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Physics Aspects of the Dynamic Ergodic Divertor (DED)

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Abstract

The Dynamic Ergodic Divertor (DED) is presently being installed in the TEXTOR tokamak. It consists of 16 helical coils wound helically around the torus at the high field side (HFS). The perturbation currents in these coils generate predominantly islands of m=10...14 and n=4 leading both to rather closed ergodic and to open laminar structures. In the "laminar mode", the DED forms a helical divertor. 3D modelling (2D finite element/1 D finite volume) of the plasma transport in the laminar zone has started. By the "dynamic" operation of the DED, the heat is deposited to a wide area and forces are transferred from the currents in the DED-coils to the plasma edge.

Keywords:
ergodization, 3D modelling, force transfer

1. Introduction

The formation of an ergodic layer can be an interesting means of destroying the good confinement properties of closed flux surfaces at special locations. Such a location of interest is the boundary of the plasma: The power - with the exception of the radiated fraction - leaves the plasma conductively or convectively and passes through a relatively thin boundary layer. In order to spread the heat to a larger area, the Dynamic Ergodic Divertor (DED) [1] has been developed and is presently being installed in the TEXTOR tokamak. The DED will create an ergodic boundary layer of the plasma and thus it is expected to allow for wider power deposition pattern, for an improved screening of impurities, and for an enhanced particle removal by the pump limiter ALT-II. The expression "dynamic" refers to a rotating perturbation magnetic field imposed by the DED coils. For the rotation, different frequencies are foreseen: At few Hertz, the heating pattern of the divertor strike zone is smeared out over the large area of the divertor target plate; at frequencies up to 10 kHz, locked modes can be unlocked, or a differential rotation in the plasma edge can be imposed with hopefully favourable effects on the confinement. It is estimated that the rotating DED current generates a torque at the plasma edge.

2. The Experimental Set-Up

The Dynamic Ergodic Divertor (DED) is shown in Fig. 1. The main component of the DED is a set of magnetic perturbation coils whose purpose is to ergodize the magnetic field structure in the plasma edge region; these coils are located inside the vacuum vessel at the high field side of the torus at a minor radius of r_{coil} = 53.25 cm. The set consists of 16 individual coils (4 quadruples) plus two compensation coils. The individual perturbation coils follow the direction of the equilibrium magnetic field of the plasma edge helically once around the torus. The maximum coil currents

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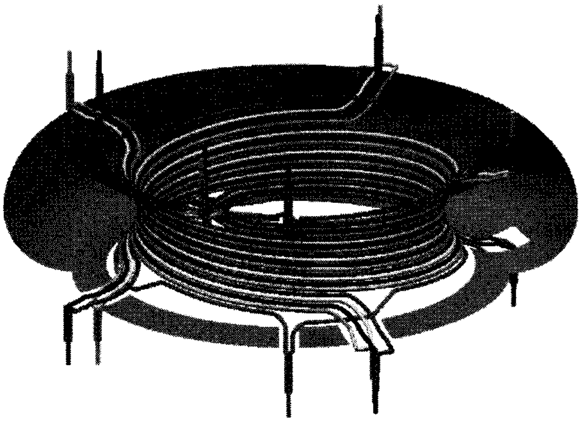

Fig. 1 Schematic view of the DED-coils.

amounts to 15 kA.

The main perturbation modes (m = 10...14, n = 4) create chains of magnetic islands destroying the resonant magnetic surfaces $q = m/n$. Due to a strong radial decay of the modes they do not disturb the plasma core. The DED has the unique feature that the perturbation field is not static as in most other devices but that it has the option of rotation. To our knowledge only the tokamak CSTN [2] at Nagoya University has similar features and - at low perturbation current levels - also the TEXT [3] tokamak. The DED can be operated DC, around 50 Hz or at 7 frequencies in the band from 1 kHz to 10 kHz.

3. The Ergodic Layer

The perturbation coils impose structures with different properties in the plasma boundary: The interior closed flux surfaces, $q(r) \le 2$, remain nearly undisturbed and form for at least the well structured Kolmogorov, Arnold, Mozer (KAM)-surfaces [4]. Further towards the boundary, islands develop and start to grow; finally, different islands overlap and form an ergodic sea [5-7] such that the magnetic surfaces are destroyed. The very outermost magnetic field lines intersect the divertor target plate. These field lines form the so called laminar zone [8]; here the transport changes character from diffusive to convective with plasma streaming to the plasma facing components as in the conventional scrape-off layer.

Field line tracing and field line mapping [9,10] are basic techniques for investigating the ergodic structure. These techniques provide a picture of the areas with intact magnetic surfaces, of island structures and of ergodized regions. The resonant radius can be adjusted via the plasma current; in this way the ergodic zone can be shifted radially in the range $0.9 \le r/a \le 1$ keeping the Chirikov parameter above one. Individual adjustment of the coil currents allows the superposition [11] of different base modes. In order to minimise the interaction with the core plasma, high m/n (e.g. m/n = 12/4) are preferred; for the given coil arrangement, Fourier mode numbers $m \le 8$ can be neglected. This choice creates many small islands instead of a few islands with large poloidal extent.

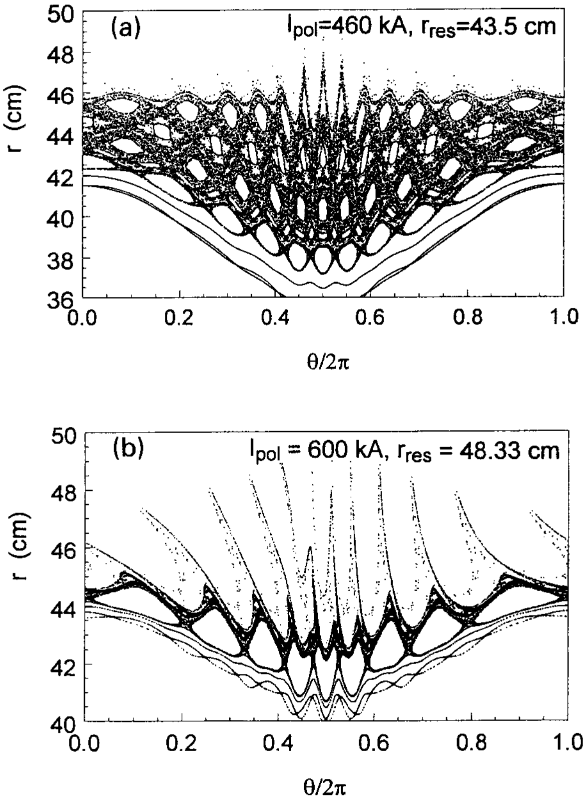

Fig. 2 Variation of the ergodization pattern with increasing plasma current (at full perturbation current) (a) I_p = 460 kA, (b) I_p = 600 kA. Due to the shift of the resonant q-surfaces towards the DED-coils, the edge Chirikov parameter increases leading to an opening of the laminar zone (field lines with short connection length).

Figures 2(a) and (b) show Poincaré plots –obtained by field line mapping - for "low" and "high" plasma currents (a: 460 kA, b: 600 kA) at the full perturbation current. The starting points were taken at the ergodic zone (dark regions). These field lines intersect the wall elements along the elongated areas (fingers); they do not enter the white area located between the fingers which correspond to the field lines of short connection length.

With increasing plasma current, the resonant surfaces ($2.25 \leq q \leq 3.75$) move towards the outside, closer to the DED coils. Highest ergodization levels with Chirikov parameters up to 6 are expected for plasma currents around 600 kA. The results of the field line mapping seem at a first glance to be in conflict with this expectation: the radially widest ergodic zone is found at the relatively low plasma current of 460 kA while at 600 kA the properly ergodic zone is only a small band at a radius at about $r = 44$ cm. The outer zone of Fig. 2(b) is nearly empty of Poincaré intersection points and appears white. The absence of the intersection points is a consequence of the fact that the field line tracing is stopped after an intersection with a wall element. We have stopped the tracing because the field lines represent also particles which would be neutralised and can leave their field line. The "white" area contains the field lines with a short connection length, i.e. a few poloidal turns. This area of short connection length is called the "laminar zone" [12,13] and is discussed in the next section. Because of its short connection lengths, the laminar zone is related to the scrape-off layer properties. The attempt to increase the ergodic zone by increasing the resonant perturbation at the edge evidently leads more to an increase of the laminar layer than to a widening of the ergodic zone.

4. Modelling of the Transport in the Laminar Zone

Properties of the laminar zone are best represented in a poloidal cut of the plasma edge at the low field side (LFS) where areas are ordered according to the connection lengths of the magnetic field lines between two intersections with the walls. The poloidal width of the laminar plot corresponds to the $m = 12$ mode, the dominant mode of the DED. By this choice all field lines intersect for at least once the reference frame; in addition this area is opposite of the perturbation area and it contains the stagnation areas for those field lines which have an odd number of poloidal turns connecting the walls.

For the case of a strong laminar zone, the areas shortest connection length (one poloidal turn) is relatively large, followed by successively smaller areas of two and three poloidal turn areas. The structure of the laminar zone are simple as compared to the one of the ergodic zone, which has fractal properties. The channel of field lines connecting the inner ergodic zone with the wall is narrow (called fingers), for some conditions even smaller than the Larmor radius. In our picture, the area with field lines of short connection length region will be most responsible for the final step of the transport of energy and particles to the wall. In this sense the laminar zone is similar to the scrape-off layer of a divertor tokamak.

The topology of the flux tube is now three dimensional. Figure 3 shows one of the examples for 2 poloidal turn region, where the area is mapped in counter-clockwise direction and is projected onto the same poloidal plane after each 90 degrees mapping along torus. Starting from the stagnation point at HFS (0), the flux tube is traced following the consecutive number shown in the figure and after (10) it reaches the wall. The clockwise mapping creates the same but symmetric pattern around the stagnation point, which are not plotted in the figure. The flux tube experiences a large deformation especially in front of the DED coils, i.e., HFS, due to the strong perturbation there. The area is stretched, bended and compressed, it can be attributed to one of chaotic properties.

As in a normal SOL model, the transport is assumed to be convective along the field lines and diffusive perpendicularly. The numerical scheme is a splitting method with a finite element method (FEM) for a cross-field transport, where we use the FEM solver PDE2D [14], and with a finite difference method for parallel one. Based on the argument above, we take up the one and two poloidal turn regions, and others are considered as an ergodic region where the physics are reflected in the increased transport coefficients. Simple

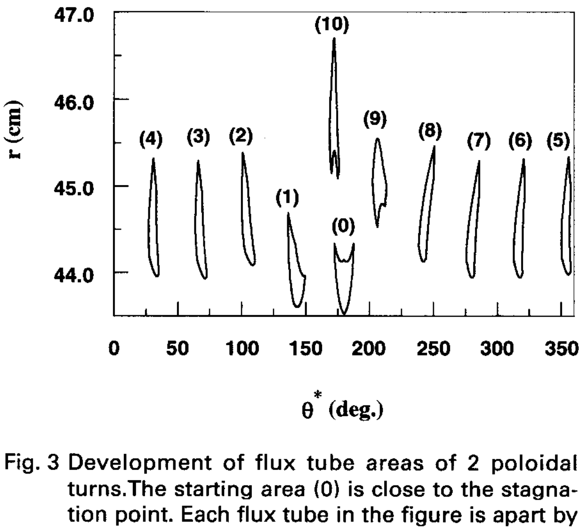

Fig. 3 Development of flux tube areas of 2 poloidal turns.The starting area (0) is close to the stagnation point. Each flux tube in the figure is apart by 90 degrees of toroidal angle from each other, those are projected onto the same poloidal plane.

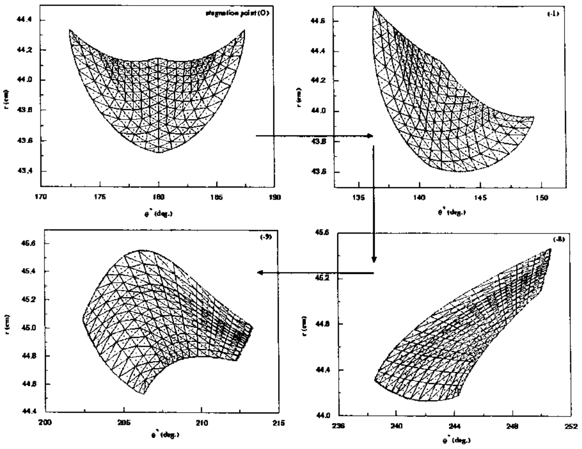

Fig. 4 3D grid for 2 poloidal turn flux tube. The grid was created first at the stagnation point (0), which was mapped in both clock and counter clockwise direction to obtain the grid over the whole length of flux tube. The figure shows only the counter clockwise mapping. The dots inside the triangles represent the centre of gravity.

estimates indicate that the transport in the laminar zone is predominantly convective while in the other mainly diffusive. The flux tubes of the laminar zone are triangulated first at the symmetric point (stagnation point) and those are mapped along the field lines to obtain the 3D grid over the whole length of flux tube. Figure 4 shows the grid for 2 turn region. The grid is optimised to fit the deformation by carefully studying the direction of stretching, bending and compression of the flux tube. The scheme was tested with a simple heat conduction problem in cylindrical geometry, where we obtained a good agreement with analytic solution. A straight SOL model is now under processing. After carefully checking the results, the calculation will be extended to the real DED geometry.

5. Dynamic Aspects

The dynamic option of the DED has been introduced in order to distribute the heat flow to the divertor target plate to a large area. During the static DED operation, the heat flux is guided towards the divertor target plate; the divertor strike points follow helically the DED coils. By the rotation of the perturbation field, the heat load is distributed over the whole target area.

The high frequency aspect of the DED-field has been analysed in cylindrical approximation [15]. It has been shown that the "low frequency" (relative to Ω_i) electromagnetic wave of the DED effectively propagates in the area between coils and resonance layer as the compressional Alfvén wave (fast wave) [16]. At the resonance layer of the plasma different approximations is described either by a resistive annulus or by tearing modes. The interaction of the external rotating field with the current driven in the shielding layer results in the transfer of angular momentum between DED-coil and plasma [15]. The maximum poloidal torque applied to the plasma amounts to about 100 Nm; this maximum occurs at a frequency which seems to depend mainly on the width of the current layer. In detail it depends on the assumed plasma temperature, on the applied frequency and on the assumed island or ergodization width. The toroidal projection of the applied force has about the same value as the one imposed by tangential NBI. Due to the combined action of the DED and NBI torques, a differential rotation may be induced. It may be speculated whether the differential rotation suppresses convective cells and thus improves the confinement.

6. Summary

Considerable progress has been made in recent years in the understanding of the static ergodic divertor [12], both theoretically and experimentally. It has been understood that the ergodic zone with very long magnetic field lines – which show (sub-) diffusive properties in a finite volume – and the laminar zone with open field lines are important, and that both regions have different and partially complementary properties. For analysing the ergodic zone and the transport in that region, powerful mapping methods have been developed.

The understanding of a *rotating* perturbation magnetic field on the other hand is very new ground and this contribution is one of the first steps into the field. A first basic question concerns the physics of the reconnection of the magnetic field in an ergodized layer and what assumption to make about the thickness of the induced shielding current layer there. An earlier model of the shielding current is extended and new results are presented for the torque exerted by the external field on the plasma.

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