Quantitative analysis on tungsten spectra of W$^+$ to W$^{45+}$ ions

S. Morita$^{1,2}$, C.F. Dong$^3$, D. Kato$^1$, Y. Liu$^2$, L. Zhang$^4$, Z.Y. Cui$^3$, M. Goto$^{1,2}$, Y. Kawamoto$^1$, I. Murakami$^{1,2}$ and T. Oishi$^{1,2}$

$^1$National Institute for Fusion Science, Toki 509-5292, Gifu, Japan
$^2$The Graduate Univ. for Advanced Studies (SOKENDAI), Toki 509-5292, Japan
$^3$Southwestern Institute of Physics, P.O. Box 432, Chengdu 610041, China
$^4$Institute of Plasma Physics Chinese Academy of Sciences, Hefei 230031, Anhui, China

E-mail: morita@nifs.ac.jp

Abstract. Tungsten ion densities are determined by measuring radial profiles of line emissions in LHD. Zn-like (W$^{44+}$) and Cu-like (W$^{45+}$) ion densities are determined from line emission at 60.9 Å and 127.0 Å, respectively. Ion densities of W$^{24+}$, W$^{25+}$ and W$^{26+}$ are also determined from tungsten pseudo-continuum (so-called unresolved transition array (UTA)) at 29-33 Å. Observations of magnetic dipole (M1) forbidden lines at 3377Å enable evaluation of the ion density of W$^{27+}$. In EAST tokamak the tungsten concentration is estimated by a combination of the UTA and total radiation loss. In HL-2A the tungsten influx is evaluated from line emission of W$^{6+}$ ions at 216.2 Å and 261.4 Å, which are measured during the tungsten reappearance phase after tungsten laser blow-off. All these results demonstrate a good approach towards quantitative tungsten analysis.

1. Introduction
In recent fusion research tungsten studies, e.g. tungsten physical properties, plasma-tungsten divertor interaction and tungsten transport in plasmas, have become crucially important for the sustainment of long-pulse discharges with good plasma performance of ITER. Accordingly, with the importance of tungsten transport study, tungsten spectroscopy also becomes important. In particular, quantitative analysis of the tungsten concentration is required to accurately evaluate any effect of the tungsten on the plasma performance.

The quantitative analysis of tungsten ions from W$^{6+}$ to W$^{45+}$ has been attempted by a variety of unique methods in LHD, EAST and HL-2A fusion devices as collaborative work [1]. Here, a brief report is given of the results from the collaboration on tungsten spectroscopy.

2. Quantitative analysis of tungsten spectra in Large Helical Device
In LHD a coaxial tungsten pellet (outside: graphite, inside: tungsten) [2] shown in figure 1(a) is injected during discharges to observe the tungsten spectra. A tungsten wire, of diameter 0.01-0.15 mm and length 0.7 mm (2.9×10$^{15}$-6.6×10$^{17}$ tungsten particles) is generally used. Typical time behaviors of the electron density and temperature are plotted in figure 1(b), for the largest tungsten pellet injection case with a 0.15 mm diameter. The density increase is mainly due to a change in the edge particle confinement, while the temperature drop is induced by ionisation of the tungsten and radiation losses.
2.1. Density evaluation of $W^{44+}$ and $W^{45+}$ ions

Since Zn-like ($W^{44+}$) and Cu-like ($W^{45+}$) tungsten ions have a simple electronic configuration, i.e. one or two electrons in the outer $n = 4$ bound orbit, the resultant spectra have a simple structure. Figure 2 shows the tungsten spectrum at 45-70 Å observed from LHD plasmas. When the electron temperature is low, the wavelength range is fully occupied by an UTA, in which the transition type is determined by the electron temperature. For example, the UTA spectrum at $T_e=0.54$ keV in figure 2(a) is dominated by 5d-4f transitions, while the UTA at $T_e=1.7$ keV in figure 2(b) is dominated by 4f-4d transitions [3]. However, the UTA feature entirely disappear and are replaced by line emission from higher ionisation stages up to $W^{45+}$ ions, as shown in figure 2(c), when $T_e$ increases to a range of $2.3 \leq T_e \leq 3.2$ keV. If the $T_e$ increases further above 3.2 keV, the intensity of such line emission becomes weak. The tungsten spectrum at 59-64 Å, denoted by the hatched range in figure 2(c) is expanded in figure 2(d). Several emission lines from $W^{42+}$-$W^{45+}$ ions are identified in this figure.

The radial profile of the tungsten emission is measured with a space-resolved EUV spectrometer [4], where the absolute spectral intensity is accurately calibrated using visible and EUV bremsstrahlung continua from LHD [5]. The local emissivity profile of the Zn-like $W^{44+}$ 4s4p-4s$^2$ transition at 60.9 Å shown in figure 2(d), which is reconstructed from the measured radial profile, is plotted in figure 3(a). Here, the horizontal axis represents the normalized plasma radius, i.e. the plasma centre is at $\rho=0$ and the plasma boundary is at $\rho=1$. The centrally peaked profile indicates that Zn-like tungsten ions exist in the plasma centre. Another emission line located in plasmas outer region, near $\rho = 0.7$, may be blended with the Zn-like transition. However, it has not been identified at present. The local emissivity profile of the Cu-like $W^{45+}$ 4p-4s transition at 127 Å is also plotted in figure 3(b). As the $W^{45+}$ line is measured at a lower electron temperature ($T_e=2.5$ keV), the profile is more peaked in the plasma centre, compared to the $W^{44+}$ profile in figure 3(a).

2.2. Temporal evolution of the tungsten spectrum

Since $W^{44+}$ and $W^{45+}$ ions may be present in the plasma boundary, it is of interest to study the temporal evolution of the tungsten spectrum in different plasma stages up to $W^{44+}$ ions. In figure 4, the evolution at a lower electron temperature ($T_e=0.7$ keV) is plotted in (a) and the evolution at a higher electron temperature ($T_e=1.7$ keV) is plotted in (b). As the temperature increases, the number of transitions that dominate the spectrum increases, and the intensity of the tungsten spectrum also increases. The figure shows that the tungsten spectrum at 59-64 Å at $T_e=0.7$ keV is entirely due to the Zn-like transitions, while at $T_e=1.7$ keV the Cu-like transitions dominate the spectrum. The degree of dominance of the Cu-like transitions increases with increasing electron temperature, and the intensity of the tungsten spectrum also increases.

Figure 1. (a) Coaxial tungsten pellet and (b) time behaviours of $n_e$ and $T_e$ for a 0.15($\phi$) × 0.7 (L) mm tungsten wire size.

Figure 2. Tungsten EUV spectra in 45-70 Å; (a) $T_e=0.54$ keV, (b) 1.7 keV, (c) 2.7 keV and (d) 2.9 keV. The abscissa in (d) is enlarged at 59-64 Å showing the hatched range in (c).

Figure 3. Radial profiles of local emissivity in (a) $W^{44+}$: 4s4pP$^3/2$-4s$^2$S$^0$ at 60.93 Å and (b) $W^{45+}$: 4p$^5$P$^3/2$-4s$^2$S$^0$ at 127.0 Å, transitions, which are taken at $T_e=2.9$ keV and 2.5 keV, respectively.
The density of Zn- and Cu-like tungsten ions is evaluated to be $1.0 \times 10^6$ cm$^{-3}$ and $7.8 \times 10^8$ cm$^{-3}$, respectively, using the ADAS code [6]. The electron temperature and density profiles necessary for the analysis are accurately measured in LHD with 136 data points in the radial direction.

2.2. Density evaluation of $W^{24+}$ to $W^{26+}$ ions in UTAs

The ion composition of the UTA spectra is investigated by measuring the intensity and radial profile. For this purpose, the UTA spectra at 15-70 Å, which mainly consist of $\Delta n = 0, 1$ and 2 transitions for $n = 4$ in partially ionised tungsten ions, are divided into a narrow wavelength intervals, $(\lambda)$~0.1 Å. As an example, the UTA spectrum at 27-34 Å is shown in figure 4 with two adjacent vertical lines indicating the wavelength intervals. Then, the UTA intensity is plotted against the central electron temperature at every wavelength interval. If a certain wavelength interval is due to a single ionisation stage, a clear single peak can be obtained in the plot [7].

In addition, the radial profile of UTA intensity along the vertical direction of LHD plasmas is compared for different wavelength intervals to re-examine the ion component. The radial profile at 32.28-32.39 Å, determined as emission from $W^{24+}$ ions, is compared with that from 47.94-48.15 Å, as shown in figure 5. It is clear that both profiles are identical. Since the radial profile is different for each ionisation stage, the ion composition of the UTA spectra can be accurately determined at the all wavelength intervals. The grey-hatched regions in figure 4 indicates the wavelength ranges composed of a single ionisation stages, while the non-hatched regions indicate the wavelength ranges composed of several ionisation stages.

![Figure 4. Tungsten UTA spectrum. Radial profiles are measured at each wavelength interval denoted by two adjacent vertical lines.](image1)

![Figure 5. Radial profile of $W^{24+}$ emission intensity.](image2)

Based on the ion composition analysis of the UTA spectra mentioned above, the radial profile for local emission is reconstructed from the observed profile, taking into account the magnetic surface structure of LHD plasmas when the data is acquired. An example is shown in figure 5 for $W^{24+}$ ions. The radial position and local emissivity at the peak position change with the central electron temperature, $T_{e0}$, of LHD plasmas. In particular, the radial position of $W^{24+}$ ions move inwardly when $T_{e0}$ decreases. This is very reasonable as the tungsten ion is present in a fixed temperature range, e.g. ~0.9 keV for $W^{24+}$ ions, if the radial convection is not large.

![Figure 6. (a) Radial profiles of (a) local emission and (b) density of $W^{24+}$ ions analysed at 32.16-33.32 Å as a parameter of central electron temperature, $T_{e0}$.](image3)
The density of W\textsuperscript{24+}, W\textsuperscript{25+} and W\textsuperscript{26+} ions is determined from radial profiles of the local emission and electron temperature and density [8]. The photon emission coefficient is obtained from the ADAS code (CL version) [9]. A result for W\textsuperscript{24+} ions is plotted in figure 6. The peak density of W\textsuperscript{24+} ions ranges between 1.2-1.7x10\textsuperscript{19} cm\textsuperscript{-3} at 1.82≤T\textsubscript{e}≤2.19 keV. It is confirmed that the densities of W\textsuperscript{25+} and W\textsuperscript{26+} ions also have similar values to the W\textsuperscript{24+} ion.

2.3. Density evaluation of W\textsuperscript{27+} ions from magnetic dipole (M1) forbidden transition

Visible M1 lines from highly charged tungsten ions are investigated in LHD by injecting a large tungsten pellet with cylindrical dimensions of 0.15 mm diameter and 0.7 mm length, i.e. 6.6x10\textsuperscript{17} particles. Several M1 lines are successfully observed with sufficient intensities to enable the radial profile measurement [10-12]. The tungsten ion density evaluation is then attempted from the radial profile of M1 emission lines.

Figure 7(b) shows a CCD image of the visible spectrum from 3300-3400 Å observed with 44 parallel optical fibers positioned at -0.5≤Z≤0.5 m in figure 7(a). Magnetic surface structures are also plotted in figure 7(a). The arrows A-F in figure 7(b) represent spectral lines which are not observed before the tungsten pellet injection. It is clear from the figure that all of the lines (A-F) are emitted from the core plasma within -0.4≤Z≤0.4 m, while other visible lines are emitted from the stochastic magnetic field layer at ρ>1.0 in the plasma edge, which is shown by the hatched contour. Since visible lines are generally emitted from neutral and low-ionised impurity ions, e.g. Cl-CIII, the lines A-F must be M1 lines arising from highly charged ions [13]. At present, three lines (B at 3337 Å, E at 3357 Å and F at 3377 Å) are identified as M1 transitions 1\textsuperscript{F\textsubscript{4}} – 1\textsuperscript{F\textsubscript{3}} and 3\textsuperscript{F\textsubscript{4}} – 1\textsuperscript{G\textsubscript{4}} from W\textsuperscript{26+} (4\textsuperscript{f}) ions and 3\textsuperscript{F\textsubscript{7/2}} – 3\textsuperscript{F\textsubscript{5/2}} from W\textsuperscript{27+} (4\textit{f}) ions, respectively.

![Figure 7](image_url)

Figure 7. (a) Magnetic surfaces of the LHD with 44 horizontal observation chords (solid lines) for visible spectroscopy (Z (m): vertical distance, R (m): major radius) and (b) CCD image (Z (m) vs λ (Å)). Shaded area in (a) represents peripheral region outside ρ=1. Six arrows in (b) indicate tungsten M1 lines (A: 3320 Å, B: 3337 Å, C: 3342 Å, D: 3345 Å, E: 3357 Å and F: 3377 Å).

A vertical intensity profile of line F, measured at 3377 Å, is plotted in Fig. 8, which is taken at 0.1s after the tungsten pellet injection. Since the central electron temperature is still high at the timing of the profile acquisition, i.e. T\textsubscript{e}=1.5keV, compared with the ionisation energy of the W\textsuperscript{27+} ion, E\textsubscript{i}=0.88keV, the W\textsuperscript{27+} ion locates around the middle of the plasma radius, i.e. Z=±0.2m.

The M1 line intensity is calculated using a collisional-radiative (CR) model. Since the transition energy of M1 line is generally small, the proton impact becomes important in calculating the intensity. Effect of the proton collision is examined based on the CR model. The result is also shown in Fig. 8. The solid and dashed lines indicate results from the CR-model calculation with and without proton impact, respectively. We understand the effect of proton collision is sufficiently large. The density of W\textsuperscript{27+} ions is also evaluated based on the CR model calculation. The result is shown in Fig. 9. Since the amount of tungsten particles injected for the M1 line study is one order of magnitude larger than the
case in section 2.2, the density obtained here seems to be reasonable. It also indicates a tolerant plasma sustainment against such a high tungsten concentration in LHD.

3. Tungsten density evaluation from radiation power and UTA intensity in EAST tokamak

After installation of the tungsten monoblock on the upper divertor of EAST tokamak, shown in figure 10, optimum tungsten divertor operations have been energetically explored for the past four years to achieve long-pulse high-performance plasmas. One of the key issues to realise the high-performance plasma, e.g. long-pulse H-mode discharges, is good control of tungsten ions, which originate from physical and chemical sputtering at the divertor, entering the plasma. For this purpose tungsten spectra have been measured in the EUV range to diagnose the tungsten ions, which to study their transport in the EAST plasma. A typical tungsten spectrum is shown in figure 11 in the wavelength range 15-40 Å [14]. The tungsten UTA is clearly observed, with impurity emission lines from carbon, oxygen and iron that are generally observed in fusion devices as intrinsic impurities.

It is crucially important for tungsten divertor tokamaks to control the edge localised mode (ELM) associated with the H-mode because intermittent heat pulses induced by the ELM greatly enhance tungsten sputtering at the divertor. In EAST, the tungsten concentration, C_W, is evaluated from the total radiation loss. A tungsten dust sometimes drops to the plasma in EAST discharges. It leads to a sudden increase in tungsten line emission, as shown in figures 12(a) and (b). The tungsten density increase due to the dust is estimated from the increase of the total radiation loss in figure 12(a), \( \Delta P_{\text{rad}} \), based on the theoretically predicted tungsten cooling rate. The UTA intensity increase to the electron density, \( \Delta n_{\text{UTA}}/n_e \), can be correlated with the tungsten density increase. Thus, the tungsten concentration is studied against the frequencies of ELM bursts, \( f_{\text{ELM}} \) [15]. The result is shown in figure 12(c). It is observed that C_W is reduced when the \( f_{\text{ELM}} \) is increased.
4. Tungsten influx analysis from WVII spectra in HL-2A tokamak

In HL-2A a laser blow-off (LOB) technique using a YAG laser is used for tungsten injection. A glass target with a 5 μm thick tungsten coating, shown in figure 13(a), is placed in a cubic vacuum chamber 2.38 m from a diagnostic port of HL-2A. The circular white spots in figure 13(a) indicate a successful tungsten injection. EUV spectra from lowly-ionised tungsten ions are studied at long wavelength side of EUV range [16]. After optimising the LOB system W VII and W VIII spectra are successfully observed in wavelength range of 200-300 Å. A typical spectrum is shown in figure 13(b). Two W VII lines appear at 216.218 Å and 261.366 Å and several W VIII lines also appear in the vicinity of 200 Å in the spectrum after the LBO, while no emission lines are observed at these wavelengths in the spectrum before the LBO. The intensity ratio between two W VII lines observed here shows a good agreement with CR model calculations [17].

Figure 13. (a) Glass target with 5μm thick tungsten coating with 'footprint' after laser blow-off (LBO) experiment and (b) EUV spectra at 130-300Å before and after LBO.

It is found that the W VII lines can reappear in discharges with the tungsten LBO [18]. Figure 14(a) shows the temporal behaviour of the W VII intensity during the reappearance phase at 0.14s after the LBO. A sudden increase in the W VII emission is seen at t=0.84-0.86 s. The tungsten reappearance seems to originate in enhanced sputtering at a certain areas on the divertor, which has been already coated with tungsten from the LBO as there is no other tungsten source in HL-2A. Therefore, the tungsten reappearance found here can simulate the tungsten influx from the tungsten divertor tokamak.

In general, the particle influx is given by \( \Gamma = \frac{I \times (S/X)}{XB} \), where I is the observed line intensity and S/XB is the inverse photon efficiency (S: electron impact ionization rate, X: electron impact excitation rate and B: branching ratio). The value of S/XB obtained from the ADAS code is plotted in figure 14(c) as a function of electron temperature. The electron temperature where the W\(^{6+} \) ion exists in HL-2A plasmas is estimated to be 40 eV. The tungsten influx is thus obtained from figures 14(a) and (c). The result is shown in figure 14(b). The tungsten density is evaluated from the influx rate assuming a uniform distribution of the W VII emission, i.e. \( n_W \sim 10^9 \text{cm}^{-3} \) and \( n_W/n_e \sim 10^{-4} \). These values are thought to be reasonable when checked against the total radiation loss from tungsten in the HL-2A discharge.
Summary
Qualitative studies of W$_{6+}$ to W$_{45+}$ ions was performed to determine the ion density, tungsten concentration and tungsten influx rate in LHD, EAST and HL-2A based on a variety of spectroscopic methods. In particular, the tungsten ion density determined using visible M1 lines may be important for next generation fusion devices as the use of optical fibers can possibly avoid an effect of extremely large neutron and $\gamma$-ray fluxes due to D-T discharge operation.

The next subject of the tungsten spectroscopic study will be the tungsten transport. Based on the present equipment and knowledge, uncertainties of the tungsten ionization and recombination rates will need to be verified for reliable transport study.

Acknowledgements
This work was partly supported by the LHD project (NIFS18ULPP010) and JSPS Grant-in-Aid for Scientific Grant Numbers 16H04088. The authors wish to thank for successful Japan-China joint research based on JSPS-NRF-NSFC A3 Foresight Program and Post-CUP.

References
[1] Morita S et al. 2018 Plasma Fusion Res. 13 3502046
[2] Huang X L, Morita S, Oishi T, Goto M and Zhang H M 2014 Rev. Sci. Instrum. 85 11E818
[3] Morita S, et al. 2013 AIP Conf. Proc. 1545 143
[4] Zhang H M, Morita S, Oishi T, Goto M and Huang X L 2015 Jpn. J. Appl. Phys. 54 086101
[5] Dong C F, Morita S, Goto M and Wang E H 2011 Rev. Sci. Instrum. 82 113102
[6] Summers H P 2004 The ADAS User Manual version 2.6 (www.adas.ac.uk)
[7] Liu Y, Morita S, Huang X L, Oishi T, Goto M and Zhang H M 2017 Jpn. J. Appl. Phys. 56 233301
[8] Liu Y, Morita S, Murakami I, Oishi T, Goto M and Huang X L 2018 Jpn. J. Appl. Phys. 57 106101
[9] OPEN-ADAS http://open.adas.ac.uk
[10] Kato D, et al. 2013 Phys. Scr. T156 014081
[11] Shinohara, Fujii K, Kato D, Nakamura N, Goto M, Morita S and Hasuo M 2015 Phys. Scr. 90 125402
[12] Fujii K, Takahashi Y, Nakai Y, Kato D, Goto M, Morita S and Hasuo M 2015 Phys. Scr. 90 125403
[13] Kato D, Sakaue H A, Murakami I, Goto M, Oishi T, Fujii K, Nakamura N and Morita S 2016 Proc. 26th IAEA Fusion Energy Conf. (Kyoto) EX/P8-14
[14] Zhang L, et al. 2015 Rev. Sci. Instrum. 86 123509
[15] Zhang L, et al. 2017 Nucl. Mater. Energy 12 774
[16] Cui Z Y, Dong C F, Zhou H Y, Morita S, Sun P, Fu B Z, Lu P, Ding X T, Yang Q W and Duan X R 2014 Rev. Sci. Instrum. 85 11E426
[17] Murakami I, Sakaue H A, Suzuki C, Kato D, Goto M, Tamura N, Sudo S and Morita S 2015 Nucl. Fusion 55 093016
[18] Dong C F, et al. 2019 Nucl. Fusion 59 016020

Figure 14. Time behaviours of (a) WVII intensity and (b) W$^7+$ influx rate during sudden tungsten reappearance phase and (c) inverse photon emission coefficient.