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Observation of the toroidal plasma rotation during injection of a high energy atomic beam and L−H-transition in the TUMAN-3M tokamak

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The toroidal rotation velocity in the TUMAN-3M tokamak peripheral plasma was measured in the regime of high energy atomic beam injection directed along the plasma current and in the ohmic H-mode regime. It was found out that time evolution and steadystate velocity of the peripheral toroidal rotation directed against the injection and plasma current are the same in both scenarios. The observed toroidal rotation is associated with generation, during the L−H-transition, of a peripheral negative (directed towards the plasma center) radial electric field.

Keywords: plasma, tokamak, plasma rotation, radial electric field, L−H-transition.

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The high energy atomic beam injection (neutral beam injection, NBI) is one of the main techniques for additional heating of plasma in installations with magnetic confinement of hot dense plasma whose parameters are close to those necessary for the controlled thermonuclear fusion. An especial role is played by the rotation occurring in plasma under the influence of NBI and by the radial electric field associated with it. The radial electric field plays an important role in initiating switchover between the confinement modes in toroidal setups. Studies of this type have been conducted on various tokamaks and stellarators for many years [1,2], however, mechanisms for generating plasma rotation and radial electric field have not yet been fully elucidated. Mechanisms responsible for the plasma rotation generation are numerous (direct momentum transfer, radial currents of non-confined particles, artificially created electric fields, etc.); they manifest themselves differently in different spatial regions of plasma and in different experimental geometries, e.g. with co- and counterinjection [3].

This paper presents the results of measuring the toroidal plasma rotation velocity in the TUMAN-3M tokamak during the neutral beam co-injection; estimation of the radial electric field generated in this case is also given.

The experiments were carried out on the TUMAN-3M tokamak (R=0.3 m, a=0.23 m, $T_e(0) = 400(\mathrm{L})-700(\mathrm{H})$ eV, $\langle n_e\rangle = 1.5\cdot 10^{19}(\mathrm{L})-4\cdot 10^{19}(\mathrm{H})\,\mathrm{m}^{-3}$, $I_p = 123-150$ kA, $B_t = 0.7-1$ T, neutral beam energy $W_b \sim 18-20$ keV, injection power $P_b \geq 150$ kW, letters L and H mark the quantities that are different in the L- and H-modes). In some discharges, the L−H-transition was initiated prior to the NBI pulse. The hydrogen beam was injected along the plasma current with the impact parameter of 0.42 m. The toroidal rotation was measured by the Doppler shift of doublet spectral lines of singly ionized carbon (C^+) CII (657.8 and 658.3 nm) with the ionization potential of 11.26 eV. The main goal of these experiments was to check the possibility of implementing the FIDA (Fast Ion D-alpha) diagnostics for studying the fast ions (FI) distribution function [4]; observation of Doppler shifts in the carbon line spectrum appeared to be an additional diagnostic capability. Generally speaking, the impurity rotation velocity is not expected to coincide with the main ion rotation velocity; however, this method is often used both to measure the rotation velocity and to determine the magnitude and spatial distribution of the radial electric field [5]. The measurement scheme is presented in Fig. 1, *a*. It includes monochromator MDR-2 with CCD-camera HS103H [6] installed in place of exit slit, optical fiber, lens, and a mirror installed inside the tokamak chamber to ensure the required direction of the observation line. This direction makes the angle of 61° with the direction of neutral beam injection.

Time dependences of the main signals are shown in Fig. 1, *b*. In this discharge, the hydrogen neutral beam was injected into hydrogen plasma in the time interval $t = 60-84$ ms. At the moment of $t = 49.5$ ms (i.e. about 10 ms prior to the start of the neutral injection pulse), the ohmic L−H-transition was initiated in plasma by a short (5 ms) gas puffing pulse in order to increase the plasma density during neutral injection. Fig. 2 presents the unprocessed emission spectra of the CII line doublet in discharge 22041927. One can clearly see nonmonotonic variations in the CII doublet line positions from frame to frame during the transition from the ohmic discharge phase (frames 2 and 3) to the ohmic H-mode (frame 4) and then to the NBI phase (frames 5 and 6). The line centers shift is small as compared to the contour width, but may be reliably determined by using the Gaussian fitting. Fig. 3, *a* demonstrates the results of this processing. Positions of centers of the CII doublet lines in frames 2 and 3 are almost identical and were taken as the starting point of

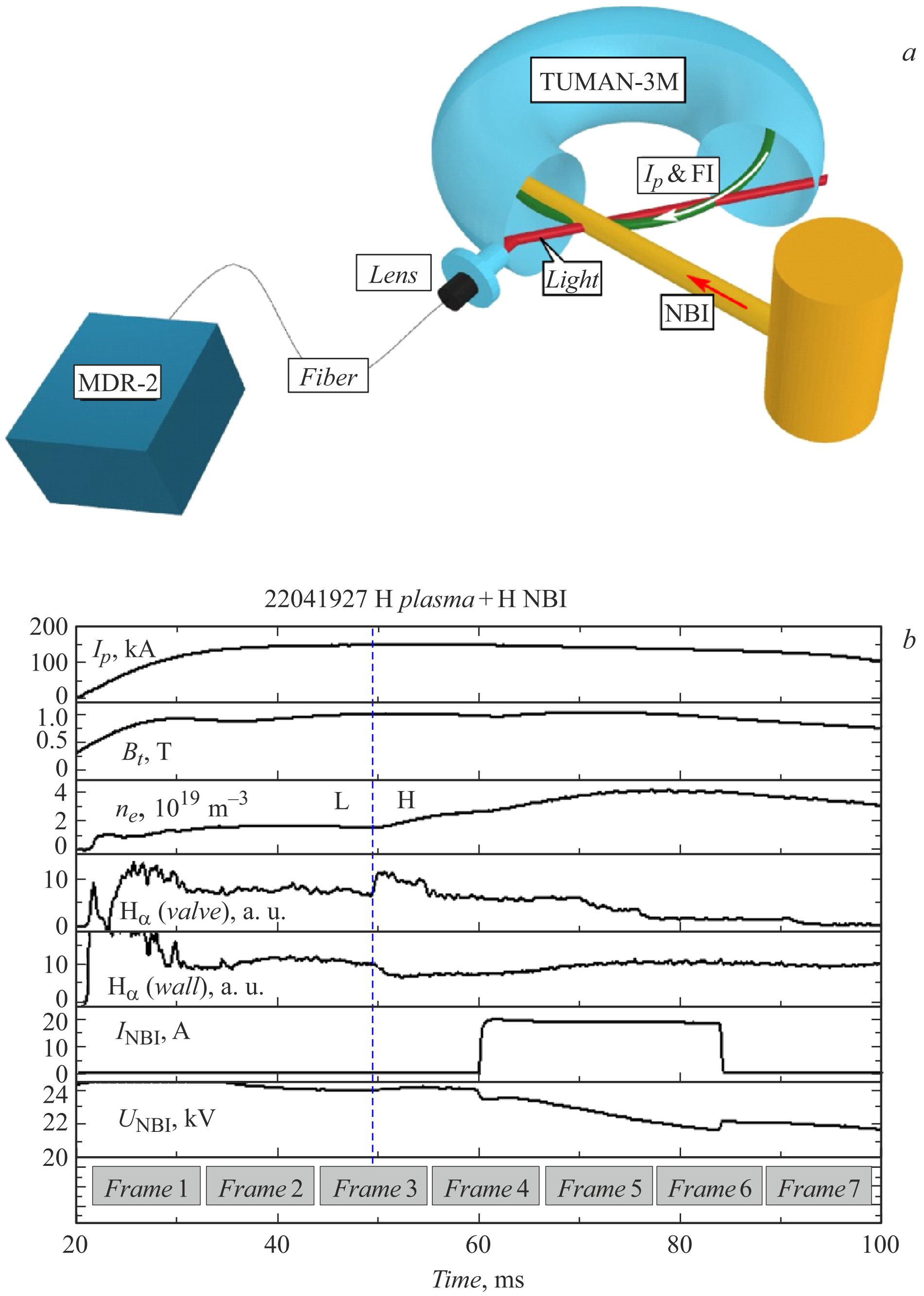

Figure 1. *a* — optical measurement system; *b* — time evolution of the discharge parameters. Top-to-bottom: plasma current, toroidal magnetic field, meanchord central density, H_α line emission near the gas puffing valve and near the wall, NBI pulse, CCD-camera frames. NBI energy is $W_b \sim 22$ keV, beam current is 19 kA.

spectral shifts since in this phase of discharge there are no supposed external sources of plasma rotational momentum, and velocity of the possible intrinsic plasma rotation (the so-called intrinsic toroidal rotation) is very low [1]. Frame 4 demonstrates a shortwave shift by $\Delta\lambda = 0.03$ nm; in frames 5 and 6, this shift changes to the shifts towards long waves by $\Delta\lambda = 0.03$ and 0.02 nm, respectively. In these experiments, a nonoptimal choice of the synchronization modes of CCD-camera and tokamak acquisition system made the L–H-transition occurring approximately in the middle of frame 3, while the NBI pulse started approximately in the middle of frame 4. Therefore, the observed evolution of spectral shifts and toroidal rotation velocity from the purely ohmic mode to ohmic H-mode and then to the NBI mode looks somewhat distorted. Nevertheless, we may state that, while the additional gas puffing pulse initiating the L–H-transition in the interval $t = 49-55$ ms is active, there is observed an increase in the toroidal rotation velocity

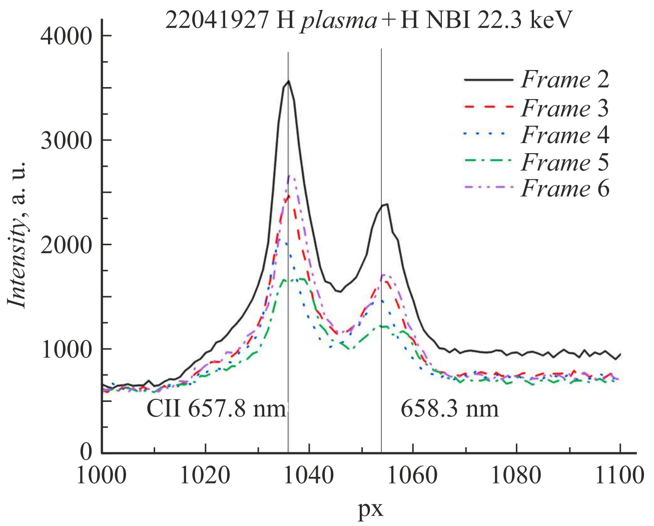

Figure 2. Emission spectrum of the CII doublet line (657.8 and 658.3 nm) in discharge 22041927 with NBI and L–H-transition. Vertical lines mark the positions of the nonshifted doublet components.

along plasma current; after time moment $t = 65$ ms (when turning from frame 4 to frame 5), rotation velocity changes its direction to the opposite one. An estimate of the toroidal rotation velocity projection onto the observation line yields a value of -12.5 km/s in frame 4 (sign „minus" corresponds to rotation towards the observation receiver, i. e., along the plasma current and in the direction of neutral beam injection, see Fig. 1). In frames 5 and 6, the toroidal rotation velocity is directed against the plasma current and injection; its projection onto the observation line is 13.2 and 8.5 km/s, respectively.

Let us discuss the physical effects that may be in charge of the observed evolution of the CII line spectra. First of all, it is important to elucidate spatial localization of the region from which the CII line radiation is received, as well as excitation process giving rise to that radiation. Since the intensive radiation of the CII doublet (657.8 and 658.3 nm) is recorded in the ohmic phase of the discharge, this radiation cannot be associated in frames 2 and 3 with the C^{2+} ion charge exchange on beam atoms in the absence of the NBI. Ionization potential of the neutral carbon ion with formation of the C^{+} ion is 11.26 eV. This means that this ion exists predominantly at the periphery of the tokamak plasma (where $T_e \sim 20$ eV as per the Thomson diagnostics). Estimation performed taking into account the dependence of the atomic carbon ionization rate on the electron density and temperature allowed us to assert that the C^{+} ion exists at a depth of up to 3–5 cm from the plasma boundary. Thus, the most probable is the C^{+} ion excitation by an electron impact at the plasma column periphery where the angle between the ion toroidal velocity direction and observation line is approximately 45°. If this is taken into account, toroidal rotation velocities in frames 4, 5 and 6 are -17.6, 18.6 and 12 km/s, respectively. Fig. 3, *b* shows the measurements of toroidal rotation in the purely ohmic discharge 22041921 (without injection but with the L–H-transition). This figure also demonstrates the results of measuring the shift of CII line 657.8 nm in discharge 22052506 without of the L–H-transition (triangles). As the figure shows, the carbon line shift in this discharge is negligible. This fact also allows us to conclude that the observed shifts are free of noticeable acoustic or electromagnetic interference on the measuring devices.

As the comparison illustrated in Figs. 3, *a* and *b* has shown, the toroidal rotation velocity evolution is almost the same in the two scenarios, with the neutral beam injection and without it. This allows us to assert that the observed rotation is not associated with the presence of a fast ion beam and its interaction with plasma, but stems from other effects. On the other hand, the L–H-transition took place in both the considered discharges at $t = 50$ ms, i. e. approximately in the middle of frame 3. It is reasonable to assume that it is the L–H-transition that is the source of the observed evolution of the toroidal rotation velocity. In the TUMAN-3M tokamak, the ohmic transition is initiated by a short additional gas puffing pulse which is clearly identifiable by enhancement of the H_α line emission near the gas-injection valve (Fig. 1, *b*, signal $H_\alpha(valve)$, $t = 49$–55 ms) and is accompanied by a remarkable short-term disturbance of the peripheral plasma. The source of such an effect of the pulsed gas puffing on the peripheral toroidal rotation has not been elucidated yet. Known are studies where a strong jumpwise perturbation of the toroidal rotation velocity was observed along with the density increase [7,8]. On the other hand, an increase in the peripheral neutral density should, on the contrary, promote the rotation damping [1]. After the completion of the L–H-transition (and after the completion of the gas puffing pulse stimulating it, see frames 5 and 6 in Figs. 3, *a* and *b*), namely, in the self-sustaining H-mode (which is purely ohmic in discharge 22041921), the toroidal rotation velocity amounts to about $V_t \sim 18$ km/s in the opposite direction, i. e. against the plasma current. Previously [9], no considerable toroidal rotation was registered in the ohmic H-mode in measuring the shift of the boron BIV line spectrum; this may be due to the fact that this ion possesses a higher ionization potential (259.37 eV) and, hence, radiates from another, deeper plasma region. The toroidal rotation contribution to the radial electric field formation may be estimated as $E_r = -V_t B_p = -1.6$ kV/m (here B_p is the poloidal field). This estimate is significantly lower in absolute value than that measured earlier in the ohmic H-mode by using the Langmuir probes: $E_r = -3$ kV/m [10]; this may be explained both by that this estimate ignores contribution from the neoclassical electric field and also by that the probe measurements are well localized radially, while the above estimate for the toroidal rotation velocity is averaged over a certain spatial region near the plasma periphery. More accurate determination of E_r needs better spatial resolution of measurements of the toroidal and poloidal rotation velocities and numerical simulation.

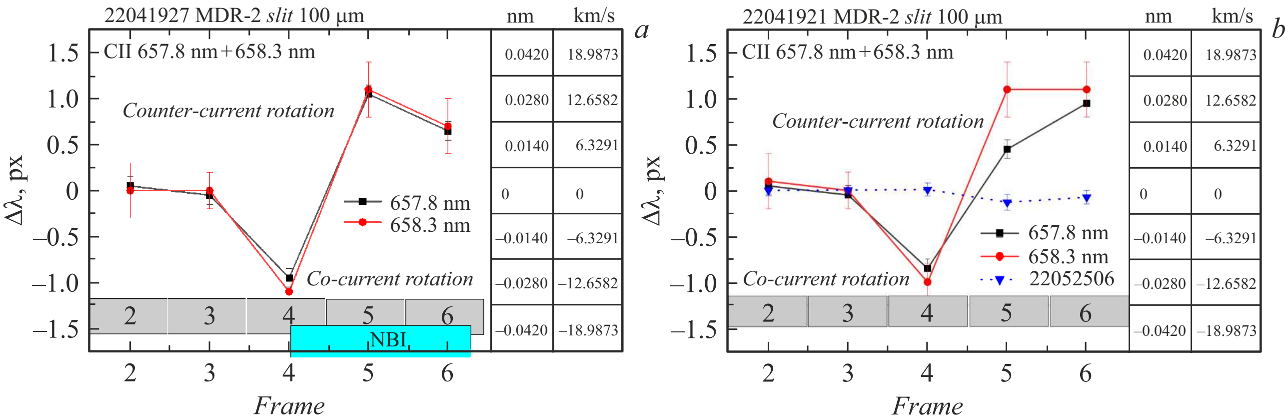

Figure 3. Time evolution of the spectral shift of CII doublet lines: *a* — in discharge 22041927 with NBI and L–H-transition (circles and squares), *b* — in discharge 22041921 with the L–H-transition but without NBI (circles and squares) and in discharge 22052506 with NBI but without the L–H-transition (triangles).

Thus, investigation performed in the NBI mode under consideration ($W_b \sim 22$ keV, o-injection, H → H or D) showed no influence of injection on the electric field and toroidal rotation. The main contribution to the generated E_r and V_t is made by the transition to the H-mode.

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Conflict of interests

The authors declare that they have no conflict of interests.

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