Numerical study of tearing mode seeding by externally provided perturbation of resonant surface

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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 tearing modes after sawtooth crashes [1] and for the formation of magnetic islands when non-axisymmetric magnetic perturbations (MP) are externally applied [2]. Both cases were extensively investigated on the ASDEX Upgrade tokamak.

Such MP, 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. Additionally to driving magnetic reconnection, magnetic perturbations produce torques to the plasma slowing down the plasma rotation. In this paper we present first results dedicated to the direct quantitative comparison of numerical simulations with the experiments which have been performed in order to investigate the evolution of the rotation effects during the mode penetration process in detail. The experiments, we refer to, have been performed at the ASDEX Upgrade tokamak in L-mode plasmas [2]. In ASDEX Upgrade the non-resonant effects, like the neoclassical toroidal viscosity (NTV), are assumed to be small, thus only the resonant contribution of magnetic perturbations(RMP) is considered here. The results of numerical simulations which we present in this work, are obtained with the toroidal, two fluids, non-linear MHD code JOREK [3]. Simulation parameters are chosen to be as close as possible to the experimental values.

Recall of the experimental results

Here we refer to the ASDEX Upgrade discharge number #30734. Three phases were distinguished in this experiment while current in the MP field coils with the dominant mode number $n = 1$ was slowly rumped up (figure 1 a)): In the first phase, which was called "linear", the plasma response follows the amplitude of the magnetic perturbation. In this phase screening is strong and the residual perturbation on the resonant surface is not sufficient to drive magnetic reconnection. 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 it is interrupted by some minor disruptions.

During the first phase (figure 2) the core toroidal rotation [4] 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 the motion of the electron fluid across the field lines at the resonant surfaces screens the RMPs. In the presence of such a motion, 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 [5, 6]. 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.

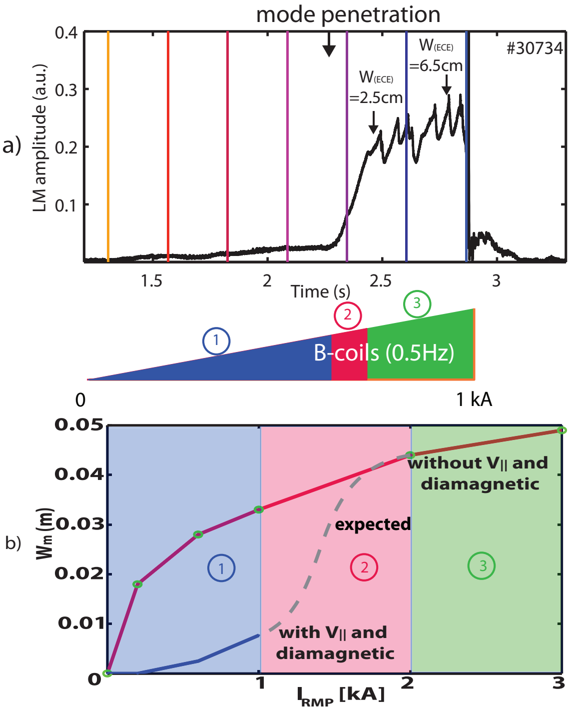

Figure 1: *(a) Amplitude of* $n = 1$ *plasma response and evolution of the current in the B-coils (below). (b) Result of the JOREK simulations of island width with (lower brunch) and without (upper brunch) toroidal rotation, diamagnetic effects and neoclassical toroidal viscosity. Dashed line represents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

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 $\chi_\perp \sim 1 m^2/s$ and parallel heat diffusion coefficient $\chi_\perp \sim 10^9 m^2/s$ at the plasma center were used. Two sets of

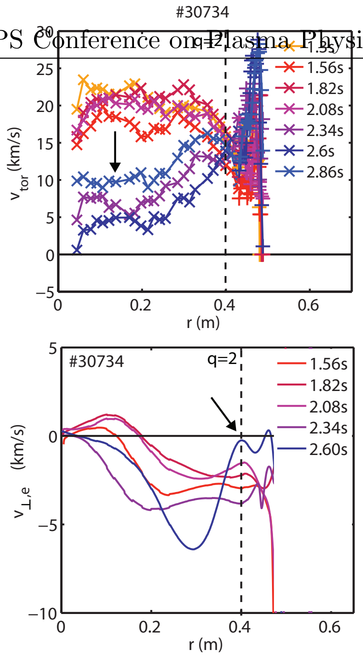

Figure 2: *Experimental toroidal rotation (upper) and perpendicular electron velocity (lower) profiles*

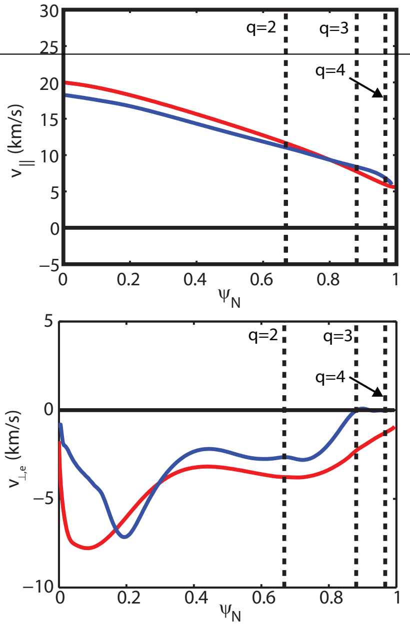

Figure 3: *Toroidal rotation (upper) and perpendicular electron velocity (lower) profiles from JOREK simulations*

simulations were carried out to be compared to experimental observations. The lower curve on the 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 [7], 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. In this case small islands are formed on the resonant surface $q = 2$ together with the kinking of this surface, as seen on the Poincare plot (figure 4 (right)). Their width is typically below the diffusive length-scale W_c [8] and thus do not cause significant flattening of the temperature profile and therefore are not visible on ECE diagnostic in the experiment. For the input parameters mentioned above, diffusive length scale is $W_c \sim 3.2cm$. This branch corresponds to the "linear" phase on figure 1 a). The upper curve on the same figure does not assume toroidal and diamagnetic rotations. This corresponds to the case of $V_{\perp,e} = 0$ at the resonant surface (figure 2) 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 4 (left)). In order to reproduce the second phase, i.e. the transition from the "linear" phase to the fully formed island, we run the simulations with a current in the RMP coils $I_{RMP} = 2kA$. This value is higher than the experimental one, but it should also lead to the more efficient plasma breaking and thus faster transition, which would allow to decrease the computational time. The results of this simulation are show in figure 3. The core toroidal velocity decreases, at the same time the edge toroidal velocity tends to increase. This corresponds to the experimental behavior in the "linear" phase. The perpendicular electron velocity also exhibits behavior similar to the one reported in the experiment. It drops to zero at the resonant surfaces

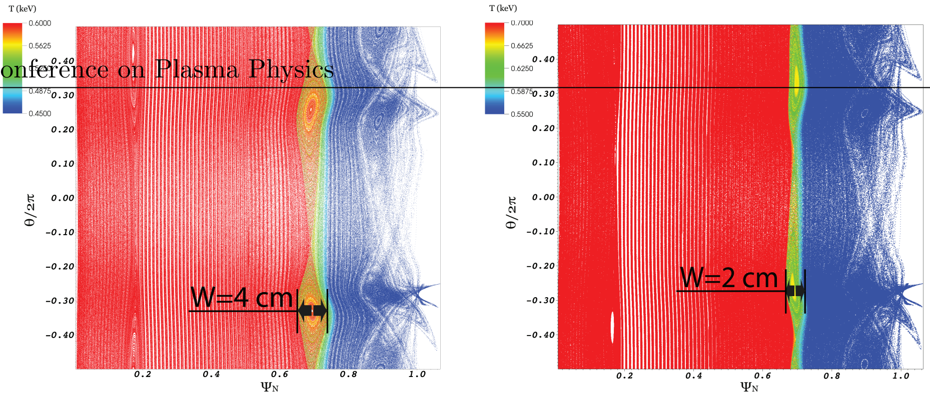

Figure 4: *Poincare plot from simulation with no diamagnetic and toroidal rotations included and no neoclassical toroidal viscosity (left) and with these effects included (right).* $I_{RMP} = 2kA$

$q = 3$ and $q = 4$. It also decreases at $q = 2$. However the electron perpendicular velocity does not satisfy the condition $V_{\perp,e} = 0$ yet, which is necessary for perturbation propagation. There are two main components in $V_{\perp,e}$ leading to a screening of RMP in our case: diamagnetic rotation and perpendicular component of the toroidal velocity. As the island grows, it leads to a flattening of the temperature profile and as a result to the loss of the diamagnetic component. This effect is particularly strong when the island size exceeds the diffusive length-scale, i.e. the parallel heat transport dominates over the perpendicular one leading to the strong flattening of the temperature. The island size in the simulations is still below W_c, thus diamagnetic screening is still strong. Therefore, these simulations will have to further be continued to reach the transition point.

Conclusions

The toroidal, two fluids, non-linear MHD simulations are performed with the experimental input parameters. Two phases of the magnetic perturbation penetration observed in the experiment, "linear" response and fully formed island state, are reproduced. The simulation aimed to reproduce the transition between these two phases shows a decay of the toroidal rotation and $V_{\perp,e}$ similar to the experimental one. However the transition point hasn't been reached yet and longer simulations are required. More detailed quantitative comparison to the experiments, like comparison of the fully formed island width, the transition threshold, transition and phase evolution of the mode etc., is planned.

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