Study of suppressed tearing modes seeded with non-axsisymmetric magnetic perturbation fields at the ASDEX Upgrade tokamak

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1. Introduction

Non-axisymmetric magnetic perturbation (MP) fields arise in every tokamak e.g. due to misalignments in the positioning of the external field coils. Many tokamaks are equipped with an additional set of coils, which produce a 3D MP field, which is mainly used to either compensate for the intrinsic error field or to mitigate ELMs.

These perturbation fields give rise to a global plasma response. Depending on plasma parameters such as rotation and resistivity, they can either deform the plasma, mainly at the boundary, or lead to the formation of magnetic islands (mode penetration) by reconnection, and ultimately to a slowing down, locking to the vessel wall and the occurrence of a disruption. This can be avoided due to the fact that magnetic islands normally rotate together with the plasma. This hampers magnetic islands to lock and screens the effect of the external MP field. However beside driving magnetic reconnection, MP fields additionally exert torques to the plasma, which slow down the plasma rotation. This rotation damping again increases the sensitivity to MP field induced effects and favours the locking of islands.

Several studies exist where the formation of islands and rotation damping due to MP fields are investigated and modelled. These modelling results can explain experimental phenomena, but no direct quantitative comparison with experimental data has been done. In this paper dedicated experiments are presented which have been performed in order to investigate the evolution of the rotation effects during the mode penetration process in detail. In addition a direct modelling of these experimental data using a non-linear error-field penetration model [1] of Fitzpatrick is presented. This model is developed for low beta, circular plasmas, and describes the influence of MP fields on the plasma response, including magnetic island formation and induced torques. The study has been performed at the ASDEX Upgrade (AUG) tokamak in low collisionality ($\nu^*_{\mathrm{core}} \approx 0.01$) L-mode plasmas. AUG is equipped with a set of 16 in-vessel saddle coils [2]. These B-coils enable the generation of resonant and non-resonant, static and rotating MP fields.

2. Basic theory

The mode penetration process is mainly dominated by resonant MP field effects. Since the non-resonant effects, like the NTV, are assumed to be small at AUG only the resonant contributions are considered in the following calculation.

In a conducting plasma the resonant MP field components induce helical shielding currents at the corresponding resonant surfaces (r_s). Depending on the phase of the shielding current, it can influence the plasma or a magnetic island in two ways. The sine component of this current leads to an electromagnetic torque in the presence of a current at the resonant surface, which influences the rotation frequency ω. Secondly the cosine component of the current modifies the island stability and hence the evolution of the island width W. This can be expressed in two equations based on a model derived by Fitzptarick [1].

$$\frac{dW}{dt} \approx 2m\left(\frac{W_{\rm vac}}{W}\right)^2 \cos(\Delta\phi) - \Delta' + \Delta_{\rm pol} \quad (1)$$

$$\frac{d\omega}{dt} \approx (W\, W_{\rm vac})^2 \sin(\Delta\phi)\, \delta(r - r_s) + T_{\rm intrinsic}(r) + T_{\rm viscous}(r) \quad (2)$$

The evolution of the full island width W is described by the modified Rutherford equation (MRE) (eq. 1). The equation of motion (EOM) (eq. 2) describes the evolution of the island or plasma frequency ω at the resonant surface. In this model the amplitude and phase of the resonant MP field is parameterised using the concept of a vacuum island W_{vac}, which is the island resulting from the superposition of the equilibrium and the perturbation field. The parameter $\Delta\phi$ is the phase difference of the O-points of the vacuum island and the actual magnetic island. In addition to the resonant MP field effects also the Delta prime term ($r_s\Delta' = -2m$) and the polarisation current effect ($\Delta_{\rm pol} \propto -1/W^3$) according to [3] are included in the MRE. The EOM is extended (see also [4]) compared to [3] in order to included a radially dependent viscous and intrinsic torque. Both are adjusted to match the initial velocity profile without MPs. Equations 1 and 2 are a coupled system of non-linear differential equations which describes the slowing down, locking and growth of a pre-existing island [5] but also the mode penetration by the MP field.

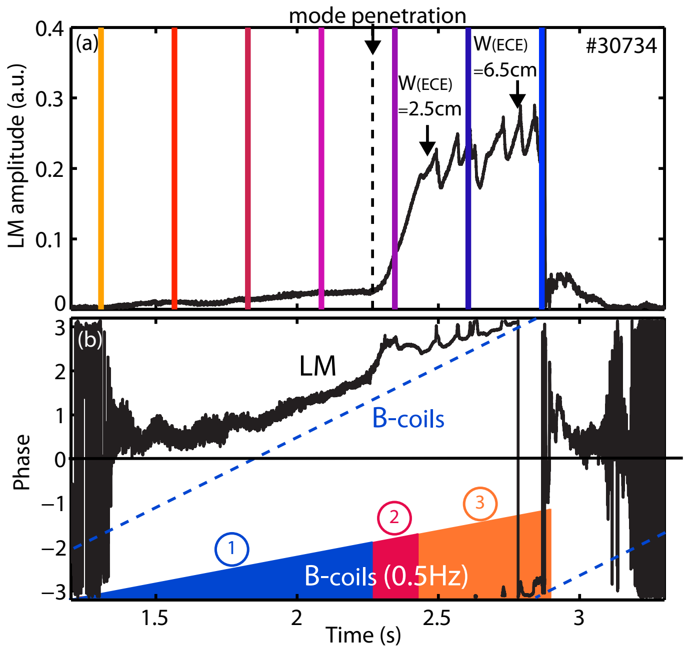

Figure 1: (a) Amplitude and (b) phase of the n=1 plasma response measured with saddle coils at the HFS [6]. In (b) also the programed phase of the rotating B-coils is indicated in blue.

3. Experimental results

In AUG mode penetration caused by resonant MP fields is only observed in low density ($< 2.5 \times 10^{19}\ 1/m^3$), low rotation discharges. Therefore the toroidal plasma rotation was only measured within NBI beam blips. In addition the MP field frequency was restricted to 0.5 Hz due a strong shielding of the MP field amplitude at rotation frequencies larger than 1.5 Hz. This is caused by shielding currents induced in the copper structure on which the MP coils are mounted.

By ramping up a slowly rotating MP field three phases can be distinguished (figure 1):
The phase of "linear" plasma response [6] (blue region), where the MP field induces a deformation of the plasma but the amplitude is not high enough to drive full magnetic reconnection. In this phase the plasma response follows the MP field amplitude. In the second phase of mode penetration (red region) the MP field exceeds a threshold which initiates full forced reconnection at the q=2 surface. The related non-linear formation of a (2/1) magnetic island is observed in the magnetic data and in the electron temperature. In the third phase (orange region) a new 3D equilibrium is established which is interrupted by some minor disruption events which flush out part of the plasma energy. In this phase the island is further growing to a size larger than W_{vac} (≈4.6cm). It is also visible that the island phase decouples from the MP field (different slope of phase in (b)). This means that the island rotates slightly slower than the MP field, due to additional torques acting on the island.

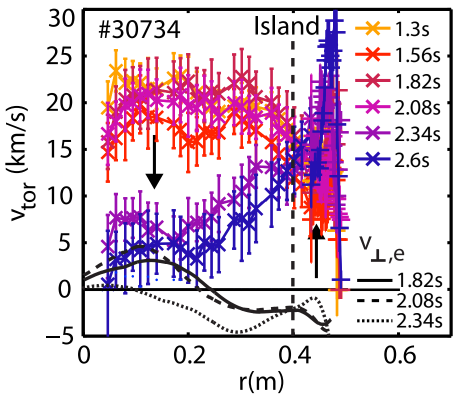

Figure 2: Evolution of the measured toroidal rotation profile and the calculated electron perpendicular velocity.

During the mode penetration process (fig. 2) the core toroidal rotation decreases up to the point of mode penetration. After the mode penetration it drops suddenly and stays almost constant during the locked island phase. In contrast the toroidal rotation at the edge seems to increase like observed at TEXTOR [7]. As theoretically expected the perpendicular electron velocity is around zero. However when a magnetic island of a sufficient size is present also the toroidal plasma rotation at the island surface is expected to be zero. One explanation for this observation is that against expectations the kinetic profiles are not completely flattened inside the island.

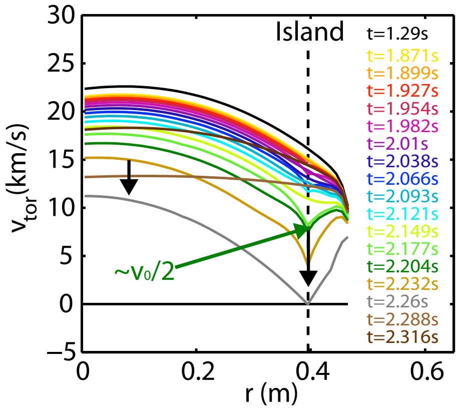

Figure 3: Evolution of the modelled toroidal rotation profile.

In any case these experiments confirm the predicted slow decrease of the plasma rotation towards the time of mode penetration and the small electron perpendicular velocity when an island is formed.

4. Modelling

To model the mode penetration equations (1) and (2) have to be solved simultaneously. Since this is not possible for $W \to 0$ the following substitution has to be made: $W^3 \to Y$ and $(1/W^2)\, dW/dt \to dY/dt$ [3]. In the modelling all quantities are taken from the experiment to be able to make a qualitative but also quantitative comparison. The effects at different resonant surfaces are treated by modelling the radial rotation profile and are coupled via the radially dependent viscous torque in the EOM, whereas the MRE is solved for each surface (q=1,2,3) individually.

Taking the experimental vacuum values for W_{vac} (7, 5 and 3cm at q=1,2,3) results in a slowing down of the plasma rotation (fig. 4 (blue)). Small islands are induced at the three surfaces but the overall influence of the MP field on the island stability and plasma rotation is too small to achieve mode penetration. To achieve mode penetration and a concomitant stronger slowing down of the toroidal plasma rotation, W_{vac} at q=2 had to be increase by 40 % (fig. 4 (black)) to 7cm. With this the theoretically expected time variation of the $\Delta\Phi$ and W before the mode penetration ((c) and (d)) and the later abrupt growth of a (2/1) island are well reproduced. In the modelling the (2/1) island grows to maximum W_{vac} due to the choice of Δ' and Δ_{pol} and the missing bootstrap drive in the model. Only small islands with $W \ll W_{vac}$ are induced at q=1 and 3 which decay as soon as the MP field is switched off. Also the large island at q=2 decays without MP field due to the missing bootstrap drive. The global toroidal plasma rotation (fig. 3) decreases strongly and stops at the q=2 surface. This is in contradiction to the experiment where only $v_{\perp,e}$ is around zero but v_{tor} remains around 10 km/s. In both modelled cases the contribution of Δ' and Δ_{pol} are negligibly small compared to the influence of the resonant MP field, which means that the plasma is in the Rutherford regime.

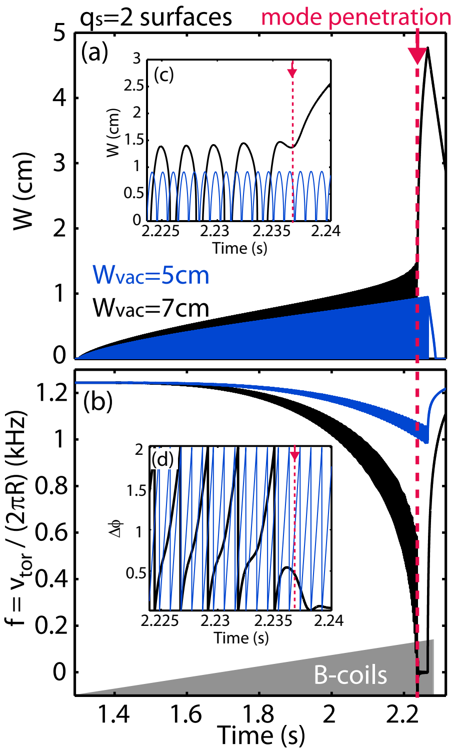

Figure 4: Modelled (a) size and (b) frequency at $q = 2$ for two different $W_{vac}(q = 2)$. (c) Detailed evolution of the island width and (d) differential phase.

5. Conclusion and Outlook

Mode penetration is achieved in low density, low rotation L-mode discharges at AUG. Plasma rotation measurements confirm the predicted decrease of plasma rotation before the mode penetration. The mode penetration process with the concomitant slowing down of the plasma rotation can be modelled but higher MP fields are required compared to the experiment. This indicates that effects are missing in the model e.g. the non-resonant braking by NTV, which enhance mainly the effect on the plasma rotation. Therefore additional effects are planned to be implemented in the basic model and also the difference in the evolution of the toroidal rotation in the modelling and the experiment will be investigated in more detail..

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