Coaxial Helicity Injection and n=1 Relaxation Activity in the HIST Spherical Torus

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Abstract. In order to understand comprehensively the role of the *n*=1 instability and relaxation on current generation processes in helicity-driven spherical systems, we have investigated dynamics of ST plasmas produced in the HIST device by decreasing the external toroidal field (TF) and reversing its sign in time. In result, we have discovered that the ST relaxes towards flipped ST configurations through formation of reversed-field pinches (RFPs)-like magnetic field profiles. Surprisingly, it has been observed that not only toroidal flux but also poloidal flux reverses sign spontaneously during the relaxation process. The dynamics associated to self-reversal of the magnetic fields is presently investigated by using three-dimensional magnetohydrodynamic (MHD) numerical simulations. Furthermore, we have first demonstrated that a flipped ST plasma can be successfully sustained by CHI. The *n*=1 relaxation activity is found to be essential in the current sustainment of the flipped ST as well as the spheromak and the unflipped ST.

1. Introduction

Coaxial Helicity Injection (CHI) has demonstrated non-inductive current generation of spherical tokamak (ST) and spheromak plasmas on HIST, HIT-II, SPHEX and SSPX [1-4]. The larger-scale, higher-performance NSTX device [5] has quite recently succeeded in attaining 390 kA of plasma current for 300 ms by using only CHI without Ohmic induction. Those recent experimental results prove that CHI technology is a promising means of non-inductively sustaining current in high β spherical tori. However we should note that there are presently discussions of whether closed flux in an ST can be created by CHI. The important issue of flux closure is closely linked with identification of the mechanism of helicity injection current drive that is strongly related to the non-axisymmetric (*n*=1) relaxation involving flux conversion and magnetic reconnection. The *n*=1 mode activities are significantly affected by the strength of the external toroidal field (TF). Thus it is important to study comprehensively the essential role of the *n*=1 kinking behavior and relaxation on current generation processes as a function of TF in the total context of helicity-driven spherical systems: STs, spheromaks and spherical reversed-field pinches (RFPs).
From above point of view, in the HIST device [1], we have investigated how internal magnetic field structures of ST plasmas change by decreasing the TF utilization, i.e. safety factor q, furthermore, reversing the direction of TF coil current I_{tf} during the helicity injection phase. This is a useful way to cause the *n*=1 resonant mode in a tokamak although it is not normally carried out, since ST plasmas, which are usually operated with the safety factor on axis $q_{axis} > 1$, must pass through the *m*=1/*n*=1 rational barrier, i.e. the Kruskal-Shafranov limit. Here, the following question arises: Does the ST plasmas collapse rapidly after they pass through the q_{axis}=1 rational barrier? It is known that RFP plasmas are usually produced by reversing the current in the TF coils quickly during the early stage of current ramp-up phase. The RFP configuration is experimentally realized without a major disruption through

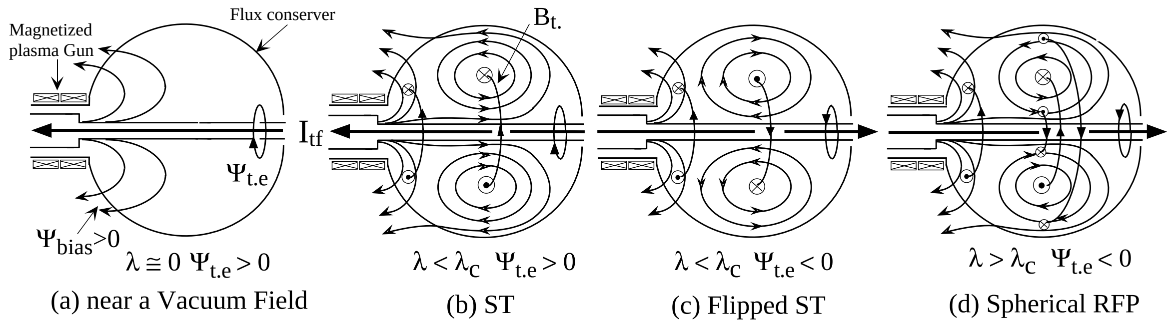

FIG. 1. Sequence of poloidal flux topologies of helicity-driven spherical plasmas as λ is increased from zero to above the resonance value λ_c. Relaxed states in toroidal systems depend on the direction of the external toroidal flux $\Psi_{t.e}$.

spontaneous dynamo related to the excitation of resistive tearing modes (low n=1,2,3 modes are resonant in the case of a low aspect ratio RFP). In the CHI discharges without an ohmic transformer, we could not expect that the configuration is formed and maintained by flux conversion that regenerates toroidal flux lost by resistive diffusion. According to the equilibrium analysis on the basis of the helicity-driven relaxation theory [6,7], we can predict that a flipped ST plasma is formed when the TF current is reversed. Figure 1 illustrates sequence of poloidal flux topologies of force-free equilibria ($\nabla\times\mathbf{B}=\lambda\mathbf{B}$) with open field lines as the force-free parameter $\lambda = \mathbf{j}\bullet\mathbf{B}/B^2$ is increased from zero or very small to above the resonance value λ_c. Poloidal flux contours and the direction of poloidal and toroidal magnetic fields are shown. We can see a clear difference in magnetic topology between "normal" ST and "flipped" ST. It should be noted that the open flux no longer surrounds the closed flux in the flipped state, but directly joins the gun electrodes and the flux conserver (FC) by the shortest path. If λ can pass through a resonance λ_c, the configuration reaches the RFP state ($\Psi_{t.e}<0$).

2. Experimental set-up

The HIST device, shown in Fig. 2, has a major radius R = 0.30 m, minor radius a = 0.24 m, aspect ratio A = 1.25, toroidal field $B_t < 0.2$ T, plasma current $I_t < 150$ kA and discharge time t < 5 ms for the ST configuration. The magnetized coaxial plasma gun (MCPG) is operated with formation capcitor banks (12.5 kJ, 5 kV) and sustainment banks (61 kJ, 600V). The injection current and voltage are ≈ 25 kA, and < 0.5 kV respectively. The outer bias solenoid coil produces the bias poloidal flux of < 2.5 mWb around the MCPG muzzle.

A three axis magnetic probe (9 channels each for B_r, B_ϕ, B_z) is located in a plasma at a distance of z = - 0.75 m from the midplane (z = 0 m) of the flux conserver. Magnetic pick up coils (26 channels each for B_p, B_t) are located in the poloidal direction along the inner surface of the spherical solid copper FC (diameter: 1.0 m, thickness: 3 mm) to calculate the total toroidal current I_t. A six channels λ probe incorporating small size Rogowski and flux loops is used to measure toroidal current density and toroidal flux profiles on the FC midplane. The toroidal n mode number of the magnetic fluctuations of B_t is measured using eight magnetic pick up coils distributed toroidally at equal angles over 360 degrees and around the outer edge. The line averaged electron density measured by a CO_2 laser interferometer is in the range of $1\text{-}5 \times 10^{19}$ m^{-3}.

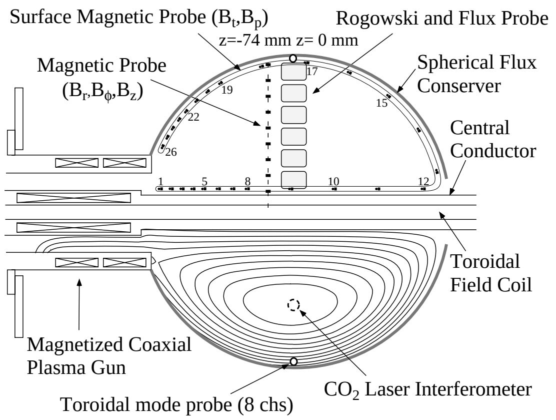

FIG. 2. The schematic drawing of the HIST device and diagnostics

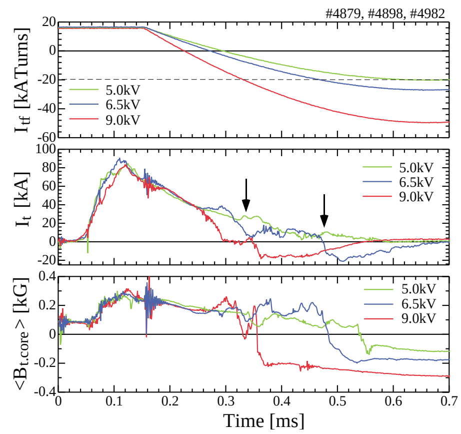

FIG. 3. The time-dependent data from CHI discharges in reversing the TF coil current.

3. Experimental Results

3.1. Effect of Reversing TF Coil Current on ST Plasma Driven by CHI

The ST plasmas with a peak toroidal current I_t of 80 -100 kA are initially produced by CHI and the reversed-TF circuit is triggered at t = 0.15 ms during the current ramp-down phase. Figure 3 shows the time evolution of I_t for three different value of the reversed I_{tf} (-20, -27, -50 kAturns at the peak time). For the negative values of $I_{tf} < -20$ kAturns, we can see that the direction of I_t and the averaged paramagnetic toroidal field $<B_{t.core}>$ in the core region has been reversed in about 10 μs. For increasing negative values of I_{tf}, the reversal time of I_t tends to shift to earlier times. In these discharges, the I_t decays smoothly due to its resistivity and is not sustained for a longer time by CHI. This event is recognized as the transition from the ST to the flipped ST configurations through MHD relaxation.

Reversing the TF coil current during the early stage of current ramp-up phase, we found that the RFP-like profile is transiently created during the discharge. Figure 4 shows the time evolution of I_t and radial profiles of poloidal magnetic field B_p, toroidal magnetic field B_t and vacuum toroidal field (dotted line) at each time (A, B, C, D). An initial plasma produced by CHI presents a ST configuration (see A). After turning on the reversed-TF circuit at t = 0. 43 ms in the ramp-up phase, the paramagnetic toroidal field in the core region has increased due to inward diffusion of poloidal current induced at edges (compare B with A). After that, the toroidal field at the inner edge region decreases rapidly and reverses the sign slightly, which results in the formation of an RFP configuration (see C). At this time, the current profile becomes peak at the magnetic axis so that λ approaches the resonance value λ_c (= 9.3 m^{-1}). This RFP does not remain for a long time and quickly changes

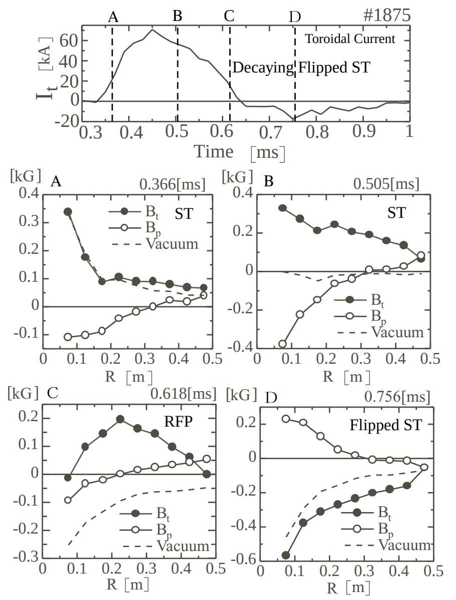

FIG. 4 Radial profiles of poloidal field B_p, toroidal field B_t and vacuum toroidal field of ST (A, B), spherical RFP (C) and flipped ST (D) formed in a decaying mode.

to the flipped ST configuration since the poloidal field also reverses sign (see D).

3.2. Sustainment of the Flipped ST Plasma

In the above operational condition with a short gas puff time, the flipped ST plasma decays in a very short time as shown in Fig.3. By extending the gas puffing time and delaying the triggering time of the reversed-TF, we have found that the flipped ST plasma can be maintained for about 1 ms by CHI as shown in Fig. 5. The q_{axis} value is approximately given by the formula of $q_{axis} = 2/R\lambda$ where $\lambda = \mu_0 I_t/\Psi_t$ is measured around the magnetic axis [7]. When q_{axis} passes through the $q_{axis} = 1$ rational barrier around t = 0.35 ms, the ST plasma becomes unstable and relaxes directly towards a flipped ST plasma. In this sustainment discharge as well, we can see the self-reversal phenomenon of both the toroidal and poloidal magnetic fields. In this shot, the temporal evolution of q_{axis} shows large fluctuations during the transition phase (t = 0.35 - 0.8 ms) including the reversal process of magnetic fields. The safety factor is not well defined in this phase, because the magnetic structures are non-axisymmetric. After the transition phase, the flipped ST plasma appears to settle down around t = 1.0 - 1.2 ms, then λ exhibits a large amplitude fluctuation which means intermittent generation of toroidal current around the magnetic axis during the sustainment phase (t = 1.2 - 1.6 ms). We have observed magnetic fluctuations at the outer boundary while q_{axis} repeatedly rises up and down through $q_{axis} = 1$. The toroidal mode measurement exhibits that the *n*=1 mode is dominant and grows and dumps down repeatedly during the sustainment. The repetitive generation of the current appears to be closely correlated to *n*=1 fluctuation-induced dynamo.

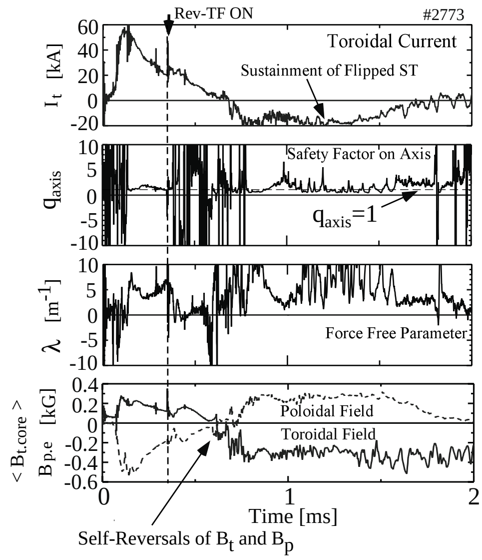

FIG. 5 Time evolutions of toroidal plasma current, safety factor on axis, pinch parameter, averaged toroidal field in the core region and edge poloidal field of the inboard side during the helicity injection process.

In the driven-spheromak, the current drive by CHI is thought to be associated with the helical central open flux encircling the closed flux. But for the flipped states, there is no the central open flux (see Fig.1(c))! The flipped ST plasma is isolated from the gun. The question is that how helicity is transported from the helicity injector to the confinement region. It is impossible to drive magnetic reconnection of the closed polodal field with the poloidal field shorted around the gun. Although a sustainment mechanism has not enough understood, we are considering that reconnection between the toroidal component of the magnetic field in each region could account for the issue of helicity transport since the toroidal field is in the opposite direction each other as shown in Fig.1 (c).

4. Numerical Simulation Results

Three-dimensional MHD simulations have succeeded in demonstrating the self-reversal of the magnetic fields [8]. Figure 6 shows the temporal evolution of poloidal and toroidal magnetic fields on the poloidal cross section of FC and gun regions. We see a large distortion of magnetic fields around the central conductor at t= $117\tau_A$, where τ_A is Alfvén transit time, as the toroidal field at the inner edge is reversed. The n=1 mode starts to grow before the reversal and becomes the dominant mode. After reconnection proceeds, the distorted magnetic field pattern occurred at the inner boundary is spreading to the outer boundary (Fig.6 (d)) and the direction of the toroidal and poloidal fields is reversed over almost of the region at t = 485 τ_A . At this time, the toroidal field in the gun region is in the opposite direction to the FC region. At t = 820 τ_A after a sufficient dumping of the amplitude of the n=1 mode, the flipped configuration has been established. We confirm that the open field lines directly connect between the electrodes without encircling the closed flux.

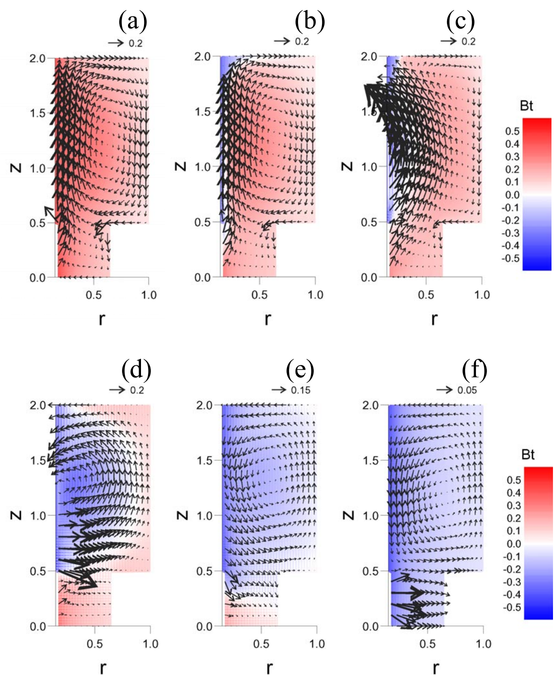

FIG. 6. Vector plots of B_p and cotour plots of B_t in the FC and in the gun regions at (a) t = 0, (b) t = 90, (c) t = 117, (d) t = 222, (e) t = 485, and (f) t = 820 τ_A.

5. Summary

The most important discovery of this experiment is that the ST plasmas tend to relax towards the flipped ST state while reversing the direction of TF. We can predict the existence of this relaxed state by the helicity-driven relaxation theory. Using three-dimensional MHD simulation, we have demonstrated the formation of this flipped configuration accompanied by field reversal. We believe that this current reversal is evidence for global helicity conservation. Furthermore, this flipped ST plasma has been successfully sustained by CHI by very carefully adjusting the operation condition.

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