Impact of Dynamic Ergodic Divertor on Plasma Rotation in the Small Tokamak HYBTOK-II

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Plasma rotation or its shear is important on the formation of transport barrier. It is thought that the rotating helical magnetic field generated by Dynamic Ergodic Divertor (DED) could generate a rotational torque in tokamak plasmas and control rotation profiles as a result. In order to measure the plasma rotations and to investigate the effect of DED on them, we developed a passive spectroscopic measurement system for the small tokamak HYBTOK-II to measure plasma rotations. A spontaneous toroidal plasma rotation in co-current direction and the poloidal plasma rotation in electron diamagnetic drift direction have been observed without DED. Considerable changes of the plasma flow have been obtained with DED to show some reduction of toroidal and poloidal rotation velocity near the resonant magnetic surface. The modification of plasma rotation velocity was found to couple to the change of the radial electric field.

Keywords: plasma rotation, dynamic ergodic divertor, passive spectroscopy, radial electric field, HYBTOK-II

1. Introduction

To achieve high performance in magnetically confined plasmas, control of plasma rotations and their profiles play important roles on forming and sustaining transport barrier through the modification of radial electric field [1,2]. In burning plasma, it is not easy to control plasma properties by external current drive or auxiliary heating (i.e. controlling current and temperature profiles) due to large bootstrap current and self-α heating. However, in present devices, neutral beam injection is useful to control the plasma rotations as an external momentum source.

Dynamic ergodic divertor (DED), which has been developed to control energy and/or particle transport at the edge region, is believed to generate rotational torque on plasmas. Modulation of particle and/or energy transport in DED comes from the magnetic field structure caused by magnetic islands induced by externally-applying Rotating Helical magnetic perturbation Field (RHF) [3-7]. Mechanism of controlling of plasma rotation by use of DED relates to the Lorentz torque due to interaction between shielding current produced by the rotating perturbation field in plasmas and perturbation field itself [7]. The torque is expected to be large when the relative angular frequency between plasma and RHF in DED is large. However, the high frequency RHF in the plasma becomes weak due to the shielding effect of the vacuum vessel because the helical coils are wound outside of the vacuum vessel. On the other hand, lower frequency RHF can penetrate much deeper inside of plasma. Therefore, in the present paper, we focus on the lower frequency RHF (~ several kHz) case to investigate the effect of stochastic magnetic field formed inside the separatrix in this paper.

In order to study the effect of DED on plasma rotation in the small tokamak HYBTOK-II, an optical measurement system, which may observe the inner plasma region, has been developed with the working gas of helium.

2. Experimental Setup

The experiments have been performed on the small tokamak HYBTOK-II (the major radius R_0 = 40 cm, the plasma minor radius $a \approx 10$ cm, the limiter radius a_w = 11 cm). In the machine operation, the main plasma parameters were as follows: the plasma current I_p = 5 kA, the toroidal magnetic field B_t = 0.28 T, and the pulse duration time is 10 ms. The HYBTOK-II is equipped with DED coils, which consist of two sets of coils that are wound on the out-vessel locally in the toroidal direction. The RHF with

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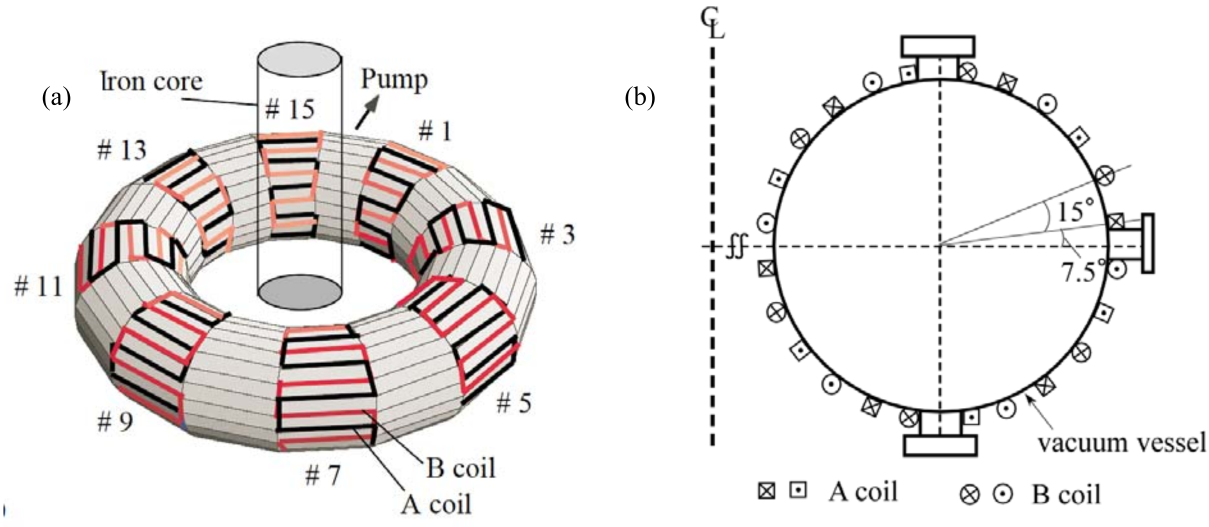

Fig. 1 Arrangement of the DED coils (a) bird's eye view (b) on poloidal cross section [5].

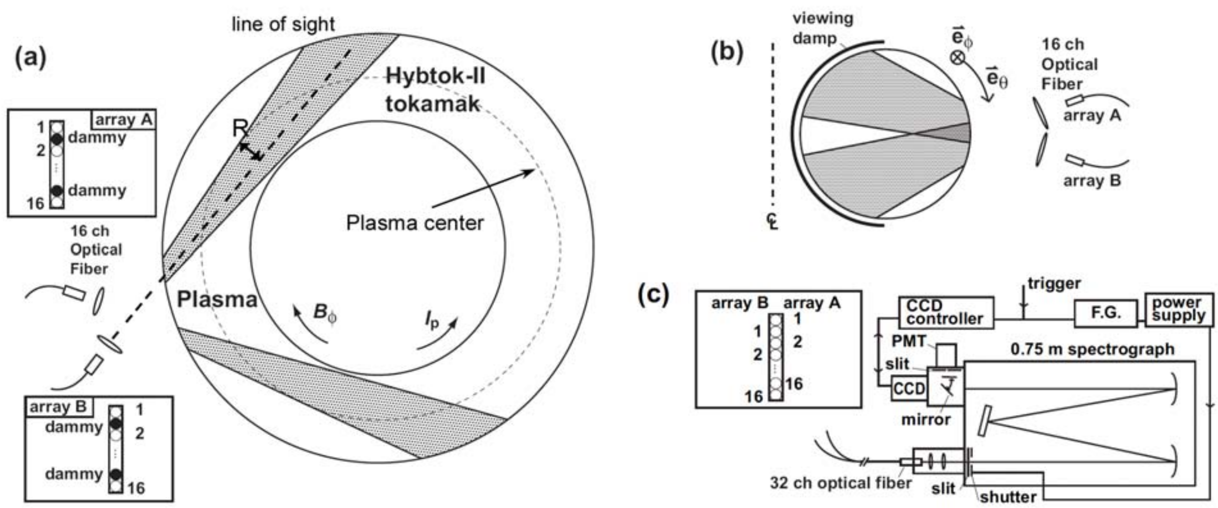

Fig. 2 Optical arrangements for (a) toroidal and (b) poloidal flow velocity measurements. (c) Spectrometer, detection device and synchronized system with external trigger.

the poloidal and toroidal mode numbers of m/n = 6/1 resonates with magnetic rotational transform at q = 6 magnetic surface (Fig. 1) [5]. These two sets of coils are powered independently by insulated gated bipolar transistor inverter power supply with a phase difference of ± 90°. We can control the poloidal rotation direction of RHF by changing the phase difference between two coils. RHF's rotation frequency of 3 kHz was selected. Duration of the RHF was 10 msec.

The optical measurement system consists of bifurcated 32 ch (16 ch×2) optical fiber arrays, focusing lens (103 mm focal length in a toroidal direction, 34.5 mm in a poloidal direction), Czerny-Turner spectrometer (1800 gr/mm grating, 1.0 m focal length and 0.01 nm resolution) and 1024×256 pixels CCD detector (Fig. 2). By changing the position of the fiber arrays using by movable stages, the distance between the line of sight and the plasma center, r, can be varied from r = 0-100 mm. The flow velocity, V, is given by $V = c\cdot \Delta\lambda/\lambda$, where c is the speed of light, $\Delta\lambda$ the Doppler shift and λ the central wavelength of the observed spectrum. The shifted value $\Delta\lambda$ was estimated by $\Delta\lambda = (\lambda_{blue} - \lambda_{red})/2$ in this system, where λ_{blue} and λ_{red} are the central wavelength of the spectrum observed from the upstream, and downstream of the plasma flow, respectively. Thus, one branch of bifurcated arrays faces upstream-side and another looks forwards the downstream-side as shown in Fig. 2. In this experiments, singly ionized helium emission (n = 3 – 4, λ = 468.54 – 468.59 nm) was employed for the flow measurements. The spectrum was fitted with multi-Gaussian functions considering the fine

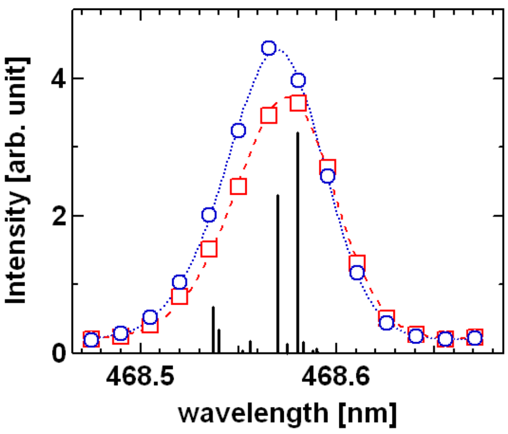

Fig.3 Observed spectra at both upstream- (open circle) and downstream-side (open square), with fitted curves.

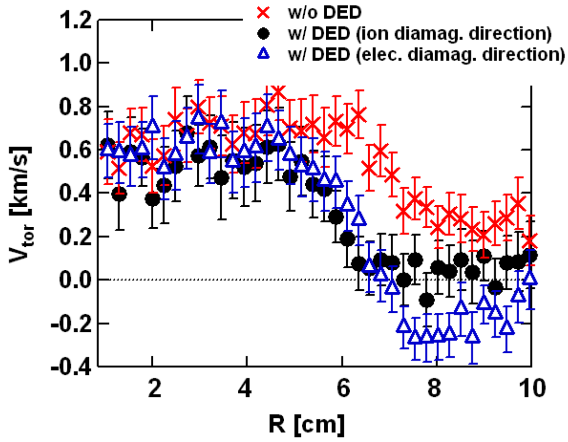

Fig. 4 Toroidal rotation velocity profile without (cross) and with DED in the direction of ion diamagnetic drift (closed circle) and in that of electron (triangle).

structure of the transition [9].

A triple probe which is accessible up to the center of plasma column is installed to measure the electron temperature T_e, the electron density n_e and the floating potential V_f. The Plasma potential V_p is estimated by using the relation $V_p = V_f + 3T_e$.

3. Results and Discussion

In the measurements, pure helium plasma was employed to improve S/N ratio by obtaining the strong He II emission. Typical electron density and electron temperature are $n_e \sim 6 \times 10^{18}$ m^{-3} and $T_e \sim 30$ eV, respectively. At first, we briefly present the fundamental spectral measurements obtained from the passive spectroscopy. Figure 3 shows the spectra observed both at the upstream-side and at the downstream-side with the relative strength of the fine structure multiplet. The observed spectra are fitted by multi-Gaussian functions. The ion temperature obtained from the Doppler width with considering an instrumental width and the fine structure is about 5 eV, and it is found that there is no clear radial positional dependence. The toroidal plasma rotation velocity profiles are shown in Fig. 4 as a function a distance R between a line of sight and the center of the plasma column, which lies on 1 cm inside that of the vacuum vessel, as shown in Fig. 2(a). It is noted that the velocity does not shows the local value because of the limitation of the passive spectroscopy owing to line integration. Thus, only the averaged value over the line of sight is available at the moment, especially for the toroidal direction. A spontaneous plasma rotation in the co-current direction has been observed. The maximum velocity is about 0.8 km/s. By applying RHF with 150 A of the maximum coil current, a reduction of plasma rotation is

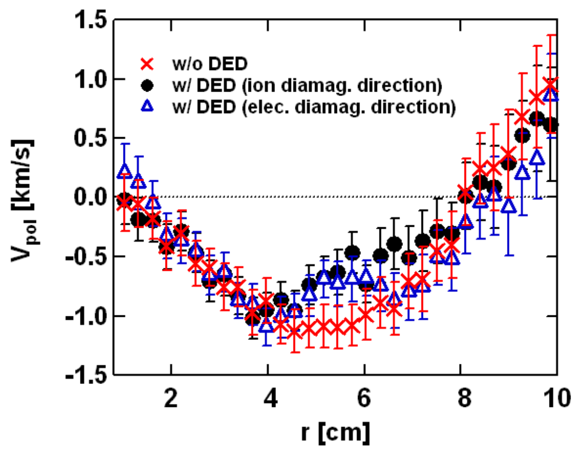

Fig.5 Poloidal rotation velocity profile. The markers of each cases are same as Fig. 4.

clearly observed around R = – 4 cm in both RHF rotation directions. Figure 5 shows poloidal plasma rotation velocities without and with 3 kHz DED. "r" in horizontal axis means distance between the line of sight and the plasma center. Without DED, the direction of plasma rotation is the same as that of the electron diamagnetic drift from r = – 2 to r = – 8 cm. With DED case, plasma rotation is damped around r = – 4 cm. Radial electric field E_r derived by the plasma potential profile is shown in Fig. 6 for both without and with DED cases. $E_r \times B$ drift direction matches the poloidal rotation, and reduction of E_r at inside r ~ 7.5 cm agrees with the reduction of the poloidal rotation. The variations of the plasma rotations by DED were found to be coupled with radial electric field.

In the low frequency case (3 kHz DED), the changes in rotation due to DED was observed at the same location

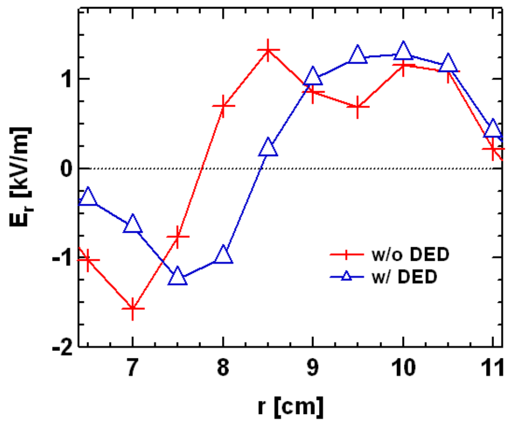

Fig. 6 Radial electric field evaluated by using the triple probe. Negative E_r means inward field.

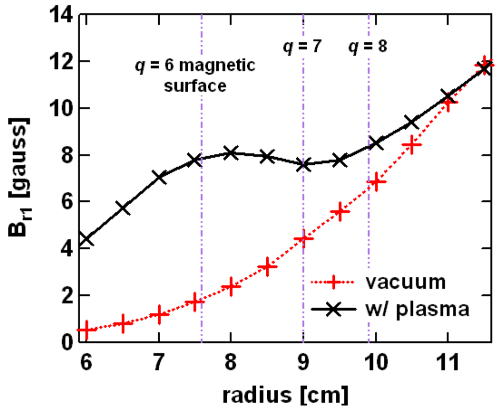

Fig. 7 Perturbation component of radial magnetic field The locations of rational surface of q = 6, 7, 8 are also shown.

for both toroidal and poloidal rotations. Perturbation component of radial magnetic field B_{r1} was measured by using a radially movable magnetic probe and is shown in Fig. 7. The B_{r1} in vacuum decreases with distance from the coil placed on out-vessel. However, B_{r1} in the plasma was amplified compared with that in vacuum near resonance surface (r ≈ 7.6 cm). This can be contributed to the re-distribution of plasma current due to the growth of the magnetic island structure [6,7]. It is thought that poloidal rotation damping was caused by the enhancement of poloidal parallel viscosity due to the island formation. In steady-state plasma, the radial component of equation of motion for ion fluid in the toroidal coordinates is as follows:

$$E_r = (1/eZ_i n_i)(\partial P_i/\partial r) - V_\theta B_\phi + V_\phi B_\theta \,. \qquad (1)$$

Here, eZ_i, n_i and P_i are the electrical charge, the number density and pressure of the ion, respectively. V and B are the flow velocity and the magnetic field, respectively. The changes of E_r estimated from eq. (1) using the results of the rotation measurements are in agreement with the experimental results, qualitatively. On the other hand, the toroidal rotation decrease seems to be caused by friction increase due to variation of magnetic structure at the edge region or friction with neutral helium which exists more near the edge region. Thus, it could be said that changes of the rotations originate in the magnetic island structure, and consequently the E_r changes, in these cases.

4. Conclusion

A modification of plasma rotation properties with DED is reported. The plasma flow was measured by the optical emission spectroscopy developed in HYBTOK-II. Doppler shift of He II line obtained from the system is large enough to estimate the rotation velocity and its direction in pure helium discharge. The spontaneous toroidal plasma rotation in the co-current direction and the poloidal rotation in the electron diamagnetic drift direction were observed without DED. By applying a low frequency RHF (~ 3 kHz), both the toroidal and the poloidal rotations decreased. It is likely that they are caused by magnetic island formation. Modification of Radial electric field was also observed.

In future, it is necessary to generate plasma with higher electron temperature in order to study an influence of shielding current in the plasma. As a modification of radial electric field due to enhancement of electron transport in the stochastic region are observed on the TEXTOR [10], there is also need to consider these effects.

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