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LH-transition initiation and dynamics in a conventional tokamak

Gulnara Abdullina[1], Leonid Askinazi [1], Alexander Belokurov [1,2 a)], Victor Bulanin[2], Laurent Chôné [3], Alexei Gurchenko[1], Evgenii Gusakov[1], Timo Kiviniemi [3], Vladimir Kornev[1], Sergei Krikunov[1], Denis Kouprienko[1], Sergei Lashkul[1], Sergei Lebedev [1], Susan Leerink [3], Paavo Niskala[3], Alexander Petrov[2], Alexander Tukachinsky [1], Alexander Yashin[2], Nikolai Zhubr [1]

1 Ioffe Institute, Politeknicheskaya 26, Saint-Petersburg, 194021 Russia
2 Peter the Great Polytechnic University, Politeknicheskaya 29, Saint-Petersburg, 195251 Russia
3 Aalto University, Otakaari 24, Espoo, 11000 Finland

[a)]Corresponding author: belokurov@mail.ioffe.ru

Abstract. Radial electric field shear is crucial for turbulence suppression and transition to the H-mode, although the high shear value alone may not be sufficient for the LH-transition initiation. Temporal and spatial parameters of shear perturbation, particle source and turbulence parameters are the main factors responsible for LH-transition initiation. Different plasma discharge scenarios in two Ioffe Institute conventional tokamaks are analyzed using the model of plasma density and ion temperature evolution to clear up the role of aforementioned factors.

INTRODUCTION

Initiation of transition to improved confinement mode, or H-mode [1] (LH-transition) is an important task of fusion technology, and the role of different factors responsible for LH-transition initiation should be determined.

Radial electric field inhomogeneity, or shear, ω_{ExB}, is the crucial factor for turbulent transport suppression, which could result in LH-transition initiation [2]; turbulence suppression occurs if $\gamma < \omega_{ExB}$ [3], where γ is turbulence growth rate. Another factor necessary for LH-transition is threshold heating power [4,5] and threshold density (and thus particle source) [1,6].

Experiments on Ioffe Institute tokamaks TUMAN-3M and FT-2 provide wide range of scenarios with radial electric field and particle source perturbation [6, 7-11]. The interplay between the particle and heat source, E_r shear and turbulence level could be analyzed using the theory of LH-transition initiation [12]. According to this theory, to initiate LH-transition required are: 1) value of E_r shear exceeding turbulence growth rate; and 2) particle source level high enough to provide stabile solutions.

Diffusion coefficient is accepted in the form (1) [13]:

$$D_{eff}(r,t) = D_{ANO}(r)\cdot\left(k(r)+\frac{1}{1+\left(\omega_{E\times B}(r,t)/\gamma\right)^2}\right)$$

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Here $k(r)$ is ratio of suppressed and unsuppressed (anomalous) diffusion coefficients. In the stationary case particle flux dependency on density gradient $\Gamma(\partial n/\partial r)$ using this form of diffusion coefficient could be graphically represented as non-linear so called "N-curve" [12] with asymptotes representing anomalous and suppressed diffusion levels. Number of solutions of stationary particle diffusion equation represents possible confinement regimes: in case of single solution it could be only L-mode or H-mode, in case of three solutions confinement regimes bifurcation is possible.

One of the less investigated scenarios is a regime with geodesic acoustic mode (GAM): GAM could initiate LH-transition under special conditions, depending on GAM and plasma parameters [14]. In FT-2 low-density regimes with GAM LH-transition was not observed [14]. Another scenario is pellet-injection in TUMAN-3M [11].

To understand an interplay of different factors, a numerical model was developed [11, 14].

GAM SCENARIOS

GAM oscillations are observed in low-density discharges in TUMAN-3M [7, 8] and FT-2 [9, 10] tokamaks. GAM in TUMAN-3M usually exist as a series of short bursts; in most GAM discharges LH-transition is observed, simultaneous with GAM decay. In FT-2 GAM usually exist through the whole discharge, no LH-transition is observed.

In the model [14] particle diffusion coefficient was considered in a form (1) considering turbulence suppression by E_r shear. Stationary L-mode was chosen as initial state for the modeling. GAM oscillating radial electric field was represented as $E_{GAM}(r,t) = E_{GAM}\cos(2\pi ft - \frac{2\pi}{\lambda}r)\exp\left(-\frac{(r-r_0)^2}{w^2}\right)$. Parameters of oscillating field: amplitude E_{GAM}, frequency f, radial wavelength λ, spatial localization (r_0 and w); GAM existed during the time t_{GAM}.

Gyrokinetic simulation with ELMFIRE [15] code for TUMAN-3M and FT-2 tokamaks shows that in the presence of GAM diffusion coefficient does oscillate with GAM frequency. Also, gyrokinetic ELMFIRE simulation provides the turbulence parameters used for the modeling of density profile evolution.

Experiments show that in TUMAN-3M GAM manifest as a series of short bursts with duration 0.1 - 0.5 ms [16]. One of the characteristic LH-transition scenarios is a burst series with variable GAM frequency. Another scenario is long sequence of GAM burst series with about 0.2 ms duration and 1 ms period; amplitude of GAM varies with 5 ms period. For the first scenario (fig. 1 a) modeling shows that in case of decreasing frequency mean density gradient grows from burst to burst, leading to LH-transition. If in the same scenario frequency is manually made constant, no transition occurs. For the second scenario (fig. 1 b) evolution of density gradient from the beginning of GAM activity to LH-transition lasts approximately 30 ms. This duration is in a good agreement with experiment. If GAM amplitude is manually changed, than in case of higher amplitude LH-transition occurs earlier, in case of lesser amplitude LH-transition does not occur.

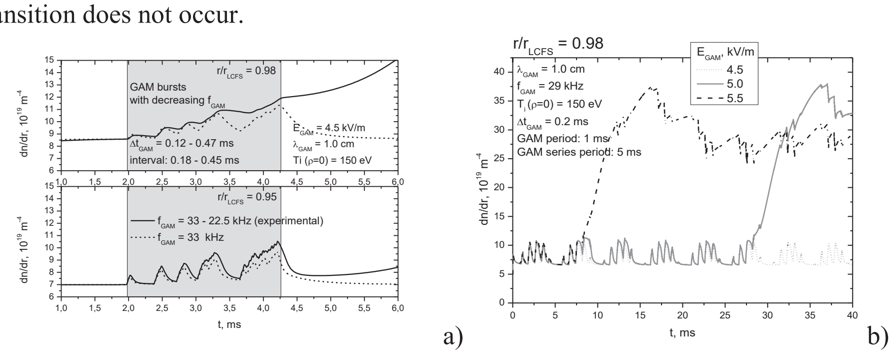

FIGURE 1. a) Evolution of peripheral density gradient under the effect of short GAM burst series with varying frequency (TUMAN-3M). Decreasing GAM frequency plays crucial role in LH-transition initiation. b) Evolution of peripheral density gradient under the effect of complex GAM evolution (TUMAN-3M). Mean Er "build up" exceeding the relaxation between GAM burst series is necessary for LH-transition initiation.

For FT-2 tokamak, as the modeling shows [14], LH-transition does not occur for experimental GAM parameters, and also for the GAM with amplitude and duration significantly exceeding the experimental values. This result is in agreement with experimental observations: in FT-2 tokamak in low density discharges the LH-transition was never observed.

According to theoretical considerations discussed above, the reason for the presence of H-mode in one case and absence of H-mode in the other case could be the value of particle source, which defines possible stationary confinement regimes. In fig. 2 non-linear $\Gamma(\partial n/\partial r)$ curves for TUMAN-3M and FT-2 are presented in the point of GAM maximum where the formation of transport barrier is most possible. One can see that for TUMAN-3M two stationary solutions for two confinement regimes are possible. For FT-2 tokamak integral particle source intersects $\Gamma(\partial n/\partial r)$ curve in only one L-mode point.

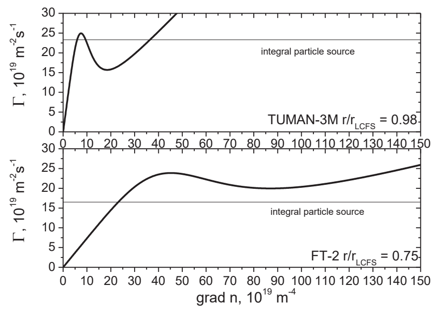

FIGURE 2. Local non-linear flux dependency on density gradient for TUMAN 3-M and FT-2 low density GAM scenarios. Two stationary solutions are possible for TUMAN-3M, only stationary L-mode is possible for FT-2.

PELLET INJECTION SCENARIOS

In case of pellet evaporation in plasma all the parameters responsible for LH-transition (E_r, particle and heat source and turbulence parameters) are perturbed.

Fuel pellet tangential injection was performed in TUMAN-3M tokamak [11,17], two characteristic scenarios with confinement improvement were observed: if pellet was partially broken up in the pellet-guide and gas cloud was injected in plasma alongside with pellet, LH-transition occurred. In case of deeper evaporation of solid pellet only transient confinement improvement was observed.

These two cases were modeled [11]. In the model turbulence suppression affects only particle diffusion, ion heat conductivity is considered neoclassical. Electron temperature was considered constant and not affected by the pellet.

Modeling results have shown that in the first case gas cloud accompanying pellet penetration plays crucial role in LH-transition initiation (fig. 3 a). Gas increases particle source so the value of particle source becomes large enough to provide the existence of two stationary solutions of diffusion equation (see N-curve in fig. 4). In the second case with deeper pellet evaporation area with steep gradient exists during the pellet evaporation process; afterwards it decays to initial state (fig. 3 b). N-curve in fig. 4 shows that only L-mode is possible.

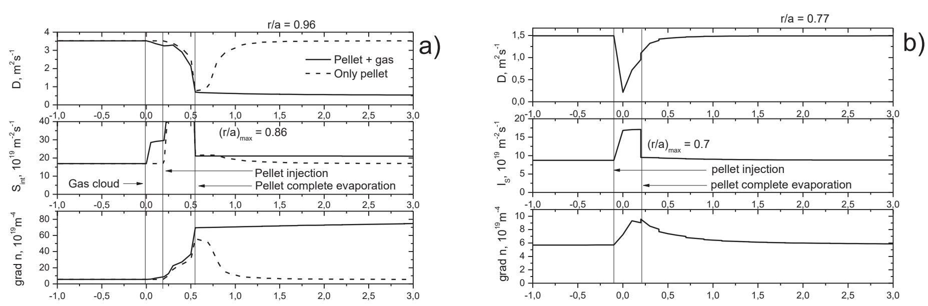

FIGURE 3. Evolution of peripheral density gradient under the effect of pellet injection (TUMAN-3M): a) LH-transition scenario; b) transient confinement improvement scenario. Peripheral evaporation and additional source increase from gas cloud facilitated LH-transition.

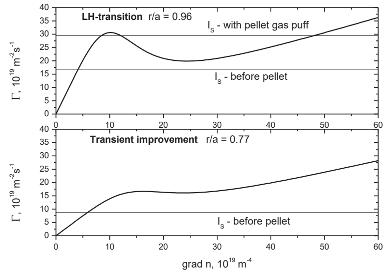

FIGURE 4. Local non-linear flux dependence on density gradient for pellet injection scenarios in TUMAN-3M. In case of LH-transition additional particle source provides the existence of the second stationary solution. I_S is the integral particle source.

Modeling shows good agreement with experiment; the only discrepancy is the duration of improved confinement state in the transient confinement case – modeling yields 0.5 ms duration, while in experiment it is about 1.5 ms. Most possible answer, according to gyrokinetic simulation, is the modification of turbulence properties during the pellet evaporation [18].

CONCLUSION

With the use of the density profile evolution model and LH-transition initiation theory in GAM scenarios in TUMAN-3M and FT-2 and in pellet injection scenarios in TUMAN-3M it is possible to predict the conditions and existence of LH-transition. Specific relation between main factors responsible for LH-transition (E_r shear perturbation, particle source value and turbulence level) in each case determines if LH-transition is possible and what are the conditions for transition initiation.

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