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Rotation evolution of tearing modes during feedback stabilization of resistive wall modes in a reversed field pinch

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Introduction

A reversed field pinch (RFP) is a toroidal axisymmetric configuration that uses a conducting wall for kink mode stabilization, similarly to the advanced tokamak. In absence of rotation the kink modes are converted into unstable resistive wall modes (RWMs) that grow on a time scale equal to the magnetic flux penetration time of the wall τ_W. The RFP is characterised by poloidal and toroidal magnetic fields of comparable amplitudes and therefore the RWMs spectrum contains a large number of unstable modes. Active feedback stabilization of multiple RWMs has been experimentally demonstrated in the EXTRAP T2R RFP [1]. The EXTRAP T2R device is a medium-sized RFP with major/minor radius of R_0 = 1.24/a = 0.183 m respectively. Outside the vacuum vessel, a close-fitting shell (conducting wall) is characterised by τ_W = 6.3 ms. The radial and toroidal magnetic fields outside the plasma are measured by two arrays of 4 poloidal × 64 toroidal pick-up sensor coils m = 1 coupled (top-bottom and inboard-outboard). The radial field sensors are used for measuring the amplitude of both the m = 1 RWMs and the internally-resonant tearing modes (TMs) as well as their helical angular phase velocities. The toroidal field sensors are used to measure the helical angular phase velocities of the (m = 1, n = -31 – -12) TMs. The helical angular phase velocity for the mode (m; n) is defined as $\Omega^{(m;n)} = d\Phi^{(m;n)}/dt = m\omega_\theta + n\omega_\phi$, where $\Phi^{(m;n)}$ is the argument of the 2D Fourier decomposition coefficient of the 2 × 64 magnetic signals for mode (m; n) and ω_θ, ω_ϕ are the poloidal and toroidal angular velocities respectively. The RWMs active feedback system consists of an array of saddle coils placed outside the conducting wall and a digital controller [2] that has as inputs the time integrated flux loop voltages of a subsets of the radial sensors (2 × 32) and as outputs control voltages to amplifiers that drive currents in the saddle coil proportional to the negative of the sensor fluxes. The magnetic field generated by the saddle coils during plasma discharges is approximately 1% of the equilibrium field. In the study here presented the saddle coils are used in 4 poloidal × 16 toroidal configuration and the active feedback employed is the "wise shell" scheme in which the feedback gains for all the targeted modes (m = 1, $-15 \le n \le 16$)

are the same with the exception for modes (m = 1, -2 ≤ n ≤ 2) for which feedback is removed in order to avoid negative effects on the TMs arising from their coupling via the feedback coils (side-band effect) [1].

Tearing modes rotation profiles

In addition to the simultaneous suppression of several non-resonant RWMs, active feedback also affects a range of TMs resonant in the plasma centre resulting in a significant prolongation of the plasma discharge duration. The non-linearly saturated m = 1 TMs are intrinsic to the RFP configuration and co-rotate with the plasma at angular frequencies much larger the inverse wall time. In absence of active feedback stabilization, TMs rotation slows down after one τ_W until it approaches zero causing mode-locking to the wall. In presence of active feedback stabilization, the TMs rotation is sustained for 3-4 τ_W before approaching zero. A comparison between discharges with and without feedback is shown in figure 1. Similar results are also obtained when feedback is applied only to the RWMs as shown in figure 2, where the targeted modes are (m = 1, -11 ≤ n ≤ -4) thus suggesting the presence of a coupling between the RWMs and the TMs.

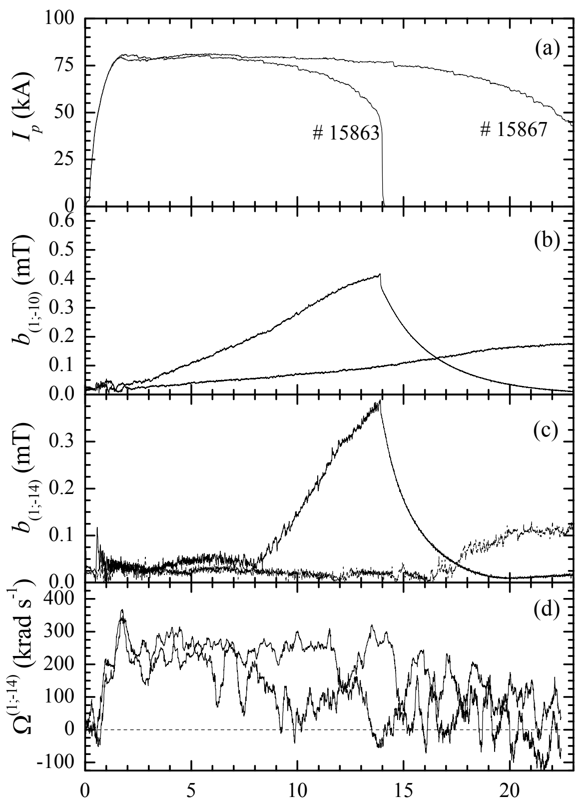

Figure 1 Feedback on (m=1,-15≤n≤16): (a) plasma current, (b) amplitude of a RWM, (c) amplitude of a TM and (d) its helical phase velocity. (#15863 Refer.)

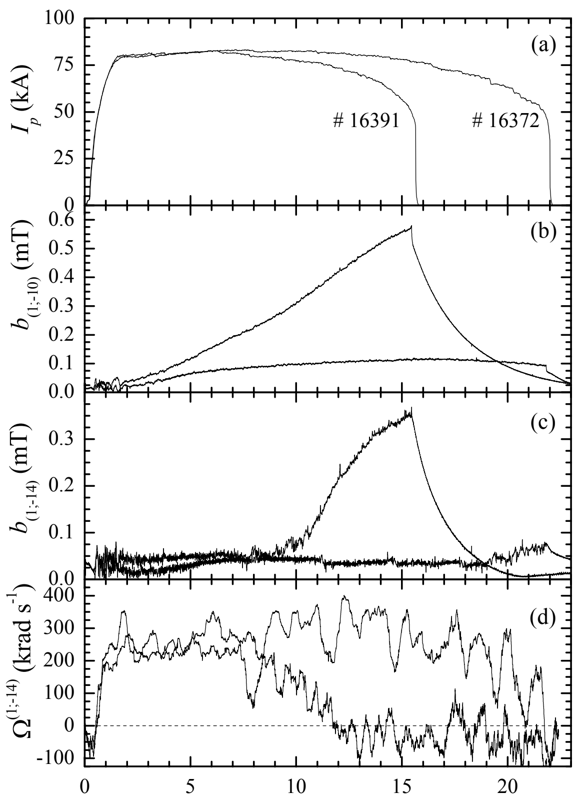

Figure2 Feedback on (m=1,-11≤n≤-4): (a) plasma current, (b) amplitude of a RWM, (c) amplitude of a TM and (d) its helical phase velocity. (#16391 Refer.)

Reconstruction of the equilibrium magnetic field, using the α-Θ_0 model [3], gives an highly sheared radial profile of the helical angular phase velocity, as shown in figure 3(a), which is maintained throughout the discharge both with and without feedback. This profile can be explained assuming a toroidal angular velocity profile given by $\omega_\phi = \omega_\phi(0)[1-(r/r_{rev})^2]$ where r_{rev} is the radius of the reversal surface and $\omega_\phi(0)$ is chosen so as to have a zero poloidal angular velocity in the plasma centre thus assuring that no change of sign occurs in either velocity profiles (see figure 3(b)). As a result, the most centrally resonant modes ($n \approx -12$) rotate in the plasma current toroidal direction with velocities of the order of 70 kms^{-1}, while those closest to the reversal surface ($n \approx -30$) have a poloidal velocity of 70-100 kms^{-1}. The $m = 1$ TMs are phase-locked and a slinky structure is formed and maintained throughout the discharge as indicated by the linear dependence of $\Omega^{(m;n)}$ on the mode number n, as shown in figure 3 (c). The linear dependence is preserved in time as the most centrally resonant modes ($n \approx -12$) slows down (see figure 3 (d)). The overall behaviour shows that the slinky mode rotation is maintained at the same velocity during the central mode slow down. From linear interpolation the toroidal velocity of the slinky mode is calculated as being 50 km/s. Deviation from this rigid body rotation are observed late in the discharges for those mode closer to the reversal surface ($n \leq -26$).

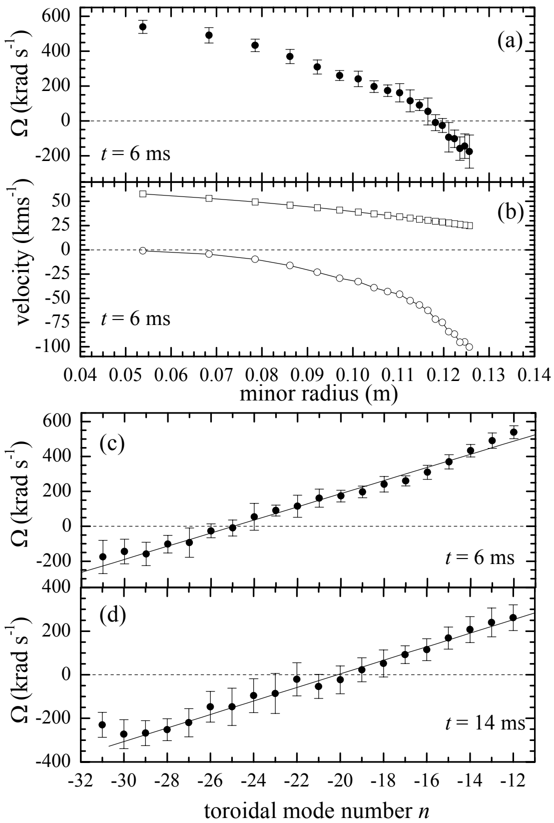

Figure 3 (a) Angular helical phase velocity radial profile; (b) corresponding toroidal (squares) and poloidal (circles) velocity radial profiles; (c) slinky at t=6ms and (d) at t=14ms.

Electromagnetic and viscous torques

Rotating TMs induce in the shell eddy currents that exert electromagnetic (EM) torques on the plasma in the vicinity of the TMs rational surfaces (the EM torque due to resonant fields errors is here neglected). The EM torque, when the TMs amplitude is small, is balanced by the viscous torque (VS). A detailed analysis of the effect of a resistive shell on the TMs in RFPs is given in reference [4], where it stated that in the thin-shell regime, the condition for mode locking requires $b_s^{m,n} > \Lambda` B_0$ where $b_s^{m,n}$ is the amplitude of the perturbed radial magnetic field at the ($m$; $n$) rational surface, $B_0$ the equilibrium magnetic field and $\Lambda`$ is a parameter that takes into account the stability indexes of the standard and modified tearing eigenfunctions, the modes toroidal angular velocity, the wall time and the plasma viscosity [4]. The thin-shell approximation $\delta_b/b \ll n\omega_\phi\tau_W \ll b/\delta b$ is satisfied in EXTRAP T2R, since $n\omega_\phi\tau_W$ is in the range 1.4×10^{-3} – 900 while $\delta_b/b \approx 5 \times 10^{-4}$ and $b/\delta b \approx 2 \times 10^3$. For the calculation of the mode locking condition the TMs toroidal angular velocity is obtained from the toroidal array sensors and their amplitude from the radial array sensor. The condition for mode locking is both a function of toroidal mode number and time as shown in figure 4. It is evident that when the TMs amplitudes are small and the rotation velocity is large (see figure 4 (a)), the EM torque is small and the condition $b_s^{m,n} < \Lambda` B_0$ holds for all the modes (see figure 4(b)). When the TMs amplitudes are large and the rotation velocity is small (the slinky mode is wall-locked) the condition $b_s^{m,n} > \Lambda` B_0$ holds for the most internal modes (the ones that have the largest amplitude) as shown in figure 4 (c) and (d). In the present analysis the EM torque between TMs due to their non-linear coupling are neglected since it has been shown that the locking threshold is not affected by them [5]. As clearly shown in figure 4 (a) $\Omega^{(m;n)}$ is changing in time and is characterised by a constant deceleration. Sample calculations for mode m = 1, n = -12 give an EM torque increasing in time from 0.0017 Nm (t = 6 ms) to 0.3 Nm (t = 20 ms) while the overall torque calculated from $d\Omega^{(m;n)}/dt$ is approximately constant at 0.084 Nm. From the torque balance equation it follows that a large change in the toroidal angular velocity due to eddy currents is required to justify the increase in the VS torque.

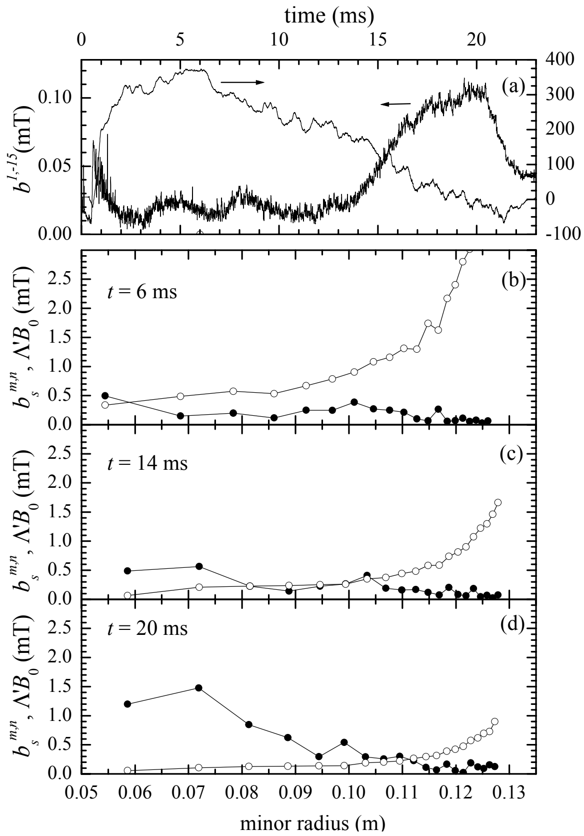

Figure 4 (a) Time evolution of a TM amplitude and of its helical phase velocity; locking condition (open cirlces) at (b) t = 6 ms; (c) t = 14 ms and (d) t = 20 ms compared with $b_s^{m,n}$ (solid circles).

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