Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 363–365 (2007) 371–376
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Observation of the heteroclinic tangles in the heat flux pattern of the ergodic divertor at TEXTOR

M.W. Jakubowski [a,*], A. Wingen [b], S.S. Abdullaev [a], K.H. Finken [a], M. Lehnen [a], K.H. Spatschek [b], R.C. Wolf [a], The TEXTOR Team

[a] *Institut für Plasmaphysik, Forschungszentrum Juelich GmbH, Association EURATOM-FZJ, D-52425, Trilateral Euregio Cluster, 52425 Jülich, Germany*
[b] *Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany*

Abstract

A fine structure of open chaotic field lines, namely, a heteroclinic tangle, in the ergodic divertor has been observed by measurements of heat deposition pattern on the divertor plates at TEXTOR. Calculations show that magnetic footprints on the divertor plates are formed by open field lines coming from the plasma along narrow stripe regions called fingers. The latter are determined by the structure of stable and unstable manifolds of the outermost resonant magnetic island. This fact is confirmed by observations of the bifurcations of the heat flux pattern on the divertor plates with changing edge safety factor.

PACS: 52.55.Fa

Keywords: Divertor plasma; Edge plasma; Power deposition; Stochastic boundary; Thermography

1. Introduction

The concept of ergodic divertors is based on the stochastization of the magnetic field lines in the plasma edge by a helical, multipolar magnetic perturbation resulting from the external currents. The dynamic ergodic divertor [1,2] in the TEXTOR tokamak consists of sixteen perturbation coils, which cover about 72° of the vessel poloidal circumference on the HFS. The spectrum of the magnetic perturbation is controlled by the current distribution in the coils. The base mode of the magnetic perturbation can be varied by the connections of the power supplies to the coils among $m/n = 12/4$, 6/2 and 3/1, where m, n refers to the poloidal and toroidal mode number. Each of the base modes is accompanied by side bands, e.g., the perturbation with the base mode $m/n = 12/4$ consists of modes from the range of $8/4 \leqslant m/n \leqslant 16/4$. Resonant components of magnetic perturbation act on field lines at certain flux surfaces and create open chaotic system, which consists of the different regions: an ergodic region adjacent to the confined plasma region and a laminar region close to the target plates with

* Corresponding author.
E-mail address: ma.jakubowski@fz-juelich.de (M.W. Jakubowski).

0022-3115/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2007.01.158

helical flux tubes of field lines with short connection length to the target [3]. The laminar zone [4] is equivalent to the scrape-off layer of a poloidal divertor, but it has a complicated three-dimensional structure. It consists of relatively large areas with small connections lengths alternating with narrow stripes areas (a so-called 'fingers') with large connection lengths. As was shown in [2] the boundary between flux tubes with different connection lengths has a fractal structure. The width and spatial structure of the fingers is of particular interest for the plasma flow pattern toward the divertor since they determine a heat and particle deposition pattern on the divertor target plates [5].

In this paper we report a new experimental finding on the structure of a heat deposition pattern on divertor plates and its relation with the structure of fingers. Specifically, it was found that the heat deposition pattern is predominately determined by the finger structure of the outermost resonant magnetic island chain at the plasma edge. This effect has been found by the experimental observation of the bifurcation of the heat deposition pattern with the change of the edge safety factor q_a. It was also confirmed by the numerical calculations of the magnetic footprints on the divertor plates and the structure of so-called stable and unstable manifolds of field lines of the outermost resonance magnetic island. The finger structures are formed near these manifolds and contain field lines with long connections lengths.

It is known that the onset of chaotic field lines appears near the separatrix in the presence of non-axisymmetric magnetic perturbations which splits stable and unstable manifolds of the separatrix. The transversal intersections of these manifolds create an infinite number of unstable periodic fixed points [6,7]. Such a complicated structure called a homoclinic (heteroclinic) tangle is a signature of a chaotic motion. The described heteroclinic tangles appear also for the magnetic field lines in the ergodic layer of the plasma. They are the mechanism for non-diffusive transport towards the target plates [6,8]. Their structure determines the particle and heat deposition pattern on the divertor plates since electrons and ions predominantly follow magnetic field lines.

2. Dependence of the strike zone on the edge safety factor

Regular patterns of the heat deposition, which are formed by the fingers and adjacent to the flux tubes formed by field lines with short connection lengths can be seen on Fig. 1. The image presents the temperature distribution over the divertor target plates (visible as a false-color scale) with the DED operating in the 6/2 mode. It is visible that the

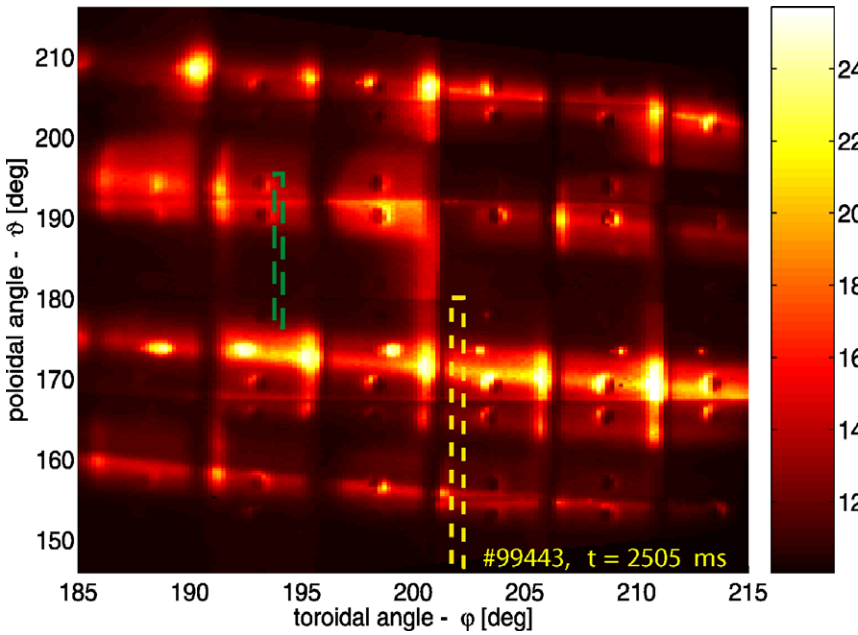

Fig. 1. The temperature distribution over the DED target plates in Celsius centigrade. The image of the curved and oblique surface is corrected with LEOPOLD [12], such that the tiles form a regular pattern. The yellow ($m/n = 6/2$) and green ($m/n = 12/4$) rectangles indicate the areas, where the heat flux density is evaluated with the THEODOR code.

helical heating stripe has a slight slope from the bottom left to the right; the stripe follows the direction of the DED coils behind the target plates. The color represents the temperature as indicated by the color bar on the right-hand side. Unfortunately, the tiles are not ideally mounted and, as a result, the protruding edges of the graphite tiles receive an enhanced heat flux.

Each pair of 'power-stripes' contains a colder region in between. At the lower degree of ergodization these pairs merge together. The relation of the target surface temperature distribution to the structure of the magnetic field and thermographic setup has been discussed in [5]. Here, it is important to mention, that the energetic electrons, which follow magnetic field lines are directed from the ergodic layer towards the plasma boundary along the fingers. Part of the heat and particles is transferred to the adjacent flux tubes of the laminar zone by perpendicular transport, but still a large fraction of the energy is deposited on divertor target plates via stochastic field lines forming the fingers [9,10]. The comparison of the heat flux density structure and the distribution of the field line connection lengths shows, that most of the energy reaches target plates via the field lines with short connection lengths. However the maximum of the heat flux density falls into region, where the stochastic field lines intersect with the divertor surface, due to the fact that the most energetic particles hit the target plates at those places. The structure of the resulting heat flux pattern as discussed in [5] is defined by the field lines with short and long connection length.

As stated above, the magnetic perturbation created by the DED consists of several Fourier components. The maximum of the ergodization is reached, when the pitch of the field lines on a given magnetic flux surfaces matches the helicity of the Fourier component of the perturbation. Thus the structure of the perturbed volume strongly depends on the quantities, which modify plasma magnetic equilibrium, i.e., edge safety factor or poloidal beta. The safety factor profile defines which resonant magnetic surfaces are within the bulk plasma and their distance from the source of the perturbation. In order to see how, the heat flux pattern depends on the magnetic equilibrium the experiments have been performed in all three configurations of the DED, where the plasma current was ramped up (or down) in order to vary the edge safety factor. The heat flux density was time resolved using the THEODOR code [11] at the areas marked with yellow and green rectangles in Fig. 1. The results are shown in Fig. 2: the heat flux density is presented as a function of the edge safety factor (the abscissa) and poloidal angle along the tiles (the ordinate). At first the experiments in the 12/4 mode were performed, one of the results is presented in Fig. 2(a). Here the edge safety factor has been varied in the range of ($q_a \approx 5.0 \rightarrow q_a \approx 2.4$). It is found that the structure of the strike zones is strongly correlated to the value of the edge safety factor. The general tendency is that the strike zone splits, if $q_a \leqslant 3.25$. However, one can identify substructures, which can be attributed to a certain range of the edge safety factor, i.e., they appear at q_{a1} and disappear at q_{a2}. One should notice the slight asymmetry between the top and bottom structures. Each of the substructures disappears, when the q_a is close to the rational value. It would indicate that the topology of the footprints is defined by the outermost resonant flux surface. The variation of the structures is strongest for $q_a < 16/4$, i.e., where the effect of the magnetic perturbation on the field lines is strongest. Characteristic is that the substructures are overlapping, i.e., the new one appears, while the previous is still present.

To prove the resonant nature of the heat flux pattern evolution with changing plasma current the experiments have been performed in other configurations, e.g. in 3/1 and 6/2 mode. It has been found that the behavior of the heat flux density patterns is similar to these in 12/4. However due to different shape of the perturbation spectrum, there are fewer substructures within each of the stripes. An example for the base mode 6/2 is shown in Fig. 2(b). The variation of the heat flux density with q_a during the discharge #99443 is shown in Fig. 2(b). Here variation of the edge safety factor was in the range of ($q_a \approx 3.1 \rightarrow q_a \approx 5.0$). As expected the number of the substructures appearing within the stripe is reduced. Again the structures are correlated with $q_a \approx m/n$. The dependence of the footprint topology on the resonant flux surfaces is clearly visible. The substructures can be attributed to a certain resonances as indicated on the graph. As it will be shown in the next section, crucial for the heat flux pattern formation is the topology of the stable and unstable manifolds of the given island chain.

3. Formation of the fingers by stable and unstable manifolds

A periodic fixed point with period n can be followed using the Hamiltonian formalism and

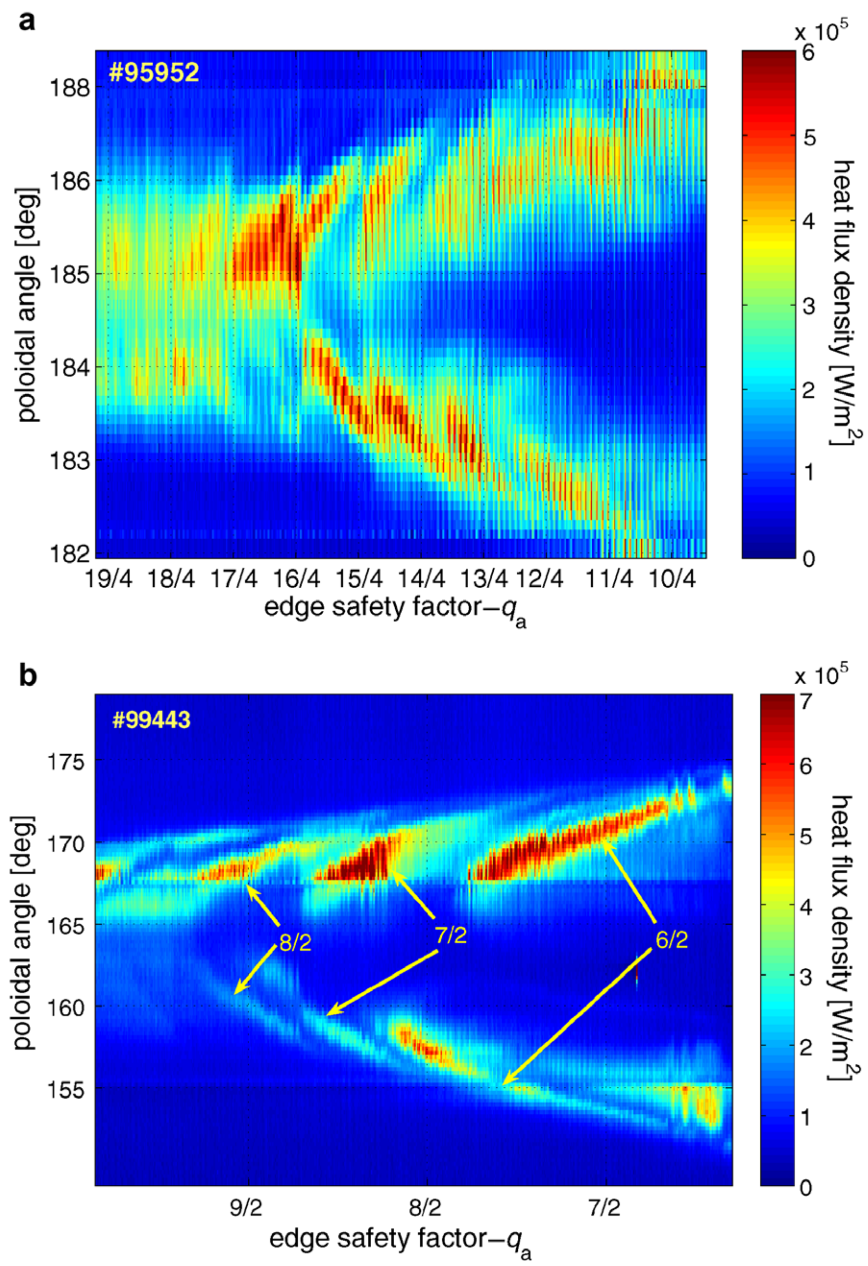

Fig. 2. Heat flux to the divertor target plates as a function of the edge safety factor and the poloidal angle: (a) in the 12/4 mode; (b) in the 6/2 mode.

mapping methods (see, e.g., [2,7,8]). There are two types of the fixed points: elliptic and hyperbolic ones. As discussed above, the chaos in fusion plasmas arises around the hyperbolic fixed points. A field line close to the hyperbolic point will follow a hyperbolic orbit away from the fixed point. An unstable manifold of a hyperbolic fixed point is defined as the set of points which converge under the map towards the fixed points for $n \to -\infty$. A stable manifold is the unstable manifold of the inverse map, i.e. it converges towards the fixed points for $n \to +\infty$. The method of calculating the trajectories of the (un)stable manifolds of the fixed points has been discussed in [7].

The sketch of the trajectories of the stable and unstable manifolds is shown in Fig. 3. Manifolds start to oscillate when approaching the hyperbolic fixed points and intersect each other infinite times.

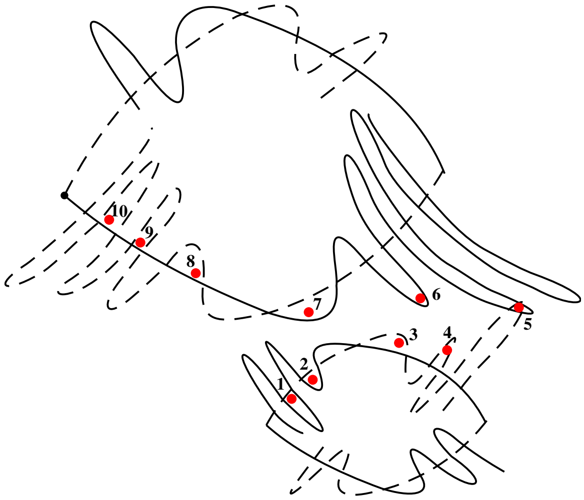

Fig. 3. The sketch presenting the intersections of the stable and unstable manifolds of two different resonances. Stable manifolds are plotted with solid lines, the unstable ones with dashed lines.

The magnetic flux enclosed by the intersections of the manifolds is preserved. However due to increasing amplitude of the oscillations the areas are getting long and thin. This results in enhancing of the chaotic behavior of the field lines. In Fig. 3 a field line, marked as a red circle, iterates from position 1–10. Close to the hyperbolic points the amplitudes of the oscillations are large enough to intersect the manifolds of the neighboring resonances resulting in the transport of the magnetic flux from the one resonance to the other. In Fig. 3 it happens at fifth iteration of the field line.

The DED creates an open chaotic system, therefore the stable and unstable manifolds have large influence on the target patterns. It has been shown [7], that the finger structure is constrained to the trajectories of the stable and unstable manifolds of the outermost island chain. To show the relation of the manifolds and the heat deposition patterns the calculations for the discharge presented in Fig. 2(a) has been performed using a method discussed in [7]. In Fig. 4 the paths of the manifolds calculated for $q_a = 3.03$ are presented. They are overlaid with the corresponding Poincaré plot. The abscissa represents the poloidal angle θ and the ordinate – minor radius r. The divertor target plates are localized at minor radius of 47.7 cm and poloidaly in the range of $150° \leqslant \theta \leqslant 210°$. The (un)stable manifold oscillates around island until it is strongly deflected by the near field of the DED towards the target plates. The dominance of the 10/4 resonance can be concluded from the behavior of the manifolds. The manifolds of the 9/4 resonance oscillate around their fixed points until the oscillations are large enough to intersect 10/4 island chain and hit the target plates. The position of the intersection is therefore defined by the 10/4 island chain. One should note that the rational surfaces 11/4 and 12/4 are still existing inside the plasma volume, however the near field of the DED destroyed them completely. For the slightly lower q_a 10/4 island chain would be shifted outwards, closer to the DED coils and destroyed as well. Then the 9/4 island chain would become dominant. The modification of the magnetic structure with variation of the edge safety factor is presented in Fig. 4(b). The graph shows the dependence of the magnetic footprints on the edge safety factor (the abscissa) and the poloidal angle

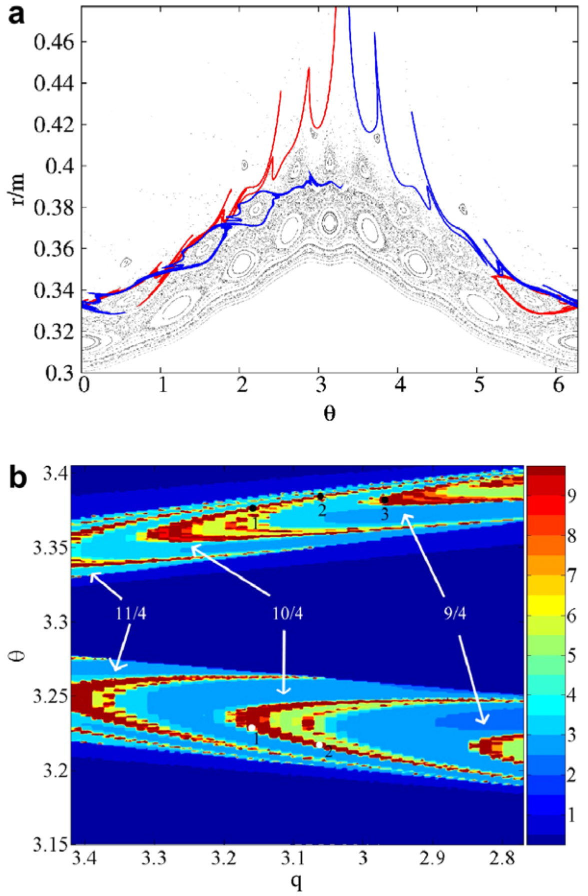

Fig. 4. Calculated topology of the (un)stable manifolds for the case of the DED (#95952): (a) the stable (red) and unstable (blue) manifolds of the outermost existing island chain ($m/n = 9/4$); (b) the structure of the magnetic footprints as a function of the edge safety factor q and poloidal angle θ. The color scale refers to the connection length of the magnetic field lines expressed in toroidal turns.

(the ordinate). The colors correspond to different connection lengths of the field lines expressed in toroidal revolutions around the torus, e.g., dark red structures represent the field lines intersecting the divertor surface after 10 toroidal turns. The calculations are held for a set of parameters from Fig. 2(a). In order to show details of the structures, the edge safety factor is varied from $q_a = 3.5$ to $q_a = 2.7$. The variation of the magnetic footprints resembles the changes in the heat flux pattern presented in Fig. 2(a). One can clearly identify three substructures corresponding to three different resonances. Each of the structures forms a c-like shape. The calculations allow to identify dominant resonances forming each of them. They are correspondingly 11/4, 10/4 and 9/4. The intersections of the stable and unstable manifolds (marked with black dots – for unstable manifolds and with white – for the stable ones) fall within the areas of the longest connection length. One should note that the inner branches are not present in the heat flux pattern in Fig. 2(a). Most likely these inner branches are created by the field lines with shallower penetration after first few toroidal revolutions.

4. Summary

The heat flux pattern of the fusion devices with the stochastic edge are defined by the stable and unstable manifolds of the homo- and heteroclinic tangles. These structures have been observed by measurements of heat deposition patterns on the divertor target plates at TEXTOR. In the case of the DED the manifolds form a 'skeleton' for the fingers structure and the laminar zone. The position of the strike zone is influenced by the outermost dominant island chain.

Acknowledgement

This work has been partially supported by the Deutsche Forschungsgemeinschaft (DFG) through the project Sonderforschungsbereich (SFB) 591.

References

[1] Special Issue: Dynamic Ergodic Divertor, Fusion Eng. Des., 37, 1997.
[2] K.H. Finken, S.S. Abdullaev, et al., The structure of magnetic field in the TEXTOR-DED, Forschungszentrum Jülich, Series: Energy Technology, vol. 45, Jülich, 2005.
[3] M.W. Jakubowski, O. Schmitz, et al., Phys. Rev. Lett. 96 (2006) 035004-1.
[4] T. Eich, D. Reiser, K.H. Finken, Nucl. Fusion 40 (2000) 1757.
[5] M.W. Jakubowski et al., J. Nucl. Mater. 337–339 (2005) 176.
[6] T.E. Evans, R.K.W. Roeder, J.A. Carter, et al., J. Phys.: Conf. Ser. 7 (2005) 174.
[7] A. Wingen, K.H. Spatschek, S.S. Abdullaev, Contrib. Plasma Phys. 45 (2005) 500.
[8] R.K.W. Roeder, B.I. Rapoport, T.E. Evans, Phys. Plasmas 10 (9) (2003) 3796.
[9] O. Schmitz et al., J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.01.067.
[10] M.W. Jakubowski et al., Nucl. Fusion 44 (2005) S1.
[11] A. Herrmann, in: Proc. of Contributions to the EPS Conference on Plasma Physics, Madeira, 2001.
[12] Th. Eich, private communication, MPI Garching, 2003.