method for obtaining two-quantum negative absorption is connected with the possibility of working with radiation pulses having an intensity lower by two or three orders of magnitude than in the case of generation. This is due to the relatively long pulse time ($>10^{-9}$ sec) in the case of generation, owing to the finite dimensions of the resonator. In the amplification method it is possible to operate with pulses shorter by several orders of magnitude.

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[1] N. G. Basov, R. V. Ambartsumyan, V. S. Zuev, P. G. Kryukov, and V. S. Letokhov, Zh. Exp. Teor. Fiz. 50, 23 (1966) [Sov. Phys.-JETP 23, 16 (1966); ZhETF Pis. Red. 4, 19 (1966) [JETP Lett. 4, 12 (1966)].
[2] N. G. Basov, V. S. Zuev, P. G. Kryukov, V. S. Letokhov, Yu. V. Senat-skii, and S. V. Chekalin, Zh. Eksp. Teor. Fiz. 54, 767 (1968) [Sov. Phys.-JETP 27 (1968)].
[3] A. J. De-Maria, D. A. Stetser, and H. A. Heynau, Appl. Phys. Lett. 8, 174 (1966).
[4] A. J. De-Maria, R. Gagosz, H. A. Heynau, A. W. Penney, and G. Wisher, J. Appl. Phys. 38, 2693 (1967).
[5] A. M. Prokhorov, Usp. Fiz. Nauk 85, 599 (1965) [Science 149, 828 (1965)].
[6] P. P. Sorokin and N. Braslau, IBM Journal of Research and Development 8, 177 (1964).
[7] S. A. Akhmanov and R. V. Khokhlov, Problemy nelineinoi optiki (Problems of Nonlinear Optics), VINITI, 1964 [Gordon and Breach, in prep.].
[8] N. Bloembergen, Nonlinear Optics, Benjamin, 1965.

TURBULENT HEATING OF A PLASMA BY ELECTROMAGNETIC WAVES

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It was observed in a number of experiments on plasma heating by high-frequency electromagnetic waves [1,2] that the rate of absorption of the energy of the hf field is anomalously large compared with the value calculated with only pair collisions taken into account. Thus, in experiments of plasma heating by a magnetosonic wave [1] it was established that the protons are heated to a temperature 100 eV. The main parameters of the experiments were: generator frequency $f = 2 \times 10^7$ sec^{-1}, constant magnetic field intensity $H_0 = 2 \times 10^3$ Oe, alternating field intensity $H_\sim < 60$ Oe, charged-particle concentration $n \sim 10^{13}$ cm^{-3}, electron temperature $T_e \leq 10$ eV, transverse dimension of plasma pinch $r_0 = 3$ cm, and magnetosonic wave damping decrement 2×10^7 sec^{-1} [sic!].

We shall show theoretically in this note that under the conditions of the experiments of [1] the electric current flowing through the plasma can be the cause of the instability. We present an equation for the heating of the plasma ions, determine the limiting values of the ion temperature and the wave decrement in the plasma, and compare them with the experimental results of [1].

1. The electromagnetic wave produces a current in the plasma. We are interested in the instability of a current-carrying plasma under conditions when the ion temperature exceeds the electron temperature. This problem was analyzed in [3,4]. The instability can be determined from the following dispersion equation:

$$\epsilon = 1 + \frac{k_\perp^2\,\omega_{pe}^2}{k^2\,\omega_{He}^2} - \frac{k_Z^2\,\omega_{pe}^2}{k^2(\omega - \mathbf{ku})^2} + \frac{\omega_{pi}^2}{k^2}\int \frac{(\mathbf{k}(\partial f_i/\partial \mathbf{v}))}{(\omega - \mathbf{kv})}d\mathbf{v} + i\frac{\sqrt{\pi}\,\omega_{pe}^2(\omega - \mathbf{ku})}{k^2 v_{Te}^2\,k_z v_{Te}}\exp -\left(\frac{\omega - \mathbf{ku}}{k_z v_{Te}}\right)^2 = 0, \qquad (1)$$

which is valid under the condition

$$\left(\frac{v_{Te}}{\omega_{He}}\right)^{-1} >> k >> \left(\frac{c}{\omega_{pe}}\right)^{-1}, \quad \frac{\omega}{k_z} >> v_{Te}.$$

Here

$$k_z = (\mathbf{kH})/H, \quad k_\perp = (k \times H)/H, \quad v_{T\alpha} = (2p_\alpha/m_\alpha)^{1/2},$$

P_α is the partial pressure (α = e, i).

In the simple but important case when $\omega \ll kv_{Ti}$, the frequency ω and the increment γ are determined by the expressions

$$\omega = \mathbf{ku} + k_z\left(\frac{T_i}{m}\right)^{1/2}\alpha^{-1}, \quad \alpha = \left(1 + \frac{k_\perp^2\,v_{Ti}^2}{2\omega_{He}\,\omega_{Hi}}\right)^{1/2}, \qquad (2)$$

$$\gamma = -\sqrt{\pi}\,|k_z|\left(\frac{T_i}{m}\right)^{1/2}\alpha^{-3}\left[\frac{\omega}{kv_{Ti}} + \left(\frac{T_i}{T_e}\right)^{3/2}\frac{1}{\alpha}\exp -\left(\frac{T_i}{2T_e\alpha^2}\right)\right]. \qquad (3)$$

The limit of the instability with respect to the current velocity may lie much higher than the ion thermal velocity if $T_i \gg T_e$. The oscillations are unstable if $\omega < 0$ or

$$k_z < -\frac{(ku)}{v_{Ti}}\left(\frac{2m}{M}\right)^{1/2}.$$

The maximum value of the increment is $(\omega_{Hi}\omega_{He})^{1/2}$.

2. Ion heating due to Cerenkov absorption and emission of oscillations of the type under consideration is described by the following quasilinear equation

$$\frac{\partial f}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r\nu_\phi \frac{v_\perp^2}{\omega_{Hi}^2}\frac{\partial f}{\partial r} + \frac{v_{Ti}^2}{v_\perp}\frac{\partial}{\partial v_\perp} v_\perp\,\nu_v \frac{\partial f}{\partial v}. \qquad (4)$$

ν_φ and ν_v are the effective frequencies of the variations of the momentum and energy of the ions, respectively. They are expressed in terms of the spectral density of the noise energy

$$W_k = \frac{k^2|\phi_k|^2}{8\pi}\omega\frac{\partial \epsilon}{\partial \omega}.$$

$$\nu_\phi = \frac{8\pi^2 e^2}{M^2}\frac{1}{v_\perp^3}\int \frac{W_{k,\phi'}}{\omega}\left(\frac{\partial\epsilon}{\partial\omega}\right)^{-1}\cos^2\phi' dk\, d\phi',$$

$$\nu_v = \frac{8\pi^2 e^2}{M^2}\frac{1}{v_\perp^3}\int\frac{W_{k,\phi'}}{\omega}\left(\frac{\partial\epsilon}{\partial\omega}\right)^{-1}\frac{\omega^2}{k^2 v_{Ti}^2} dk d\phi', \quad \phi' = L\, \mathbf{k}\, \mathbf{u}.$$

Equation (4) has been derived under the assumption that $\omega_{Hi}/\nu_\varphi \gg 1$ and $\omega/k \ll v$. The rate of change of the longitudinal energy of the ions is

$$\left(\frac{k_z}{k}\right)^2\left(\frac{k^2 v_{Ti}^2}{\omega^2}\right) \simeq \frac{m}{M}$$

times smaller than the rate of change of the transverse energy.

From (4) we can estimate the limiting ion energy if we assume that the spatial diffusion is the decisive form of the losses:

$$\frac{\rho_{Hi}^2}{(r_0/2)^2} < \frac{u^2}{v_{Ti}^2} \quad \text{or} \quad T_i \leqslant \frac{M r_0 \omega_{Hi}\, u}{4}. \tag{5}$$

Substituting in the estimate (5) the data cited at the beginning of the article, we get $T_i \leq 250$ eV. It is difficult to expect better agreement with the experimental value (T_i = 100 eV), especially if we recognize that, in accordance with the calorimetric measurements, half the energy dissipated in these experiments escapes along the magnetic field.

In the experiments discussed here, measurements of the Doppler widths of the lines of the small amounts of impurities Si^{++} and O^+ yielded approximate temperatures of 50 and 30 eV for Si^{++} and O^+, respectively.* Heating of a small addition of heavy ions with $v_\perp \ll u$ is described by the equation

$$\frac{\partial f_a}{\partial t} = \frac{1}{v_\perp}\frac{\partial}{\partial v_\perp} v_\perp \nu v_{Ta}^2 \frac{\partial f_a}{\partial v_\perp},$$

$$\nu_v = \frac{16\pi^2 e^2}{M^2 v_\perp^3}\int_{\pi/2 - v_T/u}^{\pi/2}\frac{W_{k,\phi'}}{\omega}\left(\frac{\partial\epsilon}{\partial\omega}\right)^{-1}\frac{u^2}{v_{Ta}^2}\frac{\cos\phi' dk d\phi'}{\sqrt{1-\frac{u^2}{v_T^2}\cos^2\phi'}}.$$

The rates of heat transfer to the wall are determined by the same effective frequency. This means that the limiting temperature of the impurity ions is determined by the condition $\rho_{Hi} \leq r_0/2$, which agrees with experiment within the accuracy limits.

Besides the foregoing results, measurements were performed in which helium was used as the working gas. To maintain the condition for magnetosonic resonance, the constant magnetic field was chosen to be twice as strong as in the experiments with hydrogen. The amplitude of the alternating magnetic field in the plasma and the remaining parameters were unchanged.

The measured maximum temperature of the helium amounted to 200 eV. The doubling of the temperature on doubling the magnetic field agrees with formula (5).

3. To determine the rate of heating it is necessary to know the noise energy density. It seems obvious that the amplitude of the electron-velocity oscillations $v_\sim$ cannot exceed the phase velocity of the oscillations $\omega/k \simeq u$. The energy density of the oscillatory motion of the electrons $nmv_\sim^2/2$, can therefore be assumed to be the limiting noise energy w. If we substitute this estimate in (4), we obtain for the ion heating rate the expression

$$n\dot{T}_i = \gamma_i w \lesssim (\omega_{Hi}\omega_{He})^{1/2}\frac{nmu^2}{2}. \tag{6}$$

We chose for γ_i the maximum possible increment. We can now estimate the damping decrement of the electromagnetic wave $\delta = 4\pi P_i/H_\sim^2$. For a forward magnetosonic wave:

$$u = \frac{2\pi f}{\omega_{Hi}}\frac{H_\sim}{\sqrt{4\pi n M}}, \quad \delta = \frac{(2\pi f)^2}{(\omega_{Hi}\omega_{He})^{1/2}}. \tag{7}$$

The value of δ calculated from (7) agrees with the experimentally measured value.

[1] I. A. Kovan and A. M. Spektor, Zh. Exp. Teor. Fiz. 53, 1278 (1967) [Sov. Phys.-JETP 26, 727 (1968)].

[2] V. V. Chechkin, M. P. Vasil'ev, L. I. Grigor'ev, and B. I. Smerdov, Nuclear Fusion 4, 145 (1964).

[3] V. I. Aref'ev, Zh. Tekh. Fiz. 38, No. 12 (1968) [Sov. Phys.-Tech. Phys. 13, No. 12 (1969)].

[4] V. L. Sizonenko and K. N. Stepanov, Nuclear Fusion 7, No. 2 (1967).

* The measured temperature of the ions in the center of the heating circuit are given in [1].

"DISSIPATIVE" INSTABILITY OF A LIGHT WAVE IN A NONLINEAR DIELECTRIC

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It is well known [1-3] that a plane wave in a nonlinear self-focusing medium is unstable. We shall show in this paper that if account is taken of the finite relaxation time of the nonlinearity, the wave turns out to be unstable also in a defocusing medium. In addition, introduction of a finite relaxation time changes strongly the character of the instability of a plane wave in a self-focusing medium.

We write down the equations for the eikonal Φ and the amplitude A in the form (see [3])

$$\left(\frac{\partial}{\partial t} + v_{gr}\frac{\partial}{\partial x}\right)\Phi + \frac{\omega_k''}{2}\left(\frac{\partial\Phi}{\partial x}\right)^2 + \frac{v_{gr}}{2k_0}(\nabla_\perp\Phi)^2 =$$