CXRS measurements of ion temperature profile in NBI shots of the Globus-M spherical tokamak.

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Abstract. Ion temperature is one of the most important parameters of high-temperature plasma. Information on the ion temperature spatial distribution is necessary for understanding and modelling of particle and energy transport processes, evaluating the effectiveness of plasma heating system operation.

Active spectroscopy also known as CXRS (Charge eXchange Recombination Spectroscopy) is a powerful diagnostic tool for measurements of local values of ion temperature, and is widely used in experiments with magnetic confinement of high-temperature plasma.

Active spectroscopy diagnostics on the Globus-M tokamak utilizes a tangentially injected heating beam of neutrals (hydrogen or deuterium atoms). The CXRS-system setup is described.

The results of ion temperature measurements for the last Globus-M experimental campaign before the machine shutdown and further upgrading to higher values of magnetic field and plasma current are presented. Ion temperature significant rise in the experiments with moderate increasing of toroidal magnetic field and plasma current is detected and discussed.

1. Introduction
The spherical tokamak provides a unique environment to perform complementary and exacting tests of the tokamak physics required for a burning plasma experiment, while also having the potential for long-term fusion applications [1-3]. The main goals of the experiments on the spherical tokamak Globus-M are investigations of plasma equilibrium, stability, fast particle confinement, particle and energy transport and investigation of noninductive current drive. [4,5].

The temperature of the ion component is one of the key physical parameters of high-temperature plasma. Data on the ion temperature spatial distribution are necessary for transport processes calculations of and evaluation of the plasma heating efficiency.

The most commonly used method [6-8] to measure the local values of ion temperature is the Charge eXchange Recombination Spectroscopy (CXRS) diagnostic. CXRS is based on the charge exchange process of light impurity nuclei (from Helium to Oxygen, mostly Carbon) on fast neutrals (hydrogen or deuterium atoms) of a diagnostic or heating beam. In the process, the neutral atom gives an electron to the plasma ion and hydrogen-like impurity ion in exited state (in general case) is formed. Its relaxation to the ground state goes down through a cascade of transitions with the emission of corresponding spectral lines in different wavelength ranges. These spectral lines are broadened due to motion of emitting ions and the Doppler effect. From handling the data of spectral line shape, one can get the information on the impurity ion temperature. In the tokamak plasma, the time of energy transfer between the impurity ions and the main plasma ions is much less than the energy confinement time. Thus, the impurity ion temperature and temperature of the main plasma ions can be considered...
equal. Consequently, the diagnostics allows one to obtain the ion temperature. The ion temperature spatial distribution could be obtained using multi-chord observation.

2. Experimental setup
Globus-M is a spherical tokamak with a major and minor radii $R=0.36$ m and $a=0.24$ m, aspect ratio $R/a=1.5$, discharge duration $\sim200$ ms [2]. Experiments with NBI (Neutral Beam Injection) heating with toroidal magnetic field $B_{\text{tor}}=0.4$ T and $B_{\text{tor}}=0.5$ T, with plasma current $I_p=180$ kA and $I_p=225$ kA respectively were carried out during last campaign, before the machine shutdown for further upgrade up to Globus-M2 [13]. A deuterium beam with an energy of 26 keV and power of 0.65 MW was injected [9] tangentially in co-current direction at the quasi-stationary stage of the discharge during 30 ms.

The CXRS diagnostics system consists of a specially developed optics with seven observation «chords» to collect the light signal, a set of 15m-long SMA-SMA silica fiber cables with numerical aperture NA=0.22 for the collected light transportation and high-resolution double-diffraction spectrometer «Spectraltech» SPT-DDHR-04 (operating range is 4300-8000 Å, dispersion $\approx1.5$ Å/mm, $F=300$mm, $F/7.5$). The spectrometer is equipped with an input fiber collector and the «Andor» iXon Ultra EMCCD camera as a detection system (image 512x512 pixels, pixel size 16x16 microns, quantum efficiency $>90\%$). The spectrometer was tuned to measure the carbon ion $\text{C}^{5+}$ emission line shape ($n=8\rightarrow7$, 5290.5 Å). The system time resolution was 5 ms, spectral accuracy $\approx0.024$ Å/pixel, the Full Width on Half Magnitude for instrument contour was $\approx0.3$ Å for 200 μm width of the spectrometer input slit.

Every observation «chord» indeed is an observation region and can be depicted approximately as a cone in the equatorial plane of the tokamak (Fig.1). Their axes were crossing the neutral beam axis at points with coordinates shown in the table:

| Chord number | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|--------------|---|---|---|---|---|---|---|
| $R$, mm      | 388 | 405 | 437 | 465 | 492 | 516 | 536 |

![Figure 1](image_url). Experimental setup. Numbered lines represent axes of every CXRS observation cones. The NBI beam axis and observation line of the Neutral Particle Analyzer ACORD-12 [10] are also shown.

In comparison with previous ion temperature measurements [11,12], the spatial range and resolution were significantly improved.
3. Data processing and results

Each of measured spectra represents an integral along the line of sight of observation chord. The total signal is a sum of the background (Bremsstrahlung radiation + dark signal of the detector), a “passive” component of the signal coming from the plasma periphery and an "active" charge exchange component caused by the neutral beam. In order to determine the ion temperature from the measured spectra an approximation was used which consists of a background constant and two Gaussian functions describing "passive" and "active" signals:

$$signal = a_{background} + a_{CXRS} \cdot \exp\left(-\frac{m_{\text{carbon}} c^2}{2T_{\text{CXRS}}} \left(\frac{\lambda}{\lambda_0} - 1 + \frac{V_{\text{CXRS}}}{c}\right)\right) + a_{periphery} \cdot \exp\left(-\frac{m_{\text{carbon}} c^2}{2T_{\text{periphery}}} \left(\frac{\lambda}{\lambda_0} - 1 + \frac{V_{\text{periphery}}}{c}\right)\right)$$

where $a_{background}, a_{CXRS}, T_{i \text{CXRS}}, V_{\text{CXRS}}, a_{periphery}, T_{i \text{periphery}}, V_{\text{periphery}}$ are the fitting parameters. Example of the fitted spectrum is shown in the Figure 2.

![Figure 2. Example of the measured spectrum and signal fitting.](image)

An example of CXRS and NPA data on the ion temperature measurements are shown in Fig.3 for two discharges with different values of toroidal magnetic field and plasma current: $B_{tor}=0.5 \text{ T}, I_p=225 \text{ kA}$ in shot 37067 and $B_{tor}=0.4 \text{ T}, I_p=180 \text{ kA}$ in shot 37069. Obviously, both diagnostics data are in a good agreement with each other.

![Figure 3. Left: ion temperature profiles $T_i(R)$ in shots 37067 and 37069 with $B_{tor}=0.5 \text{ T}, I_p=225 \text{ kA}$ and $B_{tor}=0.4 \text{ T}, I_p=180 \text{ kA}$ respectively. NPA data are also shown. Right: the same data but in the flux coordinates compartment $T_i(\rho)$.](image)
Moderate increasing of toroidal magnetic field and plasma current leads to significant (~50%) increase of the core ion temperature and notable profile peaking due to, perhaps, fast ions confinement improving [14].

4. Conclusion
Multi-chord CXRS measurements using CV1 (5290.5 Å) spectral line were performed in NBI shots of the Globus-M spherical tokamak with different values of the toroidal magnetic field and plasma current. NPA and CXRS diagnostics data on ion temperature exhibit a good agreement each with other. Ion temperature significant rising (~50%) and its profile sharpening were observed in experiments with moderate (~25%) toroidal magnetic field and plasma current increase. The most obvious reason is improvement of fast ion confinement and decreasing of fast particle losses.

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