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Measurements of plasma and neutral beam composition and impurity rotation using spectroscopy on TUMAN-3M tokamak

L.G. Askinazi, V.A. Kornev, S.V. Krikunov, S.V. Lebedev, A.I. Smirnov, A.S. Tukachinsky, M.I. Vildjunas, N.A. Zhubr

A.F. Ioffe Physico-Technical Institute, St.Petersburg, Russia

Experimental setup

Optical spectroscopy is widely used in fusion experiments to control plasma impurity and isotopic content, to investigate plasma rotation and in a lot of other applications. The main aims of the presented studies were: comparison of impurity influx in plasma in different modes of TUMAN-3M operation, determination of the neutral beam composition and estimation of plasma rotation velocities by Doppler shift of impurity spectra.

The studies were performed with the following plasma parameters: R_0=0.53 m; a_l=0.22 m; B_T=0.7–0.9 T; I_p=130–150 kA; $q^{cyl}\geq 2.5$; $\langle n_e\rangle=(1.2 - 4.0)\cdot 10^{19}$ m^{-3}; $T_e(0)$=0.35 – 0.6 keV; $T_i(0)$=0.12 – 0.35 keV, working gas - deuterium. Walls of the vacuum vessel are boronized to diminish high-Z impurities influx to plasma. The NBI parameters were as follows: E_0 = 18 -24 keV; P < 450 kW; duration of the injection pulse < 28 ms; the direction of injection: tangential; working gas - deuterium.

TUMAN-3M is equipped with standard multi-channel spectrometer AVANTES® - 2048, having one wide-range channel (260 - 810 nm) with relatively low spectral resolution (FWHM=1 nm) and three high dispersion channels (FWHM = 0.1 nm, resolution: 0.04 nm/pixel), adjusted for measurements in different spectral ranges. The wide range channel of the spectrometer is used as a monitor diagnostic tool for impurity control. The light from plasma volume is collected by collimating lenses (D = 6 mm, F = 8.7 mm) and then is transmitted to the spectrometer by optical fibers. Two different lines of sight were used in the described experiment. The first was nearly parallel to injection direction and crosses the injected beam under angle of about 6º. The second was oriented along the tokamak major radius in the middle plane the way it do not cross the neutral beam. Hereinafter, the first case is called “tangential” direction of observation, and the second – “radial” direction.

Impurity behavior in NBI experiments

One of the aims of the study was to compare impurity influx under co- and counter-NBI with Ohmic regime. It was found that B, C, O, are the principal impurities in TUMAN-3M plasma. As individual line intensity $I \sim n_e n_{imp} \langle\sigma v\rangle$ the discharges with similar $\langle n\rangle$ were analyzed in order to compare impurity influx by intensity of spectral lines. Plasma emission spectra for counter-NBI in comparison with Ohmic H-mode [1] are presented in Fig.1. An increase in all the impurity lines intensity (BIV – up to twice) is observed during counter-NBI. Evolution of some plasma parameters for these discharges is presented in Fig 2. Loop voltage U_p is typically increased during NBI which correlates with a rise in emission of the principal impurities (B, C). In co-injection discharges the impurity radiation increase in comparison with Ohmic discharges is less pronounced if at all.

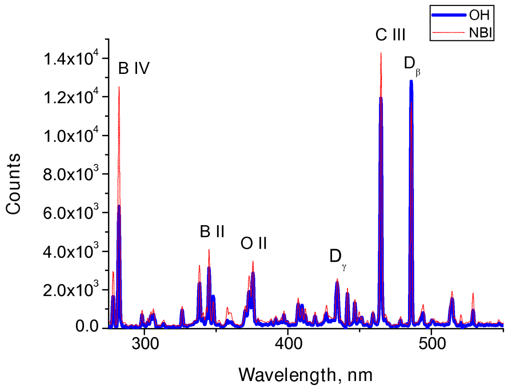

Fig.1 Plasma emission spectra in Ohmic H-mode in comparison with counter-NBI regime

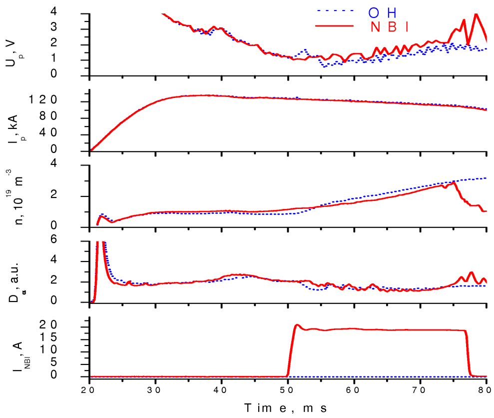

Fig.2 Evolution of loop voltage U_p, plasma current I_p, average density n, D_α intensity and NBI emission current I_{NBI} in Ohmic H-mode (dotted) in comparison with counter-NBI regime (solid)

Noteworthy, in the discharges with co-NBI when no impurity emission increase was detected, no increase in loop voltage was observed as well. The correlation between U_p and impurity emission lets to conclude that impurity ions radiation displays the impurity influx in the discharges with similar plasma parameters (density, T_e, confined mode). The most possible reason for increase in impurity influx during NBI is an interaction of lost fast particles with walls of the vacuum vessel. Then, spectroscopy indicates that counter- NBI results in intensive losses of fast ions in comparison with co-NBI. Hence, the efficiency of the NBI heating in TUMAN-3M should be better for co-NBI, which is confirmed by comparison of ion temperature measurements in these two regimes [2].

Neutral beam composition measurements

Spectroscopy was used to study the neutral beam composition by Doppler shift of deuterium Balmer-α lines using a high resolution channel of the spectrometer. In the experiment the neutral beam was injected in gas (deuterium) target. Collisions of the beam particles with the target result in the colliding atoms excitation and emission of corresponding spectral lines. If line of sight is oriented along the NBI direction then the spectral lines of the beam particles are Doppler shifted and the shift determines the particle kinetic energy. A typical spectrum of the D_α line in the experiment where NB was injected in deuterium target is presented in Fig. 3. Each spike in the spectrogram originates from either simple ion of deuterium $(D)^+$ (or hydrogen $(H)^+$) or from molecular ions (say, $(D_2)^+$, $((D_3)^+$, $(D_2O)^+$) accelerated in the ion gun of the injector. Dissipation of the complex ions in the charge exchange volume of the injector results in presence of deuterium (hydrogen) atoms with different velocities in the beam. The kinetic energies of main composites of the beam and corresponding originating ions are shown in Fig.3. Assuming the spectral line intensities are proportional to concentration of corresponding particles, the neutral beam composition is: $D^0(E):D^0(E/2):D^0(E/3):D^0(E/10):H^0(E)$ = 54: 27:4:11:4. Thus, the full-energy component can be roughly estimated as only 50-60% of total amount of neutrals in the beam. It was also found up to 7% of hydrogen in the neutral beam though deuterium was used both as the target and as the working gas in the injector. The hydrogen admixture may be explained by H accumulation in the injector during previous experiments.

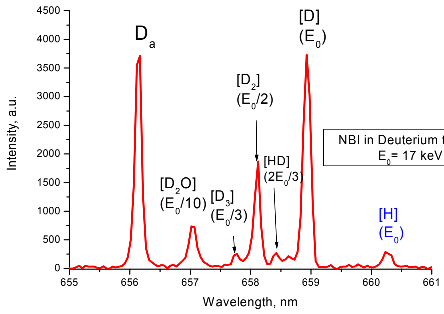

Fig. 3 Deuterium D_α emission spectra measured in tangential direction when NB is injected in gas (deuterium) target.

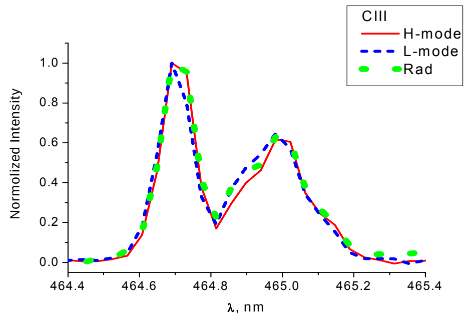

Fig.4 C III spectra in Ohmic H- and L-modes measured in toroidal direction in comparison with reference (non shifted) spectrum measured along the major radius (Rad)

Measurements of toroidal rotation of impurities

Toroidal rotation velocity V_φ of impurity ions was derived from the Doppler shift of the spectral lines (C III and B IV) measured with the high resolution channels of AVANTES spectrometer with 0.04 nm/pixel resolution. At given pixel resolution only 2 - 3 pixels corresponds to FWHM of the spectrometer for the minimal available entrance slit. Thus a small Doppler shift (less than FWHM) will be displayed not as a shift of the maximum of the spectrum but as a redistribution of the signal intensities in the pixels within the line under investigation. Then, a small Doppler shift detection is possible only if signal to noise ratio is high enough to distinguish between the noise and the signal redistribution in the spectrum. In the described experiments long light accumulation time (15 ms) was chosen to increase signal to noise ratio up to S/N~50. Spectrograms measured in toroidal direction of observation were compared with reference ones measured in the “radial” direction.

The spectral lines chosen (C III and B IV) were emitted from the peripheral region of the TUMAN-3M plasma (r > 0.8a). The measurements were performed in Ohmic L- and H-modes and in NBI heated shots. It was found, that in ohmic H-modes (with or without counter-NBI injection) the shift of C III and B IV lines is negligible in comparison with the reference radial channel. In Ohmic L-mode a detectable shift of C III (~0.07Å) and B IV (~0.09Å) lines was observed. The spectrograms of CIII line measured in Ohmic H- and L-modes along the toroidal direction in comparison with the reference spectrum are presented in Fig. 4. Noteworthy, the spectrograms presented in the graph are repeatable from shot to shot. The results of the velocity estimation by $V=c\cdot\Delta\lambda/\lambda_0$ are presented in Fig. 5. The wavelength shift Δλ was simulated by approximation of the measured C III (464,7nm) spectral contour with Gaussian function. Taking into account the angle between line of sight and magnetic surfaces at the periphery where C III line irradiates the value of V_φ in L-mode is about 7 – 8 km/s. The V_φ value estimated by B IV line Doppler shift is about 9 – 11 km/s.

In terms of radial electric field evolution, this means that, provided that pressure gradient influence on the rotation is neglected, a positive radial electric field E_r should exist in Ohmic L-mode in the region of C III ion emission resulting in $E_r \times B_\theta$ rotation. This electric field changes to approx. zero after the Ohmic H-mode transition. This result may be better understood when compared with peripheral radial electric measurement performed earlier with Langmuire probes. Figure 6 shows the floating potential profiles measured before and after the Ohmic H-mode transition. It is seen that indeed, in the closest vicinity of the limiter, before the transition E_r=grad(Φ_{float})~3kV/m, then, in Ohmic H-mode phase the radial electric field is close to zero E_r=grad(Φ_{float})~0.

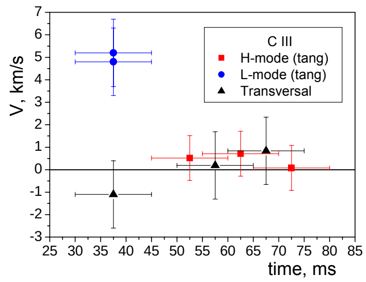

Fig.5. Estimations of toroidal rotation velocity of carbon ion C^{2+} in Ohmic L- and H-modes

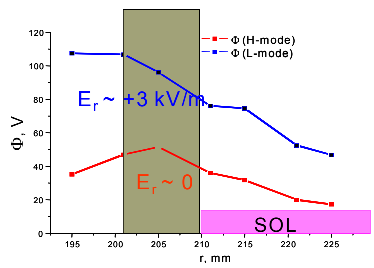

Fig. 6 Floating potential profiles measured in Ohmic L- and H-modes with Langmuire probes

Summary

An increase of C and B impurities emission was found in the TUMAN-3M during NBI which is in agreement with loop voltage increase and is likely caused by interaction of lost fast particles with vessel walls. Spectroscopy data confirmed that fast particles confinement was better in co-NBI discharges in comparison with counter-NBI. Full-energy component of the injected beam was found to be about 50-60% of total amount of neutrals. In Ohmic L-mode the Doppler shifts of C III and B IV lines corresponding to velocities of toroidal rotation V_φ ~10 km/s and to positive E_r was detected.

Acknowledgements

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References

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[2] L.G. Askinazi, et al, P1-146, this Conference