Spectroscopic problems in ITER diagnostics

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Abstract. Problems of spectroscopic diagnostics of ITER plasma are under consideration. Three types of diagnostics are presented: 1) Balmer lines spectroscopy in the edge and divertor plasmas; 2) Thomson scattering, 3) charge exchange recombination spectroscopy. The Zeeman-Stark structure of line shapes is discussed. The overlapping of isotopes H-D-T spectral line shapes are presented for the SOL and divertor conditions. The polarization measurements of H-alpha spectral lines for H-D mixture on T-10 tokamak are shown in order to separate Zeeman splitting in more details. The problem of plasma background radiation emission for Thomson scattering in ITER is discussed in details. The line shape of P-7 hydrogen spectral line having a wave length close to laser one is presented together with continuum radiation. The charge exchange recombination spectroscopy (CXRS) is discussed in details. The data on $D_\alpha$, HeII and CVI measurements in CXRS experiments on T-10 tokamak are presented.

1. Introduction
The spectroscopic diagnostics of ITER plasma includes three important types of diagnostics: 1) Balmer lines spectroscopy in the edge and divertor plasmas; 2) Thomson scattering, 3) charge exchange recombination spectroscopy.

Diagnostics of ITER plasma based on Balmer spectral line shapes measurements is one of the main spectroscopic diagnostics. The problem of spectral line shapes calculations faces with the development of the spectral line broadening theory for the broad domain of plasma densities and temperatures which change along lines of sight. The number of effects making the influence on observed line shapes is to be taking into account. One of the main effect is the presence of strong magnetic field resulting in the strong Zeeman splitting being of the same order of magnitude as the atom interaction with electric fields of surrounding plasma particles (Stark effect). This results in hard enough calculations of Zeeman-Stark structures of atomic energy levels at arbitrary orientation of magnetic and electric fields. Moreover, the electric fields are not static due to intense thermal motion of charged particles. The new version of FFM method provides fast codes for line shapes calculations [1-3]. The main goal of the calculations is to resolve between H, D, T isotopes spectra in order to determine the isotope content in ITER. The isotope spectra have to be calculated for different lines of sights. Some experimental results for isotope composition observations in T-10 tokamak are demonstrated below. General problem of edge plasma radiation blended by strong divertor radiation emission is discussed as well.

Thomson scattering in ITER is one of the one of the most important method for electron temperature measurements in thermonuclear plasmas. The signal of Thomson scattering is relatively
small and sensitive to the plasma background radiation emission. The wavelength of hydrogen P-7 spectral line is close to one of laser radiation. So the line shape of P-7 spectral line is of importance for Thomson scattering diagnostics. The intensities of nitrogen impurity spectral lines relative to the Thomson diagnostics spectral range are also of interest.

The charge exchange recombination spectroscopy (CXRS) is also the important method of active plasma diagnostics in ITER. The detail information on cross sections for charge exchanges between fast beam atoms and carbon ions are needed. The problem of halo atomic structure together with their charge exchange on carbon ions is also of importance. Some experimental data on Doppler line shapes of $D_n$, HeII and CVI charge exchange recombination spectra on T-10 tokamak are presented below.

2. Line broadening of hydrogen spectral lines in strongly magnetized plasmas. Balmer lines spectroscopy in the edge and divertor plasmas

An analysis of H-alpha spectrum for various observation chords in ITER SOL, carried out with the help of fast FFM numerical codes BALMER-SZDYN [4] for line shapes in thermonuclear plasmas with strong magnetic fields combined with the SOLPS4.3 code [5] for plasma parameters distribution along lines of sights is presented below. The results are given for the case of the vertical chord observation from the upper port UPP#2 in ITER for the conditions of the ITER SOL/divertor regime 1514. The position of observation chords are shown on figure 1. The distributions of plasma parameters (electron/ion temperatures and electron density) along horizontal chord are shown on figure 2 [5].

![Figure 1. Horizontal and vertical chords in ITER.](image1)

![Figure 2. Plasma parameters distribution on horizontal chord (outer region). SOLPS4.3 – code [5].](image2)
D-alpha, D-beta emissivity on horizontal chord is presented on figure 3. Line shapes of hydrogen isotopes in SOL for direction of observation perpendicular to magnetic field are shown on figure 4 [4]. The same line shapes of hydrogen isotopes (H, D, T) for divertor stray light and the composite spectrum for a [5%, 65%, 35%] mixture of isotopes are presented on figure 6 [4]. One can see a strong overlapping of isotopes line shapes especially for dense plasmas in divertor.

Figure 3. D-alpha, D-beta emissivity on horizontal chord SOLPS4.3 – code [5].

Figure 4. Total line shape of hydrogen isotopes in SOL [4].

The problem of SOL radiation observation is very difficult because of strong blending of the SOL radiation by intense divertor radiation emission. The reflected divertor emissivity dominates over SOL near 2-3 orders of magnitude. One need special tricks (light traps) to observe the SOL radiation on the background of divertor radiation.
Figure 5. Normalized line shapes of hydrogen isotopes (H, D, T) for divertor stray light and the composite spectrum for a [5%, 65%, 35%] mixture of isotopes [4].

Figure 6. Observation Balmer-alpha line shapes of isotopes H, D in T-10 tokamak (Medvedev A A, private communication): left hand side is observed positions of Stark components, right hand side is the fitting by Gaussian shapes.

There are some possibilities for separation of isotopes line shapes. One of them is connected with observation of atomic line shapes in polarized light. Figures 6 and 7 demonstrate such a possibility from experimental spectra observations on T-10 tokamak. One can see that the polarization measurements make it possible to separate well between $\pi$ and $\sigma$ components of the isotopes D, H mixture.

3. Radiation Background in Thomson scattering

The radiation plasma background is of importance for Thomson diagnostics because of a small value of reflected laser radiation signal. In particular the hydrogen P-7 line wavelength (10049.3 Å) is very close to laser signal. That is why the detail shape of the line is needed for foundation of Thomson diagnostic spectroscopy. Figure 7 presents lines of sight for Thomson diagnostics in ITER divertor.
The spectral intensity distributions along two lines of sight proposed for Thomson scattering observations in divertor [6] are shown on figures 8, 9.

![Figure 7](image1.png)

**Figure 7.** Line of sights for Thomson diagnostics in ITER divertor. The blue lines correspond to the chords N5 and N21.

![Figure 8](image2.png)

**Figure 8.** The intensity distribution of P7 spectral line along the chord N21 in divertor (red line). The contribution of plasma continuum is shown by the blue line.

![Figure 9](image3.png)

**Figure 9.** The same as on figure 8 but for the chord N5.

One can see a large difference between line and continuum radiation intensities for both chords. Note that the background for Thomson scattering can be due to the presence of different impurities in plasmas. Such for example, the radiation of neutral nitrogen contains strong radiative transitions at wavelengths $10^{105}-10^{114.64}$ Å (line $10^{112.48}$ Å from NIST data) in the spectral range close to laser signal. The problem is in detail line shapes calculations of the corresponding radiative transitions.

4. **Charge Exchange Recombination Spectroscopy (CXRS)**

The Charge Exchange Recombination Spectroscopy (CXRS) is one of the effective methods of active plasma diagnostics in ITER. It is based on charge exchange recombination of impurity ions in plasma on fast (near 100 keV) hydrogen neutral beam atoms injected into the hot plasma [7]. Selective charge exchange cross sections are needed for interpretation of experimental data. The example of such cross section for reaction $C^{6+} + H(n = 2) = C^{5+}(n_z, l_z) + H^+$ is presented in figures 10, 11.
The most convenient spectral line for observations for carbon (Z=6) impurity corresponds to the radiative transitions from the ion energy level with principal quantum number \( n_Z = 8 \) to the level \( n_Z = 7 \) with the wavelength 5290 Å. Observations of line intensities provide the information on local impurity contents in the plasma. The Doppler line shapes provide the information on ion temperature.
Problems with interpretation of the CXRS signals are connected with cascade processes such as:

\[ H_F + D_T^+ \rightarrow H_F^+ + D_T^+ (n); \]
\[ D_T^+ (n) + C^{+6} \rightarrow D_T^+ + C^{+5} (n_z = 4n) \rightarrow C^{+5} (n_z = 8) + h\omega \rightarrow C^{+5} (n_z = 7) + h\omega_{8-7} \]

Here index \( F \) corresponds to fast beam atoms and index \( T \) corresponds to thermal plasma ions.

The cascade processes are especially difficult for interpretation because of halo effect. The halo arises around the neutral beam due to the charge exchange of fast atoms on thermal ions. The charge exchange to the ground atomic state is followed by the electron excitation of halo atoms into excited atomic states. The charge exchange from these excited states grows very fast with principle quantum numbers of the atoms (proportional to \( n^5 \)). So the atomic energy states of impurities are effectively populated by the charge exchange from excited states of halo atoms resulting in radiative-collisional cascades to the observed impurity carbon energy level \( n=8 \). Such cascade processes result in a complicated density dependence of the CXRS signals.

5. Conclusions

The spectroscopic diagnostic methods are widely used in ITER plasma diagnostics. The passive method relates to Balmer spectroscopy; the main problems are connected with extracting of isotope effects from H-alpha observations; the problem of SOL intensity observation at the background of strong divertor radiation being of importance. The radiation trapping in divertor plasma plays an important role [10, 11]. The plasma background coming both from continuum radiation as well as line radiation from hydrogen isotopes and impurities is essential problem for Thomson scattering observation. The line shapes of line radiation are of importance in the case. Account for radiative-collisional cascade transitions in active CXRS with account of halo effect is of importance for interpretation of experimental data.

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