J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 46–50

Observation of the H-mode and Electron ITB by Heavy Ion Beam Probe on T-10 Tokamak

MELNIKOV Alexander*, ELISEEV Leonid, RAZUMOVA Ksenia, BONDARENKO Ivan[1)], KRUPNIK Ludmila[1)], KHREBTOV Sergey[1)], KOMAROV Alexander[1)], KOZACHEK Alexander[1)] and T-10 team

Russian Research Centre "Kurchatov Institute", Moscow, 123182, Russia

[1)]Ukrainian Scientific Centre "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

(Received: 18 January 2000 / Accepted: 12 May 2000)

Abstract

The Heavy Ion Beam Probe (HIBP) diagnostics on T-10 tokamak was modified to measure the local values of the plasma potential in the ECRH plasma. The Tl^+ ion beam with the energy up to 240 keV and intensity about a few dozens μA was used. The clear fall of potential in the range of –200 ~ –600 V was observed in the outward EC resonance during spontaneous improvement of plasma confinement. The fall down of the potential accompanies the fall of D_α and the density increase. The time evolution of the potential profile demonstrates formation of the thin (about 1 cm) area near the limiter with strong electric field E_r (~300 V/cm). All this means that the H-mode with ECRH as the sole source of the auxiliary heating in circular limiter tokamak was first obtained. The comparison with DIII-D and JFT-2M data demonstrates the similarity of typical features of the L-H transition.

The measurements during the electron internal transport barrier (EITB) formation show the appearance of the local negative potential well about 1 kV in the region of the barrier. The local transient values of the E_r reach ~1000 V/cm.

Keywords:

T-10 tokamak, ECRH, HIBP, H-mode, electron ITB

1. Introduction

One of the promising approaches to the steady state tokamak (SST) is the electron cyclotron current drive (ECCD). Simultaneously EC waves can heat the electrons and change the current profile, thus stabilize the MHD activity. It would be beneficial to run the SST with improvement of confinement (H-mode or ITB) [1]. Such regimes have been obtained in tokamaks with elongated cross section and divertor mainly. Recently ITB was obtained in the circular limiter tokamak T-10 with ECRH [2,3].

The importance of the radial electric field E_r for the improved plasma confinement is well recognized now [4,5]. It is expected that knowledge of E_r can help us to understand the underlying mechanisms that form transport processes in plasma. It is known [5,6] that the change of the electric field is fundamental for the H-mode. The study of E_r in the L-H transition and the ITB formation is the most desirable target for the SST relevant research now. The Heavy Ion Beam Probe (HIBP) is the only diagnostics allowing us to investigate directly the potential in the core and edge plasmas. The local value of the plasma potential can be measured by the change of the beam energy in the sample volume. The intensity of the secondary beam indicates the local density.

The first HIBP potential measurements near the

Corresponding author's e-mail: melnik@nfi.kiae.ru

separatrix during the sawtooth-triggered L-H transition were performed in JFT-2M [7]. In T-10 the hints on the confinement improvement were observed during the ECRH pulse [2], but the improvement was not pronounced clearly enough. The HIBP measurements performed during the improvement of confinement in T-10 show the strong fall down of the potential [8,9]. The present work reports the first clear observation of the H-mode with ECRH as the sole source of the auxiliary heating in circular limiter tokamak.

It also presents the first observation of the appearance of the local negative potential well in the region of the electron ITB.

2. HIBP Diagnostic Set-up

To study the ECRH-ECCD plasmas on T-10 the HIBP diagnostic was improved [8]. The energy of Tl^+ beam increased up to 240 keV. The power supply provides the measurements during the 7 ms every 20 ms.

The T-10 HIBP measures the plasma electric potential in two main modes:

Shot by shot measurements produce the time evolution of the plasma parameters in every desired point of the detector grid.

Scanning along the detector line in the single shot produce a set of plasma parameter profiles.

The energy resolution of the analyzer with parallel plates was tested by the calibration [10]. The analyzer sensitivity to the variation of the potential during the shot depends on the beam intensity. In the discussed measurements it is less than 20 V.

The spatial resolution determined as the radial size of the sample volume is 5–10 mm. The temporal resolution was limited by the data acquisition system with sampling time 16–64 μs.

3. Experimental Results

The search of the ITB on T-10 (R = 150 cm, a = 30 cm) was made by the variation of safety factor $q(r)$ using EC power deposition near the rational q values [2,3]. The off-axis ECRH experiment was done with B_0 = 2.28 T, I_p = 150 kA, $n_e = 1.2 \times 10^{13}$ cm^{-3}, P_{EC} = 0.5 MW, a_{lim} = 25 cm. The electron temperature $T_e(0)$ = 1.7 keV was measured by Thomson scattering and the ion temperature $T_i(0)$ = 0.5 keV was derived from NPA data. The EC-resonance lies at r = 14 cm. The outer area (r > 18 cm) was achievable for HIBP.

Figure 1 presents the time history of the typical shot with the spontaneous improvement of confinement (full lines) in comparison with the reference one (dash). The simultaneous effects: the rise of the line-averaged density and the decrease of D_α allow us to detect the typical features of the H-mode. The total stored energy W and soft X-rays emission increase correspondingly. The difference of the two shots lies in the small variation of I_p.

HIBP observes the following:

1. The plasma electric potential Φ at r = 18.3 cm ($x = r/a$ = 0.73) rapidly decreases during the density increase (t = 800 ÷ 850 ms). The absolute change of the potential is −600 V. Later on (t = 850 ÷ 900 ms) the density rises more slowly and the potential decreases slowly too. After the end of the gyrotron pulse (900 ms) the potential returns back to the initial Ohmic value.

2. Figure 2 shows the radial distribution of the extra potential over the initial steady state values. The D_α starts to drop at t_D = 780 ms. The time variation of profile shows three clear phases:

a) preceding phase, 730 ÷ 780 ms, when the inner region with a small local potential well is formed;

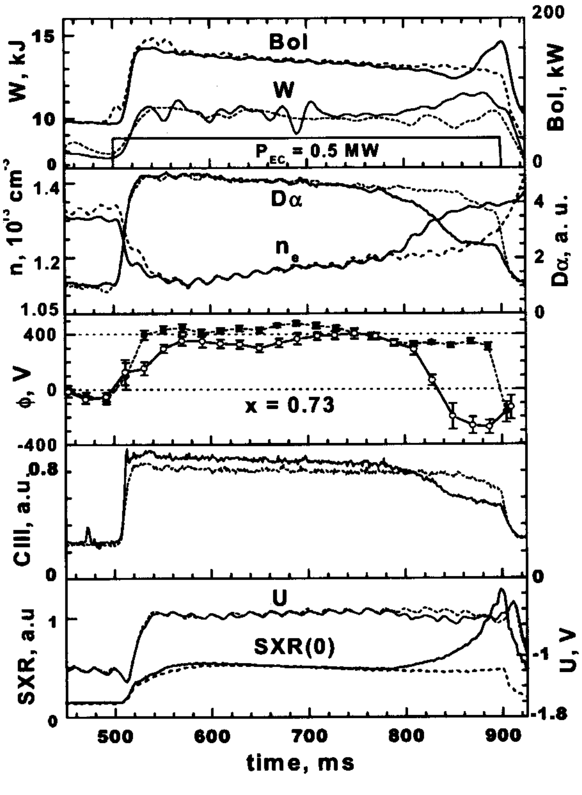

Fig. 1 Time traces of some plasma parameters in the shot with H-mode, #23702, I_p = 152 kA (full lines), and with the L-mode one, #23706, I_p = 158 kA (dashed lines).

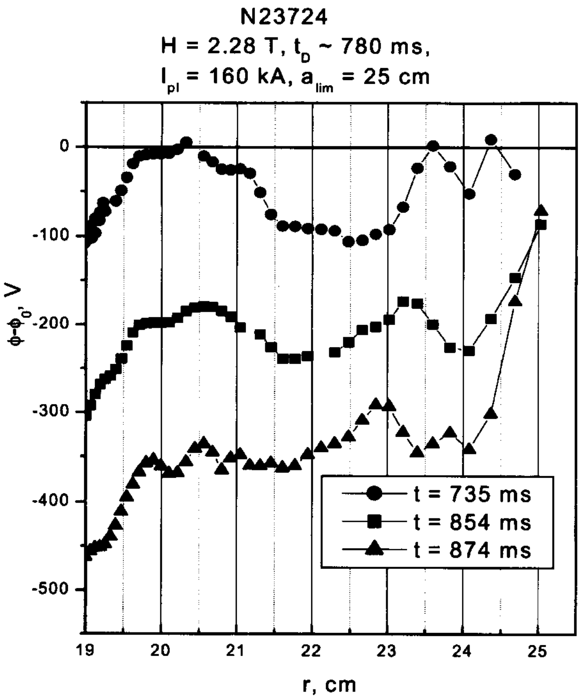

Fig. 2 The temporal evolution of the potential profiles in the shot with H-mode: circles - before transition, squares - the transient stage, triangles - after transition.

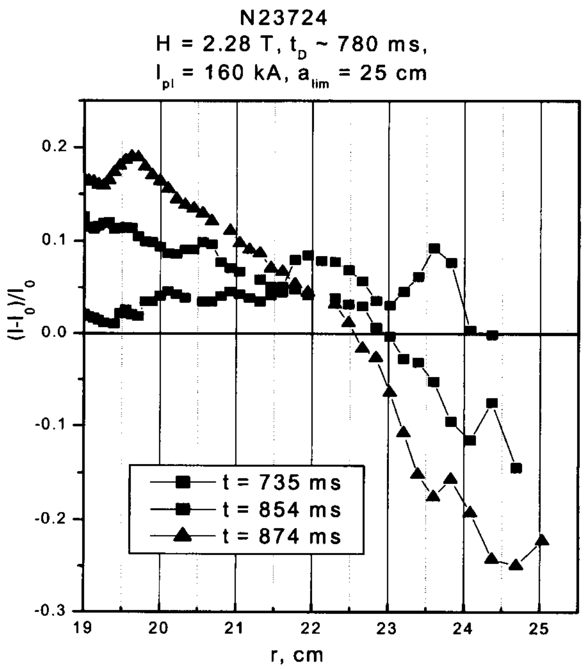

Fig. 3 The temporal evolution of the relative beam current. Indication of the formation of the density barrier in the H-mode.

b) transient phase, 780 ÷ 870 ms, when the inner potential falls down to –300 V and the limiter potential remains the same. This forms the layer (about 1 cm) with strong E_r (~300 V/cm). This layer does not change during the D_α drop.

c) the final phase, 870 ÷ 900 ms, when the potential profile reaches the steady state.

3. HIBP is sensitive to the plasma density. The secondary ion beam current is proportional to the local plasma density $I \sim nf(T_e)$ (the attenuation factors can be neglected here). The time evolution of the relative value of I with respect to the initial steady state value I_0 is presented in Fig. 3. It shows the rapid increase of the density gradient during the transition. It indicates the formation of the edge transport barrier.

4. In the experiments presented in Figs. 1–3, the EC-resonance (r = 14 cm) was outside the area available for HIBP. The decrease of the toroidal field down to B = 2.14 T leads to overlapping of these two areas. The achievable area for HIBP became $13 < r < 20$ cm while EC-resonance moves to r =17 cm). The EITB was obtained with I_p = 290 kA, $n_e = 1.2 \times 10^{13}$ cm^{-3}, P_{EC} = 0.5 MW, a_{lim} = 30 cm [3]. The local negative potential well appears simultaneously with EITB formation in its region (Fig. 4). The depth of the well is about 1 kV, the local E_r value is ~1000 V/cm.

4. Discussion

Comparison with H-modes on JFT-2M and DIII-D

The observed potential drop during the improvement of the plasma confinement in T-10 is very similar to the potential change at the L-H transition in JFT-2M [7]. In both cases the rise of negative potential indicates the improvement of the electron confinement. HIBP density data is also in a good accordance with the JFT-2M ones. In both cases I at the edge drops down to ~30% simultaneously with D_α, while the inner signal remains almost the same. The range of these phenomena in both cases are very similar, particularly:

i) the extra potential well with the flat bottom –300 V and the steep walls;
ii) the width of the gradient layer is about 1 cm, the value of the extra E_r = 300 V/cm;
iii) the time scales of the phenomena and D_α decay are the same.

The features of the edge transport, particularly the transport barrier formation in divertor (JFT-2M) and limiter (T-10) plasmas may cause the difference in the time scales of the decay.

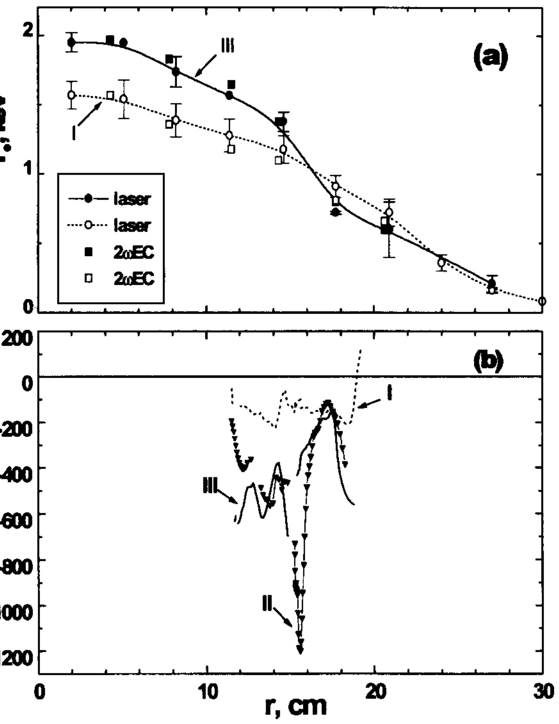

Fig. 4 The electron temperature profiles (a) and the plasma potential (b) in the similar shots #24264 and #24273 with internal transport barrier (ITB); I) t = 753 ms, before ITB, II) t = 853 ms, during ITB formation, III) t = 893 ms, after ITB formation.

Analyzing the direct measurements on JFT-2M [7] we can conclude that the fast potential drop near the edge and the formation of the thin layer with the strong electric field is the characteristic feature of the H-mode. Indirectly the E_r can be derived from the spectroscopic measurements of the rotation velocity and the ion momentum balance equation. Such measurements in the H-mode were done in DIII-D and JFT-2M for NBI divertor plasmas. Their main features are:

i) the width of the E_r shear layer just inside the separatrix is 1–2 cm,
ii) the values of the extra E_r = –300 V/cm in DIII-D [5] and E_r = –100 V/cm in JFT-2M [6],
iii) the time scales of the phenomenon and D_α decay are the same.

They all correspond to the direct measurements of [7].

The observation of the similar phenomenon on T-10 leads us to the conclusion that in the regime with off-axis ECRH we meet the H-mode.

The features of the H-mode on T-10

The improvement in confinement varies within 10–30%. This comparatively small values coincide with the limiter H-mode data in JFT-2M [11,12] where the elongation k is varied. When k decreases from k = 1.3 to k = 1.03, the improvement in the energy confinement time decreases from 30% to 10% [11]. So, the small values of the H-factor looks to be typical for the limiter H-modes obtained till the moment. This feature does not depend on the heating method: NBI that heats solely the ions, ICRH that heats mainly the electrons in JFT-2M [12] and ECRH that heats solely the electrons on T-10, lead to the similar features of the H-modes.

The main difference between the discussed experiments and the previous ones is the time scale of the L-H transition. Put the time duration of the D_α decay as a time scale of the transition, assuming the following phase with the low level of D_α as the H-mode. The time scale of the transition on T-10 is 40–90 ms, while it is 0.2 ms in the sawtooth-triggered NBI H-mode in JFT-2M. In both cases "fast" D_α decay time coincides with the inner potential drop and the strong E_r layer formation (transient phase in Sec. 3). The later steady state phase shows the slow D_α decay and the same for the potential. The papers which described the limiter H-mode do not focus on the duration of the L-H transition. On the basis of the presented time traces of the D_α we can estimate this time from less than a few ms in NBI or ICRF heated limiter and divertor plasmas in JFT-2M [11,12] and DIII-D [5] to 10 ms in NBI heated limiter plasma in JFT-2M [13]. These values are a few times less than the L-mode energy confinement time τ_E. On the contrary, the transition to the ECRH divertor H-mode in DIII-D takes 40 ms that is comparable with the L-mode τ_E = 55±6 ms [14]. Therefore, the slow L-H transition in a time scale of diffusivity looks to be a characteristic of the ECRH H-mode and it does not depend on the limiter or divertor configuration. This conclusion looks even more robust if we take into account that in T-10 we are very close to the power threshold, while DIII-D data obtained from the exact threshold to the large extra power.

5. Conclusions

Simultaneous increase of the density and the total stored energy, decrease of D_α, the formation of the thin edge layer with the strong electric field and the edge density barrier demonstrate the establishment of H-mode in the limiter circular tokamak T-10.

The similar scale machines T-10 and JFT-2M and the bigger DIII-D show the very similar scale of the phenomenon: E_r ~300V/cm in the ~1 cm layer at the plasma edge, while the former has a limiter and other ones have the divertors. The similar value of the E_r can indicate to the similar physics, for example the suppression of the same instability by $E \times B$ shear flow.

The local transient negative potential well appears during EITB formation in its region with the depth of about 1 kV.

The further measurements are necessary to know the interconnection between the internal (ITB) and external (H-mode) transport barriers in ECRH plasma to contribute the SST optimal scenario.

Acknowledgment

This work was supported by Russian Basic Research Foundation, Grant No 99-02-18457. We are grateful to Dr. S. Lysenko for the manuscript preparation.

References

[1] C. Gormezano, Plasma Phys. Control. Fusion **41**, B361 (1999).

[2] K.A. Razumova *et al.*, 26 EPS Conf. Plasma Phys. Control. Fusion, Maastricht, **23J**, 301 (1999).

[3] V.V. Alikaev, A.Ya.Kislov, K.A. Razumova *et al.*, submitted to Plasma Phys. and Control. Fusion.

[4] S-I Itoh, K. Itoh., Phys. Rev. Lett. **60**, 2276 (1998).

[5] K. Burell *et al.*, Plasma Phys. Control. Fusion. **31**, 1649 (1989).

[6] K. Ida *et al.*, Phys. Rev. Lett. **65**, 1364 (1990).

[7] Y. Hamada *et al.*, 17th IAEA Fusion Energy Conference, Yokohama (1998).

[8] A.V. Melnikov *et al.*, 26 EPS Conf. Plasma Phys Control. Fusion, Maastricht, **23J**, 829 (1999).

[9] A.V. Melnikov and L.G. Eliseev, Czechoslovak J. Phys. **49** (Suppl. 3S) 35 (1999).

[10] A.V. Melnikov *et al.*, Rev. Sci. Instrum. **68** (1) 308 (1997).

[11] H. Matsumoto *et al.*, Nucl. Fusion. **27**, 1181 (1987).

[12] H. Matsumoto *et al.*, 14 EPS Conf. Plasma Phys Control. Fusion, Madrid, **11D**, 5 (1987).

[13] S. Sengoku *et al.*, Phys. Rev. Lett. **59**, 450 (1987).

[14] J. Lohr *et al.*, Phys. Rev. Lett., **60**, 2630 (1988).