Study of NBI-caused *LH* transition at low density in the TUMAN-3M tokamak

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It is a well-known experimental fact that high heating power is an important ingredient for achieving the transition to high confinement mode in tokamaks. Vast majority of the experiments led to a scaling law for *H*-mode heating power threshold [1] $P_{thr} = 0.042 n_{20}^{0.73} B_T^{0.74} S^{0.98}$, here: P_{thr} in MW, n_{20} – average density in 10^{20} m^{-3}, B_T – toroidal magnetic field in T, S – area of the LCFS in m^2, factor 0.42 is derived for deuterium plasmas. This scaling describes well the required heating power behavior with density, toroidal magnetic field and plasma size, provided that plasma density exceeds some minimum value n_{min}. When plasma density is close or below n_{min}, P_{thr} increases dramatically, hampering the *LH* transition or even making it impossible [2,3,4,5]. Physical mechanisms underlying the above scaling, as well as increase in P_{thr} towards lower density, are not clear yet. Since *H*-mode is crucial for plasma performance in future thermonuclear reactor, i.e. ITER, it is essential to investigate processes responsible for *H*-mode power threshold. In the present paper an attempt is made to study physics behind the *LH* transition at low density.

Generally accepted paradigm states that the *LH* transition is a result of turbulent transport suppression by sheared rotation caused by $\boldsymbol{E_r}\times\boldsymbol{B}$ drift. Extensive experimental and theoretical investigation evidences to this point of view [6,7,8,9]. In the frame of this approach, plasma heating leads to E_r generation, and when $|dE_r/dr|$ is strong enough, confinement bifurcation (*LH* transition) takes place. On the other hand, if radial electric field and/or plasma rotation is created by an external source, i.e. using edge plasma polarization by a biased electrode, *LH* transition is possible without increase in plasma heating, even at low density [6,9]. Figure 1 shows operational domain of the TUMAN-3M tokamak (R_0=0.53 m, a_l=0.22 m, B_T<0.9 T) [10]. It is seen that in all the regimes heating power exceeds significantly the scaling predictions. It is natural for a small aspect ratio tokamak like the

TUMAN-3M (R/a=2.4), for high plasma current (I_p≤180kA) may be achieved at relatively low magnetic field and small plasma size. However, in spite of abundant heating power, there is some additional requirement for the *LH* transition to occur in the TUMAN-3M. It is seen that in OH [11] and Co-NBI heating [12] experiments the necessary condition for *H*-mode existence is plasma density exceeding n_{lim}~1.25×10^{19}m^{-3}. This low density limit may be shifted further to lower densities in scenarios with pellet-assisted *H*-mode (n_{lim}~$0.6\div0.8\times10^{19}$m^{-3}) [9] or edge plasma biasing (n_{lim}~0.8×10^{19}m^{-3}). Note that the both scenarios feature no increase in heating power as compared to OH regime. On the other hand, an additional radial electric field is generated in these experiments by an external source (biasing) or by the increase in edge density gradient (pellet).

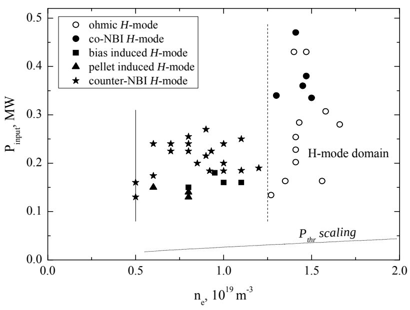

Figure 1. TUMAN-3M *H*-mode domain

In the Counter-NBI scenario (B_T=0.68 T, I_p=140 kA, E_0=20 keV) the lowest possible plasma density in which *LH* transition takes place is n_{lim}~0.5×10^{19}m^{-3}. Typical evolution of some key plasma parameters is shown in figure 2. The transition occurred shortly after Counter-NBI switch-on and is definitively connected with NBI application. Density and D_α traces in figure 2 indicate substantial increase in the particle confinement time. Two-fold increase in the energy confinement time was deduced from diamagnetic measurements. In this configuration of the experiment plasma heating by atomic beam is extremely ineffective. First of all, about 40% of beam power is lost to the wall due to the shine-through losses because of low density. Another 50% is attributed to the first orbit losses caused by very bad confinement of fast ions. In total, only 20kW of beam power is absorbed; this is less the 10% of ohmic heating power. It should be mentioned that in Co-NBI scenario total heating power (ohmic plus NBI) is up to 500kW, however the *LH* transition is impossible at densities below n_{lim}~1.25×10^{19}m^{-3}. So, at low plasma density, realization of the *LH* transition is defined not by plasma heating but by some other mechanism, the main candidate for which is the radial electric field generation.

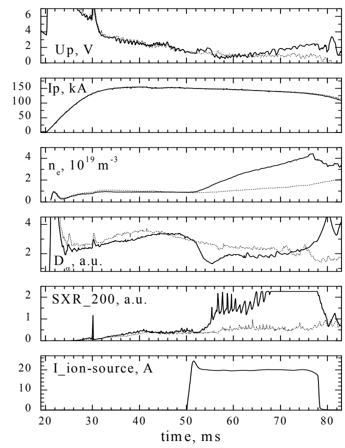

Figure 2. Time evolutions of key plasma parameters in the *H*-mode caused by Counter-NBI pulse

In order to clear up the role of the radial electric field in these experiments, measurements of central plasma potential evolution (using HIBP diagnostic [13]) and edge radial electric field and its fluctuation (electrostatic probes) have been performed. Figure 3 presents central plasma potential Φ_{pl} evolution measured in ohmic and Counter-NBI shots. Note that the diagnostic was not absolutely calibrated, so the signals obtained in OH and Counter-NBI shots were aligned to give the same value of the potential in pre-NBI phase of the shots, and the potential difference $\Delta\Phi_{pl}$ between the two shots is plotted in the figure. As it is seen, simultaneously with the *LH* transition in Counter-NBI shot, plasma potential starts to depart from its OH value, and this potential difference is negative and increase gradually up to $\Delta\Phi_{pl}$=–400V. It may be interpreted in terms of negative radial electric field generation in a region between plasma wall and radial location of beam ionisation point (~a_l/2) $\Delta E_r \approx \Delta\Phi/(a_l/2) \approx -4\cdot 10^3$ V/m. It interesting to note that in the ohmic *H*-mode shot central potential evolution is much slower, and significant potential difference between L- and *H*-mode plasma appears with τ~8ms delay [14], whereas in Counter-NBI shot this delay is very small τ~0. So, it may be speculated that Counter-NBI, even though doesn't heat the plasma, creates strong negative radial electric field, which is responsible for anomalous transport suppression and *LH* transition development. The probe measurement data evidence to this idea. It was found, that immediately after the transition both the edge floating potential and radial electric field drops, absolute value of peripheral radial electric field change is ΔE_r ~ 4 kV/m, this is in agreement with the HIBP data. In figure 4 the results of edge plasma floating potential fluctuation measurement are presented. As it is seen, the R.M.S. of the floating potential fluctuations drops very fast after the Counter-NBI pulse application, probably even ~0.5ms before the *LH* transition. This supports the hypothesis of edge E_r generation and turbulent transport suppression by the Counter NBI pulse.

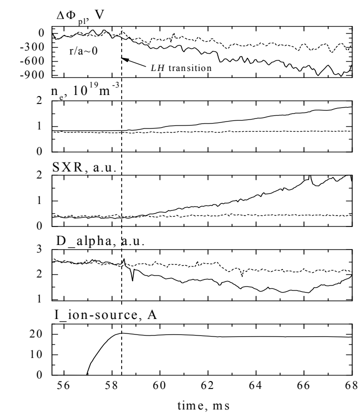

Figure 3. Time evolution of central plasma potential in the *H*-mode caused by Counter-NBI pulse

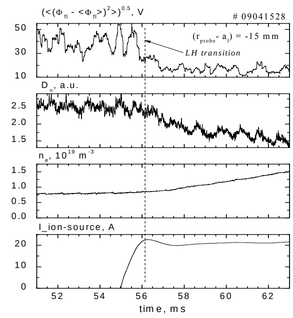

Figure 4. Time evolution of R.M.S of edge plasma potential fluctuations in the *H*-mode caused by Counter-NBI pulse

Is it was mentioned above, plasma heating is weak in Counter-NBI scenario, and could not be directly responsible for the *LH* transition triggering. Possible mechanism of E_r

generation by Counter-NBI may be connected with first orbit losses of fast ions. There is a radial current density J_r attributed to this channel of ion losses, which must be compensated by transverse conductivity current density $J_\perp = -J_r$ to sustain quasi-neutrality. In turn, to drive this current a radial electric field E_r should be generated, according to Ohm's low $J_\perp = \sigma_\perp (E_r - E_r^{neo})$, here neoclassical radial electric field $E_r^{neo} = (T_i/e)(\nabla n/n + k\nabla T_i/T_i)$, $\sigma_\perp$ is transverse specific conductivity, parameter k depends on collisionallity regime. These two currents, $J_\perp$ and J_r, are carried by different sorts of particles: J_r – by unconfined fast iones, $J_\perp$ - by thermal ions. As a result of this, the toroidal component of Amper's force applied to the latter must drive toroidal rotation of the main ions, see [15] for theoretical detail. A simple estimation based on toroidal force balance gives the toroidal rotation velocity due to this effect $V_\phi = (I_\perp B_\theta \delta r \tau_\phi)/(m_i \bar{n} V_{pl})$, here $I_\perp$ is the total fast ion losses current through the plasma surface, B_θ – poloidal magnetic field, $\delta r = a_l - r_{FI}$, r_{FI} – average radius of capture points on unconfined orbits, which was taken $a_l/2$, m_i – mass of ions (deuterons), $\bar{n}$ – average ion density, V_{pl} – plasma volume, momentum confinement time $\tau_\phi \sim \tau_E$. For the conditions of the TUMAN-3M experiment this estimation gives V_ϕ~30km/s. This is close to Doppler spectroscopy data $V_\phi^{Doppler}$~16km/s [14]. Value of the radial electric field predicted by this model is E_r~5kV/m, which is in good agreement with HIBP results.

Acknowledgements

The work was supported jointly by RAS Basic research program №30, RF Ministry of science and education state contract № 02.518.11.7112 and by Russian Foundation for Basic Research: Grant № 10-02-01414.

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