Observation of Direct Ion Heating in Double-Pulsing CHI in Helicity Injected Spherical Torus Plasmas

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Anomalous ion heating has been observed for the first time during flux/current amplification by double-pulsing coaxial helicity injection (CHI) in the helicity injected spherical torus (HIST) device. Doppler ion temperature increases significantly near the separatrix on the inboard side during the second CHI pulse, whereas electron temperature remains constant. The experimental results indicate that selective ion heating may be associated with viscous damping of poloidal flows driven by the CHI pulse.

Keywords: coaxial helicity injection, anomalous ion heating, spherical torus, viscous flow damping, current amplification

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Coaxial Helicity Injection (CHI) using a magnetized coaxial plasma gun (MCPG) is a useful method of non-inductive plasma start-up and dynamo current drive for spherical torus (ST) plasmas. The new CHI operation called "Multi-pulsing" proposed as an approach to good time-averaged confinement was successfully demonstrated for the SSPX spheromak device [1]. Multi-pulsing operation of ST devices has been applied for the first time to the HIST device. Double-pulsing CHI operation has successfully increased the sustainment time beyond that obtained with single CHI [2].

The ion temperature T_i is normally observed to be comparable to the electron temperature T_e in Ohmic tokamak plasmas. The externally input energy is predominantly dissipated by the current, leading to electron heating. Ions are then normally heated by frictional drag through collisions with electrons. Anomalous ion heating ($T_i > T_e$) has been observed in several experiments, but its mechanism is not fully understood. For example, such ion heating was observed similarly during a sawtooth crash in the MST-RFP device [3] and during a plasma merging process in the TS-3/TS-4 devices [4]. The anomalous ion heating is thought to be attributed to viscous damping of the flow associated with tearing modes, magnetohydrodynamic relaxations, and magnetic reconnections. In this article, we report the first observation of ion heating during current amplification in double-pulsing CHI experiment in the HIST. The structures, sizes, capabilities, diagnostics, and operating conditions of the HIST are described in detail in Ref. [5]. The Doppler spectroscopy diagnostic for the ion temperature $T_{i.D}$ is described briefly here. The Ion Doppler Spectrometer (IDS) system has a compact 16–channel photomultiplier tube, optical fibers, and a 1-m-spectrometer (total system resolution: 0.031 nm). The technical details, including the spatial resolution of a similar IDS system, are reported in Ref. [6]. 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 optical fiber collects the light emitted from the plasma through a quartz window with a

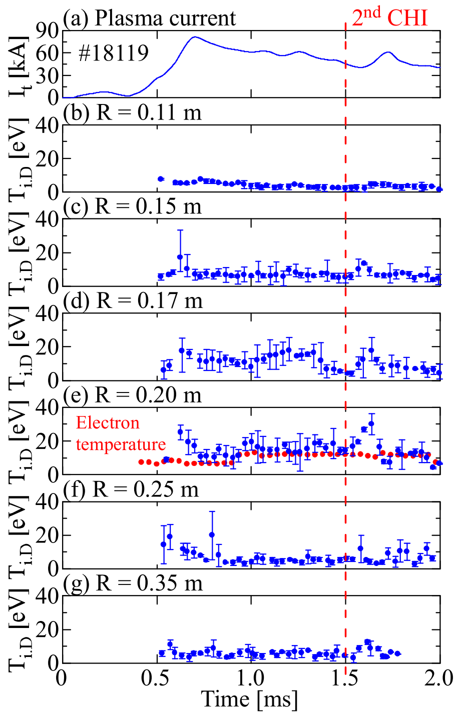

Fig. 1 Time evolution of (a) I_t and (b)–(g) $T_{i.D}$ at each radial position. The electron temperature T_e is plotted at (e) R = 0.20 m. The second CHI pulse is applied at t = 1.5 ms.

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mirror installed at the head of the glass tube. The viewing chord is on the poloidal cross section. The optical fiber is scanned radially at intervals of 0.05 m shot by shot. The IDS measured $T_{i.D}$ using the OII impurity spectral line (441.49 nm). The electron temperature was measured using a double electrostatic probe. A triangular waveform voltage with a sweep frequency of 25 kHz was applied between the double probe electrodes. The radial electric field E_r was measured by radially scanning the double probe on the midplane of the flux conserver.

In this experiment, the second sustainment capacitor bank is triggered at $t = 1.5$ ms during the decay phase of the initial plasma. Figure 1 shows the time evolution of the toroidal current I_t and $T_{i.D}$ at each radius. The second CHI pulse amplified I_t effectively against the resistive decay and extended the life-time t_{life} to ~4 ms, which is longer than that with single CHI. The time period for which the second CHI effectively provides current amplification is about 0.3 ms. The magnetic axis and separatrix of the initially formed ST configuration are located at $R \sim 0.25$ m and $R \sim 0.15$ m, respectively. During the first CHI start-up phase ($t = 0.5$ - 0.7 ms), $T_{i.D}$ at $R = 0.2$ m is higher than T_e, as shown in Fig. 1 (e). After the second CHI pulse, $T_{i.D}$ started to increase rapidly again and reached a peak value of 30 eV at $R = 0.20$ m. The increase in $T_{i.D}$ is correlated with that in I_t, whereas the electron temperature, $T_e \sim 10$ eV, remains unchanged, as shown in Fig. 1 (e). This observation of $T_{i.D} > T_e$ indicates direct ion heating, and this behavior is similar to the characteristics of reconnection events [3, 4]. After current amplification was completed, $T_{i.D}$ cooled to the original level.

Figures 2 (a) and (b) show changes in the radial profiles of $T_{i.D}$ and T_e 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 ($0.06\,\mathrm{m} < R < 0.15\,\mathrm{m}$), 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 $R \sim 0.17$ m, so the flow shear is largest [2]. In the OFC region, ion heating does not appear because of the strong toroidal magnetic field. Figure 2 (c) indicates that during the second CHI pulse, the polarity of 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 E_r at $t = 1.49$ ms may be attributed to non-ambipolarity diffusion toward the plasma core [7]. The positive E_r is oriented to the core region. When the second CHI pulse is applied between the electrodes (the center conductor is biased to be negative), E_r changes the polarity in the region

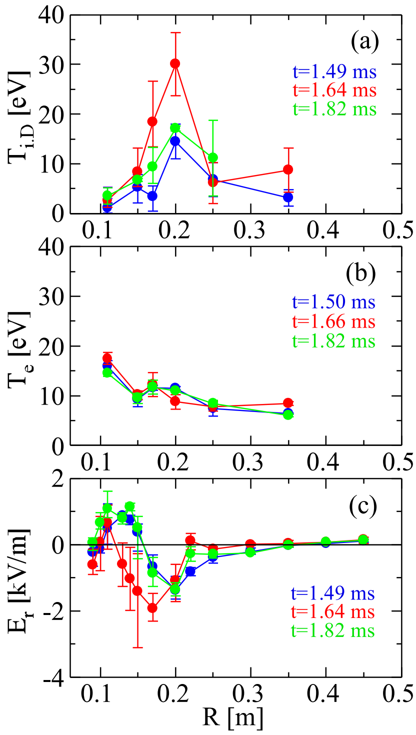

Fig. 2 Radial profiles of (a) $T_{i.D}$, (b) T_e, and (c) E_r during the second CHI pulse.

of $R = 0.12$ - 0.15 m, and its negative value at $R = 0.17$ m increases from -0.8 kV/m to -2 kV/m. This significant change in the polarity and amplitude of E_r accelerates the poloidal flow in the opposite direction owing to $\boldsymbol{E}\times\boldsymbol{B}$ drift. Poloidal shear flow is observed in this region which may be caused by the combined effects of $\boldsymbol{E} \times \boldsymbol{B}$ drift and the diamagnetic drift of ions [2]. 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.

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