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Heat deposition patterns on the target plates of the dynamic ergodic divertor

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Abstract

The dynamic ergodic divertor (DED) produces the perturbation field, which destroys the magnetic flux surfaces and creates an open chaotic system. The plasma boundary of the TEXTOR-DED contains two different domains: an ergodic and a laminar one. In this work we study the power deposition patterns produced by the DED on the divertor target plates by means of the thermography. The observed heat flux patterns consist of stripes parallel to the DED coils, which changes with the degree of ergodization. Each strike zone splits up into two parts at higher level of ergodization. The structure of the power fluxes is defined by the topology of the magnetic field in the edge.

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1. Introduction

Sixteen perturbation coils mounted on the high-field side of the torus ergodize the magnetic field in the edge of the TEXTOR tokamak [1]. The DED can be operated with different current distribution in the coils: $m/n = 12/4$, 6/2 or 3/1, where m and n refer to the base poloidal and toroidal mode numbers respectively. A perturbation field with higher multipolarity decays faster with the distance from the coils. The 12/4 perturbation field influences the topology of the flux surfaces in the outer region only, while in the 3/1 mode almost whole plasma volume is affected. In this work we consider the 12/4 mode operational regime, which was chosen as the initial one. The magnetic perturbation field can be rotated with several frequencies: 2 Hz, 50 Hz, 1–10 kHz. The slow rotation 'smears out' the heat deposition pattern over the divertor walls, while the higher frequencies induce the toroidal and poloidal rotation of the plasma, what may improve confinement and delay disruptions [2].

Previous modeling showed (e.g. [3,4] or [5]), that the structure of the magnetic field in the edge of the TEXTOR tokamak contains both the ergodic and the laminar zones. In the ergodic region the magnetic field lines experience small deflections in front of the DED coils; the field lines remain over 'long' distances in the

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ergodic volume before they finally reach the wall. Thus, each of the field lines '*fills*' the volume of the ergodic layer, what significantly changes the plasma properties in the edge. An averaged radial heat Q and particle Γ transport is enhanced in the ergodic region; in particular electron heat transport, because electrons predominantly follow the magnetic field lines [6]. The enhanced transport leads to a flattening of the electron temperature.

In the boundary, where the near field effects are significant, the field lines are strongly deflected towards the divertor target plates. Therefore, the magnetic field lines have short wall-to-wall connection lengths. The particles following the field lines hit the wall before the field lines can reveal a chaotic behavior. There is a clear separation between the parallel and perpendicular transport. In contrast to the proper ergodic zone, the connection length of neighboring magnetic field lines have smooth and continuous properties, with some sharp boundaries. This region is called laminar zone [7] and it is restricted to a small radial extent near the ergodizing coils.

The characteristic diffusion radial length is of order of 1 cm for a 30 m long flux tubes, e.g. in the scrape-off layer. In the well developed laminar zone the radial width of the flux tubes formed by the field lines with the same connection lengths exceeds 1 cm. Thus, the heat and particle transport in the plasma edge is dominated by the laminar zone, which shows a well defined structure as compared with that of the ergodic layer.

The flux tubes intersecting the divertor target plates create the specific structure of magnetic footprints. An example of the footprint structures at a high level of ergodization is presented in Fig. 1. Different colors depict different connection lengths (with poloidal turns as units). Field lines are traced with the Atlas code [9], which is based on a mapping technique [8].

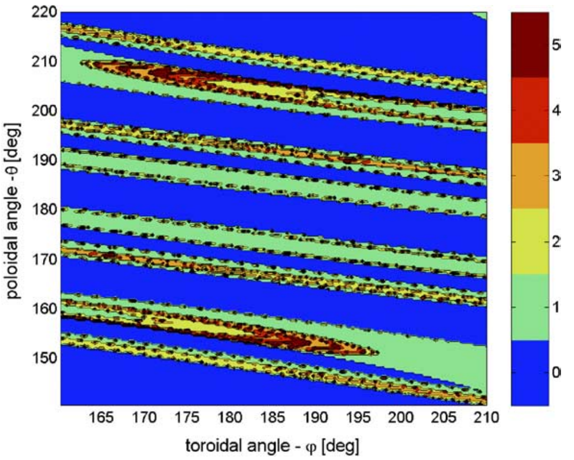

Fig. 1. The magnetic footprint structure can be presented with the footprint plot. Colors represent connection lengths of the field lines (units are poloidal turns). For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.

The magnetic footprints form the stripe-like pattern parallel to the divertor coils, which split up at the higher degree of ergodization forming the private flux zone in the middle. It was found, that at the lower level of ergodization the ergodic region is dominant, while at the higher level of ergodization the laminar zone prevails.

The level of the ergodization can be varied by many factors. The three major ones are: the plasma position (R_a), a shape of the q-profile and the Shafranov shift (expressed via poloidal beta). All these factors change the distance of the resonant flux surfaces from the DED coils. Additionally, the Shafranov shift varies the pitch angle of the field lines. The detailed discussion of the topological properties of the perturbed volume is performed in [9].

In this work we will study the heat flux patterns on the divertor target plates induced by the electrical currents flowing in the DED coils. The observation is made by a thermographic system, which contains, as a main part, a fast infrared camera SFB-125. The thermographic system is described in Section 2. In Section 3 the resolved temperature and heat flux patterns are presented. A summary is given in Section 4.

2. Thermographic setup

The main component of the setup is the infrared 14-bit camera SBF-125, which is shown in Fig. 2. The active element of the camera is the array focal plane, which

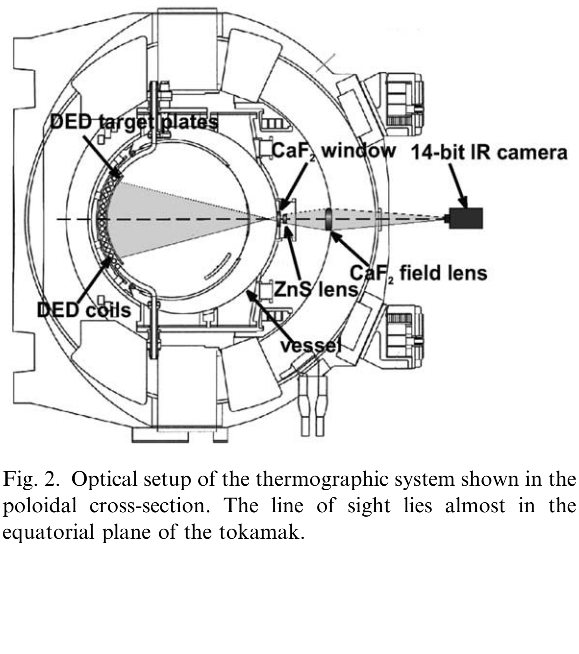

Fig. 2. Optical setup of the thermographic system shown in the poloidal cross-section. The line of sight lies almost in the equatorial plane of the tokamak.

consists of 320×256 InSb photon detectors. The camera records the light emitted by the divertor tiles in the range of 3–5 μm. The IR-induced voltage changes on the detectors are converted via a 14-bit analog-to-digital (A/D) converter and transferred to a frame-grabber of a PC via optical fibers. The system can record the full infrared images at a frequency of up to 394 Hz and a reduced size up to 13 kHz. To image the tiles onto the infrared camera array, a special optical setup was designed. The optical elements are made of CaF_2 and Cleartran™ ZnS, which assure good spatial resolution of the recorded images. The optical setup contains two lenses and a CaF_2 vacuum window mounted at the vessel wall. The size of the area seen by the camera array is about 890 mm diameter, which covers roughly five and a half rows of the divertor tiles. The size of the observed area is limited by the size of the detector (≈14 mm). The setup is optimized to reduce the errors due to aberration by the optics to a size smaller than one pixel of the camera (<30 μm). The maximum spatial resolution is about 2 mm (for surfaces normal to the line of sight).

3. Measured temperature distribution and resolved heat fluxes

3.1. The heat flux distribution over the divertor target plates

The regular patterns of heat deposition, which are formed by the laminar zone, have been identified since very first experiments with the DED (see e.g. [10]). An example of the infrared image recorded by the calibrated camera operating in the full frame mode is shown in Fig. 3. The image presents the temperature distribution over the divertor target plates. The false color scale represents the temperature in centigrade degree. The plates are visible as a rectangles; each of them is attached to the vessel by two screws. The parameters of the discharge were as follows: ($I_{plasma} = 380$ kA, $\langle n_e \rangle = 2.5 \times 10^{19}$ m^{-3}, $B_\varphi = 1.9$ T, $I_{DED} = 7$ kA, $R_0 = 1.70$ m).

The immanent features of the DED heat flux density pattern are the stripe-like structures parallel to the DED coils. One can see four pairs of strike zones formed by the incoming heat fluxes, where the half width of one of stripes is of order of 3 cm. One of the strike zones is marked with the yellow dashed line. Each pair of the 'power-stripes' contains a colder region in between. At the lower degree of ergodization these pairs merge together. The temperature distribution qualitatively resembles the footprint structure of the field lines on the divertor wall. The structure of the magnetic footprints for the same area as in Fig. 3 is presented in Fig. 1. As it can be expected from the symmetry of the magnetic footprints, the heat fluxes form pattern with the four fold symmetry.

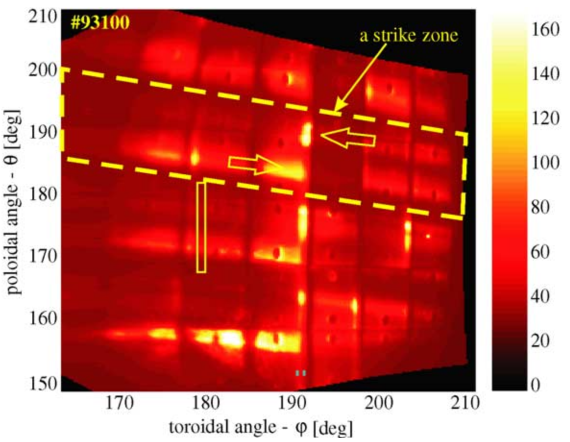

Fig. 3. The temperature distribution over the divertor target plates measured by the infrared camera, discharge #93100. Yellow dashed line marks one of the four strike zones, yellow arrows show direction of the incoming heat flux. A yellow rectangle indicates the area, where the heat flux density is evaluated. The corresponding footprint structure is presented in Fig. 1. For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.

Unfortunately, the structure of the heat flux deposition is affected by non-ideal alignment of the target plates. Protruding for 1–2 mm edges of the tiles, at $\varphi \approx 190°$ in Fig. 3, cause that some areas are shadowed from the heat flux and some of them are overexposed. Since the angles of incidence of the field lines intersecting the DED wall are very shallow (⩽1°), the heat distribution is strongly influenced. The mechanism of shadowing is visualized in Fig. 4. The incoming parallel heat flux is deposited on the protruding edge of the target plates, marked as a dark grey region in Fig. 4, therefore some other area, the light grey region in Fig. 4, does not gain all heat flux, which would be deposited there if the divertor surface would be ideal. In ideal case each of the stripes is almost the same, which is visible on the right hand side of the area highlighted with yellow dashed line. Also the general symmetry of these structures (visible in Fig. 1) is influenced by the protruding edges.

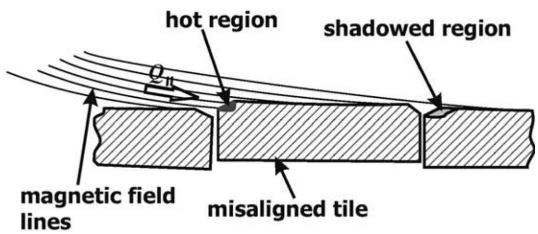

Fig. 4. Some of the heat fluxes reaching the tiles are shadowed by protruded edges of the tiles, which gain more of incoming power flux.

These feature allows to identify, that each power stripe consist of two parts, where the heat flux is incoming from opposite directions as marked with yellow arrows in Fig. 3. As already discussed in [9,11], the main channel for heat and particle flows in the laminar zone is the flux tube with a connection length equal to one poloidal turn. Its strike zones lie within the same power flux stripe.

3.2. Variation of the ergodization

The modeling shows that the structure of the power deposition pattern strongly depends on the level of ergodization. The increase of the ergodization appears as the increase of the splitting of the magnetic footprint stripe [9]. The plasma current is a key parameter to influence the topology of the ergodic and laminar zones via the q-profile. If the plasma current is higher, the ergodization of the magnetic field lines in the edge is stronger for the TEXTOR conditions.

The variation of the ergodization via the plasma current is presented in Fig. 5. The graph shows the heat flux density profile calculated using the THEODOR code [12] from the temperature evolution in the area marked with a yellow rectangle in Fig. 3. The image imperfections due to the oblique view of the camera are corrected with the LEOPOLD routines [13]. The curve with open circles is calculated for the discharge #93573 with I_p = 350 kA, the curve with closed circles for #93575 with I_p = 400 kA. In the case of lower I_p the power flux stripe has two maxima, the distance between them is 28 mm. The safety profile at the edge estimated with the DIVA equilibrium code is $q_a \approx 2.8$, which corresponds to the m/n = 11/4 resonance. In the case of I_p = 400 kA, we can clearly see the splitting of the power flux stripe ($q_a \approx 2.5$, m/n = 10/4).

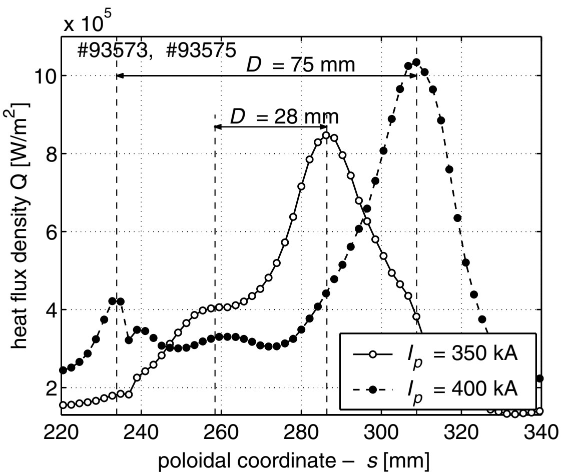

Fig. 5. (a) The structure of the heat flux pattern can be varied the plasma current: open circles – I_{plasma} = 350 kA, closed circles – I_{plasma} = 400 kA.

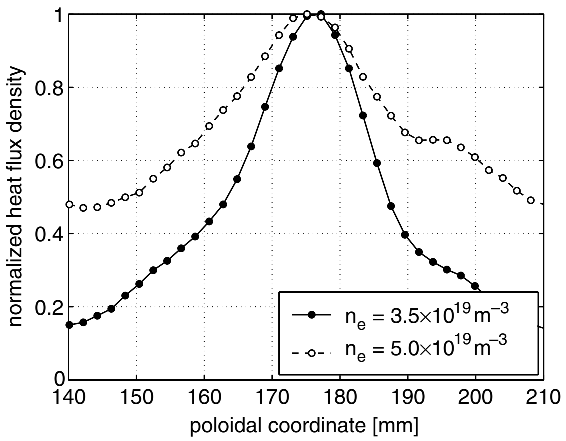

Fig. 6. The structure of the heat flux pattern for two different averaged electron densities (see legend).

3.3. Influence of the electron density on the power deposition profiles

In Fig. 6 one sees the heat flux density evaluated over the same area as in Fig. 5 for the discharges #93443 and #93448, which was obtained for the same conditions, except for $\bar{n}_e$. In the case of lower density (closed circles, $\bar{n}_e = 3.5 \times 10^{19}\ \mathrm{m}^{-3}$) one observes that the heat influx is deposited mainly within the strike zones. For higher density (open circles, $\bar{n}_e = 5 \times 10^{19}\ \mathrm{m}^{-3}$) the power flux profile becomes broader. However, the integrals along both profiles give the same power.

The power deposition pattern is determined mainly by the topology of the laminar zone. It is consistent to say, that at higher electron densities the cross-field diffusion becomes more effective and therefore, the electrons do not 'map' the structure of the laminar zone as accurate as for the lower electron densities.

4. Summary

The heat and particle exhaust during the operation of the DED is strongly influenced by the topology of the laminar zone and, in particular, magnetic footprints. The footprints form a stripe-like pattern, which is parallel to the DED coils. The structure of the footprints is sensitive to the level of the ergodization, which can be varied via several factors, e.g. q-profile, plasma position or β_{pol}. Each of the four stripes splits up at higher level of ergodization adding a private flux zone in between.

The heat deposition patterns were investigated with a fast infrared camera. It was found that the heat flux structure resembles the topology of the magnetic footprints. It is confirmed, that the structure of the incoming heat fluxes depends on the level of ergodization. The separation of the strike zones belonging to one pair varies depending on the plasma current or heating power.

The experimental results show, that at low plasma density electron heat transport better 'maps' details of the structures, while at high plasma density a transport via cross-field diffusion is more important and therefore the structures are more diffuse.

Acknowledgments

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