Tearing mode seeding by external magnetic perturbations

D. Meshcheriakov[1], M. Hoelzl[1], V. Igochine[1], S. Fietz[1], V. Bandaru[1], F. Orain[1,2], S. Günter[1], H. Zohm[1], ASDEX Upgrade Team and MST1 Team*

[1]*Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching b. M., Germany*

[2]*Centre de Physique Théorique, Ecole Polytechnique, CNRS, F-91128 Palaiseau Cedex, France*

**See author list of MST1 Team in H. Meyer et al., Nucl. Fusion 57,102014 (2017)*

Introduction

The (Neoclassical) Tearing Mode is a plasma instability that can potentially cause degradation of plasma confinement and even disruptions. These modes are typically marginally stable in present day devices and develop once being seeded by a sufficiently large perturbation. Non-axisymmetric external magnetic perturbation (MP) fields arise in every tokamak e.g. due to the imperfections in the external coils positions. Additionally many tokamaks, like ASDEX Upgrade (AUG), are equipped with, so-called, Resonant Magnetic Perturbation coils which produce a perturbation field intended towards the control of Edge Localized Modes and other magnetohydrodynamical (MHD) instabilities.

Previous results [1] of numerical simulations of the tearing mode onset with the toroidal, two fluids, non-linear MHD code JOREK [2] already showed good qualitative agreement with the experimental observations [3].

This work has been extended to parameters as close as possible to the ones of a low collisionality L-mode discharge in ASDEX Upgrade and simulation results are compared to both the experiment and analytical theory in detail.

Recall of the analytical model

An analytical model describing the evolution of magnetic islands in the presence of MP fields in a cylindrical geometry has been derived by Fitzpatrick in [4]. Externally applied MP can be treated as modified edge boundary conditions. The interaction of the helical perturbation current associated to a magnetic island results in the modification of the island width evolution and a rise of a local $\mathbf{j} \times \mathbf{B}$ torque in the vicinity of the island. If the island frequency deviates from its natural frequency, the plasma exerts a viscous restoring torque on the island. The general non-linear tearing mode stability problem is then treated as a balance of the plasma inertia in the island and the sum of the local electromagnetic and viscous torques. On the other hand, an island width evolution is defined by the local in-phase sheet currents. 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 a current hindering their penetration [5, 6].

Steady state solution is obtained when the viscous torque is exactly balanced by the electromagnetic one. Solutions corresponding to different values of initial plasma rotation (and, as a result, island natural frequency) are shown in Fig. 1. For large initial plasma rotation, a bifurcation is observed and the plasma undergoes a sudden transition at half the initial rotation frequency to a non-linear island state, characterised by a low plasma rotation and a large magnetic island. Such a transition is generally called mode penetration. It corresponds to a transition from a "weak plasma response phase" to a non-linear phase observed both experimentally [3] and numerically [1]. Due to the bifurcation, a hysteresis is expected for the back transition.

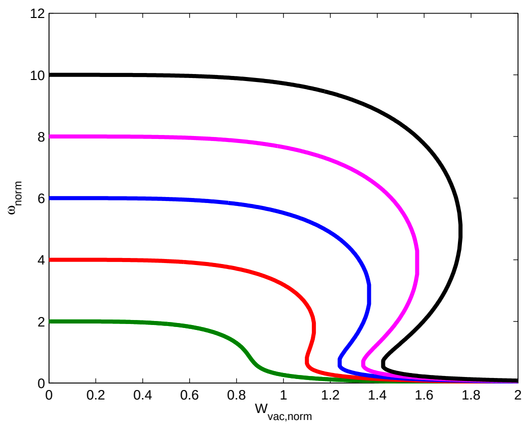

Figure 1: *Steady state solutions for the interaction of a visco-resistive tearing layer with a static magnetic perturbation. For several initial plasma rotations ($\omega_{0,norm}$), the final plasma rotation (ω_{norm}) is plotted versus the vacuum island size ($W_{vac,norm}$). See [4] for the normalization.*

Numerical simulations with JOREK

In order to be able to quantitatively compare simulations to experiments, parameters were chosen to be as close to the experiment as possible. Additional scans allow to study non-linear transition. In particular, the experimental profiles of the density, temperature and toroidal velocity as well as realistic perpendicular ($\chi_\perp \sim 1m^2/s$) and parallel heat diffusion coefficient ($\chi_\parallel \sim 10^9\chi_\perp$) at the plasma center were used. In order to reduce the computational time, simulations were performed with a Lundquist number $S = 10^7$, while the experimental Lundquist number is $S = 7 \cdot 10^7$. A lower value of the Lundquist number corresponds to a higher resistivity and therefore faster resistive mode dynamics.

Scans in both the plasma rotation velocity and the perturbation amplitude were carried out to be compared to experimental observations. It is important to note that $\mathbf{E} \times \mathbf{B}$ and diamagnetic drift 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.

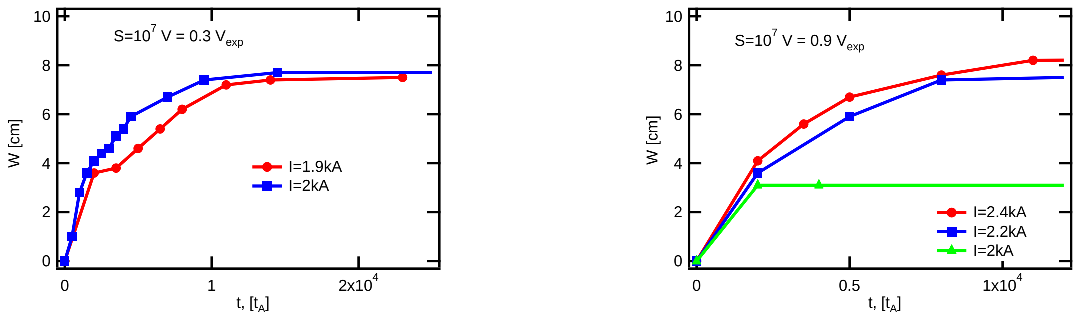

Figure 2: *Time evolution of the magnetic island size for different RMP coil currents. The left plot corresponds to a normalized electron rotation of* $V_{tor} = 0.3V_{tor,exp}$ *and the right one to* $V_{tor} = 0.9V_{tor,exp}$

Scans in the perturbation amplitude for the values of toroidal velocity $V_{tor} = 0.3V_{tor,exp}$ and $V_{tor} = 0.9V_{tor,exp}$ are shown in Fig. 2 corresponding to different rotation frequencies. The perpendicular component of the toroidal velocity is one of the contributors to the island natural frequency. Higher values of the toroidal velocity (V_{tor}) correspond to larger island natural frequency ($\omega_{0,norm}$). As the current in the RMP coils corresponding to a perturbation amplitude decreases, mode penetration slows down. Ultimately, if the strength of the perturbation is not high enough for a given plasma rotation, the electromagnetic torque is not sufficient to compensate the viscous one, and therefore the transition to the penetrated state does not take place. This situation corresponds to the upper branches in Fig. 1. The transition from weak response phase to fully formed island phase was observed experimentally [3]. Also the time, required for the mode penetration, increased with decrease of the RMP current. The threshold for the transition to the penetrated state was observed for RMP coil currents between $0.1kA$ and $0.2kA$. Lower values of the critical perturbation current in the experiment can partly be explained by the absence of the Neocalssical Toroidal Viscosity (NTV) in the simulations, which provides additional torque to the plasma in the presence of non-axisymmetric magnetic field

The scan in the plasma rotation shows (Fig. 3) delay in the mode penetration as the initial toroidal velocity increases. This is equivalent to moving from a lower to an upper curve in Fig. 1 and, as predicted by the analytical model, if rotation is strong enough for a given perturbation amplitude, there is no full slow down of the plasma and, as a result, RMP field remains partially screened (lower curve in Fig. 3). It is interesting to point out that, in the case of mode penetration, final saturated island size is defined only by the current in RMP coils and is independent of the original plasma velocity.

An additional set of simulations was performed to study the expected hysteresis (Fig. 1). The saturated island obtained in the simulation with $V_{tor} = 0.9V_{tor,exp}$ and $I_{RMP} = 2.2kA$ was chosen

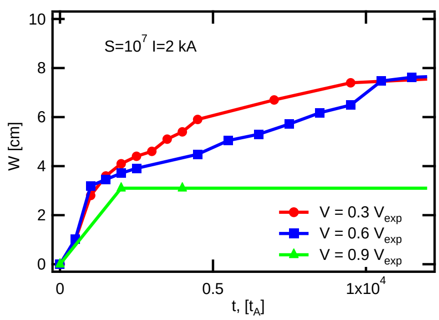

Figure 3: *Time evolution of the magnetic island size for different values of the initial toroidal rotation velocity. Current in RMP coils $I_{RMP} = 2kA$*

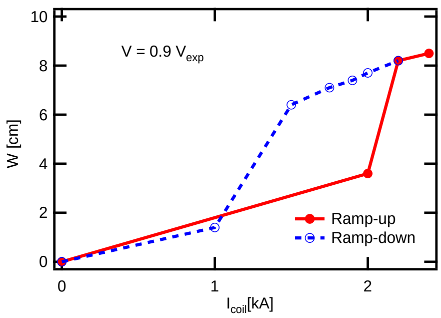

Figure 4: *Time evolution of the magnetic island size for different values of the current in RMP coils. Initial toroidal rotation velocity $V_{tor} = 0.9V_{tor,exp}$*

as a starting point and the RMP current was ramped down. It is shown in Fig. 4 that the reverse transition to a high rotation, small island regime takes place between $1kA$ and $1.5kA$ which is considerably lower than the value for a forward transition in between $2kA$ and $2.2kA$.

Conclusions

Two fluid, non-linear MHD simulations were performed with the input parameters close to the experimental ones. The simulation results were compared to the analytical model for MP penetration derived in a cylindrical geometry. Scans in a toroidal plasma rotation and a perturbation amplitude confirm the analytically predicted existence of the thresholds for the transition into low rotation regime in both quantities. A hysteresis during the RMP current ramp-down is also observed.

Acknowlegments

This work was carried out under the auspices of the Max-Planck-Princeton Center for Plasma Physics. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] *D. Meshcheriakov et al., proc. 44nd EPS conf. plasm. phys.* **P5.139**, *(2017).*

[2] *G. Huysmans and O. Czarny, Nuclear Fusion* **47**, *(2007).*

[3] *S. Fietz et al., proc. 42nd EPS conf. plasm. phys.* **P1.123**, *(2015).*

[4] *R. Fitzpatrick, Nuclear Fusion* **33**, *(1993).*

[5] *E. Nardon et al., Nuclear Fusion* **50**, *(2010).*

[6] *F. Orain et al., Phys. Plasmas* **20**, *102510 (2013).*