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# The first application of the HIBP diagnostics for co–NBI plasma potential measurement in the TUMAN–3M tokamak

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The heavy ion beam probe (HIBP) diagnostics at the TUMAN–3M tokamak was updated to provide measurements in the regime with neutral beam injection co-directed with plasma current (co-NBI). By means of HIBP, plasma potential measurements in the center of plasma were carried out. Plasma potential evolution in the discharge with the LH transition (transition to the improved confinement mode) is in good agreement with the concept of negative radial electric field generation during formation of the transport barrier.

**Keywords:** plasma physics, tokamak, heavy ion beam probe, H-mode, neutral beam injection.

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Injection of high-energy neutral atoms (neutral beam injection, or NBI) is an efficient technique for plasma heating, generation of rotation, and fuel supply to the center of plasma. Depending on the direction of the injected atom velocity vector with respect to the direction of the tokamak toroidal magnetic field, the tangential and transverse injections are distinguished. The tangential injection is possible in two versions: the beam entering the plasma may be co-directed (co-injection or co-NBI) or counter-directed (counter-injection or counter-NBI) with the plasma current. An additional toroidal plasma rotation generated by the fast ions in plasma, as well as other processes such as fast–ion losses, can lead to strong local evolution of the poloidal rotation and radial electric field [1,2]. The counter-injection regimes are characterized by a worse fast ion confinement; however, they can produce negative radial electric field $E_r$ due to fast–ion losses, which facilitates initiation of the LH transition. The tokamak TUMAN–3M experiments with the counter-NBI have been described in detail in [3]. The co-NBI regime is characterized by a better confinement of fast ions. However, in this case excitation of the injection–induced radial electric field consists of minimum two factors: generation of negative peripheral $E_r$ due to fast-ion losses and of positive $E_r$ in the central area due to the plasma rotation induced by the momentum transfer from the injected beam. The joint effect of these factors may result in generation of a strongly non-uniform $E_r$ distribution over the plasma cross-section. Plasma diagnostics such as heavy ion beam probe (HIBP) allows obtaining valuable information on the magnitude and dynamics of radial electric field in this regime, which can hardly (or never) be acquired in other ways.

The HIBP method is based on the accelerated ion beam injection into plasma in the poloidal plane [4]. Collisions of the probe beam ions (primary ions) with plasma electrons induce formation of highly charged ions (secondary ions) whose trajectories deviate from those of primary ions at the ionization point because their curvature radius in the magnetic field is two times shorter. The detector external to plasma receives secondary ions emerging from a certain spatially-localized region along the primary particle trajectory. Based on the difference between the energies of primary and secondary ions, it is possible to determine the plasma potential at the secondary ionization point.

In view of understanding physical mechanisms for plasma heating and confinement during neutral injection and association of these processes with the radial electric field generation, experimental HIBP–investigation of the co-NBI effect on the plasma potential spatial–temporal evolution is, undoubtedly, of a great theoretical and practical interest. These experiments needed re-designing the tokamak duct through which secondary ions enter the energy analyzer in the process of the experiments with HIBP. Since the TUMAN-3M neutral atom injector is fixed, the counter-NBI to co-NBI transition is performed by reversing the plasma current direction. The initial HIBP configuration at the TUMAN-3M tokamak was designed to be used in the counter-NBI mode; therefore, the energy analyzer duct was inclined relative to the poloidal plane towards the plasma current direction. Once the plasma current is reversed, the secondary ions get deviated by the poloidal field to the opposite side, and their detection using the available duct becomes impossible.

To define the optimal duct configuration, numerical simulation was carried out of the HIBP secondary beam trajectories in the experiment with the co-NBI. The simulation consisted in numerically solving motion equations for primary and secondary ions in the TUMAN-3M real magnetic fields. In order to account for the toroidal and poloidal non-uniformities of the real toroidal magnetic

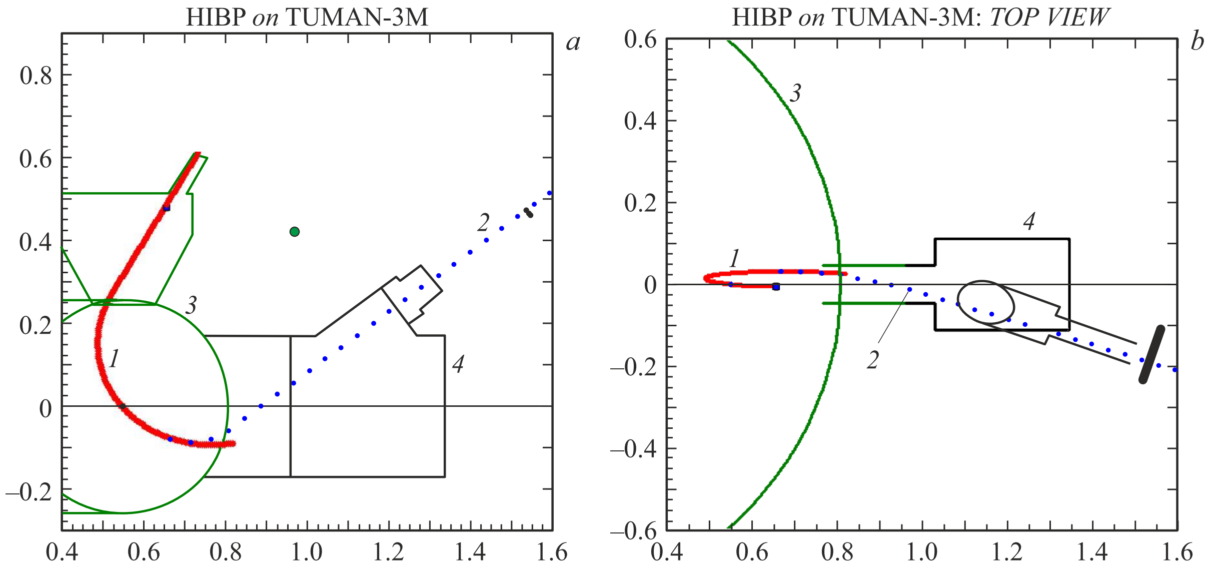

**Figure 1.** Calculated trajectories of primary potassium ions $K^+$ (*1*) and secondary ions $K^{2+}$ (*2*) in tokamak TUMAN–3M in the characteristic discharge with co–NBI. *a* — poloidal crosssection, *b* — top view. Line *3* outlines the tokamak chamber, line *4* indicates the analyzer duct dimensions and arrangement of the analyzer slits.

field which are especially significant in the gap between toroidal coils at the secondary beam exit from the tokamak chamber, the toroidal magnetic field was calculated based on the Biot–Savart law taking into account the toroidal field geometry and arrangement of coils. The poloidal field induced by the control field coils was calculated in the same way. The plasma current field was calculated using the model parabolic distribution of the current density over the plasma cross-section. In calculations we ignored the effect of the plasma electric field on the primary and secondary beam trajectories because it was quite weak: the plasma potential was relatively low (hundreds of volts to units of kilovolts) with respect to the beam energy ($\sim 50{-}80\,\text{keV}$).

In the typical scenario of tokamak TUMAN-3M with the low plasma density (toroidal magnetic field $B_T = 0.95\,\text{T}$, plasma current $I_{pl} = 150\,\text{kA}$, control coil current $I_{contr} = 105\,\text{kA}$), the beam of secondary potassium ions with energy of 70 keV gets from the plasma center into the analyzer; the calculated beam trajectories are shown in Fig. 1. By varying the primary beam energy and entrance angle, it is possible to attain the signal from both the plasma center ($r/a = 0.3$) and periphery (approximately up to $r/a = 0.8$).

In the co-NBI mode, the plasma potential evolution was measured. We selected for the analysis the scenarios enabling assessment of contribution of various factors affecting the plasma potential. These are, first, discharges with co-NBI that may be assumed to exhibit both the positive contribution to the potential due to generation of positive radial electric field by the plasma toroidal rotation and negative contribution due to first-orbit fast ion losses. Second, these are discharges with the additional-puffing pulse. As the TUMAN-3M experiments showed [5], an LH transition may be initiated in such discharges and, hence, negative radial electric field may be generated during formation of the transport barrier.

In the discharges under consideration, the characteristic magnetic field magnitude is $B_T < 0.95\,\text{T}$, plasma current is $I_{pl} < 160\,\text{kA}$, chord-averaged plasma concentration in the L mode is $n = (1{-}1.5) \cdot 10^{19}\,\text{m}^{-3}$, that in the H mode is $n < 2.5 \cdot 10^{19}\,\text{m}^{-3}$. Experiments performed at such a concentration exhibited a transition to the H mode initiated by the gas puffing pulse and co-NBI. Thereat, in order to ensure the absence of a spontaneous LH transition at the stage of ohmic heating (prior to injection), it is necessary to maintain a sufficiently low concentration of the L-mode background plasma.

Fig. 2 illustrates the comparative analysis of four typical scenarios. The first one is the ohmic discharge without extra gas puffing; it is used as a reference scenario. The second one is the discharge with neutral injection without extra gas puffing. The third one is the discharge with extra gas puffing but without neutral injection. The fourth scenario is the discharge with neutral injection occurring simultaneously with extra gas puffing. The secondary ionization point, i. e. the potential measurement point, is defined as $r/a = 0.6$.

During the neutral injection, the plasma concentration increases, however, the plasma potential evolution quite accurately replicates the plasma potential evolution in the ohmic discharge. Neither of the effects expected to be produced by the neutral injection on the plasma potential is observed. The absence of changes in the particle confinement is confirmed by the fact that the line $D_\alpha$ emission intensity on the wall, which is proportional to the particle and energy flux from plasma to physical surfaces, does not undergo the reduction characteristic of

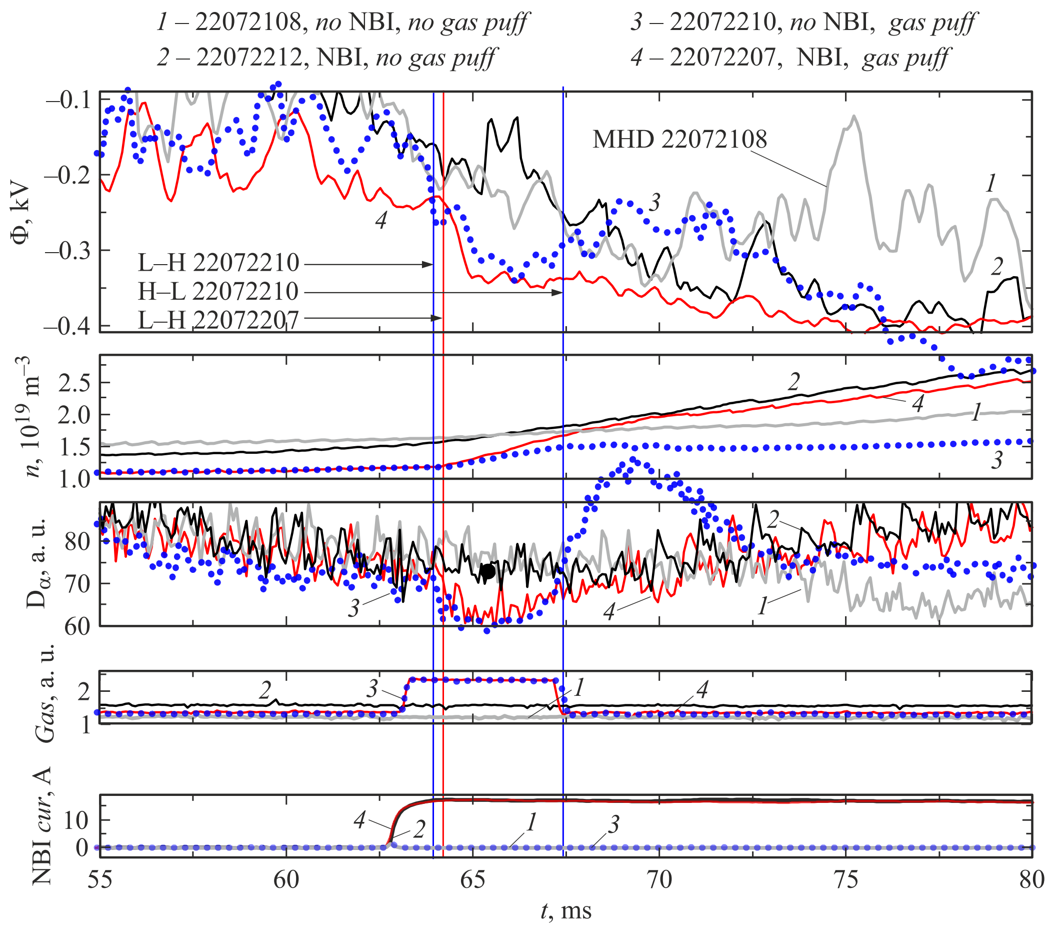

**Figure 2.** Evolution of plasma parameters in various discharges: *1* — ohmic (№ 22072108), *2* — with co-injection (№ 22072212), *3* — with extra gas puffing (№ 22072210), *4* — with co-injection combined with an extra gas puffing pulse (№ 22072207). Top–down: plasma potential, chord-averaged concentration, line $D_\alpha$ emission, gas puffing valve voltage, emission electrode current during the neutral beam injection (NBI). Essential evolution of the potential with a decrease by about 150 V, which corresponds to the LH transition, is observed in the mode of co-injection combined with an extra gas puffing pulse (lines *4*). The scenario with the extra gas puffing pulse exhibits successive LH— and HL transitions (lines *3*).

the transition to the H-mode. Nevertheless, the absence of the potential evolution cannot be associated with the detectors' sensitivity since the burst of the MHD (magnetohydrodynamic) activity in discharge 22072108 (Fig. 2) leads to a positive evolution in the potential as per [6].

At the same time, the discharge in which the neutral injection is accompanied by extra gas puffing exhibits traces of the transition to the H-mode: in 1.5 ms after the beginning of injection and gas puffing, the plasma potential sharply decreases by about 150 V; this is accompanied by a concurrent increase in concentration and reduction of the line $D_\alpha$ emission, which is typical also of ohmic LH transitions observed in the TUMAN-3M tokamak.

The discharge with an extra gas puffing pulse but without neutral injection also exhibits the LH transition with the characteristic attributes: increase in concentration, decrease in the line $D_\alpha$ emission, and reduction of the plasma potential by about 100 V. Notice that in the considered scenario with a low plasma concentration there occurs a back wards transition to the mode of normal confinement (HL transition, see Fig. 2), contrary to scenarios with higher concentrations in which extra gas puffing usually initiates the transition to the self-sustaining H-mode. This observation may be explained in the framework of the approach based on the analysis of the transport equations with a nonlinear diffusion coefficient accounting for the turbulence suppression by inhomogeneous radial electric field and influence of the particle source on the possibility of the H-mode existence. This approach was described in detail in [7–9]. Paper [8] presents the results of modeling the evolution of the plasma concentration profile with the gradually increasing source, in particular, a smooth (during a few milliseconds) LH transition upon the particle source reaches the level ensuring the existence of only one stable diffusion equation solution corresponding to the H-mode. This result agrees with experimental data: the transition to the H-mode in the scenario with additional gas puffing is initiated by an increase in the particle source. When the

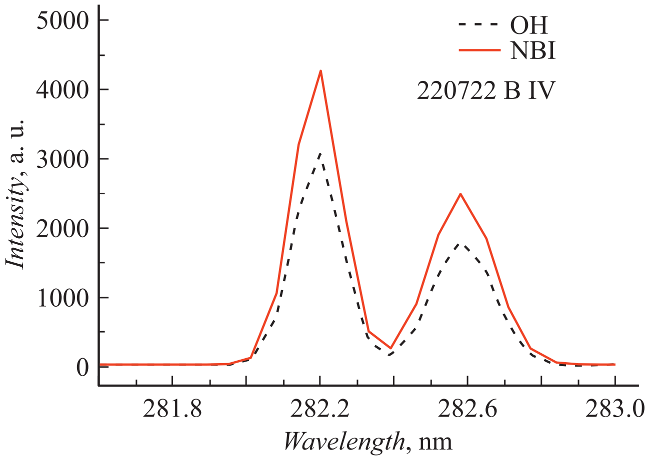

**Figure 3.** Spectra of the line B IV emission in the ohmic discharge (dashed line) and in the co-injection discharge (solid line). The Gaussian approximation shows that the line broadening and shift of the center are the same in both scenarios.

extra particle source disappears, the condition for the H-mode existence is no longer fulfilled, and the back wards transition occurs.

Thus, it is possible to conclude that initiation of the LH transition in the scenarios considered in this paper occurs due to extra gas puffing; the effect of neutral injection on the particle confinement at the given plasma and injection parameters reduces to an additional source of particles ensuring the H-mode existence in discharges with joint gas puffing and neutral injection.

Since a positive increment in the potential is not observed during injection, a conclusion could be made that the effect associated with generation of negative $E_r$ in the case if the LH transition is initiated by gas puffing appears to be much more pronounced as compared to generation of positive $E_r$ with introducing an extra toroidal rotation. It is possible to estimate the potential induced by the toroidal rotation in the middle of the minor radius. The rotation speed increment of 1 km/s, according to estimate $v_\varphi = \frac{E_r B_\theta}{B_\varphi^2}$ for the minor radius center ($B_\varphi = 0.8\,\mathrm{T}$, $B_\theta = 0.1\,\mathrm{T}$), is relevant to the radial electric field of 6.4 kV/m or, at the estimate $E_r = \Phi/(a/2)$, to potential of 700 V. The measurements show that such a positive potential excitation by the neutral injection is not observed in the described experiment. Thus we can conclude that, in the low-concentration discharges with co-NBI, the injection-initiated positive radial electric field and, hence, the co-current toroidal rotation speed, are low. The reason for such an insignificance of the neutral injection contribution to the plasma rotation may be the fact that, at such a low plasma concentration (about $(1-1.5)\cdot 10^{19}\,\mathrm{m}^{-3}$), the beam to plasma momentum and energy transfer is low, while losses (including shine-through losses) are high [10]. This may be also a reason for the absence of generation of the negative radial electric field due to the first-orbit fast ion losses.

The absence of a considerable toroidal rotation is confirmed by the measurements of the contour of line B IV ($\lambda$=282.2 nm) observed in the toroidal direction along the plasma current at the angle of about 20° to the equatorial plane. The results of spectrometric diagnostics show that discharges with neutral injection exhibit neither line shifts nor broadening as compared with analogous ohmic discharges (Fig. 3). This evidences a low efficiency of the neutral–injection energy and momentum transfer to plasma ions. This may be caused by a too low plasma density in the considered experiments, due to which a significant part of the atom beam flies through the plasma without ionization.

It seems possible that more efficient neutral injection energy and momentum transfer in the co-NBI mode may be achieved by, first of all, increasing the plasma density and electron temperature in order to increase a portion of energy transferred to ions, and also by increasing the current and energy of injected atoms. This assumption is based, among other things, on results published in [11] demonstrating the effect of co-NBI on generation of the plasma poloidal rotation in high concentration discharges.

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## Conflict of interests

The authors declare that they have no conflict of interests.

## References

[1] K. Ida, Plasma Phys. Control. Fusion, **40**, 1429 (1998). DOI: 10.1088/0741-3335/40/8/002

[2] G.D. Conway, J. Schirmer, S. Klenge, W. Suttrop, E. Holzhauer and the ASDEX Upgrade Team, Plasma Phys. Control. Fusion, **46**, 951 (2004). DOI: 10.1088/0741-3335/46/6/003

[3] S.V. Lebedev, L.G. Askinazi, F.V. Chernyshev, M.A. Irzak, V.A. Kornev, S.V. Krikunov, A.D. Melnik, D.V. Razumenko, V.V. Rozhdestvensky, A.I. Smirnov, Nucl. Fusion, **49**, 085029 (2009). DOI: 10.1088/0029-5515/49/8/085029

[4] T.P. Crowley, IEEE Trans. Plasma Sci., **22**, 291 (1994). DOI: 10.1109/27.310636

[5] S.V. Lebedev, M.V. Andrejko, L.G. Askinazi, V.E. Golant, V.A. Kornev, S.V. Krikunov, L.S. Levin, B.M. Lipin, G.T. Razdobarin, V.A. Rozhansky, V.V. Rozhdestvensky, A.I. Smirnov, M. Tendler, A.S. Tukachinsky, S.P. Yaroshevich, Plasma Phys. Control. Fusion, **38**, 1103 (1996). DOI: 10.1088/0741-3335/38/8/003

[6] L.G. Askinazi, V.E. Golant, V.A. Kornev, S.V. Lebedev, A.S. Tukachinsky, M.I. Vildjunas, N.A. Zhubr, Plasma Phys. Control. Fusion, **48**, A85 (2006). DOI: 10.1088/0741-3335/48/5A/S07

[7] M.A. Malkov, P.H. Diamond, Phys. Plasmas, **15**, 122301 (2008). DOI: 10.1063/1.3028305

[8] A.A. Belokurov, L.G. Askinazi, L. Chôné, E.Z. Gusakov, T.P. Kiviniemi, V.A. Kornev, T. Korpilo, S.V. Krikunov, S.V. Lebedev, S. Leerink, P. Niskala, R. Rochford, A.I. Smirnov, A.S. Tukachinsky, N.A. Zhubr, Nucl. Fusion, **58**, 112007 (2018). DOI: 10.1088/1741-4326/aac4e9

[9] A.A. Belokurov, G.I. Abdullina, L.G. Askinazi, V.V. Bulanin, L. Chôné, A.D. Gurchenko, E.Z. Gusakov, T.P. Kiviniemi, V.A. Kornev, S.V. Krikunov, D.V. Kouprienko, S.I. Lashkul, S.V. Lebedev, S. Leerink, P. Niskala, A.V. Petrov, D.V. Razumenko, A.S. Tukachinsky, A.Yu. Yashin, N.A. Zhubr, Phys. Scripta, **95**, 115604 (2020). DOI: 10.1088/1402-4896/abbfcc

[10] L.G. Askinazi, A.G. Barsukov, V.E. Golant, V.K. Gusev, V.V. Kusnetsov, S.V. Lebedev, V.M. Leonov, A.V. Lupin, V.B. Minaev, A.A. Panasenkov, A.R. Polevoi, G.N. Tilinin, A.S. Tukachinsky, V.A. Yagnov, Plasma Dev. Oper., **11**, 211 (2003). DOI: 10.1080/1051999031000155524

[11] A.Yu. Yashin, A.A. Belokurov, L.G. Askinazi, A.V. Petrov, A.M. Ponomarenko and the TUMAN-3M Team, Atoms, **10**, 106 (2022). DOI: 10.3390/atoms10040106