Direct Measurement of Ion Temperature and Poloidal Rotation Velocity with Doppler Spectroscopy during Bifurcation in Tohoku University Heliac*)

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Electrode biasing experiments were carried out in the Tohoku University Heliac (TU-Heliac) to investigate the role of ion viscosity maxima in the L-H transition. To investigate the relation between ion viscosity and poloidal Mach number, the driving force of the poloidal rotation and poloidal rotation velocity must be normalized by the ion temperature T_i and ion pressure P_i. Doppler spectroscopy was used to directly measure the ion temperature and the poloidal rotation velocity. Therefore, the dependence of the ion temperature and poloidal rotation velocity on the electrode current was obtained. The relation between the normalized driving force of the poloidal rotation and the poloidal Mach number M_p was non-linear. Bifurcation phenomena in the poloidal rotation appeared at $M_\mathrm{p} \sim -3$. These results qualitatively agreed with the neoclassical theory.

Keywords: plasma, heliac, electrode biasing, poloidal rotation, ion viscosity, L-H transition, bifurcation

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1. Introduction

The transition from the low confinement mode (L-mode) to the high confinement mode (H-mode) was observed for the first time in ASDEX when the NBI heating power exceeded the critical value [1]. The H-mode was also observed in various tokamak and stellarator devices, such as DIII-D [2], CHS [3], etc. When the L-H transition occurs, the poloidal rotational shear flow suppresses the anomalous transport driven by turbulence [4]. According to neoclassical theories, the ion viscosity has local maxima with respect to the poloidal rotation velocity [5, 6]. One of the L-H transition mechanisms can be explained by the bifurcation phenomena owing to local maxima in ion viscosity. The transition mechanism mentioned above is outlined in Fig. 1. The torque of poloidal rotation, which is normalized by the ion pressure, exceeds the maximum value of the ion viscosity (point A in Fig. 1), the poloidal rotation velocity increases drastically (point B in Fig. 1), and thus the L-H transition is achieved.

To investigate the role of ion viscosity maxima in the L-H transition, a biasing experiment using an electron injection electrode has been carried out in TU-Heliac [7]. In this experiment, the radial current $\boldsymbol{J}$ is generated by the electrode inserted in the plasma. The driving force of poloidal rotation is $\boldsymbol{J}\times\boldsymbol{B}$, where $\boldsymbol{B}$ is the confinement magnetic field. Therefore, the biasing experiment can control the driving force externally by controlling the radial current $\boldsymbol{J}$. In previous studies, the L-H transition was observed using the electrode biasing and the results were

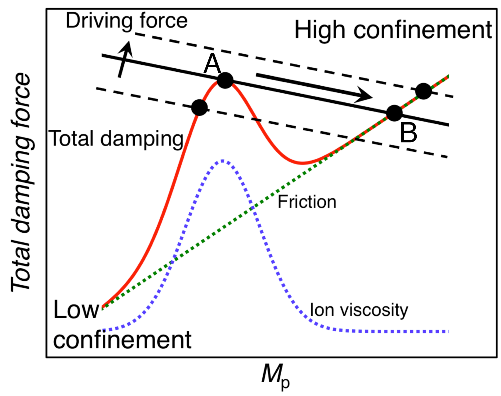

Fig. 1 Outline of the bifurcation owing to local maxima. The total damping force consists of the ion viscosity and friction. When the driving force of the poloidal rotation exceeds the peak of the damping force (point A), bifurcation will occur.

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compared with the viscosity model in TU-Heliac [8]. To evaluate the normalized driving force (discussed in section 4) and the poloidal Mach number M_p, and to compare the experimental results with theory, the ion temperature and poloidal rotation velocity are essential. However, in previous experiments, the ion temperature T_i was estimated from the electron temperature T_e assuming $T_\mathrm{i} \sim 0.2T_\mathrm{e}$. Moreover, the poloidal rotation velocity was calculated from the plasma space potential measured with a triple probe.

Therefore, we used Doppler spectroscopy in TU-Heliac and tried to measure directly the ion temperature and the poloidal rotation velocity for investigating the relation between the poloidal Mach number M_p and the external driving force in the biased plasma.

2. Experimental Setup

The TU-Heliac is a small $n = 4$ heliac device with a major radius $R_0 = 0.48$ m, a minor radius $a = 0.06$ m, and a toroidal magnetic field $B_0 = 0.3$ T. The confinement magnetic field is produced by three sets of coils. Various magnetic configurations can be widely selected by changing the ratio of coil currents.

The target plasma was produced by an alternate ohmic heating at 18.8 kHz. Helium was used as the working gas. The layout of the diagnostic tools is shown in Fig. 2. The electron temperature T_e, the electron density n_e, the floating potential V_f and the plasma space potential V_s were measured using a Langmuir probe (triple probe) at toroidal angle $\phi = 0°$. The ion temperature and poloidal rotation velocity were measured by using Doppler spectroscopy with a Czerny-Turner spectrometer at $\phi = 339°$ with a 1 m focusing length. The biasing electrode made of lanthanum hexaboride LaB_6 which induces the radial current is inserted horizontally at $\phi = 270°$ and set at $R = 86$ mm ($\rho \sim 0.6$). The electrode is of the electron emission type and negatively biased; therefore it induces the radial electric field directed to the magnetic axis. The radial plasma current (electrode current) flows from the periphery toward the magnetic axis. We used a constant current power supply for the biasing and we controlled the radial plasma current externally. The biasing system of TU-Heliac is shown in Fig. 3.

The Doppler spectroscopy system is shown in Fig. 4. Using a micrometer, we can change the vertical angle of the collecting lens holder and the focal point along the Z-direction. The performance of the spectrometer varies with changes in room temperature. To measure the ion temperature and poloidal rotation velocity with high accuracy, the spectrometer was set in a temperature-controlled room. During the experiment, the room temperature was kept within ±0.25°C. The He I line (471.3 nm) was used for correcting the pseudo-Doppler shift caused by the changes in room temperature. Furthermore, we adopted a new system to calibrate the spectrometer. A neon lamp was used to determine the resolution and the reciprocal linear dispersion, and the calibration process was done before and

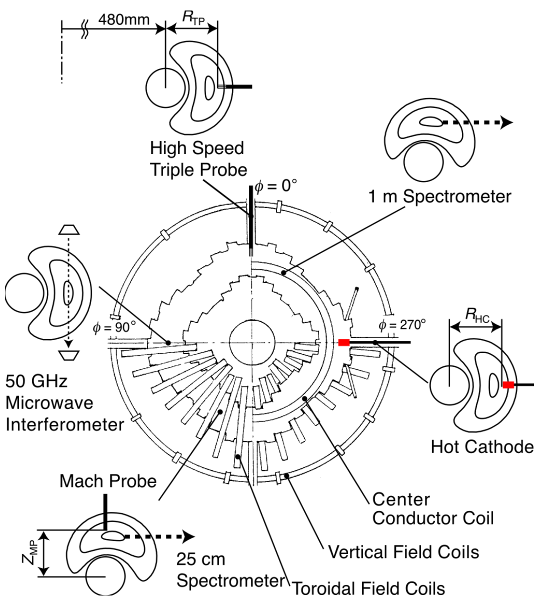

Fig. 2 Diagnostic tools in TU-Heliac. Plasma parameters are measured with the triple probe at $\phi = 0°$. The ion temperature and poloidal rotation velocity are measured with the 1 m spectrometer at $\phi = 339°$.

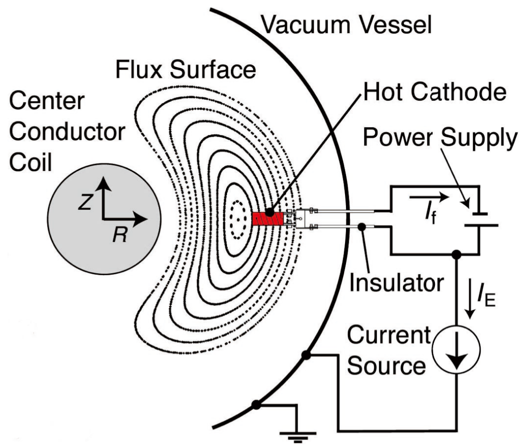

Fig. 3 The biasing system in TU-Heliac. The electrode is biased against the vacuum vessel.

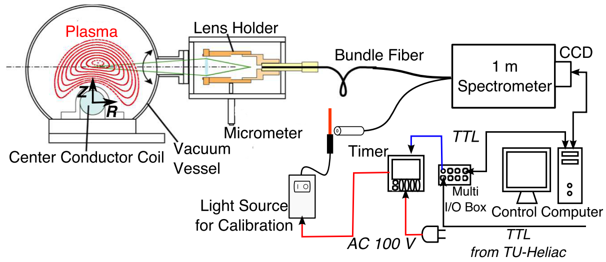

Fig. 4 The Doppler spectroscopy system in TU-Heliac.

after every plasma shot. A control circuit of the neon lamp was designed, and the calibration process was integrated into the experimental sequence. As a result, the measuring error of the ion temperature was about ±0.5 eV and that of the poloidal flow velocity was about ±0.5 kms^{-1}. We calibrated the system with a low temperature helium plasma light source whose plasma flow was sufficiently low. The Doppler broadening measured by the system corresponded to an ion temperature of ~ 1 eV. Considering the temperature of the plasma of the light source, this result was deemed reasonable. The measured Doppler shift corresponded to a flow velocity of ~ 0.2 kms^{-1}. This offset was negligibly small in the biasing experiment.

3. Experimental Results

3.1 Ion temperature and flow velocity

As the target magnetic configuration for the electrode biasing experiment, the configuration of R_{ax} = 0.079 m was selected (R_{ax} is the magnetic axis position). The target plasma electron temperature was ~ 20 eV and the electron density was ~ 1×10^{18} m^{-3}. With biasing, the electron density drastically increased and the electron temperature slightly decreased. At I_E = 5 A (maximum electrode current), the electron temperature was ~ 15 eV and the electron density was ~ 3×10^{18} m^{-3}. The Doppler spectroscopy data are shown in Fig. 5 in which (a) is the radial profile of the emission intensity of the He II line (468.7 nm), (b) is the ion temperature T_i, and (c) is the *line-integrated* poloidal rotation velocity V_{dop} for the three conditions of the electrode current I_E (I_E = 0, 1 and 5 A). V_{dop} is the measured rotational velocity in the poloidal plane of the TU-Heliac device, which mainly reflects the poloidal rotation velocity. Figure 5 (a) shows that the radial profile of emission intensity has a maximum at the magnetic axis. The ion temperature increases with increasing electrode current, as shown in Fig. 5 (b). Figure 5 (c) shows that the radial profile of the poloidal rotation velocity is flat and almost zero in the non biasing case (I_E = 0 A), whereas in the biasing case, a poloidal rotational flow structure centered on the magnetic axis forms. We compared the measured poloidal rotation velocity with the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity estimated from the radial potential profile measured with the triple probe. The direction of the rotation agrees with the $\boldsymbol{E}\times\boldsymbol{B}$ direction. The measured value was about 70% of the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity, which may be affected by the line integration effect. In conclusion, we successfully measured the radial profiles of the low ion temperature (T_i < 10 eV) and low flow velocity (V_{dop} < 10 kms^{-1}) using Doppler spectroscopy.

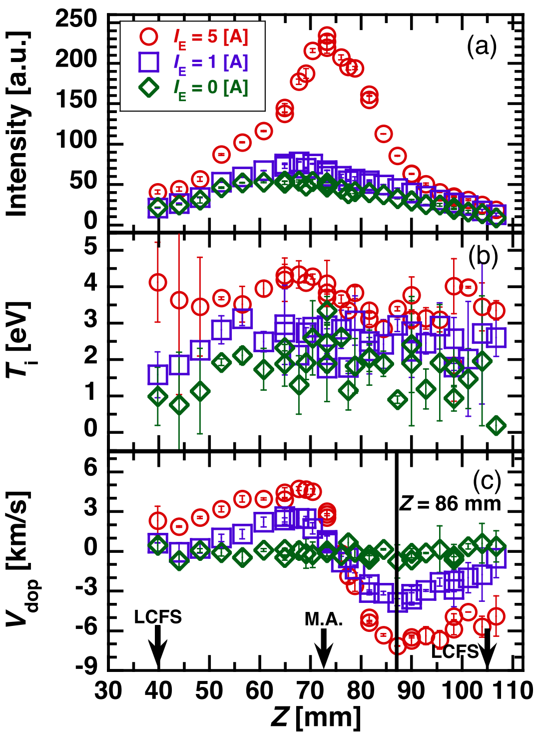

Fig. 5 Radial profile of (a) the emission intensity, (b) the ion temperature and (c) the poloidal rotation velocity measured using Doppler spectroscopy.

3.2 Dependence of ion temperature and flow velocity on electrode current

We focused on Z = 86 mm in Fig. 5 (c) where the rotation velocity peaks. We investigated the dependence of the ion temperature and the poloidal rotation velocity on the electrode current by controlling the driving force of the poloidal rotation. In Fig. 6 we show the experimental results at Z = 86 mm in the low input power (35 kW) and the high input power (46 kW) cases. The input power is the supply power to the ohmic heating coil, which corre-

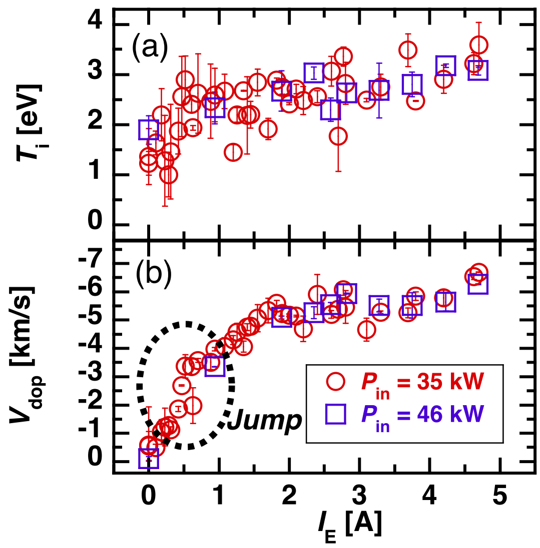

Fig. 6 The variation of (a) the ion temperature and (b) the poloidal rotation velocity against the electrode current at Z = 86 mm.

sponds to the output power of the ohmic heating system. We expected the increase in the emission of the He II line owing to the increase in the input power (35 kW → 46 kW). However, in this region of input power, the plasma parameters showed no significant differences. From Fig. 6, the ion temperature T_i and the poloidal rotation velocity V_{dop} increase with increasing electrode current. The poloidal rotation velocity V_{dop} jumps to double at $I_E \sim 0.5$ A, and the poloidal rotation velocity V_{dop} is saturated at the region $I_E > 2$ A, as shown in Fig. 6 (b).

4. Normalized Driving Force

To investigate the relation between the ion viscosity and the poloidal Mach number, the driving force of the poloidal rotation and the poloidal rotation velocity must be normalized by the ion temperature T_i and ion pressure P_i. The poloidal rotation velocity is converted to the poloidal Mach number M_p as follows:

$$M_p = \frac{V_{dop}}{\Theta V_t}, \quad \Theta = \frac{B_\theta}{B_\phi}, \tag{1}$$

where V_t is the thermal velocity of ion, B_θ is the magnetic field of the poloidal direction, and B_ϕ is the magnetic field of the toroidal direction. The driving force of the poloidal rotation normalized by the ion pressure $P_i = n_i T_i$ corresponds to the drag term (ion viscosity + friction) if the external driving force is balanced with the drag term. We assumed that the ion density n_i equals to the electron density n_e measured with the triple probe. In this experiment, we adopted the same magnetic field strength at the various conditions; therefore, the driving force depends on the electrode current. In this study, the electrode current is regarded as the driving force, and thus the normalized driving force is proportional to $I_E/n_i T_i$.

The normalized results calculated from the results in Fig. 6 are shown in Fig. 7. In the region $0 < -M_p < 3$, the driving force linearly increases with increasing poloidal Mach number. However, in the region $3 < -M_p < 5$, the driving force drops down, and in the region $5 < -M_p$, it increases linearly again. This shows the non-linear relation between the normalized driving force and the poloidal Mach number.

Neoclassical theory predicts the existence of local maxima in the ion viscosity, which causes the sudden increase in the poloidal rotation velocity. The drop-down region corresponds to $I_E \sim 0.5$ A. At this electrode current, the poloidal rotation velocity increases considerably as shown in Fig. 6. This suggests that bifurcation phenomena in poloidal rotation appear across the drop-down region. The results are qualitatively consistent with previous experiments [7,8] and qualitatively agree with Shaing's model [5, 6].

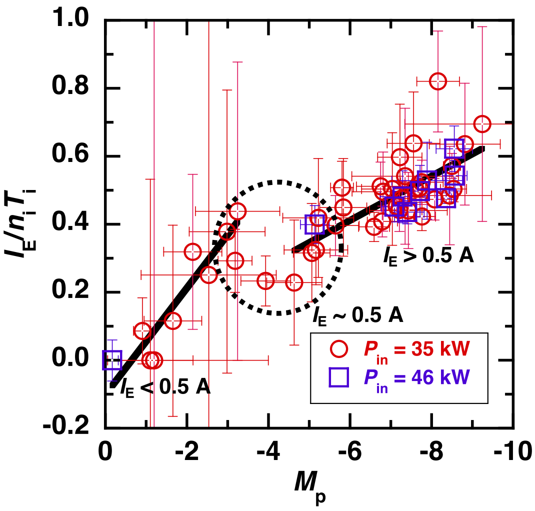

Fig. 7 The relation between the normalized driving force of poloidal rotation and the poloidal Mach number at Z = 86 mm.

5. Summary

The ion temperature and the poloidal rotation velocity were measured directly using Doppler spectroscopy for the biasing experiment in TU-Heliac. The radial profile of the emission intensity, the ion temperature T_i and the poloidal flow velocity V_{dop} were successfully obtained. The poloidal rotational flow structure centered on the magnetic axis formed in the biasing case and the direction of the rotation agreed with $\boldsymbol{J} \times \boldsymbol{B}$ direction. The ion temperature T_i and the poloidal rotation velocity V_{dop} increased with increasing electrode current. The poloidal rotation velocity V_{dop} increased significantly at the threshold electrode current and the poloidal rotation velocity V_{dop} was saturated in the region of high electrode current.

The relation between the normalized driving force and the poloidal Mach number was non-linear. At $M_p \sim -3$, the driving force decreases and the poloidal rotation velocity increases significantly at this electrode current. The results suggest that bifurcation phenomena in poloidal rotation appear across the drop-down region. The results are also qualitatively consistent with previous experiments [7, 8] and qualitatively agree with Shaing's model.

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