ROLE OF RADIAL ELECTRIC FIELD IN *LH* TRANSITION TRIGGERED BY COUNTER-NBI AT LOW PLASMA DENSITY IN THE TUMAN-3M TOKAMAK

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Threshold power needed to attain *H*-mode in a tokamak is a critical parameter for designing of future devices and in particular fusion reactor ITER [1]. According to commonly accepted scaling [2] the threshold power P_{thr} increases with average density n_e when the density exceeds some $n_{e\ min}$ at which P_{thr} is minimal. An increase in the P_{thr} towards low density was observed in many experiments [3-6], prevents the transition at lower n_e as well. Physics of the threshold power increase at low n_e is not well understood. Since the radial electric field E_r and $E_r \times B$ sheared flow play important roles in the *LH* transition one could expect these quantities effect the low $\bar{n}_e$ transitions. Toroidal rotation and radial electric field generation during counter-NBI have been studied in [7] and recently reconsidered theoretically in [8]. Thus, motivation for the presented study is to analyze effect of counter-NBI on the *LH* transition at low density.

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1. H-MODE TRIGGERING BY COUNTER-*NBI* AT LOW PLASMA DENSITY

In the TUMAN-3M (R_0=0.53 m, a_l=0.22 m, B_T<0.9 T) no transitions were observed at densities below density boundary of (1.2–1.4)·10^{19} m^{-3} in ohmic and co-NBI heating schemes [9,10]. The *H*-mode operational domain is presented in Fig.1 where vertical solid line indicates the density boundary for the heating schemes mentioned above. Relatively high input power should be noticed: P_{input} is by a factor of 6-20 higher than the threshold estimations from scaling [2]. On the other hand, LH transitions at low densities down to (0.6–0.9)·10^{19} m^{-3} were found in the TUMAN-3M in the experiments with electrode bias or with shallow pellet evaporation (squares and triangles on Fig.1) [11].

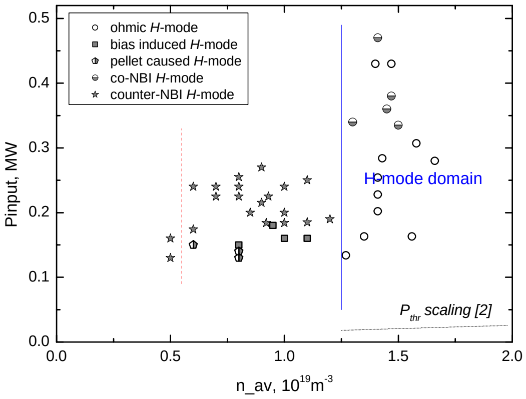

Fig.1. Input power as a function of average density at the LH transition time in various operational modes in TUMAN-3M. Vertical lines indicate density boundary for LH transitions: solid line – ohmic and co-NBI, dotted line – counter-NBI heated plasmas

According to [11] in these cases an artificially induced E_r could cause the transition at lower density.

In the recent experiments on counter-NBI (B_T=0.68 T, I_p=140 kA, E_0=20 keV) the *LH*-transition at target density as low as 0.5·10^{19} m^{-3} was 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: a time delay in the NB injection start resulted in corresponding delay in *LH*-transition. The transition indication is the D_α drop accompanied by the density rise, which demonstrate an increase in particle confinement time. Two-fold increase in energy confinement time was also found by diamagnetic measurements.

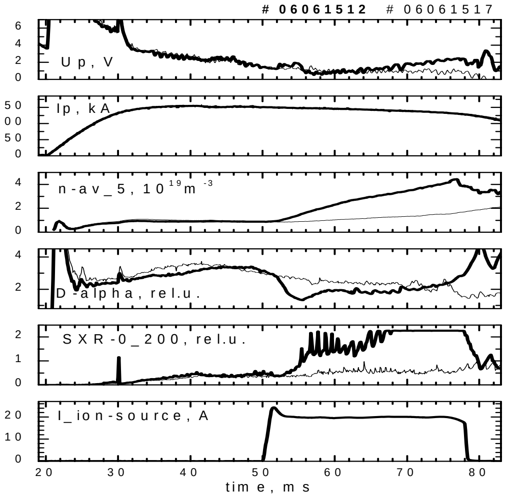

Fig.2. Example of the H-mode transition (shot #06061512 – bold curves) triggered by counter-NBI at density 0.8·10^{19} m^{-3}. Shot #06061517 (thin curves) – w/o NBI. Top to bottom: loop voltage, plasma current, density, D_α emission, soft X-ray radiation and ion source current (indicative of NBI duration)

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 $\overline{n}_e$ even with ΔP_{abs}(NBI) = 200 kW ≈ P_{OHM}. Thus, other reason allows the density boundary to move towards lower $\overline{n}_e$.

The effect of NBI direction on the *LH* threshold power has been reported recently [12].

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 adjusted the way to follow central plasma potential ΔΦ(0). The potential drop down to 400 V was found in the counter-NBI heating scheme, see Fig.3.

Estimation of corresponding radial electric field gives $E_r \approx \Delta\Phi/(a_l/2) \approx 4\cdot 10^3$ V/m, assuming uniform E_r distribution within an outer half of the minor radius. It should be mentioned that *H*-mode transition itself (without influence of counter-NB injection) results in some drop in the potential. Example of the potential evolution during the ohmic *H*-mode transition is given in Fig.4. Noteworthy, in ohmic H-mode 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 to estimate toroidal velocity V_φ of Boron and Carbon impurity ions (BIV line: λ=282.2 nm and CIII line: λ=464.7 nm). The line of sight was directed almost parallel with the NBI direction, thus allowing estimation of Doppler shifts caused by toroidal rotation of the radiating impurity. According to our estimations maximum brightness of BIV is located at r = 0.6 a (a - minor radius) and maximum brightness of CIII is nearby 0.9 a. Thus, the measured Doppler shifts provide data on V_φ in corresponding locations. It was found (see Fig.5) that counter-NBI was accompanied by the Doppler shift of BIV line corresponding to V_φ~15 km/s in the counter-current direction whereas an effect on CIII was negligible. The results may indicate a bell-shaped radial distribution of toroidal velocity. Under this assumption the central toroidal velocity up to 30 km/s can be expected.

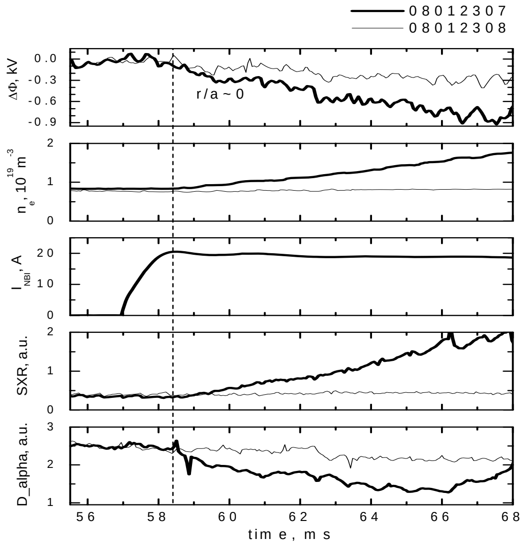

Fig.3. Evolution of plasma potential measured in the shots with low density LH transition in the presence of counter NBI (# 08012307, bold curves) and w/o transition (# 08012308, thin curves). Top to bottom: core potential, average density, ion source current, soft X-Ray radiation, D_α emission

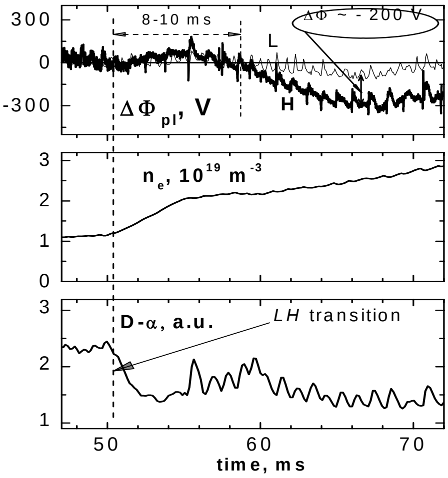

Fig.4. Evolution of plasma potential measured in the ohmic H-mode (bold curve) and in the ohmic L-mode (thin curve). Top to bottom: core potential, average density, D_α emission. Notice, the drop in the potential is lower than in counter NBI scenario, shown on Fig. 3

3. DISCUSSION AND SUMMARY

The results on plasma potential and toroidal rotation measurements presented above could be understood in the framework of the following model. In the counter NBI scheme a large amount of fast ions is captured on unconfined orbits. According to ASTRA code modeling of the experiment, about 50% of the injected deuterium atoms are captured on unconfined orbits after the ionization. Fast losses of these ions produce radial current, which in our case is ~10 A. Quasineutrality condition requires return current I_{ret} in the opposite direction (inside the plasma). Ampere force $I_{ret}\times B_\theta$ results in torque generation in the counter-current direction. Arising toroidal rotation can be estimated using the following expression:

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

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, $\overline{n}$ – plasma density. Assuming $\tau_\varphi = \tau_E$ the estimation for the toroidal velocity is $V_\varphi \approx 30$ km/s, which is in reasonable agreement with the Doppler spectroscopy data presented above. According to radial forces balance equation the Lorentz force $V_\varphi \times B_\theta$ increase due to V_φ rise may result in radial electric field rise. The estimation gives: $E_r = -5 \cdot 10^3$ V/m. The result agrees well with the E_r estimation ($\sim 4 \cdot 10^3$ V/m) based on the HIBP measurements of plasma potential (see section 2).

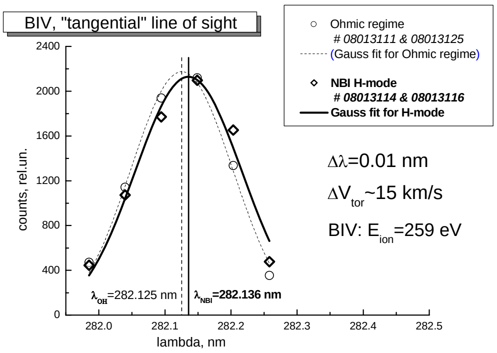

Fig.5. Measurement of toroidal velocity using Doppler shift of BIV line (λ=282,2 nm). Increase in the toroidal velocity of 15 km/s has been detected

So, the presented experimental results on plasma potential and toroidal rotation at very low density (down to $0.5 \cdot 10^{19}$ m^{-3}) in the counter-NBI experiment agree with the suggested model of rotation and radial electric field generation in presence of large ion orbit losses. The radial electric field and, possibly, sheared rotation can help *LH* transition at low density in the counter-NBI experiments.

ACKNOWLEDGEMENTS

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РОЛЬ РАДИАЛЬНОГО ЭЛЕКТРИЧЕСКОГО ПОЛЯ В *LH*-ПЕРЕХОДЕ, ВЫЗВАННОМ КОНТР-ИНЖЕКЦИЕЙ ПРИ НИЗКОЙ ПЛОТНОСТИ ПЛАЗМЫ НА ТОКАМАКЕ ТУМАН-3М

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Пороговая мощность P_{thr}, необходимая для перехода в *H*-режим, является критическим параметром при проектировании термоядерных установок, в том числе реактора ITER [1]. В соответствии с общепринятым скейлингом [2] P_{thr} увеличивается с ростом средней плотности плазмы n_e, если n_e превосходит некоторое значение, при котором P_{thr} минимальна. Увеличение P_{thr} при низких плотностях также наблюдалось во многих экспериментах [3-6]. Физика этого явления до конца не выяснена. Однако, учитывая тот факт, что радиальное электрическое поле E_r и $E_r \times B$ вращение плазмы играют важную роль в механизме *LH*-перехода, можно ожидать, что эти факторы влияют и на *LH*-переход при низких плотностях. Явления тороидального вращения плазмы и появления E_r во время контр-инжекции пучка нейтральных атомов были недавно исследованы как экспериментально [7], так и теоретически [8]. Целью представляемой работы является анализ влияния контр-инжекции на процесс *LH*-перехода при низкой плотности.

РОЛЬ РАДІАЛЬНОГО ЕЛЕКТРИЧНОГО ПОЛЯ В *LH*-ПЕРЕХОДІ, ВИКЛИКАНОМУ КОНТР-ІНЖЕКЦІЄЮ ПРИ НИЗЬКІЙ ЩІЛЬНОСТІ ПЛАЗМИ НА ТОКАМАЦІ ТУМАН-3М

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Гранична потужність P_{thr}, необхідна для переходу в *H*-режим, є критичним параметром при проектуванні термоядерних установок, у тому числі реактора ITER [1]. Відповідно до загальноприйнятого скейлинга [2] P_{thr} збільшується з ростом середньої щільності плазми n_e, якщо n_e перевершує деяке значення, при якому P_{thr} мінімальна. Збільшення P_{thr} при низьких щільностях також спостерігалося в багатьох експериментах [3-6]. Фізика цього явища до кінця не з'ясована. Однак, з огляду на той факт, що радіальне електричне поле E_r і $E_r \times B$ обертання плазми відіграють важливу роль у механізмі *LH*-переходу, можна очікувати, що ці фактори впливають і на *LH* перехід при низьких щільностях. Явища тороїдального обертання плазми і появи E_r під час контр-інжекції пучка нейтральних атомів були недавно досліджені як експериментально [7], так і теоретично [8]. Метою роботи, що представляється, є аналіз впливу контр-інжекції на процес *LH*-переходу при низькій щільності.