Impact of Stark Broadening on Ion Temperature Measurements in the ITER Divertor Plasma

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The Stark broadening of impurity ions under a magnetic field is evaluated with respect to the divertor plasma of ITER in mind. The perturbing electrons and ions are treated separately, and the perturbation due to the magnetic field is considered at the same time. The results show that the Stark broadening can be significantly large when the density exceeds 10^{21} m^{-3}, indicating that an accurate evaluation of the Stark broadening is necessary when considering the ion temperature (T_i) measurements by Doppler broadening of the emission lines.

ITER's Divertor Impurity Monitor Diagnostic (DIM), consisting of several UV-visible spectrometers, is responsible for measuring the emission lines of impurity ions in the divertor region. One of the most important requirements of the DIM is the measurement of T_i in the divertor plasma. Since the ion temperature of the divertor is an important parameter affecting the sputtering of the divertor plates, a high precision measurement is required.

On the other hand, the retention of impurity ions introduced into the divertor for radiation loss enhancement is the key challenge for efficient detachment sustainment, and it is also important to know the direction and magnitude of the impurity ion flow. For these reasons, the width, center wavelength, and intensity of the impurity ion emission lines must be accurately measured.

As coatings of low-*Z* materials such as beryllium or boron are considered for the divertor and the first wall plates in the current ITER design baseline, these impurity atoms and ions should be present in the divertor plasma and the T_i measurement can make use of the emission lines of these impurity ions.

For accurate T_i measurements, it is necessary to clarify broadening effects on the emission line profile other than the Doppler broadening. First, there is an effect caused by magnetic fields. The magnetic field strength in the ITER plasma is typically 5 T, and the emission lines would split into several components due to the Zeeman effect. If the splitting width is comparable to the Doppler broadening width, the Zeeman effect could contribute to the observed broadening width.

Second, calculations with the SOLPS-ITER code [1] indicate that the electron density in the divertor plasma could exceed 10^{21} m^{-3} near the target plates [2] where T_i is a few electron volts or less. Under such high density conditions, it is possible that the Stark broadening also affects the evaluation of the broadening width for the T_i measurement. We attempt to formulate a method for calculating the Stark broadening of impurity ion emission lines under a magnetic field.

We adopt the method of Ref. [3] for the Stark broadening calculation, i.e., the ion and electron contributions are treated as the static and impact approximation, respectively, and the convolution of these profiles is considered as the line profile to be observed. For the impact approximation, the data of Ref. [4] are used. For the static approximation, a distribution function of the electric field strength is considered as a collection of microfields generated by ions. The Holtsmark distribution [5] is used for the present calculation. The perturbations are dominated by protons and their density is assumed to be equal to that of electrons. We assume an isotropic plasma so that the resulting electric field distribution is also isotropic.

The difference to the conditions of Ref. [3] is that the presence of a magnetic field oriented in a specific direction, which makes the system asymmetric, or axisymmetric with respect to the magnetic field. We calculate the emission line profile in the presence of an electric field of a given direction and strength, together with a fixed magnetic field, and superimpose the line profiles by scanning the strength and direction of the electric field to obtain the line profile to be observed.

Figure 1 shows the spectra calculated for the Be II line ($1s^2 3d\ ^2D – 1s^2 4f\ ^2F$, 467.339 nm) as an example for some different perturbation density conditions. The thin lines show the spectra calculated with the present method. The cross symbols show the convolution of the spectra with the Doppler broadening of 1 eV. Here, we give each data point a random error according to the Poisson distribution, considering that the fit will be performed later with the Gaussian function to derive T_i. It can be seen that the line is divided into three main peaks. The central peak and the two lateral peaks correspond to the π and σ components of the Zeeman split lines, respectively. The intensity ratio of the π and σ components is mainly determined by the angle between the line-of-sight and the magnetic field, which is about 60 degrees in the present DIM design.

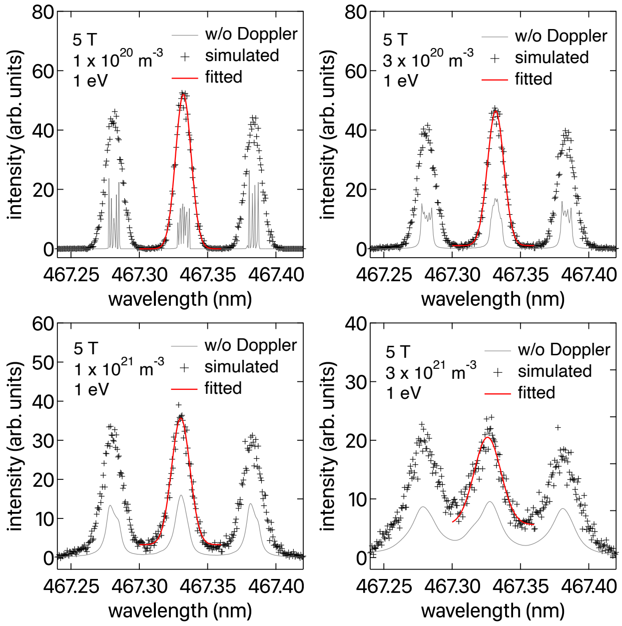

Fig. 1: Examples of calculated spectra of the Be II line ($1s^2\ 3d\ ^2D – 1s^2\ 4f\ ^2F$, 467.339 nm) for four different perturber density cases when T_i = 1 eV.

Assuming a naive T_i measurement, the central peak is fitted with a single Gaussian, and T_i is determined from its width. Figure 2 shows the results for cases of T_i = 1, 2, 5, 10, and 20 eV. It is easy to see that the evaluated T_i increases with the density especially in the range where the density is higher than 10^{21} m^{-3}. This should be an effect of the Stark broadening. The error is evaluated as the root mean square of the difference between the measured and the fitted data. It can also be seen that the error obtained in T_i increases with density because the shape of the emission lines is no longer well represented by a single Gaussian. It should be noted that even at densities lower than 10^{20} m^{-3}, the T_i obtained by fitting is slightly higher than the assumed temperature value. This is caused by the splitting of the emission line components due to the Zeeman effect.

From these results it can be concluded that when the plasma density exceeds 10^{21} m^{-3}, which is a possible condition in the ITER divertor plasma, the Stark broadening should be taken into account for the T_i measurement. One idea to solve this problem is to use the different emission lines of the same ion to simultaneously determine the ion temperature and the electron or bulk ion density. With sufficiently high sampling, it may be possible to detect changes in the temperature and density of the divertor plasma when, for example, instabilities occur in the core plasma.

Finally, we have so far considered an emission line from a beryllium ion, but it is very likely that ITER will not use beryllium. Nevertheless, the method used in this study is universal and can be easily applied to any other ion. We plan to carry out similar calculations for some boron ion lines suitable for T_i measurements.

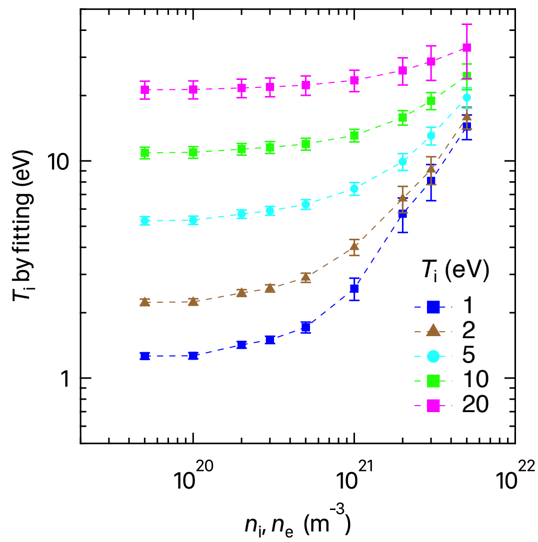

Fig. 2: Density dependence of Ti derived via fitting of calculated spectrum with a single Gaussian function.

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