Temperature dependence of the efficiency of current drive by lower hybrid waves in the T-7 tokamak

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The efficiency of the current drive by lower hybrid waves in the T-7 tokamak has been measured as a function of the electron temperature. The observed increase in this efficiency with increasing temperature is compared with the prediction of the quasilinear theory, supplemented with the assumption that a mechanism operates to broaden the lower hybrid spectrum in the short-wave direction.

How the efficiency of the current drive by lower hybrid waves in a tokamak depends on the electron temperature is of fundamental importance for the possible use of this method in a reactor. The efficiencies which have been achieved experimentally to date (Refs. 1–3, for example) are too low for a reactor. The original theory on the mechanism for the current drive[4] predicts no change in the efficiency as we scale up from the temperatures typical of the experiments being carried out today, $T_e \sim 1$ keV, to reactor temperatures, $T_e \sim 10$ keV. On the other hand, analysis of the experimental results suggests that this theory is inexact and that under actual conditions the drive efficiency should depend on the electron temperature.

Specifically, it was shown in Refs. 5 and 6 that, in contradiction of Ref. 4, the lower-velocity boundary of the quasilinear plateau on the electron distribution function, v_1, does not coincide with the short-wave boundary of the spectrum of lower hybrid waves which are launched in a plasma from an external source. The probable reason is that a particular mechanism is operating in the plasma to expand the spectrum of lower hybrid waves on the side of lower longitudinal phase velocities. This expansion proceeds to the point at which the rf power being launched in the plasma and transferred by Landau damping to resonant electrons becomes balanced by the power lost by the resonant electrons through Coulomb collisions. In a case in which the entire current is sustained by lower hybrid waves, the value of v_1 can be found from the known current density in the plasma, which corresponds approximately to the condition $q(0) = 1$, from the equation

$$j = \frac{en_e}{\sqrt{\pi}v_{Te}} \frac{v_2^2 - v_1^2}{2} e^{-v_1^2/v_{Te}^2} = \frac{cB}{2\pi R} . \tag{1}$$

Here n_e is the electron density, v_{Te} is the electron thermal velocity, B is the toroidal magnetic field, R is the major radius of the torus, and v_1 and v_2 are the boundaries of the quasilinear plateau on the electron distribution function. For ordinary experimental conditions, Eq. (1) has the approximate solution $v_1 \approx 2v_{Te}$, which depends slightly on other plasma parameters. As a result, a dependence on the electron temperature appears in the expression for the efficiency of the current drive,

$$\eta = \frac{Z_{\text{eff}} + 5}{6} \frac{\bar{n}_e I_{\text{rf}} R}{P + I_{\text{rf}} U} = \frac{m}{18\pi^2 e^3 L} \frac{v_2^2 - v_1^2}{\ln(v_2 / v_1)}, \tag{2}$$

where U is the bypass voltage, $I_{\text{rf}} = I(\Delta U/U_0)$ is the driven current, P is the lower hybrid power, and L is the Coulomb logarithm. It is assumed in (2) that the driven current flows near the axis of the plasma column, where the plasma density is $n_e \approx 1.5 \bar{n}_e$.

In the present letter we are reporting the first results of an experimental test of the dependence of the efficiency η on the electron temperature found in the T-7 tokamak. For this purpose, the apparatus was fitted with a system for electron-cyclotron heating of the plasma, including two gyrotrons operating at a wavelength of 4.6 mm, with a total power of 400 kW. The microwave power was launched on the side of the weaker magnetic field in the form of ordinary waves. The lower hybrid complex of the T-7 tokamak[1] consists of a source with a maximum power of 600 kW, which operates at a frequency of 900 MHz, and a three-waveguide grill with a spectral peak near $N_\parallel = 3$.

The experiments were carried out under three sets of tokamak working conditions. First, with a toroidal field $B = 19$ kG, a plasma current $I = 110$ kA, an effective charge $Z_{\text{eff}} = 2.5$, and a lower hybrid power $P = 40$ kW, the electron temperature was $T_e = 0.8$ keV. Second, with $B = 23$ kG, $I = 180$ kA, $Z_{\text{eff}} = 2.5$, and $P = 180$ kW, the temperature rose to $T_e = 2.3$ keV. Third, with $B = 23$ kG, $I = 180$ kA, $Z_{\text{eff}} = 5$, $P = 180$ kW, and electron cyclotron heating (not used in the first two cases), a temperature $T_e = 3.5$ keV was achieved. The plasma densities in these cases were $\bar{n}_e = (3-7)\times 10^{-12}$ cm^{-3}. The density was measured with a microwave interferometer at a wavelength of 1 mm; the electron temperature and the effective charge of the plasma were determined from x-ray spectroscopy in the energy range 3–10 keV.

The results of the measurements of the drive efficiency under these conditions are shown in Fig. 1. In determining the efficiency η, we assumed P to be the power

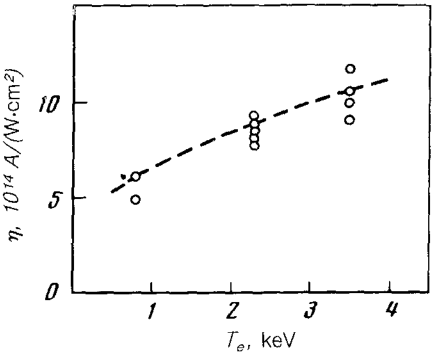

FIG. 1. Efficiency of the current drive by lower hybrid waves as a function of the temperature of the plasma electrons. The dashed line is calculated from expression (2).

launched in the form of the wave traveling in the direction of the electron current motion. According to calculations, this power was $\approx 70\%$ of the total lower hybrid power launched in the plasma in our case. Shown along with the experimental data in Fig. 1, by the dashed line, is the result of a calculation of the temperature dependence of the efficiency from expression (2). We took v_2 to be the typical phase velocity of the lower hybrid wave launched in the plasma; for definiteness, we chose $v_2 = 10^{10}$ cm/s.

It can be seen from Fig. 1 that over the temperature range studied there is a tendency for the efficiency to increase with increasing T_e. This increase agrees within the experimental error with the result calculated from expression (2).

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