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Structure of Ergodic Zone in the Dynamic Ergodic Divertor of the TEXTOR-94

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1. Introduction The Dynamic Ergodic Divertor (DED) is under construction as a novel tool for TEXTOR-94 to control transport at the plasma edge and possibly plasma rotation [1]. Its characteristic features are the long, multipolar continuous coil windings and their - toroidally uninterrupted - location at the inboard high-field side of the vacuum vessel. In addition to the capability to produce spatial and temporal magnetic field line ergodization in the plasma edge and to exert a helical torque there, the near field of the helical windings constitutes a multipolar helical divertor - with fast moving footprints - requiring currents which are one order of magnitude lower than those needed for a poloidal divertor. In the divertor mode of operation, without radiation cooling, the full convective heat load from the plasma is distributed over the relatively large area of the divertor target plates which protect the DED-coils from the plasma.

This presentation analyses the operational space of the DED, i.e., dependence of the structure and statistical properties of the ergodic zone on the plasma parameters, external perturbation modes and the positions of the main resonant magnetic surfaces. The study is based on a new method of asymptotic analysis of magnetic perturbation in a toroidal geometry, and mapping method of integration of Hamiltonian equations recently developed in [2].

2. Divertor Coils. We consider the ideal configuration of the divertor coils. Suppose that 16 identical helical coils on the inboard circumference of radius r_c start at the toroidal and the poloidal angles ($\varphi_{sj} = j\pi/8$, $\theta_s = \pi - \theta_c$) and end after one toroidal turn at $\theta_e = \pi + \theta_c$ ($j = 1, 2, \ldots, 16$), where $\theta_c = \Delta\theta/2$ is the half of the poloidal extension of the coil system. There are two types of current distributions $I_j^{(n)} = ccI_0 \sin(n\pi j/8 + \omega t)$ on each 16 coils which are designed to create the magnetic field perturbations with $n = 4$ and $n = 2$ toroidal modes ($I_0 = 15$ kA is the maximum designed current and cc ($0 \le cc \le 1$) is a current control factor). In technical implementation $n = 4$ mode has been selected as the standard mode of operation. However, a perturbation field of this mode has a strong radial decay $(r/r_c)^{m_0-1}$ ($m_0 = 20$), which weakly penetrates into the plasma and the perturbation field has practically disappeared for all radial positions interior to the $q = 3$ surface. Such a field may be not sufficiently strong to form a developed ergodized zone of field lines at the plasma edge. In order to increase the perturbation field one can add a weaker radial decaying $n = 2$ mode perturbation field to the main $n = 4$ mode. It may be achieved taking currents on coils as a linear combination of $I_j^{(4)}$ and $I_j^{(2)}$: $I_j = (1-p)I_j^{(4)} + pI_j^{(2)}$, where p ($0 \le p \le 1$) is a relative contribution of the $n = 2$ mode.

3. Hamiltonian formulation of field line equations. Field line equations in the perturbed field are found in Hamiltonian form introducing a toroidal flux ψ, an intrinsic poloidal angle θ as canonical variables, a poloidal flux as a Hamiltonian and a toroidal angle as a time variable. It is presented in the form $H = H_0(\psi) + \epsilon H_1(\psi, \theta, \varphi)$, where $H_0(\psi)$ is the unperturbed Hamiltonian related to the safety factor $q(\psi) = dH_0(\psi)/d\psi$. The perturbed Hamiltonian $\epsilon H_1(\psi, \theta, \varphi)$ is presented in Fourier decomposition $\epsilon H_1(\psi, \theta, \varphi) = \epsilon \sum_m H_m(\psi) \cos(\theta - n\varphi + \omega t)$. An asymptotic formula for Fourier components $H_m(\psi)$ is established, and its dependence on the plasma β_{pol} is studied. The Hamiltonian field line equations are integrated using a novel mapping method developed in [2].

4. Formation of ergodic zone. The ergodic zone of field lines at the plasma edge is formed due to overlapping magnetic islands formed by the destroyed resonant magnetic surfaces $q = m : n$. For the DED-TEXTOR a finite size ergodic zone is mainly created by overlapping several magnetic islands on the resonant surfaces $m : n$ with the poloidal modes m: $10 \leq m \leq 14$. The onset of the ergodic zone depends on the plasma parameter β_{pol}, the radial positions of the resonant magnetic surfaces $r_{m,n}$ ($q(r_{mn}) = m : n$) and the level of the divertor current cc.

First we present a qualitative analysis of the formation of the ergodic zone based on exact multipole field calculations, which uses the Chirikov criteria of overlapping the resonances: $s = [\Delta_{m+1,n} + \Delta_{m,n}]/2[r_{m+1,n} - r_{m,n}] \geq 1$, where $\Delta_{m,n}$ is the radial width of the magnetic islands. The critical value of the current control factor $cc^{(m,n)}$ at which the neighbouring islands (m, n) and $(m + 1, n)$ starts to overlap is found using the equality $s(cc) \approx 1$ for the different plasma parameter β_{pol}. The dependence of $cc^{(m,n)}$ on β_{pol} at the fixed position $r_{q=3}$ of the resonant magnetic surface $q = 3$ are presented in Fig. 1: a - $r_{q=3} = 43$ cm, b $-$ $r_{q=3} = 46$ cm; curve 1 corresponds to overlapping the resonant islands $m : n =$ 12:4 and 13:4, curve 2 $-$ 13:4 and 14:4, and curve 3 $-$ 14:4 and 15:4. The value of $r_{q=3}$ for the different plasma β_{pol} may be held fixed by varying the plasma current I_p. For the divertor current level $cc > cc^{(m,n)}$ the ergodic zone is formed by overlapping the corresponding islands (m, n) and $(m + 1, n)$. One can see from Fig. 1a that for $r_{q=3} =$ 43 cm the critical current $cc^{(m,n)}$ significantly depends on the plasma β_{pol}. The highly ergodized zone is usually formed for small value of $\beta_{pol} < 0.5$. With growing β_{pol} the critical divertor current $cc^{(m,n)}$ increases and thereby decreasing the ergodization level. For $\beta_{pol} > 1.4$ the ergodic zone may disappear even for the maximum divertor current $cc = 1$. From Fig. 1b follows that the outward shift of the resonant magnetic surfaces r_{mn} $[q(r_{mn}) = m/n]$ enhances the ergodization level even for the large β_{pol}.

The formation of the ergodic zone is also studied by integration of Hamiltonian field line equations using a mapping method.

5. Effect of combined $n = 4$ and $n = 2$ mode perturbations. Another way of enhancement of the ergodization level is an admixture of the $n = 2$ mode magnetic perturbation to the main $n = 4$ mode perturbation. Below we study the effect of the $n = 2$ mode on the formation of the ergodic zone using the asymptotic Hamiltonian for field lines mentioned in Sec. 3. Fig. 2 shows Poincaré sections of field lines for the "pure" $n = 4$ mode perturbation (a) and for $p = 20\%$ of the $n = 2$ mode (b) at the fixed values of $r_{q=3} = 44$ cm and $\beta_{pol} = 1.5$ at maximum divertor current level $cc = 1.0$. For the "pure" $n = 4$ mode perturbation the ergodic zone is not even formed and it only consists of isolated islands. The inclusion of the $n = 2$ mode significantly changes the structure of the field lines: the Kolmogorov– Arnold–Moser invariant magnetic surfaces between isolated islands are destroyed, and the ergodic zone is created without increasing the current level cc.

The laminar zone is also studied by analysing the fractal properties of field lines at the plasma edge [3].

6. The statistical properties of the ergodic zone are analysed by calculating the moments of radial displacements $\sigma_{r0}(l) = \langle (r(l) - r_0)^2 \rangle$ along field lines l and the radial profiles of local diffusion coefficients D_{FL} of field lines. In the ergodic zone $\sigma_{r0}(l)$ typically grows with the distance l along field lines until certain distance then it tends to a constant value if the field lines are confined in the ergodic zone, or decreases exponentially if the field lines leave the ergodic zone reaching the divertor plate. Generally, in the finite ergodic zone one cannot introduce a global diffusion coefficient as a ratio $\sigma_{r0}(l)/2l$, $l \to \infty$, because it goes to zero. However, in order to estimate the radial transport rate of field lines we have introduced the local diffusion coefficients $D_{FL}(r_0)$ at the initial linear stage of growth of $\sigma_{r0}(l)$ with l.

In Fig. 3 we have presented radial profiles of field line diffusion coefficients $D_{FL}(r)$ for the different admixture of the $n = 2$ mode for $r_{q=3} = 43$ cm (a) and for $r_{q=3} = 46$ cm (b): $1 - p = 0\%$, $2 - p = 10\%$, $3 - p = 20\%$. One can see that at $r_{q=3} = 43$ cm for the "pure" $n = 4$ mode perturbation D_{FL} is small. The inclusion of $p = 20\%$ of the $n = 2$ mode increases D_{FL} by one order of magnitude. A further growth of the diffusion rate may be achieved by the outward shift of the resonant magnetic surfaces. Fig. 3(b) clear shows that at $r_{q=3} = 46$ cm the diffusion coefficients are significantly larger even for the "pure $n = 4$ mode. One can recognize that $p = 20\%$ of the $n = 2$ mode increases D_{FL} by a factor of 4 or 5.

Conclusions. We have shown that a sufficient degree of ergodization of field lines at the plasma edge can be maintained by variation of the plasma pressure, the toroidal field B_t, i.e., β_{pol}, and/or the radius of the main resonant magnetic surfaces. A superposition of the external perturbation modes also extends the degree and depth of ergodization.

References

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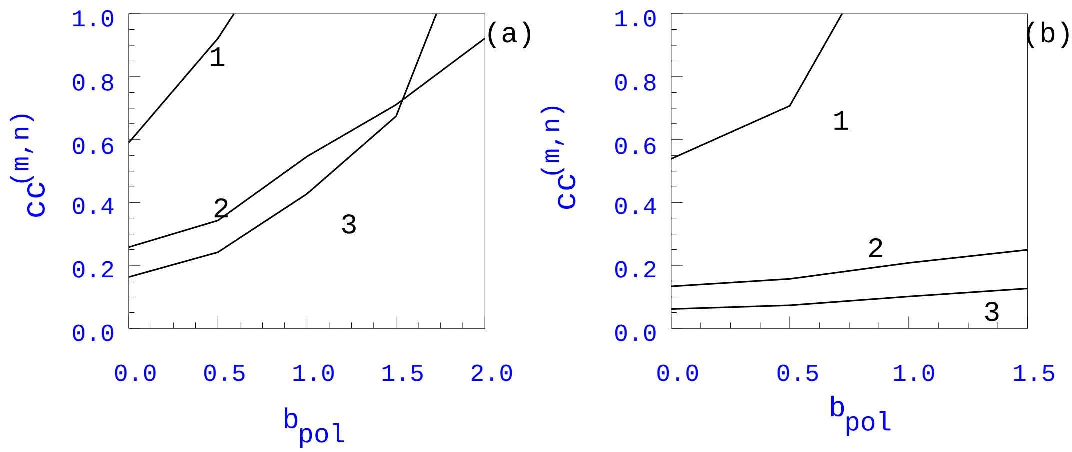

Figure 1: *(a) The critical divertor current level $cc^{(m,n)}$ versus β_{pol} at the fixed $r_{q=3} = 43$ cm: 1 – for overlapping of islands $m : n$ = 11:4 and 12:4, 2 – for 12:4 and 13:4, 3 – for 13:4 and 14:4; (b) The same as in (a), but for $r_{q=3} = 46$ cm.*

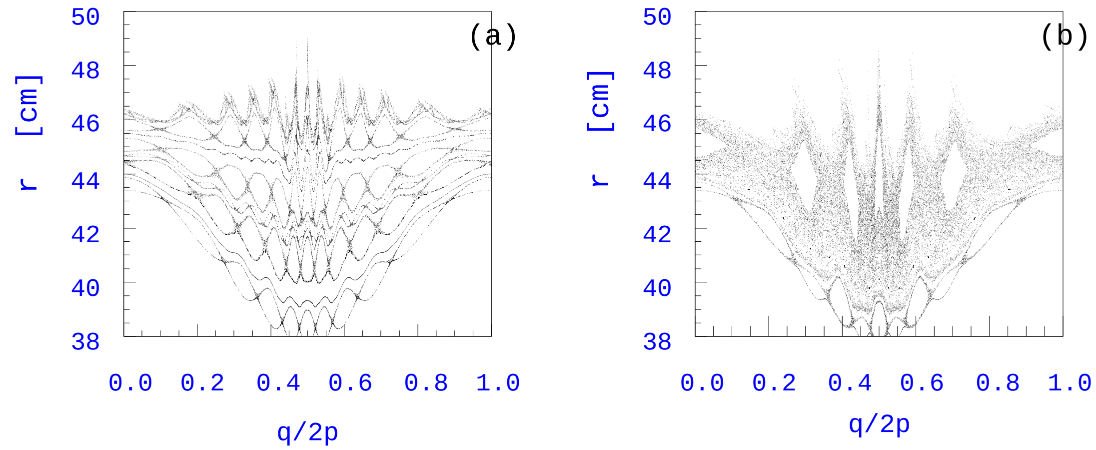

Figure 2: *Poincaré sections of field lines for the "pure"* $n = 4$ *mode (a) and* $p = 20\%$ *of the* $n = 2$ *mode. Other parameters are* $cc = 1$, $r_{q=3}$ *= 0.44 m and* $\beta_{pol} = 1.5$.

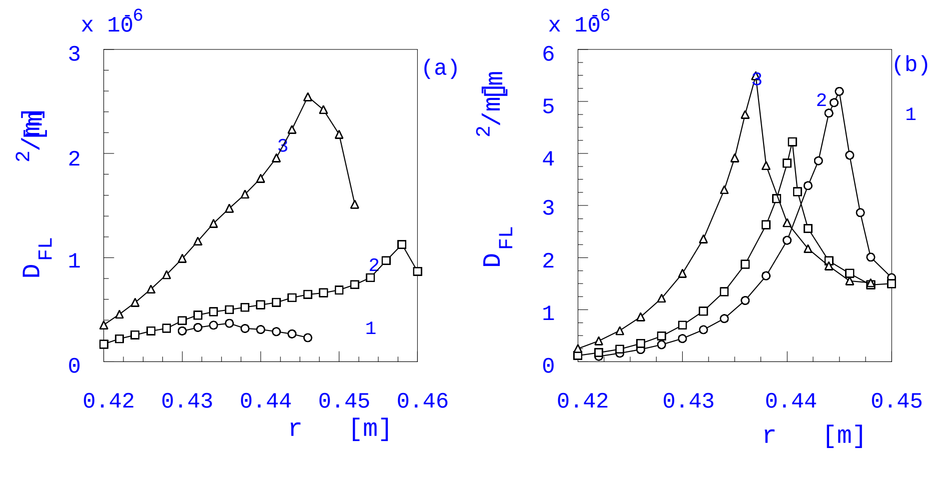

Figure 3: *(a) Radial profiles of* $D_{FL}(r)$ *for the different contributions of the* $n = 2$ *mode: 1 –* $p = 0\%$; *2 –* $p = 10\%$, *and 3 –* $p = 20\%$. *The resonant radius* $r_{q=3}$ *= 0.43 m. (b) The same as in (a), but for* $r_{q=3}$ *= 0.46 m. Other parameters are* $\beta_{pol} = 1.0$, cc *= 1.*