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Alternative schemes of power deposition with the ergodic divertor on Tore Supra

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Abstract

Two alternative schemes to distribute the energy flux over larger surfaces are proposed and tested at Tore Supra. (i) A good sharing of the energy flux to the pump limiter and the ergodic divertor (ED) is achieved at a reduced stochasticity. (ii) The operation at highest densities with the plasma leaning on the high field side is characterised by the same screening properties and achievable densities as for the standard operation. The results indicate that an efficient heat reduction and screening of impurities can be reached under ED operation. These experiments have partly been carried out in order to test special aspects of the dynamic ED (DED) at TEXTOR. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Ergodic divertor; Heat deposition; Tore Supra

1. Introduction

The ergodic divertor (ED) produces a series of resonant radial magnetic perturbations at the plasma edge [1–3]. This configuration is intended to spread out the energy flux over a large surface to increase the performance capability of the tokamak. However, it was found that regions of high heat flux evolve during the operation of the ED. These regions can be related to the so-called laminar flow, where the parallel transport is the dominant feature [4]. Therefore, the standard configuration of the ED at Tore Supra is such that the energy flux is channelled to high heat flux components. These neutraliser plates are included in the ED coils. The operation under these conditions is consistent with the requirement to screen out the wall outflow of particles by the use of a divertor and to offer the possibility to optimise a radiative layer.

The dynamic ED (DED) at TEXTOR-94 [5] will try to overcome the problem of the directed heat flow by rotating the perturbation field at different frequencies. In view of the DED experiment, two alternative configurations of the ED of Tore Supra have been investigated both theoretically and experimentally. The following section will describe a configuration which can be achieved by choosing a new operating window. The second part will describe a 'TEXTOR-DED' operation-like regime which has been tested at Tore Supra.

2. Experimental

2.1. Sharing of the energy fluxes to the ED and limiter

A detailed description of the Tore Supra ED is given in [6–9]. Six equally spaced toroidal octopolar coils are used to create the perturbation field. The perturbed magnetic field is characterised by stochastic behaviour [10]. This can be best understood by the use of the Chirikov parameter σ, which describes the island overlap as a measure of stochasticity [11]. During the plasma

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current ramp-up phase, the Chirikov parameter will change depending on the chosen conditions for the ED current, magnetic field, and plasma current. The local Chirikov parameter depends on the plasma position. Fig. 1 shows the Chirikov parameter versus the safety factor q at the edge. During the ramp-up-phase of the plasma current, q decreases, and as the ED is turned on, the Chirikov parameter changes depending on the plasma current. The change between limiter configuration and ED configuration is reached at $q_{\mathrm{edge}} = 3.8$. At this time the Chirikov parameter is one at the radius of the ED which is positioned at the major radius $R = 3.17$ m. By further increase of the plasma current, the magnetic islands which are centered at the resonant surfaces overlap up to a Chirikov parameter of 4. These operation conditions are reached at $q_{\mathrm{edge}} = 3.2$. A further increase leads to a reduction of σ.

The change of the operation condition has direct impact on the heat load pattern of the plasma facing components (PFCs) and the influx of impurities [12]. Different features of the ergodization can be diagnosed by the use of fixed or reciprocating probes and by spectroscopy. In particular, the size of the heat flux structures, e.g. due to the laminar flow [13], can be measured with infra-red thermography. We have chosen to analyse the resulting heat load pattern on the outboard pump limiter (OPL) [14]. Fig. 2 shows the time dependence of the temperature increase on one leading edge of the OPL. The poloidal extension of the OPL is marked on the left side of Fig. 2(b) by a black line. The equatorial plane is indicated by the horizontal dashed line. The false colour picture shows the temperature distribution on the leading edge.

The movable module has been inserted to $R = 3.12$ m, which is 5 cm in front of the ED module; the ED layer being about 15 cm for these experiments. First, the plasma is in limiter configuration as it can be noticed by the temperatures maximum in the middle of the OPL. After 2 s, a change in the pattern is noticed and after 3 s, the highest temperatures can be found below the midplane of the limiter. Fig. 2(a) shows the maximum temperatures on the OPL during the first 3.5 s of the discharge. With increasing plasma current I_{P} and increasing density, the temperature increases. The ED current I_{ED} is set to 38 kA for this discharge and is turned on at 1 s. After 2 s, the maximum temperature decreases and the pattern is much more irregular. When the final operation conditions are reached at 3 s, the maximum temperature rises again. The operation window between 2 and 3 s may be of interest for future experiments at other tokamaks, as a better sharing of the heat load is observed at this time.

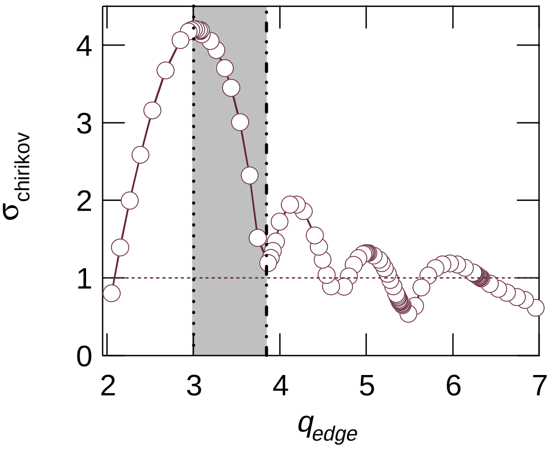

Fig. 1. Chirikov parameter σ versus the safety factor q_{edge} at the edge for the usual operating conditions at Tore Supra.

The variation of the heat load can be understood by analysing the location of the $\sigma = 1$ surface, depending on q_{edge}. For an easier comparison, the time scale for the above discharge is included in Fig. 3. Up to 2 s ($q_{\mathrm{edge}} \approx 3.8$), we find that the plasma is still in limiter configuration. But a further feature can be noticed: between $q_{\mathrm{edge}} \approx 5.5$ and $q_{\mathrm{edge}} \approx 3.8$, the ergodization takes place in the inner part of the plasma as marked by the shaded area. If any PFC, like the OPL positioned for this experiment at $R = 3.12$ m, is inside the ergodic zone a higher diffusion of impurities is possible. Indeed, an increase of Z_{eff} is noticed between 1.5 and 2.1 s. This increase might result e.g. from iron which can be found in the holding structure of the OPL. However, other PFCs, for e.g. the ICRH antennas, can be also responsible for the increase of the impurities if the OPL is retracted. At $q_{\mathrm{edge}} \approx 3.8$, the ergodic zone breaks up and a more uniform heat load can be observed. It has to be noted that this is not the usual operating ED regime of Tore Supra, as the overlap of the magnetic islands is not at its optimum. The zones of high heat load can switch to other parts of the OPL if there is only a small change in the plasma current. This configuration may open an alternative scheme for the TEXTOR-DED where the ALT-II toroidal belt limiter is the main PFC. Furthermore, it is found that the pump-rate of the OPL increases during this time which is advantageous for the particle control of the discharge [15]. The time resolution of the total pumping system is about 0.5 s and is not high enough to correlate the pump-rate directly with q_{edge}.

2.2. Heat load control on the high field side limiter

A variety of plasma properties can be influenced by the presence of islands and/or stochastic layers [16]. Of main interest in the context of this investigation is the plasma detachment, the properties of MARFEs and their onset, and the edge radiation profile. It has been shown that MARFEs can be triggered by magnetic

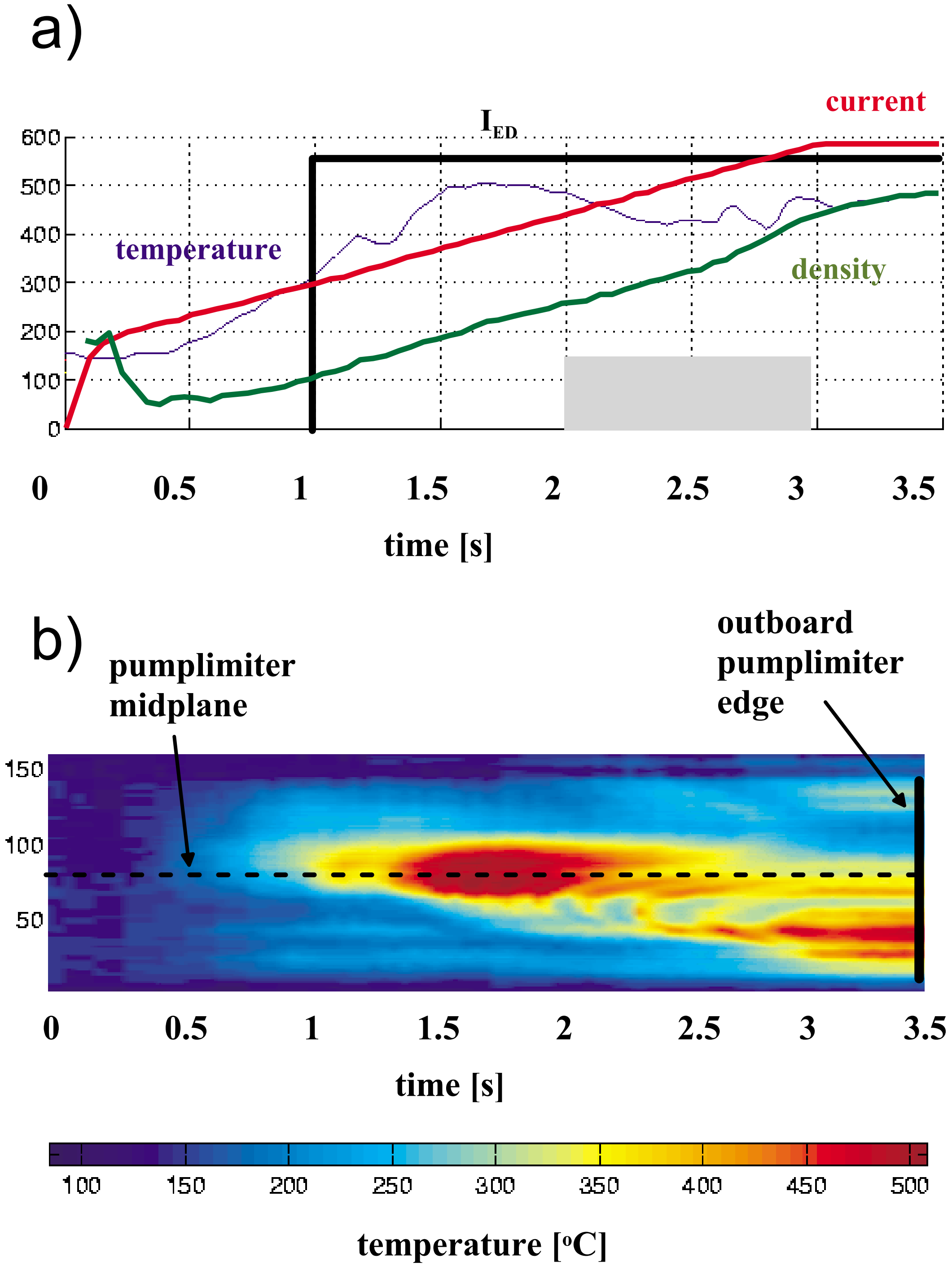

Fig. 2. (a) Maximum temperature (°C) on the outboard pump limiter, depending on the plasma current I_P (ramped up to 1 MA) and the divertor current I_{ED} (38 kA). The line averaged density increases to 2×10^{13} cm^{-3}. (b) Two-dimensional false colour picture of the time dependence of the temperature increase on one edge of the OPL. The temperature scale is from 100°C to 500°C. The poloidal extension of the OPL is marked by a vertical bar, the equatorial midplane by a horizontal line.

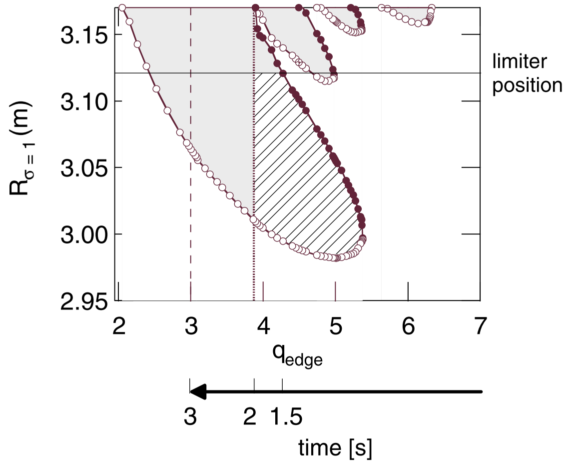

Fig. 3. Radial location of the Chirikov parameter $\sigma = 1$ versus q_{edge}. The time scale is shown as a second x-axis.

islands and stochastic layers [17]. They can be used as a method of protecting the strike point region of a divertor from thermal overload [17]. The possibility to transfer this to the future TEXTOR-DED has been tested at Tore Supra.

The operation configuration of the ED at Tore Supra has been chosen for this experiment in such a way that main features have similarities to the TEXTOR-DED magnetic configuration. The plasma is limited by the toroidal limiter located on the high field side at a major radius $R = 1.56$ m. This is similar to a possible operation scheme at TEXTOR where the curved divertor tiles on the high field will be used as plasma limiting elements. The divertor current at Tore Supra is chosen to 45 kA for this experiment. In this case, a Chirikov parameter of about 3 is achieved on the surface tangent to the inner limiter. A $q_{edge} \approx 3$ is maintained on this surface by reducing the toroidal field to $B_T = 1.5$ Tesla and the plasma current to $I_P = 0.74$ MA. The Chirikov parameter changes from 5 when the plasma is positioned against the ED to ≈3 if the gap increases to 8 cm. The q_{edge} shows a slight reduction from 3.1 to 2.95. The gap $g_{ED} = 3.17 - (R + a)[m]$ with R as major and a as minor plasma radius can be varied by a different positioning of the plasma. If the gap is increased, the parallel heat flow to the divertor is reduced. For the experiments performed with the shifted plasma, the parallel heat flux $Q_{||}$ is less than 0.1 MW/m^2 ensuring a decoupling with the ED coils.

For a constant $R = 2.32$ m, a density ramp has been performed. The edge temperature is controlled not to be less than $T_e = 10$ eV to prevent a disruption during the density ramp phase [18,19]. The plasma detaches at a Greenwald number $\bar{n}_{e,0}/n_{GW} = 0.8$, where $n_{GW} = I_P/\pi a^2$ in units 10^{20} m^3 (plasma current I_P in MA, a in m and $\bar{n}_{e,0}$ is the line averaged density). For this discharge, Z_{eff} decreases from 4 at $\bar{n}_{e,0}/n_{GW} = 0.3$ to 1.8 at the highest achievable density. For a plasma shift to the high field side and the full perturbation current (45 kA), the Chirikov parameter has about the same minor radius distribution as the one for a normal plasma position and $I_{ED} = 18$ kA. A density ramp which is performed for this condition is characterised by the same screening properties and density limit.

If the plasma is positioned against the high field side, the laminar flow region will be observed by the H_α emission originating from recycling hydrogen on the bumper limiter [4,12]. These structures can be observed by the tangential CCD camera for high density operation and detached plasma and for optimised ED conditions if the recycling is sufficiently high. The width of the laminar zone depends on the positioning of the plasma relative to the ergodic coils. In a qualitative model [4], the emission is taken constantly along the flux tubes connected to the border of the ergodic zone with a homogeneous neutral density. The H_α light reveals the structure where the transport is of laminar type. The pattern is a footprint of the magnetic connection in co- and counter-direction to the ergodic zone and does not show a magnetic island structure. The width Δx of the pattern depends on the positioning of the plasma. If the plasma is in the center position (major radius with respect to the ergodic zone $R_{de} = 2.365$ m), the experimental width is 0.045 m, about 0.002 m bigger than the calculated value. The plasma is moved to the high field side, thus the radius of the plasma decreases and the center location with respect to the ergodic zone decreases. The gap between the ergodic zone and the divertor increases. In total, the width of the laminar zone shrinks if the Chirikov parameter on the minor radius is kept constant by increasing the divertor current. The measured value $\Delta x = 0.028$ m at $R_{de} \approx 2.325$ m agrees well with the model.

2.3. Application to the TEXTOR-DED

At TEXTOR, the ergodic coils will be mounted on the high field side of the torus. The coils are covered by curved carbon tiles which are located at a minor plasma radius of $r = 47.5$ cm. The surface of the toroidal pump limiter ALT-II [20] is located at $r = 46$ cm, 45° below the equatorial midplane, usually defining the minor plasma radius. Unlike the case of Tore Supra, the limiter cannot be moved further out of the plasma volume. The resonance layer at TEXTOR will be at $r = 42$ cm for optimum ergodization. According to the results at Tore Supra, channels of high heat and particle flux will be directed towards the belt limiter.

Particle recycling and heat deposition are very sensitive to laminar transport which will be dominant at TEXTOR [21,22]. Therefore, an alternative as proposed in this paper may be useful to increase the region of high heat flux. Furthermore, gas fuelling at lower levels of ergodization should be easier and pumping with the toroidally more uniformly located ALT-II limiter might be better. Both properties are found at Tore Supra for the period between the limiter configuration and the full ergodization.

The second scheme is similar to that of the TEXTOR-DED. The plasma is limited by the inner bumper limiter, and the parallel heat flow to the divertor coils on the low field side is reduced. It has to be noted that densities well above the Greenwald density have been reached at TEXTOR for additional heated discharges [23] and for radiative improved (RI) mode discharges [24]. The operation of RI mode discharges together with the improved radiation pattern due to the application of the ergodic divertor is of major interest for the TEXTOR-DED.

If the density is further increased and the plasma detaches, the heat load on the high field side limiter will be reduced by a factor of 4 and the heat flux will be distributed more uniformly. This configuration is repeated with an inserted outboard pump limiter coming close to the experimental set up at TEXTOR. Again it should be noted that at TEXTOR-94, the MARFE formation could be stabilised by the use of additional heating [25,26], and consequently the use of the TEXTOR-DED might open new possibilities of operation.

3. Summary

Two alternative schemes of power deposition during ED operation on Tore Supra have been presented. It is possible to distribute the heat load on the toroidal limiter at Tore Supra more uniformly under a condition of reduced Chirikov parameter and reduced stochasticity. This scheme may be an alternative to the rotating perturbation fields which will be applied for the DED at TEXTOR. Strong screening of heavy impurities has been observed at this operation condition. The second scheme opens the possibility of high density operation at TEXTOR without using the external fuelling by pellet injection.

Both results show that efficient reduction of heat deposition can be achieved at the DED of TEXTOR. These operation regimes can be coupled with the dynamic aspect and can help to improve the experiments on radiative edges at TEXTOR.

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References

[1] W. Engelhardt, W. Feneberg, J. Nucl. Mater. 76&77 (1978) 518.
[2] W. Feneberg, G.H. Wolf, Nucl. Fus. 21 (1981) 669.
[3] A. Samain, A. Grosman, W. Feneberg, J. Nucl. Mater. 111&112 (1982) 408.
[4] F. Nguyen, P. Ghendrih, A. Grosman, Nucl. Fus. 37 (1997) 743.
[5] K.H. Finken (Guest Ed.), Dynamic Ergodic Divertor (special issue), Fus. Eng. Des. 37 (1997).
[6] P. Deschamps, A. Grosman, M. Lipa, A. Samain, J. Nucl. Mater. 128&129 (1984) 38.
[7] A. Samain, A. Grosman, T. Blenski, G. Fuchs, B. Steffen, J. Nucl. Mater. 128&129 (1984) 395.
[8] M. Lipa et al., in: Fusion Technology (Proceedings of the 15th Symposium, Utrecht, 1988), Elsevier, Amsterdam, 1989, p.874.
[9] A. Grosman, Plasma Phys. Control. Fus. 41 (1999) A185.
[10] G.M. Zaslavsky, B.V. Chirikov, Sov. Phys. Usp. 14 (1972) 549.
[11] B.V. Chirikov, Phys. Rep. 52 (1979) 263.
[12] A. Grosman, P. Ghendrih, C. DeMichelis et al., J. Nucl. Mater. 196–198 (1992) 59.
[13] Ph. Ghendrih, A. Grosman, F. Nguyen, J. Nucl. Mater. 220–222 (1995) 511.
[14] T. Loarer, T. Uckan, M. Chatelier et al., J. Nucl. Mater 196–198 (1992) 1078.
[15] T. Loarer et al., these Proceedings.
[16] T. Evans, Fus. Eng. Des. 37 (1997) 385.
[17] T.E. Evans, M. Goniche, A. Grosman, D. Guilhem, W. Hess, J.C. Vallet, J. Nucl. Mater. 196–198 (1992) 421.
[18] J. Gunn et al., Plasma Phys. Control. Fus. 41 (1999) B243.
[19] C. Grisolia et al., these Proceedings.
[20] D.M. Goebel et al., J. Nucl. Mater. 162–164 (1989) 115.
[21] K.H. Finken, Th. Eich, Contrib. Plasma Phys. 40 (2000) 57.
[22] Th. Eich, PhD thesis, Forschungszentrum Jülich, Berichte des Forschungszentrums Jülich (2000).
[23] P.C. de Vries, J. Rapp, F.C. Schüller, M.Z. Tokar, Phys. Rev. Lett. 80 (1998) 3519.
[24] G. Mank et al., Phys. Rev. Lett. 85 (2000) 2312.
[25] U. Samm et al., J. Nucl. Mater. 266–269 (1999) 666.
[26] G. Sergienko et al., these Proceedings.