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INSTABILITIES AND LIGHT SCATTERING IN AN EXPANDING MULTICOMPONENT PLASMA

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1. When a plasma is produced by nanosecond laser pulse, a hot expanding corona is formed, in which the laser energy is absorbed. It is known that the laser beam can produce in the corona plasma instabilities that lead to the appearance of strongly epithermal plasma-density fluctuations and scattering of the incident beam [4]. In the present article we call attention to one more possible cause of the "darkening" of the plasma corona.

If the plasma consists of ions of two or more types with different z_e/M, for example thermonuclear fuel consisting of a deuterium-tritium mixture, then the ambipolar electric field $E = -(T_e/e)\nabla \ln n_e$ of the corona will accelerate the ions unevenly. In the region of the rarefied corona, where the force of friction between the ions with different z_e/M is no longer capable of equalizing the velocities, the lighter ions will start to run away forward and a two-stream motion is produced. Such a state, as is well known, is unstable. The fluctuations of the electric field and of the density can grow in it with a characteristic scale on the order of or larger than the ion Debye radius. Scattering of the ions by the turbulent electric fields leads to effective friction between the components, and some of the work of the ambipolar electric field will be consumed in their heating. One can expect the processes occurring in this case to be similar to the turbulent heating of plasma in an electric field, which has been sufficiently well investigated theoretically and experimentally [1].

2. Let us review the qualitative arguments of the theory of turbulent heating (see, e.g., [1]) as applied to the phenomenon under consideration.

In a plasma with two types of ions ($M_2 \gg M_1$, $T_e \gg T_1 \gg T_2$) there can exist besides ordinary ion sound $\omega_1 = k(T_e/2M_1)^{1/2}$ also short-wave slow sound $\omega_2 = k(T_1/M_2)^{1/2}$ (the theory of turbulent heating is based on the existence of a small parameter m/M; the case of comparable masses can be obtained as a limiting approximation; to simplify the formulas we assume $n_1 = n_2 = n/2$ and $z_1 = z_2 = 1$). The slow sound can build up if the average velocity u of the light ions relative to the heavy ones exceeds ω_2/k. The unstable perturbations are those with wave vectors

$$k \lesssim \left(\frac{4\pi ne^2}{T_1}\right)^{1/2}, \quad \gamma_{max} \approx \left(\frac{4\pi ne^2}{T_1}\,\frac{M_1}{M_2}\right)^{1/2} u. \tag{1}$$

The light ions are scattered by the electric field of such a turbulence, with effective frequency

$$\nu(v) = \pi \frac{e^2}{M_1^2} \int \frac{|E_k^2|}{v^2} \delta(kv) dk . \quad (2)$$

They will therefore drift under the influence of the ambipolar electric field relative to the heavy component, with velocity

$$u = -\frac{T_e}{M_1 \nu_{ef}} \nabla \ln n_e \quad (3)$$

and will become heated

$$\frac{d}{dt} \frac{3}{2} n_1 T_1 = eEu . \quad (4)$$

It is shown in [2] that in the steady state with turbulent friction, the momentum acquired by the light particles from the electric field, via the resonant Cerenkov interaction, accumulates in oscillations whose wave vectors lie in a narrow cone of angles along the electric field, with apex angle $\theta_0 \sim E_{1/2}$. These oscillations do not affect the mobility of the light component even at relatively high intensity, as can be seen from (3). The momentum can be transferred from the oscillations to the heavy ions via weaker nonlinear processes, since Cerenkov resonance of the bulk of the heavy particles with unstable oscillations is impossible. In the case of "weak" turbulence, the principal process is nonlinear induced scattering (contributing to it, in particular, is the stimulated Compton scattering)

$$eEn_2 = -\int 2\gamma_k(w) \frac{w_k}{\omega_k} k\,dk \approx 2\gamma_p \frac{w}{u^2} u . \quad (5)$$

Here w is the energy density of the oscillations and $\gamma_p(w)$ is the characteristic frequency of the spectral redistribution.

In problems involving turbulent heating, there is only one branch of oscillations, ion sound. The nonlinear scattering of almost one-dimensional oscillations within a single branch has a low frequency, $\gamma_p \doteq \omega(T_i/T_e)\theta_0^2(w_1/nT_e)$ [3].

In our problem, scattering from the unstable branch 2 of the slow sound by branch 1 of the weakly-damped ion sound is possible (and conversely). This process has a frequency

$$\gamma_p \approx \omega \frac{w_1}{nT_e} \frac{T_2}{T_1} \frac{M_1}{M_2} \quad (6)$$

and leads to excitation of ion-sound oscillations with spectral density $w_k \approx w_{1/k}$ for wave vectors $k \leq (4\pi ne^2/T_e)^{1/2}$ to a level $w_1 \approx w_2(T_2T_e/T_i^2)(M_1/M_2)$ Therefore the transfer of a momentum eEn_2 to the heavy ions is attained at an ion-sound turbulence level

$$\frac{w_1}{nT_e} \left[\frac{E}{(8\pi nT_e)^{1/2}} \frac{T_e}{T_1}\right]^{1/2} \approx \left(\frac{T_e}{T_1} \frac{v_{T_e}}{\omega_p r}\right)^{1/2} . \quad (7)$$

3. A laser beam of frequency $\omega_t = k_t c$ can be reflected and scattered by the long-wave electron-density fluctuations δn_e, $k \leq 2k_t$. The beam scattering length L is connected with $(\delta n_e)^2$ by the relation

$$\frac{d}{dr} \ln w_t = \frac{1}{L} = \frac{\pi}{4}\left(\frac{\omega_p}{k_t c}\right)^4 \int_0^{2k_t} k\left(\frac{\delta n_k^e}{n}\right)^2 dk, \quad \left(\frac{\delta n_k^e}{n}\right)^2 = \frac{w_{k1}}{nT_e} \quad . \tag{8}$$

On the unstable branch of the slow sound we have $\delta n_e/n \simeq T_1/T_e$. Therefore the ion-sound fluctuations will scatter the light. According to (7)

$$\frac{1}{L} \approx \left(\frac{\omega_p}{k_t c}\right)^4 \int_0^{2k_t} \frac{w_1}{nT_e} dk \approx \left(\frac{T_e}{T_1} \frac{v_{Te}}{\omega_p r}\right)^{1/2} k_t \left(\frac{n}{n_c}\right)^2 . \tag{9}$$

The estimate of L depends strongly on the density at which the plasma is unstable. In the case of expansion of a high-temperature plasma from a mixture of deuterium and tritium, the two-stream motion occurs at

$$n < 10^{12} \frac{T_i T_e}{r} . \tag{10}$$

(T_1 and T_e in electron volts).

Thus, we have considered here the onset of density fluctuations in an expanding multicomponent plasma, and estimated the length for scattering of a laser beam by these fluctuations. This length depends strongly on the frequency of the light and on the temperatures of the electrons and ions of the plasma. This effect can greatly decrease the energy efficiency when high-power lasers are used to heat a dense DT plasma to thermonuclear temperatures. Thus, according to formulas (9) and (10), light from a neodymium laser, passing through a corona with $T_e = 10^4$ eV and r = 1 mm, encounters a critical density at which $\omega_t = \omega_p$, and strong absorption should set in if the ion temperature is less than 300 eV. A beam from a CO_2 laser, on the other hand, is scattered far from the critical density.

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