KINETIC MODELING OF EC PLASMA HEATING AND CURRENT DRIVE IN THE L-2M STELLARATOR

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Abstract

The regimes of EC plasma heating and current drive in the L-2M stellarator are analyzed theoretically and numerically. A self-consistent model taking into account the modification of both the electron distribution function and spatial attenuation of the microwave beam during EC plasma heating is developed. Results of calculations of the electron distribution function under conditions of EC plasma heating in the L-2M stellarator are presented. It is shown that the effect of the modification of the electron distribution function on the spatial profile of the energy deposition is most pronounced in the case of the on-axis heating, and, for the case of the off-axis heating, this effect is of minor importance. The formation of non-Maxwellian tails in the electron distribution function with the effective temperature several times higher than the initial electron temperature is demonstrated. It is shown that, in the case of an oblique launching of the microwave beam, an efficient current drive occurs. During the microwave pulse, the current density can attain 1 kA/cm^2. The spatial profile of the current density is close to the energy deposition profile.

1. Introduction

The electron cyclotron plasma heating at the second harmonic is characterized by a compact region of the energy deposition. The localization of this region strongly depends on the structure of the magnetic field. The influence of distortion of the distribution function on the spatial profile of the wave absorption could result in displacement of the regions of both the energy deposition and the current drive. Theory and modeling of these effects with reference to stellarators are still in embryonic state. This paper is devoted to the theoretical and numerical study of ECH and ECCD in a stellarator within a self-consistent kinetic model taking into account both the microwave energy absorption and the spatial attenuation of the microwave power.

2. Kinetic Equation

The evolution of the electron distribution function under the combined action of the microwave field and Coulomb collisions is described by the quasilinear kinetic equation

$$\nu_e \tau_b \frac{\partial f}{\partial t} = \frac{\partial}{\partial \varepsilon}\left\langle D_{QL}\right\rangle \frac{\partial f}{\partial \varepsilon} + \frac{\partial}{\partial \eta} D_C \frac{\partial f}{\partial \eta} \ . \qquad (1)$$

Here, f is the electron distribution function averaged over the magnetic surface, t is the time normalized to the collision time $v_e^{-1} = m_e^2 v_{Te0}^3 / 4\pi e^4 n_{e0} \Lambda_e$, and the thermal electron velocity is determined as $v_{Te}^2 = 2\, T_e / m_e$, the subscript 0 refers to the values on the magnetic axis, τ_b is the time between successive passes of an electron through the microwave beam. Angular brackets denote the averaging over the poloidal angle θ. We use the following variables:

$$\varepsilon = m_e c^2 T_{e0}^{-1}\left(\sqrt{1 + p^2 / m_e^2 c^2} - 1\right) , \qquad \eta = \varepsilon - \mu B^* T_{e0}^{-1} \qquad (2)$$

with **p** being the electron momentum, $\mu = p_\perp^2 / 2 m_e B$, and B^* the resonant value of magnetic field for electrons with $\mathbf{p} = 0$. In deriving the expression for $\left\langle D_{QL}\right\rangle$, as well as for τ_b, the helical modulation of the magnetic field along the force line is taken into account; i.e., we take into account both passing and trapped electrons. Nevertheless, the effects related to transport processes are not included into consideration. Consequently, equation (1) contains no terms with spatial derivatives corresponding to classical and neoclassical diffusions. Neglecting variations in parallel velocity of electrons in the course of resonant interaction, for the case of the microwave beam with a Gaussian profile $E_{eff} = E_{eff}^0 \exp(-\rho^2 / \rho_0^2)$, we obtain

$$D_{QL}^{\pm} = \pi \left(\frac{e E_{eff}^0 \rho_0 k_\perp v_{Te}}{4 \omega T_e Q^{1/4}} \right)^2 \frac{(\varepsilon - \eta)^2}{q} \exp\left\{ - \frac{\omega^2 \rho_0^2}{2 c^2 Q} \left(\frac{k_z c}{\omega} \mp \frac{1 - b + 2\gamma\varepsilon}{2\sqrt{\gamma q}} \right)^2 \right\} \ . \qquad (3)$$

Here, E_{eff} is the amplitude of the effective electric field, $b = \ell \omega_e^{nr} / \omega$, ℓ is the harmonic number, $q = v_z^2 / v_{Te0}^2 = \varepsilon(1 - b + \gamma\varepsilon) + b\eta$, $Q = 1 + q^{-1}\left(\partial B / \partial z \cdot \omega \rho_0 / 2 v_{Te} B\right)^2$, $\gamma = T_{e0} / 2 m_e c^2$, and "$\pm$" corresponds to the sign of v_z. The coefficient of collisional diffusion D_C is obtained from the angular term of the full collisional operator [1] by the averaging over the bounce period

$$D_C = \frac{\nu_e J}{T_e \varepsilon^{3/2}} \left(Z + \Phi(\varepsilon)\right)(\varepsilon - \eta) \ . \qquad (4)$$

Here, $J = m_e \oint v_z dz$ is the longitudinal adiabatic invariant, Z is the effective ion charge, $\Phi(x) = \left(1 - 1/2x\right)\mathrm{M}(x) + \mathrm{M}'(x)$, and $\mathrm{M}(x) = 2\pi^{-1/2} \int_0^x \sqrt{t} e^{-t} dt$.

3. Numerical Model

We consider ray trajectories to be straight lines. The local coefficient of spatial damping $\kappa = P^{-1}\, dP/dx$ is assumed to be constant on a given field line within the microwave beam aperture. This means that the Gaussian profile of the microwave beam along the *z*-axis is conserved in the course of the beam propagation in the plasma, which complies with the approach for the deriving of (3). The knowledge of quasilinear diffusion coefficient (3) allows the calculation of the power absorbed by electrons with the pre-calculated distribution function on the selected magnetic surface

$$\kappa = -\frac{2\pi b T_{e0}^3}{m_e^2 \int P dz} \sum_{v_z = \pm|v_z|} \iint D_{QL} \frac{\partial f}{\partial \varepsilon} d\varepsilon d\eta \ , \tag{5}$$

where P is the density of the microwave energy flux. Thus, the power absorbed by electrons and the damping of the microwave field are calculated consistently for each field line.

4. Numerical calculations

When testing the code, we use the parameters of the magnetic field, plasma, and microwave beam typical of the EC heating experiments (*X-2* wave) in the L-2M stellarator [2]. The values of plasma parameters on the axis are $n_{e0} = 1.7 \cdot 10^{13}$ cm^{-3}, $T_{e0} = 1\,\mathrm{keV}$; $n_e = n_{e0}\left(1-\left(r/a\right)^6\right)$, $T_e = T_{e0}\left(1-\left(r/a\right)^2\right)$, $a = 11$ cm, and $Z = 2$. It is assumed that the microwave beam with the effective radius $\rho_0 = 2.75$ cm, $\omega = 4.8 \cdot 10^{11}$ s^{-1}, $k_z/k = 0.1$, and the power $W = 230\,\mathrm{kW}$ is launched in a horizontal plane from the outer side of the torus. Calculations show that, in the range of super-thermal electron energies, an anisotropic non-Maxwellian tail in the electron distribution is formed. At the same time, the distribution of thermal electrons is nearly isotropic. This means that the EC heating is accompanied by a current drive. The current density gradually increases and attain a value of 1 kA/cm^2 by the end of the microwave pulse ($t = 2$ ms) on the magnetic surface on which the energy deposition is maximum. Distortion of the distribution function during ECH leads to a displacement of the region of the efficient energy deposition towards the higher magnetic field, because, in the resonance region ($B = B^*$), the electrons gain high energies and get out from the resonance due to a relativistic decrease in the gyrofrequency. At the same time, behind the resonance ($B > B^*$), an increase in the electron energy results in more efficient resonant interaction between the microwave beam and the electrons. The calculations show that, under the given conditions, this effect is insufficiently pronounced to cause a noticeable increase in the plasma transparency in course of ECH. In Figs. 1 and 2, the radial profiles of the energy deposition (averaged over the poloidal angle θ) are shown for $B^*/B_0 = 1.0$ and $B^*/B_0 = 0.97$, respectively. Dashed lines correspond the profiles at the beginning of the microwave pulse, and solid lines are for the profiles at $t = 2$ ms. Note that, in the regime of the off-axis heating, the distortion of the electron distribution only slightly affects the radial structure of the energy deposition, whereas, in the on-axis heating regime, it leads to an appreciable decrease in the energy deposition at $r = 0$.

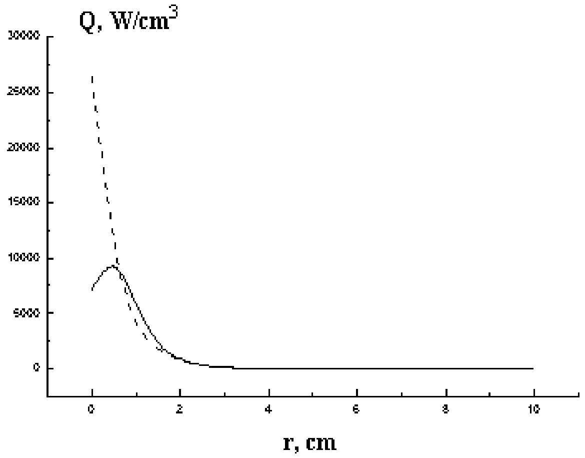

Fig. 1. Radial profiles of the energy deposition B^*/B_0=1.0

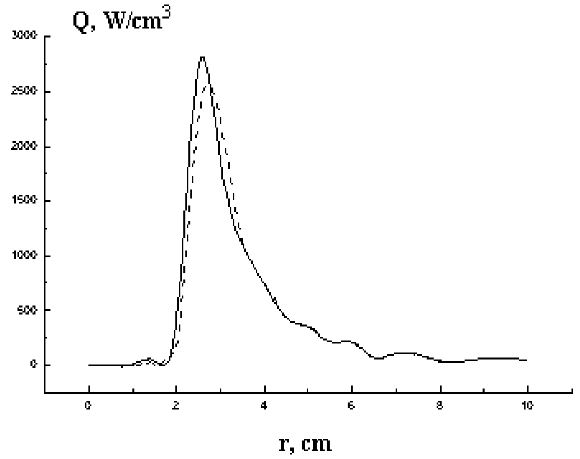

Fig. 2. The same as Fig.1 but B^*/B_0 = 0.97

Calculations show that, in the model used (i.e., in the absence of the radial energy transport), an increase in the mean electron energy occurs in a relatively small interval in *r* corresponding to the maximum energy deposition. Mean energy increases approximately by a factor of 2.1 in both the off-axis and on-axis heating regimes. The current drive is maximum in region of the efficient energy deposition. The peak current densities are almost the same for both off-axis and on-axis heating regimes.

References

[1] L.M. Kovrizhnykh: Nucl. Fusion **24**, 851, 1984.

[2] S.E. Grebenshchikov: Trudy IOFAN (Proc. Of the General Physics Institute), Moscow, Vol. **31**, p. 37, 1991 (*in Russian*).