CXRS measurements of ion temperature in NBI discharges on Globus-M spherical tokamak

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Abstract. The thesis describes the Charge-eXchange Recombination Spectroscopy (CXRS) diagnostics setup and its application to the ion temperature determination in the NBI-heated discharges in the Globus-M spherical tokamak. Measurements of the spectral line shape of the radiation emitted by the hydrogen-like carbon ion $\text{C}VI$ ($5290.5 \text{ Å}$) are presented. Comparison of CXRS and Neutral Particle Analyser (NPA) data demonstrates good agreement.

1. Introduction

The temperature of the ion component is one of the key physical parameters of a high-temperature plasma. Data on the spatial distribution of the ion temperature are necessary for understanding and modeling of the particles and energy transport and for assessment the efficiency of plasma heating systems. Thus, the ion temperature diagnostic is one of the most important components of a diagnostic complex of modern device for magnetic confinement of plasmas [1-3].

Two methods of measuring the ion temperature are available on the Globus-M tokamak: Charge-eXchange Recombination Spectroscopy (CXRS) and Neutral Particle Analyzer (NPA) diagnostic [4]. The CXRS is based on the charge-exchange reaction of impurity nuclei on the neutral atoms of a diagnostic or heating beam, produced by the neutral beam injection (NBI). Hydrogen-like ions are generated when a beam of fast neutral hydrogen particles is injected into the plasma, that results in the recharge of residual nuclei on the beam particles. If the generated ion is in an excited state, a transfer to the ground state occurs through a cascade of transitions with the emission of the corresponding spectral lines. The most convenient is the use of transitions within the range of the visible light. The energy transfer time between hydrogen particles in the main plasma and residual ions is substantially smaller than the energy confinement time. Therefore, the temperature of the impurity ions, which is determined by the CXRS diagnostic, coincides with that of ions of the main plasma. The CXRS method allows to measure the local values of plasma temperature and to obtain the temperature profile using the multichord measurements.
2. Experimental setup
Measurements were performed on the Globus-M spherical tokamak with a major radius $R = 36$ cm and a minor radius $a = 24$ cm [5]. In the analyzed discharges the average value of the plasma density was $n \sim 3 \cdot 10^{13}$ cm$^{-3}$, the toroidal magnetic field $B_{\text{tor}} \sim 0.4$ T, plasma current $I_p \sim 115\text{-}200$ kA. Typical ion temperature in the ohmic discharges is 200 eV. The beam of neutral atoms was injected in the tangential direction and had a transverse dimension (level $e^{-1}$) about 3 cm $\times$ 10 cm. The beam energy was 23-28 keV, current, 22-28 A. There were two viewing chords: first chord intersects the NBI axis at $R = 40$ cm; the second, at $R = 45$ cm (figure 1).

Two 15 m long light optical fibers transferred the radiation from the installation room to the location of measuring equipment. After passing through a simple optical system, the light from both fibers is focused on the entrance slit of the spectrometer. The images were separated by height and did not overlap. A diffraction high-resolution spectrometer [6] operates on the principle, based on the double diffraction at grazing incidence of light on the grating. The device has the input and output lenses with a focal length of $F = 300$ mm, the grating 1800 grooves / mm, inverse linear dispersion of 1.5 Å / mm and relative aperture $F/7$, the working range of 4300 - 9000 Å. The spectrum was registered with the EMCCD camera «Andor iXon Ultra», having a high quantum efficiency (up to 90% at a wavelength of 5400 Å) and the low values of noise signal (at the level of units of electrons). The optical scheme is shown in figure 2.

![Experimental setup](image-url)
3. Processing method and the obtained results

To determine the values of the ion temperature the spectral line shape of the emission of a hydrogen-like carbon ion CVI (5290.5 Å) was registered in the discharges in the Globus-M tokamak with the NBI heating. To improve the signal/noise ratio, the raw experimental data for each moment of time were averaged in a series of discharges.

Each registered spectral line shape is an integral along the line of sight of each observation chord. Since plasma contains all kinds of ions for each kind of impurity, the radiation at the same wavelength enters the line of sight of the spectrometer from the edge of plasma. Accordingly, to determine the ion temperature from the measured spectra an approximation was used which assumes the spectrum to be a sum of the background (Bremsstrahlung radiation) and two Gaussians: a "passive" component of the signal coming from the plasma edge and an "active" charge exchange component caused by the neutral beam:

$$ F = F(a_k, \lambda) = \text{Backgr} + F_{\text{active}} + F_{\text{passive}} = $$

$$ \text{Backgr} + a_{\text{active}} \cdot \exp \left[ \frac{-m \cdot c^2}{2 \cdot T_{\text{active}}} \left( \frac{\lambda - V_{\text{active}}}{\lambda_0 c} \right)^2 \right] + a_{\text{passive}} \cdot \exp \left[ \frac{-m \cdot c^2}{2 \cdot T_{\text{passive}}} \left( \frac{\lambda - V_{\text{passive}}}{\lambda_0 c} \right)^2 \right], $$

where the values for 7 coefficients, namely $\text{Backgr}, a_{\text{active}}, T_{\text{active}}, V_{\text{active}}, a_{\text{passive}}, T_{\text{passive}}, V_{\text{passive}}$, were recovered using the Levenberg-Marquardt method for every spectrum.

The effect of the fine structure and Zeeman splitting leads to overestimated values of temperature from CXRS [7] by 15% for the central plasma and 30% for the edge under Globus-M conditions. In the present results this effect is taken into account.

Figure 3 shows the results of processing the spectra and comparing with the NPA data in one of the researched regimes. The CXRS exposure time was 5 ms, that of the NPA, 9 μs. The obtained values of the ion temperature are 250-370 eV. Given the fact that these diagnostics provide local temperatures at the points where $R = 32$ cm (NPA), $R = 40$ cm and $R = 45$ cm (CXRS), their results do not contradict each other, and the temporal variation of temperature are in a sufficiently good agreement.
Figure 3 Comparison of ion temperature values obtained with the CXRS and NPA (ACORD-12) diagnostics in a regime with the plasma electric current $I = 200 \, \text{kA}$.

Figure 4 Ion and electron temperature profiles in a regime with the plasma electric current $I = 200 \, \text{kA}$. Empty markers show the electron temperature, full markers, the ion temperature. Vertical arrows indicate the separatrix position.

Figure 4 shows the profile of the ion temperature compared to the profile of the electron temperature (obtained by the Thomson scattering diagnostics) at the same time instant. One can see that by the end of the discharge (at 178 ms) the values of ion and electron temperatures are almost equal, and the profiles have the same shape.

4. Conclusion
The measurements of the spectral line shape of the radiation emitted by the hydrogen-like carbon ion CVI (5290.5 Å) were performed in the discharges in the Globus-M tokamak with the NBI heating. Comparison of the obtained results for ion temperature from the CXRS and NPA diagnostics demonstrates a good agreement.

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