Experimental study of the delay of an electromagnetic wave near a hybrid resonance

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A delay of short microwave probe pulses has been observed near a hybrid resonance in an inhomogeneous plasma. It is demonstrated that the wave vectors of short plasma waves can be measured by a method based on this effect. The frequency spectra and wave-vector spectra of ion acoustic waves have been measured simultaneously in a laboratory plasma.

According to the present understanding, the length scale of the electromagnetic field decreases sharply near a hybrid resonance in an inhomogeneous plasma, and the projection of the electric field of the wave onto the direction of the plasma variations increases.[1] According to a theoretical analysis, there should be a substantial slowing of transient processes[2] and of the propagation of electromagnetic pulses[3] in the same region. The time required for the pulse to reach a characteristic wave number k_i is proportional to the value of this wave number. The latter prediction is of interest because this slowing effect might be utilized to develop a time-of-flight procedure for the diagnostics of plasma fluctuations. This procedure would be based on the scattering of electromagnetic waves in the region of a hybrid resonance.[3,4] We should point out that there have been no previous direct observations of a delay of electromagnetic pulses near a hybrid resonance. This situation has of course held up the development of diagnostic applications.

In the present study we have filled this void. The experiments were carried out on a straight plasma device.[5] A plasma was produced in a cylinder 2 cm in diameter and 1 m long, filled with argon to a pressure of 2×10^{-2} torr. The cylinder was in a magnetic field of 3 kG. The plasma was produced by electron cyclotron breakdown. The plasma was inhomogeneous both radially and axially: $n_e=n_e(r,Z)$. The maximum electron density was $n_e\sim10^{12}$ cm^{-3}, and the electron temperature was $T_e\sim2$ eV. A waveguide antenna launched an electromagnetic wave of frequency $f_i=2.33$ GHz in the plasma. The conditions for a hybrid resonance were satisfied for this wave in the plasma at the point at which the electron density at the axis of the cylinder was equal to the critical density,[5] $n=n_c=\pi_i^2 m_e/e^2$. A specially developed modulator generated a train of microwave pulses 7 ns long with a modulation depth of 40 dB and a repetition period of 100 ns.

The slowing of the propagation of the microwave pulse in the hybrid-resonance region was studied on the basis of the delay in the signal representing the scattering of

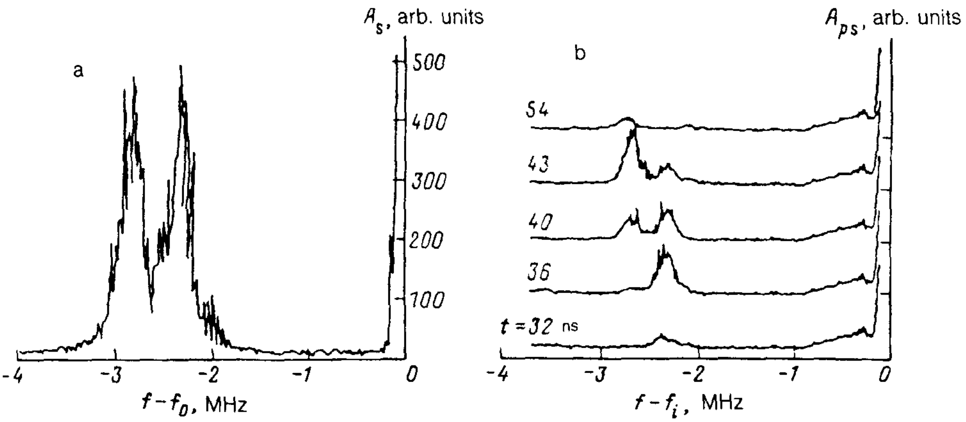

FIG. 1. a—Spectra of the scattering of a pump wave which parametrically excites an ion acoustic wave; b—spectra of the pulsed probe wave.

this pulse by ion acoustic waves, which were excited independently by means of a parametric decay instability.[6]

The delay of the scattering signal, t_d, is equal to twice the time taken by the electromagnetic wave to propagate to the point of spatial synchronization, Z_s, at which the condition $2k_{iz}(Z)=q$ holds [$k_{iz}(Z)$ and q_z are the wave numbers of respectively the probe wave and the ion acoustic fluctuations]. According to a theoretical analysis,[3] the delay time is given by

$$t_d=\int_{Z_0}^{Z_{s(q)}} \frac{dZ}{\partial\omega_i/\partial k_z}=q\frac{\partial Z_r}{\partial\omega_i}+t_w, \tag{1}$$

where $\omega_i=2\pi f_i$, $\partial\omega_i/\partial k_z$ is the projection of the group velocity of the probe wave onto the direction of the variation, Z_r is the position of the hybrid-resonance point, near which the point Z_s lies, Z_0 is the position of the radiation source, and t_w is the propagation time of a signal far from the resonance region.

The condition for a hybrid resonance in this experiment is $\omega_{pe}(0,Z)=\omega_i$. We can therefore write the expression for the delay time as follows:

$$t_d=\frac{2qa}{\omega_i}+t_w, \tag{2}$$

where $a=(1/ndn/dZ)^{-1}$ is the length scale of the variations of the plasma density along the magnetic field. According to the data from resonator diagnostics we have $a=4$ cm.

The delay of the scattering signal was measured by an arrangement which cut out a short pulse, 7 ns long, from the scattering signal. This pulse had a fixed delay $t<100$ ns with respect to the probe pulse. This method made it possible to carry out a spectral analysis of a train of scattered pulses of this sort. Figure 1 shows data from measure-

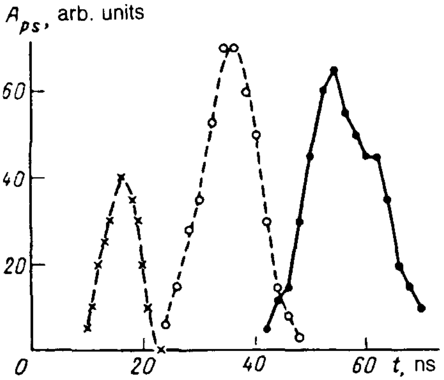

FIG. 2. Maximum amplitude of the scattering spectrum versus the delay of the measurement for various frequencies of the ion acoustic waves.

ments of the spectra of the scattered signal for various delay times in the case in which an ion acoustic wave consisting of two spectral components, with frequencies $f_s=2.3$ and 2.8 MHz, is excited by a parametric instability in the plasma (Fig. 1a).

The measurements show that the scattering signal is essentially zero at short delays, $t<30$ ns; only at $t=32$ ns does the scattering spectrum acquire one line, which is shifted 2.3 MHz from the line of the probe wave. At $t=36$ ns the amplitude of this line reaches its maximum. This amplitude falls off at a longer delay, $t=40$ ns; at the same time, a line shifted 2.8 MHz appears in the scattering spectrum. This second line reaches its maximum amplitude at $t=43$ ns and decreases sharply as early as $t=54$ ns.

Figure 2 shows the scattering amplitude A_{ps} for various frequencies of the ion acoustic waves excited in the plasma as a function of the delay in the measurement of the scattered signal. We note that the scattering signal is brief, lasting a time close to the length of the probe pulse.

Another important factor is that the delay of the scattering signal depends strongly on the frequency of the ion acoustic wave, changing from 18 ns at $f_s=1$ MHz to 57 ns at $f_s=3.6$ MHz.

Figure 3 shows the delay of the scattered signal versus the frequency of the ion acoustic wave, as found from the position of the maximum on the plot of $A_{ps}(t)$. The experimental points are grouped around the linear theoretical dependence found from (2) under the assumption $q=2\pi f_s/C_s$ and plotted for $a=4$ cm, with $C_s=\sqrt{T_e/m_{\mathrm{Ar}}}=2.2\times10^5$ cm/s, which corresponds to $T_e=2$ eV.

From this correspondence between the measured delays of the scattering signal in the hybrid-resonance region and the theoretical predictions in (2) it can be concluded that these delays are associated with a substantial slowing of the propagation of the probe wave in the resonance region. Over the time ($t_d=50$ ns) taken by the probe pulse to propagate a distance no greater than 100 cm, an electromagnetic wave in vacuum would travel a distance of 1.5×10^3 cm.

The linear dependence demonstrated here supports the theoretical argument that the time over which a pulse is slowed to a wave number k_i near a hybrid resonance is proportional to this wave number. This circumstance means that data on the scatter-

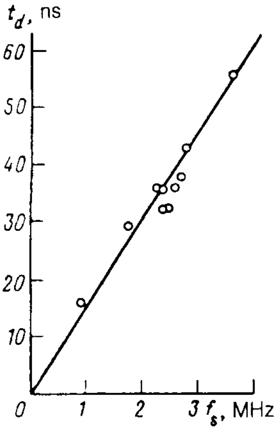

FIG. 3. Delay of the scattering signal versus the frequency of the ion acoustic wave.

ing of short pulses in the region of a hybrid resonance can be used to determine the spectra (in terms of both frequency and wave vector) of low-frequency fluctuations in a plasma.

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