

Resonant magnetic perturbation penetration and locking threshold in EXTRAP T2R

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INTRODUCTION

In a tokamak or reversed field pinch plasma with rotating tearing modes (TM), the penetration of resonant magnetic perturbations (RMPs) and/or error-fields can lead to braking of the TM rotation velocity and eventually to wall locking of the TM. The TM rotation braking may occur via the electromagnetic torque that acts locally near the rational surface [1, 2, 3]. At a critical RMP amplitude, a transition from a fast rotating TM to a slowly rotating or wall locked TM occurs. This critical RMP amplitude is referred to as the error-field penetration threshold or the TM locking threshold. In this work, the threshold is experimentally studied in the EXTRAP T2R reversed-field pinch. The experimental results are compared with a model for the non-linear TM dynamics, which incorporates the balance between the electromagnetic braking torque and the viscous drag of the rotating plasma [3].

EXPERIMENTAL

The EXTRAP T2R device ($R_0 = 1.24$ m, $a = 0.183$ m) is a medium-size reversed field pinch [4]. In this work, two cases are studied, with plasma currents $I_p \approx 50$ kA and $I_p \approx 90$ kA. The main plasma parameters for the two cases are reported in Table 1. Plasma ion temperature is estimated from OV Doppler line broadening, electron temperature is measured with Thomson scattering, and electron density with laser interferometry. TM amplitudes and phase velocities are obtained with an array of pick-up coils placed between the vessel and the shell. The measured TM amplitude is compensated for the attenuation by the vessel wall.

The MHD activity in EXTRAP T2R is characterized by a set of linearly unstable TMs with $m = 1, n = -12 \dots -15$. The TMs are non-linearly saturated, rotating toroidally with the plasma flow. The TM rotation is affected by induced eddy currents in the vacuum vessel ($r_b = 0.191$ m, $\tau_b = 0.28$ ms). There is also a copper shell, ($r_c = 0.198$ m, $\tau_c = 13$ ms) outside the vacuum vessel.

The TM rotation velocities ($v = 20 - 50$ km/s) are large compared with the inverse shell time, so the copper shell is seen as an ideally conducting wall by the TMs. (In contrast, the copper shell determines the growth of a range of non-rotating unstable resistive wall modes, which in the present experiments are suppressed by active feedback control.)

The device is equipped with a set of 128 active saddle coils ($r_d = 0.238$ m) placed external to the copper shell. The set of control coils and magnetic sensors (installed in the space between

Plasma parameters	Case 1	Case 2
I_p (kA)	50±5	90±5
T_i (eV)	150±50	500±50
T_e (eV)	180±50	250±50
n (10^{19} m $^{-3}$)	0.5±0.1	0.8±0.2
$B_\theta(a)$ (mT)	52±5	96±5
v_ϕ^{TM} (km/s)	20±5	50±5
$b_\theta^{TM}(a)$ (mT)	0.23±0.07	0.27±0.08

Table 1. Parameters of two cases studied: Plasma current, ion temperature, electron temperature, plasma (electron) density, poloidal magnetic field, TM toroidal rotation velocity and amplitude at the wall.

the vessel and the shell) are operated in a feedback loop to produce near single-harmonic ($m=1, n=-12\dots-15$) RMPs with controlled radial field wave forms. The system is in parallel performing active feedback control of a set of (mainly non-resonant) resistive wall modes [5].

MEASUREMENT OF THE TM LOCKING THRESHOLD

In the following, an RMP harmonic $(m, n)=(1, -12)$ is applied and the dynamics of the corresponding TM with $(m, n)=(1, -12)$ is studied. The harmonic corresponds to the TM which has the resonant surface closest to the magnetic axis. An example of the time evolution of characteristic parameters for the two cases is shown in Fig. 1. The plasma current and ion temperature is shown in panel (a) and (b) respectively. In panel (c) is shown the radial field amplitude of the RMP harmonic. The time evolution of the TM toroidal velocity $v=R_0\omega/n$, calculated from the TM phase velocity $\omega=-d\varphi_s/dt$ is shown in panel (d). (The TM rotation direction is assumed to be toroidal, neglecting a possible poloidal component of the velocity; the assumption is reasonable near the magnetic axis.) The velocity has been time-averaged to highlight the slow time evolution. The braking effect of the RMP on the TM velocity is evident. In the low current case TM wall locking occurs, leading to plasma disruption.

To study the TM locking threshold, discharges with the same global plasma parameters have been repeated, while systematically varying the RMP amplitude. The correlation between the RMP radial field amplitude at the shell $b_r^{\text{ext}}(r_c)$ and the TM toroidal velocity $v=R_0\omega/n$ during the perturbation phase is shown in Fig. 2. The increase of the RMP amplitude produces an evident reduction in the TM velocity, and the RMP penetration threshold is easily identified as the rapid transition from fast TM rotation to slow (or locked) TM rotation. The TM locking threshold RMP radial field clearly increases with plasma current: At $I_p \approx 50$ kA it is around $b_r^{\text{ext}} \approx 0.2$ mT while at the higher current $I_p \approx 90$ kA it is around $b_r^{\text{ext}} \approx 0.7$ mT

MODELLING OF THE TM LOCKING THRESHOLD

In the model developed in Ref. 3, it is assumed that the TM co-rotates with the plasma (the so called no-slip condition). The TM rotation velocity is obtained by balancing the viscous torque from the plasma, that tends to keep the unperturbed rotation velocity and the electromagnetic torque, acting at the mode resonant surface that tends to slow down the TM

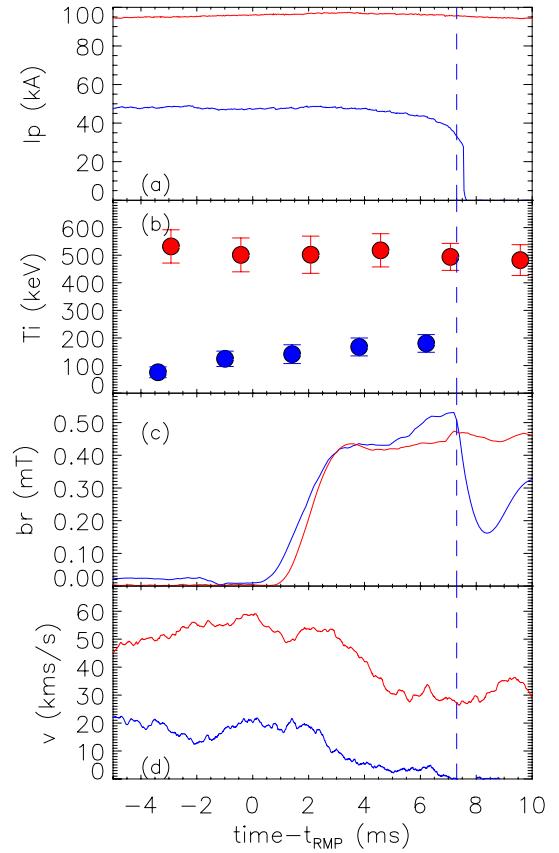


Fig. 1. (a) Plasma current, (b) ion temperature, (c) RMP $(1, -12)$ amplitude and (d) TM $(1, -12)$ toroidal velocity. Low (blue line) and high (red line) current plasma. The time traces are shifted in order to have the RMP start at $t=0$. The vertical dashed line highlights the termination of the low current discharge.

The braking effect of the RMP on the TM velocity is evident. In the low current case TM wall locking occurs, leading to plasma disruption.

rotation. The electromagnetic torque arises both from the externally applied RMP field and from eddy currents induced in the vacuum vessel (modelled as a thin resistive wall) by the rotating TM.

The basic formulae of the model in Ref. 3 are reproduced below:

$$\left\{ \begin{array}{l} \mathbf{b}(\mathbf{r}, t) = \mathbf{b}^{m,n}(r, t) \exp(i(m\theta + n\phi)) \\ \psi(r) = -irb_r^{ext}, \quad \Psi_s = \psi(r_s) \\ \Psi_s = \hat{\Psi}_s \exp(i\varphi_s), \quad -\frac{d\varphi_s}{dt} = \omega = n\Omega(r_s) \\ \Psi_c = \psi^{ext}(r_c), \quad \Psi_c = \hat{\Psi}_c \exp(i\varphi_c) \\ \Delta\Psi_s = \left[r \frac{d\psi}{dr} \right]_{r_s}^{r_s+} = f_s(\omega\tau_b)\Psi_s + f_c\Psi_c \\ \delta T_{\phi EM} = -\frac{2\pi^2 R_0}{\mu_0} \frac{n}{m^2 + n^2 \epsilon^2} \text{Im}\{\Delta\Psi_s \Psi_s^*\} \\ r\rho \frac{\partial \Delta\Omega}{\partial t} - \frac{\partial}{\partial r} \left(r\mu \frac{\partial \Delta\Omega}{\partial r} \right) = \frac{\delta T_{\phi EM}}{4\pi^2 R_0^3} \delta(r - r_s) \end{array} \right.$$

$\mathbf{b}(\mathbf{r}, t)$ is the perturbed magnetic field, $\psi^{ext} = -irb_r^{ext}$ is the magnetic flux function of the RMP field, $T_{\phi EM}$ is the electromagnetic torque acting at the mode resonant radius r_s , $\rho = nm_i$ is the mass density, μ is the plasma viscosity, $\Omega(r, t)$ is the plasma toroidal angular velocity, $\Delta\Omega = \Omega - \Omega_0$ is the modification from the unperturbed velocity Ω_0 due to the presence of a resistive wall (the vacuum vessel) and the externally applied RMP field. The TM and RMP amplitudes are experimentally measured, and the experimental density and magnetic equilibrium are used in the calculation. The unknown unperturbed angular velocity Ω_0 and the viscosity μ are kept as free fitting parameters, determined by matching the initial angular velocity Ω before the RMP is turned on and the locking threshold RMP amplitude Ψ_c to the experimental values. (Note that the sign of the toroidal mode number n is changed from that in Ref. 3 in order to agree with the RFP convention.)

When the RMP is turned on, the TM velocity has an oscillating behaviour. This is due to the cyclic time variation of the electromagnetic torque, which originates from the changing phase

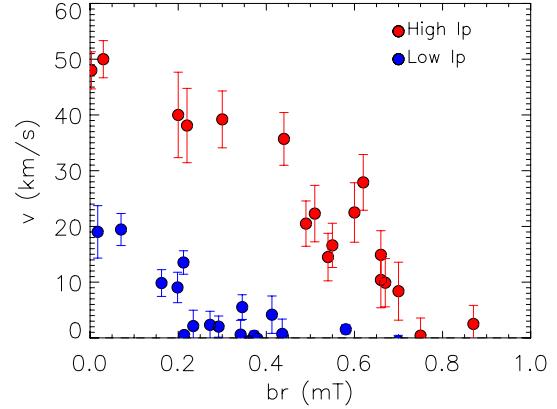


Fig. 2. TM velocity vs RMP radial field at the shell for two different plasma currents; 90 kA (red dots) and 50 kA (blue dots).

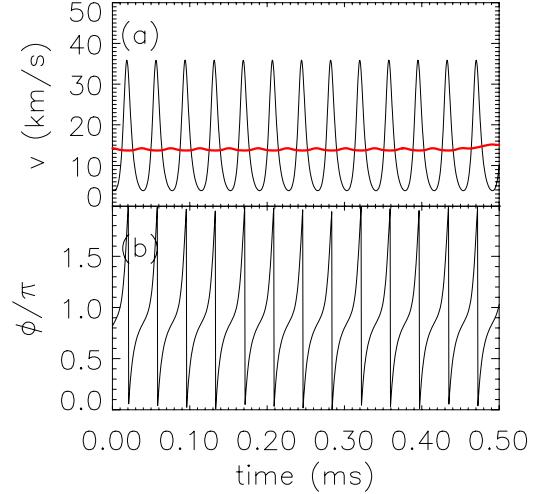


Fig. 3. Cyclic variation of the modelled TM velocity with RMP applied. (a) TM toroidal velocity, (b) relative phase difference between TM and RMP. The red line shows the time averaged velocity.

difference between the rotating TM and the static RMP field. Figure 3 shows in panel (a) the time-evolution of the TM velocity $v = R_0\Omega(r_s)$ and in panel (b) the phase difference $\phi = \varphi_s - \varphi_c$. The time averaged velocity is shown by the red line.

The simulation has been repeated, systematically varying the RMP amplitude. The modelled TM toroidal velocity $v = R_0\Omega(r_s)$ is plotted in Fig. 4 vs the RMP radial field at the shell $b_r^{ext}(r_c)$ for the two cases (low and high plasma current). The initial rotation velocity and TM locking threshold values obtained from the model calculation are reasonably close to the corresponding experimental values, shown in Fig. 3. The model values of the kinematic viscosity $\nu_{kin} = \mu / \rho$ and the unperturbed velocity $v_0 = R_0\Omega_0$, resulting from matching to the experimental data are listed in Table 2.

The present estimates of the plasma viscosity, which is of order $1 \text{ m}^2/\text{s}$, have been compared with the classical ion viscosity given by Braginskii [6], using the plasma parameters in Table 1. Taking the equilibrium field as $\mathbf{B} \approx B_\phi \mathbf{e}_\phi$ (which is a reasonable approximation near the magnetic axis) and $\omega_{ci}\tau_i \gg 1$, the approximate expression for the classical ion viscosity is

$$\mu^{(Brag)} = \mu_3^i \approx 1.2 \frac{n_i T_i \tau_i}{(\omega_{ci} \tau_i)^2}, \quad \nu_{kin}^{(Brag)} = \mu^{(Brag)} / m_i n_i$$

The parameters used in the comparison are summarized in Table 2. The viscosity estimated through the modelling of the experimentally observed TM locking thresholds is somewhat higher than the classical viscosity (although the dependence on plasma current is similar).

CONCLUSION

The RMP threshold amplitude for locking of non-linearly saturated rotating TMs in a RFP has been obtained experimentally for two different plasma currents. The experimental results have been successfully modelled, including the effects of the electromagnetic torque at the mode resonant surface and the viscous torque of the plasma flow.

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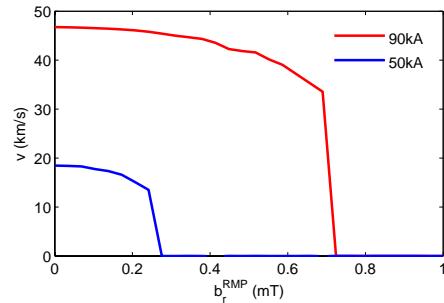


Fig. 4. Modelled TM velocity vs RMP amplitude for the high (red line) and low (blue line) plasma current.

Model parameters	Case 1 (50 kA)	Case 2 (90 kA)
v_0 (km/s)	39	80
ν_{kin} (m ² /s)	2.0	0.47
τ_i (s)	5.1×10^{-4}	2.0×10^{-3}
$\omega_{ci}\tau_i$	2.5×10^3	1.8×10^4
$\nu_{kin}^{(Brag)}$ (m ² /s)	1.4	0.32

Table 2. Model parameters resulting from matching with experimental data and parameters used in the calculation of the classical viscosity estimate.