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Poloidal rotation of main ions in the CT-6B tokamak*

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The poloidal rotation velocity of neutral hydrogen atoms is measured using the Doppler shift of the $H\alpha$ spectral line emitted in the CT-6B tokamak. The poloidal rotation of hydrogen atoms is generated through the collisions and charge-exchanges with main ions (protons). Therefore, the rotation direction of main ions can be deduced from that of neutral hydrogen atoms. The experimental results show that the main ions rotate in the electron diamagnetic drift direction, the same as the impurity ions, in the plasma core. The neutral hydrogen atoms rotate also in the electron diamagnetic drift direction in the edge region of the plasma. However, the rotation direction of main ions in the edge region cannot be judged from the experimental result due to the long mean free path of hydrogen atoms in the edge region. An inward diffusion flux of hydrogen atoms toward the torus inside with a velocity of the same order of magnitude as their poloidal rotation is also observed.

Keywords: poloidal rotation, main ions, Doppler shift
PACC: 5220, 5225

1. Introduction

The neoclassical theory of particle transport in tokamaks has predicted that the poloidal rotation velocity of impurity ions would be quite different from that of main ions.[1,2] In the H-mode operation of DIII-D device, the poloidal rotation of main ions in edge region was measured in a helium plasma, and was found to be in the ion diamagnetic direction, opposite to that of impurity ions.[3]

In the CT-6B tokamak, the Doppler shift of impurity spectral lines has been measured with optical diagnostics and was used to compute the poloidal rotation velocity of plasma.[4,5] The results showed that the rotation velocity was in the electron diamagnetic drift direction in the plasma core, and was in the ion diamagnetic drift direction in the edge region.

2. Experiment set-up

In the CT-6B, as a small device with a lower plasma temperature, atoms can penetrate into the plasma core. In order to measure the poloidal rotation velocity distribution of neutrals in the whole plasma region, the measurement system has been improved, including a newly designed fine-adjusted light reflection system. A hydrogen lamp was used as frequency standard of $H\alpha$ line in the experiment to determine the movement velocity of hydrogen atoms from the frequency shift of the spectral line. The frequency standard is necessary since the movement of hydrogen atoms is no longer symmetric to the magnetic axis due to absence of magnetic confinement for neutrals, then the zero point of velocity cannot be determined from the symmetry.

The profile of $H\alpha$ spectral line was obtained using a double grating monochromator with a high spectral resolution. The output light signals from the monochromator were detected with a MCP intensifier-photodiode array. The Doppler shifts of the line for different radii were measured shot by shot. Then the poloidal rotation velocity of neutrals in the plasma as a function of radius was deduced. The experiment set-up is shown in Fig.1, where mirror $M1$ can rotate on an axis perpendicular to the paper, and then scan the whole plasma cross section. The clock and trigger voltage pulse provide a synchronous signal for the photodiode and data acquisition system, and guarantee the synchronization of the discharge and measurement.

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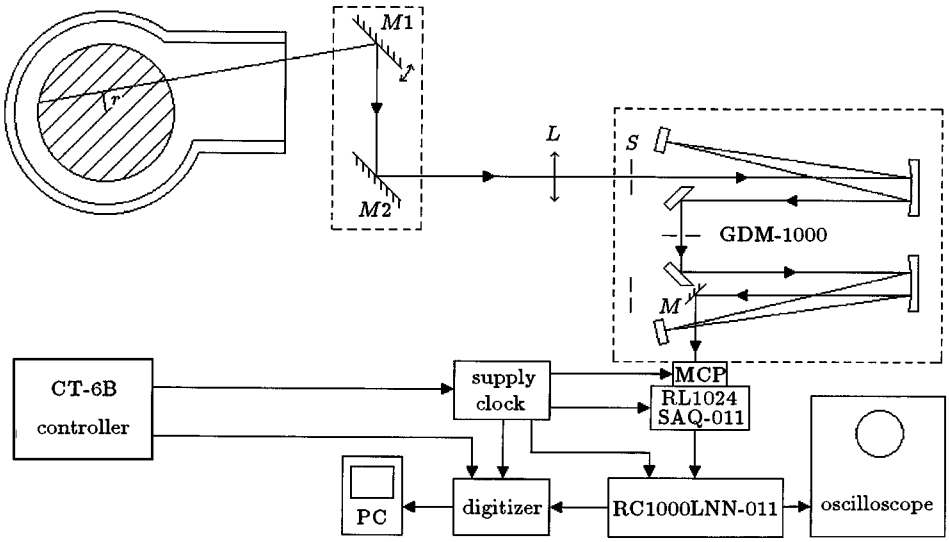


Fig.1. Experimental arrangement. $M1$: rotatable mirror, $M2$: mirror, L: lens, S: entrance slit, GDM-1000: monochromator, M: mirror, MCP: intensifier, RL1024/SAQ-011: photodiode array, RC1000LNN-011, its master board.

The experimental conditions are as follows. The major radius of CT-6B tokamak is R=45 cm, the minor radius of the plasma is a=12.5 cm, toroidal magnetic field B_t=0.68 T, plasma current I_p=13 kA, length of current plateau Δt=30–40 ms, line-averaged electron density is n_e=(0.9–1.6)$\times 10^{13}$/cm^3, gas pressure $p = 8 \times 10^{-3}$ Pa, and the pulsed gas is puffed in some cases. Two sets of typical discharge waveforms are shown in Fig.2. They are (from up to bottom) plasma current, loop voltage, plasma horizontal displacement, intensity of $H\alpha$ line, and line-averaged electron density.

The experiment is carried out in two discharge regimes. For low-density discharges, the working pressure is 8×10^{-3} Pa, the electron density is about 9×10^{13}/cm^3 as shown in Fig.2(b). For high-density discharges, the equilibrium gas pressure is the same, but with pulsed gas puffing, then the electron density doubles, as shown in Fig.2(a).

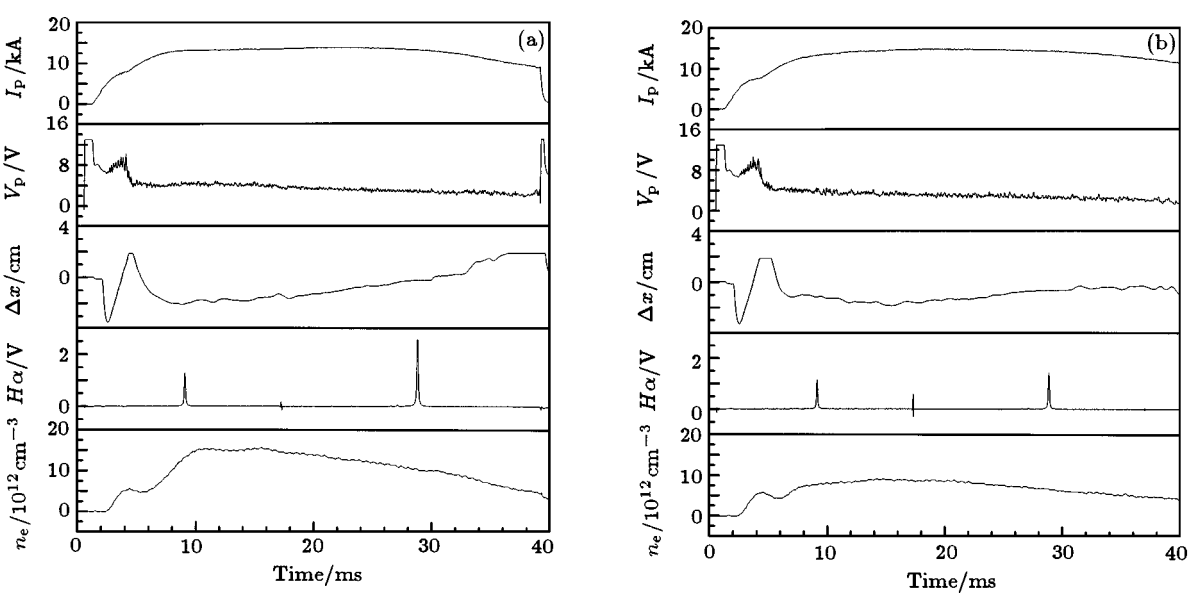


Fig.2. Discharge waveforms for high-density discharges(a) and low-density discharges(b) (from top to bottom): plasma current, loop voltage, horizontal displacement of plasma column, intensity of $H\alpha$ spectral line, line-averaged electron density.

3. Results and Analysis

The curves in the upper parts of Fig.3 show the wavelength shifts as functions of radius of measurement chord for high (Fig.3(a)) and low (Fig.3(b)) density discharges. It can be seen that the measured wavelength is always longer than the standard wavelength in both cases. In other words, the particles move away from the observer. The result indicates that the gas has a global movement toward the inside of the torus as the gas input valve (for steady gas filling and pulsed gas puffing) is located on the outside of the vacuum chamber. Another possible reason for this would be that more gas enters the plasma from outside parts of the limiter and chamber as the plasma-wall interactions and particle recycling is much stronger on the torus outside.

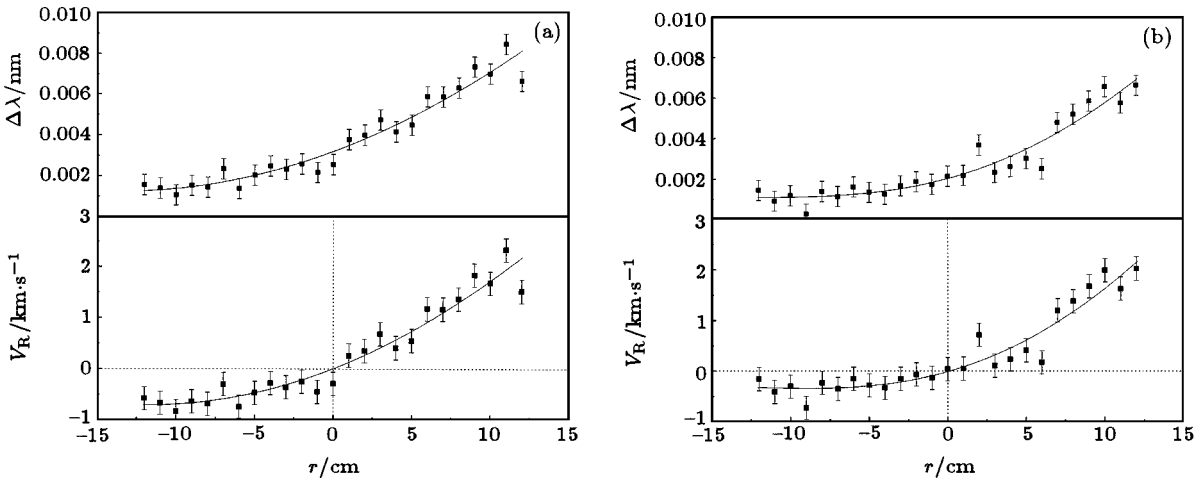


Fig.3. Wavelength shift(upper curve) and corresponding movement velocity(lower curve) for different viewing chords as functions of chord radius for high-density discharges(a) and low-density discharges(b). Positive values of radius represent up and torus inside, and negative values represent down and torus outside.

Another characteristic of the curves in Fig.3 is that the wavelength shift or inward velocity of atoms is asymmetric for negative(low-outside) and positive(up and inside) values of radius of chords. The reason is that the hydrogen gas undergoes poloidal rotation besides the inward movement. The measured results shown in Fig.3 present the resultant movement.

We will further process the measured data under certain simplifying assumptions. Firstly, we suppose that the integrated value of wavelength shift along an observed chord is the wavelength shift at the centre of the chord, and then avoid complex Abel transform. The assumption contains two points: the light emission is symmetric to the centre and its main part is emitted from the central region of the chord. Strictly speaking, these points are invalid. However, it is believed from experience that the results from the simplifying model is usually very close to the strict solution, especially in the outside region of the plasma minor cross section.

Secondly, the movement of neutral hydrogen is resolved into a movement in major radius direction and a poloidal rotation. The velocity of inward movement along the $-R$ direction is assumed to be constant in the whole plasma column, and the rotation velocity is a function of the minor radius. The former is also approximate, as shown later.

With the assumptions stated above, the movement velocity of atoms along the observed direction at any minor radius can be expressed as $V = V_R + V_D \cos\theta$, where V_R is the velocity of poloidal rotation, V_D is the movement velocity along the $-R$ direction, and θ is the angle between V_D and the observed direction. Since $V_R(0) = 0$, the value of V_D can be obtained from the solution of $V(0) = V_D \cos\theta(0)$. Its values from the experimental data are 1.4 and 0.88 km/s for high- and low-density operations respectively. The result reveals that gas puffing plays an important role in generating the direct movement of hydrogen gas. Other data (not shown here) also indicate that as the gas flux puffed increases, the direct velocity also increases.

The curves in the lower parts of Fig.3 show the velocities of poloidal rotation as functions of the minor radius for high (Fig.3(a)) and low (Fig.3(b)) density operations after removing the direct movement, respectively. The positive value in the figure shows the velocity along the observed direction. The

results indicate that the poloidal rotation of atoms is in the electron diamagnetic direction, much the same as the results previously obtained from impurity spectral lines. The maximum value of the velocity is 2–3 km/s, the same order of magnitude as that of the impurities.

The neutrals in a tokamak plasma consist of two species: the slow atoms coming from outside the plasma and the fast atoms generated through charge-exchange with hot ions. The main component of the movement velocity for slow atoms is the inward direct velocity. Their rotation component is generated from the collisions with main ions. The major contribution to the poloidal rotation of hydrogen atoms comes from fast atoms. Their rotation velocity should be higher than the measured values if the contribution from slow atoms is taken into account. Therefore, the poloidal velocity of main ions should be higher than the measured value of hydrogen atoms.

Another obvious characteristic of the velocity curves in Fig.3 is their asymmetry: the absolute value of the velocity is higher on upper-inside than that on lower-outside. This violates the assumption of constant rotation velocity for a certain radius. This is because the assumption of constant direct inward velocity in the whole plasma column is invalid. When the slow hydrogen atoms enter the plasma from outside, their energy gradually loses through collisions with ions as they penetrate into the plasma. Therefore, the inward direct velocity of hydrogen atoms should be higher on the torus outside than that on the torus inside.

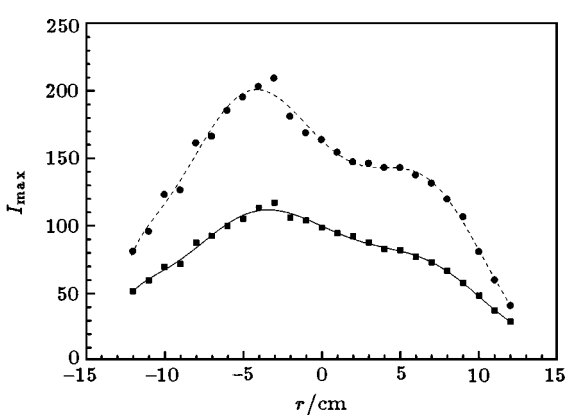


Fig.4. Intensity of $H\alpha$ spectral line for different viewing chords as functions of chord radius for high-density discharges(broken line) and low-density discharges (solid lines).

Fig. 4 shows the intensity of emitted $H\alpha$ spectral line as a function of the minor radius. It can be seen that the light intensity on torus outside is obviously higher than that on torus inside. Also the gas puffing (shown in broken curve) makes the light emission much stronger. Therefore, the above explanation is reasonable.

4. Conclusions

Though more accurate model is necessary, the obtained results have led to some useful conclusions. The main result is that the poloidal rotation of main ions in the plasma core is in the electron diamagnetic drift direction, much the same as that of impurities. The rotation of neutrals in the edge region is also in the same direction, opposite to that of impurities. Does the measured result show that the rotation of main ions is also in the electron diamagnetic drift direction? It seems not. As mentioned above, the fast atoms generated through charge-exchange are mainly responsible for the rotation movement of neutrals. Such fast atoms usually come from the hot plasma core, and thus have a longer mean free path. Their velocity would differ greatly from the local velocity of main ions in the edge region. Therefore, the rotation direction of main ions cannot be judged from the measured data.

The plasma parameters in the core region of the CT-6B are close to those in the edge region of DIII-D device. In H-mode operation of DIII-D, the poloidal rotation of main ions is in opposite direction to that of impurities. The results obtained in L-mode operation of CT-6B that main ions and impurity ions have the same poloidal direction do not violate the neoclassical transport theory.

In the above discussion, we assume up-down symmetry of the plasma parameters and absolute value of movement velocity of neutrals. In fact, due to the torus inside-outside asymmetry (gas puffing and plasma-wall interactions) and poloidal rotation movement of neutrals, the up-down asymmetry of neutral distribution is possible. As a source of up-down asymmetry of the plasma column in tokamaks, its effects on plasma stability and transport need be studied further.

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