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Variation of the ergodic and laminar zones of the Dynamic Ergodic Divertor on TEXTOR-94

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1. Introduction

The TEXTOR device will be opened in mid 2000 for the installation of the coils for the dynamic ergodic divertor (DED) [1]. The main goal of the DED is a control of the plasma edge and the plasma–wall interaction by creating external magnetic field perturbation. The coil set will be located inside the vessel at the high field side (HFS) allowing a perturbation current flowing helically parallel to the magnetic field lines in the plasma boundary. The superposition of the perturbation field and the equilibrium field of the plasma creates an ergodization of the magnetic field lines at the plasma boundary. The structure of magnetic field lines there has complicated nature. It consists of so - called ergodic layer and laminar zone. The ergodic layer is the zone where magnetic field lines exhibit a deterministic chaotic behaviour with a short correlation length. The transport of heat and particles through the ergodic and laminar zones to the divertor target plates significantly depends on the widths of these zones.

In this presentation we study a variation the degree of ergodization and the width of the ergodic layer, as well as the laminar zone with the respect to the shift of the resonant magnetic surface (RMS).

2. Models for the plasma and the divertor coils

We consider the model of the plasma with the circular cross section studied in [2,3]. Let (r, θ, φ) be toroidal coordinates. The equilibrium magnetic field $\mathbf{B}(r, \theta)$ is determined by the toroidal, $B_\varphi(r, \theta) = \mu_o I_\varphi / [2\pi R_0(r)(1 + \varepsilon\cos\theta)]$, and poloidal, $B_\theta(r, \theta) = \mu_o I_p (1 + \Lambda\varepsilon\cos\theta)/2\pi r$, components, where I_p is the plasma current and I_φ is the current of the magnetic system, $\varepsilon = r/R_0(r)$ is the inverse aspect ratio, $R_0(r)$ is the position of the centre of the magnetic surface of radius r. The Shafranov shift of $R_0(r)$ with respect to the centre of the last magnetic surface of radius a is $\Delta(r) = [R_0^2(a) + (\Lambda+1)(a^2 - r^2)]^{1/2} - R_0(a)$. The quantity Λ is determined by the ratio of the plasma pressure to the magnetic pressure of the poloidal field, β_{pol}, and the internal inductance l_i, i.e., $\Lambda = \beta_{pol} + l_i/2 - 1$. The safety factor $q(r) \approx rB_\varphi/RB_\theta$ may be presented as

$$q(r) = \varepsilon^2 \frac{I_\varphi}{I_p}\Big(1 + \frac{1}{2}a_2\varepsilon^2 + \frac{3}{8}a_4\varepsilon^4 + \cdots\Big), \tag{1}$$

where $a_m = (-1)^m \sum_{k=0}^{m}(m - k + 1)\Lambda^k$.

As in [2,3] we consider the ideal divertor coil configuration in which 16 identical helical coils located on the inboard circumference of radius r_c and uniformly distributed along the toroidal direction. The poloidal extension of coils is $\Delta\theta = \pi/5$. The current distribution on the coils is taken as $I_j = ccI_d \sin(\pi j/2 + \omega t)$, where j ($j = 1, \ldots 16$) stands for a coil number, cc is the current control factor ($0 \le cc \le 1$), $I_d = 15$ kA is the maximum designed current, ω is a rotation frequency. This current distribution creates the magnetic perturbations at the plasma edge with the toroidal mode $n = 4$ possessing the strong radial decay $\sim (r/r_c)^{m_0 - 1}$ ($m_0 = 20$).

The divertor target plates are located at $r = r_d < r_c$ at the HSF. Tracing field lines is terminated when field lines hit the divertor plate. For the DED of the TEXTOR the position of the divertor plates is $r_d = 49$ cm.

The magnetic structure at the plasma boundary is studied by integrating the field line equations in the Hamiltonian from $d\theta^*/d\varphi = \partial\psi_p/\partial\psi, d\psi/d\varphi = -\partial\psi_p/\partial\theta^*$ with the poloidal flux ψ_p as a Hamiltonian function $\psi_p = \psi_p(\theta^*, \psi, \varphi)$, a toroidal flux ψ and an intrinsic poloidal coordinate θ^* as the canonical variables ($\psi = \psi(r), \theta^* = \theta^*(r, \theta)$), and the toroidal angle φ as an independent time–like variable. [In the intrinsic coordinates (θ^*, ψ) field lines on the given magnetic surface $\psi =$ const are straight in the absence of perturbation: $\theta^* = \theta^*_0 + (\varphi - \varphi_0)/q(\psi)$]. The integration is performed using a new mapping method developed in [2-4].

3. Structures of the ergodic and the laminar zones The poloidal spectrum B_m of the magnetic perturbations

$$B_m \sim \frac{\sin[(m/\alpha - m_0)\Delta\theta/2]}{m/\alpha - m_0}\left(\frac{r}{r_c}\right)^{m/\alpha-1}, \qquad \alpha \approx \frac{d\theta}{d\theta^*}\bigg|_{\theta=\pi}, \tag{2}$$

is located near the central poloidal mode $m_c = m_0\alpha$ with the width $\Delta m = \pi\alpha/\Delta\theta$ [2,3]. In general m_c and Δm depend on the plasma parameter β_{pol} as well as on the radial coordinate r. For the standard operational regime ($\beta_{pol} = 1$) the DED perturbation coils are designed to create the ergodic zone at plasma edge near the magnetic surface $q = 3$ positioned near $r = 43$ cm. It expects that one can obtain the well–developed ergodic zone if $m_c = 12$ at the resonant magnetic surfaces $q(r_{mn}) = m_c/n = 3$. The resonant magnetic perturbations with (2) $m_c - \Delta m/2 < m < m_c + \Delta m/2$ generate the chain of islands. At the certain level of the perturbed field the interactions of these islands creates the ergodic zone at the plasma edge.

The degree of ergodization and the width of the ergodic layer increases with the perturbation current and by shifting the resonant magnetic surfaces $r = r_{mn}$ towards the DED-coils. According to (1), the resonance condition $q(r_{mn}) = m/n$ depends mainly on the plasma current I_p with a minor influence of β_{pol}. One can show that at the fixed value of β_{pol} the positions of the resonant magnetic surfaces r_{mn} increase linearly with the plasma current I_p: $r_{mn} = r^0_{mn} + r'_{mn}I_p$. For the equilibrium plasma parameters $B_t = 2.25$ T, $a = 46$ cm, $R_0 = 174$ cm and β_{pol}= 1.0 the parameters r^0_{mn} and r'_{mn} are equal to r^0_{mn}= 24.99 cm, $r'_{mn} = 3.35 \times 10^{-2}$ (kA)$^{-1}$ for the resonance $m : n = 10 : 4$; $r^0_{mn} = 26.25$ cm, $r'_{mn} = 3.43 \times 10^{-2}$ (kA)$^{-1}$ for $m : n = 11 : 4$, and $r^0_{mn} = 27.45$ cm, $r'_{mn} = 3.50 \times 10^{-2}$ (kA)$^{-1}$ for $m : n = 12 : 4$. For example the resonant surface $r_{m,n}$ ($m = 12, n = 4$) changes from 42.73 cm at $I_p = 440$ kA to 48.33 cm at $I_p = 600$ kA.

The structure of magnetic field lines for the plasma current $I_p = 480$ kA and the maximum divertor current $cc = 1$ is shown in Fig. 1 by plotting Poincaré section of field lines at the poloidal section $\varphi =$ const. Other parameters were taken as $B_t = 2.25$ T, $a = 46$ cm, $R_0 = 174$ cm and β_{pol}= 1.0. Fig. 1a shows the entire poloidal section in the polar coordinate system (θ, r), while the close up view of the plot at the plasma edge is shown in Fig. 1b.

The width of the ergodic zone formed at the plasma boundary is larger at the HSF than at the low field side (LFS). From Fig. 1b one can see that the magnetic field structure at the plasma boundary may be conditionally divided into two distinct zones: the ergodic zone ($r_{LMS} < r < r_l \approx 46$ cm) with well developed chaotic field lines (with embedded in it islands of regular field lines) and the laminar zone ($r_l < r < r_d = 49$ cm) with open field lines connecting of the divertor target with itself. Here r_{LMS} stands for the last conserved magnetic surface. The ergodic zone is connected with the divertor target plates along narrow chaotic stripes. The large white areas between these chaotic stripes in the laminar zone correspond to the field lines with relatively short connection lengths (one or a few poloidal turns). (They cannot be shown on the Poincaré plot). The radial distance r_l defines the boundary between the ergodic zone and the laminar zone. The widths of the ergodic zone and the laminar zone can be changed by varying the

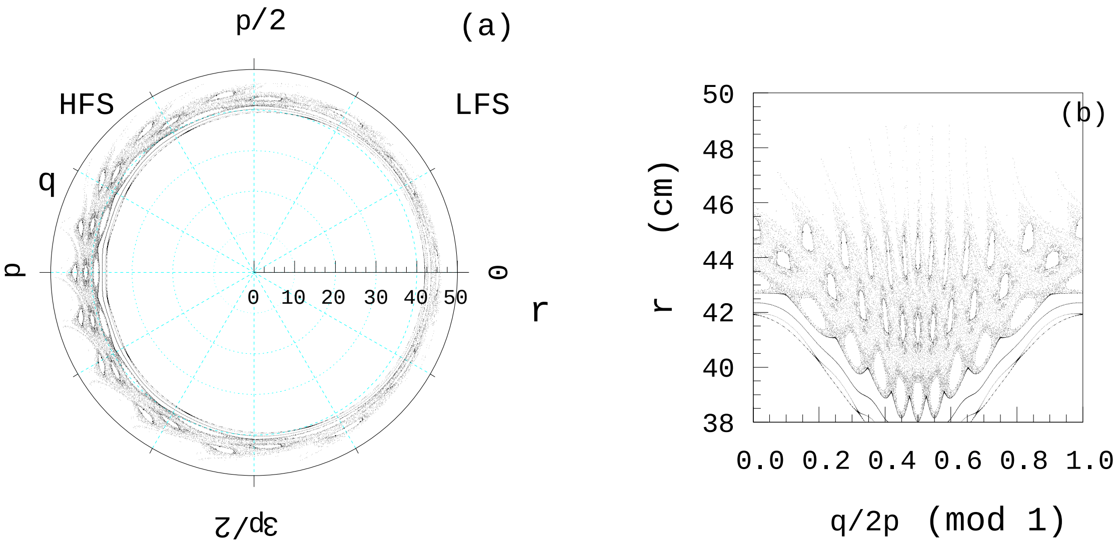

Fig. 1 Poincaré sections of magnetic field lines: (a) in a polar coordinate system (r, θ)*; (b) close up view of the ergodic zone. The poloidal current* $I_p = 480$ *kA.*

divertor current cc or by shifting the resonant magnetic surface in the radial direction by varying the plasma current I_p. Below we consider the effect of the variation of the plasma current on the ergodic and the laminar zones.

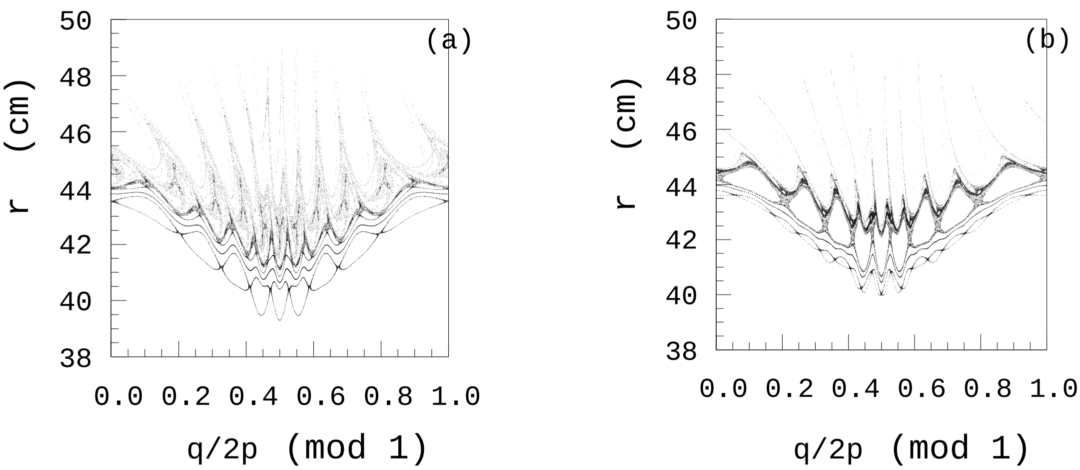

Fig.2 Poincaré sections of magnetic field lines for different poloidal currents: (a) - $I_p = 540$ *kA, (b) -* $I_p = 600$ *kA. Other parameters are the same as in Fig. 1.*

At the plasma current $I_p = 480$ kA the width of the ergodic zone is relatively large (about 8 cm at the HFS) (see Fig. 1b). The increase of I_p shifts outward the positions r_{mn} of the resonant magnetic surfaces. Due to the strong radial dependence of perturbation (2) the widths of individual islands grow further increasing their interaction. It leads to widening the laminar zone and narrowing the ergodic zone because of the domination of the resonant mode closely located to the divertor coils and diminishing the contributions of resonant modes m far from the central mode m_0 in (2). Fig. 2 shows the structure of field lines at the plasma boundary for the two values of the plasma current: (a) - $I_p = 540$ kA; (b) - $I_p = 600$ kA. The width of the ergodic zone is decreased substantially (approximately from 8 cm to 4 cm on the HFS) when the plasma current is varied from 480 kA to 540 kA, while the width of the laminar zone increased only approximately by 2 cm (compare Figs. 1b and 2a). Further increase of I_p up to 600 kA leaves only a narrow ergodic layer without noticeable change of the laminar zone's width.

The variation of the ergodic and laminar zones may be also studied by calculation of the radial profiles of local field line diffusion coefficients $D_{FL}(r)$. The profiles of $D_{FL}(r)$ is presented in Fig. 3 for the different plasma currents. In the ergodic zone ($r < r_l$) D_{FL} monotonically grows up to the boundary of the laminar zone r_l then it decreases for $r > r_l$ in spite of the growth of the perturbation. The width of the laminar zone also increases with the plasma current I_p up to its value 540 kA. For the higher values of $I_p >$ 540 kA the laminar zone does not grow any more. At the same time D_{FL} in the ergodic zone also grows with I_p up to the same value 540 kA, but for $I_p >$ 540 kA it slightly goes down. The decrease of the diffusion rate in the laminar zone is due to drastic reduction of the contribution of chaotic field lines to the diffusion process and domination of the convective field lines (connecting the divertor plates with itself in a few toroidal turns) in the transport heat and particles.

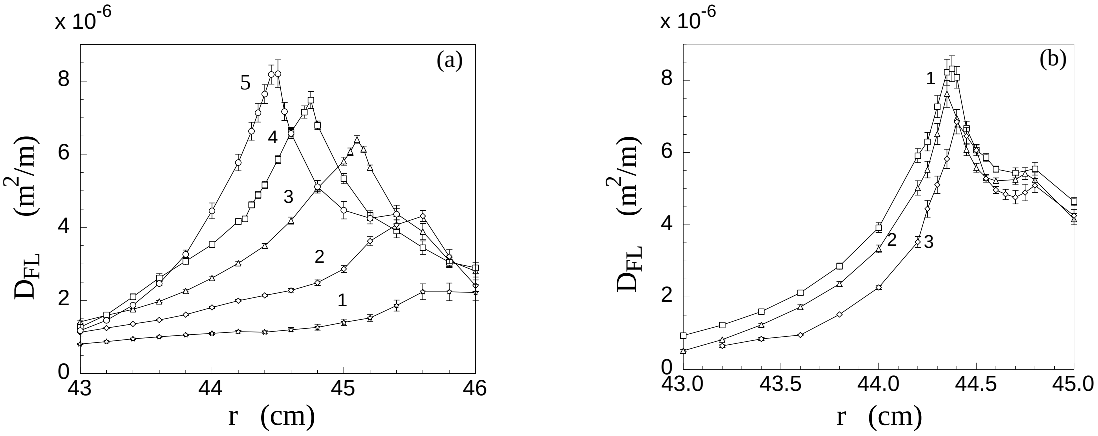

Fig. 3 Profiles of field line diffusion coefficients $D_{FL}(r)$ for different poloidal currents: (a) curve 1 - $I_p = 460$ kA, 2 - $I_p = 480$ kA, 3 - $I_p = 500$ kA, 4 - $I_p = 520$ kA, curve 5 - $I_p = 540$ kA; (b) 1 - $I_p = 560$ kA, 2 - $I_p = 580$ kA, 3 - $I_p = 600$ kA. Other parameters are the same as in Fig. 1.

4. Summary We have shown that the variation of the plasma current allows to study the transition of plasmas from regimes which are more similar to normal divertor structures to those with more ergodic dominated edge.

References

1. Dynamic Ergodic Divertor, Special Issue, *Fusion Engineering and Design* **37**, 335-448 (1997).
2. S.S. Abdullaev, K.H. Finken, and K.H. Spatschek, *Phys. Plasmas* **6**, 153 (1999).
3. K.H. Finken, S.S. Abdullaev, A. Kaleck, and G. Wolf, *Nuclear Fusion* **39**, 637 (1999).
4. S.S. Abdullaev, *J. Phys. A: Math & Gen.*, **32**, 2745 (1999).