The H-mode transition mechanism studies using different edge plasma perturbations on the TUMAN-3M tokamak

L.G. Askinazi, V.E. Golant, V.A. Kornev, S.V. Krikunov, S.V. Lebedev, L.S. Levin, V.A. Rozhansky†, M. Tendler‡, A.S. Tukachinsky, M.I. Vildjunas, S.P. Voskoboinikov†, N.A. Zhubr

Ioffe Physico-Technical Institute, 194021, St.Petersburg, Russia

† St.Petersburg State Technical University, 195251, St.Petersburg, Russia

‡Alfvén Laboratory, Royal Institute of Technology, Stockholm 10044, Sweden

Introduction

A new mechanism of a radial electric field formation in a tokamak has been proposed recently [1,2]. This mechanism is suitable for $\mathbf{E_r}$ emerging explanation in ohmically heated tokamak plasma in absence of powerful external source of toroidal momentum and heating power. The underlying idea of this approach is taking into account the electron Ware drift flow that leads to a radial current excitation and radial electric field build up. In the TUMAN-3M tokamak, this radial current is caused by the difference in electron and ion collisionalities: at the edge of the TUMAN-3M plasma electrons are in banana regime, whereas ions are in plateau. The maintenance of zero total radial current requires the transverse conductivity current, and so the radial electric field, to emerge. The accurate modeling of the TUMAN-3M H-mode discharge evolution using this approach is given in [1]. The main goal of the present study is to check the validity of the model in the greatest possible number of different experimental conditions.

As the Ware drift velocity, which is a crucial parameter of the model discussed, is proportional to the $\mathbf{E_\varphi/B_\theta}$, the experimental setup was arranged in a way that allowed creating a perturbation of toroidal electric field $\mathbf{E_\varphi}$. Two methods of $\mathbf{E_\varphi}$ perturbation were used. The first was the fast plasma Current Ramp Down/Up (CRD and CRU, correspondingly) with the average speed 25MA/s. The second method used was the magnetic compression of plasma column by a rapidly increasing toroidal magnetic field. In this scenario, a perturbation of the toroidal electric field at the plasma edge arises due to the increase in internal inductance of plasma column, caused by the compression. Both methods of $\mathbf{E_\varphi}$ perturbation were utilized in two different modes of ohmic confinement (L and H), thus leading to different consequences.

The CRD and CRU in the H- and L-modes of confinement.

Recently, it was found that CRD in the TUMAN-3M led to the H-mode termination [2]. The obvious reason for this is a change of sign of the Ware drift velocity, which caused the destruction of radial electric field $\mathbf{E_r}$ necessary for H-mode sustaining. In the present study, we have utilized a positive perturbation of the $\mathbf{E_\varphi}$ caused by the CRU as a trigger, which forces the transition from the L- to the H-mode. For this purpose, the target discharge was initially in the ordinary OH regime (ohmic L-mode). The CRU was activated at the flat top of the discharge.

If the speed and the step of the CRU exceeded some threshold values, the CRU led to the H-mode transition, Fig.1a. In a frame of the model discussed above, the cause of the transition is the increase in radial drift of trapped electrons, which leads to the negative $\mathbf{E_r}$ formation. The

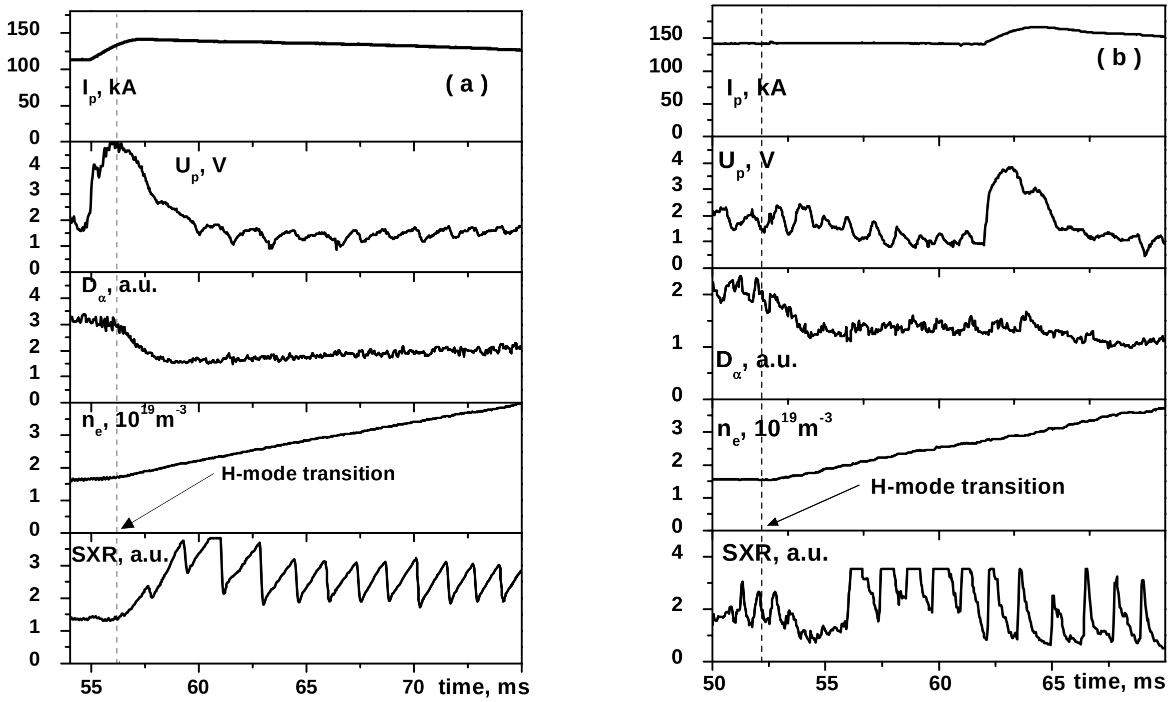

Figure 1. The Current Ramp Up (a) in the L-mode causes the L-H transition and (b) in the H-mode sustains the high level of confinement.

transition to the regime of improved confinement has a clear bifurcation character: (i) it happens only if the threshold in control parameter is exceeded, and (ii) after the transition takes place, the (high) level of confinement remains approximately constant. Another indication of the bifurcation nature of confinement in the TUMAN-3M can be found in the CRU experiment in the Ohmic H-mode, Fig.1b. In this case, the H-mode was initiated in advance by a short pulse of gas puff. The indication of the confinement improvement is drop in D_α emission accompanied by plasma density rise. Then, the confinement degraded for some reason, possibly due to the peripheral MHD activity. The CRU activated at t=66ms returned the discharge to the regular H-mode level of confinement, but no further improvement of the confinement was observed. In other words, the CRU in this experiment hasn't cause a transition to another stable state of confinement, but rather sustain the regular H-mode level.

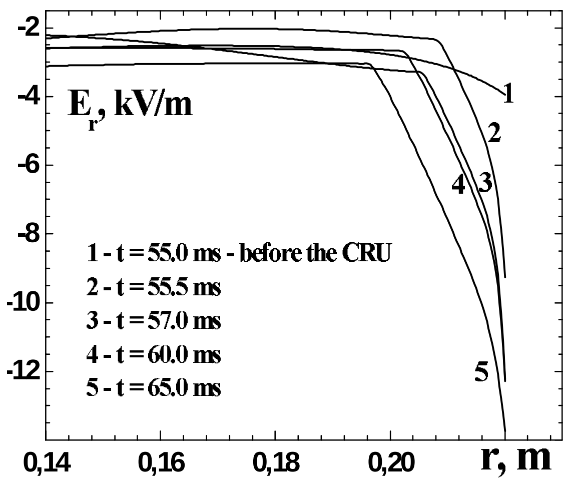

Fig.2. The calculated radial electric field profiles before (curve 1) and during (curves 2-5) the Current Ramp Up.

The L-H transition in the CRU experiment on the TUMAN-3M was simulated by the BATRAC code [3], assuming the transport coefficients to be given functions of the radial electric field shear $|\partial \mathbf{E_r}/\partial r|$. The radial electric field was calculated self-consistently, following the model discussed above. The calculated radial profiles of $\mathbf{E_r}$ are shown in Fig.2. It clearly indicates that strong inhomogeneous radial electric field generates at the plasma periphery shortly after the beginning of fast current ramp up, thus leading to the H-mode transition.

When the CRD is applied to the L-mode plasma, the reversal of the radial drift of trapped electrons leads to the positive $\mathbf{E_r}$ generation. Generally speaking, if $|\mathbf{E_r}|$ and $|\partial \mathbf{E_r}/\partial \mathbf{r}|$ are large enough, the H-mode transition should be possible in this case too. However, as it is seen from the Fig.3, the CRD didn't produce noticeable effect on confinement in this case. Reasonable explanation for this could be that $|\mathbf{E_r}|$ and $|\partial \mathbf{E_r}/\partial \mathbf{r}|$ are below the threshold level for H-mode transition.

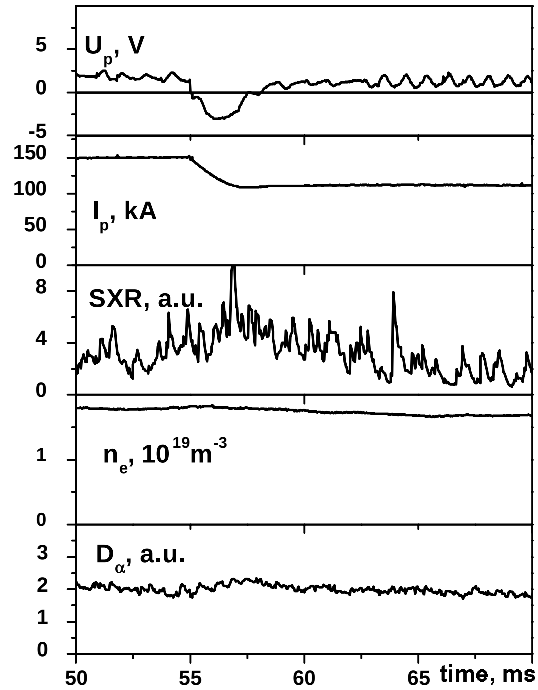

Figure 3. The Current Ramp Down in the L-mode doesn't change the confinement.

Magnetic compression in L-and H-modes

The compression of plasma column by a fast ramp of toroidal magnetic field has been used on the TUMAN-3 tokamak earlier to reach high values of plasma temperature and density. An improvement of the confinement has been observed in this case as well [5]. In order to clear up the role of this change of the confinement, the magnetic compression experiment was repeated on TUMAN-3M recently, with significant changes in scenario: (i) to minimize the power income from the compression itself, only $\delta \mathbf{B_T}/\mathbf{B_T}$=20% ramp of toroidal magnetic field was used, (ii) to increase the perturbation of toroidal electric field, the rise time of magnetic field was made as short as 1.7 ms, (iii) the gas puff rate was kept constant. It was found that even in this case the magnetic compression leads to the transition into the H-mode of confinement. Magnetic compression causes the increase in internal inductance of plasma column, and, as a result, in toroidal electric field $\mathbf{E}_\varphi$. According to the model discussed above, increase in $\mathbf{E}_\varphi$ results in radial electron current excitation, which leads to radial electric field build up, necessary for the L-H-transition. The detailed analysis of this experiment is given in [5]. Note that, contrary to the CRU case, magnetic compression causes narrowing of the plasma current profile.

Discussion

Two possible methods of $\mathbf{E}_\varphi$ perturbation: plasma current ramp and magnetic compression- were used as a trigger of confinement mode transition on TUMAN-3M tokamak. The results of these experiments are collected in Table 1.

No correlation was found between confinement switching and the plasma current profile evolution. The L-H transition was observed when plasma current profile has been broadened (fast plasma current ramp up experiment), as well as narrowed (magnetic compression experiment). Rather, confinement correlates with the sign of $\mathbf{E}_\varphi$ perturbation: positive $\delta\mathbf{E}_\varphi$ causes L-H transitions (or sustains the H-mode, if it was switched on earlier). Contrary, negative $\delta\mathbf{E}_\varphi$ leads to the H-L transition or preserves the L-mode if it was the initial state of confinement.

Initial mode of confinement	Perturbation	Current profile evolution	Peripheral E_φ evolution	Change in electron Ware drift V_r^e	Result
L	CRU	Broadening	Rise	$\lvert V_r^e\rvert$ rises, $V_r^e<0$	L → H
H	CRU	Broadening	Rise	$\lvert V_r^e\rvert$ rises, $V_r^e<0$	H
L	CRD	Narrowing	Drop	$\lvert V_r^e\rvert$ drops, $V_r^e>0$	L
H	CRD	Narrowing	Drop	$\lvert V_r^e\rvert$ drops, $V_r^e>0$	H → L
L	Compression	Narrowing	Rise	$\lvert V_r^e\rvert$ rises, $V_r^e<0$	L → H
H	Compression	Narrowing	Rise	$\lvert V_r^e\rvert$ rises, $V_r^e<0$	H

Table 1. E_φ perturbation effect on the confinement bifurcation on the TUMAN-3M.

This behavior may be understood in a frame of radial electric field generation model, which explains the $\mathbf{E}_r$ generation, by a radial current caused by the electron Ware drift in perturbed toroidal electric field $\delta\mathbf{E}_\varphi$.

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