therefore the quantities Q and $\varkappa$ in (11)–(14) are assumed to be real. If the condition (15) is not satisfied, then the radiation field is strongly damped.

It is seen from (11) and (12) that if $a \lesssim \omega^2 Q$ and $a < \omega'^2 Q$, the radiation intensity at a frequency close to ω_1 differs strongly from the Cerenkov frequency. Furthermore, according to (13) and (14), the intensity of radiation with absorption of the wave quanta is comparable in this case with the intensity of the Cerenkov radiation. Thus, the magnitude of the field E_0 influences the width $\Delta\omega$ of the frequency region in which the raciation behaves in the manner described above. Using the definition of a, we readily obtain:

$$\frac{\Delta\omega}{\omega} \sim Q \sim \frac{\xi^2 E_0^2}{|\omega_v^2 - (\omega-\omega_0)^2|}.$$

4. We indicate in conclusion conditions that favor the observation of this effect. The quantity

$$\xi^2/[\omega_v^2 - (\omega-\omega_0)^2 - 2i(\omega-\omega_0)\Gamma]$$

is the nonlinear Raman susceptibility (see[5]). As shown by Bloembergen,[5] this susceptibility in the nonresonant region of frequencies is about one-tenth the susceptibility of third order due to pure electronic transitions in atoms. On the other hand, recognizing that usually $\omega_v/\Gamma \sim 10^3$, we can, retaining the condition (15), use the resonant character of the dependence of the Raman nonlinear susceptibility on the frequency. With the aid of the experimental data of[5] we can estimate the value of the Raman susceptibility in the region $\omega_v\Gamma \ll \omega_v^2 - (\omega - \omega_0)^2 \ll \omega_v^2$ in the following manner:

$$\xi^2/[\omega_v^2 - (\omega-\omega_0)^2] \sim 10^{-12}\ [\mathrm{erg}^{-1}\ \mathrm{cm}^3],$$

which is much higher than the nonlinear third-order susceptibility ($\sim 10^{-13}\ \mathrm{erg}^{-1}\ \mathrm{cm}^3$).

The radiation considered above should arise in the vicinity of the frequency ω_1 (relation (8a)). It follows therefore that to observe this radiation it is necessary to satisfy simultaneously the two conditions:

$$\omega_v\Gamma \ll \omega_v^2 - (\omega_1-\omega_0)^2 \ll \omega_v^2,$$

$$4k_0^2 - 4\frac{\omega_1}{u}k_0 + \frac{\omega_1^2}{c^2}\varepsilon_0(\omega_1) - \frac{(\omega_1-2\omega_0)^2}{c^2}\varepsilon_0(\omega_1-2\omega_0) = 0.$$

Eliminating from these expressions the frequency ω_1, we obtain the condition imposed on the frequency of the exciting field ω_0:

$$4k_0^2 - 4\frac{\omega_0+\omega_v}{u}k_0 + \frac{(\omega_0+\omega_v)^2}{c^2}\varepsilon_0(\omega_0+\omega_v) - \frac{(\omega_v-\omega_0)^2}{c^2}\varepsilon_0(-\omega_0+\omega_v) \approx 0.$$

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Effect of a strong magnetic field on a laser plasma produced from a solid target in a gaseous atmosphere

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The effect of a magnetic field on the dynamics of the development of a laser plasma produced from a target at different pressures of the ambient gas has been investigated with the aid of a streak camera. The velocity of propagation of a laser-supported detonation wave in a magnetic field of intensity $H = 170$ kOe turned out to be higher than in the $H = 0$ case. The presence of a magnetic field leads to a more efficient generation of x rays by the laser plasma from the focal region. It has been found that a radially-confined, long-lived, hot plasma is formed in a magnetic field along the optical axis. The possibility in principle of separating with the aid of a strong magnetic field plasma formations with different parameters is demonstrated.

PACS numbers: 52.50.Jm

Laser plasmas formed in strong magnetic fields have been investigated in a large number of papers (see, for example,[1–9]). What was mainly studied in these papers was, however, either the influence of a magnetic field on the production threshold and the dynamics of a laser spark, or the effect on the flare arising during the focusing of laser radiation onto a target surface. It is of interest to investigate the influence of a strong magnetic field on the laser plasma formed in the atmosphere of the gas surrounding the target. The performance of such an experiment can give additional information about the physical processes accompanying the dispersion of the plasma flare into the ambient gas.

A thorough investigation of the heating and dispersion of a plasma under the action of a high-power (10^{12} W/

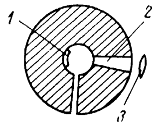

FIG. 1. Scheme of the experiment. 1) Target, 2) cone-shaped hole for the introduction of the laser beam into the active volume of the solenoid, 3) focusing lens. (The solenoid is represented in the schematic diagram by the cross section defined by the plane of the drawing.)

cm^2) laser radiation on matter in a vacuum, as well as at gas pressures of up to 50 Torr, was carried out by Basov, Krokhin, and Sklizkov in[10], where, in particular, photographs of a shock wave propagating through the ambient air were obtained. The important role played by the gas surrounding the target was noted in[11], where the dependence of the x rays from the laser plasma not only on pressure, but also on the composition of the gas was investigated. In previous papers[12–14] the influence of an $H = 210$ kOe magnetic field on the x rays of a laser plasma formed on the surface of a target in the case when the pressure of the ambient air is several Torr was investigated. The magnetic-field intensity vector in these experiments was perpendicular to the target and coincided with the optical axis. It was found, in particular, that the intensity of the x rays of the laser plasma in the field decreased several-fold. This effect was explained by noting that the screening by the developing plasma of the target from the laser radiation increases in a magnetic field of such orientation. It was noted that it was possible to decrease the screening action and improve the target-heating conditions by choosing another magnetic-field orientation.

In the present article we describe an experiment on the influence of a magnetic field on a laser plasma produced in a gaseous atmosphere from a solid target in a geometry in which the **H** vector is perpendicular to the optical axis. The constructional features of the solenoid of the pulsed magnetic device[15] used in our investigations allow, for such a magnetic-field orientation and the corresponding positioning of the target, high-speed photography of the developing plasma to be carried out together with the registration of the x rays. The scheme of the experiment is shown in Fig. 1. Neodymium-laser radiation ($\lambda = 1.06\ \mu$, $\tau = 30$ nsec, $E = 3$ J) was focused by a lens of focal length $f = 5.5$ cm onto the surface of a copper target mounted in the active volume of the solenoid. The strength of the magnetic field was 170 kOe for a duration of 70 μsec. The high-speed photography was performed in the direction perpendicular to the plane of the figure for two orientations of the entrance slit of the FÉR-2L streak camera, recording respectively the longitudinal and transverse dispersion of the laser plasma.

An investigation was carried out of the influence of a magnetic field and the parameters of the gas surrounding the target on the x-ray generation and the dynamics of the development of the plasma formation. The experiments were performed in air in the pressure range 10^{-2}–1 atm and at 1 atm in xenon and helium.

It was observed that an increase in the pressure of the gas surrounding the target leads to a decrease in the intensity of the x rays that pass through a 120-μ Be filter. In contrast to the effect of a magnetic field parallel to the laser beam, which is to sharply decrease the x-ray intensity, there is no decrease in the x-ray intensity in a field perpendicular to the laser beam. On the other hand, we have recorded at gas pressures in the range 0.05–0.2 atm some increase in the x-ray intensity in the presence of a magnetic field.

HIGH-SPEED RECORDING OF THE DEVELOPING PLASMA

1. Streak-camera slit aligned along the optical axis of the laser and perpendicular to the magnetic field

The photography of the process was performed with time bases of from 10 nsec to 3 μsec. Characteristic streakphotographs of the plasma produced on the target in an atmosphere of air are shown in Fig. 2.

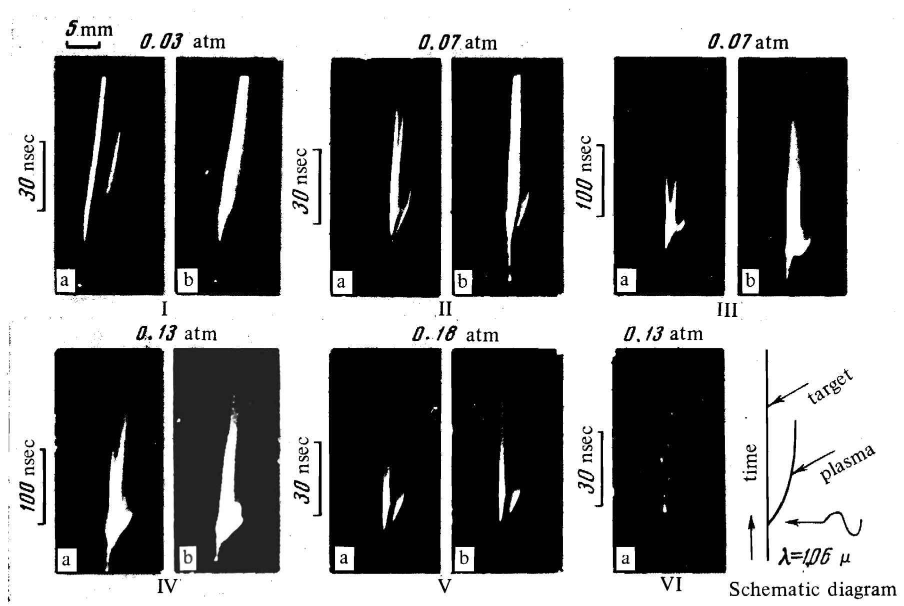

FIG. 2. Streak photographs of the dispersal of the plasma in the direction opposite to that of the laser beam. The target was in an atmosphere of air. The magnetic field was perpendicular to the plane of the photographs: a) $H = 0$, b) $H = 170$ kOe. The laser radiation was incident on the target from the right.

a) *Field* $H=0$. The bright, luminous streak corresponds to the point on the target at which the laser radiation is brought to a focus. The duration of the glow of this region depends on the pressure of the ambient gas, but does not exceed 300 nsec. At a pressure $p\approx10^{-2}$ atm (Fig. 2, Ia) the plasma formation breaks away from the surface of the target, splitting up within 20 nsec into several fronts.

As shown by streakphotographs taken through an infrared-light filter, which did not transmit radiation with $\lambda>1$ μ, the leading edge of the ionization scatters (Fig. 2, VI) and partially absorbs the laser radiation. It should be noted that the glow of the ionization front rapidly fades away after the cessation of the action of the laser pulse.

When the gas pressure is increased to 0.05–0.2 atm, there arise two distinct ionization fronts, the leading front being the sharper and faster front (e.g., Fig. 2, IIa and Va). The space between the slower front and the target is split up, and is not filled with a plasma of the ambient gas. The boundary of the target does not, however, look as bright and sharp as when the pressure is 10^{-2} atm. At a still higher pressure (0.2–0.5 atm) there arise two plasma formations. One of them forms in the near-surface region, while the other develops at the ionization front and has the appearance of a spark discharge. A further increase in the air pressure does not change the qualitative picture of the process.

In xenon we found that the plasma formed in front of the irradiated target had (in the x–t plane, where t is the time) a stratified structure (Fig. 3). The striations arising in this case are localized in space. It can be seen from this figure that the glow-front boundary, which moves counter to the laser beam, is formed from successive—in time—discharges and, consequently, the primary mechanism underlying the motion of the ionization front in the direction opposite to that of the laser beam is not directly connected with the transport of matter.

In helium we also recorded the formation of a spark discharge in front of the target surface (Fig. 4a).

b) $H=170$ kOe. At low pressures of the gas surrounding the target ($p\approx10^{-2}$ atm), a spatial partition of the ionization regions, clearly delineated as in the $H=0$ case, is not observed (Fig. 2, Ib). It is as if the glow fronts, discussed above, have been drawn closer to each other and to the target surface. The boundary of the expanding plasma is not sharp, but has a diffuse character.

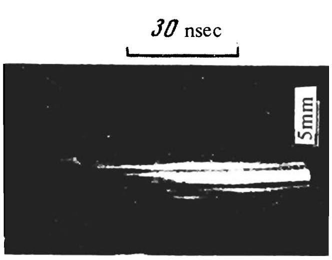

FIG. 3. Streakphotographs of the dispersion of the plasma in the direction opposite to that of the laser beam. The target was in an atmosphere of xenon ($p=1$ atm), $H=0$.

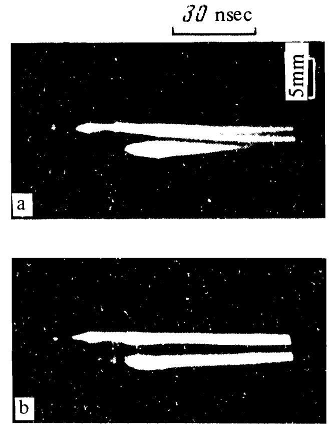

FIG. 4. Magnetic separation of the laser plasmas. The target was in a helium atmosphere ($p=1$ atm). The magnetic field was perpendicular to the plane of the photographs: a) $H=0$, b) $H=170$ kOe. The laser radiation was incident on the target from the right.

At pressures in the range 0.05–0.15 atm, instead of three, as in the $H=0$ case (Fig. 2, IIb), glow regions (the target surface and the "leading" and "trailing" ionization fronts), there are two regions, where absorption of the laser radiation occurs. These are the "leading" edge of the glow and the zone between the slower, "trailing" edge of the glow and the target surface. It should be noted that, whereas in zero field the glow in the near-surface region ceases after roughly 260–300 nsec, in a magnetic field the region remains warmed up for a period several times longer. At higher gas pressures ($p>0.15$ atm) two plasma regions are observed to exist separately. In the absence of a magnetic field these regions "intermix" in time. In a field $H=170$ kOe, there arises between them a region that is not filled by a plasma (Fig. 2, Vb). This is especially clearly visible in helium at 1 atm (Fig. 4b).

Another interesting result is our observation that the velocity of propagation of the ionization front through the gas surrounding the target in zero field is different from the velocity of propagation in the presence of a magnetic field. Whereas the maximum value of the velocity of its propagation along the optical axis in the presence of a field is the same as in zero field: $V_{\parallel}=2\times10^7$ cm-sec^{-1}, the velocities of the front toward the end of the glow turned out to be different. In a field $H=170$ kOe this velocity is roughly 10% higher than in the $H=0$ case. We did not observe a significant difference in the $V_{\parallel}$ velocities of the front of the ionization and in the extent of its attenuation as the pressure of the ambient gas is varied from 0.01 to 0.2 atm. The recorded maximum velocities, $V_{\parallel}$, of propagation of the ionization front in air, helium, and xenon are respectively equal to 2×10^7, 3×10^7, and 3.7×10^7 cm-sec^{-1}.

2. Slit of the streak camera perpendicular to the optical axis of the laser and the magnetic field intensity vector H

a) *Field* $H=0$. The high-speed photographing of the radial dispersion of the plasma was performed at distances of 1 and 3 mm from the target surface. In Fig. 5 we show some streakphotographs of the radial dispersion of the plasma formed at different pressures of the

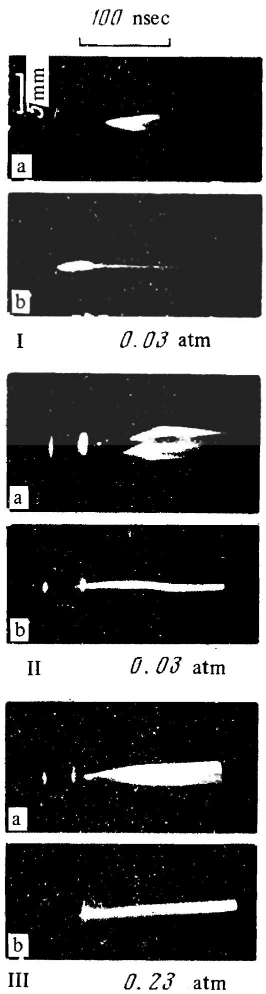

FIG. 5. Streakphotographs of the transverse dispersion of the plasma. The target was in an atmosphere of air. The magnetic field was perpendicular to the plane of the figure: a) $H=0$, b) $H=170$ kOe. I) Recording of the dispersion over a distance of 1 mm from the target surface; II) and III) over a distance of 3 mm from the target surface.

ambient gas. The higher the pressure of the gas surrounding the target, the smaller the extent of the dispersion of the plasma in the radial direction. At low pressures ($p=0.01-0.05$ atm), the turbulence of the plasma is appreciable (Fig. 5, IIa).

b) *Field* $H=170$ kOe. The application of a magnetic field changes radically the structure of the dispersing plasma. Whereas in the absence of a field the denser regions of the plasma, which can be associated with the front of a shock wave, are found at its outer boundary, in a magnetic field there arises, along with an appreciable reduction in the radial dimensions, a bright glow localized on the optical axis (Fig. 5, Ib). The same effect is also observed at a distance of 3 mm for the target (Fig. 5, IIb). The lower the pressure of the gas surrounding the target, the stronger the effect is. Notice that the velocity, $V_\perp$, of propagation of the luminous outer edge of the plasma is much lower (by a factor of 5–10, depending on the pressure of the ambient gas) than the velocity, $V_\parallel$, of the glow front along the optical axis in the direction opposite to that of the laser beam for the same distances from the target.

DISCUSSION

Above we spoke everywhere about the front of the ionization or of the glow of the gas. In doing that we did not touch upon the mechanism leading to the observed motion of the front. As is well known,[16] there exist different processes that facilitate the propagation of the ionization region in the direction opposite to that of the laser beam. An example of such processes is the appearance of a shock wave, at the front of which the energy of the laser radiation is released to support its propagation (laser-supported detonation). At a sufficiently high temperature the regime due to thermal conduction may compete with, and even be more effective than, this regime. Finally, the motion of the boundary of the glow can be caused by the photoionization of the cold gas layers adjoining the hot plasma region, in which layers absorption of the laser radiation will occur. In practice, it is not always possible to unequivocally determine the specific mechanism underlying the motion of the laser plasma, since the parameters characterizing this motion often coincide in magnitude.

An analysis of the streakphotographs in which the structure of the glow of the developing plasma is readily visible and the above-noted scattering of the laser radiation at the ionization front, scattering which, from all appearances, is caused by large density gradients, allow us, in our opinion, to assume that the propagation of the ionization (in air at $p=0.02-0.2$ atm) is largely due to the laser-supported detonation mechanism.

In the above-discussed experiment the velocity, $V_\parallel$, of propagation of the ionization front in the direction opposite to that of the laser beam turned out to be independent of the initial air density ρ_0. It must, however, be borne in mind that, as can be seen from the streakphotographs, incomplete absorption of the laser radiation at the ionization front was observed in the experiment. At the same time, in the well-known expression for the velocity of propagation of a laser-supported detonation wave $D\propto(I/\rho_0)^{1/3}$ (I is the power density of the light flux absorbed behind the front of the shock wave). As the pressure of the gas surrounding the target was increased, the fraction of the laser radiation absorbed at the ionization front increased, which could have led to the nondependence of the velocity of propagation of the laser-supported detonation wave on pressure (on the initial gas density).

As has already been noted, an increase in the pressure of the gas surrounding the target leads to a substantial decrease in the x-ray intensity. We think that this is due largely to an increase in the absorption of the laser radiation on its way to the target. Indeed, a comparison of the dependence, obtained by us, of the x-ray intensity on the pressure of the gas surrounding the target with the streakphotographs allows the following conclusion to be drawn: appreciable absorption of the laser radiation occurs at some pressure (for air $p\sim0.1$ atm) at the front of the shock wave (Fig. 2, VI) that has broken away from the target, which weakens the light flux directly warming up the focal region. This agrees with the estimate in the hydrogen-plasma approximation for the coefficient of absorption at the compression shock (whose characteristic dimension is 0.1 mm) of the shock wave. Basov, Krokhin, and Sklizkov[10] have shown that the compression ratio behind the shock-wave front is of the order of 10, which corresponds to a temperature of 60 eV. For $p \sim 0.1$ atm and an initial atomic density $n_a \sim 5\times10^{18}$ cm^{-3}, the electron concentration behind the compression shock ($\beta=10$, $Z_{eff}=4$) $n_e \sim 10^{20}$ cm^{-3} and the absorption coefficient

$$\varkappa \approx 1.45\cdot10^{-8} n_e n_i Z_{eff} / \nu^2 T_e^{3/2} \sim 60 \text{ cm}^{-1}$$

(T_e is measured in eV) turn out to be high enough for them to lead to a substantial decrease in the light flux which can be brought to a focus on the target and which is responsible for x-ray generation. Upon a still larger increase in the gas pressure, when a denser plasma formation (of the type of a spark discharge) arises, a virtually complete screening of the target occurs. The above-noted increase in the x-ray intensity in the presence of a magnetic field (in the 0.05–0.2-atm pressure range) may be connected with the fact that a magnetic field facilitates the compression of the fronts of the split laser-supported detonation wave (Fig. 2, IIb–Vb) and the contraction of them toward the target surface. This may in this case lead to the more heated-up gas near the target having such a density that will give rise to more intense x rays, since $J_{x\text{-ray}} \propto n_e^2$.

It can be seen from the streakphotographs presented that the velocity of propagation of the edge of the developing plasma has a strongly pronounced axial directivity: $V_\parallel/V_\perp = 8-10$. Such a strong anisotropy of the glow front may be due to the presence of other processes, different from the laser-supported detonation process.[17,11]

The increase, recorded by us in a magnetic field, in the mean velocity, $V_\parallel$, of propagation of the plasma front seems, on the face of it, to be unexpected. Indeed, the motion observable in Fig. 2, I–V, takes place along the optical axis perpendicularly to the magnetic field. It should, however, be borne in mind that the motion of the glow front in the direction opposite to that of the laser beam is caused mainly by the ionization of new gas layers. It is natural, therefore, that the magnetic field should not, in the first approximation, influence the velocity $V_\parallel$. The increase in the observed velocity $V_\parallel$ may be due to the higher temperature of the plasma at the front of the laser-supported detonation wave, arising upon the application of a magnetic field, which reduces the losses due to thermal conduction and inhibits cooling on account of a reduction in the adiabatic dispersion.

To explain the narrow, brightly luminous streak observed by us on the optical axis and visible only in the presence of a magnetic field (Fig. 5, Ib and IIb), it is reasonable to assume that the laser plasma produced on the optical axis by the laser-supported detonation wave in the absence of a magnetic field rapidly expands and cools off. An applied magnetic field does not allow it to expand beyond the dimensions determined by the relation between the magnetic and gas-kinetic pressures. Indeed, in order for the magnetic field to inhibit the radial expansion of the plasma arising on the optical axis, it is necessary that $H^2/8\pi \gg nkT$. For an electron density $n_e \sim 5\times10^{18}$ cm^{-3}, the temperature at which the confinement of the plasma is still possible is $T_e = 7\times10^5$ K ($H=170$ kOe). At low pressures ($p=0.01-0.1$ atm), $n_e < 5\times10^{18}$ cm^{-3}, and since $T_e < 7\times10^5$ K, the plasma-confinement effect should manifest itself quite noticeably. When the ambient-gas pressure is increased, the compression radius should, naturally, become greater, which is observed in experiment (Fig. 5, IIIb).

Of great interest, it seems to us, is the effect of the magnetic field consisting in the fact that the field inhibits the mixing of the various plasma formations. In Fig. 4 the appearance of two plasma bunches is clearly visible. The first is formed on the surface of the target; the second, after roughly 10 nsec at a distance of ~5 mm from the target surface. Expanding, these bunches penetrate each other within ~10 nsec. It can be seen from Fig. 4b that a magnetic field parallel to the target surface impedes the approach to each other of these plasma formations, which have different parameters. In particular, the intensity of the glow of the first bunch is higher and, apparently, so also is its temperature. Notice that the spatial separation of plasma formations by a magnetic field can be used to raise the efficiency of laser-plasma heating.[1)]

In conclusion the authors express their thanks to Academician A. M. Prokhorov for the interest shown in the work and for a discussion. The authors also thank P. P. Pashinin and L. I. Gudsenko for a discussion of the work and for valuable comments, E. M. Bol'shakov, who made a creative contribution to the construction of the solenoid, and M. S. Matyaev for help in the work.

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Absorption of electron plasma waves in a magnetized inhomogeneous plasma

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Results are presented of an experimental study of electron plasma wave absorption in an inhomogeneous magnetized plasma. Comparison of the experimentally-found reflection coefficients with the theoretically computed values reveals they are in fairly good agreement.

PACS numbers: 52.35.Ck

1. INTRODUCTION

The object of the present paper is to study the absorption of magnetized electron plasma oscillations in a plasma of non-uniform density. Propagating along a plasma with a decreasing density, a wave packet formed by electron plasma oscillations reduces its phase (group) velocity $\omega/k_{\parallel}(z)=\omega_{pe}(z)/k_{\perp}$, where ω and ω_{pe} are the oscillation and electron-plasma frequencies, while $k_{\parallel}$ and $k_{\perp}$ are the longitudinal and transverse components of the wave vector. As follows from the quasi-classical analysis,[1] absorption of the electron plasma wave should occur in the resonance region, where the phase velocity of the wave is comparable with the thermal velocity of the electrons. The absorption of such waves is of fundamental importance in the analysis of the stability of one of the prototypes of thermonuclear reactors—open magnetic traps. The opinion has been expressed in a number of theoretical papers (see, for example, the review article[2]) that the potential oscillations spontaneously excited in the central part of the trap should be absorbed at the trap ends. If this conclusion turns out to be correct, then we can, by creating for a plasma a special density-distribution profile, substantially improve the confinement of the plasma in an open trap. The experimental investigation of the absorption of potential oscillations in thermonuclear devices has so far not been carried out.

The results obtained in the experimental investigations[3,4] cannot be used to verify the correctness of the theoretical results.[5,6] Indeed, in[3] the authors studied the reflection of a magnetized electron-plasma wave from a plasma layer near the electrode, when the geometrical-optics approximation, on which the calculations in[5,6] are based, is not applicable. On the other hand, in[4], where the geometrical-optics approximation is applicable, the wave vector of the detected potential oscillations was such that its longitudinal component was of the same order of magnitude as, or even somewhat exceeded, its azimuthal component.

In the present investigation conditions similar to the conditions that obtain at the ends of a magnetic trap are created in a tenuous, weakly-ionized plasma produced with the aid of a gas discharge. Magnetized electron plasma oscillations (the electron cyclotron frequency, ω_{ce}, exceeds the electron plasma frequency, ω_{pe}) are excited by an external generator. The coefficients of reflection of the oscillations from a densitywise inhomogeneous plasma are measured in the cases of longitudinally uniform and nonuniform magnetic fields. The experimental data obtained in the investigation for waves with $k_{\parallel}<k_{\perp}$ are compared with the theoretical results.

2. EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

A schematic diagram of the experimental setup for the study of the reflection of waves is shown in Fig. 1. For the production of the plasma we used a discharge with oscillating electrons, I, and a stabilized current. The inside diameters of the anode A and the reflectors K and the length of the anode cylinder are each equal to 5 cm. One of the reflectors has a hole of diameter 1.5 cm at its center. In some cases the discharge was produced with the aid of a filamentary cathode. The discharge current reached 100 mA. The plasma produced in the region I filled a cylindrical glass tube, 3, of diameter 2.8 cm. The tube is located inside a multisectional solenoid, 4, of total length 150 cm. The series-parallel connection of the individual sections of the solenoid allows the production of both a uniform magnetic field[7] (the inhomogeneity along the axis does not

