Quasi-Periodic Growth of a Single Helical Instability in a Low-Aspect Ratio RFP

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Quasi-periodic growth of a single core-resonant instability has been observed in a low-aspect ratio (low-A) reversed field pinch experiment in RELAX. In round-topped current discharges, the innermost core resonant $m = 1/n = 4$ mode grows with suppression of the neighboring $m = 1/n = 5, 6$ modes. The resultant toroidal mode spectrum of the $m = 1$ modes is similar to that of the quasi-single helicity (QSH) state with higher amplitudes. These phenomena are discussed along with the low-A characteristic of RELAX, indicating simpler MHD mode dynamics and easier access to the QSH state.

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

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The reversed field pinch (RFP) is a magnetic confinement concept for compact high-beta plasmas. Recent progress in confinement improvement in RFP results from realizing the tearing-mode-stable current profile with pulsed poloidal current drive (PPCD) [1, 2]. The quasi-single helicity (QSH) RFP state, where the internally resonant single tearing mode grows significantly larger than the others, is another candidate for confinement improvement [3].

The aspect ratio A is an important parameters for characterizing the RFP properties. Recent analysis has shown that when A is lowered to 2, a neoclassical equilibrium with a bootstrap current fraction higher than 90% exists with reactor regime plasma parameters [4]. An additional advantage of a low-A RFP configuration is the possibility of simpler MHD mode dynamics because the radial separation of the mode rational surfaces increases in the core region.

We have started experiments to study low-A RFP properties in Reversed field pinch of Low-Aspect ratio eXperiment (RELAX) machine, which has the world's lowest aspect ratio of 2 ($R = 0.5\,\mathrm{m}/a = 0.25\,\mathrm{m}$) [5]. RELAX uses a 4-mm thick vacuum vessel with a field penetration time of ~1.5 ms. It is operated without any other shell structure. The edge magnetic fluctuations are measured with two toroidal arrays, each consisting of 14 pick-up coils set at the top and bottom ports, which are equally spaced in the toroidal direction except at the two poloidal gaps.

Signals from these coils are sampled with a 2 MHz sampling frequency. After integrating numerically, we use a high-pass filter to obtain a fluctuating component with $f > 0.5$ kHz. The difference of the top and bottom signals provides the odd (mostly $m = 1$) component, while the sum, the even (both $m = 0$ and $m = 2$) components. The signals are then Fourier transformed spatially to obtain a time evolution of the amplitude and phase.

Figure 1 shows the time evolution of the plasma current I_p, loop voltage V_{loop}, edge toroidal field B_{tw} and average toroidal field $\langle B_t \rangle$ of a round-topped discharge. The

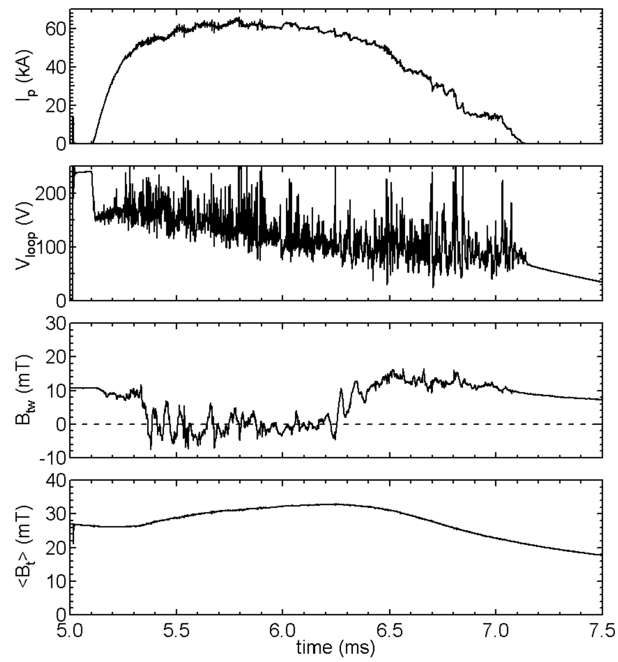

Fig. 1 Time evolution, from top to bottom, of the plasma current I_p, toroidal loop voltage V_{loop}, edge toroidal field B_{tw}, and average toroidal field $\langle B_t \rangle$ in a round-topped discharge of RELAX.

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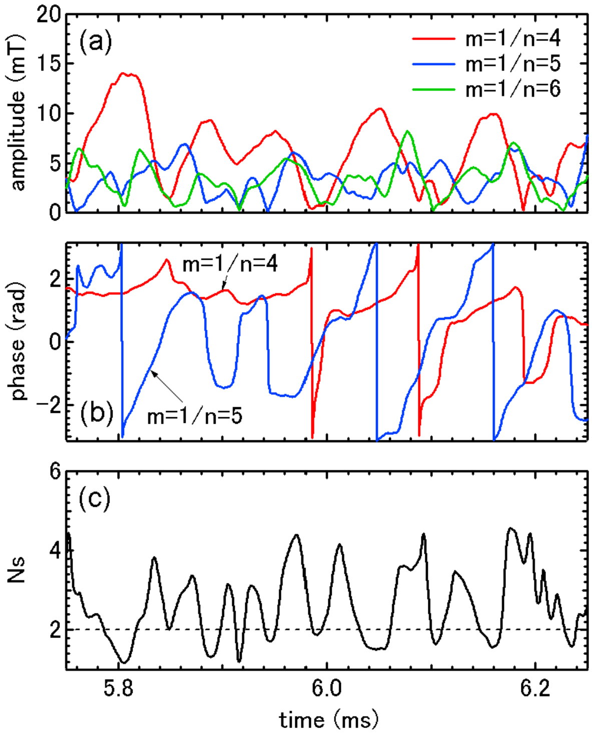

Fig. 2 Time evolution of the amplitude in $m = 1/n = 4, 5, 6$ modes (a), the phase of the $m = 1/n = 4, 5$ modes (b), and the spectral index N_s (c).

plasma current increases rapidly to ~40 kA, then increases to ~60 kA at ~1 ms. Gradual decay of the current follows. The edge toroidal field shows a quasi-periodic oscillation in the current rise phase, and oscillatory behavior persists to the end of the RFP configuration.

In most round-topped discharges, we have observed quasi-periodic growth and succeeding decay of a single helical mode. Figure 2 (a) shows the time evolution of the amplitudes of $m = 1/n = 4, 5, 6$ modes with an expanded time scale. The core-resonant $m = 1/n = 4$ mode grows from ~5.76 ms for about 0.04 ms, and then a gradual decay follows. Similar quasi-periodic growth and decay of the dominant $m = 1/n = 4$ mode continues to the end of the loss of field reversal at 6.2 ms. Amplitudes of the outer neighboring $m = 1/n = 5, 6$ modes stay lower than that of the $m = 1/n = 4$ mode. There appears to be a trend that these neighboring modes grow (decay) during the decaying (growing) phase of the $m = 1/n = 4$ mode. In Fig. 2 (b), we compare the time evolution of the phase of the $m = 1/n = 4$ mode to that of the $m = 1/n = 5$ mode. A correlation is indicated between the quasi-periodic oscillation of the mode amplitude and phase evolution. During the growth of either mode, the phase of the corresponding mode does not change much, whereas the phase changes rapidly during the decay of the corresponding mode. We have tested the accuracy of the phase evolution of these modes by using artificial data with amplitude modulation

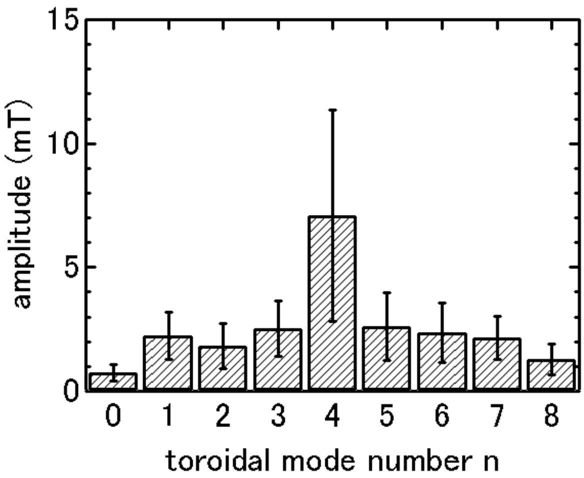

Fig. 3 The toroidal mode spectrum of the $m = 1$ modes, when $N_s < 2$.

as shown in Fig. 2 (a). The interrelationship of the mode growth and deceleration of the mode rotation has yet to be identified. Figure 2 (c) shows the time evolution of the spectral index N_s defined as

$$N_s = \left[\sum_{n=4}^{8} \left(\frac{b_{1,n}^2}{\sum_n b_{1,n}^2} \right)^2 \right]^{-1}. \tag{1}$$

When a single mode is excited, N_s becomes 1, while N_s equals the number of the modes considered when all modes have the same magnetic energy. Thus, N_s is often used as an indication of the quality of QSH in RFP. Hereafter we take the threshold as 2 to discriminate between the multi helicity (MH) and QSH states. $N_s = 2$ corresponds to the magnetic energy of the dominant mode equaling the total energy of the remaining modes. Figure 2 (c) shows that when the dominant mode grows, N_s decreases below 2. The duration of low N_s, however, does not last longer than several tens of μs in the present experiment in RELAX.

Figure 3 shows the toroidal mode spectrum of the $m = 1$ modes, time-averaged over the periods where $N_s < 2$. The spectrum has the characteristic of the QSH RFP state with a lower dominant toroidal mode number than in other RFPs. It should also be noted that the relative amplitude of the dominant mode is somewhat larger than in other devices—about 3 times larger than in a controlled QSH experiment in TPE-RX [6], for example.

The low toroidal mode number can be attributed to the low-A characteristic of RELAX. The relatively shorter sustained duration could be attributed to the difference in the typical value of the resistive time scale $\tau_R = \mu_0 a^2/\eta$, correlated with the tearing mode growth rate [7]. We can estimate the QSH duration of RELAX RFP by comparing the estimated τ_R and experimental QSH duration of other RFP machines with the τ_R of RELAX RFP, and the result is tens of microseconds, which roughly agrees with the experimental value. The larger amplitude of the dominant mode could be attributed to the relatively short time constant of the vacuum vessel, which provides a resistive wall boundary condition to the tearing modes when the mode rotation is decelerated. Further experimental study is required regarding the interaction of the field errors and mode rotation.

Characteristic behavior of the edge magnetic fluctuation has been studied in round-topped discharges in a low-*A* RFP. Quasi-periodic growth of a single helical mode has been found with a resultant mode spectrum similar to that of QSH with a lower toroidal mode number than in other RFPs. This phenomenon may be an indication of simpler MHD mode dynamics and easier transition to the QSH state in a low-*A* RFP.

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