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First results from the dynamic ergodic divertor at TEXTOR

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Abstract

Experimental results from the dynamic ergodic divertor (DED) at TEXTOR are given, describing the complex structure of the edge plasma and the properties of the divertor as well as its influence on the plasma rotation.

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1. Introduction

The dynamic ergodic divertor (DED) at TEXTOR is a divertor concept based on the generation of a stochastic boundary layer [1]. Such concepts like for example the ergodic divertor at Tore Supra have proven in the past to be capable of providing good particle and power removal properties [2]. It has been shown, that many of these divertor properties are comparable to those of axisymmetric divertors [3]. Stochastic layers also play an important role in the divertor schemes for stellarators, like the helical divertor or the island divertor [4,5]. The DED is moreover not only a tool to control the plasma wall interaction. With its unique feature of generating a rotating external perturbation field in the frequency range from a few hertz up to 10 kHz, the DED distributes the power load over a large target area and allows to control plasma rotation [6] and possibly plasma confinement. Beside the divertor aspects, the DED can provide important insight into the behaviour of stochastic plasmas not only in tokamaks, but also in stellarators [7] and reversed field pinches [8]. Also the recently found evidence for ELM mitigation by edge ergodisation at DIII-D [9] shows the importance of a deeper understanding of such structures.

The basis of the DED setup are 16 helical coils mounted on the high field side of the tokamak TEXTOR. The current distribution in these coils can be adjusted to several operating scenarios varying between high and low multipolarity. The poloidal and toroidal mode numbers of the magnetic perturbation can be chosen to be $m/n = 3/1$ for a deep penetration of the perturbation into the plasma or $m/n = 12/4$ for a restriction of

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the ergodic layer to the boundary plasma. Since the start of operation middle of 2003, these two scenarios were investigated. Due to technical constraints the perturbation field of the 12/4 mode was restricted to 50% of the nominal field. Also an intermediate mode number of $m/n = 6/2$ and mixing of these modes will be possible in the future.

2. The structure of the divertor plasma

Resonant magnetic field perturbations lead to a significant change in the plasma edge structure. Islands are created and at a sufficiently high perturbation field they overlap and an ergodic layer is established. The field lines in the ergodic layer lead to an enhanced radial transport by interconnecting different radial positions. The near field of the divertor guides field lines from this ergodic layer to the target plates. These field lines have a very long connection length up to hundreds of poloidal turns. Moreover, in the far plasma edge, a laminar region exists with field lines of short connection length to the divertor target with a few poloidal turns. The width and structure of these two edge regions is controlled by parameters like the strength of the perturbation field, the safety factor and the mode numbers of the perturbation. The width of the ergodic region-based on vacuum field calculations – varies from 20 mm to 50 mm in 12/4 mode and is substantially larger in the 3/1 operation extending up to the $q = 2$ surface. The laminar region is in both cases in the range of a few centimeter.

Fig. 1 gives an example of the CIII line emission in front of the target plates in 3/1 mode together with the vacuum magnetic field structure calculated from field line mapping [10]. The Poincaré plot shows the position of the $m = 2, 3, 4$ islands created by the perturbation. The highest CIII emission is seen at the strike zone which is defined by the near field of the divertor guiding particles from the ergodic region via 'ergodic fingers' to the target. Additionally one can see an $m = 4$ island close to the divertor plates.

In this example the current in the DED coils is time dependent and the strike zone was shifted 90° toroidally. This gives the opportunity to measure target profiles of the electron temperature and density using Langmuir probes of dome type embedded in the target plates (Fig. 2). The density exhibits an exponential increase when approaching the strike zone. The e-folding length in poloidal direction is 17 mm – not taking into account the field line inclination. This exponential increase takes place in the laminar region adjacent to the 'ergodic finger'. The density peaks at the edge of the strike zone and then increases further inside the ergodic finger. Field line tracing shows that the connection length is not continuously increasing towards the ergodic finger; in fact adjacent flux tubes touching the divertor target might originate from very different regions in the plasma edge (cf. Fig. 3). This complex magnetic structure is reflected in the target profiles.

The perturbation is not only restricted to the high field side but extents over the whole plasma edge. At

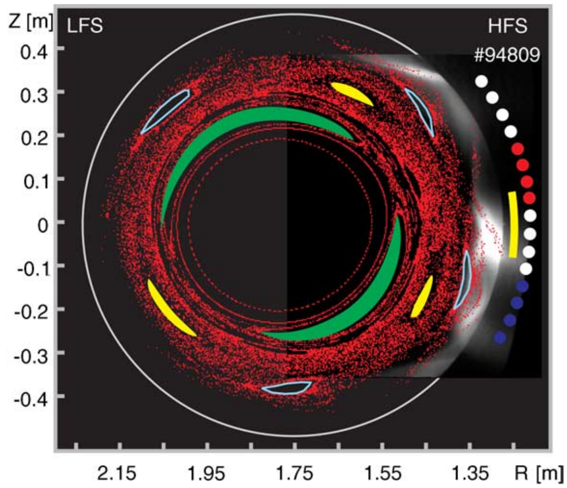

Fig. 1. CIII carbon emission in front of the DED target plates; a Poincaré plot is overlayed. Blue, red and white dots give the position of the DED coils with positive, negative and no current. The current per coil is 1.8 kA which is 48% of the nominal current. For the strike point sweep, the current is transferred to the coils marked in white.

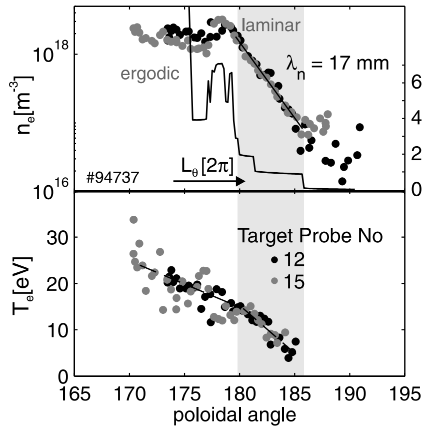

Fig. 2. Poloidal profiles of the target density and temperature in the yellow marked region of Fig. 1 (the poloidal angle is counted counter-clockwise). The field line connection length was calculated not exactly at the probe position but close to it. It is given in number of poloidal turns. The dashed lines indicate two different slopes in the temperature profile and are just guide to the eye. The grey box indicates the laminar region with connection length of mainly one or two poloidal turns.

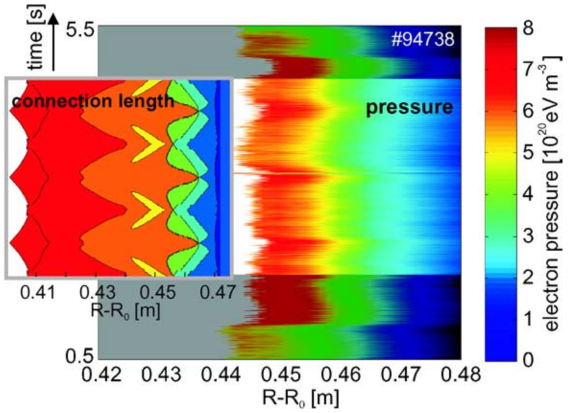

Fig. 3. Electron pressure measured with the helium beam diagnostic at the low field side of TEXTOR versus radius and time. Several sweeps of the DED current were applied in the high-lighted area. The connection length in the observation volume is shown on the left. Blue, light blue, yellow, green, orange and red give connection length of 1, 2, 3, 4, 5 and more than 5 poloidal turns.

the low field side the three-dimensional structure of the DED plasma edge is measured using helium beam spectroscopy. Fig. 3 shows profiles of the electron pressure during the sweep of the strike zone. The variation of the structure at the observation volume is given by the contour plot in Fig. 3. The zones of high plasma pressure are those with a long connection length from deep inside the plasma; the low pressure areas correspond to the laminar zone with short connection length. This behaviour is common to both operating modes $m/n = 12/4$ and 3/1 and is related to the interplay between the perpendicular transport from the 'ergodic finger' to the laminar flux tubes and the parallel transport in both regions.

3. Divertor properties

The tasks of a divertor are manifold. A divertor has to: (a) handle the power exhaust from the plasma, (b) screen impurities and (c) reduce the impurity production, (d) provide a sufficiently high pumping efficiency, i.e. high neutral pressures and (e) additionally maintain good core confinement. Naturally, these tasks should also be addressed by alternative divertor concepts.

As shown in the previous section, also an ergodic divertor creates strike zones, where most of the particle and power is deposited (q.v. [11]). The width of these strike zones varies between a few centimeter up to 0.2 m, depending on the mode of operation and discharge parameters like for example the q-profile. This power concentration is overcome by the dynamic operation of the DED, which moves the strike zone across a large target area. However, it has to be shown that the other 'good' divertor properties are preserved in dynamic operation.

The magnetic configuration of the plasma edge and especially the width of the ergodic and laminar region is controlled by non-intrinsic parameters. Thus the particle transport between plasma core and edge can be controlled by the divertor settings. It is expected and was already shown at Tore Supra [12], that impurities are well screened by the ergodic edge structure. Also the DED in 3/1 mode gives clear indication for a reduction of carbon in the plasma core. A retention of carbon in the DED divertor region and also in the main chamber was observed in the 3/1 configuration with its broad ergodic layer [13]. First signs for impurity screening were also found in the 12/4 configuration by comparing the CVI emission in the plasma core with the CI radiation at the target plates. The CI emission increased with increasing ergodisation whereas the CVI radiation kept constant. Due to the dependence of the rate coefficients on the plasma parameters, this result has to be confirmed by modelling; experiments with impurity injection are planned.

Impurity production might be reduced by creating a cold and dense divertor plasma, which is also beneficial for high neutral densities. In this respect the high-recycling regime found in axisymmetric divertors is favourable. The magnetic structure of an ergodic divertor and also the transport of particles is – as noted in the previous section – more complex as in an axisymmetric divertor. However, also in ergodic divertors the three regimes – linear, high-recycling and detachment – can be obtained [14]. We investigated the behaviour of the target density and temperature in comparison to the plasma edge density and temperature measured close to the ergodic region at the LFS. Three different density regimes were identified by the dependence of the target density on the edge density in a discharge with DED in 3/1 mode (Fig. 4). The LFS density was taken as a reference instead of the line averaged density in order to distinguish between core and edge transport. This reference is not exactly what is usually called the upstream density. The target density was measured inside the strike zone. At low plasma densities below $\bar{n} = 1.8 \times 10^{19}\,\mathrm{m}^{-3}$ a linear regime with $n_{\mathrm{target}} \sim n_{\mathrm{edge}}^{1.1}$ exists, medium plasma densities result in the high recycling regime with $n_{\mathrm{target}} \sim n_{\mathrm{edge}}^{3.2}$. The divertor detachment sets in at $\bar{n} > 2.8 \times 10^{19}\,\mathrm{m}^{-3}$ and leads to an rapid decrease of the target density, while the plasma edge density at the LFS remains increasing. The electron temperature at the target is about 10 eV when the detachment sets in. Recombination processes can be ruled out as the dominant driving mechanism for the detachment at these high temperatures. Indeed, spectroscopic measurements do not indicate volume recombination for the discharge investigated here. Such a type of detachment was

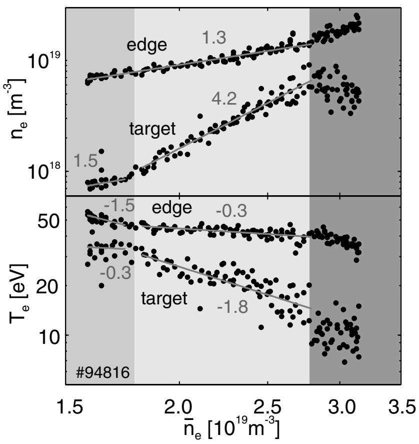

Fig. 4. Target parameters measured by Langmuir probes and plasma edge parameters measured by the helium beam diagnostic at the low field side. The numbers are the exponent according to $n, T \sim \bar{n}^{\alpha}$. The discharge was heated by NBI and the total input power is $P_{tot} = 850$ kW; the perturbation field is at 50%.

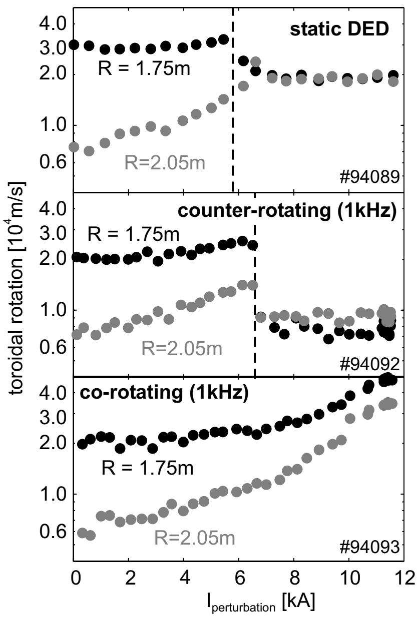

Fig. 5. Toroidal plasma rotation measured with CXRS in the plasma core ($R = 1.75$ m) and edge ($R = 2.05$ m) as function of the total perturbation current. The dashed line indicates the onset of a 2/1 tearing mode.

also observed in the ergodic divertor of Tore Supra and possible mechanisms are discussed in [15]. However, density limit discharges may also end with the formation of a MARFE in the vicinity of the strike zone which moves along the ergodic fingers towards the plasma center and leads to a disruption.

4. Plasma rotation

Beside the divertor properties described above the DED has the additional feature to strongly influence the plasma rotation. Fig. 5 gives the toroidal rotation at the plasma edge (at 65% of the minor radius) and core as a function of the perturbation current in the DED coils. In 3/1 mode a positive current is flowing in 8 DED coils and a negative one in the other eight coils. The current I_{DED} is the total current in a set of eight coils, which is proportional to the perturbation field. The maximum I_{DED} is in static operation for 3/1 and 12/4 mode 30 kA. This reduces to 21 kA in AC operation due to the 90° phase shift of the currents.

Three different scenarios are shown in Fig. 5, one with static perturbation field and two with 1 kHz rotation of the DED field. The rotation of the perturbation field in AC operation is either in co-direction or in counter-direction with respect to the plasma current. Common to all operating scenarios is the increase of plasma rotation with the DED current for low perturbation level. The edge rotation is already increased at very low DED current whereas the increase of rotation in the plasma core is delayed. Especially the dependence of the plasma rotation on the perturbation field is the same in all cases. This suggests that the toroidal rotation for low perturbation amplitude is influenced by the change in the magnetic topology rather than by a torque transfer from the rotating perturbation field. At a certain threshold a 2/1 tearing mode is excited by the perturbation field [16] for static and counter-rotating perturbation and the plasma rotation is strongly reduced. Only for co-rotating perturbation the plasma rotation continuous to increase up to the maximum applied DED current. Also in the 12/4 mode an increase of the edge toroidal rotation by up to 20% was found at 50% of the nominal perturbation field. A stronger influence on the rotation in 12/4 mode might be expected at radii further outward, i.e. closer to the ergodic layer.

5. Conclusions and outlook

In its first year of operation, the dynamic ergodic divertor has shown to provide a safe power exhaust and beneficial divertor properties like a high-recycling regime and efficient impurity screening. On top of the divertor action, the DED gives the opportunity to control plasma properties like the plasma rotation. The strong influence on the plasma rotation might even open the way to a better plasma confinement. The further analysis of these properties requires a detailed understanding about the transport mechanism in the complex magnetic structure. In this respect the code EMC3-EIRENE can give important insight. This 3D fluid code was developed for the edge plasma of stellarators and was recently adapted to the DED configuration [17]. Also the compatibility of these divertor properties with dynamic operation is one of the next tasks. For a more detailed characterisation of the plasma edge, additional edge diagnostics like the helium beam spectroscopy at the high field side and a diagnostic neutral beam to measure the poloidal rotation will be available soon.

Beside the divertor aspects, the perturbation field of the DED can be exploited to study the influence of error fields on MHD effects like mode locking [16]. As shown in the previous section, the DED field in 3/1 operation excites above a certain threshold tearing modes. It is for example a 2/1 tearing mode which is present in the discharge shown in Fig. 1. Thus the vacuum field is deformed and presumably leads to the outward shift of the $m = 4$ detected by the CIII emission. Applying electron cyclotron heating these modes can be suppressed or removed [18]. In 12/4 mode up to the maximum available DED field no excitation of tearing modes was observed so far.

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