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Original Article

Study of Lower Hybrid Current Drive for the Demonstration Reactor

Ali Asghar Molavi-Choobini [a,], Ahmad Naghidokht [b], and Zahra Karami [c]*

[a] *Department of Physics, Faculty of Engineering, Islamic Azad University, Shahr-e-kord Branch, Shahr-e-kord, Iran*
[b] *Department of Physics, Urmia University, Urmia, Iran*
[c] *Department of Engineering, Islamic Azad University, Zanjan Branch, Zanjan, Iran*

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ABSTRACT

Steady-state operation of a fusion power plant requires external current drive to minimize the power requirements, and a high fraction of bootstrap current is required. One of the external sources for current drive is lower hybrid current drive, which has been widely applied in many tokamaks. Here, using lower hybrid simulation code, we calculate electron distribution function, electron currents and phase velocity changes for two options of demonstration reactor at the launched lower hybrid wave frequency 5 GHz. Two plasma scenarios pertaining to two different demonstration reactor options, known as pulsed (Option 1) and steady-state (Option 2) models, have been analyzed. We perceive that electron currents have major peaks near the edge of plasma for both options but with higher efficiency for Option 1, although we have access to wider, more peripheral regions for Option 2. Regarding the electron distribution function, major perturbations are at positive velocities for both options for flux surface 16 and at negative velocities for both options for flux surface 64.

1. Introduction

Lower hybrid current drive (LHCD) is used in a large number of present day tokamaks in order to extend the length of operating pulses beyond what is possible with inductive current drive. Since the absorption of LHCD waves takes place away from the center of the plasma, LHCD also produces a modification of the current profile, which is useful in order to improve the stability of the machine. A major objective of research on current drives in the longer term is to find a way of driving a tokamak reactor in a steady state, while keeping the level of power that has to be recirculated back into the reactor within reasonable bounds.

One of the most crucial and challenging issues of the fusion power plant is the development of reactor scenarios that simultaneously satisfy the requirements of sufficiently high power amplification with the need for a sustainable power exhaust. The main options based on the above issue can also

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* *Corresponding author.*
E-mail address: Aliasghar.molavi64@gmail.com (A.A. Molavi-Choobini).

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be used to design the demonstration reactor (usually called DEMO) which, with respect to commercial power plants, is downscaled to an electrical power production of the order of 1 GW [1]. The DEMO project is currently at the conceptual design stage and consequently, no final configuration is defined. DEMO is hoped to be able to confirm the technological feasibility of fusion power and demonstrate its commercial viability. DEMO will be the first fusion device to export significant amounts of electrical power from fusion [2].

There are two distinct mechanism for the absorption of lower hybrid (LH) waves, one of which, electron Landau damping, is a very effective current drive mechanism. The other mechanism, stochastic ion heating, is not useful for current drive. Most LHCD experiments run in a regime where the wave frequency is above the LH frequency everywhere in the plasma, so the only damping mechanism is Landau damping. Landau damping is favored at low densities and above a certain density threshold there is a transition to ion heating. Also in the regime in which the current drive is effective, nonlinear effects such as parametric decay processes do not appear to play an important role [3].

LH waves have the attractive property of damping strongly via electron Landau resonance on relatively fast tail electrons at (2.5–3) × υ_{Te}, where $\upsilon_{Te} = \sqrt{\frac{2T_e}{m_e}}$ is the electron thermal speed. Consequently these waves are well-suited to driving current in the plasma periphery where the electron temperature is lower, making LHCD a promising technique for off-axis $\left(\frac{r}{a} \geq 0.6\right)$ current profile control in reactor grade plasmas. Indeed off-axis LHCD has already been shown to be an effective tool for optimizing the current profile for access to advanced tokamaks operating modes in JET [4] and JT-60U [5] tokamaks. In addition the RF source frequency can be chosen to be high enough to minimize the parasitic interaction of LH waves with fusion-generated α particles. The relatively high phase speed also minimizes deleterious effects due to particle trapping, which can become important in the periphery. LH waves have been successfully utilized for electron and ion plasma heating, to sustain and ramp-up toroidal plasma current, and to stabilize sawteeth in tokamaks [6]. Current carrying fast electrons are generated by LH waves through parallel electron Landau damping when the resonance condition is fulfilled. Experiments in many tokamaks such as Tore Supra [7], TRIAM-IM [8], FTU [9], JET [10], JT-60U [11], and HT-7 [12] have shown that LHCD is one of the most efficient methods to drive noninductive current in tokamak plasmas. In order to conduct the analysis of the electron distribution function, we must use a one-dimensional Fokker–Planck equation. Axial symmetry around the magnetic field allows the reduction in the complexity of the problem from three to two velocity dimensions. The reduction of velocity dimension from two to one is made under the assumption of the dependence of the electron velocity distribution function on the perpendicular velocity that supposes the electron temperature as a Maxwellian distribution [13]. For the current drive, waves with adequate phase velocity are injected along the toroidal magnetic field to resonate with plasma electrons and raise the energy and momentum of the electrons by the absorption of wave energy with Landau damping. The solution of the Fokker–Planck equation on each flux surface gives the electron distribution function, and hence the current density, on that flux surface. The mechanism is straightforward Landau damping and the experiments are well explained by a balance between wave diffusion of the particles, described by a standard quasilinear term, and collisional slowing down and velocity space diffusion, described by a Fokker–Planck collision term.

The outline of the paper is as follows: in Section 2 we write the Fokker–Planck equation with an additional quasilinear diffusion term that describes the interaction of the waves with the plasma. In Section 3 we present a numerical solution method for the Fokker–Planck equation in brief and we simulate several parameters associated with the lower hybrid wave injection (electrons current, electron distribution function, and phase velocity changes) for two options of DEMO. Option 1 is the DEMO pulsed model, where a transformer drives the main current, and Option 2 is related to *optimistic* DEMO design, pointing at steady-state operations that are at the upper limit of achievable International Thermonuclear Experimental Reactor (ITER) performance. Option 2, compared to its consecutive counterpart (Option 1), entails the most demanding challenges that the fusion community may expect in LHCD system in the coming years [14].

2. Fokker–Planck equation

With increasing energy of plasma particles, Coulomb collisions of plasma particles with each other increase. The effect of such collisions is obtained by adding a quasilinear term to the Vlasov equation, which is called the Fokker–Planck equation and gives a general description of the distribution function changes due to successive collisions. The rate of change of distribution function f due to collisions can be written as:

$$\left(\frac{\partial f}{\partial t}\right)_{coll} = \sum_{s} \frac{4\pi n_s q_T^2}{m_T^2} \left\{ -\frac{\partial}{\partial \upsilon_i}\left(f_T \frac{\partial H_s}{\partial \upsilon_i}\right) + \frac{1}{2} \frac{\partial^2}{(\partial \upsilon_i \partial \upsilon_j)\left(f_T \frac{\partial^2 G_s}{\partial \upsilon_i \partial \upsilon_j}\right)} \right\} \tag{1}$$

in which n_s is the density of typical particles (electrons or ions), q_T is the charge of the test particle, m_T is the mass of the test particle, f_T is the distribution function of test particles, and υ_i is the velocity of particle type i. Functions $G_s(\upsilon)$ and $H_s(\upsilon)$ are auxiliary functions and can be defined as follow:

$$G_s(\upsilon) = \int f_s(\upsilon')(\upsilon_T - \upsilon')d\upsilon' \tag{2}$$

$$H_s(\upsilon) = \int f_s(\upsilon') \frac{(\upsilon_T - \upsilon')}{|\mathbf{v}_T - \mathbf{v}'|^3} d\upsilon' \tag{3}$$

These describe diffusion coefficients are caused by velocity changes in the phase space [15].

2.1. *Solving method of Fokker–Planck equation*

In a strong magnetic field, the electron distribution function has cylindrical symmetry in velocity space, so the problem