Counter-NBI Assisted *LH* Transition in Low Density Plasmas in the TUMAN-3M

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Abstract. Paper reports observation of the *LH* transition at very low density in the experiments on counter-current Neutral Beam Injection (NBI) in the TUMAN-3M tokamak. The transition has been found at target average density as low as $0.5{\cdot}10^{19}$ m^{-3}. Low input power in these experiments should be noticed: $P_{input} \approx 1.3P_{OHM}$ < 240 kW. Contrary, in the case of co-current NBI the *LH* transition is difficult at low density. No transition is possible at the above density in the co-NBI heating scheme with P_{input} up to 500 kW. Model predicting generation of a negative (inward directed) radial electric field E_r, which is thought to help *LH* transition at low density, is suggested. The model conjectures the development of the E_r and toroidal rotation V_ϕ in the presence of large ion orbit losses in the counter-NBI scheme. Results of direct measurements of the plasma potential by Heavy Ion Beam Probe technique (HIBP) confirming negative E_r appearance in counter-NBI scenario are presented. Doppler spectroscopy of BIV impurity has shown an increase in the toroidal rotation of 15 km/s after application of the counter-NBI. The measured V_ϕ is in good agreement with the above model estimations.

1. Introduction

In order to obtain the *H*-mode in a tokamak certain threshold in the input power has to be exceeded. This threshold power P_{thr} is a critical parameter for designing of future devices and in particular fusion reactor ITER [1,2]. When density is above $\overline{n}_{e,\min}$ at which P_{thr} is minimal the commonly accepted scaling [2] predicts increase in the P_{thr} with the average density:

$$P_{thr} = 0.042 n_{20}^{0.73} B_t^{0.74} S^{0.98} \text{ (MW)}, \tag{1}$$

here: n_{20} – average density in 10^{20} m^{-3}, B_t – toroidal magnetic field in tesla, S – Last Closed Flux Surface area in m^2. The increase in P_{thr} with density imposes restrictions on *H*-mode accessibility in ITER at high density with planned auxiliary power, thus pushing forward concept of *H*-mode transition at lower density. On the other hand an increase in the P_{thr} towards low density, which is observed in many experiments [3,4,5,6], prevents the transition at lower $\overline{n}_e$ as well. Physics of the threshold power increase at low $\overline{n}_e$ is not well understood. Since radial electric field E_r and $E_r \times B$ sheared flow play important roles in the *LH* transition one could expect they effect transitions at low $\overline{n}_e$ also.

Generation of the radial electric field and toroidal rotation using counter-NBI has been studied in DIII-D [7]. In those experiments the clear effect of counter-NBI on E_r was observed, although V_ϕ and P_{thr} did not change compared to co-NBI setup. Recent experiments on DIII-D have shown essential reduction of P_{thr} (even below scaling prediction) with stepped lowering of co-injection torque [8]. Rotation driven by fast ions has been recently reconsidered theoretically [9].

Thus, the motivation of the presented study is to analyze role of the radial electric field and toroidal rotation produced by counter-NBI in the *LH* transitions at low density.

2. *H*-mode operational domain in the TUMAN-3M

In the TUMAN-3M (R_0 =0.53 m, a_l =0.22 m, B_T <0.9 T) the *H*-mode operational domain for typical scenarios of ohmic and co-current NBI heating [10,11] has a low density boundary of (1.2÷1.4)·10^{19} m^{-3}, as indicated by vertical solid line in FIG. 1. No transitions have been observed at densities below the boundary in these scenarios. Relatively high input power in the standard discharges should be noticed: P_{input} is by a factor of 5-15 higher than the threshold estimations from scaling [2].

In the very special cases of the *H*-modes produced with assistance of electrode bias or shallow pellet evaporation (squares and triangles on FIG. 1.), the transitions have been found at densities down to (0.6÷1.0)·10^{19} m^{-3} [12]. According to the theory developed in [12] in the electrode and pellet assisted *H*-modes an artificial radial electric field could help transition at lower densities.

In the recent experiments on NB injection in the counter-current direction (B_T =0.68 T, I_p =140 kA, E_0 = 20 keV) the *H*-mode transition at target density as low as 0.5·10^{19} m^{-3} has been found (stars in FIG. 1.). Typical example of the discharge with the transition is presented in Fig.2. The transition occurred shortly after counter-NBI switch-on and is definitively linked to NBI application. Density and D_α traces in FIG. 2. indicate substantial increase in the particle confinement time. Two-fold increase in the energy confinement time was deduced from diamagnetic measurements. It is unlikely that the increase in the absorbed power ΔP_{abs} causes the transition, since: (1) according to ASTRA transport simulations in the counter-NBI scenario ΔP_{abs}(NBI) is small (< 20 kW ≈ 10% P_{OHM}), (2) co-NBI does not trigger the transition at low $\bar{n}_e$ even with ΔP_{abs}(NBI) = 200 kW ≈ P_{OHM}. Thus, other reason allows the *LH* transitions at low density with counter-NB injection.

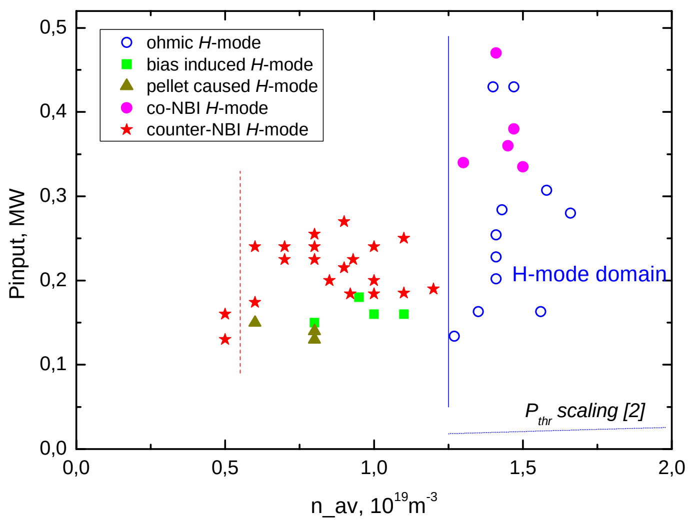

FIG. 1. Input power as a function of average density at the LH transition time in various operational modes in TUMAN-3M. Vertical lines indicate density boundary for LH transitions: solid line – Ohmic and co-NBI plasmas, dotted line – counter-NBI heated plasmas.

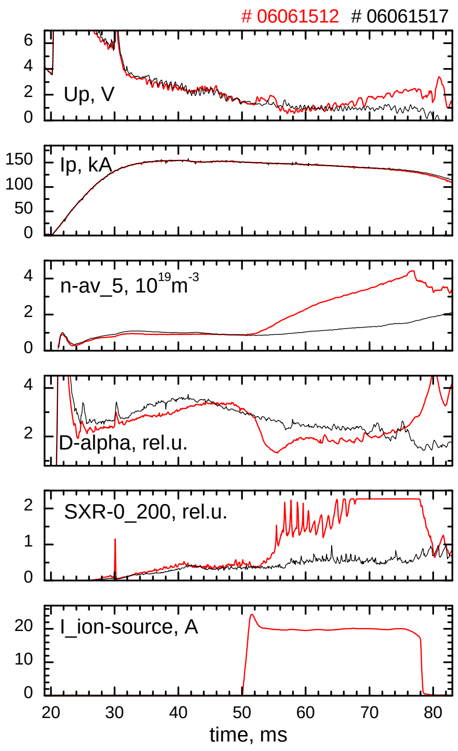

FIG. 2. Example of the H-mode transition (shot #06061512) triggered by counter-NBI at density $0.8 \cdot 10^{19}$ m^{-3}. Shot #06061517 – w/o NBI. Top to bottom: loop voltage, plasma current, density, D_α emission, soft X-ray radiation and ion source current (indicative of NBI duration).

2. Measurements of plasma potential and toroidal rotation

In order to get an idea on radial electric field evolution in the above scenario the Heavy Ion Beam Probe diagnostic was employed. HIBP setup was chosen to follow central plasma potential $\Delta\Phi(0)$. The potential drop of up to 400 V was found in the counter-NBI heating scheme, see FIG. 3. The measurement allows estimating $E_r \approx \Delta\Phi/(a_l/2) \approx 4 \cdot 10^3$ V/m. The estimation gives lower value for E_r, based on assumption of uniform E_r distribution within outer half of minor radius. It should be mentioned that in the TUMAN-3M the *H*-mode

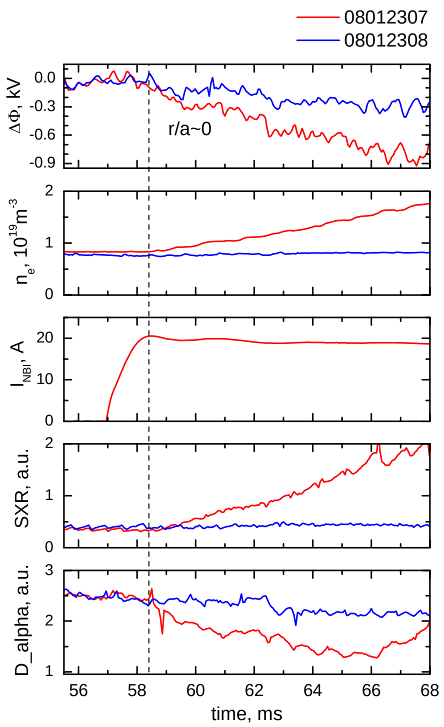

FIG. 3. Evolution of plasma potential measured in the shots with low density LH transition in the presence of counter NBI (# 08012307) and w/o transition (# 08012308). Top to bottom: core potential, average density, ion source current, soft X-Ray radiation, D_α emission.

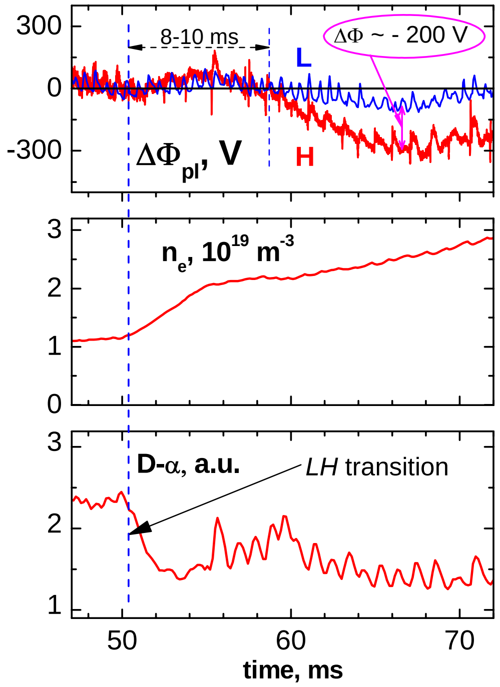

FIG. 4. Evolution of plasma potential measured in the ohmic H-mode (red curve) and in the ohmic L-mode (blue curve). Top to bottom: core potential, average density, D_α emission. Notice, the drop in the potential is lower than in counter NBI scenario, shown on Fig3.

transition itself (ohmic *H*-mode without influence of counter-NB injection) results in some drop in the potential. Example of the potential behavior during the ohmic *H*-mode transition is given in FIG. 4. Here, the potential drop is substantially lower: 200 V and, contrary to NBI case, appears with noticeable delay of approximately 8-10 ms. Difference in the ΔΦ(0) evolution in two scenarios suggest the direct effect of counter-NBI on the core plasma potential and possibly on the radial electric field.

Doppler spectroscopy was used for measurement of toroidal velocity V_ϕ of Boron and Carbon impurity ions (BIV line: λ=282,2 nm and CIII line: λ=464,7 nm). According to our estimations maximum brightness of BIV is located at r = 0.6a and maximum brightness of CIII is nearby 0.9a. Thus, the measured shifts provide data on V_ϕ in corresponding locations. Performed measurement has shown 15 km/s increase in the BIV torodal velocity in the counter-current direction following NBI application, see FIG. 5, and negligible effect on CIII toroidal velocity. The data might be considered as indication of bell-shaped radial distribution of toroidal velocity. If that's the case the central velocity of up to 30 km/s might be expected.

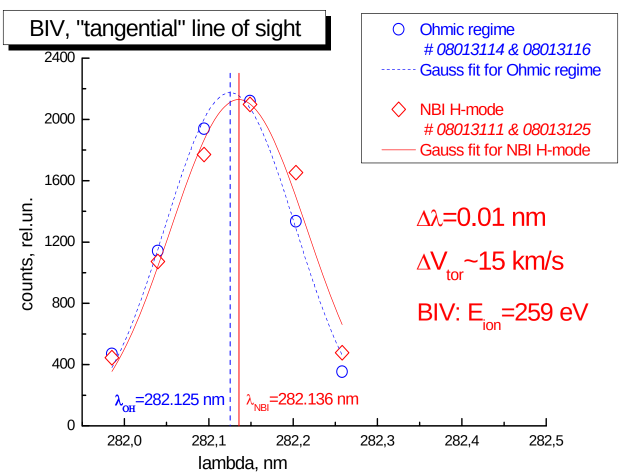

FIG. 5. Measurement of toroidal velocity using Doppler spectroscopy of BIV line (λ=282,2 nm). Increase in the toroidal velocity of 15 km/s have been detected.

3. Discussion

Observations of plasma potential and toroidal rotation presented in the preceding section could be understood in the framework of the following model. Under the conditions of counter-NBI a large amount of fast ions is captured on unconfined orbits. Fast losses of the ions produce radial current, which in our case is estimated as ~10 A. Quasineutrality condition requires fast ion radial current must be balanced by return current I_{ret} flowing in the opposite direction through the plasma. I_{ret} is carried by main ions and is equal to fast ion current. Ampere force $I_{ret} \times B_\theta$ results in torque generation in the counter-current direction. The torque spins up toroidal rotation. Resulting toroidal rotation can be estimated using the following expression:

$$\left[I_{ret} \times B_\theta\right] \cdot \delta r = (m_i \cdot n \cdot V_{pl} \cdot V_\phi) / \tau_\phi \,, \qquad (2)$$

where $\delta r = a - r_{FI}$, r_{FI} – average radius of capture points on unconfined orbits, V_{pl} – plasma volume, τ_ϕ – toroidal momentum confinement time.

Assuming τ_ϕ = τ_E the estimation of toroidal rotation velocity V_ϕ ≈ 30 km/s could be obtained. This value is in reasonable agreement with the Doppler spectroscopy data. Presuming Lorentz force $V_\phi \times B_\theta$ is balanced by the radial electric field the estimation of E_r = - $5{\cdot}10^3$ V/m is obtained. This quantity agrees well with E_r obtained by HIBP measurement ($4{\cdot}10^3$ V/m).

Thus, the model predicts that the large losses of fast ions produce substantial plasma rotation in the counter-current direction (in our geometry counter-current direction corresponds to co-NBI direction) and negative radial electric field. Toroidal rotation and radial field facilitate *LH* transition at low density.

4. Summary

LH transitions at very low density (down to $0.5{\cdot}10^{19}$ m^{-3}) in the counter-NBI experiment have been observed. According to the suggested model the large fast ion losses in this scenario cause substantial toroidal rotation and radial electric field which are thought to help *LH* transition. Measured rotation velocity and plasma potential are in agreement with the model predictions.

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