Observation and Line Analysis of Tungsten, Molybdenum and Copper Spectra at 20-150 Å Emitted from Experimental Advanced Superconducting Tokamak (EAST) Plasma*)

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Complex spectra of tungsten (W) and molybdenum (Mo) unresolved transition arrays (W-UTA and Mo-UTA) are frequently observed with isolated W, Mo and copper (Cu) lines at 20-150 Å wavelength range in EAST plasmas with limiter configuration. The high-Z impurity ions of W, Mo and Cu enter the plasma through an unavoidable plasma-wall interaction at inboard Mo first wall and outboard W/Cu limiter. The spectra were observed with a fast-time-response extreme ultraviolet (EUV) spectrometer and line identification was carefully performed referring our previous works. As a result, W-UTA at 46-64 Å and Mo-UTA at 68-96 Å are found to be composed of W^{27+}-W^{45+} and Mo^{16+}-Mo^{30+} ions, respectively. The Cu spectra from Cu^{10+}-Cu^{13+} ions are also found in wavelength range of 135-150 Å. In the analysis radial profiles of the impurity spectra are taken into account in determining the charge state in addition to the time behavior.

Keywords: EAST tokamak, EUV spectra, tungsten first wall

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1. Introduction

As a result of recent progress of fusion research on magnetic-confinement fusion device, tungsten (W) becomes one of important plasma facing materials (PFM) due to several unique material properties. Therefore, the study on W spectroscopy is important, in particular, for line identification and quantitative intensity analysis. Very recently, tungsten has been adopted as the material of first wall of International Thermonuclear Experimental Reactor (ITER). In 2024 spring campaign of Experimental Advanced Superconducting Tokamak (EAST), limiter discharge experiments using low-field side (LFS) limiter made by tungsten/copper (W/Cu) monoblocks were carried out to test the plasma start-up with full tungsten first wall, which is one of the biggest concerns in ITER discharge operation. Meanwhile, the limiter discharge performance with circular plasma was compared with discharges touched high-field side (HFS) molybdenum (Mo) tiles to study the impact of high-Z impurity source location. In these experiments, unresolved transition arrays (UTAs) with complicated spectral feature emitted from W, Mo and Cu ions have been frequently observed at 20-150 Å wavelength range with isolated line emissions. These spectra are measured with a fast-time-response extreme ultraviolet (EUV) spectrometer. In this paper results on line analysis of such UTAs from high-Z impurities are reported showing observed EUV spectra, which provide us various kinds of information on high-Z impurity behaviors in the discharge.

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2. Experimental Setup

EAST is a middle-size full superconducting tokamak with an entirely different discharge configuration of divertor and limiter configurations. Major and minor radii are R = 1.85 m and a = 0.45 m, respectively. Maximum plasma current, I_p, and maximum central toroidal field, B_{t0}, are 1.0 MA and 3.5 T, respectively. In order to enhance the divertor performance the upper and lower divertor plates were replaced by the tungsten material in 2013 and 2020, respectively. Before 2024 experimental campaign, the major limiter with poloidal curvature at LFS was also replaced by the tungsten limiter composed of 7 W/Cu monoblocks with active water-cooling. It is shown in Fig. 1 (a). The height of the limiter, L, and major and minor radii at the limiter center, R_L, and r_L, are 1.0 m, 2.35 m and 0.75 m, respectively. It is indicated in magenta color in Fig. 1 (b). Typical LFS (red circle) and HFS (blue circle) configurations touched the outboard tungsten limiter and inboard

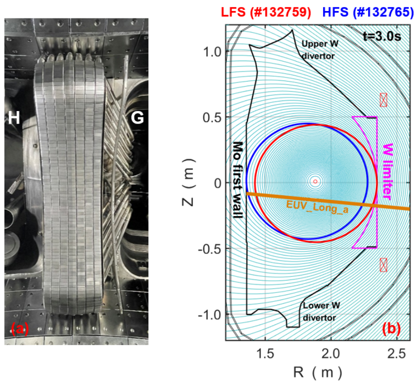

Fig. 1 (a) Front view of tungsten limiter installed between ports G and H at EAST low-field side (LFS). (b) Poloidal cross session of EAST tokamak with upper and lower tungsten divertors, tungsten limiter and molybdenum first wall. Poloidal plasma contours of Typical LFS (R_0 = 1.95 m, red circle) and HFS (R_0 = 1.91 m, blue circle) configurations and line of sight of fast-time-response EUV spectrometer (orange line) are also indicated.

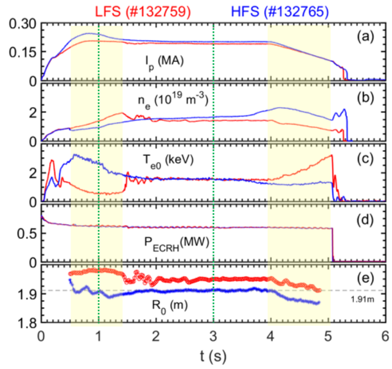

Fig. 2 Time evolutions of (a) plasma current, I_p, (b) chord-averaged electron density, n_e, (c) central electron temperature, T_{e0}, (d) power of ECRH, P_{ECRH}, (e) major radius position of magnetic axis, R_0, in two discharges of LFS (#132759) and HFS (#132765) configurations.

Mo tiles, respectively, are also illustrated as the poloidal plasma contour in Fig. 1 (b).

Time evolution of high-Z impurity behavior is observed in every 5 ms by the fast-time-response EUV spectrometer working at 20-500 Å [1]. In the present experiment, the spectrum was measured at 20-150 Å to simultaneously monitor several high-Z impurities of W, Mo, Cu and Fe. The central electron temperature, T_{e0}, and the chord-averaged electron density, n_e, are measured by heterodyne radiometer and polarimeter interferometer, respectively. Major radius position of magnetic axis, R_0, during the discharge is obtained from plasma equilibrium calculation based on measurement of poloidal magnetic probes.

3. EUV Spectra from Limiter Plasmas

In order to achieve an operation scenario similar to ITER plasma start-up phase, I_p = 200 kA and $n_e = 1.4 \times 10^{19}$ m^{-3} are preset during the discharge flat-top for two discharges of LFS (#132759) and HFS (#132765) limiter configurations. While in the case of HFS, a little higher n_e was sustained, i.e. 1.6×10^{19} m^{-3}, as shown in Fig. 2 (b). Central electron temperature, T_{e0}, is sustained at 1.5-1.6 keV in both discharges (see Fig. 2 (c)). Electron cyclotron resonance heating power greater than 0.6 MW was necessary for assisting the plasma start-up and sustainment (see Fig. 2 (d)). Plasma radial positions of R_0 = 1.95 m and 1.91 m are stably sustained in both LFS and HFS limiter configurations, respectively (see Fig. 2 (e)). However, plasma parameters mentioned above largely change in I_p ramp-up and ramp-down phases. In the case of LFS, for example, the plasma position is outwardly shifted by ~3 cm closer to the tungsten limiter (R_0~1.98 m) during I_p ramp-up phase with increased n_e up to 1.9×10^{19} m^{-3} and decreased T_e down to 0.5 keV, while the plasma position is inwardly shifted to R_0~1.91 m during I_p ramp-down phases with decreased n_e down to 0.5×10^{19} m^{-3} and increased T_e up to 3.0 keV.

Full-range EUV spectra over 20-150 Å observed at t=1.0 s and 3.0 s are compared between the two discharges in Fig. 3. At t=1.0 s during I_p ramp-up in Fig. 3 (a) W-UTAs are observed with large intensities at 20-45 Å and 45-65 Å in the LFS case due to a strong interaction with outboard tungsten limiter (R_0 = 1.98 m), where the intensity at 48-60 Å band is entirely saturated. These W-UTAs are featured as pseudo-continuum composed of W ions with ionization stages below W^{25+} because no obvious spectra are found at 20-28 Å and 45-48 Å [2] due to the low electron temperature of T_{e0}~0.5 keV. The 2nd order of W-UTA can be also observed at ~100 Å (see red line in Fig. 3 (a)). The low T_{e0} may be caused by a strong plasma cooling through the huge tungsten radiation at high n_e. Emission lines from Cu^{10+}-Cu^{13+} ions are also observed with strong intensities at long wavelength range of 135-150 Å. On the contrary, in the HFS case with higher T_{e0} of 2.6 keV, Mo emission lines clearly appear indicating a strong plasma-wall interaction with inboard molybdenum tiles. The Mo-UTA is observed with strong intensities at 68-96 Å. It seems to be composed of Mo^{16+}-Mo^{30+} ions. Isolated lines from Mo^{30+} and Mo^{31+} ions are found at 115.999 Å and 127.868 Å. The W-UTA at 46-64 Å is also observed with similar intensities to the Mo-UTA. The W-UTA from highly charged tungsten ions can be easily identified as indicated in Fig. 3 (a), e.g., W^{42+} at 47.191 Å, W^{43+} at 47.903 and 61.334 Å, W^{44+} at 60.93 Å, and W^{45+} at 62.336 Å. In addition, several lines from W^{27+}-W^{30+} and W^{35+}-W^{38+} ions are also identified as indicated in the figure. Here, it should be noted that no Mo-UTA spectra are observed in the LFS discharge and Cu lines appear with weak intensities in the HFS discharge.

Spectra observed at t=3.0 s in LFS and HFS dis-

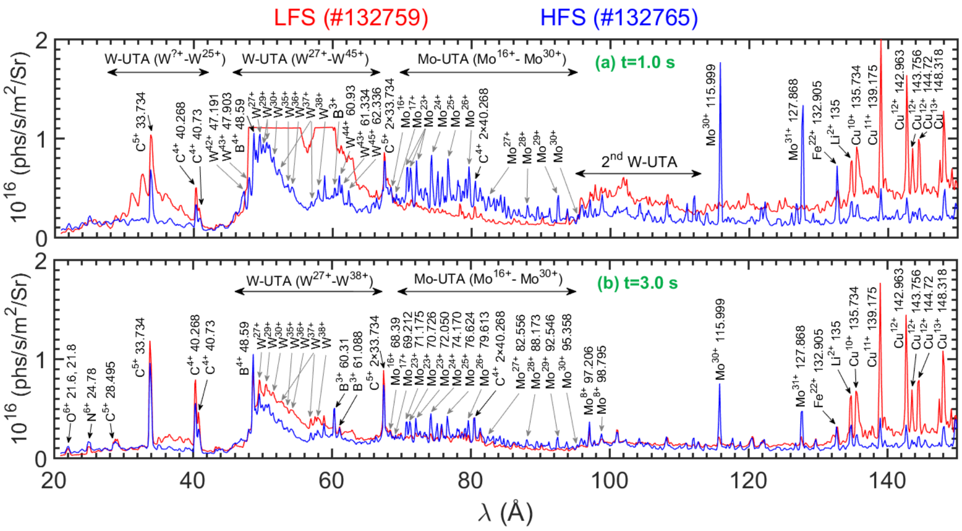

Fig. 3 Comparison of EUV spectra in 20-150 Å observed at t=1.0 and 3.0 s in LFS and HFS discharges. Note that T_{e0} varies largely at t=1.0 s in two discharges, i.e. 0.5 keV (LFS) and 2.6 keV (HFS) and is similar at t=3.0 s in two discharges, i.e. 1.55 keV (LFS and HFS).

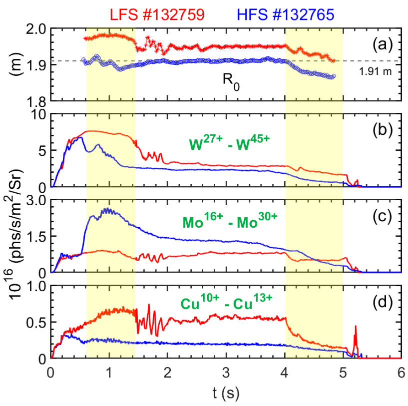

Fig. 4 Time evolutions of (a) major radius positions of magnetic axis, R_0, (b) intensities of W-UTA (W^{27+}-W^{45+} at 46-64 Å), (c) intensities of Mo-UTA (Mo^{16+}-Mo^{30+} at 68-96 Å) and (d) line intensities of Cu^{10+}-Cu^{13+} at 135-150 Å in LFS and HFS discharges.

charges during Ip flat top phase are compared in Fig. 3 (b). It is clear that the W-UTA intensity at 48-64 Å is weakened in both LFS and HFS discharges. Emission lines from W^{27+}-W^{38+} ions can be identified, although emission lines from W^{42+}-W^{45+} ions disappear due to the temperature of T_{e0} = 1.55 keV. The Mo-UTA intensity from the HFS discharge also largely decreases, while the line intensity from Cu^{10+}-Cu^{13+} ions is kept at similar levels between two different phases in the HFS discharge. Two Mo lines from weekly ionized ions of Mo^{8+} are clearly identified at 97.206 Å and 98.795 Å without overlapping of 2nd W-UTA in the HFS discharge. It may be used for Mo influx evaluation. Line identifications of low- and high-Z impurities in the present work is based on our previous works [3] and [4, 5], respectively. Time evolutions of W-UTA, Mo-UTA and Cu line intensities are plotted in Fig. 4. It is understood that all emission lines reduce the intensity during the plasma ramp-down phase.

4. Discussions and Conclusion

Complex spectra of W-UTAs and Mo-UTA and isolated emission lines from W, Mo and Cu ions were observed at 20-150 Å wavelength range in EAST limiter discharges. The line identification is performed carefully using EUV spectra observed from LFS and HFS discharges. The difference in the composition of charge states for tungsten ions in the W-UTA at 46-64 Å between the spectra observed at t=1.0 and 3.0 s in HFS discharge is consistent with the change of T_{e0} at these two time slices. For example, the highly charged tungsten ions of W^{42+}-W^{45+} are no longer present when T_{e0} decrease from 2.6 to 1.55 keV. Differences in the time evolutions and intensities of W-UTA, Mo-UTA and Cu lines observed between the LFS and HFS discharges are qualitatively understood. For example, reduction of tungsten line intensities is clearly observed when the plasma position is inwardly shifted (R_0 = 1.98 m → 1.95 m), and no Mo-UTA appears when the plasma does not touch the Mo tiles. Based on the statistic study, tungsten behavior is found to play an important role in the limiter discharge sustainment. It is also found that a stable discharge with low tungsten content can be optimized at the plasma axis position of R_0 = 1.95 m. However, there are still several open questions, e.g. source location of the copper impurity in LFS and HFS configurations, the tungsten source location in the HFS configuration and influence of Mo impurity radiation on the discharge sustainment. In the near future further data analysis will be carried out to study these issues using a combination of simulation works.

Acknowledgments

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