PHYSICS OF THE DYNAMIC ERGODIC DIVERTOR

M.W. Jakubowski[†]*, K.H. Finken, S.S. Abdullaev, M. Kobayashi, M. Lehnen, R. Wolf*

Institut für Plasmaphysik, Forschungszentrum Jülich GmbH,
Association EUROATOM–KFA, Trilateral Euregio Cluster, D-52425 Jülich Germany
[†] ***Also: Institute of Physics, University of Opole, 45 –052 Opole, Poland***

The Dynamic Ergodic Divertor (DED) of TEXTOR is presently being installed. It consists of sixteen helically wound coils occupying about 30% of the wall at the HFS. The coils follow field lines on a "pre-selected" magnetic surface and are fed individually outside the vessel. A perturbation field is created by the electrical currents in the perturbation coils with Fourier components resonant to the magnetic surfaces. The stochastic boundary layer is generated in the outermost region of the plasma, which due to long and short connection lengths can be divided into ergodic and laminar regions. Field line tracing and mapping techniques were used to analyse properties of the TEXTOR-DED plasma boundary. The DED will operate with several frequencies (DC or AC up to 10 kHz). In the "dynamic" operation the convective heat flux is deposited to a large plasma-facing surface and forces are transferred to the plasma edge, what can introduce a differential rotation of the plasma.

PACS: 52.55Fa

INTRODUCTION

The Dynamic Ergodic Divertor was developed for spreading a convective heat flux over a larger plasma-facing surface[1]. An ergodicity of the magnetic field is created by the resonant components of the perturbation magnetic field originating from the currents flowing in the DED coils. For the low perturbation current amplitude, magnetic islands centred on the resonant magnetic surfaces are created. With increasing current, the islands start to overlap destroying magnetic flux surfaces. This creates a specific topology of the magnetic field, where the field lines are not restricted to the flux surfaces, but "diffuse" over the whole ergodic region. The term "ergodic" means that the field line will pass infinitesimally close to any pre-selected point of the available space. The magnetic field in the edge is an open system; field lines intersect the wall. A distance between two intersections is called connection length. If the connection length is large as compared to the Kolmogorov length the corresponding field lines form a proper ergodic zone; if it is smaller or of the order of the Kolmogorov length, the field lines establish the laminar zone. These terms will be explained in the following sections

The magnetic perturbation field can be rotated with different frequencies (up to 10 kHz). Applied the magnetic field should:

a)Prevent the divertor plates from the overheating and excessive erosion;
b)Decrease significantly an amount of impurities entering the plasma core;
c) Create a plasma rotation (in the high frequency operation), what may improve a plasma confinement and delay disruptions.

In the following sections the DED arrangement is described and a short introduction to the Hamiltonian formalism for the calculations of the magnetic field structure is provided. A discussion of this structure and of the dynamic aspects is given.

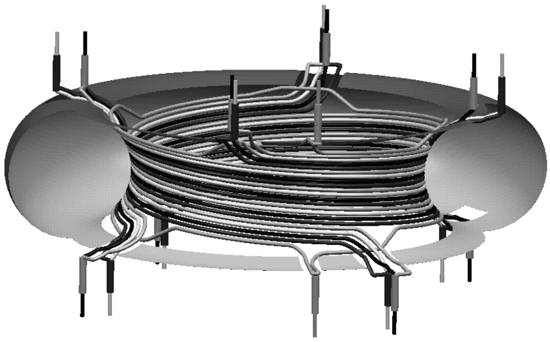

Fig. 1. Sketch of the DED coils arrangement.

THE EXPERIMENTAL SET-UP

The DED (as shown on a figure 1) consists of four quadruples of coils. Each coil goes helically once around the torus following field lines on a $q \approx 3$ surface. Every coil is supplied individually from the outside of the vessel by the 4-phase, either DC or AC (50 Hz, 1 – 10 kHz) with the current amplitude up to 15 kA. The main perturbation modes (m = 10,..,14 poloidal mode numbers, n = 4 toroidal mode number) are centred at the respective magnetic flux surface with q = 12/4. The 12/4 mode was chosen as a standard operational mode due to technical constrains (such as current density, skin effect or heat capacity) and physical requirements. One of the most important physical requirement is not to disturb a q = 2 surface (this could lead to interactions with intrinsic MHD modes and affects the plasma stability). The perturbation field for the 12/4 mode scales like $\delta B_r \propto \left(\frac{r}{r_{coil}}\right)^{m_{eff}}$, where $m_{eff} \approx 20$. It decays very rapidly with distance from the coils. The 4-phase current can be operated with several frequencies : DC, 50 Hz and at seven frequencies in the band 1 kHz — 10 kHz). These frequencies correspond to the rotating perturbation field, where the phase velocity of the propagating field projected onto a poloidal plane equals 12 m/s, 240 m/s and 2400 m/s respectively. The flexibility of the power supply system allows to connect coils in several ways creating $m = 6$, $n = 2$ and $m = 3$, $n = 1$ modes. There is also a possibility to mix the 12/4 mode with the 6/2 mode.

HAMILTONIAN FORMALISM FOR FIELD LINE TRACING

The Hamilton formalism is used to investigate the magnetic field of tokamaks and stellarators. For the destroyed magnetic flux surfaces, as it is the case for the TEXTOR-DED, the perturbation theory can be used. The field line equations can be written in the toroidal coordinates system as:

$$\frac{1}{R}\frac{dZ}{d\varphi} = \frac{B_Z}{B_\varphi}, \quad \frac{1}{R}\frac{dR}{d\varphi} = \frac{B_R}{B_\varphi}$$

By replacing the time by the toroidal direction φ, one can introduce the Hamiltonian-Jacobi equations. Supposing that

$$B_\varphi = B_0 R_0 / R \Rightarrow A_Z = -B_0 R_0 \ln R$$

and introducing new variables:

$$z = Z/R_0,\ x = (R - R_0)/R_0,\ p_z = \ln(1 + x)$$

one obtains:

$$\frac{dz}{d\varphi} = \frac{\partial H}{\partial p_z}, \quad \frac{dp_z}{d\varphi} = -\frac{\partial H}{\partial z}$$

where $H = RA_\varphi / B_0^2 R_0^2$, R_0 is the major radius of the tokamak and B_0 is the magnetic field at R_0. One can introduce the perturbation field originating from the DED coils by dividing the Hamiltonian into two parts:

$$H = H_0 + \varepsilon H_1$$

where H_0 is an unperturbed part and

$$\varepsilon H_1 = \varepsilon \sum_{m=-\infty}^{\infty} b_{mn} \cos(m\theta - n\varphi + \Omega t)$$

is a perturbed part written in the form of a Fourier series (φ, θ are toroidal and poloidal angles respectively).[2] If the spatial Fourier spectrum has more than one frequency, island chains are created. The islands are created at the $q(r_{mn}) = m/n$ flux surfaces by the perturbation field which has a spatial Fourier component b_{mn} at r_{mn}. A standard parameter to describe the degree of the ergodization is the Chirikov parameter

$$\sigma(r_{m,n}) = \frac{\Delta_{m+1,n} + \Delta_{m,n}}{2\left|r_{m+1,n} - r_{m,n}\right|}$$

$$= \frac{8r(b_{m+1,n} + b_{m,n})}{m\left|L_{sh}\right|B_t}\left(\frac{mqR}{r}\right)^2$$

It is the ratio between the islands width and the distance between island chains ($\Delta_{m,n}$ is the island width at the radius $r_{m,n}$, L_{sh} – shear characteristic length) A region of the plasma is ergodic if $\sigma \geq 1$, what simply means that islands from different island chains are overlapping. The Kolmogorov length is related to the Chirikov parameter.

$$L_K = 2\pi\, qR_0 \cdot \sigma^{-4/3}$$

It simply characterises the distance from where on initially neighbouring field lines starts to separate exponentially.

STRUCTURE OF THE MAGNETIC FIELD IN THE PLASMA BOUNDARY

For the considerations of chaotic systems so called Poincaré plots are used, which allow a two dimensional presentation of the magnetic field structure. It is created by marking intersections of field lines with a chosen poloidal plane of the torus. One example for the superposition of the TEXTOR equilibrium field and the perturbation field going from the DED is shown in Fig. 2. The figure shows an outermost region of the poloidal plane, which is bent to a rectangular shape. The low field side is at the left and right side of the graph, high field side in the centre of the picture. The DED coils and target plates are presented as a rectangle at the top of the figure. Presented an example is the case of a strong ergodization of the edge magnetic field. The island chains are indicated by the corresponding mode numbers. One can see typical features of the magnetic field structure. The inner zone is the confinement zone with non-perturbed magnetic flux surfaces and some well separated island chains. The flux

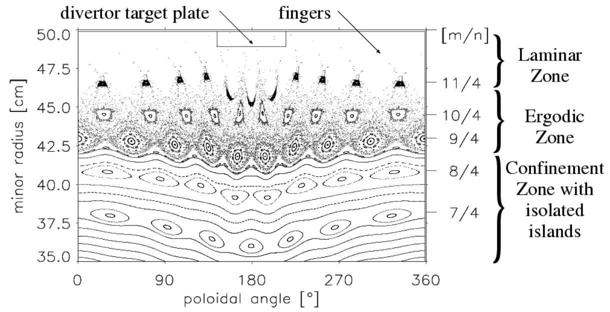

Fig. 2. Poincaré plot for the magnetic field lines in the edge at the full perturbation current

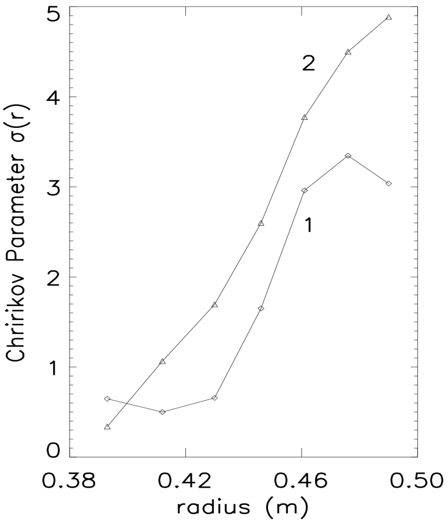

Fig. 3. The Chirikov parameter versus a plasma radius for β_{pol} = 0.0 and 1 – r_{res} = 0.43 m, 2 – r_{res} = 0.46 m

surface and island chains are bent due to the Shafranov shift. The requirement of the Chirikov parameter less than one for the $m/n = 8/4$ flux surface is fulfilled (see Fig. 3)

The ergodic region

For the second case in the Fig. 3 the region 42 cm $\leq r \leq$ 46 cm forms the ergodic layer, which shows a high level of stochasticity with some remaining island chains. The Chirikov parameter reaches a value above 4 at the very edge.

The flux surfaces are destroyed and field lines “diffuse” over the whole ergodic region. Connection lengths are of order of 10000 meters. It enhances the radial transport coefficient significantly. It is found that ergodization is not restricted to a regime close to “design parameters” in the operational space ($\beta_{\mathrm{pol}} = 1$, $r(q_{\mathrm{res}} = 3) = 42$ cm), but that it covers large operational space. Key parameters to modify the degree of ergodization are variations of the perturbation field amplitude, of the plasma current, of β_{pol}, and of the plasma position[3]. The perturbation spectrum depends on the pitch angle of the field lines, which can be adjusted by the value of beta poloidal. By modifying β_{pol} and I_{plasma} one can shift the ergodic layer either outward or inward in the range $0.9 \leq \frac{r}{a} \leq 1.0$ keeping the same level of ergodization. The ergodic region is connected with the walls only via very thin structures called fingers.

The laminar zone

The magnetic field of TEXTOR-DED is an “open” system. It means that field lines can intersect tokamak walls, and ions following the field lines will be neutralised there. The consideration of the connection lengths (relative to the Kolmogorov length) elucidates specific structure of the plasma very edge. It is found that despite of the strong ergodization, rather large continuous areas exist, with relatively short connection lengths: 4 flux tubes with $L_C = 1$ poloidal turn (because of four fold toroidal symmetry of the system), 4 with $L_C = 2$ poloidal turns continuous areas. There exist areas with even higher value of L_C, but their dimensions are small as compared to the Larmor ion orbits and have therefore no meaning for the particle orbits. Due to short connection lengths field lines in the laminar zone are not visualised on the Poincaré plot (white region in the Fig. 2). A laminar plot was developed to investigate properties of the laminar zone. The idea is similar as for the Poincaré plot, but additionally connection lengths are marked with different colours or grey tones. One example is shown in Fig. 4, each shade of grey denotes a zone with different number of poloidal turns (1 poloidal turn ≈ 30 m). The plasma current is 470 kA and $\beta_{\mathrm{pol}} = 1$. Very short connection lengths in the very edge (< 2 poloidal turns) suggest to treat that region in a similar way as the SOL of the poloidal divertor. The laminar zone comparing to the ergodic region has relatively simple structure and transport is mostly convective, along the flux tubes, what is reflected in the power deposition pattern onto divertor tiles[4].

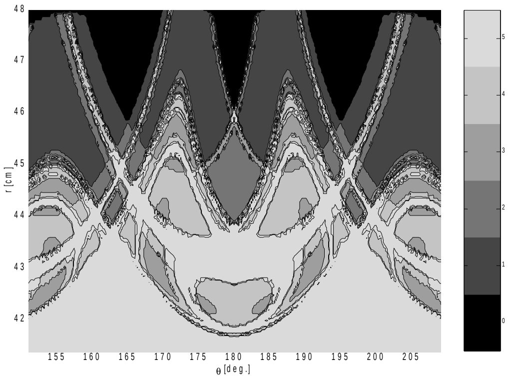

Fig. 4. The topology of the field line connection lengths of the laminar zone on the HFS of the plasma.

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[5]. 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)[6]. At the resonance layer of the plasma, different approximations are 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 the DED-coils and the plasma6. The maximum poloidal torque applied to the plasma amounts to about 50 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.

[1] Dynamic Ergodic Divertor (special issue), *Fusion Engineering and Design* **37** (1999) 335-448 (15 contributions)

[2] S.S.Abdullaev *et al.*, *Phys. Plasmas*, **6** (1999)

[3] K.H.Finken *et al.*, *Nucl. Fusion*, **39** (1999), 637

[4] Th.Eich *et al.*, *Nucl. Fusion,* **40** (2000), 1759

[5] Finken, K.H., *Nucl. Fusion*, **30** (1999) 707

[6] Faulconer, D.W., Koch, R., *Fusion Engineering and Design*, **37** (1997) 399