Magnetic reconnection driven by plasmoid instability in coaxial helicity injection current drive on HIST

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Abstract.

Multiple plasmoid reconnection required for the flux closure in the transient-coaxial helicity injection (T-CHI) start-up process has been demonstrated in the Helicity Injected Spherical Torus (HIST) device. Two or three plasmoids are generated after the tearing instability of an elongated Sweet-Parker current sheet during the T-CHI. Here, we report that in the T-CHI start-up plasmas (H, D and He) with the strong toroidal (guide) field (I_{TF}=140 kA), (i) the frequency of regular oscillations of reconnecting magnetic field decreases as the mass number increases, i.e., 250 kHz (H), 150 kHz (D) and 60 kHz (He). (ii) the oscillation propagates radially with 30 km/s (H), 20 km/s (D) and 12-18 km/s (He) from R= 0.25 m at the X-point toward the outboard side. It has been found that the propagation speed agrees with the Alfven speed. Consequently, the plasmoid reconnection could be related to the excitation of Alfven wave, leading to the ion heating in the T-CHI start-up plasmas.

1. Introduction

The Spherical Tokamak (ST) is a leading candidate for an advanced fusion reactor due to its compact size. If the central solenoid coil could be eliminated, the ST design would be allowed access to lower aspect ratio configurations. The CHI-based non-inductive plasma current drive method is necessary for the viability of the ST concept without the central solenoid coil. Transient CHI (T-CHI) is one of CHI schemes, and it is used to generate and ramp-up the plasma current at the initial phase of a discharge. The T-CHI method has been successfully applied to NSTX for the start-up followed by inductive ramp-up [1]. One of the most important issues in T-CHI is whether it can establish a plasma current sufficient for succeeding current drive and heating. In order to generate the sufficient closed plasma current, the fast magnetic reconnection at the X-point is required in the short CHI start-up time. Understanding the fast reconnection mechanism for the flux closure is the primary purpose of the T-CHI experiment on HIST. It is well known that the Sweet-Parker (S-P) steady-state reconnection model, which is characterized by the long current sheet, cannot account for fast events with the high Lundquist number *S* such as the solar corona and sawtooth crashes in tokamaks. A similar difficulty appears for the T-CHI plasma with the high *S* in the presence of the high toroidal (guide) field in achieving the closed flux formation within a start-up period. As a result from lots of theoretical and computational studies within the resistive MHD mode framework, it has been recognized that the plasmoid instability [2] realizes a reconnection rate larger than the S-P rate as well as mechanism based on Hall effects and electromagnetic turbulence. The recent MHD simulation on T-CHI predicts the formation and breakup of an elongated S-P current sheet and a transition to plasmoid-driven reconnection during T-CHI [3]. According to this simulation, the reconnection rate based on the plasmoid instability is faster than that by the S-P model and becomes nearly independent of the Lundquist number *S*. However, the multiple small-scale plasmoids have not experimentally identified in any fusion devices. In this experiment, we have found two or three plasmoids in the elongated current sheet which is very similar to that demonstrated in the MHD simulation. In this paper, we report the details of plasmoid reconnection observed during the T-CHI by the internal magnetic field measurements.

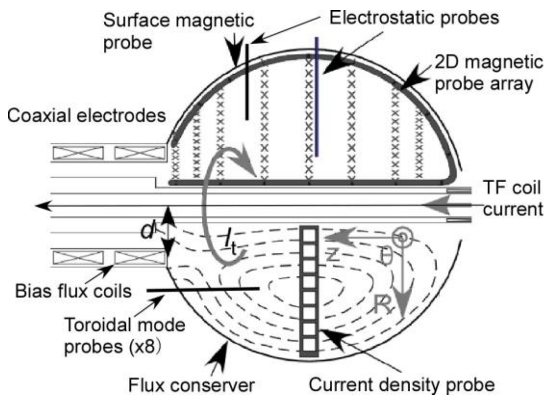

Fig. 1 Schematic diagram of the HIST device and internal diagnostics.

The HIST device (major radius R = 0.3 m, minor radius a = 0.24 m, aspect ratio A = 1.25), shown in Fig. 1, produces the ST plasmas and is characterized by utilizing the variation of the external toroidal field (TF) coil current I_{tf} = 0~219 kA. The TF coil current I_{TF} = 160 kA produces the vacuum toroidal field $B_{t.v}$ = 0.13 T at R = 0.25 m. Details of the HIST are provided in the reference [4].

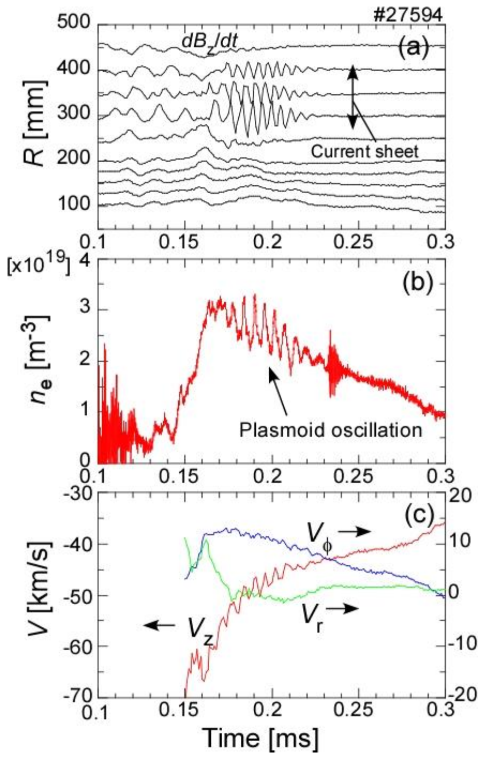

Fig.2 Time evolution of the derivative of axial magnetic field dB_z/dt (a), the electron density n_e (b), the ion flow V_r, V_ϕ, and V_z (c) in an H_2 discharge.

2. Experimental results

2.1 Regular oscillations related to plasmoid reconnection

Figure 2 shows the time evolution of the derivative of poloidal magnetic field dB_z/dt measured at each radial location on the midplane (Z=0 m) in the flux conserver (FC), the electron density n_e, and the ion flows (V_r, V_ϕ, and V_z) measured by Mach probe at R=0.35 m and Z=0 m. The regular fluctuations can be seen in all signals between t=0.178-0.22 ms and between R=0.3-0.4 m. The electron density n_e =2-3x10^{19} m^{-3} is measured at R=0.35 m and Z=0 m. The density fluctuation δn_e~1x10^{19} m^{-3} is well correlated with the B_z fluctuation. These observations obtained in H_2 discharges indicate that a small-size plasmoid is repeatedly generated by the reconnection and moves toward the right side (-Z direction) as the out flow. The velocity of the accelerated plasmoid in an oscillation cycle is δV_z=3-5 km/s that superposed on the background poloidal flow.

Figure 3 shows the frequency of the reconnecting poloidal field measured at R=0.3 m. The frequency depends on the discharge gas (H, D and He) and decreases as the mass number increases, i.e., 250 kHz (H), 150 kHz (D) and 60 kHz (He).

Figure 4 shows the poloidal flux Ψ_p contours of a He discharge in the whole FC region. It can be seen that two or three small-size plasmoids (R with a radial width <0.1 m) are generated during the rise phase of I_t as well as in H_2 discharges. The reconnection speed in the He discharge is relatively slower compared to the H_2 discharge. As the reconnection proceeds, the plasmoid with the closed current in the right side grows up, leading to a double-type configuration.

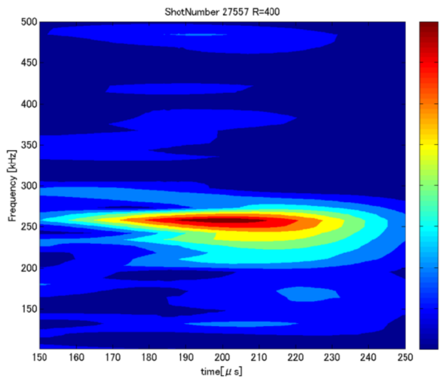

Fig.3 Frequency (~250 kHz) of B_z magnetic oscillations by FFT in an H_2 discharge.

2.2 Propagation of magnetic oscillation

Figure 5 shows the radial position of the magnetic oscillation strengths as a function of time. The magnetic oscillation propagates radially with 30 km/s (H), 20 km/s (D) and 12-18 km/s (He) from R= 0.25 m at the X-point toward the outboard side. The propagation speed has been found to agree with the Alfven speed. The small-size plasmoid does not move out of the current sheet. The magnetic reconnection event based on plasmoid behaviour drives the Alfven wave at the X point. The Alfven wave may cause the ion heating observed in the T-CHI start-up plasmas

3. Summary

The fast reconnection driven by plasmoid for the flux closure has been demonstrated by T-CHI in the HIST device. The intensive measurement of internal magnetic structures indicates that two or three plasmoids are generated as an elongated Sweet-Parker current sheet becomes unstable due to the tearing instability during the T-CHI. The experimental findings are as follows; (1) The observation of the regular oscillations of B_z, n_e and V_z in the current sheet provides a strong evidence of the plasmoid reconnection. (2) In the He discharges, the two discrete closed flux surfaces have been established after the mini-plasmoid develops to the large-size plasmoid by the reconnection with a slower rate as compared to H_2 discharges. (3) The oscillations of B_z propagates radially with Alfven speed, decreasing as the mass number increases.

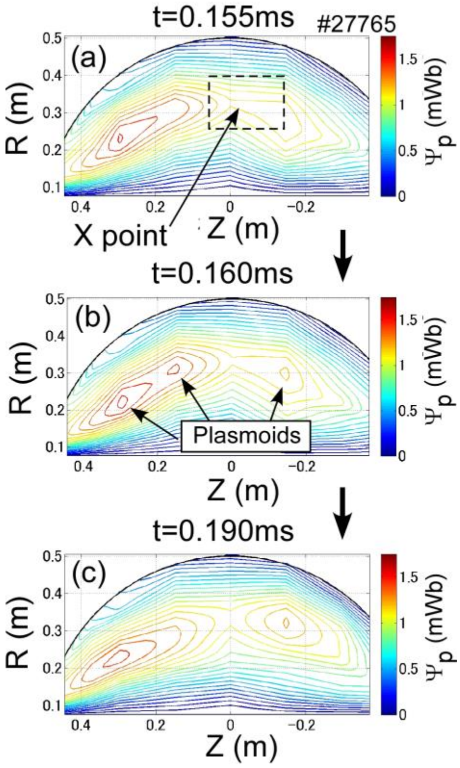

Fig.4 Ψ_p contours in He discharges. Three small-scale plasmoids can be seen at t=0.16 ms (b). Doublet type closed flux surfaces are formed at t=0.19 ms (c).

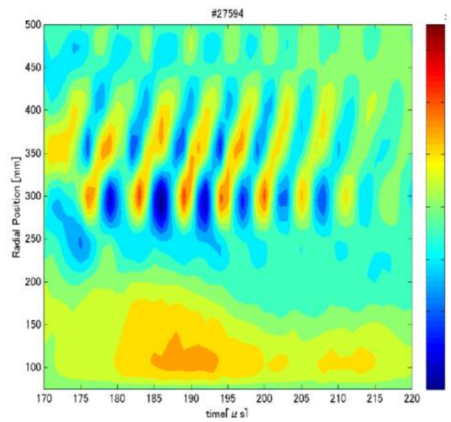

Fig.5 Radial propagation of B_z oscillations in time in an H_2 discharges.

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