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**Stabilization of a Plasma by High-Frequency
Electromagnetic Fields**

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**Stabilization of a Plasma by High-Frequency
Electromagnetic Fields**

by

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STABILIZATION OF A PLASMA BY HIGH-FREQUENCY ELECTROMAGNETIC FIELDS

by

R. A. Demirkhanov

ABSTRACT

A survey is given of studies of the possibility of suppressing hydrodynamic and kinetic instabilities in a magnetized plasma by means of high-frequency electromagnetic fields.

Results are given for experiments carried out at the Sukhumi Physico-Technical Institute in which the possibilities of suppressing a flute hydrodynamic instability, and a drift-type microinstability by high-frequency fields were studied.

The problems of the interaction of large-amplitude high-frequency fields in the region of the skin layer are discussed. Results of a study of the plasma-column equilibrium in a torus in the presence of helical high-frequency electromagnetic fields of the quadrupole type are also given.

I. THEORETICAL DISCUSSION

A. Introduction

Interest in the study of the interaction of high frequency (H. F.) electromagnetic fields with a magnetized plasma is related to the search for a possible means of suppressing the hydrodynamic and kinetic instabilities in thermonuclear devices.

The problems of high-frequency stabilization of hydrodynamic instabilities were discussed in the review of Osovetz.¹ Here, we will consider the possibility of stabilizing drift and flute instabilities, and the use of high-frequency fields to create equilibrium toroidal configurations of a plasma.

A detailed study of the vibration spectra of a homogeneous plasma in a high-frequency electromagnetic field was first made by Aliev,² Silin,³ and Gorbunov.⁴

Questions on the behavior of a nonhomogeneous magnetized plasma in a high-frequency electromagnetic field, and the suppression of drift instabilities, were considered in work by Mikhailovskii

and Sidorov;⁵ Fainberg and Shapiro;⁶ Demirkhanov, Gutkin, and Lozovskii;⁷ and Ivanov, Rudakov, and Teikhsman.⁸

B. Stabilization Models

The stabilizing mechanisms studied up till now (stabilization is generally understood as reduction of the instability region and decrease in the increments) were obtained from studying the following models.

(1) Models which consider nonhomogeneous high-frequency fields, and the averaged forces acting on the particles from the H. F. field.⁷

(2) Models which consider only the stabilizing effect of a longitudinal high-frequency homogeneous electrical field.⁶

(3) Models which consider only the magnetic component of an H. F. field, penetrating into a magnetized plasma, and the stabilizing effect of the variation with time of the force line near the average location.⁸

In the first two models, stabilization appears with weak high-frequency fields when the long wave

disturbances of the plasma equilibrium (usually assumed to be derivable from a potential) are large compared to the oscillations of the charged particles and the Debye radius. In this case, the effect of the H. F. field on the plasma particles can be described by the averaged forces (H. F. potential). It is assumed that the frequency of the external H. F. field exceeds the frequency of the disturbances considered. This condition is apparently necessary for all the mechanisms of dynamic stabilization. The indicated forces can also be interpreted as some effective "gravity field," $\vec{g}$. However, there are two possibilities; (1) when the averaged forces differ from zero even in the undisturbed state (uniform H. F. electrical field) and, (2) when the averaged forces appear only in the presence of disturbances as a result of inhomogeneity of the perturbed H. F. field (external homogeneous electrical field). These two possibilities also correspond to the first two mentioned mechanisms of stabilization which we will call, respectively, g-stabilization (with forces in the unperturbed state) and δg -stabilization.

C. g-Stabilization

Let us consider g-stabilization in more detail.

If a collisionless plasma is in a strong constant magnetic field, H_0 , and in the field of an E-wave with components $\vec{E}_z$ and $\vec{H}_y$, where the z-axis is directed along H_0 and the x-axis in the direction of nonhomogeneity of the plasma, then in the unperturbed state there acts on the plasma particles from the H. F. field the averaged force, $\vec{F}_\alpha = -m\vec{\nabla}\phi_\alpha$, where

$$\phi_\alpha = \frac{e^2 \langle \vec{E}_{z0}^2 \rangle}{4m_\alpha \Omega^2}$$

is the high-frequency potential for particles of type α [$\alpha = e, i$], for electrons and ions, respectively. The angular brackets designate averaging over the period of the H. F. field. As a result of the action of this averaged force on the particles, a paramagnetic drift of the electrons arises, the rate of which is determined by the expression

$$|v_{gp}| = \frac{|\nabla\phi|}{\omega_{He}}.$$

The possibility of stabilization of the drift instability in field showing such a skin effect can be explained by the fact that, owing to the paramagnetic drift of electrons (directed to the opposite side of the space of the drift-wave propagation by Doppler shift), the effective frequency of the wave increases, leading to an increase in Landau damping. With an increase in the increment of drift-wave frequency, the stabilizing term is increased.

In the approximation of geometric optics, when

$$v_{Te} > v_\phi > v_{Ti} \text{ and } \omega \ll \omega_{Bi}, \frac{k_z v_{Ti}}{\omega_{Hi}} \ll 1,$$

i.e., when the lateral length of the perturbation wave is great compared to the Larmor radius of the ions, the frequencies and increments, respectively, are equal to:

$$\omega = \omega_e^* (1 + F) + \omega_0$$

$$\gamma = - \frac{\sqrt{\pi} \omega_e^{*2}}{|k_z| v_{Te}} (F + \xi + \frac{\eta_e}{2})$$

$$\omega_e^* = \frac{k_y v_{Te}^2}{\omega_{He}} \frac{\kappa}{n}; \quad \xi = \frac{\omega_0}{\omega_e^*} \sim \frac{L}{\delta_s} \frac{H_0^2}{16\pi nT}$$

$$\omega_0 = \frac{k_y g}{\omega_{He}}; \quad \eta_e = \frac{d \ln T_e}{d \ln n}.$$

$\vec{g} = -\nabla\phi$ is the effective acceleration caused by the H. F. pressure. F is determined by the ratio of the H. F. pressure to the plasma pressure and is some function which is dependent on the wave-vector components of the perturbation, the external field frequency, and the characteristic plasma frequencies. At sufficiently low frequencies, F is negative, and, (approximately, is) equal to

$$F \sim - \frac{\tilde{H}^2}{16\pi nT}.$$

From the expression given for the increment, it is evident that the plasma is stable when $\eta_e > -2(F + \xi)$.

F is negative and leads to destabilization, while ξ is always positive and promotes stabilization of the plasma.

With total H. E. confinement, $\tilde{B} = 1$ for long waves, i.e., when

$$\frac{k_{\perp} v_{Ti}}{\omega_{Hi}} \ll 1,$$

the plasma is stable for $\eta_e > -\frac{2}{3}$, and in the absence of an H. F. field the plasma is stable for _____.(1)

For short waves, i.e., when

$$\frac{k_{\perp} v_{Ti}}{\omega_{Hi}} \gg 1,$$

a region of stability occurs when $-\frac{2}{5} < \eta_e < 2$, while in the absence of an H. F. field there is no region of stability.

The possibility of stabilizing drift instabilities by uniform high-frequency electrical fields can be explained as follows. In a high-frequency field of high intensity, the vibrations of the electrons in the wave field become important. Then, with excitation of the plasma electrons in the drift waves, the additional force of the pressure in the high-frequency electrical field, $E_0(t) + E_1(t)$, equal to

$$\frac{\epsilon_{zz}(\Omega) - 1}{4\pi} \frac{\partial}{\partial z} \langle E_0 E_{1z} \rangle$$

acts in the direction of the magnetic field. (ϵ_{zz} is the longitudinal component of the tensor of the dielectric constants, E_1 is the high-frequency part of the field of the vibrations, and the brackets indicate averaging over the period of high-frequency vibrations.)

When this force is in phase with the force caused by gas kinetic pressure, the field intensity in the drift wave $\langle E \rangle$ and its frequency, ω , increase.

(1) Translator's note: Term omitted in original paper.

With increased ω in the increment of growth of the drift vibrations (collisionless drift instability) for

$$\sqrt{\frac{T}{m_i}} \ll \frac{\omega}{k} \ll \sqrt{\frac{T}{m_e}},$$

the stabilizing term, proportional to

$$\frac{\partial f_o^e}{\partial v_z} \left(\frac{\omega}{k_z} \right) \approx - \frac{m_e \omega}{T k_z} f_o^e(0),$$

increases (Landau damping), and instability can develop only with sufficiently large gradients.

The physical picture of the stabilizing effect for both mechanisms consists of causing increased vibration frequency upon application of an H. F. field, which increases the Landau damping of electrons. It is assumed that the phase velocity of the perturbation wave, $\frac{\omega}{k_z}$, is less than the thermal velocity of the electrons.

In the case of g-stabilization, the increase in frequency can be related to the Doppler shift of the frequency due to the drift of plasma particles under the action of the field, $\vec{g}$ (with a velocity g/ω_H). It is important that the electrons and the ions drift with different velocities (in the expression for the increments, only the velocity differences enter). In addition, g-stabilization is effective only when both kinds of charged particles participate in the development of the considered instability. Therefore, g-stabilization does not affect the drift-thermal instability which is purely ionic.

Study of g-stabilization with the averaged forces different from zero, when both the perturbed and unperturbed conditions are taken into account, leads to the conclusion that it is possible to suppress the universal drift instability of long perturbation waves, both larger and smaller than the ion Larmor radius.

Tables 1 and 2 give the characteristics of the drift instability of a collisionless plasma in the high-frequency field of an E-wave.

D. dg-Stabilization

While the mechanism of g-stabilization acts at all H. F.-field frequencies that exceed the fre-

TABLE I
DRIFT INSTABILITY OF COLLISIONLESS PLASMA IN THE
HIGH-FREQUENCY FIELD OF AN E-WAVE

Type of Instability	Characteristics of Instability		Reference
	Without H. F.	With H. F.	
Universal instability	$\gamma = \frac{\sqrt{\pi} \omega^*{}^2}{ k_z v_{Te}} \frac{\eta_e}{2}$	$\gamma = - \frac{\sqrt{\pi} \omega^*{}^2}{ k_z v_{Te}} (F + \xi + \frac{\eta_e}{2})$	[40] [7]
	$\omega^* = \frac{k_y v_{Te}^2}{2\omega_{He}}$	$\xi = \frac{\omega_o}{\omega^*} \sim \frac{L}{\delta_s} \frac{\tilde{H}\phi^2}{16\pi nT}$	
Model taking into account $\langle \tilde{g}_e \rangle$	$\eta_e = \frac{d \ln T}{d \ln n}$	$\omega_o = \frac{k_y \langle \tilde{g} \rangle}{\omega_{He}}$	
	$\omega = \omega^*$ when $k_{\perp} \rho_i \gg 1$ plasma is stable $\eta_e > 0$	$F \sim \frac{\alpha_e^2}{2k_{\perp}^2 \lambda_o^2} \varphi(\Omega) \sim - \frac{1}{\tilde{\beta}}$ $\alpha_e = \frac{k_z e E_o}{m_e \Omega^2}$ $\eta_e > -2(F + \xi)$ if $\tilde{\beta} = 1$, $k_{\perp} \rho_i \ll 1$ stable for $\eta_e > -4 \Omega > \Omega_{crit}$ $\eta_e > -2.5 \Omega < \Omega_{crit}$	
	$k_{\perp} \rho_i \ll 1$ no region of stability	$k_{\perp} \rho_i \gg 1$ region of stability $-\frac{2}{5} < \eta_e < 2$ for $\Omega > \Omega_{crit}$ $0 < \eta_e < 2$	

quency of the perturbations, δg -stabilization occurs, in practice, only for fairly high frequencies (those that exceed the characteristic frequencies of the natural potential plasma oscillations). For low frequencies,

$$\ll \frac{k}{k} \omega_{pe},$$

the corresponding mechanism leads, as a rule, to destabilization of the plasma.

A significant increase in the stabilizing

effect can be expected at frequencies close to the resonance between the external H. F. field and the natural longitudinal potential oscillations of the plasma from one side of the resonance. At the same time, none of the indicated mechanisms leads to suppression of the low-frequency instability which occurs when the phase velocity of the perturbation is less than the thermal velocity of the ions. For total suppression of the drift instability in the region of possible stabilization H. F.-field

TABLE II
DRIFT INSTABILITY OF COLLISIONLESS PLASMA IN THE
HIGH-FREQUENCY FIELD OF AN E-WAVE

Type of Instability	Characteristics of Instability		Reference
	Without H. F.	With H. F.	
Model taking into account longitudinal electrical high-frequency field		$k_{\perp} \rho_i \ll 1$	
		$\Omega > \left[\left(\omega_{pe} \frac{k_z}{k} \right)^2 + \omega_{pi}^2 \right]^{1/2} = \Omega_{crit}$	[6]
		region of stability	
	$\eta_e > 0$	$\eta_e > -2$	
		$\Omega < \Omega_{crit}$	
		region of stability	
	$\eta_e > 0$	$\eta_e > 2$	
	$k_{\perp} \rho_i \gg 1$	$k_{\perp} \rho_i \gg 1$	
	no region of instability	no region of stability	[6]

amplitudes are needed such that the H. F. pressure is not less than $\delta_s/L_{\perp}$ of the gas kinetic pressure, where δ_s is the depth of the skin, and $L_{\perp}$ is the characteristic distance of the inhomogeneities.

Taking into account that under real conditions δ_s and $L_{\perp}$ can be close in magnitude, the H. F. pressure must approach the gas kinetic pressure (correspondingly, the electron oscillatory velocity is comparable to the thermal velocity).

E. Dynamic Shear Stabilization

The third possible mechanism for suppression of instabilities (the so-called dynamic shear) uses the effect of the fluctuation with time and space of the force line of the magnetic component of an H. F. field penetrating into a magnetized plasma. In this, it is assumed that the variable magnetic-field amplitude, $\tilde{H}$, is small compared to the constant magnetic-field amplitude, H_0 ,

$$\frac{\tilde{H}^2}{16\pi nT} \ll 1.$$

The frequency of the field fluctuations is greater

than the characteristic increments, but small compared to ω_{H1} .

The expectation of stabilization in such a model is related to the fact that during the turning of the force line relative to the perturbation, the particles moving along the magnetic field with thermal velocities manage to pass through several spatial periods of the perturbation.

To suppress the more dangerous drift-thermal instabilities⁸ the following conditions must be fulfilled:

$$\frac{\tilde{H}}{H_0} > \frac{\Omega}{k_{\perp} v_{Te}} \sim \frac{\rho_i}{L_{\perp}} \left(\frac{T_e}{T_i} \right)^{1/2}$$

(standard nomenclature). In this case, conditions opposite to those indicated in the analysis of g- and δg -stabilizations must be fulfilled. The perturbation wavelength must be large compared to the distance that particles can pass both along and across the force line of the magnetic field during

the period of the H. F. field.

In contrast, the reason for the development of a stabilizing effect in the case of drift-thermal instability is the decrease in frequency and increment of the fluctuations as a result of averaging the electrical field action of the particle perturbation during their oscillatory movement. This effect is analogous to that of dispersion in a strong constant magnetic field.

Essentially, with increasing variable magnetic-field amplitude, $\tilde{H}$, the phase velocity of the perturbation decreases and Landau damping of the ions becomes important. In other words, averaging of the electrical fields of the perturbation in the process of oscillatory movement of the particles across the magnetic field decreases the particle drift velocity in the perturbed electrical field and, consequently, the frequency and increment of the drift fluctuations.

To strengthen the effect of suppressing the instability, an H. F. field representing a superposition of fields with different frequencies can be used.

In the presence of n frequencies of differing magnitude greater than the frequency of the suppressed instability, the increment of the drift-thermal instability is decreased by A^n times ($A < 1$).

As studies show,⁸ it is possible to partially or completely stabilize a large class of plasma instabilities in a magnetic field by dynamic shear, which are dangerous to, magnetic confinement of the plasma.

From a general consideration of the dynamic-shear model, it follows that a number of field configurations cannot show a stabilizing effect on a plasma. This refers to Alfvén waves in a plasma. The displacement of such waves in the field is the same for all particles. On the strength of the "frozen-in" state of the magnetic field in the plasma, the perturbations will travel with the magnetic force line. Just as with the effect on the instability, the force line of the magnetic field must be turned relative to the perturbation of the ion density.

Fields of currents flowing in a plasma or in the outer circuit of the conductors can be more suitable for plasma stabilization. However, in

this case, the variable electromagnetic field penetrates into the plasma to the depth of the skin layer, and since one can hardly expect that L_1 will differ from δ_s , large, high-frequency, magnetic-field amplitudes are required for stabilization.

Note that most of the results given above refer to a high-frequency field realized in the form of an E-wave with an electrical vector parallel to a constant magnetic field (axis of the plasma column).

In considering other electromagnetic-field configurations for suppression of microinstabilities, it will be possible to determine the limits of the stabilizing possibilities of low-frequency fields.

F. MHD Instabilities

Problems of suppressing hydrodynamic instabilities (flute, hydrodynamic drift, and other types) were considered by Volkov, Kadomtsev, and Glagolev⁹ for the case of UHF electromagnetic waves, and by Sidorov¹⁰ for the high-frequency megahertz region.

The flute modes that develop in a bounded plasma in a nonuniform magnetic field are impossible if an additional high-frequency field is applied on the plasma and the condition

$$\frac{nT}{\tilde{H}^2/8\pi} < \frac{R_{||}\delta_{\text{exp}}}{\delta_o^2}$$

is fulfilled, where $R_{||}$ is the longitudinal dimension of the device and δ_{exp} is the experimental skin layer.

$$\delta_{\text{exp}}^{-1} = \frac{1}{\tilde{E}_o} \frac{d\tilde{E}_o}{dx}, \quad \delta_o = \frac{c}{\omega_o};$$

$\tilde{H}$ is the H. F. amplitude at the plasma boundary.

As a result of adding the longitudinal constant magnetic field and the variable field, $\tilde{H}_\phi$, the magnetic force line of the total field is a helical line whose configuration changes with time. Under the effect of the electromagnetic field, the charged particles move along the magnetic force lines. Since the rate of movement of a particle and the direction of the helix change cophasally, the particle is displaced in the ϕ -direction.

Since the electrons and ions move in opposite directions, such a movement of the charged particles leads to the appearance of a paramagnetic current.

The stabilizing effect of the high-frequency field consists in that the paramagnetic electron currents arising under the action of the H. F. pressure compensate the polarization currents caused by ionic gravitational drift.

The hydrodynamic drift instability of a collisionless plasma, characteristic of sufficiently long devices

$$(R_{\parallel} \gtrsim \sqrt{\frac{m_i}{m_e}} R_{\perp}),$$

is also stabilized by the high-frequency pressure.¹⁰ For $\omega \gg k_z v_{Te}$, the effect of stabilization is analogous to the effect of a magnetic field with a negative curvature, and, as studies show, suppression of this instability, developing from transverse inertia of the ions, occurs at relatively small H. F.-field amplitudes, namely,

$$\frac{\tilde{H}^2}{8\pi n T} \gtrsim \frac{R_{\perp}^2 \exp}{k_{\perp}^2 \rho_1^2 \delta_0^2}.$$

Here,

$$R_{\perp}^{-1} = \frac{df_{np}}{dx}; \quad \rho_1 = \frac{T_e}{m_i \omega_{Hi}^2}.$$

Experimentally, the external field often has the form of a traveling (or rotating) wave,

$$\tilde{E}_z = \tilde{E}_{z0}(x) e^{-i\Omega t + ik_y^0 y}.$$

Then, in the presence of collisions, the traveling (rotating) field entrains the plasma. The high-frequency forces acting on a unit mass of electron gas have the form:

$$\langle g_x \rangle = - \frac{f_e^2}{4m_e^2(\Omega_e^2 + v_e^2)} \left\{ \frac{\Omega_e^2}{\Omega^2} \nabla_x |\tilde{E}_z|^2 - \frac{\Omega_e v_e}{\Omega^2} |\tilde{E}_z|^2 \frac{\lambda \varphi}{\lambda x} - 2 \frac{v_{ex} v_e}{c^2} \frac{\Omega_e^2 - v_e^2}{\Omega_e^2 + v_e^2} |\tilde{H}_y|^2 \right\},$$

$$\langle g_y \rangle = - \frac{f_e^2}{2m_e^2} \frac{v_e}{\Omega_e^2 + v_e^2} \frac{k_y^0}{\Omega_e} \left\{ \left(\Omega_e + v_{ex} \frac{\Omega_e^2 - v_e^2}{\Omega_e^2 + v_e^2} \right) |\tilde{E}_z|^2 - v_{ex} \frac{v_e \Omega_e}{\Omega_e^2 + v_e^2} \nabla_x |\tilde{E}_z|^2 \right\},$$

$$\Omega_e = \Omega - K_y^{(0)} v_{ey}^{(0)}; \quad \varphi = \arctan \frac{\text{Im} \tilde{E}_z}{R_e \tilde{E}_z}.$$

From these expressions it follows that:

- (1) The entraining force $\langle g_y \rangle$ vanishes if $v_e = 0$ or $k_y^{(0)} = 0$ (standing wave).
- (2) In the process of entrainment there must be a rearrangement of the electron-density profile.
- (3) For $v_e = 0$ $\langle g_x \rangle$, the force changes to the known high-frequency force

$$\langle g_x \rangle = - \frac{f_e^2}{4m_e^2 \Omega^2} \nabla_x |\tilde{E}_z|^2.$$

The stability of such a collisional plasma was studied by Mikhailovskii and Sidorov.⁵ They showed that the potential oscillations with a wavelength less than the collisional skin layer (which in order of magnitude coincides with the characteristic inhomogeneity dimension) were unstable, with an increment lying between the H. F.-field frequency and the inverse time of entrainment of the ions.

Here one should distinguish a "weak" H. F. field when

$$\frac{\tilde{H}}{H_0} \ll \sqrt{\frac{v_e}{\Omega_{He}}}$$

(for this the increment of instability is

$$\gamma = \frac{1}{k_{\perp}^2 \rho_i^2} \sqrt{\frac{\omega^* \omega^s}{2}},$$

where

$$\omega^* = \frac{k_{\perp} T_e \kappa_n}{m_e \omega_{He}}; \quad \omega^s = \frac{T_e}{m_e} \frac{|\langle \vec{k}_{\perp} \Sigma_{1,2} \vec{\omega} \vec{H} |^2}{4 \omega_{He}^2 \nu_e}$$

and a "strong" H. F. field when the condition

$$\frac{\vec{H}}{H_0} \sim \sqrt{\frac{\nu_e}{\omega_{He}}}$$

is fulfilled. In this case, the complex frequency is $\omega = \omega^* (1 + i \frac{\omega^*}{\omega_s} k_{\perp}^2 \rho_i^2)$.

This instability can be explained as follows: Calculations show that H. F.-pressure perturbation is equivalent to some effective tensor friction force. But it is well known that taking the friction into account both in a weakly ionized plasma (collisions of electrons and ions with neutral conductors) and in a completely ionized plasma (electron-ion collisions) leads to the development of a drift-dissipative instability. The increment of instability from the "tensor friction force" for small H. F.-field amplitudes

$$\left(\frac{\vec{H}}{H_0} \sim \ll \sqrt{\frac{\nu_e}{\omega_{He}}} \right),$$

as follows from the equations given above, increases linearly with $\vec{H}$; however, with increasing H. F.-field amplitude

$$\left(\frac{\vec{H}}{H_0} \sim \sqrt{\frac{\nu_e}{\omega_{He}}} \right),$$

it falls quadratically with $\vec{H}$. It can be expected that for $\vec{H} = 1$ this type of instability will not be dangerous.

One of the peculiarities of the interaction of an H. F. field with a plasma is that usually it acts only on electrons. The force acting on ions is small, as the ratio of the masses, m_e/m_i . As a result of this effect, quasistatic electrical fields can arise in the plasma and lead to rotation. Study of the effect of rotation on the convective instabilities¹¹ shows that the oscillation frequency is essentially determined by the two first derivatives of the quasistatic electrical field. In particular,

with fulfillment of the condition

$$\nu'_0 \frac{d \ln(n_0 \nu'_0)}{d \ln(n_0 T_0)} < 0,$$

rotation of the plasma has a stabilizing effect on the convective instabilities. It is clear that in practical situations fulfillment of this condition depends on the nature of the penetration of the H. F. field and on the profile of the plasma density. Analogous results were reported in Refs. 12 and 13.

Characteristic frequencies and growth rates and stabilization conditions for various instabilities discussed in the last two sections are given in Tables 3 and 4.

G. High-Frequency Equilibria

High-frequency electromagnetic fields can be used for equilibrium confinement of a plasma column in a toroidal constant magnetic field. In combined systems (confinement within a small radius), the gas kinetic pressure of the plasma is counterbalanced by the pressure of the constant magnetic field. The high-frequency electromagnetic field serves to compensate the toroidal drift, and its pressure can be small compared to that of the plasma.^{14,15}

Owing to toroidal drift, in a constant magnetic field, a plasma column is displaced toward the external wall of the chamber. With the application of a multipole H. F. field, the field intensity increases toward the walls of the discharge chamber, and a difference in the H. F.-field pressures on the outer and inner sides of the plasma column occurs.

For a definite value of plasma-column displacement, this difference in pressures can counterbalance the force caused by the toroidal inhomogeneity of the constant field.

In contrast to a system with helical magnetic fields, in which the toroidal-drift compensation is realized owing to a rotational transformation, and the degree of compensation is determined by the integral behavior of the magnetic force line during use of an H. F. field; a local compensation of the toroidal drift occurs as a result of redistribution of the pressure in the transverse cross section of the displaced plasma column. Therefore, the ac-

TABLE III
STABILIZATION CONDITIONS WITH DYNAMIC SHEAR

Model and Type of Instability	Condition of Stabilization	Reference
Model taking into account fluctuations of the magnetic component of the field	$\delta \underline{H} = \delta H \sin \Omega t \underline{e}_y, \quad \delta \underline{E} = \delta E \cos \Omega t \underline{e}_z$	[8]
<u>Drift-thermal instability</u>	Condition of stabilization $\frac{\delta H}{H} > \frac{\Omega}{k_1 v_{T1}} \sim \frac{\rho_1}{L_1} \left(\frac{T_e}{T_i} \right)^{1/2}$ $\omega H_1 > \Omega > \omega^*$	
Conical instability	Condition of stabilization $\frac{\omega}{kv_{T1}} < 1$ $\frac{\delta H_y}{H} > \frac{v_{T1}}{v_{Te}}$	[8]

TABLE IV
CHARACTERISTIC AND STABILIZATION CONDITIONS FOR FLUTE
AND DRIFT-CONVECTIVE INSTABILITIES

	Type of Instability	Characteristic Frequencies and Increments	Condition of Stabilization	Reference
1	<u>Flute instability</u> $k_z = 0$	$\omega_{12} = \frac{1}{2} \left[\omega_{pe}^* - \frac{k_y (n_o v_o')}{k_1^2 n_o} \right]$ $\pm \left\{ \frac{1}{4} \left[\omega_{pe}^* - \frac{k_y (n_o v_o')}{k_1^2 n_o} \right]^2 + \frac{k_y^2}{k_1^2} \mathcal{K}_n(\bar{g} - \langle g \rangle) \right\}^{1/2}$	$1 \ll \tilde{\beta} \ll \frac{\delta R_{ }}{\delta_s^2}$ $\delta^{-1} = \frac{d \ln \tilde{\beta}}{dx}; \quad \delta_s = \frac{c}{\omega_o}$	[11]
2	<u>Drift-convective instability</u>	Without H. F. $\gamma \approx \omega \approx \omega^* \approx \frac{k_z}{k_y} \sqrt{\frac{m_i}{m_e}} \omega_{H1}$	$1 \ll \tilde{\beta} \ll \frac{1}{k_y^2 p_1^2} \frac{a \delta}{\delta_s^2}$	[10]
3	Instability with "tensor friction force"	$\omega = \pm (1+i) \frac{1}{k_y p_1} \sqrt{\frac{\omega^* \omega_s}{2}}; \quad \tilde{\omega}_{He}^2 \ll v_e \omega_{He}$ $\omega = \omega^* (1+i) \frac{\omega^*}{\omega_s} k_y^2 p_1^2; \quad \tilde{\omega}_{He}^2 \sim v_e \omega_{He}$		[5]

curacy requirements for technical realization of the combined systems can be significantly lowered.

H. Equilibrium Configurations

Equilibrium of the plasma column can be accomplished by H. F. fields of different configurations.

For rotating H. F. fields excited by currents (i.e., fields proportional to $e^{i(-\Omega t + n\phi)}$), the magnitude of the plasma-column displacement is determined by the expression:

$$\frac{\Delta}{r_p} = \frac{16\pi p_0 r_p}{R(n-1)\left(\frac{4\pi J_0}{c}\right)^2} \left(\frac{r_k}{r_p}\right)^{2(n-1)} \frac{J_{n-2}\left(\frac{r_k}{\delta_s}\right)}{J_n\left(\frac{r_p}{\delta_s}\right)}; \quad n > 1,$$

where J_n is the Bessel function, r_p is the plasma-column radius, r_k is the circuit radius, R is the large radius of the torus, p_0 is the kinetic pressure of the plasma, J_0 is the current amplitude in the circuit, and

$$\delta_s = \frac{c}{\omega_p}$$

is the depth of the skin layer.

The magnitude of the plasma-column equilibrium displacement is inversely proportional to the H. F.-field pressure and does not depend on the intensity of the constant field. Thus, as has been noted, equilibrium can be accomplished for an H. F.-field pressure that is small compared to the kinetic pressure of the plasma. The amount of plasma-column displacement depends on the type of H. F. field used and is minimal for a quadrupole ($n = 2$). For a rotating homogeneous ($n = 1$) field, the equilibrium confinement of a plasma column is inefficient in practice.

For helical H. F. fields, i.e., fields proportional to $e^{i(-\Omega t + n\phi + k_{\parallel} Z)}$, excited by helical currents with a ratio of amplitudes

$$J_{z0} + \frac{n}{k_{\parallel} r_k} J_{\phi 0} = 0,$$

the equilibrium conditions differ somewhat from those in rotating H. F. fields. In this case, the equilibrium displacement is determined by the expression:

$$\frac{\Delta}{r_p} = \frac{16\pi p_0 r_p}{R(n-1)\left(\frac{4\pi J_{z0}}{c}\right)^2} \left(\frac{r_k}{r_p}\right)^{2(n-1)} \left(1 - \frac{H_0^2}{H_{res}^2}\right); \quad n > 1,$$

(for $\frac{\delta_s}{r_p} \ll 1$, $\lambda_{\parallel} = \frac{2\pi}{k_{\parallel}} \gg r_p$), where H_{res} is the

magnitude of the constant field corresponding to the geometric resonance that is specific for helical fields. The most characteristic feature of this case is the dependence of the column's equilibrium displacement on the intensity of the constant magnetic field; namely, stable equilibrium of the plasma column in the presence of a helical H. F. field is possible only for the condition $H_0 < H_{res}$ with other parameters unchanged. For $H_0 \gg H_{res}$, the equilibrium displacement is negative, i.e., the plasma column is displaced toward the inner wall of the toroidal chamber, but such an equilibrium, apparently, must be unstable with respect to displacement of the column as a whole.

The existence of H_{res} was first indicated in a consideration of the theory of helical wave excitation by Lozovskii¹⁶ for the case of a bounded plasma in a longitudinal magnetic field.

The electromagnetic field in a cylindrical plasma column, neglecting space dispersion, is a superposition of waves of two types that differ in their radial penetration into the plasma for a given longitudinal wavelength. A wave called the second type under the condition $\lambda_{\parallel}, \lambda_{\alpha} \gg r_p$ penetrates completely into the plasma, and does not differ in configuration from a wave excited under the same conditions in a vacuum where $\lambda_{\parallel}$ is the wavelength of current in the excitation circuit, λ_{α} is the Alfvén wavelength, and r_p is the plasma-column radius. A wave of the first type is strongly damped radially if the constant magnetic field, H_0 , is less than some critical value

$$H_{crit} = \sqrt{4\pi n m_i f \lambda_{\parallel}}$$

where n is the plasma density, m_i is the ion mass, and f is the frequency of the H. F. field. The phase velocity of the waves in the longitudinal direction coincides with the Alfvén velocity. The

corresponding degree of damping is

$$\delta_s = \frac{c}{\omega_p} \frac{1}{\sqrt{1 - \left(\frac{H_0}{H_{crit}}\right)^2}}, \text{ where } \omega_p = \sqrt{\frac{4\pi e^2 n}{m_e}}$$

is the electron plasma frequency. For $H_0 > H_{crit}$, this wave is propagated transversely with a wave length

$$\lambda_{\perp} = \frac{2\pi c}{\omega_p} \frac{1}{\sqrt{\left(\frac{H_0}{H_{crit}}\right)^2 - 1}}.$$

Another characteristic property of helical fields in a plasma is a peculiar geometric resonance occurring for

$$H_0 = H_{res} = \frac{H_{crit}}{\sqrt{2}}.$$

For frequencies corresponding to this condition (i.e., for

$$f = \frac{H_0}{\sqrt{2\pi n m_1} \lambda_{\parallel}}), \text{ eigen oscillations of the plasma}$$

column are possible, and resonance phenomena set in when this frequency coincides with the frequency of the forced vibrations in the circuit. It is possible that this resonance can be used for heating the plasma.

The result obtained by Soldatenkov¹⁷ in a consideration of the movement of charged particles in a toroidal constant magnetic field,

$$H_z = H_0 \left(1 + \frac{x}{R}\right)^{-1}, \text{ and in a rotating H. F. mul-}$$

tipole is of interest. For example, for a rotating H. F. dipole,

$$H_x = \tilde{H} \cos \omega t$$

$$H_y = \tilde{H} \sin \omega t$$

$$E_z = \tilde{H} \frac{\omega}{c} (x \cos \omega t + y \sin \omega t),$$

the particle is moved on a circumference the center of which is displaced relative to the axis of the torus by the value

$$\Delta X = \frac{x_0^2 + y_0^2}{R} + \frac{v_{\perp 0}^2 + 2(v_{\parallel 0} + \tilde{\omega} y_0)^2}{R \omega^2},$$

where

$\tilde{\omega} = \frac{e\tilde{H}}{mc}$, $v_{\perp 0}$, and $v_{\parallel 0}$ are the initial particle velocities and R is the large radius of the torus. Also, because of the different displacement value; Δx , of the ions and electrons, a polarization of the plasma, directed along the x -axis, is possible. Therefore, displacement of the plasma, as a whole, is possible as a result of toroidal drift along the x -axis, and a displacement of the plasma is also possible along the y -axis owing to drift in the crossed E_x and H_z fields.

Taking into account the effect of the electrical field of polarization due to separation of the charges in the toroidal field does not disrupt the conditions of finiteness. The particles in the transverse cross section oscillate with vibrations whose amplitude does not exceed

$$\Delta r \approx \left(1 + \frac{2\omega}{\gamma^2}\right) \frac{cE_y}{\omega H_0}.$$

In this case, the movement of both ion and electron particles must be finite. If the vector of the angular velocity, $\tilde{\omega}$, is parallel to the vector of the constant magnetic field, $\vec{H}_0$, the condition of finiteness is satisfied for $\omega > \gamma^2 \omega_{H1}$,¹⁸ where $\gamma = \tilde{H}/H_0$. Note that for the reverse direction of H. F.-field rotation, the conditions of finiteness for electrons are fulfilled for frequencies or intensities of the constant field, $\omega > \gamma^2 |\omega_{He}|$.

I. Plasma Entrainment

In considering the use of H. F. fields, it is logical to comment on the distribution of the rotating fields and the entrainment of the plasma by these fields. In a rotating H. F. field, the interaction of the electron-entrainment current with the longitudinal constant magnetic field creates an additional force,

$$F = \frac{1}{c} j_{\omega} H_0, \text{ confining the plasma under certain conditions.}^{19}$$

As was shown by Volkov,²⁰ the entrainment current leads to increased depth of penetration of the H. F. field. A possible explanation of the increased thickness of the skin layer is that the nonlinear interaction of the electrons with an electromagnetic traveling field (Hall effect) leads to entrainment of the electrons in the direction of propagation of

the variable field. The electron entrainment is equivalent to some slowing of the field movement relative to the electrons. Thus, in the expression for obtaining the skin layer it is logical to replace ω with the effective frequency, $\omega_{\text{eff}} < \omega$, determined by the difference in the electron velocities, $\vec{v}_0$, and the field, $\vec{v}$: $\omega_{\text{eff}} = k|\vec{v} - \vec{v}_0|$, where k is the wave vector of the rotating magnetic field (i.e., an unusual "Doppler effect" occurs). Decreased frequency leads to increased depth of penetration of the field.

Soldatenkov showed that for a rotating dipole the depth of penetration is increased by

$$\frac{\omega^2 + 2(v^2 + \omega^2)}{2(v^2 + \omega^2)}$$

times, and becomes comparable to the transverse dimension of the system, r_0 , for

$$\frac{\delta_s^2 [2(v^2 + \omega^2) + \omega^2]}{2(v^2 + \omega^2)} = r_0^2;$$

where

$$\delta_s = \frac{c}{\omega_p} \left(1 + \frac{v^2}{\omega^2}\right)^{1/4}$$

is the thickness of the skin layer in the absence of an entrainment current,

$$\omega_0^2 = \frac{4\pi n e^2}{m_e}$$

is the plasma electron frequency, and ν is the frequency of collisions of ions with electrons.

In estimating the magnitude of rotating H. F.-field pressures, it is logical to keep in mind the effect of plasma entrainment. As is known, in a rotating electromagnetic field, the plasma as a whole is entrained during a time

$$\tau = \frac{\nu}{\omega^2} \frac{e i}{H e}$$

where

$$\mu = \frac{m_e}{m_i} \quad 21$$

The time of entrainment is inversely proportional to the square of the variable magnetic-field amplitude. Thus, the entrainment current decreases, and the rate of rotation of the plasma as a whole converges to the phase velocity of the wave; i.e., in practice, the high-frequency field becomes stationary relative to the plasma. The magnitude of the deviation is determined by the dissipative processes. In the determination of τ , the mechanism of entrainment is assumed to be a collision process. Here it is naively assumed that the lifetime of the particles is as great as desired. In real systems this condition cannot be fulfilled; i.e., the particles leave the system without having attained the phase velocity.

The effect of plasma entrainment as a whole can be limited by application to the plasma of a second electromagnetic wave rotating in the opposite direction. The use of two opposite fields has been discussed repeatedly by Pottier.²² The rate of plasma rotation, v_ϕ , is determined by the amplitudes and frequencies of the external fields,

$$v_\phi = \frac{\omega_1 H_1^2 + \omega_2 H_2^2}{H_1^2 + H_2^2} r,$$

obtained from the condition of equality of the inhibiting and entraining momenta. The total entrainment current apparently is absent, but the H. F. pressure is determined by the sum of the pressures of both fields. As studies show, the rate of plasma rotation in opposite fields is stable with regard to small perturbations.

J. Destabilizing Effects

Besides the stabilizing effect, application of H. F. fields can also have a destabilizing effect on the plasma. This should be expected since an H. F. current analogous to a constant one can cause a whole series of instabilities, both hydrodynamic and kinetic, if the amplitude of the current velocity,

$$u_0 = \frac{e E_0}{m \Omega},$$

exceeds some critical value.

The nature of the developing instability depends on the ratio of the frequency of the external field, Ω , to the increment of instability, γ . For $\gamma \gg \Omega$ a high-frequency field hardly affects the instability development mechanism. However, in this, the region of existence of the instability is determined by the parameters of the high-frequency field. For example, instability of the "Bukeshanovskii" type, as was shown by Nekrasov,²³ arises for frequencies

$$\Omega \ll \omega_{pe} \left(\frac{m_e}{m_i} \right)^{1/3}$$

in the region of wave numbers

$$\frac{1}{\delta_s^2} \ll k^2 \ll \frac{\omega_{pe}^2}{u_o^2}, \quad \delta_s = \frac{c}{\omega_p}$$

if the oscillatory velocity, u_o , of the particles exceeds their thermal velocity. For example, with the realization of paramagnetic conditions, the greatest increment of this instability,

$$\gamma = \frac{k_z}{k} \omega_{pe} \left(\frac{m_e}{m_i} \right)^{1/3},$$

is attained near the right-hand boundary of the region.

For $\Omega \gg \gamma$, the situation is complicated by the fact that this condition does not always hinder the development of instabilities; for example, if

$$\gamma \ll \Omega \ll \omega_{Hi}, \quad \frac{k_z}{k} \omega_{pe},$$

for $u_o > v_{Te}$ there is a "nonresonance" instability in the region of longitudinal wave numbers

$$\frac{k_z u_o}{\Omega} < 1.$$

As has been shown,²³ its increment is equal to

$$\gamma = \sqrt{\frac{m_e}{m_i} \frac{k_z u_o}{\sqrt{2}}}.$$

Here, as in the case of Ref. 6, the condition $\Omega \gg \gamma$ is insufficient. To prevent an instability,

it is necessary to fulfill more rigid conditions, namely,

$$\Omega \gg \frac{k_z}{k} \omega_p.$$

Among the "resonance" instabilities that can arise for

$$\Omega \ll \frac{k_z}{k} \omega_p,$$

it is logical to note that caused by the parametric oscillation of the ionic-acoustic vibrations. As a rule, the resonance instabilities are characterized by large increments and mild excitation conditions. Nekrasov's study of the parametric excitation of ion-acoustic vibrations, $\Omega \simeq \omega_s$,²⁴ showed that they arose for $u_o < v_{Te}$. The width of the excitation zone is determined by the inequality:

$$-\frac{1}{8} \frac{u_o^2}{v_{Te}^2} < \frac{\omega_s - \Omega}{\Omega} < \frac{1}{8} \frac{u_o^2}{v_{Te}^2}.$$

The increment of instability, γ , is about equal to

$$\frac{u_o^2}{v_{Te}^2} \omega_s.$$

The lower boundary of the oscillator velocity, at which the instability begins, is determined from the condition of equality of the growth exponent due to parametric excitation and the exponent of the kinetic damping of these vibrations on the thermal electrons of the plasma. This condition gives

$$u_{o,crit} \approx v_{Te} \left(\frac{m_e}{m_i} \right)^{1/4}.$$

A detailed study of the instability in the region $\Omega \gg \omega_{Bi}$ has been reported.²⁵ Under real conditions, the oscillatory velocity can be less than thermal. Simple calculations show that u_o will be

$$\sim v_{Te} \frac{\delta_{crit}}{\delta_{eff} \sqrt{\beta}}$$

where

$$\delta_{\text{crit}} = \frac{c}{\omega_{pe}},$$

and δ_{eff} is the effective thickness of the skin layer. Decreasing the oscillatory velocity lowers the values of the corresponding increments.

K. Diffusive Effects in Dynamic Stabilization

A number of investigations have been made of the linear theory of skin stability. There is still no complete theory. So long as there is no non-linear theory of a turbulent plasma state caused by the action of strong high-frequency electromagnetic waves within the limits of the skin, it will be impossible to determine the coefficients of particle transfers across the magnetic field.

One can expect, however, that the excitation of high-frequency instabilities will lead to no noticeable increase in plasma diffusion. The effect of plasma turbulence (arising after the development of instabilities by application of a high-frequency electromagnetic field) on low-frequency instabilities, which are most dangerous, and on the possibility of stabilization by high-frequency fields, is still unclear. It is apparent that in the near future a theory must be created to account for the indicated effects.

II. EXPERIMENTAL RESULTS

The theoretical models presented above for stabilization of a plasma by H. F. fields require experimental checking. Only by experiment can one ascertain the possibility of suppressing instabilities by means of H. F. fields, considering the present state of the theory of interaction of large-amplitude H. F. fields with a plasma. One should especially keep in mind the tendency of a plasma to develop different types of current instabilities and the appearance of a type of parametric resonance leading to oscillation of the plasma modes.

A. Sukhumi Experiments

Let us consider some results of experiments carried out at the Sukhumi Physico-Technical Institute in 1961 to 1967.

These studies were conducted in devices with a hydrogen plasma with $nT \approx 10^{15}$ to 10^{16} eV/cm³ and models of Q-machine type. Let us consider the results obtained in a Q-machine by Khorasanov, Sidorova, Zverev, and the author^{26,27} of the pres-

ent report. The effect of a longitudinal H. F. current on the kinetic stability of the magnetized plasma of a Q-machine was studied. The conditions of the experiment were chosen so that the electrical field could be assumed to be strong

$$\left(\frac{eE}{m\Omega} \gg v_{Ti} \right)$$

and uniform, and the effect of the magnetic component of the H. F. field could be neglected.

The experiments were carried out with the following parameters: plasma density: 1×10^{10} to 5×10^{10} cm⁻³; initial plasma temperature: $T_e \approx T_i \approx 0.2$ eV; degree of ionization: 20 to 30%; and longitudinal constant magnetic field: 2000 to 4000 Oe.

Instability was observed in a plasma with the indicated parameters in the absence of external perturbations. The instability appeared as fluctuations of the potential and density of the plasma. Harmonic vibrations, the intensity of which decreased with increasing harmonic number, were observed. The frequency of the observed first harmonic was in the region $f \approx 13$ to 15 kHz for $H = 3000$ Oe. The vibration frequency changed with magnetic-field variation proportional to $1/H$. The vibration amplitudes were greatest at the boundary of the column ($r \approx R$), and reached the level

$$\frac{e\varphi}{T} \sim \frac{n}{n_0} \sim 10^{-2}.$$

Instability was observed under conditions very close to those of the experimental work^{28,29,30} in which a similar instability was classified as drift (drift-dissipative).

The flow of an H. F. longitudinal current in an unstable plasma led to decreased vibration amplitude with increased oscillatory velocity of the electrons, u_0 , of about 2×10^6 cm/sec; i.e., for $u_0 \gg v_{Ti}$, $v_{Ti} = 5 \times 10^4$ cm/sec, and $v_{Te} = 3 \times 10^7$ cm/sec for $T_e = T_i = 0.2$ eV. The electrons gained velocity in a variable electrical field with an intensity of 0.1 V/cm ($f_0 = 15$ MHz). With increased electrical H. F.-field intensity, the drift-vibration amplitude fell and the frequency increased (Figs. 1, 2). The greatest amplitude decline in the first harmonic of these vibrations was ~ 20 dB. It was attained by increasing the H. F.-field intensity to 0.3 V/cm ($u_0 = 6 \times 10^6$ cm/sec). Thus

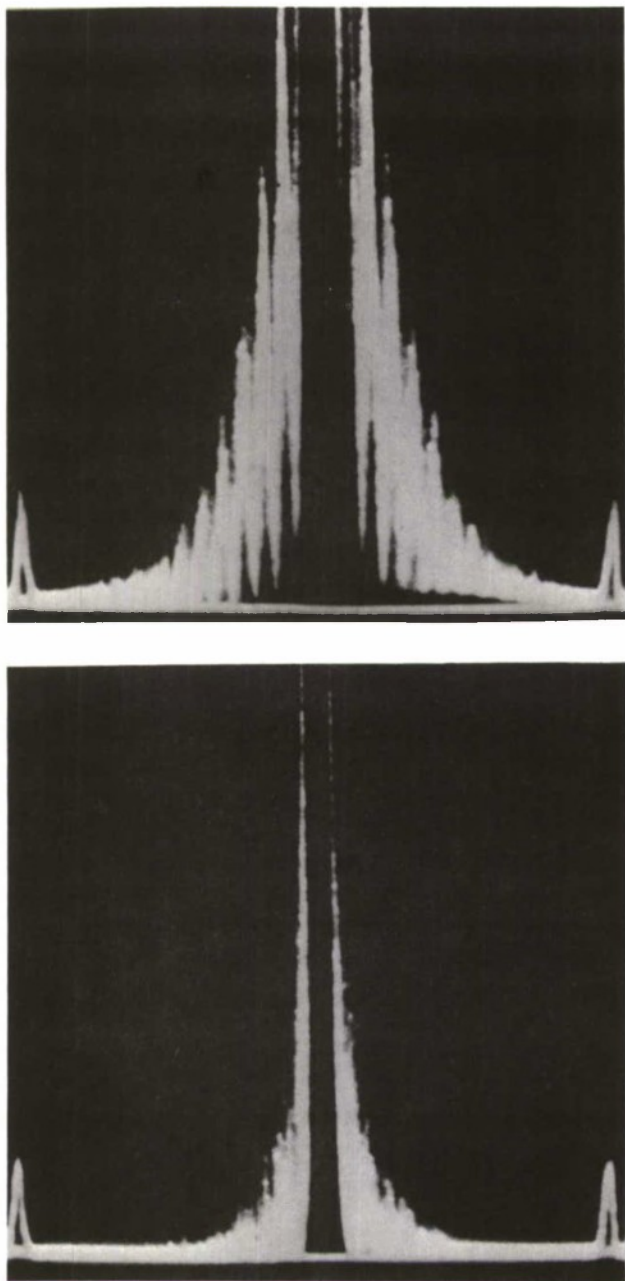


Fig. 1. Spectra of plasma vibrations in the region of 20- to 200 kHz frequencies in the absence of an H. F. field (top) and with the application on the plasma of an H. F. electrical field of 0.3-V/cm intensity (bottom). $n = 3 \times 10^{10} \text{ cm}^{-3}$; $H = 3000 \text{ Oe}$; $f_0 = 15 \text{ MHz}$.

the frequency shift of the first harmonic of the vibrations was $\Delta f \approx 3 \text{ kHz}$, i.e., $\sim 20\%$ of the primary frequency. Probe measurements show that in H. F. fields with an intensity of 0.1 to 0.3 V/cm, the initial parameters of the thermally ionized plasma (temperature, and density profile) do not undergo

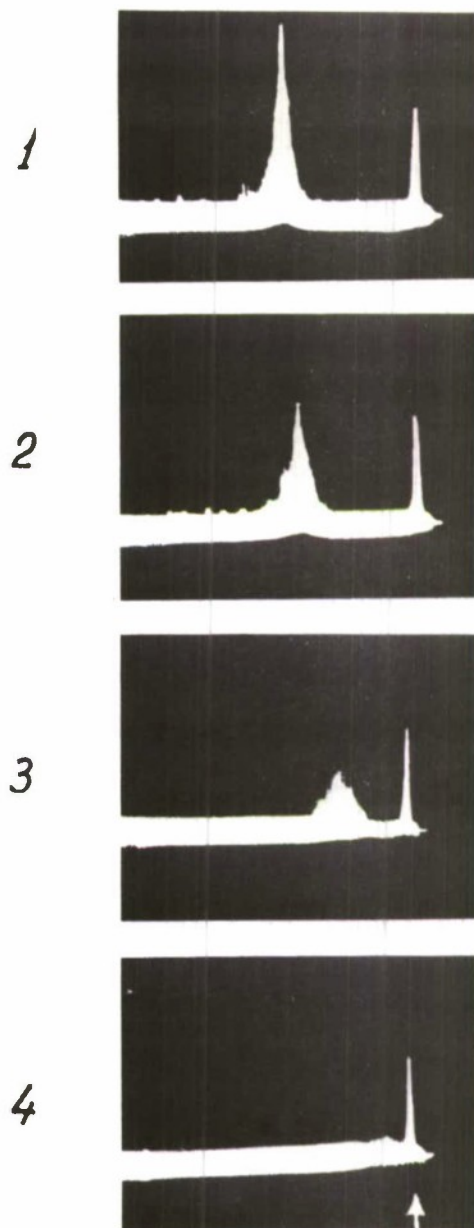


Fig. 2. Spectrograms showing change in amplitude and frequency of first harmonic ($f = 13 \text{ kHz}$) of drift vibrations in H. F. electrical fields. (1) $E = 0$; (2) $E = 0.1 \text{ V/cm}$; (3) $E = 0.2 \text{ V/cm}$; (4) $E = 0.3 \text{ V/cm}$; $n = 3 \times 10^{10} \text{ cm}^{-3}$; $H = 3000 \text{ Oe}$; $f_0 = 15 \text{ MHz}$. Arrow shows 17-kHz calibration marking.

important changes. This indicates the advantage in that the decreased vibration amplitude is caused by the presence of an H. F. field.

Figure 3 shows the spectra of vibrations recorded with Langmuir probes, one of which was on the boundary ($r \approx R$) of the column (Fig. 3a), and

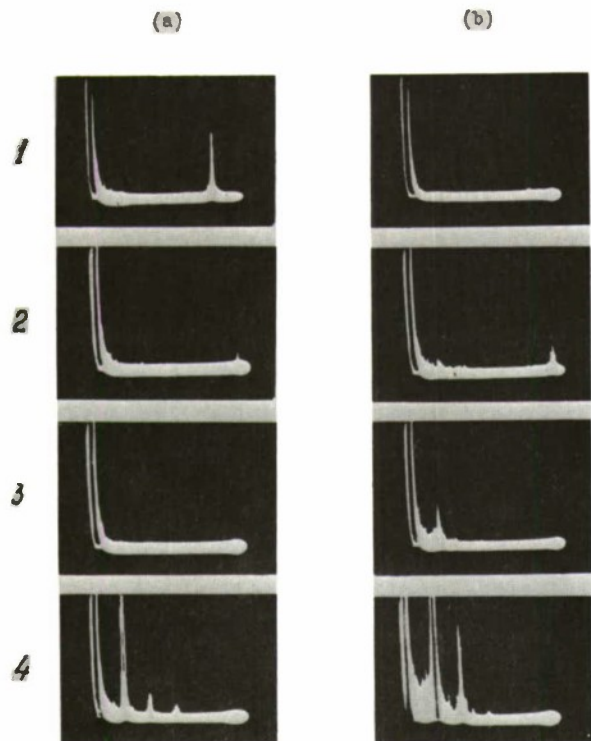


Fig. 3. Spectra of plasma vibrations in the region of 1- to 18-kHz frequencies. (a) Signal from Langmuir probe on column boundary ($r \approx R$); (b) signal from probe at column axis. (1) $E = 0$; (2) $E = 0.2$ V/cm; (3) $E = 0.3$ V/cm; (4) $E = 0.5$ V/cm.

the other on its axis (Fig. 3b). The spectrograms show that the suppression of vibrations at the column boundary is accompanied by excitation in the plasma of a new low-frequency branch of the vibrations.^{26,27} The amplitude of these vibrations was greatest at the column axis. The vibration frequencies lay in the region of characteristic frequencies of ionic sound and its harmonic; they did not depend on the magnetic-field intensity. When the intensity of the H. F. field was increased above 0.3 V/cm, the plasma drift vibrations remained suppressed to a level of 20 dB, but the intensity of the low-frequency vibrations excited by the current increased (Figs. 3a and b). Analogous vibrations were observed^{30,31} in a thermal plasma with a "supercritical" ($j \gg j_{nc}$) constant current flowing in it, and were attributed to ion-acoustic vibrations. However, the spectrum of vibrations excited by an H. F. current differed from that excited during the passage of a constant current through the plasma by a greater amplitude of vibrations and a shift of the principal harmonic of the

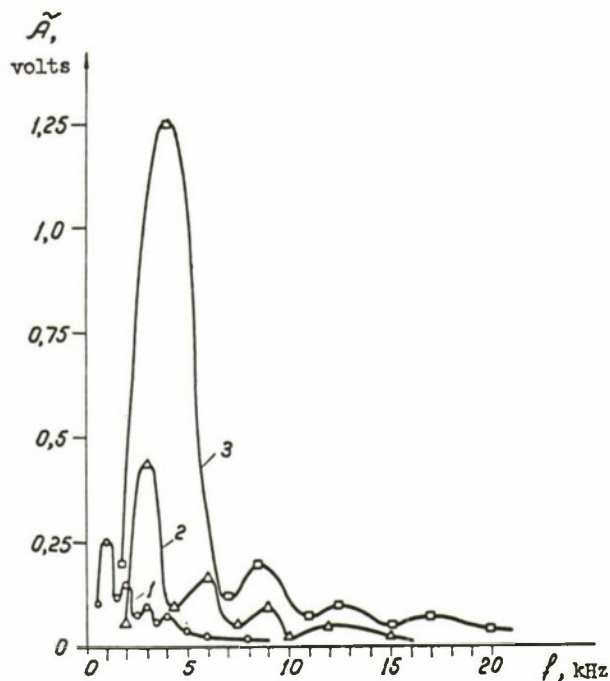


Fig. 4. Spectra of plasma-potential vibrations at column axis. (1) $f_0 = 0$; $f_0 = 5$ MHz; (2) $f_0 = 10$ MHz; (3) $f_0 = 15$ MHz. $n = 1 \times 10^{10}$ cm⁻³; $H = 3500$ Oe; $E = 1$ V/cm.

sound and its overtones toward larger frequencies (Fig. 4). The dependence of the amplitude, A , and frequency, f_1 , of the first harmonic of the ionic sound on the frequency of the external high-frequency field, Ω , the amplitude of which was held constant at $E = 1$ V/cm, is shown in Fig. 5. It indicates the temperature increase of the plasma electron component with increased external-field frequency. Moreover, the increased frequency of the ionic sound in our case can be related to the electron heating,

$$(f \sim \sqrt{\frac{T_e}{m_1}} / L) .$$

The increased amplitude of the vibrations of the plasma potential is explained if it is assumed, in accordance with the results of the experiment of Ref. 31, that the amplitude of the ion-acoustic vibrations is approximately T_e/e . Our probe measurements of the electron temperature support these concepts of H. F. plasma heating. It has been established that with increased external H. F.-field frequency, the volt-ampere characteristics of single and double Langmuir probes are considerably altered. One of the characteristics of a single probe in the

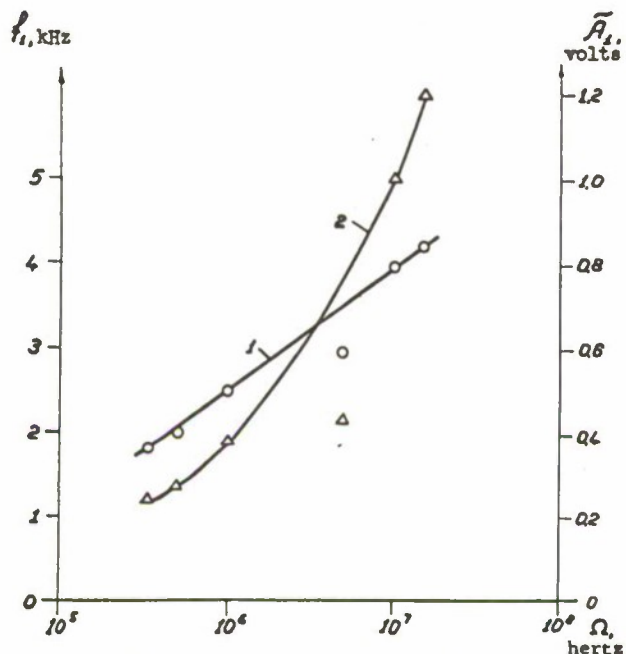


Fig. 5. Frequency (curve 1) and amplitude (curve 2) dependence of first harmonic of ion-acoustic vibrations on the external variable-field frequency. $n = 1 \times 10^{10} \text{ cm}^{-3}$; $H = 3500 \text{ Oe}$; $E = 1 \text{ V/cm}$.

absence of an H. F. field (curve 1), and with the imposition on the plasma of an H. F. field with an amplitude of 1 V/cm (curve 2), is shown in Fig. 6. The plasma-electron temperature, determined by the slope of the probe characteristics, reached several electron volts for frequencies of 5 to 50 MHz. Note that in constant electrical fields plasma heating did not exceed 0.4 to 0.5 eV.

We can assume that the observed electron heating is associated with the collective processes developing in the plasma during passage of the current.³² Turbulent heating of a plasma by a current is usually accompanied by anomalously high resistance to passage of the current.³³ An analogous effect is observed in our experiment. Figure 7 shows oscillograms of an H. F. voltage and current in a plasma. From them it follows that for low field intensities (oscillograms 1 to 3), the current in the plasma is inductive. For $E = 1 \text{ V/cm}$, the H. F. current, having achieved the critical value, is purely ohmic and is limited in amplitude by the high resistance of the plasma (oscillogram 4). The effective frequency of electron collisions in the plasma, calculated by the equation

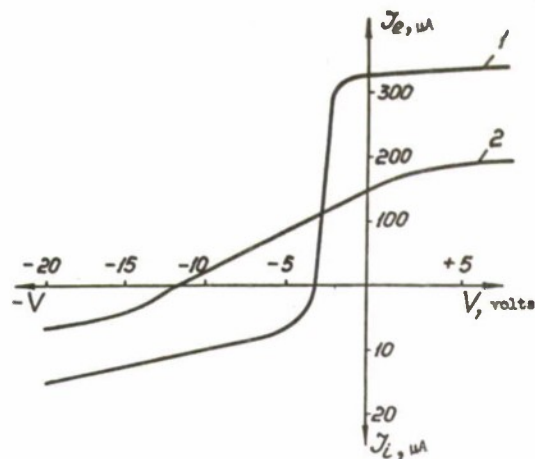


Fig. 6. Typical characteristics of single Langmuir probe without an H. F. field (curve 1) and with the application on a plasma of an H. F. electrical field of 1-V/cm intensity (curve 2). H. F.-field frequency $f_0 = 15 \text{ MHz}$; $E = 1 \text{ V/cm}$.

$$\nu_{\text{eff}} = \frac{eE}{mu_0}$$

is equal to $\nu_{\text{eff}} \sim 10^8 - 5 \times 10^8 \text{ sec}^{-1}$; i.e., it far exceeds the frequency of the coulombic collisions for $T_e \sim 0.2 \text{ eV}$ and $n \sim 5 \times 10^{10} \text{ cm}^{-3}$ ($\nu_{e1} \sim 10^7 \text{ sec}^{-1}$). The plasma-density fluctuations, which occur with the frequency of the ionic sound, led to low-frequency amplitude modulation of the H. F. current. Smearing of the current signal in Fig. 7 (oscillogram 4), obtained by repeated start-up of the sweep oscillograph shows this. Note that the single-half-period rectification of the H. F. current observed on the oscillograms is caused by the presence of an emitting surface on only one end of the Q-machine. In these experiments, the second electrode-collector was not heated.

Some experiments on the simplest model have been presented in which the stabilizing and destabilizing properties of strong H. F. electrical fields were examined. The experiments indicate that by means of H. F. fields, it is possible to lower the level of plasma-drift vibrations. Since, in the described experiments, the magnetic H. F.-field intensity was small, the observed suppression of plasma instability could have been related to the principles of drift-instability stabilization with a strong H. F. electrical field that were developed in Ref. 6. According to the concepts

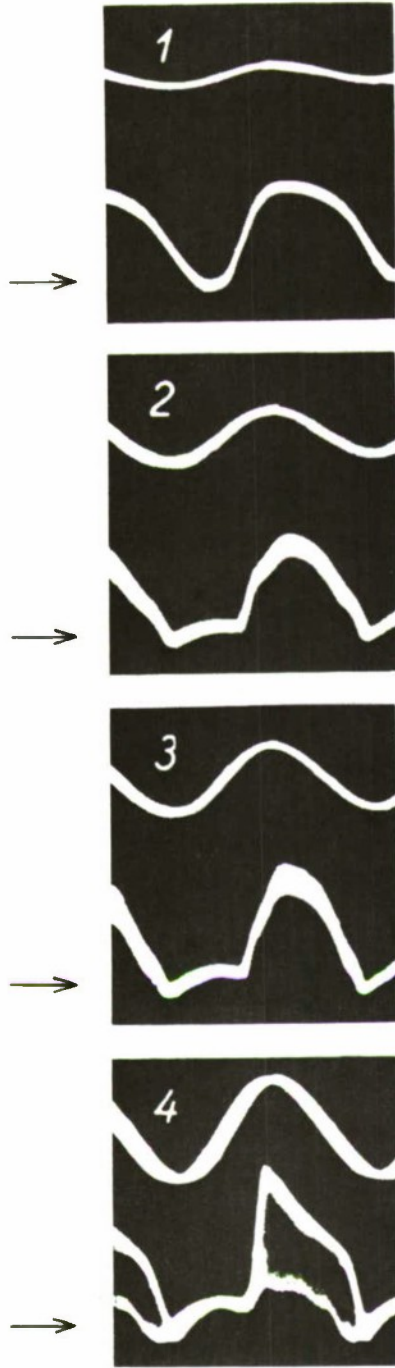


Fig. 7. Oscillograms of the H. F. voltage (upper beam) and H. F. current in a plasma (lower beam). (1) $E = 0.25$ V/cm; (2) $E = 0.5$ V/cm; (3) $E = 0.75$ V/cm; (4) $E = 1$ V/cm. H. F.-field frequency - 500 kHz. Oscillograph sweep startup - multiple. Arrow shows zero level of H. F. current.

presented in Ref. 6, a strong H. F. electrical field exerts an additional pressure on the plasma. Under the action of the H. F. field, the field intensity in the drift wave and its frequency in-

crease. With increased frequency, the damping of the drift waves by thermal electrons increases and the instability is suppressed. However, the results of the present experiment do not fit into the framework of the theory recorded in Ref. 6. Suppression of drift-type instabilities, according to Ref. 6, occurs for frequencies

$$\Omega \gg \frac{k_z}{k} \omega_{pe} \quad (\text{for } \Omega \ll \frac{k_z}{k} \omega_{pe},$$

the H. F. field acts in a destabilizing manner). In our experiments, a suppression of drift instability was observed in the frequency region

$$\omega^* \ll \Omega \ll \frac{k_z}{k} \omega_p.$$

Apparently this circumstance requires another mechanism to explain the observed stabilization of the entrainment.

B. Ion-Acoustic Waves and H. F. Heating

Let us dwell on ion-acoustic vibrations and H. F. heating of a plasma. The existence of low-frequency vibrations in a plasma in a strong H. F. electrical field has been predicted.²⁵ The authors showed that for $u_o > v_{Te}$, $\omega < \omega_{pe}$ in a plasma vibrations oscillate with a wavelength greater than the amplitude of the electron oscillations

$$\left(\frac{\vec{k}u_o}{\Omega} \ll 1 \right).$$

The vibrations are analogous to ion-acoustic vibrations oscillating in a nonisothermal plasma. Our data can serve as a basis for the assumption that the observed low-frequency branch of the vibrations in a strong H. F. field belongs to the predicted theory.²⁵ The condition

$$\frac{\vec{k}u_o}{\Omega} \sim \frac{u_o}{L\Omega} \ll 1,$$

in our case, is fulfilled for $\Omega \sim 10^7 - 10^8$, i.e., for those frequencies for which a sharp increase in amplitude of low-frequency vibrations is observed (Fig. 5). However, note that the condition remains unfulfilled in these experiments. The oscillatory velocity of the electrons exceeded by two orders the thermal velocity of the ions, v_{Ti} , but did not reach v_{Te} .

According to Refs. 34 and 35, turbulent plasma

heating occurs as a result of the development of intensive ion-acoustic vibrations. On the basis of these concepts, one can attempt a qualitative explanation of the increase in plasma temperature with increased H. F.-field frequency observed in the experiment. With increased H. F.-field frequency, the oscillation amplitude

$$(u_o = \frac{eE_o}{m\Omega_o^2})$$

decreases, and can lead to oscillation of shorter-wave vibrations, satisfying the inequality _____.(2) These vibrations have a large reserve energy which is transferred to the charged particles as a result of particle scattering on the waves. Unfortunately, turbulent H. F. heating of a plasma has not been considered theoretically, although in this case new possibilities can appear.

C. Summary of Q-Machine Results

The results of the experiments with the Q-machine can be summarized as follows:

(1) The flow of a longitudinal H. F. current in a plasma considerably suppressed the amplitude of the drift vibrations which arose spontaneously in a bounded magnetized plasma.

(2) For sufficiently strong H. F. electrical fields,

$$u_o = \frac{eE_o}{m\Omega_o} \gg v_{Ti},$$

in a plasma, a new branch of vibrations, which can be attributed to ion-acoustic vibrations, is excited.

(3) With the development of intensive ion-acoustic vibrations in a plasma in an H. F. field, turbulent heating of the plasma is observed, and the efficiency is increased with increased H. F.-field frequency.

D. Stabilization of Flute Modes

For experimental study of the suppression of long-wave flute instabilities, a magnetic trap with a pyrotron configuration and two counter-rotating electromagnetic fields was used. (See diagram in Fig. 8.) Selection of plasma parameters excluded the possibility of development of high-frequency ($\omega \gg \Omega$) ion-acoustic collisionless instabilities

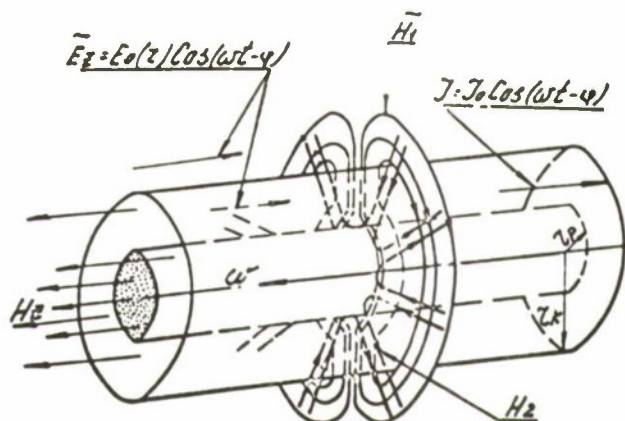


Fig. 8. Magnetic field configuration of device. H_z - constant field, H_1 - dipole field, H_2 - octupole field.

$$(v_{ei} \gg v_{max} = \sqrt{\frac{m_e}{m_i} \frac{u_o}{v_{Te}}} \omega_s,$$

where v_{max} is the maximal increment of the ion-acoustic instability obtained for the condition $\omega_s = \omega_{pi}$, and u_o is the electron oscillatory velocity).

A quasistationary magnetic field was created by traps uniformly distributed along a tube. The wiring scheme of this field permitted creation of a magnetic field of pyrotron and antipyrotron (diverging force lines) configuration. The magnetic-field intensity could reach 10,000 Oe. A rotating dipole, H_1 , was created by a circuit consisting of eight rods located along the tube and excited by currents successively shifted in time by an angle of 45° . The direction of the vector of angular rate of rotation of the dipole coincided with the direction of the constant magnetic field. The field frequency was 1.25 MHz; the pulse duration, 4 msec; the intensity, 100 to 120 Oe, and the length of the working part of the circuit, 800 mm.

The scheme of the H. F. circuit permitted passing a constant current together with the H. F. current and created an additional constant magnetic field of octupole configuration, H_2 (Fig. 8). The octupole-field intensity on the plasma surface varied from zero to 140 Oe.

A plasma column, 1200 mm long and 60 mm in diameter, was created in a cylindrical discharge

(2) Translator's note: Inequality referred to is lacking in original paper.

chamber. Studies were carried out in hydrogen at pressures of about 10^{-3} to 10^{-2} mm Hg.

The behavior of the plasma column was studied by different methods. The plasma density and the behavior of its boundary were determined by the passage and reflection of 2-, 4-, 8-, and 32-mm microwaves. The degree of plasma isolation was measured by four probes located 110 mm apart along the tube wall. A cycle of spectroscopic measurements including photographic and photoelectric recording in the visible region of the spectrum was carried out.

As is known, in the case of a rotating field, besides the variable current, J_z , an azimuthal current, J_ϕ , which has a constant component, is excited.¹⁹ The nature of the azimuthal current depends on the ratio of frequency of electron collision with the ions, ν_{ei} , to the frequency of rotation of the H. F. field, Ω . When $\nu_{ei} > \Omega$, and the vector of the angular velocity of the H. F. field coincides with the direction of the longitudinal constant magnetic field, the azimuthal current is diamagnetic. The interaction of this current with a longitudinal magnetic field creates a force acting towards the axis and constricting the plasma into a column.

Under the conditions of the experiment (in the diamagnetism region) plasma compression with an initial rate of $\sim 6 \times 10^3$ cm/sec was observed. In the final compressed state, the plasma-column diameter was 3 to 5 cm, and the maximal plasma density at the axis reached $2 \times 10^{14} - 10^{15}$ particles cm^{-3} . Figure 9 shows the curve of the dependence of charged-particle concentration on the radius measured by the microwave method, for 2-, 8-, and 32-mm wavelengths. From these experiments it follows that, even at a distance of 1.5 to 2 cm, the plasma concentration is reduced by three orders of magnitude.

Spectroscopic measurements of the qualitative composition in hydrogen showed that where the plasma is not torn from the walls, in addition to hydrogen lines there are a large number of impurity lines (about 150). Where the plasma is torn from the walls, the whole spectrum of impurities is sharply weakened. There remain only the weak lines of the high ionized atoms of several impurities (about 20 lines). Thus, spectroscopic measurements also show

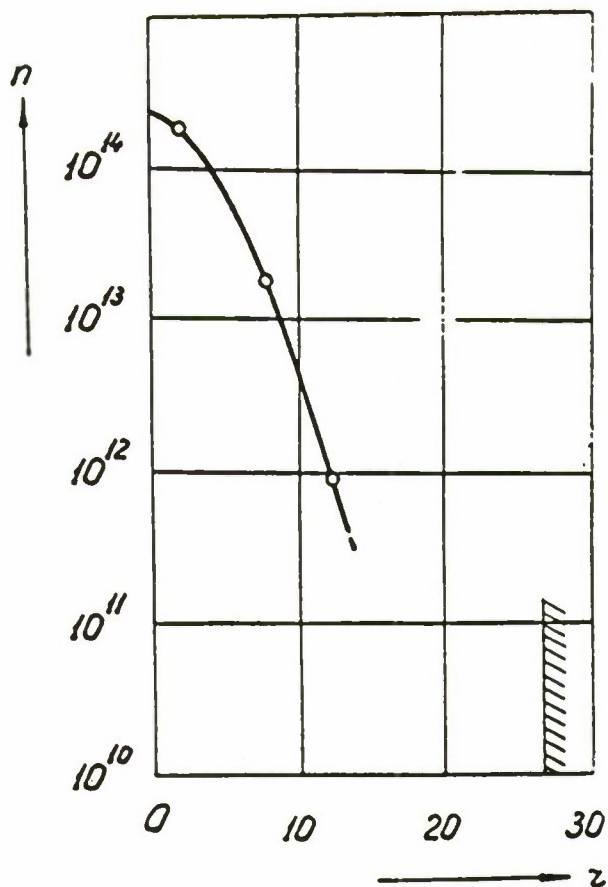


Fig. 9. Distribution of charged-particle concentration in column, over radius of discharge chamber, measured by 2-, 8-, and 32-mm.

that in the region of detachment the contact of the plasma with the walls is sharply weakened. Time analysis of the H_α and H_β spectral-line intensity showed that where the plasma was not torn off, the hydrogen lines maintained their intensity during the whole pulse. In the region of detachment, the intensity of hydrogen-line illumination at the beginning of the pulse increases, and then (in the central part of the tube) falls abruptly to ~ 0.02 of maximum and remains practically constant until the end of the pulse. From these measurements it follows that in the working part of the discharge tube, hydrogen ionization is close to total. The oscillogram of the current at the wall probe shows that, at the end of the process of detachment of the plasma from the walls, there is practically no current at the wall probe.

Calculation of the electron temperature by the diamagnetic signal and Thomson scattering of laser radiation showed that the value of T_e , depending on

the conditions, changes within the limits 4 to 10 eV.

Study of the spectrum of the scattered laser radiation by plasma probing showed that the plasma in a uniform magnetic field has a low turbulence.³⁶ In the spectrum of scattered radiation a number of pronounced satellites were observed; however, approximate calculation of the ratio of the plasma-vibration energy densities to the energy density of the "thermal" electrons gives a maximal value of about 0.05. In this, the highly polarized laser radiation, with a pulse power of 10 MW, was directed along the axis of the discharge chamber and focused in its center. The scattered radiation was recorded at an angle of 90° to the incident beam and to the vector of the electrical field, $\vec{E}_0$, of the incident wave.

Studies of the behavior of a plasma in a magnetic field of a pyrotron configuration, for which the mirror ratio was varied within the wide limits of 1.1 to 2 with 46 cm between mirrors, and $H_0 = 2 \times 10^3 - 15 \times 10^3$ Oe, showed that the plasma behavior depended considerably on the shape of the field. In the magnetic field of a pyrotron, the level of observed vibrations increased and, correspondingly, the degree of plasma turbulence increased. Instabilities arose on the plasma surface, and a flux of the plasma across the magnetic field occurred.

E. Convective Plasma Loss Across Magnetic Field

To study the nature of the transfer across the magnetic field, 8-mm waves reflected from the plasma surface were measured. A system of horn antennae was located near the discharge tube according to the scheme shown in Fig. 10. With the passage of "tongues" under the corresponding antenna, there was a sharp increase in the microwave signal reflected from the plasma, and a pulse developed in the oscillogram of the reflection. Figure 10 shows the oscillograms of reflected signals taken by antennae 1, 3 and 1, 2, respectively. The reflection pulses on the oscillograms are shifted in Fig. 10b by $1/2$ and in Fig. 10c by $1/4$ of the time interval between neighboring pulses. Consequently, the "tongue" is rotated in the direction indicated by the arrow in Fig. 10a, which coincides with the direction of rotation of the H. F. field.

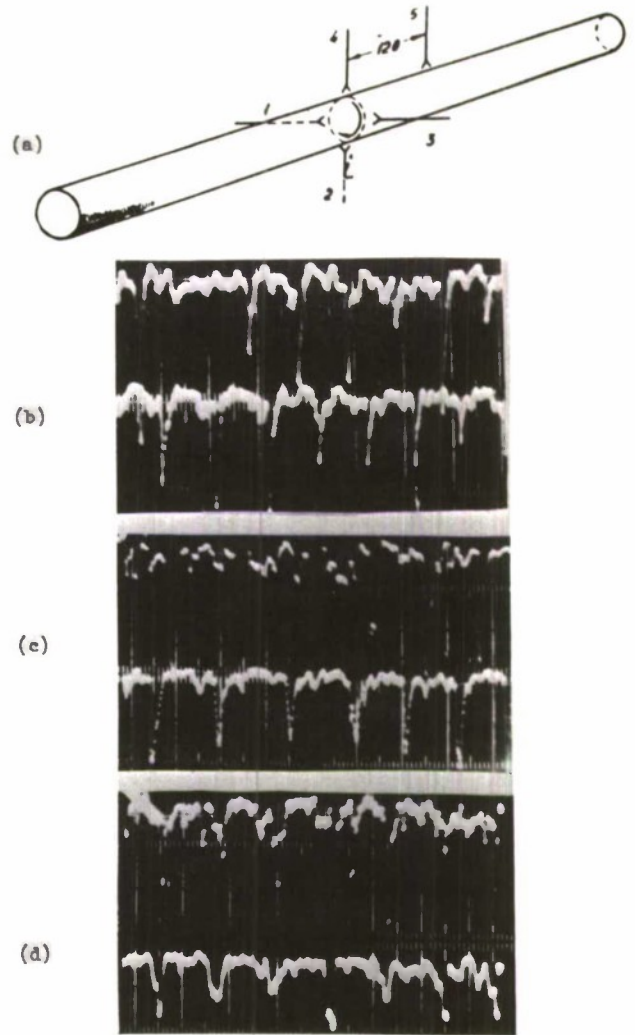


Fig. 10. (a) Antenna arrangement scheme. Oscillograms of signals reflected from an 8-mm wave for location of antennae: (b) at an angle of 180° , 1-3; (c) at an angle of 90° , 1 2; (d) along the chamber, 4-5. Sweep duration - 5 $\mu\text{sec/cm}$; $H = 6$ kOe.

The frequency of rotation of the "tongue", calculated from analysis of the oscillograms, lies between 100 and 300 kHz.

Calculation of the increment of perturbation growth from microwave-measurement data shows that this value is within 2 to $5 \times 10^5 \text{ sec}^{-1}$.

Figure 11 shows oscillograms of the same process taken at different sweep rates. At the high sweep rates, the separate surges of reflected signals are clearly seen. Note that besides the pronounced deformation corresponding to the mode $m = 1$, there are also modes of higher orders. For

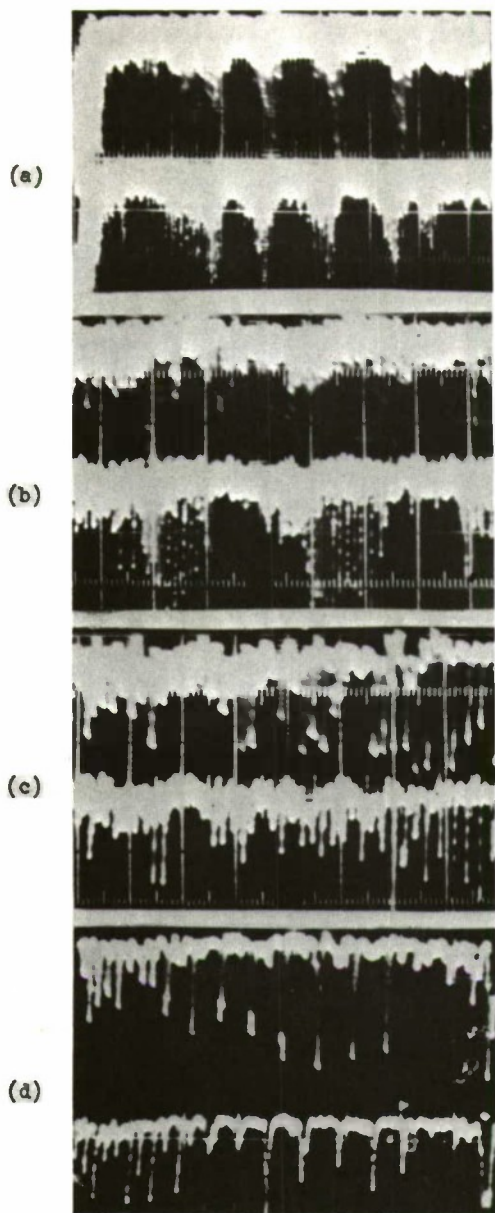


Fig. 11. Oscillograms of signals reflected from an 8-mm wave for scan durations of: (a) 250 $\mu\text{sec}/\text{cm}$; (b) 50 $\mu\text{sec}/\text{cm}$, 1250- μsec delay; (c) 10 $\mu\text{sec}/\text{cm}$, 1300- μsec delay; (d) 5 $\mu\text{sec}/\text{cm}$, 1650- μsec delay. Arrangement of antennae 1-2, $H = 6 \text{ kOe}$.

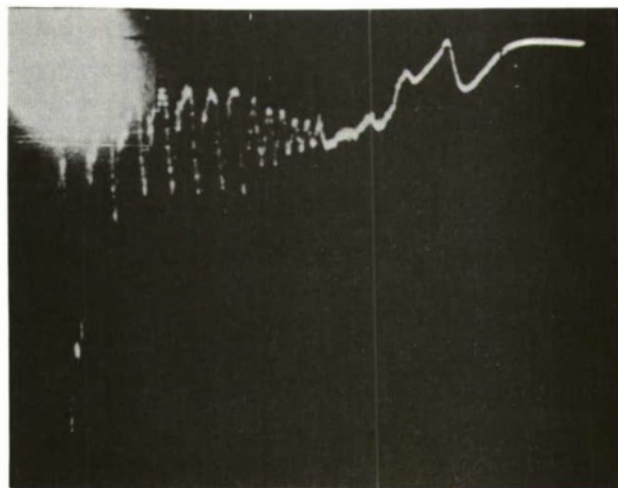
example, in Fig. 11d perturbations with $m = 2$ are observed.

From Fig. 11a, which in essence is an envelope of reflection pulses, one can see that "low-frequency" ($\sim 8 \text{ kHz}$) vibrations are superimposed on the general picture of "high-frequency" plasma ejections. The correlation between the fluxes of the plasma across the field, the current on the wall probe, the luminance of the H_α lines, and the

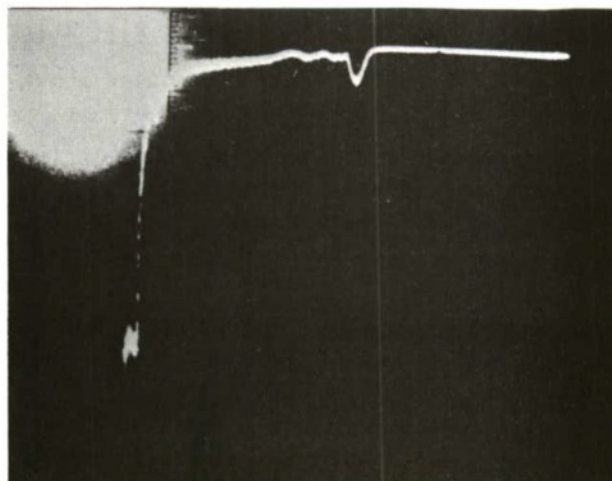
voltage on the H. F. circuit was studied and showed that the breakaway of the packet of high-frequency ejections has a relaxation character.

"Low-frequency" vibrations of H_β were observed on the oscillograms (Fig. 12a) and by the current in the wall probe (Fig. 13a).

Analysis of the reflected microwave signals (Fig. 10d) and of the wall probes shows that the ejections occur simultaneously over the whole length of the plasma column and have a constant phase. There is practically no phase shift at different

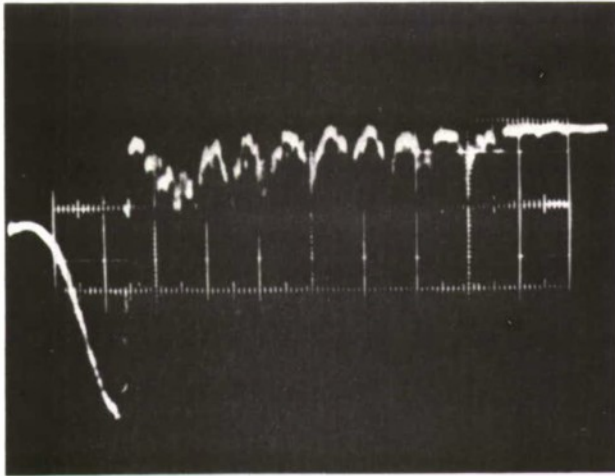


(a)

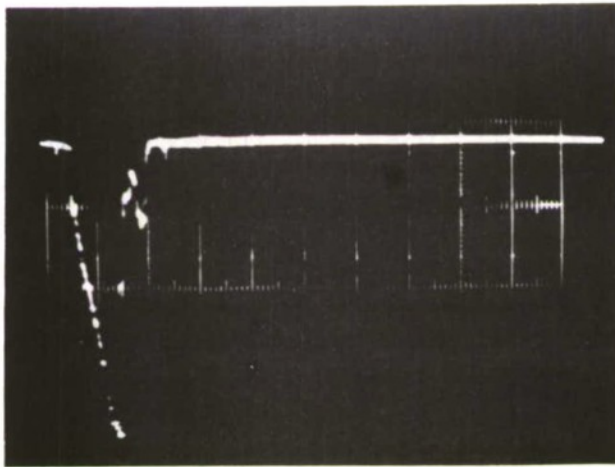


(b)

Fig. 12. Oscillograms of H_α -line luminance in center of discharge chamber: (a) in unstable condition (octupole field = 0); (b) in stable condition (octupole field = 60 Oe). Duration of process $\sim 4 \text{ msec}$.



(a)



(b)

Fig. 13. Oscillograms of current on double wall probe: (a) in unstable condition octupole = 0); (b) in stable condition (octupole field = 60 Oe).

points along the axis. Together with this, the perturbation amplitude decreases with increased magnitude of the constant magnetic field.

Measurement of the plasma rotation rate by an electron-optical transducer using the slope of the spectral lines due to the Doppler effect showed that a plasma in the magnetic field of a pyrotron is entrained to values of $\sim 2 \times 10^6$ cm/sec,³⁷ which is 0.1 of the phase rate of the dipole rotation. The rotation rate of plasma ejections, according to microwave measurements, is also $\sim 2 \times 10^6$ cm/sec; i.e., the "tongue" of the plasma is, in practice, rotated together with the plasma.

Thus, one can assume that the observed instability is convective because of the curvature of the force lines and the centrifugal effect of the plasma rotation.

As was discussed earlier, to suppress the lower modes of a flute instability caused by the curvature of the magnetic field, the intensity of the H. F. field must be

$$\frac{\tilde{H}^2}{16\pi} \geq \frac{v_{i\parallel}^2}{R} \delta_s n_i m_i.$$

In a rotating plasma, for suppression of convective instability, the H. F. field determined by the relation

$$\frac{\tilde{H}^2}{16\pi} \geq \left(\frac{v_{i\parallel}^2}{R} + \frac{v_{i\perp}^2}{\tau_p} \right) \delta_s n_i m_i$$

is required, where $v_{i\perp}$ is the rate of plasma rotation. Thus, the higher instability modes can be stabilized by the effect of dynamic shear.

F. Use of Rotating Fields

In the described experiments, with the dipole-field intensity, $H_{10} \sim 100$ to 120 Oe, the contribution to instability from the centrifugal effect of a rate of plasma increase, $v_{i\perp} \sim 2 \times 10^6$ cm/sec ($R \approx 46$ cm, $\delta_s \approx 0.5$ cm, and $n_e \approx 5 \times 10^{14} - 10^{15}$ cm⁻³) is large, and the conditions for plasma stabilization are not fulfilled. An oppositely rotating octupole wave was used to control the effect of rotation.

It is as if two fields rotating in opposite directions act on the rotating plasma. As would be expected, microwave and optical measurements established that with increased constant octupole field, $\tilde{H}_2$, the rate of plasma rotation decreased to 2×10^5 cm/sec for $\tilde{H}_2 = 60$ Oe on the plasma surface. Figure 14 shows the change of the values of interest as a function of the intensity of the constant octupole field. The data for this drawing were taken from experiment; however, the possible deviations, caused by errors in the determination of such values as the plasma density and the intensity of the H. F. field at the plasma boundary, should be kept in mind. As is seen, the region of stability corresponds to the constant field intensity

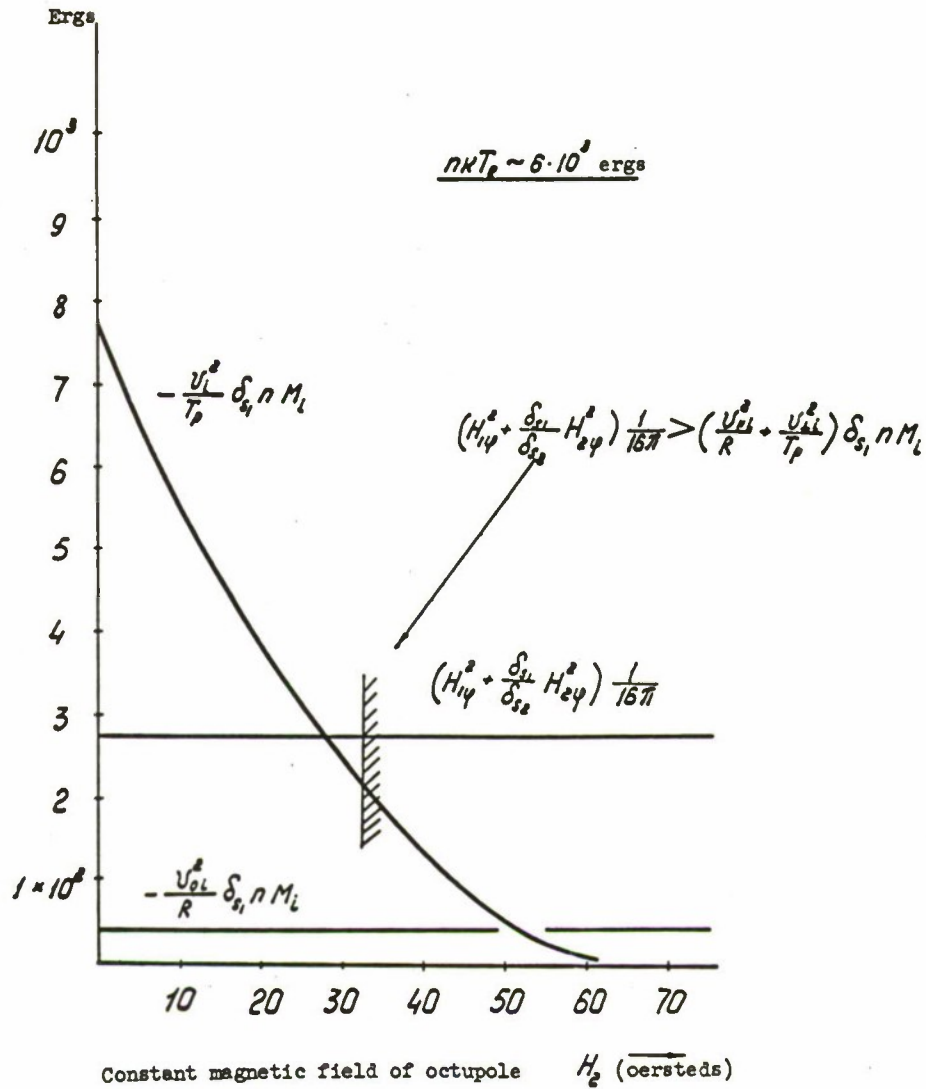


Fig. 14. Diagram of plasma stability boundary relative to convective instability.

of the octupole $H_2 \approx 30$ to 40 Oe. Thus, the plasma-rotation rate is reduced to such a degree that the high-frequency field, $\tilde{H}_{1\phi}$, is sufficient to compensate the diamagnetic velocity of the electrons, caused by the centrifugal effect and curvature of the pyrotron field.

Actually, in the experiment, the transition of the plasma into a stable state was observed at $H_2 \approx 30$ Oe. The change in amplitude of the signal reflected from the plasma surface in an 8-mm wave was recorded. Figure 15 shows the oscillograms for the antennae A_1 and A_2 . In Fig. 15a, the octupole field is zero. For Figs. 15b, c, and d, the octupole field on the plasma surface was 20, 40, and 60 Oe, respectively. From these oscillograms it

follows that with a 40-Oe field, the plasma column becomes stable. The stable state of a plasma column is also indicated by absence of a current in the wall probe (Fig. 13b), voltage increases in the H. F. circuit due to sharp decreases in the plasma losses, and the type of high-speed sweep taken from the end of the chamber (Fig. 16a and b). Under stable conditions, there is no H_{β} -line luminance in the central part of the discharge chamber (Fig. 12b). On the oscillograms, Fig. 17a, taken at $H_2 = 100$ Oe, at the high sweep rate, even with a large amplification, it is seen that the instability is suppressed, the "tongue" of the plasma is not developed, and there are only insignificant vibrations of the plasma boundary.

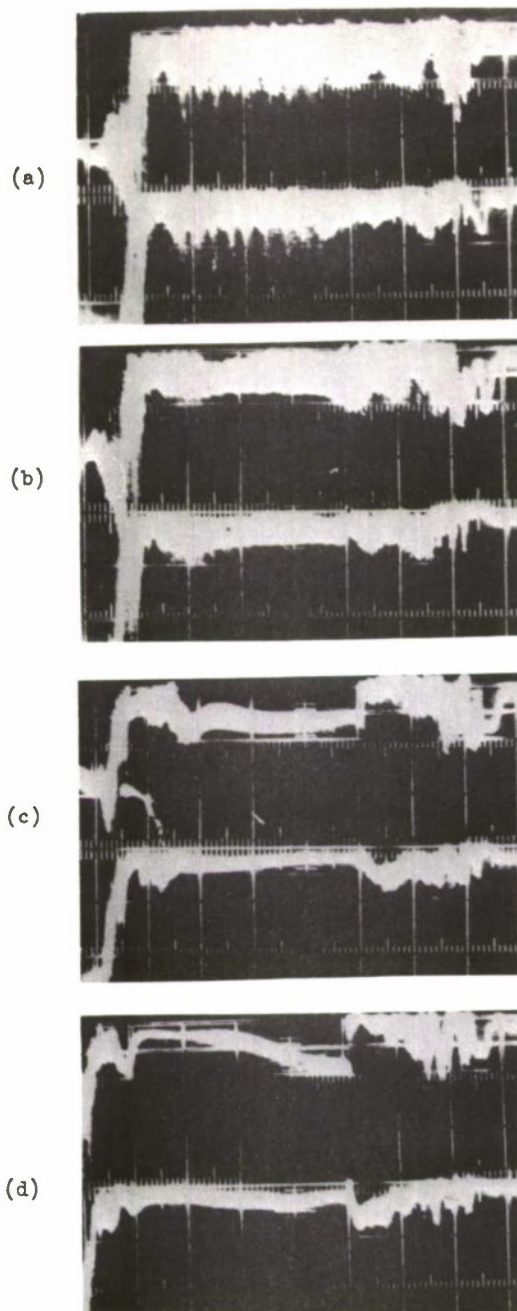


Fig. 15. Oscillograms of signals reflected from an 8-mm wave for octupole values from 0 to 60 Oe. Arrangement scheme of antennae 1-2. Sweep duration - 500 $\mu\text{sec/cm}$; $H = 6 \text{ kOe}$.

With decreased H. F. field intensity at the end of the pulse, development of convective "tongues" is again observed (Fig. 17b). Since the centrifugal effect is suppressed, the emergence of convective ejections can be explained by the fact that the H. F.-field pressure is insufficient to suppress the instability caused by the curvature

of the pyrotron field. The appearance of ejections in a slowly rotating plasma was also observed in other experiments when the H. F.-field intensity became less than some critical value. Also characteristic of an entrained plasma is the emergence of radial vibrations, illustrated by Fig. 17c.

In Fig. 18 are plotted the experimental points corresponding to different intensities of the constant field of a pyrotron in the center of the discharge tube, and the intensity of the constant field of an octupole. The boundary of the instability region with regard to convective perturbations, shown in Fig. 18 by line a-a, corresponds to $H_2 \sim 30$ to 40 Oe, which agrees well with the calculations of Fig. 14. The boundary of the instability region, line b-b, is determined by the value of the critical field, H_2 , and the conditions of formation and equilibrium at the plasma radius.

In these experiments, ionization and heating of the plasma were accomplished by the action of high-frequency stabilizing fields. Therefore, the plasma had a relatively low temperature and high density, and its pressure was $\sim 6 \times 10^3$ ergs. Thus, the ratio of stabilizing H. F.-field pressure to plasma pressure, $1/\beta$, does not exceed 5×10^{-2} .

G. Stabilization of Convective Instabilities

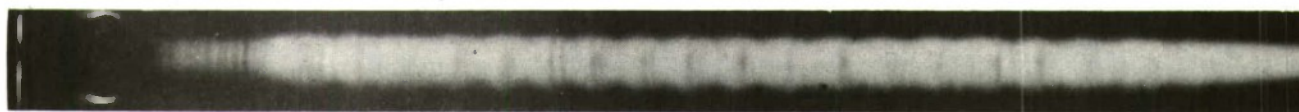
Study of the dynamic stabilization of a plasma with convective instabilities is not complete; however, the experiments presented indicate promise in further study of this problem.

Gubin, Gutkin, N. I. Malykh, L. Ia. Malykh, Besshaposnikov, Zverev, Simonova, Iampol'skii, Doroshenko, Zhdanov, Kursanov, Soldatenkov, Rakhel'kin, and the present author participated in the experiments.

H. Toroidal Systems

Experimental examination of the possibilities of combined systems, in which high-frequency megahertz fields are combined with strong quasiconstant magnetic fields, was conducted in several toroidal devices. The conversion to experiments in tori removes the effect of the ends, while the question of compensation of the toroidal drift remains.

Solution of the problem of equilibrium on the large radius is a necessary condition for conversion to experimental examination of plasma stabilization by an H. F. field in a toroidal system. This is because toroidal drift is the strongest

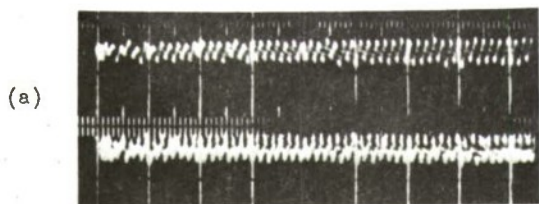


(a)



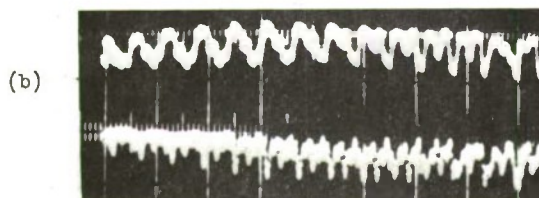
(b)

Fig. 16. High-speed sweep of discharge luminance in a pyrotron, taken from the end of the chamber: (a) in unstable condition (octupole field = 0); (b) in stable condition (octupole field at plasma surface = 40 Oe). Duration of process ~ 4 msec.



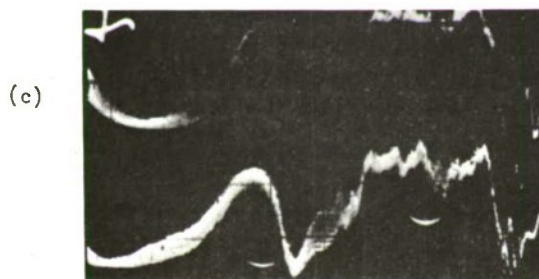
(a)

Duration of sweep - 5 $\mu\text{sec/cm}$, delay of 1000 μsec . Location of antennae 1-2; $H = 6$ kOe; $H_{\text{Oct}} = 100$ oersteds.



(b)

Duration of sweep - 5 $\mu\text{sec/cm}$, delay of 2000 μsec . Location of antennae 1-2; $H = 6$ kOe; $H_{\text{Oct}} = 100$ oersteds.



(c)

Duration of sweep - 250 $\mu\text{sec/cm}$, delay of 3000 μsec . Location of antennae 1-2; $H = 6$ kOe; $H_{\text{Oct}} = 120$ oersteds.

Fig. 17. Oscillograms of signals reflected from an 8-mm wave.

mechanism for transfer of a plasma across the magnetic field.

As the theory presented above shows, a rotating H. F. multipole magnetic field of the E-wave type (electrical vector directed along the torus being formed parallel to the constant magnetic field) can compensate the toroidal drift. This method probably has some advantages since compensation of the toroidal drift must occur locally. While theory predicts that equilibrium is easier to achieve than stabilization of the more dangerous magnetoactive plasma instabilities (of a drift type, for instance), from the point of view of the H. F. field amplitudes $\tilde{H}$ always is larger than or equal to 1. In this sense, it is tempting to combine these two effects in the hope that with small-scale instability stabilization the problem of toroidal drift compensation will be solved automatically.

The "R-0" device is an example of a toroidal device with combined high-frequency and quasiconstant magnetic fields.^{34,38}

The main problem brought to the experiment in the device was to determine the nature of the interaction of a megahertz H. F. magnetic field with a plasma, and to ascertain the possibility of toroidal-drift compensation.

The first, more concrete, part of the problem reduces to the question of the nature of the propagation of a weakly helical H. F. multipole rotating magnetic field in a magnetoactive plasma, and, more important, the nature of the H. F.-field skin effect when the H. F. pressure is comparable to the gas kinetic pressure of the plasma, $\tilde{H} \approx 1$, and the

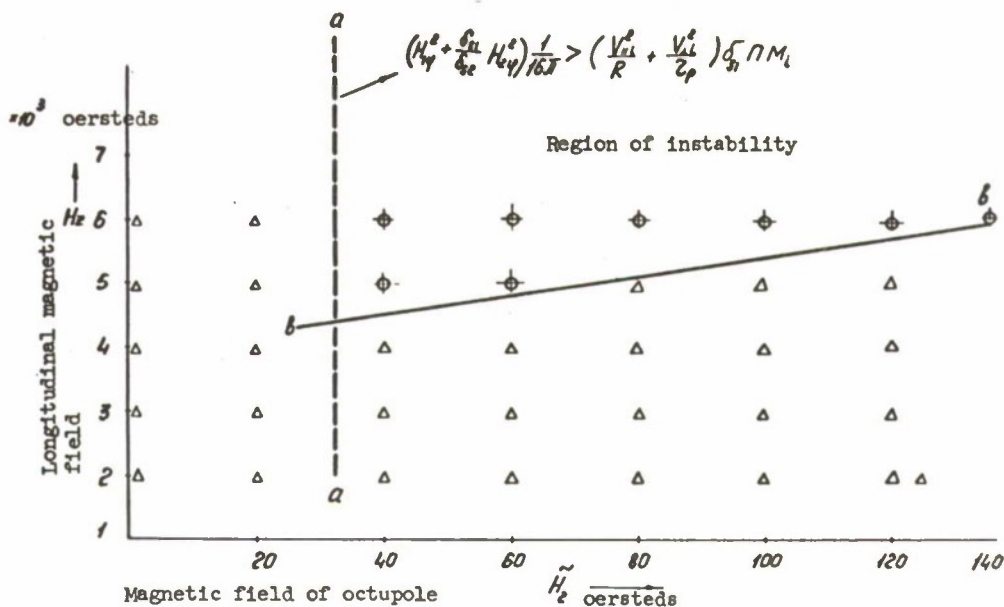


Fig. 18. Plasma conditions corresponding to different magnetic-field intensities in the center of a pyrotron and in an octupole on the plasma surface. (Dipole magnetic-field intensities ~ 100 Oe.)

development of intensive turbulent instabilities is possible in the skin layer where the current density can become large and the electron oscillatory velocities can be of the order of thermal velocities. Concern with the skin effect is related to the fact that toroidal-drift compensation and some types of stabilization depend on whether the H. F. field penetrates into the plasma and how it penetrates, i.e., what determines the depth of the skin layer.

It is clear that the stabilization by an H. F. field showing a skin effect occurs only to the depth of the skin layer. Meanwhile, for $\tilde{\beta} \approx 1$, which theory requires for stabilization of drift-type instabilities, it can be expected that the density and temperature drops will occur at approximately the characteristic depth of the skin.

The question of skin-layer type is important in stabilization of instabilities leading to plasma transfer. No less important, is the effect of processes occurring in the skin layer on the rate of energy transfer from the H. F. field to the plasma, in particular, to electrons. "Parasitic" electron heating can take the plasma out of the region of stabilization (or equilibrium) rapidly, and a high stability state will exist for only a short time. Such contradiction is generally characteristic of the problem of plasma confinement by H. F. fields in quasicontinuous conditions: an

H. F. field not only confines a plasma, but also effectively heats it.

If one takes into account only coulombic collisions, this contradiction reduces to an increase in plasma temperature and a corresponding rapid decrease in v_{ei} . However, if we take into account that in the skin layer, for $\tilde{\beta} \approx 1$, the electron oscillatory velocity is approximately thermal (for

$$\delta \approx \frac{c}{\omega_{pe}}),$$

this can cause small-scale turbulence (in particular, of the ion-acoustic or electron-plasma vibration type), which can increase considerably the effective collision frequency, ν_{eff} , and again lead to rapid "parasitic" plasma-heating. Macroscopically, this leads to increased depth of the skin layer, to

$$\delta \approx \frac{c}{\omega_p} \quad \text{and} \quad \frac{1}{\sqrt{\beta}},$$

as Riutov and Soldatenkov have shown.

The program of experiments in the "R-O" device provides for investigation of this range of questions. At present answers have been obtained for only some of them.

The device is a quartz torus (diameter

$D = 100$ cm and $d = 10$ cm) encircled by a system of coils that create a quasiconstant and H. F. magnetic fields. The quasiconstant toroidal field is created by 48 coil traps uniformly spaced along the toroidal chamber; its maximum intensity is 10 kG. Along the chamber are eight coils, which in passing along the torus make one revolution around its longitudinal axis; i.e., they are helical (Fig. 19). These coils are the inductances of the H. F. circuit, and in them, by means of an H. F. generator (operating power up to 20 mw), there oscillate H. F. currents of different types. Initially, the coils were made as helices from purely radio engineering considerations, since in a toroidal system this ensures good H. F.-circuit symmetry and relieves its oscillation. However, it developed that such a circuit expands the possibilities for physics experiments. The H. F.-field parameters of the device are as follows.

Type: rotating helical quadrupole field,

Frequency: $f = 0.7$ MHz,

Field intensity at plasma boundary: $\tilde{H}_\varphi \approx 250$ Oe,

Duration of H. F. field: $\tau = 1$ to 2 msec.

Hydrogen and helium at pressures $P_0 \approx 1$ to 5×10^{-3} torrs served as the working gases. A pre-plasma was created by a special generator oscillat-

ing in the coils. The current fluctuated with a zero-made frequency, f_p of 1.8 MHz. An overall view of the device is shown in Fig. 20.

The fact that the coils of the H. F. circuit are helices, i.e., the electrical vector of the H. F. field is directed at some angle to the force lines of the strong quasiconstant magnetic field, causes specific conditions for the propagation of this field in the magnetoactive plasma in accordance with the theory given by Lozovskii.¹⁶

The experiments corroborated the theoretical calculation. Actually, there is some critical value of the quasiconstant field, $\bar{H}_z$, -- we will call it H_{zcrit} -- which separates two sharply contrasting conditions for propagation of the helical H. F. quadrupole in the plasma in a strong quasiconstant magnetic field, H_z . If $H_z > H_{zcrit}$, we will call it condition I; the H. F. field, in practice, penetrates into the plasma. If the field H_z is smaller than H_{zcrit} , the high-frequency field shows a skin effect (Fig. 21).

In considering the experimental results, one should return to the equation that describes the distribution of the H. F. field ($\bar{H}_\varphi$ -component) in the plasma:¹⁶

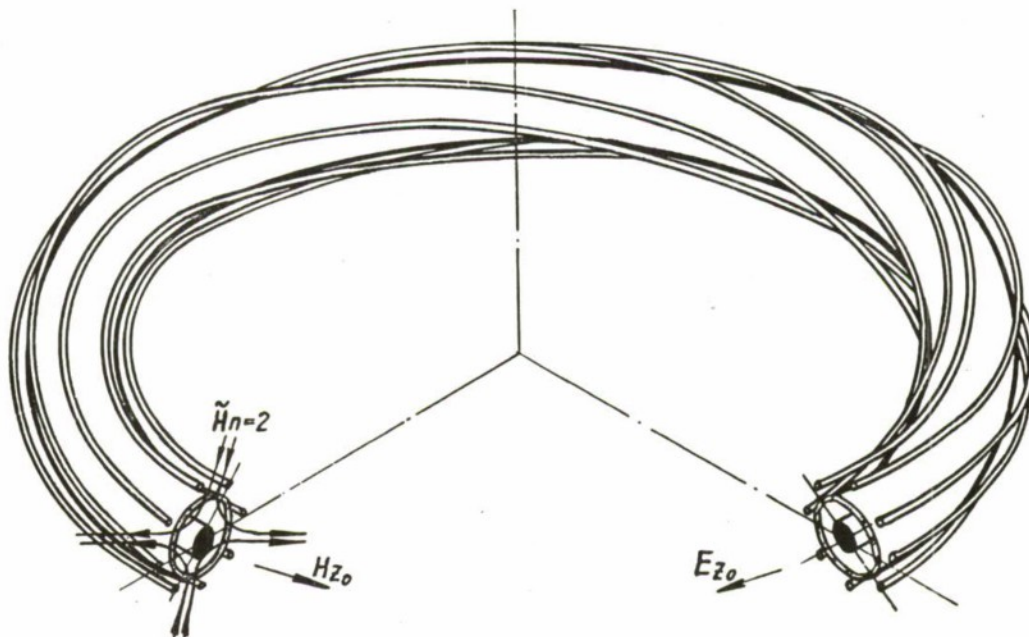


Fig. 19. "R-O" device H. F.-circuit schematic.

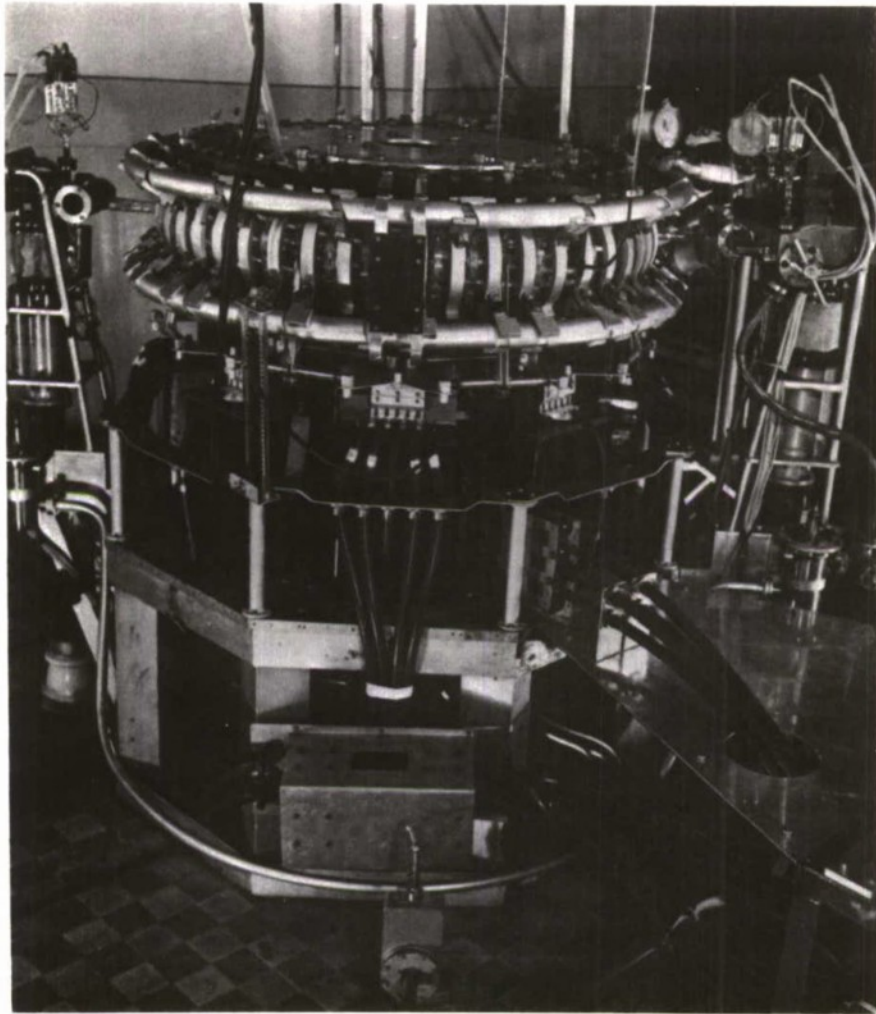


Fig. 20. Overall view of "R-O" device.

$$\tilde{H}_{\phi} \sim \frac{A}{\alpha(H_z)} \cdot \left[e^{-\frac{r_p - r}{\delta}} - R(H_z) \frac{r}{r_p} \right].$$

Here

$$R(H_z) < 1 \quad \text{for} \quad H_z < H_{z \text{crit}},$$

and

$$R(H_z) > 1 \quad \text{for} \quad H_z > H_{z \text{crit}}.$$

The first term describes the skin effect of the field in a plasma and the second is analogous to the vacuum effect in form. The properties following from this equation appear clearly in the experimentally measured distribution of $\tilde{H}_{\phi}$ and $\tilde{H}_r$, the components of the H. F. field in the plasma.

In Fig. 21 there is seen some increase in the H. F. field near the center of the chamber caused by the second term.

The absolute value of the critical field for given plasma parameters measured by different diagnostic methods coincides well with the theoretical values obtained from the condition:

$$\frac{H_{z \text{crit}}}{\sqrt{4\pi n_i m_i}} = \lambda f, \quad (1)$$

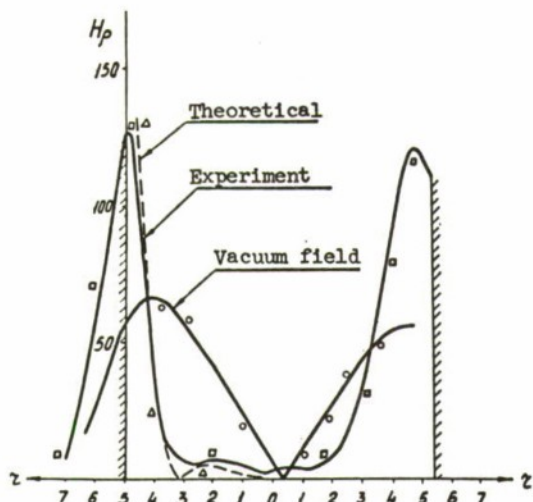


Fig. 21. Curve of critical-field dependence, H_z , on initial pressure of working gas.

where λ is the pitch of the helical winding of the H. F. circuit, and f is the H. F.-field frequency.

For our initial densities, $n_e \approx 10^{13} \text{ cm}^{-3}$, the experimental critical field value is approximately $4 \times 10^5 \text{ Oe}$ (for H_z). The functional dependence of H_{zcrit} on the plasma density, proportional to the initial pressure, is also described fairly well by Eq. (1).

The depth of the skin layer, which can be found from distributions of the type shown in Fig. 21, in our experimental conditions changes within the limits $\delta \approx 5$ to 15 mm . In absolute value, this coincides with that given both by the equation for the classical collision skin,

$$\delta = \frac{c}{\omega_{pe}} \sqrt{\frac{2 \nu_{ei}}{\omega}},$$

and by the equation for a turbulent skin,

$$\delta = \frac{c}{\omega_{pi}} \frac{1}{\sqrt{8}}.$$

In experiments in the "R-0", the coulombic-collision frequency is still quite large ($\nu_{ei} \approx 10^8 \text{ sec}^{-1}$), and the turbulent expansion cannot be isolated in pure form at present. Experiments are being set up to do this.

The existence of two conditions for propagation of an H. F. field in a plasma permitted experiments

on the equilibrium of the toroidal column with two sharply contrasting values of plasma parameters and different conditions of H. F. Power consumption.

If only the generator of the zeroth mode operates, a pre-plasma is created in the chamber, filling the whole cross section of the tube (Figs. 23a and b). Figure 23a shows the scan of the plasma-column luminescence with time; 23b shows the signal of the reflection of a wave with $\lambda = 17 \text{ mm}$. When an H. F. quadrupole field is superimposed on such a pre-plasma and $H_z > H_{zcrit}$, a macroscopically stable plasma column is formed in the center of the discharge chamber (Figs. 24a and b). The withdrawal of the plasma from the walls is indicated by the decrease in the reflected signal (Fig. 24b). The absence of circuit-frequency drift and the probe measurements tell that the H. F. field shows a weak skin effect in the plasma.

The localization indicates that the toroidal drift of the plasma column is compensated. This confirms the rough calculation of the particle lifetime, approximately 50 msec. However, the plasma-energy parameters are low: $T_e \approx 3$ to 5 eV , $n_e \approx 2 \times 10^{13} \text{ cm}^{-3}$; ionization is about 20 to 30%; and consumption of H. F.-circuit power by the plasma is below the sensitivity of the measuring apparatus.

The localization and the absence of any great tendency to displacement towards the outer wall is well explained, theoretically, both by the single-particle model, which indicates the finiteness of

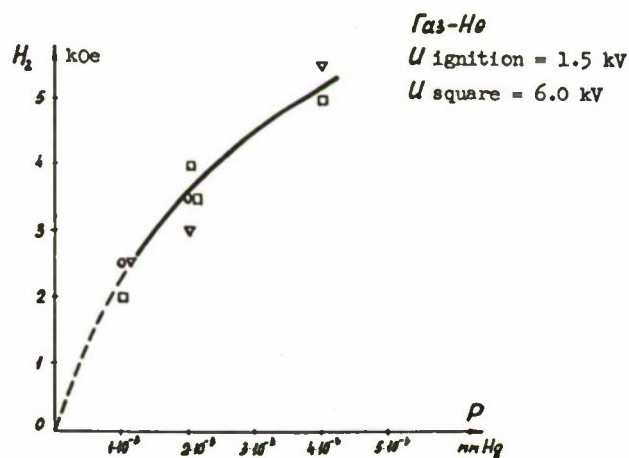


Fig. 22. Distribution of H. F. fields (H_p component) in a plasma. $H_z < H_{zcrit}$. $P_0 = 5 \times 10^{-3} \text{ mm Hg}$, working gas - He.

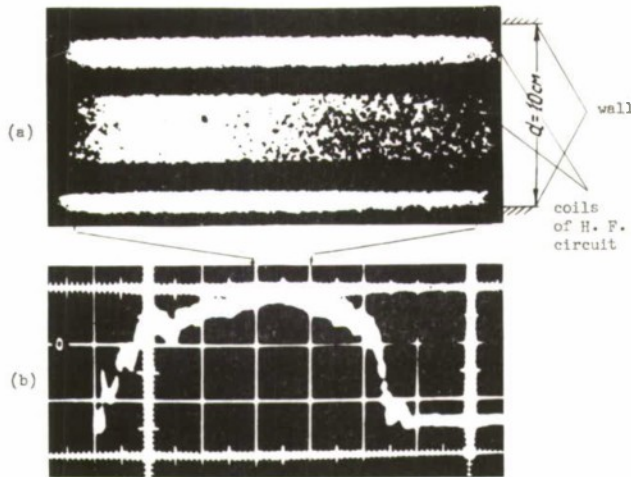


Fig. 23. (a) Sweep of plasma-column luminescence in time; (b) oscillogram of wave signal with $\lambda = 17$ mm, reflected from plasma boundary. $H_z > H_{zcrit}$, working gas - He, $P_0 = 1 \times 10^{-3}$ mm Hg.

ion and electron motion in such a penetrating H. F. rotating quadrupole field, and from the macroscopic point of view, in which the force of the toroidal drift is compensated by the force of the high-frequency pressure, although this is also small owing to the inefficient skin effect. Meanwhile, owing to the great penetration, the density of the H. F. currents in the plasma is low and "superheating" does not occur.

The use of the device in the second condition, when $H_z < H_{zcrit}$ and the H. F. field has an efficient skin effect, considerably increases the plasma parameters (density, temperature, and specific energy), to approximately $T_e = 10$ to 40 eV (depending on the initial pressure); $n_e \approx 5 \times 10^{13} - 5 \times 10^{14} \text{ cm}^{-3}$; and $\langle nT \rangle \leq 2 \times 10^{15} \text{ eV/cm}^3$. The magnetic probes show that the column is torn from the inner wall of the discharge chamber and contacts the outer wall, and its "center of mass" (center of symmetry of the H. F.-field distribution curves in the plasma) is displaced toward the outer wall. The displacement of the "center of mass" is fairly well described by the equation for the plasma-column equilibrium displacement,¹⁴ both as to absolute value and as to the functional dependence of the magnitude of plasma-parameter shift and the intensity of the H. F. field (Fig. 25). The energetic lifetime of the plasma in this condition is small, about $5 \text{ } \mu\text{sec}$, and the plasma consumes much power from the H. F. circuit.

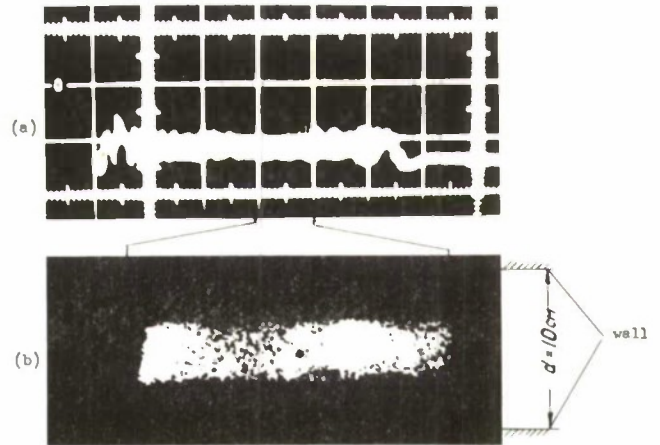


Fig. 24. (a) Sweep of plasma-column luminescence in time. (b) Oscillogram of wave signal reflected from plasma boundary; $H_z < H_{zcrit}$, working gas - He, $P_0 = 1 \times 10^{-3}$ mm Hg.

The increase in plasma temperature with decreased density and increased average specific energy, proportional to the square of the H. F.-field intensity, shows that $\langle nT \rangle$ always reaches equilibrium within the limits of accuracy of the measurement. On the average, this value does not change with time during the pulse; although for our densities, electron temperatures, and high-frequency field intensities, and with sufficient thermal insulation, the plasma must be rapidly heated.

Analysis of the diamagnetic signals shows that there are periodic pulsations $\langle nT \rangle$ with a characteristic time of several μsec . This indicates that the plasma column periodically discards part of its energy, which also explains the low energetic lifetime of the plasma. The discarded energy probably goes to the outer wall.

All these experimental data can be assembled into one model by assuming that the column is on the average near the location of the equilibrium determined by the time-averaged $\langle nT \rangle$. At the moment of total compensation of the toroidal drift there is a rapid "superheating" of the plasma; a disruption of the equilibrium; a deposition of the excess energy at the outer wall as a result of the toroidal drift; and return of $\langle nT \rangle$ to the equilibrium value. These cycles are repeated periodically. Such a state with the time-averaged $\langle nT \rangle$ equal to the equilibrium value can be called a state of "quasi-equilibrium".

The whole complex of experiments conducted in

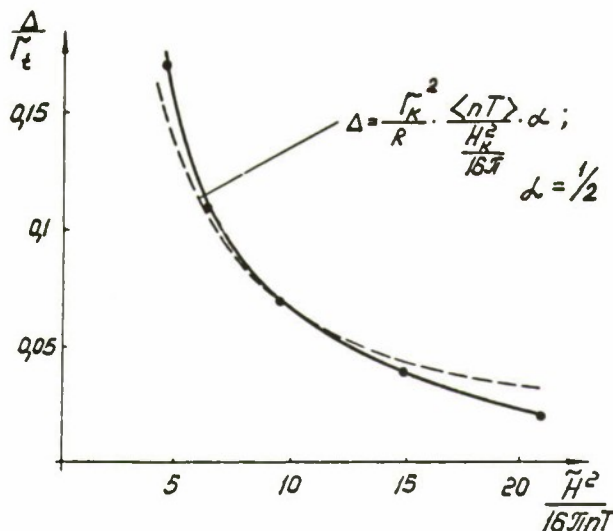


Fig. 25. Curve of dependence of relative shift of plasma-column "center of mass" on $\tilde{H}$ (the value

$$\tilde{H} = \frac{H^2}{16\pi nT}$$

is given in arbitrary units).

the "R-0" device by the author with Kirov, Stotland, Malykh, and Khorasanov,³⁹ permits concluding with assurance that a high-frequency field of the quadrupole type can compensate the toroidal drift. However, with a dense, low-temperature plasma and a skin effect, the effect of compensation is periodically liquidated by the superheated plasma.

III. CONCLUSION

In conclusion it can be said that the experimental results are encouraging and indicate promise in the use of H. F. fields; although the study of this problem is in the beginning stage. On one hand, this can explain the tendency to set up such experiments, because study of plasma behavior in high-frequency fields as applied to controlled thermonuclear fusion was started considerably later than study of plasma in constant magnetic fields. On the other hand, the development of these investigations is presently limited by the radio engineering and diagnostic possibilities. In all probability, one of the most important problems for study at the present time is the behavior of magnetized plasma in H. F. electromagnetic fields of large amplitude, $\tilde{H} = 1$, with different configurations.

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