Concerning one possibility of plasma heating in a tokomak

A. V. Longinov and K. N. Tepanov

Physico-technical Institute, Ukrainian Academy of Sciences

(Submitted August 23, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **24**, No. 8, 457–461 (20 October 1976)

It is shown that in large-dimension toroidal installations it is possible to use fast modes of magnetosonic waves (*H* waves) to heat plasma by electromagnetic waves of frequency on the order of the lower hybrid frequency.

PACS numbers: 52.35.Ck, 52.35.En, 52.50.Gj, 28.50.Re

It is proposed to use the slow branch, or *E* wave of fast magnetosonic waves[1-6] (FMS) for high-frequency heating of a plasma under conditions of the lower hybrid resonance (LHR). The use of this heating method in large thermonuclear installations can encounter a number of difficulties[4,7]:

a) The danger of the appearance, on the plasma periphery, of plasma instabilities that lead to turbulent heating and anomalous absorption of the RF power in this region.

b) The possibility of strong Cerenkov absorption of the RF power on the periphery of the plasma by electrons (particularly in the presence of runaway electrons).

c) The entry of the RF energy into the interior of the plasma may be hindered by the fact that for the slow waves the angle between the group velocity and the magnetic field is very small. Strong absorption of the RF energy on the periphery of the plasma pinch upon excitation of a slow wave was observed in experiments[8-11] on RF heating of plasma in tokamaks.

It is shown in the present paper that these difficulties can be overcome (or greatly weakened) if the RF heating of the plasma in the tokamaks is effected not by a slow wave but by a fast wave (*H* wave) excited from the internal side of the torus. In this case the fast wave, propagating into the interior of the plasma, reaches a critical point where it is transformed into a slow wave; the latter propagates in the opposite direction, reaches the point of the lower hybrid resonance where it is transformed into a plasma wave. In the case of a plasma with sufficiently high density, as shown in [5], the fast wave can reach the LHR point directly. This possibility is brought about by the toroidality effect, which leads to a change of the longitudinal component of the wave vector, as well as of the magnetic field, in the direction of the major radius.

We consider the passage of waves through the plasma in the central plane of the torus when the waves are excited from the internal side of the torus. Let the exciting system produce a wave with a longitudinal wave number $k_{\parallel 0}$. The longitudinal refractive index of the wave of the plasma is equal to

$$N_{\parallel}= N_{\parallel 0}\frac{A-1}{A-x}\quad\left(N_{\parallel}=\frac{k_{\parallel}c}{\omega},\quad N_{\parallel 0}=\frac{k_{\parallel 0}c}{\omega}\right). \tag{1}$$

Here $A=R/a$ is the aspect ratio, R is the major radius of the torus, a is the radius of the chamber and the quantity $x=(r/a)\cos\theta$ (r is the distance from the axis of the plasma cylinder and θ is the minor azimuthal angle) ranges from $x=-1$ ($\theta=0$, $r=a$) on the inner side of the chamber to $x=-1$ ($\theta=0$, $r=a$) on the outer side. The difference between $N_{\parallel}$ and $N_{\parallel 0}$ is due to the fact that when a wave $\sim \exp i\chi m$ (χ is the major azimuthal angle) propagates in the torus the value of the azimuthal number $m=(k_{\parallel}/2\pi)(R-r\cos\theta)$ is conserved.

When waves with $N_{\parallel}>1$ propagate in the plasma, the transverse refractive index $N_{\perp}$ of the slow wave has a singularity (in the case of a cold plasma) at two points of the LHR, $x=x^{(1,2)}$, where the wave frequency ω is equal to the LHR frequency

$$\omega_{LH}=\frac{\omega_{pi}}{\sqrt{1+q}}\quad\left(q=\frac{\omega_{pe}^2}{\omega_{Be}^2}\right). \tag{2}$$

here $\omega_{pe,i}$ is the Langmuir frequency of the electrons or ions; the cyclotron frequency $\omega_{Be}=eB/m_ec$ of the electrons depends on the coordinate x, since $B=B_0A/(A-x)$.

The conditions from the propagation of a wave in the plasma depend on the ratio of $N_{\parallel 0}$ and the critical values of this quantity, N_1 and N_2, where

$$N_1=\max N(x)=N(x_1^*)\qquad(-1<x<x_\infty^{(1)}),$$

$$N_2=\max N(x)=N(x_2^*)\qquad(x_\infty^{(2)}<x<1),$$

$$N(x)=\frac{A-x}{A-1}\left[\sqrt{1+q\left(1-\frac{\omega_{Be}\omega_{Bi}}{\omega^2}\right)}+\sqrt{q}\right]. \tag{3}$$

At $N_{\parallel 0}=N_{1,2}$ the values of $N_{\parallel}^2$ for the slow and fast waves coincide at the points $x=x^*_{1,2}$. The condition for reaching the LHR point $x=x_\infty^{(2)}$ when a slow wave is excited from the inner side of the torus is $N_{\parallel 0}>N_2$. If we neglect the dependence of n and B on x (i.e., the toroidality effects), then we obtain from this the known[5] criterion $N_{\parallel 0}^2>1+q(x_\infty^{(2)})$.

If the density n has one maximum, then $N_1>N_2$. The difference between N_1 and N_2 is due to the toroidal dependence of $N_{\parallel}$ at $q\ll 1$ and also to the toroidal dependence of $B(x)$ at $q\gtrsim 1$.

The behavior of N^2 for the fast and slow waves as a function of x turns out to be substantially different in three regions of variation of $N_{\parallel 0}$: a) $N_{\parallel 0}>N_1>N_2$, b) $N_1>N_{\parallel 0}>N_2$ and c) $N_1>N_2>N_{\parallel 0}$. The qualitative behavior of N^2 in these cases is shown in Figs. 1a, 1b, and 1c. Figure 1d shows the dependence of the plasma density n and of the magnetic field B on x. The shift of the density maximum relative to the center of the chamber ($x=0$), which is typical of tokamaks, does not change qualitatively the behavior of N^2 illustrated in Fig. 1e.

In cases (a) and (b), the LHR point $x=x_\infty^{(2)}$ is accessible for excitation of a slow wave from the inner side of the torus. In the case (c) the point $x=x_\infty^{(2)}$ ceases to be accessible, because of the appearance of an opacity barrier at $x_\infty^{(2)}<x<x_2^*$.

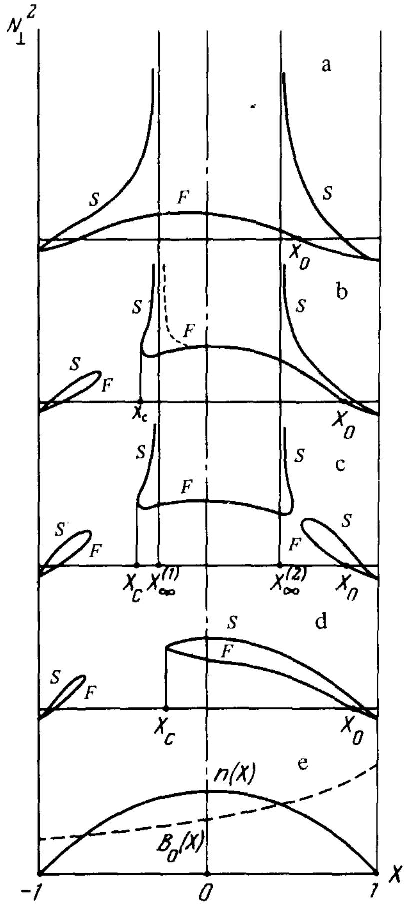

FIG. 1.

It is seen from Fig. 1b that the LHR point $x=x_\infty^{(1)}$ becomes accessible if a fast wave is excited rather than a slow wave. It is just this case which uncovers new possibilities of using the LHR for RF heating of a plasma with large dimensions. The fast wave penetrating into the plasma through the opacity barrier ($x_c < x < 1$), propagates into the interior of the plasma up to the transformation point $x=x_c$, where it is transformed into a slow wave that reaches the LHR point $x=x_\infty^{(1)}$, where it is transformed into a plasma wave propagating towards the outer side of the torus. If the plasma density is high enough $q(x_\infty^{(1)}) > q_{cr} \gtrsim 1$, then the fast wave reaches directly the point $x^{(1)}$ (the plot of $N_\perp^2$ for the fast wave in this case is shown dashed in Fig. 1b). This possibility was first indicated by Golant[5] for the case $q \gg 1$.

If $q(0) \ll 1$, then $N_2 \approx 1$ and $N_1 = A + 1/(A-1)$, while for $q(0) \gtrsim 1$ we have $N_2 \approx 1$ and N_1 increases rapidly with increasing $\omega^2/\omega_{Be}\omega_{Bi}$, so that the interval variation of $N_{\parallel 0}$, in which the regime corresponding to Fig. 1b can be realized, is quite large (at not too large values of A).

Let us note the possible advantages of excitation of fast waves:

a) For the same RF power flux into the plasma, the oscillatory velocity of the electrons in the field of a fast wave is much smaller than in a slow wave, if $q \ll 1$ (their ratio is of the order of $(m_e/m_i)^{1/3}$ at $q \sim \omega/\omega_{Be} \sim \sqrt{m_e/m_i}$), and this can greatly weaken the action of the parametric instabilities for the fast waves in the low-density region.

b) At $q \ll 1$, the coefficient κ_F, of the electron Cerenkov damping of the fast wave is small in comparison with the damping coefficient κ_S of the slow wave, $\kappa_F \sim q^{3/2}\kappa_S$, which also decreases the absorption of the fast wave at the edge of the plasma.

c) The angle between the group velocity and the magnetic field for the fast wave in the region $q \ll 1$ is much larger than for the slow wave.

We note that under real conditions, for the large-tokamak designs considered at present, the RF power needed to heat the plasma to 5 – 10 keV is large, so that parametric instabilities will develop in the interior of the plasma also for fast waves (particularly near the point $x = x_c$, where the amplitude of the electric field of the fast wave increases), and the fast wave can attenuate in the region $x_c < x < 1$ on account of nonlinear parametric effects.

In this case, for RF heating of plasma, the presence of the LHR point is not essential. For example, at $\omega > \sqrt{\omega_{Be}\omega_{Bi}}$ the excitation of the fast wave from the inner side of the torus makes it possible to use, in order to attain effective excitation, waves with minimum deceleration $N_{\parallel 0}$, and to ensure the presence in the interior of the plasma of a region where the fast wave is transformed into a slow one. The behavior of $N_\perp^2(x)$ at $1 < N_{\parallel 0} < \max N(x)$ ($|x| < 1$) for this case is shown in Fig. 1d.

In conclusion, we thank V. V. Alikaev, V. E. Golant, A. D. Pilliya, and V. V. Fedorov for a useful discussion of the work and for critical remarks.

[1] V. E. Golant and A. D. Piliya, Usp. Fiz. Nauk **104**, 413 (1971) [Sov. Phys. Usp. **14**, 413 (1972)].
[2] A. V. Longinov and K. N. Stepanov, Prepring KhFTI 72-1, Khar'kov, 1972; L. I. Grigor'teva *et al.*, Plasma Physics and Controlled Nuclear Fusion Research 1971, vol. III, IAEA, Vienna, 1971, p. 573.
[3] E. Cannobio, Sixth European Conference on Controlled Fusion and Plasma Physics, Moscow, 1973, vol. II, p. 81.
[4] V. V. Alikaev, V. E. Golant, and K. N. Stepanov, Sovetsko-amerikanskiĭ seminar, Sistemnyĭ analiz i konstruktsii termoyadernykh élektro-stantsiĭ (Soviet American Seminar System Analysis and Designs of thermonuclear Electric Stations), NIIEFA, Leningrad, 1974.
[5] V. E. Golant, Zh. Tekh. Fiz. **41**, 2492 (1971) [Sov. Phys. Tech. Phys. **16**, 1980 (1972)].
[6] V. M. Glagolev, Preprint IAE-2339, Moscow, 1973.
[7] V. V. Alikaev *et al.*, Soveshchanie ékspertov MAGATE po bol'shim sistemam (Conference of IAEA Experts on Large Systems), Dubna, 1975.
[8] V. E. Golant *et al.*, Plasma Physics and Controlled Nuclear Fusion Research, 1974, vol. I, IAEA, Vienna, 1975, p. 231.
[9] B. Richard, and R. R. Parker, Bull. Am. Phys. Soc. **29**, 1313 (1975).
[10] W. M. Hook, ibid.