Measurements of dynamo effects in the HIST helicity-driven spherical torus plasma

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Abstract.
Flux amplification and sustainment of the spherical torus (ST) configurations by operating in Multi-pulsing Coaxial Helicity Injection (M-CHI) method have been demonstrated in the Helicity Injected Spherical Torus (HIST) device. We have studied the plasma flow structures and the dynamo electric field necessary to balance Ohm's law in the double pulsing CHI discharges. The experimental results indicate that two-fluid effects are necessary to understand the CHI current drive.

1. Introduction

Coaxial Helicity injection (CHI) is an efficient current-drive method used in many spheromak and ST experiments. A critical issue for CHI is achieving good energy confinement and sustainment simultaneously, since it relies on the magnetic relaxation. This is essentially because CHI cannot drive a dynamo directly inside a closed magnetic flux surface, so that the field lines become stochastic and the flux surface is only an approximate, i.e. "mean-field" one during the sustainment. A new approach of CHI so called multi-pulsing or "refluxing" has been proposed to overcome this weak point [1]. The multi-pulsing operation is that after the plasma partially decays, a new CHI pulse is applied and the cycle process repeated which yields a quasi-steady-state plasma. This multi-pulsing experiment was demonstrated in the SSPX spheromak device at LLNL [2]. The one of main objectives of this experiment is to explore the usefulness of the M-CHI for the ST configurations.

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 play a role in the dynamo activity needed for driving a current in the closed flux regions. This paper will present the results from double pulsing operations on HIST and mesurements of the dynamo effect.

2. The HIST devise and diagnostics

The structures, sizes, capabilities, diagnostics, and operating conditions of HIST (R = 0.30 m, a = 0.24 m, A = 1.25) are described in detail in Ref. [3], but some diagnostic and additional capacitor bank systems for M-CHI are also described briefly here. The capacitor banks (V_{max} = 10 kV, C = 0.6-2.6 mF) are used for ST formation. The two sustainment banks (V_{max} = 900 V, C = 195 mF and 335 mF) have been prepared for the double gun pulsing experiment.

The HIST device has surface poloidal pick-up coils, a current density probe, internal magnetic probing arrays, Ion Doppler Spectrometer (IDS), three-axis Dynamo probes, three-axis Hall probe and a CO_2 laser interferometer. Three-axis magnetic probes are inserted in the plasma from the midplane of the flux conserver (FC). MHD dynamo electric field and ion flow measurements have been conducted by a three-axis dynamo probe. The dynamo probe consists of nine tungsten rods surrounding glass-ceramic and three-axis magnetic pick-up coils. Ion flows and magnetic fields can be simultaneously measured in the three-axis directions. Radial electric field E_r can be computed from the difference in the measured plasma potential $V_p=V_f+cT_e$ (c~3.5), where V_f is floating potential and T_e electron temperature by using one pair of tungsten tips on it. An ion flow velocity v_i is calculated by $v_i = C_s M_i$, where C_s is an ion sound velocity (~30 km/s). An ion Mach number M_i can be obtained from $M_i = M_c \ln(J_{up}/J_{down})$, where M_c is a proportionality constant, and where J_{up} and J_{down} are ion current densities measured by upstream and downstream rod probes, respectively.

3. Recent experimental results

The HIST device can form and sustain the ST (high-q: q>1 and low-q including spheromaks: q<1) by utilizing the variation of the external toroidal field (TF) coil current I_{tf}. The flux amplification rate of the low-q ST is higher than that of the high-q ST. By operating the magnetized coaxial plasma gun (MCPG) with the condition of $\lambda_{gun} > \lambda_{FC}$, here $\lambda_{gun} = \mu_0 I_{gun}/\Psi_{bias}$ and λ_{FC} is the eigenvalue (λ_{FC} = 8.53) of the FC, required during the driven phase, we can inject helicity continuously into the plasma. Figure 1 illustrates temporal evolutions of I_t, $\langle n_e \rangle$, $B_{p.in}$, and $B_{p.out}$ in the comparison of single and double pulsed discharges. The injection gun current is I_{gun} ~30 kA in both operations and the gun bias flux Ψ_{bias} is adjusted properly. By pulsing the MCPG secondly at t ~ 2.5 ms, we have observed that the toroidal current I_t is effectively amplified against the partially resistive decay. In addition, the life time t_{life} has increased up to 8-10 ms which is longer than that in the single CHI case (t_{life} ~ 4 ms). The edge fields, $B_{p.in}$ and $B_{p.out}$ last between t = 0.5 ms and t = 6 ms like a repetitive manner as shown by Fig.1 (c) (d). After t ~ 6 ms, the poloidal fields decay exponentially. Fig.1 (e) shows that the $J_{t.in}$ produced mainly by the injected gun current drops down quickly which means the peaking of the current profile during the decay phase.

To study the dynamo model with two-fluid effect, we start from the generalized Ohm law, $\eta \boldsymbol{j}=\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}-\boldsymbol{j}\times\boldsymbol{B}/en+\nabla p_e/en$, where η is the plasma resistivity, n the electron density and p_e the electron pressure. We decompose each quantity into mean and fluctuating part, and take the ensemble average of the parallel component of it for turbulent equilibrium plasmas to yield the parallel mean-field Ohm's law $\eta \boldsymbol{j}_{\|} = \boldsymbol{E}_{\|} + \langle\delta\boldsymbol{v}\times\delta\boldsymbol{B}\rangle_{\|} - \langle\delta\boldsymbol{j}\times\delta\boldsymbol{B}\rangle_{\|}/en \approx \boldsymbol{E}_{\|} + \langle\delta\boldsymbol{v}_e\times\delta\boldsymbol{B}\rangle_{\|}$, where $\boldsymbol{v}_e$ is electron velocity, δ denotes a fluctuating quantity, $\langle\rangle$ denotes a mean quantity [4]. The right-hand side includes the MHD dynamo $\langle\delta\boldsymbol{v}\times\delta\boldsymbol{B}\rangle_{\|}$ term and the Hall dynamo term $\langle\delta\boldsymbol{j}\times\delta\boldsymbol{B}\rangle_{\|}$. The aim of the present experiment is to identify the CHI dynamo current drive mechanism by measuring directly both the dynamo terms. Figure 2 displays a comparison of the radial profile of poloidal and toroidal flows (a)(b), electron density (c) and radial electric field E_r (d) between before and after the second CHI pulse. The result from the measurements shows that poloidal shear flow exists between the central open flux column (COFC) and the last closed flux surface (R~0.15 m), i.e., at the separatrix. The velocity shear may be caused by the diamagnetic drift of ions because of a steep density gradient there as shown in Fig. 2 (c). This is consistent with that the COFC has a diamagnetic toroidal magnetic field structure. This poloidal flow velocity is increased and the toroidal (parallel) flow is reduced by the second CHI pulse. The measured E_r is produced by the cross field flow and the density gradient through charge separation. The

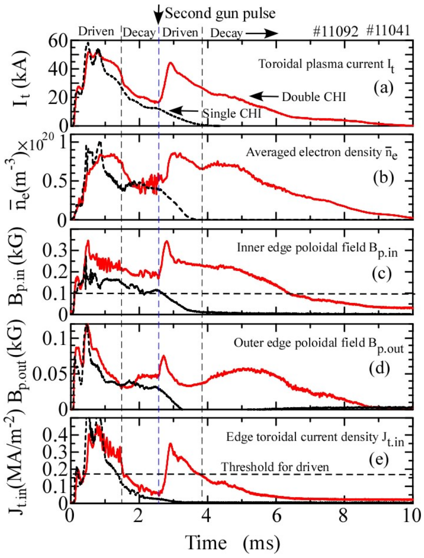

FIG. 1. Time evolution of (a) I_t, (b) $\langle n_e\rangle$, (c) $B_{p.in}$ (R=0.15 m), (d) $B_{p.out}$ (R=0.45 m), (e) $J_{t.in}$ (R=0.1 m) in the comparison of single and double pulsed discharges.

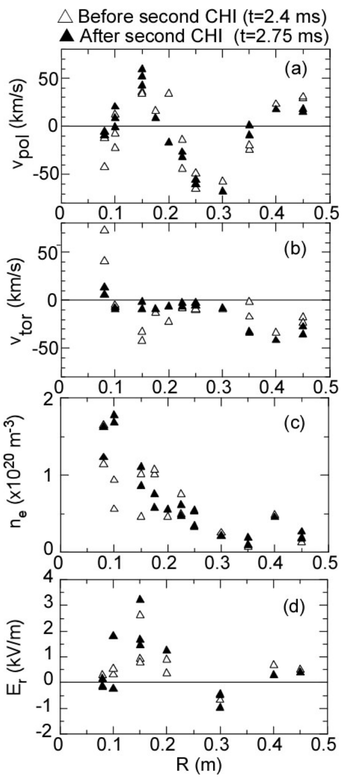

FIG. 2. Radial profiles of (a) v_p, (b) v_t, (c) n_e (I_{sat}), (d) E_r.

reversal of E_r at the separatrix may be caused by the poloidal flow shear.

Figure 3 shows the temporal evolution of the MHD dynamo $<\delta\boldsymbol{v}\times\delta\boldsymbol{B}>_{||}$ measured at each radial position. The result shows that the induced electric field $<\delta\boldsymbol{v}\times\delta\boldsymbol{B}>_{||}$ is large enough to sustain the mean toroidal current against resistive decay in the core region ($E_{||}$=0). We have found that the $<\delta\boldsymbol{v}\times\delta\boldsymbol{B}>_{||}$ term is comparable to the resistive term ηj~2.5 V/m at R=0.25 m. On the other hand, the anti-dynamo effect in the $<\delta\boldsymbol{v}\times\delta\boldsymbol{B}>_{||}$ term has been observed in the COFC region ($E_{||}\neq 0$). This occurs due to the phase difference between the fluctuating velocity and the fluctuating magnetic field. From the viewpoint of two-fluid theory, the ion diamagnetic drift observed in the COFC is opposite to the electron diamagnetic drift, resulting in the anti-dynamo effect in the driven region. The Hall dynamo arises from the fluctuating electron diamagnetic current due to electron pressure gradient which may be large at the separatrix. The CHI process may be explained by electron dynamics like the electron locking model [5].

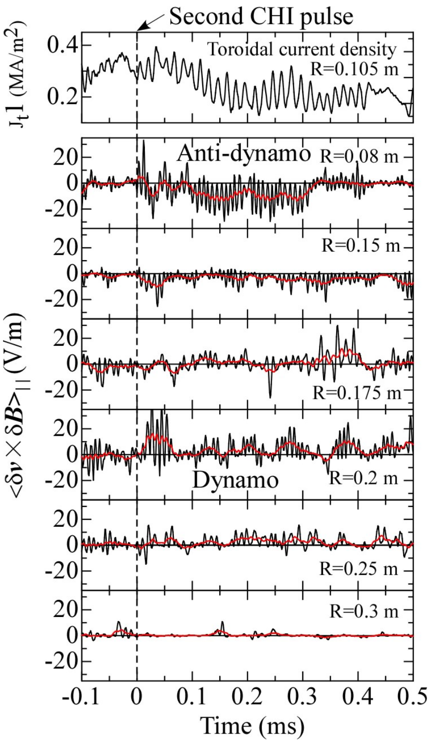

FIG. 3. Time evolution of MHD dynamo activity driven by the second CHI pulse. Anti-dynamo in the COFC and dynamo in the core are observed.

4. Summary

We have measured spatial profiles of the plasma flow and the magnetic field fluctuations in the successful double pulsing CHI discharges. The ion diamagnetic drift due to the density gradient may account for the reversal of the poloidal flow at the separatrix and hence the dynamo effects beyond single-fluid MHD are important for the CHI current drive on STs.

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