Stabilization of cone instability of collisional plasma in a mirror trap

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It is shown experimentally that the previously established low-frequency cone instability (drift cone mode) which develops in a collision dominated plasma with $T_i \gg T_e$ in a min–B mirror trap can be stabilized by the addition of a small number of cold ions. This can be done either by admitting a small amount of cold plasma from outside, or by setting up conditions in the trap which facilitate the containment of cold ions. This can be achieved by anisotropic overheating of some of the electrons with microwave radiation.

1. INTRODUCTION

In our previous paper,[1] we described experiments on the containment of collisional hot-ion plasma in the PR-6 mirror trap. The experiments were performed in order to investigate plasma stability under conditions simulating a future mirror-type thermonuclear reactor. This refers, above all, to the form of the ion and electron distribution function which should have the self-consistent collisional form. Our results show that a strong instability develops in plasma under such conditions, and this leads to intensive anomalous losses. In this paper, we report further experimental studies in which we have investigated the possibility of suppression of this instability.

We have found that the instability is caused by a factor which is fundamental to mirror traps, because it is connected with the existence of a forbidden region in v space, i.e., in the simplest case, the loss cone. The presence of loss cones leads to the deformation of the ion distribution function as compared with the Maxwellian distribution, and is seen as a reduction in the population of the cold part of the transverse-energy spectrum (Fig. 1, curve b). Inversion of this type can feed a number of instabilities which can be designated as cone instabilities. The particular instability in which we are interested belongs to this class and, judging by its properties, is one of the most dangerous forms. It is the so-called drift cone mode.[2] It is important to note, however, that, in contrast to the theoretical representation, the instability which is actually found in practice requires greater deformation for development (it is represented not by curve b but by curve c in Fig. 1). This deformation arises from the positive ambipolar potential in the contained hot-ion plasma. The loss cones merge into a hyperboloid of one sheet under these conditions, and a hole is produced near the origin in v space, the size of which has a very strong effect on the instability intensity.

Since the reason for the cone-type instability is the depletion of the cold part of the spectrum, it is natural to suppose that one way of suppressing it is to repopulate this region artificially. This idea was put forward in[3] and then systematically investigated in[4,5]. It was found that the addition of a small amount of cold plasma had a very considerable stabilizing effect. In view of these hopeful signs, attempts at an experimental verification of this stabilization principle are particularly interesting. The present paper reports experiments of this kind.

Let us first briefly review the experimental conditions. The magnetic field at the center of the trap was

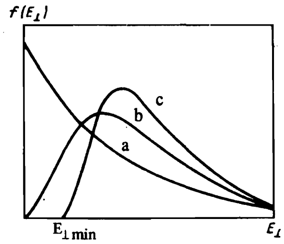

FIG. 1. Distribution of transverse-ion energy in collisional equilibrium. a—Maxwellian; b—distribution with forbidden cone; c—distribution with forbidden hyperboloid.

5 kG, the mirrors were 1 m apart, and the magnetic well was produced by six rods. The trap was filled with plasma by the "hf ion magnetron" method. The plasma parameters were as follows: $n_0 \approx 10^{12}$ cm^{-3}, $T_i \approx 100$ eV, $T_e \approx 5$ eV, and the diameter of the plasma bunch was $d \approx 10$ cm. The process under investigation was the free decay of the plasma. The characteristic decay time was 100–200 μsec. The neutral-gas density in the presence of the plasma was $\approx 10^{10}$ cm^{-3}. The probes mentioned below were located on the periphery of the trap, where the disturbance produced by them had no substantial effect on the confinement time.

2. SUPPRESSION OF INSTABILITY BY ADMISSION OF COLD PLASMA

The most direct method of adding cold ions to hot plasma can be described as follows. Cold plasma is produced outside the confined hot plasma by, say, an auxiliary discharge, and arrangements are made to allow this plasma to flow freely along the magnetic field into the hot plasma bunch. However, in reality, the influx of cold ions may not, in fact, occur because such ions encounter the barrier presented to them by the positive potential of the hot plasma bunch. A simplified but, nevertheless, adequate for these experiments, approach is to suppose that, when the cold and hot plasmas come into contact, their electrons are exchanged. This is justified because the initial electron temperatures in the auxiliary discharge and the confined plasma are not very different (5–10 eV), and the strong Coulomb interaction ($\tau_{ee} \approx 10^{-7}$ sec) probably removes this difference. The distribution of the exchanged electrons is nearly Maxwellian and, therefore, the connection between the potential and density at different points along the magnetic field can be approximately described by the following formula which follows from Boltzmann's law:

$$\varphi(z) = \varphi_0 - (T_e/e)\ln[n_0/n(z)].$$

We thus see that for very cold external ions ($T_{i\,cold} \ll T_e$) the potential barrier can be penetrated only when the density of the external plasma reaches the density of the plasma confined in the trap. When the external plasma density becomes higher than the initial density of the hot bunch, the density along the magnetic field becomes almost uniform and, eventually, cold ions collect in the trap in amounts equal to the external density surplus. When the ions in the external plasma are not very cold, so that $T_{i\,cold} \approx T_e$, they can appreciably penetrate the plasma even at lower external-plasma densities (see Fig. 2). When $n_{cold}/n_0 \ll 1$ (see Fig. 2 for notation), the penetration of external ions is described by

$$n^*_{cold}/n_0 = (n_{cold}/n_0)^{T_e/T_{cold}+1}.$$

In our experiments the cold plasma was admitted as follows. The external auxiliary discharge was produced in the same plasma source which was used to fill the trap with hot plasma. When the usual injection process was complete, the source was switched over into the low-power state, and the hf voltage used to heat the ions was not applied to the plasma column. The cold plasma ($T_i \approx 10$ eV) freely diffused along the axis of the magnetic field, and the diameter of the cold column at the center of the trap was about 3—4 cm. The auxiliary discharge was switched on immediately after the termination of the usual injection process, and was kept going for the necessary time.

The result of admitting cold plasma is illustrated in Fig. 3. These oscillograms show the hf-potential oscillations during the development of instability, as recorded by a floating probe. The time base is triggered at the end of injection. It is clear that if the cold plasma source is switched on at the beginning of decay, the instability does not develop throughout the entire interval during which the source is on. However, when the auxiliary discharge is switched off, and the cold plasma leaves the trap, instability begins to develop in the usual way but at a slower rate because the temperature and density of the confined plasma fall while the cold plasma is admitted into the trap.

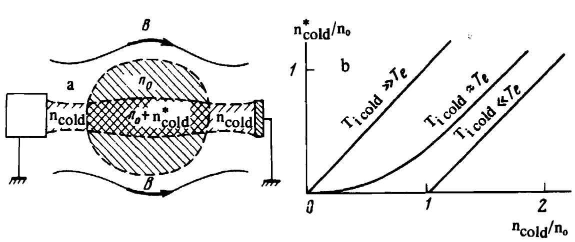

FIG. 2. a—Injection of cold plasma (source on the left); b—relative cold-ion increment as a function of external plasma density (n_0 is the hot plasma density; n_{cold} is the density of external cold plasma; n^*_{cold} is the density of cold ions inside the trap; $T_{i\,cold}$ is the temperature of cold ions).

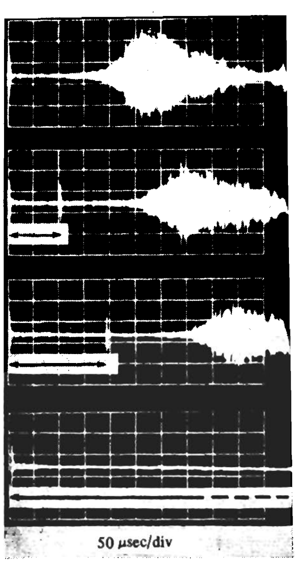

FIG. 3. Blocking of instability development by the introduction of cold plasma. Arrows show the time interval during which the auxiliary discharge is on.

It is not entirely clear how much cold plasma is injected in the course of the above experiments because the cold density increment cannot be separated with sufficient accuracy from the hot plasma density background. Interferometric data show that the increment $n^*_{cold}d$, which is necessary to ensure that instability development is completely stopped, is unlikely to exceed 10%. It may also be supposed that the considerable difference between the diameters of hot and cold plasmas (≈10 and ≈4 cm, respectively), is not favorable for stabilization and that, when the diameter of the cold column becomes closer to that of the contained plasma, the required increment will be smaller still.

Although the above experiment is based on the assumed possibility that the observed instability can be suppressed through the addition of extraneous cold ions, this explanation is not unique. Thus, it was established in previous experiments[1] that the growth of instability was a direct result of an increase in the contained plasma potential. It may then be supposed that, when the auxiliary discharge is switched on, instability does not develop because there is no increase in the potential. Firstly, the hot plasma potential may turn out to be fixed because it is in contact with the cold plasma column, the potential of which may, in turn, be set by the conditions prevailing in the gas-discharge source. If the fixed potential is small, the instability will remain at a practically negligible initial level. Secondly, another possibility whereby the increase in the potential is restricted is the "freezing" of the electron temperature. The increase in the potential in a freely contained hot plasma occurs precisely because of the increase in T_e. On the other hand, when the auxiliary discharge is switched on, the temperature of electrons in the contained plasma cannot substantially increase (because of the rapid heat transfer to the electrons in the external plasma) and there is then no increase in the potential, so that the instability does not grow.

These alternative explanations of the observed stabilization depend not so much on the addition of cold ions from outside as on the maintenance of the plasma potential at a low level. However, even in this case, the stabilization occurs essentially because the cold part of the ion distribution is sufficiently populated as a result of the fact that the hole in v space created by the potential is small. It follows that this explanation of stabilization will also fit into the framework of "stabilization by the addition of cold plasma" except that the word "addition" must now be taken to represent the maintenance of the initial relative proportion of cold ions for which the plasma remains stable.

Finally, there is one further possible explanation, i.e., stabilization due to the conductivity of external (outside the trap) plasma in the cold column. It may be that this produces at least partial shorting of the high-frequency potential to the conducting wall, and the oscillations cannot develop. This stabilizing effect is similar to the process described in[6]. However, this mechanism is somewhat speculative and has not been supported by detailed analysis. One argument against it may be the fact that the regions outside the trap contain highly conducting plasma even in the absence of the auxiliary discharge (because of escape through the forbidden cone), but instability still develops, even under these conditions.

3. STABILIZATION BY ANISOTROPIC OVERHEATING OF SOME ELECTRONS

Experiments on microwave heating of electrons described in [1] have revealed the phenomenon of instability quenching which we shall now examine. These experiments were designed to demonstrate the expected enhancement of instability which should accompany the increase in electron temperature. This effect was, in fact, confirmed when the microwave pulse used to heat the electrons was applied at the initial stage of the discharge. However, when the pulse was applied later, so that the density had fallen by a substantial factor and the instability had become highly developed, the application of microwaves led to an apparently unexpected effect, namely, instability quenching. Detailed studies of this phenomenon show that this quenching is due to the appearance of a specific group of electrons with anomalously high transverse energies. We shall say that these electrons are anisotropically overheated (AO).

Leaving on one side the question of the mechanism responsible for quenching, let us consider the experimental material.

The 2-cm microwave pulse corresponded approximately to electron-cyclotron resonance in the central part of the trap. Its length was 30–50 μsec. It was injected into the chamber through a diagnostic port, so that the chamber itself acted as a multimode resonator. The nominal generator power was approximately 10 kW, but only a small fraction of this was transferred to the plasma. Figure 4 illustrates the result of the application of the microwave pulse. Oscillogram a shows the signal due to the unstable hf oscillations during the free decay of the plasma, and oscillogram b shows the situation when the microwave pulse was applied. It is clear that, in the latter case, the unstable oscillations are completely quenched and did not reappear for a considerable time. The suppression of the instability is also confirmed by the disappearance of other effects, for example, the anomalous increase in the overall plasma potential and the enhanced decay rate.

Oscillogram c shows the low-frequency signal from the floating probe in the central section. It is clear that, when the microwaves are introduced, the probe potential rapidly becomes negative and retains this sign for roughly the same time as the instability remains quenched. The reason for the change in sign of the potential is the anisotropic overheating of electrons which reach the probe in greater numbers than the ions and charge it negatively. Their anisotropy is confirmed directly by the fact that no overheated electrons were detected to one side of the central cross section (at the point $B = 1.6B_0$ for a total mirror ratio $R = 2.4$).

Probe characteristics provide a considerable amount of information about the anisotropically overheated electrons. Curve a in Fig. 5 shows the region of the characteristic which includes the saturation ion current and the initial part of the electron branch which is exponential despite the magnetization of the electrons. The characteristic refers to a certain definite instant of time in freely decaying plasma. Curve b shows the analogous characteristic obtained at the same instant of time but with the microwave pulse applied just before this instant. This curve has a number of features which we shall now discuss.

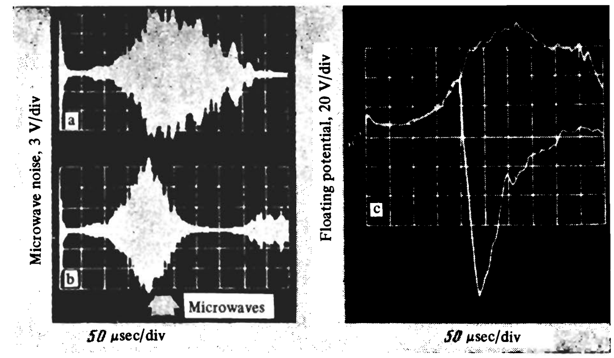

FIG. 4. Quenching of instability by microwave pulse. a—development of instability during free decay; b—ditto, when microwave pulse is applied; c—signal from floating probe with and without microwave pulse.

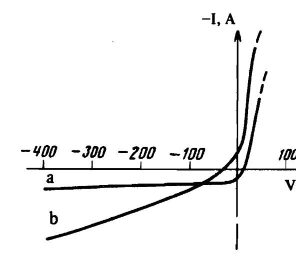

FIG. 5. Current-voltage characteristic of the probe. a—free decay; b—after microwave pulse.

First, consider the increase in the ion current. This increase may have been partly genuine and connected with the increased plasma density in the region of the probe. However, it is difficult to explain because the microwaves have no direct effect on ions, and the change in their motion and distribution in space occurs only under the action of changes in the plasma potential, which are the result of changes involving electrons. However, in the case we are considering, these changes in potential have the scale T_e/e, i.e., they are small in comparison with the ion temperature, so that the distribution of ions in space should not be substantially modified. It is probable that the increase in the ion current is spurious and connected with the arrival of electrons with increased energy at the probe, this energy being such that the secondary emission coefficient is greater than unity. The escape of the secondary electrons is then seen as an increase in ion current.

Second, the important feature is that the ion branch of curve b has a large positive slope. It is clear that the true ion current to the probe must be the same as for curve a, i.e., it should remain virtually steady. On the other hand, the secondary-emission current mentioned above cannot produce the positive slope because this current increases with increasing probe potential. Thus, the observed slope definitely indicates the presence of a substantial current of electrons, the energy distribution of which can be characterized by a "temperature" with the scale $eI(dI/dV)^{-1} \approx 100$–$200$ eV. We note that this is in complete agreement with the temperature estimated from the relaxation time of the floating-probe signal which represents the anomalous overheating of electrons (Fig. 4), if we assume a Coulomb mechanism for the relaxation process.

Third, the rapid rise of the right-hand end of curve b shows that the initial cold component with $T_e \approx 5$–10 eV has remained. The fact that the probe currents due to the cold and hot electron components are roughly equal when the probe and plasma potentials are also roughly equal, probably indicates that the densities are also comparable.

Fourth, we note that regions corresponding to a rapid rise in the electron current occupy roughly the same positions on the two curves, and this shows that, although the floating-probe potential is sharply reduced, the total plasma potential does not undergo a substantial change after the arrival of the microwave pulse (a quantitative estimate of the change in this potential is given below).

Finally, we recall that, if we take a similar pair of probe characteristics to one side of the central section, both curves are found to be similar to curve a, and there are no overheated electrons.

The above data, deduced from the probe characteristics, refer, strictly speaking, only to the peripheral region in which the probes are located. It has, however, been frequently confirmed that peripheral measurements of the energy parameters of plasma components and its potential do provide an adequate picture of the situation inside the plasma.

As noted at the beginning of this Section, the quenching effect occurs when the microwave pulse is applied during the later stages of decay. When the microwave pulse is applied at the beginning of the decay process, the opposite effect, i.e., increased instability, is observed. Figure 6 shows a series of oscillograms illustrating the behavior of the instability as a function of position of the microwave pulse relative to the onset of decay. As can be seen, there is a gradual transition from the predominance of the instability enhancement effect to the predominance of the quenching effect. The question is: which particular differences in the state of the plasma are responsible for the change in the rate of quenching and instability enhancement in these particular cases?

Comparison with data similar to those described above shows that delay of the microwave pulse results in a sharp increase in the anisotropic overheating of the electrons. This probably occurs as a result of the increase in plasma density. It is well-known that the interaction between microwaves and plasma electrons near the cyclotron resonance has two main features. Firstly, the whole mass of electrons is heated, i.e., there is an increase in the overall electron temperature T_e. Secondly, a small group of electrons breaks off and becomes anisotropically overheated, i.e., it acquires much higher energy, but only in the direction perpendicular to the magnetic field. Anisotropic overheating is most clearly defined at low densities when $\omega_{pe} \ll \omega_{Be}$. When the plasma frequency approaches the cyclotron frequency, the relative role of this effect is gradually reduced and general heating becomes the main effect. In the experiments which we are considering, the condition $\omega_{pe} \approx \omega_{Be}$ is satisfied precisely at the beginning of the decay process. It follows that when the microwave pulse is applied at later instants of time, when the density is lower, there is a rapid increase in anisotropic overheating.

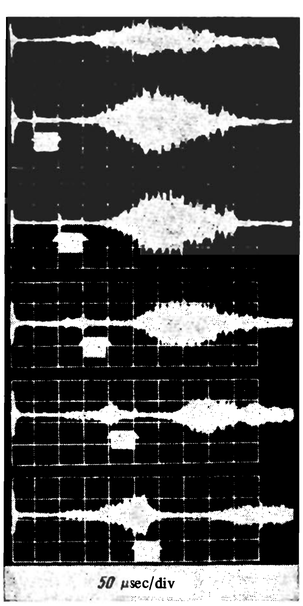

FIG. 6. Reaction of instability to the microwave pulse applied at different times (shown by arrows). Top oscillogram—without microwave pulse.

The application of the microwave pulse thus brings into operation two factors which have opposite effects on instability: the first is the general increase in T_e, which enhances instability, and the second is the anisotropic heating of electrons, which quenches instability. Competition between them provides an explanation of the successive transition from enhancement to quenching, illustrated in Fig. 6. When the microwave pulse is applied early, there are few overheated electrons and their energy is low so that they rapidly relax. Quenching is only slight in this case and ceases before the instability burst develops. This is why, while the burst develops, there is an unimpeded enhancement due to the general increase in T_e, which is probably due not only to primary heating by the microwave pulse but also secondary heating during relaxation of the anomalously overheated electrons. When the microwave pulse is applied later, there are many AO electrons with high energies, and strong quenching persists for a long time. The quenching phase occurs during the strong instability development, which emphasizes the effect. After some time, when the AO electrons have succeeded in relaxing, so that the quenching effect can no longer suppress the tendency to instability development which is enhanced by the higher T_e, the burst succeeds in appearing again, but is weaker than usual.

The foregoing is the empirical material on the formation of AO electrons and the resulting quenching of instability. We must now turn to the main problem, namely, why does the presence of AO electrons result in the quenching of instability?

The most satisfactory explanation relies on the same stabilizing factor that was used above, namely, repopulation of the ion energy spectrum near the origin, which makes the distribution function more stable. Let us therefore consider how the transfer of a fraction of the electrons to the AO state leads to the population of the cold part of the spectrum.

As noted in the Introduction, the shape of the ion spectrum of collisional plasma is determined by the configuration of the forbidden part of v space (Fig. 1) which, in turn, is influenced by the plasma potential. At the same time, both the absolute magnitude of the potential and the form of its longitudinal distribution are important.[7] This is illustrated in Fig. 7. If the fall in potential away from the center of the trap is sufficiently rapid (curve a), the loss surface is a hyperboloid of one sheet. When the top of the potential profile is flatter (curve b), the loss surface is deformed, tending to reduce the size of the "hole". Finally, when a local potential well of depth u (curve c) is produced at the center of the trap, the hole becomes a closed barrier of thickness $2v_u \equiv 2(2eu/M)^{1/2}$. It is readily seen that these forms of allowed space correspond to the spectra shown by the third group of curves. This group also includes the spectrum marked c′, which appears in the last variant when a source of cold ions is available (e.g., charge transfer and ionization in the residual gas). It is clear that spectra b and c, and, especially, c′, are less inverted than spectrum a and ensure more stable states of the plasma.

In the usual plasma state with the equilibrium collisional distribution of ions and electrons, the normal situation is that close to a. The appearance of AO electrons leads to a reduction in the potential at the center of the trap and a transformation of its profile to that shown by curves b and c. The origin of the reduction in potential is as follows. Prior to the microwave pulse, the plasma electrons are contained mainly by the high potential barrier ($\approx 5T_e/e$), and have a practically Maxwellian distribution, so that the potential profile is related to the density profile by the Boltzmann law. However, when a fraction of electrons in the region of the central section becomes anisotropically overheated, and is then contained by the magnetic field, the density of the cold Maxwellized electrons is reduced by the same amount (so that the total density remains the same because the spatial distribution of ions is unaltered). The reduction in the density of Maxwellized electrons leads, in accordance with Boltzmann's law, to a corresponding reduction in the potential in the central section relative to the lateral regions, where there are no AO electrons. This is accompanied by a broadening of the allowed region in v space toward lower energies (curve b or c in Fig. 7). This is the general situation which obtains as a result of the appearance of AO electrons.

We must now estimate the amount of cold ions which must be added and which appear in the central part of the trap in case c′, i.e., when there is a potential well which captures ions produced during charge transfer and ionization. Suppose that the fraction of AO electrons which appears in the central section is α relative to the initial density n_0 (we are neglecting the increase in density due to the accumulation of cold ions). The total reduction in potential is then, clearly, $\Delta\varphi = (T_e/e)\ln[1/(1-\alpha)]$. However, the depth of the potential well will be less than this, i.e., $u = \Delta\varphi - \delta\varphi$ (Fig. 8). Suppose that the AO

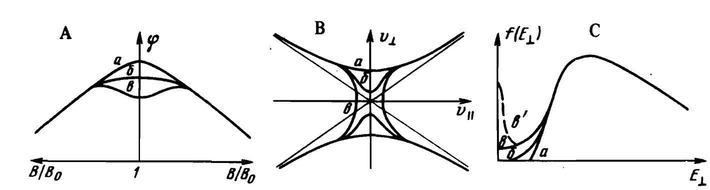

FIG. 7. Effect of the shape of the longitudinal distribution of potential on the shape of the loss surface and the energy spectrum of contained ions. A—different potential distributions; B—corresponding loss surfaces; C—transverse energy distributions (at the center of the trap).

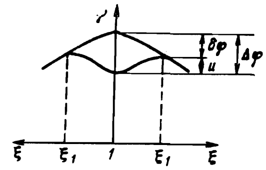

FIG. 8. Potential well produced by the appearance of AO electrons.

electrons have an anisotropy index $\langle E_\parallel\rangle/\langle E_\perp\rangle = \gamma$. Since the adiabatic invariant is conserved, it follows that their mean spread over the magnetic coordinate $\xi = B(z)/B_0$ is $\xi_1 = 1 + \gamma$. This can also be regarded as the edge of the potential well. According to Boltzmann's law, the drop in potential $\delta\varphi$ is obviously equal to $(T_e/e)\ln[n_0/n(\xi_1)]$, where $n(\xi_1)$ can be represented by the expansion $n_0[1 - c(\xi_1 - 1) + \ldots) \approx n_0(1 - c\gamma)]$. The coefficient c is determined by the longitudinal profile of the ion density, and for the collisional distribution has the scale 2. Finally, the depth of the potential well is given by

$$u \approx \frac{T_e}{e}\ln\frac{1-c\gamma}{1-\alpha}.$$

Let us estimate the number of cold ions which will accumulate in this well. The lifetime τ_{cold} of an ion created at the center of the well with zero energy is determined by its diffusion in v space due to collisions with hot ions in the contained plasma, and has the scale v_u^2/D, where v_u is the velocity corresponding to energy eu and D is the diffusion coefficient in v space. Substituting for the respective quantities (according to [9], $D = v^2/6\tau_{ii}$, where v is the root mean square of the hot ions and τ_{ii} their collision time), we obtain

$$\tau_{cold} \approx 4\tau_{ii}\frac{T_e}{T_i}\ln\frac{1-c\gamma}{1-\alpha}.$$

The steady density of cold ions is then clearly

$$n_{cold} \approx 4n_0\frac{\tau_{ii}}{\tau_{gas}}\frac{T_e}{T_i}\ln\frac{1-c\gamma}{1-\alpha},$$

where τ_{gas} is the time characterizing the rate of formation of slow ions (per hot ion) from the residual gas.

Substituting approximate numerical values corresponding to our experimental conditions for the various quantities in these formulas, we find that the addition of cold ions may amount to, say, 5%. According to [4], this has a strong stabilizing effect. We have considered the accumulation of only secondary ions, without taking into account collisional diffusion of primary ions into the additional volume of allowed v space. When this is taken into account, the amount of cold ions will increase.

It has been noted that the drift-cone instability found in these experiments has a softer character than predicted by theory and, in principle, its rapid development occurs only when there is a sufficiently large hole between the loss cones. The modification of the spectrum which is sufficient to suppress the instability is therefore weaker than that considered above. What is required is a contraction of the hole rather than its total closure (case b).

It is convenient at this point to note an experimental fact which reinforces the above explanation. This is the delay of the quenching effect relative to the appearance of AO electrons. Figure 9 shows, on a larger time scale, the instability quenching process when the microwave pulse is applied. Although the formation of the entire AO electron group ends simultaneously with the end of the microwave pulse, it is clear from the oscillogram that the instability quenching finally ends only some tens of microseconds after this time. This extension of the process is naturally explained by the fact that the modification of the cold part of the ion spectrum is not accomplished simultaneously with the change in the configuration of the allowed part of v space (this change occurs practically simultaneously with the formation of the AO group), but only after the time necessary to fill

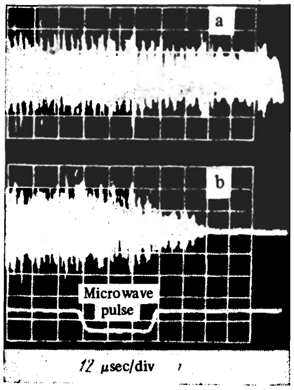

FIG. 9. Delay of quenching effect relative to the microwave pulse. a—Microwave noise for free decay; b—ditto in the presence of microwaves.

the initial empty additional v space. Estimates of the time necessary to fill this space are in agreement to within an order of magnitude with the observed delay.

This explanation of instability quenching in terms of AO electrons seems to be the most likely. The essential element is the appearance of contained cold ions as a result of the deformation of the longitudinal potential profile. In principle, it is possible to use a simpler explanation which would not involve containment but would regard the increase in the cold-ion density as being due to only a more rapid ionization of the residual gas by AO electrons. However, even if there is no doubt about the sufficiency of the small addition of cold ions produced in this way (fractions of a percent if the transit time is taken as the lifetime), it seems relatively unlikely that a small increase in the total rate of formation of cold ions (hardly more than by a factor of two) should have a strong effect. Moreover, quenching should not then exhibit any appreciable time delay relative to the appearance of AO electrons.

4. CONCLUSIONS

The experiments discussed above show that the drift-cone instability of hot-ion collisional plasma, which develops in a mirror trap, can be suppressed by the injection of a small amount of cold plasma and also by anisotropic overheating of some of the electrons. Although the various details of the mechanisms capable of explaining the quenching effect may be interpreted in different ways, the overall physical picture is now firmly established: it involves the additional population of the cold part of the ion spectrum, which reduces the degree of cone inversion. It may therefore be concluded that the theoretical suggestion that cone instabilities can be suppressed through the addition of a small number of cold ions, put forward in 1968, [4] has been confirmed by these experiments. The method used in the present work to calculate the ion spectrum may not be the best. However, in any case, if cone instabilities do appear not only in the model but in the practical reactor, the selection of methods suitable from the standpoint of energy balance, and optimal in practice, will require separate investigation.

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