Cyclotron absorption of fast magnetosonic waves in the TM-1-VCh tokamak in the presence of a small group of resonant ions

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Strong absorption of fast magnetosonic waves (FMS) was observed in the TM-1-VCh tokamak at the second harmonic of the ion-cyclotron frequency $\omega = 2\omega_{iB}$ in deuterium. The absorption is due to small addition of hydrogen ($\sim 1\%$), for which $\omega = \omega_{Bi}$. The protons acquire energy effectively from the left-polarized components of the electric field of the FMS wave and the distribution function acquires a proton energy "tail," a fact that can find important application in a two-component tokamak.

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The possibilities of absorption of fast magnetosonic (FMS) waves at a cyclotron resonance $\omega = \omega'_{Bi}$ by ions of small concentration ($\sim 1\%$), specially intro-

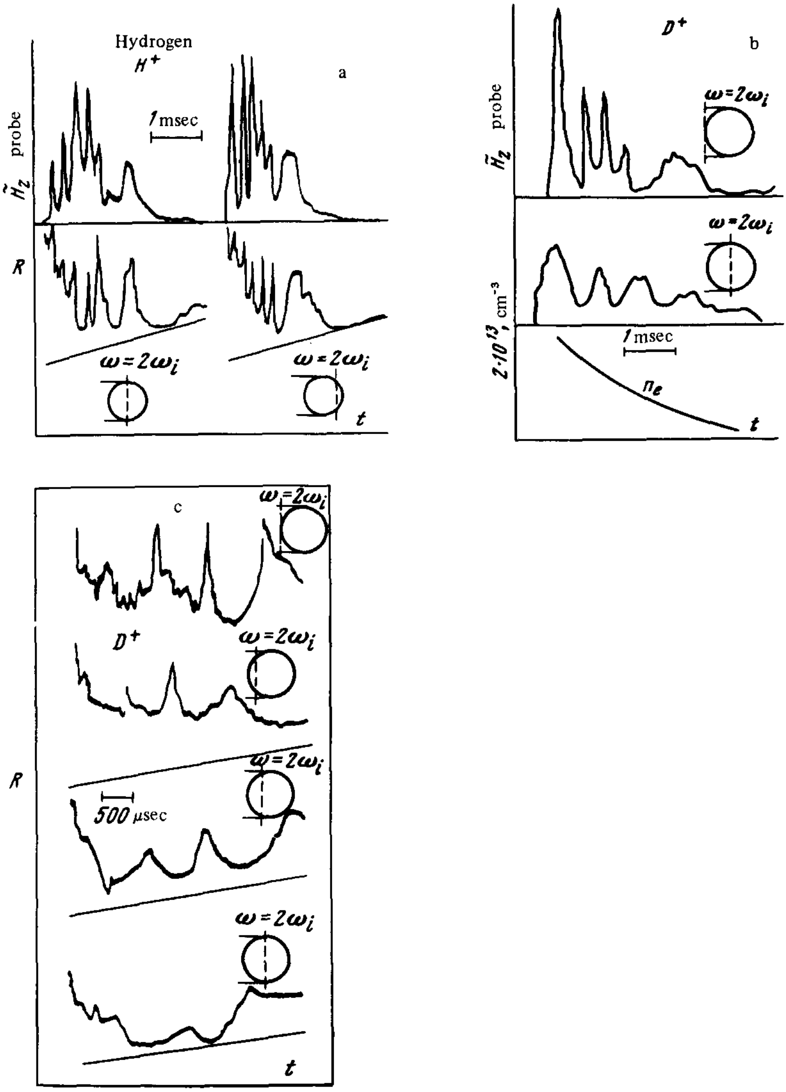

FIG. 1. Signals from the probe and from the load resistance R, and the density variation in hydrogen and deuterium at different values of $\Omega=\omega/\omega_{Bi}$ ($J=16$ kA, $P=1$ kW, $f=21$ MHz): a—hydrogen, b,c—deuterium.

duced in to the plasma, has been extensively discussed theoretically of late.[1-4] The absorption is quite large even in the inhomogeneous magnetic field of the tokamak, and is characterized by a quality factor[4] which is minimal.

$$Q_{min} \approx 3\frac{\omega_{Bi}^{H}}{k_{\parallel}}\left(\frac{\pi m_H}{2kT_H}\right)^{1/2}\frac{a}{R} \qquad (1)$$

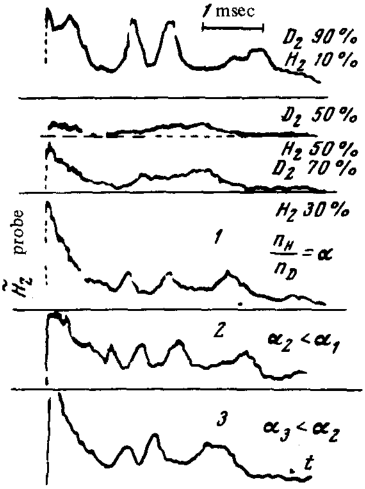

FIG. 2. Probe signals in mixture of deuterium and hydrogen ($\omega = 2\omega^D_{Bi}$). The three lower oscillograms demonstrate the role played by decreasing the residual hydrogen in three successive pulses.

when approximately 1% protons are added (index H)[2] to a deuterium plasma. Another significant prediction of the quasi-linear theory[4] is the formation of a large tail of resonant protons, and this can be a serious alternative of neutral injection in a two-component reactor tokamak.[4]

We have investigated experimentally the dispersion and damping of FMS waves in a deuterium plasma of a TM-1-VCh tokamak, resulting from cyclotron absorption of this wave by a small group of added protons, as well as the change of the distribution function by heating. We investigated also the absorption following introduction of an appreciable fraction of the impurity.

Experiment. The waves were excited by means of a decelerating structure consisting of two loops stretched along the plasma pinch and enclosed in quartz

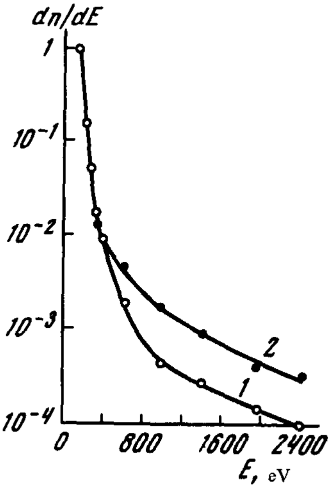

FIG. 3. Formation of an energy tail of resonant protons (≈ 1%) in a deuterium plasma ($\omega = 2\omega^D_{Bi}$) at two values of the parameter ξ.[4]

insulation.[5] By using 12 HF magnetic probes we were able to identify the excited modes and to measure their attenuation along the plasma pinch. With increasing density, the plasma waveguide cuts off (Figs. 1(a) and 1(b)) for the mode with $|m|=1$, followed by excitation of a wave with $m=0$, in accord with the theory.[7] A study of the axial damping of the magnetosonic waves has shown that they travel along the torus many times, so that standing waves are produced. These natural toroidal modes are observed also in measurements of the load resistance, and correspond to large peaks on the load curve (Figs. 1(a) and 1(b)). When the resonant surface $\omega=2\omega_{B1}(R)$ moves towards the center of the chamber in the hydrogen, a certain decrease of the Q of the mode is observed (Fig. 1(a)). This manifests itself much clearer in deuterium: the amplitude of the buildup of the alternating magnetic field decreases, the width of the peaks increases (Fig. 1(b)), and the introduced resistance R decreases (Fig. 1(c)).

This circumstance is due to the approximately 1% hydrogen additive which is always present in the tokamak chamber (the measurements of the intensity of the H_β and D_β lines and the data of the charge-exchange neutral-particle detector). It is seen from Fig. 1(b) (deuterium) that the buildup amplitude of the shorter-wavelength modes along the torus axes has decrease more strongly (left-hand peaks), in accord with formula (1).

An adjustable increase of the amount of hydrogen influences the wave damping greatly (Fig. 2). We see that at a 50% hydrogen content there is no buildup resonance: the absorption is by the ion-cyclotron wave, which can already propagate at these densities. At first glance the large absorption of the magnetosonic waves when 10% hydrogen is added seems strange (at this proton density the left-polarized component of the electric field of the wave should decrease), but it can be attributed to the appearance of an ion-ion hybrid resonance surface in the section of the plasma pinch.[2,6]

Particular interest attaches to the spectrum of the protons of the small additive (~1%) to the deuterium discharge ($\omega=2\omega_{B1}^{D}$). Starting with a power input of several kilowatts, an energy tail of the distribution function of the protons is produced (Fig. 3, $\xi_1=10$). The value of ξ in the Stix theory[4] is given by the formula

$$\xi=\frac{M<P>}{8\pi^{1/2}n_e nZ^2e^4\ln\Lambda}\left(\frac{2kT_e}{m_e}\right)^{1/2} \qquad (2)$$

and is directly proportional to the HF heat power $\langle P\rangle$ per unit volume transferred to the impurity ions (M,n,Z). The distribution of the deuterons remains in this case almost unchanged, in accord with the theory.[4] With increasing power input (Fig. 3, $\xi_2\approx 40$), the fraction of high-energy particles of the tail increases. At a power input ~100 kW, an energy tail (but a weaker one) is produced also for the deuterons. The lifetimes of these (trapped) high-energy protons is of the order of the period of the oscillations over a banana trajectory, and an appreciable power can be lost to these nonconfirmed orbits, thus determining the observed heating efficiency.[7] In large tokamaks of the T-10, PLT type and others, the discharge currents exceed the currents in TM-1-VCh by more than 40 times and the confinement of the high-energy ions is greatly improved.

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