Observation of bursts of plasma microwave fields in an inhomogeneous collisionless plasma slab

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The application of 10-cm radiation to a dense collisionless plasma results in the appearance of small-scale plasma microwave fields in brief bursts.

An important role is played in the interaction of microwave fields with slightly inhomogeneous plasmas by processes that occur near the plasma resonance. A case of particular interest is that in which the dynamics of the fields in the resonance region is determined by nonlinear processes, as it is in practice at quite moderate fields.

This letter reports measurement of the longitudinal plasma fields with the help of an electron beam. In contrast with some earlier studies,[1] the diagnostic beam is directed parallel to the density gradient, so that a microwave modulation of the beam current is analyzed.[2] The experimental layout is shown in Fig. 1. The plasma slab, produced by spark sources, is bombarded by a 10-cm microwave signal of rather high intensity.[3] The diagnostic 10-keV beam intersects the critical-density surface at some distance from the axis of the slab, so that the beam trajectory passes near the maximum of the longitudinal field component, $E_z \approx 0.5 E_0$. The longitudinal velocity modulation acquired by the beam leads to a modulation of the beam current beyond the plasma slab. The beam then passes along the axis of a cylindrical resonator in which a TM_{110} circularly polarized mode is excited at the pump frequency ω_0. As a result, the beam is deflected along a conical surface, tracing out a circular trajectory on a fluorescent screen or scintillator plate. When the beam leaving the plasma acquires a modulation at the frequency ω_0, the brightness of the ring is modulated along the azimuthal direction. If the beam modulation frequency is $\omega = \omega_0 + \Delta\omega$, the brightness modula-

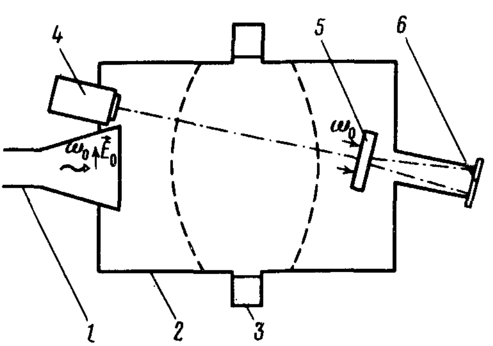

FIG. 1. The experimental layout. 1—Microwave source; 2—vacuum chambers; 3—spark sources; 4—electron gun; 5—resonator, 6—scintillator.

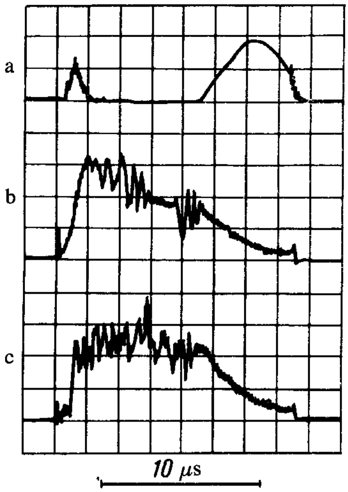

FIG. 2. a—Transmitted microwave signal; b—photomultiplier output signal, $v_E/v_{Te} = 2\times 10^{-2}$; c—the same, with $v_E/v_{Te} = 3\times 10^{-2}$.

tion travels around the ring, completing a full revolution in a time $2\pi/\Delta\omega$. For an analysis of the modulation, the emission from a small region of the ring is monitored by a photomultiplier. A two-channel detection arrangement makes it possible to simultaneously analyze the emission from two elements of the ring and to determine the sign of the frequency shift $\Delta\omega$. We might note that the observation of a microwave modulation of the beam is evidence of the onset of a small-scale (scale dimension $a \leqslant 1$ cm) microwave field in the plasma at a frequency that differs from the pump frequency by an amount equal to the observed modulation frequency.

Figure 2 shows oscilloscope traces of the microwave signal transmitted through the plasma slab (a) and of the photomultiplier output signals (b and c) for various levels of the incident microwave power. A modulation of the beam is observed only during the existence of a plasma slab with a density above the critical level (with a cutoff of the transmitted signal). The nature of the modulation depends strongly on the parameter v_E/v_{Te}, where v_E is the electron oscillation velocity in the pump field, and v_{Te} is the electron thermal velocity. Specifically, at $2\times 10^{-3} \leqslant v_E/v_{Te} < 10^{-2}$ the modulation is seen as an isolated brief burst, which arises at random during the cutoff of the transmitted signal. The burst is most likely to occur in the time interval before the decay of the plasma slab with a density above the critical level, when the plasma density at the center of the slab is $n = (1.2\text{–}1.4)n_{cr}$. At $10^{-2} \leqslant v_E/v_{Te} < 3\times 10^{-2}$, two or three bursts of modulation occur during the existence of the dense slab (Fig. 2b), while at $v_E/v_{Te} \geqslant 3\times 10^{-2}$ the separate burst overlap, and the modulation is noisy in nature (Fig. 2c).

Let us summarize the major features of the bursts. 1) The duration of a burst is $\tau = 0.5\text{–}2.5$ μs. 2) The typical frequency shift is $\Delta f = 1\text{–}10$ MHz; the shift is negative. 3) For most of the bursts, the frequency shift typically increases over time, in accordance with a decrease in the frequency of the modulating field. 4) The modulation

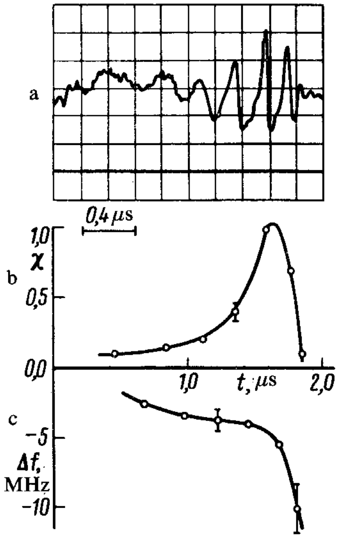

FIG. 3. a—Oscilloscope trace of a burst; b—the corresponding behavior of the bunching parameter χ; c—the frequency shift Δf.

depth of the beam current can reach 100% in some bursts. This modulation amplitude corresponds to a bunching parameter $\chi = (\omega L / v_b)/(v_{\sim} / v_b) \approx 1.0$, where L is the distance from the modulation source to the resonator, $v_{\sim}$ is the amplitude of the beam velocity modulation, and v_b is the velocity of the beam electrons.

If the modulating field is concentrated in the part of the resonant surface ($\epsilon = 0$) nearer the radiator, we find a bunching length $L \approx$ 50 cm. We can thus estimate the microwave potential difference that modulates the beam, $U_{\sim} \approx 100$ V, and the electric field, $E_{\sim} = U_{\sim}/a \geqslant 100$ V/cm. For comparison, the pump field is $E_0 \approx 10$ V/cm in this case.

Figure 3a shows an oscilloscope trace of one of the beam-modulation bursts; Figs. 3b and 3c show the bunching parameter χ and the frequency shift Δf calculated from this trace as functions of the time during the development of this burst. We see that there is a relatively slow increase in the modulation amplitude, followed by a rapid decay at the end of the burst, which is accompanied simultaneously by a rapid increase in the frequency shift.

It is natural to attempt to interpret the observed burst dynamics in terms of the formation of cavitons in the $\epsilon = 0$ layer.[4] We stipulate at the outset that it is apparently impossible to explain the measured frequency shift on the sole basis of the directed motion of cavitons (without a nonlinear frequency shift). To account for the observed frequency shift (up to 10 MHz), we would need a caviton velocity reaching $v_c \approx 3 \times 10^7$ cm/s, which is more than ten times the ion acoustic velocity. Furthermore, during the decay of the plasma slab the $\epsilon = 0$ region moves away from the radiator and should cause a positive frequency shift, while a negative shift is observed experimentally.

A negative frequency shift could arise during the formation of a caviton when a density well forms, and there is an adiabatic tuning of the frequency of the plasma waves trapped in this well. In our case, even in the linear range of the pump field, the scaling dimension of the field-localization region near the $\epsilon = 0$ layer is quite small, $\Delta l = (r_{De}^2 l)^{1/3} = 0.1$ cm $= 10 r_{De}$, where r_{De} is the Debye length, and l is the scale length of the density inhomogeneity. When the nonlinearity threshold $[(v_e/v_{Te})_{thr} \approx 2 \times 10^{-3}$ according to our estimates] is exceeded, the caviton-formation mechanism comes into play, and there is a further decrease in the size of the field-localization region. At the same time, the frequency shift increases in magnitude. At a certain stage, while the caviton becomes quite small, Landau damping sets in and causes a rapid field decay. It is this effect that we are apparently observing during the sharp cutoff of the beam modulation.

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