High-Frequency Operation of the Dynamic Ergodic Divertor (DED)

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Abstract. After the introduction of the experimental options with the DED, the dynamic features of the rotating DED field are emphasised. The rotating perturbation field induces a shielding current which is modelled under different assumptions. A result of the interaction of the shielding current with that of the DED coils is a torque exerted by the coils on the plasma. The location of the maximum of this torque with respect to the frequency depends critically on the width of the shielding current. The toroidal velocity of the plasma is first computed from the torque, then the radial electric field is estimated on the basis of a revisited neoclassical theory.

1. Introduction

A problem for fusion devices will be the highly concentrated heat flux in the scrape-off layer which 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 extremely high for any material choice to handle. To mitigate the problem, the concept of a radiative mantle has been introduced and basic investigations have been performed e.g. on the TEXTOR tokamak. A similar aim - namely to distribute the heat flux over a large wall area - is shared by the new TEXTOR proposal, the Dynamic Ergodic Divertor (DED)[1] which is presently under construction. It is expected that the DED will create an ergodic boundary layer of the plasma[2] and thus allow for improved screening of impurities, for optimised use of noble impurities under high performance RI-mode operation, and for enhanced particle removal by a pump limiter. The expression "dynamic" refers to a rotating perturbation magnetic field imposed by the DED coils. For the rotation, different frequencies are foreseen such as a few Hertz for distribution of the heating pattern of the divertor strike zones over the large area of the divertor target plate, or frequencies up to 10 kHz which can lead to an unlocking of modes or impose a differential rotation in the plasma edge and improve confinement.

In this context, the high frequency operation of the DED at frequencies between 1 kHz and 10kHz is of particular interest. The 4-phase AC current in the DED coils generates a rotating magnetic field pattern which imposes a torque at the plasma edge. The force underlying the torque is directed mainly in the poloidal direction while a relatively small fraction (10%) is oriented toroidally; this force generates a radial electric field and a rotation of the plasma. The rotating field induces shielding in the highly complicated ergodic structure, the physics of magnetic field line reconnection in this region being a new field for investigation where little is known. Accounting for this, we first calculate the torque generated by the DED coils. This section is followed by an evaluation of the induced toroidal rotation. Estimates of the expected radial electric field and current magnitudes are final topics of this contribution.

2. The Experimental Set-up

The Dynamic Ergodic Divertor (DED) is a new conceptual approach which will be installed in TEXTOR-94 in the year 2001. The main component of the DED is a set of magnetic perturbation coils whose purpose is to ergodize the magnetic field structure in the plasma edge region; these coils are located inside the vacuum vessel at the high field side of the torus as shown in Fig. 1. The set consists of 16 individual coils (4 quadruples) plus two compensation coils. The individual perturbation coils, each winding once around the torus, follow the direction of the equilibrium magnetic field of the plasma edge (i.e. helically); the radial location where coil and field pitches match exactly can be fine tuned e.g. by varying the plasma current. By this means, a resonant effect of the external perturbation field is obtained on the edge plasma at a pre-selected radius whereby a perturbation current of only 15 kA is sufficient to create a substantial stochastic structure.

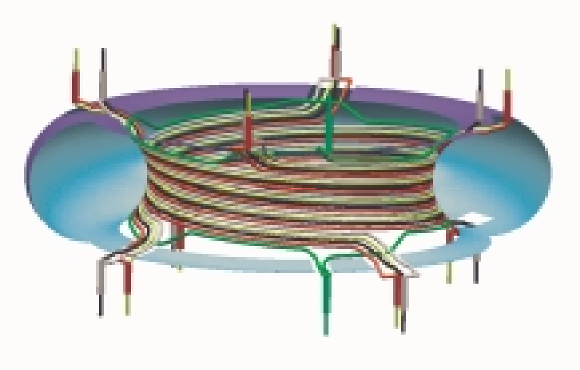

Fig. 1: Experimental set up of the DED-coils. The perturbation coils are located inside the vacuum vessel at the high field side. Each coil goes helically once around the torus and is oriented parallel to the magnetic field lines of the q=3 surface.

The main perturbation modes (number of modes=5) are centred at $m/n = 12/4$; this has been selected because it creates only small local perturbations (magnetic islands) and avoids undesired disturbances in the plasma core. By connecting certain perturbation coils in series, the use of lower dominant m,n is possible which is of interest for exciting and systematically analysing modes located deeper inside the torus. The power supplies are laid out to allow for a superposition of the base 12/4 mode with either the 6/2 mode or the 3/1 mode. This option allows to some degree a decoupling of the perturbation's strength at the plasma edge from its penetration depth into the plasma.

The DED has the unique feature that the perturbation field is not static as in most other devices but that it has the option of rotation. To our knowledge only the small research tokamak CSTN[3] at Nagoya University has similar features and at low perturbation current levels, also the TEXT[4] tokamak. The DED can be operated DC, around 50 Hz or at 7 frequencies in the band from 1 kHz to 10 kHz. At low perturbation current (1.5 kA), the perturbation field can be applied across the whole frequency band of interest for feed-back stabilisation experiments.

3. Dynamic Aspects

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 propagates as a compressional Alfvén wave[6] in the area between coils and resonance layer. At the resonance layer of the plasma different approximations have been made[5]: The interaction layer is described by an annulus of finite resistivity which is a function of the local electron temperature (skin effect). A theoretical uncertainty is the question of the radial width of this layer (2ε). One reasonable choice is the width of the ergodic zone derived from the Poincaré plots which gives a typical value of $2\varepsilon = 2.5$ cm.(a); under a second assumption (b) the characteristic shielding width has been taken as the width of the statically calculated islands.(typically 0.5 cm). This width is compatible with experiments made on TEXT[4] for a situation of a not fully ergodized edge field. Under a third assumption (c) a linear MHD theory has been applied which results in a shielding thickness of less than a millimetre.

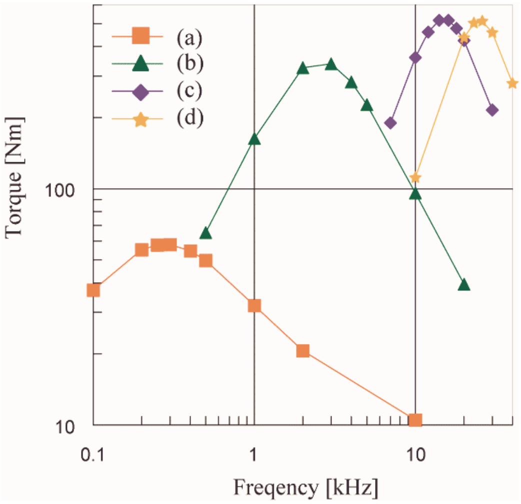

Fig. 2: Poloidal torque for different assumptions about the induced shielding in the plasma. Model (a) has a skin layer of the width of the ergodic layer (2.5 cm), cases (b)-(d) show results from a linearised model where the interaction with the equilibrium current is taken into account.(b) shows the parabolic current distribution case, (c) has a peaking exponent of 2 and (d) a peaking exponent of 5.

It has also been shown that the interaction of the external rotating field with the current driven in the shielding layer results in the transfer of poloidal and toroidal angular momentum between DED-coil and plasma[5]. The maximum poloidal torque applied to the plasma is of the order of 100 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. Examples [(a) - (c)] of this torque calculated for different conditions of the shielding current width are shown in Fig. 11 in a previous publication[5]. Even if a poloidal rotation of the plasma is limited by neoclassical effects, the toroidal torque is similar in magnitude to that imposed by the neutral beams (2 – 6 Nm). In TEXTORA combined operation of the high frequency DED with NBI will allow imposing interesting differential rotations between the plasma edge (action of the DED) and the core (by NBI).

Recently the model (c) [5] has been improved taking into account the interaction of the background plasma equilibrium current with the wave field [3]. As in the previous attempt, the plasma is described by the single-fluid MHD-equations. The essential term for the plasma interaction stems from the linearised radial component of the oscillating plasma velocity:

$$-\rho\frac{\partial \mathrm{v}_r}{\partial t} = i\omega\rho\,\mathrm{v}_r = \frac{\partial p}{\partial r} + j_z^{(1)} B_\Theta^{(0)} + j_z^{(0)} B_\Theta^{(1)} . \qquad (1)$$

Fig. 2 shows the poloidal torque for three different choices of ν which describes the peaking of the current profile. Here ν=1 represents a parabolic profile of the equilibrium current while $\nu \approx 5$ may be more appropriate for a current distribution of $q(a)$=4[7]. The parameters ν in Fig. 2 are ν = 1, 2, and 5. Only for the relatively broad current distribution of $\nu = 1$, is the effect with the equilibrium current distribution dominant.

The equilibrium current on the shielding and on the applied torque is important only for the wide plasma current distribution.For the DED operation in the narrower sense, this condition will not be fulfilled. However, one future DED aim will be the study of the interaction of magnetic island structures with the plasma; the DED will also allow to excite internal modes in a reproducible way. For this case, the interaction with the background current will indeed be important.

4. Estimates of the Toroidal Plasma Rotation.

The velocity pattern and the electric field strength are closely coupled. The sheared velocity distribution is of prime interest because it is presumed to be the main cause for destruction of convective cells in the plasma which are identified as one of the major channels of energy loss in a tokamak. Barriers inside the plasma or at its edge are explained in this way.

The driving force for the plasma rotation is the torque applied by the rotating external DED-field to the plasma. We consider the effect of the underlying force component in the toroidal direction separately from the poloidal one because different models have to be considered. According to conventional neoclassical theory, a free toroidal motion of the plasma is allowed and the accelerating forces are balanced by viscous forces such that we can write

$$\nu^{*}\ \mathrm{v} = \frac{F_t}{M}. \qquad (2)$$

Here ν^{*} is the rate with which the particles in the boundary exchange their momentum with the wall. A characteristic exchange rate between plasma edge and wall is given by the particle confinement time, a quantity which is experimentally available on TEXTOR. To simplify the treatment, a constant value of τ_p = 30 ms is used:

$$\nu^{*} = {}^{1}\!/_{\tau_p} = 1/0.03 = 33\ s^{-1} \qquad (3)$$

The mass M is the total mass of the plasma because we assume that in the toroidal direction the whole plasma will rotate as a rigid body if no additional toroidal forces are applied (e.g. due to NBI). As particle content for the total plasma $N = 2.4\mathrm{x}10^{20}$ particles are taken, which corresponds to a medium density value of TEXTOR.-94 ($\overline{n}_e = 4\cdot 10^{19}\ m^{-3}$, $n_{e\text{-}edge}$ = $1\cdot 10^{19}\ \mathrm{m}^{-3}$).

The force component in the toroidal direction F_t has been treated in the preceding paragraph; the calculations were done, however, for a non-rotating plasma. The rotation is taken into account by writing (F_0 being the force in a frame without plasma rotation):

$$F_t = F_0\left(1-\frac{\mathrm{v}}{\mathrm{v}_0}\right);\ \ \mathrm{v}_0 = {}^{R\Omega}\!/_{n_{eff}} = 1.1\cdot 10^{5}\ m/s \qquad (4)$$

where R = 1.75 m is the major radius, $\Omega = 2\pi\ 10^{4}\ \mathrm{s}^{-1}$ is the angular frequency of the DED field, and n_{eff} = 1 is the toroidal mode number under consideration; here we have chosen the m/n = 3/1 mode for the DED to obtain the highest plasma rotation. With these assumptions, the toroidal rotation velocity of the plasma is determined as

$$\frac{\mathrm{v}_{tor}}{\mathrm{v}_0} = \frac{\frac{\tau_p}{M}\cdot\frac{F_0}{\mathrm{v}_0}}{1+\frac{\tau_p}{M}\cdot\frac{F_0}{\mathrm{v}_0}} = 0.66 \qquad (5)$$

This estimate shows that the DED field will most likely induce a substantial toroidal plasma rotation velocity; the plasma velocity, however, does not reach the full velocity of the perturbation field but remains at about half of this value.

5. The Poloidal Force

The following considerations on the radial electric field and poloidal force are based on the revisited neoclassical transport theory [8,9,10]. In the conventional theory, usual viscous effects lead to a finite poloidal velocity, but the toroidal velocity - and hence the radial electric field - cannot be predicted. In the revisited version, the gyroviscosity [8,9] and (at very high collisionalities [8-10]) energy transfer between electrons and ions along the magnetic field lines are taken into account, these processes allowing calculation of both the toroidal rotation and the radial electric field.

In the following estimations we take a constant poloidal force of F_{pol} = 100 N to act on the whole plasma, corresponding to a force per particle of $f=F_{pol}/2\pi^2Ra^2N$. If the average density is $N = 4x10^{19}$ m^{-3}, we obtain $f = 3x10^{-19}$ N. This would lead, order of magnitude wise, to a relative velocity between electrons and ions of $U_{r,e} - U_{r,i} = -(f_{\theta,i} + f_{\theta,e})/eB = 1\, m/s$ if the plasma did not react. This drift velocity of ions and electrons in opposite radial directions corresponds to a total current of about I_r = 50 A if an edge electron density of $n_{e\text{-}edge}$ = 1x10^{19} m^{-3} is assumed (this value is about the same current as is observed during polarisation experiments). The radial electric field is obtained from $E_r = U_\varphi B_\theta - U_\theta B_\varphi + (eN_i)^{-1}\partial P_i/\partial r$ leading - order of magnitude wise - to a value of $E_r \approx (3-30)\, kV/m$; this is comparable to values reported in H-mode transport barriers and polarisation experiments.

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