Direct Observation of Soft-X Ray Filament Structure and
High Current Operation in Low-Aspect-Ratio RFP

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Abstract. We have made a direct observation of the soft-X ray (SXR) helical structure in the quasi-single helicity (QSH) phase in a low-aspect-ratio (low-A) reversed field pinch (RFP) machine RELAX. The field line trace has shown a large helical deformation in the core with closed flux surfaces, being consistent with the present and previous SXR imaging diagnostics. The helical core with higher temperature and/or density are easily formed in RELAX which may be attributable to the characteristic q profile in low-A RFP configuration. Discharge optimization at high current (~100 kA) has shown possibilities of improved performance of low-A RFP plasma.

1. Introduction

The reversed field pinch (RFP) is a compact, high-beta magnetic confinement concept. The great advantage of the RFP is that it requires weak external toroidal magnetic field. Recent RFP research has revealed two scenarios for confinement improvement. One is the plasma current profile control to suppress the core resonant dynamo modes [1]. The other is the quasi-single helicity (QSH) scenario which allows only a single dominant mode to grow. In this QSH scenario, magnetic surfaces recover inside the magnetic island associated with the dominant mode. As an extreme case, the Single Helical Axis (SHAx) state has emerged as a new self-organized helical RFP state [2].

2. RELAX machine

An equilibrium analysis has shown that the aspect ratio A (=R/a) is an important parameter for optimization of the RFP configuration because the q profile is closely connected to A in the self-organized state. Furthermore, some theories show that the pressure-driven bootstrap current increases as A is lowered to less than 2. RELAX is a RFP machine (R=0.5m/a=0.25m: A=R/a=2) to explore the plasma characteristics in low-A regime. The RFP configuration is often discussed in (Θ, F) space, where the pinch parameter Θ is the ratio of edge poloidal field Bp(a) to the average toroidal field <Bt>, and the field reversal parameter F is the ratio of the edge toroidal field Bt(a) to <Bt>. Experimentally achieved wide discharge regions in (Θ, F)
space in RELAX are discussed in ref. [3]. In shallow reversal plasmas, the discharge tends to transit to the QSH state [4], or helical Ohmic equilibrium state which is essentially the same as the SHAx state. Experimental internal field profiles of $B_r$, $B_p$, and $B_t$ showed good agreement with the theoretical helical Ohmic equilibrium state [5].

3. Soft-X ray imaging diagnostic

Recent progress in high-speed soft-X ray (SXR) imaging diagnostic has made it possible to observe time evolution of the tangential SXR image. We take SXR images at a rate of $10^5$ frames per second with a high-speed camera. When subtraction technique is applied to the images with 10 μs time interval, we can identify a simple helical structure as shown in Fig.1. By subtraction, the background SXR radiation which corresponds to an axisymmetric equilibrium component is removed, and the remaining structure originating from time evolving asymmetric component is enhanced. The color code in Fig.1 shows that a helically deformed core with higher SXR emissivity is rotating. The radial location of the filament agrees with the location of the $q=1/4$ resonant surface, and the poloidal location of the helical filament corresponds to the O-point of the magnetic island associated with the dominant $m=1/n=4$ mode. The rotation speed of the helical structure is $\sim 1.6 \times 10^4$ rad/s, almost the same as that of the $m=1/n=4$ mode. These results are consistent with the SXR emissivity profile measurement which suggested improved confinement in the helically deformed core [4].

Figure 2 shows a Poincare plot of the magnetic field lines in a poloidal cross section during the QSH phase in RELAX. It is the result of ORBIT code, in which the radial eigenfunctions of the resonant modes were obtained by solving the Newcomb equations. Experimental magnetic fluctuation spectra at the edge were used as the boundary conditions. We can identify the helically deformed nested flux surfaces in the core region. One of the characteristics in RELAX is that helical RFP state is realized with lower current (and lower current density) than in other RFPs. The magnetic Reynolds number $S$ is also lower. The easier access to the helical state may result from the $q$ profile in low-$A$ RFP where wider space without major resonance allows the island to grow without interacting neighboring mode.

![Fig.1: An example of SXR helical structure enhanced by applying subtraction technique to the experimental tangential images taken by a high-speed camera (10^5 fps).](image)

![Fig.2: (a) Poincare plot of the field lines using ORBIT code. (b) equilibrium field. (c) q profile. (d) edge magnetic fluctuation spectrum.](image)
4. Electron temperature measurement with Thomson scattering diagnostic system

A Thomson scattering diagnostic system using Nd:YAG laser has been installed very recently in RELAX to measure the central electron temperature. The laser beam is injected from top to bottom of the vacuum vessel, and 90-degree scattered light is collected from an outer port in the equatorial plane. We have used essentially the same polychromator as that used in MST RFP [7].

Figure 3 shows the plasma current dependence of the electron temperature at 1 ms into the discharge in standard RFP plasmas with axisymmetric equilibrium. The general trend is that the central temperature increases almost linearly with plasma current up to ~110 kA. The typical temperature is $T_e(0) \approx 150$ eV at $I_p \approx 100$ kA. The SXR temperature is also estimated from signal ratio of the photo diodes with two different filters. Comparison of the Thomson temperature with the SXR temperature would provide us with profile information.

5. Active control of MHD instabilities for high current operation

The MHD behavior of RELAX plasmas has been studied in detail in the current region from 40 kA to 80 kA in ref [3], where two possible improved confinement regions were suggested: QSH-dominated shallow-reversal region and deep-reversal region with low magnetic fluctuation level. In both regions, further improvement of confinement can be expected with higher $S$ because quality of the QSH is improved at higher $S$, and magnetic fluctuation level decreases with increasing $S$ in the RFP. In order to improve plasma performance we have started optimization of high current operation.

In our previous experiment, we observed growth of the $m=1/n=2$ mode with time scale of the field penetration time of the vacuum vessel. When the radial amplitude of the mode reached to ~1% of the edge poloidal field, the plasma current started decreasing. The $m=1/n=2$ mode was externally non-resonant kink mode, which was shown to be the most unstable resistive wall mode for peaked current profile in RELAX by analytic calculation with cylindrical approximation and 3-D nonlinear MHD simulation with A=2 RFP configuration.

One of the optimization techniques applied in RELAX is active control of MHD instabilities using saddle coil array as actuator coils. 64 saddle coils (4 in poloidal direction x 16 in toroidal direction) cover the whole outer surface of the vacuum vessel. The similar saddle coils are used as the sensor loops for radial component Br. In the initial experiment, the
actuators and sensor coils are connected in series for the control of the single \(m=1/n=2\) mode. An example of the optimized 100kA discharge is shown in Fig.4. As a result of active control of the single \(m=1/n=2\) mode, the mode amplitude remains lower than \(~0.25\%\) of the edge poloidal field during the flat-topped current phase with lower discharge resistance. Next step of the active MHD being considered is simultaneous multi-mode control, which requires more power supplies and development of control model appropriate for low-\(A\) configuration.

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References