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Plasma rotation during operation of the dynamic ergodic divertor in TEXTOR

M. De Bock[1], C. Busch[2], K.H. Finken[2], S. Jachmich[3], R. Jaspers[1], M. Van Schoor[3]

1. FOM institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, Trilateral Euregio Cluster, NL-3430 BE Nieuwegein, The Netherlands, www.rijnh.nl

2. Institute für Plasmaphysik, Forschungszentrum Jülich GmbH, Association EURATOM-FZJ, Trilateral Euregio Cluster, D-52425 Jülich, Germany

3. Laboratory for Plasma Physics, Association EURATOM-Belgian State, KMS-ERM, Trilateral Euregio Cluster, B-1000 Brussels, Belgium

1. INTRODUCTION

Plasma rotation and velocity shear is believed to be closely related with heat and particle transport. Velocity shear is thought to reduce turbulence correlation lengths and thus reducing transport [1]. Apart from transport, the MHD behaviour of plasmas is influenced by plasma rotation. The rotation velocity of a plasma has a clear effect on the penetration of external perturbation fields [2,3]. On the other hand perturbation fields influence plasma rotation, e.g. through magnetic braking [2]. The influence of external perturbation fields on plasma rotation will be discussed in this paper.

The tool used for these experiments is the Dynamic Ergodic Divertor (DED) that is installed at the TEXTOR tokamak (circular, R = 1.75 m, r = 0.46 m) [4]. This DED consists of a set of helical perturbation coils at the high field side of the torus. Different configurations of connecting the coils to the power supplies result in perturbations with mode numbers m/n = 3/1, 6/2 or 12/4. The current fed through the coils can be DC or AC in two opposite directions, resulting in a static respectively dynamic, i.e. rotating, perturbation field. Co-rotation (AC^-) is defined by toroidal projection of the phase velocity of the perturbation field in the direction of the plasma current, and the poloidal component in the direction of the poloidal magnetic field (which is also the ion diamagnetic drift direction). The DED gives the means to apply a wide range of perturbation fields onto the plasma. The data shown in this paper were mainly obtained during static and dynamic 3/1 operations of the DED, as the effects were strongest in these cases.

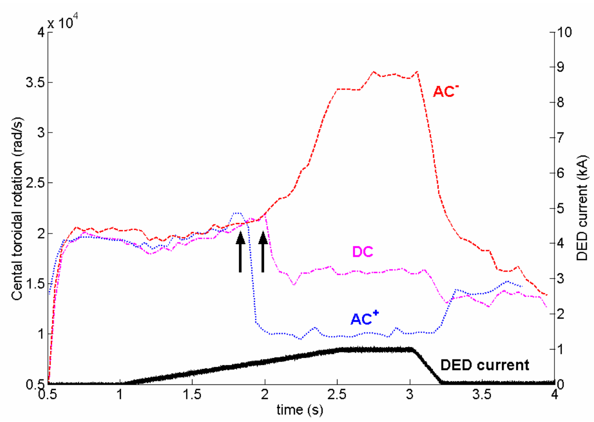

Figure 1 *Increase of the toroidal plasma rotation for DED in DC, AC^+ and AC^- operation. For DC and AC^+ operation a 2/1 tearing mode is excited, for a certain value of the DED current, which breaks down the rotation (black arrows). For AC^- the threshold for 2/1 mode excitation lies much higher and the rotation increases as long as the DED current increases.*

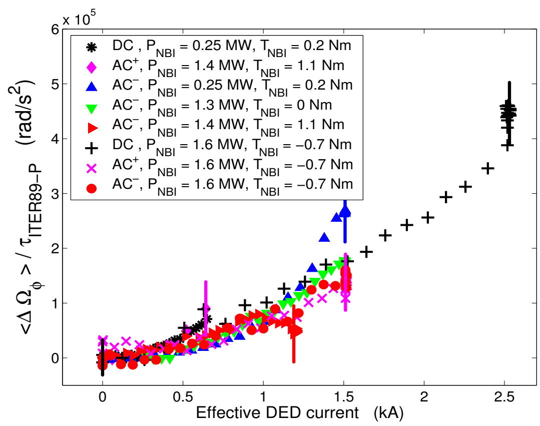

Figure 2 *The change in rotation, scaled with energy confinement time, plotted against the DED current. The increase in co-direction occurs for DC, AC^+ and AC^- operation, for different power inputs and different momentum inputs.*

The observed effect of the DED field on plasma rotation can be divided in two regimes: a change of plasma rotation in the co-direction – independent of the rotation direction of the perturbation field – for low perturbation field amplitudes and a plasma rotation that is connected with the DED rotation frequency once the perturbation field amplitude exceeds a certain threshold value (Figure 1 and [5]) and a tearing mode at the q=2 surface is excited.

2. CHANGE IN PLASMA ROTATION WITH DED BEFORE MODE ONSET

Operating the DED below the threshold value for mode onset, initially co-rotating plasmas show an increase in rotation velocity – measured with charge exchange recombination spectroscopy (CXRS) in the range ρ=0-0.6 – while counter-rotating plasmas slow down, indicating the change in plasma velocity is always in the co-direction. The shape of the rotation profile does not change, it is only lifted. Figure 2 plots the increase in co-rotation versus effective DED current for different situations. It is seen that the increase in co-rotation scales with the DED current. It was found that differences in the amount of generated rotation could be related to the momentum confinement time, where the momentum confinement time was assumed to be equal to energy confinement time (τ_e). In Figure 2 the change in rotation is therefore scaled with the τ_e (using the ITER89-P scaling); τ_e going from 28 ms, for the shots with high power input, to 60 ms for those shots with low input power. Also in 12/4 operation of the DED, where the perturbation is much more located at the edge of the plasma, the toroidal rotation shows an increase in the co-direction. However, this change in rotation is mostly smaller than in 3/1 DED operation.

The poloidal velocity at the edge of the plasma – measured with both CXRS and passive emission of CIII just inside the last closed flux surface – shows a change in the co-direction as well during DED [6]. Also turbulence rotation measured with reflectometry shows an increase in the ion diamagnetic drift direction during DED [7]. A fourth observation made during DED operation is a positive change ΔE_r of radial electric field at the very edge of plasma [8]. This is seen in Figure 3 where the floating potential profile in the outer few centimetres of the plasma gets less steep during DED operation. Also sign reversal of the edge electric field has been observed in some cases [8].

As the change in rotation is always in one direction and scales with the DED current, rather than with the DED frequency (DC, AC +1 kHz and AC -1 kHz) a resonant coupling of the dynamic perturbation field with the plasma seems incapable to explain the observed behaviour [9]. According to this model, the torque applied to the plasma by the DED field, and therefore the change in plasma rotation, depends on the relative velocity between plasma and perturbation field, conflicting with the experimental results of Figure 2.

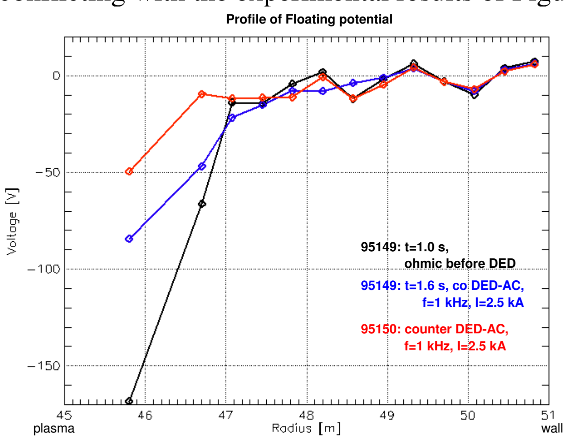

***Figure 3** The plasma potential in ohmic discharges before DED and during AC^+ and AC^- DED operation. For both AC^+ and AC^- operation the floating potential in the plasma becomes less negative[8].*

A kinetic treatment of this resonant interaction, including finite larmor radius effects, could overcome this discrepancy [10]. For a finite electron diamagnetic velocity the torque resulting from the rotating perturbation field tends to bring the electron fluid to the rest frame of this field. For perturbation field frequencies lower than the electron diamagnetic frequency (in the lab frame not the plasma frame) the torque would then be in the ion diamagnetic direction even for a perturbation field rotating in the electron diamagnetic direction. However, a dependence on the relative velocity between perturbation field and plasma still remains.

Apparently a non-resonant effect plays a more dominant role. The DED creates a laminar zone where loss of electrons occurs along open field lines. This loss current gives rise to a positive change in the electric field as seen in Figure 3. The radial electron current will be balanced by a neoclassical current j_r which in turn gives rise to a j_rxB force that is for both toroidal and poloidal rotation in the co-direction, independent of the direction of the DED field. Furthermore, increasing the amplitude of the perturbation will increase the width of the laminar zone, leading to a larger loss current [11]. Moreover, a perturbation field width higher m and n numbers will in general have a narrower laminar region and thus a smaller change in E_r and plasma rotation, consistent with measurements of the change in plasma rotation [11]. The radial return current j_r can be expressed by equation (1), where σ_{lam} represents the radial projection of the parallel conductivity along the open field lines and depends on the field line diffusion (D_{FL}) [12]:

$$j_r = \sigma_{lam}\left(-E_r + \frac{T_e}{eL_n} + \frac{1.71T_e}{eL_T}\right) \quad (1)$$

The j_rxB term results in an extra source term in the momentum balance equation (2), where T_{CXedge} and T_{NBI} are the torques imposed by neutrals in the plasma edge and the neutral beams [13]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial mnv_\phi}{\partial r}\right) = -\frac{j_r B_\theta}{(2\pi)^2 Rr} + (T_{CXedge})_\phi + (T_{NBI})_\phi \quad (2)$$

Integrating (2) results in a change of the toroidal velocity in the plasma core in the order of $1\text{x}10^4$ rad/s for typical temperature and density gradients and a D_{FL}=$2\text{x}10^{-6}$ m, consistent a perturbation coil current of 1.5 kA in 3/1 operation.

3. PLASMA BRAKING AND 2/1 TEARING MODE ONSET

Once the DED perturbation reaches a high enough amplitude a 2/1 tearing mode is excited. ECE, Mirnov and CXRS data indicate that the rotation frequency of this mode is equal to the perturbation field frequency; i.e. the 2/1 tearing mode is locked to the DED field. During the onset of the 2/1 mode plasma rotation changes very rapidly form a peaked – due to momentum input by the neutral beams – to a flattened rotation profile (Figure 4).

It is seen in Figure 4 that the braking of the plasma occurs over the whole plasma and not only at the resonant surface where the 2/1 tearing mode is located. Such behaviour has also been seen at perturbation field experiments performed at JET [2]. For these experiments a weak resonant braking of the plasma at the q=2 surface is observed before perturbation field penetration, while a strong anomalous braking over the whole rotation profile occurs at the moment of penetration. The braking before mode penetration is not observed in the TEXTOR experiments, but the braking at mode onset shows reasonable agreement with the observations in the JET experiments. The fast braking of rotation at mode onset can be attributed to the non-linear growth of the tearing mode. Additionally break up of the axisymmetry due to the magnetic islands leads to a neoclassical toroidal viscous force that causes the global braking of plasma rotation.

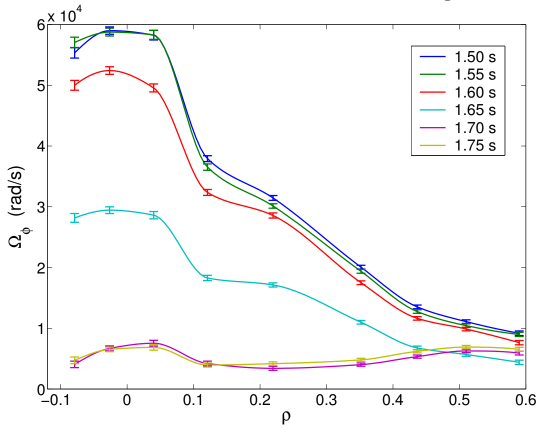

Figure 4 *Profile evolution of the toroidal rotation during mode onset. Plasma braking occurs over the whole profile, not only at the resonant surface ($\rho \simeq 0.55$). Braking time is about 100 ms.*

The threshold for excitation of the 2/1 mode depends on the plasma conditions. It increases with β_p, counter-rotation and n_e [3]. Experiments done in at several tokamaks and theoretical modelling show an increase in perturbation threshold for higher plasma velocities, but no influence of the direction of rotation [2,14]. In TEXTOR however an asymmetry between co- and counter-rotation thresholds is observed, where co-rotation decreases the penetration threshold, while counter-rotation increases it [3].

4. CONCLUSIONS

It is believed that an electron loss current along the open field lines in the laminar layer created by the DED results in a changed radial electric field at the plasma edge. This electric field causes in turn an increase of toroidal (and poloidal) co-rotation. Momentum transport from the plasma edge to the core leads to a change in rotation over the whole plasma. So far no evidence has been found for an electrodynamic torque at the resonant surfaces. Possibly the influence of electrodynamic forces at the resonant surfaces – before field penetration – is negligible compared to the contribution of the changed radial electric field.
At high perturbation amplitudes field penetration occurs; a 2/1 tearing mode is excited and locked to the perturbation field frequency. The non-linear growth of this island is accompanied by strong magnetic braking. The anomalous rotation damping is global and can be explained by a neoclassical toroidal viscous force that appears when axisymmetry assumptions are no longer valid. The threshold for field penetration is asymmetric in co- and counter-rotation, in contrast to threshold scalings on other tokamaks and in theory.

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