Role of Magnetic Flux Perturbations in Confinement Bifurcations in TUMAN-3M

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Abstract. Poloidal magnetic flux variations in the small tokamak TUMAN-3M allowed observation of transitions between different confinement modes. The possibility of switching on/off the ohmic *H*-mode by edge poloidal magnetic flux perturbations has been found. The flux perturbations were created by fast current ramp up/down or by magnetic compression/decompression produced by fast increase/decrease in the toroidal magnetic field. It was found that positive flux perturbations (current ramp-up and magnetic compression scenarios) are useful means of *H*-mode triggering. If a negative flux perturbation (current ramp-down or magnetic decompression) is applied, the *H*-mode terminated. Various mechanisms involved in the *L-H* and *H-L* transition physics in the flux perturbation experiments were analyzed. The experimental observations of the transitions between confinement modes might be understood in terms of the model of a sheared radial electric field generation, which takes into account the electron Ware drift in a perturbed longitudinal electric field. Another scenario of improved confinement was observed in the initial phase of an ohmic discharge, when change in the poloidal flux is associated with current ramp-up. Variation of the rates of current ramp-up and working gas puffing in the beginning of a discharge resulted in a fast increase in the electron temperature near the axis. The increase correlates with low m/n MHD mode growth. The observed core electron confinement improvement is apparently connected with the rate of current ramp. Deviation from the optimal rate results in disappearance of the improvement. The role of magnetic shear profile and rational magnetic surfaces in the core electron confinement improvement in the initial phase of ohmic discharges is discussed.

1. Confinement bifurcations produced by edge poloidal magnetic flux perturbations

Magnetic flux perturbations in a tokamak can facilitate or hamper the *L-H* and *H-L* transitions [1-6]. In [1,2,5] the peripheral current density effect on MHD activity level through magnetic shear modification or MHD mode drive was concluded to be the main factor influencing the transitions. Flux perturbations produce changes in input power, which can affect the transition physics as well. In our study the poloidal magnetic flux perturbations were created by current ramps [6,7] and by toroidal magnetic field modifications. The perturbations were applied to *L* and *H*-mode plasmas with the following parameters: R_0=0.53 m, a_l=0.22 m, B_t=0.7-0.8 T, I_p=115-150 kA, $\langle n \rangle = (1.4\text{-}4.0)\cdot 10^{19}$ m^{-3}, $T_e(0)$=0.4-0.5 keV, $T_i(0)$=0.15-0.2 keV.

Details of the current ramp experiments are given in [6,7]. The rate of the current ramps was up to $2\cdot 10^7$ A/s. This rate allowed the appearance of strong negative/positive perturbations of the toroidal electric field E_φ owing to a decrease/increase in the poloidal flux. An example of the *L-H* transition caused by the fast current ramp-up (CRU) is shown in Fig.1. In this case the initial plasma is in the ordinary ohmic regime and the positive E_φ perturbation near the periphery is associated with an increase in the poloidal magnetic flux. If the rate of the CRU exceeds the threshold value of $1.4\ 10^7$ A/s, the *H*-mode transition is triggered. An indication of the confinement improvement is the drop in the D_α emission (56 ms), accompanied by a density increase.

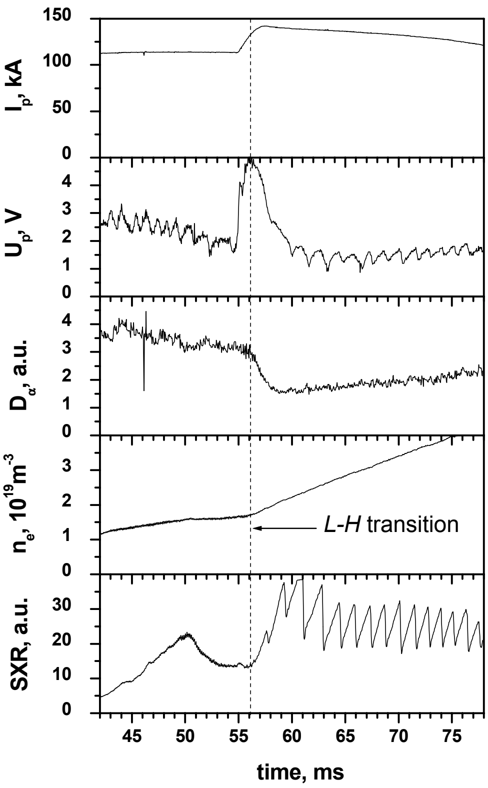


FIG.1. Waveforms of the plasma current – I_p; loop voltage – U_p; working gas emission in the midplane – D_α; average electron density – n_e; and soft X-ray emission – SXR in a discharge with the L-H transition caused by positive E_φ perturbation in the CRU scenario in the L-mode.

The transition into the regime of improved confinement in the CRU scenario has a clear bifurcation character: (i) it happens only if the critical value of $\partial I_p/\partial t$ is exceeded, and (ii) after the transition takes place, the (high) level of confinement is preserved till the end of the shot. Other evidence of the bifurcation nature has been found in the CRU experiment in the ohmic *H*-mode [7]. In this case, the ohmic *H*-mode was triggered in advance by a short pulse of working gas (D_2) puff and the CRU sustained the plasma in the regular ohmic *H*-mode, but no further improvement of confinement was observed. In other words, the CRU did not cause a transition to another state of confinement in this experiment.

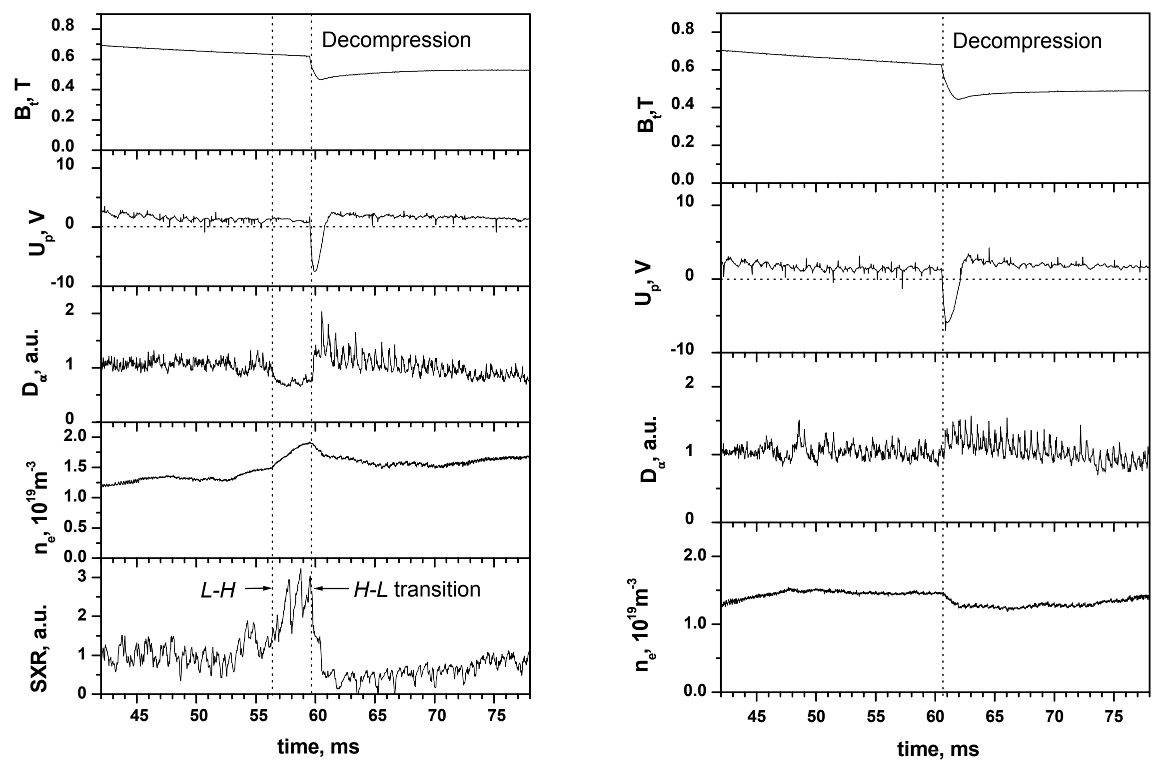
In terms of the model described in [8], the cause of the *L-H* transition in the CRU experiment is an increase in the radial drift of trapped electrons. Because of the essential difference between the electron and ion collisionalities at the edge of TUMAN-3M ($T_{e,b}>>T_{i,b}$), the neoclassical Ware radial drift of ions is negligible ($\nu_i^*>>1$) [7]. As a result of the non-ambipolarity in the Ware drift, a negative component appears in the radial current. An analytical and numerical consideration in [8] showed the formation of the negative E_r in these conditions. It is thought that this field facilitates the *L-H* transition.

The decrease in the poloidal flux in the current ramp-down scenario (CRD) was produced by negative perturbation of the boundary E_φ [6,7]. For the CRD scenario, the above model predicts an outward drift of trapped electrons. As a result, a positive radial electric field must emerge, which is considered unfavorable for the *H*-mode. In accordance with the expectations, the CRD in the ohmic *H*-mode resulted in a clear *H-L* transition. When applied to the *L*-mode, the CRD does not trigger the *H*-mode transition [7].

The current density profile j(r) is broadened by current ramp-up and narrowed by current-ramp down. Modification of j(r) could be produced by magnetic compression (MC) or decompression (MDC) as well. In these scenarios, j(r) is narrowed by MC and broadened by MDC. It should be noted that CRU and MDC affect j(r) in a similar way (broadening), whereas their effects on peripheral E_φ are different (co-current for the CRU and counter-current for the MDC case). In the CRD and MC scenarios (j(r) narrowing) the peripheral E_φ perturbations are different also (counter-current for CRD and co-current for MC). Thus, compression/decompression experiments may shed light on factors controlling the transitions.

A minor radius magnetic compression was performed by rapidly raising the toroidal magnetic field strength [4,9]. The compression ratio was chosen to be small: 1.15, providing $P_{\partial B/\partial t}/P_{OH}$=0.2-0.3 [9]. The MC causes an increase in the poloidal flux and the corresponding rise in the peripheral E_φ. According to the model, the increase in E_φ results in the appearance of inward directed E_r, which is favorable for the *L-H* transition. In agreement with the model the experiment has shown that MC is a useful means of *H*-mode triggering. Applying MC to the ohmic *H*-mode does not lead to triggering of transition and confinement improvement. In this case, only an adiabatic increase in the temperature and density was observed.

In the recent experimental run, MDC was investigated. MDC was performed by rapidly lowering the toroidal magnetic field with a typical ratio of B_t^{DC}/B_t^{OH} = 0.75-0.8, and the time of field decrease τ^{DC} = 1.5-1.7 ms, which is small compared with the current penetration time $\tau_I \cong 30$ ms. Decompression results in a decrease in the poloidal flux and the corresponding negative perturbation of the loop voltage. In these regimes, the plasma current was kept constant, I_p = 120 kA. The MDC was applied to the ohmic *H*-mode and ordinary ohmic regime (*L*-mode). Typical waveforms of discharges with MDC are shown in Fig.2. Noteworthy is a strong negative spike in the loop voltage trace, observed during field decrease. Decompression in the ohmic *H*-mode (Fig.2a) led to a clear *H-L* transition, with the density and SXR emission intensity rise termination and D_α intensity increase. No confinement bifurcation was found in the MDC scenario in the ordinary ohmic regime, see Fig.2b. Only a small steplike decrease in the density and SXR emission was observed. The decrease is attributed to adiabatic expansion during the MDC. The obtained results are in agreement with the above model of transitions between confinement modes in the presence of a varying toroidal electric field at the periphery.



a *b*

FIG.2. Waveforms of the toroidal magnetic field – B_t; loop voltage – U_p; working gas emission in the midplane – D_α; average electron density – n_e; and soft X-ray emission – SXR in a discharge with (a) the H-L transition and (b) L-mode preservation n the MDC scenario accompanied by negative E_φ perturbation, I_p=120 kA.

Results of the experiments performed are summarized in Table 1. The first column of the table presents the initial state of confinement. In the second column the type of applied perturbation is given. The measured sign of the edge toroidal electric field perturbation is presented in the third column. In columns 4, 5 and 6 the results of transport simulations using the ASTRA code [10] are given: the qualitative estimation of current profile evolution, the change in the edge magnetic shear *s* and the evolution of the input power. The last column represents the result of the flux perturbation. The data presented indicate that no correlation exists between the result and either the j(r) evolution or the edge magnetic shear evolution. Some correlation between the direction of confinement evolution and the change in the input power exists: with more power input, the *H*-mode develops or is sustained; with less power input, the *H*-mode terminates or the *L*-mode is sustained. But the input power seems unlikely to be the main factor controlling the transitions, because of the relatively small change of P_{inp} (10-45%). The direction of confinement evolution correlates with the sign of the E_φ perturbation: positive δE_φ causes the *L-H* transition or preserves the *H*-mode. In contrast, negative δE_φ leads to the *H-L* transition or preserves the *L*-mode. This behavior can be understood in terms of the model of radial electric field generation, which takes into account the electron Ware drift in a perturbed toroidal electric field δE_φ [8].

Table 1. EFFECT OF E_φ PERTURBATION ON THE CONFINEMENT

Initial state	Type of perturbation	**E_φ perturbation**	j(r) evolution	Edge *s* evolution	**P_{Input} evolution**	**Result**
L	CRU	**positive**	broadening	25% drop	**45% rise**	***L* → *H***
H	CRU	**positive**	broadening	30% drop	**45% rise**	***H***
L	CRD	**negative**	narrowing	35% rise	**30% drop**	***L***
H	CRD	**negative**	narrowing	40% rise	**25% drop**	***H* → *L***
L	MC	**positive**	narrowing	5% rise	**15% rise**	***L* → *H***
H	MC	**positive**	narrowing	5% rise	**10% rise**	***H***
L	MDC	**negative**	broadening	10% drop	**15% drop**	***L***
H	MDC	**negative**	broadening	10% drop	**10% drop**	***H* → *L***

2. Observation of improved electron confinement in the current ramp phase of the ohmic discharge

Variation of the rates of current ramp-up and working gas puffing in the beginning of a discharge allowed observation of a fast increase in the electron temperature near the axis and formation of a steep T_e gradient region in the core (0.2a<r<0.5a). The phenomenon was found in ohmically heated plasma with q^{cyl}=3-4, I_p≅130 kA, $<n_e>$=(1.4-2.0) 10^{19} m^{-3}, $T_e(0)$=350-600 eV. A typical discharge with core electron confinement improvement in the initial phase is shown in Fig.3. The core confinement improvement exists during ~ 10 ms at the beginning of the current flattop ($\tau_{flattop}$≅45 ms). The improvement is apparently connected with the rate of current ramp $\partial I_p/\partial t$. The optimal rate is 12 MA/s. A 15% deviation of $\partial I_p/\partial t$ from the above value results in disappearance of the improvement. The electron temperature increase ΔT_e rises with the density until the disruptive limit is achieved. The highest density at this stage of a shot is close to 2.0 10^{19} m^{-3}. Attempts to exceed the above limit result in MHD mode

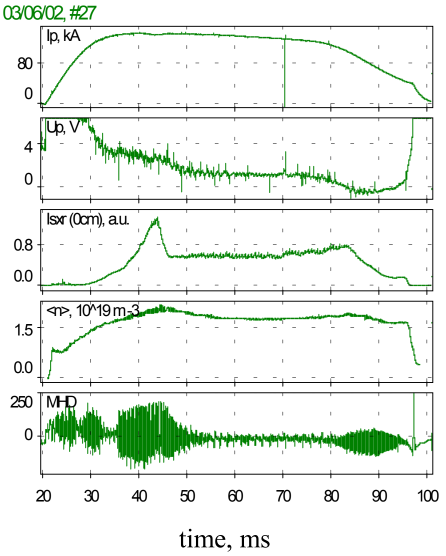


FIG.3. Evolution of plasma current – I_p; loop voltage – U_p; SXR intensity – I_{SXR}; Mirnov coil signal – MHD in the discharge with improved core confinement.

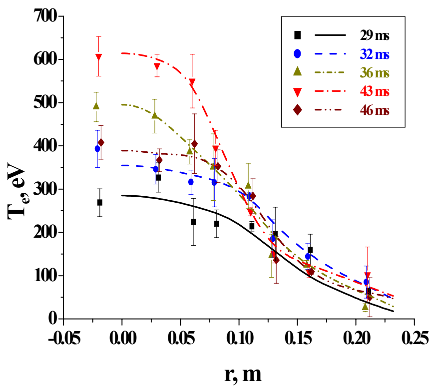


FIG.4. TS electron temperature profile evolution

locking and a major disruption. The maximum $T_e(0)$ measured by Thomson scattering during the confinement improvement phase is ~ 600 eV, whereas before and after the improvement period the central temperature is 400 eV, see Fig.4.

In all discharges obtained up to now the improved confinement decays at some phase of j(r) relaxation. The decay time is much longer than the minor disruption duration. Shortly after the improvement decay an ordinary sawtooth activity starts, indicating that j(r) reaches a relaxed quasi-stationary state. The existence of the q=1 surface during the period of improved confinement was concluded from the multi-chord SXR signals analysis, although the sawtooth activity develops well after the end of this phase.

A possible explanation of the core electron confinement improvement in the initial phase is the formation of a magnetic shear profile favourable for turbulence damping, although the existence of the negative/low shear zone in this phase is not proved. Further analysis is necessary in order to derive current density distribution.

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References:

[1] Toi K., et al., Phys. Rev. Lett., **64** (1990), 1895.
[2] Lao L.L., et al., Plasma Phys. and Controll. Nucl. Fusion Res., 1992 (Proc. 14th IAEA Conf. Wuerzburg, 1992), IAEA, Vienna (1993), Vol.1, 565.
[3] Martin Y., presentation at the Meeting of ITER Expert Group on Transport and Internal Barrier Physics, Naka, 2000 // personal communication.
[4] Akatova T.Yu., et al., Plasma Phys. and Controll. Nucl. Fusion Res., 1990 (Proc. 13th IAEA Conf. Washington, 1990), IAEA, Vienna (1991), Vol.1, 509.
[5] Fielding S.J., et al., Plasma Phys. Controll. Fusion, **42** (2000), A191.
[6] Askinazi L.G., et al., Plasma Physics Reports, **25** (1999), 110.
[7] Askinazi L.G., et al., Controll. Fusion and Plasma Phys. (Proc. 27th EPS Conf. Budapest, 2000), EPS, Geneva (2000), 520.
[8] Rozhansky V., Czech. J. Physics, **48/S3** (1998), 72; Rozhansky V., et al., Plasma Phys. Rep., **27** (2001), 205.
[9] Lebedev, S.V., et al., Controll. Fusion and Plasma Phys. (Proc. 27th EPS Conf. Budapest, 2000), EPS, Geneva (2000), 524.
[10] Dnestrovsky A.Yu., et al., Preprint IAE-5358/6 (1991).