Modeling edge MHD instabilities and their interaction with Magnetic Perturbations in ASDEX Upgrade

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[7]*See H. Meyer et al., Nuclear Fusion FEC 2016 Special Issue (2017)*

Introduction: Edge Localized Modes (ELMs) are magnetohydrodynamic (MHD) instabilities occuring in high confinement regime of tokamak plasmas, quasi-periodically expelling strong bursts of plasma out of the confined region. Their potentially deleterious effect on divertor targets makes it necessary to find reliable ELM control methods. The application of non-axisymmetric resonant magnetic perturbations (RMPs) proved its efficiency in either mitigating or suppressing ELMs and is therefore foreseen in ITER [1]. The original purpose of the RMP application was to create a stochastic layer at the plasma edge due to magnetic reconnection (so-called tearing response) on resonant surfaces, thus increasing the edge perpendicular transport and reducing the edge pressure gradient below the ELM-triggering threshold [2]. Significant progress has been made in the last decades to understand the plasma response to RMPs: plasma flows are likely to induce response currents counteracting the effect of RMPs and preventing magnetic reconnection [3]. In addition to this potentially screened tearing response, the amplification of metastable peeling-kink modes by RMPs was recently identified to be correlated with the most efficient ELM mitigation or suppression in DIII-D and ASDEX Upgrade (AUG) [4,5]. The poloidal mode coupling between peeling-kink and tearing modes may simultaneously induce the amplification of the tearing response when peeling-kink modes are excited by RMPs [6,7]. which we term tearing-kink amplification in the following. The paper investigates the influence of strong or weak tearing-kink amplification onto ELM-RMP interaction..

This interaction is modeled with the non-linear resistive MHD code JOREK [8] including two-fluid effects [9]. Modeling is performed using equilibrium reconstruction and profiles from experimental ASDEX Upgrade discharges. First, the experimental case studied and the set-up of modeling is described. Second, the two opposite effects of RMPs on ELMs, observed in modeling, are described: no effect on ELMs *versus* full ELM suppression. Third, a scan on diamagnetic rotation is shown to highlight the bifurcation from unmitigated ELM to ELM mitigation and to ELM suppression.

Input and simulation set-up: Equilibrium reconstruction and plasma parameters from the AUG discharge #31128 were used as input for modeling. First, the axisymmetric equilibrium including diamagnetic flows, neoclassical effect and toroidal rotation source is calculated. In a second step, non-axisymmetric toroidal Fourier modes $n > 0$ are added and the non-linear evolution between these modes is studied. In these simulations, modes $n = 0$ to 8 are considered. The main limitation of this modeling is that resistivity was increased by a factor of ~ 20 due to numerical limitations. In AUG experiments, $n = 2$ perturbations are applied by 2 rows of 8 in-vessel coils. Depending on the phase $\Delta\Phi$ between upper and lower coil currents, the poloidal mode spectrum (m) differs, inducing a different plasma response. For the series of discharges considered (#31128 and #30835), the strongest ELM mitigation was obtained for $\Delta\Phi = +90°$ while no ELM mitigation was obtained for $\Delta\Phi = -90°$. Modeling showed that the tearing-kink amplification at the edge was maximum in the first case (called here "resonant") and minimum in the second case ("non-resonant"). We consider here the ELM interaction with the RMP spectrum in both "resonant" and "non-resonant" cases.

ELM-RMP coupling: In this section, the non-linear interaction between $n = 1 - 8$ modes is studied in the three following cases: without RMPs and with RMPs in both configurations. Without RMPs, the peeling-balloning (PB)-unstable profiles induce the exponential growth of medium n modes, $n = 7$ and 8 being the most unstable modes (Fig.1(a)). Note that $n \geq 9$ were neglected in modeling since they are linearly less unstable. After the linear growth, non-linear coupling between medium n-s induces the drive of low-n structures until all modes saturate and the crash occurs.

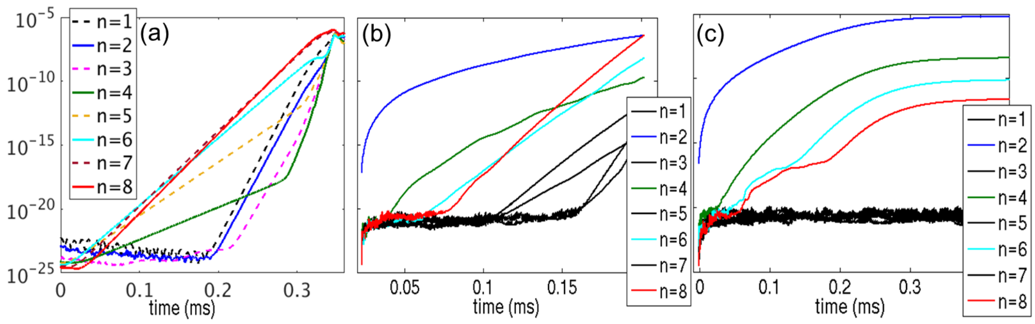

FIG. 1: Time evolution of the magnetic energies of $n = 1 - 8$ modes: (a) without RMP, (b) with non-resonant RMP, (c) with resonant RMP.

When RMPs are applied, two opposite types of behaviour can be observed depending on the tearing-kink amplification: when this amplification is minimum ("non-resonant" case Fig.1(b)), the $n = 2$ RMPs drive the growth of the $n = 2$ mode. The $n = 4$ mode follows the same evolution as $n = 2$ with lower amplitude due to quadratic coupling of $n = 2$. However the $n = 6$ and $n = 8$ modes are not affected by RMPs and grow exponentially, leading to an ELM crash, similarly to the case without RMPs. The growth rate of the $n = 8$ mode is just slightly reduced as compared to the case without RMPs, due to the slight degradation of the pedestal by RMP application. On the contrary, when the tearing-kink amplification is maximum ("resonant" case, Fig.1(c)), the external drive of the $n = 2$ mode is strong enough to non-linearly drive all even modes $n = 4, 6$ and 8, then these modes don't grow linearly anymore as ELMs, but follow the dynamics imposed by external perturbation. Thus a continuous MHD activity is present at the plasma edge instead of the ELMs, resulting in a full stabilization of the ELMs. As for the odd modes, they are completely damped by the activity of even modes. An important question is then: what induces the ELM suppression? Is it the reduction of the pressure gradient by RMPs? To check this, a simulation is run with a pressure profile reduced exactly as in the ELM suppression case, but this simulation is run **without** RMP. In this case, edge-localized modes $n = 6$ and 8 grow exponentially and lead to an ELM crash. Only the linear growth rate is reduced by the degradation of the pressure gradient. Therefore, ELM suppression in our simulation requires toroidal mode coupling with the dominant external RMP mode, the reduction of the pedestal pressure is not sufficient (note that small $n = 6, 10...$ sidebands produced by RMPs are neglected).

Bifurcation from unmitigated ELM to ELM mitigation and suppression:

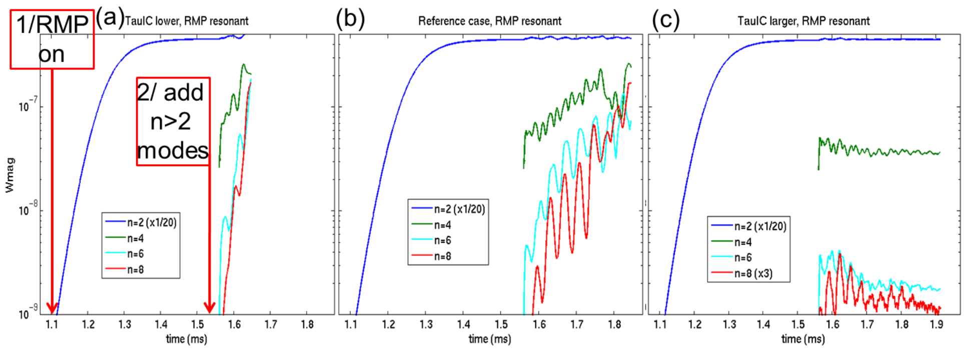

FIG. 2: Magnetic energy of the $n = 2, 4, 6$ and 8 modes for reduced, standard and enhanced value of the diamagnetic rotation. The $n = 2$ mode, driven by RMPs, is included first alone in simulation to model a $3D$ non-axisymmetric equilibrium. In a second step, other harmonics $n > 2$ are added in the simulation.

Since diamagnetic rotation is known to affect both the ELM dynamics and RMP penetration, its impact on ELM-RMP interaction is studied for three amplitudes: reduced by 20%, realistic amplitude and increased by 20%. In the "resonant" case, for low diamagnetic rotation, the mode coupling with RMP is low, such that $n = 6$ and 8 are barely influenced by RMPs and grow exponentially, leading to an ELM crash (Fig.2(a)). At medium perpendicular rotation (realistic value, Fig.2(b)), the $n = 6$ and 8 modes have a 4 times smaller initial linear growth rate and then non-linearly saturate at a lower level: this regime possibly corresponds to the ELM mitigation regime. Due to the coupling with $n = 2$, these modes also show an oscillation frequency corresponding to the fluctuation frequency of the $n = 2$ mode: $f = nqV_\theta/(2\pi a) \sim 20kHz$, where $n = 2$, $q = 4$ is the location where the modes are maximum, V_θ is the poloidal velocity at $q = 4$ and a is the minor radius. At even larger diamagnetic rotation (Fig.2(c)), the toroidal coupling between $n = 4, 6, 8$ modes and $n = 2$ RMPs is large enough to get full ELM suppression: the medium-n modes show small fluctuations at very low amplitude, decreasing until the modes become static. In this case, all even modes are fully locked to the external RMPs. A similar bifurcation from ELM mitigation to ELM suppression when increasing the RMP amplitude was reported in [10]. Note that a similar variation of the diamagnetic rotation in the "non-resonant" configuration did not allow to observe ELM suppression: a larger perpendicular rotation decreases the linear growth rates of modes but $n = 6$ and 8 systematically grew into an ELM in all three cases. It is interesting to compare the 2 regimes obtained in "resonant" configuration (fluctuating modes in ELM mitigation and low amplitude static modes in ELM suppression) with the analysis of the mode spectrum through measurement of magnetic fluctuations in the experimental discharge #33133. In this discharge with higher triangularity, a bifurcation from ELM mitigation to ELM suppression was observed. In the ELM mitigation phases, rotating modes are observed at the edge (negative mode numbers in Fig.3(a)), while in ELM suppression phases (Fig.3(b)), no fluctuating modes are observable: this may suggest the mode locking to the static RMPs. Note that positive mode numbers correspond to core modes. Closer comparison between experiment and modeling will be done to check the systematic presence or absence of rotating modes in both regimes.

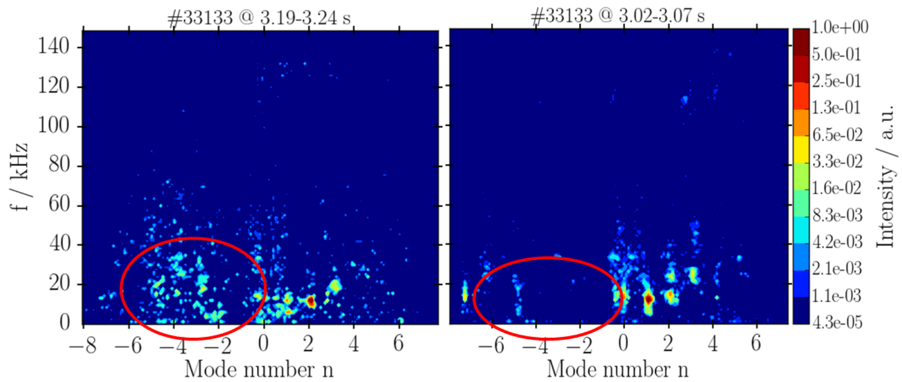

FIG. 3: Mode intensity depending on the toroidal mode number and the frequency in (a) ELM mitigation and (b) ELM suppression phases.

Conclusion: In configurations where both tearing and edge-kink response are amplified by RMPs, ELM mitigation or suppression is observed in the modeling of AUG discharges. The ELM suppression is not only due to the reduction of the pressure gradient generated by RMPs, but is induced by the toroidal coupling of medium-n modes with $n = 2$ RMPs. This coupling prevents unstable modes to grow into an ELM and these modes instead saturate at lower level, inducing a continuous transport instead of the ELM crash. The difference between mitigation and suppression is likely related to a different strength of this coupling: at low coupling, peeling-ballooning modes are rotating and are not locked to RMPs (potentially mitigation), while for stronger coupling, all harmonics become static and are driven by RMPs (potentially suppression). In this case, the saturated modes are possibly saturated kink modes similar to EHO observed in QH-mode [11].

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Acknowledgement: *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.*