Paramagnetic properties of plasma produced by a powerful microwave beam

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Experiments performed with plasma produced at the surface of an insulator in vacuum by a powerful pulsed microwave radiation showed that this plasma formation (microwave plasma burst) exhibits paramagnetic properties, amplifying an externally applied axial magnetic field. The observed phenomenon is attributed to the nonlinear interaction of a powerful electromagnetic wave with the supercritical plasma produced by the wave in the resonance region of the plasma. © *1995 American Institute of Physics.*

The plasma burst produced at the surface of an insulator in vacuum (see Ref. 1) by a powerful microwave radiation beam is a plasma formation consisting mainly of nearly completely ionized ($n_e \geqslant 10^{13}$ cm^{-3}), hot ($T_e \geqslant 100$ eV), collisionless hydrogen plasma. The typical diagram of a plasma burst is shown in Fig. 1.

The investigations performed in Ref. 1 showed that the properties of the microwave plasma burst are largely determined by the nonlinear processes which develop in the "resonance" region of the plasma produced at the surface of the insulator (the region where the circular frequency ω of the microwave radiation is equal to the characteristic plasma frequency ω_{pe}). The generation of strong plasma waves and their "breaking" are accompanied by anomalous heating of the electronic component, the appearance of a high-energy tail in its energy distribution function, jump-like growth of the plasma potential, acceleration of the ions up to high energies, and other effects. The resonance phenomena explain the generation of the spontaneous self-closed currents J_s (see Fig. 1) which were measured in Ref. 2, and also the quasistationary currents in the circuit of the electrode introduced into the burst from the outside.[1,3]

The isotropic plasma formations excited in the absence of external magnetic fields were investigated in an extensive series of studies[1-3] of the interaction of powerful microwave beams with supercritical plasma ($n_e > n_{ecrit} = m\omega^2/4\pi e^2$) produced by the beams.

Our objective in the present work is to investigate experimentally intraplasma currents in a microwave burst under conditions where static magnetic fields B_{0z} are imposed on the discharge region. The magnetic fields employed in the present experiment were chosen low enough to avoid having an appreciable effect on the dynamics of the plasma burst and on the plasma formation parameters which are obtained in the microwave pulse. In particular, we note that the conditions of the experiment being described here are far

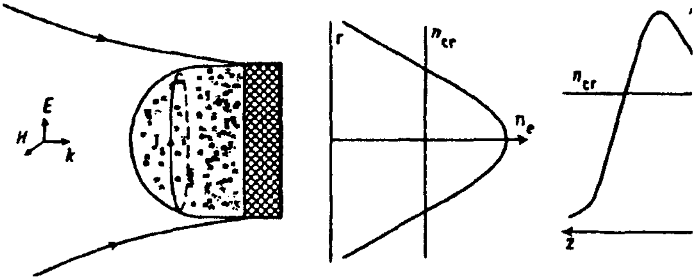

FIG. 1. Diagram of the production of a plasma burst by a microwave radiation beam.

from cyclotron resonance: $\omega \gg \omega_c$, where ω_c is the Larmor rotational frequency of an electron in an external magnetic field.

The experimental arrangement is shown in Fig. 2. A powerful converging beam of pulsed microwave radiation 1 is introduced into a cylindrical vacuum chamber 2 (residual pressure $\leq 10^{-5}$ torr). The parameters of the microwave radiation are as follows: wavelength $\lambda_f = 2.5$ cm, peak power $P_f \leq 600$ kW, and microwave pulse duration $\tau_f \leq 20$ μs. An insulator (or metal-insulator) target 3 is placed in the focus of the microwave beam. Under irradiation with the powerful microwave beam a plasma — microwave plasma burst — appears at the surface as a result of partial sublimation of the target material and ionization of the vapors. A solenoid 4 placed on the outside surface of the chamber produces a static magnetic field $B_{0z} \leq 10$ Oe. A system of coils (magnetic probes) 5 with

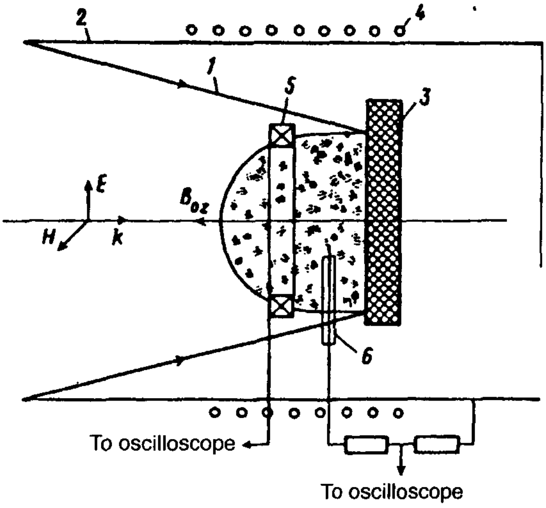

FIG. 2. Experimental arrangement with excitation of a microwave plasma burst with stationary magnetic fields applied to the discharge region: *1* — microwave beam; *2* — vacuum chamber; *3* — dielectric target; *4* — solenoid producing an axial stationary magnetic field; *5* — magnetic probe coil; *6* — Langmuir probe.

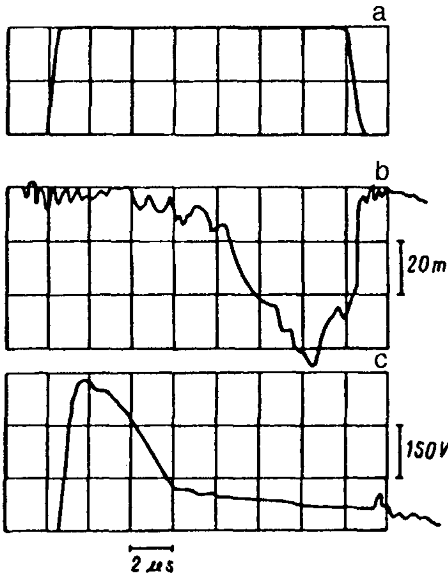

FIG. 3. Typical oscillograms of the signals: a — envelope of the microwave pulse; b — signal from the diagnostics magnetic probe coil; c — signal from the "floating" Langmuir probe.

different radii measures the change in the magnetic flux along the cross section of the coils when the pulsed plasma burst is produced at the surface of the target.

Figure 3 shows the simultaneously recorded envelope of the microwave pulse (a) and the signals from the diagnostic probe coil (b) and the Langmuir probe 6 (c) which measures the plasma potential. We see from the figure that the intraplasma currents and the associated magnetic fields are first manifested with a definite time delay. This delay is always greater than the time interval from the time at which the microwave radiation is switched on up to the jump-like increase in the plasma potential, which is correlated (see Ref. 1) with the moment the critical concentration is reached in the plasma burst and, correspondingly, with the development of nonlinear microwave–plasma interaction processes in the resonance region ($\omega=\omega_{pe}$).

The signals from the diagnostic magnetic coils, which are similar to the signals displayed in Fig. 3, appear only when stationary magnetic fields B_{0z} (produced by an external solenoid), which are substantially stronger than the signals associated with the spontaneous currents arising in the unmagnetized plasma, are imposed on the space inside the chamber.

The characteristic dependence of the pulsed magnetic fields ΔB_z, which accompany the appearance of a microwave burst, on the magnitude of the applied stationary magnetic field B_{0z} is shown in Fig. 4. We see that without the external field B_{0z} there are no intraplasma azimuthal currents (more accurately, they reach the level of the spontaneous, quasistationary, azimuthal currents observed in Ref. 2) and they change sign when the direction of the external field changes. The pulsed magnetic fields are oriented in the

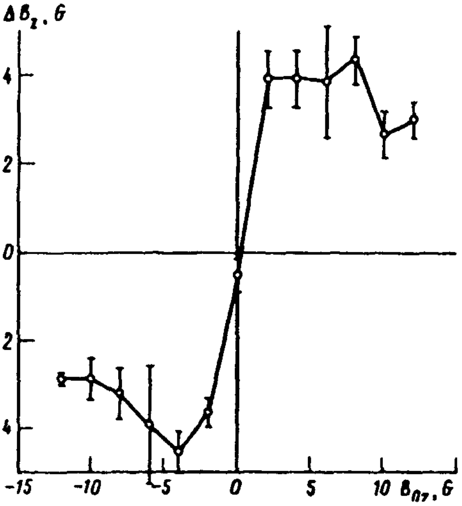

FIG. 4. Characteristic dependence of the change produced in the external field by the microwave discharge as a function of the initial value of the external field.

same direction as the external stationary field. This makes it possible to attribute *paramagnetic* properties to the plasma in the microwave plasma burst.

The paramagnetism of the microwave burst can be interpreted as yet another consequence of the nonlinear processes which develop in the region of the plasma resonance. The energy distribution of the electrons which acquire energy near the "resonance" can play a determining role in the generation of the azimuthal currents. As shown in Ref. 1 , the generation of strong plasma waves in this region of the plasma burst leads to heating of the main mass of the electrons with formation of a Maxwellian part of the distribution function characterized by the temperature T_e and to the formation of a suprathermal "tail" of high-energy electrons with average energy $\epsilon_h \gg T_e$. The characteristic energy distribution of the electrons in the burst is shown in Fig. 5.

According to Ref. 1 , the potential acquired by the plasma burst after the critical concentration is reached is, in order of magnitude, $\varphi_p \approx \epsilon_h / e$ and the radial electric field is $E_r \approx \epsilon_h / e\delta$, where δ is the characteristic size of the region of the plasma potential drop (near the "resonance" surface). According to Ref. 4 , it can be assumed that $\delta \cong 3c/\nu_{eff}$, where ν_{eff} is the effective electron collision frequency in the burst: $\omega_{pi}, \nu_{ei} \ll \nu_{eff} \leqslant \omega_{pe}$.

Under the conditions of the present experiment upon application of an external static magnetic field, the following inequalities are satisfied:

$$\rho_{ie} \ll a \ll \rho_{li}, \tag{1}$$

where ρ_{li} is the Larmor radius of the protons, ρ_{le} is the Larmor radius of the electrons, and a is the characteristic size of the plasma formation (according to Ref. 1 , a$\cong 2-3\lambda_f$). This means that azimuthal electron drift currents

$$J_D \sim c n_{em} E_r / B_{0z} \sim n_{em} \epsilon_h / B_{0z} \delta \tag{2}$$

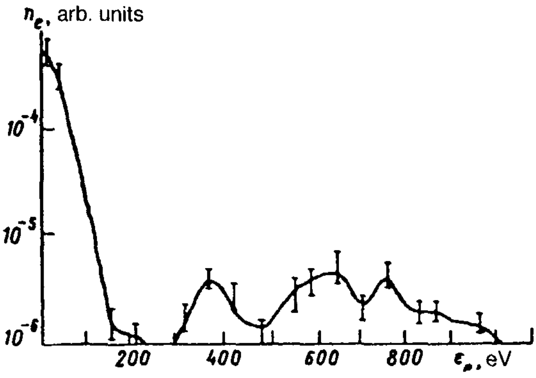

FIG. 5. Characteristic energy distribution of the electrons in the microwave plasma burst.

can be excited in the plasma burst. The potential of the plasma burst φ_p is positive, the electron drift produces currents which amplify the external magnetic field B_{0z}, and n_{em} is the maximum electron density in the burst.

On the other hand, so-called diamagnetic currents, which decrease the external magnetic field, can also be excited in the plasma burst.[5] The diamagnetic current is determined by the relation

$$J_d \sim \nabla n_e T_e / B_{0z} \sim n_{em} T_e / B_{0z} \mathbf{a}. \tag{3}$$

As follows from Eqs. (2) and (3), the ratio of the "drift" and "diamagnetic" currents in the burst is proportional to the ratio of the average energy of the high-energy "tail" to the average energy of the thermal electrons:

$$\frac{J_D}{J_d} \sim \frac{\epsilon_h}{T_e} \frac{a}{\delta}. \tag{4}$$

Under the conditions of the experiment being described, where $\epsilon_h \gg T_e$, the electron drift currents can be much stronger than the diamagnetic currents. This circumstance could account for the observed "paramagnetism" of the microwave plasma burst.

To calculate the magnitude and the distribution of the magnetic fields associated with the drift currents, it would certainly be of interest to apply the arsenal of the current theory of interaction of strong electromagnetic waves with a collisionless, nonuniform, supercritical plasma (see, for example, Ref. 6). Here, however, we can only present an approximate expression for the increase in the axial magnetic field under the assumption that the drifting electrons form a current ring with a large radius of the order of $a/2$ and with a cross section of the order of δ^2:

$$\Delta B_z \sim n_e (E_r / B_{0z}) (\delta^2 / \mathbf{a}). \tag{5}$$

The electric field E_r remains virtually constant during the microwave pulse. This seemingly contradicts the Langmuir probe oscillogram in Fig. 3c. It must be kept in mind, however, that this oscillogram determines the temporal behavior of the *plasma potential* at a fixed point near the plasma-forming target and indicates, strictly speaking, only the moment at which the critical concentration is reached and the "resonance" interaction begins. Analysis of the total spatial pattern of the potential distribution recorded by the probes (see, for example, Refs. 1 and 7), and also the electron distribution functions obtained at different times[8] indicates that E_r decreases slowly (the region of the potential drop — the resonance region — moves in space, separating itself from the plasma-forming target with time). Keeping in mind what we have said above, the slow growth of ΔB_z (Fig. 3b) measured in the experiment can be attributed to the increase in the electron density, whose rate, according to the results presented in Ref. 1 , increases after n_e reaches the critical value.

It follows from Eq. (4) that the ratio of the drift currents to the diamagnetic currents does not depend on the magnitude of the external magnetic field. For this reason, in the approximation of weak magnetic fields the observed defect should be of a paramagnetic character irrespective of B_{0z} (which is confirmed experimentally). At the same time, for sufficiently strong magnetic fields, in which the ions become magnetized, the drift currents vanish and the diamagnetic effect should become determining.

In summary, yet other property observed experimentally by us—specifically, the paramagnetism of the plasma burst generated by a microwave beam at the surface of the target irradiated in vacuum—can be attributedo the specific features associated with the nonlinear resonance interaction of a powerful electromagnetic wave with the plasma which it produces.

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