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First results on H-mode generation in the Globus-M spherical tokamak

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Preceding investigation of confinement regimes did not provide reliable H-mode generation in spite of some confinement improvement [1]. The situation was significantly improved after the alteration of the toroidal magnetic field direction in Globus-M ($\mathbf{I}_p$ became $\uparrow\uparrow\mathbf{B}_T$) [2].

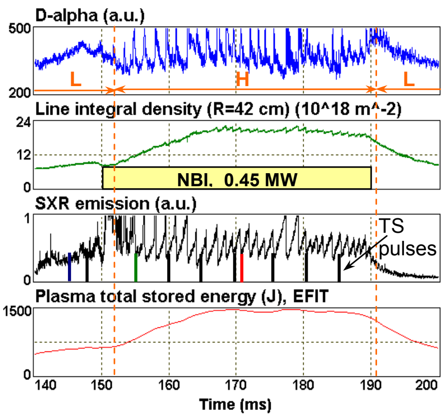

Fig.1. L-H transition in the NBI heated Globus-M shot # 19518

The most stable H-mode operation was achieved in auxiliary (NBI) heated discharges. The H-mode regimes were obtained in the limiter and single null divertor configurations. Also H-mode regimes are accessible in boronized vacuum vessel as well as in conditions with poor or without (degraded) boronization. The lowest density at which L-H transition was obtained $\sim 1\cdot 10^{19}m^{-3}$. The highest density at which H-mode regime was conserved $\sim 7\cdot 10^{19}m^{-3}$. Time history of NBI heated ($P_{NBI} \approx 0.45$ MW) H-mode discharge in the limiter inner wall plasma configuration is shown in Fig.1. Traces of D-alpha, line integrated density, the beam heating pulse, SXR intensity and plasma total stored energy (EFIT) are shown for the plasma current plateau phase.

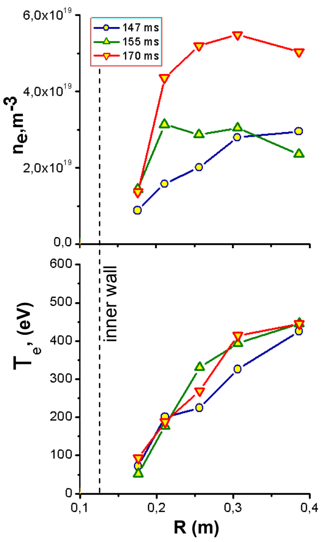

Fig. 2. Radial profiles of electron density (upper) and temperature (lower) evolution during H mode in the shot # 19518

For this discharge time evolution of electron temperature and density profiles were measured by multipulse TS diagnostics (Fig.2). As an example 3 profiles are shown – one before the transition (-5ms), one after (+3ms) and one at the density flat top (+18ms after the L-H transition). Corresponding laser pulses indicating the time of TS measurements are marked in color in Fig.1. Only the inner part of plasma column (from inner wall to

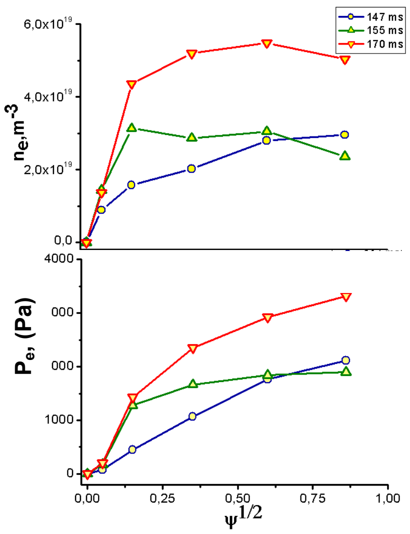

Fig. 3. Magnetic surface related density and pressure profiles evolution during H-mode in the shot # 19518. 1 – corresponds to magnetic axis, 0 – corresponds to plasma boundary

the plasma center) is currently accessible for TS measurements in Globus-M, where magnetic surfaces diverge during plasma heating.

To make the localization of transport barrier clearer the R coordinate was recalculated into magnetic surface number, using EFIT equilibrium reconstruction. Corresponding graphs for the density and electron pressure profiles are shown in Fig.3. One can see that the density increased at the plasma periphery shortly after L-H transition from $\sim 1.5 \cdot 10^{19} m^{-3}$ to $3 \cdot 10^{19} m^{-3}$ and plasma pressure increased more than 2 times formatting rather steep gradients. Such kind of profile with steep edge gradient and very flat density profile in the bulk plasma is conserved during the whole H-mode phase and specific only for the density profile. At the initial stage of the H-mode, 3ms just after transition, the density profile is slightly hollow demonstrating small peripheral "ears". H-mode transition in the single null divertor plasma configuration with 1X-point located downward in the direction of ion grad B drift was also recorded. In that case there was no such strong (two times) increase of peripheral density (and hence pressure), probably due to higher initial values in the L-mode phase of the discharge.

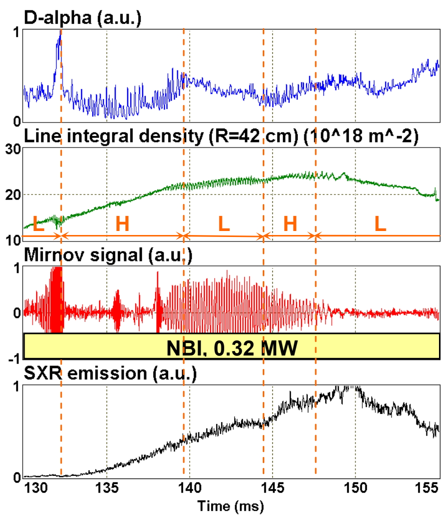

Fig. 4. L-H mode transitions recorded in early beam heated shot #19612. First L-H transition is triggered by MHD event, the second one is spontaneous.

It was recognized that L-H transition in Globus-M can be triggered by MHD events, such as sawtooth crash or internal reconnections. Such MHD events are characterized by expelling heat and particles to the periphery from the central plasma region thus increasing edge pressure and simplifying L-H transition. "Spontaneous" L-H transitions sometimes took place, when any fast perturbations on density, magnetic probe, or SXR signals are not detectible. H-mode triggering is illustrated in Fig.4. The traces of D-alpha, line integrated density, MHD (Mirnov) and SXR emission are shown for the discharge with early NB heating, which exhibit no sawteeth in the first half of the shot. Periods of H-

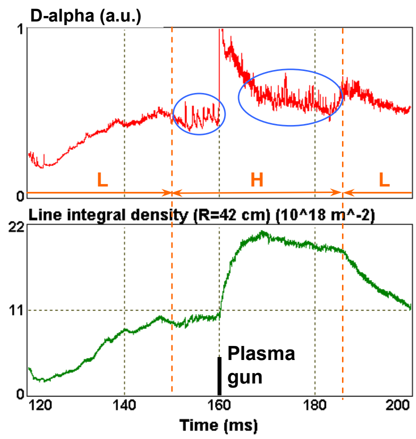

Fig. 5. Demonstration of fast density rise during H-mode shot #19416 with the plasma gun injection. ELMs frequency increase is also fast.

mode triggered by MHD event and H-mode triggered spontaneously could be seen from the figure.

ELMs are characteristic feature of H-mode regimes. ELMs in Globus-M auxiliary heated H-mode are synchronized more often with sawtooth crashes. In this case they look like type-I ELMs. In the case of lower loss power (OH H-mode) sometimes type-III ELMs are observed. ELMs frequency seems to increase with density. To underline this effect the experiment with the plasma gun was performed. The feature of fast density increase by the plasma gun without target plasma perturbation was utilized in this experiment [3, 4]. Fig.5 demonstrates the ELMs frequency increase with density rise. As the density increase was fast (~1 ms) the ELMs frequency changed quickly and unambiguous.

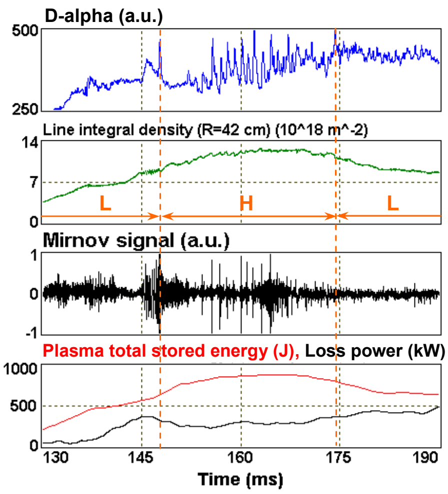

Fig. 6. OH heated H-mode shot #19415. Loss power (P_{loss}=P_{OH}-dW/dt-P_{rad}(core)) about 280 kW is necessary to provide conditions for L-H-transition.

Inner wall limiter OH discharge with the plasma current of ~200kA, toroidal magnetic field ~0.4T, edge safety factor, $q_{edge} \approx 4$, vertical elongation 1.5-1.6, average density (L-mode level) ~$1.5{\cdot}10^{19}m^{-3}$, was chosen for threshold power estimates. The traces of the D-alpha emission, line density; MHD (Mirnov) and plasma total stored energy (from EFIT reconstruction) are shown in Fig.6. L-H transition is triggered at 147.5 ms by MHD event. Time interval from 148 till 174 ms where traces of line integrated density and D-alpha are in counter phases is the period of H-mode regime. According to EFIT reconstruction plasma total energy content after the transition increases to about 40 %. Also the value of loss power is plotted. It exceeds 250 kW at the moment of L-H transition. Interesting is that in this discharge L-H transition happened at the time when plasma elongation value had local minimum (κ=1.5), thus utilizing the maximum of specific power flux through the plasma surface.

Threshold power was compared with the value derived from the formula corrected to aspect ratio [5]:

$P_{LH}=0.07\cdot n_{20}^{0.7}\cdot B_T^{0.7}\cdot S^{0.9}\cdot(Z_{eff}/2)^{0.7}\cdot F(A)^{\gamma}$, where S is plasma column surface area, $F(A)=0.1A/f(A)$, $f(A)=1-[2/(1+A)]^{0.5}$, $\gamma=0.5$, $A=R/a$ is the aspect ratio.

For $Z_{eff}\approx 2$, we obtain a small value of threshold power, $P_{LH} \approx 40\ kW$. One can see that in reality power required for L-H transition is 6-7 times higher.

The neoclassical electric field has been calculated for the OH shots with the profiles simulated by ASTRA transport code. The typical radial electric field at the separatrix before transition was a few kV/m and shear of the poloidal $\boldsymbol{E}\times\boldsymbol{B}$ rotation had the order of a few $10^5\ s^{-1}$. These values are close to ones required for the transition both for ASDEX Upgrade and MAST [6]. The higher experimental power threshold than predicted in [4] may be caused by the large difference in electron and ion temperatures in low density OH shot. The OH power is mainly spared to heat electrons and less goes to the ion channel, while the high ion temperature at the edge is required for the transition. Additional sophistications typical for small tokamaks (MHD events, large viscous damping, error fields, etc.) might also play a role. Note that for Globus-M, as well as for other tokamaks, one would expect lower power threshold for the favorable direction of the magnetic field (ion ∇ B drift is directed towards the X-point).

To summarize we can state that reliable H-mode operation was achieved in the Globus-M spherical tokamak in conditions of low q_{edge} and close fitting wall. The most probable reason for this was switch to the favorable direction of the magnetic field. The accompanied spontaneous stray field compensation might also play a role.

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