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Control of Rotational Transform by ECCD in Heliotron J
ヘリオトロンJにおけるECCDを用いた回転変換制御

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Second harmonic 70GHz X-mode electron cyclotron current drive (ECCD) is studied for control of rotational transform profile in the Heliotron J device. Ray-tracing calculation results using TRAVIS code show that the current position can be varied from on-axis to off-axis while keeping the total current constant by choosing the magnetic field strength and/or changing the poloidal angle. A localized EC driven current of a few kA is enough to change the rotational transform profile. The time evolution of rotational transform is calculated by solving a current diffusion equation. At the initial ECCD phase, the opposite current flows around the magnetic axis due to induced electric field, reducing the rotational transform for co-ECCD.

1. Introduction

Noninductive current plays an important role in the realization of high-performance plasmas and the sustainment of steady-state plasmas in toroidal fusion devices. In stellarator/heliotron (S/H) systems, no Ohmic current is required for equilibrium since the confinement magnetic field is generated by external coils. However, it is known that noninductive current flows as well as in tokamaks. Both bootstrap and neutral beam currents modify the rotational transform profile, thereby affecting the equilibrium and stability.

Electron cyclotron current drive (ECCD) is recognized as being a useful scheme for stabilizing MHD instabilities. In S/H systems, ECCD is expected to be an effective current drive scheme to suppress the noninductive current and to tailor the rotational transform profile, particularly in low-shear devices. We demonstrated that a net zero current state was maintained by cancelling the bootstrap current with ECCD [1]. In this paper, we discuss control of rotational transform profile by using ECCD in Heliotron J.

2. ECCD Experiment

Plasmas are produced and heated by a 70-GHz second harmonic X-mode ECH in Heliotron J. We have recently installed an upgraded EC launching system in order to extend the controllability of EC driven current [2]. The steerable mirror enables us to change the beam angle flexibly in the toroidal and poloidal directions. A low power test shows that the beam radius of $1/e^2$ power is 3 cm at the magnetic axis, smaller than the minor radius, $a \sim 17$ cm, and the available $N_{\parallel}$ ranges from -0.05 to 0.6.

ECCD experiments have been conducted in the Heliotron J [3, 4]. The maximum ECH power is 350 kW, and the pulse length is up to 140 msec. The EC driven current is experimentally estimated by excluding the bootstrap current from the total current. The experimental results show that the EC driven current can be controlled by $N_{\parallel}$ and depends on the magnetic configuration. The maximum EC driven current is attained when the EC power is deposited nearly at the top of the magnetic ripple, and the EC driven current is nearly zero independent of $N_{\parallel}$ when the EC power is deposited near the bottom of the magnetic ripple. The experimental results including the B and $N_{\parallel}$ dependences agree with ray tracing simulations using the TRAVIS [5] code in which the parallel momentum conservation with trapped particle effect is considered. Comparing between the collisional and collisionless limit models indicates clear influence of trapped electrons on the ECCD.

3. Control of Rotational Transform Profile

3.1 Dependence on EC current profile

The EC driven current observed in the experiment is of the order of a few kA in the Heliotron J. However, it is large enough to modify the rotational transform profile and to suppress net current. Modification of the rotational transform profile is estimated by using the EC current calculated by the TRAVIS code. For simplicity, we assume that the plasma is cylindrically symmetric. The calculation shows that the EC current profile is localized within the radial width of $\Delta r/a < 0.1$ at the resonance position and the peak position can be changed from on-axis, r/a=0.0, to off-axis, r/a=0.4, by the poloidal injection angle of EC waves or the magnetic field strength with keeping $N_{\parallel}$ fixed.

Figure 1 shows calculation results on steady-state rotational transform profiles with ECCD. For co-ECCD, the rotational transform has a local maximum, forming a negative magnetic shear. On the other hand, ctr-ECCD decreases the rotational transform, forming a positive magnetic shear. Formation of the sheared rotational transform profile is expected to affect MHD instabilities such as interchange modes and Alfvén eigenmodes, which have been observed in NBI plasmas of Heliotron J.

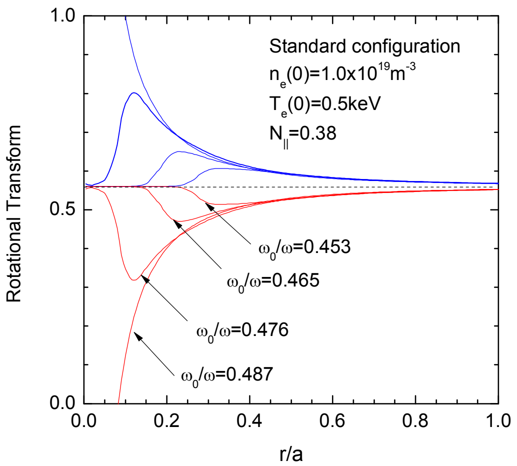

Fig.1 Rotational transform profiles modified by ECCD

3.2 Time evolution of rotational transform profile

The time evolution of rotational transform is estimated by solving the following one-dimensional current diffusion equation.

$$\mu_0 \frac{\partial I_p}{\partial t} = 4\pi S \frac{\partial}{\partial S}\left\{ \frac{1}{\sigma}\frac{\partial}{\partial S}\left(I_p - I_{NI}\right)\right\}$$

Here $I_p(S)$, $I_{NI}(S)$, S and σ are the total current, noninductive current, $S=\pi r^2$, electrical conductivity, respectively. Figure 2 shows an example of time evolution of rotational transform. The current diffusion time is about 100 msec for these plasma parameters. At the initial phase of ECCD, the electric field is induced at the magnetic axis, reducing the rotational transform. It takes the current diffusion time to reach the steady state.

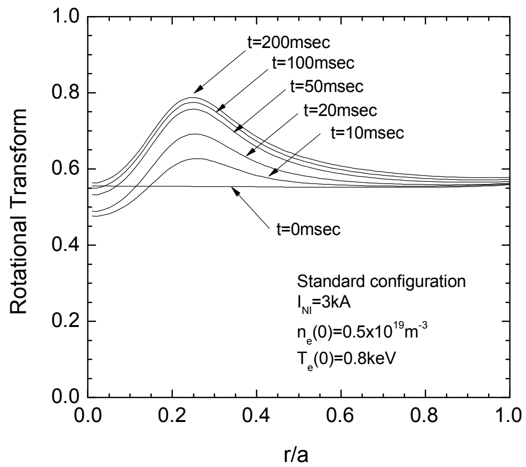

Fig.2. Rotational transform profile EC current density profiles calculated by TRAVIS code

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