Control of RFP Dynamics with Rotating Helical Fields

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Abstract Control of MHD mode dynamics is essential to improving the reversed field pinch (RFP) experiments as a part of the fusion research programs. The STE-2 RFP has been operated only with a vacuum vessel ($\tau_w \leq$0.15 ms) to test the idea of driving MHD mode and/or plasma rotation by using resonant **r**otating **h**elical **f**ield (RHF) which is applied from outside of the vessel. We report new results which indicate direct interaction between the RHF and inherent tearing modes. Without the RHF, the magnetic disturbance outside the vessel is dominated by almost locked m/n=1/8 core resonant tearing modes, growing with the scale of vessel time constant. The RHF tends to drive the mode rotation with a transient suppression of the mode growth. Improved RFP performance has not become clear yet. Stabilization of the external kink modes will also be discussed.

1. Introduction

The reversed field pinch (RFP) is characterized by low-q (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. Suppression of the magnetic fluctuations due to tearing modes by current profile modification has resulted in the improved confinement modes in large RFPs surrounded by an ideal wall[1].

As in tokamaks, the resistive wall modes (RWM) (both tearing and ideal kink modes) are thought to be serious problems in future RFPs in which the discharge duration far exceeds the field penetration time of a conducting wall. Theories have predicted that the growth of tearing modes or their saturation amplitudes can be reduced by moderate toroidal rotation of the plasma[2]. On the other hand, stabilization of the external kink modes requires sub Alfvénic rotation speed which is much faster than the natural rotation speed of the tearing modes[3].

In the RFP, it appears to be difficult to use the neutral beam injection for plasma rotation drive because the diameter of port holes is restricted by the unfavorable field errors. Thus, development of other techniques for rotation drive is one of the urgent issues in the RFP research. The internally resonant rotating helical field (RHF) applied from outside of the resistive wall may be able to provide accelerating torque to the magnetic island, if the phase is adequately controlled. The external kink modes may be stabilized by externally nonresonant rotating helical field which resembles the rotating secondary shell concept[4].

2. Experiments

The STE-2 RFP (R/a=0.4m/0.1m, $I_p \sim$60 kA, pulse length$\sim$0.7 ms)[5] has been operated only with a resistive vacuum vessel (field penetration time $\tau_w \leq$0.15 ms), to test the idea of driving MHD mode and/or plasma rotation by using resonant rotating helical field (RHF). In what follows, m (n) and M (N) stand for the poloidal (toroidal) mode number of the inherent mode and the external field, respectively. In the preliminary experiments[6], we used helical coils covering a half of the torus (two quarters), which provided M/N=1/8 resonant RHF. The discreteness of the helical coil produced the low N ($\sim$2) components of the M=1 field as well. No significant influence of the RHF was observed on the m=1 mode dynamics. However, toroidally localized m=0 (toroidal flux) disturbance was accelerated or decelerated depending upon the direction of the RHF. This result may indicate that the m=0 disturbance was a result of the m=1 mode coupling.

In this paper, we report new results which indicate direct interaction between the rotating M=1 helical field and the inherent m=1 core resonant tearing modes. The helical coils have been modified to cover the whole torus, which has resulted in a rather sharp toroidal mode spectrum of the RHF; the amplitudes of the M/N=1/7,9 components are about a half of that of the main M/N=1/8 component, while the rest is negligibly small. In most experiments reported here we used LC damping oscillation to obtain alternating current; effective duration of the rotating field was restricted to not longer than 0.3-0.4ms. The frequency was 10-20kHz, and the toroidal phase velocity of the RHF was 4-7 km/s. The amplitude of the oscillating field $|B_{ra}|$ is defined as an average from the second to the fifth peak values which were measured inside the vessel. In some experiments, we have used a pulsed oscillator which provides triangular shaped oscillating current with frequencies $\sim$15 kHz (variable) and pulse length longer than 1 ms. The perturbation level is defined by $|B_{ra}|/B_{\theta a}$ in both cases, where $B_{\theta a}$ is the edge poloidal field.

3. Results and Discussion

In STE-2 discharges without a conducting shell, the plasma current I_p is around 60 kA with discharge duration τ_d of around 0.7 ms[6]. Figure 1 shows the time behavior of the m=1 edge radial magnetic fluctuations $\tilde{B}_{ra}$ measured with a toroidal array of sine/cosine coils attached onto the outer surface of the vacuum vessel and covering over a half of the torus. Immediately after attaining the RFP configuration at about t=0.25 ms, the magnetic fluctuations grow with the time scale of τ_w, and the dominant toroidal mode number n appears to be around 8, maintaining the structure for the rest of discharge. The fluctuations remain almost nonrotating (i.e., locked to the vessel). The measurement of radial magnetic field profile shows that the m/n=1/8 mode is the tearing mode whose resonant surface is located at r/a $\sim$0.4.

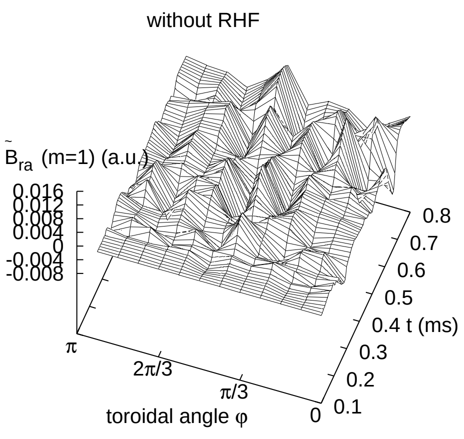

FIG. 1. Time evolution of $\tilde{B}_{ra}$ over a half of the torus without RHF.

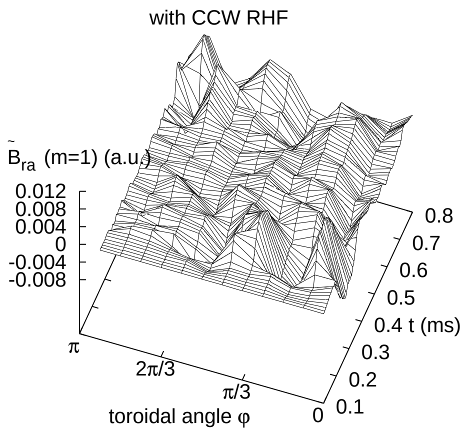

FIG. 2. Time evolution of $\tilde{B}_{ra}$ with RHF applied at 0.3 ms.

When the RHF was applied at 0.3 ms with a frequency of 15 kHz and a perturbation level of 0.5 %, as shown in Fig.2, the amplitude of magnetic fluctuations is reduced, and, furthermore, the fluctuations rotate toroidally in the direction of the applied RHF. The phase velocity of magnetic fluctuations is slightly lower than that of the RHF. It should be noted that there is a critical perturbation amplitude; When the perturbation level is lower than 0.4 %, neither the reduction of the fluctuation amplitude nor their toroidal rotation has been observed.

The toroidal mode spectrum of the $\tilde{B}_{ra}$ shows that most of the fluctuation power is distributed among the m/n=1/7,8,9 modes. Figure 3 shows the time evolution of the amplitudes of these m/n=1/7,8,9 modes together with the plasma current waveform without the RHF. The amplitudes of the modes increase immediately after setting up the RFP configuration with the time scale of the vacuum vessel until the end of discharge. When the RHF is applied at 0.3 ms with relative amplitude of 0.5 %, the time evolution of the mode amplitudes changes, as shown in Fig.4. The growth of the modes is suppressed transiently for 0.2-0.3 ms, and, moreover, the amplitudes are reduced for the rest of the discharge. Ensemble average over several tens of shots has revealed that the amplitudes of these modes are reduced by 20-30 % at 0.5 ms.

The time behavior of the toroidal phases of the m/n=1/6-10 modes shows that the core resonant (or internally nonresonant) m/n=1/$\leq$8 modes are almost locked to the vessel, while the m/n=1/9,10 modes rotate in the opposite direction to the toroidal plasma current (ctr-direction) with a phase velocity of $\sim 5\times10^3\pi$rad/s. It may be interesting to note that in the ultra-low-q (ULQ) discharges in the STE-2, the dominant m/n=1/5-7 modes rotate rigidly in the same (ctr-) direction with almost the same phase velocity. When the RHF is applied at 0.3 ms, as shown in Fig.5, the m=1/n=8 mode keeps moving (or rotates) for $\geq$0.2 ms, and at the same time, the m/n=1/9 mode, which otherwise ctr-rotates, reverses the rotation direction and keeps moving for the same period. The m/n=/10 mode may also be decelerated for the remaining period of the discharge. Further discussion on the behavior of these m=1 modes, which probably includes the effect of resonant three wave coupling through nonlinearly excited m=1/low n modes, requires simultaneous measurements of the m=1 and m=0 modes. Unfortunately, it is beyond the capability of our present magnetic diagnostics. Nevertheless, we may conclude that the above result is the first demonstration in the RFP of the direct interaction between the rotating M=1 helical field and inherent m=1 core resonant tearing modes.

In the present experiments with improved helical coil configuration, it has also been observed that the toroidally localized m=0 disturbance, which usually rotates in the ctr-direction, is either accelerated or decelerated depending upon the RHF direction, as in the previous experiments. The influence of the M=1 RHF on the toroidal rotation of the m=0 localized disturbance has also been identified

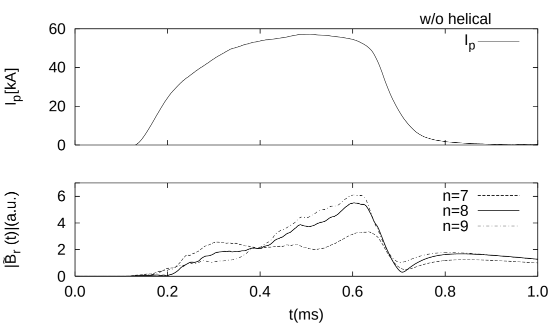

FIG. 3. Time evolution of the m/n=1/7,8,9 mode amplitudes without RHF.

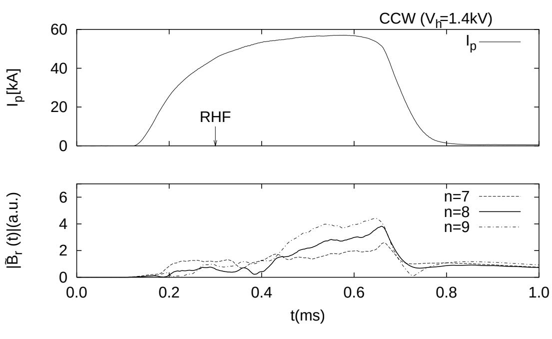

FIG. 4. Time evolution of the m/n=1/7,8,9 mode amplitudes with RHF applied at 0.3 ms.

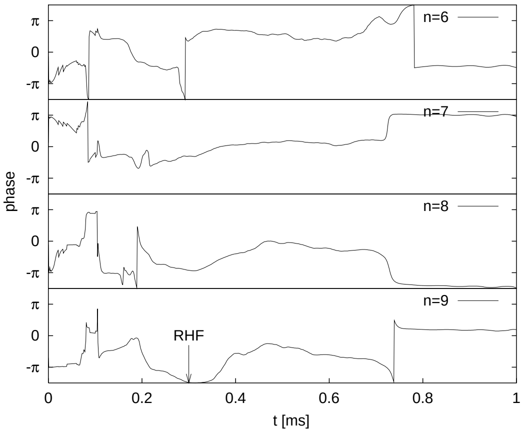

FIG. 5. Time evolution of the toroidal phase of the m/n=1/6,7,8,9 modes with RHF applied at 0.3 ms.

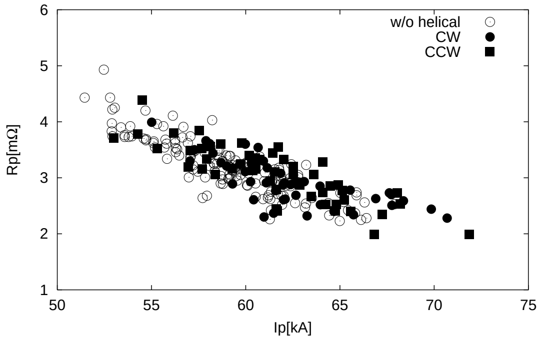

FIG. 6. Plasma resistance vs. toroidal plasma current in standard and RHF-applied discharges.

Figure 6 shows the resistance vs. toroidal plasma current in standard and RHF-applied discharges. The resistance decreases with an increase in the plasma current in both cases. No significant improvement of the dependence of the resistance on plasma current has not been made clear yet. However, it may be noted that the plasma current tends to increase with the RHF. Influence of the RHF on high frequency magnetic fluctuations has not been observed yet. Further optimization of both the frequency (rotation speed) and amplitude of the RHF appears to be needed for the evident improvement of RFP performance.

A linear stability analysis of the external kink modes has revealed that m/n=1/-2,-3,-4 modes can be unstable RWM in the STE-2, depending the current profile. We have also revealed that the external helical current has a stabilizing effect on these kink modes[7]. We plan to test the effect of rotating externally nonresonant helical field (M/N=1/-4) on the stability of external kink modes, which is similar to the idea of rotating secondary shell.

4. Summary

The STE-2 RFP has been operated with only a vacuum vessel to test the idea of driving the mode and/or plasma rotation using resonant RHF applied from outside of the vessel. It has been observed that the growth of dominant magnetic fluctuations is suppressed with transient rotation which are otherwise almost locked to the vessel. It is a direct demonstration of the interaction between the externally applied M=1 modes and the inherent core resonant tearing modes. The external helical field appears to be useful in controlling the RFP dynamics.

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