ELSEVIER

Journal of Nuclear Materials 290–293 (2001) 985–989

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Characterisation of the separatrix position in the ergodic divertor discharges of the Tore Supra tokamak

M. Zabiégo *, P. Ghendrih, M. Bécoulet, L. Costanzo, C. De Michelis, C. Friant, J. Gunn

Association Euratom-CEA sur la fusion, DRFC, Batiment 513, CEA Cadarache, F-13108, Saint-Paul-lez-Durance, France

Abstract

The control of particle and heat fluxes at the plasma edge is a critical issue on the path to achieving fusion in a magnetic confinement device. Over the past 10 years, the ergodic divertor was successfully operated on the Tore Supra tokamak to fulfil this task. In ergodic divertor discharges, a magnetic perturbation, superimposed upon the equilibrium magnetic field, modifies transport properties by creating open field lines at the plasma edge. The characteristics of the resulting edge ergodic layer (hence, the induced effects on transport, MHD stability and other physical properties) depend on the features of both the existing equilibrium and the applied perturbation. Until recently, the description of the ergodic layer was solely based upon results from numerical simulations which had been poorly validated against experimental data. We report here on the results of a series of experiments dedicated to this issue, and particularly to locating the separatrix position (i.e., the boundary between closed and open field lines). © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Tore Supra; Ergodic divertor; Stochastic boundary

1. Introduction

Divertors are widely used in magnetic confinement fusion devices, in order to handle the critical interaction between the plasma and the in-vessel components. A possible alternative to the axisymmetric divertor concept [1] is the ergodic divertor (ED), a concept which has been studied in several tokamaks [2,3]. In particular, Tore Supra successfully operated an ED over a 10-year campaign which ended in 1999 [3]. On the other hand, Textor should start operating a *dynamic* ED in 2001 [4].

An ED consists of a set of in-vessel current-carrying conductors which generate a magnetic field perturbation. This perturbation, superimposed upon the equilibrium magnetic field used to confine the plasma, creates open field lines at the plasma edge, over the so-called divertor volume, radially bounded by the plasma facing components (PFC) on its outer side and the last-closed flux-surface, also termed the separatrix, on its inner side. The proper analysis of the physical properties of such a system (e.g., particle screening effects), as well as its optimum operation (e.g., minimising the current in the conductors for achieving a given performance in terms of plasma edge control), critically depend on the accuracy of the description of the divertor volume, and especially of the separatrix position.

The magnetic perturbation induced by an ED is resonant on specific flux surfaces (labelled by the flux function Ψ) where the safety factor is rational ($q = m/n$, with m and n integers, respectively, termed the poloidal and toroidal mode number). There it creates magnetic islands whose radial extent w_Ψ is proportional to the square root of the current I_{ED} flowing in the conductors. For a large enough current in the conductors (a small fraction of the plasma current I_p, though), magnetic islands resonant on neighbouring flux surfaces can overlap, thus allowing magnetic field lines to wander ergodically in between the resonant surfaces, above a

---

* Corresponding author. Tel.: +33-44 22 54 862; fax: +33-44 22 56 233.

E-mail addresses: maxime.zabiego@cea.fr, zabiego@drfc.cad.cea.fr (M. Zabiégo).

PII: S0022-3115(00)00658-9

certain threshold in I_{ED}. A useful quantity, for characterising the degree of stochasticity in between two resonant surfaces Ψ_1 and Ψ_2, is the Chirikov parameter σ_{12} defined as the ratio of the half-widths sum $(w_{\Psi_1} + w_{\Psi_2})/2$ of two neighbouring islands to the radial distance $|\Psi_2 - \Psi_1|$ in between the flux surfaces [5]. It is generally considered that the threshold for *large-scale* stochasticity is at $\sigma \approx 1$.

Given a divertor set-up and the equilibrium it perturbs, the magnetic field perturbation can be Fourier decomposed along the poloidal and toroidal directions, and thus characterised by its spectrum [6], i.e., the distribution of perturbation amplitudes upon the poloidal (m) and toroidal (n) mode-number grid, at radius r

$$\delta B(r,\theta,\varphi) = \sum_{m,n} \tilde{B}_{mn}(r)\cos(m\theta - n\varphi).$$

A perturbation with a spectrum involving several poloidal and/or toroidal Fourier modes, resonant on edge flux surfaces of the equilibrium it is applied to, can create a broad ergodic layer with open field lines, provided the domain with Chirikov parameter greater than 1 continuously extends from the separatrix out to the PFC that is the closest to the plasma. By designing a concept characterised by high mode numbers, the radial decay of the perturbation, as $\tilde{B}_{mn}(r) \propto r^{m-1}$ in vacuum, ensures that field-line stochasticity only affects the plasma edge.

In Tore Supra, the conductor geometry was designed such that, in standard operating conditions (mostly characterised by a Shafranov parameter $\beta_{\mathrm{p}} + l_{\mathrm{i}}/2$ of order 0.7), the broad perturbation spectrum is centred at $\bar{m} \approx 18$ and $n = 6$, i.e., with the main resonance at the $q \approx 3$ surface [2,3]. The *reference* ED operation then mostly consists in setting $q_a = 3$ (at the relevant PFC, i.e., generally at the divertor modules) and the maximum current in the conductors (i.e., $I_{\mathrm{ED}} = 45$ kA, for a plasma current $I_{\mathrm{p}} \approx 1$ MA), such that the radial profile of the Chirikov parameter is monotonically decreasing from the edge ($\sigma \approx 4$) towards the core, with the separatrix ($\sigma = 1$) at about 80% of the plasma radius and a divertor volume of about 36% of the plasma volume [2,3]. However, it appears that such a scenario can depart from an optimised operation. The most critical observation is that, while Tore Supra demonstrated that the ED opens ways to MHD-stable operations at moderate I_{ED} through its stabilising effect on the $m/n = 2/1$ tearing mode, a disruption can be triggered by exciting the $m/n = 3/2$ tearing mode above a certain I_{ED} [7] which sets a *hard* limit to the ED operational domain. This point is illustrated in Fig. 1, which shows the comparison of experimental observations and numerical simulations regarding the ED-perturbation effect onto the tearing modes. On the other hand, observations on both impurity screening [8] and heat-load spreading [9] point at alternative ED operations (with the main resonant surface deeper into the plasma than at the last-closed flux-surface and/or I_{ED} values short of the maximum 45 kA). These have been identified in dedicated discharges where either I_{p} or I_{ED} was ramped (up or down), in order to vary the position of the main resonance and/or the ergodic layer width, for characterising experimentally observed thresholds on physical behaviours and relate them to the evolution of the separatrix position as obtained from numerical computations of the Chirikov parameter profile with the DIVERGQL code [10]. These analyses, and their implications on further ED studies, are discussed in the following sections, with the emphasis on the transition from limiter to ED configuration (the analogue of limiter to X-point transition with an axisymmetric divertor).

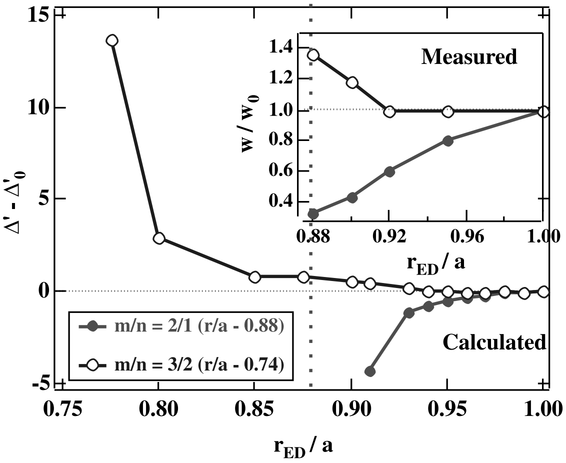

Fig. 1. Evolution of the calculated Δ' and island width w (as measured from magnetics), as a function of the ergodic layer width, for the $m/n = 2/1$ and 3/2 tearing modes (both Δ' and w are displayed relative to their value at $I_{\mathrm{ED}} = 0$).

2. Experimental results versus modelling

2.1. Dependence on the position of the main resonance

Experiments with a I_{p}-ramp performed at fixed I_{ED}, allow to analyse the dependence of ED operations on the position of the main resonant surface. As the plasma current is ramped up, the safety factor q_{ED} at the divertor modules decreases, so that edge resonances with decreasing poloidal mode number m successively come into play, thus generating ergodic layers of varying radial width at the plasma edge. This quasi-static process is illustrated in Fig. 2, which shows the radial extent of the domain with $\sigma > 1$, obtained from DIVERGQL simulations with input magnetic equilibrium data from the experiment, as a function of q_{ED}. Then, it is interesting to compare Fig. 2 with the behaviour of some

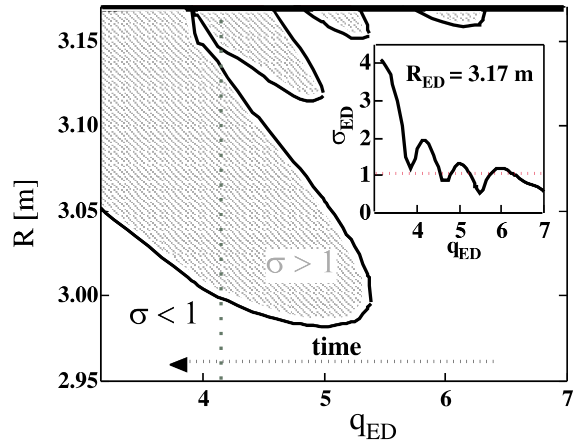

Fig. 2. Radial extent of the ergodic domain as a function of the safety factor, q_{ED}, at the divertor modules, $R_{\mathrm{ED}} = 3.17$ m, during a ramp in I_{p}. Inset: same for the Chirikov parameter at the divertor modules, σ_{ED}.

physical quantities which are expected (and indeed observed) to abruptly react to the step-like ergodic layer evolution. In particular, edge transport properties are expected to change abruptly at the point where the ergodic layer (i.e., the hatched domain of Fig. 2, along a vertical line) connects to the vessel from deep into the plasma, owing to the transition from transverse to parallel transport (relative to magnetic field lines) as open field lines are created. Such a change is indeed observed on various physical quantities which provide an interesting comparison between DIVERGQL simulations and the experiment regarding the prediction of the open field line transition. One such quantity is the plasma internal inductance l_{i}, which characterises the plasma current distribution. At the time when an inner ergodic layer connects to the vessel, the longitudinal resistivity in the layer strongly increases from neoclassical to sheath-like, so that the current is abruptly expelled from the layer. The signature of this phenomenon is a sharp increase in l_{i}, also observed in the surface loop-voltage V_{loop}. This is illustrated in Fig. 3, for the I_{p}-ramp of Fig. 2, with a fair agreement between the predicted and observed condition for the transition to the open-field-line regime, which also shows on the parallel heat flux measured by a Langmuir probe located at a divertor module (the agreement is considered fair on the basis that the radial resolution of equilibrium reconstruction is of order 1 cm).

2.2. Dependence on the ergodic layer width

A series of experiments with an I_{ED}-ramp was performed at fixed I_{p}, which allows to analyse the dependence with respect to the ergodic layer width.

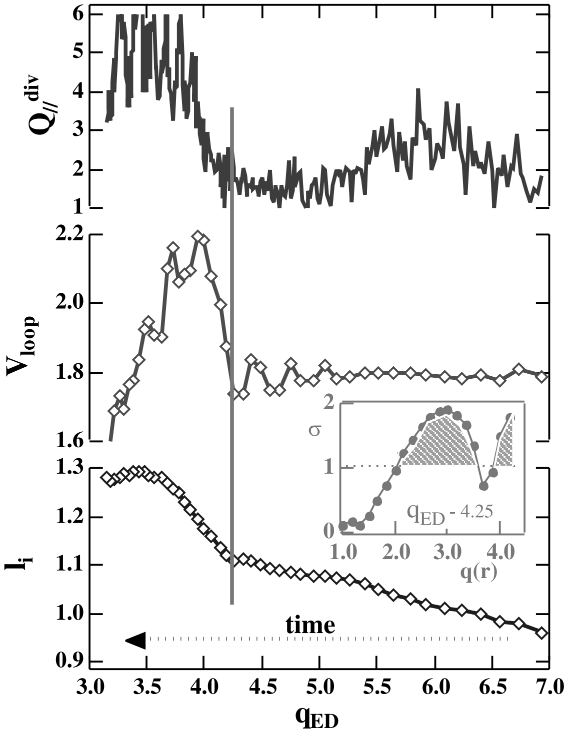

Fig. 3. Evolution of the parallel heat flux at the divertor modules $Q_{\parallel}^{\mathrm{div}}$, the surface loop voltage V_{loop} and the internal inductance l_{i}, as a function of the safety factor at the divertor modules, during the I_{p}-ramp of Fig. 2. Inset: radial profile of the Chirikov parameter at the time of the sharp transition, for $q_{\mathrm{ED}} \approx 4.25$.

One such experiment is illustrated in Fig. 1, in terms of the effect observed on the MHD activity: both the $m/n = 2/1$ and 3/2 tearing modes. For the conditions of this discharge ($q_{\mathrm{ED}} = 3$, $\beta_{\mathrm{p}} + l_{\mathrm{i}}/2 \approx 0.7$), it is clearly seen that there is a MHD-safe operating window for an ED perturbation with the separatrix as deep into the plasma as at about 80% of the minor radius, at which point a disruption is triggered by the sudden growth of the 3/2 mode, owing to the current redistribution induced by both the ED perturbation and the sawtooth activity [7]. Over this operating window, the otherwise dangerous 2/1 mode is stabilised, following a scenario discussed in [7].

Threshold effects similar to those discussed in Section 2.1 (particularly in Fig. 3) are observed in experiments with an I_{ED}-ramp. Again, the related observations are in fair agreement with predictions of the open-field-line transition obtained from simulations with the DIVERGQL code, as illustrated in Fig. 4 regarding impurity screening effects, and Fig. 5 regarding effects on the parallel heat flux spreading on the PFC.

Fig. 4 shows the evolution of the brightness of the 247 Å spectral line of the NIV impurity ion as a function

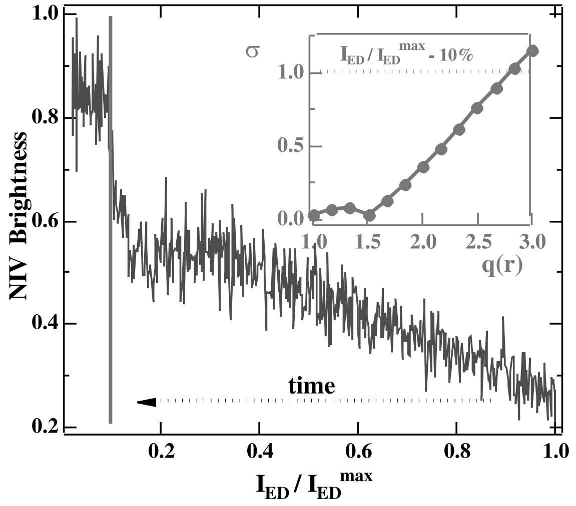

Fig. 4. Brightness of the 247 Å spectral line of the NIV impurity ion as a function of the ED perturbation, in a discharge with an I_{ED} ramp down during continuous nitrogen gas injection at a divertor module. A sharp transition occurs at the time the DIVERGQL code predicts to correspond to the vanishing of the ergodic layer and its associated impurity screening effect (inset).

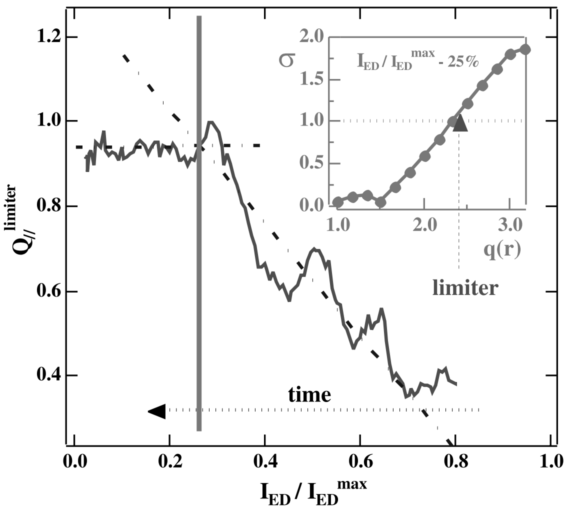

Fig. 5. Parallel heat flux at a limiter, kept a few centimetres ahead of the divertor modules, as a function of the ED perturbation, in a discharge with an I_{ED} ramp down. The saturation at the transition from the ED regime to the limiter regime occurs in fair agreement with predictions from the DIVERGQL code (inset) regarding the conditions for having the ED separatrix ($\sigma \approx 1$) at the limiter's head.

of the ergodic layer width, in a discharge where the ED perturbation was slowly ramped down during a continuous N2 gas injection through a divertor module. The brightness increases as I_{ED} is ramped down, indicating a less efficient impurity screening. In contrast with the otherwise smooth behaviour, a sharp increase is observed at 10% of the maximum ED perturbation. This transition corresponds to the loss of the ED impurity screening effect, in conditions that DIVERGQL simulations predict to be close to the transition from an ED to a limiter plasma (vanishing ergodic layer, as shown in the inset of Fig. 4).

Fig. 5 shows the evolution of the parallel heat flux obtained from infra-red measurements on a limiter kept a few centimetres ahead of the divertor modules during an I_{ED} ramp down. As the ED perturbation slowly decreases, the heat flux at the limiter increases roughly linearly (while the flux at the divertor module, not shown on the graph, decreases exponentially). This is the signature that the heat flux at the edge changes from channelled onto the divertor modules ($q_{ED} \approx 3.2$) to deposited onto the limiter ($q_{\mathrm{limiter}} \approx 2.45$). The parallel heat flux at the limiter is expected to saturate at a maximum value when the ED separatrix ($\sigma \approx 1$) reaches the limiter. Such a saturation is indeed observed, in Fig. 5, at about 25% of the maximum ED perturbation, which the DIVERGQL code predicts to roughly correspond to the vanishing of the ergodic layer (which only extends beyond the limiter's head) and its associated redistribution of the parallel heat flux to the divertor modules.

3. Discussion

In this paper, we have analysed the effect of the structure (position and/or radial extent) of the ergodic layer, in ED discharges, upon physical properties of the confined plasma: MHD activity, current distribution, heat flux, impurity screening, etc. We have shown the existence of both a wide MHD-safe operating domain and some threshold effects in the physical impact of ED operations. Threshold effects have been shown to correspond to a transition from closed to open field-line confinement at the plasma edge (the analogue of the X-point transition with an axisymmetric divertor), in fair agreement with calculations with the DIVERGQL code. This agreement indicates that the experience gained over the 10-year operation of the ergodic divertor in the Tore Supra tokamak now allows some good predictive capability for further ED analyses and designs [11].

References

[1] J. Neuhauser et al., in: Proceedings of the 13th IAEA Conference, Washington, vol. 1, 1990, p. 365.
[2] P. Ghendrih et al., Plasma Phys. Control. Fus. 38 (1996) 1653.

[3] P. Ghendrih et al., Progress in ergodic divertor operation on Tore Supra, Report EUR-CEA-FC-1675, CEA-Cadarache, France, September 1999, Nucl. Fus., submitted.

[4] K.H. Finken et al., J. Nucl. Mater. 220–222 (1995) 448.

[5] B.V. Chirikov, Phys. Rep. 52 (1975) 265.

[6] P. Ghendrih, Resonance du divertor ergodique, Report EUR-CEA-FC-1537, Association Euratom-CEA, CEA Cadarache, France (in French).

[7] M. Zabiégo et al., Plasma Phys. Control. Fus. 41 (1999) B129.

[8] C. de Michelis et al., these Proceedings.

[9] G. Mank et al., these Proceedings.

[10] P. Ghendrih et al., Contrib. Plasma Phys. 32 (1992) 179.

[11] A. Azéroual et al., in: Proceedings of the 20th Symposium on Fusion Technology, vol. 2, Marseille, France, 7–11 September 1998, p. 1705.