RMP ELM suppression analysis by means of a low-dimensional model system for quasi-periodic plasma perturbations

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Edge localized modes (ELM) are a significant concern in magnetically confined toroidal fusion plasmas because they can rapidly erode plasma facing material surfaces, cause edge melting and surface cracking. They also reduce the coupling efficiency of rf antennas and trigger other MHD instabilities. The importance of ELM control was realized many years ago and different means of their control were developed. ELM suppression/control is required for a steady state operation of ITER. The natural ELM frequency should be decreased by a factor ~ 30. Two main control strategies are foreseen for ITER: 1) injection of small deuterium pellets, 2) resonant magnetic perturbations (RMP). We investigate possible mechanisms of RMP ELM suppression in a low-dimensional model system for quasi-periodic plasma perturbations.

I. Introduction

In ASDEX Upgrade, a stable operation in a type-I ELMy H-mode at rather low ELM frequencies can be provided by means of pellet injection [1]. Subsequent experiments [2] demonstrated that the ELM frequency becomes identical to the driving frequency in a steady state and is about twice the value corresponding to an intrinsic ELM event. In [3] it was shown that in DIII-D plasmas RMPs completely eliminate ELMs by inducing a chaotic behaviour in the magnetic field lines, which reduces the edge pressure gradient below the ELM instability threshold. First experiments with magnetic perturbations in ASDEX Upgrade [4] show clear mitigation of ELMs in H-mode plasmas above a certain density threshold, but in contrast to DIIID results no density pump-out is observed.

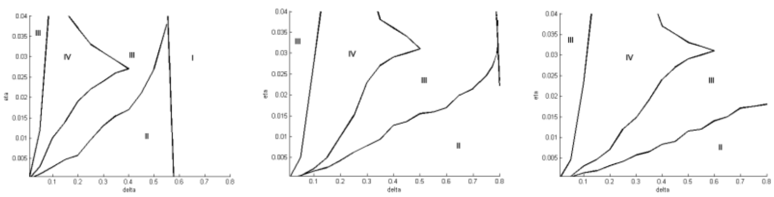
II. A low-dimensional model system

Our low-dimensional model [5] is given by the system of equations:

$$\begin{cases} \dfrac{d^2}{dt_n^2}\xi_n = \left(p_n{}' - 1\right)\cdot \xi_n - \delta \cdot \dfrac{d}{dt_n}\xi_n \\ \dfrac{d}{dt_n}p_n{}' = \eta \cdot \left(h - p_n{}' - \xi_n^2 \cdot p_n'\right) \end{cases} \tag{1}$$

where ξ_n is the amplitude of the displacement of the magnetic field, p_n' is the plasma pressure gradient at the plasma edge, δ is dissipation/relaxation of the instability responsible for the ELM burst, η is diffusion, h is input power in the system, and t_n is time. The index n means that all quantities are normalized. The first equation describes evolution of the magnetic field perturbation and relaxation dynamics. The second equation describes power balance in the system with and without unstable modes.

For all positive values of the parameters δ, η, and h, the system is dissipative. This means that all orbits $\{(\xi_n(t_n), p_n{}'(t_n))\ ,\ t_n \geq 0\}$ asymptotically approach the attractor of the system and the values of ξ_n and $p_n{}'$ exhibit temporal oscillations independently of the initial conditions. However their pattern, damped (I), ELM (II), periodic (III), or stochastic (IV), depends on the parameter values, as shown in Fig. 1.



(a) (b) (c)

Fig. 1. Dynamical zones of oscillations of system (1) for (a) h=1.2, (b) h=1.5, and (c) h=1.8.

III. RMP in the power balance and driver dynamics

Presuming stochasticity hypothesis for the ELM suppression, one can model the density pump-out effect in DIII-D. This implies modification of the second equation (energy balance). The first equation remains the same because the mode dynamics is assumed unchanged. The system is moved into the stable operation region with smaller pressure gradients.

$$\begin{cases} \dfrac{d^2}{dt_n^2}\xi_n = \left(p_n{}' - 1\right)\cdot \xi_n - \delta \cdot \dfrac{d}{dt_n}\xi_n \\ \dfrac{d}{dt_n}p_n{}' = \eta \cdot \left(h - \left[1 + a \cdot RMP(t)\right] p_n{}' - \xi_n^2 \cdot p_n'\right) \end{cases} \tag{2}$$

To illustrate how the model works in the case of RMP, we take the same values of the parameters as in [5]: $\eta = 0.009$, $\delta = 0.2$, and $h = 1.5$, which lead us into the space, where ELMs exist (zone II in Fig. 1b). We consider the function $RMP(t)$ as a single step function, which is switched on at $t_n = 1000$ and switched off at $t_n = 7000$. The corresponding results are shown in Fig. 2 for different perturbation amplitudes.

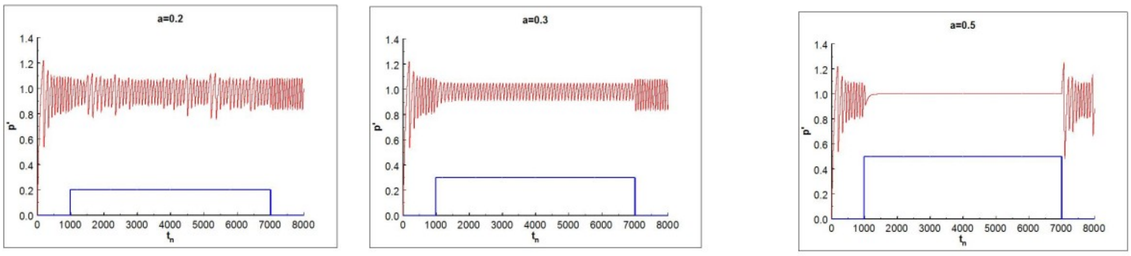


FIG. 2. Plasma pressure gradient (red) and perturbation (blue) as a function of time.

It is seen that with increasing RMP amplitude ELMs are suppressed and the pressure gradient becomes constant.

IV. RMP in the changes of MHD relaxation.

In AUG the density pump-out is not observed and non-resonant magnetic perturbations act in the same way as resonant ones. We assume that magnetic perturbations influence the mode stability. This can be implemented in the model by changing parameter δ in the first equation.

$$\begin{cases} \dfrac{d^2}{dt_n^2}\xi_n = \left(p_n' - 1\right)\cdot \xi_n - \delta\left[1 - a\cdot RMP(t)\right]\dfrac{d}{dt_n}\xi_n \\ \dfrac{d}{dt_n}p_n' = \eta\cdot\left(h - p_n' - \xi_n^2\cdot p_n'\right) \end{cases} \quad (3)$$

The corresponding results are shown in Fig. 3.

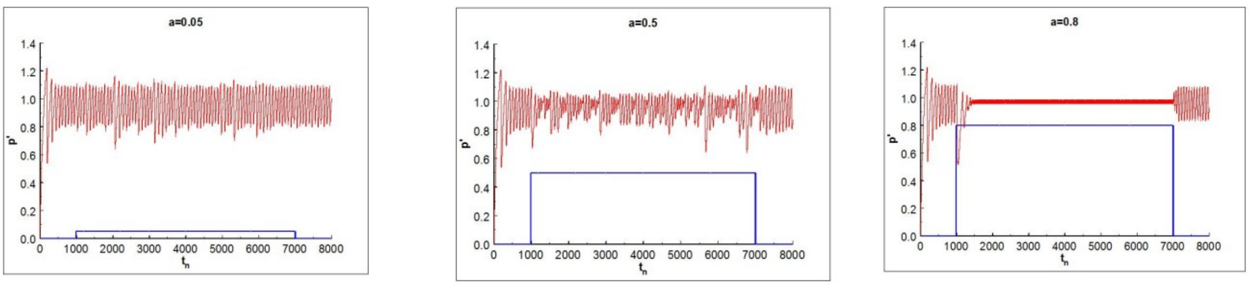


FIG. 3. Plasma pressure gradient (red) and perturbation (blue) as a function of time.

These results are understandable: the dissipation parameter δ is renormalized. Its effective values are 0.19, 0.10, and 0.04 for a=0.05, 0.5, and 0.8, respectively, which means that in Fig. 1b we are moving to the left, leaving the ELM region and entering the region of periodic oscillations.

V. Some observations

The pressure gradient changes (ELMs size) depends nonlinearly on RMP amplitude exhibiting a certain threshold (Figs. 4 and 5) which is connected to the coil current and stochasticity degree in the experiment.

In AUG a hysteresis was observed during the ramp up and ramp down of the coil current (see Fig. 6 in [4]): the coil current amplitude to enter the ELM mitigation regime is higher than in the ramp down phase (reappearance of ELMs). Our model reproduces this behaviour. We do not find this phenomenon in DIII-D. A possible explanation of this is that we indeed modify ELM stability in AUG in contrast to modification of the stability boundary in DIII-D.

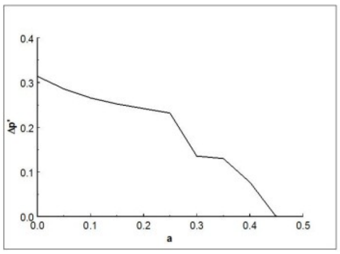


Fig. 4. Dependence of the ELM amplitude on the perturbation amplitude (Eq. 2).

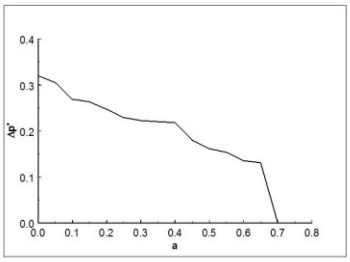


Fig. 5. Dependence of the ELM amplitude on the perturbation amplitude (Eq.3).

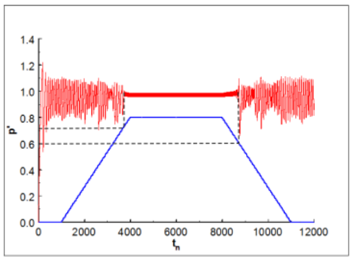


Fig. 6. Hysteresis (Eq. 3).

VI. Discussion

We investigated the behaviour of a simple ELM model in the presence of magnetic perturbations. Two modifications of the system of equations were proposed corresponding to two methods of the ELM suppression/mitigation achieved in DIII-D and ASDEX Upgrade tokamaks. In both cases the ELM amplitude depends nonlinearly on perturbation amplitude in agreement with experiment. The hysteresis observed in AUG can be reproduced by the model.

[1]P.T. Lang et al., Nucl. Fusion **44**, 665 (2004).

[2]P. T. Lang et al., Plasma Phys. Control. Fusion **46,** L31 (2004).

[3]T. E. Evans et al., Nature physics **2**, 419 (2006).

[4]W. Suttrop et al., Phys. Rev. Lett. **106**, 225004 (2011).

[5]D. Constantinescu, O. Dumbrajs, V. Igochine, K. Lackner, R. Meyer-Spasche, H. Zohm, and ASDEX Upgrade Team, Phys. Plasmas **18**, 062307 (2011).