EXPERIMENTAL STUDY OF HELICITY-DRIVEN MHD ACTIVITY AND CURRENT PROFILES IN THE HIST SPHERICAL TORUS

M. Nagata, M. Haruoka, S. Kano, N. Yuasa, N. Fukumoto and T. Uyama

Faculty of Engineering, Himeji Institute of Technology
Shosha, Himeji, Hyogo 671-2201, Japan

1. Introduction

Helicity injection current drive (HICD) [1] using the magnetized coaxial plasma gun (MCPG) is expected to be the most attractive current-drive method for toroidal configuration plasmas, especially for Spherical Torus (ST). So far, HICD has been first employed to sustain spheromaks in the CTX [2], SPHEX [3] and FACT [4] devices. Its ability to drive a plasma current substantially has been experimentally verified and further the relaxation phenomena during the helicity injection process have been manifested in these gun-spheromak machines. Recently, it is the remarkable achievement that a plasma current drive of over 200 kA by only coaxial helicity injection (CHI) has been successfully demonstrated in the HIT spherical tokamak [5]. However, the current drive mechanism in the tokamak has not yet been established and also it is still questionable even whether closed poloidal flux can be actually created by CHI. Hence, the most important requirement for HICD in the ST research is to reveal the key features such as magnetic field structures, current density profile, $\lambda = \mu_0 J_{\parallel} / B$ profile and MHD activity.

2. HIST device and typical ST discharges

The Helicity Injected Spherical Torus (HIST; major radius R=0.30 m, minor radius a=0.24 m, aspect ratio A=1.25), shown in Fig.1, was built to generate ST plasmas. The HIST device 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 the formation capacitor banks (30 kJ, 10 kV) and the sustainment banks (138 kJ, 900V). The outer bias solenoid coil produces the bias flux Ψ_{bias}<2.5 mWb. The spherical solid copper flux conserver (FC) is 1 m in diameter and 3 mm in thickness. The toroidal field (TF) coil, which can be maximally driven by capacitor banks of 9 kV, 0.4 MJ, is normally operated to generate the toroidal field B_t of 0.2 T at the magnetic axis.

The HIST experiment has successfully demonstrated 4 ms CHI sustainment of ST plasmas with peak total toroidal current I_t<150 kA and average electron density $< n_e >= 2\times10^{19}\,m^{-3}$, as shown by Fig. 2. Wall conditioning is conducted by intense titanium coating on the FC inner surface, which results in that a vacuum base pressure reaches 3×10^{-9} Torr. Typical parameters for the tokamak operation are gun current $I_g \leq 25$ kA, gun voltage $V_g \leq$ 500 V, TF coil current I_{tf} =200 kAturns.

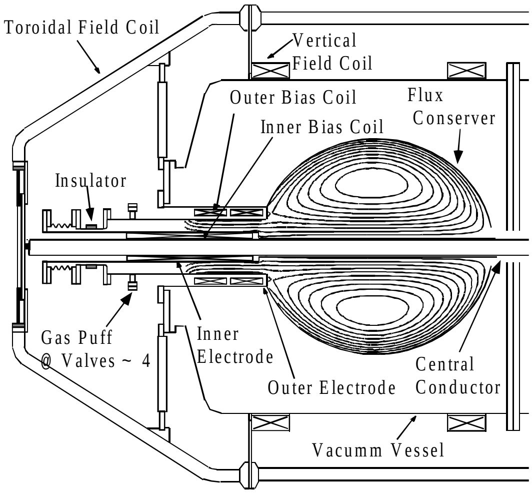

Figure 1. Schematic diagram of the HIST device

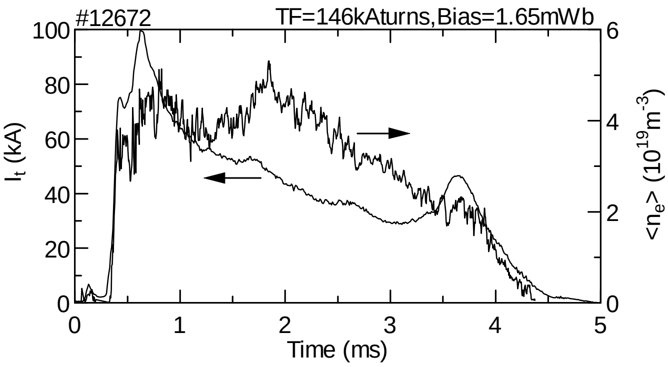

Figure 2. Time evolutions of I_t and $< n_e >$ in the tokamak operation

3. Toroidal current and flux amplification vs TF coil current

Figure 3 shows plots of I_t as a function of I_{tf} for fixed I_g. I_t rises up as I_{tf} is increased in the range of a safety factor $q = I_{tf}/I_t$ <1, but saturates in the range of q>1, namely the current amplification stops. Fig. 4 shows experimental evaluations of the poloidal flux amplification ratio A_Ψ defined by the ratio of the total poloidal flux Ψ_p to Ψ_{bias} and the ratio of M_Ψ of the closed poloidal flux $\Psi_{p.c}$ to Ψ_p. Both A_Ψ and M_Ψ decrease with increasing I_{tf}. We note that the spheromak-like configuration (I_{tf} =0) has largest M_Ψ ~88 % and A_Ψ ~7 in spite of a low current amplification $A_I \le I_t/I_g$ ~1.5. The M_Ψ is 40~50 % and A_Ψ is 2.0~3.0 in the tokamak case. These results imply that HICD becomes less effective as the configuration approaches a high q tokamak, because the n=1 kink deformation of the open central column [4][6] being essential for the current drive process may be stabilized in the high TF current regime.

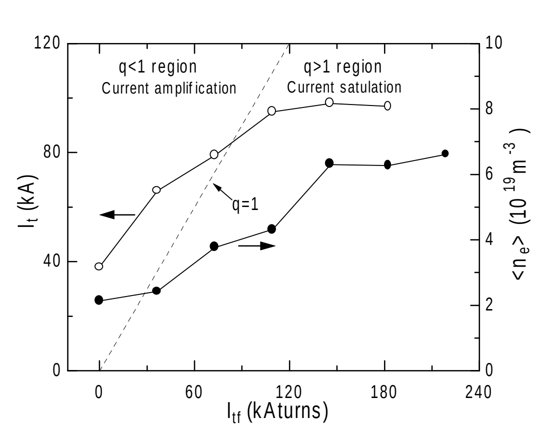

Figure 3. I_t, $< n_e >$ vs. TF coil current

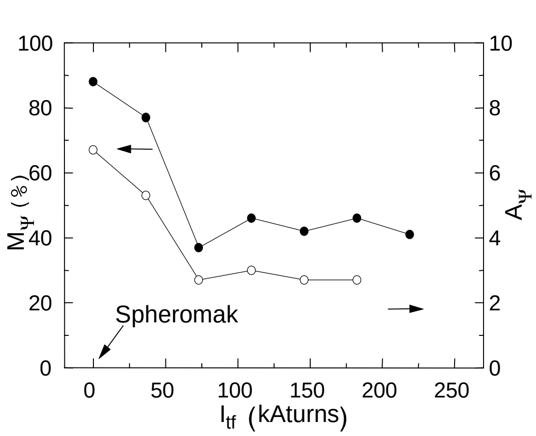

Figure 4. M_Ψ, A_Ψ vs. TF coil current

4. Hollow and peaked current density profiles

Figure 5 shows the typical temporal evolutions of the toroidal current densities J_t measured at each radial position on the midplane of the FC using a six channels λ probe incorporating small size Rogowski loops and flux loops. We note that the toroidal current is driven at the magnetic axis and also there exist current fluctuations that have larger amplitude than those on the both edges. The fluctuations on $J_{t.in}$ on the inboard side are clearly stabilized by TF. The $J_{t.axis}$ at the magnetic axis consists of intermittently fluctuated component and increasing pedestal component. Here, we notice that $J_{t.axis}$ is increasing until t=2 ms, meanwhile $J_{t.in}$ and $J_{t.out}$ are decaying quickly. Hence, the current density profile changes from a hollow profile around the time of peak current to a peaked profile during the sustainment phase. This peaked profile can not be explained by MHD dynamo model.

Now, we need to discuss the cause of the peaked current profile. The formation of the peaked current profile can be explained by an OH transformer effect of open flux around the center conductor. The gun current follows initially along the open field lines surrounding the closed flux surfaces during the formation phase. The injection current winds around the open field lines on the center conductor just like 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 injected current path shorter. Hence, the gun current flowing around the central open field lines decreases so quickly; as a result, an amount of the voltsec around the magnetic axis in the direction of positive current drive is produced inductively. The pedestal component of J_t on axis is attributed to the OH transformer action and the fluctuated one is thought to be generated from helicity injection process.

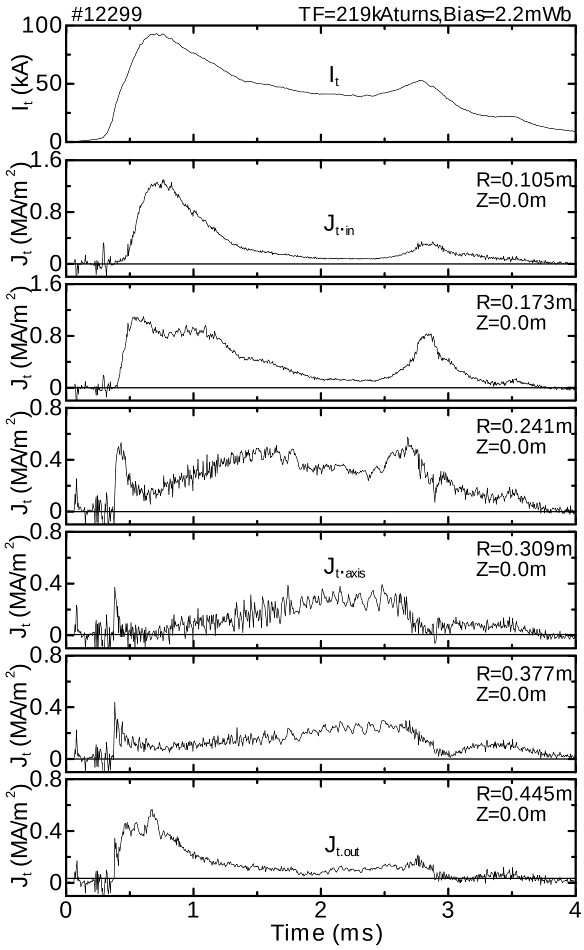

Figure 5. Time evolution of current density at each radial position

5. Magnetic fluctuations and toroidal mode structures

Fig.6 shows the toroidal mode number n of the magnetic fluctuations measured at the magnetic axis. It is found in the tokamak case that the amplitude of n=0 is larger than n=0 as shown in Fig. 6 (a). In the spheromak case, the fast large growing of n=1 mode ($A_{n=1}/A_{n=0}$ >8) leads to the generation of the n=0 mode which means the substantial flux amplification. So these results suggest that HICD in the tokamak operation works in a almost axisymmetrical manner in contrast to the spheromak. We have observed that the electrostatic fluctuations (20 kHz) in the gun voltage showing strong correlation with fluctuations in the toroidal current. The toroidal current may be intermittently driven through axisymmetric merging processes by the repetitive injection of tokamak-like plasmoid [7] (mainly ions flow) accelerated in both the axial and $\mathbf{E}\times\mathbf{B}$ directions from the gun.

6. Conclusions

The internal magnetic structures and relaxation activity of the helicity-driven spheromak/tokamak plasmas have been revealed by intensive internal magnetic measurements. We have observed the fluctuations on axis and the formation of the peaked current profile during the helicity injection process. These observations are characterized by intermittent plasma injection process in combination with ohmic induction effect of the open flux column.

Acknowledgement. The authors are grateful to P.K. Browning, M.G. Rusbridge, S. Woodruff, B.A. Nelson, T.R. Jarboe and J.S. Sarff for many valuable discussions.

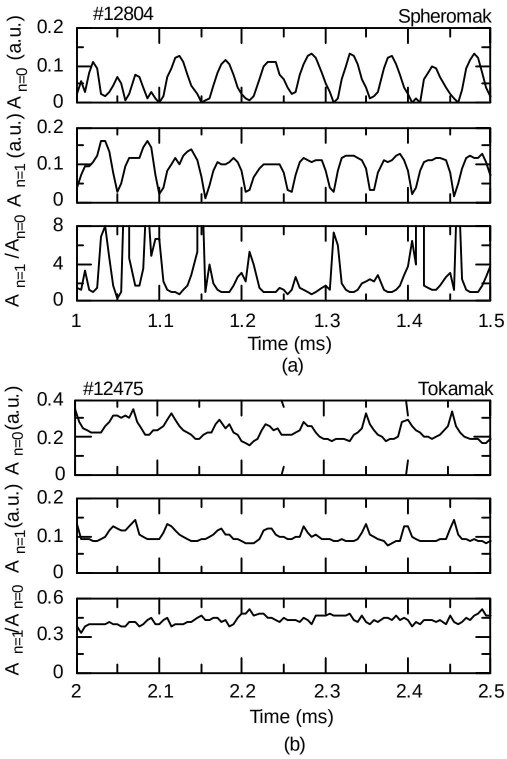

Figure 6. Comparison of toroidal mode number between spheromak (a) and tokamak (b)

References

[1] T. H. Jensen and M.S. Chu: J. Plasma Phys. **25**, 459 (1981).
[2] S.O. Knox et al.: Phys. Rev. Lett. **56**, 842 (1986).
[3] P.K. Browning et al.: Phys. Rev. Lett. **68**, 1718 (1992).
[4] M. Nagata et al.: Phys. Rev. Lett. **71**, 4342 (1993).
[5] B.A. Nelson et al.: Phys. Rev. Lett. **72**, 3666 (1994).
[6] R.C. Duck et al.: Plasma Phys. Control. Fusion **39**, 715 (1997).
[7] R. Frarengo and T.R. Jarboe: Fusion Technology **20**, 407 (1991)