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Inboard/outboard asymmetry of poloidal flow observed in the Compact Helical System

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The poloidal flow velocity and the density of fully ionized carbon were measured in the Compact Helical System [K. Ida *et al.*, Phys. Rev. Lett. **67**, 58 (1991)] using the charge exchange spectroscopy with the bidirectional viewing. The poloidal asymmetry of the poloidal flow velocity observed in the outward shifted plasma is due to the electrostatic potential being constant on the magnetic flux surfaces. The poloidal asymmetry of the ion density can be explained by the conservation of the poloidal ion flux under the strong toroidal viscosity. © 2000 American Institute of Physics. [S1070-664X(00)04002-7]

The spectroscopic measurements of plasma rotations are widely used to evaluate radial electric fields in magnetically confined toroidal plasmas. The rotation velocity is connected to the radial electric field and the ion pressure gradient by the radial force balance. In general, radial electric fields, ion pressure gradients, and rotation velocities are not constant on magnetic flux surfaces, since electrostatic potentials and ion pressures are considered to be constant on the magnetic flux surfaces. When the plasmas have toroidal curvatures (toroidal effects), the conservation of the poloidal plasma flux causes the difference of the poloidal rotation velocities between the inboard region of the magnetic axis ($R < R_{ax}$, where R_{ax} is the major radius of the magnetic axis) and the outboard region ($R > R_{ax}$). The standard neoclassical theory^{1,2} predicts an inboard/outboard asymmetric parallel flow (a “Pfirsch–Schlueter-like” toroidal flow) to compensate for the unbalance of the perpendicular fluxes on the inboard and the outboard regions and to make the flow incompressible ($\nabla \cdot \mathbf{v} = 0$) in a steady state. In heliotron/torsatron,^{3–7} however, the strong toroidal viscosity due to helical ripples³ damps this toroidal flow, as well as the net toroidal flows due to the radial electric field, the ion pressure gradient, and the toroidal momentum injection by neutral beams. This damping is strong in the peripheral region where the helical ripple is large. The poloidal rotation of impurity ions is also large in this peripheral region, since it is mainly driven by the radial electric field determined by the ambipolar condition of ripple diffusion fluxes.^{4–6} Therefore, the flow of impurity ions may not be incompressible as assumed in the neoclassical theory.

The difference of poloidal rotation velocities and densities between the inboard and the outboard regions has not been studied in detail in either tokamaks or helical systems. In tokamaks, the poloidal rotation measurements are restricted in the outboard regions^{8–11} because of the difficulty of installing chords viewing vertically the inboard regions where there are only very narrow spaces between toroidal and poloidal coils. In order to study the inboard/outboard

asymmetry of poloidal flow, very precise measurements of Doppler shifts of impurity lines are required. The inboard/outboard asymmetry has never been reported for lack of the accuracy of the absolute Doppler shift values even in $l=2$ heliotron/torsatron devices^{4,7} where there are spaces to install the chords at the inboard regions. The best approach for measuring Doppler shifts is the measurement with the bidirectional viewing (simultaneous views along opposite viewing directions).¹⁰ In this paper, we present the observation of the inboard/outboard asymmetric poloidal flow velocity and the density of fully ionized carbon in the neutral beam injection (NBI) heated plasma in the Compact Helical System (CHS)^{3–5} using charge exchange spectroscopy (CXS)^{12,13} with bidirectional viewing.

CHS is a heliotron/torsatron type helical torus with major and minor radii of $R_0 = 1$ m and $a = 0.2$ m, and poloidal and toroidal period numbers of $l=2$ and $m=8$. The aspect ratio $R_0/a=5$ is the lowest one in existing helical devices. The rotational transform ($\iota/2\pi$) and the helical ripple (ϵ_h) at the plasma edge are ~ 1 and ~ 0.3 , respectively. The magnetic field strength is 0.9–1.8 T. The poloidal rotation velocity, the temperature, and the density of fully ionized carbon on the inboard and outboard regions of the midplane ($Z=0$ plane) are measured with charge exchange spectroscopy using a tangentially injected heating neutral beam ($E_b < 40$ keV, $P_{NBI} < 1$ MW). Two fiber arrays (30 channel/array) viewing the beam line upward and downward simultaneously are installed at one vertically elongated cross section. The average of the wavelength measured from both sides gives the true wavelength of the spectral line without Doppler shifts. The background radiation¹² is measured at another vertically elongated cross section where there is no beam passing. The difference between the background intensities in these two sections, which is checked in NBI plasmas sustained by another neutral beam (not the neutral beam used for the CXS) and electron cyclotron heated plasmas without NBI, is negligibly small compared with the intensity of the charge exchange excited radiation. All of these fibers (90 channel) are connected to the entrance slit of one spectrometer and the diffraction image is detected with a two-

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dimensional charge coupled device (CCD) detector coupled with an image intensifier. The radial profile of the toroidal rotation velocity on the midplane at the vertical elongated cross section is also measured with another CXS system (16 toroidal channels for the charge exchange emission, 16 toroidal channels for the background emission, and another 4 poloidal channels with bidirectional viewing as the reference of wavelength). There are several problems that cause apparent wavelength shifts, which make it difficult to measure the plasma rotation velocities of a few km/s using spectral lines in visible range; (1) the mechanical wavelength offset of the spectrometers ($\Delta\lambda \sim 0.5 \text{ \AA}$), (2) the distortion of the diffraction image of spectrometers ($\Delta\lambda \sim 0.1 \text{ \AA}$), (3) the horizontal displacement of the fibers at the entrance slits ($\Delta\lambda \sim 0.01 \text{ \AA}$), and (4) the spectral fine structure of hydrogen-like ions.¹³ The mechanical wavelength offset in our measurement system is completely canceled by the bidirectional viewing as mentioned previously. The apparent wavelength shifts due to the distortion of the diffraction image and the horizontal fiber displacement were calibrated with a mercury lamp. The wavelength shifts are calculated by the nonlinear least-squares fitting of the superposition of Doppler broadened fine structural line components, since the red-side/blue-side asymmetric splitting of the spectral line of hydrogen-like carbon ions is not negligible compared with the Doppler broadening and the Doppler shift in the CHS plasmas.¹⁴ The electron temperature and density profiles are measured with a 24 channel yttrium aluminum garnet laser Thomson scattering system and a hydrogen cyanide laser interferometer.

The experiment was done on the plasmas with an outward shifted configuration with the vacuum magnetic axis of $R_{ax} = 99.5 \text{ cm}$ in which the parallel viscosity is relatively strong.³ Figure 1 shows the cross sections of magnetic flux surfaces and the Doppler shifts of the charge exchange excited CVI line ($\Delta n = 8-7$, $\lambda = 5290 \text{ \AA}$) at the vertically elongated section. The line averaged electron density, the central electron temperature, and the central ion temperature in this discharge are $n_e = 1.7 \times 10^{13} \text{ cm}^{-3}$, $T_e(0) = 200 \text{ eV}$, and $T_i(0) = 140 \text{ eV}$, respectively. The working gas is hydrogen. Since the charge exchange excitation by the second energy (20 keV) and the third energy (13 keV) components of the beam is negligibly small, the density profile of fully ionized carbon [$n_i(R)$] was given by dividing the intensity of the charge exchange excited CVI line at the poloidal array by the density of the full energy component (40 keV) of the beam. In the vertical direction, the beam radius at the vertical elongated cross section (half-wide at half-maximum $\sim 6 \text{ cm}$) was neglected compared with the plasma size. The major radial profile of the density of this "sheet" beam in the plasma was calculated using the measured density and temperature of electron assuming the multistep ionization of beam atoms through excited states¹⁵ due to ion impact processes (charge exchange, ionization, and excitation) and electron impact processes (ionization and excitation). The initial beam density profile without the attenuation was measured with the intensity of H_α line from the beam in vacuum. The dependence of the attenuation on the concentration and charge (Z_i) of impurity ions is negligibly small. This is because the impact cross sections of ion impact processes depend on Z_i as

FIG. 1. (a) The cross sections of magnetic surfaces. (b) The Doppler shifts of charge exchange excited CVI line ($\Delta n = 8-7$, $\lambda = 5290 \text{ \AA}$) at the vertically elongated section in the outward shifted configuration with the vacuum magnetic axis of $R_{ax} = 99.5 \text{ cm}$.

proportional to Z_i in the beam energy range of $E_b < 10Z_i$ (keV/amu). The beam attenuation is less than 50% even at the inboard edge of the vertically elongated cross section and the calculated beam density varies only $\pm 4\%$ for the range of $2 < Z_{eff} < 6$ when the dominant impurity is C^{6+} as observed in NBI heated plasmas.^{16,17} Figure 2(a) shows the obtained density profile of fully ionized carbon. The normalized averaged minor radius ρ is determined from the magnetic flux surface calculated with the three-dimensional equilibrium code VMEC (Variational Moment Equilibrium Code)¹⁸ giving the best fit to the measured ion temperature profile. This is because the plasmas may have large Shafranov shifts due to the beam parallel pressure.¹⁹ The region $\rho < 0$ denotes the inboard region and $\rho > 0$ denotes the outboard region. The background radiation, which is partially caused by the charge exchange with thermal neutrals, measured at the background viewing array is subtracted from the radiation observed at the beam charge exchange array. Therefore the thermal neutrals, which may have a poloidally nonuniform density, do not affect the measured impurity density profile. The poloidal nonuniformity of the impurity source also is not the possible cause of the inboard/outboard asymmetry of fully ionized carbon density, since the ioniza-

FIG. 2. The radial profiles of (a) the density of fully ionized carbon, (b) toroidal rotation velocity in the cases with the clockwise toroidal magnetic field and the counterclockwise toroidal magnetic field, and (c) radial electric field. The solid line in (b) is the fitting function for the electric field calculation. The dashed lines in (b) are the “Pfirsch-Schluter like” flow velocity $V_{PS} \sim (4\pi/\epsilon)V_p$ calculated using the poloidal rotation velocity in Fig. 1.

tion mean free path required for the complete ionization of carbon is longer (~ 100 m) than the plasma size. The observed density profile is slightly hollow. It is noted that the bulk plasma electron density is also slightly hollow in the outward shifted configurations of CHS.²⁰ Figure 2(b) shows the measured toroidal rotation velocity and the Pfirsch-Schluter-like toroidal flow velocity $V_{PS} \sim (4\pi/\epsilon)V_p$. It is noted that the poloidal rotation V_p is reversed when the direction of the helical magnetic field is reversed from clockwise (CW) to counterclockwise (CCW). The spatial resolution of the toroidal rotation measurement is not as good as that of the poloidal rotation measurement due to the chord integration across the tangentially injected beam. The toroidal rotation velocity profiles are almost independent from the direction of magnetic field. It indicates that the toroidal rotation in CHS is determined by the balance of the toroidal

FIG. 3. (a) The electrostatic potential obtained by integrating the radial electric field. (b) The poloidal flux on the midplane integrated in the inside of magnetic surfaces per unit toroidal angle $\int V_p n_i R dR$. The solid lines are the inboard/outboard symmetric functions (the polynomials of $|\rho|$) fitted to the datum.

momentum input of the neutral beam and the toroidal viscosity due to helical ripples,³ not by the “Pfirsch-Schluter-like” and/or the “bootstrap like” toroidal flows.

The radial electric field E_R on the midplane can be calculated from the measured poloidal and toroidal rotation velocities and the ion pressure with the radial force balance equation as

$$E_R = V_p(R)B_t(R) - V_t(R)B_p(R) + \frac{dp_i(R)/dR}{eZ_i n_i(R)}. \quad (1)$$

Figure 2(c) shows the radial profiles of these terms. The dominant term contributing to E_R is the poloidal rotation term. The pressure gradient term is smaller by factor $1/Z_i$ ($Z_i = 6$) compared with that of the bulk ions. The contribution of the toroidal rotation to E_R is also smaller than that of poloidal rotation because of the toroidal rotation damping. Figure 3(a) shows the electrostatic potential obtained by integrating the calculated radial electric field. The potential as the function of the averaged minor radius ρ has an inboard/outboard symmetry which indicates that the electrostatic potential is almost constant on the magnetic flux surface. The poloidal ion flux on the midplane integrated in the insides of magnetic flux surfaces per unit toroidal angle is given by $\int_{axis}^R V_p n_i R dR$. The inboard/outboard symmetry of the integrated poloidal ion flux shown in Fig. 3(b) indicates the toroidally local poloidal ion flux conservation on both regions.

When the electrostatic potential and the ion pressure are constant on the magnetic flux surfaces, the inboard/outboard asymmetry of poloidal rotation velocity under the

toroidal rotation damping is given as $V_p(\text{in})/V_p(\text{out}) = \Delta R(\text{out})/\Delta R(\text{in}) \cdot B_t(\text{out})/B_t(\text{in})$, where ΔR is the distance between adjacent surfaces. By combining the poloidal ion flux conservation condition at a given toroidal angle $n_i(\text{in})V_p(\text{in})R(\text{in})\Delta R(\text{in}) = n_i(\text{out})V_p(\text{out})R(\text{out})\Delta R(\text{out})$, the impurity density should have inboard/outboard asymmetry as $n_i(\text{in})/n_i(\text{out}) = (V_p(\text{out})R(\text{out})\Delta R(\text{out})/V_p(\text{in})R(\text{in})\Delta R(\text{in}) = B_t(\text{in})/B_t(\text{out}) \cdot R(\text{out})/R(\text{in})$. For example, $B_t(\text{in})/B_t(\text{out}) \cdot R(\text{out})/R(\text{in}) = 1.3$ at $\rho = 0.6$, which is consistent with the measured inboard/outboard asymmetry of the density shown in Fig. 2(a) within the uncertainty ($<10\%$). The toroidal rotation measurement result shown in Fig. 2(b) indicates the reduction of the “Pfirsch-Schluter-like” toroidal flow, which is the consequence of the $\nabla \cdot \mathbf{v} = 0$ condition assumed in the neoclassical theory. However, the ion flux must satisfy the divergence free condition ($\nabla \cdot (n_i \mathbf{v}) = 0$), which results in the nonuniform density on the magnetic flux surface.

In conclusion, the inboard/outboard asymmetric poloidal rotation velocity of fully ionized carbon is observed in CHS where the neoclassically predicted “Pfirsch-Schluter-like” toroidal flow velocity is damped. The measured density profile of the impurity ion also has an inboard/outboard asymmetry. These asymmetries can be explained by the electrostatic potential being constant on the magnetic flux surfaces and the toroidally localized conservation of poloidal ion flux under the toroidal rotation damping. The poloidally nonuniform density is not predicted by the neoclassical theory for axisymmetric tori having no toroidal viscosity. However, it can be expected even in tokamaks for the plasmas with the anomalous toroidal rotation damping as observed in so-called locked mode²¹ or the high confinement-mode (H-mode) plasmas with the supersonic flows.^{22–25}

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