after quenching from high temperatures there are possible formations with non-statistical distribution of the Ni atoms, leading to coexistence of the ferromagnetic and antiferromagnetic phases, in analogy with [7].

The proposed magnetic two-phase model of the invars differs from the model of concentration fluctuations [8] in the presence of correlation in the distribution of the Fe and Ni atoms. At the same time, alloyed invars can be analyzed within the framework of the proposed model with allowance for the influence of the alloying elements on the Ni_3Fe superstructure [9].

[1] E. A. Owen and H. H. Sully, Phil. Mag. 27, 614 (1939).
[2] V. I. Goman'kov, I. M. Puzei, A. A. Loshmanov, and E. P. Mal'tsev, Metally No. 1, 160 (1971).
[3] I. M. Cowly, Phys. Rev. 77, 669 (1950).
[4] A. Guinier, X-ray Crystallographic Technology, Higer & Watts, London, 1952.
[5] M. F. Collins, Proc. Phys. Soc. 86, 973 (1965).
[6] G. I. Johnson, H. B. McGirr, and D. A. Wheeler, Phys. Rev. B1, 3208 (1970).
[7] E. I. Kondorskii, Zh. Eksp. Teor. Fiz. 37, 1819 (1959) [Sov. Phys.-JETP 10, 1264 (1960)].
[8] S. Kachi and H. Asano, J. Phys. Soc. Japan 27, 536 (1969).
[9] V. I. Goman'kov, I. M. Puzei, and E. P. Mal'tsev, Dokl. Akad. Nauk SSSR 194, 309 (1970) [Sov. Phys.-Dokl. 15, 874 (1971)].

OBSERVATION OF SELF-FOCUSING OF ELECTROMAGNETIC WAVES IN A PLASMA

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The possibility of self-focusing of electromagnetic waves in a plasma had been discussed already in the first papers on the theory of this phenomenon [1]. It was shown later that self-focusing effects can play an important role in the propagation of electromagnetic waves of moderate intensity in a laboratory or a cosmic plasma [2]. Insofar as we know, however, no direct experiments have been performed as yet on these effects under laboratory conditions. We report here observation of self-focusing of millimeter waves in a weakly-ionized plasma.

We used an experimental setup similar to that described in [3]. A vacuum cylindrical volume (length 100 cm and diameter 30 cm, working pressure 0.25 Torr) was filled with plasma with maximum concentration $N_e \approx 8 \times 10^{13}$ cm^{-3}. After the end of the work of the source (a coaxial injector), plasma decay began, with a characteristic time $\tau \approx 1$ msec and with $\omega_p < \omega$ (ω_p is the plasma frequency), and a microwave pulse of duration 0.4 msec was fed to the plasma. The microwave source was a maser at cyclotron resonance (MCR), capable of producing up to 15 kW power at $\lambda = 5$ mm. The radiator was a conical horn, and the receiving antenna consisted of five standard rectangular waveguides for the 4-mm band (1.8 x 3.6 mm). Four of them were arranged pairwise in the vertical and horizontal planes, at equal distances (15 mm) from the fifth central waveguide, which was tuned to the maximum of the field in the "cold" system (without the plasma). The distance between the radiator and the receiver was 21 cm and remained fixed during the course of the work. The received signals were detected and registered with a five-beam oscilloscope. In the data reduction, the amplitudes of the signals passing through the plasma were determined with allowance for the detector characteristics and were normalized to the amplitude of the maximal "cold" signal.

We present estimates illustrating the possibility of observing thermal self-focusing of waves with the setup described above. The plasma parameters are: neutral concentration $N_m \approx 10^{16}$ cm^{-3}, charged particle concentration $N_e \approx 2 \times 10^{13}$ cm^{-3}, component temperatures $T_e = T_i = T_m = 3 \times 10^3$ °K, effective collision frequencies $\nu_{ei} = 2 \times 10^9$ sec^{-1}, $\nu_{em} = 2 \times 10^8$ sec^{-1}, and $\nu_{im} = 5 \times 10^6$ sec^{-1}, and $\delta_m = 2 \times 10^3$ (δ_m is the fraction of the energy lost by electron in one collision with the molecule). In such a plasma, the principal role is played by nonlinear effects connected with ohmic heating and subsequent forcing out of the charged particles from the heated region. Since the experimental conditions were such as to satisfy the inequalities $\omega \gg \omega_p$ and $ka \gg 1$, where a is the beam radius and $k \approx (\omega/c)\sqrt{1 - (\omega_p^2/\omega^2)}$, we can use for the estimates the results of the quasioptical theory of thermal self-focusing of waves in a plasma [4]. In particular, by virtue of the relation $a \leq L$, where $L = 1.45(T/m\nu_{ei}\nu_{em}\delta_m)^{1/2}$ is the characteristic dimension of the electronic thermal conductivity of a strongly ionized plasma ($\nu_{ei} \gg \nu_{em}$) [5], the formulas for the aberration-free approximation for a medium with nonlocal nonlinearity can be used to estimate the power at which the focal spot should fall in the plane of the receiving waveguides. For a collimated beam this power is $P_0 \approx 3\omega^4 T^2 c n_0 a_0^2/\omega_p^2 \nu_{ei}^2 e^2 L^2 \approx$ 3 W, and when account is taken of the experimentally measured beam divergence it increases to 6 W ($P_0 \approx 6$ W). However, the characteristic time of relaxation of the thermal nonlinearity, defined in the case of weak perturbation as the time of ambipolar diffusion of charged particles through the transverse dimension of the beam, $\tau_p \geq 4a_0^2\nu_{im}M/2T \approx 3 \times 10^{-3}$ sec, greatly exceeds the pulse duration $\tau_{pulse} = 4 \times 10^{-4}$ sec. Therefore noticeable self-focusing effects should be expected at radiation powers $P \geq P_0\tau_{pulse}/\tau_p \approx 50$ W.

Figure 1 shows the results of the reduction of one of the typical oscillograms, corresponding to a delay time $\tau_d = 1.8$ msec between the high-frequency signal and the start of the operation of the plasma source (the average electron concentration in the volume at that instant was $N_e \approx 2 \times 10^{13}$ cm^{-3}) and to an incident power $P_{inc} = 500$ W. As follows from the curves, the signal in the central waveguide is first much smaller than the "cold" one, and then it increases and exceeds the "cold" one at the maximum by a factor 3.0. Simultaneously with the growth of the central signal, the signals in the side channels decrease. This is followed by weakening of the central signal and a strengthening of the side ones, the greatest growth occurring in the third (upper) channel (curve 3), so that toward the termination of the microwave pulse it exceeds the maximum level of the "cold signal by 2.2 times.

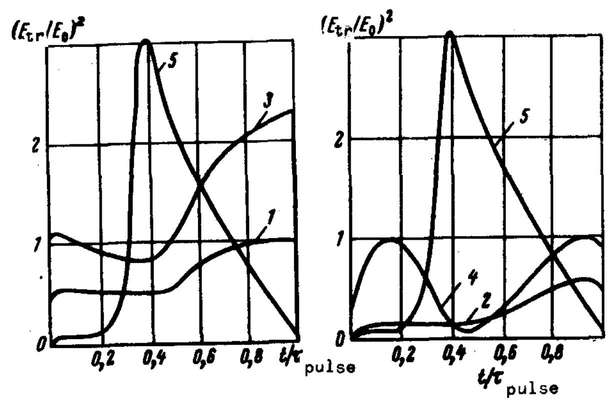

Fig. 1. Oscillograms of pulses passing through the plasma.

In comparing the oscillograms obtained at identical values of the power and of the delay time but at different injector shots, a noticeable scatter of the results is observed, owing to the lack of complete reproducibility of the plasma parameters. In practice, however, in all cases the maximum amplitude of the signal in the central channel exceeded the signal in vacuum at 25 W < P_{inc} < 4 x 10^3 W. The greatest excess was observed at P_{inc} ≈ 500 W. With further increase in power, this excess decreases and at P_{inc} ≥ 4 kW we have E_{tr}^2/E_0^2 ≈ 1. In the side channels, to the contrary, this excess increases with increasing incident power, and there is a noticeable tendency for the beam to shift in the direction of the third channel. The power dependence of the maximum values of the ratio E_{tr}^2/E_0^2 (at the given delay time τ_d = 1.8 msec) on the central and upper channels is shown in Fig. 2.

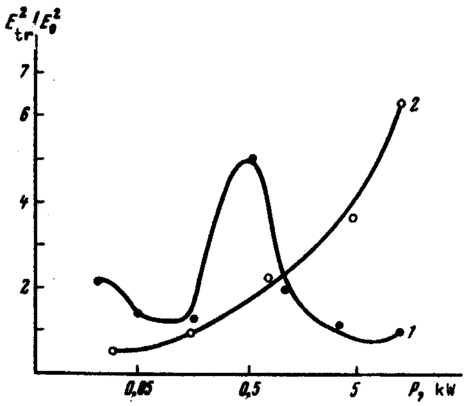

Fig. 2. Maximum values of E_{tr}^2/E_0^2 vs. incident power: 1 - channel 5, 2 - channel 3.

The noticeable enhancement of the signal passing through the plasma in comparison with the vacuum level and the character of the dependence of the change of the spatial structure of the electromagnetic waves on the power offers undisputed evidence of the realization of self-focusing of the electromagnetic waves in the described experiments. The experimental results obtained at low power levels are in qualitative agreement with the theoretical notions. On the whole, however, the observed picture is more complicated than the one following from the elementary theory. This is connected, first, with the nonstationary character of the nonlinear processes (including the nonstationary character of the plasma), and with the need for taking into account the nonlinearity-saturation effects (under stationary conditions, the perturbations of the temperature and of the concentration become of the order of the unperturbed values of these quantities at P ≥ 200 W). Apparently it is precisely the saturation effects at P ≥ 4 kW which are responsible for the absence of an excess of the signal on the beam axis above the vacuum level (the near-axis part of the beam propagates in the vacuum channel) and for the presence of considerable focusing on the periphery of the beam. The asymmetry of the self-refraction of the beam in the vertical and horizontal planes can be connected with either the regular inhomgeneity of the plasma or the possible asymmetry of the distribution of the field in the initial section of the beam.

The results indicate that self-focusing effects should play an important role in the interaction of electromagnetic radiation with plasma. It is of interest to perform further experimental and theoretical investigations of specific "plasma" singularities of this phenomenon.

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[1] G. A. Askar'yan, Zh. Eksp. Teor. Fiz. 42, 1567 (1962) [Sov. Phys.-JETP 15, 1088 (1962)]; V. I. Talanov, Izv. vuzov, Radiofizika 7, 564 (1964).

[2] A. G. Litvak, Izv. vuzov, Radiofizika 11, 1433 (1968); Zh. Eksp. Teor. Fiz. 57, 629 (1969) [Sov. Phys.-JETP 30, 344 (1970)].

[3] Yu. Ya. Brodskii, B. G. Eremin, A. G. Litvak, and Yu. A. Sakhonchik, ZhETF Pis. Red. 13, 136 (1971) [JETP Lett. 13, 95 (1971)].

[4] A. G. Litvak, Phenomena in Ionized Gases, Contributed Papers, Vienna, 1967, p. 409.

[5] A. V. Gurevich, Geomagnetizm i aeronomiya 7, 291 (1967).