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PLASMA INSTABILITY AND NUCLEAR FUSION

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SUMMARY

This paper discusses the various forms of plasma instabilities, whose if only partial stabilization is necessary to control thermonuclear reactions. A preliminary conclusion is derived that plasma instability can be substantially decreased by increasing the magnetic field, by increasing the criss-cross of the lines of force and also the dimensions of the system. Tentative values are given for the dimension of a thermonuclear reactor and the intensity of its magnetic field.

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As is well known, the principal obstacle to obtaining a controllable thermonuclear or fusion reaction is the instability of the plasma. This is precisely the area where all the hopes of rapidly resolving this problem on the basis of utilization of self-constricting high-current discharges have been frustrated. The instability and the collective processes linked with it made clearly evident the insufficiency of the available knowledge for the understanding of the processes taking place in the plasma, and switched the investigations according to nuclear fusion program to the path of obstinate and painstaking study of plasma physics. It may be said, without exaggeration that at present either aspect or form of instability has to be studied on each of the installations used for obtaining high-temperature plasma.

As to the theoretical research, a very substantial share of efforts is now expended on the detection and study of various types of plasma instability. Some time ago, when new or newer forms of unstable rarefied plasma were revealed in an intense magnetic field, it seemed that we should never attain their full description. Fortunately, the situation has now begun to improve. Though the activity in the study of instabilities is maintained at the former level, it becomes clear at present that only a certain limitation of their number constitutes a real menace for confining high-temperature plasma in a magnetic field.

(*) [NEUSTOYCHIVOST' PLAZMY I UPRAVLYAYEMYYE TERMOYADERNYYE REAKTSII]

As to why this is so may be understood from the following line of reasoning. Any nonequilibrium state serves as the source of plasma instability: the inhomogeneity in space, the nonisothermicity, the anisotropy, the presence of beams and so forth. From the thermodynamic point of view a nonequilibrium plasma constitutes a metastable state of the matter (provided we neglect the collisions), and the build-up of oscillations on account of instability corresponds to one of the possible ways of establishing a thermodynamic equilibrium. The stabilization of instability corresponds to the imposition to the given form of transition of a prohibition, similarly to what happens when at prohibition of one of the schemes of radioactive nucleus decay there is realized another one, less probable, as well as when suppressing one of the basic instabilities there emerges another one, less turbulent.

For example, in the experiments by M. S. Ioffe and co-workers on the behavior of plasma in traps with magnetic plugs, the suppression of the most dangerous flute instability* leads to the emergence in foreground of a thinner cyclotron instability. And inasmuch as the total stabilization of all instabilities of a rarefied plasma is apparently impossible, there exists in each concrete experiment a limited group of most dangerous nonstabilized instabilities responsible for the collective processes in the plasma.

As to which group of instabilities is the most dangerous, it depends on concrete experimental conditions, that is, on the configuration of the magnetic field, the temperature and density of the plasma, the methods of its creation and so forth. Having in mind the problem of controllable theormonuclear reactions we shall consider here only toroidal systems endowed with a much greater "reserve of strength" by comparison with the adiabatic traps, i. e., less sensitive to accretion of losses over the classical traps.

If we digress from the possibilities of stabilization, the greatest danger is most certainly constituted by magnetohydrodynamic instabilities in which the macroscopic portions of the plasma may shift with velocities of the order of the thermal velocity of ions;

$$v_i = \sqrt{T / m_i},$$

where T is the temperature, and m_i is the mass of the ion. Depending upon the energy sources conditioning the character of plasma oscillations, three particular forms of magnetohydrodynamic instabilities may be distinguished: the corkscrew, the flute and the kink* instability. The former may develop in toroidal systems in the presence of longitudinal current; its energy reservoir is precisely constituted by the energy of current's magnetic field. However, in reality the corkscrew instability must not be considered as dangerous, for it is comparatively easily stabilized by superimposition of an intense longitudinal magnetic field, when the Kruskal-Shafronov criterion** begins to be fulfilled. Nor is great danger offered by the corkscrew instability with finite conduction (tearing-mode). As to the flute and the kink instability closely linked to it, that develop as a result of diamagnetic plasma extrusion toward the side of convex lines of force, it is also easily stabilized at comparatively low plasma pressure p by comparison with that of

* [this is the best equivalent to the Russian expression "zhelobkovoy", which means "groove"]. ** [in transliteration].

the magnetic field $H^2/8\pi$ and the presence of the "shear" they also lend themselves easily to stabilization. Therefore, taking into account the possibilities of stabilization, the magnetohydrodynamic instabilities may be considered as not dangerous. In other words, the attaining of plasma decay prohibition through magnetohydrodynamic instabilities offers no particular difficulties.

It is not difficult to understand why one succeeds in attaining the prohibition. The fact is that rapid plasma displacements with velocities of the order of thermal velocity of ions v_i take place with lines of force of the magnetic field frozen into the plasma. In toroidal geometry such displacements lead in the absence of closed lines of force to the distortion of the latter, i. e. to the disturbance of the magnetic field. The potential barrier linked with magnetic field energy increase at perturbation, precisely creates this stabilizing effect.

In conditions when the magnetohydrodynamic plasma is stable, most dangerous are the slow instabilities, and the drift instabilities in the first place. They may develop on potential oscillations, at which the magnetic field is not disturbed. Their characteristic development time is of the order of the time of particle revolution a / v_d around the plasma pinch at drift motion with velocity

$$v_d \sim v_i \rho_i / a \sim v_e \rho_e / a.$$

where v_i is the thermal velocity of ions $\rho_i = \frac{v_i}{\Omega_{ui}} = \frac{v_i m_i c}{eH}$ is their mean Larmor radius, v_e, ρ_e are the same quantities for electrons, $\underline{a}$ is the radius of the plasma pinch. The development time of drift instability with a not too small wavelength is $a/\rho_i \ll 1$ times greater than the characteristic time of magnetohydrodynamic oscillations.

The drift instabilities do not lend themselves to full stabilization; however, in this case too one may take advantage of the prohibition effects. One of them is linked with the fact that the electron component of the plasma has a tendency to be "glued" to the lines of force of the magnetic field. And namely, if the Boltzmann distribution has time to settle, the electrons can not shift across magnetic surfaces even at slow density oscillations. In other words, the development of instabilities linked with density gradient and the anomalous transverse diffusion on oscillations take place only at the expense of the disruption of Boltzmann distribution.

In a rarefied plasma such a disruption arises because the collisions do not succeed in restoring the Maxwellian distribution. For very scarce collisions this leads to the possibility of instability development on locked particles; in a nonuniform magnetic field of toroidal systems there exists always a group of particles, locked between "plugs" -- regions with increased magnetic field, and in the absence of collisions, an instability of the flute type may develop on these particles. If the collisions are not very scarce, the instability on locked particles is absent, and the disruption of the Maxwellian distribution takes place either at the expense of interaction of resonance electrons with drift waves, or of the longitudinal inertia of electrons, or of electron-ion friction force, that is, of finite conduction. At the same time, the temperature-drift instability emerges in the foreground.

As may be seen from its denomination, it belongs to the class of drift instabilities, and it is linked with the temperature gradient. This instability does not lead to strong plasma diffusion, but it induces a large heat flow across the magnetic field. It develops only for a sufficiently large temperature gradient, and namely for

$$\frac{d \ln T}{d \ln n} > 1 .$$

This is why, by striving to lower the plasma density at chamber walls it is possible to bring down noticeably the value of anomalous heat conductivity from the given form of instability.

The second prohibition effect existing in drift instabilities consists in the following. They all develop on slow oscillations, spreading along the small azimuth with phase velocity of the order $v_d \sim v_i\rho_i / a$. The drift waves exist also in the case when their phase velocity along the magnetic field exceeds the thermal velocity of ions v_i, that is, provided the corresponding disturbances are strongly stretched along the magnetic field. In the presence of "shear" this effect leads to strong localization of oscillations in a radial direction (of the order of several ρ_i). whereupon the waves, localized at different points along the radius, must have a different number of nodes by azimuth. As a result of this, the various waves are found to be little connected with one another and the heat convection or that of particles assumes a relay character — the heat, transferred by one cell is catched up by the following one, etc. The transfer process suggests the standard heat conductivity or diffusion, and inasmuch as the localization of cells may be amenable to several ρ_i, and the characteristic transfer velocity constitutes a magnitude of the order $v_d \sim \rho_i v_i / a$, the effective coefficient of temperature conduction (an the more so of diffusion) in systems with great "shears" may be brought down to a magnitude of the order $\chi \sim \rho_i v_d \sim \rho_i^2 v_i / a$.

However, the corresponding losses still are much higher than the classical. What do such losses mean from the standpoint of attaining a self-sustaining fusion reaction , and to what requirements do they lead ?

In an equicomponent mixture of deuterium and tritium, for

$$\beta = \frac{8\pi p}{H^2} < 1$$

in order to attain the self-sustaining reaction it is necessary to assure a confinement time $\tau > 6 \cdot 10^7 / H^2\beta$. If we take for the scale the Bohm time

$$\tau_0 = \pi a^2 eH / cT,$$

and take into account the possibility of accruing τ by a multiplier $\alpha^{-1} > 1$, the condition for a self-sustaining reaction will be written in the form

$$a^2H^3 > 2 \cdot 10^7 \frac{\alpha}{\beta} \frac{cT}{e} . \qquad (1)$$

Hence it may be seen that for a self-sustaining reactor the maximum attainable magnetic field must be utilized. There exists at present the possibility in principle of creating with the aid of superconducting windings magnetic fields of the order H = 10^5 oe. Substituting this value in (1) and assuming T = 10 kev, we obtain

$$a > 1{,}4 \cdot 10^2 \sqrt{\frac{\alpha}{\beta}} .$$

With $\beta = 10^{-2}$ and a Bohm leakage ($\alpha = 1$) the minor radius of the tore is found to be equal to 14 m. With a leakage twice smaller ($\alpha = 10^{-2}$) the value of the radius a becomes more acceptable, that is, 1.4 m. At the same time $\rho_i / \alpha \sim 10^{-3}$, i. e., the possibility of reaching $\alpha = 10^{-2}$ and even lower values seems to be quite realistic. For $\beta \sim 10^{-2}$ (this corresponds to density $n \sim 10^{14} \div 10^{15}$ cm^{-3} at temperature T = 10 kev) one should expect that the magnetohydrodynamic plasma will be steady and that only drift instabilities must lead to leakage. As to the instability on locked particles, for the density indicated it will not be dangerous either. Therefore, the values $a \approx 10^2$ cm, $H \approx 10^5$ oe may be considered as tentative for the dimension of the thermonuclear reactor and its magnetic field.

Summing up and summarizing we shall note that although nearly no hope remains for achieving a complete stabilization of the plasma, it is found to be possible, in theory, to substantially lower the instability effect by way of increasing the magnetic field, the criss-crossing of the lines of force and the dimensions of the system. At the same time the fast magnetohydrodynamic instabilities of an ideal plasma must be fully stabilized, while the danger-wise next drift instabilities must be strongly depressed. In order to control thermonuclear reactions over this path enormous technical difficulties must be overcome, which are connected with the problem of creating a magnetic field of the order of 10^5 oe in a volume of the order of numerous cubic meters.

These conclusions have a preliminary character. In order to be assured of their validity broad physical investigations must be carried out with the aim of creating more complete representations on the collective processes in the plasma.

*** T H E   E N D ***

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