Two-fluid dynamo relaxation in the HIST spherical torus plasma

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

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

**Japan Coast Guard Academy, Kure, Hiroshima, Japan*

1. Introduction

Non-inductive start-up and steady-state current drive by using the coaxial helicity injection (CHI) were studied for spheromaks and ST plasmas. The HIST device has been developed towards high-β and quasi-steady-state sustainment of ST plasmas by Multi-pulsing CHI method [1]. In the double-pulsing experiment, we have examined the properties related to the two-fluid effect and dynamo of ST plasmas sustained by CHI. We have observed the strong poloidal flow shear near the separatrix layer in the inboard side. The ion diamagnetic drift and the self-generated $\boldsymbol{E}_r \mathrm{x} \boldsymbol{B}_t$ could account for it. Two-fluid effects become significant when the characteristic spatial scales are on the order of the skin depth d_i and the characteristic time scales are on the order of $1/\omega_{ci}$ [2]. The skin depth d_i~0.14 m (n_e=1x10^{20} m^{-3}) is comparable to the pressure gradient scale in the separatrix layer (L=0.05 m), namely the ratio S* of d_i to L is slightly larger than one. The two-fluid relaxation theory assumes that electron and ion helicity are conserved separately. Ions are not tied to the B in the two-fluid region for $S^*>1$. In the other hand, MHD is valid for $S^*<1$.

Two-fluid model allows a Hall dynamo effect from the correlation of the fluctuating current density and magnetic field in addition to the MHD dynamo effect. It has been for the first time to measure the time evolution of Hall $\langle \delta \boldsymbol{j} \times \delta \boldsymbol{B} \rangle_{||}/en$ and MHD $\langle \delta \boldsymbol{v} \times \delta \boldsymbol{B} \rangle_{||}$ dynamo electric fields during the sustainment. The Hall and MHD dynamo induced electric fields transport injected current from the inboard open flux region to the core region. This means that the current density profile becomes from follow to peaked one. The relative contributions of the two different dynamo electric fields on the current generation have been investigated to verify the parallel mean-field Ohm's law balance. The Hall dynamo acts to generate the mean current density in the both regions, although anti-MHD dynamo is effective in the open flux column region. Contribution from the MHD dynamo effect on current drive becomes more dominant in the core region. In this conference, we report poloidal flow, radial electric field, ion heating and momentum transport during two-fluid relaxation process in the dynamo current drive.

2. Experimental setup

The HIST device (R=0.30 m, a=0.24 m, A=1.25) can form and sustain the ST plasmas and is characterized by utilizing the variation of the external toroidal field (TF) coil current I_{tf}=0~125 kA turns. Figure 1 shows the schematic diagram of the HIST device. The detail explanation of the HIST is represented in the reference [3]. The HIST device has surface poloidal pick-up coils, a current density probe, Ion Doppler Spectrometer (IDS) and a CO_2 laser interferometer. The spatial profiles of the MHD and Hall dynamo electric fields are measured by using Mach probe and Hall probe involving 3-axis magnetic pick-up coils. Ion flows and magnetic fields can be simultaneously measured in the three-axis directions. We have measured the radial profile of the electron temperature and the density by using a new electrostatic probe with voltage sweeping. Radial electric field $\boldsymbol{E}_r$ 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 a double probe. The IDS system has a compact 16 channel photomultiplier tube, optical fibers, and a 1-m-spectrometer (total system resolution: 0.031 nm). In this experiment, an optical fiber covered with a glass tube is inserted into the plasma to measure the radial profiles of the Doppler ion temperature $T_{i.D}$. The viewing chord is on the poloidal cross section.

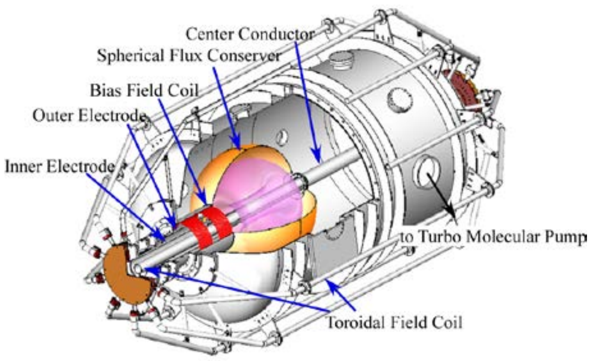

Fig. 1 Schematic diagram of the HIST device.

3. Experimental results

Figure 2 shows the time evolution of the toroidal current I_t. The second CHI pulse has amplified I_t effectively against the resistive decay and extended the life time t_{life} up to 4-8 ms which is longer than that in the single CHI case. The magnetic axis and the separatrix of the initially formed ST configuration is located at R ~ 0.25 m and R ~ 0.15 m, respectively. Figure 3 illustrates changes in the radial profiles of the poloidal flow v_{pol}. This result shows that the reversal of poloidal flow exists at the separatrix. It should be emphasized that the direction of the positive poloidal flow is parallel to that of $\boldsymbol{E}_r \times \boldsymbol{B}_t$ drift where $\boldsymbol{E}_r$ is the radial electric field.

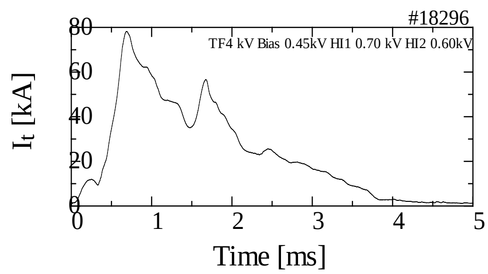

Fig. 2 Time evolution of the toroidal current.

Poloidal shear flow is observed in this region which may be caused by the combined effects of $\boldsymbol{E}_r \times \boldsymbol{B}_t$ drift and the diamagnetic drift of ions.

Figure 4 show changes in the radial profiles of $T_{i.D}$, T_e and the radial electric field E_r during the second CHI pulse. The radial profiles of $T_{i.D}$ peak at R = 0.20 m. The electron temperature T_e is almost uniform in the closed flux region, whereas in the open flux column (OFC) region (0.06 m < R < 0.15 m), T_e is higher. Ion heating occurs mostly in the region between R = 0.15 m and R = 0.20 m, where the direction of the poloidal flow is reversed at R ~ 0.17 m, so the flow shear is largest. In the OFC region, ion heating does not appear because of the strong toroidal magnetic field. The polarity of $\boldsymbol{E}_r$ in the OFC region of R = 0.10–0.15 m is positive, whereas it is negative in the closed flux region. This self-generated radial profile of $\boldsymbol{E}_r$ at t = 1.49 ms may be attributed to non-ambipolarity diffusion toward the plasma core. The positive $\boldsymbol{E}_r$ is oriented to the core region. This is generally called the edge negative $\boldsymbol{E}_r$ that is an important signature of the L-H transition in tokamak plasmas. When the second CHI pulse is applied between the electrodes (the center conductor is biased to be negative), $\boldsymbol{E}_r$ changes the polarity in the region of R = 0.12–0.15 m, and its negative value at R = 0.17 m increases. This significant change in the polarity and amplitude of $\boldsymbol{E}_r$ accelerates the poloidal flow in the opposite direction owing to $\boldsymbol{E}\times\boldsymbol{B}$ drift. The second CHI pulse enhances the poloidal flow there by $\boldsymbol{E}\times\boldsymbol{B}$ drift. Consequently, the acceleration of this perpendicular flow in the region is thought to produce direct heating of ions through viscous flow damping.

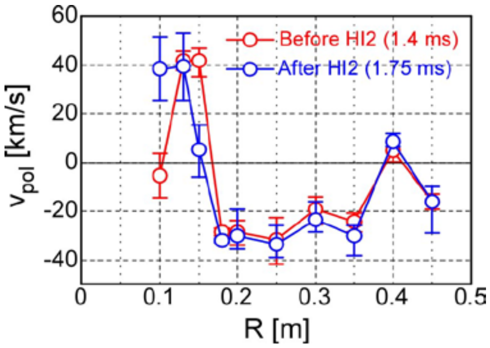

Fig. 3 Radial profile of the poloidal flow before and after the second CHI pulse.

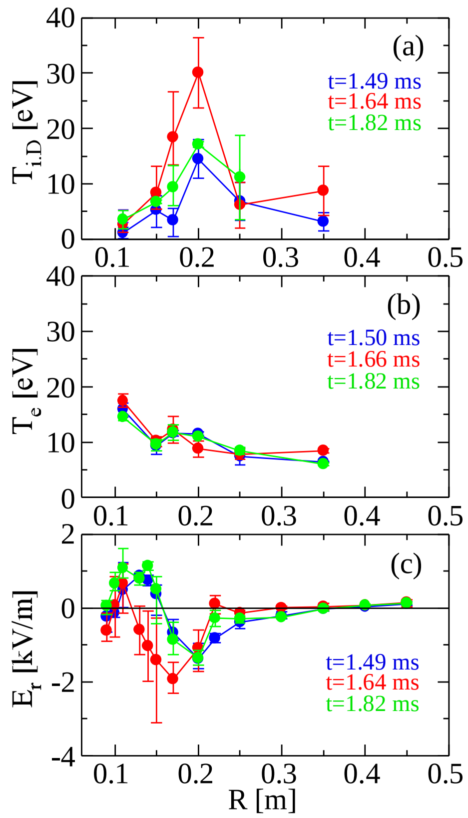

Fig. 4 The radial profiles of (a) $T_{i.D}$ (b) T_e and (c) $\boldsymbol{E}_r$ during the second CHI pulse.

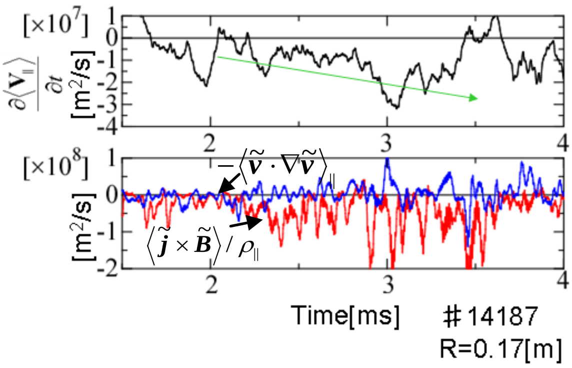

Fig 5. Parallel momentum balance near the separatrix layer

Flux amplification is attributed to dynamo action induced by the electrostatic helicity injection. The recent experimental result demonstrated that the parallel mean-field Ohm's law balance is roughly satisfied both in the OFC driven-region and the core region. We have shown the radial profile of MHD dynamo and Hall dynamo in the partially driven phase [1]. Each dynamo induced-electric field has the largest amplitude near the separatrix during the driven phase although each polarity is opposite.

It is shown that momentum dynamics is closely coupled to the dynamo current drive [4]. The fluctuation-induced Maxwell stress $<\delta\boldsymbol{j}\mathrm{x}\delta\boldsymbol{B}>_{\parallel}$ enters Ohm's law as the Hall dynamo. Both Hall dynamo and Maxwell stress are shown to be large near the separatrix and are responsible for driving plasma current and toroidal flow, respectively. The parallel momentum balance equation (1) can be represented in a fashion similar to the parallel Ohm's law.

$$\rho\frac{\partial \boldsymbol{V}_{\parallel}}{\partial t} = -\rho\left\langle \tilde{\boldsymbol{v}}\cdot\nabla\tilde{\boldsymbol{v}}\right\rangle_{\parallel} + \left\langle \tilde{\boldsymbol{j}}\times\tilde{\boldsymbol{B}}\right\rangle_{\parallel} \qquad (1)$$

Here, the term on the left hand side is the ion inertia and ρ is the mass density. The term on the right hand side (RHS) are the fluctuation-induced Reynolds and Maxwell stresses, respectively. The Reynolds stress can be represented as follows;

$$\rho\left\langle \tilde{\boldsymbol{v}}\cdot\nabla\tilde{\boldsymbol{v}}\right\rangle_{\parallel} \approx \rho\left\langle\left(\frac{1}{r}\tilde{v}_r\tilde{v}_t + \tilde{v}_r\frac{\partial\tilde{v}_t}{\partial r}\right)\right\rangle \qquad (2)$$

We calculate the first term only on the RHS. The radial derivative in the second term on the RHS is neglected. Figure 5 shows the time evolution of all three terms in Eq. (1) which is measured at R=0.17 m. The Maxwell stress is larger than the Reynolds stress at R=0.17 m. This indicates that the Maxwell stress related to the Hall dynamo drives the toroidal flow in the open flux column region.

In conclusion, we have studied the momentum transport based on two-fluid dynamo theory. The momentum dynamics has been shown to be closely coupled to the CHI current drive.

References

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