Lower-hybrid heating of a plasma in tokamaks

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We consider plasma heating by an RF field at frequencies close to the lower hybrid frequency. Calculations are performed for heating by a fast and a slow wave. The spatial distribution of the absorbed power is obtained.

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1. In the usual scheme of the lower-hybrid heating, the energy should be released mainly at the center of the apparatus, owing to the transformation of the electromagnetic wave into a plasma wave.[1-2] Recent experiments with large installations[3] have shown, however, that the greater part of the microwave power is released on the periphery of the plasma pinch. This absorption is most readily due to the development of parametric instabilities.[3-4]

The strong energy absorption due to the collective processes makes it possible, in contrast to the usual scheme, to optimize the characteristics of the heating without tying them rigidly to the existence of a transformation point. We show in this paper that by choosing the frequency, the deceleration, and the type of excited oscillations it is possible to obtain sufficiently uniform heating of the plasma.

2. We consider an isothermal plasma ($T_e \sim T_i$) whose density changes smoothly across the magnetic field. We direct the field along the z axis and the density gradient along the x axis. Let the electromagnetic wave propagate along x and let its energy vary in accordance with the equation

FIG. 1.

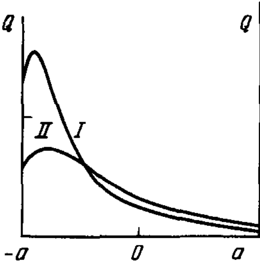

FIG. 2.

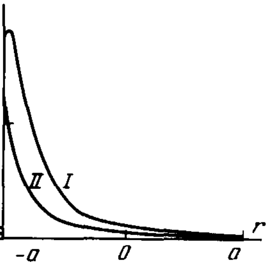

FIG. 1. $P(-a)=3$ kW/cm^2. Curve I corresponds to $\omega = 1.5\omega_{LH}$, $P(a)/P(-a)=0.13$. Curve II corresponds to $-\omega=2.5\omega_{LH}$; $P(-a)=0.29$.

FIG. 2. $\omega=1.5\omega_{LH}$. Curve I corresponds to $P(-a) = 6$ kW/cm^2, and curve II corresponds to $P(-a) = 3$ kW/cm^2; $\alpha=2$.

$$\frac{\partial}{\partial x}(v_{gr}\,\mathcal{E}) = -\gamma\mathcal{E} - Q. \tag{1}$$

The energy influx into the plasma due to the parametric instabilities was determined in[6]. If the rather easy condition $\omega_H > \omega_p$; $\omega_p^2 > \omega\omega_H$ is satisfied, then

$$Q = \begin{cases} 0.1\dfrac{\omega_p^4 E_x^2}{\omega\omega_H^2\, 8\pi n T}\left(\dfrac{E_x^2}{8\pi} - \dfrac{E_{th}^2}{8\pi}\right); & E_x > E_{th} \\ 0; \quad E_x < E_{th} \end{cases}, \tag{2}$$

where $E_{th} \approx 12\sqrt{nT}\,(\omega_H\sqrt{\nu_{ei}\omega}/\omega_p^2)$ is the threshold value of the field.1) We chose the density and the temperature profiles to be close to those observed in tokamaks

$$n = n_0\left(\frac{1}{10} + 1 - \frac{x^2}{a^2}\right); \quad T = T_0\left(1 + \frac{1}{10} - \frac{x^2}{a^2}\right)^a; \quad 1.5 \leqslant a \leqslant 2, \tag{3}$$

where a is the minor radius of the torus.

In the considered range of frequencies there exist two types of electromagnetic waves—fast and slow. Until recently, the heating of the plasma was attributed mainly to the slow waves, for which it is easier to satisfy the transformation conditions and for which the opacity region is narrower.[2]

3. For the slow wave we have $v_{gr} \approx c(\omega/\omega_p n_z)$; $\mathcal{E} = E_x^2/8\pi$; $\gamma \approx \nu_{ei}$. In the actual calculations we used the plasma parameters corresponding to the TM-3 installation: $T_0 = 900$ eV, $n_0 = 5\times 10^{13}$; $\omega_H = 7\times 10^{11}$. The power $P(-a) = \mathcal{E}(-a)v_{gr}(-a)$ incident on the boundary ranged from 3 kW/cm^2, corresponding to the parameters of the customarily employed microwave generators, to 30 kW/cm^2. Typical results of the calculations at $n_z = 1.5$ are shown in Figs. 1 and 2. It follows from the figures that by choosing the pump frequency and power it is possible to attain a sufficiently uniform plasma heating. The situation, however, is quite critical to variation of the heating parameters. It is seen from Figs. 1 and 2 that the fraction of the energy absorbed at the center is decreased by a factor of three when the power is doubled, is decreased to approximately one-half when the frequency is decreased from $2.5\omega_{LH}$ to $1.5\omega_{LH}$, and is decreased by a factor of 2.5 when α is increased [see (3)] from 1.5 to 2. With increasing frequency ω, as noted in[4,5], the anomalous absorption of the energy on the periphery decreases, since the growth rates of the parametric instabilities decrease like ω_{LH}/ω, while v_{gr} increases like ω/ω_{LH}. Really, the absorbed power $Q \sim n^2/T$ depends little on x. Therefore a noticeable shift of the maximum towards the center takes place only at very high frequencies $\omega \gg \omega_{LH}$, corresponding to small rises above threshold. An appreciable fraction of the energy input is dissipated after numerous reflections from the opacity region on account of the collisions, i.e., again on the periphery.

It must be noted that in all the presented calculations an appreciable fraction of the energy is absorbed on the edge of the interval, $x \approx -a$. This means that the energy absorption unaccounted by us can be quite appreciable in the region $x < -a$ near the diaphragm.

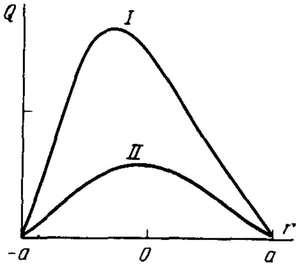

FIG. 3. Heating by a fast wave, $P(-a)=15$ kW/cm^2. Curve I—$\omega=\omega_{LH}$; curve II—$\omega=2\omega_{LH}$.

Plasma heating by fast waves has started to attract attention most recently.[8] The reason is that the transformation point can be attained for the fast waves only when it is extracted from the internal side of the torus,[2,8] and in addition the opacity zone is large in comparison with the slow waves. Without considering accessibility questions, we note that in the scheme considered by us energy input is possible also from the external side of the torus.

For the fast waves we have

$$v_{gr} \approx c\frac{\omega\omega_H}{\omega_p^2}n_z; \quad \mathcal{E}=\frac{E_x^2}{8\pi}n_z^2; \quad \gamma \approx 2\nu_{ei}\frac{\omega_p^2}{\omega^2}. \tag{4}$$

We see that on the periphery the group velocity of the fast waves exceeds that of the slow waves, and at the center they are of the same order. Therefore, at identical pump powers, the amplitude of the fast wave, and consequently its anomalous absorption on the periphery, are noticably decreased and the region of energy release shifts towards the center ($Q \propto n^3/T$). As seen from Fig. 3, only a negligible part of the energy is released on the periphery of the plasma.

The strong dependence of the fast-wave energy release on n_z turns out to be very substantial and it is seen from (1) and (4) that $Q \propto n_z^{-6}$. Even at $n_z=2$—3, the energy release decreases to such an extent that an appreciable fraction of the energy is absorbed by collisions. Formulas (1) and (3) show that in the case of the fast wave even collision damping leads to heating of the central regions of the plasma.

The small release of the fast-wave energy on the periphery and the relatively large absorption length make it possible, in principle, to combine the collective method of heating with the method based on linear transformation, and make the fast wave promising for heating in large-scale installations.

1)The coefficient in (2) was taken by us from[7], where the nonlinear stage of parametric instability was numerically simulated.

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[1] T. Stix, Theory of Plasma Waves, McGraw, 1962.
[2] V. E. Golant and A. D. Piliya, Usp. Fiz. Nauk **104**, 413 (1971) [Sov. Phys. Usp. **14**, 413 (1971)].
[3] V. V. Alikaev *et al.*, Zh. Tekh. Fiz. **45**, 523 (1975) [Sov. Phys. Tech. Phys. **20**, 327 (1975)]; V. E. Golant *et al.*, Nuclear Fusion, 1975; W. Hook, E. Richard, and R. P. Parker, Bull. Am. Phys. Soc. **20**, 1313 (1975).

[4] S. L. Musher, A. M. Rubenchik, and B. I. Sturman, Nuclear Fusion (in press).

[5] A. M. Rubenchik, Pis'ma Zh. Tekh. Fiz. **2**, 21 (1976) [Sov. Tech. Phys. Lett. **2**, 7 (1976)].

[6] B. I. Sturman, Zh. Eksp. Teor. Fiz. **71**, 613 (1976) [Sov. Phys. JETP **44**, 522 (1976)]; A. Hasegawa and L. Chen, Phys. Fluids **18**, 1321 (1975); A. Rogister, Phys. Rev. Lett. **34**, 80 (1975).

[7] L. Chen, R. L. Berger, P. P. L. Matt, 1169 (1975) [sic!]

[8] A. V. Longinov and K. N. Stepanov, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 457 (1976) [JETP Lett. **24**, 419 (1976)].