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X-ray spectroscopy of tungsten impurity ions in magnetically confined high-temperature plasmas and its application to ion and electron temperature measurements

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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 the Large Helical Device (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.

In the present study, the X-ray spectra measured by an X-ray crystal spectrometer (XCS) in LHD were carefully examined to explore the emission lines that are useful for the tungsten impurity diagnostics. 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}, 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.

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. The possibility of measuring the electron temperature using the line intensity ratio method and the ion temperature using the Doppler broadening may also be investigated using the emission lines observed in this study.

References

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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+}