Investigation of instability of a collision plasma in a mirror trap

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The aim of the present work was to investigate the possibility of stable confinement of a plasma in a mirror trap by using a model that imitates the reactor state with allowance for the main requirements of similarity. A hot-ion plasma with $n \approx 10^{12}$ cm^{-3} and $E_i \approx 100$ eV, which decays freely in a "magnetic hole," is studied. It is found that the decay proceeds first in accordance with the classical model for Coulomb scattering without exhibiting any serious "anomalies." Subsequently, however, an intense instability of the ion-cyclotron type arises and results in large ion losses, anomalous electron heating, and other macroscopic effects. The development of the instability has a close causal relation with the plasma ambipolar potential. The instability is identified as a drift-cone mode which, however, requires greater deformation of the distribution function than in the case of the simple loss cone.

INTRODUCTION

The use of a mirror trap or probkotron to develop a thermonuclear reactor is one of the oldest proposals from among those that have "survived" to date. And although this method is not among the most popular ones, nonetheless its adherents maintain firm positions of cautious optimism, assuming that a positive energy balance is attainable in a probkotron if a number of conditions are satisfied. Among these conditions, one of the most necessary and at the same time the most problematic is that there be no kinetic instabilities.

Kinetic plasma instabilities, as is well known, result from the non-equilibrium character of the velocity distribution function. For a plasma contained in a mirror trap, the distribution function, even in the most favorable case, must inevitably deviate from equilibrium, owing to the presence of the forbidden cone. The aforementioned favorable case is realized when the retained particles assume in velocity space a distribution having the largest statistical probability. This distribution, which is automatically established via Coulomb collisions, is known as the collision-equilibrium distribution. The plasma of a mirror reactor should have precisely this distribution. Its "equilibrium" is merely terminological, for in the thermodynamic sense it is, as emphasized above, not at equilibrium. This is manifest, in particular, in an underpopulation of the cold region of the ion distribution with respect to the transverse energies $f(E_\perp)$ (see curve b of Fig. 9 below), in other words, in its inversion. An inversion of this kind is called a cone inversion, and the instabilities caused by the inversion are called instabilities of the cone type.

The theory has revealed several forms or modes of cone instabilities[1], the most dangerous among which are the high-frequency ($\omega \approx \omega_{pi}$) cone instability[2] and the low-frequency ($\omega \lesssim \omega_{Bi}$) drift-cone instability[3]. In the theoretical analysis it is difficult, however, to take into account all the factors that exist in a real installation, and yet some of them (the spatial inhomogeneity, the character of the boundary conditions, the presence of small additions of cold plasma, etc.) can greatly influence the degree of instability. Therefore the final answer to the question of how large the real danger is should, as usual, be given by experiment.

It follows from the foregoing that the most adequate experimental model in an investigation of the instability is a plasma that satisfies the collision condition, i.e., its confinement time τ is comparable with the ion time τ_{ii} of the Coulomb collisions. Since the confinement time can be limited in experiment by one factor or another (for example, by charge exchange or by instability development), to attain collision dominance it is necessary to reduce the Coulomb time τ_{ii}. The most effective way is lower appreciably the temperature of the model plasma in comparison with the reactor temperature. In addition to collision dominance, other important similarity conditions are that the parameter $\epsilon = (\omega_{pi}/\omega_{Bi})^2$, which characterizes the density, have the "reactor" value $\approx 10^3$, and that the Larmor radius of the ions ρ_i be much smaller than the plasma dimensions. The present paper is devoted to an investigation of plasma stability in a mirror trap when the indicated similarity conditions are satisfied. It can be regarded as a logical continuation of the research performed with the same setup a number of years ago with a lower-density plasma which was not collision-dominated[4]. It was shown then that in spite of the theoretical misgivings, the plasma behaved in stable fashion. The question of the stability at higher densities remained open. A number of preliminary results of the present paper were reported in[5-8].

1. EXPERIMENTAL SETUP AND DIAGNOSTICS METHODS

The experiments were performed with the PR-6 setup, which is a "min-B" mirror trap having the following parameters: distance between mirrors 1 meter, chamber diameter 30 cm, number of stabilizing rods 6, magnetic field intensity B_0 at the center of the trap 2–6 kG (in the present experiments), maximum longitudinal mirror ratio R = 2.4, maximum transverse mirror ratio $R_\perp = 2.0$. The mirror was filled with a hydrogen plasma in the following manner. A cold-plasma filament passed along the axis of the trap and emerged freely along the magnetic field from the chamber of an arc gas-discharge source; the filament diameter was 3 cm. An alternating voltage of frequency close to ω_{Bi} and amplitude on the order of several kV was applied to the filament; under these conditions, the ions were stochastically heated and captured in the trap. The filling pulse usually lasted 400 μsec, and a plasmoid of approximately 10 cm diameter was produced in the trap with density n (averaged over the diameter) up to 3×10^{12} cm^{-3}, an average ion energy E_i from 50 to 300 eV, and an electron temperature T_e respectively from 3 to 15 eV. The neutral-gas density after the filling pulse was $\lesssim 2 \times 10^{10}$ cm^{-3}; at this density, the charge-exchange time, the ionization time, and the times of the other processes connected with the gas greatly exceed the plasma-decay time, i.e., these processes are inessential in first-order approximation.

The plasma containment in the trap was investigated by studying its free decay.

a) The plasma density was measured with a 4-mm microwave interferometer. These measurements were then duplicated by the method of attenuating a beam of fast cesium atoms. The results of both methods turned out to agree.

b) The ion energy was measured by three different methods. The first was based on the use of a fast-neutral-atom spectrometer with stripping by a superthin carbon foil. One of the energy spectra of the plasma ions, obtained by this method (assuming charge exchange with atomic hydrogen), is shown in Fig. 1. Although the energy region $E < 200$ eV is not accessible to measurements, it seems reasonable to extrapolate the spectrum by a Maxwellian curve towards the cold side (as shown in the figure, bearing in mind that statistical equilibrium is established in this energy region during the injection time. Then the average ion energy can be estimated as three-halves of the temperature of the approximating Maxwellian distribution.

The second method consisted of measuring the energy spectrum of the ions that passed through the mirrors during the decay process. The measurements were performed by the retarding-potential method using a multiple-grid receiver located far behind the mirror in the region of a weak magnetic field, where almost the entire energy of the departing particles is transformed into the longitudinal component.

The third method, which seems to be the most representative with respect to the principal (i.e., most populated) part of the ion spectrum of the plasma, is to plot the current-voltage characteristic of a very thin (20–50 μ) probe that collects the ion current in the orbital-limitation regime. The dependence of the square of the ion current I_i on the negative potential U of the probe is approximately a straight line, $I_i^2 = \text{const} \cdot (1 + eU/T_i)$, where T_i is a certain quantity close to $2E_i/3$ at all realistic forms of the distribution. The intercept of the quadratic characteristic with the potential axis makes it possible to determine T_i. In these measurements, the probe was located on the periphery of the central cross section of the trap in such a way that its "erosion" of the plasma be negligible.

The results of the measurements performed by the three foregoing methods turned out to be in satisfactory agreement. In the subsequent exposition we shall use as the energy characteristic of the ion not the average energy, but the "temperature" T_i measured directly in the experiment.

c) The electron temperature T_e could be measured approximately in the plasma stream going through the mirror, by using the multiple-grid receiver mentioned above. For more accurate measurements we used the method of characteristics of a Langmuir probe (the initial part of the electron branch), located at the same point where the probe was placed for the measurement of T_i. Finally, definite information concerning the time variation of T_e was also obtained by comparing the signal due to absorption of a cesium beam with the density signal obtained from the microwave interferometer. The data obtained for T_e by the different observation methods were in agreement.

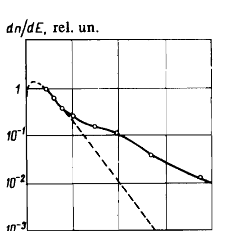


FIG. 1. Plasma-ion energy spectrum at the start of the decay. The cold part is extrapolated by a Maxwellian distribution with T = 150 eV.

d) The plasma potential was measured initially by determining the current of the secondary ions produced in the trap as a result of charge exchange and ionization. These ions are expelled by the positive potential and go off along the magnetic field, acquiring an energy equal to the plasma potential. To separate the stream of the secondary ions from the much stronger stream of primary hot ions scattered into the loss cone, a multiple-slit collimator was placed in the mirror region, on the path to the multiple grid receiver, and transmitted only ions with small transverse energy. The plasma potential was determined from the energy spectrum of the transmitted secondary ions.

It was established later on that if a floating probe is placed on the periphery of the trap, then its potential behaves qualitatively like the plasma potential measured with the aid of the secondary ions, and has approximately half the value of the latter. A floating probe was therefore used subsequently to observe the plasma potential in operation.

e) Measurements of the high-frequency oscillations. To observe the possible potential oscillations due to the development of the instabilities, we placed a floating probe of small internal capacitance on the periphery, in direct contact with the plasma. The signal from this probe duplicated the oscillations of the potential of the surrounding plasma in a wide range of frequencies[9].

2. INITIAL STAGE OF PLASMA DECAY

We proceed to analyze the experimental results. Figure 2 shows the variation of the plasma density during the decay. The time origin is the instant after the end of the injection. The figure shows also the RF noise signal (1–15 MHz) and the floating-potential signal; the potential, as will be shown later on, is one of the decisive characteristics of the state of the plasma.

The behavior of the three indicated quantities shows clearly that the considered decay period breaks up into two stages, an initial quiescent-decay stage that gives way to a stage of patently unstable decay, in which the loss rate is increased, intense RF noise appears, and the potential increases.

Let us examine in greater detail, for the time being, only the first stage. The central question is to what degree does the observed decay rate differ from the rate of the Coulomb collision loss. To estimate the latter, we used the formula

$$n\tau_{\text{Coul}} = CE_i^{3/2} M^{1/2} L^{-1} \lg R$$

(E is in keV, M in the mass of the ions in atomic mass units, and L is the Coulomb logarithm) with the constant C equal to 3×10^{11}[10]. In the described case of decay, E_i amounts to ~0.15 keV, so that $\tau_{\text{Coul}} \approx 210$ μsec, as against the actually observed 250 μsec. Thus, there is

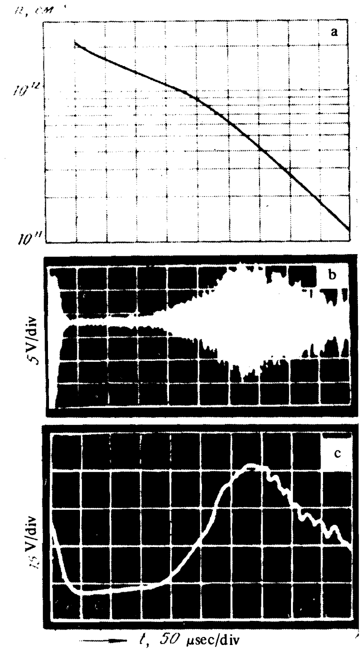


FIG. 2. Plasma decay process: a—variation of density, b—RF-noise signal; c—floating-potential signal.

agreement, although the numerical proximity of the values is, of course, accidental, since the estimated τ_{Coul} is accurate only to within a factor 2–3, because, first, the distribution function in the free decay differs from that used in[10], and second the experimental values of n and E_i are not particularly accurate.

Another indication of the Coulomb mechanism of the loss in the considered stage is that when the plasma parameters are varied the decay process exhibits qualitatively features inherent in the Coulomb mechanism. One of these features, which is particularly weighty evidence of the Coulomb character of the losses, is the decrease of the rate of the initial decay with increasing initial ion temperature, as can be seen clearly in Figs. 5 and 6 (Sec. 3, below). Another analogous feature is that in a regime with a prolonged quiescent stage, the loss rate decreases quite noticeably as the density decreases with time (curves a in the same figures).

The temperature of the electrons at the start of the decay is uniquely connected with the ion temperature, amounting to approximately 5% of the latter. The positive plasma potential φ, which results because the electrons are scattered into the loss cone more rapidly than the ions, and which serves to equalize the rate of escape of the electrons and ions, is approximately (4 to 5)T_e/e. These values of T_e and φ agree with the calculation given (e.g., in[11]) for a decaying plasma. This calculation agrees qualitatively also with the slow increase of T_e and φ as the decay progresses (this is the result of the predominant escape of the colder ions, i.e., of the increase of E_i).

It should thus be concluded from the foregoing that the initial stage of decay is similar in its principal characteristics to the theoretically well investigated state of Coulomb collision equilibrium, the very state whose maintenance is necessary for the reactor to be realizable. It is possible, however, that the decay is still not pure-Coulomb. This is suggested by the fact that the aforementioned dependences of the decay time on the density and on the energy turn out to be apparently weaker than the expected $\propto 1/n$ and $\propto E_i^{3/2}$. In addition, even in this stage, which is arbitrarily called quiescent, one can notice in fact a certain "priming" level of the same oscillations which are subsequently multiplied by hundreds of times and take the form of an instability burst.

3. STAGE OF UNSTABLE DECAY

The considered quiescent decay gives way during a certain state which is distinctly defined under the specified conditions, to the next stage, during which the all-deciding factor becomes the instability. Without dwelling for the time being on why a plasma can be brought in a perfectly reproducible manner each time to the threshold of the unstable state, we turn to consider the phenomenological properties of the instability, in order to be able to use them later on as the basis for the establishment of the nature of this phenomenon.

The instability becomes manifest in the development of oscillations of the potential in the plasma, shown in general form in Fig. 2, and on a "microscopic scale" in Fig. 3. The maximum amplitude of the oscillations can reach several dozen volts. Their fundamental frequency is connected with the magnetic field and amounts to approximately 0.7 ω_{Bi}. In addition, one can observe a second harmonic of this frequency, particularly at the start of the growth of the oscillations, whereas at later instants of the flash there appear, following each other in succession, subharmonics of the fundamental frequency, i.e., 1/2, 1/3, etc. The waves of the oscillations traveling in the direction of the diamagnetic current, having a scale length of 5 mm. The longitudinal wavelength in the central region of the trap is large, and the oscillations here are close to those of the flute instability.

Neutral-atom spectrometer observations show that the instability leads to a multiple absolute increase of the number of ions with kilovolt transverse energies—Fig. 4. It is more likely that this heating is stochastic in nature, being the result of random diffusion of the

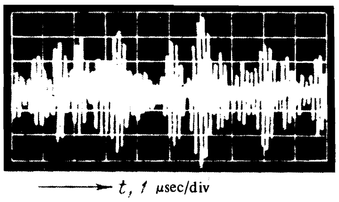


FIG. 3. "Microstructure" of unstable oscillations.

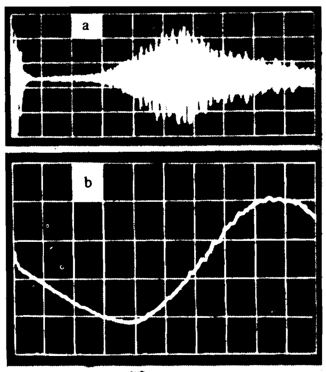


FIG. 4. Production of hot ions under the influence of instability: a—RF-noise signal, b—signal of neutral atoms with E = 2 keV.

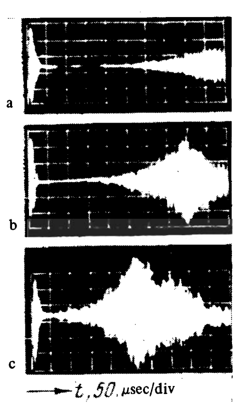
ions along the $E_\perp$ axis, which lifts the hot tail of the spectrum.

The principal adverse effect of the instability lies in the appearance of anomalous losses that lead to a clearly seen acceleration of the decay. The intensity of these losses, in a fully developed instability, can exceed by more than one order of magnitude the intensity of the Coulomb losses at the same density. The losses occur most probably along the magnetic field, via the forbidden cone. However, the transverse plasma transport is also appreciable, as is observed by the appearance of currents in the electrodes located on the lateral wall.

A clearly pronounced property of the instability is its strong dependence on the initial ion temperature, as illustrated in Figs. 5 and 6. This dependence is of twofold character. First, the intensity of the oscillations increases with increasing T_i, and furthermore at a much faster rate than T_i itself. As a result, the rate of the anomalous decay also turns out to be large. Second, the larger T_i, the shorter the initial stage of the quiescent decay, and at the maximum value $T_i \sim 250$ eV attained in these experiments, this stage practically disappears completely. In final analysis, the hotter the plasma the faster its decay.

Great interest attaches to the dependence of the intensity of the instability on the magnetic field. However, it is difficult to obtain information of this kind because any change of the magnetic field changes the conditions of the internal injection used in the given experiments, and the plasma parameters turn out to be unequal. To the extent that this circumstance can be taken into account, the observations indicate a more intense instability development with decreasing magnetic field.

Finally, a circumstance worthy of attention is the dependence of the instability on the perfection of the vacuum conditions. When the chamber walls are insufficiently outgassed and the pressure increases strongly during the time of the injection pulse, the instability weakens and even disappears completely if the pressure reaches $\gtrsim 1 \times 10^{-5}$ Torr. The same occurs if, under conditions when the walls are clean, the pressure is increased by admitting gas from the outside. Thus, the instability develops only under conditions of sufficiently good vacuum.



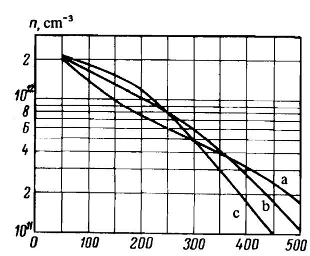


FIG. 5. Development of plasma instability at different initial ion temperatures: a—$T_i \approx 50$ eV, ordinate scale 0.5 V/div; b—$T_i \approx 100$ eV, scale 2.0 V/div; c—$T_i \approx 150$ eV, scale 5.0 V/div.

FIG. 6. Plasma-decay curves: a—at $T_i \approx 50$ eV, b—$T_i \approx 100$ eV, c—$T_i \approx 150$ eV.

4. CONNECTION OF INSTABILITY WITH POTENTIAL

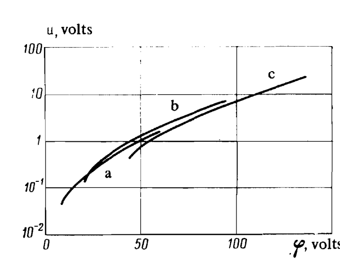
The most important feature providing a key to the understanding of the nature of the instability, is its close genetic connection with the plasma potential. A few words concerning its behavior during the decay process. In the initial quiescent stage, as already noted, the potential is close to the "classical" value $\varphi \approx 0.2T_i/e$, and increases slightly. In the unstable phase, the potential increases much more rapidly to a value approaching T_i/e. The evolution of the potential is shown in Fig. 2 above.

A comparison of the RF noise with the potential signal indicates that they are closely correlated. An examination of similar joint oscillograms under all possible conditions indicates that the instability constantly behaves as if the potential were its cause. A practically unique relation of the type $u \sim \exp\sqrt{\varphi}$ exists in this case between the value of φ and the amplitude u of the unstable oscillations. By way of illustration, Fig. 7 shows plots of $u(\varphi)$ for three decay regimes, that differ in the initial temperature T_i; it is seen that all three functions $u(\varphi)$ fall on a common curve, although on different sections of the curve.

The causal role of the potential is most clearly confirmed by an experiment in which the potential of the plasmoid was artificially increased. This was done with an electrode placed in one of the mirrors on the axis of the trap. Good electric contact was produced between this electrode and the hot plasma in the trap via the outgoing plasma, so that the increase of the electrode potential was transferred to the central plasmoid, and this was reflected in the readings of the corresponding pickups. The experiment consisted in the following: During the quiescent stage of the decay, when there was practically no instability, a potential was applied to the electrode in the form of an approximately rectangular pulse obtained from a generator with a sufficiently low output resistance. The pulse amplitude amounted to several dozen volts or more. The result of the experiment is shown in Fig. 8. It is seen that an increase in the plasma potential causes a burst of instability. This instability is perfectly identical in its properties with the instability that develops in natural fashion.

How can one explain the connection between the instability and the potential? Since the instability seems to be kinetic, i.e., it is based on some sort of a defect in the velocity distribution function, let us turn to the question of the influence of a positive potential on the ion distribution function in the case of collision equilibrium in a mirror trap. The ejecting action of the potential becomes formally manifest in the fact that the loss cone in velocity space is transformed into a single-cavity hyperboloid of dimension $v_{\perp\min} = [2e\varphi_R/M(R-1)]^{1/2}$, where φ_R is the potential difference between the center of the trap and the mirror.

FIG. 7. Dependence of the unstable-oscillation amplitude u on the plasma potential at different initial ion temperatures: a—$T_i \approx 50$ eV, b—$T_i \approx 100$ eV, c—$T_i \approx 150$ eV.



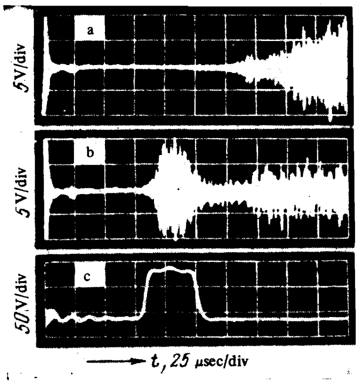


FIG. 8. Excitation of instability by artificially raising the plasma potential: a—RF-noise signal in ordinary decay; b—the same when a potential pulse (100 V) is applied, c—applied potential pulse.

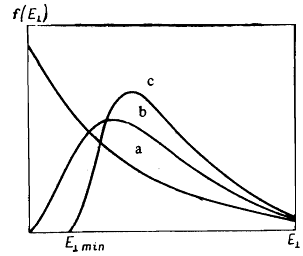


FIG. 9

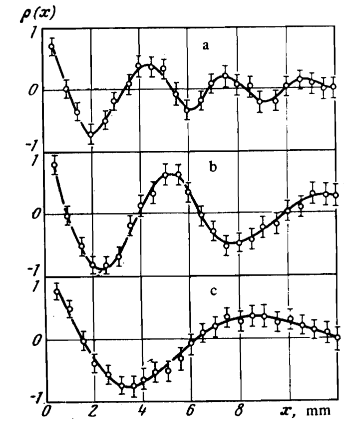


FIG. 10

FIG. 9. Distribution functions with respect to the transverse energies under collision equilibrium: a—Maxwellian distribution, b—distribution with forbidden cone, c—distribution with forbidden hyperboloid.

FIG. 10. Evolution of spatial correlation function of the unstable oscillations during their growth, evidencing an increase of the wavelength: a—t = 150 μsec, $\lambda \approx 4$ mm; b—t = 250 μsec, λ = 6-7 mm, c—t = 300 μsec, $\lambda \approx$ 8-10 mm.

Figure 9 shows schematically the transverse-energy distribution functions for three cases: equilibrium (Maxwellian), with forbidden cone, and with forbidden hyperboloid. The latter distribution is the most inverted, since it is characterized not simply by an underpopulated cold part, like the cone distribution, but has a completely depleted region down to the energy $E_{\perp\,\min} = e\varphi_R/(R-1)$. It is natural to assume that this additional deformation of the distribution function is indeed the circumstance responsible for the observed instability. An indirect indication is the very strong influence of the dimensions of the hole on the intensity of the instability, namely, it follows from the data presented above that this dependence is exponential.

The following was proposed as a possible method of experimentally verifying the foregoing arguments. If the instability is indeed connected with the considered deformation of the distribution function, then it is natural to expect the dominant role in the buildup of the oscillations to be played by those ions which belong to the region of the maximum positive derivative of the spectrum, i.e., have an energy somewhat larger than $e\varphi_R/(R-1)$. They interact most effectively with the waves whose transverse phase velocity $\omega\lambda_\perp/2\pi$ is in a certain optimal ratio to the transverse velocity of the considered ions. It is these waves that will predominate among the produced oscillations. But the potential φ does not remain constant, increasing as the instability develops, i.e., the velocity of the ions that form the group that builds up the oscillations also increases. One should therefore expect an increase in the transverse wavelength of the oscillations $\lambda_\perp$, and this can be observed experimentally.

Inasmuch as the oscillations are most frequently strongly randomized (see Fig. 3), measurement of the wavelength by direct observation of the phase shift of the signals from two closely-lying probes is quite difficult. We therefore used a method of measuring the spatial correlation function $\rho(x)$. The measurements were performed for different instants of time with the aid of a specially constructed correlation meter with the investigated process repeated many times. A filter was used to cut out only the fundamental frequency ($0.7\,\omega_{Bi}$) of the oscillations. Figure 10 shows the obtained plots of the function $\rho(x) = \langle u_1u_2\rangle/(\langle u_1^2\rangle\langle u_2^2\rangle)^{1/2}$, where $u_{1,2}$ are the signals from the two probes, x is the azimuthal distance between the probes, and the averaging is carried out with respect to time over an interval of approximately 20 μsec. The period of the function $\rho(x)$ corresponds to the wavelength $\lambda_\perp$ of the investigated oscillations. It is seen that $\lambda_\perp$ indeed increases with time. A number of similar measurements of the dependence of $\lambda_\perp(\varphi)$ under different conditions shows that during the time of increasing instability this dependence does not differ in general strongly from the predicted form $\lambda_\perp \sim \sqrt{\varphi}$.

5. NATURE OF INSTABILITY

The instability-investigation results reported in the preceding sections provide sufficient material for assessing its possible nature. Judging from the oscillation frequency ($\omega \lesssim \omega_{Bi}$), from the transverse wavelengths ($k_\perp\rho_i \approx 4$), and the density region ($\epsilon \approx 10^2$–10^3), this can be either a Dory-Guest-Harris instability[12], a "double hump" instability[13], or a drift-cone instability[3]. However, from among these three "candidates," the first two should be rejected on the basis of other established characteristics of the plasma state. The Dory-Guest-Harris instability can be produced only if the distribution $f(E_\perp)$ is quite close to a δ function, whereas the investigated plasma, being collision-dominated, has a broad energy distribution, which is stable against the indicated oscillation mode[14]. The "double-hump" instability calls for the presence of a second peak in the distribution, in the low-energy region, yet in the considered unstable states the region of low energies is forbidden because of the appreciable potential (the hole region), and the existence of a cold peak is excluded. Thus, we are left only with the assumption that the observed instability is of the drift-cone type.

This assumption, on the other hand, is confirmed by the main features of the instability. These include, first, the dependence of the instability on the potential, i.e., on the hole deformation of the distribution function. By its nature this deformation is perfectly identical to the usual cone deformation: both consist of depopulation of the cold part of the spectrum, except that in the cone deformation this depopulation is not complete, and in the hole deformation it is complete, down to zero. Thus, the hole deformation is in essence a further increase of the cone deformation, and therefore its strong influence on the instability should be regarded as strong proof of the cone nature of this instability. As to the "drift" property, which calls for an enhancement of the degree of instability with increasing inhomogeneity parameter ρ_i/a (a is the plasma radius), a confirmation of this property can be seen in the noted enhancement of the instability both when T_i is increased and when the magnetic field is decreased. The propagation of the waves in the direction of the diamagnetic currents also agrees with the assumption that they have a drift character.

While identifying the observed instability as a drift-cone mode, it must be emphasized that in its actual realization it has a number of significant deviations from the theoretical prototype. The first of them is that although, according to the theory, a simple cone deformation of the distribution function suffices for the onset of the instability, actually the instability develops significantly only under the stronger hole deformation. Thus, the character of the real instability turns out to be softer. This may be due to the presence, under our conditions, of some stabilizing factor, say a small number of cold ions produced by ionization and charge exchange. According to[15], fission of several percent of these ions is already capable of stabilizing the plasma. This, incidentally, provides a natural explanation also of the increase of the stability when the vacuum is deteriorated.

Another heretofore unforeseen property of a real instability, to the contrary, makes the instability more rigid, namely, the instability is capable of self-amplification. In view of the importance of this phenomenon from the practical point of view, and in view of its unique character from the physical aspect, we must dwell on it in greater detail.

We have presented above a number of facts indicating that the potential is the cause of the instability. At the same time, however, other facts are observed, which represent the potential more readily as a consequence of the instability. The most significant of them is the experimentally observed increase of the electron temperature, by an approximate factor of four, during the time when the instability increases in the usual decay. The only cause of this increase may be the heating of the electrons by the oscillations themselves, although the heating mechanism is not quite clear. What is important is that the electron heating is accompanied by an almost proportional increase of the ambipolar potential. The rapid growth of this potential, which is observed simultaneously with increasing instability (see Fig. 2), is precisely of this origin. Thus, when looked from this point of view, the growth of the potential appears to be a consequence of the instability.

The existence of facts, some of which represent the potential as the cause of the instability and others as its consequence, is not a paradox; this duality is indeed inherent in the potential and its relation to the instability. From the practical point of view, it leads to important consequences. It is easy to see that a closed positive-feedback loop is produced: the growth of the oscillations leads to an increase of the electron heating and to a growth of T_e, and this causes a growth of the potential; the growth of the potential causes an increase of the deformation of the distribution function, and this leads to an increase in the intensity of the instability, i.e., again to a growth of the oscillations. If the regeneration coefficient in this loop becomes larger than unity, then the instability level begins to grow exponentially and is self-intensified.

Judging from all the foregoing, this is precisely the mechanism whereby the instability grows in the start of the second stage of the decay. An illustration is Fig. 11, which shows on an enlarged scale the oscillograms of the oscillations and of the potential of the plasma. The exponential character of the process in the second half of the oscillograms is quite clearly seen. The first half, on the other hand, is the "quiescent decay stage"[1]. During this stage, the level of the unstable oscillations is small to such an extent that the electron heating produced by them is negligible in comparison with the Coulomb heating due to the ions, and the increase of the oscillation level does not lead to a noticeable increase of T_e.

Therefore the regeneration coefficient is smaller than unity, and the self-amplification loop remains turned off. The potential growth that occurs during this stage is due to other causes, which were briefly discussed in Sec. 2. On the other hand, the self-amplification becomes turned on during a later stage (it is difficult to indicate the exact instant), approximately when the intensity of the electron heating by the instability becomes comparable with the intensity of their Coulomb heating.

The described ability of the instability to become self amplified makes it many times more harmful. In fact, it is seen from the foregoing information that when the plasma state is close to the classical collision equilibrium (first decay stage), the instability, even if it exists, does not produce noticeable damage. One might assume that this state would be preserved at all times were it not for the considered feedback. On the other hand, the presence of a self-amplification loop leads to a growth of the instability to levels that exceed by dozens of times the initial value, and transform the plasma into a state much worse than the collision-equilibrium state, with unacceptably large anomalous losses. An appropriate term with which to describe this property would be "malignancy."

6. EXPERIMENT WITH MICROWAVE HEATING OF ELECTRONS

One of the cornerstones supporting the drift-cone interpretation of the instability is the concept that the hole produced by the potential in the ion distribution function is the cause of the instability. To confirm this

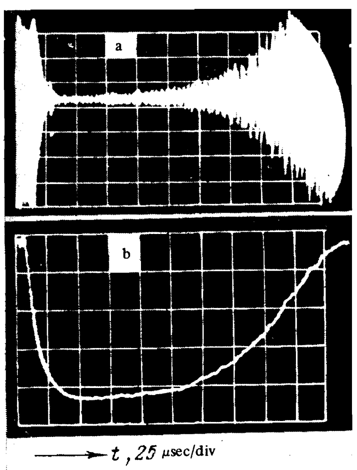


FIG. 11. Growth of instability in increased scale: a—RF-noise signal, b—potential signal.

directly, the previously-described experiments were performed with a positive-potential pulse applied to the plasma and the dependence of the oscillation wavelength on the plasma potential was studied. The results of these experiments agree well with the system of the developed concepts, but it cannot be assumed that they proved it completely. Thus, the established dependence can be due to other causes; as to the excitation of the instability by a forced increase of the potential, this result, albeit outwardly convincing, still contains one unclear circumstance.

The point is that, at a potential φ, a hole of prescribed dimension $E_{\perp\,min} = e\varphi/(R-1)$ is produced only when this potential is distributed sufficiently smoothly over the entire length of the trap, something possible only at large values of φ, comparable with T_e/e. On the other hand, if $e\varphi \gg T_e$, then most of the potential drop is concentrated in a layer produced where the magnetic force lines come up against the wall, and the size of the hole is determined actually only by that part of the potential, amounting to several times T_e/e, which is distributed over the principal length of the trap[16, 17]. An increase of the potential hardly increases the dimension of the hole. The uncertainty of the discussed experiment is that there is no assurance that application of a potential ($\varphi \gg T_e/e$) leads to an appreciable broadening of the hole in comparison with its initial value.

In view of the special importance of the causal role of the hole in the interpretation of the instability, it is desirable to obtain more reliable proof of this role.

The neatest way of increasing the potential, which guarantees a broadening of the hole, would be to heat the electrons in one way or another until T_e is increased, say, by two or three times. If the idea that the potential plays a causal role is correct, then the instability should become stronger. In addition, this result would confirm the reality of the electron feedback considered in the preceding section.

The electrons were heated with a microwave pulse having $\lambda = 2$ cm, corresponding approximately to the electron cyclotron resonance in the central region of the trap. The microwave power was introduced into the chamber through a horn placed in one of the diagnostic nipples. The length of the pulse was 50 μsec, and the instant of the "injection" of the microwave was chosen to occur soon after the start of the decay process. The introduced power was sufficient to approximately double the electron temperature.

The result of the electron heating is shown in Fig. 12. Oscillogram a shows the instability flash in free decay without any external action. Oscillogram b shows that when the electrons are heated the instability-development becomes more intense. Oscillogram c shows the increase of the plasma potential as a result of the electron heating.

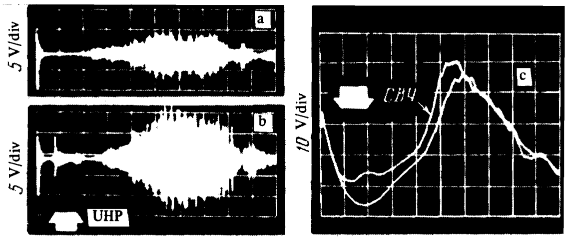


FIG. 12. Enhancement of instability by microwave heating of the electrons: a—RF-noise signal in ordinary decay, b—the same after application of microwave pulse, c—potential signal without microwave pulse and with pulse. The time of application of the microwave pulse is designated by the thick arrow.

Thus, the experiment with microwave heating of the electrons yielded the expected result. Taking also the earlier experiments into account, we can also regard it as proved with sufficient reliability that the hole deformation of the ion distribution function, due to the positive potential, plays a causal role with respect to the instability.

CONCLUSION

The described experiments with a hot collision plasma, imitating the reactor state, have shown that the answer to the question of the stability of this model is not unequivocal and includes both the elements "yes" and "no." On the one hand, the existence of an initial state in which the decay has all the characteristics of a Coulomb decay indicates the attainability of a collision state in which the instability, if it exists at all, causes no noticeable harm. On the other hand, bearing in mind the second stage of the decay, the behavior of the plasma as a whole must be recognized to be strongly unstable. It must be remembered here that the instability has the property of behaving all the more aggressively the hotter the plasma—this property can obviously make things more unpleasant when thermonuclear parameters are reached.

Nevertheless, when speaking not of this model but of a full-scale reactor state, the available information is insufficient to extrapolate which of the two aspects of the plasma behavior, "stable" or "unstable" (with respect to the observed mode), will predominate. Inasmuch as the instability, judging from all the foregoing, is quite sensitive to relatively subtle details of the plasma state, to obtain an assured answer to this question it is necessary to bring the parameters of the experimental model close to the reactor parameters.

The instability observed in these experiments is apparently the drift-cone mode, which was deduced theoretically earlier. Though agreeing with the theoretical prototype in its principal outlines, the real instability exhibits, however, certain important differences. First, it is softer in character in the sense that a simple cut-out cone is not sufficient for its intensive development, but an additional deformation of the distribution function, of the hole type, produced by positive potential, is needed. It is possible that this softening is not universal and obtains only under the conditions of these experiments. Second, the real instability has the rather unpleasant property of becoming self-amplified as a result of a unique nonlinear feedback produced via such microscopic characteristics of the plasma as the electron temperature and the potential.

The establishment of the drift-cone nature of the encountered instability raises hope of obtaining a reactor state that is stable to it, since the theory has long ago demonstrated the possibility of greatly increasing the stability of the plasma relative to cone modes, by introducing a cold component small enough not to upset the energy balance[15].

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V. P. Pastukhov, and A. V. Timofeev. A most important contribution was also the engineering help by Yu. T. Baĭborodov and A. A. Smirnov.

[1)]It should be noted, however, that the presence of oscillations in the first stage is not always so distinct.

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