If we use our result (5) to estimate the role of the hadron mechanism of γ-quantum absorption, then we can easily obtain for the absorption probability P per unit length $P_T \approx 1.5 \times 10^{-29}$ cm^{-1} (absorption by photons of "relict" radiation [4]) and $P_R \approx 3.2 \times 10^{-30}$ cm^{-1} (absorption by photons of extragalactic radio emission [5]). For photons with $E > 7 \times 10^{23}$ eV, the contribution of the hadron mechanism prevails over the contribution made to P_T by the pair-production process, and does not vary with energy.

We see that the mechanism under consideration does not change essentially the question of the absorption of photons in the universe for reasonable values of the γ-quantum energies.

The authors thank A. I. Alikhanyan for interest in the work. One of the authors (S.M.) thanks O. V. Kancheli for discussions.

[1] J. G. Asbury et al., Phys. Rev. Lett. 19, 865 (1967).
[2] A. I. Nikishov, Zh. Eksp. Theor. Fiz. 41, 549 (1961) [Sov. Phys.-JETP 14, 393 (1962)].
[3] P. Goldreich and P. Morrison, ibid. 45, 344 (1963) [18, 239 (1964)].
[4] J. V. Jelley, Phys. Rev. Lett. 16, 479 (1966).
[5] R. J. Gould and G. P. Schreder, Phys. Rev. 155, 1408 (1967).
[6] A. A. Penzias and R. W. Wilson, Astrophys. J. 142, 419 (1965).

[*] In the estimate (4) we confined ourselves only to the most intense $\gamma\rho$ transition. Inclusion of $\gamma\omega$ and $\gamma\varphi$ transitions leads to an increase in the cross sections in (4) and (5) by approximately 30%.

ION-CYCLOTRON INSTABILITY IN A PLASMOID

V. I. Pistunovich and D. D. Ryutov

Submitted 18 January 1968
ZhETF Pis'ma 7, No. 7, 234-237 (5 April 1968)

Plasmoids obtained in pulsed plasma injectors usually contain ions having a considerable thermal scatter both in the longitudinal and transverse directions, with $T_{\parallel i} \sim T_{\perp i}$. It is shown in this paper that motion of such a plasmoid along a homogeneous magnetic field excites in the latter, under certain conditions, ion-cyclotron oscillations that lead to a "conversion" of the transverse thermal energy of the ions into energy of longitudinal translational motion. Such a "conversion" can cause an appreciable decrease of the energy of the transverse motion of the tions, compared with the energy immediately after the emission of the plasmoid from the injector.

We confine ourselves for simplicity to the one-dimensional problem, i.e., we assume that the parameters of the plasmoid depend only on the coordinate x directed along the magnetic field. We assume further that at the initial instant of time the ion temperature greatly exceeds the electron temperature. Under this condition, the electric fields produced in the plasma do not influence the motion of the ions, i.e., each ion emitted from the injector moves along the magnetic field with constant velocity (we neglect pair collisions). The presence of initial thermal scatter of the ions causes the plasmoid to spread apart in the course of time, and its characteristic length L increases like $L \simeq L^{(0)} + v_{Ti}^{(0)} t$, where $L^{(0)}$ is the initial length of the plasmoid and $v_{Ti}^{(0)}$ is the initial thermal velocity of the ions.

It is easy to see that during the process of the spreading of the plasmoid, the scatter of the ions with respect to the longitudinal velocities, at each fixed point of space, decreases with time approximately like $L^{(0)}/t$, and that when $t \gg L^{(0)}/v_{Ti}^{(0)}$ it becomes much smaller than the initial scatter. At the same time, the transverse scatter of the ions remains of the same order as the initial one, i.e., the ion distribution function at each point of space becomes strongly anisotropic: $T_{\perp i} \gg T_{\parallel i}$. This produces in the plasma an ion-cyclotron instability (see [1]), as a result of which $T_{\perp i}$ decreases and $T_{\parallel i}$ increases. With further spreading of the plasmoid, $T_{\parallel i}$ again decreases, the instability is again turned on, $T_{\perp i}$ decreases, etc. Such a process leads in final analysis to a conversion of the entire energy of the transverse thermal motion into energy of longitudinal spreading of the plasmoid, and $T_{\perp i}$ becomes much smaller than its initial value.

In the case considered by us, when $T_{\parallel i} \gg T_e$, the principal role in the ion isotropization process is played by cyclotron instability at the electron Langmuir oscillations with $k_\perp \sim \omega_{Hi}/v_{Ti}$, $k_\parallel \sim (m/M)^{1/2} k_\perp$, and a characteristic increment $\operatorname{Im} \omega \sim (m/M)^{1/2} \omega_{Hi}$. Allowance for the spatial inhomogeneity of the parameters of the plasmoid and the direction of the magnetic field does not influence the instability, provided the following inequality holds:

$$L \gg (M/m)^{1/2} v_{Ti}/\omega_{Hi}. \qquad (1)$$

In the case of free spreading of the plasmoid (i.e., in the absence of instability), the characteristic time τ of the increase of the anisotropy of the distribution function by an amount of the order of unity is approximately equal to L/v_{Ti}. It is easy to see that when condition (1) is satisfied there is simultaneously satisfied the condition $\tau \operatorname{Im} \omega \gg 1$, i.e., the instability develops very rapidly, compared with the time τ. This means that the instability retains all the time the anisotropy of the ion distribution function near the critical value corresponding to the threshold of the occurrence of the instability.

In order to investigate the motion of the plasmoid in greater detail, we shall use the kinetic equation for the ions:

$$\frac{\partial f}{\partial t} + v_\parallel \frac{\partial f}{\partial z} = St, \qquad (2)$$

where St stands for the collision term describing the interaction of the ions with the unstable oscillations. We note that the collision term "acts" only in one direction: it reduces a larger-than-critical anisotropy to the critical level, but St = 0 if the anisotropy is lower than critical, since there are no oscillations in the system.

As indicated above, the anisotropy of the ion distribution function is close to the critical value at all times. Therefore the energy of the cyclotron oscillations in the system is small compared with the thermal energy of the ions. Consequently, we can assume that the collision term conserves the energy and the longitudinal momentum of the ions. We assume further that the interaction between the ions and the unstable oscillations leads to establishment of a two-temperature Maxwellian distribution, for which the ratio $\alpha = T_{\perp i}/T_{\parallel i}$ is determined from the condition that the system be situated on the instability boundary. Using these properties of the collision term, we can obtain from (2) in the standard manner the hydrodynamic equations describing the longitudinal motion of the plasmoid. The result coincides exactly with the hydrodynamic equations for an ideal gas with an adiabatic exponent $\gamma = (3 + 2\alpha)/(1 + 2\alpha)$.

In our problem we are interested in those solutions of those hydrodynamic equations which correspond to the spreading of a gas cloud in vacuum. An investigation of such a problem can be found, for example, in the book of Zel'dovich and Raizer [2]. It turns out that when $t \gg L^{(0)}/v_{Ti}^{(0)}$ the boundaries of the plasmoid move apart at a constant velocity $\sim v_{Ti}^{(0)}$, and the transverse temperature of the ions decreases like

$$T_{\perp i} \sim T_{\perp i}^{(0)} \left(\frac{L^{(0)}}{v_{Ti}^{(0)} t}\right)^{\gamma-1} .$$

The foregoing investigation pertains to the case when $T_{\parallel i} \gg Te$. However, a similar effect can exist also when $T_{\parallel i} \ll T_e$, for in this case the spreading of the plasma cloud leads to a decrease in the longitudinal thermal scatter of the ions [3]. When $T_{\parallel i} \ll T_e$ the isotropization of the ions is due to the excitation of oscillations of the ion-sound type. We note that the corresponding increments can greatly exceed the value $\sqrt{m/M}\,\omega_{Hi}$.

The described effect can be used in experiments on charge exchange of a plasmoid with a gas target. The atoms produced during the charge exchange leave the target at an angle $\sim v_{\perp}/v_{\parallel}$ to the plasmoid direction of motion. Therefore the decrease of the transverse ion velocity as a result of the "conversion" of the transverse energy into longitudinal-motion energy will cause the divergence of the atom plasmoid to decrease greatly compared with the case when the charge exchange is effected near the injector and the cyclotron instability does not have time to develop.

The authors are deeply grateful to I. N. Golovin and A. V. Timofeev for useful discussions.

[1] A. V. Timofeev and V. I. Pistunovich, In: Voprosy teorii plazmy (Problems of Plasma Theory) No. 5, Atomizdat, 1967, p. 351
[2] Ya. B. Zel'dovich and Yu. P. Raizer, Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavlenii (Physics of Shock Waves and High-temperature Hydrodynamic Phenomena), Fizmatgiz, 1963, p. 92.
[3] A. V. Gurevich, L. V. Pariiskaya, and L. P. Pitaevskii, Zh. Eksp. Teor. Fiz. 49, 647 (1965) [Sov. Phys.-JETP 22, 449 (1966)].

NONSTATIONARY NONLINEAR OPTICAL EFFECTS AND FORMATION OF ULTRASHORT LIGHT PULSES

S. A. Akhmanov, A. I. Kovrigin, A. P. Sukhorukov, R. V. Khokhlov, and A. S. Chirkin
Moscow State University
Submitted 19 January 1968
ZhETF Pis'ma 7, No. 7, 237-242 (5 April 1968)

1. An important recent accomplishment in laser physics is the generation of picosecond giant pulses (of duration $\tau_p \simeq 10^{-11}$ sec for single pulses and $\tau_p \simeq 10^{-12}$ for pulse trains, see [1]). Inasmuch as the reduction of the pulse duration leads to an increase of the threshold of the light-field intensity E_{br} at which breakdown of the medium takes place (see