DIVERTOR CONCEPTS II: THE DYNAMIC ERGODIC DIVERTOR (DED)

K.H. Finken
Institut für Plasmaphysik, Forschungszentrum Jülich, Euratom Association
Trilateral Euregio Cluster, 52425 Jülich,Germany
TEL. +49 2461 61 5646; Fax +49 2461 61 5452

ABSTRACT

The Dynamic Ergodic Divertor (DED) has recently been taken into operation on the TEXTOR tokamak. One of the aims is the study of the mitigation of the heat flux by rotating the divertor strike points. After an introduction into the theory of ergodization, the design of the DED is presented. The Chirikov parameter describing the level of ergodization reaches a level of up to four if the perturbation current is applied in an optimized way. Finally the rich physics options of the DED are discussed.

I. INTRODUCTION

During the last two decades, considerable progress has been made in improving the plasma confinement. The sufficiently low error margin from the different devices makes it now possible to extrapolate the confinement data to a reactor scenario such it can be expected that the plasma of the proposed ITER experiment will most likely ignite. The essential ingredient for a good confinement is the existence of magnetic flux surfaces which form - typically eccentric - onion shell like structures inside the fusion devices. Magnetic field lines stay always on "their" magnetic surface and for a non-streaming plasma these surfaces also form isobars.

Nevertheless, the existence of flux surfaces is generally not guaranteed; other - "ergodic" - solutions of the magnetic field line structure are possible as well. Ergodicity in our special case means that any magnetic field line comes infinitely close to any point in a given volume. This property is obviously not compatible with flux surfaces where a field line is restricted to one surface.

The formation of an ergodic layer can be an interesting method to destroy the good confinement properties of closed flux surfaces on special locations. Such a location of interest is the boundary of the plasma: All power introduced into the plasma either by heating or by α-particles – as far as not radiated - leaves the plasma conductively and convectively through a thin boundary layer. Even in a fusion reactor, this boundary layer will be only one or few centimeters thick. The highly concentrated heat flux of this scrape off layer follows the magnetic field lines and hits the divertor target plate or the pump limiter surface. It has been shown that the heat flux density is at the limit or above for any material. To mitigate the problem, the concept of a radiative mantle has been introduced and basic investigations have been performed e.g on the TEXTOR[1] tokamak. A similar goal, namely to distribute the heat flux to a large wall area, has the new TEXTOR experiment, the Dynamic Ergodic Divertor (DED)[2]. It is expected that the dynamic feature of the DED in addition enhances the ergodization level, allows for an enhanced particle removal by a pump limiter, unlocks modes, imposes a differential rotation in the plasma edge and improves the confinement.

In the following, a short introduction into the background for the ergodization is provided, followed by a description of the proposed DED experiment, then the magnetic field line structure is discussed and finally the dynamic option is highlighted.

II. THE DED-ARRANGEMENT

The coil arrangement of the proposed DED[2,3,4] is shown in Fig. 1. It consists of a quadruple set of four helical conductors, installed on the inboard side of the TEXTOR vessel and aligned parallel to the magnetic field lines (for $\beta_{pol} \approx 1$) at the nearby q=3 surface. Taking into account the available space, the technical constraints (such as current density, skin effect, heat capacity, cooling aspects, etc.) and the physics requirements, an m = 12, n = 4 perturbation field structure has been selected. This can be achieved by using coils which cover about 30 % of the inboard vessel surface on the high field side and which will be energized by a 4-phase current (up to 15 kA) at selected frequencies (DC, 50 Hz, 1 kHz and a band of 1 kHz to 10 kHz). These frequencies correspond to a rotation of the perturbation field around the torus similar to the propagating field of an AC motor; the phase velocities projected on the poloidal coordinate of v_{ph} = 12 m/s, 240 m/s, 2400 m/s respectively. The coils can be connected in several ways allowing a certain range of different mode structures such as the *m*=6*, n*=2 and *m*=3, *n*=1 modes. The poloidal velocities will then be higher by a factor of two or 4, respectively.

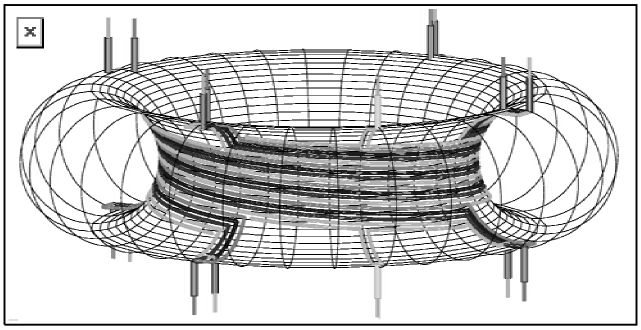

Fig.1: Schematic arrangement of the perturbation coils in TEXTOR

III. THE ERGODIC STRUCTURE GENERATED BY THE DED

The ergodic structure resulting from this perturbation is often shown in the so-called Poincaré plot. In this plot a characteristic plane has to be defined which for a tokamak is a poloidal cut of the torus with the coordinates *r* for the minor radius and Θ for the poloidal angle. In this plane starting points for magnetic field line tracing are selected and marked by a dot. The field lines are traced many times (typically several 1000 times) around the torus and every time the location of the intersection of the field line and reference plane is marked by a dot (puncture plot). If the perturbation field is not applied, the puncture sequence will remain on a flux surface - in the Poincaré plot thus forming a closed curve.

If the starting point is on a (preferentially low) rational q-number surface, the curve will degenerate to individual points - e.g. at the *q*=3 surface to three points per starting condition. With applied perturbation field, the pattern will be modified in a characteristic way. The big advantage of the Poincaré representation is that the 3-D chaos problem can be cast into a 2-D picture which is easily graphically represented. Two Poincaré plots for the TEXTOR DED are shown in Figs. 2 and 3. The figures are cut at the outer equator *(Θ=0)* and unfolded; the abscissa is the poloidal angle and the ordinate the radius. This representation has been selected to enhance the radial resolution with respect to the poloidal one. In Fig. 2 the perturbation current is relatively low, 30% of the maximum allowed value. The rectangle on the center top represents the location of the DED coils and the object on the top left is the pump limiter ALT-II.

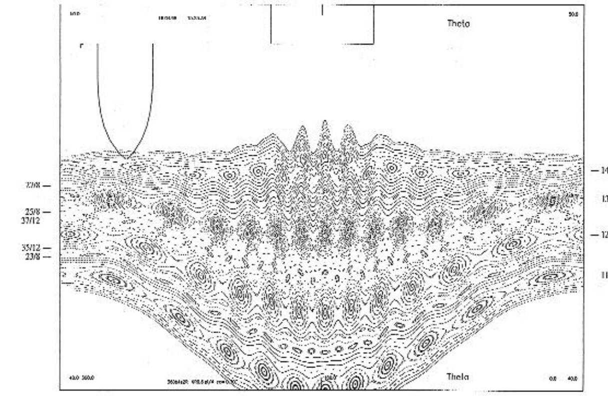

Fig.2: Poincaré plot for a low perturbation field (I_{pert}/I_{max}=0.3). As expected, magnetic islands develop at low rational q-values. The ordinate represents the radial direction (plasma side to the bottom) and the abzissa is the poloidal angle.

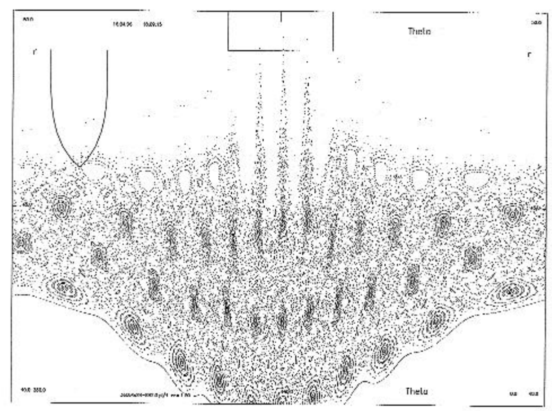

Fig. 3: Poincaré plot for the perturbation current conditionI_{pert}/I_{max}=1. The whole outer plasma boundary is ergodized

The Poincaré plot shows all the structures expected in the sub-ergodic phase: At the *q* = 3, 3.25 and 3.5, the main islands are formed with mode numbers *m/n* = 12/4, 13/4 and 14/4 (*m* stands for the number of poloidal knots and *n* for the one of toroidal ones; the resonance condition requires *q=m/n*). Towards the plasma core (bottom part of the figure) the flux surfaces are nearly unchanged resulting in well ordered puncture curves. In between the main islands, intact surfaces are clearly visible. Between the *q*=3 and *q*=3.25 surfaces, smaller island chains are found; these and sub-islands in the main islands result from second order perturbation theory. The structures are well described by the KAM (for Kolmogorov, Arnold and Mozer) theory which is treated in text books [3-7].

With increasing perturbation amplitude, the island width increases and the islands start to overlap. In particular the region between the q=3 and 3=3.25 surfaces becomes ergodic, i.e. field lines from any starting point reach any other point in that area. Between the q=3.25 and the q=3.5 surfaces, a barrier surface stays intact at low perturbation levels preventing a "diffusion" of the field lines. With increasing perturbation strength, also the barrier disappears in the whole boundary and allows for an enhanced field line diffusion as shown in Fig. 3.

IV. HAMILTON FORMALISM FOR MAGNETIC FIELD LINE TRACING

One important path to describe the development of chaos - and with it ergodization - in physics systems starts from the Hamiltonian formalism. This method is not the most general one and it is only applicable as long as e.g. friction forces can be neglected. If the problem can be cast into a Hamiltonian form, important laws as the conservation of the phase space can immediately be applied.

The Hamiltonian form for the field line tracing can be applied if the magnetic field depends at most weakly on one coordinate. In a Tokamak or Stellarator this is e.g. the toroidal coordinate. For simplicity let us consider here a magnetic field with the main component in z-direction. The equation of motion for field line tracing is then written as:

$$\frac{dx}{ds} \cong \frac{dx}{dz} = \frac{B_x}{B_z} = \frac{\partial a_z}{B_z \partial y} - \frac{\partial a_y}{B_z \partial z} \tag{1}$$

$$\frac{dy}{ds} \cong \frac{dy}{dz} = \frac{B_y}{B_z} = \frac{\partial a_z}{B_z \partial x} - \frac{\partial a_x}{B_z \partial z} \tag{2}$$

By equating t≡z, q≡x, p≡y, H≡a_z/B_z and assuming that the derivatives with respect to z are of the order ε only the equations of motion for the field line tracing become:[5,6,7,8]

$$\frac{dq}{dt} = \frac{\partial H_o}{\partial p} + \varepsilon \cdot \frac{\partial f}{\partial t} \tag{3}$$

$$\frac{dp}{dt} = - \frac{dH_o}{dq} + \varepsilon \cdot \frac{\partial g}{\partial t} \tag{4}$$

$$\frac{\partial f}{\partial p} = \frac{\partial g}{\partial q} \tag{5}$$

If ε=0, i.e. if the problem does not depend on z, this formalism describes a 1-dimensional motion of a particle. The system is integrable and the path curve is not subjected to any ergodization. A rather simple analogon is the motion of a pendulum[9] which has been analyzed extensively with respect to the development of chaos and which is considered prototypical: The pendulum frequency depends on the amplitude of the motion; it spans a frequency band from its maximum at small amplitudes to zero frequency at the separatrix (which divides the oscillating motion (H < 0) from the free rotation (H > 0)).

For ε>0, the Hamilton function depends on time and the problem has a dimension of 1.5. For the pendulum, this corresponds to the interaction with an external force. If this force has one Fourier component with one frequency in the band of the unperturbed motion, a resonance close to a specific amplitude is imposed and the motion has a maximum disturbance there. The resonant excursion cannot grow to infinity since otherwise the resonance condition is lost again; in the phase space, the resonance forms an "island".

If the Fourier spectrum of the perturbation has more than one frequency in the band of the unperturbed motion, several resonant islands are generated. The width of the island increases with the perturbation level; at a sufficiently high amplitude they start to overlap. From then on, the motion jumps irregularly from one island to another and in this band it becomes chaotic or ergodic.

The formulae of the most important quantities in the ergodization theory are given below, namely for the island width Δ_{mn}, the poloidal and toroidal mode numbers m and n, the Chirikov parameter σ, the Kolmogorov length L_k, and the quasi linear diffusion coefficient D_Q. A magnetic island is generated (in first approximation) at the magnetic surface with the safety factor $q(r_{mn})=m/n$ by an perturbation field which has a spatial Fourier component b_{mn} at r_{mn}:

$$\Delta_{mn} = \sqrt{\frac{16 r b_{mn}}{m B_t} \cdot L_{sh}} \tag{6}$$

here B_t is the toroidal field strength and L_{sh} is the shear length

$$L_{sh} = \frac{q^2 R_0}{r} \cdot 1 \bigg/ \frac{dq}{dr} \tag{7}$$

The Chirikov parameter characterizes the overlap of different islands and is a measure for the degree of ergodicity:

$$\sigma(r)^2 = \frac{8r(b_{mn} + b_{m'n'})}{m|L_{sh}|B_t} \cdot \left(\frac{mqR}{r}\right)^2 \tag{8}$$

for 0≤σ≤1, islands dominate the magnetic stucture while for σ>1 the magnetic field line pattern is ergodic. The Kolmogorov length characterizes the distance from where on initially neighboring field lines start the separate exponentially:

$$L_k = 2\pi\, qR_0 \cdot \sigma^{-4/3} \tag{9}$$

The quasi linear field diffusion coefficient finally is

$$D_Q = 2\pi\, qR_0 \cdot \left(\frac{b_{mn}}{B_t}\right)^2 \tag{10}$$

particle diffusion coefficients are linked with D_Q by a multiplication of a characteristic velocity for either ions or electrons.

V. EXPECTED PLASMA RESPONSE

V.1 ERGODIC ZONE

In a first approximation the influence of the Ergodic Divertor can be described by the following cycle: The ionized plasma particles, also following the magnetic field lines in the ergodized zone, are guided rather rapidly towards the walls where they are neutralized. There - no longer coupled to the magnetic field lines - they are scattered back into the plasma. If the ergodic layer is thick enough, the back-scattered neutral particles will be reionized before entering the bulk plasma. Due to collisions with the plasma flow from the confinement zone and as a result of the enhanced radial transport in the ergodized zone, they will be swept back to the walls. This circle results in an enhanced density near the walls. In addition to the cooling of the electrons by ionization and radiation, the electron temperature is lowered by the enhanced heat conductivity along the field lines in the ergodic zone; as a consequence, the ionization and excitation zones are broadened and shifted inward. Moreover, the impurity release due to energy dependent processes (e.g. sputtering) can be reduced significantly. Thus the combined effects of the increased electron density and decreased electron temperature at the plasma boundary in conjunction with the enhanced radial transport are responsible for the beneficial effects observed on devices with ergodic divertors[10,11,12]; from those the expected improved radiation efficiency of the impurities and the better impurity screening will be important issues for future TEXTOR experiments.

V.2 LAMINAR ZONE

In the "near field" region of the helical coils (creating the multipolar perturbation field) the magnetic field lines are displaced radially. This deflection depends on the specific configuration and on the amplitude of the perturbation field. As a consequence, the magnetic field lines can intersect the target plates which cover the helical coils with resultant high particle and heat fluxes there, establishing a multipolar helical divertor localized in front of the perturbation coils. This region of open magnetic flux surfaces is called the laminar zone; the plasma properties resemble in many aspects those of the poloidal divertor: Modelings[13,14] of the area of both the ergodic zone and laminar zone have been performed. The top of subfigure 4 shows a recently measured power deposition pattern on the divertor target plates during DED operation while the lower subfigure shows the result of a 3D plasma transport modeling for the same condition. The agreement of simulation and measurement is very good. The toroidal un-uniformities in the measured heat flux are due to misalignments of the divertor target graphite tiles.

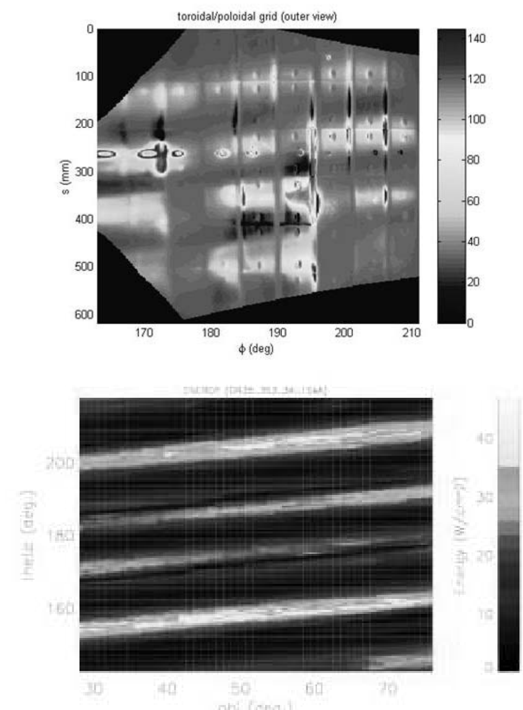

Figure 4: The top of the subfigure shows a recently measured power deposition pattern on the divertor target plates during DED operation while the lower subfigure shows the result of a 3D plasma transport modeling for the same condition.

V.3 DYNAMIC ASPECT

The distinguishing feature of the Dynamic Ergodic Divertor, however, is the establishment of a rotation of the applied magnetic perturbation pattern. This is motivated by a variety of applications which are related to the frequency range of the applied rotation.

The application of a low frequency - 50 Hz (v_{ph} = 12 m/s) proposed for technical convenience - is aimed at spreading the heat load evenly either over the protection tiles of the helical divertor located at the high field side or over the pump limiter located at the low field side. Shifting the plasma position and/or changing the plasma aperture allows control of the relative distribution of the total heat and particle flux between these two main plasma facing components. This puts the proposed DED program in a unique position to answer a number of critical questions which address the physics of mixed ergodic-island layers and how they can be used as an adaptive interface between hot, well-confined plasmas and plasma facing components.

In contrast to the 50 Hz case, the medium frequency of 1 kHz (v_{ph} = 240 m/s) opens experimental access to the interesting question of whether a rotation of the perturbation pattern which is faster than the transit time of recycling particles - penetrating the boundary layer - will affect particle transport and in consequence also the recycling process and the screening efficiency.

Last but not least, by applying the upper frequency band of 1 kHz to 10 kHz ($v_{ph} \leq$ 2400 m/s) - the velocity of the perturbation is then of the same order as the natural diamagnetic drift velocity of the plasma - one can investigate whether the rotating field will induce an angular momentum in the plasma and whether the resulting torque[15] will affect confinement and stability properties. A particularly interesting case may occur when the plasma rotation coincides with the rotation of the applied perturbation field. Moreover, the currents induced in the plasma by the rotating field pattern and their feedback on the resulting structure of the ergodized layer may become relevant at higher frequencies. Thus, besides the issues of particle and heat exhaust, the DED also directly addresses questions of plasma confinement and stability including locked modes and their interaction.

The technical solution for the DED on TEXTOR has been chosen to provide a wide range of experimental possibilities with a limited investment, the aim being the exploration of the potential and the limits of the DED as a means to influence and control plasma-wall interaction. The benefit of the intended studies is seen in the improvement of the understanding of edge transport, island formation, effects of ergodicity etc. which may lead to the incorporation of some features of the TEXTOR DED into other exhaust concepts and may also stimulate the search for novel concepts and technical solutions which would have potential for development towards ultimate application on a burning fusion plasma.

REFERENCES

1. U. Samm, G. Bertschinger, P. Bogen et al., „Radiative Edges under Control by Impurity Fluxes“, *Plasma Phys. Control. Fusion*, **35**, B167,(1993)

2."Dynamic Ergodic Divertor (DED) for TEXTOR-94", Editor: K.H. Finken, Berichte des Forschungszentrums Jülich, 3285 (1996)

3 S.S. Abdullaev, K.H. Finken, K.H. Spatschek, „Asymptotical and Mapping Methods in Study of Ergodic Divertor Magnetic Field in a Toroidal System“, *Physics of Plasmas*, **6** (1999) 153

4 K.H. Finken, S.S. Abdullaev, A. Kaleck, G.H. Wolf, „Operating Space of the Dynamic Ergodic Divertor for TEXTOR-94“, *Nucl. Fusion*, **39** (1999)637

5. J.A. Lichtenberg, M.A. Liebermann, „Regular and Stochastic Motion“, *Applied Mathematical Sciences 38*, Springer Verlag, New York, 1983

6. M.C. Gutzwiller, „Chaos in Classics and Quantum Mechanics“, *Interdisciplinary Applied Mathematics*, Springer Verlag, New York, 1990

7. W. Horton, Y-H Ichikawa, „Chaos and Structures in Nonlinear Plasmas“, *World Scientific*, Singapore, 1996

8. R. J. Goldston, P.H. Rutherford, „Introduction to Plasma Physics“, in *IOP Publishing Ltd*, 1995

9. B.V. Chirikov, *Physics Reports*, „A Universal Instability of Many-Dimensional Oscillator Systems“ **52** 265,(1979)

10. A. Samain, T. Blenski, Ph. Ghendrih et al., „Theory of the Ergodic Divertor“ *Contrib. to Plasma Physics*, **30** (1990) 157

11. Ph. Ghendrih, H. Capes, J. Nguyen, A. Samain, „Control of the Edge Transport with the Ergodic Divertor“ *Contrib. to Plasma Physics*, **32** (1992) 179

12. C. de Michelis, A. Grosman, X. Garbet et al., „Characteristics of Ergodic Divertor Plasmas in the TORE SUPRA Tokamak“ *Nucl. Fusion*, **35,** 1133,(1995)

13 K.H. Finken, T. Eich, A. Kaleck, „First Modelling of the TEXTOR DED Near Field Divertor“, *Nucl. Fusion*, **38** (1998) 515

14 M. Kobayashi, “Modelling approach to 3D simulation of transport in the TEXTOR-DED Laminar Zone with a Finite Element method”, J. Nucl. Mater., 313 (2003) 1056

15 K.H. Finken, „Perturbation Field Penetration into the TEXTOR Tokamak and the Resulting Torque“, *Nucl. Fusion*, **39** (1999)707