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Abstract

It is shown that a small, low-phase-velocity part of a power source spectrum can strongly enhance the amount of the current generated in lower-hybrid current-drive experiments. A good agreement between the calculated and observed current is found.

The generation and maintenance of a continuous toroidal current in a plasma by rf waves has received much attention in view of the interest in the steady-state operation of a tokamak fusion reactor. Recently, efficient current sustainment by lower-hybrid waves has been demonstrated experimentally on a number of tokamaks.[1] One of the principle problems in these experiments is the explanation of the mechanism by which the superthermal electrons are generated by high-phase-velocity waves in a relatively cold target plasma. Specifically, there is considerable discrepancy between the current observed and the much smaller prediction of the "classical" theoretical model of Fisch.[2] Although a number of theoretical models have been proposed to explain the mechanism that would bridge the velocity gap between the waves and the low-velocity electrons, none of them appears to be satisfactory.[3] In this letter we shall show that a small tail at the high-$n_\parallel$ side of a power source spectrum (which is the case in most of the experiments) can largely close the gap.

In order to investigate the dependence of the rf-sustained current on the shape of the power source spectrum we use the following model. The evolution of the electron distribution function is governed by

$$\frac{\partial f}{\partial t} = \frac{\nu}{2} \{ (\frac{1}{v_\perp}\frac{\partial}{\partial v_\perp} v_\perp^2 + \frac{\partial}{\partial v_\parallel} v_\parallel) \frac{1}{v^3} [2+(\frac{2}{v^2} - 1 - Z)(v_\perp \frac{\partial}{\partial v_\perp} + v_\parallel \frac{\partial}{\partial v_\parallel})]$$

$$+(1+Z)(\frac{1}{v_\perp} \frac{\partial}{\partial v_\perp} \frac{v_\perp}{v} \frac{\partial}{\partial v_\perp} + \frac{\partial}{\partial v_\parallel} \frac{1}{v} \frac{\partial}{\partial v_\parallel})\} f + \frac{\partial}{\partial v_\parallel} D \frac{\partial f}{\partial v_\parallel} , \qquad (1)$$

where the term involving $\nu = \omega_{pe}{}^3 \ln\Lambda/(4\pi n v_{te}{}^3)$ represents the electron-electron and electron-ion collisional effects and Z denotes the ion charge state. The quasilinear diffusion coefficient resulting from the resonant Čerenkov interaction between the electrons and the lower-hybrid waves is given by

$$D = \frac{1}{2\pi v_{\parallel}^{3}} \int_{0}^{\pi/2} d(\cos\Theta)\ \cos\Theta\ W(k = v_{\parallel}^{-1}, \Theta). \tag{2}$$

The wave spectrum, W, evolves according to

$$\frac{\partial W}{\partial t} = 2(\gamma - Z\nu/4)W + S(k,\Theta), \tag{3}$$

with the quasilinear damping rate

$$\gamma = \frac{\pi}{2}\frac{\cos\Theta}{k^2} \int d^2v \frac{\partial}{\partial v_{\parallel}} f(v_{\parallel} = k^{-1}). \tag{4}$$

Here, the dispersion relation of the waves is assumed to be $\omega = \cos\Theta$, Θ being the angle between the magnetic field and the wave vector $\vec{k}$. The term S, in Eq. (3), represents the spectrum of an external power source. For simplicity, its form is assumed to be

$$S(k,\Theta) = S(k)\ \delta(\cos\Theta - \cos\Theta_0), \tag{5}$$

$$S(k) = \begin{cases} S & , \quad k_2 < k < k_m \\ \sigma S & , \quad k_m < k < k_1 \\ 0 & \quad \text{elsewhere} \end{cases}, \tag{6}$$

where S and σ are constants, and $\sigma \ll 1$. All the quantities in Eqs. (1)-(6)

are normalized according to $k \to k\lambda_D$, $v \to v v_{te}$, $t \to t/\omega_{pe}$, $f \to fn/v_{te}^3$, and $W \to W 4\pi n T_e \lambda_D^3$.

The equations (1) and (3) were solved numerically using the finite-element method with the additional ansatz: $f = F(v_\parallel)\exp[-v^2/2T(v_\parallel)]/2\pi T(v_\parallel)$. The details of the procedure can be found elsewhere.[4] The distribution function (initially Maxwellian) and the wave spectrum (initially the thermal noise) were advanced in time until the system reached a steady-state. The electron current density was then calculated according to $j = \int v_\parallel F(v_\parallel) dv_\parallel$. In convenient units:

$$I[kA] = 6.66\ n[10^{13}cm^{-3}] T_e^{1/2}[keV] a^2[cm] j, \tag{7}$$

where a is the radius of the current column. The power required to sustain the current is given by:

$$P[kW] = 9.52 \times 10^6\ R[m] a^2[cm] n^{3/2}[10^{13}cm^{-3}]\ T_e[keV] \times S[(k_1^3 - k_m^3)\sigma + k_m^3 - k_2^3]. \tag{8}$$

Before presenting the numerical results we would like to make a few remarks on certain novel features of our model. In previous work[5] the diffusion coefficent, D, was assumed to be a given quantity irrespective of the magnitude of the power source. In our model we do not make any assumption concerning D but self-consistently follow the time evolution of the wave spectrum. Once the steady state is attained the diffusion coefficient becomes a particular function of $v_\parallel$ which depends on the ratio

γ/ν, unless $\gamma \ll \nu$. This ratio, in turn, is determined by the source strength, S, as well as by the location of its lower edge, $(v_\parallel)_1 \equiv v_1 = 1/k_1$, and cannot be assessed a priori. Thus, the self-consistent approach allows us to vary the parameters S, σ, and v_1 over a range of values even where the condition $\gamma \ll \nu$ is not satisfied. In doing so we can optimize σ and v_1 in such a manner that the maximum current is obtained for a fixed power P.

We have performed a series of computations with different values of the parameters S, σ, v_1, and Z while the value of $\cos\Theta_0$ was fixed at 0.7 for convenience. (This choice is immaterial unless the waves are nearly perpendicular.) The values of S and σ were varied in such a manner that the total power was constant. The results presented below were obtained for typical PLT (Princeton Large Torus) parameters[6]: $n = 5\times10^{12}$ cm^{-3}, $T_e = 1$ keV, R = 1.3 m, a = 15 cm, P = 130 kW, $v_m = 7.5$, and $v_2 = 16$. Figure 1 shows the dimensionless current density, j, as a function of σ for three different values of v_1, and Z = 1. For reference, the dashed line indicates a total current of 100 kA. One can see that a tail of the power source spectrum with $\sigma = 0.05$ is able to generate a total current of about 200 kA for $v_1 = 3$. This value is fairly close to that observed in the experiment.[6] Moreover, we observe that the values of the current density for $v_1 = 2$ are smaller than those for $v_1 = 3$ and $v_1 = 4$. This fact indicates that, at the power level considered, Landau damping is still efficient in preventing the formation of a complete plateau on the electron distribution function. A further remarkable feature is the saturation of j as σ is increased over a certain value, typically 0.1. This is due to the fact that an increasing fraction of the total power is transferred into the tail of the spectrum at the expense of its main component. As a result, a partial destruction of the plateau at high velocities occurs. Figure 2 shows the dimensionless current density as a function of σ for three different values of Z, and $v_1 = 3.5$. We note that with increasing Z the current density decreases as $(5 + Z)^{-1}$, in agreement with analytical estimates.[7]

In summary, we have shown that the inclusion of a small tail of a power spectrum in the modelling of lower-hybrid current-drive experiments can provide an explanation for the interaction between the launched waves and the low-velocity electrons. This interaction can reasonably well account for the observed values of the rf-sustained current. Certainly, other mechanisms could be considered in the interpretation of the experiments. However, the explanation we have presented in this letter seems to be the simplest one.

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Figure Captions

Fig. 1 Dimensionless current density vs. the fractional tail strength of the source spectrum for typical PLT parameters and three different values of v_1. The dashed line corresponds to 100 kA of total current.

Fig. 2 Dimensionless current density vs. the fractional tail strength of the source spectrum for typical PLT parameters and three different values of Z; $v_1 = 3.5$.

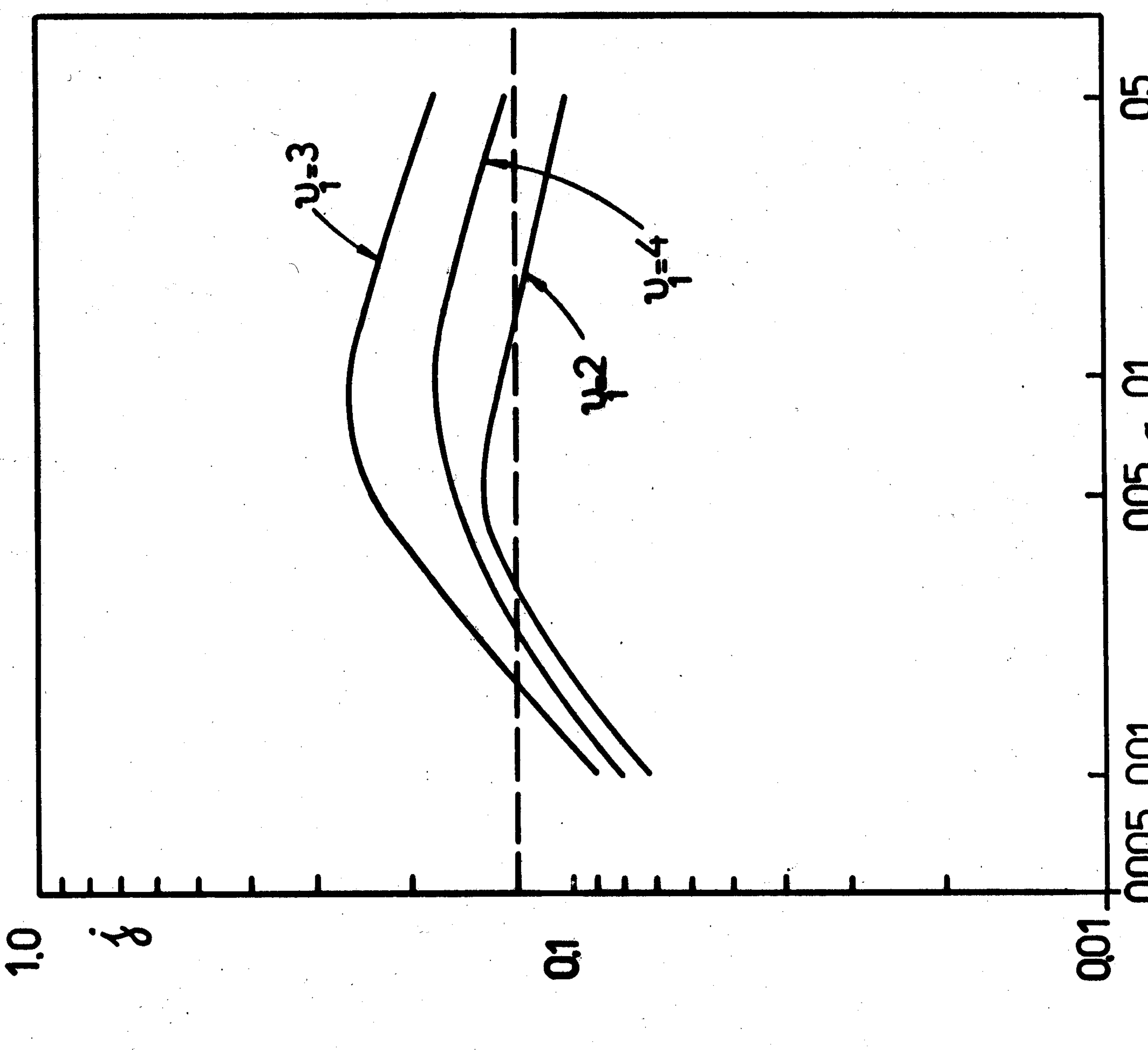

Fig. 1

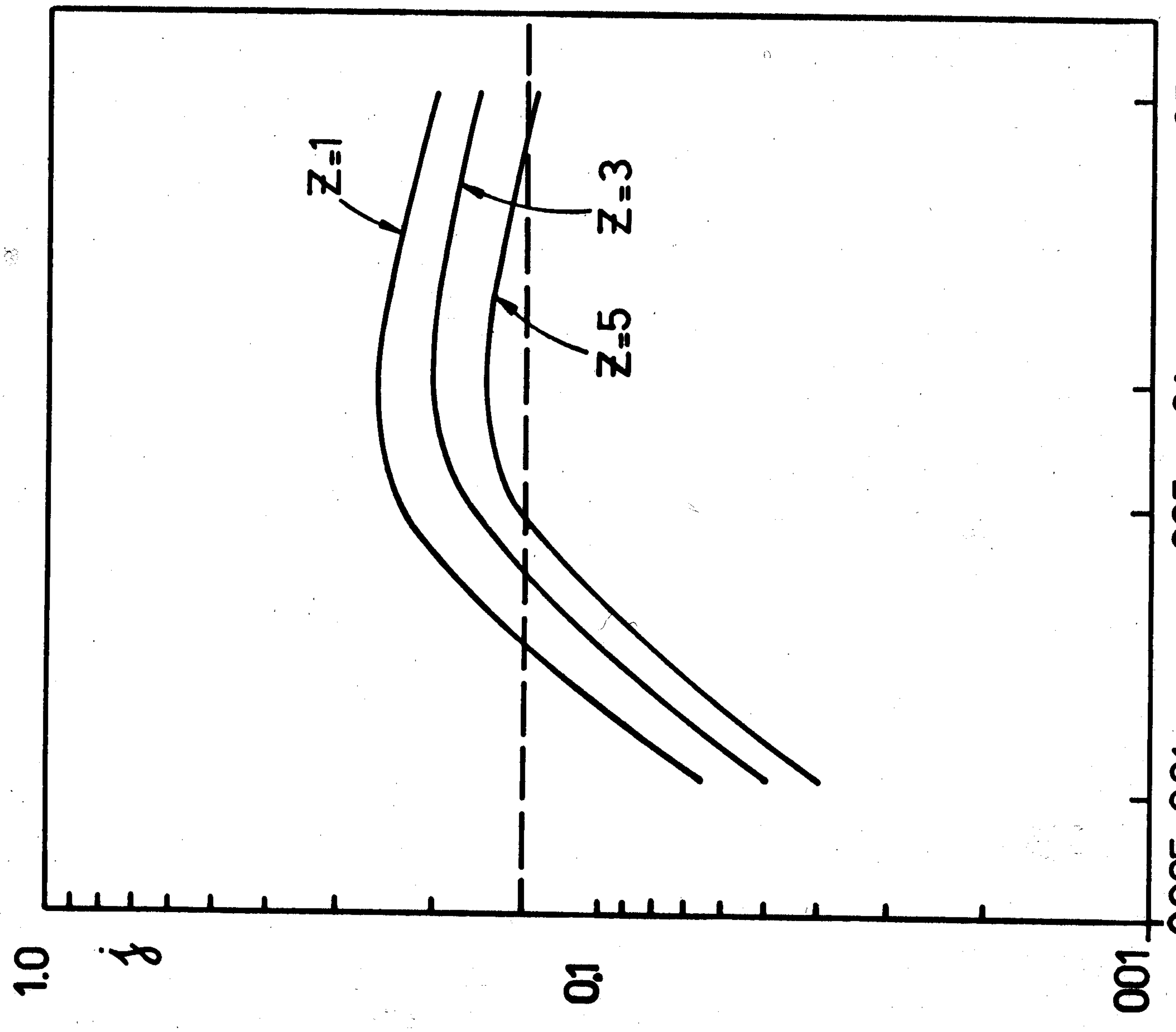

Fig. 2