J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 243–248

Edge Structure in JT-60U High Density H-mode Plasmas

FUKUDA Takeshi*, TSUCHIYA Katsuhiko, HATAE Takaki, URANO Hajime[1], KAMADA Yutaka, SAKAMOTO Yoshiteru, SAKURAI Shinji, TAKENAGA Hidenobu, KUBO Hirotaka, ASAKURA Nobuyuki, FUJITA Takaaki and TAKIZUKA Tomonori

Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Naka-machi, Naka-gun, Ibaraki-ken 311-0193, Japan

[1]Hokkaido University, Kita 8 Nishi 5, Kita-ku, Sapporo-shi, Hokkaido 060-0808, Japan

(Received: 5 December 2000 / Accepted: 27 August 2001)

Abstract

The edge structure of the high density H mode has been investigated with emphasis on the L-H transition and degradation of improved confinement. It was thereby found that the substantial increase of the L-H threshold power at high density is related to the nonlinear increase of edge density, which significantly raises the edge collisionality. As to the quality of the edge barrier, the width of E_r shear layer is reduced in high density ELMy H mode, which corroborates the decrease of the pedestal width. The interaction between the internal and edge structures has also been studied in JT-60U, where the effectiveness of the active control of internal barrier has been manifested to increase the edge density and induce the L-H transition. In addition, the role of neutral particles at the edge on L-H transition and sustainment of the edge barrier quality is addressed in this paper.

Keywords:

H-mode, JT-60U, pedestal structure, internal transport barrier, confinement, L-H threshold power, neutral particle

1. Introduction

Sustainment of the improved confinement at high density is one of the serious issues of concern especially in large tokamaks, and it is therefore considered as one of the urgent topics of R&D for ITER. Accordingly, intensive investigation has been carried out in various tokamaks to resolve how the collisional edge degrades the core confinement [1]. It is also urged to understand how the H mode quality is degraded and edge pedestal structure is modified at high density. In this respect, the physics of edge pedestal structure produced at the L-H transition is re-visited, based on the recent experimental results accumulated in JT-60U. Various features of edge pedestal structure and its interaction with the internal structure are also discussed in this paper. The reduction of edge temperature is generally observed with an increase of the edge density in ELMy H mode plasmas in JT-60U, which results in the decrease of central temperature as well as the degradation of global confinement. In regard to the properties of edge E_r shear in high-density plasmas, the role of neutral particles has been investigated. The influence of edge magnetic shear on the barrier formation in the plasma interior and edge was also studied. However, as for the issue of how the collisional edge is linked to the core confinement degradation, it is being explored in terms of the profile "stiffness," of which detailed investigation is in progress, incorporating the ITG based fluid simulations. However, it is outside of the scope of this paper.

The study of density dependence of the L-H threshold power has also been intensively carried out,

*Corresponding author's e-mail: tfukuda@naka.jaeri.go.jp

and significant increase of the threshold power at high density is documented in JT-60U [2] and ASDEX-U. Substantial difference is produced between the cases when the high density data are treated as a scatter [3] or as a systematic tendency. The causalities of increased L-H threshold power at high density, exceeding the ITER scaling have also been investigated emphasizing the edge parameters.

In this paper, global features of the high density H mode plasmas observed in JT-60U is first reviewed in subsection 2.1, followed by the description of edge features in subsection 2.2. The edge structure and its interaction with internal structure is discussed in subsection 2.3, and the influence of neutral particles on the edge structure and quality of the pedestal is reported in subsection 2.4.

2. Structures of High Density H Mode

2.1 Global Features Related to the Confinement and L-H Threshold Power at High Density

The degradation of global confinement with density in ELMy H mode is pervasively observed, and the general observation is that the critical density above which the global confinement starts to degrade with gas puffing under fixed triangularity is lower for large devices, namely JET and JT-60U, unless some other fuelling method is applied, such as pellets. In the case of JT-60U, the degradation starts approximately at n/n_{GW} ($n_{GW} = I_P/\pi a^2$) of 0.4 – 0.5, as shown in Fig. 1. However, it has been found that either high triangularity plasmas with $\delta \geq 0.3$ or discharges with ITB, which stands for the internal transport barrier, can sustain the confinement at much higher range of averaged density. This is indicative of the fact that the edge plasma region may carry a decisive role. In Ar seeded plasmas, the edge radiation is lower than discharges at similar edge densities with only D_2 fuelling. As a result, the edge temperature is higher in Ar seeded plasmas, and the confinement was improved by 40%, yielding H factor over the L mode confinement scaling of 1.4 at $\bar{n}/n_{GW} = 0.7$. In addition, it is often observed that the density profile is moderately peaked, though not as much as the typical RI-mode plasmas in smaller devices. Therefore, the suppression of edge recycling and sustainment of edge temperature at high density is substantial to raise the core temperature, assuming the profile stiffness. In addition, the production of peaked density profile in the core seems to be a key to realize improved confinement in high density ELMy H mode, which reduces the linear growth rate of ITG turbulence. Accordingly, plasmas with ITB, which resultantly accompanies the relatively peaked density profile in the core, owing to the existence of the barrier, can realize the improved confinement. However, as the density of dominantly ion-heated plasmas by the neutral beam (NB) increases and the equipartition of energy between the ions and electrons becomes more vigorous, which is equivalent to an increase of T_e/T_i, the H89 factor indicating the confinement improvement over the ITER L mode scaling starts to decrease. The dedicated experiment in JT-60U to examine the confinement properties of dominantly electron heated plasmas, aiming at the simulation of alpha particle heated reactor plasmas, H factor of around 2 was sustained at $T_e/T_i = 1.2$. In this campaign, T_e profile responded well to the ECH, whilst the T_i profile remained the same, indicating no signs of additional turbulence.

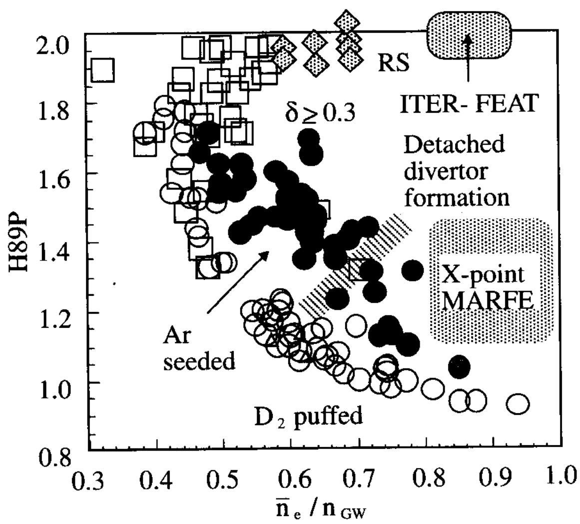

Fig. 1 Improvement in confinement over the L mode scaling in ELMy H mode plasmas against the normalized density. Solid circles and open squares respectively correspond to Ar seeded and high triangularity discharges, whilst the shaded diamonds are for reversed shear plasmas.

Another issue of concern at high density is the L-H threshold power, namely the condition of producing the edge pedestal structure. In the recent dedicated experiment in JT-60U, the range of density was extended to $0.5 \times n_{GW}$, where substantial increase of the threshold power was observed, as shown in Fig. 2 [2]. Similar observation is reported also from ASDEX-U. In the recent paper from the ITER database group [3], it is treated as a scatter and scaling law is elaborated to predict the necessary heating power for ITER to attain the H mode of 23 MW. However, should the significantly high threshold power at high density be the inherent nature at high density and taken into account, the density exponent is raised from 0.58 to 1.25 and the predicted heating power increases to 93 MW. The causality of the increase in the threshold power at high density is discussed in the following subsection.

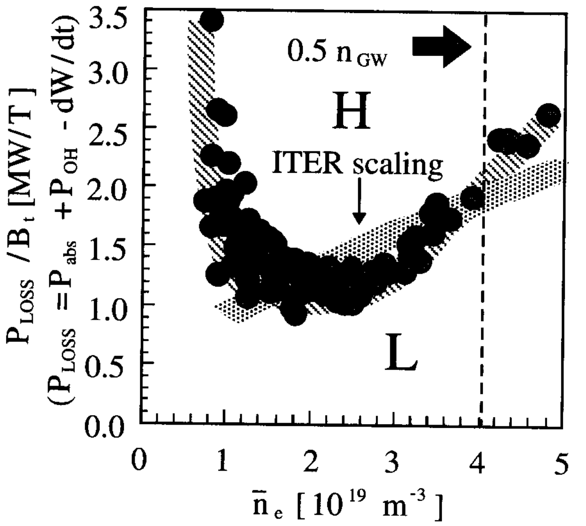

Fig. 2 L-H threshold power normalized by B_t against the averaged density. The ITER scaling is also indicated with dotted line.

2.2 Edge Characteristics Related to the L-H Threshold Power at High Density

The edge density at 95% of the normalized radius was evaluated and depicted in Fig. 3(a). It increases nonlinearly with the line-averaged density, namely $n_e^{95} \sim \bar{n}_e^{1.41}$, which may be related to the significant increase of L-H threshold power. It was thereby found that the threshold power is scaled with $[n_e^{95}]^{0.75}$, similar to the ITER scaling derived from the database, large portion of which was accumulated in smaller tokamaks with much higher density than JT-60U. The significance of edge density is also reported from JET. The relationship between T_i^{95} and n_e^{95} right before the L-H transition is also shown in Fig. 3(b), where gradual increase of T_i^{95} is indicated at higher density. The reduction of T_i^{95} at high density makes it even more difficult for plasmas to attain H mode. It was also found that T_i^{95} and T_e^{95} are similar except for the density range $\bar{n}_e < 2.5 \times 10^{19}$ m^{-3}, which may be the result of intensive ion heating with NB. The dimensionless scaling of the threshold power with edge quantities [4] indicates the strong contribution of ρ^{*95} and β^{95}, acting conversely to each other with the exponents of 1.2 and -1.1, respectively, and weaker effect of ν^{*95}. As it is observed in JT-60U that the pedestal beta does not exhibit apparent changes with increasing density, the influence β^{95} of can be excluded. On the other hand, the reduction of edge temperature at high density reduces the value of ρ^{*95} and accordingly the threshold, which is contradictory to the experimental

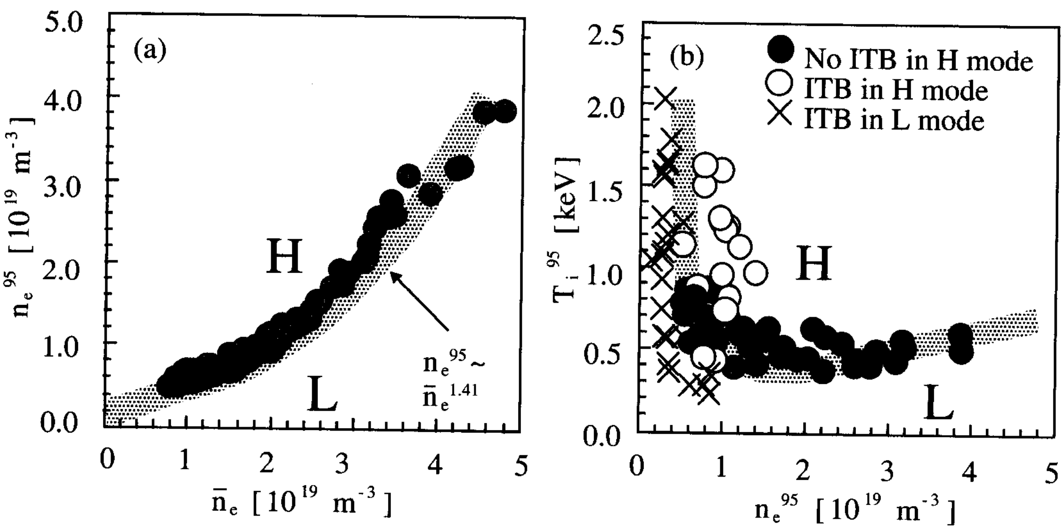

Fig. 3 (a) The relationship between the edge and averaged density right before the L-H transition. (b) Edge ion temperature and electron density right before the L-H transition. Open and solid circles respectively represent the cases with and without ITB. Cross marks are for L mode with strong ITBs.

observation. Therefore, an increase of edge collisionality is considered to be playing a decisive role in the increase of threshold power at high density.

2.3 Edge Structure in High-density ELMy H-mode Plasmas and Interaction between the Edge and Internal Structures

The E_r profiles have been experimentally evaluated and compared, using the kinetic profiles and CVI flow velocity measurement, between the cases for $\bar{n}_e = 2.5 \times 10^{19}$ m^{-3} and 3.5×10^{19} m^{-3} [5]. Here, the result of CXRS diagnostic was implemented to experimentally evaluate the E_r in the edge. The edge E_r shear near the separatrix is stronger at low density, and the width of E_r shear layer is reduced at high density, as indicated in Fig. 4. The region of large pressure gradient is also broader for the low density case, whilst the maximum values of ∇P and E_r are similar. The pedestal width scaling developed based on an international database [6] also indicates that it decreases with the reduction of the edge temperature, under the assumption that the $\varepsilon^{0.5}\rho_{pi}$ scaling is valid. Here, ε and ρ_{pi} are respectively the inverse aspect ratio (= a/R) and ion poloidal gyro-radius proportional to $T_i^{0.5}/RB_P$. With an increase of the edge density, the pedestal edges of n_e and T_e profiles are extended to outside of the separatrix, and T_i pedestal disappears. The density pedestal grows remarkably at high density, producing steep gradient at the edge and flat profile in the interior. It is often observed that the ion and electron temperatures are stiff in the ELMy H mode but not the density profile.

The correlation lengths of density fluctuations both at the edge and ITB are reduced, which indicates the reduction of the radial scale length of turbulence in a similar manner and corroborates the EXB shear stabilization model. The correlation lengths in the edge and ITB are both 1–2 cm under the shear stabilization, and it is noteworthy that the correlation length is much smaller than the pedestal width. Therefore, turbulent transport is not the sole determinant of the width of ITB layer and edge pedestal for electrons.

Another issue of concern in resolving the causality related to the deterioration of confinement at high density is ELM. The ELM frequency is practically determined by the absorbed heating power and ballooning parameter, written in a form $P_{abs}/\{B_t^2/(2\mu_0 \cdot R_P \cdot q_{95}^2) \cdot l_i\}$. So long as the Type I ELMs do not turn into Type III, the ELM characteristics do not exhibit substantial changes at high density, seemingly due to an increase of the edge radiation power, although ELM frequency slightly increases with density in the low density range at low triangularity. Therefore, ELMs do not seem to directly influence the confinement properties at high density. The reduction of ELM frequency is also observed in Ar seeded experiment, in which the edge radiation also increases. However, it is also observed that the baseline of divertor recycling flux increases with density, and the amplitude of ELM is remarkably enhanced at higher densities.

In relation to the issue of edge structure, influence of the local magnetic shear on the barrier formation in the edge and at the interior of plasmas has been intensively studied. In a dedicated experiment in JT-60U, the net heating power was reduced to 89% of the threshold power during the current ramp down. In case the current was ramped down at 2 MA/s, the value of l_i increased from 1.2 to 2.7. Even if the rate of current ramp down was finally increased up to 3 MA/s, the plasma stayed in L mode. Here, no sign of malign MHD activities was observed. The JT-60U database compiled in the last 5 years neither supports the evidence of l_i dependence. In addition, the influence of edge magnetic shear is not obvious also in the pedestal width scaling. On the other hand, recent investigation on the formation condition of ITB in JT-60U indicates that the threshold power for the ITB formation decreases as the local magnetic shear at the location of ITB goes from positive to negative. The fact that application of the LHCD preheating at JET and counter ECCD at ASDEX-U produce ITBs in T_e at remarkably low heating power is

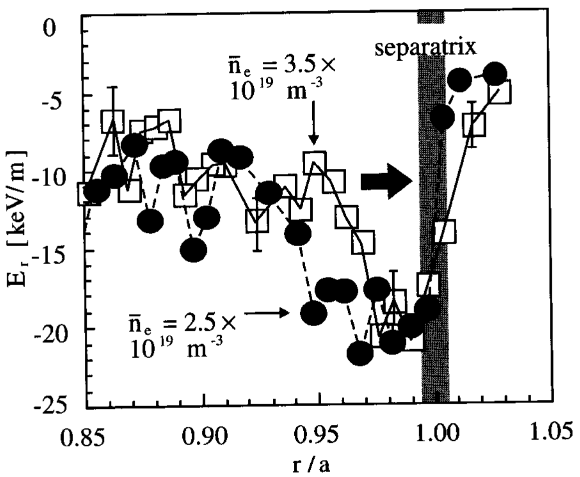

Fig. 4 Edge radial electric field profiles at two different densities. Solid circles indicate the case of $\bar{n}_e = 2.5 \times 10^{19}$ m^{-3}, whereas the open squares are for $\bar{n}_e = 2.5 \times 10^{19}$ m^{-3}.

consistent with the above result. The off-axis ICRH at similar coupled power as LHCD did not reduce the input power to produce ITB at JET, which is an evidence of the significance of the negative shear profile. Therefore, it can be concluded that the local magnetic shear influences the ITB but not the H-mode.

In addition, interaction between the ITB and H mode has been first examined in JT-60U. It is often observed in improved confinement plasmas with strong ITB that the L-H threshold power is considerably higher than the scaling. It has been hereby found that the edge density and temperature ranges for the formation of the edge barrier are the same regardless of the existence of ITB, and the edge density is extremely low for the case of strong ITB. The edge density is in the far left-hand side of Fig. 3(b), and the edge temperature is significantly high. Therefore, it is necessary to raise the edge density by the intensive fuelling. Alternative approaches are either to produce the edge barrier before the ITB formation or to modify the internal structure to induce the L-H transition. However, in case the strong ITB is formed, particle diffusion from inside the ITB is reduced, which results in the increase of edge temperature. Accordingly, the gas puffed particles were shielded at the plasma surface, being not able to penetrate into the plasma. For the effective formation of ITB in H mode plasmas, it is necessary to apply substantial central heating either by the on-axis heating or increasing the triangularity in JT-60U. However, the formation of H mode generally increases the edge density and broadens the pressure profile, and it makes the central heating more difficult. The modification of the ITB quality is routinely performed in JT-60U reversed shear experiments, based on the ω_{EXB} shear stabilization model. Namely, switching to the purely co-directed tangential NB momentum input in the direction of the plasma current changes the toroidal flow velocity profile, or equivalently the $\omega_{EXB}/\Gamma_{LIN}$ profile. The pressure gradient at the ITB is thereby reduced and the edge density is simultaneously increased to induce the L-H transition. Thus, the modification of the internal structure affects the edge structure.

2.4 Influence of the Neutral Particles on L-H Transition and Confinement at High Density

Influence of neutral particle density on L-H transition has been intensively investigated not only in JT-60U [7,8] but also in DIII-D [9] and ASDEX-U. The nonintuitive behaviour of edge neutral density has been hitherto documented both in JT-60U and DIII-D. Namely, higher plasma density which corresponds to higher D_α emission intensity originated outside of the separatrix is related to lower neutral density inside separatrix, as shown in Fig. 5(a). It is interpreted in a way that an increase of neutral density in the SOL

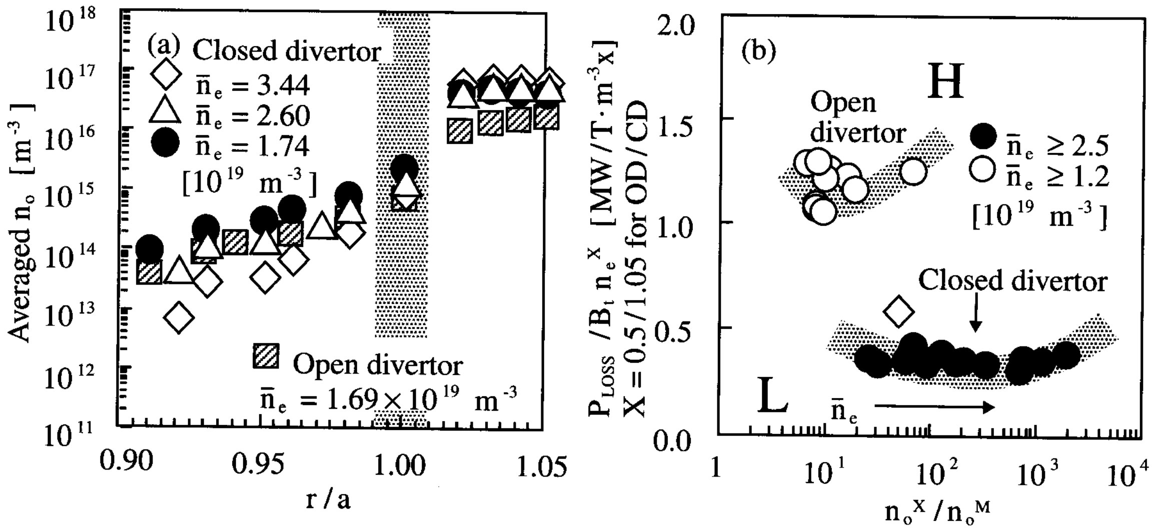

Fig. 5 (a) Radial distribution of the neutral particle density in the edge plasma region at 3 different densities for closed divertor and one for open divertor. (b) L-H threshold power normalized by the scaling law against the compression ratio of neutral particles inside the separatrix, which is shown by n_o^X/n_o^M. Here, the values of X are 0.5 for the open divertor and 1.25 for the closed divertor.

creates an increase of plasma density that in turn increases the opacity to the neutrals and results in reduced neutral penetration. It was also documented using DEGAS in JT-60U that larger compression of the edge neutral particle density in closed divertor geometry may be effective to reduce the L-H threshold power. This hypothesis was extended to claim that substantial loss of homogeneity on a flux surface could be one of the potential tools to reduce the L-H threshold power. Loss of homogeneity to induce the H mode at substantially lower heating power has been observed in the strong gas puff experiment in JFT-2M and pellet induced H mode experiment in DIII-D. The comparison of the L-H threshold power normalized by the scaling law derived for JT-60U is shown in Fig. 5(b) for the open and closed divertor geometry, as a function of the ratio of edge neutral particle density near the X-point and the midplane. It indicates that the inhomogeneity of the neutrals is larger for closed divertor and the threshold power may be reduced. However, the compression of the neutrals inside the separatrix increases with density. Therefore, the influence of edge neutrals on the substantial increase of threshold power is not obvious, and it is hereby speculated that the substantial increase of the threshold power at high density may instead be related to an increase of edge density itself.

As to the influence of neutral particles on confinement properties, direct evidence of neutral particles was not documented. H factor does not exhibit apparent dependencies on any variables related to the neutral particle density, including the charge exchange rate. A small increase of the H with n_0^{95}/n_e^{95} factor was observed, however, it may be ascribed to the decrease of edge density, relevant to higher edge temperature. As the neutral particle density inside the separatrix is reduced at high density, the role of neutrals does not seem significant. Instead, an increase of the edge density seems to be more influential to the deterioration of the global confinement, where the edge temperature is substantially decreased. Therefore, it can be concluded that the role of edge neutrals on the confinement remains indirect, being only the source of edge density.

3. Conclusions

In order to explore the physics of confinement degradation at high density, which has been an issue of controversy in the ITER design, the edge structure and its interaction with the core structure has been intensively investigated. In this respect, this paper has addressed that the width of the E_r shear layer is reduced with an increase of edge density, and the pedestal width is concomitantly reduced. However, the correlation length of the density fluctuations is much less than the pedestal width. It was also found that the direct influence of the neutrals on the global confinement is not obvious. In addition, the interaction of ITB and H mode was first addressed in this paper, in terms of the modification of edge conditions through the changes of $\omega_{EXB}/\Gamma_{LIN}$ profile in the plasma interior.

The causalities of increased L-H threshold power at high density, exceeding the ITER scaling, have been intensively investigated emphasizing the edge parameters, including the neutral density. It was hereby found that an increase of edge collisionality caused by the substantial reduction of the edge temperature could be a direct candidate. It was also suggested that the substantial increase of the threshold power at high density might be related to an increase of the edge density itself, exceeding the counter effect of inhomogeneity of neutrals on the flux surface.

References

[1] N. Asakura *et al.*, J. Nucl. Mater. **266–269**, 182 (1999).

[2] T. Fukuda *et al.*, Plasma Phys. Control. Fusion **42**, A289 (2000).

[3] J.A. Snipes *et al.*, Plasma Phys. Control. Fusion **42**, A299 (2000).

[4] T. Fukuda *et al.*, Plasma Phys. Control. Fusion **40**, 827 (1998).

[5] N. Asakura *et al.*, Plasma Phys. Control. Fusion **39**, 1295 (1997).

[6] T. Hatae *et al.*, Plasma Phys. Control. Fusion **42**, A283 (2000).

[7] T. Fukuda *et al.*, Nucl. Fusion **37**, 1199 (1997).

[8] T. Fukuda *et al.*, Plasma Phys. Control. Fusion **40**, 543 (1998).

[9] B. Carreras *et al.*, Phys. Plasmas **5**, 2623 (1998).