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Calculation of torque applied to plasma in NBI injection experiments on the TUMAN-3M tokamak

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Received July 23, 2024
Revised October 7, 2024
Accepted October 8, 2024

The results of calculations of the torque generated in the TUMAN-3M tokamak plasma during a high-energy neutral beam injection (NBI) in the co- and counter-current directions are presented. The dependences of the magnitude of the torque in the central and edge regions of the plasma on the NBI power, plasma concentration, isotopic composition of the beam and the background plasma and on some other parameters were investigated. Optimal concentration to provide the maximum value of the torque was found. The calculations demonstrated that injection of hydrogen beam into a hydrogen plasma ($H_b \to H_p$) near the axis results in higher values of the the torque in comparison with the scenarios $D_b \to H_p$, $D_b \to D_p$, $H_b \to D_p$. The radial electric field generated at the plasma boundary was estimated based on the torque simulations.

Keywords: tokamak, plasma potential, radial electric field, neutral injection, toroidal plasma rotation.

DOI: 10.61011/TPL.2025.02.60629.20070

Injection of high-energy neutral atoms is an effective method for plasma heating, generating of rotation and radial electric field in modern facilities for controlled thermonuclear fusion. Toroidal rotation of the plasma generated by fast ions, as well as by fast ions losses, can lead to strong spatial inhomogeneity of the radial electric field [1,2]. The spatial distribution of the velocity of toroidal rotation and the associated radial electric field depend not only on the parameters of the background plasma and the NBI power, but also on the geometry of the injection, in particular, on whether the velocity of the injected atoms is directed along the plasma current (co-injection) or towards him (counter-injection). The generation of toroidal rotation during NBI is of interest from the point of view of its influence on the possibility of suppressing magnetohydrodynamic instabilities [3]. It is worth noting that the generation of a non-uniform electric field at the periphery of the plasma can contribute to the initiation of the L$-$H transition [4].

The article is devoted to the calculation of the torque generated in plasma by fast ion beam under various injection scenarios in the TUMAN-3M tokamak. It should be noted that the modeling of the rotational momentum, which involves solving a self-consistent problem using the rotational momentum diffusion equation, is beyond the scope of this article and will be the subject of further research, so the turm „calculation" is used instead of „simulation".

The external source of the torque in the TUMAN-3M tokamak plasma is the tangential injection of high-energy $(15-24\,\mathrm{keV})$ hydrogen or deuterium atoms. Calculations of the torque arising in the plasma during NBI allow optimizing the parameters of the plasma and the heating beam in order to maximize the toroidal rotation velocity. The calculations were carried out using the ASTRA code (Automatic System of Transport Analysis) version 6 [5] and NUBEAM code [6]. NUBEAM is a comprehensive computational platform designed to simulate processes caused by neutral beam injection into magnetically confined plasmas.

The following parameters of the plasma and injection beam were used in the calculations: major radius of the plasma $R_p = 0.53\,\mathrm{m}$, minor radius of the plasma $a_p = 0.23\,\mathrm{m}$, electron temperature at the plasma center $T_e(0) = 400-700\,\mathrm{eV}$, average electron concentration along the central chord $\bar{n}_e = (1-6) \cdot 10^{19}\,\mathrm{m}^{-3}$, plasma current $I_p = 120-180\,\mathrm{kA}$, toroidal magnetic field $B_t = 0.7-1\,\mathrm{T}$, heating beam energy $E_b \geq 16\,\mathrm{keV}$ and injection power $P_b \geq 150\,\mathrm{kW}$.

To determine the radial distribution of the safety factor $q(r)$ and the input ohmic heating power $P_{joul} = E(r)j(r)$, the ASTRA code was used. In the model, the equation of the poloidal magnetic field diffusion was solved with the experimentally measured evolution of the plasma current $I_p(t)$ as the boundary condition. In this case, neoclassical conductivity according to Hirschman was used [7], the value of the effective charge was $Z_{eff} = 2-3$. Experimentally measured profiles $n_e(r,t)$ and $T_e(r,t)$ were used in the model. Fig. 1, a demonstrates the $n_e(r)$ and $T_e(r)$ distributions corresponding to the ohmic regime.

Evolution of the ion temperature $T_i(r)$ was obtained by solving the transport equation for $T_i(r,t)$ using ASTRA code. In the model, the thermal diffusion equation for the

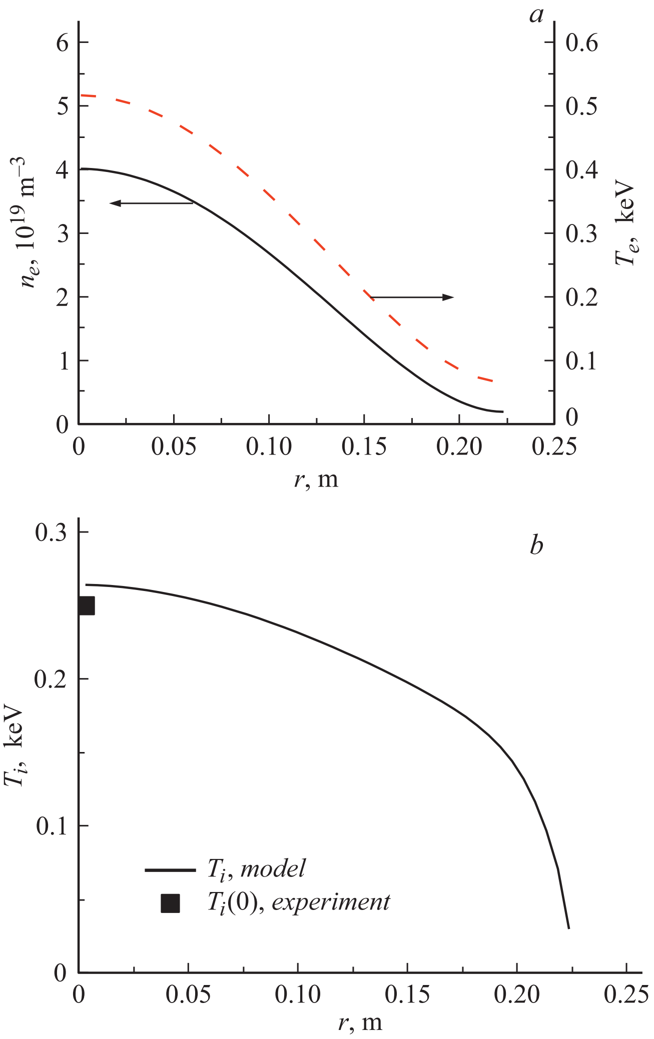

Figure 1. Experimental profiles used in NUBEAM code calculations: electron density n_e and electron temperature T_e (a); ion temperature profile T_i (b) simulated with the ASTRA code.

ion component was solved under the assumption of neoclassical ion thermal diffusivity, multiplied by the „anomaly coefficient", which was selected to match the simulated $T_i(0)$ at the plasma center with the experimental one obtained with the charge exchange ion energy analyzer [8]. The ion temperature profile $T_i(r)$ in the ohmically heated plasma is shown in Fig. 1, b.

The torque density distribution $M_T(r)$ was calculated using the NUBEAM code. Fig. 2, a presents the results of the calculation for the components $M_T(r)$. Here *tqbe* and *tqbi* characterize the collision transfer of momentum from captured ions to the electron and ion components of the plasma, respectively, *tqjxb* characterizes the transfer of momentum through the Ampere force $J_r \times B$, arising due to the appearance of a radial current, which compensates the outward-directed radial current of fast ions. Fig. 2, b shows the results of calculating the dependence of M_T^{core} in the central region of the plasma ($r < 0.22a_p$) on the beam power P_b in the cases of co- and counter- injection. In these calculations, the beam current varied according to the law $j_b \propto E_b^{1.5}$ corresponding to the current-voltage characteristic of the ion source used in the TUMAN-3M neutral injection system. An increase in the beam power from 190 to 350 kW results in 65 % M_T^{core} increase. In the case of counter-injection, the sign of the torque becomes negative, and the absolute M_T^{core} value also slowly increases with P_b increase.

Fig. 2, c shows the calculated dependence of M_T^{core} on $n_e(0)$ in the case of co-current NBI with the beam power $P_b = 250$ kW. The graph demostrates an increase of M_T^{core} in the central region of the plasma with the rise of electron concentration up to $n_e(0) = 3 \cdot 10^{19}\,\mathrm{m}^{-3}$; if $n_e(0)$ exeeds this value the torque M_T^{core} does not depend on $n_e(0)$. The described dependance of $M_T^{core}(n_e(0))$ may be caused by an incomplete ionization of the injected neutral beam particles at $n_e(0) \leq 3 \cdot 10^{19}\,\mathrm{m}^{-3}$, whylist the saturation of $M_T^{core}(n_e(0))$ growth may be explained by complete beam capture at $n_e(0) \geq 3 \cdot 10^{19}\,\mathrm{m}^{-3}$. Fig. 3 presents the results of calculations of $M_T(r)$ profiles in various co-injection scenarios: injection of a hydrogen beam into hydrogen plasma — $\mathrm{H}_b \to \mathrm{H}_p$, injection of a deuterium beam into hydrogen plasma — $D_b \to \mathrm{H}_p$, injection of a hydrogen beam into deuterium plasma — $\mathrm{H}_b \to \mathrm{D}_p$, injection of a deuterium beam into deuterium plasma — $\mathrm{D}_b \to \mathrm{D}_p$. In all the scenarios the beam energy was $E_b = 26$ keV. In the simulation P_b was increased by factor of 1.4 when changing from deuterium beam to the hydrogen one due to the corresponding increase in the beam current. When changing to a lighter isotope it compensates for the decrease in the input momentum which is proportional to the square root of the injected atoms mass (at a constant E_b).

Fig. 3 demonstrates that in the central plasma region ($r < 0.22a_p$) the value of $M_T(r)$ in the $\mathrm{H}_b \to \mathrm{H}_p$ scenario is higher than in the other scenarios. This indicates a higher efficiency of hydrogen beam power absorption in hydrogen plasma.

At the plasma periphery, at $r > 0.5a_p$, $M_T(r)$ changes direction, which is a consequence of the generation of a negative moment *tqjxb* due to the appearance of an outward-directed radial current of fast ions (see Fig. 2, a), a compensating current inward-flowing through the plasma which is accompanied by a corresponding radial electric field directed inward [9]. This effect should be more pronounced with counter-injection due to the worse confinement of fast ions, but it also occurs with co-injection.

The measurements of the plasma potential evolution during co-injection, were performed using the heavy ion beam probing (HIBP) diagnostic [10]. A decrease in the plasma potential by about 100–150 V was observed. It corresponds to the generation of a more negative radial electric field, $E_r \propto 1.0$–1.5 kV/m. The simulation of the scenario with similar plasma parameters, but in the case of counter-injection shows a greater value of the negative the torque at the periphery. This comparison is in qualitative agreement with the fact that in the TUMAN-3M tokamak

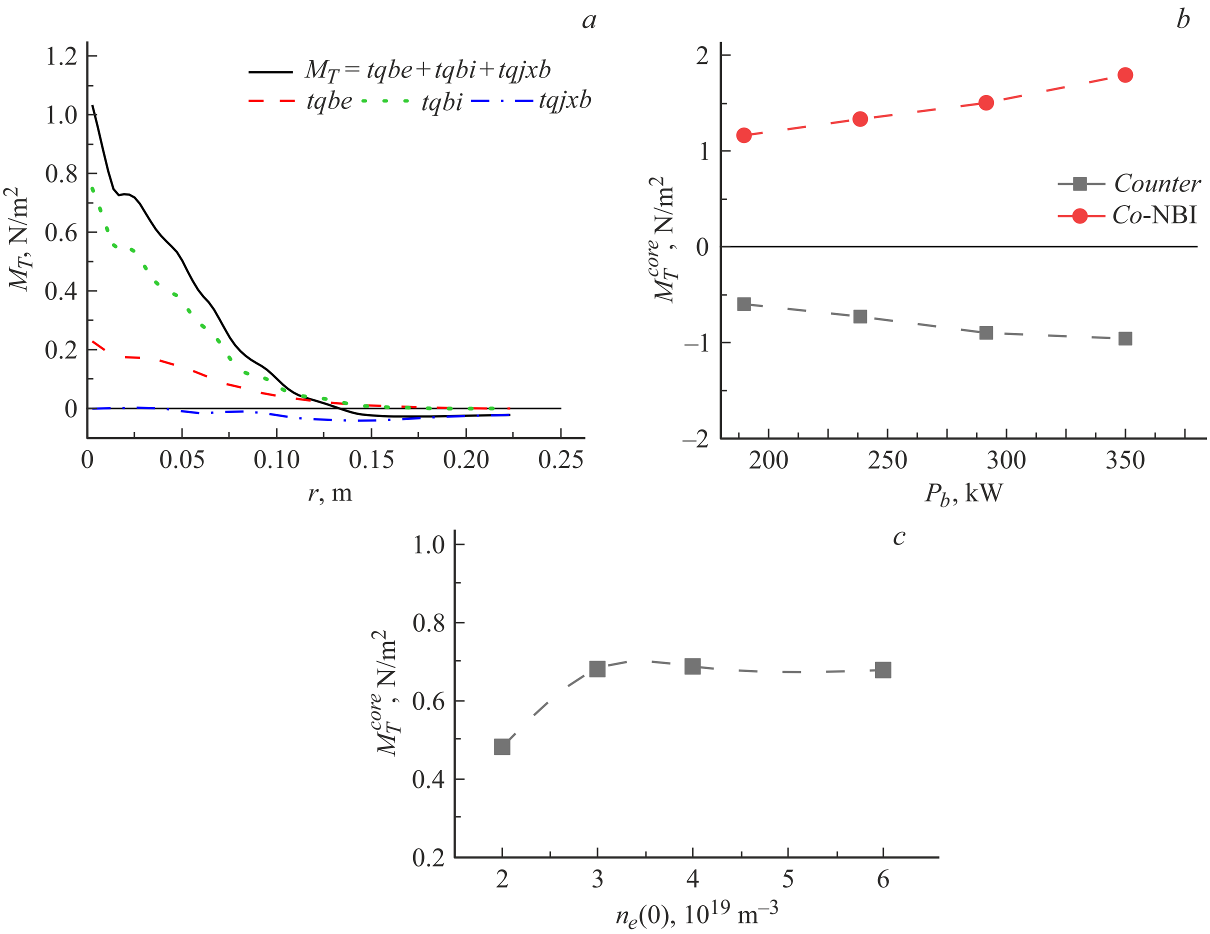

Figure 2. Calculated profiles of external torque components M_T^{core} (a); M_T^{core} dependence on the beam power P_b (b); M_T^{core} dependence on the value of the central concentration $n_e(0)$ (c).

the L–H transition is easier to achieve with counter-injection. With co-injection the transition is hampered and requires additional effects on the plasma, for example, a gas injection pulse. Earlier, in the experiments with counter-injection on the TUMAN-3M tokamak [11], a noticeably stronger radial electric field was observed at the periphery — $E_r \propto 4{-}5$ kV/m.

Thus, the calculation results indicate that for the NBI experiments on the TUMAN-3M tokamak there exists an optimal plasma concentration $n_e(0) = 3 \cdot 10^{19}\,\mathrm{m}^{-3}$, at which the value M_T^{core} reaches maximum. In addition, the calculations demonstrate a strong dependence of M_T^{core} on the beam power P_b. An increase in P_b from 190 to 350 kW leads to an increase in M_T^{core} by 65 %, while the increase in M_T^{core} with increasing P_b is slower than expected. After taking into account the direct beam power losses, the change in M_T^{core} is in good agreement with the change in the absorbed beam power. The calculation results allowed us to select the optimal isotopic composition of the plasma and the heating beam for generating the torque. The change in M_T^{core} is in good agreement with the change in the absorbed beam power depending on the isotopic composition. Under the $H_b \to H_p$ conditions, the M_T^{core} value in the central region of the plasma has a maximum value compared to the other injection scenarios.

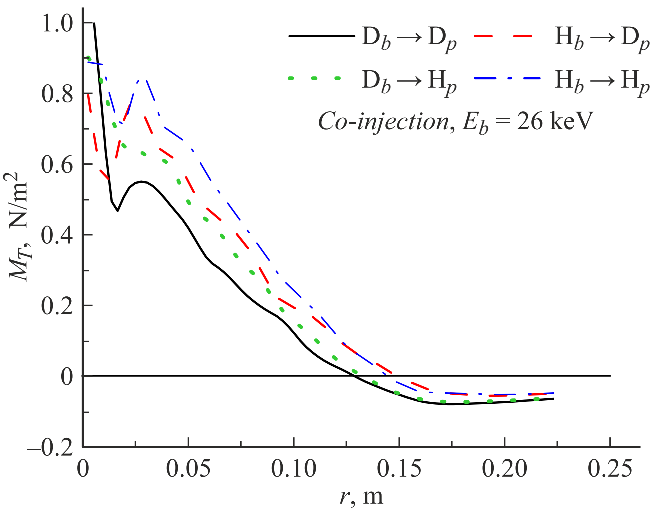

Figure 3. Caculated external torque $M_T(r)$ for various injection scenarios.

The negative value of the injected torque at the periphery is due to the electrodynamic component $J_r \times B$, which in turn occurs due to the presence of a noticeable internal radial current through the plasma, compensating for the outgoing current of fast ions caused by orbital effects.

In future work, we plan to use the calculated spatial distribution of the torque as a source for the numerical solution of the toroidal momentum transfer equation using the ASTRA code version 7. This will allow a comparison to be made with the experimentally measured value of the toroidal rotation velocity, as well as obtaining the profile of the radial electric field associated with the toroidal rotation.

Funding

The work of standard diagnostics of the TUMAN-3M tokamak was carried out with the support of the state contract of the Ioffe Institute 0040-2024-0028. Experiments with neutral beam injection were carried out with the support of the state contract of the Ioffe Institute 0034-0021-0001. Research of the radial electric field on the TUMAN-3M tokamak was supported by a grant from the Russian Science Foundation (project 22-12-00062).

Conflict of interest

The authors declare that they have no conflict of interest.

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