Confinement Bifurcation by Current Density Profile Perturbation in TUMAN-3M Tokamak

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Abstract. In the recent experiments performed on TUMAN-3M the possibility to switch on/off the *H*-mode by current density profile perturbations has been shown. The j(r) perturbations were created by fast Current Ramp Up/Down or by Magnetic Compression produced by a fast increase of the toroidal magnetic field. It was found that the Current Ramp Up (CRU) and Magnetic Compression (MC) are useful means for *H*-mode triggering. The Current Ramp Down (CRD) triggers *H-L* transition. The difference in the j(r) behavior in these experiments suggests the peripheral current density may not be the critical parameter controlling *L-H* and *H-L* transitions. Confinement bifurcation in the above experiments could be explained by the unified mechanism: variation of a turbulent transport resulting from radial electric field emerging near the edge in the conditions of alternating toroidal electric field E_φ and different electron and ion collisionalities. According to the suggested model the toroidal field E_φ arising in the periphery during the CRU and MC processes amplifies Ware drift, which mainly influences electron component. As a result the favorable for the transition negative (inward directed) E_r emerges. In the CRD scenario, when E_φ is opposite to the total plasma current direction, the mechanism should generate positive E_r, which is thought to be unfavorable for the *H*-mode. The experimental data on *L-H* and *H-L* transitions in various scenarios and the results of the modeling of E_r emerging in the CRU experiment are presented in the paper.

1. Introduction

Current density in the peripheral region j_b essentially influences the *L-H* and *H-L* transitions and the *H*-mode performance. Active control of j_b can be realized by plasma current I_p ramps or by other means of the magnetic flux change (i.e. Magnetic Compression, Elongation Ramp…). In the JIPP T-IIU tokamak the 30-50 % reduction of the *L-H* transition power threshold in the CRD scenario was reported [1]. The *L-H* transition was triggered by the CRD and by elongation ramp up in the DIII-D [2]. Similar observation was made on the TCV: small negative I_p ramp (CRD) triggers the *H*-mode, whereas the CRU was found to be the way to avoid the *H*-mode [3]. Decrease in the j_b in the MC experiment on the TUMAN-3 facilitated *L-H* transition [4]. In other experiments reduction of the j_b was found to be unfavorable for *H*-mode and vice versa. The CRD lead to the *H*-mode termination and the CRU to the *H*-mode establishing in the COMPASS-D [5]. Termination of the *H*-mode by CRD was observed in our earlier experiments on TUMAN-3M [6]. ELM suppression and destabilization by Current Ramps were observed in the JET [7] and COMPASS-D [8]. Many authors suggest that the peripheral current density essentially influences MHD activity through magnetic shear modification and MHD mode drive [1,2,5,7,8]. Decay or growth of MHD activity by Current Ramps facilitate or hamper *L-H* and *H-L* transitions.

Another mechanism of an influence of magnetic flux change on transition between confinement modes is discussed in the paper. The mechanism is based on the possibility of a radial electric field E_r formation in a tokamak in the presence of variable toroidal electric field

E_φ [9] or difference in the electron and ion collisionalities [10]. The mechanism is suitable for E_r emerging explanation in ohmically heated tokamak plasma in absence of an external source of toroidal momentum and powerful auxiliary heating. The underlying idea of this approach is to take into account the electron Ware drift that leads to a radial current excitation and radial electric field build up. Since the Ware drift is proportional to E_φ/B_θ the direction of the radial current and sign of E_r depends on toroidal electric field direction and relationship between electron/ion collisionalities. Arising inward or outward E_r helps to trigger or terminate *H*-mode. Thus, the mechanism suggests the peripheral E_φ influence the transition processes, whereas j_b is less important. The main goal of the recent study was to check the validity of the model in different schemes of magnetic flux change. In the paper the results of the experiments with the CRD, CRU and MC in the *L* and *H*-modes in TUMAN-3M are presented.

2. Current Ramp Down in the *H* and *L*-modes

In the earlier experiments in the TUMAN-3M it was found the CRD led to the *H*-mode termination [6]. We suggest the reason for this is a change of a sign of the Ware drift velocity, which causes the destruction of the radial electric field E_r necessary for *H*-mode sustaining. Recent experiments with the CRD were performed in the ohmically heated plasma with the following parameters: R_0=0.53 m, a_l=0.22 m, B_t=0.7÷0.8 T, I_p=150 kA, $\langle n \rangle = 1.8 \cdot 10^{19}$ m^{-3}, $T_e(0)$=0.4÷0.5 keV, $T_i(0)$=0.15÷0.2 keV. The CRD was produced by the additional power supply with negative polarity incorporated into the ohmic heating primary. The magnitude of the plasma current perturbation ΔI_p was ±20÷30 kA, what is in the range of 15÷20% I_p. When the CRD is applied to the *L*-mode plasma, no change in the confinement mode was found: discharge remains in *L*-mode, see FIG. 1. In this case the reversal of the radial drift of trapped electrons leads to the positive E_r generation which is unfavorable for *H*-mode. Generally speaking, if $|E_r|$ and $|\partial E_r/\partial r|$ are large enough, the *H*-mode transition should be possible in this case. However, as it is seen from the FIG. 1, the CRD does not produce noticeable effect on confinement. Reasonable explanation for this could be that $|E_r|$ or $|\partial E_r/\partial r|$ are below the threshold level for the *H*-mode triggering [11].

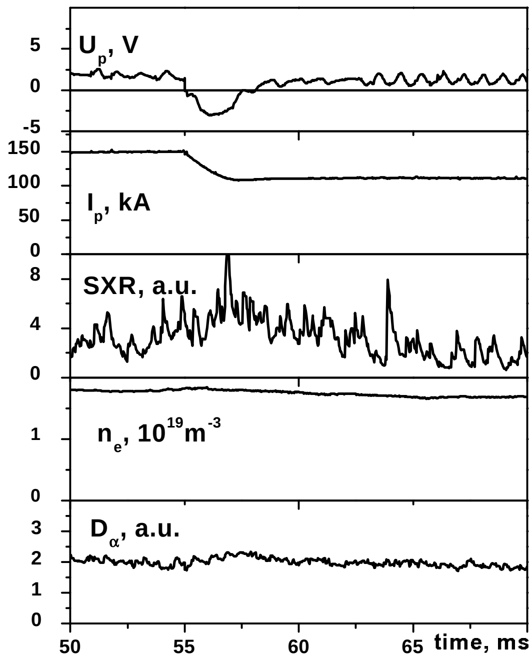

FIG. 1. The Current Ramp Down in the L-mode doesn't change the confinement.

3. Current Ramp Up in the *L* and *H*-modes

The positive E_φ perturbation near periphery was produced by the Current Ramp Up. The CRU was applied at the flat top of the discharge with plasma current 120-130 kA. If the initial plasma is in the ordinary ohmic regime (ohmic *L*-mode) and the rate of the CRU exceeds some threshold value, the CRU leads to the *H*-mode transition, see FIG. 2a. The indication of the confinement improvement is the drop in the D_α emission accompanied by plasma density increase. Another evidence of the confinement improvement in the CRU scenario was found using reflectometry measurements. The substantial drops in the amplitude of the high frequency density fluctuations and in the fluctuation spectrum width in the periphery were observed by this technique. Based on these measurements estimations showed 4 to 6 fold decrease of the turbulent diffusion coefficient after the *H*-mode transition [12].

In the frames of the model discussed above, the cause of the transition in CRU experiment is the increase in the radial drift of trapped electrons, which leads to the negative E_r formation. The transition to the regime of improved confinement has a clear bifurcation character: (i) it happens only if the threshold in control parameter ($|\partial I_p/\partial t|$) is exceeded, and (ii) after the transition takes place, the (high) level of confinement holds out till the end of the shot. Another indication of the bifurcation nature of confinement in the TUMAN-3M can be found in the CRU experiment in the ohmic *H*-mode, see FIG. 2b. In this case, the ohmic *H*-mode was triggered in advance by a short pulse of gas puff. The CRU switched on at t=66ms sustained the plasma in the regular *H*-mode, but no further improvement of the confinement was observed. In other words, the CRU in this experiment did not cause a transition to another state of confinement.

The L-H transition in the CRU experiment was simulated by the BATRAC code [13], assuming the transport coefficients to be given functions of the radial electric field shear $|\partial E_r/\partial r|$. The radial electric field was calculated self-consistently, following the model discussed above. The calculated radial profiles of E_r are shown in FIG. 3. The figure clearly indicates that strong inhomogeneous radial electric field is generated at the plasma periphery shortly after the beginning of fast Current Ramp Up resulting in the *H*-mode establishing.

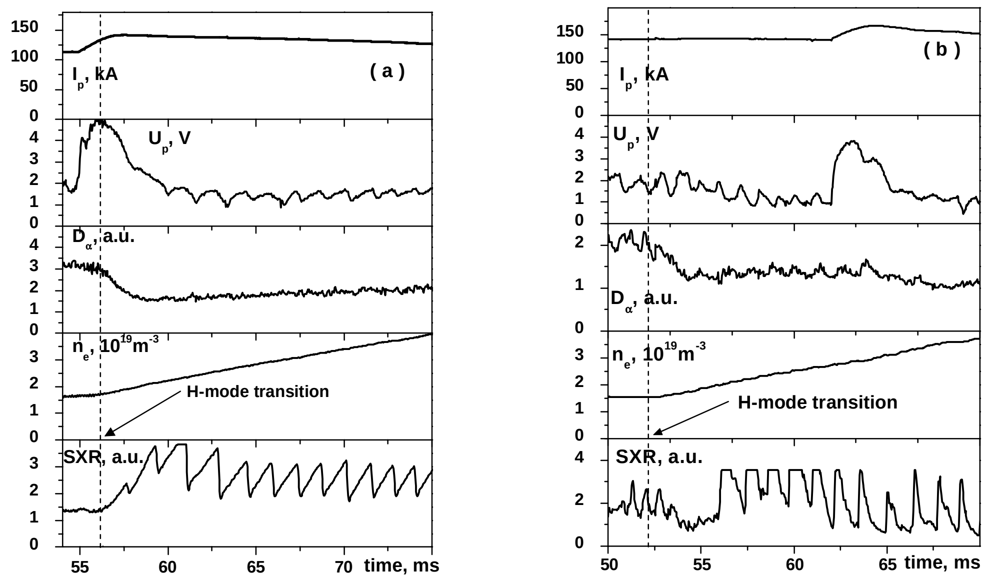

FIG. 2. The Current Ramp Up in the L-mode triggers the L-H transition – a and in the H-mode sustains the high confinement – b.

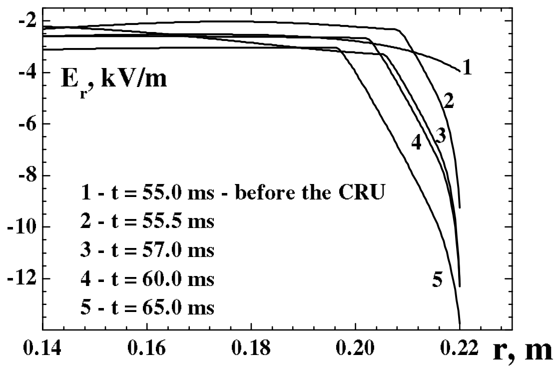

FIG. 3. Calculated radial electric field profiles before (1) and during (2-5) the CRU.

4. Magnetic Compression in the *L* and *H*-modes

In the earlier experiments on two-fold minor radius Magnetic Compression in the TUMAN-3 the transition into the *H*-mode has been found [4]. Because of large compression ratio (B_t^C/B_t^0=2) in those experiments the auxiliary input power was essential, thus enabling transition due to exceeding the *L-H* transition threshold power. In order to reduce the input power and to clarify the mechanism of the transition in the recent experimental run the compression ratio was reduced to 1.15, providing $P_{\partial B/\partial t}/P_{OH}$= 0.2÷0.3 [14]. It was found that the MC with small ratio is useful mean for *H*-mode triggering as well. An example of the *L-H* transition caused by the MC is presented on FIG. 4a. The MC causes the increase in plasma internal inductance l_i and, as a result, the increase in the peripheral E_φ. According to the model discussed above, increase in E_φ results in emerging of the inward radial electric field, which is favorable for the *L-H* transition. Applying MC to the ohmic *H*-mode does not lead to triggering another transition and further improvement in the confinement. In this case only adiabatic increase in the temperature and density was observed, see FIG. 4b.

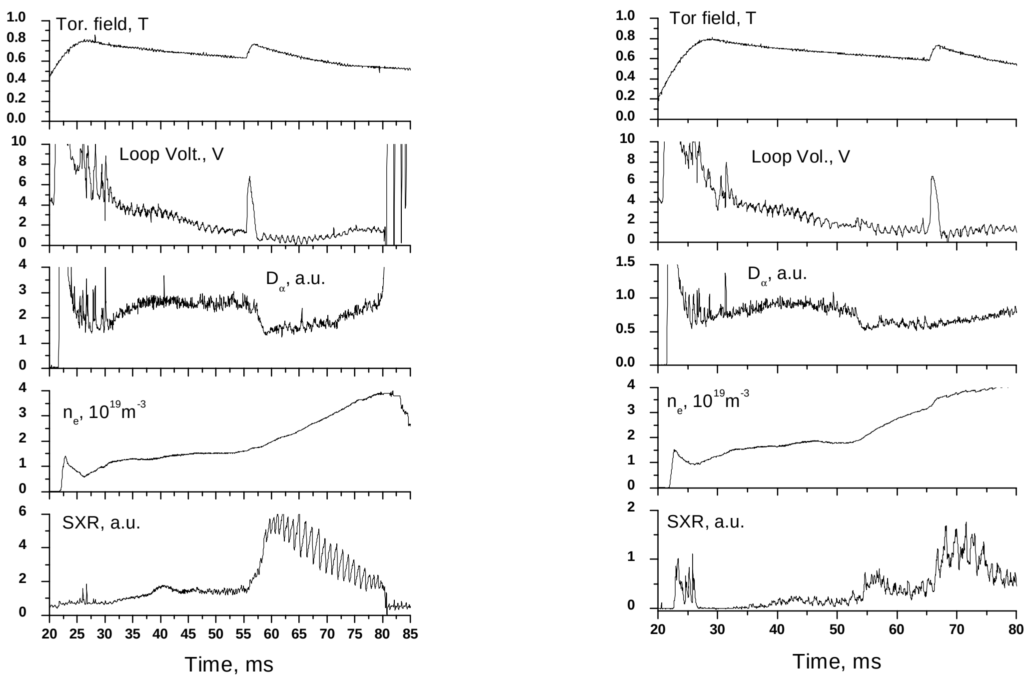

FIG. 4. The Magnetic Compression in the L-mode triggers the L-H transition – a and in the H-mode sustains the high confinement – b.

5. Summary

Two methods of magnetic flux perturbation: Current Ramps and Magnetic Compression were used to trigger transitions between confinement modes in the TUMAN-3M. The results of these experiments are collected in Table 1.

TABLE I: E_φ PERTURBATION EFFECT ON THE CONFINEMENT.

Init. state	Perturbation	j(r) evolution	E_φ evolution	Change in "e" Ware drift	Result
L	CRU	Broadening	Rise	$\|V_r^e\|$ rises, $V_r^e<0$	L → H
H	CRU	Broadening	Rise	$\|V_r^e\|$ rises, $V_r^e<0$	H
L	CRD	Narrowing	Drop	$\|V_r^e\|$ drops, $V_r^e>0$	L
H	CRD	Narrowing	Drop	$\|V_r^e\|$ drops, $V_r^e>0$	H → L
L	Compression	Narrowing	Rise	$\|V_r^e\|$ rises, $V_r^e<0$	L → H
H	Compression	Narrowing	Rise	$\|V_r^e\|$ rises, $V_r^e<0$	H

No correlation was found between confinement mode transitions and the plasma current profile evolution. The *L-H* transition was observed when j(r) has been broadened (CRU experiment), as well as narrowed (MC). Confinement correlates with the sign of E_φ perturbation: positive δE_φ causes the *L-H* transition (or sustains the *H*-mode). Contrary, negative δE_φ leads to the *H-L* transition or preserves the *L*-mode. This behavior may be understood in the frames of the suggested model of a radial electric field generation, which takes into account the electron Ware drift in perturbed toroidal electric field δE_φ .

Acknowledgement. Authors are grateful to RFBR, RF Ministry of Science and INTAS for providing support, which made this study to be possible.

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