

# Experimental study of tearing mode locking and unlocking in EXTRAP T2R

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## 1. Introduction

The locking and unlocking of the tearing modes (TMs) is studied in EXTRAP T2R reversed-field pinch (RFP) and compared with the predictions from theory [1]. Plasma flow braking due to magnetic perturbations has previously been observed both in tokamaks, such as COMPASS-C [2], and reversed-field pinches, such as EXTRAP T2R [3].

A locked TM enhances the plasma-wall interaction and can lead to disruptions. The locking is due to the electromagnetic torque acting on the TM. The torque can be produced by a magnetic error-field or by a resonant magnetic perturbation (RMP) [1], [3]. If the RMP amplitude is above a threshold the TM goes through a transition from fast rotation to a wall locked state. To unlock the TM the RMP has to be reduced to a much lower amplitude than the locking threshold.

The aim of the present work is to experimentally study the mechanism behind the hysteresis in the locking/unlocking process. An RMP with poloidal  $m=1$  and toroidal  $n=-15$  harmonic and varying amplitude was applied to study the RMP effect on tearing mode (TM) dynamics and plasma flow braking. In a first approximation, the TMs co-rotate with the plasma in EXTRAP-T2R. Hence, the measurement of the TM velocities gives a good estimation of the plasma flow velocity profile [4]. The results have been compared to a theoretical model [1] of the magnetic island temporal evolution.

## 2. The Device and magnetic coils

The EXTRAP-T2R [5] device ( $R_0=1.24$  m,  $a=0.183$  m) is a medium-size reversed field pinch. Typical plasma parameters are: plasma current  $I_p \approx 70-100$  kA, electron temperature  $T_e \approx 200-300$  eV and electron density  $n_e \approx 10^{19}$  m<sup>-3</sup>. In this work the plasma current was  $I_p=80$  kA, the pinch parameter  $\Theta=1.6$ , the reversal parameter  $F=-0.2$  and the resonant harmonics are ( $m=1$ ,  $n \leq 12$ ).

The device is equipped with a real-time control system that suppresses error fields and resistive wall modes (RWMS). In addition, the control system can produce external

magnetic perturbations in a controlled fashion, i.e. with harmonic, amplitude and phase decided by the user.

### 3. Tearing mode locking/unlocking process

In a stationary phase before the locking, the EM torque (that breaks the plasma) is balanced by the viscous torque (that tends to avoid changes in the plasma rotation), i.e.  $T_{visc} = T_{EM}$  is expected in this phase. The viscous torque is described by Equation 1 [3]:

$$T_{visc} = \frac{R^2}{r} \frac{\partial}{\partial r} \left( r v_{kin} \frac{\partial}{\partial r} (\rho \Delta \Omega) \right), \quad (1)$$

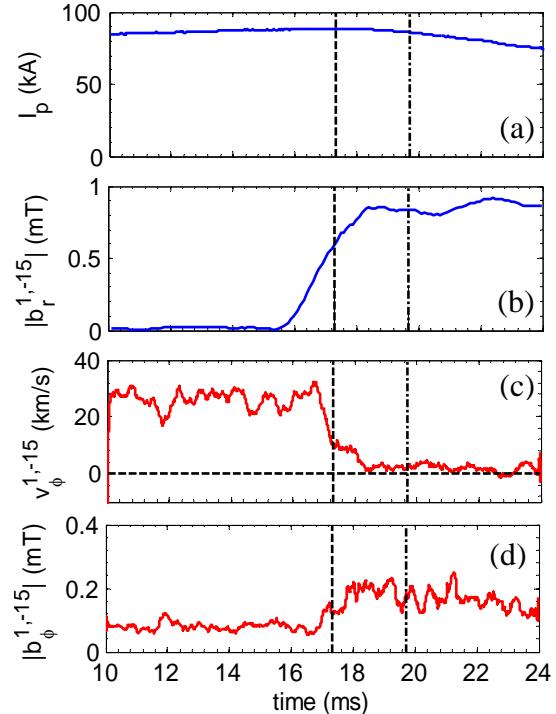
where  $R$  is the major radius,  $r$  the minor radius,  $v_{kin}$  the kinematic viscosity,  $\rho$  the plasma density profile and  $\Delta \Omega$  the angular velocity profile modification due to the RMP.

The electromagnetic torque is proportional to both the TM and the RMP amplitudes and sine of their phase difference  $\Delta\phi$  as described by Equation 2 [3]:

$$T_{EM} = -k^{1,n} |b_\phi^{1,n}| |b_r^{1,n}| \sin(\Delta\phi) \delta(r - r_s), \quad (2)$$

where  $k^{1,n}$  is a constant and the delta function shows that the torque is acting at the rational surface  $r_s$ . Here  $k^{1,n}$  is determined using the condition  $T_{visc} = T_{EM}$  in the stationary phase, i.e. before the TM velocity reduces significantly.

Several shots have been analysed, all with similar equilibrium parameters. The applied RMP amplitude was varied from shot to shot. Fig. 1 shows one of the plasma shots (24770). The dashed and dotted-dashed vertical lines in Fig. 1 highlights the time instants for which the modification of the plasma velocity profile is plotted in Fig. 2. At first, the RMP brake the velocity at  $r_s$  (Fig. 2 blue circles), as is predicted theoretically by Equation (2). Thereafter the velocity reduction spreads to the core. When the TM is wall-locked the velocity reduction profile relaxes (Fig. 2 red diamonds).



**Figure 1.** Plasma current (a), RMP amplitude (b), TM velocity (c) and TM amplitude (d). The dashed and dotted-dashed vertical lines in (a-d) show the time instants of the velocity modification profiles in Fig 2. Data from shot 24770.

The experimental behaviour of the TM island is modelled using the approach described in reference [1]. Fig. 3 shows the results from the simulation when an RMP of harmonic ( $m=1, n=-15$ ) and amplitude  $0.6 \text{ mT}$  is applied. The velocity, Fig. 3(c), goes through phases of acceleration and deceleration, which depend on the phase difference between the tearing mode and the RMP.

However, on average the tearing mode velocity is reduced until the TM locks to the wall (at  $\sim 3 \text{ ms}$ ).

The TM starts to spin up when the RMP is turned off (at  $7 \text{ ms}$ ). In Fig. 3(d) the velocity reduction profile is shown at different time instants during the island evolution. The profile goes from being peaked at  $r_s$  at the time of wall-locking to a relaxed profile when velocity the reduction has spread to the core (notice the similarity with the experimental case in Fig. 2).

To examine the TM locking and unlocking threshold, the RMP amplitude was ramped-up and subsequently ramped-down. The experimental Fig. 4(a) and simulated Fig. 4(b) TM velocity is plotted against applied RMP amplitude. For both the experimental and theoretical cases the TM locks at much higher amplitude than it unlocks.

Fig. 5 shows the viscous and EM torques from experiment. The locking occurs at  $\sim 0.6 \text{ mT}$  (highlighted by the grey area). After the locking, the velocity profile reduction gets relaxed (see Fig. 2). As a result, the volume integrated viscous torque has a sudden reduction from  $0.5 \text{ Nm}$  to  $0.3 \text{ Nm}$ .

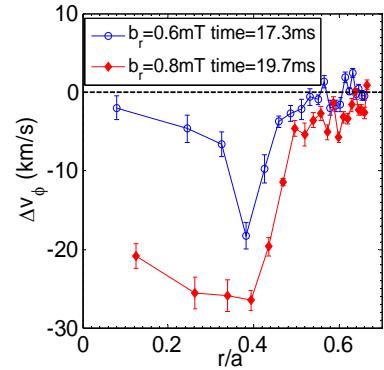


Figure 2. Velocity profile modification at  $17.3 \text{ ms}$  (blue circles) and  $19.7 \text{ ms}$  (red diamonds).

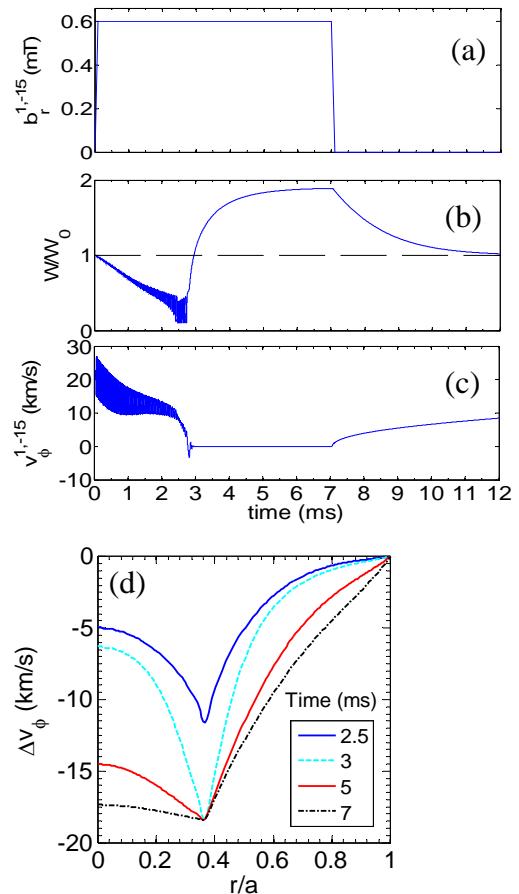


Figure 3. Simulation of the island evolution equations. (a) shows the applied RMP, (b) the island size and (c) the tearing mode velocity. (d) Radial profile of the velocity modification due to the applied RMP obtained from simulation.

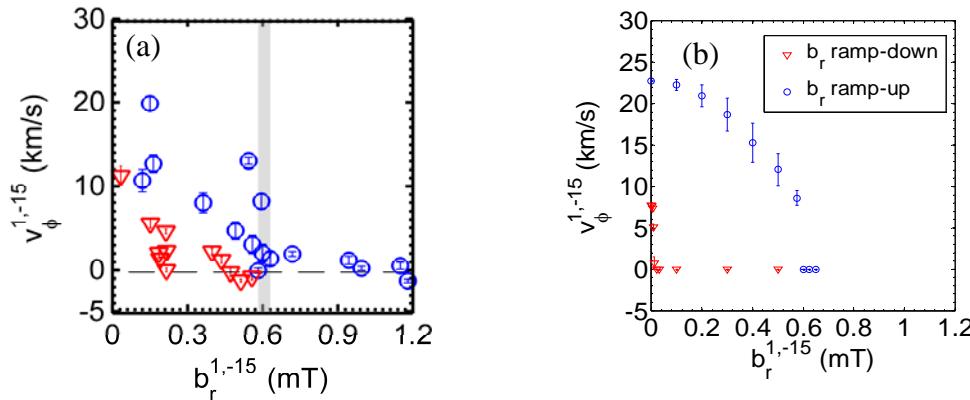


Figure 4. Experimental (a) and simulated (b) tearing mode velocity versus applied RMP amplitude. The blue circles show the velocity reduction during the RMP ramp-up and the red triangles show the velocity during the RMP ramp-down.

#### 4. Conclusions

The island evolution equations can explain the basic mechanism behind the locking/unlocking process. However, there are several uncertainties for the parameters used in the modelling, especially the kinematic viscosity, which affect the quantitative agreement.

The viscous torque is proportional to the second derivative of  $\Delta\Omega$  (the angular velocity profile modification due to the RMP). When the plasma rotates the velocity profile modification (at first) is local at the resonant radius. As the RMP increases the reduction becomes higher at the resonant radius and hence the viscous torque increases. Indeed, the results (Fig. 5) indicate that viscous torque increases (almost) linearly proportional to RMP amplitude. However, when the plasma locks the velocity profile modification relaxes (Fig. 2 and Fig. 3(d)). Hence, the viscous torque drops (Fig. 5). To re-start the plasma rotation the EM torque has to be reduced below this lower viscous (restoring) torque.

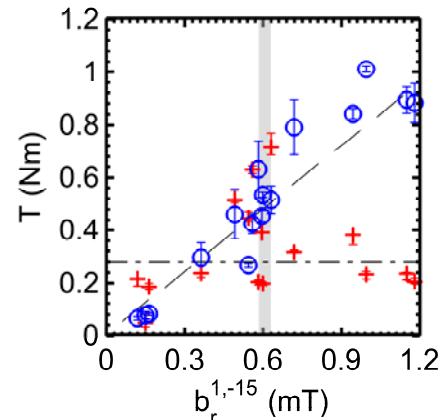


Figure 5. Volume integrated viscous (red crosses) and EM (blue circles) torque during the ramp-up phase.

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