INTERNAL TRANSPORT BARRIER AND β LIMIT IN OHMICALLY HEATED PLASMA IN TUMAN-3M.

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

Ioffe Physico-Technical Institute, Russian Academy of Sciences, St.Petersburg, RUSSIA
[@] St.Petersburg State Technical University, St.Petersburg, RUSSIA
[#] Alfven Lab., EURATOM-NFR Assoc., Royal Institute of Technology, Stockholm, SWEDEN

Abstract

An Internal Transport Barrier (ITB) was found in ohmically heated plasma in TUMAN-3M (R_0 = 53 cm, a_l = 22 cm – circular limiter configuration, $B_t \le 0.7$ T, $I_p \le 175$ kA, $<n> \le 6.0 \cdot 10^{19}$ m^{-3}). The barrier reveals itself as a formation of a steep gradient on electron temperature and density radial profiles. The regions with reduced diffusion and electron thermaldiffusivity are in between r = 0.5a 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 of 9-18 ms. The enhancement factor over ITER93-H(ELM-free) scaling is up to 2. The results of experimental study of β_N limit in the ohmically heated plasma are presented. Stored energy was measured using diamagnetic loops and compared with W calculated from kinetic data obtained by Thomson scattering and microwave interferometry. Measurements of the stored energy and of the β were performed in the ohmic H-mode before and after boronization and in the scenario with the fast Current Ramp-Down in the ohmic H-mode. Maximum value of β_T of 2.0 % and β_N of 2 were achieved. The β_N limit achieved is "soft" (nondisruptive) limit. The stored energy slowly decays after the Current Ramp-Down. No correlation was found between beta restriction and MHD phenomena.

1. INTERNAL TRANSPORT BARRIER FORMATION IN OHMICALLY HEATED PLASMA

In the freshly boronized vessel the attainable plasma current was increased up to 175 kA [1]. This allow to perform study of plasma confinement in the ohmic H-mode in the increased plasma current range. Stored energy was measured by diamagnetic loops and calculated using kinetic data. The measurements have shown the noticeable enhancement in the energy confinement time as compared with ITER93-H(ELM-free) scaling predictions, see Fig. 1. The enhancement factor H_H in this scenario is up to 2.0 and absolute values of τ_E are in the range 9-18 ms. H_H appears to be larger when I_p is more than 120 kA. At lower plasma currents the H_H is close to 1. The increase in H_H indicates some improvement in the confinement above standard H-mode at higher currents.

Typical waveforms of some plasma parameters in the shot with 150 kA ohmic H-mode are shown on Fig. 2. The distinctive feature of the shot is slow decay of the D_α emission during the transition into the regime with improved confinement. The slow decay 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 core confinement improvement) and corresponding drop of the D_α are very fast (typical timescale is 100 μs) [2]. The difference in the decay times supports the conjecture that in the high current case the confinement improves in the core as well resulting in delayed effect on flux at the edge.

Formation of Internal Transport Barrier was observed on electron temperature profiles measured by Thomson scattering technique. Measured on 68.5 ms T_e profile exhibits two regions of steep gradient, see Fig. 3. First region is located at the very edge – r > 20 cm and corresponds to the normal H-mode transport barrier (edge barrier). The second region is in the core plasma – 10 < r < 16 cm. This steep gradient zone we consider as Internal Transport Barrier [3]. The steep gradient zone in plasma core is seen on $n_e(r)$ also. The regions with steep ∇T_e and ∇n_e coincide well and are in between r = 0.5a and r = 0.7a. 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 $T_e(r)$ and n(r) could not be explained by magnetic island. Also on Fig. 3 the $T_e(r)$ measured before transition (50 ms) is shown. It is seen that before transition $T_e(r)$ is smooth.

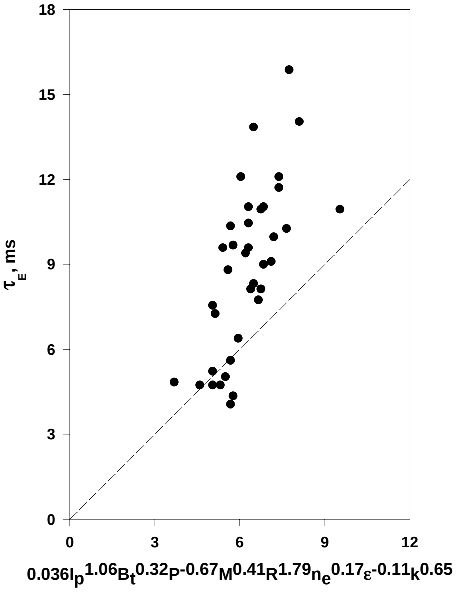

FIG. 1. Thermal energy confinement time in the ohmic H-mode as a function of ITER93-H(ELM-free) predictions.

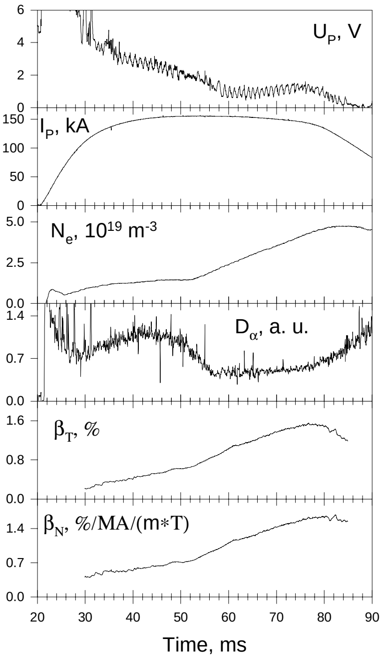

FIG. 2. Temporal behavior of the loop voltage, plasma current, averaged density, D_α emission and toroidal and normalized betas in the shot with ITB in the ohmic H-mode.

Data presented on Figs. 2 and 3 as well as $n_e(r,t)$ measured by microwave interferometry [3] were used in transport simulations. The purpose of the simulations was to quantify changes in electron thermaldiffusivity through the transition. The simulations were performed using transport code ASTRA [4]. The $\chi_e^{eff}(r)$ are shown on Fig. 4 for ordinary ohmic regime – 50 ms and after the transition into 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 core transport barrier the different mechanisms were considered. First, we have analyzed possibility of nonmonotonic q(r) formation which might be the cause of some MHD modes stabilization [5]. Our simulations evidenced that at 50th ms q(r) is monotonic and very close to the stationary one. This allows to conclude that the above mechanism is

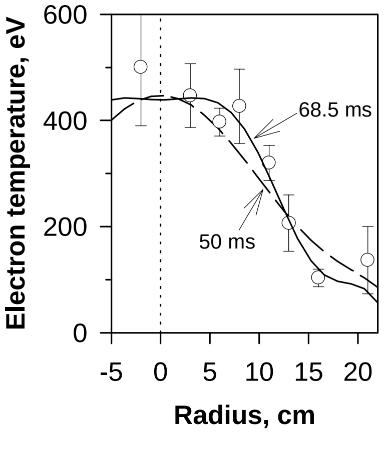

FIG. 3. $T_e(r)$ profiles measured before - "50 ms" and after - "68.5 ms" transition into the ohmic H-mode with ITB.

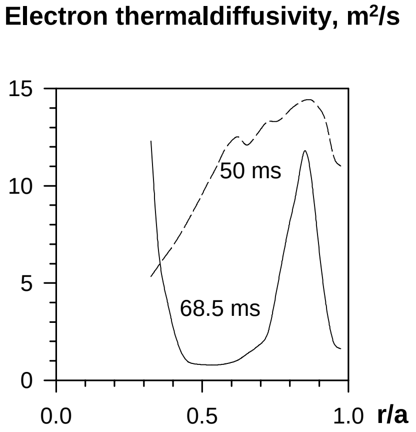

FIG. 4. Effective electron thermaldiffusivity before - "50 ms" and after - "68.5 ms" transition into the ohmic H-mode with ITB.

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 [5]. According to [6] the drift velocities of trapped electrons and ions in the presence of spatially inhomogeneous or time dependent longitudinal electric field E_ϕ are different. This may result in establishing radial electric field E_r which exceeds the standard neoclassical one. The simulations have shown that the radial inhomogeneity of E_ϕ in the current ramp up phase is not enough to provide strong $\partial E_r/\partial r$ necessary for E×B turbulence suppression. 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 appear during internal disruption events if Kadomtsev model is valid for sawtooth oscillations description [7]. Coincidence of sawteeth produced strong $\partial E_\phi/\partial r$ zone and substantial ∇T_e and ∇n location allowed to assume a key role of sawteeth in generation of $\partial E_r/\partial r$ and subsequent ITB formation if mechanisms described in [6] are taken into account.

2. STUDY OF THE β LIMIT IN THE OHMIC H-MODE

Ohmic H-mode reveals good energy confinement [8]. Further increases of the energy content could be expected during density ramp-up, if the confinement does not degrade at high density. In the described experimental run, attempts to achieve high β_T and β_N were undertaken using density ramp-up. An example of a shot in which density was ramped up is shown on Fig. 2. Temporal behaviors of β_T and β_N shown in bottom boxes in Fig. 2 were measured by diamagnetic loops. After the transition into the ohmic H-mode (~ 50th ms) the density was increased by gas puff. β_T as well as β_N grow simultaneously with density until 78 ms, when confinement degradation appeared. Further increases of the density and energy contents were impossible because of enhanced transport. The degradation reveals itself as saturation of β_T appearing before density saturation, and as saturation of density despite of continuous gas puffing. No significant MHD activity was found in the shots with highest attainable β_N. These circumstances allow to conclude that restriction in the beta in our experiments is connected with "soft" (transport) saturation but not with MHD phenomena.

Diamagnetic data obtained before and after boronization are collected on the diagram displaying β_T as a function of parameter I/aB – Fig. 5. Diamagnetic measurements agree with kinetic data within 15 %. Data shown on the diagram indicate the substantial increase in the β_T as a result of boronization. At similar I/aB the maximum toroidal beta is by a factor of 1.5 higher in boronized vessel compared to unboronized. Also I/aB ratio appears to be higher after boronization. Highest achieved β_T was 2.0 % at $\langle n_e \rangle = 6 \cdot 10^{19} m^{-3}$. Corresponding β_N was 2.0.

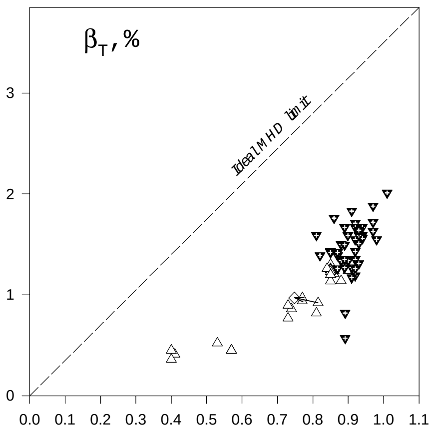

FIG. 5. β_T as a function of parameter I/(aB) before and after boronization in TUMAN-3M.

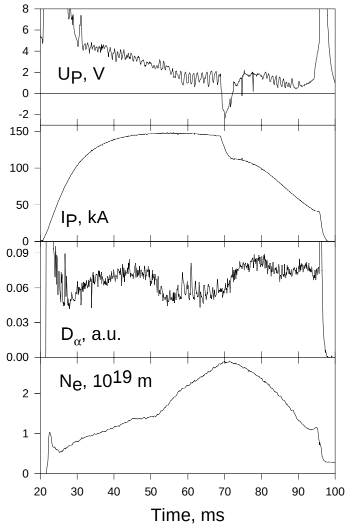

FIG. 6. Temporal evolution of loop voltage, plasma current, D_α radiation and averaged density in the shot with Current Ramp-Down.

The value of $\beta_N = 2$ is less than Troyon limit [9] which is also shown on Fig. 5. Experiments on other ohmically heated tokamaks also indicate lower level of the beta limit compared with auxiliary heated devices. In T-11 maximum β_T was 1.7 % and β_N was 1.5 without NB heating [10]. Similar limitations were found in the ohmic regime of START [11]. Note that in both the T-11 and START the β studies were performed in ordinary regime and transition into the H-mode was not reported.

The promising scenario of β_N increasing is the fast Current Ramp-Down (CRD). Although stored energy cannot be increased by CRD the parameter I/aB can be reduced substantially allowing β_N to increase. The attempts have been performed to achieve β_N limit using above scenario. Waveforms of some plasma parameters in the shot with CRD in ohmic H-mode are shown on Fig. 6. Although density in this regime was far from the limit and the puff was not changed compared to the quasistationary case, the $\langle n_e \rangle$ increase ceased just after CRD. It is clearly seen that CRD led to H-L transition (D_α increases and density decays). Possible explanation for the termination of the H-mode is reduction of the input power below the threshold value. Mentioned in previous section mechanism of E_r generation in presence of a radially inhomogeneous E_ϕ facilitates the H-mode termination in CRD scenario [12].

The drop in the energy content was less pronounced during CRD stage and this allowed β_N to increase during the first 2-3 ms after CRD. The subsequent decrease in the stored energy was due to transport enhancement. The highest β_N achieved using CRD was less than β_N obtained in best quasistationary shots. This result is shown on Fig. 5 by an arrow starting from triangle corresponding to the ohmic H-mode and directed to diamond displaying the CRD scenario.

3. CONCLUSIONS

Internal Transport Barrier in ohmically heated plasma has been observed in the ohmically heated plasma. The indications of ITB formation in the high current ohmic H-mode are: the increased up to 2 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.

The experiments on density ramp up in ohmic H-mode have shown that the maximum values of β_N of 2 can be achieved in circular crossection tokamak without auxiliary heating. The β_N limit achieved reveals itself as "soft" (nondisruptive) limit. The stored energy saturates during the density rise or slowly decays after the Current Ramp-Down.

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REFERENCES

[1] M.V. Andreiko, et al, Proc. 24th EPS Conf. on Contr. Fusion and Plasma Phys., Berchtesgaden, 1997, (EPS, Geneva), v.21A, part II, p.693.

[2] A.N. Arbuzov, et al, Proc. 17th EPS Conf. on Contr. Fusion and Plasma Heating, Amsterdam, 1990, (EPS, Geneva), v.14B, part I, p.299.

[3] S.V. Lebedev, et al, Plasma Phys. Control. Fusion, v.40 (1998), p.741.

[4] A.Yu. Dnestrovsky, et al, preprint IAE N 5358/6 (in russian), (1991).

[5] G.M. Staebler, Plasma Phys. Control. Fusion, v.40 (1998), p.569.

[6] M.G. Haines and P. Martin, Phys. Plasmas, v.3 (1996), p.4536.

[7] B.B. Kadomtsev, Sov. J. Plasma Phys. (“Fizika plasmy” in russian), v.1 (1975), p.710.

[8] S.V. Lebedev, et al, Plas. Phys. Control. Fusion, v.38 (1996), p.1103

[9] F. Troyon, et al, Plas. Phys. Control. Fusion, v.26 (1984), p.209

[10] A.G. Barsukov, et al, Proc. IX IAEA Conf. on Plasma Phys. and Control. Nucl. Fusion Res., IAEA, 1982, v.1, p.83

[11] M. O'Brien, et al, Proc. XVI IAEA Fusion Energy Conf., IAEA, 1997, v.2, p.57

[12] L.G. Askinazi, et al, to be publ. in Proc. Workshop on Electric Fields in Plasmas, Prague, 1998.