

OBSERVATION OF INTERNAL TRANSPORT BARRIER IN OHMICALLY HEATED PLASMA IN TUMAN-3M TOKAMAK

S.V. Lebedev, M.V. Andreiko, L.G. Askinazi, V.E. Golant, V.A. Kornev, S.V. Krikunov,
L.S. Levin, G.T. Razdobarin, V.V. Rozhdestvensky, V.A. Rozhansky[@], A.I. Smirnov,
M. Tendler[#], A.S. Tukachinsky, S.P. Yaroshevich and N.A. Zhubr

A.F.Ioffe Phys.-Techn. Institute, Russian Academy of Sciences, 194021, St.Petersburg, Russia

[@] *St.Petersburg State Technical University, 195251, St.Petersburg, Russia*

[#] *Alfven Lab., Euratom NFR Association, Royal Institute of Technology, Stockholm, Sweden*

An Internal Transport Barrier (ITB) was observed in ohmically heated plasma in TUMAN-3M ($R_0 = 53$ cm, $a_1 = 22$ cm (circular limiter configuration), $B_t \approx 0.7$ T, $I_p \approx 150$ kA, $\langle n \rangle \leq 6.0 \cdot 10^{19} \text{ m}^{-3}$). The ITB reveals itself as a formation of a steep gradient on electron temperature and density radial profiles. The regions with reduced diffusion and electron thermal diffusivity are in between $r = 0.45a$ and $r = 0.7a$. The ITB appears more frequently in the shots with higher plasma current. At lower currents ($I_p < 120$ kA) the ITB is rare. In the ohmic H-mode with ITB the thermal energy confinement is in the range 9-18 ms. The enhancement factor over ITER93-H(ELM-free) scaling is up to 2.0.

1. Experimental evidences of Internal Transport Barrier in the ohmic H-mode

Recent experiments were performed in the freshly boronized vessel. In these conditions plasma current was increased up to 175 kA [1]. Diamagnetic measurements of a stored energy in the ohmic H-mode have shown noticeable enhancement in the energy confinement time as compared with ITER93-H(ELM-free) scaling predictions. H_H factor in this scenario is up to 2.0 and absolute values of τ_E are in the range 9-18 ms. The enhancement factor H_H is larger when I_p is more than 120 kA. At lower plasma currents the H_H is close to 1, see Fig. 1. The increase in the H_H factor reflects some additional confinement improvement in the high current shots as compared with edge improvements in the ohmic H-mode in low current shots [2].

Temporal behaviors of some plasma parameters in the shot with ITB in the ohmic H-mode are shown in Fig. 2. In this case plasma current was 149 kA. The distinctive feature of the shot is slow drop of the D_α emission during the transition into the regime with improved

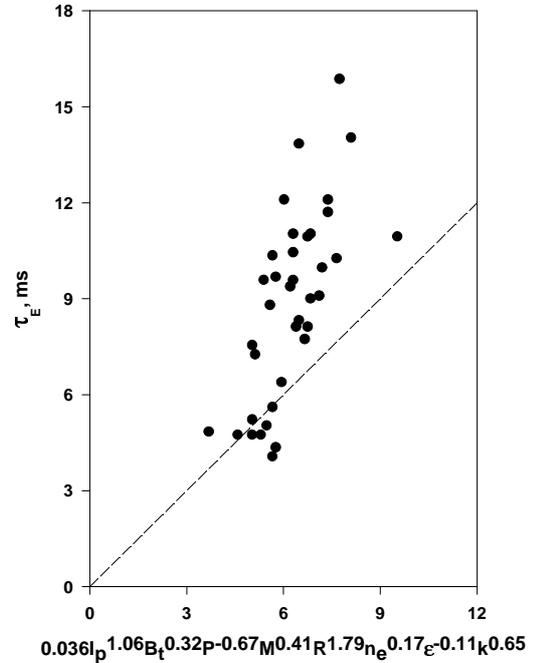


Fig. 1. Thermal energy confinement time in the ohmic H-mode as a function of ITER93-H(ELM-free) predictions.

confinement. The slow drop means gradual reduction of the particle/energy outflux near the edge. Note that in the shots with $I_p < 120$ kA the transition into the ohmic H-mode (without ITB) and corresponding drop of the D_α are very fast (typical time scale is 100 μ s) [2]. The difference in the time scales indicates that confinement improvement in the high current case may appear in the core, thus resulting in delayed effect on flux at the edge.

It was difficult to determine experimentally where confinement improvement starts: in the core or near the edge. But after the transition T_e profile exhibits two regions of steep gradient, see $T_e(r)$ measured on 68.5 shown in Fig. 3. First region is located at the very edge - $r > 20$ cm and corresponds to the normal ohmic H-mode transport barrier (edge barrier). The second region is in the core plasma - $10 \text{ cm} < r < 16$ cm. This steep gradient zone we consider as Internal Transport Barrier [3]. Edge and internal barriers are separated by a flat gradient zone with relatively high transport. It should be mentioned that no MHD activity was observed in the shots with ITB and therefore plateau on $T_e(r)$ could not be attributed to magnetic island existence. This observation is contradictory to data presented in [4] where plateaus on radial profiles were explained by magnetic islands. Also in Fig. 3 the $T_e(r)$ measured before transition (50 ms) is shown for comparison. It is seen that before transition the radial profile is smooth.

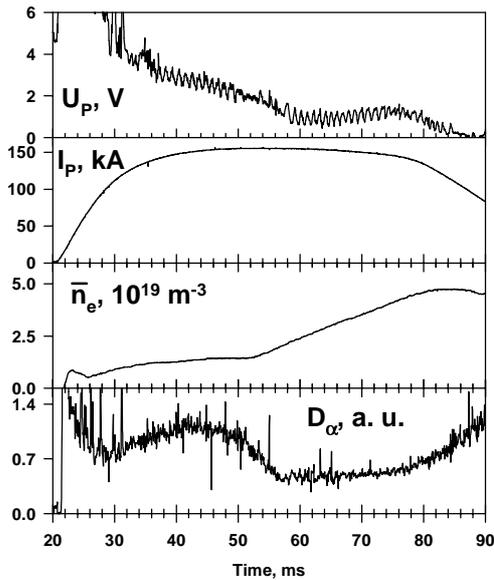


Fig. 2. Temporal behavior of the loop voltage, plasma current, averaged density and D_α emission in the shot with ITB in the ohmic H-mode.

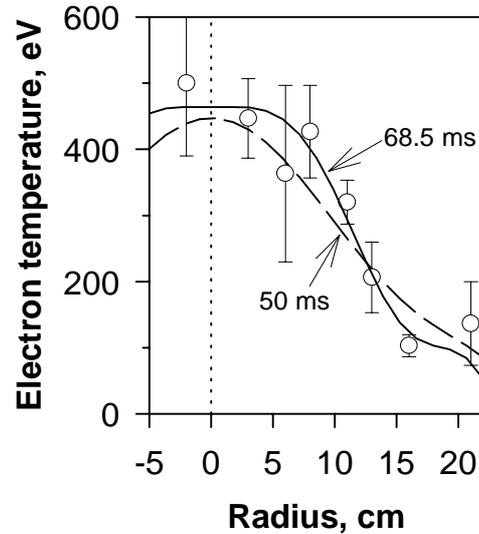


Fig. 3. $T_e(r)$ profiles measured before - "50 ms" and after - "68.5 ms" transition into the ohmic H-mode with ITB.

2. Transport simulations of the shot with Internal Transport Barrier

Data presented in Figs. 2&3 as well as $n_e(r,t)$ measured by microwave interferometer [3] were used in transport simulations. The purposes of the simulations were to quantify changes in electron thermal diffusivity through the transition and to analyze a role of transient

phenomena in the ITB formation. The simulations were performed using transport code ASTRA [5].

Radial profiles of the χ_e^{eff} are shown in Fig. 4 for ordinary ohmic regime – 50 ms and after the transition into the ohmic H-mode with ITB – 68.5 ms. Later profile is characterized by two wells located in the regions of internal and edge barriers and separated by a zone with χ_e^{eff} increased by an order of magnitude.

In order to explain formation of the reduced transport zone in the core the different mechanisms were considered. First, we have analyzed possibility of nonmonotonic q profile formation which might be the cause of some MHD modes stabilization [6]. Results of the calculation of q(r) on 50 ms are presented in Fig. 5. The data evidences that q(r) is monotonic and very close to stationary one. This allows to conclude that the above mechanism is likely not valid in our case.

Another possible explanation for ITB formation is the suppression of a turbulence by sheared rotation resulting from radial electric field emerging in the core [6]. According to [7,8] the radial current can arise in the core as a result of nonambipolar drift of banana particles in the presence of spatially inhomogeneous or time dependent longitudinal electric field E_ϕ , thus resulting in E_r appearance. The simulations have shown that radially inhomogeneous E_ϕ exists before stationary current density profile $j_\phi(r)$ is achieved in the current ramp up phase. Radial distribution of E_ϕ on 50 ms is shown in Fig. 6 by solid line. Our estimates have shown that in this case $\partial E_\phi / \partial r$ is small and resulting $\partial E_r / \partial r$ can not provide sufficient $\omega_{E \times B}$ necessary for turbulence suppression.

Electron thermal diffusivity, m²/s

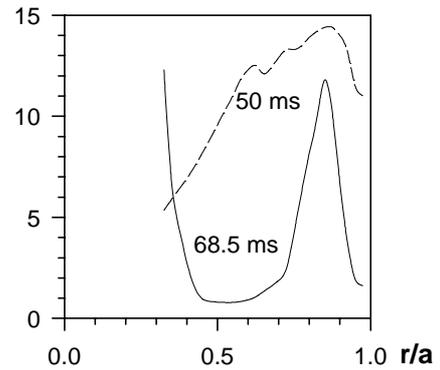


Fig. 4. Effective electron thermal diffusivity before - "50 ms" and after - "68.5 ms" transition into the ohmic H-mode with ITB.

Safety factor q^{cyl}

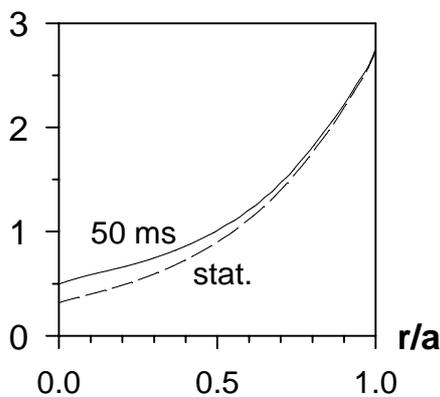


Fig. 5. Safety factor profile calculated taking into account $j(r)$ evolution in the current ramp up stage - "50 ms" and for stationary $j(r)$ - "stat.".

Longitudinal electric field, v/m

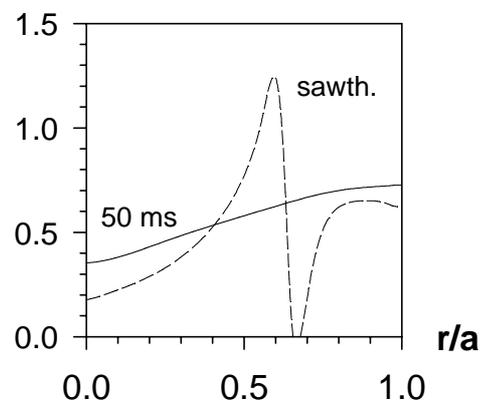


Fig. 6. Toroidal electric field profile at the end of current ramp up stage - "50 ms" and after sawtooth crash (Kadomtsev model) - "sawth.".

Substantial $\partial E_\phi/\partial r$ appears in the calculations if a strong perturbation of the $j_\phi(r)$ is included. Perturbations of that kind might appear during internal disruption events if Kadomtsev model is valid for sawtooth oscillations description [9]. Sawtooth oscillations of $j_\phi(r)$ produce strong $E_\phi(r)$ perturbations which are sufficient for generation of the strong $\partial E_r/\partial r$. In assumption that the model [9] is valid the $E_\phi(r)$ was calculated. Results are shown in Fig. 6 by dotted line. Coincidence of strong $\partial E_\phi/\partial r$ and ITB zones allows to assume that internal disruptions might play a key role in generation of $\partial E_\phi/\partial r$ and subsequent ITB formation if mechanisms described in [7,8] are taken into account.

3. Conclusions

Formation of Internal Transport Barrier in ohmically heated plasma has been observed in the experiments on TUMAN-3M tokamak. The indications of ITB appearance in the high current ohmic H-mode are: the increased up to 2.0 enhancement factor H_H , the slow reduction of a plasma outflux and the formation of a steep gradient zone on T_e and n_e profiles.

Transport simulations of the electron heat balance have confirmed the formation of two regions of reduced transport in the ohmic H-mode: Edge and Internal Transport Barriers.

Formation of the ITB is likely caused by a turbulent transport suppression by sheared $E \times B$ rotation. The possible mechanism of a strong $\partial E_r/\partial r$ generation in the ohmically heated plasma is the nonambipolar drift of banana particles provided by substantially inhomogeneous and time dependent longitudinal electric field arising during sawtooth crashes.

Acknowledgments

This work was performed with financial support from INTAS-RFBR Grant N 95-0575 and from RFBR Grant N 97-02-18107.

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