Recent Progress in Low-A RFP Plasma Research in RELAX

Akio SANPEI, Ryuya IKEZOE, Takumi ONCHI, Kensuke OKI, Masaki SUGIHARA, Yuusuke KONISHI, Shin-ichi FUJITA, Mitsuru NAKAMURA, Akio HIGASHI, Hidehiko MOTOI, Haruhiko HIMURA and Sadao MASAMUNE

Kyoto Institute of Technology, Kyoto 606-8585, Japan

(Received 24 January 2010 / Accepted 18 May 2010)

Recent results from a low-aspect-ratio (low-A) reversed field pinch (RFP) machine with an aspect ratio of 2 (R/a = 0.51/0.25) are reported. The discharge characteristics of low-A RFP plasmas are described. The discharge regime in $F - \Theta$ space indicates that lowering the aspect ratio expanded the operational $F - \Theta$ space to the extremely high-Θ (> 3), deep-reversal ($F < -1$) region and to the non reversal ($F > 0$) region. A rotating helical Ohmic equilibrium RFP state could be realized in shallow-reversal discharge on REversed field pinch of Low Aspect eXperiment (RELAX). A preliminary feedback system is developed that results in plasma current with a longer discharge duration of ~2 ms.

Keywords: reversed field pinch (RFP), low-aspect ratio (low-A), nonlinear MHD

DOI: 10.1585/pfr.5.S2063

1. Introduction

The reversed field pinch (RFP) is a compact, high-beta magnetic confinement concept, characterized by self-organization of the magnetic configuration and dominated by magnetic fluctuations that are excited by resistive magnetohydrodynamic (MHD) instabilities. Recent progress in RFP research has demonstrated some attractive features of this concept. A high value of β, the averaged plasma pressure normalized to the magnetic field pressure, has been achieved by injecting deuterium pellets into Madison symmetric torus (MST) plasmas with inductive current profile modification, a technique for controlling the current profile to stabilize the plasma to the tearing mode and improve confinement [1]. With pulsed poloidal inductive current drive (PPCD) operation, β_θ reaches ~30% in TPE-RX [2]. A new self-organized state, the single helical axis (SHAx) state, has been found in RFX. In this state, the amplitude of the dominant mode becomes so high that the separatrix of the island produced by the mode disappears, and the magnetic axis of the unperturbed equilibrium merges with the island axis. This offers a possible improved confinement state wherein magnetic surfaces recover because of the transition to helical RFP equilibrium [3]. Equilibrium analyses have shown that mode rational surfaces are sparsely spaced at a lower aspect ratio ($A = R/a$) of the RFP configuration, where R (a) is the major (minor) radius of the plasma column. Therefore, simpler MHD mode dynamics is expected in a low-A RFP. The trapped particle fraction is also expected to increase at low-A. Moreover, in low-A equilibrium, the self-induced bootstrap current tends to increase [4], which may reduce the electric current needed from an external source.

To study these attractive characteristics of low-A RFP configurations, experimental study has been performed in the REversed field pinch of Low Aspect eXperiment (RELAX) [5] device with $R = 0.51$ m/$a = 0.25$ m, $A = 2$. The device is operated with a 4 mm stainless-steel vacuum vessel (field penetration time $\tau_w < 3$ ms). Recent experimental results have shown that low-A RFP plasmas have been obtained with a plasma current I_p of up to 100 kA and a loop voltage V_l as low as ~30 V. The pinch parameter Θ ($= B_p(a)/\langle B_\phi \rangle$) ranges from ~2.0 to 3.5 with a field reversal ratio F ($= B_\phi(a)/\langle B_\phi \rangle$) ranging from slightly positive (~0.1) to deep reversal (~ −1.0). Further studies to improve the RFP plasma performance are in progress.

In low-A RELAX plasmas, the configuration tends to relax to a quasi-single helicity (QSH) state in which the internally resonant single tearing mode grows significantly larger than other modes, with low current. A high-speed camera diagnostic has revealed a simple helix structure in visible light images [6]. In the extreme case, a rotating helical Ohmic equilibrium (HOE) state has been realized [7]. The pressure-driven bootstrap current fraction is shown to be less than 5% of the total current in the present RELAX plasmas [8]. Interferometric measurement has identified an electron density of ~3 $\times 10^{19}$ m^{-3} [9]. Studies of the stability or spectrum of unstable modes with the help of three-dimensional MHD simulations are in progress. Recent progress in confinement includes a test of feedback control with saddle coils at an insulated poloidal gap. It has been demonstrated that our controllers can compensate for vertical and horizontal field errors, resulting in a plasma current with longer discharge duration of up to ~2 ms.

author's e-mail: sanpei@kit.ac.jp

This paper presents recent progress in low-A RFP plasmas research in RELAX. In Section 2, the characteristic features of low-A RFP discharge are described. In Section 3, we report the observed helical structure in shallow-reversal discharge in RELAX. We present some progress on the control apparatus in RELAX in Section 4 and a summary in Section 5.

2. Characteristics of Low-A RFP Discharge

Figure 1 shows typical waveforms of the RELAX RFP plasma: from top to bottom, the plasma current I_p, toroidal loop voltage V_l, edge toroidal field $B_\phi(a)$, and cross-sectional average toroidal field $<B_\phi>$. The maximum value of I_p is about 100 kA, and V_l is as low as ~30 V. The RFP configuration is set up in about 0.25 ms and sustained for about 1.2 ms. A gradual increase in $<B_\phi>$ is observed during the flat-topped current phase.

The RFP operational regime is often discussed in $F-\Theta$ space, where the pinch parameter is the ratio of the edge poloidal field $B_p(a)$ to $<B_\phi>$, and the field reversal parameter F is that of $B_\phi(a)$ to $<B_\phi>$. The operational regimes in $F-\Theta$ space attained to date in RELAX are indicated in Fig. 2 by plus symbols. In conventional RFP configurations, the typical operational region lies in the ranges $1.4<\Theta<2$ and $-0.5<F<-0.1$. The discharge regime in $F-\Theta$ space indicates that lowering the aspect ratio has expanded the operational $F-\Theta$ space to the extremely high-Θ (>3), deep-reversal ($F<-1$) region and the non-reversal ($F>0$) region. Figure 2 clearly shows that in RELAX discharges, extremely high-Θ, deep-F regions can be attained. Moreover, shallow-F regions can be attained without significant disruptive phenomena.

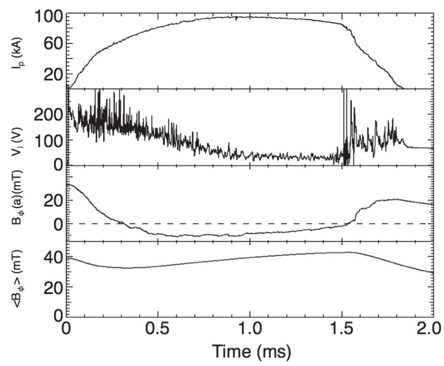

Fig. 1 Time evolution of plasma current I_p, toroidal loop voltage V_l, edge toroidal field $B_\phi(a)$, and cross sectional average toroidal field $<B_\phi>$ in a typical low-A RFP discharge in RELAX.

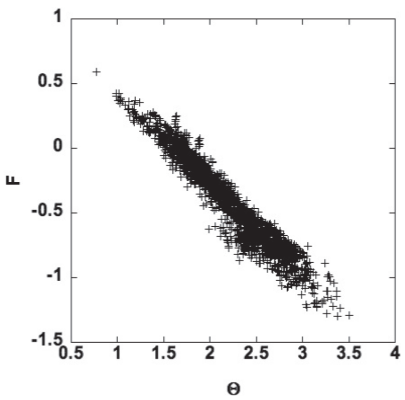

Fig. 2 Discharge regimes of low-A RFP plasmas in RELAX in $F-\Theta$ space.

The MHD behavior in a low-A RFP depends strongly on toroidal field reversal and falls into three types. Thus, in terms of MHD, RELAX discharge can be divided into three regimes: the deep-reversal, shallow-reversal, and non-reversal regimes [10]. In deep-reversal plasmas, the edge magnetic fluctuation has a broad toroidal mode spectrum, and its amplitude tends to be suppressed. On the other hand, the toroidal mode spectrum is narrowed with reduced toroidal field reversal, and a spontaneous transition to the QSH state is realized in shallow-reversal discharges. The results may suggest that two possible approaches to reduce magnetic chaos have been found in RELAX. One is the suppression of mode amplitude in deep-reversal discharge; the other is improvement of the confinement by realizing the QSH state in shallow-reversal discharges.

3. Observed Helical Structure in RELAX

An interesting experimental result is the observation of helical structure in shallow-reversal discharges on RELAX [7]. To measure the magnetic profile, a radial array of magnetic probes is inserted into a poloidal cross section of RELAX from the outboard port to 250 mm inside the plasma. In some shallow-reversal discharges, each measured magnetic profile shows a significant change and appears to oscillate at a frequency of approximately 10 kHz. In Fig. 3, we compare the measured magnetic field profiles with those of an HOE [11] solution. Figure 3 (a) denotes the experimental radial profiles of the non-oscillating part of the magnetic field, B_r, B_p, and B_ϕ with solid circles, triangles, and squares, respectively. Note that r is defined as the distance from the center of the poloidal cross section. Figure 3 (a) also shows radial profiles of the equilibrium component of the HOE solution displayed with solid, dashed-dotted, and dashed lines. These are theoretical solutions for a cylindrical plasma with helical symmetry having a finite Ohmic current density. Figure 3 (b) shows the experimental radial profiles of the oscillating and helical components of the HOE. The experimental radial profiles and amplitudes both agree well with the HOE solution. Equilibrium reconstruction shows that the innermost resonant mode is $m=1/n=4$ located at $r/a=0.32$ from the shifted magnetic axis of the unperturbed equilibrium $r/a=0.22$, estimated from the non-oscillating component. In this discharge, the $m=1/n=4$ mode is dominant, but other modes, in particular $m=1/n=5$, are not negligible. Thus, a rotating HOE RFP state may be realized in shallow-reversal discharge in RELAX.

We have also identified a simple helical structure in RELAX plasmas using a fast camera diagnostic. The helical structure and its radial location agreed well with those of internally resonant $m = 1/n = 4$ instability [6]. Here, we show a recent experimental result in which we observed horizontal images from the initiation to the termination of RFP discharges at a maximum speed of 300,000 frames/s with an image size of 128×64 pixels. Figures 4 (a) and (b) show snapshots of horizontal images of the RELAX plasma at 380 μs and 437 μs after plasma ignition, respectively. Helical structure clearly appears in visible light rotating at ~2.5 kHz. The result of mode analysis from edge magnetic measurements is consistent with the features of the observed visible light structure. Figures 4 (c) and (d) show the simulated helix tubes of the $m = 1/n = 4$ mode coming into view, corresponding to (a) and (b), respectively. Figure 4 (e) shows a bird's-eye view schematic of the $m = 1/n = 4$ structure. The structures observed in Figs. 4 (a) and (b) are very similar to the simulated helix tubes in (c) and (d). More detailed analysis is in progress.

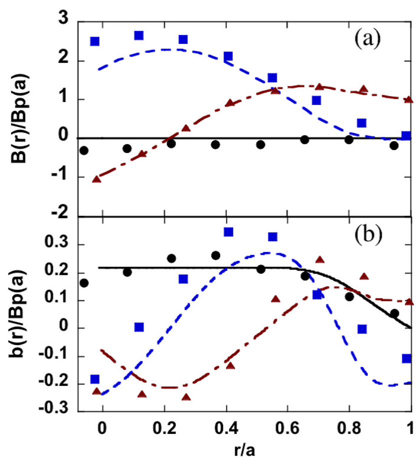

Fig. 3 Radial profiles of experimentally obtained B_r (solid circles), B_p (solid triangles), and B_ϕ (solid squares), and radial B-field profiles (solid, dashed-dotted, and dashed lines) in a theoretical helical Ohmic equilibrium solution for the non-oscillating (a) and oscillating (b) components.

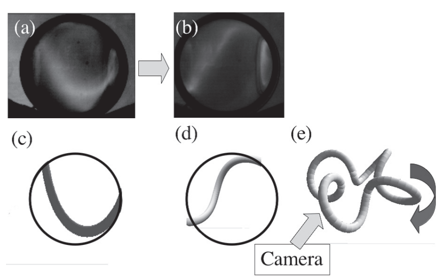

Fig. 4 Snapshots of visible light at (a) 380 μs and (b) 437 μs. (c) and (d) Simulated helix tubes of $m = 1/n = 4$ coming into view. (e) Bird's-eye view schematic of $m = 1/n = 4$ structure.

4. Preliminary Feedback System in RELAX

Finally, the initial results of a preliminary feedback system for controlling the resistive wall mode (RWM) are presented. A three-dimensional MHD simulation using the RELAX configuration predicts that the RWM will be problematic with longer pulse operation. A simulation with the DEBS code suggests initial growth of the $m = 1/n = 4$ resonant mode, followed by growth of the non-resonant $m = 1/n = 2$ external kink mode with a growth time of the resistive wall time constant. Some hints regarding the RWM in experimental results from RELAX tend to confirm this prediction. To circumvent this serious problem, we are developing a feedback control system with saddle coils. The first experiments in an RFP with feedback suppression of RWMs using saddle coils were performed in EXTRAP [12]. The results showed significant improvement in global plasma performance, i.e., a 50% increase in the pulse length.

In RELAX, a preliminary feedback control system for gap field errors using saddle coils at an insulated poloidal gap is being developed. The system consists of four pick-up coils that detect radial components and four correction coils. All of the coils are located on the outer surface of the insulated poloidal gap, as shown in Fig. 5 (a). The pick-up coils and correction coils have the same shape, and the correction coils are placed neatly on top of the pick-up coils. The ability of the system to compensate for vertical and horizontal field errors is shown in Fig. 5 (b). Upward and downward pick-up coils are linked to each other to detect vertical components of magnetic flux leaks, which is the r component of the magnetic flux penetrating the insulated poloidal gap. Horizontal coils are designed with a similar mechanism. Such magnetic flux leaks correspond to the field error at the gap. When a magnetic flux leak detected with the pick-up coils exceeds a certain threshold, a control system applies current to the correction coils to suppress the leak. Figure 5 (c) compares $I_{\rm p}$, $V_{\rm l}$, and the measured

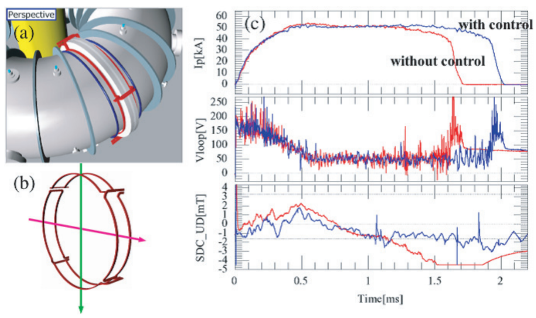

Fig. 5 (a) Poloidal gap with four saddle coils (in red). (b) Four saddle coils for controlling the $m = 1$ component. (c) Comparison of $I_{\rm p}$, $V_{\rm l}$, and measured leak magnetic flux B_r with/without control.

magnetic flux leak B_r for pick-up coils with and without control. Compensating for gap field errors clearly resulted in a longer discharge duration of up to ~2 ms. We plan to extend the saddle coil for full-coverage of the surface of RELAX for RWM control.

5. Summary

In summary, recent progress in low-A RFP plasma research in RELAX has been reported. The operational regime in $F - \Theta$ space has been extended to a higher- and deeper-reversal regime, which may be attributable to the low-A characteristics. The new RFP machine supports our study of new regimes in RFP configurations. Helical structure in shallow-reversal discharge in RELAX has been identified, and progress on the control apparatus in RELAX has been reported.

Acknowledgments

One of the authors (A. S.) thanks Photoron for cooperation with the high-speed camera. The authors are very grateful to Dr. Paccagnella for calculation of the RWM in RELAX. This study is supported by a U.S.-Japan collaboration and by a Grant-in-Aid for Scientific Research (No.17360441) from the Ministry of Education, Culture, Sports and Technology, Japan. The study is performed with the support and under the auspices of the National Institute for Fusion Science (NIFS) Collaborative Research Program (NIFS07KOAH022).

[1] M. D. Wyman *et al.*, Phys. Plasmas. **15**, 010701 (2008).
[2] H. Koguchi *et al.*, Plasma Fusion Res. **2**, 050 (2007).
[3] R. Lorenzini *et al.*, Nature Physics **5**, 570 (2009).
[4] S. Shiina *et al.*, Phys. Plasmas. **12**, 080702 (2005).
[5] S. Masamune *et al.*, J. Phys. Soc. Jpn. **76**, 123501 (2007).
[6] T. Onchi *et al.*, Plasma Fusion Res. **3**, 005 (2008).
[7] K. Oki *et al.*, J. Phys. Soc. Jpn. **77**, 075005 (2008).
[8] A. Sanpei *et al*., J. Phys. Soc. Jpn. **78**, 013501 (2009).
[9] M. Sugihara *et al.*, *poster P2-34 in this conference*.
[10] R. Ikezoe *et al*., J. Plasma Fusion Res. SERIES **8**, 1031 (2009).
[11] R. Paccagnella, presented at IEA/RFP Workshop, Madison (2000).
[12] P. R. Brunsell *et al.*, Phys. Rev. Lett. **93**, 225001 (2004).