HELICTY INJECTION CURRENT DRIVE OF SPHERICAL TOKAMAK & SPHEROMAK PLASMAS IN HIST

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Abstract

In the Helicity Injected Spherical Torus (HIST) device, spherical torus (ST) plasmas with 100 kA toroidal currents have been successfully sustained by coaxial helicity injection. Internal magnetic configurations with the closed poloidal flux of helicity-driven ST plasmas have been revealed by intensive internal magnetic measurements. As the configuration approaches a tokamak from a spheromak, the n = 1 mode being essential for current drive becomes less effective, resulting in the flux amplification level being decreased although the total toroidal current has increased. The transition from a hollow current profile to a peaked one in the tokamak operation has been observed for the first time during the helicity injection process. This may be explained by an Ohmic induction effect using the open flux column.

1. INTRODUCTION

Helicity injection current drive (HICD) [1] using a magnetized coaxial plasma gun (MCPG) is expected to be the most attractive current-drive method for a spherical torus (ST) [2] mainly represented by a low-aspect-ratio tokamak and a spheromak in which the central columns are extremely minimized. HICD was first employed to sustain spheromaks in the CTX [3], SPHEX [4] and FACT [5] devices. Its ability to drive a substantial plasma current has been experimentally verified and further the relaxation phenomena and the relaxed states during the helicity injection process have been manifested in those gun-spheromak machines. Recently, HICD on the tokamak configuration has been successfully demonstrated on CDX [6], CCT [7] and HIT [8]. However, the current drive mechanism in the tokamak has not yet been established and also it is difficult to determine closed flux without internal magnetic measurements. Hence, the most important requirement for HICD on ST is to reveal the details of the internal magnetic field structures and the current drive mechanism.

2. EXPERIMENTAL DEVICE

The Helicity Injected Spherical Torus (HIST; major radius R = 0.30 m, minor radius a = 0.24 m, aspect ratio A = 1.25) [9], shown in Fig. 1, was built to generate a helicity-driven tokamak and a spheromak with a central conductor by utilizing the variation of toroidal field (TF) coil current from 0 to maximally 0.3 MAturns. The HIST uses a 1.5 m diameter, 3 m long, 9 mm thick stainless steel vacuum chamber. The MCPG is 0.9 m long, with inner and outer electrode diameters 0.18 m and 0.28 m, which is operated with formation capacitor banks (30 kJ, 10 kV) and sustainment banks (138 kJ, 900 V). The outer bias solenoid coil produces the bias flux Ψ_{bias} of < 2.5 mWb which is measured around the gun muzzle. The spherical solid copper flux conserver (FC) is 1 m in diameter and 3 mm in thickness. The TF coil, which can be maximally driven by capacitor banks to 9 kV, 0.4 MJ, and is normally operated to generate the toroidal field B_t of 0.2 T at the magnetic axis. Wall conditioning is performed by intense titanium coating on the FC inner surface which results in a vacuum base pressure of $\approx 3\times10^{-9}$ Torr.

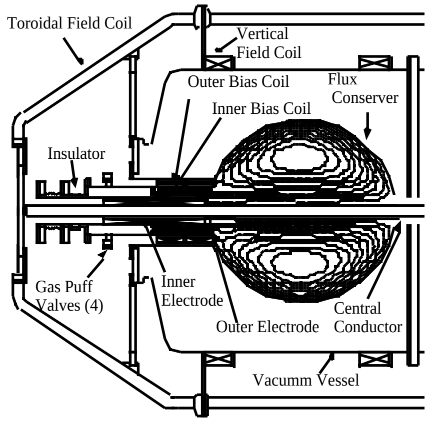


FIG.1. Schematic diagram of the HIST device

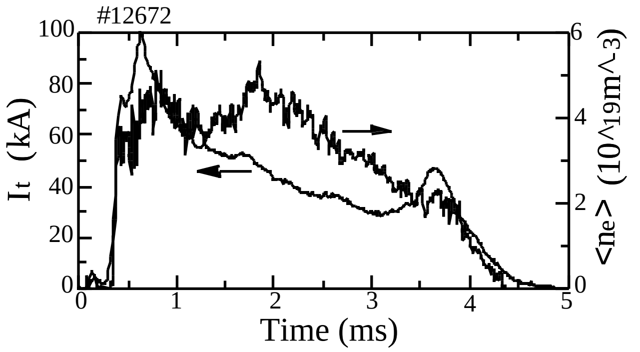
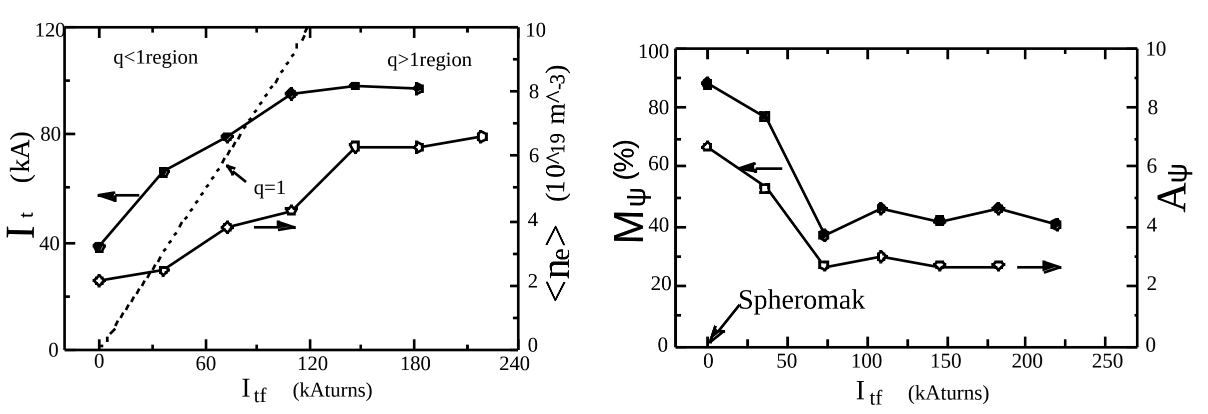


FIG.2. Time evolutions of toroidal current I_t and average electron density $<n_e>$ in the tokamak operation

3. EXPERIMENTAL RESULTS

3.1. Effects of the external toroidal field on generation of closed flux and flux amplification

The HIST experiments have successfully demonstrated CHI sustainment of ST plasmas for 4 ms with peak total toroidal current $I_t \approx 100$ kA and average electron density $<n_e> = 2\text{-}8\times10^{19}\mathrm{m}^{-3}$. Typical parameters for these shots are gun current $I_g = 25$ kA, gun voltage $V_g \leq 500$ V, and TF coil current $I_{tf} = 0\text{-}200$ kAturns. A typical tokamak discharge shot is shown in Fig. 2. Figures 3 (a) and (b) show I_t and $<n_e>$ as a function of I_{tf} (a), and the ratio M_Ψ of closed poloidal flux $\Psi_{p.c}$ to total poloidal flux Ψ_p (4-6 mWb) and the poloidal flux amplification ratio A_Ψ defined by the ratio of Ψ_p to Ψ_{bias} (b). These are plotted at the time of the peak I_t on the condition of optimum Ψ_{bias}. I_t and $<n_e>$ rise as I_{tf} is increased in the range of the operational safety factor $q = I_{tf} / I_t < 1$, but saturate values of $I_t \approx 100$ kA and $<n_e> = 6\times10^{19}$ m^{-3} in the $q > 1$ region. Figure 3 (b) shows that M_Ψ and A_Ψ decrease with increasing I_{tf}. Note here that $I_{tf} = 0$ kAturns corresponds to a spheromak configuration with a central conductor. We find that the spheromak-like configuration with $q < 1$ has the largest $M_\Psi \approx 90$ % and $A_\Psi > 6$ in spite of a low current amplification ratio $A_I = I_t / I_g \approx 1.5$. M_Ψ is 35-50 % for the tokamak, which is in agreement with results of MHD equilibrium fitting calculations. This result implies that the HICD becomes less effective for generation of closed flux as the configuration approaches a tokamak from a spheromak.



(a) (b)

FIG. 3. Toroidal current I_t, average electron density $<n_e>$ (a) and the ratio of closed flux to the total poloidal flux M_Ψ, flux amplification ratio A_Ψ (b) as a function of TF coil current I_{tf}.

3.2. Transition of current density profile during helicity injection

Figure 4 shows the typical temporal evolution of the toroidal current densities J_t measured at each radial position on the midplane of the FC using a six channel $\lambda=\mu_0\mathbf{J}\cdot\mathbf{B}/B^2$ probe incorporating small size Rogowski loops and flux loops with a rectangular cross section. We note that toroidal current is driven at the magnetic axis (R≈ 0.30 m) and also there exists regular magnetic fluctuations which have larger amplitudes than those on both edges. The fluctuations on $J_{t.in}$ of the inboard side (R= 0.105 m) is clearly stabilized by TF. The $J_{t.axis}$ at the magnetic axis consists of intermittently fluctuating component and an increasing pedestal component. Here, we notice that $J_{t.axis}$ is increasing until the sudden current drop occurs, whereas, $J_{t.in}$ and $J_{t.out}$ of the outboard side (R= 0.445 m) decays quickly on both edges. Hence, the current density profile changes from a hollow profile around the time of peak current to a peaked profile during the sustainment phase. Therefore, The safety factor q_a on axis changes from 15-20 (t ≈ 0.6 ms) to 3-4 (t ≈ 1.8 ms). The hollow J_t and λ profiles measured at the earlier time are expected in the driven system, but the MHD dynamo theory cannot explain the peaked profiles formed during the later sustainment phase as shown in Fig. 4.

3.3. Comparison of toroidal mode structure between tokamak and spheromak

The dominant measured toroidal n mode of the magnetic fluctuations (≈ 20 kHz) generated at the magnetic axis is n = 0 ($A_{n=1}/A_{n=0}$ ≈ 0.4) for the tokamak case as shown in Fig. 5 (a). The n = 0 mode is primarily composed of unperturbed axisymmetric poloidal field. On the other hand, the spheromak shows the fast large growth of the n = 1 mode leads to the generation of the n = 0 mode which means strong flux amplification (Fig. 5 (b)). This result agrees with the result of the flux amplification shown in Fig. 3 (b). The relative amplitude of $A_{n=1}/A_{n=0}$ jumps above 8. This result suggests that HICD in the high q tokamak operation may work intermittently in an almost axisymmetric manner in contrast to the spheromak.

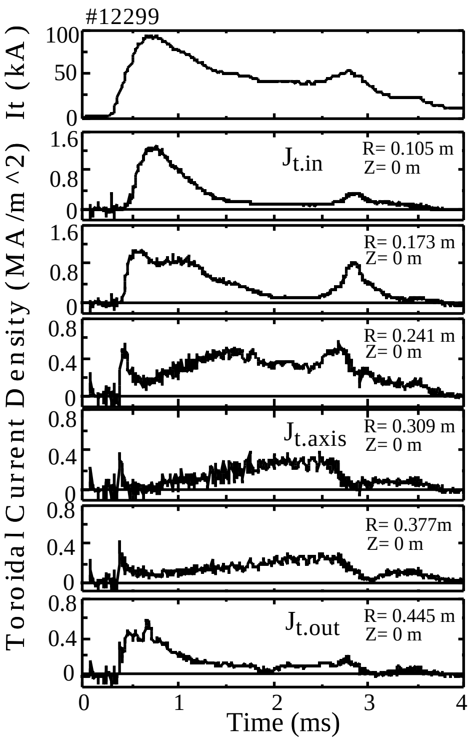


FIG.4. Time evolution of toroidal current density measured at each radial position.

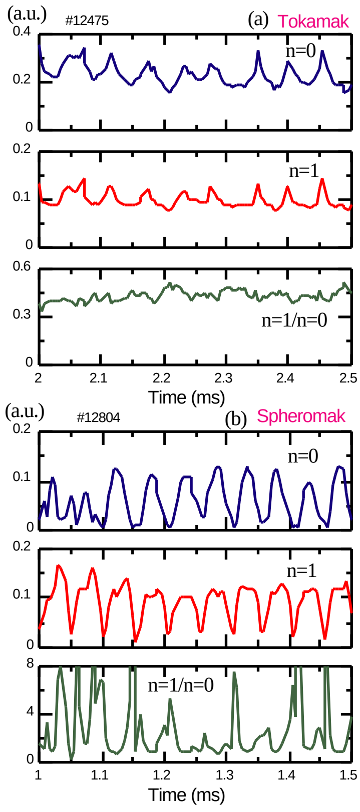


FIG.5. Comparison of toroidal mode behavior between tokamak (a) and spheromak case (b).

We have observed that the electrostatic fluctuations in the gun voltage have a strong correlation with fluctuations in the toroidal current and the floating potential in the confinement region. The toroidal current may be driven directly by plasma flow injected from the MCPG through an axisymmetric merging.

4. DISCUSSION AND CONCLUSIONS

We need to discuss the cause of the peaked current and λ profiles and the features of the magnetic fluctuations observed at the magnetic axis. First, this peaked current profile may be explained by an OH transformer effect for the open flux around the central conductor. The gun current follows initially along the open field lines surrounding the closed flux surfaces during the formation process. The injection current winds around the open field lines on the central conductor just like the current in an OH transformer coil. Then the gun current changes its path after the time of peak current and so comes to flow along the short bias field lines linking the electrodes directly around the gun muzzle. Increasing the bias flux tends to force the main part of the injected current path shorter. Hence, the part of the gun current flowing around the central open field lines decreases quickly; as a result, an amount of the volt seconds at the magnetic axis in the direction of positive current drive is produced inductively. The pedestal component of $J_{t.axis}$ is attributed to the OH transformer action and the fluctuating component is generated from HICD. These results suggest that the combination of the OH current drive and helicity injection may control the current profile of ST plasmas.

In conclusion then, we have found the details of current and flux amplification, current density profiles and magnetic fluctuations in the spheromak/tokamak hybrid regime by increasing the TF coil utilization, As the TF coil current increases, the closed flux decreases as accompanied by a decrease in the amplitude of the n = 1 mode fluctuation. We think that the stabilization of n = 1 mode by TF lead to a better confinement of the helicity-driven ST plasmas, and also HICD combined with Ohmic induction current drive avoids the decrease in closed flux which may degrade a plasma confinement. We have observed regular fluctuations at the magnetic axis and the formation of a peaked current profile during the helicity injection process. The features of these observations may be explained by the combination of helicity injection and Ohmic drive using the central open flux column and repetitive merging process with a plasma injection from the MCPG.

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REFERENCES

[1] JENSEN, T.H., CHU, M.S., J. Plasma Phys. **25** (1981) 459.
[2] PENG, Y-K.M., STRICKLER, D.J., Nucl. Fusion **26** (1986) 769.
[3] KNOX, S.O., et al., Phys. Rev. Lett. **56** (1986) 842.
[4] BROWNING, P.K., et al., Phys. Rev. Lett. **68** (1992) 1718.
[5] NAGATA, M., et al., Phys. Rev. Lett. **71** (1993) 4342.
[6] ONO, M., et al., Phys. Rev. Lett. **59** (1987) 2165.
[7] DARROW, D.S., et al. Phys. Fluids B**2** (1990) 1415.
[8] NELSON, B.A., et al., Phys. Rev. Lett. **72** (1994) 3666.
[9] NAGATA, M., et al., Proc. of the 1996 International Conference on Plasma Physics, **2** (1996) 1210.