J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 167–172

Rational Surfaces, $E\times B$ Sheared Flows and Transport Interplay in Fusion Plasmas

HIDALGO Carlos*, PEDROSA María A., ERENTS Kevin[1], GONÇALVES Bruno[2], MATTHEWS Guy F.[1], CASTELLANO Javier, GARCÍA Luís[3], BALBÍN Rosa, SÁNCHEZ Edilberto and DIAMOND Patrick H.[4]

Laboratorio Nacional de Fusión, Euratom-Ciemat, Madrid, 28040 Spain

[1]*UKAEA Fusion, Culham Science Centre, Culham, Abingdon, Oxon, OX14 3EA, UK*

[2]*Euratom - IST, 1049-001 Lisbon, Portugal*

[3]*Universidad Carlos III, Madrid, Spain*

[4]*University of California, San Diego, La Jolla, California 92093-0319, USA*

(Received: 5 December 2000 / Accepted: 18 August 2001)

Abstract

Experimental evidence of a strong interplay between magnetic topology (rational surfaces) and the generation of $E\times B$ sheared flows has been observed in the plasma edge region of stellarator (TJ-II) and tokamak (JET) devices. Constant and varying in time $E\times B$ sheared flows are close to the critical value to trigger the transition to improved confinement regimes. The plasma conditions where this has been observed are clearly below the power threshold to trigger the formation of transport barriers. Flows driven by fluctuations are candidates to explain these experimental results.

Keywords:

$E\times B$-shear flow, turbulence suppression, rational surface, transport barrier, Reynolds stress, magnetic viscosity

1. Introduction

Since the first generation of edge transport barriers in tokamak plasmas [1], significant progress has been made to understand the mechanisms that control their generation. One of the great achievements of the fusion community in the last years has been the development of techniques to control plasma turbulence based in the $E\times B$ shear stabilization mechanism [2-4]. The generality of this mechanism is based on the fact that the drift of charged particles in the presence of an electric (E) and magnetic field (B) does not depend on the mass or charge of the particles. When the $E\times B$ shearing rate ($\omega_{E\times B}$) approaches the growth rate of the dominant instability (γ), $\omega_{E\times B} \approx \gamma$, a reduction in the radial correlation length is predicted. The earliest theory of $E\times B$ shear suppression is valid when the time variation of the radial electric field is much slower that the correlation time of the ambient turbulence [5]. The theory of $E\times B$ shear suppression of turbulence has been recently extended to include time dependent $E\times B$ flows [6]. The best performance of existing fusion plasma devices has been obtained in plasma conditions where $E\times B$ shear stabilization mechanisms are likely playing a key role [7-8]. Both edge and core transport barriers are related to a large increase in the $E\times B$ sheared flows. Direct measurements of transport and fluctuations during the generation of edge transport barriers show that concurrent changes in turbulence amplitudes, spatial scales, and multi-field phase angles lead to a reduction of turbulent particle flux during the formation of the H-mode transport barrier [9].

*Corresponding author's e-mail: carlos.hidalgo@ciemat.es

Confinement properties are strongly linked to the magnetic topology of the magnetic trap. The presence of rational surfaces can cause the formation of island or magnetic ergodic regions, which can degrade the quality of confinement in magnetically confined plasmas in some cases. Low order resonances are often associated with "hard" MHD events such as disruptions or "soft" MHD events, which limit the plasma performance in tokamaks. On the other hand, the generation of internal and edge transport barriers is linked to plasma regions with a unique magnetic topology [7,8,10,11]. In configurations with low or negative magnetic shear, internal transport barriers (ITBs) are formed close to the location of q_{min}, in the proximity of low order rational surfaces. Edge transport barriers are located close to the boundary between the region with open and closed magnetic field lines, and in this plasma region there are strong gradients in the level of fluctuations [12]. In the context of stellarator physics, global confinement depends strongly on the value of the edge rotational transform [13]. Latest results from LHD stellarator have shown the possible role of low order resonances in the generation of edge transport barriers [14].

This paper reports the influence of magnetic topology (rational surfaces) in the generation of ***E***×***B*** sheared flows in tokamaks and stellarators, and experimental evidence of DC and time dependent ***E***×***B*** sheared flows in the range of $\omega_{E\times B}$ critical.

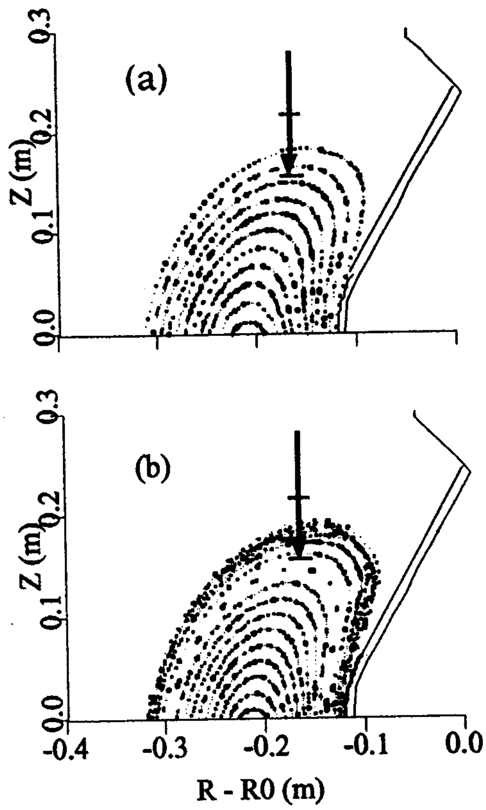

Fig. 1 TJ-II vacuum configuration (a) without and (b) with medium size island (n/m = 8/5) in the plasma boundary region.

2. Experimental Set-Up

Experiments were carried out in the plasma edge region of the JET tokamak and TJ-II stellarator. Plasmas investigated in this paper were ECRH plasmas (f = 53.2GHz, $P_{ECRH} \approx$ 300kW) in the low magnetic shear TJ-II stellarator (B = 1T, $n = 5 \times 10^{18}\mathrm{m}^{-3}$) and X-point configurations in JET tokamak (B = 1–2T, I_p = 1–2MA, $n = 2\text{–}3 \times 10^{19}\mathrm{m}^{-3}$). Radial profiles of the ion saturation current and floating potential have been measured using a fast movable Langmuir probe system, both in JET and TJ-II. Plasma potential (Φ_p) profiles have been estimated from electron temperature (T_e) and floating potential (Φ_f) profiles using $\Phi_p = \Phi_f + \alpha T_e (\alpha \approx 2.5)$. The experimental set up allows to investigate the radial and poloidal structure of fluctuations.

The existence of closed and nested magnetic surfaces in good agreement with the calculated ones has been demonstrated by magnetic surface measurements in the TJ-II stellarator [15,16]. To study the effect of rational surfaces on radial electric field we have chosen the plasma configurations with iota (a) ≈ 1.6 and 2, and focused in the $n = 8/m = 5$ and $n = 4/m = 2$ resonances, which are located near the last closed flux surface. Figure 1 shows TJ-II vacuum configuration with and without medium size island (n/m = 8/5).

3. Plasma Profiles and *E*×*B* Sheared Flows

Typically, ion saturation current signals show a smooth increase as the probe moves radially inwards in the plasma edge. This behaviour is shown in figure 2 for TJ-II and JET edge plasma profiles. This is a characteristic behaviour previously reported in tokamak, stellarator and RFPs devices [17-19].

The presence of natural resonances ($n = 8/m = 5$), as predicted by vacuum field line calculations, has been observed as a flattening in the edge plasma profiles in the TJ-II stellarator (Fig. 3). Experiments carried out in the JET plasma configurations with B = 1T and I_p = 1MA have also shown evidence of flattening in edge plasma profiles, which might be assigned to the $q = 4$ surface (Fig. 3). These observations have been interpreted in terms of the influence of rational surfaces on

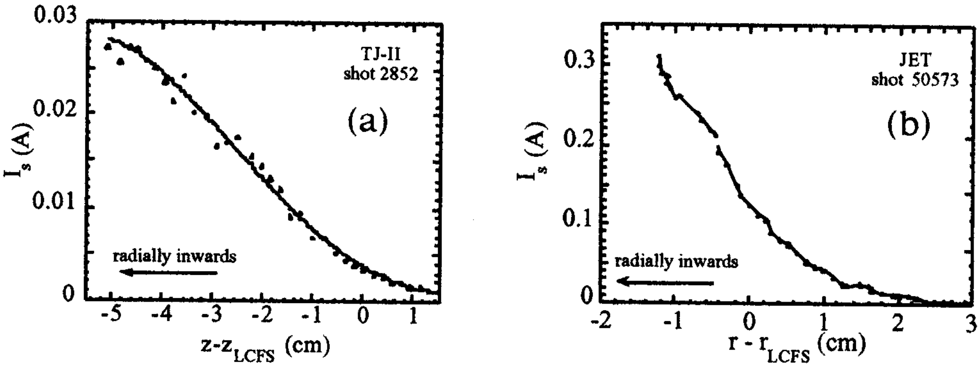

Fig. 2 Radial profile of the ion saturation current (a) in the TJ-II stellarator for a plasma configuration with iota (a) ≈ 1.9 (i.e. with the 4/2 surface located out of the plasma boundary region) and (b) for the shot 50673 (B = 2T, I_p = 2MA) in JET.

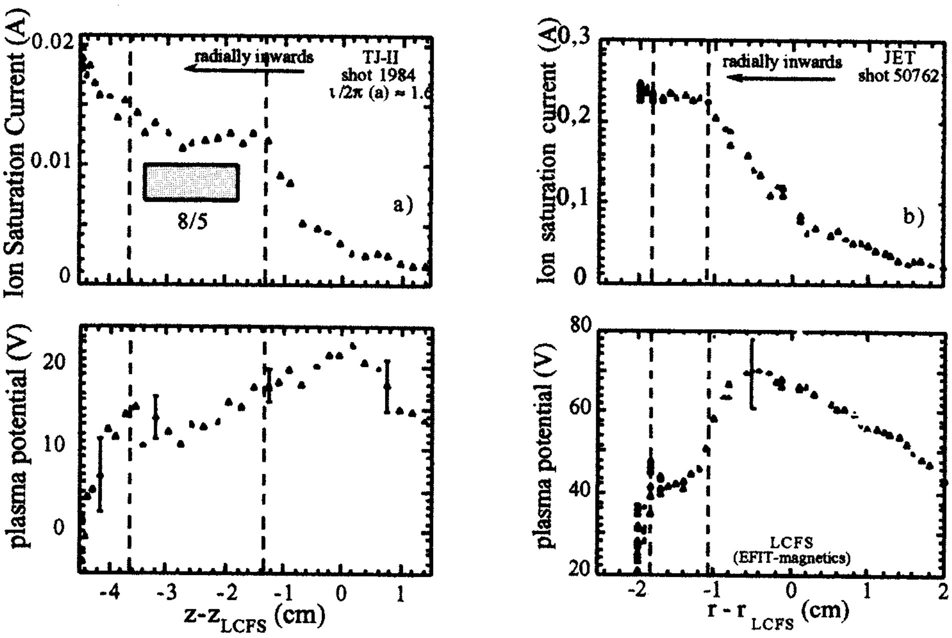

Fig. 3 Radial profiles of the ion saturation current, floating potential and plasma potential (a) in a TJ-II plasma configuration with a low order resonance (8/5) located near the plasma boundary (b) for the JET shot 50762 (B = 1T, I_p = 1MA).

plasma profiles [20,21].

There is a significant variation in the plasma potential and poloidal phase velocity of fluctuations linked to the flattening of plasma profiles. The resulting ***E***×***B*** sheared flow is of the order of $10^5 s^{-1}$ near the radial position where there is a flattening in the density profile. This value turns out to be comparable to the inverse of the correlation time of fluctuations ($\tau \approx 10\mu s$). This observation implies that ***E***×***B*** sheared flows with de-correlation rates close to the critical value to reduce turbulence (i.e. $\omega_{E\times B} \approx 1/\tau$, τ being the correlation time of fluctuations) are linked to rational surfaces well below the L-H power threshold.

These results illustrate the link between significant ***E***×***B*** sheared flows and rational surfaces in stellarator and tokamak devices, which might explain the strong interplay between the magnetic topology and the generation of transport barriers in fusion plasmas.

4. Dynamical *E*×*B* Flow and Transport in Tokamak and Stellarator Plasmas

Recent gyrofluid and fluid simulations have observed small scale fluctuating sheared ***E*×*B*** flows [22,23]. These flows are driven by fluctuations and, according to these simulations, they can substantially reduce turbulent transport. The effective sheared rate of fluctuating ***E*×*B*** flows is less effective than the slowly varying component in reducing turbulent transport. This reduction in the effectiveness is particularly important when the ***E*×*B*** flow patterns changes in a time scale faster than the eddy turn over time [6].

From this perspective, two open (and connected) question for experimentalists are the following: What is the level of fluctuations in the radial electric field?, and: Is the effective shearing rate of fluctuating radial electric fields high enough to control transport?. In order to answer these questions, it is important not only to measure the radial electric field, but also to investigate the coupling between fluctuating radial electric fields and ***E*×*B*** transport.

The radial profiles of fluctuations in the radial electric field have been investigated in the plasma edge region of the JET tokamak and in the TJ-II stellarator, neglecting electron temperature fluctuations effects (Fig. 4). The rms level of fluctuations increases as the probe is inserted into the plasma edge region, reaching values in the range of 1000 – 2000V/m in the plasma boundary region. The averaged frequency of E_r fluctuations is comparable to the width of the turbulent spectra. A rough estimation of the effective shearing rate of the fluctuating radial electric fields can be computed as

$$\tilde{\omega}_{E\times B} \approx \frac{(E_{radial})_{rms}}{B\lambda_c} f\left(\frac{\omega_f}{\Delta\omega_T}\right), \qquad (1)$$

where ω_f and $\Delta\omega_T$ are the mean frequency of fluctuating radial electric field and the width of the turbulent spectra respectively, λ_c is the radial correlation of fluctuations and B is the toroidal magnetic field. The function $f(\omega_f / \Delta\omega_T)$ takes into account the reduction of the effective shearing rate when the time scale of the fluctuating radial electric field is faster than the correlation time of fluctuations: $f(\omega_f / \Delta\omega_T) \approx 1$ if $\omega_f << \Delta\omega_T$; $f(\omega_f / \Delta\omega_T) \approx 0$ if $\omega_f >> \Delta\omega_T$ [6].

In the case of JET and TJ-II edge plasma conditions, $(E_{radial})_{rms} \approx 1000$V/m, $\omega_f \approx \Delta\omega_T$ and the average radial correlation is in the range of 1cm. Using expression (1), the effective decorrelation rates are close to the critical value to regulate turbulent transport ($\omega_{E\times B} \approx 10^5 s^{-1}$), well below the L-H power threshold power in JET and in ECRH plasmas in the TJ-II stellarator. A more accurate computation of the fluctuating $\omega_{E\times B}$ shearing rate requires the simultaneous measurements of the radial electric field at different radial locations.

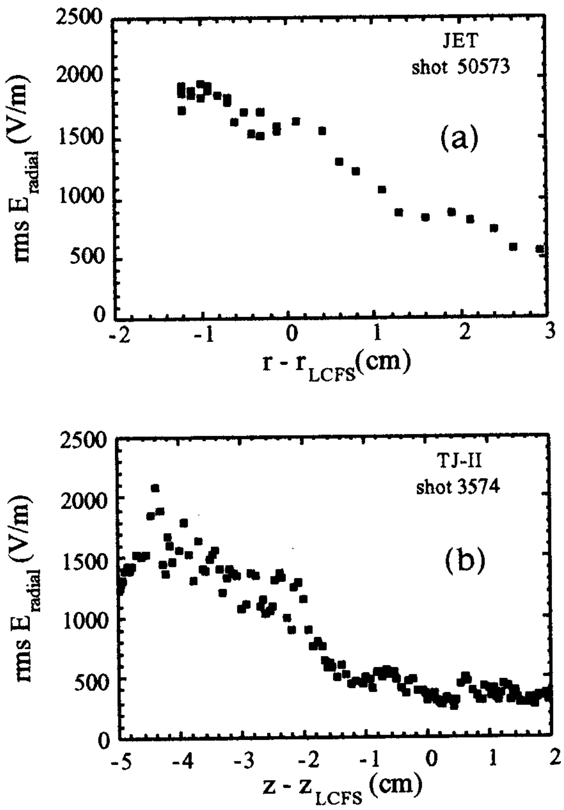

Fig. 4 Root mean square (r.m.s.) value of fluctuations in the radial electric field in the TJ-II stellarator (a) and JET tokamak (b) computed neglecting T_e fluctuation effects.

5. Why *E*×*B* Sheared Flows?

Understanding the mechanisms which drive ***E*×*B*** sheared flows is an important physics issue in tokamaks and in stellarator devices. The present experimental results show the development of both DC and fluctuating radial electric fields with decorrelation rate ($\omega_{E\times B}$) comparable to the growth rate of plasma instabilities (10^5 – $10^6 s^{-1}$) in plasma regimes well below the power threshold for the transition to improved confinement regimes. This result strongly suggests the role of turbulent driven fluctuating radial electric field (via Reynolds stress). The Reynolds stress measures the degree of anisotropy in the structure of fluctuations. Radially varying Reynolds stress allows the turbulence to rearrange the profile of poloidal momentum, generating sheared poloidal flows. In the plasma boundary region, strong gradients in the level of fluctuations can provide the radial-poloidal non-isotropic turbulence. In the plasma core region a modification in the degree of anisotropy in the radial-poloidal structure of fluctuations is expected at the rational surfaces, where fluctuations show maximum amplitude.

5.1 Link between low and high frequency fluctuations via Reynolds stress

A quantitative estimate of the importance of fluctuation induced flows requires comparison of the damping rate of poloidal flows (i.e. μV_θ) with the driving term via Reynolds stress in the equation describing the time evolution of the poloidal flows:

$$\frac{\partial \langle V_\theta \rangle}{\partial t} = -\mu \langle V_\theta \rangle - \frac{\mathrm{d}}{\mathrm{d}r} \langle \tilde{V}_r \tilde{V}_\theta \rangle . \qquad (2)$$

Assuming that the frequency of fluctuating poloidal flows (ω_θ) is much smaller than the damping rate (i.e. $\omega_\theta << \mu$), that poloidal flows are directly related with radial electric fields ($V_\theta \approx E_r/B = (1/B)\, \mathrm{d}\Phi/\mathrm{d}r$, Φ being the plasma potential) and that the term of the Reynolds stress tensor can be related to the ***E***×***B*** velocities, it follows that

$$\langle V_\theta \rangle = -\frac{1}{\mu B^2} \frac{\partial}{\partial r} \langle \tilde{E}_r \tilde{E}_\theta \rangle , \qquad (3)$$

$$\Phi \propto \frac{1}{\mu B} \langle \tilde{E}_r \tilde{E}_\theta \rangle \approx \frac{\gamma k_\theta k_r}{\mu B} \langle \tilde{\Phi}^2 \rangle , \qquad (4)$$

k_θ and k_r being the poloidal and radial wave-number of fluctuations, and γ is the correlation parameter between poloidal and radial electric fields. Expressions (3) and (4) show the relation between low frequency fluctuations in the plasma potential (Φ) and the high frequency fluctuations.

The plasma potential is related with the floating potential and electron temperature by the expression $\Phi_p = \Phi_f + \alpha T_e (\alpha \approx 2\text{–}3)$. Figure 5 shows the correlation between the floating potential (Φ_f) and the electrostatic Reynolds stress in the plasma edge of JET tokamak. Interestingly both quantities are clearly correlated. Assuming a linear behaviour and using expression (4), it follows that $\mu \approx 5 \times 10^4 \mathrm{s}^{-1}$, which turns out to be close to the expected damping rate due to magnetic pumping for JET edge parameters. A systematic investigation of the relation between plasma potential (Φ) and its fluctuations, both in the plasma edge region (using probes) and in the plasma core region (by means of the HIBP), is needed to clarify the importance of the coupling between low and high frequency fluctuations via Reynolds stress.

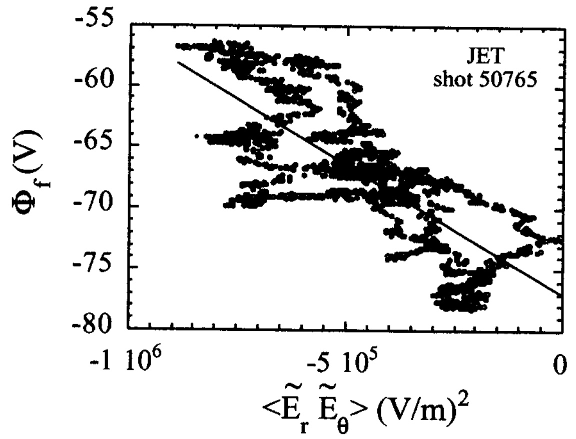

Fig. 5 Correlation between floating potential and the electrostatic Reynolds stress in the plasma edge of JET tokamak.

5.2 Rational surfaces and Reynolds stress driven flows

A possible explanation of the flow structure near rational surfaces is the coupling of flow generation and turbulence (i.e. sheared flows driven by fluctuations via Reynolds stress). In the absence of ***E***×***B*** sheared flows, fluctuations are expected to show maximum amplitude at the rational surface. The corresponding instability mode width will depend on the nature of the instability and on the magnetic shear scale length. As a consequence, a modification in the degree of anisotropy in the radial-poloidal structure of fluctuations (i.e. Reynolds stress) is expected at the rational surface. This mechanism can provide sheared poloidal flows linked to the location of rational surfaces.

A model has been developed based on the reduced MHD equations for the evolution of the poloidal magnetic flux and vorticity plus separated evolutions for the electron density and temperature [24]. Density and temperature profiles show the flattening caused by the presence of the magnetic island. Another effect of the vacuum magnetic island is the generation of a global poloidal flow through Reynolds stress. This flow oscillates in time and changes direction in a quasiperiodical manner. The poloidal propagation shows a continuos change with increasing vacuum magnetic island width. Below a threshold, the electrostatic and magnetic components of the Reynolds stress have similar size and radial profiles, but the opposite sign. This causes a near cancellation of these two terms, as it happens in the case of electromagnetic turbulence.

Above the threshold, the vacuum magnetic island induces a non-negligible contribution to the magnetic component making the latter dominant, and a strong sheared flow is established. These findings are consistent with the interpretation of the TJ-II and JET experimental results in terms of the rational surface induced anisotropy in the structure of turbulence.

6. Conclusions

The important role of magnetic topology (rational surfaces) in transport can be understood in terms of the competition between fluctuation induced transport mechanisms (which would deteriorate transport) and ***E*×*B*** sheared flow mechanisms linked to rational surfaces (which would improve confinement). The resulting ***E*×*B*** sheared flows associated to rational surfaces would depend on the competition between mechanisms driving flows (e.g. Reynolds stress) and damping flow processes (i.e. magnetic viscosity). When the ***E*×*B*** shear flow reaches a critical value, a spontaneous transport barrier will be formed near rational surfaces, provided that the width of the rational surface (i.e. instability mode width) is comparable to the radial correlation length of fluctuations. Both DC and time dependent large ***E*×*B*** shear has been observed in plasma conditions below the power threshold to trigger the formation of transport barriers. These results support the importance of fluctuation induced flows to self-regulate transport in fusion plasmas.

References

[1] F. Wagner *et al.*, Phys. Rev. Lett. **49**, 1408 (1982).

[2] B.A. Carreras, IEEE Trans. Plasma Sci. **25**, 1281 (1997).

[3] E. Sydnakowski, Plasma Phys. Control. Fusion **40**, 581 (1998).

[4] K. Burrel, Phys. Plasmas **4**, 1499 (1997).

[5] H. Biglari, P.H. Diamond and P.W. Terry, Phys. Fluids **B 2**, 1 (1990).

[6] T.S. Hahm, M.A. Beer, Z. Lin *et al.*, Phys. Plasmas **6**, 922 (1999).

[7] E.J. Strait, L.L. Lao, M.E. Mauel *et al.*, Phys. Rev. Lett. **75**, 4421 (1995).

[8] F.M. Levinton, M.C. Zarnstorff, S.H. Batha *et al.*, Phys. Rev. Lett. **75**, 4417 (1995).

[9] J. Boedo, D. Gray, S. Jachmich *et al.*, Nuclear Fusion **40**, 1397 (2000).

[10] Y. Koide and the JT-60 team, Phys. Plasmas **4**, 1623 (1997).

[11] N.J. Lopes Cardozo, G.M.D. Hogeweij, M. De Baar *et al.*, Plasma Phys. Control. Fusion **39**, B303 (1997).

[12] C. Hidalgo, C. Silva, M.A. Pedrosa *et al.*, Phys. Rev. Lett. **83**, 2203 (1999).

[13] F. Wagner *et al.*, Plasma Phys. Control. Fusion **36**, A61 (1994).

[14] N. Ohyabu *et al.*, Phys. Rev. Lett. **84**, 103 (2000).

[15] C. Alejaldre *et al.*, Plasma Phys. Control. Fusion **41**, A539 (1999).

[16] E. Ascasíbar *et al.*, J. Plasma Fus. Res. **1**, 183 (1998).

[17] Ch.P. Ritz *et al.*, Phys. Rev. Lett. **65**, 2543 (1990).

[18] C. Hidalgo, J.H. Harris, T. Uckan *et al.*, Nuclear Fusion **31**, 1471 (1991).

[19] V. Antoni, D. Desideri, E. Martines *et al.*, Phys. Rev. Lett. **79**, 4814 (1997).

[20] M.A. Pedrosa, C. Hidalgo, A.L. Fraguas *et al.*, Czech. J. Phys. **50**, 1463 (2000).

[21] C. Hidalgo, M.A. Pedrosa, E. Sánchez *et al.*, Plasma Phys. Control. Fusion **42**, A153 (2000).

[22] Z. Lin *et al.*, Science **281**, 1835 (1998).

[23] Z. Lin *et al.*, Phys. Rev. Lett. **83**, 3645 (1999).

[24] L. García, B.A. Carreras, V.E. Lynch *et al.*, Phys. Plasmas **8**, 4111 (2001).