

H-mode investigation under ECRH on T-10. Density limit experiments under ECRH (ECCD) and gas-puffing on T-10.

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This paper is the result of the cycle of experiments which were carried out on T-10 (limiter tokamak with circular cross-section, $R_0=1.5$ m, $a_L=0.3$ m) under ECRH/ECCD (2nd harmonic ECR, X-mode, launch angle $\psi=21^\circ$ to R_0 , absorbed power P_{ab} up to 1 MW).

1. H-mode investigation on T-10.

Improved confinement regimes with external transport barrier were observed on T-10 in a wide range of plasma parameters: $q_L=2.2\div 4.1$ (at $B_T=2.42$ T it corresponds to plasma current variation from 330 to 180 kA); $\bar{n}_e=(1.2\div 3)\times 10^{19}$ m $^{-3}$; $B_T=2.42$ T (on-axis ECRH) \div 2.14 T (strongly off-axis ECRH with ECR zone shift ~ 19 cm to the high field side); $P_{ab}=0.5\div 0.8$ MW.

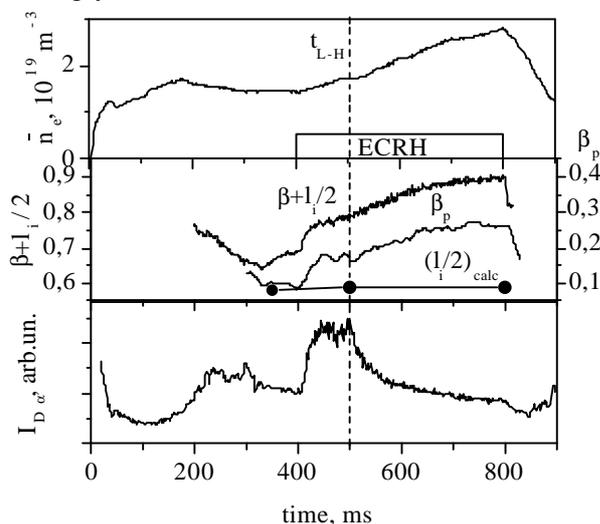


Fig. 1 Traces of the plasma parameters in regime with L-H transition. $B_T=2.42$ T, $q_L=2.2$ ($I_p = 330$ kA), $P_{ab} = 0.75$ MW. $\beta_p = \beta_p^{dia}$

ECRH pulse. In this case confinement time τ_E in L-mode was found to be close to one in H-mode.

2) Threshold power, P_{th}^{LH} , is 0.6 MW at on-axis ECRH (ECCD) at $\bar{n}_e = 1.5 \times 10^{19}$ m $^{-3}$ (before L-H transition), that is in agreement with ITER scaling law [1]. Enhancement factor H_L

L-H bifurcation is shown as a spontaneous plasma density increase (up to 2 times) at the D_α intensity, $I_{D\alpha}$, drop (fig.1). Gas-puffing valve included into the feedback system, switches-off completely. Density growth is accompanied by density gradient increase near the limiter. Enhancement factor $H_L = \tau_E^H / \tau_E^L$ increases up to 1.6 in the best regimes. H-mode on T-10 has the following peculiarities.

1) Transport barrier for particles plays a general role in confinement enhancement. In spite of thermal transport barrier is formed also, its contribution to the energy content increase is relatively small. It was confirmed experimentally. Plasma density on L-phase was increased up to the same value, which was achieved in H-mode at the end of the

decrease with \bar{n}_e increase also agrees with dependence of P_{th}^{LH} on plasma density. At $\bar{n}_e \cong 3.4 \times 10^{19} \text{ m}^{-3}$ P_{tot} is close to P_{th}^{LH} (P_{tot} - total heating power) and L-H transition is not observed.

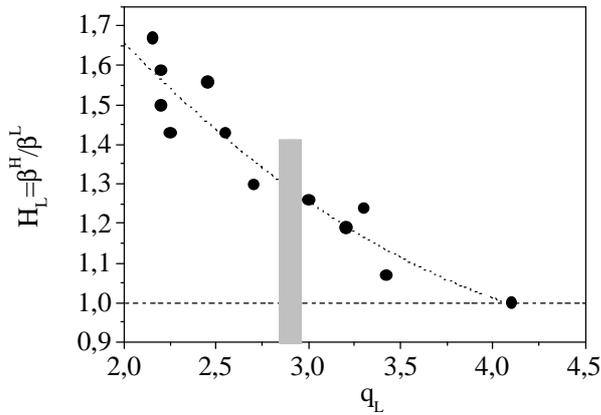


Fig. 2 Dependence of H_L value on q_L

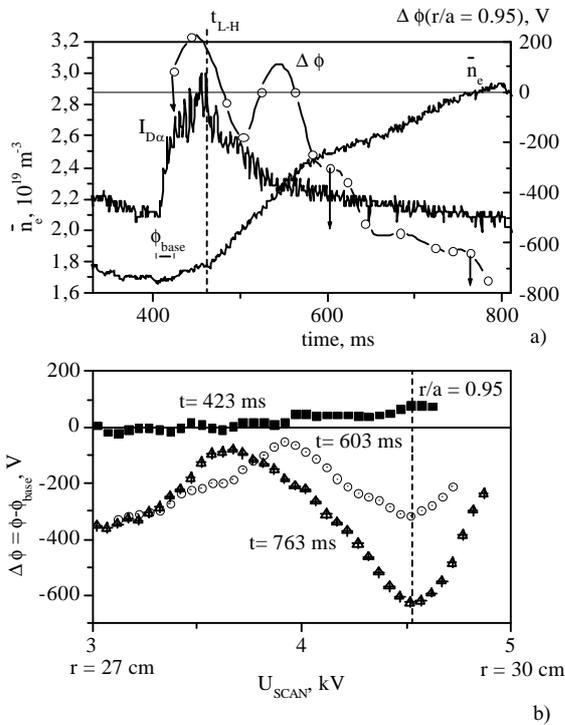


Fig. 3 Results of the plasma potential $\Delta\phi$ measurements by HIBP in H-mode discharge. $B_T=2.42 \text{ T}$, $q_L=2.2$ ($I_p = 330 \text{ kA}$), $P_{ab} = 0.75 \text{ MW}$.

a) $-\Delta\phi$ trace for $r(\phi_{min})$. Time interval for base potential level is shown. b) – radial distributions of $\Delta\phi$ for instants marked by arrows on fig 10,a).

3) Investigations show that dependence of enhancement factor on q_L is feature of H-mode on T-10 (fig. 2). The highest H_L value is achieved at low q_L values ($q_L \approx 2$). H_L decreases with q_L rise and at $q_L \cong 4.1$ L-H bifurcation does not exist. On T-10 $T_e(r)$ and $j(r)$ profiles are peaking to axis with q_L increase [4]. In this case $T_e(r)$ gradient drops on the periphery and, therefore, decrease of H_L factor with q_L increase appears to be because of P_{th}^{LH} enhancement with q_L rise on T-10 (not because of more strong τ_E dependence on I_p in H-mode in comparison with L-mode).

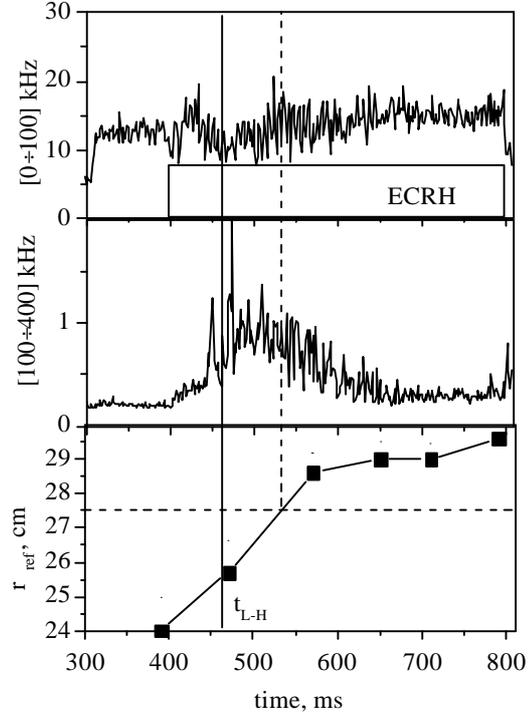


Fig. 4 Results of the turbulence measurements in regime with $B_T=2.42 \text{ T}$, $q_L=2.2$ ($I_p = 330 \text{ kA}$), $P_{ab} = 0.75 \text{ MW}$. Time behaviour of the reflection layer radius r_{ref} is shown.

4) Plasma potential depositions at the plasma periphery ($r/a \geq 0.65$) observed by Heavy Ion Beam Probe [2] demonstrate formation of the negative (directed inward) radial electric field E_r

just prior the limiter: $a_L - 2.5 \text{ cm} \leq r \leq a_L$ (fig. 3). It should be noted that E_r forms with characteristic time of $I_{D\alpha}$ drop and $|E_r|$ achieves maximal value when H-mode is close to steady-state phase, i.e. density and β_p are close to their maximal values.

5) Turbulence amplitude reduction in frequency range $f > 100 \text{ kHz}$ (fig. 4) is observed by reflectometry in the same region (near the limiter). Smooth decrease of fluctuation amplitude takes place when the radius of the reflection layer r_{ref} increases to $r_{\text{ref}} = 27 \div 28 \text{ cm}$ [3]. No turbulence reduction inside of this area was observed.

6) Langmuir probes measurements demonstrate decrease of decay length λ for T_e and n_e in the SOL at the instant of L-H bifurcation.

Therefore, transitions to the improved confinement regime with external transport barrier located at $a_L - 2.5 \text{ cm} \leq r \leq a_L$ are observed on T-10 in limiter discharges. These regimes on T-10 have all character signs of H-mode and some peculiarities. Note that the particle transport barrier forms at the L-H transition not completely and develops during H-mode phase with characteristic time about $I_{D\alpha}$ decay time.

2. Density limit experiments on T-10.

As it was shown in earlier experiments [4], limit density $(\bar{n}_e)_{\text{lim}}$ on T-10 depends on input power as $(\bar{n}_e)_{\text{lim}}^{\text{ECRH}} = (\bar{n}_e)_{\text{lim}}^{\text{OH}} \cdot \sqrt{P_{\text{tot}}/P_{\text{OH}}}$, where P_{OH} – ohmic heating power. It allows us to supply a problem about exceeding of Greenwald limit [5],

$$\bar{n}_{\text{Gr}} = I_p / (\pi a^2), \quad (1)$$

at gas-puffing using high enough ECRH power. Experiments were carried out at different plasma current values: $I_p = 230 \text{ kA}$ ($q_L = 3.2$, $\bar{n}_{\text{Gr}} = 8.1 \times 10^{19} \text{ m}^{-3}$); $I_p = 150 \text{ kA}$ ($q_L = 4.8$, $\bar{n}_{\text{Gr}} = 5.3 \times 10^{19} \text{ m}^{-3}$); $I_p = 90 \text{ kA}$ ($q_L = 8.2$, $\bar{n}_{\text{Gr}} = 3.2 \times 10^{19} \text{ m}^{-3}$). In all cases the value of toroidal magnetic field $B_T = 2.42 \text{ T}$ corresponded to on-axis ECRH.

Experiments shown that the most exceeding of Greenwald limit was observed at higher q_L values $((\bar{n}_e)_{\text{lim}}/\bar{n}_{\text{Gr}} \sim 1.8$ at $q_L = 8.2$, in contrast with $(\bar{n}_e)_{\text{lim}}/\bar{n}_{\text{Gr}} \sim 1$ at $q_L = 3.2$). Dependence of exceeding of $(\bar{n}_e)_{\text{lim}}$ value above one predicted by (1) on q_L is shown on fig. 6. It is necessary to call attention that on T-10 $T_e(r)$ profile, and also $j(r)$ profile, are peaking to axis when I_p decreases [4]. Under these conditions dependence of $(\bar{n}_e)_{\text{lim}}/\bar{n}_{\text{Gr}}$ on q_L allows us to suppose that not a_L , but radius of magnetic surface inside of which the main part of the plasma current flows (so called «current» radius, a_{cur}) is an adequate parameter for determination of limit density in the (1). If the value a_{cur} is included in to (1) as a determining value, then limit density becomes close to $(\bar{n}_e)_{\text{Gr}}^{\text{mod}} = I_p / (\pi \cdot a_{\text{cur}}^2)$ for all q_L values (as it is shown on fig.6). Here a_{cur} were determined as the radius of the magnetic surface inside of which the current value was $I = 0.95 \times I_p$.

Probably, those physical \bar{n}_e restrictions that are the basis of Greenwald limit were not exceeded in T-10 experiments.

It is necessary to note that at such high density values refraction of the HF-wave becomes significant that can change absorbed power profile.

Additional features of $(\bar{n}_e)_{\text{lim}}$ experiments on T-10 are following. Radiation losses P_{rad} increased with density increase in these experiments and at $\bar{n}_e = (\bar{n}_e)_{\text{lim}}$ the value of P_{rad} became close to P_{tot} . There was no clear evidence of MARFE existing in experiments discussed. In

regimes with maximal heating power tendency of density profile peaking at approaching to $(\bar{n}_e)_{\text{lim}}$ was observed.

As it is shown on fig.7 there is no clear β_p decrease, i.e. confinement degradation up to $\bar{n}_e \approx 0.9(\bar{n}_e)_{\text{lim}}$ in these T-10 experiments. Only just prior $(\bar{n}_e)_{\text{lim}}$ slight decrease of plasma energy content takes place. It is shown as weak β_p drop, which does not exceed 5%. It corresponds to decrease of energy confinement time not stronger then 10 %.

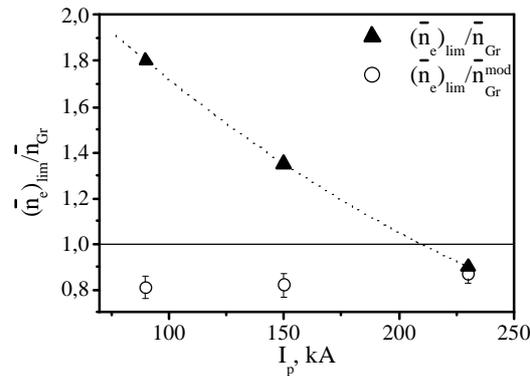


Fig. 6 Dependence of $(\bar{n}_e)_{\text{lim}}/\bar{n}_{\text{Gr}}$ on I_p

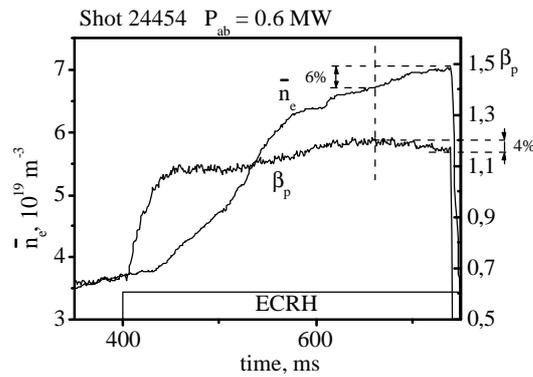


Fig. 7 β_p changing close to $(\bar{n}_e)_{\text{lim}}$ in regime with $I_p=150$ kA.

This work is supported by Ministry of Atomic Energy of Russia (contract 69F) and by Ministry of Science and Technology of Russia (Federal Program “Control Thermonuclear Fusion and Plasma Processes”).

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