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Local density profiles of impurities in KSTAR and WEST plasmas by spectroscopic diagnostics and forward modelling

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Control of impurity species in fusion plasmas is one of the main issues for long and stable plasma operation. The impurities can be generated by interaction of the plasma with its facing materials and/or by intentional injection for the purpose of maintaining radiative mantle. These impurities can cause detrimental radiation cooling and fuel dilution as they become accumulated inside the plasma. In this regard, impurity transport study should necessarily be conducted and the first step would be obtaining their local concentration distribution. The research framework that we have been developing consists of spectroscopic impurity diagnostics, tomographic reconstruction of the chord-integrated atomic emissions, and forward modelling using the KAIST Impurity Modelling (KIM) code. The main impurity diagnostics in this study are Compact Advanced EUV Spectrometer (CAES) [Ref. 1] in KSTAR and WEST, and the grazing incidence spectrometer [Ref. 2] in WEST. Based on the diagnostic measurements, a new tomography algorithm developed for limited viewing angle [Ref. 3] and forward modelling using the KIM code were utilized to deduce the local distributions of emission intensity and density of impurity species.

Previous research revealed that the centrifugal force due to the rapid toroidal plasma rotation brings about significant poloidally asymmetric distribution and also modifies neoclassical transport of heavy impurities. Since the toroidal rotation speed of KSTAR plasmas reaches several hundreds of km/s, low-Z impurity species such as carbon and oxygen ions also showed poloidally asymmetric distribution as shown in Figure 1. The top row images in the figure are space-resolved EUV spectra measured by CAES, and the bottom ones are the tomographically-reconstructed emission intensity profiles of the 3.37 nm C VI line (yellow), 3.80 nm O VIII line (green), and 4.03 nm C V line (blue) on the midplane by using our new reconstruction code for the limited viewing angle [Ref. 3]. The core rotation speeds in the figure are (a) 138 km/s, (b) 291 km/s, and (c) 318 km/s, respectively, and the effective Mach numbers of the impurities are larger than the unity when the toroidal speed is higher than 320 km/s. For example, the effective Mach numbers of C VI and O VIII at 320 km/s are 1.0 and 1.2, respectively. During the early phase of the plasma, which does not have a sufficiently high rotation speed, the carbon and oxygen line emission profiles show centrally-peaked and poloidally symmetric features as seen in figure 1(a). On the other hand, radially-hollow and poloidally asymmetric distributions are clearly seen in Figure 1 (b) and (c) as the plasma rotation becomes faster. This implies that the poloidal asymmetry effect can be non-negligible for the rapidly rotating plasma with the impurity Mach number exceeding the unity. From the view point of impurity transport, this is important because flux-averaged transport analysis without taking this effect into account may mislead the real phenomena.

In the WEST tokamak, where tungsten (W) is employed as a divertor material, analyses were performed to obtain the 2D distribution of W ions. Since there are a large number of W transition lines known as quasi-continuum radiation in the EUV range, the reconstruction method to find their local distributions is inappropriate due to the convoluted line emissions. However, the forward model using the KIM code enables deducing the local density profiles by comparing the synthetic data and the measured data by chi-square fitting. Figure 2 shows the comparison of the three W lines (4.86 nm $W^{28}+$, 6.09 nm $W^{44}+$, and 6.23 nm $W^{45}+$) measured by the grazing incidence spectrometer. Assuming that the plasma is in steady-state, the emission spectra at different time points can be treated as space-resolved spectra. The simulated W emission profiles are also analyzed for different impurity transport coefficients (diffusion coefficient and convection velocity) cases. The result suggests that $W^{28}+$ line emission seems a good candidate for studying impurity transport because it is more sensitive to the convection compared to the emissions from highly charged ions ($W^{44}+$ and $W^{45}+$) that are localized mostly in the core region. Thus, the convection characteristics of the W ions can be investigated through $W^{28}+$ lines under various plasma situations such as applying actuators to reduce the core accumulation of W. Although the sensitivity calibration is needed to determine the absolute value of the density, the calculated fractional abundance and Zeff profile can provide valuable information how W ions are distributed inside the plasma. The analysis result suggests that a considerable amount of tungsten exists in the core.

In summary, we observed that even the light impurity species under the fast toroidal plasma rotation show significant poloidal asymmetric distribution in KSTAR and tungsten impurity shows core accumulation even under the slowly rotating plasma in WEST. This work emphasizes the importance of the analysis of the local impurity density profiles in parallel to the development of impurity control methods. This study is expected to contribute to the impurity transport study in ITER with the ITER VUV spectrometer [Ref. 4] that also has a capability similar to CAES to resolve spatial distribution of the impurity line emissions.

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