a reduction in opacity and an enhancement of EUV emissions. Due to the size of 150-ps pre-pulse plasma being much smaller than that of 10-ns one, the coupling condition would be better for the pulse separation time of 1 - 3 ns to produce higher charge states that attribute the 1.0 - 1.8 nm emission, while the 10-ns pre-plasma for the pulse separation time of 7 - 20 ns is too expanded to produce the higher charge states. Appropriate control of both the duration time of the pre-pulse and the pulse separation time enables us to control the charge states in plasma, namely the EUV emission.

4. Summary

In summary, we have observed the EUV spectra from laser-produced W plasmas under optically thick conditions and plasma density (optical thickness)-controlled conditions. The spectral structures were compared by optical thickness due to two different critical densities of 1×10^{21} cm^{-3} and 4×10^{21} cm^{-3}. We found some spectral structure changes, an increase of emission in 1 - 3 nm under an optically thick condition while a decrease of a peak near 5 nm for unresolved transition array of 4d - 4f transitions. Some 1.3 - 2.5 nm peaks were attributed to charge states higher than W^{30+}. We have also observed the EUV spectral change in the optical thickness change by double laser pulse irradiation. The time control of both the duration time of the pre-pulse laser and the separation time enables us to control the plasma condition, i.e. the density of charge states in the plasma, to produce the EUV emission.

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