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Transport modelling of TEXTOR-DED laminar zone

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Abstract

In the case of a strong ergodisation of the plasma edge of TEXTOR-DED, the edge magnetic field forms an extended laminar zone, which is established by magnetic field lines with short connection lengths (open ergodic system). In the laminar zone the parallel transport can compete with the cross-field transport and the situation is similar to that in a regular divertor. For an analysis of the generic effects of the laminar zone on the plasma transport, the LUPUS code is developed taking flux tubes with short connection lengths into account. The ergodic zone with rather high connection lengths is described by enhanced perpendicular diffusion coefficients. As important results, which differ significantly from common SOL's, the expected power load and the flow pattern to the plasma facing components are presented. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Ergodic divertor; TEXTOR-DED; Plasma edge; Edge modelling

1. Introduction

The dynamic ergodic divertor (DED) is presently under construction for TEXTOR-94 [1]. The main scientific goal of the DED perturbation coil device in the static and (quasi-static) low frequency operation is the distribution of the power fluxes from the core plasma to the wall elements over a large area. In the high frequency mode (up to 10 kHz), in addition a substantial torque will be applied to the plasma edge which may induce a sheared plasma rotation and suppress turbulent cells. The rotation may also help to compress the edge plasma into the scoop of the pump limiter and thus enhance the pumping efficiency [2].

Fig. 1 shows the schematic setup of the perturbation coils for the DED. Sixteen perturbation coils are installed inside the vessel at the high field side. Each of the 16 coils is aligned to the field lines of the $q = 3$ magnetic surface ($\beta_{\mathrm{pol}} = 1$) for one toroidal turn. The entrance and the exit locations of each coil are nearly at the same toroidal angle. The coils can either be supplied by DC or AC up to 10 kHz. The phasing between the currents in the coils is 90° forming a base $m = 12$, $n = 4$ mode. The maximum perturbation current for each coil amounts to 15 kA in the static mode and 7.5 kA in the high frequency mode. The coils are protected by graphite tiles facing the plasma and forming the divertor target plates.

Experimental results for the TORE-SUPRA ergodic divertor (ED) [3–5] have shown, that the local heat and particle fluxes are determined both by the near field of the coil device and the ergodic layer. Numerical studies on the perturbation field generated by the DED coil device confirmed these results for TEXTOR-DED [6]. The slightly disturbed inner zone of confinement is surrounded by the ergodic zone which itself is surrounded by the so-called laminar zone. This laminar zone is characterised by relatively short connection lengths. Different modelling concepts are developed to calculate the plasma properties and power fluxes for (partly ergodic) 3D magnetic field structures [7–10]. For TORE-SUPRA ED the MASTOC model has been developed for the laminar zone calculating the power deposition via the balance of the radial field line penetration into the plasma and the connection length of the field lines [11].

In this article a computational model of the plasma edge structure of the static DED-operation is presented. At this state of understanding of an ergodic boundary

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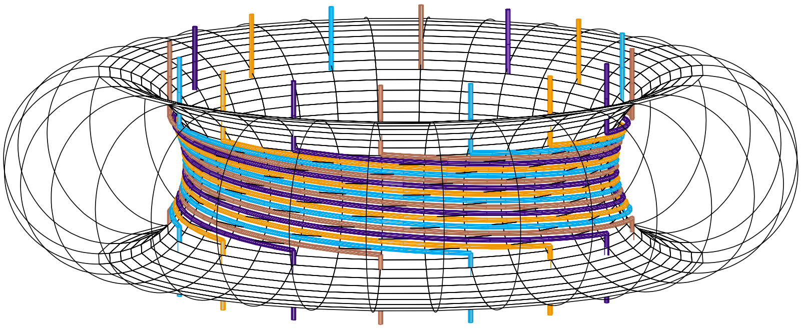

Fig. 1. Sketch of the DED coils: 16 perturbation coils located on the high field side of the torus follow the field lines of the $q = 3$ magnetic surface for one toroidal turn.

layer, the aim is not to develop a sophisticated edge code but rather to obtain a code which describes important generic properties of the edge-laminar zone of an ergodized plasma. Despite the rather complex ergodic field line topology, the laminar zone is in some sense equivalent to the conventional scrape-off-layer (SOL), so that similar techniques for the modelling can be applied. However, magnetic field lines with different connection lengths and radial deflections have to be included. In this article, the connection lengths describe the distance along the magnetic field from a target to a target (in meter). The targets are the divertor target plates or the first wall. Moreover, in some cases the connection length is given not in meter but corresponding to poloidal turns. Neglecting the slight variation of the connection lengths with the radius, one poloidal turn corresponds to a distance of ≈33 m for TEXTOR-DED.

2. The edge field line topology

The key for developing an edge transport model of a strongly ergodized plasma are considerations on the topology and structure of the magnetic field lines. In a fully ergodized area, a magnetic field line connects any point there with any arbitrary starting point. The connection length of a field line with the wall is in general a complicated – and practically unpredictable – function of the starting point. Indeed, the connection length has fractal properties such that it can be strongly different for neighbouring starting points. Typical connection lengths – used for determining the local field line diffusion coefficient – are corresponding to hundreds up to thousands of poloidal turns around the torus.

If, however, only field lines with short connection lengths are considered, the picture becomes quite different. Now the areas of constant connection lengths (corresponding to 1, 2, 3 poloidal turns) are no longer fractal but are continuous and of considerable size. This is illustrated in Fig. 2 in form of the so-called laminar plot. The laminar plot has some similarities with a Poincaré plot representing a 3D structure in a 2D-plane. Like there, magnetic field lines are followed until they hit the wall. As a reference plane for the laminar plot we chose a plane of maximum symmetry, namely a plane in the outer equatorial mid-plane opposite to the DED coils. The co-ordinates are the minor radius and toroidal angle. Because of the fourfold symmetry of the DED coils and applied perturbation currents, a span of the toroidal angle from 0° to 90° is adequate. The parameters used for the magnetic field calculations are: $I_p = 550$ kA, $B_{tor} = 2.25$ T, $\beta_{pol} = 0$. The resonant $q = 3$ magnetic surface is determined by a minor radius of $r_{q=3} = 48.2$ cm for a major radius of $R_{q=3} = 174.6$ cm.

Fig. 2 shows the connection length of the magnetic field lines in colour representation. Field lines corresponding to a connection length of one poloidal turn are plotted in blue; those corresponding to two poloidal turns in green, in yellow those corresponding to three poloidal turns, etc. The black area belongs to 'long' magnetic field lines, i.e., those of the proper ergodic zone and the closed field lines from magnetic islands embedded in the ergodic region. The largest area is the blue one. Here, a part of the field lines ($r \geqslant 48.3$ cm) is already intersected by the wall before they reach the divertor target plates. This 'blue' area corresponds to the conventional SOL of a poloidal divertor or limiter. The otherwise coloured areas are generic for edge ergodisation and have no counterpart in the conventional devices. The second largest area is the green one corresponding to two poloidal turns; in the selected reference frame, one finds two image-symmetric green areas. These two areas are connected with each other along the magnetic field lines. The areas with higher connection length are still visible, but become progressively smaller and less important for the modelling. As long as the connection length of these areas are in the order of the Kolmogorov length (for definition see [1]), the shape of the areas and the association of neighbouring field lines are kept. The magnetic field lines from the ergodic region progress towards the wall only through the small channel between the blue and green areas which we have

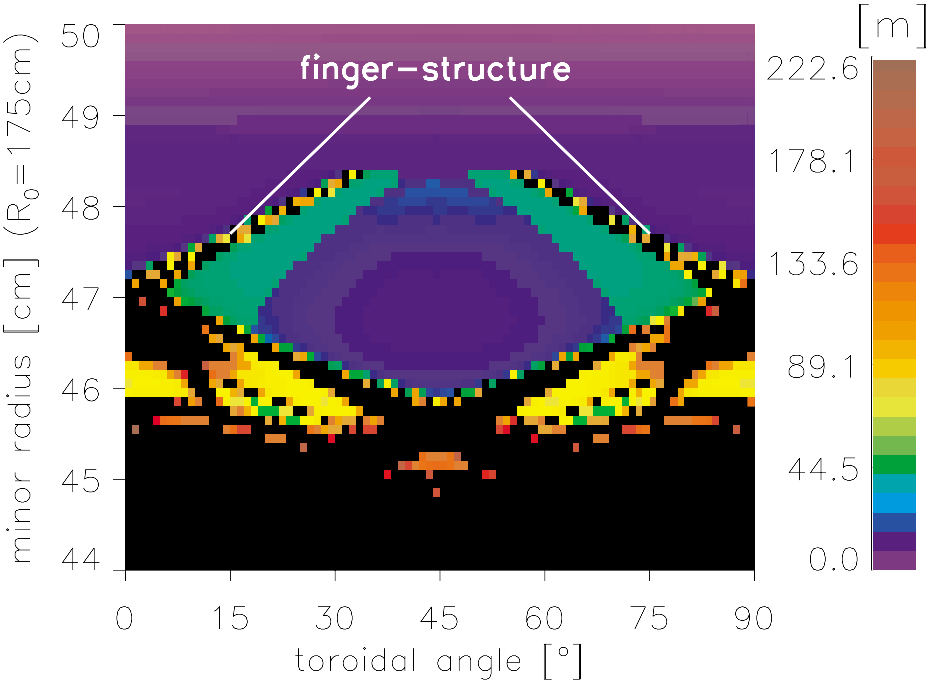

Fig. 2. The laminar plot characterises the topology of the magnetic field in the poloidal reference sector by colouring the plane corresponding to the connection lengths of the field lines.

called fingers. In this example, the radial width of the 'fingers' is about 1–2 mm.

It is the conventional assumption that in the SOL particles (and energy) diffuse over the width of an e-folding length, i.e., typically over 1–2 cm for a connection length of some 10 m. This diffusion width is considerably larger than the width of the 'fingers'. Therefore, we assume that particles and power are not guided along the magnetic field lines and are channelled though the 'finger' region towards the divertor target plates. Our picture is instead that the – anomalous – diffusion processes are so dominant that particles and power penetrate the edge of the laminar zone easily and flow convectively along the open field lines of the laminar zone. This picture is supported by the fact that the diffusion in the proper ergodic zone ($D_{\mathrm{erg}} < 0.5\ \mathrm{m}^2/\mathrm{s}$ for 50 eV deuterium ions) practically never exceeds the conventional anomalous transport ($D_\perp \approx 0.5\ \mathrm{m}^2/\mathrm{s}$ for TEXTOR-94); if the maximum field line diffusion coefficient at the edge increases, the laminar zone opens up automatically and changes the transport characteristics from diffusive to convective at the very edge [12].

3. The modelling

The modelling is oriented on simple SOL codes and based on recent numerical transport studies for TEXTOR-DED laminar zone [13,14]. It is assumed that power and particles diffuse perpendicular to the magnetic field lines and stream convectively along them. For simplifying the situation, we take as laminar zone only those areas with a connection length corresponding to one or two poloidal turns into account. The rest is counted as ergodic (this part can easily be refined). The complications with respect to the conventional SOL modelling are twofold:

1. In a conventional SOL, the transport results only in radial variation of the plasma parameters while here they are expected to vary in the radial and poloidal directions.
2. In the conventional SOL one has only one class of connection length; here one has at least those corresponding to one or two poloidal turns.

In addition those field lines progressing poloidally twice around the torus do not remain on the same radius; in front of the DED coils the field lines are deflected such that they will leave their original radius after the passage in front of the perturbation coils. This radial deflection can amount up to 2 cm for the given example. The different radial location of the field lines generates exchange fluxes of particles and heat along the field lines. These exchange fluxes are a new generic feature of the laminar zone leading to an enhanced non-diffusive transport.

A method is developed to generate a 3D grid which is oriented along the magnetic field lines in one dimension (for conductive and convective transport) and perpendicular in the other two (poloidal and radial for the diffusive transport). Therefore, the 3D grid consists of a highly irregular 2D grid perpendicular to the magnetic field and a set of 1D grids each following a magnetic field line. In the laminar region the parallel and perpendicular transport equations are taken into account while in the ergodic region the parallel transport is described by enhanced perpendicular transport coefficients neglecting any plasma flow along the field lines. For the perpendicular transport on the 2D grid an upgraded version of commercial finite element code is used [15] while for the the parallel transport a finite volume code (DR1) is developed. The boundary condition are stated for the parallel transport and the perpendicular transport separately. For the parallel transport along the field lines the plasma flow is assumed to reach sound velocity at the targets (Bohm criterion). The sheath transmission factor for energy amounts to about 7.5. The boundary conditions for the perpendicular are stated on two arcs. The inner arc describes the transitions of the ergodic region to the confinement region (KAM-surface). Here, the plasma density is chosen to be 1×10^{19} m^{-3} and the fluid temperature is 50 eV. The outer arc describes the divertor target plates and the first wall enveloping the plasma volume. Here, the perpendicular flows of density and temperature fulfilling a radial decay are chosen as the boundary condition. It should be noted, that for the geometrical complicated transition between the ergodic and the laminar region no boundary conditions have to be stated and therefore no boundary has to be defined. The transport coefficients and the assumption about the parallel transport switch depending on whether the area is assumed to be laminar or ergodic. The perpendicular transport and the parallel one are treated consecutively for finite time steps. The procedure is repeated until convergence. For the plasma single fluid particle, momentum and energy conservation equations are applied.

$$\nabla \cdot (n\vec{v}_{\parallel} - D_{\perp}\nabla_{\perp}n) = 0$$

$$\nabla_{\parallel}(m_i n\vec{v}_{\parallel}^2 + 2nT) = 0$$

$$\nabla \cdot (-\kappa_{\parallel}\nabla_{\parallel}T - \chi_{\perp}n\nabla_{\perp}T - 5TD_{\perp}\nabla_{\perp}n) = 0$$

For the laminar region $D_{\perp} = 0.5$ m^2/s and $\chi_{\perp} = 1.5$ m^2/s are chosen while in the ergodic region $D_{\perp} = 1.0$ m^2/s and $\chi_{\perp} = 3.0$ m^2/s are used.

Two interesting results of the so-called LUPUS code are shown in Figs. 3 and 4. Fig. 3 gives the power flux density distribution on the divertor target plates in front of the DED coils. It is obvious that the heating pattern follows closely the helical direction of the coils. Because of the chosen mode and coil number one finds four pairs of helical stripes. Otherwise the stripe has many similarities to the footprints of poloidal divertors. The whole structure can be rotated toroidally leading to a significant reduction of the average heating of the target plate. One also finds a moderate helical variation of the stripe. This variation is (a) due to the variation of the angle of incidence of the magnetic field lines with respect to the graphite tiles and (b) due to a variation of the radial deflection depth in front of the DED coils. Fig. 4 shows the predicted flow pattern in a poloidal cross-section. Blue colour means streaming clockwise around the torus and red in the opposite direction. One finds that a single

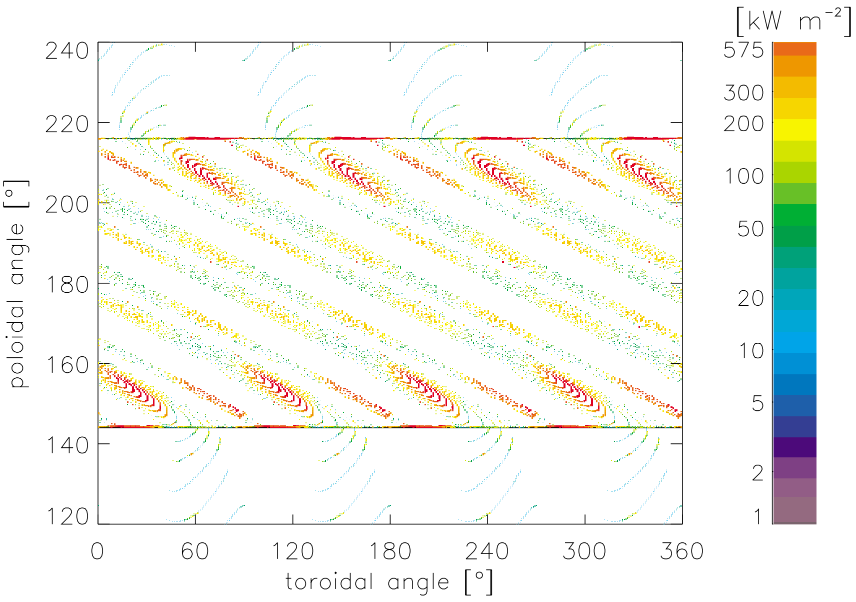

Fig. 3. The calculated power load on the divertor target plates shows a strong variation along the helical direction and normal to it.

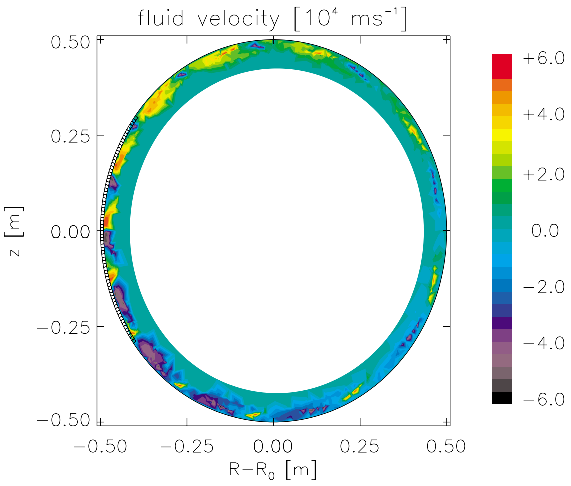

Fig. 4. Flux tubes of different connection lengths lead to a complicated pattern of the plasma flow to the plasma facing components.

stagnation point of the flow cannot really be defined. Even at the low field side, i.e., the side opposite of the target plate, one has positive and negative flows. These flows stem from areas of connection lengths corresponding to two poloidal turns. Here, the flows in these flux tubes have their stagnation point in front of the DED coils where the flux tube with a connection length corresponding to one poloidal turn assumes already nearly sound speed. Although no experimental data for TEXTOR-DED are yet available, experimental results for Tore Supra ED coincide in principal with these basic modelling results [16,17].

4. Conclusions

A detailed topological analysis of the edge structure of the ergodic zone manifests the importance of the laminar zone which can be regarded as a generalisation of the conventional SOL. Due to the quick intersection of the field lines with the walls, a simple ordering of continuous areas of reasonable size can be accomplished. This ordering is the basis for the application of reasonably simple SOL-MHD codes. The calculations have been performed with the combined 3D finite element/finite volume code LUPUS. Up to now, only the most important generic properties of the transport have been worked out.

The structure of the code is flexible enough for various improvements. Obvious improvements are the inclusion of more sophisticated transport codes than just the simple, single fluid code and an extension to flux tubes with even higher connection lengths. Here, the work is in progress. In a later phase of the modelling, also the recycling and ionisation in the boundary layer should be treated. However, before we take into account any higher order effects such as viscous or thermal forces, the role of the electric field and resulting ExB drifts in the laminar zone should be understood. Like in the conventional SOL, the connection of the plasma with the wall (together with a sheath voltage drop of 3 kT) will create an electric field both in the laminar zone but also in the ergodic zone. It may become necessary to wait for experimental results before these effects can be treated accurately in a model.

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