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INSTABILITY OF PLASMA ON TRAPPED PARTICLES

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As is well known, flute instability can set in in magnetic-mirror traps and in toroidal traps with closed force lines [1,2]. This instability is the result of the oppositely directed drifts of the electrons and ions in the inhomogeneous electric field (force-line curvature radius R) with velocities $v_j = cT_j/e_jHR$ (H = magnetic field, T_j = temperature, e_j = charge of particle of species j). This drift causes polarization of the plasma in perturbations of the "tongue" type on the plasma surface, and if the magnetic field decreases in the outward direction, then the electric field due to the polarization causes plasma to be ejected. Flute instability was investigated experimentally by Ioffe et al. [3,4].

Analysis in the hydrodynamic approximation [5,6] has shown that in toroidal systems with open force lines lying on toroidal surfaces the plasma should be stable if the pressure is low enough. In a rarefied plasma, however, when the hydrodynamic approximation does not hold, the deduction that flute instability is stabilized by the crossing of the force lines is no longer valid. In fact, this deduction is based on the notion that in a high-temperature plasma the charges due to the magnetic drift should cancel each other as a result of flow along the force lines. Such a cancellation effect does indeed occur, but it applies only to the so-called transit particles, which move freely along the force line. If the magnetic field varies along the force lines, then there is present, besides the transit particles, also a group of "trapped" particles, which oscillate between the magnetic mirrors, i.e., between regions with stronger magnetic fields. If the change of the magnetic field along the force lines is small, then the mirror ratio $P = H_{max}/H_{min}$ is close to unity, and the fraction of particles trapped between mirrors is small, $\epsilon \cong \sqrt{P - 1}$. Since the captured particles are trapped between the mirrors, they cannot move freely along the force lines, and consequently an instability of the flute type can develop on them, and can be naturally called trapped-particle instability.

It differs from flute instability in that the charges due to the trapped particles are cancelled out to a considerable degree by the transit particles. Owing to this effect, the growth increment becomes small, and the transit particles have time to acquire a Boltzmann distribution, i.e., the perturbation of their density is equal to $-e_j\varphi n/T_j$, where φ is the electric field potential and n the unperturbed density. For the perturbation n_t' of the trapped-particle density we have in the quasiclassical approximation, when the perturbation of the potential is in the form of a plane wave, and neglecting the scatter in the drift velocities, the following continuity equation:

$$(-\omega + k_y v_{jt}) n_t' + \frac{k_y c\varphi}{H} \epsilon \frac{dn}{dx} = 0. \quad (1)$$

Here $dn/dx = \nabla n$, k_y is the wave-vector component perpendicular to ∇n and to $\vec{H}$, and v_{jt} is the drift velocity of the trapped particles (all quantities are assumed to be suitably averaged along the force lines of the magnetic field). The last term in (1) takes into account the drift in the electric field, It is shown in [7] that the drift velocity v_{jt} of the trapped particles is proportional to the gradient of the longitudinal invariant

$$J_{\parallel} = \int m v_{\parallel} d\ell, \quad (2)$$

where the integration is along the force line between the turning points. In order of magnitude, $v_{jt} \sim v_j$.

Thus, taking (1) into account, we get for the total density perturbation n_j' of the particles of species j the following experession

$$n_j' = -\frac{e_j\varphi}{T_j} n + \frac{k_y c\epsilon}{(\omega - k_y v_{jt})H} \frac{dn}{dx} \varphi. \quad (3)$$

The first term on the right is the perturbation of the density of the transit particles.

From the quasineutrality condition $n_i' = n_e'$ we can readily obtain a dispersion equation for ω. For the case of equal temperatures $T_i = T_e = T$ this dispersion equation is

$$\omega^2 = (k_y v_{jt})^2 (1 - \epsilon R/a), \quad (4)$$

where $a = -n(dn/dx)^{-1}$ is the characteristic dimension.

We see that when $\epsilon > a/R$ instability sets in with a growth increment $\gamma \sim cT/eHR$. Since $\epsilon \sim \sqrt{\delta H/H}$ and $R \sim LH/\delta H$ (where δH is the amplitude of magnetic-field modulation and L the length over which the field changes), we get $\epsilon R/a \sim (L/a)\sqrt{H/\delta H} > 1$ for systems with moderately modulated magnetic fields. Thus, an instability of this type should develop, generally speaking, in a system with a moderately inhomogeneous field. This instability should cause ejection of the captured particles, and then collisions or instabilities on high-frequency longitudinal oscillations will cause the cone of captured particles (in velocity space) to be continuously filled with transit particles. When $R \sim a$ the developed instability can lead to plasma leakage of the same order as by the Bohm mechanism.

Trapped-particle instability should certainly not occur in a dense plasma, when the frequency of the ion-ion collisions is larger than γ/ϵ^2 (the factor ϵ^{-2} takes account here of the diffusion character of the Coulomb collisions). In a rarefied plasma there is no instability if the particles' drift is favorable [1]. To this end it is sufficient to have the longitudinal invariant decrease towards the periphery, for a given energy $mv^2/2$ and for a transverse adiabatic invariant $\mu = v_\perp^2/H$. In apparatus of the Tokomak type, for example, such conditions are realized in the region where the quantity $q = rH_z/R_0H_\vartheta$ decreases sufficiently rapidly with r (r is the running minor radius, H_z and H_ϑ the longitudinal and azimuthal magnetic fields, and R_0 the major radius of the torus). The condition $\delta J_\parallel < 0$ replaces the hydrodynamic condition $\delta\oint dl/H < 0$, which is used to find the so-called "minimum-H configurations." A detailed investigation of the trapped-particle instability in a toroidal discharge of the Tokomak type was made by the author jointly with O. P. Pogutse.

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PROPAGATION OF A LIGHT PULSE IN A NONLINEARLY AMPLIFYING AND ABSORBING MEDIUM

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1. In our paper [1] we reported an investigation of the propagation of a pulse of coherent light in a medium with nonlinear gain. It was also noted there that when a light pulse propagates in a medium with nonlinear gain and nonlinear absorption, unlike a medium with nonlinear acceleration, the duration will become shorter regardless of the shape of the initial pulse, provided absorption saturation sets in much earlier than amplification saturation. In this letter we report on successful experiments in this direction, and show that to obtain compression of a propagating light pulse it is necessary to eliminate the structure connected with the transverse development of the pulse emitted by a Q-switched laser [2,3].

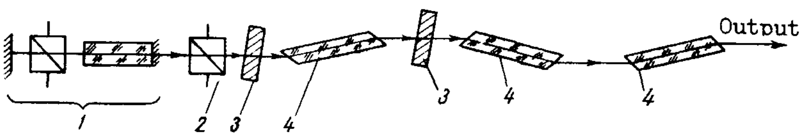

Fig. 1. Experimental setup

2. The setup of the experiment on the propagation of a high-power light pulse in a two-component nonlinear medium is shown in Fig. 1. The pulse was applied to the input of the medium from a Q-switched ruby laser (1) by means of a Kerr shutter (2). The amplifying component consisted of three ruby crystals (4) (each 24 cm long and 1.6 in diameter) with overall initial gain up to 10^4. The absorbing component consisted of two cuvettes (3) filled with a solution of vanadium phthalocyanine in toluene and placed before and after the first crystal;