Role of the *q*(*r*) Profile in Transport Barrier Formation on the T-10 Tokamak

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Abstract. The effect of the $q(r)$ profile on transport barrier formation has been investigated in the T-10 tokamak using rapid current ramp-up with ECR heating. At various q-profiles, internal and edge barriers were observed.

1. Introduction

At the present time numerous research efforts, performed at many small and large tokamaks, are being devoted to investigation of internal (ITB) and edge (ETB, or H-mode) transport barriers. It is very important for the ITER project to understand what factors are responsible for transport barrier formation, and what the scaling for the threshold power is (if such a threshold exists). Experiments have shown that three main factors are essential for ITB formation:

i) *The $q(r)$ profile and the absolute q value in the barrier zone* [1, 2]. It was shown that typically the barrier is formed in the region where dq/dr is low and the $q= m/n$ value is near the rational one. Here m and n are the poloidal and toroidal mode numbers.

ii) *The pressure gradient*. One may assume that the ITB occurs in the zone where the pressure gradient is greater than some critical value [3, 4]. In this case, for ITB appearance we should input a rather large power inside the zone of the forthcoming ITB.

iii) *The local radial electric field E_r*. If a zone of enhanced $E\times B$ drift rotation with considerable radial shear appears in the plasma, then, as theory predicts, some modes can be stabilized (particularly the ITG mode) and the confinement is improved [5].

To understand the physical mechanisms of ITB and H-mode formation it would be desirable to find the 'necessary' and 'sufficient' conditions of their formation. It may be that all three factors strongly interact in this plasma phenomenon. So we try to clarify if we can stimulate ITB formation by varying $q(r)$ profile alone, without changing the deposited power.

2. Experimental conditions

Experiments were performed in T-10 (major radius R=1.5 m; minor radius of the rail limiter a=0.3 m). For solution of the above issues, we need to have the possibility to flatten the $q(r)$ profile in the central zone. This may be attained either by off-axis ECRH (and current drive, ECCD), or by additional rapid ramp-up of the plasma current, I_p, at the steady state for the main discharge parameters. In the latter case there is no additional power deposition in the plasma core, but the current density profile is slowly varied, that is we can verify the effect of time variation of one of the aforementioned factors, $q(r)$, on ITB formation.
During the current ramp-up we should avoid the appearance of the resonance conditions at the edge for m=3, otherwise MHD activity destroys the prepared current density profile $j(r)$. Therefore we have two options: either to augment the current from the value which corresponds to q=4–5 till $q\geq3$, or from $q\leq3$ till $q\geq2$. The following regimes were realized:

A-1) B=2.56 T (B is the toroidal magnetic field), I_{p1}=150 kA, I_{p2}=250 kA (q=5.1→3.1), two gyrotrons with f=140 GHz deposited EC power at the low field side (LFS), $r_0 \cong 7$ cm.
A-2) B=2.33 T, I_{p1}=180 kA, I_{p2}=230 kA (q=3.9→3.04), 4 gyrotrons with f=140 GHz, resonance at the HFS, r_0= -10 cm.
B-1) B=2.15 T, I_{p1}=230 kA, I_{l2}=300 kA (q=2.8→2.15), 4 gyrotrons, f=140 GHz, r_0 = -18 cm,
B-2) B=2.33 T, I_{p1}=240 kA, I_{p2}=280 kA (q=2.9→2.5), 4 gyrotrons, f =140 GHz, r_0= -10cm.

In cases A-1 and B-1, EC power up to P_{ab}=800–900 kW from gyrotrons with f=140 GHz was oblique launched at an angle 21° to the major radius and co-ECCD was realized. In cases A-2 and B-2, EC power was launched perpendicularly to the magnetic field and only ECRH was realized, and then the additional gyrotron for on-axis heating with P_{ab}=450–500 kW, f=130 GHz was switched on after the current ramp-up. This allowed us to analyze the confinement in the plasma core. In experiments A) the sawtooth oscillations were totally suppressed, in case B-2 they were partly suppressed, and in the case B-1 strong sawtooth oscillations were observed.

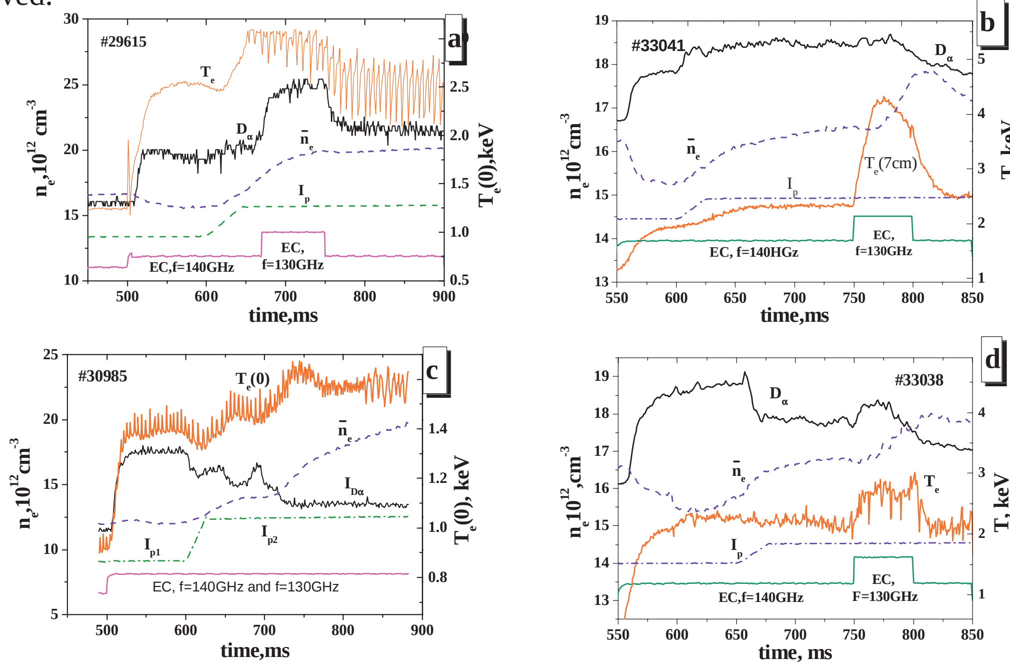


FIG. 1. Temporal behavior of the main plasma parameters: temperature $T_e(0)$, D_α emission $I_{D\alpha}$, density n_e, current I_p and EC power for regimes A-1 (a), A-2 (b), B-1 (c) and B-2 (d).

3. Experimental results

Regimes A-1 and A-2. In both cases the results are very similar in spite of rather different values of B, but the same q_L: this means that the absolute value of B does not play an important role in the given process (*FIG.* 1). During the current ramp-up, the plasma core is shifting inward (*FIG.* 2) due to change of equilibrium along the major radius, when the edge value of β_p is changed. (The equilibrium feedback system on T-10 maintains the position of the edge magnetic surface.) However, for both A) experiments we see the growth of T_e inside the radius r<12–15 cm with a simultaneous shift inward (*FIG.* 3). Figures 1,a and 1,b show that the average plasma density n_e and electron temperature $T_e(0)$ begin to rise with a time delay of 10 ms after the current ramp-up, but the intensity of the D_α line, $I_{D\alpha}$ and the SOL plasma parameters measured by Langmuir probes (*FIG.* 4a) are not changed. The penetration of additional current density into the plasma after current ramp-up was calculated by the ASTRA code. *FIGURE* 5 shows changes in the $q(r)$ profile. We see that $q(r)$ does not change in the zone of T_e increase during the first 20–30 ms. So only the equilibrium along the major radius during the beginning of I_p increase may influence the plasma core parameters. The experimental behavior of the $q(r)$ profile may be seen in shot # 29615 (regime A-1), where we can see simultaneous development of several resonant modes. *FIGURE* 6 shows the distribution of amplitudes of I_{SXR} oscillations for two time instants. The signs + and – give the relations between the phases of oscillations. At the inner side of the plasma we clearly see the odd (m=1) and even (m=2) modes. On the outer side these modes are coupled at the beginning and are well divided 38 ms later. This permits us to conclude that at least for this case the ∇T_e increase (ITB) takes place near the q=2 surface.

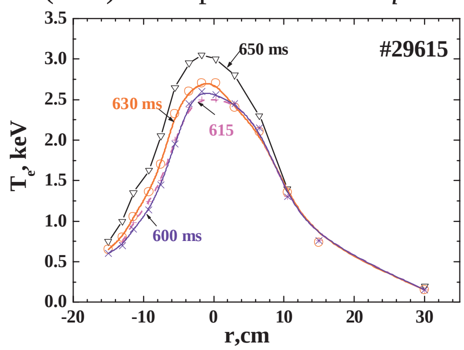


FIG. 2. Regime A-1. $T_e(r)$ before and after the current ramp-up.

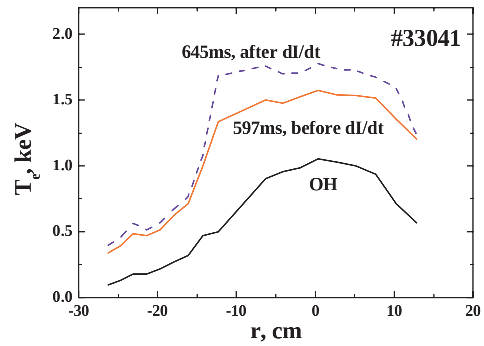
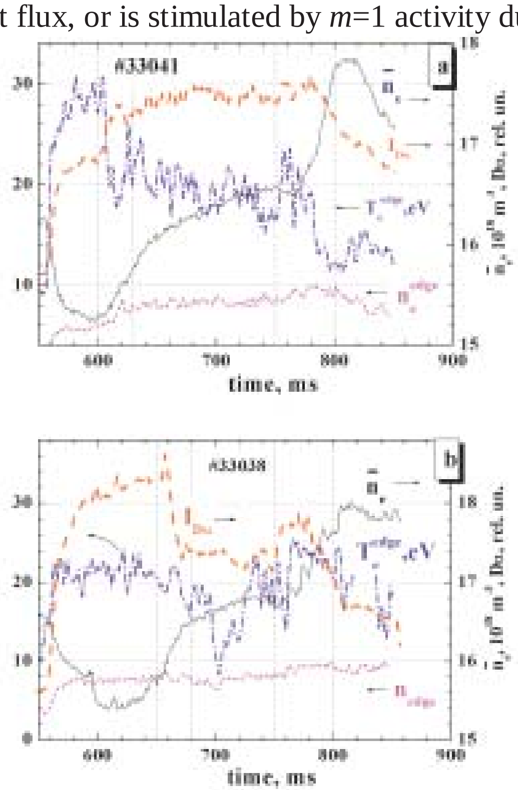


FIG. 3. Regime A-2. Temperature $T_e(r)$ before and after the current ramp-up.

FIGURE 7a shows that on-axis ECRH switch-on (regime A-2) leads to a strong increase of $T_e(0)$ inside a small central region, presumably inside the q=1 surface (the phase inversion radius of sawteeth in OH and after their appearance at the end of the process). Then the increase spreads to the ITB zone, formed after the current ramp-up. In the same time MHD m=1 activity appears in the core (*FIG*. 7b), and ETB formation with n_e increase at the edge and $I_{D\alpha}$ decrease takes place (*FIG*. 1b). As the $j(r)$ distribution in this case is already stationary, we have to conclude that this barrier near q=3 is formed either due to the increased heat flux, or is stimulated by m=1 activity due to the toroidal mode coupling.



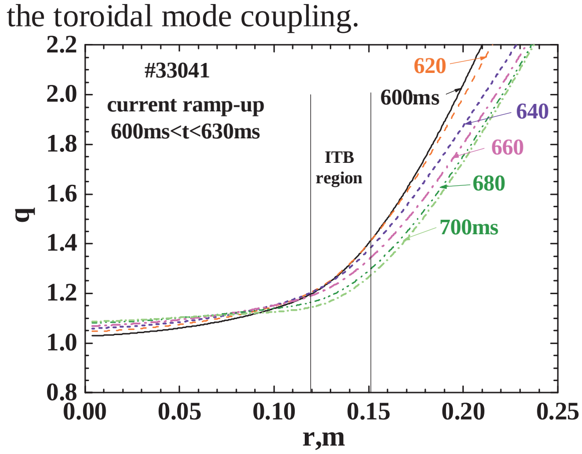


FIG. 5. The q(r) profile calculated by the ASTRA code in the A-2 regime.

FIG. 4. Temporal behavior of SOL plasma parameters measured by the Langmuir probes: the density n_{edge} and temperature T_{edge}..
The line-averaged density and D_α intensity are shown also. a) Regime A-2 with the internal barrier; b) B-2 with the edge barrier.

Regime B-2. In this case the position of the ECR is the same as in case A-2, but owing to higher I_p, r_s is a little larger and the sawteeth are not totally suppressed. Current ramp-up has no effect in the core (*FIG*. 8), but we can see the features of the edge (H-type) barrier formation: the increase of edge ∇n_e, the decrease of $I_{D\alpha}$, typical effects in the limiter shadow (*FIG*. 4b), although with about 10 ms delay. Additional on-axis ECRH leads to three times less T_e increase and 1.5 times less increase of the total energy content than in case A-2, but the external barrier becomes more pronounced.

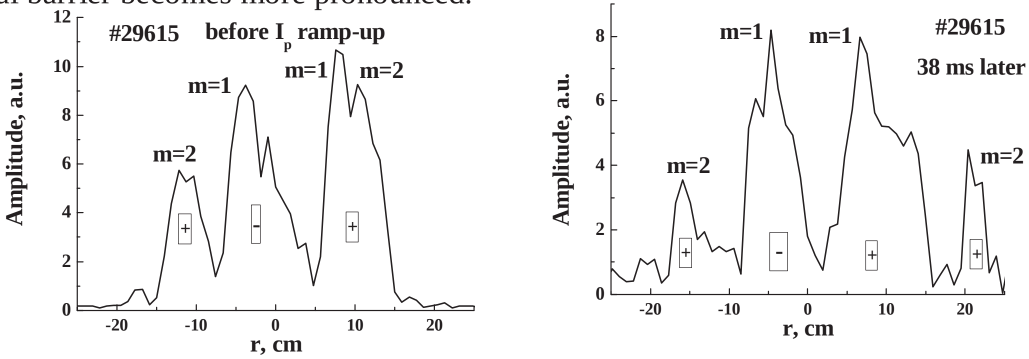


FIG. 6. Regime A-1. Fourier analysis of the temporal changes of the SXR intensity fluctuations. The signs + and – give the relations between fluctuation phases.

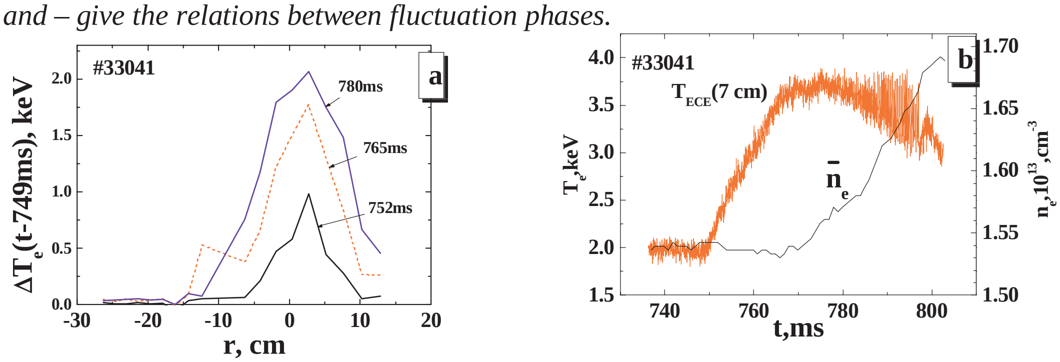


FIG. 7. Regime A-2. a) The $T_e(r)$ profile changes after the on-axis ECRH switch-on at t=750 ms; b) temporal behavior of T_e and average plasma density n_e during on-axis ECRH. m=2 mode activity is seen.

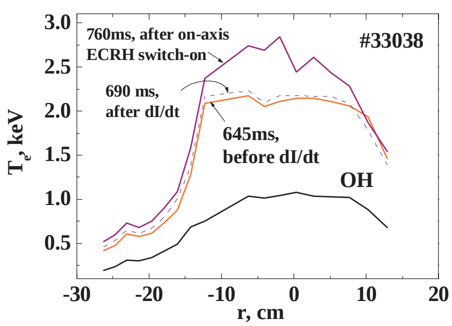


FIG. 8. Regime B-2. The temperature changes during the current ramp-up and on-axis ECRH.

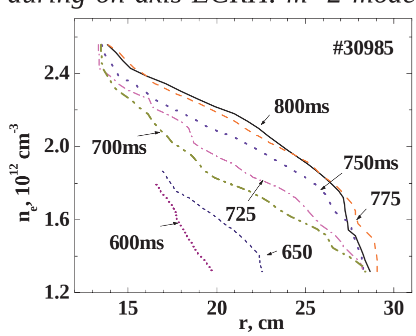


FIG. 9. Regime B-1. Density profile steepening during the external barrier formation.

Regime B-1. This regime is very similar to the regimes with two transport barriers, described in [6]. Current ramp-up leads to the barriers′ appearance 30–40 ms earlier, 15 ms after I_p ramp-up. In this case the transition was more drastic than in the constant current case, and the sawteeth are not quite stabilized. The ITB, manifested in the $\nabla T_e(r)$ and $\nabla I_{SXR}(r)$ increase, takes place some centimeters outside r_s. The edge barrier is accompanied by the usual effects of $n_{e\ edge}$ increase, $I_{D\alpha}$ decrease and typical effects in the limiter shadow. *FIGURE* 9 presents $n_e(r)$ profiles measured by reflectometry, showing the formation of the edge barrier on the density. So in the ETB we see a ∇n_e increase; and in the ITB a ∇T_e increase.

4. Discussion

In the experiments with current ramp-up under off-axis ECRH, a small, but well pronounced ITB was formed that was not due to insertion of angular momentum into the plasma — ECRH cannot do this — and was not due to the heat flux increase: calculations show that during the first 30 ms the additional current density cannot penetrate inside the ITB region, and $q(r)$ remain the same inside the ITB region during this time interval and to be changed at the edge only. So only the displacement of the plasma core due to changed toroidal plasma equilibrium may be responsible for the ITB formation. This process leads to the rarefaction of the magnetic surface density at the outside of the toroidal plasma. This can increase the distance between adjacent magnetic islands, and if the $q(r)$ configuration is appropriate for barrier formation, the barrier may be realized by the current ramp-up as in cases A-1, A-2 and B-1. Note that the central ECRH in the regime A-2, but without the current ramp-up, also gives a high T_e increase inside the q=1 region. So in such a $q(r)$ configuration the increased thermal flux also can form a barrier. Another situation pertains in the regime B-2, when r_s slightly increases, and its position in relation to the EC resonance becomes not optimal. Neither the current ramp-up, nor the increased heat flux from the on-axis heating leads to ITB formation. Only the ETB is seen in this case, maybe because the q=2 magnetic surface slowly approaches plasma edge after I_p has been increased. Simultaneous ITB and ETB formation takes place in case B-1, when the sawtooth activity is strong. As was shown in [6], in this kind of regime, a flattened $q(r)$ exists in a distinct region outside r_s. This may be favorable for ITB formation. In all T-10 experiments, the existence of the q=2 surface near the plasma edge under ECRH leads to ETB formation (H-mode?). For q_L=3, the ETB may be formed by enhancement of the heating power or perhaps is stimulated by internal MHD activity due to the modes coupling.

5. Conclusions

1. Regimes with ITB only, with ETB only, and with both ITB and ETB are obtained.
2. It is shown that the q value and its radial profile near the resonance magnetic surface with low m and n values play the determining role in the barrier formation.
3. Small changes in the $q(r)$ profile provide an effective influence on ITB formation, if an appropriate $q(r)$ profile is first established.
4. The increased level of the heat flux may lead to ETB formation (may be due to internal-external mode coupling), again if an appropriate $q(r)$ profile has been prepared.

Acknowledgments

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