Conversion of Compressional Alfvén Waves into Ion-Cyclotron Waves in Inhomogeneous Magnetic Fields

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Axisymmetric compressional Alfvén (fast) waves, which propagate into a region of increasing magnetic field in a cylindrical plasma, are observed to be converted into ion-cyclotron (slow) waves via ion-cyclotron resonances.

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The mode conversion of Alfvén waves or their resonant coupling has received much attention because of the relevance to the origin of micropulsations in the magnetosphere,[1,2] and to the additional plasma heating to thermonuclear temperature. The main idea of Alfvén wave heating is to use the Alfvén wave "resonance" and the resulting mode conversions in an inhomogeneous density plasma, as proposed by Hasegawa and Chen[3] and by Tataronis and Grossmann.[4] In recent years, the importance of the two-ion hybrid resonance on fast-wave damping has been observed in several tokamaks,[5-7] and has received considerable theoretical analysis.[8-10] When the minority-ion concentration is sufficiently high, the tunneling and mode conversion of the fast wave occur in the vicinity of the ion-ion hybrid resonance and lead to wave damping by both the electrons and the resonant ion species. However, instead of these extensive studies, few observations of mode conversions related to Alfvén waves have been made so far.

In this Letter, we report the observation of a conversion of Alfvén waves which occurs in an inhomogeneous magnetic field; i.e., the compressional (fast) Alfvén waves propagating along a static mirror magnetic field are found to be converted into ion-cyclotron waves via the ion-cyclotron "resonance layer," at which substantial plasma heating can be expected.

The experiments were carried out in the TPH device of Nagoya University which has been described in detail previously[11] (chamber diameter, 15 cm; chamber length, 2 m). In this device, with linear or mirror magnetic field configuration, a quasisteady (~ 1 ms), current-free, high-density streaming plasma has been established by developing a pulsed magneto-plasma-dynamic (MPD) arcjet with an anode of 3–8 cm diameter. In this experiment, a 5-cm-diam anode was used. Plasma parameters were measured with an HCN laser interferometer ($\lambda = 337\ \mu$m), a spectrometer, double probes, magnetic probes, and diamagnetic loops. Typical plasma parameters are as follows: electron and helium-ion temperatures $T_e \simeq T_i \sim 4$ eV; plasma density $n_e \sim 4\times 10^{14}$ cm^{-3}; ionization degree $\gtrsim 70\%$; β value ~ 1%. Inhomogeneous magnetic fields were produced by modifying the configuration of the magnetic coils. Axisymmetric compressional waves were launched with use of a Helmholtz-like coil (6.8 cm diam × 6.8 cm) placed outside the plasma column. This coil is very inefficient for the excitation of shear Alfvén waves. Wave magnetic fields (b_z component) were detected by a small magnetic probe (5 mm diameter) which can be moved along the field B and were analyzed by means of fast Fourier transform in order to obtain an auto- or cross-power spectrum and correlation functions.

As is well known, axisymmetric compressional waves propagating along a uniform field B incur a low-frequency cutoff in a plasma with a conducting wall boundary. The cutoff frequency is estimated as $\omega^* = 3.83V_{A0}/r_a$ for the uniform-plasma case[12] or $\omega^* = 4.68V_{A0}/r_a$ for the parabolic-density case,[13] where V_{A0} is the Alfvén velocity at the center of the column and r_a is the radius of the conducting chamber (in our case $r_a = 7.5$ cm). The cutoff frequency, however, is not sharply defined if the finite resistivity or the existence of neutral gas is taken into account; in this case the fast waves still can propagate below ω^* with strong attenuation rates and a phase velocity much faster than V_{A0}. We call this domain the "quasi-evanescent region (QER)." If we approximate the inhomogeneous density profile in the radial direction by a central homogeneous plasma column of radius r_p surrounded by a vacuum annulus of thickness $r_a - r_p$, we obtain the dispersion relation of the fast wave extending into the QER by making use of the relation given by Woods[14]:

$$[sk^2 - k_A^2(1+i\delta_\perp k^2 + i\delta_\parallel k_c^2)]\{s(k^2+k_c^2) - k_A^2[1+i\delta_\perp(k^2+k_c^2)]\} \equiv k^2(k^2+k_c^2)\Omega^2, \qquad (1)$$

where Ω is the ratio of the wave frequency to the ion-cyclotron frequency, k_A is the Alfvén wave number, and s and δ are terms related to the percentage ionization and resistivity of the plasma. The values of k_c are estimated from the boundary conditions[11] at $r = r_a$ and $r = r_p$. In Fig. 1, theoretical curves including the attenuation rate for an effective plasma radius of $r_p = 3.5$ cm are presented and compared with the experimental results which were obtained in the case of a uniform field B.

Next we present the experimental evidence on the conversion of compressional waves in the QER. Figure 2 shows the measured plasma density and mirror field along the axis of the column from the wave coupler. The axisymmetric waves launched into the QER from the coupler at $z = 0$, where the applied frequency is below ω^*, first propagate with the fast phase velocity approximately in agreement with the prediction for uniform field $\mathbf{B}$. After passing through the position where $\omega = \omega_{ci}$ (ion-cyclotron frequency), the phase velocity drastically slows down in a continuous way as shown in Fig. 3(a), where a coherency defined by the absolute cross- and autopower densities of the received and reference signals is also shown. Figure 3(b) shows the variation of the wave amplitudes normalized by that of the reference signal, and the variation of the longitudinal refractive index $N = kc/\omega$ averaged over 2 cm which is calculated from the dashed line in Fig. 3(a). The data shown in Figs. 3(a) and 3(b) are consolidated in Fig. 3(c). One should note in Fig. 3(b) that the measured refractive indices deviate largely from that of the predicted fast mode at the transition layer and then turn to that of the slow mode. Another deviation near the throat of the mirror field is also observed, which may be mainly attributed to the limited validity of the WKB approximation at long wavelength. The maximum N at nearly $z = 40$ cm corresponds to the maximum wave number of

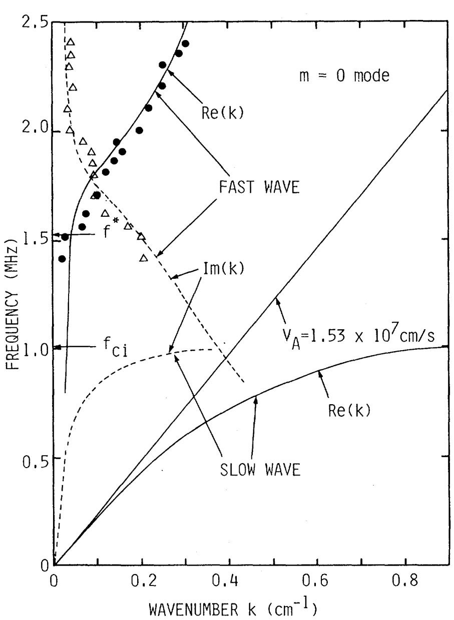

FIG. 1. Dispersion relation of $m = 0$ compressional (fast) and shear (slow) Aflvén waves. The circles refer to the real part and the triangles to the imaginary part of the wave numbers. The solid and dashed lines represent, respectively, the theoretical real and imaginary parts of the wave numbers for a plasma radius of 3.5 cm, resistivity of $\eta_\parallel = 5.0\times 10^{-5}$ Ω m, $\eta_\perp = 2\eta_\parallel$, plasma density of 4.0×10^{14} cm^{-3}, and $B = 2.8$ kG. $f^* = \omega^*/2\pi$ denotes the cutoff frequency for a parabolic density profile.

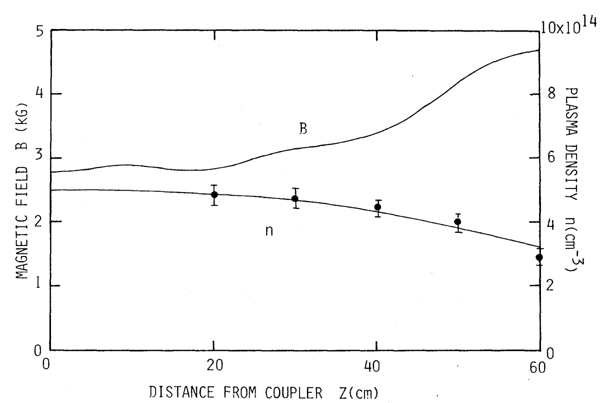

FIG. 2. Variation of the plasma density n and steady magnetic field B as the wave propagates into the mirror field.

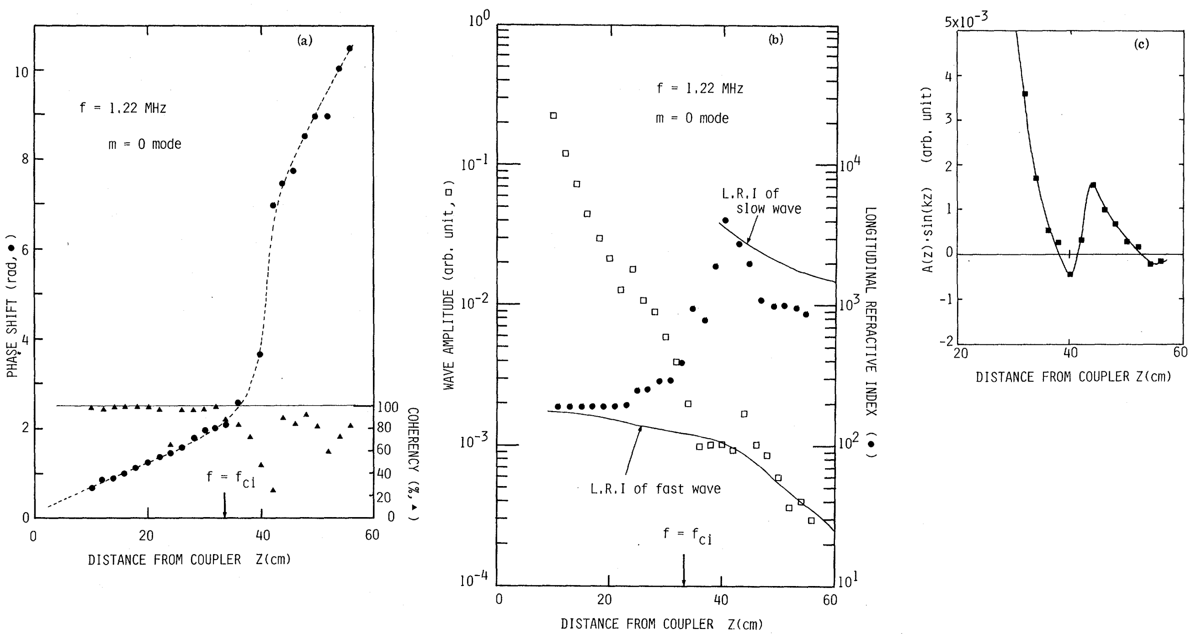

FIG. 3. (a) Variation of the phase shift of the b_z component ($m = 0$ mode, 1.22 MHz) and of the coherency between the received and reference signals. (b) Variation of the amplitude of the b_z component and of the longitudinal refractive index (kc/ω). The solid curves represent the theoretical longitudinal refractive indices (L.R.I.) of slow and fast waves which are calculated from Eq. (1) by using the values of the local plasma density and of the magnetic field shown in Fig. 2. (c) $A(z)\,\sin(kz)$ as a function of the distance z, where $A(z)$ is the relative amplitude of b_z shown in (b).

$k_{\max} \simeq 1.0\ \mathrm{cm}^{-1}$, which approximately coincides with the value calculated from Eq. (1) for slow Alfvén waves. One can therefore expect the occurrence of an ion-cyclotron resonance[15] of the fast wave propagating through the QER. This measured maximum wave number is compatible with the predicted one of the ion-cyclotron wave at resonance which is between 0.9 and 1.2 cm^{-1} for the case of finite perpendicular wave number. The resonant positions move toward stronger (weaker) fields B for higher (lower) wave frequencies, and a slight reflection before entering the resonant layer was observed, depending on the applied frequency and the profile of the field B. Such conversion into slow waves is accompanied by less attenuation or even amplification of the wave amplitude at the resonant layer; this may be due to the decrease of the phase velocity[16] or the increase of the perpendicular plasma temperature $T_\perp$,[15,17] though the present experiments lack the measurement of $T_\perp$ at the resonant layer. The possibility of plasma heating can be presumed from another point of view, i.e., the smaller coherency of the cross correlation function at the resonant layer as shown in Fig. 3(a).

The same type of measurements were also done for the $m = +1$ (right-hand rotation) fast wave excited by a helical coupler.[11] There exists no cutoff for the $m = +1$ mode propagating in a cylindrically bounded plasma, so that a Helmholtz-type or a single-loop coupler for nonaxisymmetric waves generates simultaneously both the $m = -1$ slow and $m = +1$ fast modes of frequency below ω_{ci}, but the helical coupler used here can successfully launch only the preferred mode as described in the literature.[11] Figure 4 shows the measured phase-distance relation for the $m = +1$ fast wave and its coherency. One can see no drastic changes in phase velocity around the resonant layer. This suggests that the $m = +1$ fast wave can hardly be converted into the slow wave as it experiences no evanescent layer, propagating with less attenuation rate in an increasing field B.[11] As another possible consideration, the $m = +1$ (or $m = -1$) slow wave, which is also generated, cannot be observed because of the presence of the $m = +1$ fast wave which propagates in the same range of frequency. We plan to measure the power spectrum of the propagating wave in k space in order to clarify this problem.

In conclusion, we have observed the mode conversion of the axisymmetric ($m = 0$) compressional waves to ion-cyclotron waves in a cylindrical plasma confined by a steady mirror field. The

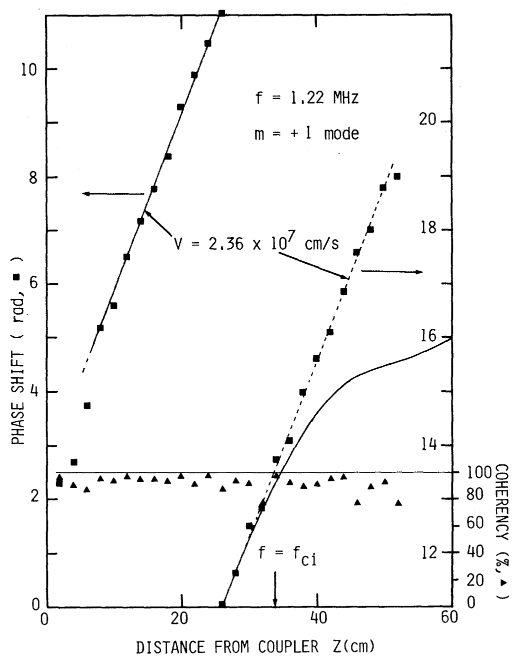

FIG. 4. Variation of the phase shift of the b_z component ($m=+1$ mode, 1.22 MHz) and of the coherency between received and reference signals. Solid lines: calculated from Eq. (1).

experiment suggests that in addition to many proposals concerning mode conversions in the vicinity of the ion-ion hybrid resonance, one can expect another type of conversion for one species of ion in an inhomogeneous field B such as mirror or tokamak type devices at the frequency $\omega \lesssim \omega_{ci}$. The conversion efficiency cannot be discussed at present, but the conversion described here may be useful for heating plasma in an actual device since the fast wave launched from antennas couples much better than the slow wave in a large size plasma and repeated transits through the resonant point due to reflection of the fast wave can be expected in a mirror field.

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