Determination of tungsten and molybdenum concentrations from an X-ray range spectrum in JET

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Introduction

It has been decided that ITER will be operated from day one with W divertor and Be first wall. In such a wall configuration, one of the most significant issues is impact of W accumulation on plasma fusion performance. In order to investigate the impact, in JET, experiments with ITER-like wall configuration have been performed with an upgraded high-resolution X-ray crystal spectrometer. This X-ray spectrometer originally monitored Ni concentration [1], and has now also started monitoring W concentration since a second crystal and detector were installed [2–4]. Coincidentally, Mo spectral lines are found in the same wavelength range as the W spectral lines. Hence, from the measured absolute intensities of W and Mo spectral lines, it is possible to evaluate the W and Mo concentrations simultaneously. The present report provides the first output of W and Mo concentrations from the upgraded spectrometer.

Spectrometer setup

The present X-ray spectrometer is built in Johann mounting with a Rowland circle radius of 12.5 m and a new Gas Electron Multiplier (GEM) detectors [2–6]. The measurable spectral band for the W channel is 0.0043 nm with 256 strips of the detector at a wavelength of 0.52 nm, or a photon energy of ~ 2.4 keV, and an inverse linear dispersion of 2.1×10^{-5} nm/mm. The sensitivity is calculated as a product of photon-throughputs at each component of the spectrometer: X-ray reflectivity of the crystal, transmittance of a 150 μm Be window at the torus, a 9 cm He gas buffer in front of the detector, a 12 μm Mylar window at the detector, resulting in 5.4×10^{-11} [counts ph^{-1}m^{2}sr] for the first order diffraction spectrum and 7.2×10^{-12} [counts ph^{-1}m^{2}sr] for the second one [4]. The diagnostic line-of-sight is on the mid-plane of JET, 0.2 m below the magnetic axis of typical diverted plasmas.

Line identification

One of the difficulties in high resolution spectroscopy is line identification due to the difficulty in determining the wavelength; slight misalignments of the instrument result in large uncertainties in wavelength and also known lines rarely fall in a very narrow spectral band, making the experimental wavelength calibration uncertain. To overcome these drawbacks, we employed the following two methods: i) laser-blow-off experiments and ii) validation of the modelled spectrum using Flexible Atomic Code (hereafter, FAC) [7], by comparing it with published spectra [8]. Mo laser-blow-off experiments confirm that the central two spectral lines, shown in Fig. 1, are from Mo. Furthermore, comparison with the calculated spectrum indicates that the two lines are due to Mo^{32+} (2s - 3p : λ= 0.52069 nm [9] and 0.5217 nm [10]). The remaining lines are well reproduced by a validated W spectrum, resulting in the following identification: W^{45+} (3p-4d : λ = 0.52289 nm [9]), and W^{46+} (3p-4d : λ = 0.52004 nm [9]). Note that slight difference in the above wavelengths from the positions of the spectral lines in Fig. 1 is due to Doppler shift.

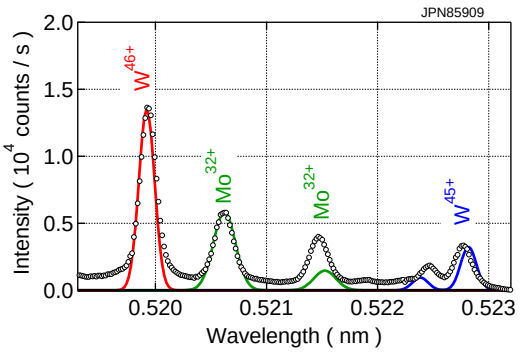

Figure 1: *Comparison of the spectrum measured by the upgraded X-ray spectrometer [4] with that calculated by Flexible Atomic Code [7] for W^{46+}, W^{45+} and Mo^{32+} at an electron temperature of 5 keV and a density ratio of 1:1.8:0.4, respectively.*

W and Mo concentrations

From the measured intensities, core W and Mo concentrations, n_W/n_e and n_{Mo}/n_e, respectively, are determined from the following equation (a similar equation for Mo):

$$c_W = n_W/n_e = \frac{I^{W^{46+}}}{\int \mathrm{PEC}^{W^{46+}}(R)\, n_e(R)^2\, \mathrm{FA}^{W^{46+}}(R)\, dR} \quad , \tag{1}$$

where $I^{W^{46+}}$ [ph $m^{-2}s^{-1}$] is the measured W^{46+} intensity, $\mathrm{PEC}^{W^{46+}}$ [ph m^3s^{-1}] the photon emission coefficient calculated by FAC [7], $\mathrm{FA}^{W^{46+}}$ the fractional abundance under coronal ionization equilibrium calculated with ADAS ionization/recombination rates [11], R [m] the major radius along the line-of-sight of the X-ray spectrometer. Below an electron temperature of ~5 keV, $\mathrm{PEC}^{W^{46+}}(R)\, n_e(R)^2\, \mathrm{FA}^{W^{46+}}(R)$ is peaked at the very centre of the plasma, indicating that the W concentration determined from eq. (1) is a good measure for the core W concentration, although the line-of-sight of the X-ray spectrometer does not passes through the very centre but up to a normalised poloidal flux of 0.05. The determined c_W and c_{Mo} are shown in Fig. 2 (a). The W and Mo concentrations are in the range of 10^{-5} and 10^{-7}, respectively, both in non-seeded and in N_2 or Ne seeded ELMy H-mode plasmas with a plasma current of 2-2.5 MA, a toroidal magnetic field of 2.7 T, a neutral beam heating power of 15-18 MW, an ion cyclotron resonance heating power of 3.5 MW (N_2- seeded plasma only), a central electron temperature and density of $3-4$ keV and $6-9\times10^{19}$ m^{-3}, respectively. The ratio of Mo to W concentration is ~ 5%.

Because the Mo concentration seems to be proportional to the W concentration, it is suggested that Mo sources are not special locations which plasmas attach occasionally but should be usual plasma wetted areas, similar to W sources. One of the possible sources is a Mo marker tile installed as an inner vertical divertor target [12]. It will be confirmed whether this tile can be a sufficient source for the determined Mo concentration.

Figure 2 (b) shows comparison of the W concentration from the X-ray spectrometer with those from a Vacuum Ultra Violet (VUV) spectrometer [13] and a soft X-ray (SX) array measurement [14], which are respectively determined mainly from the intensity of W^{45+} (4s-4p : $\lambda = 6.2336$ nm [9]) and from the sum of the intensities of the modelled W spectral lines in the wavelength range below ~ 0.5 nm, which can pass through a 250-μm-Be filter. It is known that in toroidally rotating plasmas, the W emission tends to relocate to the low field side due to centrifugal effects [14]. Thus the VUV spectrometer, whose line-of-sight passes through the very centre of the plasma, typically misses the significant part of the W emission. For this reason, only W concentrations in plasmas with low toroidal rotation velocity are compared in this discussion. As shown in Fig 2 (b), the W concentration from the VUV spectrometer is in good agreement with that from the X-ray spectrometer. In contrast, the W concentration from the SX measurement is about a factor of seven higher than that from the X-ray spectrometer. The discrepancy is beyond the uncertainty of the sensitivity in the X-ray spectrometer. The reasons for this discrepancy are not yet understood and will be investigated in future work.

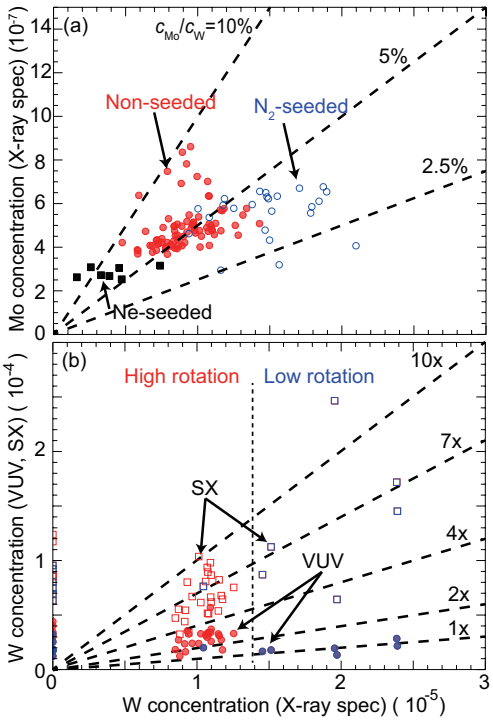

Figure 2: *(a) Mo concentration and (b) W concentrations from a VUV spectrometer [13] and a soft X-ray array measurement [14] as a function of the W concentration from the X-ray spectrometer.*

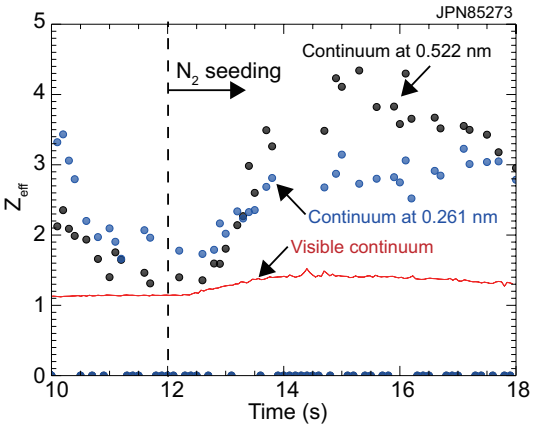

Figure 3: *Z_{eff} evaluated from 0.522 nm and 0.261 nm continua measured by the X-ray spectrometer and that from a visible spectrometer [15] in a N_2 seeded plasma, as a function of time.*

Continuum intensity

As Figure 1 shows, continuum emission is clearly observed in the X-ray spectrum. We use this additional spectral information to independently validate the sensitivity of the X-ray spectrometer. In order to determine the plasma effective charge, Z_{eff}, from the continuum intensity, it is required that another continuum component such as continuum emission due to W ion recombination is sufficiently small. Detailed calculations, which consider not only recombination to the ground levels of W ions but also to the excited levels, show that the recombination contin-

uum intensity is 1% of the measured continuum intensity, therefore recombination continuum is only a minor contributor. Z_{eff} can thus be determined from the measured continuum intensity with a small correction for the recombination continuum contribution. Comparison of Z_{eff} from the X-ray spectrometer and from a visible spectrometer [15] results in agreement within a factor of three, on the assumption of spatially uniform Z_{eff} profile. This means that the sensitivity of the X-ray spectrometer, and therefore the Mo and W concentrations, are valid within a factor of three.

Conclusions

W^{45+} and W^{46+} 3p-4d inner shell excitation lines in addition to Mo^{32+} 2p-3s lines were identified at a wavelength of ~ 0.52 nm (X-ray range). From the absolute intensities of the W^{46+} and Mo^{32+} lines, W and Mo concentrations were determined: respectively, $\sim 10^{-5}$ and $\sim 10^{-7}$ range. Comparison of the W concentration from the X-ray spectrometer with that from the VUV spectrometer [13] in plasmas with low toroidal rotation velocity, in order to avoid known underestimation [13] of the W concentration from the VUV spectrometer, showed good agreement. In addition, comparison of Z_{eff} from the X-ray spectrometer with that from a visible spectrometer [15] showed an agreement within about a factor of three. From these results, the sensitivity of the X-ray spectrometer is validated at this level of uncertainty, and therefore, the W and Mo concentrations from the X-ray spectrometer are valid within a factor of three. However, the W concentration from the SX measurement [14] is about a factor of seven higher than that from the X-ray spectrometer, and this discrepancy is larger than the uncertainty of the sensitivity of the X-ray spectrometer (about a factor of three). The discrepancy of the W concentrations between the SX measurement and the X-ray spectrometer is not yet understood and will be investigated in more detail in future work.

Acknowledgments

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