J. Plasma Fusion Res. SERIES, Vol. 5 (2002) 509–513

Resistive Wall Mode Studies in a Reversed Field Pinch with Rotating Helical Field

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(Received: 12 December 2001 / Accepted: 24 May 2002)

Abstract

In standard RFP plasmas in STE-2, the magnetic fluctuations are dominated by core resonant tearing modes which grow with the time scale of the resistive wall, and these modes are identified as the resistive wall tearing modes. The growth of these modes are shown to be suppressed by the resonant rotating helical field (RHF). The response of m=1 modes to the RHF has been studied in detail. In RFP plasmas, the RHF has the effect on the rotation of neighboring modes as well as of the resonant mode. In ULQ plasmas, where there is no m=0 resonant surface, only the resonant mode tends to be influenced by the external resonant perturbation. The importance of the m=0 mode in the mode coupling process is discussed.

Keywords:
reversed field pinch, tearing mode, rotating helical field, mode control, external kink modes

1. Introduction

The reversed field pinch is characterized by low-q_a (safety factor), high shear magnetic configuration, and believed to be dominated by anomalous transport due to strong fluctuations. Control of the MHD mode dynamics is therefore essential to improving the RFP experiments as a part of the fusion research programs. The magnetic fluctuations due to tearing modes can be suppressed by current profile modification, the improved confinement modes being realized in large RFPs surrounded by an ideal conducting wall [1].

As in tokamaks, the resistive wall modes (both tearing and ideal kink modes) are thought to be serious problems in future RFPs. Theories have predicted that the growth of tearing modes or their saturation amplitudes can be reduced by moderate toroidal rotation of the plasma column [2]. On the other hand, stabilization of the external kink modes require sub Alfvénic rotation speed which is much faster than the natural rotation speed of the tearing modes [3]. Thus, development of the techniques for mode rotation drive is one of the urgent issues in the RFP research.

We have proposed the use of resonant rotating helical field (RHF) for the mode or plasma rotation drive [6]. The internally resonant RHF, applied from outside of the resistive wall, may be able to provide accelerating torque to the magnetic island, and eventually drive toroidal rotation of the plasma column, if the phase of perturbation field is adequately controlled. In this paper, we describe the recent results on resistive wall mode studies from Separatrix Test Experiment-2 (STE-2) with external helical fields.

2. Experiments

The STE-2 [4-6] (R/a = 0.4 m/0.1 m, I_p < 60 kA), pulse length $\tau_d \leq$ 1 ms) has been operated only with a SS vacuum vessel (field penetration time $\tau_w \leq$ 0.15 ms) to test the idea of driving tearing mode and/or plasma rotation by using internally resonant RHF. In what

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follows, $m(n)$ and $M(N)$ stand for the poloidal (toroidal) mode numbers of the inherent mode and external field, respectively. Two pairs of the helical coils cover the whole torus, producing a rather sharp toroidal mode spectrum of the external field; The amplitudes of the neighboring M/N=1/7,9 components are about 10 % of the main M/N=1/8 component, while the rest is less than that. A pulsed oscillator provides triangular shaped orthogonal oscillating currents with variable frequency from 10–20 kHz. The perturbation level is defined $|B_{ra}|/B_{\theta a}$, where $|B_{ra}|$ is the perturbation amplitude and $B_{\theta a}$, the edge poloidal field. The edge magnetic fluctuations $\tilde{B}_{ra}$ were measured with a toroidal array of sine/cosine coils attached onto the outer surface of the vacuum vessel covering over half of the torus.

3. Results and Discussion

3.1 Suppression of magnetic fluctuation with RHF

In STE-2 discharges without a conducting shell, the plasma current I_p is around 60 kA with discharge duration τ_d of about 0.7 ms. The discharge characteristics of the STE-2 together with the time behavior of magnetic fluctuations have been described elsewhere [5,6].

Figure 1 shows the toroidal mode spectrum of the m=1 magnetic fluctuations. Immediately after attaining the RFP configuration at about t = 0.25 ms, the magnetic fluctuations grow with the time scale of τ_w. The fluctuation power distributes mainly among the modes with $n \geq 6$. The mode with maximum amplitude changes from shot to shot within the range of n from 7–9. The fluctuations remain almost nonrotating (i.e., locked to the wall), or sometimes rotate very slowly in the direction of plasma current (co-direction). The measurement of radial profile of the magnetic field has shown that the m/n=1/8 mode is the tearing mode whose resonant surface is located at r/a~0.4.

Figure 2 shows the time evolution of the amplitudes of these modes together with the plasma current waveform without the RHF. The amplitudes of the modes continue to grow after setting up the RFP configuration with the time scale of τ_w. We should note our previous observation that in RFP plasmas with conducting shell, the fluctuation amplitude did not continue to grow but rather remained almost constant during the discharge with lower level than without the conducting shell [5]. Comparing these different behaviors of magnetic fluctuations, we may conclude that these modes are resistive wall tearing modes whose saturation amplitudes are enhanced by the resistive wall effect.

When the RHF is applied at 0.3 ms with relative amplitude of 0.5 %, the time evolution of the amplitudes of dominant modes changes as shown in Fig. 3. The growth of the modes is suppressed transiently for 0.2–

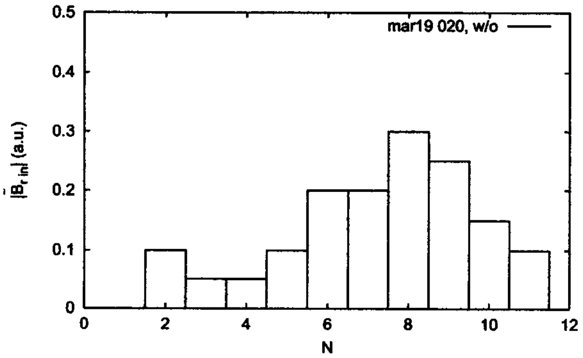

Fig. 1 Toroidal mode spectrum.

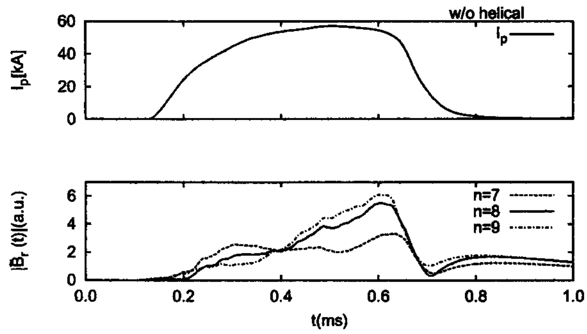

Fig. 2 Time behavoir of the m/n=1/7–9 mode amplitudes without RHF.

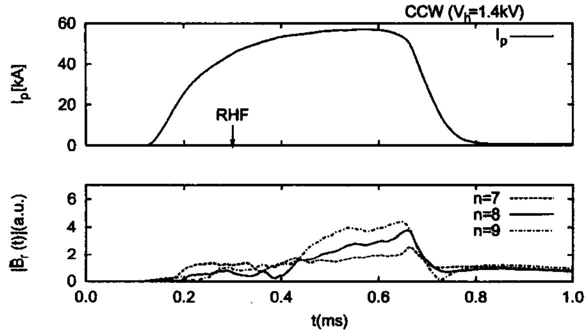

Fig. 3 Time behavoir of the m/n=1/7–9 mode amplitudes with RHF.

0.3ms, and, moreover, the amplitudes are reduced for the rest of the discharge. Ensemble average over several tens of shots has revealed that the amplitudes are reduced by 20–30 % at 0.5 ms (current peak). No significant influence on the loop voltage or discharge duration has been observed yet; It appears that careful optimization of the frequency and amplitude is required for favorable effect on the RFP discharge.

3.2 Mode coupling studies

The time behavior of the toroidal phases of the $m/n=1/6$–11 modes shows that the core resonant (or internally nonresonant) $m/n=1/<8$ modes are almost locked to the vessel. In both cases, the higher modes ($n>9$) tend to rotate in the opposite direction to plasma current (ctr-direction) with a phase velocity of about $5\times10^3\pi$ rad/s.

When the co-RHF is applied from the start of discharge to RFP plasmas, as shown in Fig. 4, the $m/n=1/8$ mode is accelerated in the same direction (the phase increases with time). Moreover, the $n=7$ mode is also accelerated in the same direction. On the contrary, $m/n=1/9$ mode, which otherwise rotate in the ctr-direction, is locked to the vessel, and the phase velocity of the $m/n=1/10$ mode is decreased. That is, the lower ($n<8$) modes are accelerated, while the higher modes are decelerated; It is evident that the effect of co-RHF can be observed not only on the rotation of resonant mode but also for the neighboring modes. We may note that the rotation velocity (phase velocity) is much lower than the phase velocity of the applied RHF.

The effect on the neighboring modes are also observed for the ctr-RHF, as shown in Fig. 5. In this case, the $m=1/n=8$ resonant mode rotates in the ctr-direction; The resonant mode is accelerated in the same direction as the RHF. The neighboring $n=7$ mode shows the similar trend. The higher modes tend to rotate in the opposite direction to the applied ctr-RHF; They tend to rotate in the co-direction in this case.

A theory [7] predicts that the electromagnetic torque T_k^{NL} acting on a magnetic island arises as a result of interaction between the magnetic fluctuation of the mode $\tilde{B}_k$ and nonlinearly produced perturbation current $\tilde{j}_k^{NL}$ on that mode rational surface. If we apply this idea, the torque on $m=1/n=8$ mode can be written down as follows,

$$T^{NL}_{(1,8)} = \sum_{(m,n)} C^{(1,8)}_{(m,n),(m-1,n-8)} \tilde{B}_{(1,8)} \tilde{B}_{(m,n)} \tilde{B}_{(m-1,n-8)} \sin\left(\delta_{(m,n)} - \delta_{(1,8)} - \delta_{(m-1,n-8)}\right) \qquad (1)$$

where C is the coupling coefficient, $\tilde{B}_s$ are the magnetic fluctuation amplitudes and δ_s are the phases of the corresponding modes. The electromagnetic torque on other modes can be expressed in a similar form. Although we need simultaneous measurements of the $m=1$ and $m=0$

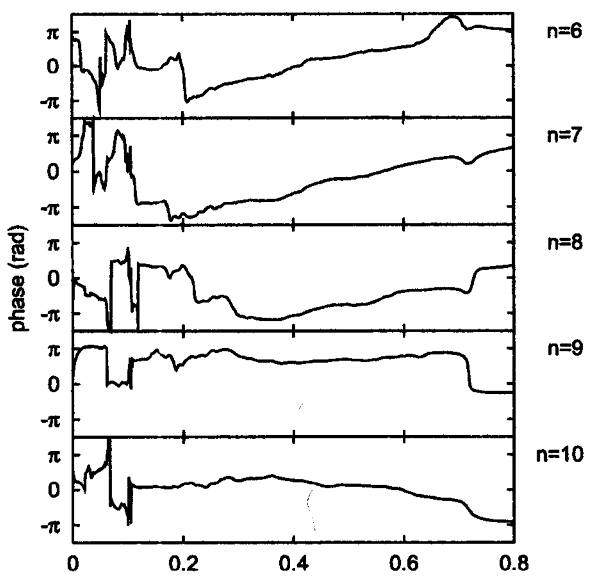

Fig. 4 Toroidal phase of $m=1$ modes in RFP when co-RHF was applied from the start of discharge.

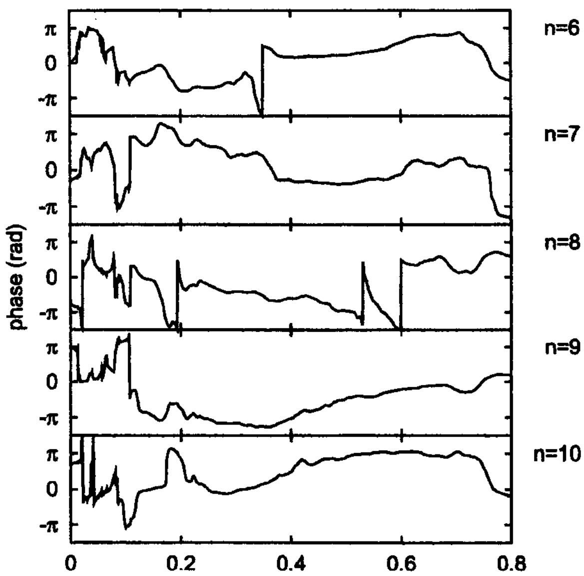

Fig. 5 Toroidal phase of $m=1$ modes in RFP when ctr-RHF was applied from the start of discharge.

mode behavior to estimate the nonlinear electromagnetic torque, the relation shows the importance of the m=0/n=1 mode.

Here we will show the importance of the m=0 mode rational surface (i.e., field reversal surface) for the response of m=1 modes to the resonant helical perturbation. The ultra-low-q (ULQ) plasmas are produced in STE-2 with the edge safety factor q_a of about 0.1 [6]. In ULQ plasmas in the STE-2, the dominant magnetic fluctuation mode shifts to m/n=1/6,

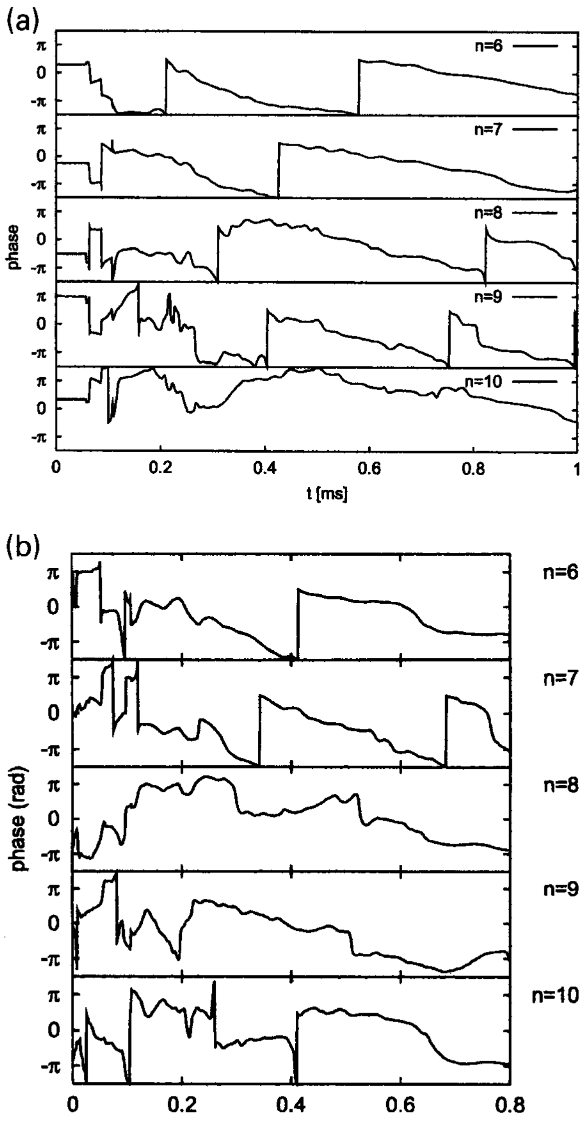

Fig. 6 (a): Toroidal phase of the m/n=1/6–10 modes in ULQ plasma without helical parturbation.
(b): Toroidal phase of the m/n=1/6–10 modes in ULQ plasma with static helical parturbation applied st 0.2ms.

and m=1/n=8 mode still has a nonnegligible amplitude. These modes usually rotate in the ctr-direction, as shown in Fig. 6(a). We applied static (non-rotating) M/N=1/8 resonant helical perturbation to ULQ plasmas to see the m=1 mode response. The static perturbation was applied at t = 0.2 ms, with rise time of 0.05 msec and decay time of 0.5 ms. No significant influence has been observed on the global parameters of the ULQ plasma. Figure 6(b) shows the time behavior of toroidal phases of the m/n=1/6–10 modes with static helical field. As is evident, only the m=1/n=8 resonant mode has a trend to be locked (the phase remains constant with time) slightly after the helical field is applied. That is, in ULQ plasmas, where there is no m=0 more rational surface, only the resonant mode is influenced by the helical perturbation. Thus, the importance of the m=0 mode in the mode coupling process has been indirectly demonstrated by comparing the different response of the m=1 mode(s) to external resonant helical perturbations in RFP and ULQ plasmas.

Improvement of the magnetic diagnostics is in the process for the simultaneous measurement of m=0 and m=1 modes to estimate the electromagnetic torque on the basis of eq. (1).

4. Summary

In STE-2, when operated only with a vacuum vessel, core resonant tearing modes are observed to grow with the time scale of field penetration time of the vessel, and these modes are identified as the resistive wall tearing modes. Resonant rotating helical field has been applied to control the dynamics of these modes.

The growth of the amplitudes of these modes is shown to be suppressed with the RHF. The effect of the RHF on mode rotation is observed not only for the resonant mode but also for the neighboring modes, indicating the importance of coupling of m=1 modes. The role of m=0 mode is studied by applying static (non-rotating) helical perturbation to ULQ plasmas, which have no m=0 mode resonant surface. In ULQ plasmas, only the resonant m=1 mode is affected by the perturbation. These results suggest the importance of nonlinear coupling of the m=1 modes through m=0 (and probably n=1) mode. Detailed simultaneous measurements of the dynamics of m=1 and m=0 modes are in progress.

The effect of RHF on global discharge parameters has not become clear yet In STE-2, the resistance decreases with an increase in the plasma current irrespective of the RHF. No significant improvement of the current dependence of discharge resistance has been made clear yet. However, it might be noted that the plasma current tends to increase with the RHF. It appears that careful optimization of both the frequency (rotation speed) and amplitude of the RHF is required.

A linear stability analysis of the external kink modes has shown that m/n=1/–2, –3, –4 modes can be unstable in the STE-2 depending upon the current profile [8]. We have shown that the external helical current of several % of the toroidal plasma current has a stabilizing effect on these kink modes. We look for the possibility of sustaining a steady state with reduced amplitude of the external kink modes by using externally nonresonant rotating helical field (M/N=1/–4).

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