

## **On the influence of the magnetic resonances on the heat flux structure of the dynamic ergodic divertor\***

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The dynamic ergodic divertor in TEXTOR provides an ergodized edge of the plasma in order to control heat and particle exhaust. The sixteen perturbation coils are mounted on the inner side of the tokamak vessel and are parallel to the field lines at a resonant flux surface [1]. Depending on the currents distribution in the coils, a helical magnetic perturbation field with the different base mode number  $m/n = 3/1, 6/2, 12/4$  is created. The  $m$  and  $n$  refer to a poloidal and toroidal mode number. Each of the base modes has its sidebands (e.g. the perturbation with the base mode  $m/n = 12/4$  consists of  $8/4 \leq m/n \leq 16/4$ ). The qualitative picture of the formation of the ergodic and laminar zone is following: magnetic perturbation creates the island chains at the rational surfaces. If the perturbation is large enough island chains overlap creating the ergodic layer. In this region the axis-symmetry of the nested flux surfaces is broken and the field lines create a “woven” structure. The near field of the DED deflects the magnetic field lines such that they intersect the walls. In the ergodic layer the field lines have very long connection lengths, whereas in the outermost layer the region of short connection lengths exists, which is called a laminar zone. The laminar zone is equivalent to the scrape-off layer of a poloidal divertor. However, the length of the flux tubes is not uniform but varies. The flux tubes of similar connection lengths form continuous areas, and at the boundaries between the areas of different connection lengths one finds fine scale structures of magnetic field lines (so-called “fingers”) which can e.g. connect the ergodic zone with the wall [2]. The width and structure of the flux tubes and of the fingers is of particular interest for the plasma flow pattern towards the walls.

Each of the island chains possess set of heteroclinic fixed points: elliptic fixed points at island centers (O-point) and hyperbolic fixed points in between the islands. The field line trajectories always stay close to the elliptic fixed points “gyrating” around them. In contrary, the hyperbolic fixed points are unstable; the nearby field lines are easily perturbed and will follow a hyperbolic orbit away from the fixed points. The rigorous mathematical approach to the onset of the chaos is based on the study of the stable and unstable manifolds of the hyperbolic saddle points [6]. Any nonaxisymmetric perturbation splits the stable and unstable manifolds from the hyperbolic

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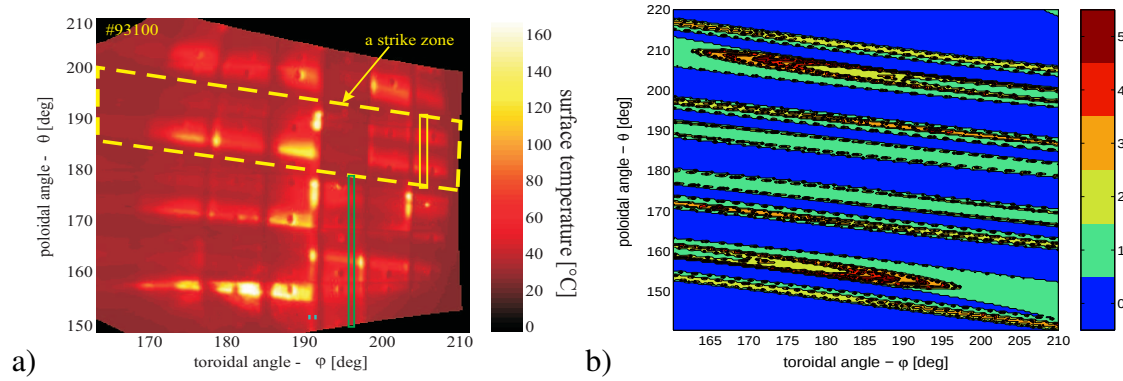


Figure 1: a) The temperature distribution over the divertor target plates measured by an infrared camera, discharge #93100. The characteristic stripe-like pattern is visible with one of the stripes indicated by the yellow dashed line. Yellow and green rectangles indicate areas, where the heat flux density is evaluated. b) Contour plot of the field line connection lengths as calculated by the ATLAS-code [3] for the conditions from Fig. 1a. Colors represent connection lengths of the field lines (units are in poloidal turns).

fixed points and their intersections create complicated structure, which is responsible for the chaotic motion. e.g. it is shown in [7] that the fingers are formed by the field lines following the unstable manifolds form the finger structure in the DED experiment.

The transport in the laminar zone is expected to be governed by the competition of the transport along the magnetic field lines to the perpendicular one. The heat and particles are channeled to the target plates by the flux tubes formed in the laminar zone and deposited on the divertor target plate forming a characteristic stripe-like pattern. The typical example of the heat flux deposition pattern and the corresponding footprints plot is presented in Fig. 1. The temperature distribution is measured with the thermographic system [2]. The main part of the system is an infrared camera SFB-125 equipped with an InSb focal plane array. The spatial resolution of the measured data is of order of 2 mm. In Fig. 1a the abscissa represents the toroidal angle and the ordinate - poloidal angle, view covers about 50 degrees in toroidal direction and about 60 degrees in poloidal. The false color represents the temperature scale in centigrade degree. The characteristic stripe-like pattern parallel to the DED coils is visible; one of the stripes is marked with the yellow dashed line. The overexposed areas are caused by the misalignment of the tiles. The structure of the heat flux deposition is mostly determined by the topology of the magnetic field lines. The corresponding magnetic footprints structure is presented in Fig. 1b. It is a contour plot of the connection lengths of the field lines, which intersect the wall. The grid for calculations is spanned on a surface observed by the camera.

The structure of the perturbed volume strongly depends on the safety factor profile and the plasma pressure [3]. At the higher level of ergodization (i.e. at higher plasma current and lower beta poloidal) the laminar zone is dominant, while at the lower level of ergodization the ergodic region dominates. The features of the ergodized volume produced by the DED are also discussed in [4, 5]. To investigate the influence of the  $q$ -profile on the heat flux pattern few

series of the discharges were performed, where the plasma current was ramped in order to vary the edge safety factor ( $q_a \simeq 5 \Rightarrow q_a \simeq 2.3$ ). The heat flux density was time resolved using the THEODOR code [8] at the areas marked with yellow and green rectangles in Fig. 1a. The results are shown in Fig. 2: the heat flux density is presented as the function of the edge safety factor (the abscissas) and poloidal angle along the tiles (the ordinates). At first the experiments

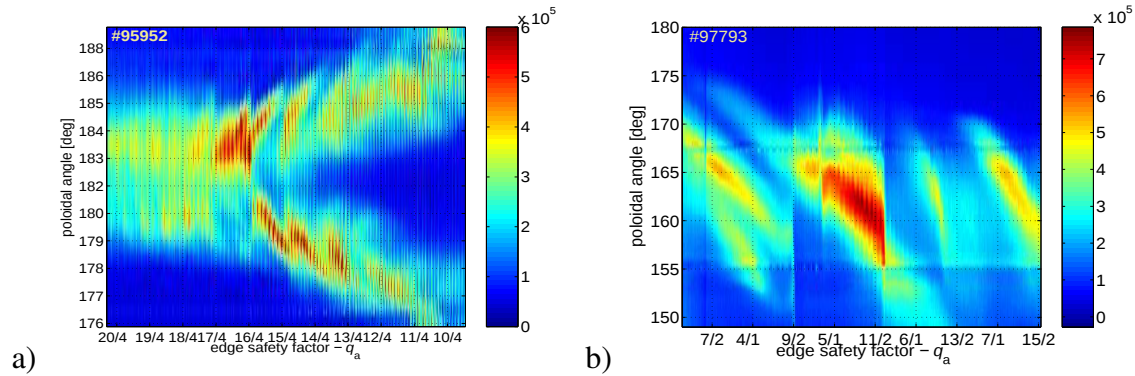


Figure 2: Heat flux to the divertor target plates as a function of the edge safety factor and the poloidal angle: a) in the 12/4 mode; b) in the 3/1 mode

in the 12/4 mode were performed (Fig. 2a). 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  $q \lesssim 3.25$ . 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  $q_{a2}$ . However, one should notice the slight asymmetry between the top and bottom structures. Nevertheless, one can identify that these substructures disappear at  $q_a \simeq m/n$ , where  $20 < m < 10$  is the poloidal mode number. It would indicate that the topology of the footprints is defined by the outermost resonant flux surface. The variation of the structures is strongest if  $q_a < 16/4$ , i.e. where the perturbation field is strongest. To prove the statement, we have performed similar experiments with the DED in the 3/1 mode. The spectrum of the magnetic perturbation of the 3/1 mode contains fewer components than 12/4 perturbation, while the dominant modes are these with  $n = 1$  and 2. Therefore, the number of substructures should be smaller than in the previous case. The variation of the heat flux density with  $q_a$  during the discharge #97793 is shown in Fig. 2b. Here variation of the edge safety factor was in the range of ( $q_a \simeq 7.5 \Rightarrow q_a \simeq 3.2$ ). As expected the number of substructures appearing within the stripe is reduced. Again the structures are correlated with  $q_a \simeq m/n$ . Unfortunately, the structure of the footprints is affected by the neo-classical tearing modes, which are triggered by the perturbation field, e.g. (2/1) tearing mode at  $q_a \approx 11/2$ . Nevertheless the dependence of the footprint topology on the resonant flux surfaces is clearly visible.

The dependence of the magnetic footprints structure on the edge safety factor has been modeled with the Atlas-code. The evolution of the footprints with changing  $q_a$  is presented in Fig. 3a. The calculation was held for the same conditions as in Fig. 2a. Calculated structure of the magnetic footprints resemble quite well measured heat flux patterns. One can identify flux

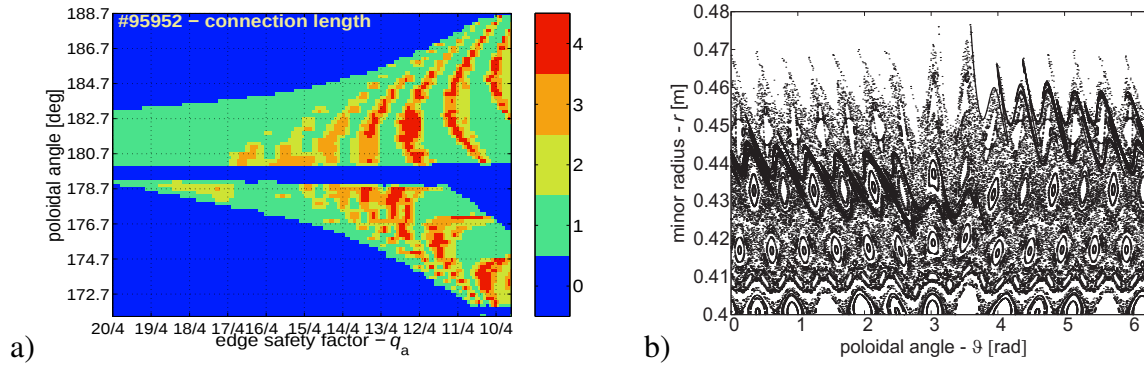


Figure 3: a) The contour plot of the field lines connection lengths calculated for the same conditions as in Fig. 2a. b) Illustration of the unstable manifolds for discharge #96411 calculated in a cylindrical approximation. The intersection of the unstable manifold with the wall is defined by the 15/4 island.

tubes intersecting the wall, which disappear at a given value of the edge safety factor. These flux tubes are formed by the field lines, which hit the wall along the fingers. As stated in [7] the unstable manifolds of the hyperbolic fixed points of the last island chain are responsible for the transport to the wall. An example of the evolution of the unstable manifold towards the wall is presented in Fig. 3b by the black curve. It is the unstable manifold of a hyperbolic fixed point with period 7, as a part of the 14 over 4 resonance. It is overlayed with the Poincaré plot presenting the topology of the magnetic field lines for discharge #95952 with  $q_a = 4.25$ . The abscissa represents the poloidal angle and the ordinate the minor radius of the TEXTOR vessel. The trajectory of the unstable manifolds proceeds from island chain to island chain, finally intersecting the wall. The place of intersection is defined by the last island chain. As the topological properties of the fingers are defined by the unstable manifolds, therefore they are so sensitive to the edge safety factor.

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