Studies of the halo effect in the charge exchange recombination spectroscopy edge measurements at ITER

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Abstract. Active charge exchange spectroscopy will be used for measuring the ion temperature, density and rotation velocity of the ITER plasma. Because of the halo effect, the measurement accuracy can get worse. In this paper, the active spectroscopy measurement errors caused by the halo effect are estimated for ITER. The estimates were performed using the Simulation of Spectra (SOS) code. According to the simulation results, the halo effect decreases the density measurement accuracies by less than 4% and 1% for the impurity and bulk ions, respectively, and the measurement errors for the temperature and velocity are less than 1%. It was also obtained, that the halo effect can decrease the active spectroscopy spatial resolution by 1.5 and 2.5 cm for impurities and bulk deuterium atoms, respectively. The measurement errors were also estimated for determining the deuterium-to-tritium concentration ratio.

1. Introduction

Charge Exchange Recombination Spectroscopy (CXRS) is used on the majority of modern tokamaks. It allows measuring the temperature, density and rotation velocity of the plasma ions with good spatial resolution. CXRS will be also used at the ITER facility [1, 2].

CXRS is based on the charge exchange process. The high-energy atomic (e.g., hydrogen) beam is injected into the hot plasma, where the charge exchange occurs between the beam atoms and the fully ionized low-Z elements. The subsequent photon emission is detected along the lines of sight (l.o.s.) and transported to the spectrometers. The ion temperature, rotation velocity and density can be calculated using data on the Doppler widths, Doppler shifts and intensities of the corresponding spectral lines, called the active CX lines.

The charge exchange process between plasma protons and beam atoms also occurs. As a result of this process, the cloud of neutral hydrogen atoms is produced, which is called the beam halo. Therefore, the fully ionized elements emit photons due to the charge exchange with both the beam atoms and beam halo. The halo effect results in an increase in the active CX line intensity and could affect the locality and accuracy of the CXRS measurements [3, 4]. To study the influence of the halo effect on the CXRS measurements at ITER, the simulations were performed to estimate the measurement errors caused by this effect.

2. Simulation principles and input data

In this paper, the Simulation of Spectra (SOS) code [5] that allows calculating the CXRS spectra for different fusion facilities was used. In this code, the beam is considered as the source of the halo atoms, which diffuse into the plasma and become ionized in collisions with the plasma particles.
The density of the halo atoms is calculated by means of solving the set of equations consisting of the continuity equation and the Fick diffusion law. Next, the SOS code calculates the intensities of the active CX line and halo lines by means of performing integration along the l.o.s. In the case of hydrogen isotopes, when calculating the halo emission intensity, the halo cloud emission is also considered. It is caused by the excitation of the halo atoms in collisions with the plasma particles. Therefore, the influence of the halo effect on the measurements of hydrogen isotopes parameters can be stronger than that on the impurity parameters.

The simulations were performed for deuterium and the He, Be, C and Ne impurities with relative concentrations of 4%, 2%, 0.1%, and 0.3%, respectively. Three basic ITER scenarios were considered:

- Steady state scenario (the ratio of the fusion power to the heating power is $Q = 5$, the plasma current is $I = 9$ MA),
- Hybrid scenario ($Q = 5$, $I = 13.8$ MA) and
- Inductive scenario ($Q = 10$, $I = 15$ MA).

The hydrogen neutral beam was simulated with energy of 100 keV and one energy component. At ITER, the beam is located in the equatorial plane of the torus almost parallel to the radial direction. Lines of sight intersect the beam at angles from 73° to 87°. The simulations were performed for the CXRS Edge system, in the field of which the outer plasma region falls; therefore, only the region with $0.5 \leq \rho \leq 1$ was considered ($\rho$ is the normalized minor plasma radius).

3. Simulation results

3.1. The halo effect contribution to the intensity of the active spectral line

The intensity of the active CX spectral line increases due to the halo effect. Actually, this can even be a positive result, which allows reducing the statistical errors due to an increase in the signal intensity. However, the simulations are required to calculate the halo contribution to the intensity of the active spectral line. The ion density is proportional to the corresponding spectral line intensity and, if not accounted for, the halo effect can result in the overestimation of the ion density. This contribution was calculated and the corresponding radial dependencies are shown in Figures 1a and 1b for the He spectral line (because for the He line, the contribution of the halo emission is the largest) and the D spectral line, respectively.

![Figure 1.](image1.png)  
(a)  
(b)

Figure 1. The radial dependencies of the contribution of the halo-induced emission to the intensity of active spectral line: (a) He; (b) D.

It is seen that an increase in the intensity caused by the halo effect reaches 20% and 32% for impurities and deuterium, respectively. The inaccuracy of the halo simulations should be estimated. The most contribution is given by the atomic data errors. The conservative estimate will probably be
less than 20%. Therefore, the additional error of the density measurements introduced in the course of the halo simulations is lower than 4% and 6% for impurities and hydrogen isotopes, respectively. Moreover, due to the small difference between the D and T emission rates, the halo simulation error has almost no effect on the measurements of the deuterium-to-tritium concentration ratio.

3.2. Temperature and rotation velocity errors caused by the halo effect

The halo effect could also distort the shape of the active CX spectral line. In the case of the ITER facility, the volume occupied by the beam halo exceeds the beam volume. We believe that the emission caused by the charge exchange between the beam atoms and the plasma ions comes from the intersection point of the beam and the l.o.s., whereas the emission caused by the charge exchange between the halo atoms and the plasma ions comes from the volume of the halo cloud surrounding the beam. As a result of integration along the l.o.s., the halo spectral contour could have a complex shape, which complicates the measurements of ion parameters.

The active CX spectral line is assumed to have the Gaussian shape. It is necessary to examine, whether this assumption remains true after taking into account the halo effect. For this purpose, the active spectral line with allowance for the halo effect was approximated by the Gaussian function and the standard deviation was calculated. It turned out that the standard deviation is negligible, as compared to the active line intensity. It can be concluded that active spectral line is well fitted with the Gaussian function. The simulated CX line of He and the corresponding halo line are shown in Figure 2a.

The ion temperature and rotation velocity were calculated based on data on the simulated active spectral lines with allowance for the halo effect and without it. The obtained relative errors caused by the halo effect don’t exceed 1%.

3.3. The halo effect influence on the spatial resolution

The CXRS spatial resolution \( \sigma_\rho \) was estimated using the equation \( \sigma_\rho = (\langle \rho^2 \rangle - \langle \rho \rangle^2)^{1/2} \). The \( \langle \rho \rangle \) and \( \langle \rho^2 \rangle \) radii were obtained by means of averaging along the l.o.s. with weighting coefficients, which were the intensities of the charge exchange emission lines in the corresponding point. That is, the spatial resolution was considered as a possible deviation of the emission region from the center of the expected emission region \( \langle \rho \rangle \). The obtained radial resolutions at different minor plasma radii are presented in Figure 2b. The radial resolutions for the He impurity are also shown, because, in this case, the influence of halo effect is the most pronounced. It can be seen that the radial resolution is minimal at \( \rho \sim 0.7 \). The reason for this is that in this point, the l.o.s. is normal to the radial direction.

![Figure 2](image_url)

**Figure 2.** (a) Simulated CX line with and without the halo line and the halo line for the He impurity; and (b) radial resolution of the CXRS Edge diagnostic with allowance for the halo effect and without it for the measurements using the He and D CX lines. The steady state ITER scenario is considered.
3.4. Comparison with the ITER requirements

Table 1 lists the plasma parameters that should be measured in the ITER plasma using the CXRS Edge diagnostic system. The requirements for the accuracy and spatial resolution of measurements are indicated. The estimate of the statistical errors of the impurity parameter measurements was taken from [6]. To estimate the statistical errors of the measurements of the deuterium-to-tritium concentration ratio, the additional simulations were performed. The spectra obtained in the simulations were approximated by a set of the Gaussian contours using the least-square minimization procedure, and the error of calculating the D and T concentrations was estimated. The obtained errors for calculating the deuterium-to-tritium ratio could reach 70% at low tritium concentrations. The measurement accuracy for this ratio meets the ITER requirements only in the range of the deuterium-to-tritium concentration ratios from 0.1 to 10.

The additional errors caused by the halo are also listed in table 1. These halo-induced errors are placed against the statistical errors obtained when approximating the spectrum by the set of the Gaussian contours without taking the halo effect into account. The similar comparison is done for the spatial resolutions. It could be stated, that:

- The halo effect will not considerably affect the measurements of the plasma rotation velocity, ion temperature and ratio of the deuterium-to-tritium concentrations, but should be considered and simulated for the light impurity concentration measurements,
- The halo effect decreases the spatial resolution of the CXRS Edge system in the plasma center, but it still meets the ITER requirements.

### Table 1. ITER requirements to the measurement accuracy and error estimates obtained in simulations.

| Plasma parameters | Range          | Accuracy, % | Spatial resolution, cm |
|-------------------|----------------|-------------|------------------------|
|                   | Required       | Without halo| Addition due to halo   | Required          | Without halo | With halo |
| $\nu$             | 1–200 km/s     | <30         | 20<sup>a</sup>         | 0.6               | 6            | 2.2       | 3.3       |
| $T_i, \rho < 0.85$| 0.5–40 keV     | <10         | 10<sup>a</sup>         | 0.8               | 6            | 1.8       | 3.3       |
| $T_i, \rho > 0.85$| 0.05–10 keV    | <10         | 2<sup>a</sup>         | 0.8               | 2            | 2.2       | 2.2       |
| $n_{He}/n_e$      | 0.01–0.1       | <10         | 3<sup>a</sup>         | 4                 | 20           | 1.8       | 3.3       |
| $n_{He}/n_e, \rho < 0.85$ | 0.005–0.2   | <20         | 5<sup>a</sup>         | 2                 | 20           | 2.2       | 3.3       |
| $n_{He}/n_e, \rho > 0.85$ | 0.005–0.2   | <20         | 1<sup>a</sup>         | 2                 | 5            | 2.2       | 2.2       |
| $n_T/n_D$         | 0.01–10       | <20         | 70<sup>a</sup>        | 1                 | -            | 2.2       | 2.2       |

<sup>a</sup> Data from [6].

4. Conclusions

As a result of simulations, it was demonstrated that for the CXRS measurements at ITER, the halo effect should be taken into account. The halo effect considerably contributes to an increase in the active spectral line intensity, which reaches 20% and 32% for impurities and deuterium, respectively. The errors introduced by the halo simulations result in the errors of the concentration measurements of less than 4%. Although the halo effect slightly distorts the active spectral line shape, it can be still considered as the Gaussian curve, and the measurement errors for the ion temperature and velocity caused by the halo effect don’t exceed 1%. The halo effect can decrease the spatial resolution of the active spectroscopy by 1.5 and 2.5 cm for helium and bulk deuterium, respectively, but it still remains within the ITER requirements. The measurement error for $n_T/n_D$ ratio was also estimated. According to this estimate, it is possible to measure this parameter with the required accuracy in the range $n_T/n_D > 0.1$. 
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