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# Measurement of S/XB values of W I atomic lines for tungsten diagnostics in KAERI divertor simulator device

Changmin Shin [a,b], Duck-Hee Kwon [b], Haewon Shin [b], Kil-Byoung Chai [b*] and Wonho Choe [a*]

[a]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology*
[b]*Nuclear Physics Application Research Division, Korea Atomic Energy Research Institute*

[*]*Corresponding author: kbchai@kaeri.re.kr, wchoe@kaist.ac.kr*

## 1. Introduction

Tungsten (W) is a promising candidate for the armor material of the divertor in future tokamaks including ITER and DEMO. The effect of sputtered tungsten on the plasma performance is important due to its strong radiative loss. Therefore, it is essential to accurately evaluate and characterize the sputtered W atom influx into the plasma.

The spectroscopic diagnostics of the tungsten influx using the S/XB method has attained recent attention because it provides a real-time measurement capability of the sputtered tungsten flux from neutral tungsten (W I) line emission intensities. The S/XB value is a coefficient derived from the relation between the line intensity of sputtered tungsten atoms and the tungsten particle influx, which is defined as a ratio of the effective ionization rate coefficient (S) to multiplication of the excitation rate coefficient (X), and the radiative branching ratio (B). The S/XB value can be obtained either theoretically using an atomic process model or experimentally [1].

In this study, we experimentally obtained the S/XB values in the KAERI divertor simulator device and compared them with the theoretical calculations of the atomic process model of tungsten atom from Ref. [2]. We also discuss a correction factor with respect to the ionization mean free path of the W atoms to compensate for the geometrical loss of tungsten flux. This study aims at providing reliable data for determining tungsten fluxes from emission lines, which is crucial for optimizing the performance of nuclear fusion reactors.

## 2. Principle of the S/XB method

### *2.1 Atomic process model of W I*

To investigate the theoretical value of S/XB and validate experimental results, it is necessary to model the atomic levels. In this study, the corona model from Ref. [2] was used, where the population of level *k* is balanced between the electron impact excitation from the ground state and the lowest metastable level and the radiative decay to the lower levels *k*'. The S/XB value can be given by

$$\frac{S}{XB} = \frac{\langle v\sigma_{iz}\rangle}{Q_{k,k'}}, \tag{1}$$

where, $v$ is the electron speed and $\sigma_{iz}$ is the electron impact ionization cross section. $Q_{k,k'}$ is the excitation rate for $k \rightarrow k'$ expressed as

$$Q_{k,k'} = \frac{A_{k,k'}}{A_k}\sum_{k_0} N_{k_0}\langle v\sigma_{k_0,k}\rangle, \tag{2}$$

where $A_{k,k'}$ is the Einstein coefficient of the radiative transition of $k \rightarrow k'$, $A_k$ is the sum of all possible Einstein coefficients of radiative decay from state *k*, $k_0$ is the metastable states, $N_{k_0}$ is density of ground and metastable states, $v$ is the electron speed, and $\sigma_{k_0,k}$ is the excitation cross section of $k_0 \rightarrow k$ by the electron collision. Based on these equations, the theoretical values of S/XB were obtained in Ref. [2]. The measured S/XB values are compared to theoretically calculated curves.

### *2.2 Principle theory and assumptions*

Some of the tungsten atoms sputtered from the wall are ionized while the others leave the plasma before being ionized [2]. Therefore, the sputtered tungsten flux $\Gamma_W^{Spt}$ can be expressed as a sum of the ionization flux $\Gamma_{W^+}$ and the geometrical loss flux $\Gamma_W^{GL}$:

$$\Gamma_W^{Spt} = \Gamma_{W^+} + \Gamma_W^{GL} \tag{3}$$

If most of the sputtered tungsten atoms are ionized before leaving the plasma, the geometrical loss can be neglected. In this case, the following relation holds:

$$\Gamma_W^{Spt} \approx \Gamma_{W^+} = 4\pi\left(\frac{S}{XB}\right)I_{WI}, \tag{4}$$

where, $I_{WI}$ is the line integrated intensity of sputtered tungsten atoms, observed in the direction of the influx. Thus, the S/XB value can be obtained experimentally from the relationships

$$\frac{S}{XB} = \frac{\Gamma_W^{Spt}}{4\pi I_{WI}} = \frac{Y\Gamma_i}{4\pi I_{WI}}, \tag{5}$$

where $Y$ is the sputtering yield, $\Gamma_i$ is the flux of bombarding ions. It is noteworthy that S/XB only depends on atomic physics and is independent of the origin of tungsten. Therefore, as it is measured experimentally by optical spectroscopy of W I, $\Gamma_W^{Spt}$ can be obtained by Eq. (4).

## 3. Experiments

### *3.1 Experimental setup*

The KAERI divertor simulator, utilizing a MagnetoPlasmaDynamic (MPD) thruster as a plasma source, is used to study S/XB method. The KAERI divertor simulator produces a plasma by applying DC voltage across the anode and cathode. The produced ions are then accelerated by the magnetic nozzle effect and directed towards a tungsten target, causing sputtering of the target material. Figures 1(a) and (b) show the schematic diagram of the plasma source and a photo of the KAERI divertor simulator, including the plasma source, chamber, and target, respectively. Figure 1(c) shows a photo of produced deuterium plasma.

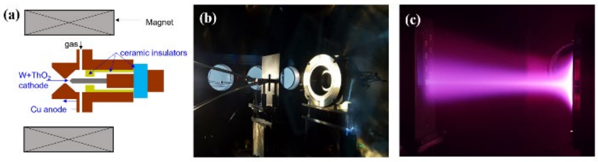

Fig 1. Description of KAERI divertor simulator: (a) schematic diagram of AF-MPD plasma source, (b) photograph of the KAERI divertor simulator, (c) operation of KAERI divertor simulator

To determine the experimental value of S/XB, plasma parameters such as ion flux, electron temperature, and electron density were measured. The electron temperature and density were measured using a planar-type Langmuir probe, while the ion particle flux was obtained by measuring the current flowing through the sample when a negative bias voltage was applied. Additionally, the amount of light emitted from tungsten atoms was measured using an optical diagnostic system. In this study, radiative transitions of W I lines with the wavelength of 429.6, 498.8, and 505.3 nm were used. Two different lines of sight were measured: perpendicular (LOS-D) and parallel (LOS-A) to the sample surface. Figure 2 shows the line of sight for optical diagnostic system. The LOS-D directly measures the line-of-sight integrated tungsten emission intensity, while LOS-A scans in the z-axis direction to measure the tungsten emission intensity and the emission intensity decay length. In the S/XB method, the ionization rate is assumed to be proportional to the line emission intensity. Therefore, the emission intensity decay length is same as the ionization mean free path of sputtered tungsten atoms [1].

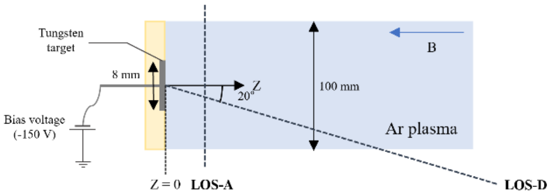

Fig 2. Schematic diagram of line of sights for optical diagnostic in KAERI divertor simulator

During the experiment, a bias voltage of -150 V was applied to the sample, and therefore ions with an energy of 150 eV were irradiated onto the sample. The discharge current of the plasma source ranged from 75 A to 175 A, and 1000 sccm of argon gas flowed. The operation pressure during the discharge was 2 mTorr.

### *3.2 Experimental results*

In the experiment, the S/XB values were obtained through a combination of probe and optical measurements. Figure 3 shows the measured data of electron temperature, density, and ion saturation current obtained using the Langmuir probe at various discharge currents.

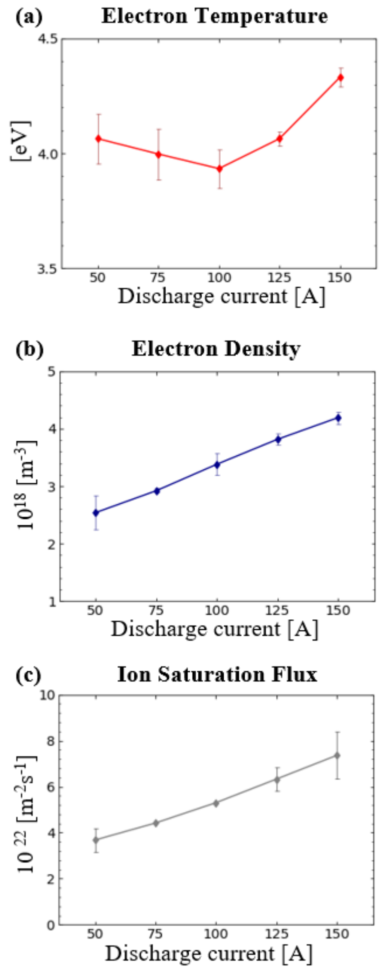

Fig 3. Measured data of (a) electron temperature, (b) electron density, (c) ion saturation flux obtained from the Langmuir probe

The S/XB value was directly obtained from the photon emission via LOS-D, as shown in Figure 4. Eq. (4) was used to calculate the S/XB value, and the sputtering yield was assumed to be 0.06 based on Ref. [3] because the energy of the irradiated argon ion was 150 eV.

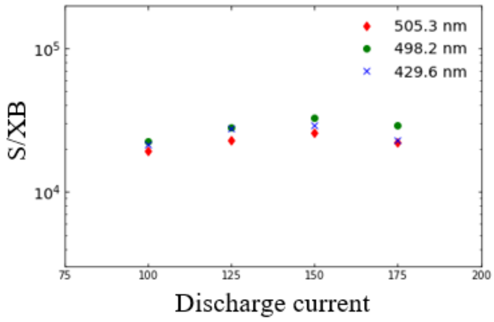

Fig 4. S/XB value obtained from LOS-D with the wavelength of 505.3 nm, 498.2 nm, and 429.6 nm with respect to the discharge current

The spatial profile of the 505.3 nm photon emission from the tungsten atoms as a function of the distance from tungsten target ($z$) was obtained via LOS-A, as shown in Figure 5. Fitting was performed using the following equation, assuming that the profile decays exponentially with respect to $z$:

$$I(z) = I_0 \exp\left(-\frac{z}{\lambda_{mfp}}\right). \quad (6)$$

In this equation, $\lambda_{mfp}$ represents the ionization mean free path of sputtered W atoms, which can be obtained experimentally from the emission intensity decay length of the axial emission profile [1]. $I_0$ represents the photon emission intensity on the tungsten surface. The ionization mean free path was measured to be 20.1 mm and 14.2 mm in the 100 A and 150 A discharge cases, respectively.

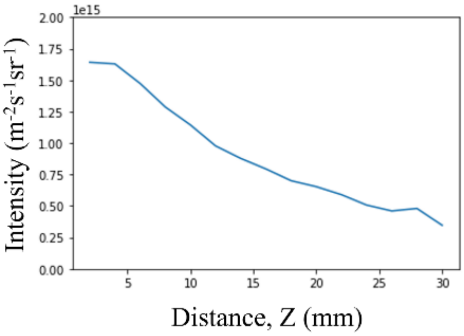

Fig 5. The spatial profile of the 505.3 nm photon emission according to z was obtained via LOS-A.

### *3.3 Comparison with experimental measurements and theoretical results*

The experimental method for obtaining the S/XB values neglected the geometrical loss of sputtered tungsten as discussed in section 2.2. However, the effect of geometrical loss is significant in our experimental case because the ionization mean free path (~20 mm) of neutral tungsten is nearly comparable to tungsten target size (8 mm). Therefore, a correction factor with respect to the ionization mean free path of the tungsten atoms is required to compensate for the geometrical loss of tungsten sputtering flux. The ratio of the geometrical loss to the sputtered tungsten can be expressed as [1]

$$\frac{\Gamma_W^{GL}}{\Gamma_W} = \exp\left(-\frac{L}{\lambda_{mfp}}\right), \quad (7)$$

where $L$ is the characteristic length taken as the half length of the tungsten target (4 mm) in this system. Thus, the fraction of the ionization to the sputtered flux can be expressed as

$$\frac{\Gamma_{W+}}{\Gamma_W} = 1 - \exp\left(-\frac{L}{\lambda_{mfp}}\right). \quad (8)$$

The S/XB value can be obtained as follows:

$$\frac{S}{XB} = \frac{\Gamma_{W+}}{4\pi I_{WI}} = \frac{Y\Gamma_i}{4\pi I_{WI}} \times \left\{1 - \exp\left(-\frac{L}{\lambda_{mfp}}\right)\right\}, \quad (9)$$

where $1 - \exp\left(-\frac{L}{\lambda_{mfp}}\right)$ is the correction factor for the geometrical loss.

Using Eq. (9), the obtained S/XB values were corrected and compared with the theoretical model mentioned in section 2.1. The results are shown in Figure 6, where solid lines are the theoretical values (Eq. (1)) for different tungsten temperature ($T_w$) taken from Ref. [2] and dots are the corrected S/XB values for line (a) 505.3 nm, (b) 498.2 nm, and (c) 429.6 nm with respect to the electron temperature ($T_e$).

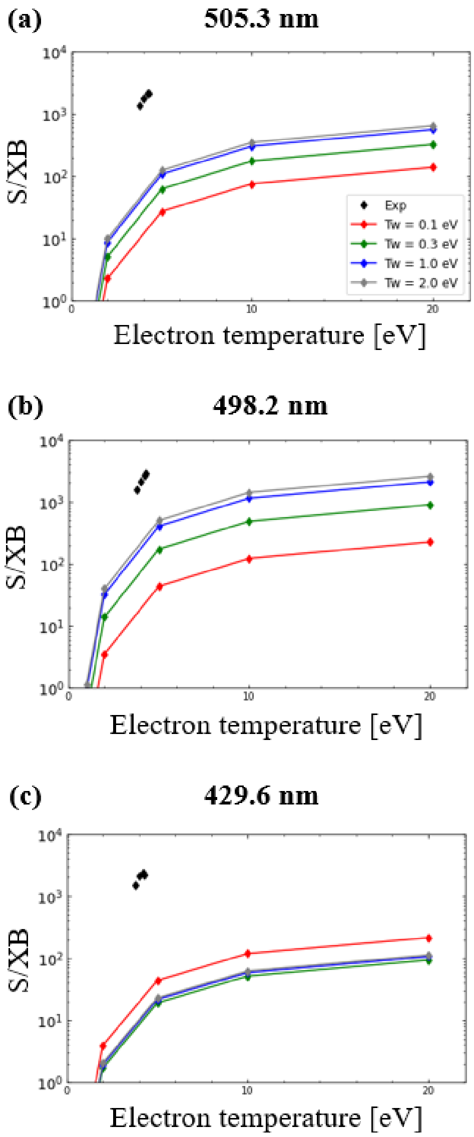

Fig 6. Theoretical values (solid line) for different tungsten temperature taken from Ref. [2] and measured S/XB values (dots) for line (a) 505.3 nm, (b) 498.2 nm, and (c) 429.6 nm with respect to the electron temperature

As a result of the comparison, measured S/XB values are overestimated compared the theoretical values. Therefore, details of the theoretical calculations should be improved to accurately predict the measured S/XB.

## 4. Conclusions

We have measured S/XB values from sputtered tungsten flux using the KAERI divertor simulator and compared with the theoretical calculations of the atomic process model from Ref. [2]. Additionally, we suggested a correction factor to compensate for the geometrical loss of tungsten flux. As a future work, we plan to improve the theoretical model based on the experimental cases. Furthermore, the works will be expanded to develop the system for real-time diagnostics of tungsten sputtering flux from the tungsten divertor of the KSTAR.

## REFERENCES

[1] D. Nishijima et al., "Experimental determination of S/XB values of WI visible lines." Physics of Plasmas 16.12 (2009)
[2] I. Beigman et al., "Tungsten spectroscopy for the measurement of W-fluxes from plasma facing components." Plasma Physics and Controlled Fusion 49.11 (2007)
[3] W. Eckstein, “Sputtering by Particle Bombardment”, Springer-Verlag, Berlin (2007)

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