Multiple-harmonics RMP effect on tearing modes in EXTRAP T2R

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Introduction

The application of a resonant magnetic perturbation (RMP) causes braking and locking of the tearing mode (TM) with the corresponding harmonics in EXTRAP T2R reversed-field pinch (RFP) [1, 2, 3]. The experimental TM dynamics showed qualitative agreement with a theoretical model [4]. The viscosity is the only free-parameter in the model and it can be estimated by fitting the experimental TM deceleration-curve. This estimation has been performed in EXTRAP T2R and Madison Symmetric Torus (MST) RFPs [2, 5]. The estimated viscosity was 10-100 times larger than the classical prediction, which is related to the stochastic magnetic field in the RFP core-region. In the MST the RMP spectrum is inherently multi-harmonic, so the RMP brakes all the TMs simultaneously. The previous experiments in EXTRAP T2R have used a single-harmonics RMP, but the machine has the capability to apply a multi-harmonics RMP that is resonant with several tearing modes. The spectrum and amplitudes can be pre-selected from shot-to-shot, which allows for a test of the theoretical model in varying conditions.

EXTRAP T2R RFP, the RMP system and the TM diagnostics

EXTRAP T2R is an RFP with relatively large aspect ratio ($R_0/a = 1.24\text{m}/0.18\text{m} \approx 7$). It has a vacuum vessel made of stainless steel with wall time constant $\tau_v \approx 0.02$ ms. Outside of the vessel is a conducting copper shell with wall time constant $\tau_w \approx 13.8$ ms, which allows time to mitigate the resistive-wall mode (RWM). The RWM mitigation is performed by a feedback system that controls the radial magnetic field. The feedback system consists of actuator coils, senor coils and a feedback controller. The actuator coils cover the copper shell in an array of 32 toroidal and 4 poloidal positions. The same number of sensor coils are located in-between the vacuum vessel and the copper shell. The coils are pair-connected (up-down and inboard-outboard) to control the $m = 1$ modes. The feedback controller can also be used to apply a $m = 1$ magnetic perturbation of pre-set toroidal n, phase and amplitude.

During operation EXTRAP T2R has several unstable tearing modes, which are resonant inside the plasma at $q(r) = m/n$. The main modes in the core region are the poloidal $m = 1$ and the toroidal $|n| \gtrsim 12$. The tearing mode dynamics is recorded by a set of pick-up coils located in-between the vacuum vessel and the conducting shell, see, e.g., the Refs. [1, 3, 6].

Modelling the tearing mode dynamics

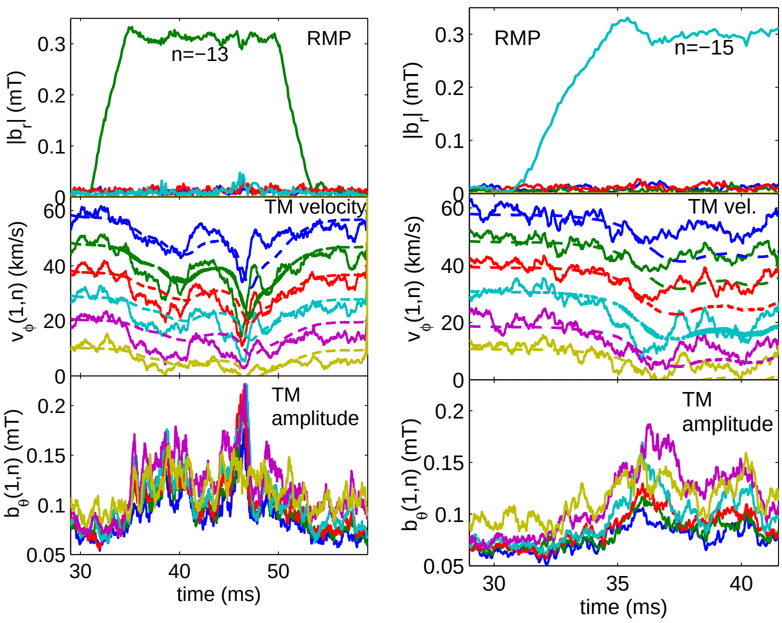
The model uses the two coupled equations [4, 5]: (I) the equation of fluid motion and (II) the no-slip condition. The equation of fluid motion describes the momentum balance in the plasma. The poloidal component can be neglected in the EXTRAP T2R core and the present model includes only the toroidal component

$$\rho(r)\frac{\partial\Delta\Omega_\phi}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\rho v_\perp(r)\frac{\partial\Delta\Omega_\phi}{\partial r}\right) + \sum_n \frac{T^{m,n}_{EM,\phi}(t)}{4\pi^2 r R^3}\delta(r - r_s^{m,n}), \qquad (1)$$

where r is the minor radius, R is the major radius, $\rho(r)$ is the plasma density radial profile, $\Delta\Omega_\phi(r,t) = v_\phi R_0$ is the toroidal component of the perturbed angular plasma velocity, $T^{m,n}_{EM,\phi}(t)$ is the electromagnetic torque caused by the interaction between the tearing mode and the external resonant fields. The $\delta(r - r_s^{m,n})$ indicates that the $T^{m,n}_{EM,\phi}$ acts locally at the resonant surface $r_s^{m,n}$. The single free parameter is $v_\perp$ and it is estimated by matching the experimental TM velocity evolution. The magnitude of the electromagnetic torque caused by the RMP–TM interaction is proportional to the amplitude of both the TM ($|b_{TM}|$) and the RMP ($|b_{RMP}|$). The model was run including the modes of the same harmonics as the applied RMP.

Results and Discussion

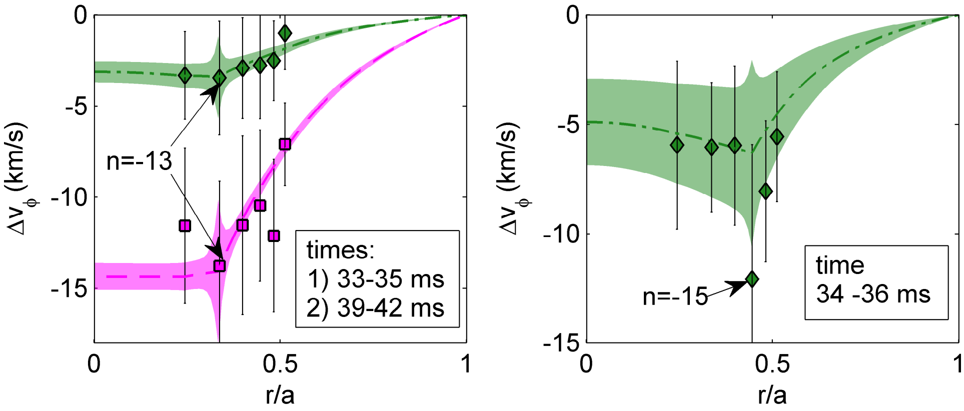
Figure 1 shows two shots with a single-harmonics RMP. In the left hand side (Fig. 1(a)) the $n = -13$ RMP was applied, which produces a torque on the $n = -13$ TM. The effect of the RMP is a deceleration of all the rotating TMs. The almost simultaneous deceleration of the modes located near the $n = -13$ indicates that the viscosity is relatively high, which leads to quick radial transport of momentum. The local effect of the torque on the $n = -13$ mode can be observed in the perturbed velocity profile ($\Delta v_\phi(r)$) that is showed in Figure 2 (a). The



(a) $n = -13$ RMP

(b) $n = -15$ RMP

Figure 1: Time evolution of the experimental RMP, TM velocity and TM amplitude (full lines). The modelled TM velocities are the dashed lines. The plotted modes counted from highest to lowest rotation are the $n = -12, -13 \ldots -17$.



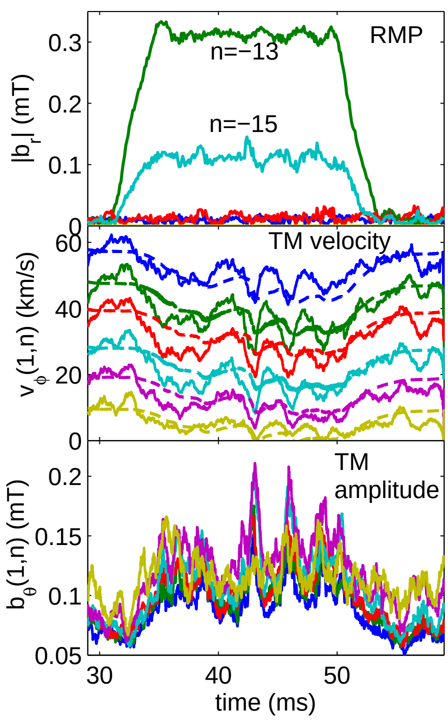
(a) $n = -13$ RMP (b) $n = -15$ RMP

Figure 2: The velocity reduction profiles in the case of a $n = -13$ RMP (a) and a $n = -15$ RMP (b). The TM velocity in a time instant during the RMP is subtracted by the pre-RMP velocity. The modes from the core and outwards are the $n = -12, -13, \ldots, -17$. The lines are the simulated velocity reduction.

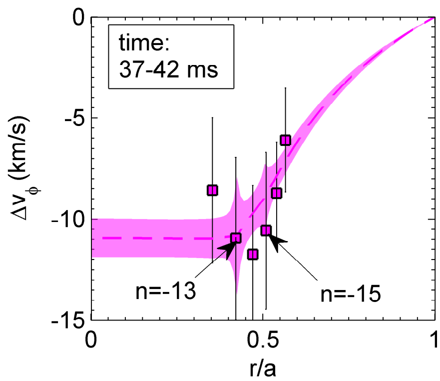
figure shows that the $n = -13$ is decelerated more than the other modes in both the first time interval (33-35 ms) and in the second one (39-42 ms). This is replicated by the model, where the surrounding modes are decelerated via the viscous transfer of momentum. The bottom frame in figure 1 shows that the amplitude of the TMs is increased during the RMP time interval. The increase seems to occur simultaneously with the decrease in TM velocity. When the RMP is turned off the TM spins up to its pre-RMP velocity and the amplitude also returns to its pre-RMP value. In the figure 1 (b) the $n = -15$ RMP was applied, which means that the torque is on the more outer $n = -15$ TM. The $n = -15$ TM velocity is clearly braked the most (figure 1 (b) and 2 (b)), and the more central modes ($n = -12$ to -14) are less braked than in the shot with the $n = -13$ RMP. Furthermore, those central modes are also less increased in amplitude compared with the $n = -13$ RMP case. This might suggest that the increase in mode amplitude is related with a decrease in rotation velocity. It is expected that the copper shell can stabilize modes that are rotating faster than the inverse shell time, but the exact velocity dependence can be more complicated and has not been investigated. A second possibility is that the current profile, and thus the TM stability, could be changed in a different way due to the different RMPs ($n = -13$ and $n = -15$). However, the plasma equilibrium magnetic field is not evidently changed by the RMP. A third possibility is that the increase in the signal of the pick-up coils is not caused by an increase in mode amplitude, but instead by increased field penetration trough the stainless steel vacuum vessel at the lower rotation. However, the shell time constant of the vessel is very short and is not expected to significantly alter the signal at any of the experimental rotation velocities.

In figure 3 the applied RMP was the two harmonics $n = -13$ and $n = -15$. The $n = -13$ amplitude is the same as in the single harmonics case, but the $n = -15$ amplitude is 1/3 of that in the single harmonics case. This means that total RMP torque is higher than in the single harmonics cases, which can explain the quicker mode deceleration observed in figure 3 (a)). The velocity reduction profile at steady state (figure 3 (b)) is similar to a combination of the two single harmonics cases (figure 2). The amplitude of all the TMs are increased, similar to the $n = -13$ RMP case.

It can be noted that, the model cannot describe the quick deceleration to the steady state in any of the cases. One possible explanation is that the viscosity increases when the TM amplitudes increases (i.e. after the initial deceleration), whereas it is kept constant in the model. The increase of the TM amplitudes is expected to increase the island overlapping, which leads to increased transport. The model-required viscosity in the above cases is $\nu_\perp \approx 2$ m^2/s, which is anomalous [1].



(a)



(b)

Figure 3: (a) Time evolution of the experimental RMP, TM velocity and TM amplitude (full lines). The modelled TM velocities are the dashed lines. (b) Shows the velocity reduction profile.

Conclusion and future work

The theoretical model shows a qualitative agreement with the experiment in the case of a single-harmonics RMP and in the case of a two-harmonics RMP. In future work, it is straight forward to add more or different harmonics in the applied RMP, both in the experiment and in the model. The variation of the RMP spectrum may possibly be used for estimations of the viscosity at different resonant surfaces in EXTRAP T2R or other devices with rotating modes.

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