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2nd Harmonic ECCD experiment using 84 GHz EC-wave in LHD

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Second harmonic electron cyclotron current drive (ECCD) experiments were performed in Large Helical Device (LHD) to investigate the characteristics of the EC-driven current and its profile, and to investigate the possibility of controlling the current and rotational transform profiles by ECCD. By a scanning of EC-wave beam direction, a systematic change of plasma current is observed, and the direction of the plasma current is reversed by a reversal of the beam direction. Motional Stark Effect (MSE) measurement revealed tentative behavior of plasma current profile. At the early phase of ECCD, the EC driven current at the plasma core is mostly cancelled by counter current driven by an inductive electromagnetic force. It takes a few seconds for the inductive electromagnetic force to disappear, and the total plasma current gradually approaches to a constant value.

Keywords: ECCD, current profile, rotational transform, MSE, LHD

1. Introduction

Electron cyclotron current drive (ECCD) is an attractive tool to control plasmas. Using well-focused EC-wave beam, plasma current can be driven locally so that ECCD can control the profiles of plasma current and rotational transform which affect the magnetohydro-dynamics (MHD) activities [1-3]. In tokamak-type plasma confining devices, the effectiveness of ECCD on stabilization of neoclassical tearing mode (NTM) which is one of the harmful MHD activities has been demonstrated by driving current within the magnetic island [4]. Moreover, ECCD can be available for supporting ohmic plasma current startup in tokamaks.

Also for stellarators which do not need plasma current for plasma confinement, the capability of current profile control is effective for fine plasma control. In the Wendelstein 7-AS stellarator, clear ECCD experiments have been carried out and the results were investigated precisely [5]. Also in Heliotron-J [6] and the compact helical system (CHS) [7,8], ECCD was successfully observed.

In this paper, results of ECCD experiment in the large helical device (LHD) are described. LHD and the system for ECCD experiment are briefly explained in Sec. 2. Section 3 describes some results obtained in ECCD experiment such as EC-wave beam direction scan and long pulse ECCD. In Sec. 4, time evolution of plasma current and future plan of ECCD experiment are discussed. Then, the content of this paper is summarized in Sec. 5.

2. LHD and the system for ECCD

The LHD is a helical device with the toroidal period number m = 10 and the polarity l = 2. The magnetic field structure with the rotational transform for plasma confinement is generated totally by the external superconducting coils such as a couple of helical coils and three pairs of poloidal coils [9]. The major radius, or, the position of magnetic axis R_{ax} of LHD plasma can be varied in a range from 3.42 m to 4.1 m. The averaged plasma minor radius is about 0.6 m, and the maximum magnetic field at the magnetic axis is about 3 T. Those values and characteristics of the magnetic field configuration such as rotational transform profile and magnetic field along magnetic axis are dependent on R_{ax}.

The magnetic fields along magnetic axis for 3 cases are plotted in Fig. 1 as functions of toroidal angle. In the case of R_{ax} = 3.75m, the magnetic field on magnetic axis is nearly constant, while with R_{ax} = 3.6 m or 3.9 m magnetic ripples of about 5 % exist. The ECCD experiments described in this paper were performed with the magnetic

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configuration of R_{ax} = 3.75 m to minimize the effect of magnetic ripple on ECCD. The magnetic field on axis is 1.5 T, that is, the second harmonic resonance field for the frequency of 84 GHz.

The EC-wave beam injection systems of LHD furnish 2-dimensionally steerable mirror which enables the beam direction control. One of the beam injection systems which is used for ECCD experiment is composed of two inner-vessel mirrors. One of them focuses the EC-wave beam radiated from the waveguide inserted to LHD vacuum vessel as a circular Gaussian beam. The other plane mirror is used for changing the beam direction. The focused beam has a beam waist on the equatorial plane with a radius of 30 mm. The injection system is installed at the bottom port of LHD (1.5-L port), and the beam is injected from the low magnetic field side (LFS). The toroidal angle at the 1.5-L port is 0 (or 36) degrees.

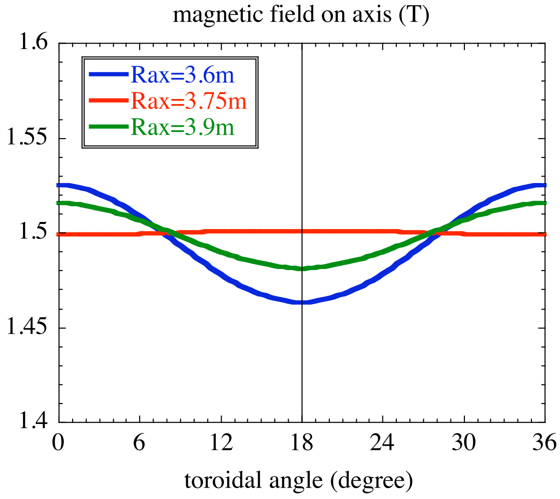

Fig. 1 Distributions of magnetic field along magnetic axis for the magnetic axis positions of 3.6, 3.75 and 3.9 m. With the magnetic axis position of 3.75 m, magnetic ripple is negligible so that trapping effect for electrons near the magnetic axis is minimized.

3. Results of ECCD experiment

The EC-wave beam direction was toroidally scanned keeping the beam aiming position on the magnetic axis. A schematic drawing to clarify the experimental configuration, definitions of EC-wave beam direction ($N_{//}$) and plasma current direction is seen in Fig. 2. $N_{//}$ is defined as a projection of beam unit vector on the toroidal direction.

The plasmas were generated and sustained only by the EC-wave power of 310 kW in the right-hand circular polarization for non-$N_{//}$ case, which is close to X-mode in the case of oblique injection. It has been confirmed that by an obliquely injected EC-wave beam with the left-hand circular polarization, plasmas can not be generated and can not be sustained effectively. The pulse length is limited to 600 ms due to operating duty cycle of used EC-wave power source (gyrotron). For $N_{//}$ = 0, that is, for normal injection case the polarization was set as linear X-mode.

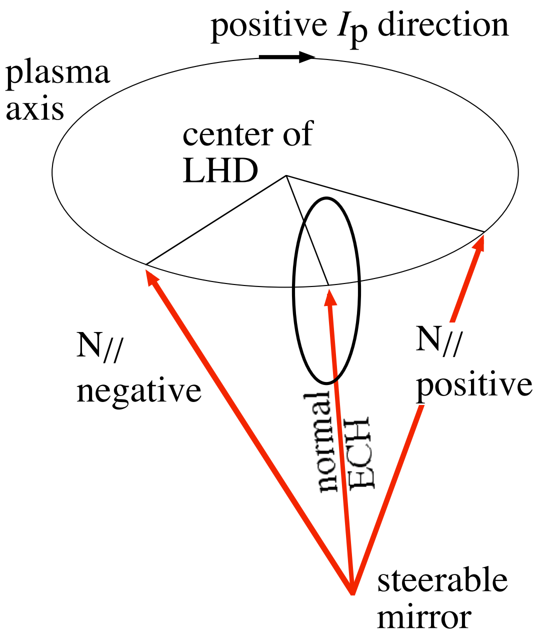

Fig. 2 A schematic drawing showing experimental configuration of EC-wave beam injection and definitions of directions of $N_{//}$ and plasma current.

During the beam direction scanning, electron density was kept at rather low density around 0.08x10^{19} m^{-3}. The plasma current at the end of plasma discharge is plotted against $N_{//}$ in Fig. 3. The total plasma current changes its direction according to the change of the sign of $N_{//}$, and the direction agrees with the theoretical prediction from the Fisch-Boozer theory [10] in the case of the beam injection from LFS. When the toroidal component of EC-wave beam is clockwise with negative $N_{//}$, (counter-clockwise with positive $N_{//}$), the current is driven counter-clockwise (clockwise). Here, the current direction of clockwise (counter-clockwise) is defined as positive (negative) direction.

The total plasma current shows negative and positive peaks against negative and positive variations of $N_{//}$, respectively. The peak values are about +- 1 kA. Though precise dependence of driven current on electron density has not been investigated, higher driven current with higher density can be expected. With the density of 0.5x10^{19} m^{-3} and with $N_{//}$ of 0.2, plasma currents of more than 3 kA by 600 ms pulse width were observed in other discharges. The density region lower than 0.1x10^{19} m^{-3}

might be too low to assure sufficient power absorption.

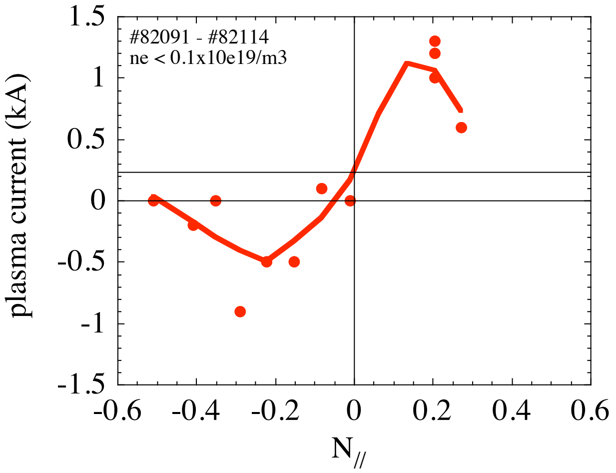

Fig. 3 Dependence of plasma current on EC-wave beam direction. $N_{//}$ is defined as a projection of beam unit vector on the toroidal direction.

Here it should be noted that during the 600 ms pulse width, the plasma current is continuously developing and is not saturated. Figure 4 shows waveforms of plasma current and electron density in a long pulse ECCD experiment done to investigate the long time evolution of plasma current. ECCD was performed with $N_{//}$ of -0.29, rather low EC-wave power of 100 kW and long pulse width of 10 s using a gyrotron which can be operated continuously. Plasma startup was supported by another EC-wave power of 300 ms and the plasma was sustained with the 100 kW EC-wave power for ECCD.

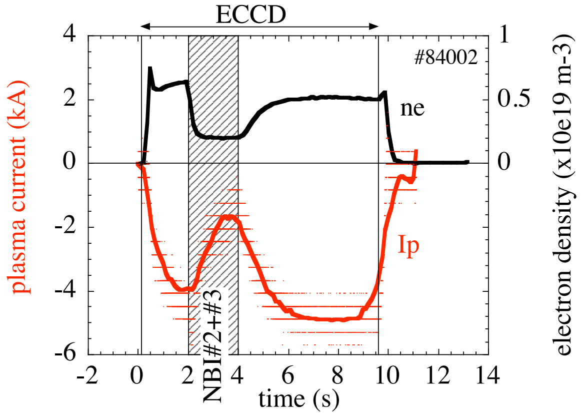

Fig. 4 Time evolution of plasma current and electron density in 100 kW, 10 s ECCD experiment.

Excluding the perturbation by the neutral beam injection (NBI) from 2 to 4 s, it is seen that it takes a few seconds for plasma current to saturate, and the saturated value is about -5 kA. In this case, an ECCD efficiency γ defined using electron density n_e, major radius R, plasma current I_p and absorbed power P_{abs} is evaluated as

$$\gamma = n_e R I_p / P_{abs} = 9\text{x}10^{17}\ \text{A/Wm}^2.$$

This value is comparable to that obtained in Wendelstein 7-AS [5].

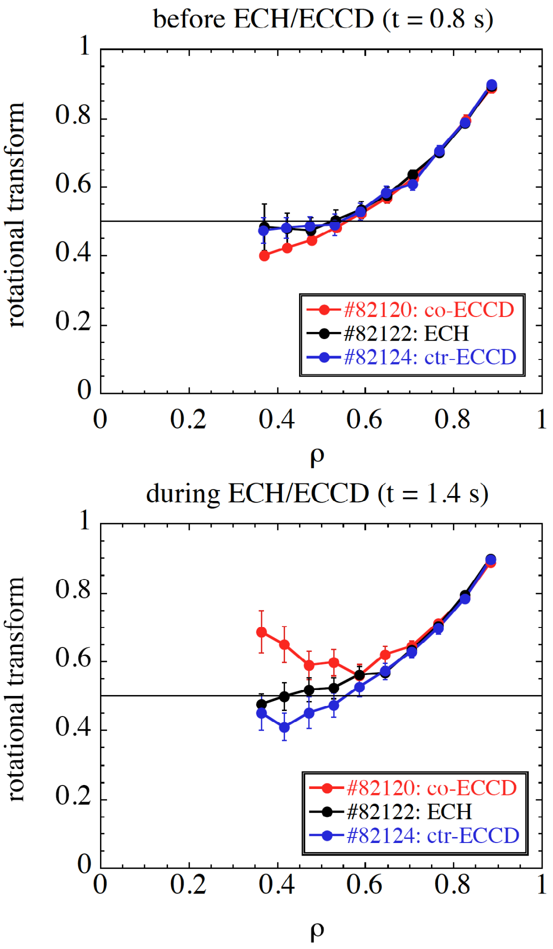

Fig. 5 Distributions of rotational transform measured with MSE measurement for the cases of co-ECCD, counter-ECCD and ECH just before applying ECCD/ECH (0.8 s) and during ECCD/ECH (1.4 s).

Setting the $N_{//}$ values at the optimum ones for ECCD ($N_{//} = 0.27$ for co-ECCD and $N_{//} = -0.29$ for counter-ECCD, respectively) and at zero for ECH, distribution of the rotational transform was measured with the motional stark effect (MSE) measurement. The MSE measurement needs NBI. The plasmas were generated and sustained with the NBI power injected from 0.5 s, and the EC-wave power of 370 kW, 600 ms was superposed on the plasma from 1.0 s to 1.6 s. Just before the EC-wave power injection at 0.8 s, the distributions of the rotational transform in the cases of co-ECCD, counter-ECCD and ECH do not differ so much as seen in Fig. 5. On the other hand, during the superposition of ECCD and ECH at 1.4 s, the distribution of the rotational transform in the case of co- (counter-) ECCD shows significant increase (decrease) from that in the case of ECH at 1.4 s, or those at 0.8 s. The estimated driven currents inside the normalized radius of 0.5 which cause the changes in the rotational transform are more than 10 kA. From this result of MSE measurement, possibility of the control of rotational transform profile by ECCD was proved. Especially, removing of rational surface of 0.5 would be effective for suppression of MHD activities concerning with the existence of the rational surface.

4. Discussion and future plan

In Fig. 5, there is no significant change in rotational transform at the peripheral region, $\rho > 0.7$. It means that though an EC-driven current over 10 kA flows at core region, the EC-driven current is cancelled by a counter-flowing current so that the residual total current is not so much. The counter-current is caused by an inductive electromagnetic force. This is consistent with the fact that in the ECCD experiment with 600 ms pulse width and over 300 kW power, the total plasma current at the end of the discharge measured with a Rogowski coil surrounding the plasma is up to 4 kA. The counter-current should decay with a time constant of L/R (L: plasma inductance, R: plasma resistance here). Simply estimated L/R time for the plasmas in the ECCD experiment exceeds 10 s mainly due to large plasma volume of ~30 m^3 in LHD. So the estimated L/R time qualitatively agrees with the experimental observation of current ramp up time of 3-4 seconds as seen in Fig. 4 but not quantitatively. Precise estimation of L/R time in LHD would be needed.

To clarify the precise evolution of the rotational transform distribution, or, EC-driven current profile, MSE measurement for long pulse ECCD experiment of over 5 s with NBI is necessary. At LHD, construction of ECH system by introducing higher power (up to 0.8 MW for 10 s) gyrotrons with operating frequency of 77 GHz is undergoing [11]. By using new ECH system, higher driven current at higher density can be achievable, and then ECCD would contribute to improvement of plasma performance in LHD.

Also, to investigate characteristics and physics in ECCD for further application of ECCD, basic experiments which reveal the dependences of driven current on plasma density, absorbed EC-wave power, configuration of magnetic field and so on, should be performed.

5. Conclusions

In LHD, 2nd harmonic ECCD experiments were performed using 84 GHz EC-wave. So far, effective ECCD by scanning EC-wave beam direction was successfully observed. A long pulse ECCD experiment of 10 s indicated that the time constant of plasma current saturation is a few seconds. At the early phase of ECCD, counter-current caused by an inductive electromagnetic force exists and cancels the EC-driven current. To evaluate ECCD results and investigate ECCD physics precisely, long pulse ECCD experiment over a few seconds and MSE measurement for it is necessary. New high power, long pulse 77 GHz ECH system would enable the next ECCD experiment.

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