Demonstration of Plasma Current Control by Using High Power Millimeter-Waves

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Active current drive is one of promising tools to improve plasma quality even in the helical devices through the control of the rotational transform or magnetic shear profiles and suppression of some magnetohydrodynamics activities. The current drive by electron cyclotron waves is the most suitable actuator for these purposes in terms of controllability of driven current with high density. Optimum conditions for efficient electron cyclotron current drive (ECCD) in large helical device (LHD) are explored using 3-dimensional ray-tracing code which can treat electron cyclotron waves with large parallel refractive index. In the experiment, inversion of plasma currents corresponding to injected ECCD modes is first demonstrated and the result can be elucidated by the Fisch-Boozer theory. Displacements of rotational transform are also verified by use of the motional stark effect polarimetry.

Keywords: electron cyclotron resonance heating, electron cyclotron current drive, plasma current control, magnetic shear control, rotational transform control, gyrotron.

1. Introduction

The current drive to form the poloidal magnetic field is vital in the Tokamak devices. There is no necessity to drive plasma current externally in the helical devices because the magnetic fields to confine plasmas can be yielded by only external coils. However, the plasma currents driven by plasma pressure gradients or powerful neutral beam injection change the magnetic field structure such as rotational transform and magnetic shear. Plasma performances will degrade according to these changes. Therefore, the study of controlling the plasma current is significant even in the helical devices.

Electron cyclotron current drive (ECCD) is the most prospective tool to control plasma current profile because the power transitions from electron cyclotron waves to resonant electrons are take placed very locally which lead to locality of plasma current with high density [1-2]. Besides, we can select the location of driven plasma current almost arbitrarily by adjusting some parameters such as magnetic field strength, wave-frequency, parallel refractive index and so on.

This paper consists of following sections. The section 2 describes inspection for effective ECCD in LHD configurations. The section 3 is devoted to explanation of experimental results. The plasma current control by ECCD is firstly demonstrated and shift of rotational transformation is observed. Finally, our research is summarized in the section 4.

2. Scrutiny for ECCD in LHD

In an inward shifted configuration of large helical device (LHD), improvements of not only neoclassical transport but also anomalous one are observed experimentally. According to a linear MHD theory, on the one hand, it is predicted that some MHD instabilities affect plasma confinement in such inward shifted configurations due to the magnetic-hill structure. As one of the reasons for present fine confinement capability in the configuration, some non-linear effects are pointed out. They may prevent MHD activities from growing further. However in order to extend an operation parameter range of LHD, MHD activities should be suppressed by some kind of ways because they must cause severe degradation to plasma confinement in high β plasmas. ECCD has possibility that it can improve MHD properties only by local current control without degradations both of

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neoclassical and anomalous transports even in the inward shifted configurations.

To improve plasma confinement capability by ECCD in LHD, two schemes can be conceivable. One of them is ECCD to co-direction (Co-ECCD) which raises rotational transform and result in exclusion of low-order rational surfaces at plasma core region where magnetic shear is very weak. The other is ECCD to counter-direction (Ctr-ECCD) which can enhance negative magnetic shear locally. Therefore, driving plasma current to arbitrary directions is desirable as current drive actuator.

The mechanism of ECCD is based on asymmetric modification of electron resistivity in the momentum space formed by selective electron cyclotron resonance. Electron cyclotron waves are absorbed by electrons that have velocity component satisfying the following condition taking Doppler up-shift and relativistic down-shift into consideration [3-5].

$$\frac{\omega^2 N_\parallel^2 + l^2\Omega^2}{\omega^2 N_\parallel^2 + l^2\Omega^2 - \omega^2}\left(\frac{v_\perp}{c}\right)^2 + \frac{\omega^4 N_\parallel^4 + 2\omega^2 N_\parallel^2 l^2\Omega^2 + l^4\Omega^4}{\omega^2 N_\parallel^2 l^2\Omega^2 + l^4\Omega^4 - \omega^2 l^2\Omega^2}\left(\frac{v_\parallel}{c} - \frac{\omega^2 N_\parallel}{\omega^2 N_\parallel^2 + l^2\Omega^2}\right)^2 = 1$$

Where $N_\parallel, l, \Omega, \omega$, $v_\perp$, $v_\parallel$ and c mean parallel refractive index, harmonic number of cyclotron resonance, electron cyclotron frequency, wave frequency, perpendicular thermal velocity, parallel thermal velocity and light velocity, respectively. For $N_\parallel<1$, this equation describes an ellipse, and resonant interaction is only possible for

$$l\Omega/\omega > (1 - N_\parallel^2)^{0.5}$$

which excludes anomalous cyclotron resonance. On the other hands, for $N_\parallel>1$, it represents a hyperbolic curve in the velocity space. As for an example, the calculated resonant curves in the momentum space under the certain parameters are shown in Fig.1. In the case of large $N_\parallel$ injection, the resonant curves move toward high parallel velocity regions in velocity space due to strong up-shift of cyclotron resonance frequency. And the resonance begins to arise even in the lower magnetic field side than 3 Tesla corresponding to fundamental resonance condition of usual ECRH for 84GHz-waves. These findings indicate that electron cyclotron waves with large $N_\parallel$ tend to interact with electrons having higher parallel velocity component. Therefore, injecting electron cyclotron waves with large $N_\parallel$ must be effective in terms of collisionality to achieve high ECCD efficiency

The effect of electron trapping is another critical issue. Trapped electrons reduce the ECCD efficiency or may reverse the direction of the driven current since the diffusions in velocity space involved with electron cyclotron damping is mainly to perpendicular directions [6]. Especially, LHD has not only toroidicity but also helicity and the fraction of them strongly depends on magnetic configurations. In order to avoid such trouble, depositing the wave power at magnetic ripple top region is ideal. Fig.2 shows contour plots of magnetic ripples for the two magnetic configurations of LHD. Upper column corresponds to the case of magnetic axis is set at 3.5m which is one of the inward shifted configurations. This configuration has fine confinement performance and suitable for effective ECRH. On the other hand, lower column shows magnetic ripples when the magnetic axis set at 3.75m which is standard magnetic configuration of LHD. This configuration may be more suitable from the viewpoint of the ECCD efficiency because it hardly has magnetic ripple near the magnetic axis. So, the improvement of the efficiency degradation due to trapped electrons can be expected. However, only 84GHz gyrotoron is available in this configuration by the limit of achievable magnetic field strength. As shown in the Fig.2, magnetic ripples are more enhanced in the peripheral regions. Unfortunately, it is not compatible that to inject electron cyclotron waves with large $N_\parallel$ component and to deposit it near the magnetic axis where magnetic ripples are weak since strong Doppler up-shift is induced. To inspect more rigorously, we have to solve the Fokker-Planck equation under the 3-dimensional LHD configuration.

To try higher power ECCD experiments, the survey of optimum condition under the inward shifted configuration is considered in this paper.

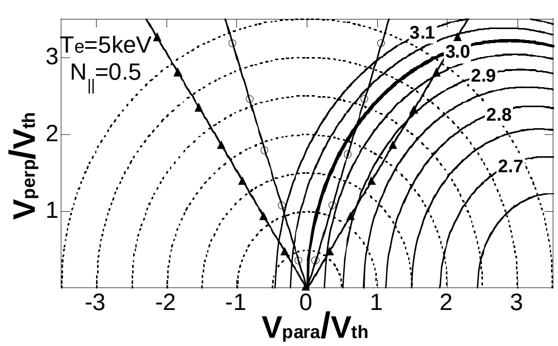

Fig.1. Resonance curves in the velocity space. Here, electron temperature, parallel refractive index, harmonic number and wave frequency are set to 5keV, 0.5, 1 and 84GHz respectively. Numerics on the lines indicate magnetic field strength.

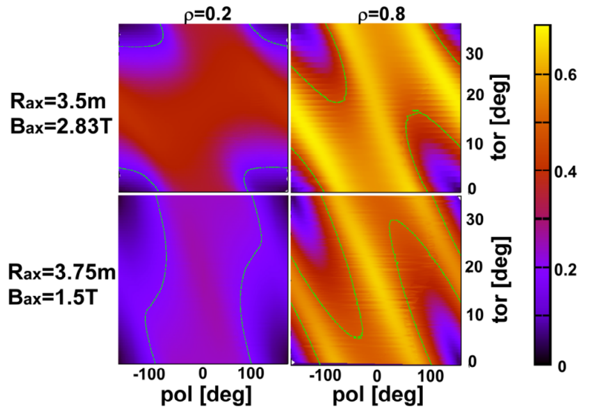

Fig.2. The profiles of magnetic field strength normalized by the maximum value on the each flux surfaces. Zero of toroidal and poloidal angles correspond to vertically elongated cross section and inside of equatorial plane respectively.

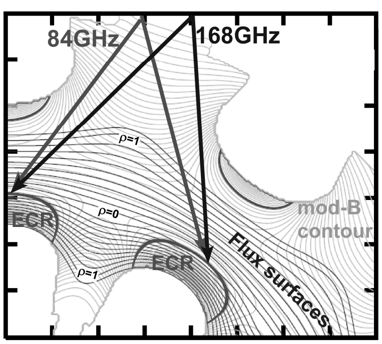

Fig.3. The ECCD configuration by using 2O-port antenna. Two gyrotrons whose frequencies are 84 and 168GHz are connected to the port.

To investigate optimum incident angle for ECCD, a ray-tracing calculation is carried out. Ray-tracing is a sophisticated technique, providing quite a little insights on wave-propagation and absorption in dispersant fusion plasmas. Its condition of validity called WKB approximation is the following.

$$|\nabla k| \ll k^2$$

Electron cyclotron waves in the wavelength range of millimeters are sufficiently adequate for existing fusion research machines. Ray-tracing code had developed for ECRH in the 3-dimensional magnetic field structure of LHD, but by that code quasi-perpendicularly propagating waves with respect to magnetic field lines in weakly relativistic thermal plasma can only be treated [7]. Therefore existing ray-tracing code is extended in order to deal with obliquely propagating waves. Under the propagation angles satisfying following condition,

$$N|\cos\theta| > |1 - l\Omega/\omega|; \quad v_t/c;$$

the relativistic down shift of the cyclotron frequency can be neglected because Doppler effect become dominant. Where θ and v_t mean propagation angle with respect to magnetic field lines and electron thermal velocity, respectively. So, we can use absorption coefficients obtained from the non-relativistic dielectric tensor for a hot Maxwellian plasma [8]. In this frame, power absorption line is decided using the conventional Fried-Conte function described by

$$Z(\zeta) = i\sqrt{2}\exp(-\zeta^2)\int_{-\infty}^{\sqrt{2}i\zeta}\exp(-t^2/2)dt$$

which can be calculated numerically. Here, an argument ζ is defined as follows.

$$\zeta \equiv c(\omega - \omega_c)/(\sqrt{2}v_t\omega N\cos\theta)$$

The 2O-port antenna installed the horizontally elongated cross section of LHD is suitable for ECCD because it can swing the beam to toroidal directions widely. From this port, we aim a beam at magnetic axis of neighbor vertically elongated cross sections as shown in Fig.3. According to the Fisch-Boozer theory, plasma currents by ECCD are supposed to be driven to clockwise/counterclockwise directions corresponding to the beam injection to counterclockwise/clockwise directions respectively.

Fig.4 shows parameter changes along the central ray obtained from multi ray-tracing calculation applied to 84GHz beam from 2O-port antenna [9]. Here, the magnetic axis of 3.5m and average magnetic field strength of 2.829T is employed and beam is aimed at magnetic axis of vertically elongated cross section. In this configuration, on-axis ECCD will be possible because the power of electron cyclotron waves almost absorbed within the ρ=0.2.

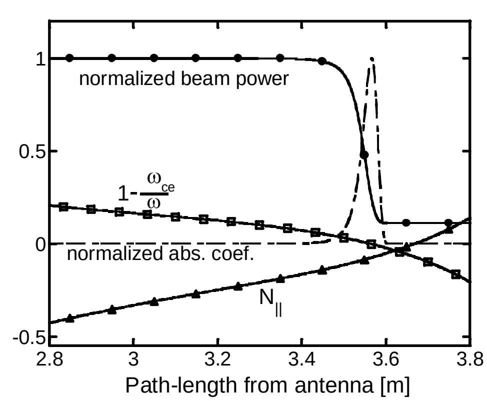

Fig.4. Ray-tracing result for the fundamental O–mode ECCD obliquely injected from 2O-port antenna.

3. Experimental results and discussion

In LHD, ECCD is tried using 2O port antenna at the magnetic configuration of Rax=3.5m. Magnetic field strength, injection angle and wave polarization [7-8] are optimized based on oblique ray-tracing code as mentioned above. Target plasma is sustained by only ECRH to omit NBCD effects and ECCD is superposed to the target plasma from 0.25s to 0.75s. Fig. 5 shows comparison of temporal evolutions of total plasma currents measured with Rogowski coil. Bootstrap current is contained in the total plasma currents, but that contribution is weak judging by balanced ECCD discharge. For Co- and Ctr-ECCD discharges, directions of driven plasma current are consistent with linear theory. Therefore authentic plasma current control by ECCD is demonstrated successfully. However, absolute values of plasma currents are still very low because of high electron temperature which leads to huge L/R time compared with ECCD duration. So some extent of the driven current may be cancelled by the induced back electromotive force. However, certain shifts of polarization angle which reflect changes of rotational transform are observed by the motional Stark effect polarimetry [10] as shown in the Fig.6. This result very encourages us to control magnetic field structure and then improve confinement capability of LHD plasma. However, further experiments are needed with higher power and longer pulse duration time to impact drastically the plasma performance through the modification of plasma current profile and magnetic field structures.

4. Summary

With a view to control of plasma current and magnetic field structure in LHD, the application of ECCD is considered in detail and actually tested. The inversion of directions of plasma currents is clearly observed. So plasma current control by ECCD is successfully demonstrated for the first time in LHD because this inversion is consistent with conceptual prospect. ECCD will be expected as an indispensable tool in order to improve plasma performance.

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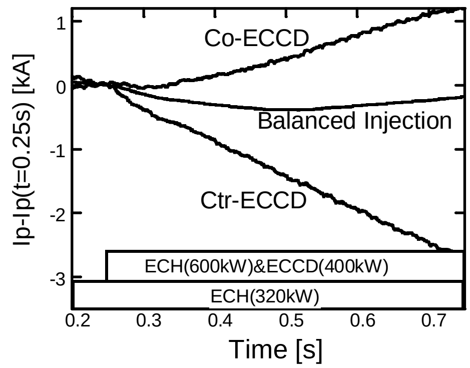

Fig.5. Temporal evolution of the total plasma currents. Plasma currents are normalized by the values at the ECCD is injected (t=0.25s.)

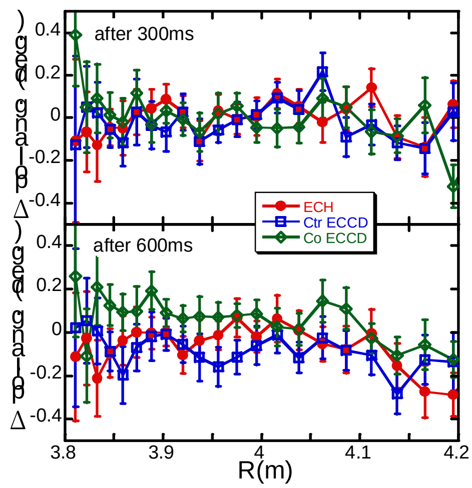

Fig.6. Change of polarization angle during ECCD diagnosed by MSE polarimetry measurement.

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