Experimental observation of nonlinear effects upon the excitation of large-amplitude cyclotron waves in a plasma

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A diamagnetic current flowing across the magnetic field has been detected in a system of a rotating electron beam and a plasma. This current is caused by the rf pressure of a packet of cyclotron waves excited in the plasma. The current flow is accompanied by intense electromagnetic emission from the plasma and by the appearance of electrons with a large transverse energy.

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There is active experimental research on rf heating of plasmas in closed magnetic confinement systems by intense electromagnetic waves with frequencies near harmonics of the electron cyclotron frequency.[1] There is accordingly a need for a detailed study of the physical processes which occur in the interaction of intense cyclotron waves with plasmas.

In this letter we are reporting experiments on the nonlinear effects which accompany the excitation of large-amplitude cyclotron waves in a system of a rotating electron beam in a plasma. The experiments were carried out in a straight magnetic-mirror system ($L = 150$ cm, $d = 15$ cm, mirror ratio of 1.25). The region of the uniform magnetic field is 50 cm long; the guiding magnetic field is 6 kOe. The plasma is produced by a pulsed electron beam with a current of 2.5 A, an energy of 20 keV, a pulse length of 300 μs, a diameter of 1 cm, and transverse and longitudinal electron velocities in a ratio of ½.

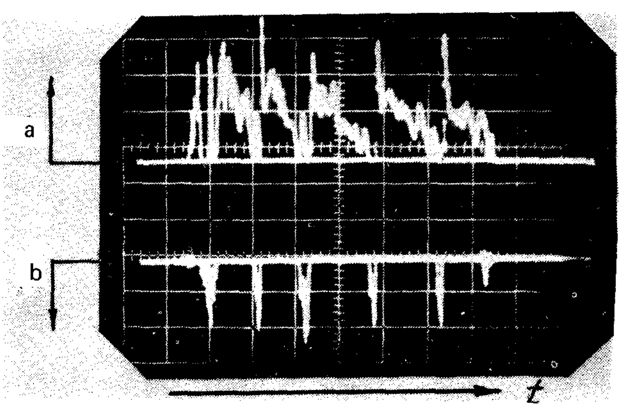

FIG. 1. a–Oscilloscope trace of the electromagnetic radiation at the second harmonic of the electron cyclotron frequency; b–at the fundamental frequency.

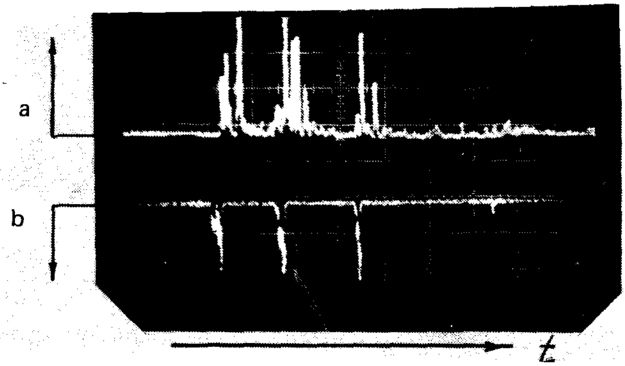

FIG. 2. a–Oscilloscope trace of the emission at the electron cyclotron frequency; b–intensity of the 500-keV x radiation.

In the experiments we measure the intensity and energy of the x-ray emission from a target in the beam-plasma interaction region, the electromagnetic emission in the frequency range 10-30 GHz, the radial profiles of the fast electrons and of the microwave amplitude, the current of the electron beam after it passes through the interaction region, and the weakening of the magnetic field in the course of the interaction of the plasma with the cyclotron waves.

At an initial pressure of 2×10^{-5} Torr of the working gas (atmospheric air), a plasma with a density $\sim 10^{10}$-10^{11} cm^{-3} is produced. At a magnetic field corresponding to one of the zones of intense electromagnetic emission at the frequency $f = 30$ GHz ($f \approx 2f_{ce}$), intense x-ray emission appears, indicating the appearance of fast electrons with an energy of 500 keV in the plasma. Under the conditions corresponding to the maximum x-ray intensity, we observe a total amplitude modulation of the electromagnetic emission at the second harmonic of the cyclotron frequency. It follows from Fig. 1 that the dips in the second-harmonic emission are correlated with bursts of emission at the fundamental cyclotron frequency. The x-ray bursts are synchronized with the bursts of electromagnetic radiation at the cyclotron frequency (Fig. 2). Synchronized with the x-ray and cyclotron emission is a decrease in the current (or a slowing) of the electron beam, measured by a collector; this current decrease is accompanied by a decrease in the magnetic field (Fig. 3). There is a resonant increase in the diamagnetic signal when the wave frequency is equal to a harmonic of the cyclotron frequency (the width of the resonance along the magnetic-field scale is $\Delta B_0 = \pm 10$ Oe).

The electric field amplitude at which electrons can acquire the energy observed experimentally is estimated to be ~ 10 kV/cm, or two orders of magnitude higher than the fields which actually exist in cyclotron-resonance masers with electron beams with similar properties. A determination of the energy of the accelerated electrons from the absorption of the x radiation yields a value which agrees with the value found from estimates of the Larmor radius of the fast electrons based on measurement of the radial profile of the intensity of hard x radiation. A microwave probe revealed that the waves at the electron frequency are confined to the region near the beam boundary.

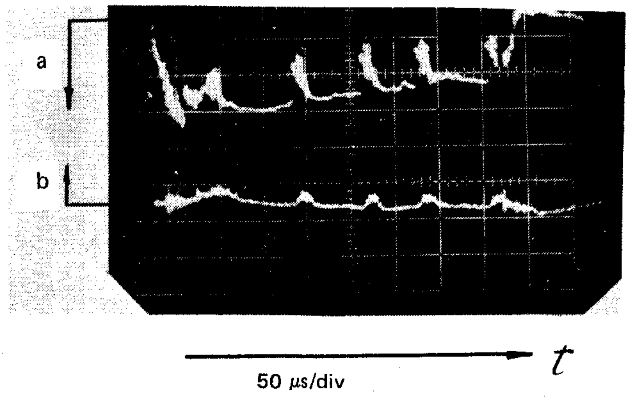

FIG. 3. a—Oscilloscope trace of the current of the electron beam after passage through the interaction region; b—diamagnetic signal.

According to the present theoretical understanding,[2,3] the nonlinear effect which primarily governs the spatial and temporal evolution of a packet of large-amplitude cyclotron waves which are propagating through a plasma is the decrease in the magnetic field caused by the rf pressure near the wave packet. This "rf diamagnetism"[2] results from the appearance in the plasma of a diamagnetic current which flows across the magnetic field. This current is driven by the rf pressure. The formation of a magnetic well is accompanied by the buildup of cyclotron-wave energy in this well; this energy buildup leads to the formation of cyclotron solitons containing rf waves.

Borodachev *et al.*[4] have reported a one-dimensional numerical simulation which incorporated in a self-consistent fashion the nonlinear and kinetic effects which occur during the interaction of a homogeneous plasma with electrostatic cyclotron waves at frequencies near twice the electron cyclotron frequency. Their results[4] support the theoretical predictions of Refs. 2 and 3 that cyclotron solitons (magnetic wells filled with rf waves) will appear in the plasma. The kinetic effects resulting from the resonant interaction of the plasma electrons and ions with the ensemble of cyclotron solitons were not studied in Ref. 4, however.

To explain the mechanism for the appearance of electrons with a large transverse energy in our experiments, we will work from the qualitative arguments of Refs. 2 and 3, which have been the starting point for analytic and numerical studies of the collapse of plasma waves (or Langmuir waves).[5] The basis for analogies of this sort is the formal similarity between the physical processes which accompany the formation of Langmuir and cyclotron solitons. This similarity is a result of a universal nonlinear mechanism for the extrusion of the density wells (in the case of a Langmuir soliton) or of the magnetic-field wells (in the case of a cyclotron soliton), because of the effect of the ponderomotive force of the cyclotron waves on the plasma.

The electric-field amplitude of the cyclotron waves in the magnetic well increases to a substantial level. The plasma electrons which interact with the ensemble of cyclotron solitons acquire a large transverse energy as the result of a resonance between the cyclotron-revolution frequency of the electrons and the frequency of the electric field in the soliton[6] (for an isotropic plasma, the electrons are accelerated through Landau damping[5]). Some of the energy of the cyclotron waves is emitted from the plasma in the form of electromagnetic radiation as a result of linear and nonlinear conversions of electrostatic cyclotron waves into electromagnetic waves.

A quantitative comparison of the experimental and theoretical results will require consideration of several factors which were not incorporated in the numerical simulation in Ref. 4 (in particular, the inhomogeneity of the plasma density and of the static magnetic field[7]), and it will be necessary to carry out a detailed theoretical study of the collapse of cyclotron waves in a plasma.

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