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Self-Reversal and Sustainment of Magnetic Fields in Helicity-driven Toroidal Plasmas

NAGATA Masayoshi, TAKAMIYA Tetsuhiro, HASEGAWA Hiroyuki, KAWAMI Kazuhiro, FUKUMOTO Naoyuki, UYAMA Tadao, MASAMUNE Sadao[1] and KATSURAI Makoto[2]

Himeji Institute of Technology, Hyogo 671-2201, Japan

[1]Kyoto Institute of Technology, Kyoto 606-8585, Japan

[2]University of Tokyo, Tokyo 113-8656, Japan

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Abstract

In the HIST experiment, self-organizing transition studies between helicity-driven relaxed states of the low-aspect-ratio toroidal plasmas have been made by means of a rapid reversal of the external toroidal field. Results show that the spherical torus (ST) relaxes towards flipped ST states, which is accompanied by spontaneous reversal of plasma currents. It has been found that an intermittent behavior of the non-flipped region at the outer edge of the flipped ST plasma plays an important role in its current sustainment by coaxial helicity injection.

Keywords:

self-organization, current reversal, coaxial helicity injection, flipped ST, current sustainment

1. Introduction

Coaxial helicity injection (CHI) using a magnetized coaxial plasma gun (MCPG) is expected to be the attractive non-inductive current-drive method for a spheromak [1] and a spherical tokamak (ST) [2]. The CHI current drive based on Taylor relaxation theory provides us with broad interests concerning magnetic reconnection, magnetohydrodynamic (MHD) relaxation and self-organization. In the Helicity Injected Spherical Torus (HIST) experiment, we have investigated dynamics of self-organizing toroidal plasmas during the helicity injection process [3,4].

The relaxed toroidal plasmas in the driven system, as well as in the closed one, are described by the force-free equilibrium equation, $\nabla\times\boldsymbol{B} = \lambda\boldsymbol{B}$, where the force-free parameter $\lambda = \mu_0\boldsymbol{J}\cdot\boldsymbol{B}/B^2 = \mathrm{const}$ [5,6]. The relaxed states in toroidal systems are characterized by the strength and sign of the external toroidal field (TF), and the value of λ determined by coupling to a helicity source. Figure 1 illustrates comparison of poloidal flux topologies between relaxed configurations with "open" magnetic field lines penetrating the boundaries in both the cases of positive and negative TF with $\lambda < \lambda_{en}$, where λ_{en} is the lowest eigenvalue. There are clear differences in magnetic topology between "normal" ST (N-ST) and "flipped" ST (F-ST). It should be noted that the open flux no longer surrounds the closed flux in the F-ST since the toroidal current is in the opposite direction although the gun bias flux Ψ_{bias} and the gun current I_{gun} are applied in the same direction. The open flux that directly joins the gun electrodes by the shortest path is defined as a non-flipped region.

From the viewpoint of the CHI current drive, it is conceivable that the F-ST, which consists of only closed flux surfaces, compares favorably with the N-ST with open field lines. It has not yet been verified whether the CHI method can create enough closed flux surfaces in the N-ST plasmas

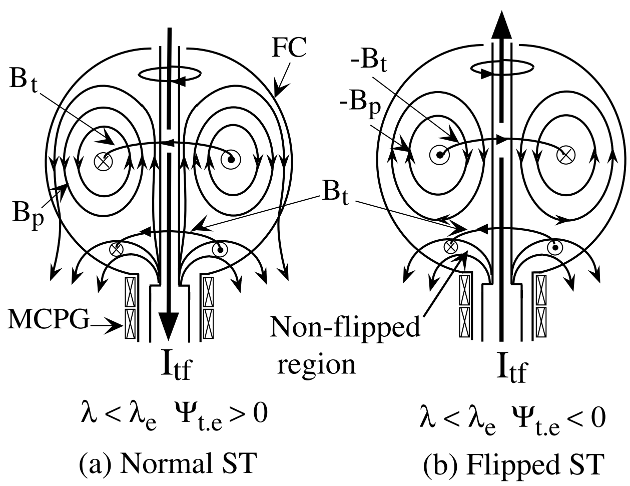

Fig. 1 Comparison of poloidal flux topologies between two kinds of relaxed states (ST (a) and F-ST (b)) in driven-toroidal systems which depend on the direction of the external toroidal flux $\Psi_{t.e}$.

Corresponding author's e-mail: nagata@elct.eng.himeji-tech.ac.jp

or not. Accordingly, it is interesting and worthwhile to investigate how the F-ST plasma is sustained, although it is isolated from the gun electrodes working as a helicity source.

2. Experimental setup

The HIST device (a major radius R = 0.30 m, a minor radius a = 0.24 m and an aspect ratio A = 1.25) produces low-aspect-ratio torus plasmas by utilizing the variation of the TF coil current I_{tf} from zero to maximally 0.25 MAturns. Figure 2 depicts a schematic diagram of HIST and diagnostics. The detail experimental description concerning the HIST devise is presented in ref. [3].

In this experiment, the ST plasmas with a peak toroidal current I_t of 60–80 kA are initially produced by CHI and then the reversed-TF circuit is triggered at t = 0.16–0.35 ms during the current ramp-down phase. The I_{gun} and gun voltage V_{gun} are ≈ 25–30 kA, and ≤ 0.8 kV respectively and the bias flux Ψ_{bias} produced around the MCPG muzzle is 0.8–1.1 mWb in this experiment. The TF-coil current I_{tf} is varied from +20 kAturns to 0 ~ –60 kAturns. The time scale over which I_{tf} changes is quite slow (≈ 0.5 ms) compared with an Alfvén time.

A three axis magnetic probe (9 channels each for B_r, B_ϕ, B_z) is located in the plasma at a distance of z = –0.75 m from the midplane (z = 0 m) of the flux conserver (FC). Magnetic pick up coils (26 channels each for B_p, B_t) are located in the poloidal direction along the inner surface of the FC to calculate the total toroidal current I_t. Note that the I_t measured by the surface magnetic coils includes not only the flipped region but also the non-flipped region. A fast framing camera measurement was performed in order to investigate dynamics of current reversal.

3. Experimental results

Experimental results showed that the ST plasma becomes unstable when I_{tf} decreases by –4 kAturns because of violation of the Kruskal-Shafranov stability condition and afterward its toroidal current starts to drop suddenly and reverse its sign as shown in Fig. 3. The F-ST plasma decays resistively after the reversal. Internal magnetic measurements indicated that toroidal and poloidal magnetic field profiles reverse sign and the relaxation to the F-ST magnetic field structures takes place. Figure 3 (a–f) implies a non-axisymmetric topological change of magnetic field lines during the transition. Fast camera image in Fig. 3 shows the helical deformation of plasma around the central conductor at the initial growth time (a, b, c) of the reversal. Three-dimensional MHD numerical simulations succeeded in demonstrating the formation of the flipped ST and substantially enabled us to understand the non-linear dynamic field-reversal mechanisms [7]. The simulation results indicate that a large helical distortion of the open flux and the following magnetic reconnection between open and closed field lines play a major role in the self-reversal process. The experimental results are almost in good agreement with those of simulation (see Fig. 2 C in ref. [7]).

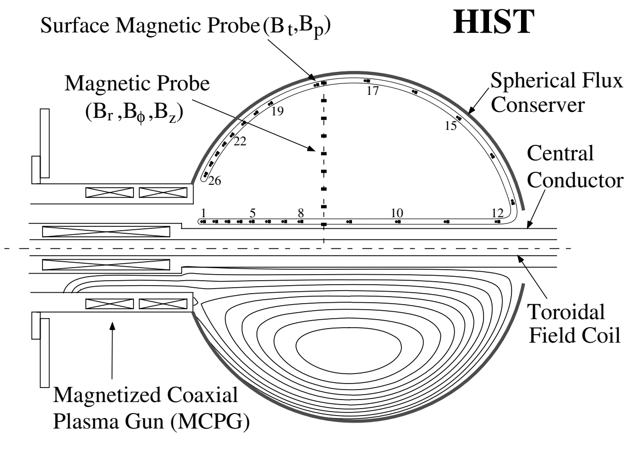

Fig. 2 The schematic drawing of the HIST device and diagnostics.

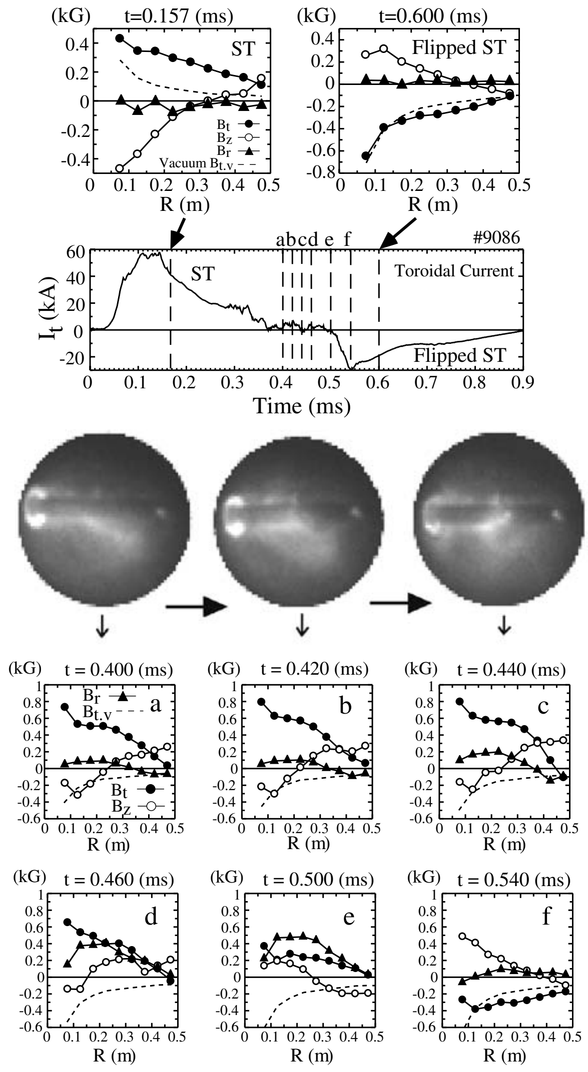

Fig. 3 Time evolution of toroidal current, and the radial profile of magnetic fields of ST, F-ST, and during the transition process from ST to F-ST. Fast framing camera image corresponds to the magnetic field profile of (a, b, c).

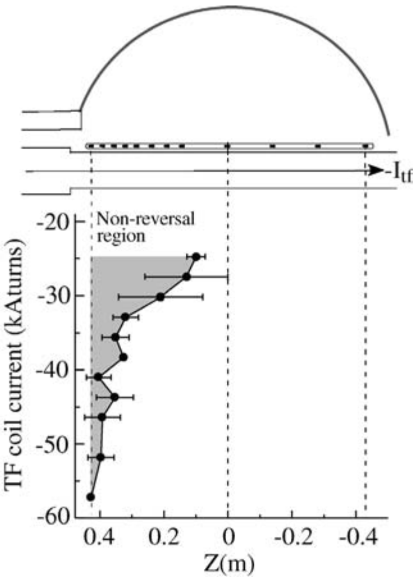

Fig. 4 Dependence of the axial length Z of the non-flipped (non-reversal) region on the reversed-TF coil current $-I_{tf}$.

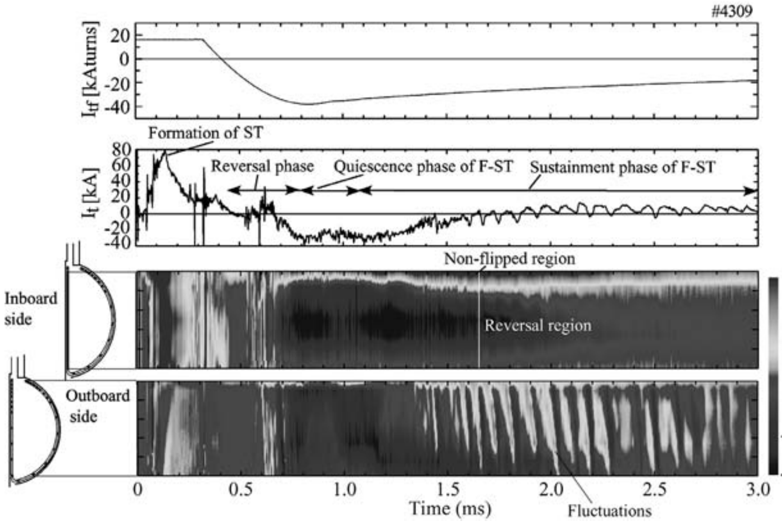

Fig. 5 Time evolutions of F-ST plasmas sustained by helicity injection.

The helicity-driven relaxed theory [5,6] indicates that there exists a non-flipped region in the F-ST configuration as shown in Fig. 1. We have experimentally verified the existence of the non-flipped region near the gun. Figure 4 shows the axial length of the non-flipped region as a function of the reversed TF coil current $-I_{tf}$. We can see that the non-flipped region shrinks towards the gun electrodes and the flipped region becomes dominant in the FC as $-I_{tf}$ increases. This is because the Lorentz force by I_g is reduced by the increase in $-I_{tf}$. The condition of $|-I_{tf}| < I_g$ for continuous or intermittent ejection of plasma with helicity from the gun should be satisfied for the successful sustainment of the F-ST plasmas.

At present, we have successfully demonstrated the sustainment of the F-ST plasmas by adjusting $-I_{tf}$. Figure 5 shows that the toroidal current in the F-ST is maintained for longer time (≈ 2 ms) than a resistive decay time (≈ 0.2–0.3 ms) after the quiescence phase (≈ 0.25 ms). The non-flipped (non-reversal) region starts to extend gradually towards the midplane of the FC from t = 1.2–1.3 ms because $|-I_{tf}|$ decreases from the peak value in time. Note that the amount of $|+I_t|$ in the non-flipped region is comparable with $|-I_t|$ in the flipped region after t = 1.7 ms, so we have observed that the measured I_t oscillates regularly around zero. The boundary magnetic probe signals show interesting behaviors. There are almost no regular magnetic fluctuations in the inboard side. In the other hand, signals in the outboard side show intermittent fluctuations in the same period as the oscillation of I_t. The observations suggest that the fluctuations at the outboard side are related to the current drive.

4. Summary

The most interesting finding of this experiment is that ST plasmas tend to self-organize to the flipped states while reversing the direction of TF. The observation of the self-reversal phenomena suggests strongly that the sign of magnetic helicity $K = c\Psi_p\Psi_t\,(1 < c < 2)$, where c depends on the plasma shape and current profile, is conserved with resistive loss in the magnitude during the transition process, namely when Ψ_t in the flipped plasma region becomes negative, then Ψ_p must also be so. A quantitative proof of the helicity conservation is an important work in our future experiments and numerical simulations. The reversal mechanism is closely associated with the kinking behavior of the open field lines around the central conductor. We have been able to maintain successfully the F-ST configuration by CHI, although the mechanism has not been understood adequately. We are considering the possibility that the helically kinked magnetic flux of the non-flipped region causes fluctuations at the outer edge region of the F-ST and the following magnetic reconnection transports intermittently helicity from the gun to the F-ST plasma interior.

References

[1] H.S. McLean *et al.*, Phys. Rev. Lett. **88**, 125004 (2002).
[2] R. Raman *et al.*, Phys. Rev. Lett. **90**, 075005 (2003).
[3] M. Nagata *et al.*, Phys. Plasmas **10**, 2932 (2003).
[4] M. Nagata *et al.*, Phys. Rev. Lett. **90**, 225001 (2003).
[5] J.B. Taylor and M.F. Turner, Nucl. Fusion **29**, 219 (1989).
[6] P.K. Browning *et al.*, Plasma Phys. Control. Fusion **35**, 1563 (1993).
[7] Y. Kagei *et al.*, Plasma Phys. Control. Fusion **45**, L17 (2003).