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Characterization of MHD behavior in a low-aspect ratio RFP

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MHD properties of low-aspect-ratio (low-A) reversed field pinch (RFP) plasmas have been studied in RELAX machine with aspect ratio of 2. The MHD behavior appeared in edge magnetic field fluctuations shows strong dependence on toroidal field reversal. In standard or deep-reversal plasmas, the edge magnetic fluctuation has broad toroidal mode spectrum, while it is narrowed by reducing the toroidal field reversal. The spontaneous transition to quasi-single helicity state is realized in shallow reversal discharges. The results may suggest that shallow-reversal operation is desirable to realize favorable characteristic of low-A RFP configuration.

Keywords: RFP, aspect ratio, magnetic fluctuation, tearing mode, mode dynamics

1. Introduction

The reversed-field pinch (RFP) is a compact, high-beta magnetic confinement system characterized by MHD relaxation and self-organization of the magnetic configuration. Unlike the tokamak, both of the two confining magnetic field components, toroidal field B_t and poloidal field B_p, have the same order of magnitude. Typical safety factor $q(r) = rB_\mathrm{t}(r)/RB_\mathrm{p}(r)$ is close to $a/2R$ in the plasma core and decreases monotonically towards the edge with a slightly negative value. Here a, R is minor, major radius of torus plasma and q indicate the torsional degree of magnetic field. The rational surfaces where $q(r_\mathrm{s}) = (m = 1)/n$ (m, n are poloidal, toroidal mode number) is satisfied are densely spaced in most area and there is a field reversal surface, where $B_\mathrm{t}(r_0) = 0$ and $m = 0$ modes resonate. In RFPs, these modes can be simultaneously destabilized and many $m = 0$ and $m = 1$ modes with different toroidal mode numbers n grow to similar amplitude. As a result, the MHD instabilities have a wide wavenumber spectrum in the standard multiple helicity (MH) RFP state. Since these MHD instabilities drive the self-generation of the reversed toroidal magnetic field and sustain the RFP configuration, through the mechanism so called dynamo effect, MHD instabilities are very important in the RFP.

Recent experimental measurements in RFPs have shown that a new MHD dynamo regime is present,the quasi-single-helicity (QSH) regime. The QSH state is expected a strong candidate for confinement improvement of the RFP, where the single dominant tearing mode grows significantly larger than the remaining modes and the associated large magnetic island is immersed in otherwise stochastic core region[1, 2, 3]. Within the large magnetic island of the dominant mode, favorable confinement has been realized.

The aspect ratio A ($= R/a$) is an important parameter for characterizing the RFP properties[4, 5, 6]. Recent equilibrium analyses have shown that by lowering the aspect ratio, mode rational surfaces are less densely spaced in the core region in the RFP. And numerical simulations indicate that $m = 1$ spectrum are contributed by fewer toroidal modes as A becomes smaller. These results suggest that the low-A RFP may expand the region to which the dominant single island can grow without interacting the neighboring islands and bring about simpler MHD dynamics and easier access to the QSH state[7].

This paper is organized as follows. The device and the diagnostics are described in the following section. In Sec. 3, the characteristic of the RELAX RFP plasma is explained. Observed MHD characteristics are shown in Sec. 4. In Sec. 5, comparing with other RFPs, we discuss the low-A properties and make men-

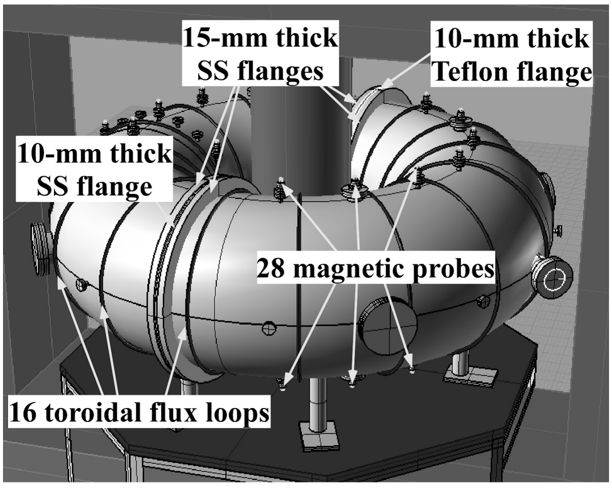

Fig. 1 Schematic view of the magnetic diagnostics and the gap structures of RELAX.

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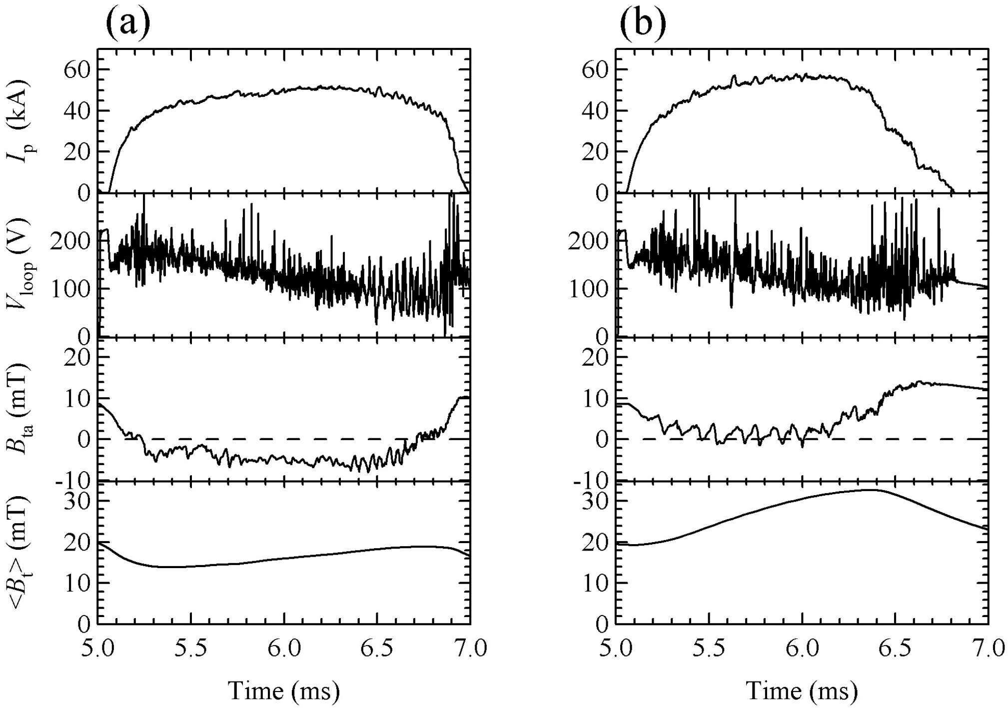

Fig. 2 Time evolution of plasma current I_p, toroidal loop voltage V_loop, edge toroidal field B_ta, and cross sectional average toroidal field $\langle B_\mathrm{t} \rangle$ for the typical (a) deep-reversal and (b) shallow-reversal discharge of RELAX.

tion about the realization of favorable characteristic of low-A RFP configuration. And finally, the conclusion is presented in Sec. 6.

2. Experimental Setup

In order to investigate MHD properties of low-A RFP plasmas, we have carried out experimental studies in RELAX machine (R = 0.51 m, a = 0.25 m) with the aspect ratio of 2[8]. Figure 1 shows the vacuum vessel with magnetic diagnostic arrangement of RELAX. In RELAX we have used a 4-mm thick SS vacuum vessel without outer conducting shell, and therefore, the vacuum vessel acts as a resistive wall with field penetration time of ~1.5 ms. In RELAX machine, 15-mm thick SS flanges are attached at the two poloidal gaps. One of them is electrically insulated with a 10-mm thick Teflon flange. The other one is electrically connected with a 10-mm thick SS flange. There is no insulated toroidal gap in RELAX.

In order to measure the edge magnetic fluctuations, RELAX is equipped with two toroidal arrays of 14 toroidal and poloidal field pick-up coils inserted from top and bottom ports equally distributed toroidally (with toroidal separation angle of 22.5 degree), except at two poloidal gap locations (see Fig. 1). The difference of the top and bottom signals provides the odd component of the edge magnetic fields, while the sum, the even component. RELAX is also equipped with 16 equally separated 1-turn toroidal flux loops at just outside the chamber for the measurement of the toroidal distribution of toroidal magnetic flux.

All these pick-up coil signals are sampled at a frequency of 2 MHz and numerically integrated. After the integration, we use a 2 kHz high-pass filter to obtain the fluctuating component.

3. RELAX RFP plasma

Figure 2 shows two types of typical waveforms of the RELAX RFP plasma : from top to bottom, the plasma current I_p, toroidal loop voltage V_loop, toroidal field at the edge B_ta and cross sectional average toroidal field $\langle B_\mathrm{t} \rangle$, respectively. Main difference of these two types of discharges is obvious when the magnetic field behaviors are compared. In Fig. 2(a), the edge toroidal field B_ta clearly reverses its sign in the current rise phase at ~5.2 ms and the average toroidal field $\langle B_\mathrm{t} \rangle$, once decreases in the initial phase due to the strong toroidal field reversal, slowly increases up to about the same value as the initial bias field at the end of discharge with flat-topped I_p waveform. On the other hand, in Fig. 2(b), toroidal field reversal is not so clear. The plasma current I_p keeps rising to ~6 ms, with monotonic increase in $\langle B_\mathrm{t} \rangle$ to the end of discharge. These difference arises mainly from the difference in the toroidal field reversal. The discharge in Fig. 2(a) is the result of strong external toroidal field reversal. On the other hand, the discharge of Fig. 2(b) often observed with weak toroidal field reversal or in self-reversal operation.

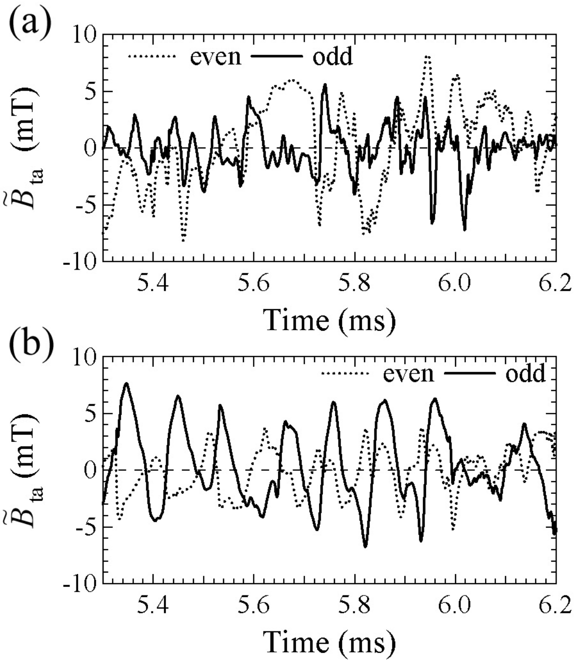

Fig. 3 Time evolution of odd and even components of edge toroidal field fluctuations in (a)deep-reversal and (b) shallow-reversal discharge.

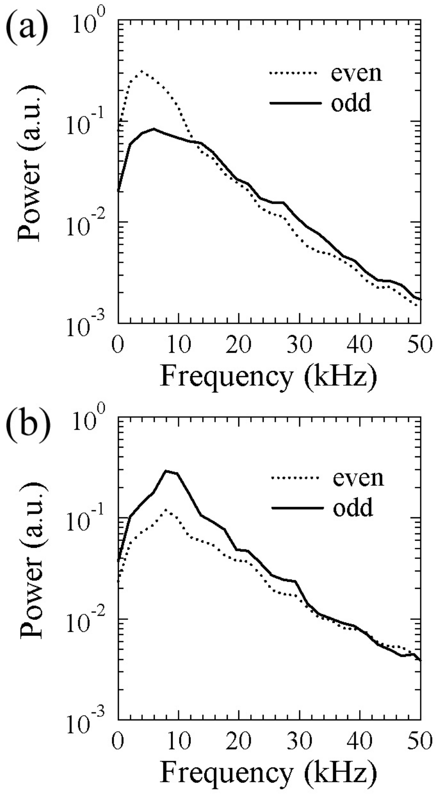

Fig. 4 Frequency spectra of odd and even components of edge toroidal field fluctuations in (a) deep-reversal and (b) shallow-reversal discharge.

We will refer to these two types of discharges as deep-reversal or shallow-reversal according to the edge toroidal field. In the following section, we will compare the magnetic MHD fluctuation behavior in these two types of discharges.

4. MHD characteristics in RELAX

Figure 3 shows time evolution of edge toroidal field fluctuations. In Fig.3(a), the odd and even components are shown in deep-reversal RFP case, while in Fig.3(b) in shallow-reversal case. In deep-reversal RFP plasma, the odd component (mainly $m = 1$) shows random fluctuation with root-mean-square(RMS) amplitude (between 5.3 s to 6.2 s) of ~2 mT without characteristic frequencies. The time behavior of the even component is similar to that of the odd component with slightly higher amplitude and lower frequency. There appears to be no clear phase relationship between the odd and even components.

In Fig.3(b), the similar time traces of fluctuations are shown in shallow-reversal case. The fluctuation of the odd component becomes more coherent and its amplitude increases up to ~3.5 mT (RMS value) by reducing the field reversal. The amplitude of the even component is smaller than the odd component with clear phase relationship that the even component is out of phase with the odd component.

Figure 4(a) shows the frequency spectrum of the odd and even components of edge toroidal field fluctuations in the frequency range up to 50 kHz in deep-reversal case. The magnetic fluctuation signals in the flat-topped current phase (from 5.4 to 5.9 ms in Fig.2(a)) are Fourier analyzed in each shot, then ensemble averaged over 30 shots to obtain the frequency spectrum. In deep-reversal case, the fluctuation power of even component is higher than that of the odd component in the frequency region lower than ~10 kHz, while we can find no significant difference in the high frequency region. Figure 4(b) shows the similar spectra in shallow-reversal case. As pointed out in raw data, the fluctuation power of odd component increases in shallow-reversal case over the entire frequency region, with maximum power at the frequency of ~10 kHz. This frequency corresponds to the characteristic fluctuation in Fig.3(b). Comparing Figs. 4(a) and 4(b), we can conclude the effect of toroidal field reversal on the magnetic fluctuation spectra as follows. By reducing the field reversal, the power of even component decreases in the frequency region lower than ~15 kHz, while it increases in the higher frequency region where $f > 15$ kHz.

Figure 5(a) shows the toroidal mode spectra of even and odd components of edge toroidal field fluctuations in deep-reversal case. As pointed out previously, the odd component is essentially the $m = 1$ component. The significant amount of fluctuation

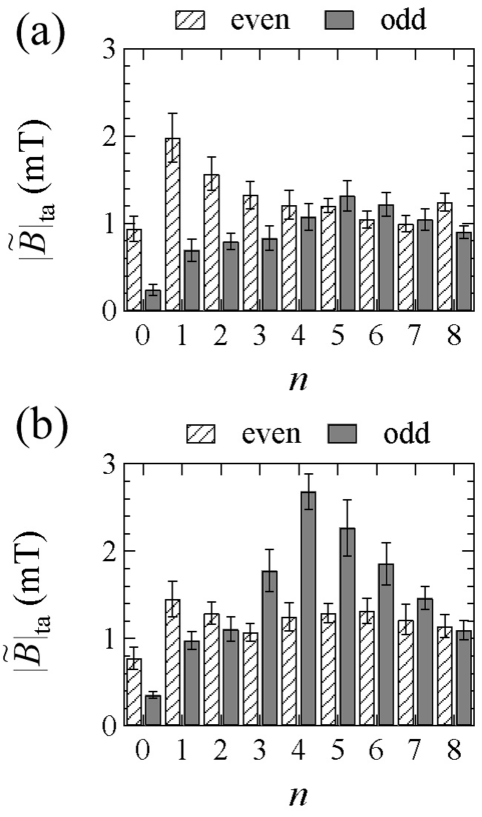

Fig. 5 Toroidal mode spectra of even and odd components of edge toroidal field fluctuations in (a) deep-reversal and (b) shallow-reversal discharge.

power of the $m = 1$ modes distribute among the $m = 1/n = 4$-8 modes, which are internally resonant tearing modes. (Note that the $n = 8$ is the maximum toroidal mode number of the present capability of our toroidal magnetic probe array.) This property is similar to the observation in MH RFP state in other RFP machines. The fluctuation power of even components distributes almost equally among the toroidal modes in deep-reversal case.

Figure 5(b) shows the similar mode spectra in shallow-reversal case. In shallow-reversal case, the toroidal mode spectrum of the $m = 1$ (odd) modes has a peak at $m = 1/n = 4$, and the power decreases rapidly with increasing the mode number. As described in ref.[9], quasi-periodic transition to QSH RFP state has been observed in RELAX particularly in shallow-reversal discharges. During the QSH state, the fluctuation power is concentrated to the dominant $m = 1/n = 4$ mode. Since the spectra is obtained from time period of ~0.5 ms, which is longer than the QSH duration in RELAX, the mode spectrum looks broader than that of typical QSH state. The mode spectrum of the even component in shallow-reversal case shows that the power of high-n modes increased by a factor ~2.

5. Discussion

As shown in Figs. 3(a) and 4(a), the MHD characteristics observed in deep-reversal RELAX plasmas is not much different than the observation in MH RFP state in other RFP machines. In fact, it is difficult to identify spontaneous transition to QSH RFP state in deep-reversal RELAX discharges. In deep-reversal RFP configuration, toroidal plasma current tends to have a peaked profile with lower value of on-axis safety factor q_0. In addition, the field reversal surface r_0 shifts inward by deepening the field reversal. The lower q_0 and inward shift of r_0 have the effect of inward shift of the innermost m=1 mode resonant surface, thus reducing the favorable aspect of low-A configuration. The resultant q profile may not be very much different from that in medium-aspect-ratio RFP profile. On the other hand, the tendency that toroidal mode spectrum of the odd ($m = 1$) modes concentrates in the dominant $m = 1/n = 4$ mode by reducing the field reversal. This is similar to the condition to realize QSH in other machines. In shallow-reversal plasmas, the toroidal plasma current tends to have a broad profile, and the resultant RFP configuration has the favorable low-A character, opposite to the deep-reversal case. The phase correlation between the odd and even components may suggest their coupling. One of the possibilities is nonlinear coupling of the dominant $m = 1$ modes to drive the $m = 0$ and $m = 2$ modes. The bispectral analysis is in progress for the detailed study of even modes.

The above observation in RELAX has indicated that shallow-reversal RFP operation is desirable to realize the favorable low-A RFP configuration. We may also need some means to control the current profile in order to enhance spontaneous transition to QSH in deep-reversal RFP.

At the end of this section, we summarize some remarkable characteristic behaviors related to MHD instabilities observed in RELAX to date. In shallow-reversal discharges, we have observed following distinctive MHD properties; (1) Quasi-periodic growth of the dominant $m = 1/n = 4$ mode with a resultant mode spectrum similar to that of the QSH state with a lower toroidal mode number than in other RFPs[9]. (2) Large scale profile change of magnetic structure. The magnetic configuration has good agreement with helical ohmic equilibrium state[10, 11]. (3) Observation of simple $m = 1/n = 4$ helical structure (single helix in the extreme case) in fast camera visible-light images[12].

6. Conclusion

The MHD behavior in low-A RFP shows strong dependence on toroidal field reversal. In standard or deep-reversal plasmas, the edge magnetic fluctuation amplitude has broad toroidal mode spectrum. On the other hand, the amplitude increases and the mode spectrum is narrowed by reducing the toroidal field reversal. The quasi-single helicity state is realized spontaneously in shallow-reversal discharges. The results suggest that shallow-reversal operation is desirable to realize favorable characteristic of low-A RFP configuration. It also suggests the necessity of some means to actively control the current or pressure profiles to realize QSH in deep-reversal RFP plasmas where fluctuation amplitude is low.

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