Improved Low-Aspect-Ratio RFP Performance with Active MHD Control and Associated Change in Magnetic Topology in RELAX

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Abstract. We have modified the active MHD control system in RELAX in order to compensate for the sideband effect arising from two poloidal gaps of the vacuum vessel. As a result, the discharge duration has reached core-saturation-limited level with stabilization of the resistive wall mode (RWM). The plasma performance has also been improved; the central electron poloidal beta β_{pe} (=$2\mu_0 p_{e0}/B_{pa}^2$) has reached ~15% from ~10% with the previous control system. After the modification, self-organization to Quasi-Single Helicity (QSH) state has been observed even in deep-reversal discharges. Magnetic field line trace shows that helical closed flux surfaces recover during the QSH state, although the region is narrower than that in the conventional shallow-reversal case. The transition to QSH and associated change in magnetic topology may be related with improved axisymmetry of the magnetic boundary and resultant improved RFP plasma performance in deep-reversal regime.

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 developed two scenarios for confinement improvement: plasma current profile control to suppress the core-resonant dynamo modes, and QSH scenario which allows only a single dominant mode to grow. In the 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. RELAX machine with MHD feedback control

RELAX is a low-A (R/a=0.5m/0.25m) machine whose major objectives include exploration of the geometrical optimization of the RFP configuration. One of the characteristics of low-A RELAX plasmas is that stable RFP discharges are realized over a wide range in (Θ, F) space where Θ (=$B_{pa}/\langle B_t \rangle$) is the pinch parameter and F (=$B_{ta}/\langle B_t \rangle$), the field reversal parameter, with poloidal field B_p and toroidal field B_t [1]. In deep-reversal region where F=-0.5~-1.0, axisymmetric RFP with low fluctuation level is realized.

In RELAX, we used a 4-mm thick stainless steel (SS) vacuum vessel. Linear stability analysis of the resistive wall mode (RWM) in cylindrical approximation showed that an externally non-resonant m=1/n=2 kink mode is the most unstable RWM in RELAX without the outer conducting shell [2], where m is the poloidal mode number and n, the toroidal one. Since the field penetration time of the 4-mm thick SS chamber is ~1.5 ms, 64 saddle coils (4 in poloidal direction and 16 in toroidal direction) cover the outer surface of the vacuum vessel of RELAX for MHD stability control. It was reported that active feedback stabilization of a single m/n=1/2 mode, the most unstable RWM in RELAX, resulted in longer discharge duration with improved electron poloidal beta β_{pe} ($=2\mu_0 p_{e0}/B_{pa}^2$) [3, 4].

3. Modified feedback control system and improved plasma performance

The feedback system has been modified in order to compensate for the sideband effect arising from two poloidal gaps in the vacuum vessel; we have used additional independently controlled six (6) power supplies for the saddle coils at the two (2) poloidal gaps. In Fig. 1, we compare typical discharges in three cases: without feedback, with feedback before modification, and after the modification. As a result of modification of the control system, the discharge duration has been further improved to the iron-core-saturation-limited longest one. The bottom trace in the figure shows time evolution of the m/n=1/2 mode amplitudes measured with sine and cosine coils for B_r on the outer surface of the vacuum vessel. Before the modification, the amplitude of the mode increases slightly with application of the feedback control, which is attributable to the sideband effect of the poloidal gaps of the vacuum vessel. After the modification, the mode amplitude is lowered particularly in the current rise phase due to compensation for the sideband effect by the independent control localized near the gaps.

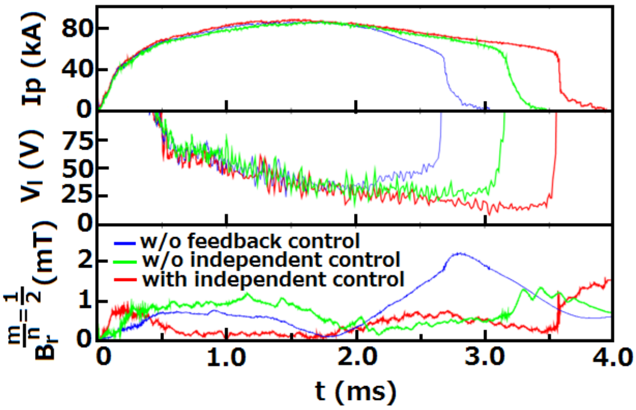

Fig. 1: Time evolution of the plasma current, toroidal loop voltage and m/n=1/2 mode amplitude measured with sine and cosine coils for B_r on the outer surface of the vessel. A slight increase in B_r with previous feedback control (green), is suppressed in the current rise phase by modifying the control system (red), indicating successful compensation for the sideband effect.

The RFP plasma performance has also been improved. In Fig. 2 we plot β_{pe}, almost equal to the total electron beta in the RFP configuration, vs. electron density normalized to the Greenwald density, n_G, showing that β_{pe} reached 15% at n/n_G~0.3 with T_{e0} of 100~200 eV. The trend can be interpreted as follows. Since the slope of the plotted data points corresponds to (p_{e0}/nI_p), the central electron temperature is approximately proportional to I_p, provided that the density profiles are nearly the same. The data points scattered to the higher beta region may indicate a change in temperature or density profile. We run the machine with pre-filling the working gas; the higher pressure, required for higher density, degrades the discharge during the current rise phase, determining operational density regime.

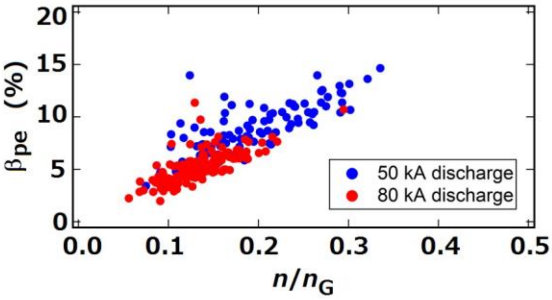

Fig. 2: Dependence of $\beta_{pe} = 2\mu_0 p_{e0}/B_{pa}^2$ *on density normalized to the Greenwald density* n_G*.* β_{pe} *increases with* n/n_G*, reaching the maximum value of ~15%.*

4. QSH in deep-reversal regime

In RELAX, QSH state tends to be realized spontaneously, as is also the case in other RFPs. Characteristics of QSH in RELAX was reported in previous meetings [5]. The new finding is that the magnetic fluctuation spectrum shows spontaneous transition and back transition to QSH even in deep-reversal region with active feedback control of RWM. Figure 3 shows time evolution of the m=1 magnetic modes along with soft-X ray (SXR) emission. The dominant m/n=1/4 mode grows spontaneously with suppression of the remaining modes, typical to QSH. The QSH transition accompanies the enhanced SXR emission in flat-topped current phase, the most prominent case being identified at 1.6-1.8 ms. In the figure, we also show a Poincare plot during the QSH at 1.7 ms. The field line tracing is performed using the ORBIT code in which eigenfunctions of the magnetic modes are reconstructed using the edge magnetic fluctuation measurements. The change in magnetic topology in deep reversal

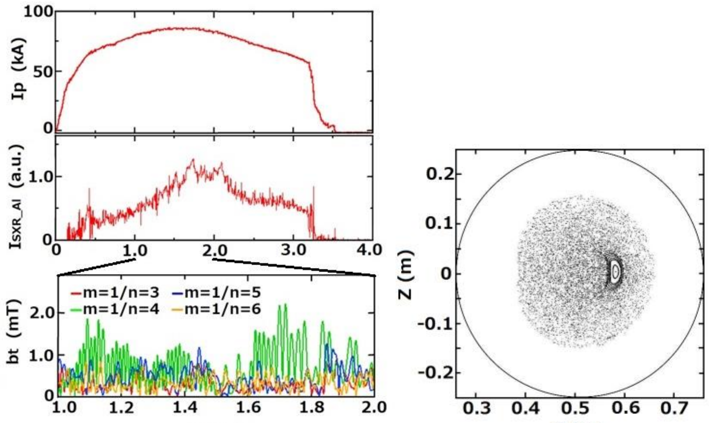

Fig. 3: Time evolution of the dominant and secondary mode amplitudes in deep-reversal (F~-0.8) discharge, showing spontaneous growth and decay of the dominant mode. A Poincare plot of the magnetic field lines during the QSH at 1.7 ms in the right hand side trace shows recovery of the closed magnetic surfaces.

discharges may be related to the improved axisymmetry of the magnetic boundary by the modified feedback control system.

5. Summary

We have modified the active MHD control system in RELAX in order to compensate for the sideband effect arising from two poloidal gaps of the vacuum vessel. As a result, the discharge duration has reached core-saturation-limited level with stabilization of the resistive wall mode (RWM). The plasma performance has also been improved; the central electron poloidal beta βpe (=2μ0pe0/Bpa2) has reached ~15% from ~10% with the previous control system. After the modification, self-organization to Quasi-Single Helicity (QSH) state has been observed even in deep-reversal discharges. Magnetic field line trace shows that helical closed flux surfaces recover during the QSH state, although the region is narrower than that in the conventional shallow-reversal case. The transition to QSH and associated change in magnetic topology may be related with improved axisymmetry of the magnetic boundary and resultant improved RFP plasma performance in deep-reversal regime.

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