

## Tearing mode seeding by externally provided resonant magnetic perturbations

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### Introduction

Physics of forced magnetic reconnection in magnetically confined plasmas is crucial to understand because it leads to formation of magnetic islands which can degrade the plasma confinement and eventually cause disruptions. This type of magnetic reconnection is thought to be responsible for the appearance of neoclassical tearing modes after sawtooth crashes [1] and for the formation of magnetic islands when non-axisymmetric magnetic perturbations (MP) are externally applied [2].

Externally applied MPs cause a global plasma response. The perturbation field amplitude as well as plasma parameters like toroidal rotation and resistivity define the effects on a plasma such as a deformation of the flux surfaces or magnetic island formation [3]. Additionally to drive magnetic reconnection, MP produce torques to the plasma slowing down the plasma rotation.

The results of numerical simulations of the forced magnetic reconnection with the toroidal, two fluids, non-linear MHD code JOREK [4] are presented. A set of parameters is chosen to be as close as possible to one of the low collisionality L-mode plasma discharges with externally applied MP fields from ASDEX Upgrade.

### Recall of the experimental results

Here we refer [2] to the ASDEX Upgrade discharge number #30734. Three phases were distinguished in this experiment while the current in the MP field coils with the dominant mode number  $n = 1$  was slowly ramped up (figure 1 a)): In the first phase, which was called "weak response phase", the plasma response follows the amplitude of the magnetic perturbation. Therefore, we assume that the residual perturbation on the resonant surface is not sufficient to drive magnetic reconnection due to a strong screening. In the second phase the perturbation exceeds a certain threshold and becomes strong enough to force the reconnection at the  $q=2$  surface. The resulting  $(2/1)$  magnetic island is observed in the magnetic data and in the electron temperature. In the third phase the island growth slows down and is interrupted by some minor disruptions.

During the first phase (figure 3) the core toroidal rotation [5] decreases up to the point of mode penetration. It then suddenly drops and stays almost constant during the whole third phase. Contrary the edge toroidal rotation seems to increase. The perpendicular electron velocity profile was calculated using the experimentally measured toroidal rotation and electron temperature profiles. The mode penetration corresponds to the drop to zero of the perpendicular electron velocity as it is expected. Indeed, in the presence of perpendicular electron velocity, static RMPs in the laboratory frame correspond to time varying RMPs in the electron fluid frame, and therefore induce an electron current hindering their penetration [6, 7]. These experiments confirm the 'expected' slow decrease of the plasma rotation towards the time of mode penetration and the small electron perpendicular velocity when an island is formed.

### Numerical simulations with JOREK

In order to be able to quantitatively compare simulations to experiments, simulation parameters were chosen to be as close to the experiment as computationally possible. In particular, the experimental profiles of the density, temperature and toroidal velocity as well as the experimental Lundquist number  $S = 1.4 \cdot 10^8$ , perpendicular heat diffusion coefficient  $\chi_{\perp} \sim 1m^2/s$  and parallel heat diffusion coefficient  $\chi_{\parallel} \sim 10^9\chi_{\perp}$  at the plasma center were used.

Two sets of simulations were carried out to be compared to experimental observations. The lower curve on figure 1 b) is obtained with diamagnetic effects, toroidal rotation and neoclassical toroidal viscosity included. It is important to underline that, additionally to the physics considered in the work of Fitzpatrick [8], diamagnetic effects are important in our case since the contribution of the diamagnetic velocity to the perpendicular electron velocity is almost equal to the contribution of the toroidal one. This branch corresponds to the "weak response" phase on

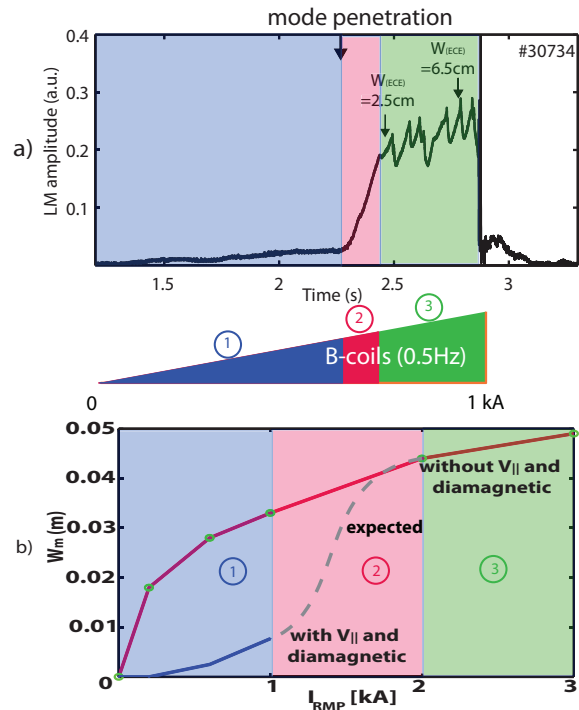


Figure 1: (a) Amplitude of  $n = 1$  plasma response and evolution of the current in the B-coils (below). Taken from [2] (b) Result of the JOREK simulations of island width with (lower branch) and without (upper branch) toroidal rotation, diamagnetic effects and neoclassical toroidal viscosity. Dashed line represents expected transition between the phases.

figure 1 a). The upper curve in figure 1 b) does not assume toroidal and diamagnetic rotations. This corresponds to the case of  $V_{\perp,e} = 0$  at the resonant surface (figure 3) i.e. already damped rotation. The described assumption is consistent with the third phase, with a perturbation which penetrated to the resonant surface and caused a large island.

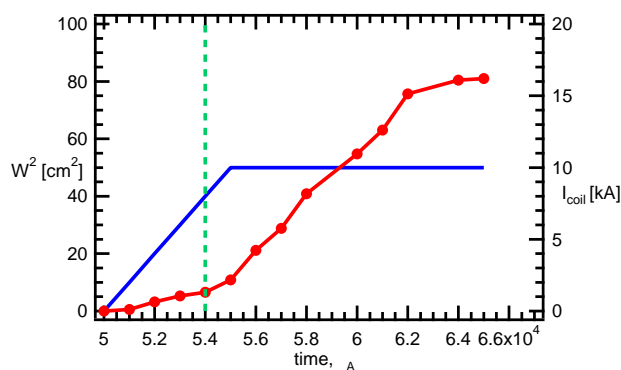


Figure 2: Square of the island size (left axis) and current in the RMP coils (right axis).

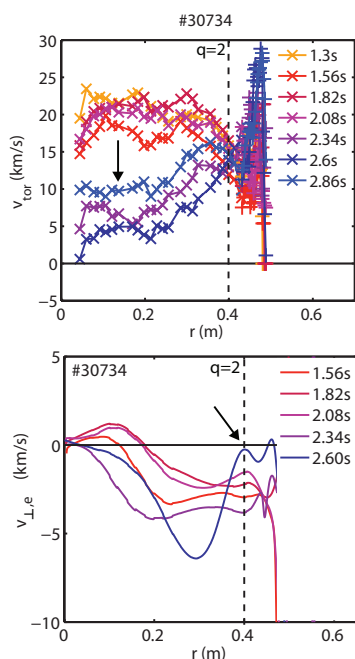


Figure 3: Experimental toroidal rotation (upper) and perpendicular electron velocity (lower) profiles

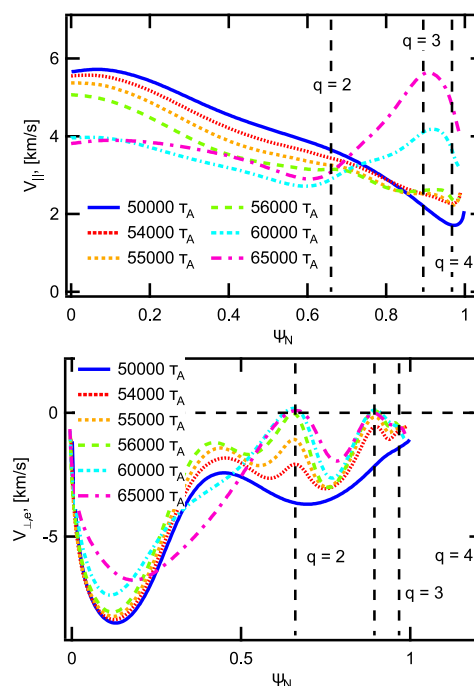


Figure 4: Toroidal rotation (upper) and perpendicular electron velocity (lower) profiles from JOREK simulations

Also, in order to reduce the computational time, the simulations with a Lundquist number  $S = 10^7$  and a value of toroidal velocity  $V_{tor} = 0.1V_{tor,exp}$  were performed. A lower value of the Lundquist number corresponds to a higher resistivity and therefore faster resistive mode

dynamics. The results of this simulation are shown in figure 2. The square of the island width is proportional to the current perturbation at the resonant surface and, as a result, in the magnetic saddle coils. Such a representation simplifies a comparison to the experimental observations. Similar to the experimental observations, three phases are observed. First, the plasma exhibits weak response to the applied perturbation. Once the threshold is reached, the mode growth accelerates until the final mode saturation. The physical mechanism of such behavior is clarified by Fig. 4. Initially the non-zero electron perpendicular velocity leads to the screening of the magnetic perturbation. However, it starts to drop down due to the loss of the perpendicular component of the toroidal velocity and flattening of the temperature leading to the loss of diamagnetic component. Finally, once the condition  $V_{\perp,e} = 0$  is satisfied, the transition phase is reached. In this phase the perturbation propagates without screening, forcing a magnetic reconnection at the resonant surface. The core toroidal velocity shown in Fig. 4 decreases. At the same time a strong increase of the edge toroidal velocity which starts around the  $q = 2$  surface and has a peak around  $q = 3$  surface is observed.

## Conclusions

Two fluid, non-linear MHD simulations are performed with the input parameters close to the experimental ones. All three phases of the magnetic perturbation penetration observed in the experiment: "weak" response, a fully formed island state and a transition between these two regimes are reproduced. A decay of the core toroidal rotation and its increase at the edge similar to the experimental one is observed. A decay of the electron perpendicular velocity is fully consistent with the experimental observations, meaning that the drop of  $V_{\perp,e}$  to 0 corresponds to the perturbation penetration in both cases.

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