The concentration of the neutral atoms in the plasma column, under the conditions investigated by us, was $(1 - 7) \times 10^9$ cm^{-3}. During the time interval from 2.5 to 4 msec following the start of the discharge, the concentration of the neutral atoms in the column decreased. Figure 3 shows a plot of the neutral-atom concentration against the initial pressure for the 2.5-th and 4-th milliseconds of the discharge, averaged over several discharges for each set of experimental conditions. The concentration of the neutral atoms increases with increasing initial pressure. The relative content of the neutral atoms at an electron density 2.5×10^{13} cm^{-3} amounts to 2×10^{-4}, and increases to $(0.8 - 1) \times 10^{-3}$ when the electron density decreases to 3×10^{12} cm^{-3}.

Using the obtained values of the densities of the neutral hydrogen atoms and of the electrons, and also the electron temperatures, it is possible to estimate the temperature to which the ions can be heated by Coulomb collisions, with allowance for the loss to charge exchange.

At large densities, the electron temperature was of the order of 400 eV, and the density ratio was $(1 - 2) \times 10^{-4}$. The calculated ion temperature is 140 - 210 eV, and that measured from the spectrum of the neutral charge-exchange atoms[7] is 150 eV. At low densities, the ion temperature calculated in the same manner is 40 - 50 eV, and the measured value is 50 eV. This makes it possible to assume that the energy loss due to charge exchange, under the conditions investigated by us, can play an important role in the ion energy balance.

The concentration of the neutral atoms remains practically the same for different values of the discharge current and for different intensities of the longitudinal magnetic field.

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LOW-FREQUENCY INTENSITY OSCILLATIONS OF HELIUM-PLASMA RADIATION AT LOW TEMPERATURES

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While investigating a pulsed hf discharge in a helium plasma, we observed low-frequency oscillations of the radiation intensity. The oscillations were observed only when the discharge vessel was cooled to low temperatures. They were seen both during the time of the pulse (in the glow) and after its termination (in the afterglow). There were no radiation oscillations at room temperature. Figure 1 shows the time dependence of the afterglow intensity of the 4650 Å molecular band of helium under different conditions of cooling the discharge vessel. With decreasing temperature, the amplitude of the oscillations increases and their frequency decreases. Similar intensity oscillations of the glow and afterglow were

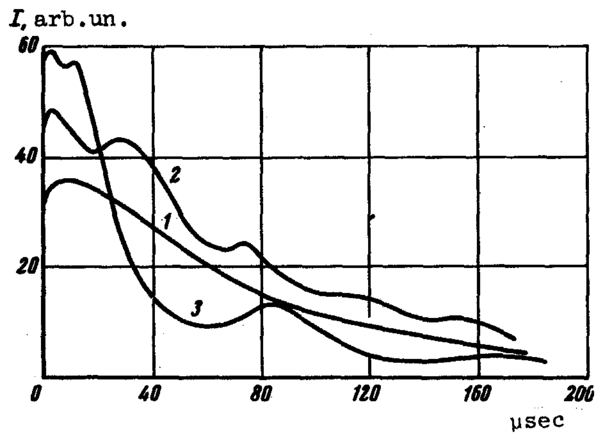

Fig. 1. Afterglow intensity of 4650 Å molecular band of helium. τ = 30 μsec, i = 2.3 A, R = 2 cm, N = 1.8 × 10^{17} cm^{-3}; 1 - room temperature, 2 - liquid-nitrogen cooling, 3 - liquid-helium cooling.

observed for all molecular bands (4430, 3989 Å etc.) and atomic lines of helium (4026, 5876, 4471 Å etc.). The oscillation periods, under the same excitation conditions, were the same for all lines and bands.

A high-frequency electrodeless discharge (8 MHz) was excited in sealed spherical bulbs (4 and 2.5 cm in diameter) filled with very pure helium. The duration τ of the rectangular current pulse ranged from 4 to 200 μsec, and the pulse repetition frequency was 25 - 5 Hz. The discharge buildup time was a fraction of a microsecond. After one microsecond, the plasma resistance was already much smaller than the generator resistance, and the magnitude of the current was determined by the parameters of the external circuit. The generator voltage was 2.1 and 3.6 kV, the discharge current in the pulse reaching 1 and 2.3 A, respectively. The discharge bulbs were immersed directly in liquid nitrogen or helium inside a cryostat with windows. The radiation intensity was measured with an UM-2 monochromator and an FEU-64 photomultiplier, connected to an S1-8 oscilloscope. The investigated pressure range was from 2 to 12 mm Hg at room temperature (the helium atom concentration was (0.7 - 4) x 10^{17} cm^{-3}).

The oscillations of the afterglow intensity were periodic and damped. Up to ten periods of the oscillations could be observed. The magnitude of the period depends on the cooling conditions and on the dimensions of the discharge vessel, the magnitude of the current, the duration of the excitation pulse, and the concentration of the atoms. Figure 2 shows the afterglow curves for two values of the current. At i = 1 A the oscillation period is ΔT = 175 μsec, and at i = 2.3 A, ΔT = 117 μsec. The period of the oscillations decreases with increasing current. An investigation of the dependence of ΔT on the current under these and other excitation conditions has made it possible to deduce that the period of the oscillations is proportional to $i^{-1/2}$.

The period of the oscillations decreases with increasing pulse duration τ. The maximum periods are observed if the plasma is excited by the shortest pulse at minimum discharge current. In vessels cooled with liquid helium, under the best excitation conditions realized by us, the period was ΔT = 180 μsec (for bulbs with diameter 2R = 4 cm). If the discharge vessel was cooled with liquid nitrogen, the oscillations could be excited only at relatively large currents. We were unable to register radiation-intensity oscillations at $i = 1$ A; the oscillations were observed at $i = 2.3$ A. For a short pulse duration, $\tau = 5$ μsec and $i = 2.3$ A in a bulb of 4 cm diameter, cooled with liquid nitrogen, the period ΔT reaches 51 μsec.

The character of the dependence of the period of the oscillations ΔT on the vessel dimensions varies with the pulse duration and with the current. At minimum values of τ and i, the periods ΔT are proportional to the bulb diameter. Deviations from this relation are observed at larger values of τ and i.

We proceed now to discuss the nature of the observed low-frequency oscillations of the radiation intensity of the helium plasma. The glow of most helium lines and bands, and the afterglow of all of them, is the result of different processes in which the electrons recombine with atomic or molecular ions in the plasma. The intensity oscillations are therefore due to oscillations of the densities of the individual components of the plasma. It is obvious that the longitudinal Langmuir oscillations have too high an oscillation frequency f_L, viz., at electron densities $n \sim 10^{12} - 10^{13}$ cm^{-3}, which are typical of the plasma investigated by us, $f_L = 0.9 \times 10^4\sqrt{n} \approx 10^{10}$ Hz. The ion-acoustic oscillations, having a frequency $f_i \sim (kT_e/MR^2)^{1/2}$, can likewise not explain the observed intensity oscillations. Inasmuch as the characteristic electron temperature T_e range from 1 to 3 eV, the periods of the ion-acoustic oscillations do not exceed several microseconds, which is smaller by 1.5 - 2 orders of magnitude than the observed periods. In our opinion, the observed low-frequency oscillations are oscillations of ordinary sound in the plasma. We could find no other explanation of the nature of these oscillations.

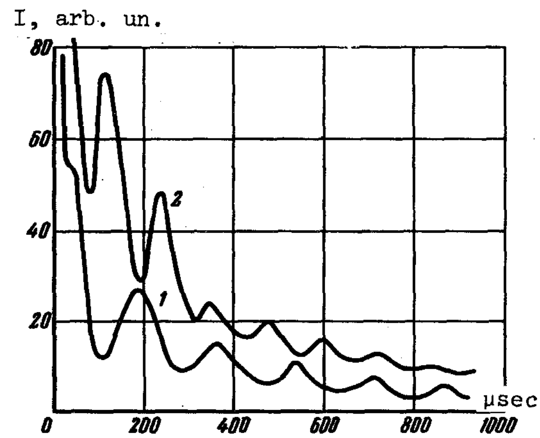

Fig. 2. Afterglow intensity oscillations of 4650 Å band. Cooling with liquid helium, $\tau = 7.5$ μsec, $R = 2$ cm, $N = 1.8\times10^{17}$ cm^{-3}; 1 - $i = 1$ A, 2 - $i = 2.3$ A.

The passage of a current pulse through a plasma leads to the appearance of electrodynamic forces that cause compression of the plasma and spatial variation of the charged-particle concentration. As a result of charge exchange, neutral gas is entrained by these oscillations. Standing sound waves are then produced in the vessel. According to [1], the lowest natural frequency of a spherical vessel is given by the formula

$$\omega = 4.49sR^{-1}, \qquad (1)$$

where $s = (5/kT/3M)^{1/2}$ is the adiabatic speed of sound in helium, T the gas temperature, and M the mass of a helium atom. It follows from this formula that at $T = 4.2$°K and $R = 2$ cm the period of the oscillations is $\Delta T = 2\pi/\omega = 230$ μsec, and $\Delta T = 54$ μsec at $T = 77$°K. We see

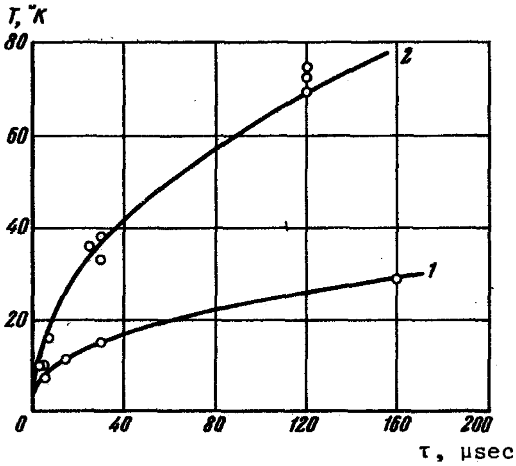

Fig. 3. Gas temperature T vs. pulse duration τ. Liquid-helium cooling, $N = 4\times10^{17}$ cm^{-3}, i = 2.3 A, circles - experimental points. 1 - R = 1.25 cm, 2 - R = 2 cm. The solid curves are plots of the following formulas: 1 - $T = 4.2° + 2\sqrt{\tau}$ μsec, 2 - $T = 4.2° + 6\sqrt{\tau}$ μsec.

that these values of the periods agree well with the experimental values of ΔT. The disparity with the experimental data is due to heating of the gas during the time of the pulse. On the basis of this interpretation, we calculated the gas temperature from the measured values of ΔT under different conditions of excitation. Figure 3 shows plots of the gas temperature T against the pulse duration. The gas temperature (T - 4.2°) increases in proportion to $\sqrt{\tau}$.

The heating of the gas is due to inelastic collisions between the hot electrons and the neutral atoms. Analysis of the kinetics of a pulsed hf discharge[1)] leads to the following expression for the heating of the gas in one pulse:

$$T - T_0 = \frac{\varepsilon_0 n(\tau)}{kN} = \frac{j}{kN}\left(\frac{\varepsilon_0 \tau}{e\mu}\right)^{1/2}, \qquad (2)$$

where T_0 is the temperature at the start of the pulse, $\varepsilon_0 \sim 100$ eV is the "value of the electron," connected with the ionization and excitation of the atoms, j is the average current density in the pulse, e is the charge, and μ is the mobility of the electrons. This formula agrees with the experimental data on the dependence of the gas heating on the pulse duration. It also confirms the experimentally observed relation between the period of the oscillations and the current. For $N = 4 \times 10^{17}$ cm^{-3} we find from (2) that the heat rise of the gas is

$$T - T_0 \sim 5j\sqrt{\tau} \qquad (3)$$

(j is in A/cm^2 and τ in microseconds). In order of magnitude, the coefficient preceding $\sqrt{\tau}$ in (3) coincides, when $j \leq 1$ A/cm^2, with the experimental value (see Fig. 3).

The proposed interpretation of the low-frequency oscillations of the glow makes it also possible to explain qualitatively the increase of the oscillation amplitude when the gas tem-

[1)]This analysis, as well as detailed experimental material, will be published in a separate article.

perature is lowered. The electrodynamic forces exciting the sound oscillations are determined by the current density and do not depend on the gas temperature. Therefore the density-oscillation amplitude A is inversely proportional to the square of the sound frequency, i.e., $A \sim T^{-1}$. Consequently, the amplitudes of the oscillations at room and helium temperatures differ by a factor of several times ten.

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SUPPRESSION OF CYCLOTRON INSTABILITY OF A RAREFIED PLASMA WITH THE AID OF A FEEDBACK SYSTEM

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It is known (see, e.g., the survey [1]), that a magnetized plasma with an anisotropic ion velocity distribution ($\tau = T_\perp/T_\parallel > 1$, $T_\perp$ and $T_\parallel$ are the transverse and longitudinal temperatures) should be unstable at the ion cyclotron frequency and its harmonics $\omega \approx n\omega_{Hi}$, $n = 1, 2, \ldots$ If τ is not too large, the buildup takes place at the intersection ("resonance") of the Langmuir and cyclotron branches of the oscillations: $\omega_{0e} \approx n\omega_{Hi}$, where ω_{0e} is the electron Langmuir frequency. It is obvious that the resonance, and with it the instability, can be disrupted by turning on some mechanism of sufficiently strong damping of the Langmuir oscillations. In our investigation we introduced the damping by means of a special electronic system with feedback to controll the perturbed fields outside the plasma.

The requirements that must be satisfied by this system can be obtained by considering a simple model, viz., a cylinder ($r < a$, $|z| < b$) of a rarefied plasma ($\mu^{1/2}\omega_{0e} \ll \omega_{Hi}$, where μ is the ratio of the electron and ion masses), with z axis directed along an external homogenerous field $\vec{H}$. We assume for simplicity that the plasma is of uniform density and touches the metallic wall of the chamber at $r = a$. Then the perturbations of the electric potential in the natural oscillations take the form $(\phi(z)J_m(k_\perp r)\exp(im\vartheta - i\omega t)$, where ϑ is the azimuthal angle and $J_m(k_\perp a) = 0$. Assume that beyond the ends of the cylinder, on the surfaces $z = \pm d$, a certain electronic circuit maintains the conditions

$$\phi_{z=\pm d} = \delta\phi_{z=\pm b}, \qquad (1)$$

where the coefficient δ, generally speaking, is complex and depends on ω. We assume also that the inequalities

$$\tau \gtrsim (\mu\zeta_n)^{-1/3}, \quad |k_z|^2\rho^2 \gg (\mu\zeta_n)^{1/3}.$$

are satisfied, where ρ is the average Larmor radius of the ions, $\zeta_n = I_n(k_\perp^2\rho^2)\exp(-k_\perp^2\rho^2)$, and k_z is the wave number of the perturbation in the direction of $\vec{H}$. Then the dispersion equation takes the form

$$\frac{\omega_{0e}^2}{\omega^2} - 1 + \frac{\mu\omega_{0e}^2\zeta_n}{(\omega - n\omega_{Hi})^2} = \frac{k_\perp^2}{k_z^2}, \qquad (2)$$

where k_z are the roots of the equation