Effects of Lowering the Aspect Ratio on MHD Behaviour in a Reversed Field Pinch

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Abstract. The reversed-field pinch (RFP) is a compact, high-beta magnetic confinement concept with a great advantage of weak external toroidal magnetic field. Lowering the aspect ratio (*A*) of RFP has the possibilities of enhanced neoclassical bootstrap current and simpler magnetic mode dynamics. Initial results from a low-*A* RFP machine RELAX is reported. The low-A equilibrium analyses with reconstruction technique have shown that the bootstrap current fraction is less than 5% in the present RELAX plasmas, and, the fraction of ~25% would be expected with improved plasma parameters having beta value of ~30%. The following indications of simple MHD mode dynamics have been observed. In round-topped discharges, transient QSH state dominated by m/n=1/4 mode appears A simple helical structure has been identified in a visible-light with fast camera diagnostic. An indication of Helical Ohmic State has been observed in round-topped discharges with very shallow reversal. These observations are consistent with MHD expectations in low-*A* RFP configuration.

1. Introduction

The reversed-field pinch (RFP) is a compact, high-beta magnetic confinement concept, having a great advantage that it requires relatively weak external toroidal magnetic field. As a result of the great efforts for the last decades, two possible solutions to the confinement problem have been demonstrated: current density profile control to realize the tearing-mode-stable profile, and attaining a (quasi-) single helicity ((Q)SH) RFP state in which a large magnetic island grows in an otherwise stochastic field. One of the remaining issues for RFP fusion reactor scenario is a means for steady-state operation. The Oscillating Field Current Drive (OFCD) is a technique of AC modulation of toroidal and poloidal voltages with phase difference of $\pi/2$ for time-averaged DC helicity injection, and ~10% increase of toroidal plasma current has been demonstrated with OFCD[1].

Recent equilibrium analysis has shown another possibility that lowering the aspect ratio (*A*) of RFP results in an increase in bootstrap current mainly due to the enhanced neoclassical viscosity[2]. Specifically, it has been demonstrated that a neoclassical RFP equilibrium having the bootstrap current fraction of higher than 90% does exist in reactor regime parameters with beta values as high as 60%[2]. Another advantage of low-*A* RFP configuration may be its simpler magnetic mode dynamics because mode rational surfaces are less densely spaced than in conventional (i.e., high- or medium-*A*) RFPs. Thus, the low-*A* RFP has the possibility to lead to a new RFP regime. Motivated by these attractive features, we have constructed a low-A RFP machine RELAX with aspect ratio of 2[3,4]. In this paper, we describe the initial results from RELAX with emphasis on MHD characteristics of low-A RFP plasmas.

2. Description of RELAX machine

Motivated by the possibility of developing a new RFP research regime, we have constructed a low-A RFP machine “RELAX” (REversed field pinch of Low-Aspect ratio eXperiment). We have used a 4-mm thick SS vacuum vessel with major radius *R* of 0.51 m and minor radius *a* of 0.25 m with *A*=2, the lowest-*A* RFP machine to date. The vessel has two poloidal gaps but no toroidal gap; The field penetration time is about 1.5 ms, much shorter than in other resistive wall RFPs. No conducting shell has been attached, with the aim at active control of MHD instabilities by means of external magnetic fields in low-*A* RFP configuration. The toroidal field is produced by 16 toroidal field coils together with some auxiliary windings to reduce the toroidal ripple. The resultant ripple has been estimated at about 5% on the plasma surface, and 2-3% at r/a =0.9. In this paper we will describe the initial results of discharge characteristics in RELAX.

RELAX is equipped with two toroidal arrays of 14 magnetic probes inserted from top and bottom ports equally spaced toroidally with toroidal separation angle of 22.5 degrees, except at two poloidal gap locations. Each probe measures toroidal and poloidal fields. The difference of the top and bottom signals provides the odd components of the edge magnetic fluctuations, while the sum, the even components. RELAX is also equipped with a poloidal array of 6 magnetic probes each of which measures the edge totoidal field. A radial array of 13 magnetic probes is used to measure the radial profiles of B_r, B_θ and B_ϕ at 0.6<*r*/*a*<1.0. In addition, toroidal arrays of toroidal flux loops, sine and cosine coils for B_r measurement outside the vessel, are attached on the outer surface of the vessel. All these pick-up coil signals are sampled at a frequency of 2 MHz and then numerically integrated. After the integration, we use a 0.5-kHz or 2-kH high-pass filter to obtain the fluctuating component.

3. Characterization of RELAX Plasmas

3.1. Characterization of Equilibrium of Low-A RFP

Figure 1 shows an example of the flat-topped discharge with toroidal plasma current of ~50 kA maintaining the flat-topped phase for ~1.5 ms[4]. The bottom trace in Fig.1 shows time evolution of the m=1/low-n mode amplitudes measured with a toroidal array of flux loops for radial magnetic field on the outer surface of the vacuum vessel. The m=1/n=2 mode starts to grow at 6.5 ms, which mode we suspect of resistive wall mode. Characteristics of the MHD equilibrium have been studied using an equilibrium reconstruction code RELAXFit, which was developed by modifying the MSTFit code[5] to low-A regime and by taking into account the neoclassical effect. The parallel bootstrap current has been estimated on the basis of Hirshman model[6]. By using a model equilibrium profile, it has been confirmed that the trapped particle fraction f_t increases by lowering the aspect ratio; The fraction is 30-40% for A=4 case over most part of the minor cross section, while f_t increases to 50-60% by lowering A to 2. As one of the constraints for the equilibrium reconstruction, we have used the poloidal and toroidal magnetic field profiles at *r*/*a* > 0.6 measured with the vertically inserted radial array of magnetic probes. Figure 2(a) shows an example of the reconstructed toroidal and poloidal magnetic field profiles (vertical profiles at R = 0.51 m) together with experimental measurements at *r*/*a* > 0.6. The reconstructed profiles agree well with the experimental profiles denoted by the crosses. In Fig.2(b), the estimated bootstrap current profiles are shown for this experimental profile. The characteristics of the bootstrap current profiles in the RFP are that the

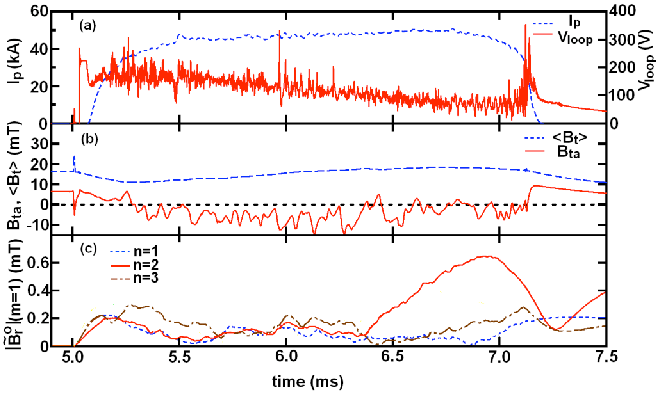


Fig.1. A flat-topped low-A RFP discharge in RELAX. (a) toroidal loop voltage V_{loop} and plasma current I_p, (b) average toroidal field $\langle B_t \rangle$ and edge toroidal field B_{ta}, and (c) m=1/low-n radial field fluctuation amplitudes $|B_r^o|$ measured on the outer surface of the vessel.

poloidal component is larger than toroidal one in magnitude, and edge poloidal component is important. These characteristics arise from RFP configuration where the poloidal field is the major component in the outer region. The bootstrap current fraction has been estimated to be less than 5 % for the present parameters of RELAX plasma.

The equilibrium calculation has been performed using the developed RELAXFit code to obtain an idea of plasma parameters in RELAX in order to identify the effect of bootstrap current experimentally. The results have shown that if we could achieve the electron temperature of ~300 eV with density of ~4×10^{19} m^{-3} at toroidal plasma current of ~100 kA, then we would expect the bootstrap current fraction of ~25 %, which might be identifiable experimentally.

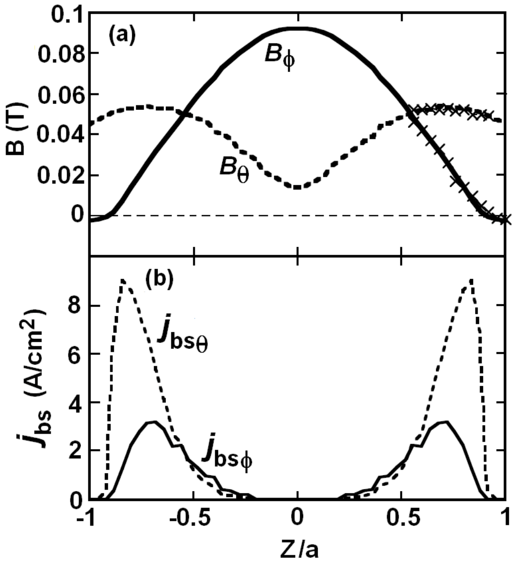


Fig.2. Results of equilibrium reconstruction. Reconstructed vertical (Z) profiles of toroidal and poloidal fields at R=0.51 m compared with experimental profiles denoted by the crosses in (a), and vertical profiles of the bootstrap current

3.2. Quasi-periodic Growth of Single Helical Instability

Figure 3 shows the time evolution of the plasma current I_p, loop voltage V_{loop}, edge toroidal field B_{tw} and average toroidal field $<B_t>$ of a round-topped discharge. In round-topped discharges, the plasma current increases rapidly to ~40kA, then increases to ~60kA at ~1ms. A gradual decay of the current then 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[7]. Figure 4 (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/n=1/4 mode grows from ~5.76ms for about 0.04ms, and a gradual decay then follows. Similar quasi-periodic growth and decay of the dominant m/n=1/4 mode continues to the end of the RFP configuration or loss of field reversal at 6.2 ms. Amplitudes of the outer neighboring m/n=1/5,6 modes stay lower than that of the dominant mode. There appears to be a trend that these neighboring modes grow (decay) during the decaying (growing) phase of the dominant modes. In Fig. 4(b), we compare the time evolution of the phase of m/n=1/4 mode to that of m/n=1/5 mode. There appears to be

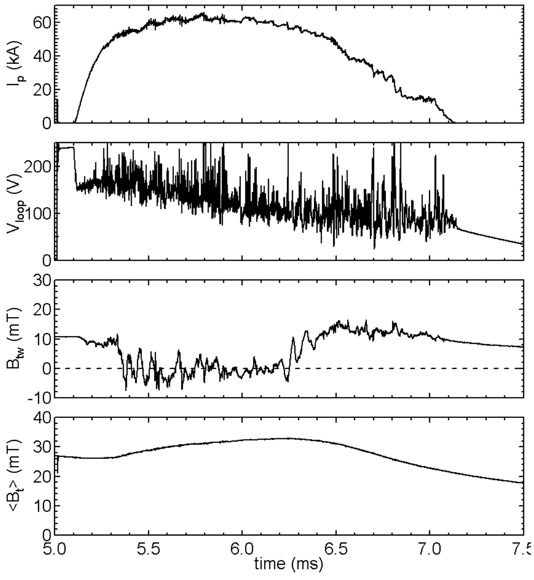


Fig.3: Time evolution, from top to bottom, of the plasma current I_p, Toroidal loop voltage V_{loop}, edge toroidal field B_{tw}, and average toroidal field $<B_t>$ in a round-topped discharge in RELAX.

an anti-correlated growth and decay between the dominant and neighboring modes. 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 as shown in Fig.4 (a). The interrelationship of the mode growth and deceleration of the mode rotation has yet to be identified. Figure 4 (c) shows the time evolution of the spectral index N_s defined as

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

When a single mode is excited, N_s becomes 1, while when N_s equals the number of 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 the RFP. Hereafter we take the threshold as 2 to discriminate between the multi-helicity (MH) and QSH state. N_s=2 corresponds to the case where the magnetic energy of the dominant mode equals the total energy of the remaining modes. Figure 4 (c) shows that when the dominant mode grows, Ns decreases below 2. The duration of low N_s, however, does not last longer than several tens of μ s in the present RELAX plasmas.

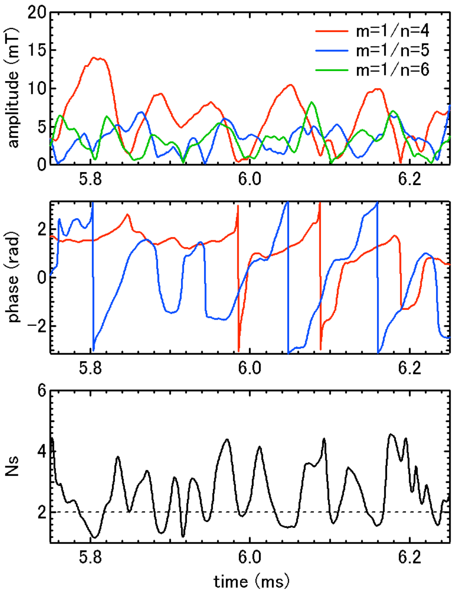


Fig.4. Time evolution of the amplitudes of m/n=1/4,5,6 modes (a), the phases of the m/n=1/4,5 modes (b), and the spectral index N_s (c).

Figure 5 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 toroidal mode number than in other RFPs. The toroidal mode number of n=4 agrees with the value of 2(R/a), corresponding to the most unstable innermost core resonant tearing mode. It should also be noted that the relative amplitude of the dominant mode in RELAX is somewhat larger than in other devices–about 3 times larger than in a controlled QSH experiment in TPE-RX[8], for example.

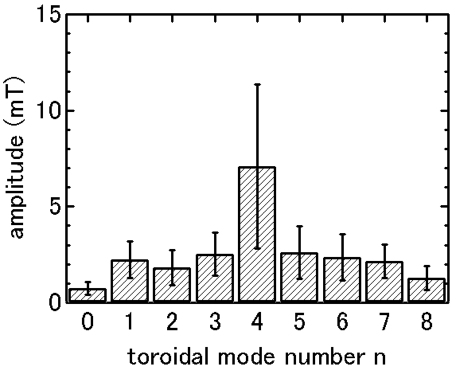


Fig.5: Toroidal mode spectrum of m=1 modes averaged over the periods where N_s<2.

The low toroidal mode number can be attributed to the low-A characteristic of RELAX. The relatively shorter sustained duration could be attributable to the difference in the typical value of resistive diffusion time $\tau_R=\mu_0 a^2/\eta$, correlated with the tearing mode growth rate[9]. 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, 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.

3.3. Observation of Simple Helical Structure

We have installed a fast camera in RELAX to obtain plasma images through a tangential port[10]. The fast camera diagnostic has been applied to tokamak, stellarator, and mirror plasmas, providing useful information on edge instabilities or edge turbulence. In the present experiments in RELAX, our attention has been focused on the internal structure of the visible-light image of a low-A RFP plasma, and we have observed a simple helical structure for the first time in the RFP configuration. As shown in Fig. 6, we have obtained tangential images from the initiation to the termination of RFP discharges at a maximum speed of 80,000 frames/s with an image size of 96 times 80 pixels. As the discharge evolves to the RFP configuration, the visible-light emission, mainly Hα-line radiation, decreases and characteristic structures become observable.

In Fig.7, we compare the observed helical structure of the strong emission area (a) with a simulated helical tube of m/n=1/4 (b). Note that the curved region behind the bright helix is the insulated poloidal gap of the vacuum vessel. In Fig. 3(b), the helical tube with a 2-cm diameter was located on the m/n=1/4 mode rational surface whose radial location was estimated from the equilibrium reconstruction using the RELAXFit code.

The toroidal mode spectrum of the simultaneously measured edge B_ϕ fluctuation shows that the internally resonant m/n=1/4 mode dominates the spectrum with non-resonant m/n=1/1,2 components, and the helicity of the observed helical structure agrees with that of the dominant internally resonant mode. Growth of the non-resonant modes accompanies the deformation of the plasma column, leading to enhanced recycling. In fact, an increase in the brightness of the plasma image (background brightness) has been observed with growth of the non-resonant modes in RELAX. However, in the present experiment, it is difficult to identify the low-n structure in the enhanced background visible-light image. One of the reasons for this difficulty may be the low-n nature of the non-resonant modes. Another is that neutral particles might be released from the wall surface region whose structure is characterized by the helicity of the non-resonant mode; however, the source structure fades away at one mean free path (for excitation) from the wall into the plasma, because recycling neutrals are released in all directions.

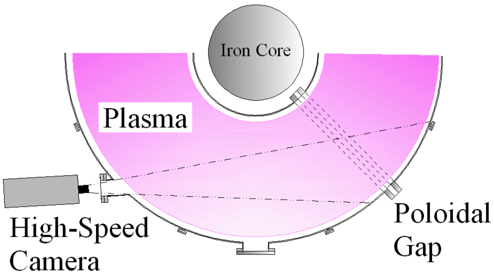
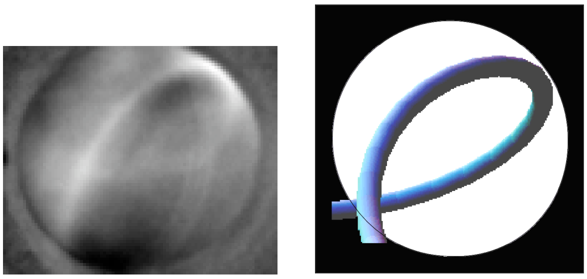


Fig.6. Experimental setup of the installation of a fast camera in RELAX from a tangential port.



(a) (b)

Fig.7. (a)A simple helical structure observed by fast camera through tangential port in RELAX. (b)Simulated helix on the q=1/4 rational surface.

On the other hand, the mean free path of 1-eV atomic hydrogen for electron impact ionization can be estimated as follows: It ranges from 75cm (for n_e=10^{18}m^{-3} and T_e=20eV) to 4 cm (n_e=10^{19}m^{-3} and T_e=50eV) for plausible plasma parameters of RELAX. In reality, the penetration length of the neutrals may be of the order of plasma minor radius. Therefore, when the electron density and temperature have structures corresponding to the resonant mode at r/a~0.5 (12.5 cm into the plasma from the wall), it is likely that the Hα-line radiation exhibits a similar structure. Therefore, in the present experiment, the observed simple helix is probably an indication of the simple structure of electron density and temperature on the q=1/4 mode rational surface. We have observed this kind of structure only transiently in the present stage of RELAX experiment.

3.4. Large Scale Profile Change — Possibility of Ohmic Helical State

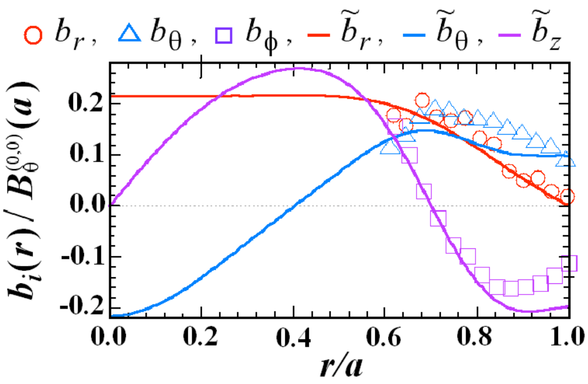


Fig.8. Comparison of measured profiles of the fluctuating components with theoretical solution of Helical Ohmic Equilibrium Solution (HOES).

In round-topped discharges with shallow reversal, which are often realized in self-reversal operation without external toroidal field reversal, we have observed a large-scale change in magnetic field profiles using the radial array of magnetic probes[11]. The large-scale change appears as an oscillation at a frequency of around 10 kHz. In Fig. 8, we have compared the measured radial profiles of the oscillating components $b_i(r)$ (i=r, θ, z) with theoretically calculated Helical Ohmic Equilibrium state (HOES) solution[12]. The HOES is an equilibrium of a cylindrical plasma having helical symmetry and a finite Ohmic current density[13]. The measured profiles agree well with the theoretical solution at the outer region where the probe measurements are made. Since the edge toroidal field oscillation propagates in the toroidal direction, the profile change may indicate the toroidally or poloidally rotating helical structure. We may note theoretical prediction that the magnetic surfaces recover in HOES in spite of relatively large amplitude of the helical components[12]. The rotating HOES may have the possibility of improved confinement without magnetic chaos in the RFP.

4. Summary

Lowering the aspect ratio of RFP has the possibilities of enhanced neoclassical bootstrap current and simpler magnetic mode dynamics. Initial results from a low-A RFP machine RELAX has been reported. The low-A equilibrium analysis has revealed that the bootstrap current fraction of ~25% would be expected in RELAX with improved plasma parameters having beta value of ~30%. The following indications of simple MHD mode dynamics have been observed in the initial stage of the RELAX experiments. Flat-topped current discharges are realized with Ip~50kA and duration>2ms, with growth of a non-resonant kink modes towards the end of a discharge. In round-topped discharges, transient QSH state dominated by m/n=1/4 mode appears for the periods of several tens of μs. A simple helical structure has been identified in a visible-light image with fast camera diagnostic. An indication of Helical Ohmic Equilibrium State has been observed in round-topped discharges with very shallow reversal. These observations are consistent with MHD expectations in low-A RFP configuration.

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