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Monte-Carlo simulation of electron cyclotron current drive in NTM magnetic islands

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1. Introduction

The control of neoclassical tearing modes (NTMs) is considered as one of the most important issues of burning plasmas such as ITER. The electron cyclotron current drive (ECCD) attracts much attention as an effective method for stabilization of NTMs. Recently, by taking advantage of highly localized driven current by ECCD, experiments of the ECCD inside a magnetic island in phase with the toroidal rotation of magnetic island are expected.

The current driven by EC waves is evaluated by a spacial profile of EC power deposition and deformation of velocity distribution. As a conventional numerical method, the EC power deposition is calculated by a ray tracing method and the velocity distribution is evaluated by a bounce-averaged Fokker Planck (FP) equation. In the analysis of bounce-averaged FP equation, the magnetic field is assumed to be axisymmetric. When the magnetic islands are formed by NTMs, however, this assumption becomes incomplete and the validity of ECCD analysis based on the bounce-averaged FP equation becomes questionable. Because the electron motion is close to the magnetic field line and may be strongly dependent on the structure of magnetic surfaces. In this paper, the ECCD in the magnetic island is studied on the basis of electron drift motion with Coulomb collisions and velocity diffusion by the EC waves.

2. Simulation model

We use the following simulation model as a first step of the study. The electron motions are followed by the non-relativistic drift orbit equation with non-relativistic Coulomb collisions and the quasi-liner velocity diffusion due to EC waves, which are described by Monte-Carlo techniques. In this study, the problem is treated as a test particle problem. The simulation is performed by an adapted code for electron orbit from the orbit following Monte-Carlo code for ion orbit with ion cyclotron resonance heating [1].

The plasma configuration is assumed as follows: the poloidal cross section is circular, the major radius is 3.5m, the minor radius is 1m, the toroidal magnetic field is 2T, and the q-profile is $q(\rho) = 0.75 + \rho^2$, where ρ is the normalized radius. The magnetic island of $m/n = 1/1$ is located around the $q = 1$ rational surface at the radial location $\rho = 0.5$. The magnitude of helical field is assumed to be about 9% of poloidal magnetic field. Though we treat here the $m/n = 1/1$ mode magnetic island, present results are applicable universally to any m/n mode.

The bulk plasma parameters are assumed to be flat, $n_e = n_i = 3\times10^{19}\mathrm{m}^{-3}$ and $T_e = T_i =$

10keV. Test electrons are initially generated according to uniform spatial profile and the Maxwell velocity distribution of 10keV.

Figure 1 shows the helical magnetic surfaces in the magnetic islands. In order to specify the helical magnetic surface, we introduce a coordinate ξ. The definition of ξ is $\xi = \sqrt{S/S_X}$, where S is the area surrounded by poloidal cross section of magnetic surface and the suffix "X" indicates the separatrix of the island. The O-point of magnetic island corresponds to $\xi = 0$. We assume that electrons resonate with the EC waves, when they pass through the area of $\xi < 0.2$ at the specific toroidal position. The simulation is performed in two cases. One is that the O-point of EC resonance region is located at the high field side (HFSR) and the other is that the O-point of resonance region is located at the low field side (LFSR). In this paper, the toroidal rotation of the magnetic island is not taken into account for simplicity.

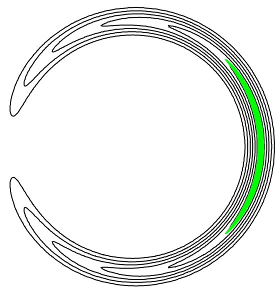

Figure 1: Helical magnetic surfaces. The area of $\xi < 0.2$ is shown by green.

3. Simulation results

Figure 2 shows the time evolution of the absorbed EC power P(blue), the driven current I(green), and the current drive efficiency I/P(red). In order to show the characteristic of ECCD in the magnetic island shown in (a) and (b), we also show the results of ECCD in an axisymmetric magnetic field without islands in (c) and (d). The HFSR cases are shown in (a) and (c) and LFSR cases in (b) and (d).

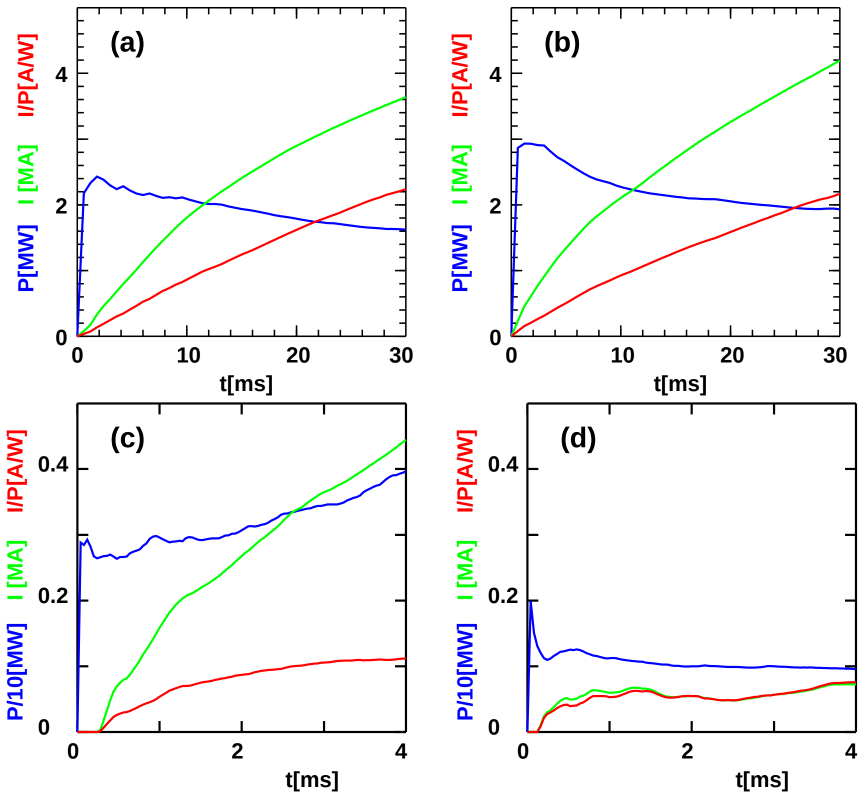

Figure 2: Time evolution of ECCD. The absorbed power P, driven current I, and efficiency I/P are shown by the blue, green, and red curves, respectively. (a) and (b) are the cases of ECCD in the magnetic island. (c) and (d) are the cases of no island. (a) and (c) are HFSR case and (b) and (d) are LFSR case.

In the case of no

magnetic island, the current drive efficiency of LFSR is reduced from that of HFSR due to trapped particle effects. The current drive efficiency tends to saturate after 2ms, since the acceleration of particle speed by EC waves is balanced by the slowing down due to Coulomb collisions. According to the nonlinear bounce averaged FP code [2], the current drive efficiency is evaluated as about 0.18. Major cause of the difference between the efficiencies of simulation and the FP calculation is the treatment of Coulomb collisions. In the FP calculation, the electron momentum is conserved for the electron-electron collision. On the other hand, in the simulation, test electrons collide with the bulk electrons and the momentum is lost from the system of test electrons.

For the case of ECCD in the magnetic island, the current drive efficiency is not much dependent on the location of EC wave resonance (see Fig. 2(a) and (b)). The increasing of driving efficiency continues up to 30ms and the current drive efficiency exceeds 10 times of axisymmetric case. The increasing of efficiency may continue up to the relativistic region.

The driven current density is shown as a function of ξ in Fig. 3 for the HFSR (a) and the LFSR (b). In this figure, thin curves indicate the time variation and the red curves correspond to $t = 30$ ms in the Fig. 2(a) and (b). The driven current is mainly confined inside the helical magnetic surface $\xi < 0.2$ where electrons absorb the EC waves. The transit electrons move almost along the magnetic field line. Therefore, the transit electrons in this region pass through the EC resonance area many times continuously. The magnetic island acts like a rational volume on these transit electrons. In the axisymmetric configuration, however, the population of electron on a rational surface is negligibly small because there are innumerable irrational surfaces in both side of the rational surface. The current outside the EC resonance region ($\xi > 0,2$) is carried by the slowing down electrons which are diffused from the EC resonance region.

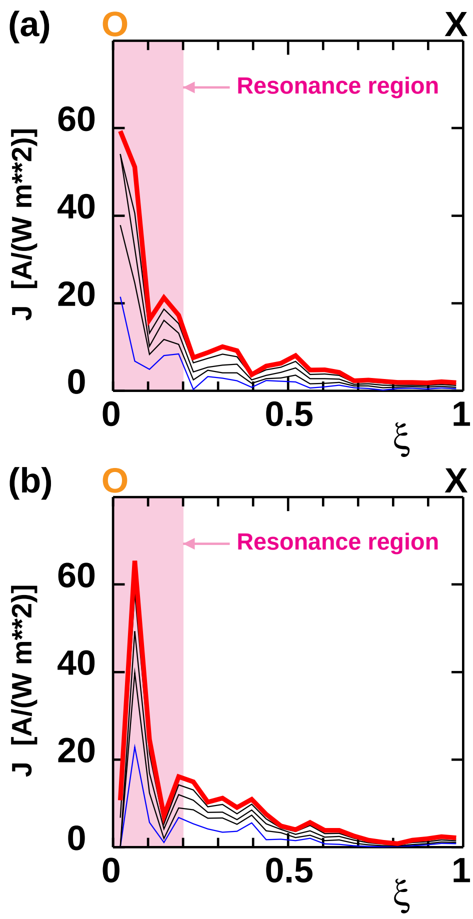

Figure 3: Driven current density as function of ξ (a) is HFSR and (b) is LFSR.

The current densities of HFSR and LFSR show very different shapes around the O-point($\xi = 0$). When a electron resonates with the EC waves on the O-point in the high field side, its orbit does not leave the magnetic field line of O-point. And this electron remains an untrapped electron. Therefore the current density of HFSR peaks at the O-point. On the other hand, when a transit electron on the O-point in the low field side can be trapped by the EC waves, its orbit leaves the magnetic field line of O-point. And consequently, the current density profile becomes hollow.

Figure 3 is the result observed at a certain toroidal position. However, this result does not depend on the toroidal position, i.e., the driven current peaks along the magnetic field line of O-point. The driven current profile of HFSR against the poloidal angle θ is shown in Fig. 4 by shifting the toroidal position. The EC resonance region is indicated by colored region in Fig. 4(a). The magnetic island forms a helical driven current profile like “SNAKE”. In the case of LFSR, a similar profile is also obtained.

4. Summary and discussions

To study the ECCD in the tokamak configuration with the magnetic island, electron drift orbits are followed with Coulomb collisions and velocity diffusion by the EC waves. It is found that the current drive efficiency in the magnetic island is much larger than the efficiency without the island. In this study, the toroidal rotation of magnetic island are not considered. The study of its effect is left for the future plan.

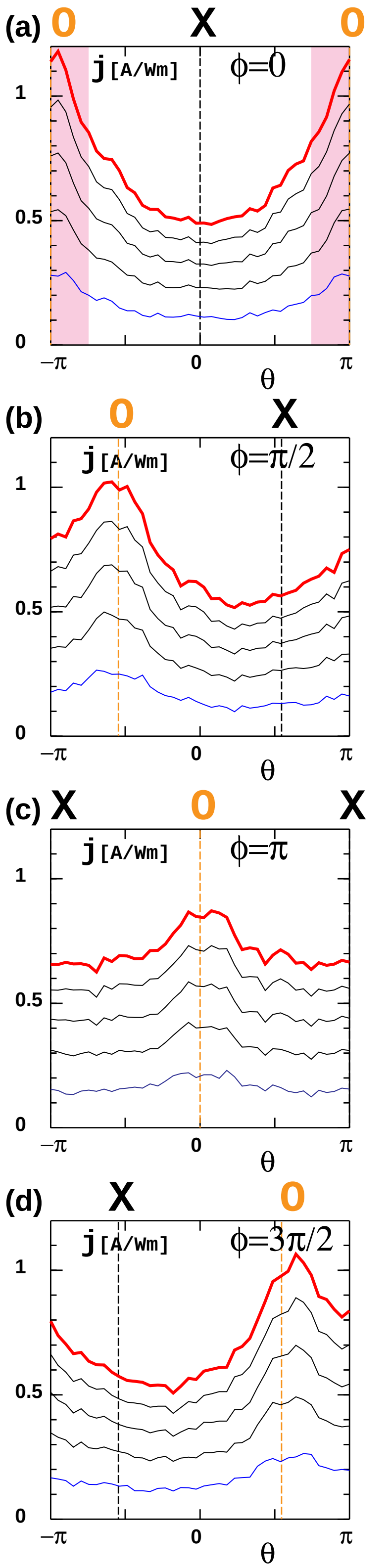

Figure 4: Driven current profiles as functions of poloidal angle θ

References

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