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Effect of Resonant-to-Bulk Electron Momentum Transfer on the Efficiency of Electron-Cyclotron Current Drive

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Abstract

Efficiency of current drive by electron-cyclotron waves is investigated numerically by a bounce-averaged Fokker-Planck code to elucidate the effects of momentum transfer from resonant to bulk electrons, finite bulk temperature relative to the energy of resonant electrons, and trapped electrons. Comparisons are made with existing theories to assess their validity and quantitative difference between theory and code results. Difference of nearly a factor of 2 was found in efficiency between some theory and code results.

Introduction

Among various current-drive schemes for tokamaks, electron-cyclotron current drive, (ECCD) is considered to be a viable option for a steady state tokamak reactor. Many studies, both analytical and numerical, have been carried out and their results are currently applied to assess the feasibility of ECCD in reactor-grade plasmas. The most important parameter for that purpose is the efficiency of current drive given by \( \eta = n_{20}IR/W \) where \( n_{20} \) is the local electron density in units of \( 10^{20} \text{ m}^{-3} \), \( I \) is the driven current in amps, \( W \) is the power required in watts, and \( R \) is the major radius in m.

In most of the analytical works, an expression for the efficiency is obtained by assuming the bulk electron temperature to be much smaller than the energy of resonant electrons. In addition, a linearized collision operator is employed to make analysis tractable. The work of Karney and Fisch\(^1\) does not require these two assumptions, though it still requires numerical solution of a differential equation. Their differential equation is, however, much simpler to solve than the original Fokker-Planck equation.

When the effect of trapped electrons has to be taken into account, a Karney-Fisch approach is difficult. Cohen’s\(^2\) work includes the effect of trapped electrons, but it still makes two assumptions mentioned above.

According to a numerical study by Smith et al.\(^3\) of ECCD efficiency for ITER (International Thermonuclear Experimental Reactor), the optimum efficiency is realized for the resonant electron energy is about 1 to 3 times the bulk temperature.

The purpose of our study is to elucidate the difference between a linearized and a fully nonlinear collision operator, the effect of finite bulk temperature, and the effect of trapped particles on current-drive efficiency. In this report we only consider weak rf cases so that the distortion of the electron distribution is small and the efficiency is independent of the
rf strength. We use $\ln \Lambda = 15$ for both electron-electron and electron-ion collisions, and ion charge number $Z = 1$.

We employ a bounce-averaged Fokker-Planck code, SMOKE$^4$, to obtain current-drive efficiency numerically and compare the results with existing analytical results.

Effects of Momentum Transfer and Finite Bulk Temperature

We consider driving current near the magnetic axis of a tokamak (or in a uniform plasma). In this case, we can ignore trapped particles, i.e., no bounce-averaging is necessary. To illustrate the effects of interest here, we fix the values of $Y = \Omega / \omega$ and $N_\parallel = c k_\parallel / \omega$ and vary the bulk electron temperature. The resonance curves are fixed in phase space. We chose $Y = 0.8$ and $N_\parallel = 0.7893$, which give the minimum resonant energy $\epsilon^* \simeq 25\text{keV}$ as shown in Fig. (1). We also assumed that only the parallel electric field is non-zero (O-mode type). The results of calculations by the Fokker-Planck code are shown in Fig. (2) along with the results of Karney and Fisch (K-F Theory)$^1$ and Cohen$^2$. One set of code results is from the use of a linearized collision operator and the other from the use of a fully nonlinear collision operator. We have used a non-relativistic collision operator but a relativistic treatment is used for the rf. In the range of energy in this study, the difference in the results due to relativistic or non-relativistic collision operators is small.

Figure (2) shows, first of all, that the efficiency calculated with a linearized collision operator can be significantly smaller than that calculated with a full nonlinear operator especially when $T_e / \epsilon^* \approx 1$. This is due to the momentum transfer from the resonant electrons to the bulk electrons.

In the Fokker-Planck equation for electrons,

$$\frac{\partial f_e}{\partial t} = C(f_e, f_e) + C(f_e, f_i) + Q(f_e), \quad (1)$$

$Q(f_e)$ is the quasilinear rf term and the first term can be approximated as,

$$C(f_e, f_e) = C(f_m, \delta f) - C(\delta f, f_m) \quad (2)$$

by putting $f_e = f_m + \delta f$, where $f_m$ is a Maxwellian. The second term in Eq. (2) is the linear operator and the first term contains momentum transfer from $\delta f$ to $f_m$, which gives rise to the enhancement in the efficiency. Karney and Fisch$^1$ solved Eq. (1) with the approximation Eq. (2) using a Spitzer-Härm function. Their results agree well with the Fokker-Planck code results as shown.

Secondly, we find that the effect of finite bulk temperature relative to the resonant energy is important. The efficiency can differ by a significant factor depending on whether or not
it is taken into account in a theory. This fact is seen by comparing the code results with the linearized operator and the analytical results of Cohen\(^2\). Cohen’s analysis (along with other theories) is based on a linearized operator and an expansion in \(T_e/\epsilon^*\). Therefore Cohen’s result approaches the linearized Fokker-Planck code result as \(T_e/\epsilon^*\) becomes smaller. In fact we see that as \(T_e/\epsilon^* \rightarrow 0\), the efficiencies calculated from the code, linearized or fully nonlinear, and the two theories approach the same value as expected. This study shows that the efficiency calculated with a linearized operator and an expansion in \(T_e/\epsilon^*\) can be off by nearly a factor of 2.

**Trapped-Particle Effects**

Existence of trapped particles degrades the current-drive efficiency because they cannot carry current. The momentum-transfer effect described in the previous section also tends to be negated by trapped particles. Therefore, the efficiency of current drive away from the magnetic axis is expected to be reduced significantly from that at the magnetic axis.

We consider a case of 25keV bulk temperature and the minimum resonant energy of 25keV fixing the value of \(\gamma' = 0.8\) and \(\gamma_{0} = 0.7893\) with localized illumination by microwave power on the outside of a tokamak flux surface. Again, the electric field has only a parallel component. We use a fully nonlinear collision operator. Figure (3) shows the efficiency as a function of \(r/R_0\) where \(r\) is the minor radius of the flux surface and \(R_0\) is the major radius. This figure illustrates the effect of the size of the trapped region, given a temperature and a resonant curve. The degradation of the efficiency is seen to be quite severe as \(r/R_0\) increases.

At present, there is no analytical treatment available for comparison with the results shown in Fig. (3) except in the limit \(r/R_0 \rightarrow 0\) (K-F Theory). Cohen’s analysis is not valid in this case because \(T_e \approx \epsilon^*\).

Let us now turn to a study similar to that shown in Fig. (2). We show in Fig. (4) the efficiency vs. bulk temperature for \(r/R_0 = 0.2\) instead of \(r/R_0 \approx 0\). The difference in behavior of the efficiency when compared with the case with \(r/R_0 \approx 0\) is noteworthy; the efficiency decreases as \(T_e\) increases. Cohen’s results are also plotted to show that the code results agree with them as \(T_e/\epsilon^* \rightarrow 0\). The code also shows that the efficiency calculated with a linearized collision operator is no worse than that with a fully nonlinear operator.

**Summary**

We have numerically studied the effects of trapped electrons, finite bulk temperature, and momentum transfer from resonant to bulk electrons, on the current-drive efficiency of electron-cyclotron waves. The purpose was to quantitatively evaluate the importance of these effects by comparing the code results with the existing theories. In particular, we were interested in the departure of the code results from the analytical results of a bounce-averaged theory of Cohen who used a linearized collision operator and an expansion in
We found that in cases of practical interest the use of a fully nonlinear operator could give efficiency up to a factor of 2 larger than that given by the use of a linearized operator and an expansion in \( T_e/\varepsilon^* \). This is due to the effect of the momentum transfer from resonant electrons to the bulk electrons and of finite \( T_e/\varepsilon^* \). The enhancement was found in cases where there are few trapped particles, and the code results agree well with the theory of Karney and Fisch\(^1\). When the trapped-particle fraction increases, i.e., at large \( r/R_0 \), however, this enhancement vanishes and degradation is observed as \( T_e/\varepsilon^* \) increases.

We also found that the effect of trapped particles is quite severe in degrading the efficiency. However, the results shown in Fig. (3) may be pessimistic because the code results were for cases with absorption localized at the outside of the flux surface, (i.e., where poloidal angle \( \theta = 0 \)). For a more favorable case of \( \theta \approx \pi/2 \), the combined effects of trapped particles, momentum transfer, and finite \( T_e/\varepsilon^* \) are still to be investigated.

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References


3. G.R. Smith, Lawrence Livermore National Laboratory Theory Memorandum, June 1988 (Presentation to ITER Specialists' Meeting on Current Drive and Heating, Garching)


Figure Captions

1. Resonance curve in momentum space for \( Y=0.8 \) and \( N_\parallel = 0.7893 \). The minimum resonant energy \( \varepsilon^* \), is about 25keV.

2. Efficiency vs bulk temperature for \( r/R_0 \to 0 \), \( Y=0.8 \), and \( N_\parallel = 0.7893 \).

3. Efficiency vs inverse aspect ratio for \( T_e = 25 \text{keV}, Y=0.8 \), and \( N_\parallel = 0.7893 \).

4. Efficiency vs bulk temperature for \( r/R_0 = 0.2 \), \( Y=0.8 \), and \( N_\parallel = 0.7893 \).
SMOKE (nonlinear)