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Application of HIBP for measuring evolution of radial electric field and plasma potential in the TUMAN-3M tokamak

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In the TUMAN-3M tokamak high-density scenarios with line-averaged density $n > 2 \cdot 10^{19}\,\mathrm{m}^{-3}$, evolution of plasma potential towards positive values was detected using the heavy ion beam probe (HIBP) diagnostics in co-NBI (neutral beam injection in the direction of plasma current). The results show that efficiency of the plasma rotation generation by the neutral beam injection (NBI) depends on the plasma density. In addition, radial electric field was directly measured in ohmic discharges by using HIBP in the two-point probing scheme; the effect of density on the radial electric field was detected.

Keywords: plasma physics, tokamak, heavy ion beam probe, radial electric field, neutral beam injection.

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Injection of high-energy neutral atoms is an efficient technique for plasma heating, generation of plasma rotation, and fuel supply to the plasma column center. Toroidal plasma rotation induced by ions in plasma, as well as fast ions losses may lead to strong local evolution of the radial electric field E_r [1,2]. Counter-injection (against the plasma current direction) is less efficient in terms of heating and rotation generation because of poorer confinement of fast ions in plasma; however, loss of fast first-orbit ions may, in turn, help initiate the transition to the mode with improved confinement. Earlier, the effect of counter-injection on plasma confinement was studied at the TUMAN-3M tokamak [3]. Co-injection (in the direction of plasma current) of a neutral beam is more efficient in terms of capturing fast particles, however, the co-injection influence on plasma confinement is governed by the joint effect of positive radial electric field E_r generation (mainly in the plasma column central part) due to the torque transmission from the injected beam and generation of negative E_r (mainly at the periphery) due to fast ions loss.

Radial force balance for the ionic plasma component

$$E_r = (Z_i e n_i)^{-1} \frac{\partial p_i}{\partial r} - v_{\theta i} B_\phi + v_{\phi i} B_\theta$$

(Z_i is the ion charge number, n_i is the ion density, e is the electron charge, p_i is the ion pressure, B_ϕ, B_θ and $v_{\phi i}$, $v_{\theta i}$ are the toroidal and poloidal magnetic field and rotation speed, respectively) determines the magnitude of the radial electric field in the tokamak plasma, which has been confirmed by experiments [4].

The contribution of co-injection to the radial electric field generation may be divided into two main parts. The first one is the effect of plasma rotation and variations in density and ion temperature gradients due to plasma heating and fuel delivery to the plasma central part; the E_r perturbation is determined via formula

$$E_r = \frac{T_i}{e}\left[\frac{1}{n}\frac{\partial n}{\partial r} + k_T \frac{1}{T_i}\frac{\partial T_i}{\partial r}\right] + v_\phi B_\theta,$$

where n is the plasma density, T_i is the ion temperature, k_T is the neoclassical coefficient [5], e is the electron charge, v_ϕ is the speed of plasma toroidal rotation, B_θ is the poloidal magnetic field; here only toroidal rotation is taken into account. The second one is the effect of fast particle loss generating radial fast-ion current j_r^{FI}. The condition of quasineutrality conservation leads to emergence of compensating radial current $j_r = -j_r^{FI} = \sigma(E_r - E_{NEO})$, where σ is the plasma conductivity, E_r is the radial electric field perturbation, E_{NEO} is the neoclassical radial electric field generated by the pressure gradient. By measuring evolution of the radial electric field or plasma potential, it is possible to assess the effect and role of these contributions.

As shown earlier, in the case of low plasma density (line-averaged plasma density $n < 1.2 \cdot 10^{19}\,\mathrm{m}^{-3}$) neutral injection proves to be inefficient in terms of plasma heating, generation of rotation, and initiation of the L–H transition because of high losses (primarily, shine-through losses) [6,7]. This manifested itself in the lack of evolution of the potential measured by the heavy ion beam probe diagnostics (HIBP) during neutral injection, while in the case of co-injection there may be observed both the evolution of potential towards positive values (relative to those prior the start of injection) associated with initiation of rotation of plasma by confined fast particles (and with generation of relevant radial electric field perturbation), and evolution of the potential towards negative values associated with the first-orbit fast ion losses. Achieving more efficient transfer of the neutral beam injection energy

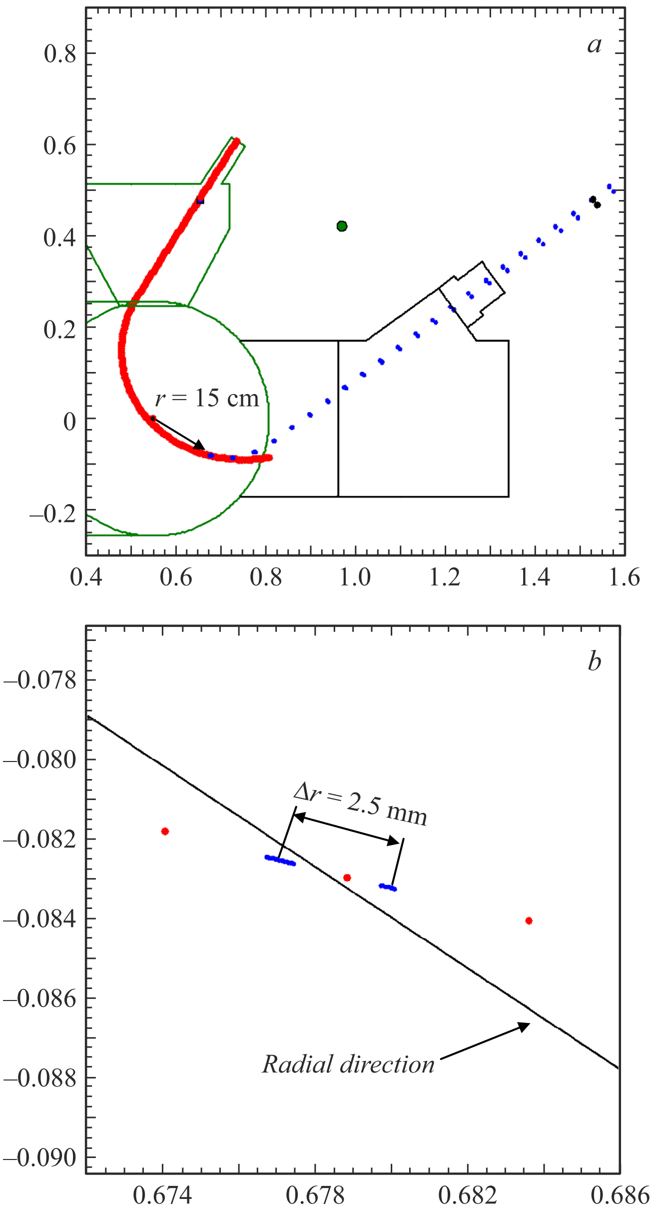

Figure 1. Schematic diagram of the HIBP measurements at TUMAN-3M in the poloidal cross-section. *a* — general view, *b* — localization of the secondary ionization volumes.

and momentum in the co-injection mode seems possible primarily due an increase in plasma density, since in this case the energy portion transferred to ions increases.

The plasma potential evolution was measured by using the HIBP method. The TUMAN-3M HIBP complex provides direct local measurement of the plasma potential, as well as of the radial electric field, by using the two-point probe scheme [8]. A beam of K^+ ions 60–70 keV in energy was injected into plasma. At such an energy, proper selection of entrance angles makes the secondary ion beam stably getting into the energy analyzer over much of the discharge. In this case, the point of secondary ionization and, hence, the measurement area, match a minor radius of 15 cm or $r/a = 0.7$ (Fig. 1, *a*). Since the plasma potential (or, more exactly, the potential difference between the secondary ionization point and chamber wall with radial coordinates r_{HIBP} and a, respectively) is measured using HIBP as $\Phi = \int_a^{r_{\mathrm{HIBP}}} E_r dr$; measuring at point $r/a = 0.7$ provides detecting disturbances associated with both the E_r generation at the periphery (loss of fast ions) and in the column central part (generation of rotation, impact parameter of neutral injection in TUMAN-3M is 42 cm at the large and small radius ($R = 53$ cm and $a = 22$ cm, respectively)).

The TUMAN-3M HIBP analyzer prowides operation in the two-point probe mode when secondary ion beams from adjacent plasma regions separated mainly in the radial direction by 2.5 mm get into the analyzer through two closely spaced entrance slits (Fig. 1, *b*). Such a distance between the secondary ionization volumes ensures the locality of measurements of radial electric field to be determined via the potential difference between adjacent points, since (i) linear size of the secondary ionization volume does not exceed 1 mm, and therefore, the secondary ionization regions do not overlap; (ii) characteristic length of the radial electric field variation in the given region, which is defined as $L = \frac{E_r}{\nabla E_r}$, is 5–6 cm for the calculated neoclassical radial electric field profile (as well as for the E_r profiles obtained by the Doppler backscattering diagnostics in similar discharges [9]), which significantly exceeds the distance between the secondary ionization points.

HIBP-measurements were performed in two scenarios. First consider the scenario involving the neutral beam co-injection.

In scenarios with line-averaged density $n > 2 \cdot 10^{19}\,\mathrm{m}^{-3}$ (at the moment of the neutral beam injection), the plasma potential evolution was measured (Fig. 2). A beam of neutral atoms was injected into the plasma in discharges with different densities; the potential was measured in the plasma column central part at point $r = 15$ cm, or $r/a = 0.7$. Since the plasma potential measured using the heavy ion beam probe is defined as the electric field integral from the measurement point to the chamber wall coordinate; such localization of measurements makes it possible to detect both the peripheral E_r disturbances associated with fast ions loss and the effect associated with plasma rotation induced by confined fast ions.

The measurements show that at a higher plasma density after beam injection, the plasma potential evolution towards more positive values takes place. This evidences that an additional toroidal rotation associated with fast ions arises in the plasma. The effect is more pronounced in denser plasma (red lines *2* in Fig. 2), the potential increment reaches 300 V. In less dense plasma (blue lines *3* in Fig. 2), the potential increases by 100 V. Apparently, the contribution to the potential associated with the plasma rotation generation proves to be dominant: significant fast-ion losses would lead to the potential evolution towards negative values after starting the injection, since this would cause generation of

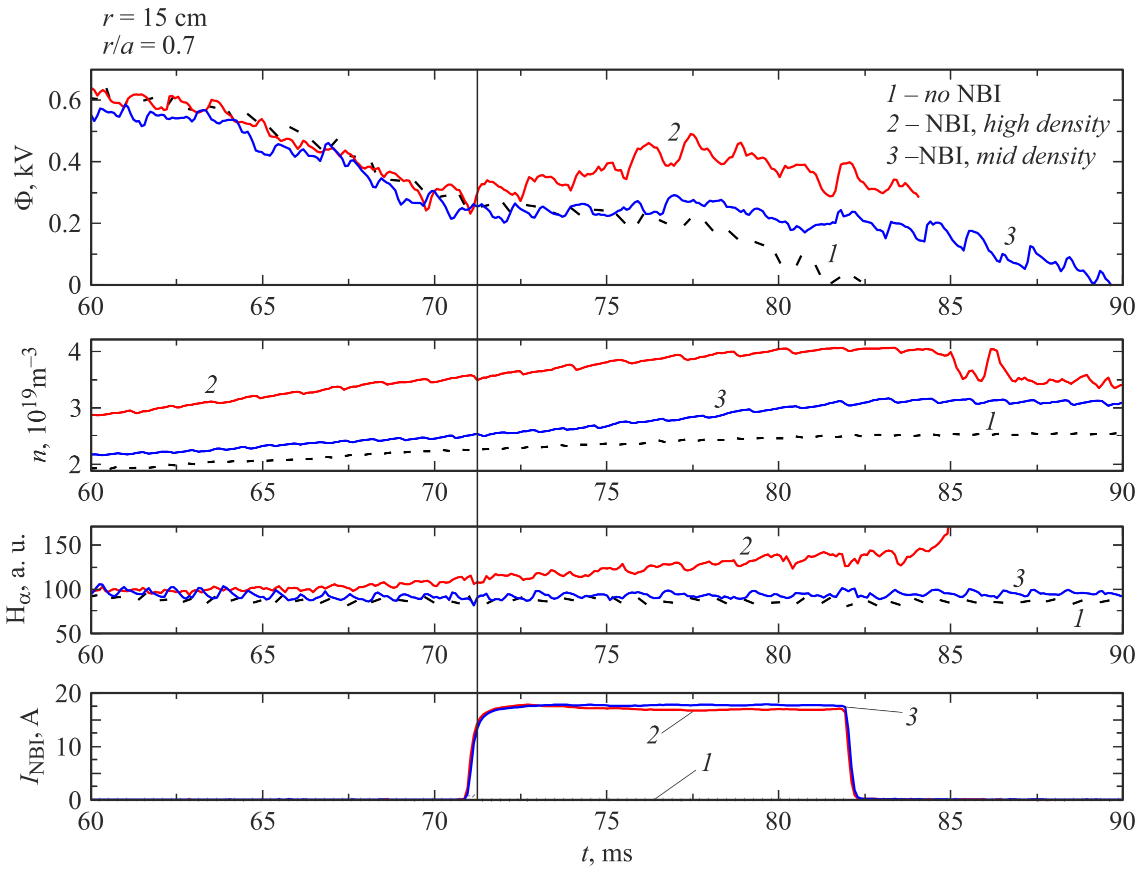

Figure 2. Evolution of the plasma potential, line-averaged density, luminescence of the H_α line, and current of the neutral-injection emission electrode in discharges with injecting into plasma high (red lines *2*) and medium (blue lines *3*) densities. The black dashed lines *1* represent the reference discharge free of injection. At the moment of injection, there is observed the plasma potential evolution towards positive values. The colored figure is given in the electronic version of the paper.

negative radial electric field at the plasma periphery. Notice also that significant fast ion losses in discharges with density of $(2-3)\cdot 10^{19}\,\mathrm{m}^{-3}$ would initiate the transition to the mode of improved confinement [3], which was not observed in the discharges under study.

Based on the magnitude of the potential disturbance, the induced toroidal rotation of plasma may be assessed. For the potential measurement point, the contribution to the radial electric field may be calculated as $E_r = \Delta\Phi/(a-r)$; in the case of a higher density ($\Delta\Phi = 300\,\mathrm{V}$) this relation gives $E_r \approx 7.5\,\mathrm{kV/m}$, while at a lower density ($\Delta\Phi = 100\,\mathrm{V}$) the result is $E_r \approx 2.5$ kV/m. The induced toroidal rotation velocity may be estimated via the increment to E_r as $\upsilon_\phi = \frac{E_r B_\theta}{B_\phi^2}$. At the measurement point, $B_\phi \approx 0.75\,\mathrm{T}$ and $B_\theta \approx 0.1\,\mathrm{T}$. Thus, at a higher density the increment to the toroidal rotation speed due to co-injection is $\upsilon_\phi = 1.4\,\mathrm{km/s}$, that at a lower density is $\upsilon_\phi = 0.45\,\mathrm{km/s}$.

Besides measuring the potential in discharges with neutral injection, the radial electric field at radius $r = 15\,\mathrm{cm}$ $(r/a = 0.7)$ were measured at TUMAN-3M directly by HIBP using the previously described (Fig. 1) two-point probe scheme. The measurements were performed in ohmic discharges in hydrogen and deuterium with identical plasma parameters: toroidal magnetic field $B_\phi = 0.96\,\mathrm{T}$, plasma current $I_{pl} = 150\,\mathrm{kA}$, line-averaged density $n = (1.8-3.0)\cdot 10^{19}\,\mathrm{m}^{-3}$. The inter-point distance is approximately 2.5 mm with predominantly radial spacing (Fig. 1, *b*).

In the TUMAN-3M ohmic discharges in hydrogen and deuterium with similar plasma parameters, a similar radial electric field evolution is observed (Fig. 3, *a*). At minor radius $r = 15\,\mathrm{cm}$, E_r magnitudes ranging from -4 to $-8\,\mathrm{kV/m}$ are close to estimates of the local neoclassical E_r at the ohmic discharge stationary phase, which is about $-3\,\mathrm{kV/m}$. In turn, the estimate of the average radial electric field defined as $E_r = \Phi/(a - r_{\mathrm{HIBP}})$ for these discharges is approximately 2.8 kV/m. Such radial electric field magnitudes appear to be close to those obtained by measuring in ohmic discharges using Doppler backscattering diagnostics [9].

The E_r evolution towards more negative values, which is observed in the deuterium discharge (red line *1* in Fig. 3, *a*) in 60 ms, may be associated with a faster increase in density (Fig. 3, *b*), since at this moment the given ohmic discharge does not exhibit other factors affecting E_r, except for gas puff at 60 ms leading to the density increase without changes

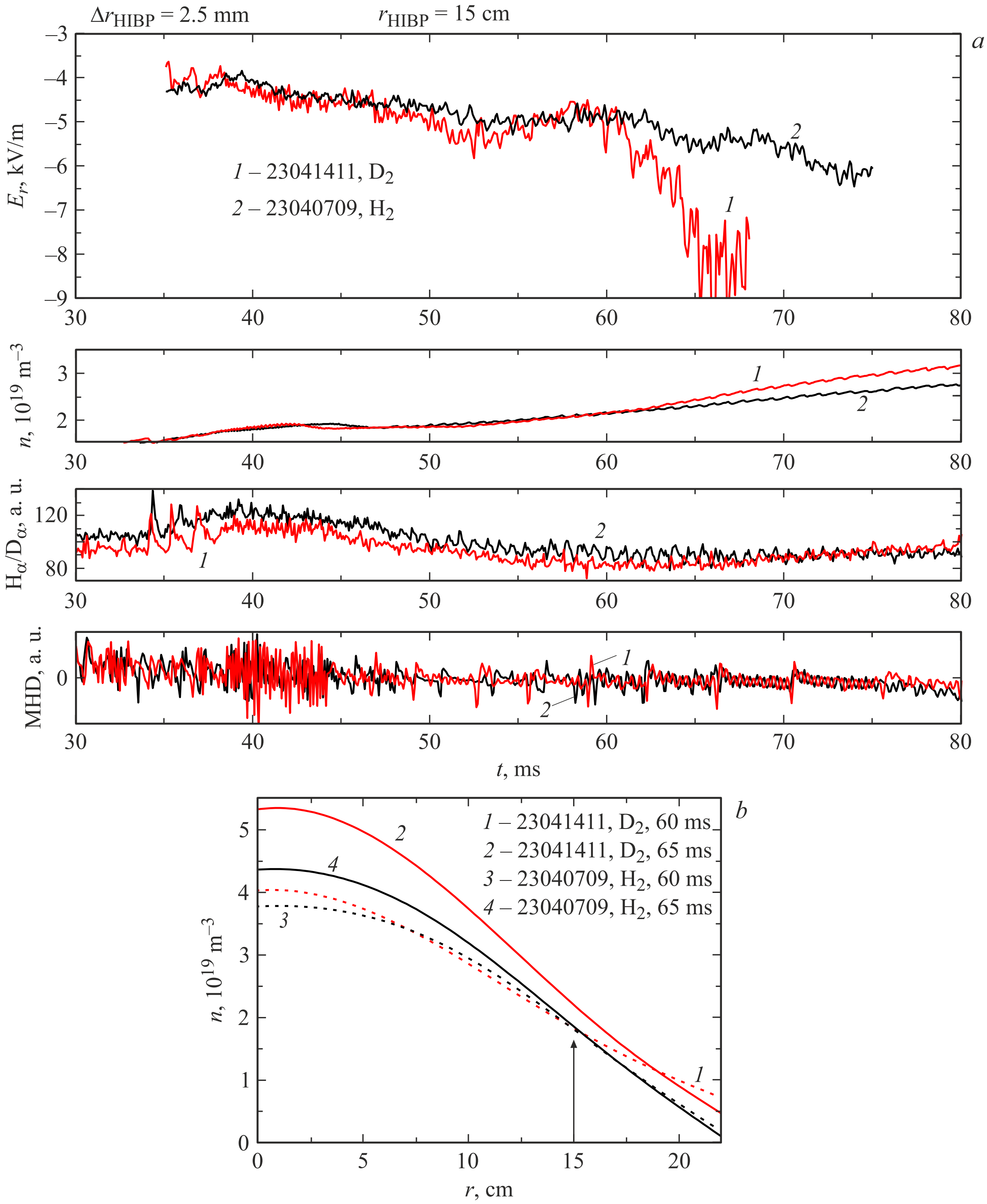

Figure 3. *a* — evolution of the radial electric field, line-averaged density, H_α/D_α line luminescence, and magnetohydrodynamic (MHD) activity in the deuterium (red lines *1*) and hydrogen (black lines *2*) high-density discharges; *b* — evolution of density profiles in the discharges under study. The colored figure is given in the electronic version of the paper.

in the mode of confinement. The contribution to the negative E_r in a deuterium discharge may be caused by both an increase in the density gradient in the measurement area and increase in the density itself, since the lower plasma density promotes generation of more positive values of E_r and plasma potential [10,11]. In the hydrogen discharge (lines *3, 4* in Fig. 3,*b*) both the density and the density gradient variation in the E_r measurement area are insignificant.

The studies of the plasma potential and radial electric field in the case of the neutral beam co-injection show that the plasma density plays a decisive role in terms of the neutral beam injection efficiency. When the plasma line-averaged density increases to $(2-3)\cdot 10^{19}\,\mathrm{m}^{-3}$, the toroidal plasma rotation gets generated during co-injection. Thereat, HIBP shows a positive plasma potential increment, which evidences the torque transfer from the beam to plasma and sufficiently low fast-particle loss.

The HIBP diagnostic was also used to perform for the first time direct measurements of the radial electric field in the two-point probe scheme in the TUMAN-3M discharge configuration corresponding to discharges with the neutral beam co-injection. The observed radial electric field magnitudes in the ohmic discharge match quite well the neoclassical values. The effect of density on the radial electric field magnitude is qualitatively consistent with theoretical concepts.

The measurements are consistent with data obtained in experiments with HIBP at the T-10 setups [12] (evolution of potential towards more negative values with increasing plasma density) and TJ-II setups [13] (evolution of potential towards more negative values during neutral injection). Notice that in experiments at the T-10 and TJ-II facilities there was also observed the potential evolution towards more positive values during ECR heating (ECR is the electron cyclotron resonance), which motivates further research.

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Conflict of interests

The authors declare that they have no conflict of interests.

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