EXPLORATION OF EMISSION SPECTRA FROM HIGHLY CHARGED TUNGSTEN IMPURITY IONS IN X-RAY WAVELENGTH RANGE OF 3.7–4.0 Å IN THE LARGE HELICAL DEVICE FOR FUSION PLASMA DIAGNOSTICS

[1]T. OISHI, [1]R. NISHIMURA, [2,3]S. MORITA, [2,3]M. GOTO, [2,3]Y. KAWAMOTO, [4]T. KAWATE, [2,3]I. MURAKAMI, [2,5]D. KATO, [2]H.A. SAKAUE, [1]H. TAKAHASHI, [1]K. TOBITA

[1]Department of Quantum Science and Energy Engineering, Tohoku University, Sendai, Japan
[2]National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Japan
[3]The Graduate University for Advanced Studies, SOKENDAI, Toki, Japan
[4]Naka Institute for Fusion Science and Technology, National Institutes for Quantum Science and Technology, Naka, Japan
[5]Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Japan

Email: tetsutarou.oishi.a4@tohoku.ac.jp

The emission spectra of highly charged tungsten ions distributed in plasmas with electron temperatures of about 4 keV in the Large Helical Device (LHD) have been studied using X-ray crystal spectroscopy. As a result, tungsten ion emission lines ranging from W^{43+} to W^{47+} were observed in the wavelength region of 3.7-4.0 Å. The spectral data in this charge region are useful for the diagnostics of tungsten impurities in the edge plasma from the outermost magnetic surface to the pedestal region in ITER. Especially, W^{47+} plays an important role as a signal to indicate tungsten impurity penetration close to the pedestal top.

In fusion plasma confinement devices that employ tungsten as a plasma facing material, it is necessary to measure the emission from tungsten ions in order to monitor whether tungsten impurities are penetrating into the plasma. For the purpose of understanding impurity transport and expanding the database of tungsten line emission, simultaneous measurement of multiple charge states ranging from W^{0} to W^{46+} has been successfully conducted in LHD by combining tungsten pellet injection with spectroscopic measurements in the visible light, vacuum ultraviolet (VUV), extreme ultraviolet (EUV), and X-ray wavelength regions [1,2]. Since the dominant charge states of these depend on the electron temperature, the electron temperature can be controlled and the charge distribution is varied by adjusting the power and timing of the plasma heating. At present, the electron temperature at the center of the plasma, T_{e0}, that can be achieved while sustaining significant tungsten ion content in the plasma is about 4 keV. In this electron temperature region, impurity ions emit strongly in the X-ray wavelength range, and the spectroscopic data will contribute to the monitoring of impurities in the edge plasma of ITER. Therefore, in the present study, the X-ray spectra in LHD were carefully examined to explore the emission lines that are useful for the tungsten impurity diagnostics.

Figure 1(a) shows the spectra of tungsten ions measured by an X-ray crystal spectrometer (XCS) during the time period when T_{e0} was around 4 keV. Since the wavelength range that can be measured per discharge is limited, the spectra measured at different wavelength ranges during 10 discharges were merged to cover the 3.7-4.0 Å wavelength range. The working gas of the plasma discharge was hydrogen, the magnetic axis position, R_{ax},

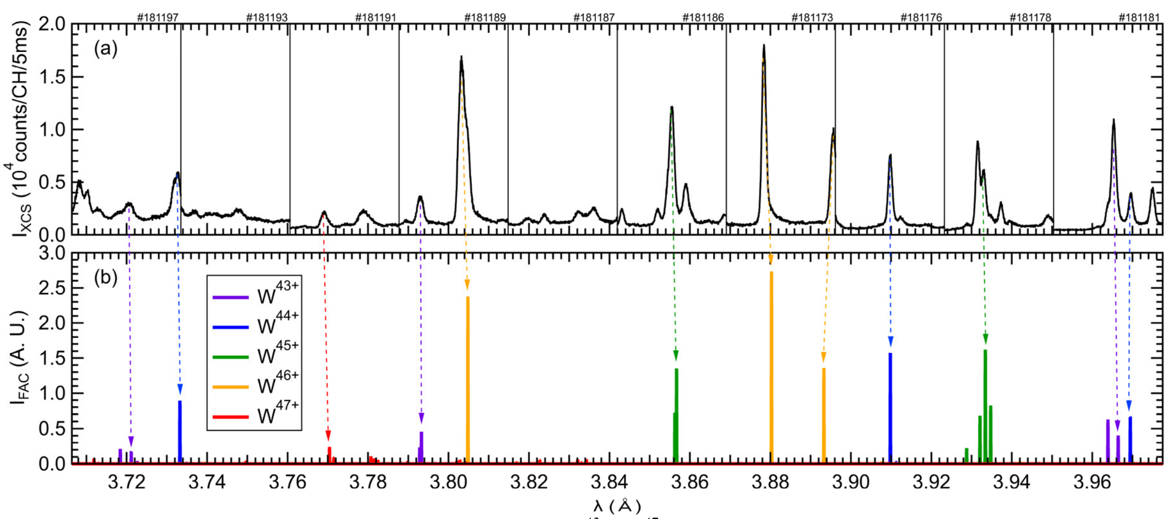

Fig. 1. X-ray spectra including the emission lines ranging W^{43+}–W^{47+}, comparing (a) the spectra observed at LHD and (b) the spectra calculated by the flexible atomic code (FAC).

was 3.6 m, and the toroidal magnetic field, B_t, was 2.75 T in the counterclockwise direction viewed from the top. Tungsten ions were distributed in the LHD plasma by injecting a pellet consisting of a small piece of tungsten metal wire, equivalent to 3.5 × 10^{17} tungsten atoms, enclosed in a carbon tube. For identification of the observed lines, we calculated the emission spectra from W^{43+} to W^{47+}, of which the fractional abundance is large at around T_{e0} = 4 keV, using an atomic structure calculation code Flexible Atomic Code (FAC) [3] combined with a collisional-radiative (CR) model. For each charge state, energy levels and rate coefficients for elementary atomic processes were calculated, and the spectra were synthesized using the CR model under an electron temperature of 4 keV and an electron density of 2 × 10^{13} cm^{-3}. The obtained spectra are multiplied by the fractional abundance ratios calculated from the ionization and recombination rate coefficients in the ADAS database, and are shown in Fig. 1(b). The wavelengths of the emission lines with strong intensity are compared with the measured and calculated values, and are shown together with the corresponding charge states in Table 1. The observed and calculated wavelengths are in good agreement, and these lines are expected to be useful for monitoring ions in each charge state. The emission line observed at 3.7691 Å is considered to be W^{47+}, which extends the charge region observed so far at LHD, and becomes a tool of the diagnostics with higher electron temperatures.

Table 1. Wavelengths of tungsten emission lines observed using XCS, λ_{XCS}, and calculated with FAC, λ_{FAC}, together with the charge states.

λ_{XCS} (Å)	λ_{FAC} (Å)	Ion
3.7204	3.7212	W^{43+}
3.7323	3.7332	W^{44+}
3.7691	3.7704	W^{47+}
3.7930	3.7933	W^{43+}
3.8033	3.8048	W^{46+}
3.8555	3.8567	W^{45+}
3.8784	3.8803	W^{46+}
3.8956	3.8933	W^{46+}
3.9098	3.9098	W^{44+}
3.9330	3.9334	W^{45+}
3.9655	3.9664	W^{43+}
3.9694	3.9694	W^{44+}

Figure 2 shows the temporal evolution of the heating power, electron temperature and density, and tungsten emission intensities observed in the X-ray and EUV wavelength regions for the discharge in which the W^{47+} emission line was observed at 3.7691 Å. The port-through injection power of electron cyclotron heating (ECH), negative and positive ion sourced neutral beam injection (n-NBI and p-NBI, respectively) are shown in Fig. 2 (a). T_{e0} and the line-averaged electron density, $\bar{n}_e$, were around 3 keV and 2 × 10^{13} cm^{-3} before the pellet injection, respectively, as shown in Fig. 2 (b). The pellet was injected at t = 4.08 s, and T_{e0} once decreased to 1.7 keV, but eventually recovered to about 5 keV as the ECH was superimposed during t = 4.2-5.2 s. Figure 2(c) shows the intensity of a quasi-continuous spectrum called unresolved transition array (UTA) observed at 45-55 Å. This UTA is the most widely used indicator of tungsten impurity content in the fusion plasma experiments. However, since the charge range which constitutes this UTA is from W^{27+} to W^{42+}, the tungsten content cannot be monitored only by this signal when higher charge ranges dominate. In fact, even in Fig. 2(c) after t = 4.5 s, when the electron temperature increased, the signal began to decrease, and as shown in Figures 2(d-f), W^{41+} to W^{47+} appeared one after another. In particular, as well as W^{46+} in Fig. 2(e), W^{47+} in Fig. 2(f), newly observed by the X-ray spectroscopy, reached its maximum at t = 4.9 s, when T_{e0} = 4.3 keV, indicating that it is an appropriate signal for monitoring tungsten impurities in the electron temperature range around 4 keV.

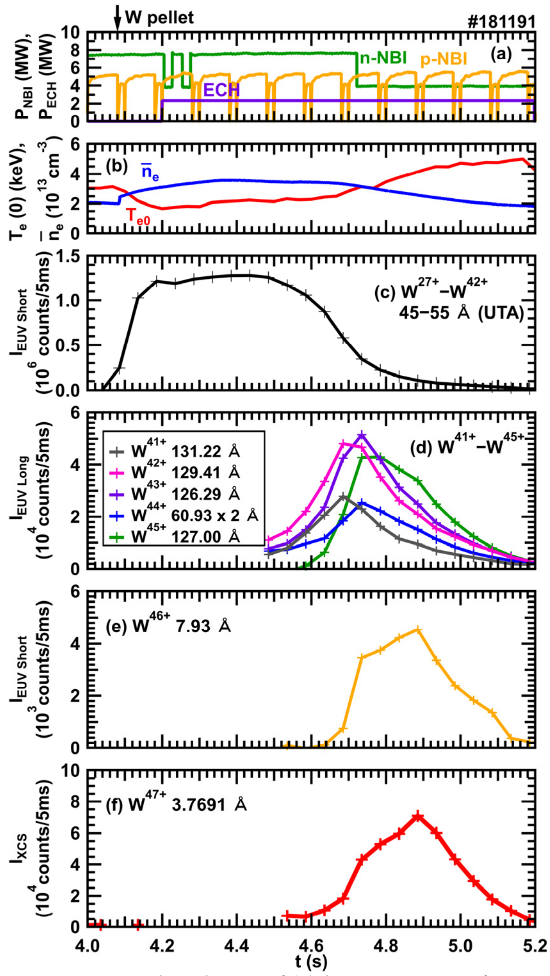

Fig. 2. Temporal evolution of (a) heating power of ECH and NBI, (b) T_{e0} and $\bar{n}_e$, emission intensities of (c) UTA spectra consisting of the charge range from W^{27+} to W^{42+}, (d) line spectra from W^{41+} to W^{45+}, (e) W^{46+}, and (e) W^{47+}. (c-e) and (f) are observed in the EUV and X-ray wavelength ranges, respectively.

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