MEASUREMENTS OF TOROIDAL ROTATION IN TUMAN-3M TOKAMAK IN NBI AND H-MODE REGIMES

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Abstract

The velocity of the toroidal rotation in the peripheral plasma in the TUMAN-3M tokamak was measured in two scenarios: co-current NBI H-mode and in ohmic H-mode using Doppler-shifted CII impurity line. It was found that the time evolutions and steady-state velocity values of the toroidal rotation velocity at the periphery are very similar in both cases, indicating that the effect of the L-H transition prevails over the direct influence of the beam injection. The observed toroidal rotation is associated with the generation of negative radial electric field at the periphery during the L-H transition.

1. MOTIVATION

In this paper we present first results of toroidal rotation studies in the tokamak TUMAN-3M [1] performed in co-current NBI regime with L-H transition and in a pure ohmic H-mode as well. The main goal was to identify the main processes responsible for plasma rotation and radial electric field formation, such as direct beam-plasma momentum transfer, fast ion losses or H-mode influence

Neutral Beam Injection (NBI) is one of the main methods of auxiliary plasma heating in magnetic confinement fusion devises. Together with energy transfer from beam to the plasma, NBI also leads to the mechanical momentum and radial electric field generation in plasma. The radial electric field plays an important role in turbulence and anomalous transport suppression. It is known to be a trigger for the confinement mode switching toroidal devices. Such studies have been conducted on various tokamaks and stellarators for many years [2, 3], but the mechanisms for generating plasma rotation and radial electric field have not yet been fully elucidated. The mechanisms responsible for affecting plasma rotation profile are numerous (direct momentum transfer, radial currents of uncontained particles, artificially created electric fields, plasma viscosity etc.) and manifest themselves differently in different spatial regions of the plasma and with different experimental geometries, in particular, with co- and counter-injection [4]. In addition, intrinsic generation of plasma rotation was also identified [2], even in the absence of external source of mechanical momentum or electric field.

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2. EXERIMENTAL LAYOUT

The experiments were carried out on the TUMAN-3M tokamak (R = 0.53 m, a = 0.23 m, $T_e(0)$ = 400(L) – 700(H) eV, $<n_e>$ = 1.5(L) – 4(H) 1019 m-3, I_p = 123-150 kA, B_t = 0.7 – 1 T, NBI energy W_b ~ 18 – 20 keV, NBI power Pb ≥ 150 kW, the symbols L and H indicate the values that are different in the L- and H-modes). In some discharges, the L-H transition was initiated before the NBI pulse. Hydrogen NBI was performed in co-current direction with tangency radius of 0.42m. Time evolution of some plasma parameters are shown in Fig.1. In this scenario the neutral beam was injected with ~10 delay after the ohmic L-H transition initiated at t=50ms in order to provide a higher plasma density – up to 3-4 $10^{13}m^{-3}$ – during the injection. The toroidal rotation measurements were performed using the Doppler-shifted spectral lines of the singly ionized carbon (C+) CII doublet (657.8 nm and 658.3 nm) with an ionization potential of 11.26 eV. Experimental layout is schematically shown in Fig.2. The main goal of these experiments was to investigate the possibility of implementing the FIDA (Fast Ion D-alpha) diagnostics to study the fast ion distribution function [5], and observing the Doppler shifts in the CII lines was an additional diagnostic opportunity. Generally speaking, the impurity rotation velocity does not necessarily equal to the rotation velocity of the main ion, but this method is often used both to measure the rotation velocity and to determine the magnitude and spatial distribution of the radial electric field [6]. The experimental layout included an MDR-2 monochromator with an HS103H CCD camera [7] installed in place of the exit slit; this setup has inverse linear dispersion 1/D = 0.028 nm/pix. An optical fiber was used to connect the observation port with the monochromator placed in a control room of the tokamak for elimination of the acoustic and electromagnetic interference. The fiber was equipped with an appropriate lens to collect light from the desired plasma volume, and a mirror installed inside the tokamak vessel to provide the required direction of the observation line. The latter was directed towards the beam and formed an angle of 61° with it. Fig. 1 shows some plasma parameters together with Doppler-shifted CII 658.3 nm line relative position as a function of time in a shot with NBI pulse in an interval t = 60 - 84 ms. Temporal behaviour of the two lines was nearly identical, so only 658.3 nm line evolution is shown in Fig.1.

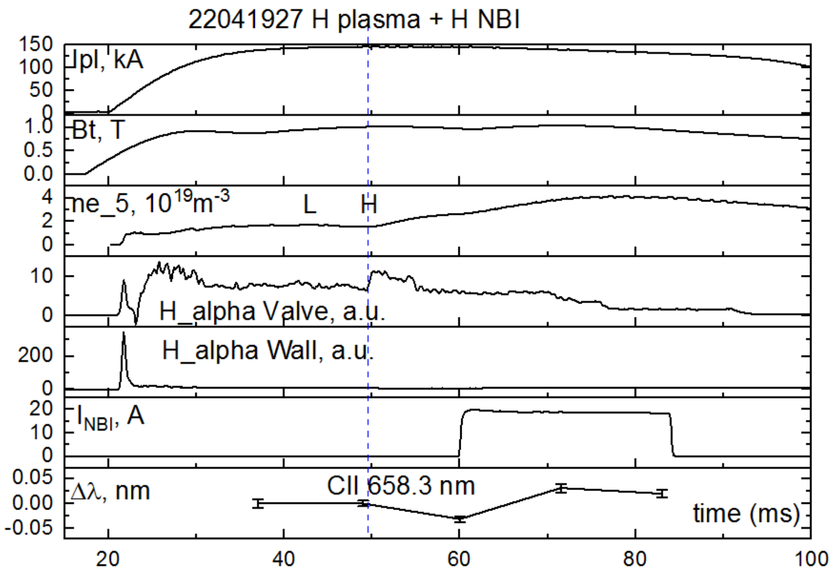

FIG.1. From top to bottom: plasma current, toroidal magnetic field, central chord-averaged density, H_α emission near the gas valve and near the wall, NBI pulse current, relative shift of CII line measured in five 11.4 ms frames (points in the center of each window are connected by a line for visibility). Points corresponding to the frames 2,3,4,5 and 6 are shown.

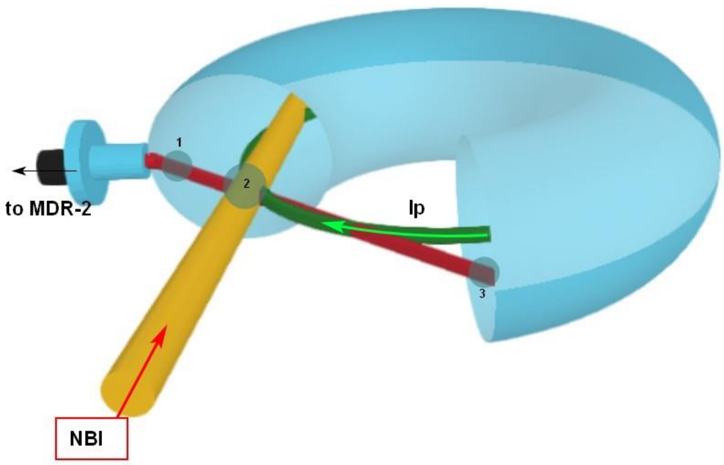

FIG.2. Experimental setup of Doppler spectroscopy on the TUMAN-3M tokamak. The direction of NBI and plasma current is indicated by red and green arrow, respectively. Dark red region shows the sample volume of plasma observed by the spectroscopy diagnostic through the lens and in-vessel mirror (not shown in the figure.

At time t = 49.5 ms (i.e. approximately 10 ms before the start of the neutral injection pulse), the ohmic L-H transition was initiated in the plasma by a short (5 ms duration) gas puffing pulse to increase the plasma density during atomic injection. Spectra of CII lines were time-averaged over 11.4ms frames; there were 10 frames registered during the plasma shot. Points shown in Fig.1 corresponds to frames 2 to 6. Measurements were also performed in shot 22052506 with similar NBI but without the ohmic L-H transition, hence lower density during NBI pulse. This scenario was used as a reference to separate the influence on rotation from the NBI and the L-H transition.

Electron density radial profile was reconstructed from a chord-averaged profile measured using 10-chanel microwave interferometer with the account of possible refraction of microwave radiation. The result of reconstruction is shown in Fig.3a in several characteristic time slices: in ohmic L-mode before the L-H transition, after the transition but before the NBI, during the NBI pulse, and after it.

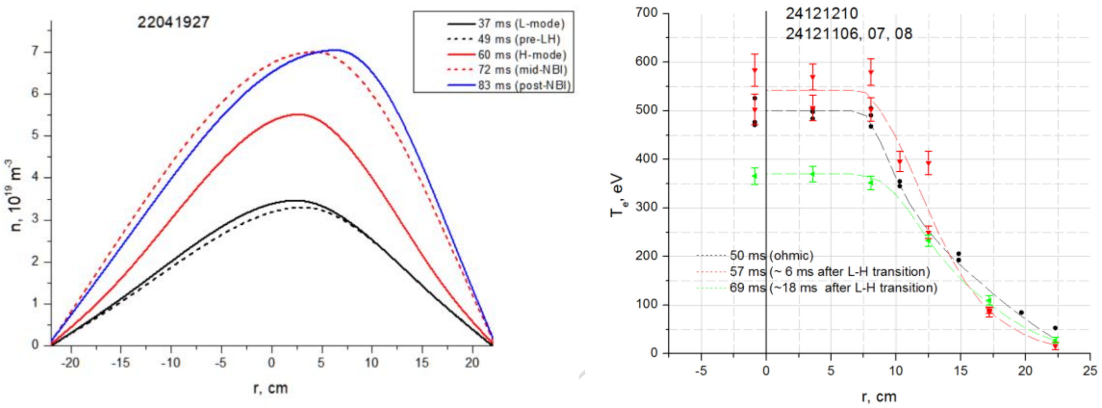

FIG.3.(a) Electron density profile evolution reconstructed from the microwave interferometry data in the shot 22041927 with ohmic L-H transition and NBI heating; (b) electron temperature profile measured by TS along vertical chord in ohmic discharges otherwise similar to 22041927

Note the pronounced Shafranov shift due to the plasma pressure increase after the L-H transition. The electron temperature profiles were not measured in the experimental session, so we use the profiles measured in similar shots by Thomson scattering diagnostic [8] in 2024 and shown in Fig.3b. The electron temperature profile was measured in a single time moment per plasma shot in three spatial location along the vertical chord, so Shafranov shift should not affect the result of the measurements.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The intensity of CII lines was found to be similar in the shots with and without the atomic beam injection. It means the CII emission was not a result of charge-exchange process double ionized carbon ions and fast hydrogen beam atoms $C^{2+} + H \rightarrow C^{*+} + p$ (in the region 2 in Fig. 1), but was rather produced by another processes, predominantly by electron impact excitation of neutral carbon near the edge (in regions 1 and 3). As for spectral shift, it was found to be small as compared to the FWHM of the spectral lines, however it was still measureable, see Fig.4.

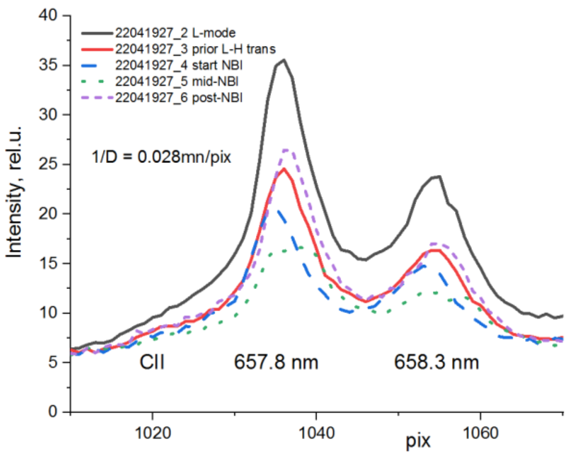

Fig.4. Spectral contours of the CII doublet (657.8nm and 658.3 nm) measured in 5 consecutive frames indicated in Fig.1. Line broadening is due to the instrumental counter (2.3 pix, 0.065 nm) and plasma Doppler broadening.

To quantitatively characterize the spectral shift of the CII lines, measured line contours were fitted by the Gaussians. Results of the fitting is presented in Fig.5. Figure 5 shows a comparison of CII line spectral shifts obtained in 3 typical scenarios of TUMAN-3M: NBI plus ohmic H-mode (a), pure ohmic H-mode (shot 22041921) and NBI without the L-H transition (shot 22052506) (b).

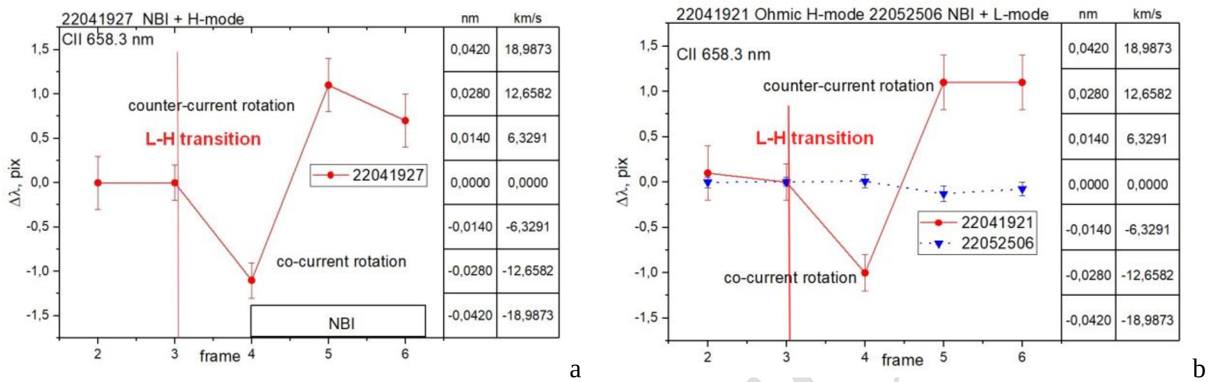

Fig.5. *Temporal evolution of Doppler-shifted CII 658.3 nm line in NBI plus H-mode shot (a) and in ohmic H-mode and NBI plus L-mode shots (b). Tables to the right show spectral shift in nm and toroidal rotation velocity corresponding to the spectral shift in CCD camera pixels shown on the left vertical axis. Note that here a negative velocity means co-current direction. Vertical red line marks the L-H transition.*

Spectral line positions before the L-H transition (frames 2 and 3) were taken as a reference, as there were no measurements along the radial line of sight that would have provided an unshifted spectral line. As it seen, in both shots 22041927 (Fig.4a) and 22041921 (Fig.4b, red line), after the L-H transition plasma starts to rotate in co-current direction (frame 4), increase in the toroidal velocity is up to 12.6km/s. Later on, as NBI is applied in the shot 22041927, toroidal rotation velocity reverses (frames 5 and 6) and reaches approximately the same value but is directed counter-current (and counter-NBI). This may be an indication of a complicated interplay of different processes that govern the plasma rotation under the influence of L-H transition and NBI heating, as discussed below.

On the other hand, in the shot 22052506 with NBI but without the L-H transition (see blue line in Fig.4.b) the toroidal rotation velocity remains close to zero all through the shot. Technically, the absence of significant variation of the spectral shift in shot 22052506 indicates the low level of acoustic and electromagnetic interferences in the current setup.

4. RESULTS AND DISCUSSION

First, it is necessary to discuss the location of the region in which the toroidal rotation was measured in the experimental setup described above. It was already mentioned that that could be only a peripheral region near the plasma wall, where CII line might be excited by electron impact (regions 1 and 3 in Fig.2) rather than the region 2 where charge-exchange process with atomic beam may produce C^{+*} ions from C^{2+}. To quantitatively characterize the localization of the C^+ ions at the plasma periphery, a simple modelling of diffusive-convective transport of C^+ ions in 1D cylindrical geometry was performed, taking into account C^+ ion source from electron impact ionization of neutral carbon deposited from the wall, and sink due to ionisation from C^+ to C^{2+} and C^{3+}. Diffusion constant and convective velocity was taken to be 3m^2/s and -10m/s, respectively. Data on carbon ionization cross-sections were found in [9]. Electron density and temperature profiles were taken as shown in Fig.3; electron density profile was symmetrized to be used in 1D calculations. The calculated radial profiles of C^+ ions density is presented in Fig.5. As might be expected, concentration of C+ ion reaches its maximum at the very edge of the plasma, approx. 1.5-2 cm inside LCFS. The location of the maximum varies slightly when plasma density and electron temperature profiles change due to the L-H transition, but remains in close proximity to the plasma edge. As a result, line of sight of the spectrometry diagnostic forms the angle of ~45°

with the toroidal rotation velocity in this region; this angle was taken into account when calculating toroidal rotation velocities from spectral shift in fig.4.

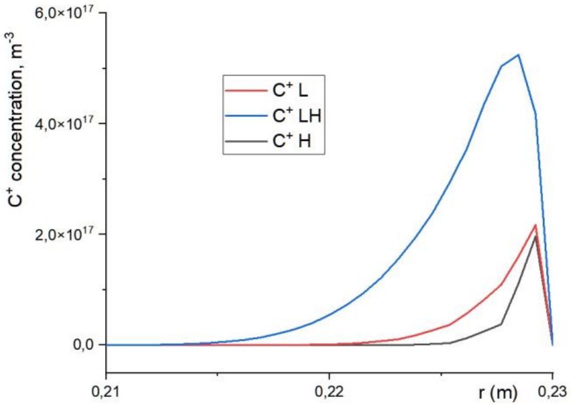

Fig.5. Radial profiles of the C+ ion concentration near the plasma edge in TUMAN-3M in ohmic L-mode (red), during the ohmic L-H transition (blue) and in a developed ohmic H-mode (black). Electron density and temperature profiles presented in Fig.3 were used in 1D modeling of C+ ion transport and source/sink.

Comparison of the spectral shift of CII lines in the shots 22041927 with L-H transition and NBI (Fig.5.a, red line) and 22041921 with L-H transition but without NBI (Fig.5.b, red line) shows that edge toroidal rotation evolution is approximately the same in these scenarios. Toroidal rotation evolves in time from zero in ohmic L-mode to a co-current velocity of 12.8 km/s during L-H transition and then flips to the counter-current 12.8 km/s in developed H–mode. It means that the rotation here is governed by the L-H transition; the effect of injected atomic beam is negligible. A similar behavior is seen if one compares pure ohmic shot 22041921 with L-H transition (Fig.5.b, redline) and shot 22052506 without the transition but with NBI (Fig.4.b, blue line). Again, L-H transition causes strong perturbation in the toroidal rotation velocity, while the NBI does not affect the rotation.

Discussing the toroidal rotation evolution one has to take into account that in this case the so-called intrinsic rotation [2] takes place, which is driven by tokamak plasma itself but not by a momentum transfer from an external source. In the L-mode in the TUMAN-3M this toroidal rotation velocity is small and below the sensitivity level of the diagnostic used, so it was taken as the reference for the measurements. The ohmic L-H transition in the TUMAN-3M tokamak is routinely triggered by short (~5ms long) pulse of gas puffing rate increase, see Fig.1, signal H_alpha Valve. It leads to the transient increase in neutral density near the plasma edge, and this may lead to enhancement in toroidal asymmetry of charge-exchange losses at the edge, hence, toroidal momentum loss misbalance. Later on, after gas puffing pulse ceases and L-H transition occurs, toroidal rotation velocity became counter-current, obviously due to the negative radial electric field formation at the edge which is typical for the H-mode. This radial electric field may be estimated as $E_r \sim -V_tB_p = -V_tB_ta/(Rq) = -1.56$ km/s, where B_t=1 T – toroidal filed, a = 0.23 m and R=0.53 m – minor and major radii, q = 3.5 – cylindrical safety factor. This estimation is close to the results of HIBP measurements in ohmic H-mode in the TUMAN-3M [10, 11]. On the other hand, this estimation neglects the possible impact from the diamagnetic effect on the spectroscopic measurement of CII line shift. Indeed, as is seen, there are strong and changing gradients of C^+ ion concentration at the plasma edge. For accurate accounting for this effect a spatially resolved multi-point measurements are needed.

To understand the role of the NBI injection in these experiments, a numerical modeling of the neutral beam power and momentum absorption was performed using the ASTRA and NUBEAM codes [12]. Toroidal torque profile in the shots 22-41927 and 22052506 are shown in Fig.6.

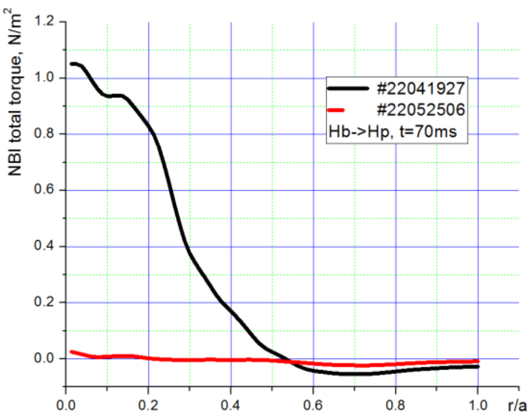

Fig.6. Toroidal torque density profile calculated using the ASTRA and NUBEAM codes for the shots 22041927 and 22052506

The modeling indicates that in the shot with higher density and beam power (shot 22041927) there is some torque applied to the plasma in co-current direction and deposited in the core region. At the plasma periphery this torque density is small and even slightly negative due to the radial current caused by fast ion losses. Obviously, the torque density in the center and rotational momentum transport from core to the edge are not sufficient to provide a measurable rotation in the edge region. This may explain why we do not see any influence of the NBI in this shot on the peripheral toroidal rotation. In the shot 22052506 calculated torque is negligibly small due to the lover density and beam power.

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