Hydrogen pellet initiated H-mode in TUMAN-3M tokamak

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H-mode is necessary operational regime for ITER, thus methods of plasma fuelling and LH-transition initiation applicable in plasma with high temperature and density should be developed. Classic technology of plasma fuelling via peripheral gas puffing proves itself ineffective when it comes to large-scale tokamaks. That is also unfortunate because in smaller devices gas puffing may also lead to LH-transition. One method that could solve both problems – fuelling and LH-transition initiation – is pellet injection. In present paper we focus on H-mode initiation aspect.

Pellet injection creates steep density gradient and also causes plasma cooling in the ablation region. These two effects are responsible for creation of strong and inhomogeneous radial electric field [1]:

$$E_r = \frac{T_i}{e}\left[\frac{\partial \ln n}{\partial r} + k_T \frac{\partial \ln T_i}{\partial r}\right] \qquad (1)$$

If the pellet is sufficiently large and the penetration depth is small, the region of pellet-induced gradients occurs close the LCFS, and shear of such perturbed radial electric field could be large enough to create a self-sustaining transport barrier. LH-transition triggering by a pellet was observed for the first time on TUMAN-3 tokamak in 1991 [2] with LiD pellets. On DIII-D hydrogen pellet injection was found to lower substantially the LH-transition power threshold [3].

TUMAN-3M tokamak is now equipped with pneumatic injector, capable of shooting up to four frozen hydrogen or deuterium pellets with diameter of 0.7-1.0 mm and velocity 150-1000 m/s in tangential direction. Tangential injection provides prolonged pellet trajectory in the peripheral plasma region and localization of the evaporation region outside $\rho = (r/a) = 0.4$. For the means of ablation measurements there are used Hα/Dα line emission detectors with aperture directed at pellet impact area. Also a triple electrostatic probe is used for peripheral electron temperature measurements.

In the recent experiments hydrogen pellets were injected into deuterium plasma. For most shots pellet diameters were chosen 0.9 and 1.0 mm, velocity 300-500 m/s. Typical average plasma density before the injection was about $(1\div1.5)\cdot10^{19}$ m^{-3}. In the experiments different types of temporal evolution of Hα/Dα emission in the evaporation region were observed, see fig. 1.

One is typical ablation curve with gradual growth during 0.2-0.5 ms and much steeper decay. The ablation curve is traditionally observed when a solid-state pellet is evaporated in tokamak plasma. Density increase with characteristic time of ablation is observed. The Hα/Dα emission evolution of another kind has smooth shape with relatively short growth period and long (up to 5 ms) decay. This type of evolution probably is a result of injection of hydrogen gas due to pellet disintegration and evaporation in the pellet-guide. Difference in density growth rate depends on pellet evaporation localization – solid pellet, evaporated inside the plasma, yields fast increase (fig. 1a), while gas, only spreading on periphery, leads to slow density increase (fig. 2b).

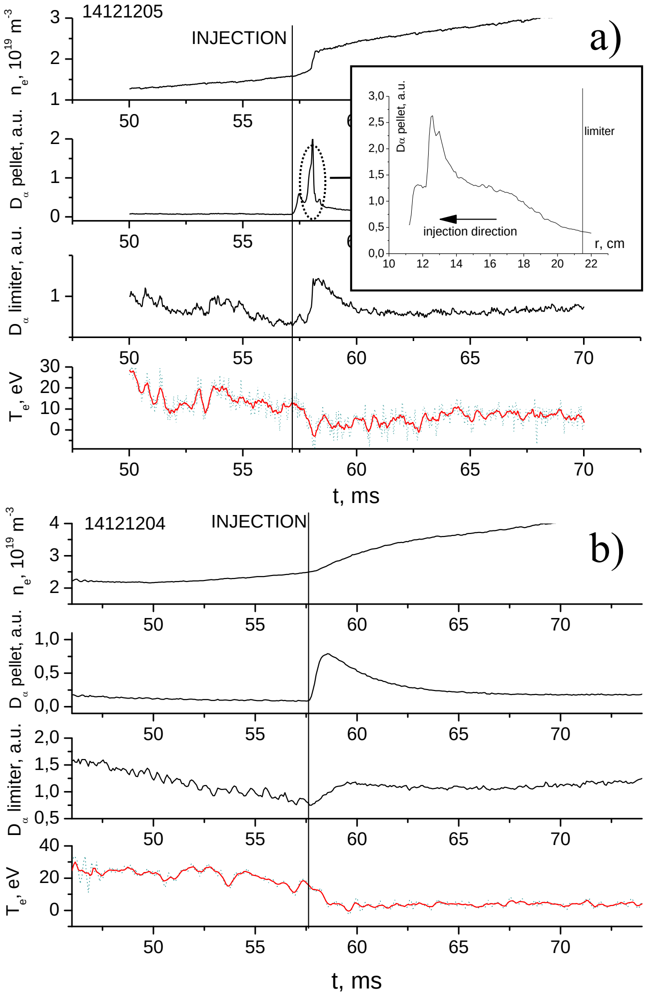

Fig.1 Evolution of plasma density, Hα/Dα emission and peripheral electron temperature for two types of experimental ablation scenarios: a) solid pellet evaporation with slow growth and steep decay; b) snow-like disintegrated pellet evaporation with steep growth and long decay. «Dα pellet» directly observes evaporation region, «Dα limiter» observes plasma periphery far from pellet and used for LH-transition indication. Fragment in a) shows the spatial distribution of emission, calculated on the base of ablation curve.

However, both scenarios of fuelling may result in LH-transition (fig. 2). In several shots the evolution of plasma parameters typical for LH-transition was observed after the injection: average density growth, continuing after the pellet ablation, and peripheral Hα/Dα emission decrease. Probe measurements near LCFS have also shown that local density and electron temperature decrease after the injection, which corresponds with predictions for evolution of n_e and T_e outside the transport barrier.

To understand possibility and criteria of pellet-induced transition, a modelling of plasma density profile evolution with pellet-modified particle source was made. There was modelled an evolution of plasma density:

$$\frac{\partial n(r,t)}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r} r \cdot \left(D(r,t) \cdot \frac{\partial n(r,t)}{\partial r} - v(r,t) \cdot n(r,t) \right) = S(r) + S_{PELLET}(r,t) \qquad (2)$$

Here diffusion coefficient D and convective velocity v are conjectured to depend on shear of radial electric field ω_{ExB} (calculated in accordance with formula (1)):

$D(r,t)=k(\omega_{ExB})\cdot D_0(r)$; $v(r,t)=k(\omega_{ExB})\cdot v_0(r)$

where $k(\omega_{ExB})$ in the form, described in [4], varies from 1 for L-mode to 0.1 for the case of strongly suppressed anomalous transport.

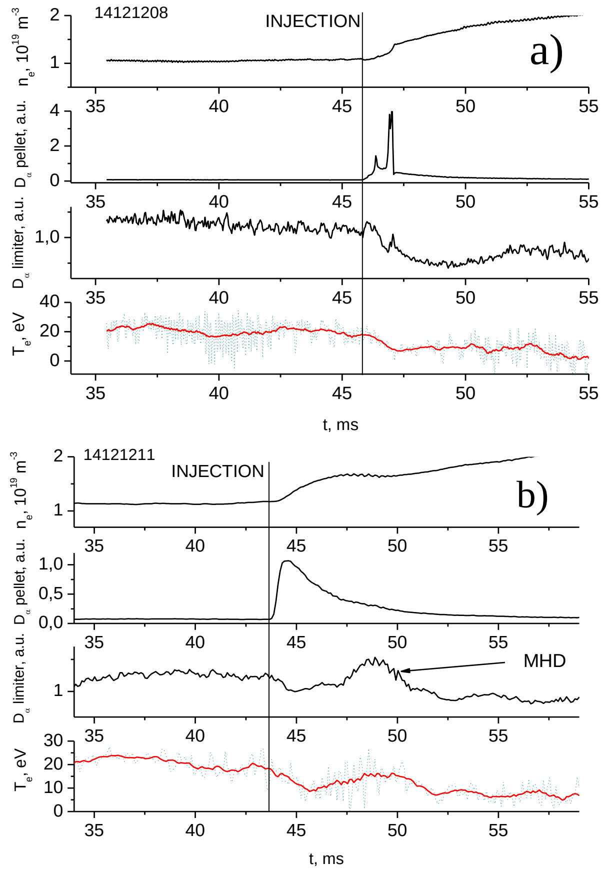

Fig.2 Evolution of plasma density, Hα/Dα emission and peripheral electron temperature in different scenarios of fueling, which result in LH-transition initiation: a) solid pellet, b) disintegrated pellet. Average density growth, peripheral Dα and Te decrease indicate the transition.

Confinement improvement mechanism, conjectured in the model, is the following: pellet ablation creates a perturbation of particle source S_{PELLET}, which is introduced into diffusion equation in the form derived from experimental pellet ablation curve (with its spatial and temporal characteristics). S_{PELLET} is normalized to full particle content in the pellet.

Localized pellet-induced source and thus density perturbation creates additional density gradient in the ablation area; based on the gradient, profiles of radial electric field and its shear are calculated. Strong shear leads to transport coefficients damping, thus modifying density profile and creating a transport barrier – if shear is strong enough, transport barrier becomes self-sustaining and system remains in state with steep peripheral gradients, which is considered as H-mode. According to modeling results, injection of pellets with low velocity, resulting in short penetration depth

($\rho = r/a > 0.8$) and ablation in the area of "essential" gradients, is the most beneficial for LH-transition initiation.

Scenarios with disintegrated pellet (long evolution) were not modeled, because it is impossible to obtain information about spatial distribution of particle source in that scenario. Also, these scenarios are similar to initiation of H-mode with gas puffing, suitable only for small-scale tokamaks, and thus are of little interest to fusion goals. Ion temperature in peripheral area is a crucial parameter, as radial electric field value depends on it. In fig. 3 there are presented several peripheral density gradient evolution curves for different ion temperature values. If this value exceeds some threshold value, system remains if state with increased gradient.

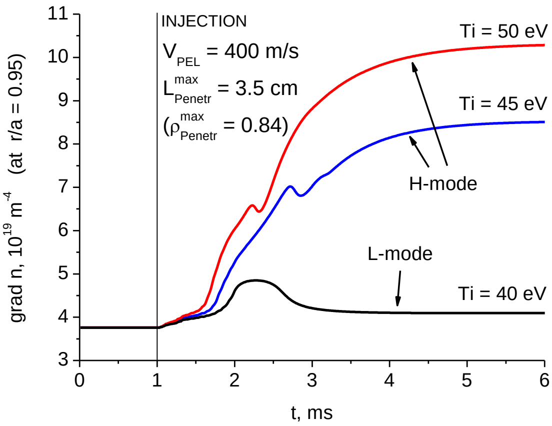

Fig.3 Modeling of peripheral density gradient during pellet-injection. If ion temperature exceeds certain value, system remains in improved confinement state with high peripheral gradient value.

This model has several drawbacks, e.g. it does not calculate temperature profile evolution due to poor knowledge about temperature (especially T_i) profiles in TUMAN-3M, thus T_i profile was taken the same as density profile.

There are more sophisticated models, simulating LH-transition [5], which conclude that gradient-driven mean flow plays major role in particle injection induced LH-transition. This conclusion makes the results of our simple modeling somewhat reliable for rough estimates of pellet-induced LH-transition possibility and criteria.

The work has been carried out with cooperation and equipment of unique scientific device "Globus-M" team. Authors thank for partial financial support Ministry of Education and Science of the Russian Federation (Agreement 14.619.21.0001, id RFMEFI61914X0001).

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