Dynamo current drive via low-frequency waves in the HIST helicity-driven spherical torus plasma

M. Nagata, T. Hanao, H. Hirono, T. Hyobu, M. Ishihara, K. Ito, T. Nakayama, K. Matsumoto, Y. Kikuchi and N. Fukumoto

Graduate School of Engineering, University of Hyogo, Himeji, Japan

Abstract.

The dynamo current drive with two-fluid effects has been investigated in the helicity-driven spherical torus (ST) plasmas on HIST. 2D internal magnetic field measurements of the ST configuration has verified the flux amplification and the generation of the closed flux during the coaxial helicity injection (CHI). We have found that not only MHD $<\delta\boldsymbol{v}\times\delta\boldsymbol{B}>_{||}$ dynamo but also Hall $<\delta\boldsymbol{j}\times\delta\boldsymbol{B}>_{||}/en$ dynamo plays an important role in the helicity transport for the current sustainment. Hall-MHD induced-electric fields satisfy the parallel mean-field Ohm's law balance. We have also observed transverse propagation and damping of a low-frequency Alfven wave. The dynamo activities for the current drive may be caused by the Alfven waves.

1. Introduction

The steady-state current drive by the coaxial helicity injection (CHI) [1] had been demonstrated for spheromaks (SSPX) and ST plasmas (HIST, HIT-II). Recently, the new approach of CHI so called the multi-pulsing CHI (M-CHI) operation [2] has been proposed for the purpose of achieving a quasi-steady-state high-β ST plasma. As an application of M-CHI for the ST configurations, we have started double-pulsing CHI experiments in the HIST device (R = 0.30 m, a = 0.24 m, A = 1.25) [3]. It is one of main objectives in this experiment to understand the underlying dynamo current drive mechanism during the helicity transfer from the coaxial plasma gun to the closed flux region. Flux amplification and current drive by dynamo effect is one of the most interesting physical phenomena in astrophysical and laboratory plasmas. The CHI pulse produces effectively fluctuating flows and magnetic fields which are considered to be dynamo activities needed for driving a current in the closed flux regions. The CHI current drive exhibits the significance of two-fluid effects. This paper will present an experimental study of flow generations and dynamo current drive with Hall-MHD based models [4]. The structures, sizes, capabilities, diagnostics, and operating conditions of HIST are described in detail in Ref. [3].

2. Experimental results

2.1 Flux amplification and generation of closed flux surfaces

The HIST device can form and sustain the ST plasmas (high-q: q>1 and low-q including spheromaks: q<1) and is characterized by utilizing the variation of the external toroidal field (TF) coil current I_{tf}. The ST plasma with typical toroidal current I_t ~100 kA (at the operation with I_{tf}=125 kAturns) is initially produced and thereafter a second gun current is additionally injected from the magnetized coaxial plasma gun (MCPG) during the decay phase. Figure 1(a) illustrates temporal evolutions of I_t and the poloidal flux Ψ_p. The I_t and Ψ_p are rebuilt by the second gun pulse at t=1.5 ms. The flux or current amplification ratio of Ψ_p or I_t to the bias flux $\Psi_{p.bias}$~1 mWb or the second injection current I_{inj} ~20 kA is about 4 in the second pulse. Figure 1(b) shows that the I_t generated by the second pulse tends to increase proportionally with the increase in I_{tf} and then to saturate at I_{tf} ~100 kAturns. The correlation between the poloidal flux and current amplifications has a good agreement as shown in Fig.1 (c). Consequently, we may conclude that the successful double pulsing process leads to the flux and current amplifications.

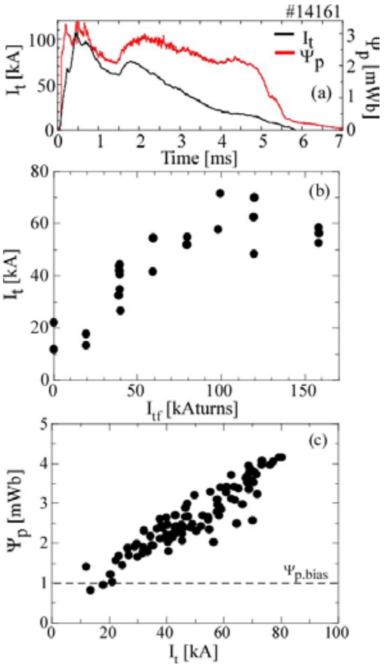

Fig. 1 *(a)Time evolution of toroidal current I_t, and Poloidal flux Ψ_p, (b) dependency of I_t on I_{tf} in the second pulse, (c) relationship between I_t and Ψ_p amplified in the second pulse.*

Figure 2 shows the contour plots of the poloidal flux formed during the partially sustainment in the discharge with the long life of t=8 ms. We can identify the existence of the closed flux surfaces and the open flux region surrounding them. The central open field line-tying with the inner electrode is so called open flux column (OFC) which plays an important role in the CHI current drive. A small scale turbulence flow enters from the MCPG to create the closed flux.

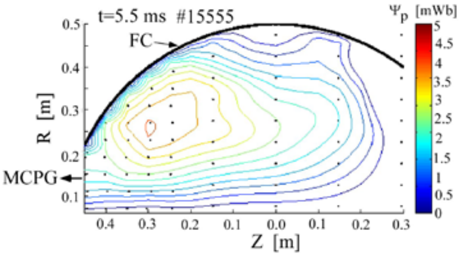

Fig.2 *Cotour plot of the poloidal magnetic flux of ST configuration sustained by double-pulsing CHI.*

2.2 Dynamo measurements

Flux amplification is attributed to dynamo action induced by the double helicity injection. Figure 3 shows the MHD and Hall dynamo induced-electric fields measured at each radial position. The direction and amplitude of each dynamo are determined by the phase difference between the fluctuating velocity or current density and the fluctuating magnetic field. The MHD dynamo has the opposite direction to the Hall dynamo. The Hall dynamo is a two-fluid effect which has been measured large between the OFC and the last closed flux surface, i.e., at the separatrix. The both fluctuation-induced electromotive forces are large enough to sustain the mean toroidal current against resistive decay in the core region. The parallel mean-field Ohm's law balance [5] is roughly satisfied both in the OFC driven-region and the core region.

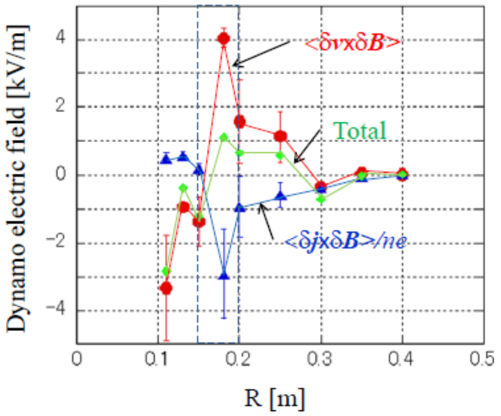

Fig.3 *Radial profile of MHD dynamo and Hall dynamo in the driven phase. Each dynamo induced-electric field has the largest amplitude (R=0.15-0.2 m) between the OFC and the last closed flux surfaces. The flow measurement at this location exhibits the strong poloial shear flow.*

2.3 Observations of a low frequency Alfven wave and ion heating

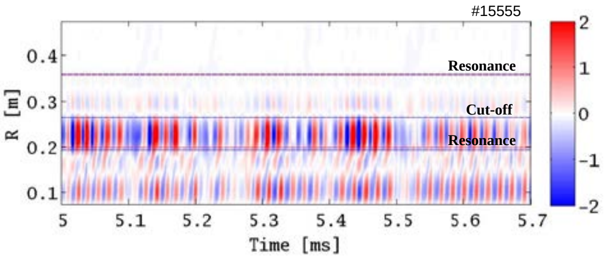

Fig.4 *Radial propagation and attenuation of magnetic field perturbations .The resonance and cut off positions are predicted theoretically. The strong poloidal shear flow around the location of R=0.15 m tends to reduce the amplitude of the flucutation.*

We have investigated propagations of magnetic fluctuations in the poloidal cross section of the plasma. The magnetic fluctuation originates from the muzzle of the MCPG like an antenna. Figure 4 shows the time evolution of the radial profile of the magnetic fluctuations. The frequency of the observed oscillation is ~80 kHz (angular frequency ω =500x10^3 rad/s =0.05ω_{ci}, ω_{ci}; ion gyro frequency in a vacuum field B_t=0.1T) and the parallel phase velocity $v_{//}$ is 321 km/s that is estimated by the axial propagation velocity ~70 km/s along the OFC, and then the parallel wave number $k_{//}$ ~ 0.25 m^{-1} can be obtained. The parallel phase velocity agrees well to the Alfven velocity v_A. The radial propagation of the Alfven wave can be calculated by a theory based on a cold plasma approximation with the Hall term [6]. The theoretical calculation using the measured $k_{//}$, the measured density profile and the magnetic field profile shows that the Alfven wave has a cut off (R=0.27 m) and two resonances (R=0.2, 0.36 m) at a radial position. The shear Alfven wave propagates inwardly towards the magnetic axis beyond the first resonance from the OFC region edge (R=0.15 m). The wave decays rapidly after encountering the cut off position. In the warm plasma model, the shear Alfven wave does not have a sharp resonance, and continuously converts to high perpendicular k mode called "kinetic Alfven wave". The experimental result indicates that the phase velocity decreases and the perpendicular k increases to the value close to that of the kinetic Alfven wave predicted from the warm plasma theory. This mode conversion leads to the heating of ion due to resistive damping [7]. As shown in Fig. 4, the wave has propagated in the perpendicular (to the vacuum toroidal field) direction in the core region across the separatrix. The observed strong attenuation in the area (R>0.28 m) indicates that the resistive damping enables possibly the heating of ions which has been observed by Doppler ion temperature measurement.

3. Summary

We have measured the spatial profiles of the MHD/Hall dynamo electric fields being associated to the flux amplification by the successful double CHI pulses. The relative contributions of the different dynamo during the current drive have been investigated to verify the parallel mean-field Ohm's law balance. Contribution of the MHD dynamo in the core region with a higher density becomes more dominant compared to the Hall dynamo. In a low density plasma, however, the Hall dynamo becomes more significant as two-fluid effects. We have identified that the low-frequency Alfven wave with the peak frequency of 80 kHz propagates to the closed flux region. Moreover, we have observed that the ion Doppler temperature increases after the second CHI pulse and so the ion heating may be due to a damping of the Alfven wave.

References

[1] T. Jarboe, Plasma Phys. Control. Fusion **52,** 045001 (2010).
[2] E.B. Hooper, Plasma Phys. Control. Fusion **53**, 085008 (2011).
[3] M. Nagata, et al., Phys. Plasmas **10,** 2932 (2003).
[4] V. V. Mirnov, C.C. Hegna and S.C. Prager, Phys. Plasmas **11**, 4468 (2004).
[5] H. Ji, et al., Phys. Plasmas **3**, 1935 (1996).
[6] S. Okada, et al., Nucl. Fusion **47**, 677 (2007).□.
[7] Q. Lu and X. Li, Phys. Plasmas **14,** 42303 (2007).