125 Weatherway

National Aeronautics and Space Administration
Goddard Space Fligh Center
Contract No. NAS-5-12487

ST-PP-10573

IONIZATION INSTABILITY OF A PLASMA WITH HOT ELECTRONS

by

E. P. Velikhov
A. M. Dykhne
I. YA. Shipuk

(USSR)

6 MARCH 1967

IONIZATION INSTABILITY OF A PLASMA WITH HOT ELECTRONS

(*)

From the 5th Symposium on
the Ionization of Gases
held in
Yougoslavia in 1965.(**)

by E. P. Velikhov,
A. M. Dykhne &
I. Ya. Shipuk

SUMMARY

This paper shows that it is possible to assert sufficiently specifically that the ionization instability is the number one problem for the utilization of a plasma with hot electrons.

A large amount of experimental work is required for the determination of realistic methods of ionization stabilization. Several such possible methods are suggested here, which, provided they are operational, will still impose hard requirements of flux homogeneity to make the instability possible.

Nor is excluded the possibility that one might have to put up with turbulent ionization, just as was done with turbulent flow of standard fluids. In this case the essential trait of turbulence phenomenon would apparently be the saturation of the Hall ratio and the corresponding rise of turbulent resistance to a current with a magnetic field.

*
*   *

1. INTRODUCTION.

One of the fundamental problems of physics of plasma flow interaction with a magnetic field is that of the stability of the flow and of description of its turbulent state. We shall consider in this report the stability of the flow of dense plasma with hot electrons. As is well known, a substantial heating of electrons in a magnetic field is possible only for a sufficiently high ratio of the frequency of the Larmor spinning of an electron Ω_- to the frequency of its collisions with heavy particles τ_-^{-1}. On the other hand the effective interaction of the flux with the field is possible only when the rate of ion slippage relative to neutral gas is small, that is, the product $\Omega_-\tau_- \times \Omega_+\tau_+$. There exist in such a plasma standard hydrodynamic motions and acoustic waves. However, inasmuch as ions are fixed relative to neutral particles and the electrons are bound with ions by the electric field, the only "degree of freedom" in an electron-ion gas is the variation of the number of particles, that is, the ionization or recombination.

(*) IONIZATSIONNAYA NEUSTOYCHIVOST' PLAZMY S GORYACHIMI ELEKTRONAMI

(**) The precise source is not knwon

As was shown earlier [1, 5, 6, 8], the anisotropy of plasma's electrical conductivity leads to the circumstance whereby the usual attenuation of acoustic waves, characterized by the times $\tau_B \sim \rho\, c^2/\sigma\, B^2$ (the so-called "interaction time", where ρ is the density, σ is the plasma conduction, B is the magnetic field), is replaced by the instability. The very same anisotropy leads also to the appearance of fluctuating Hall currents induced by the fluctuations of electron concentration. These Hall currents amplify, in their turn, these fluctuations (the so-called "ionization instability", [2, 3, 4, 5]). The development time of instability of ionization in a dense plasma is of the order of the ratio of ionization energy of plasma's unit volume, In, to Joule heating power j^2/σ (n is the concentration of electrons, I is the ionization potential and j is the density of the current). Generally $\tau_I = In/(j^2/\sigma)$ is by several orders smaller than the interaction time τ_B, since $\tau_I/\tau_B = In\,\sigma^2 B^2/\varrho\, j^2 c^2 \sim$ $\sim In/\varrho\, u^2$ (we utilized the relation $j \sim \sigma UB/c$, where U is the gas velocity), i.e. it is equal to the ionization energy ratio to kinetic energy of the flux.

Inasmuch as the ionization turbulence and the anomalous plasma resistance induced by it, are basically linked with the fluctuatuons of electron concentration, the simplest method of dealing with it consists in the utilization of plasma's "hard ionization", that is, of a plasma with a fully ionized admixture.

As was shown in the work [1], the acoustic instability, caused in such a plasma by the link between the collision frequency fluctuations with those of the Hall current, is possible as before.

In the experimental installations of [3, 4], of which the dimensions were small by comparison with interaction length, the ionization instability must have been observed in "pure form".

Therefore, the ionization instability in a plasma with hot electrons develops to a significant degree independently from the acoustical instability. Apparently, the influence of ionization turbulence is, first of all, manifest in electrical characteristics of the plasma, whereas that of acoustic turbulence is apparent in the hydraulic characteristics of the plasma.

The present report is devoted to a separate consideration of ionization instability and turbulence.

2. MODEL OF A QUASIEQUILIBRIUM PLASMA WITH HOT ELECTRONS

Both, theory and experiment indicate [9, 10, 11] that a sufficiently dense plasma (pressure of neutral component $\sim$1 atm., pressure of ionizing admixture $\sim 1 \div 10$ mm Hg) is well described by the quasiequilibrium two-temperature theory: the gas of heavy particles is characterized by low temperature T_0, and the gas of free electrons and of electrons at excited atom levels by temperature T_e. The degree of plasma ionization is determined by the Sakh* relation and the ionization time — by the rate of feed energy to electrons.

---

* [in translitaretaion]

The motion of electrons is described by the generalized Ohm law and ions move alongside with neutral atoms. For simplicity we shall consider in the following the limiting case $T_e > T_0$ In this case the energy of electrons is determined exclusively by processes of energy liberation in the electronic gas, cooling at collisions with heavy particles, transfer in the electronic gas (electronic heat conductivity and transfer of thermal energy with the current) and transfer of energy in the radiation. In a dense plasma energy is transferred mainly by linear radiation of admixture's excited atoms. The density of excited atoms does not depend on radiation intensity and is fully determined by the temperature of electrons. About one half of energy is transferred by resonance doublet, and the remainder — in all other lines. Either radiation is locked at the center of the line. The shape of the line is determined mainly by electron collisions and subsequently, for the sake of simplicity we shall consider it as Lorentz, with width proportional to the concentration of electrons. For estimates we shall limit ourselves to accounting only the resonance emission.

Because of turbulent mixing the transfer of energy in a moving gas is possible.

Thus, the current in the plasma is determined by the equation

$$\vec{j} = \sigma_{\perp}\{\nabla\varphi \times \vec{\Omega}_{\tau} - \nabla\varphi - \vec{\Omega}\tau^2(\vec{\Omega}\nabla)\varphi\}, \tag{1}$$

where $\vec{\Omega} = e\mathrm{B}/mc$, $\sigma_{\perp} = \sigma/(1+\Omega^2\tau^2)$, φ is the potential. From the condition of current conservation we determine the potential distribution: div $\vec{j} = 0$, i. e.,

$$\vec{\Omega}, \nabla\tau\sigma_{\perp} \times \nabla\varphi = \mathrm{div}\,\sigma_{\perp}\nabla\varphi + (\vec{\Omega}\nabla)\sigma_{\perp}\tau^2(\vec{\Omega}\nabla)\varphi. \tag{2}$$

For great values of $\Omega\tau$ and $(\vec{\Omega}\nabla) = 0$ $\tau\sigma_{\perp} \sim \sigma/\Omega^2\tau \sim n$, i. e. , from Eq.(2) it follows that in a plasma, equipotentials are disposed almost along the lines of equal concentration, and according to (1) the electrical current also flows along the lines n = const.

The variation in the concentration of electrons is determined by energy balance in the electronic gas:

$$I\dot{n}_e = \frac{j^2}{\sigma} - \frac{nT}{\tau}\frac{m}{M} + \mathrm{div}\,\varkappa_e\nabla T + Q_{rad}, \tag{3}$$

where κ_e is the electronic conduction factor, and $Q_{rad} = \mathrm{div}\, c\iint d\omega\, d\theta \cdot \hbar\omega$, f is the distribution function of resonance quanta, determined from the kinetic equation for photons:

$$c\nabla f = -c\varkappa(\omega) f + \frac{n^*}{\tau_e}\frac{\varkappa(\omega)}{\varkappa_0}, \tag{4}$$

n* is the density of excited atoms, τ_e is the time of spontaneous radiation

../..

$$\varkappa(\omega) = \frac{\varkappa_{y\partial}{}^0}{1 + \left(\frac{\omega - \omega_0}{\gamma_{y\partial}}\right)^2}; \quad \varkappa^0{}_{y\partial} = \frac{n_0 \lambda_0{}^2}{2\pi} \frac{g_2}{g_1} \frac{1}{\tau_r \gamma_{y\partial}} \tag{5}$$

$$\varkappa_0 = \int \varkappa(\omega)\, d\omega,$$

$\gamma_{y\partial}$ is the impact line width, n_0 is the density of atoms of the easily ionizable admixture in ground state, λ_0 is the wavelength of resonance emission, ω_0 is its frequency.

3. LINEAR THEORY OF INSTABILITY

Let us consider first of all the current perturbations perpendicular to the magnetic field. For the time being we shall drop also the dissipative terms. Then, linearizing Eqs. (1), (2) and (3), we shall obtain the following expressions for the temporal dependence of the amplitude of the k-th harmonic of electron density fluctuations: $(\bar{k}\,\bar{J}/kJ = \cos\theta)$:

$$\frac{\dot{n}_k}{n_k} = \frac{J^2}{\sigma_0 n_0 I}\left\{-2\sin\vartheta\cdot\cos\vartheta\cdot\Omega\tau_0 + 2\sin^2\vartheta\frac{d\ln\tau}{d\ln n} - 2\cos^2\vartheta - \frac{d\ln T}{d\ln n}\right. . \tag{6}$$

The fundamental term in this equation is the first term in braces, proportional to $\Omega\tau$. For $\Omega\tau > (\Omega\tau)_{kp}$ the most steady perturbations are those at the angle $-\pi/4$ to the current. The rate of ionization perturbations' accretion is found to be equal to $\tau_I^{-1}\cdot\Omega\cdot\tau$. The instability boundary is determined by the condition

$$(\Omega\tau)_{kp} \approx -\frac{d\ln\tau}{d\ln n}. \tag{7}$$

Taking into account that $I \sim 10T$ and $\Omega\tau \sim 10$, it follows from this condition that in order to assure the ionization stability, a very high degree of admixture ionization and a special law of cross section variation with temperature are required.

If we succeed in assuring this condition, two problems will arise. First, there should exist somewhere at MGD-generator input a transitional region from equilibrium (low) ionization to ionization assured by electron heating. This region constitutes in itself an ionization perturbation, i. e., it is a source of instability. Therefore, it is necessary to stabilize the transitional region .

Secondly, it is indispensable to ensure a high degree of plasma homogeneity at entry in the operational region, for otherwise there would remain perturbations of finite amplitude relative to which the flow might be unsteady (see below).

Thus, which stabization methods are available to us ?

a) First of all, we may regulate the plasma potential with the aid of conductirs located above and below the plasma flux, for the mobility of electrons along the magnetic field is $(\Omega\tau)^2$ times higher than the transverse mobility. Electrodes must be so disposed that they smooth out the potential of the most unsteady perturbations (perpendicularly to the front of these perturbations). Such a method may act effectively upon the two-dimensional ionization perturbations. The presence at extremities of conducting plates leads to a new boundary condition for the potential. These conditions admit the existence in a series of directions of only three-dimensional perturbations. From relation (2) for the electric field in the plasma at $(\vec{k}\,\vec{\Omega}) \neq 0$ we shall obtain the following expression for the fluctuations of the electrical potential:

$$\varphi_{\vec{k}} = -\mathrm{i}\,\frac{\vec{\Omega},\,\mathbf{k}\times\nabla\varphi_0\,\dfrac{d\ln\tau\sigma_\perp}{d\ln n} + \mathbf{k},\nabla\varphi_0\,\dfrac{d\ln\sigma_\perp}{d\ln n}}{\sigma_\perp\,[k^2 + (\mathbf{k}\,\vec{\Omega}\tau_0)^2]}\,n_{\vec{k}}\,. \tag{8}$$

The first term, inducing the instability, decreases $(1+\Omega^2\tau^2\cos^2\theta)$ times, where θ is the angle between the perturbation's wave vector and the magnetic field. The stabilizing term is $d\ln T/\Omega\tau d\ln n$ times (....)* as this follows from the expression for the increment (6). This is why the ionization perturbations of transverse dimension $\lambda_\perp$ may be stabilized along the magnetic field in a flow of dimension equal to:

$$\lambda_{\parallel} \gtrsim \lambda_\perp \frac{\sqrt{\Omega\tau}}{\sqrt{\dfrac{d\ln T}{d\ln n}}}\,. \tag{9}$$

The minimum dimension of ionization perturbations is determined by transfer processes.

b) They are determined in the first place by electronic heat conduction. Comparing the volume heat liberation in an electronic gas, nT/ (m/M), with the heat that may be transferred by electronic heat conduction to a distance L:

$$\frac{1}{L}\frac{\lambda_e^2}{\tau}Tn,$$

where λ_e is the length of the free path of the electron, we obtain that because of electronic heat conductivity, the minimum length of perturbations is:

$$L_{\parallel}{}^* = \sqrt{M/m}\cdot\lambda_e \tag{10}$$

along the magnetic field, and

$$L_\perp{}^* = \sqrt{M/m}\,\lambda_e\,(\Omega\tau)^{-1}. \tag{11}$$

* [Note by Translator] : the word is obviously missing in the original text, which is often found to be very poorly written.

If the dimensions of the flow are smaller than $L_{\parallel}$ or $\sqrt{\Omega\tau\frac{d\ln n}{d\ln T}}\cdot L_{\perp}$, the external conductors may effectively stabilize the plasma.

c) Besides the electronic conduction the energy transfer from hot to cold regions is materialized at the expense of resonance radiation transfer. Linearizing Eq.(4), we obtain the following expression for the k-th Fourier component:

$$f_{\bar{k}} = \frac{n^*}{c\tau_r}\frac{\varkappa_0(\omega)}{\varkappa}\frac{1}{ik\cos\varphi + \varkappa_0(\omega)}. \tag{12}$$

Substituting this expression into the expression for Q_{rad}, we obtain for $\varkappa_0 y^{\delta} \gg k$

$$Q_{rad} = \frac{n^* \hbar\omega_0}{\tau_r}\sqrt{k/\varkappa_0 y^{\delta}}\cdot G, \tag{13}$$

where $G \approx 1$. Comparing this expression with the usual energy liberation $(nT/\tau)m/M$, we obtain the following value for the minimum dimension of perturbations controled by energy transfer

$$L^r = \left\{\frac{n}{n^*}\frac{T}{\hbar\omega_0}\frac{\tau_r}{\tau}\frac{m}{M}\right\}^{-2}\cdot\frac{1}{\varkappa_0 y^{\delta}}. \tag{14}$$

This dimension is very sensitive to the degree of ionization and it may, for degrees $\sim$ 10 percent, notably exceed the dimension determined by heat conductivity. The dimension L^r at T_e = 3000°C for argon-caesium plasma at $N_{Ar} = 10^{19}$ cm^{-3} is equal to $\sim 10^{-1}$ cm [10], with $n_0 = 10^{15}$ cm^{-3}.

c) The minimum transverse dimension of perturbations may also be controlled by diffusion in the turbulent flow. Comparing again, after all, the transfer of energy with characteristic volume liberation, we shall obtain the following expression for the transverse dimension:

$$L^D = \frac{nI\sigma}{\tau J^2}\lambda \tag{15}$$

d) Still one more possible method of stabilization is the transmission of a part of the current, heating the electrons, along the magnetic field. Upon linearization, it follows from Eqs.(1), (2), (3) at range from the instability boundary, that

$$J_c \simeq J_{\perp}\cdot\sqrt{\Omega\tau}. \tag{16}$$

This current is too great and such a stabilization method is not very advantageous.

Apparently, for the creation of a steady heating of electrons a joint utilization of several methods is required. Let us note that all the characteristic scales are quite small. Thus we may really expect the existence of developed instability in a plasma with hot electrons.

4. ONE-DIMENSIONAL MODEL OF IONIZATION-UNSTABLE PLASMA

Inasmuch as the condition of ionization instability is found to be rather hard, it is sensible to represent oneself what takes place with an ionization-unstable plasma. Let us consider the spatial development of instability in plasma flox entering a magnetic field. At ingress the flow is endowed with a certain equilibrium conduction σ_S. Assume that this conduction is distributed near the mean value with a certain distribution function $\Phi(\sigma/0)$. Let us assume further that the variation along the flow (axis "y") is much slower than the variations of transverse direction (axis "x"). We shall consider the ionization perturbations disposed along plasma velocity V. In this way the picture is found to be unidimensional. The following may serve as substantiation of the above. We have seen in linear theory that the most unstable perturbations have a specific orientation relative to the medium-current. In our example the current flows across the velocity. If the perturbations have a sufficient amplitude, the optimum angle is $\sim\pi/2$ (for infinitely small perturbations it is equal to $\pi/4$). Moreover, ionization takes place in perturbations, while ions are transferred by the flow. The axis "y" corresponds to the time axis in the theory of the previous section, i. e., for the ionization it is advantageous to develop along the velocity, for otherwise additional energy expenditures are required.

From the generalized Ohm law it follows that the current density along perturbations $J_{\parallel}$ and across perturbations $J_{\perp}$ are linked by the following relations:

$$J_{\perp} + \Omega\tau J_{\parallel} = \sigma E_{\perp} \qquad (17)$$

$$J_{\parallel} - \Omega\tau J_{\perp} = \sigma E_{\parallel}$$

in a system of coordinates moving with the plasma. Preassigned in the flow are the average field $\langle E_{\perp}\rangle = UB/c$ and the longitudinal medium-current $\langle J_{\parallel}\rangle = 0$. In our particular case $\langle J_{\parallel}\rangle = 0$ and $J_{\perp}, E_{\parallel}$ do not depend on the coordinate "x" by virtue of current conservation and field poteniality. Consequently,

$$J_{\perp} = \frac{\sigma_0}{\Delta}\langle E_{\perp}\rangle ; \quad J_{\parallel} = \Omega\tau J_{\perp} - \frac{\sigma}{\langle\sigma\rangle}\langle\Omega\tau\rangle J_{\perp} \qquad (18)$$

where

$$\Delta = \sigma_0\langle\sigma^{-1}\rangle + \sigma_0\left\langle\frac{(\Omega\tau)^2}{\sigma}\right\rangle - \frac{\langle\Omega\tau\rangle^2}{\langle\sigma\rangle}\sigma_0, \qquad (19)$$

σ_0 being a certain characteristic conduction (which we shall postulate as is equal to the nonequilibrium conduction of laminar theory).

From the energy balance equation we shall obtain the following expression for $\partial n/\partial y$

$$\Delta^2 \frac{IUn_0}{E_\perp^2 \sigma_0} \frac{\partial \hat{n}}{\partial y} = \hat{\sigma}^{-1} + (\Omega\tau_0)^2 \frac{\left[\hat{\tau} - \hat{\sigma}\frac{\langle\tau\rangle}{\langle\sigma\rangle}\right]^2}{\hat{\sigma}} - \frac{\hat{n}}{\hat{\tau}} (\widehat{T_e - T_0})\, \Delta^2 . \frac{n_0 (T_e - T_0)_0}{\tau_0} \frac{m}{M} \frac{1}{E_\perp^2 \sigma_0}, \quad (20)$$

where all quantities with "hat" are $f/f_0 = \hat{f}$. Introducing a new coordinate $\hat{y}$

$$\frac{d\hat{y}}{dy} = E_\perp^2 \sigma_0 / \Delta^2 IUn_0 \quad (21)$$

and determining all the quantities with index "0" from the laminar theory, we obtain (subsequently dropping the "hats")

$$n_y = \frac{1}{n\tau} + (\Omega\tau_0)^2 \frac{(1 - n\xi)^2}{n} \tau - \frac{n}{\tau} (T_e - T_0) \Delta^2 = F(n/y), \quad (22)$$

where

$$\xi = \frac{\langle\tau\rangle}{\langle n\tau\rangle}, \text{ a } \Delta = \left\langle \frac{1}{n\tau} \right\rangle + (\Omega\tau_0)^2 \left\{ \left\langle \frac{\tau}{n} \right\rangle - \frac{\langle\tau^2\rangle}{\langle n\tau\rangle} \right\}. \quad (22a)$$

$\Delta \langle n\rangle/(\Omega\tau_0)^2$ is of the order of the root-mean-square relative width of concentration distribution. For sufficiently great initial fluctuations we may neglect in Eq.(22) the first term, not containing the great multiplier $(\Omega\tau)^2$. The right-hand part (F) of the equation has three stationary points; two near the mean value of concentration

$$n_\pm = \frac{1}{\xi \pm \sqrt{\theta}\Delta/(\Omega\tau_0)\tau}; \qquad \theta = T_e - T_0$$

and one point for $n_m \gg \langle n\rangle$. Two of them are steady: n_+ and n_m. Depending upon the quantity of admixture in the plasma the third point may lie in the region of total ionization of the admixture or in the region of prevalence of Coulomb collisions. In this region the free path time τ of the electron and the temperature break change substantially. We shall consider a simple model, in which $\tau = 1$ for $n < n_m$ and a certain τ_m at $n = n_m$.

Eq.(22) is the equation of characteristics for the kinetic equation, describing the variation of the distribution function of conduction or concentration, $\Phi(n/y)$, proportional to the fraction of flow area occupied by plasma with concentration n :

$$\frac{\partial \Phi}{\partial y} + \frac{\partial}{\partial n} \Phi F = 0. \quad (24)$$

We shall resolve this equation with the aid of the method of moments. As is usual, the moments engage and for cutting we shall postulate that $\langle 1/n^k - \langle 1/n\rangle^k$ is small by comparison with $\langle 1/n - 1/\langle n\rangle$. This assumption is linked with the circumstance that the flow in fact breaks down into two regions with essentially different concentration near n_+ and n_m. We then obtain from (22) and (24) the following equations for $\langle n\rangle$ and Δ:

$$\Delta_y = \frac{(\Omega\tau_0)^2}{\langle n\rangle^2}\Delta - \Delta^3 \qquad (25)$$

$$\langle n\rangle_y = \Delta - \langle n\,0\rangle\,\Delta^2$$

where $\theta \to 0$ as $<n> \to <n_s>$ (θ is the difference in temperatures of electrons and heavy particles, n_s is the equilibrium concentration of electrons at $T_e = T_0$).

These equations roughly describe the pattern of development of ionization instability: when the equilibrium plasma with low concentration $n_s \ll 1$ hits the magnetic field, the mean density increases at sufficiently regular conduction. At the same time the degree of inhomogeneity Δ increases also :

$$\frac{d\Delta}{d\langle n\rangle} = \frac{(\Omega\tau_0)^2 - \Delta^2\langle n\rangle^2}{1 - \langle n\rangle\Delta\theta}\,\frac{1}{\langle n\rangle^2}. \qquad (26)$$

The concentration increases to the value $<n> = 1/\Delta\theta$. Then begins the drop of concentration practically along the line $<n> = 1/\Delta\theta$ and the rise of Δ. As $\langle n\rangle \to n_s\theta \to 0$ and $d\Delta/d\langle n\rangle \to \infty$, $\langle n\rangle$ ceases to vary, and Δ continues to rise to $\Delta_{max} = \Omega\tau_0/n_s$. The relative temperature break is then found to be equal to $\theta \cong 1/\Omega\tau_0$ as an average. Thus, against the background of nearly equilibrium ionization there appear narrow regions of hot electrons (total ionization with low degree of admixture). The portion of the area Φ_r, occupied by these regions, is determined from Eqs. (25) and (22a):

$$\Phi_r \approx \frac{1}{\Omega\tau_0} n_s/n_m.$$

Obviously, the accounting for transfer processes may modify this estimate.

From (17) it follows that

$$\frac{\langle E_{\parallel}\rangle}{\langle E_{\perp}\rangle} = \frac{E}{UB/c} = \frac{\Omega\tau_0}{\langle n\rangle\Delta} \sim 1, \quad \sigma^* = \frac{\sigma_0}{\Delta} \sim \frac{\sigma_s}{\Omega\tau}$$

i. e., we again obtain the "Bom"* expression for the anomalous plasma resistance [1].

Obviously, the theory is still too rough and in need of a series of refinements; it is, in particular, necessary to take into account the role of electrons in the behavior of the plasma, but qualitatively it describes the experiment in a plasma flow [4].

---

* [in transliteration, the real name could not be ascertained]

5. QUALITATIVE CONSIDERATION OF DEVELOPED TURBULENCE

We have considered the temporal and spatial pattern of instability development. Let us now represent ourselves the qualitative aspect of the pattern of ionization instability developed in a plasma. We shall limit ourselves to the consideration of two-dimensional perturbations in a plane perpendicular to the magnetic field. A developed turbulence must be anticipated for $\Omega\tau \gg 1$. As we have seen, in such a plasma the current flows nearly along the lines of equal concentration, parallelwise to equi!otentials. In its form Eq.(2) suggests a diffusion equation with diffusion coefficient $\sim 1/\Omega\tau$: the potential settles equal along "horizontals" of density relief and diffuses in the depth of hills or hollows. The current then penetrates to a depth $\Delta n/n \sim \sim 1/\sqrt{\Omega\tau}$. Thus, in a nonuniform plasma the current flows along troughs with width. It heats and ionizes them without flowing inside the inhomogeneities. Therefore, "depressions" or "pits" must exist between the troughs. The relation between the electric fields, longitudinal and transverse relative to medium-current remains as earlier

$$\langle E_\perp \rangle \sim \langle E_\parallel \rangle,$$

which leads once more to the "Bom"* anomalous resistance and substantial decrease of average temperature break.

6. EXPERIMENTAL INVESTIGATIONS OF THE PULSE DISCHARGE IN A TRANSVERSE MAGNETIC FIELD

The saturation of the Hall ratio $\langle E_\perp \rangle / \langle E_\parallel \rangle$ for $\Omega\tau > 1$ was observed experimentally more than once in a flow transverse to the magnetic field.[4, 9]. An analogous effect was revealed in the experiment with pulse discharge by one of the authors in cooperation with A. V. Nedospasov [3]. The characteristic resultsof all the experiments is the fluctuation of the electrical potential and the anomalous transverse resistance of the plasma. However, the mechanism of the phenomenon could not be ascertained experimentally. In the following the author pursued the experiment on argon-caesium plasma. An analogous phenomenon of Hall ratio saturation was obtained and similar fluctuations of the potential were observed. In order to ascertain the structure of the plasma photographs of the discharge were taken in the light of recombination emission of caesium atoms. The exposure time was 15 μsec, which is by one order less than the characteristic time of potential oscillations. The mean current density (about 1 a/cm^2) remained constant in the course of 10 milliseconds. The photographs showing the distribution of plasma density are brought out in Fig.1. The exposure's lag time from pulse commencement was about 1 millisecond . It may be seen from the photograph that for $\Omega\tau \sim 1$ the density fluctuations have a rather regular structure and are directed at an angle $\sim \pi/4$ to the current. As the magnetic field varies, the angle changes sign.

---

* [in transliteration]

As $\Omega\tau$ increases, the characteristic dimension of density inhomogeneity decreases, while the structure becomes more chaotic. The topological difference between hot and cold regions is notable. The obtained pattern of plasma density distribution is not in contradiction with the above expounded theory. The detailed study of the structure of inhomogenous plasma is being pursued.

1a

1б

Fig.1. Photograph of a discharge in the transverse magnetic field. The cadre fully encompasses the discharge tube. Located to the left are the sectionalized cathodes, and to the right — the sectionalized anodes. The magnetic field is directed perpendicularly to the plane of the drawing. For details see [3]. 1a—$\Omega\tau \simeq 1$; 1б—$\Omega\tau \simeq 7$.

7. CONCLUSION

Thus, the sufficiently specific assertion can be made that the ionization instability is the number one problem for the utilization of plasma with hot electrons. A large experimental work is required for the determination of realistic methods of ionization stabilization. We have enumerated several possible methods. Assuming they are operational, the possibility of instability will still be imposing hard requirements on flow homogeneity. Moreover, the possibility may not be rejected, though quite regretfully, that we might have to put up with turbulent ionization, just as we submitted to the turbulence of the flow of standard fluids. In this case, the saturation of the Hall ratio and the corresponding rise of turbulent resistance to the current with a magnetic field, would apparently be the principal trait of the turbulence phenomenon.

In conclusion the author extend their thanks to A. A. Vedenov, F. R. Ulinich for useful discussions of theory and experiment and to V. Yeliseyev and V. Belousov for their assistance in conducting the experiment.

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

INSTITUTE OF ATOMIC ENERGY in the name of
I. V. Kurchtov.
Moscow, USSR

REFERENCES

1. E. P. VELIKHOV, Ist Symposium on the MHD-Method of Generation of Electrical Energy (Iyy Simpozium po MGD-metodu generatsii elektroenergii). Newcastle, 1962.

2. E. P. VELIKHOV i A. M. DYKHNE. - Paris Conference on Ionization Events in Gases, 1963.

3. A. V. NEDOSPASOV i I. Ya. SHIPUK, TVT, 4, 17, 1965.

4. J. KLEPIES and R. ROSA, VI-th Symposium on Engineering Problems of Magnetohydrodynamics, Pittsburg, 1965.

5. E. V. YELISEYEV, TVT 2, 852, 1964.

6. J. E. McCUNE, VI=th Symposium on Engineering Problems of Magnetohydrodynamics, Pittsburg, 1965.

7. J. E. McCUNE. II-nd Symposium on the MHD-Method of Generation of Electric Energy, Paris 1964.

8. W. JACKSON, Ist Symposium of Physics of Low-Temparture Plasma (YUPAK, Moscow, 1965.

9. V. S. GOLUBEV, G. A. KASABOV i V. F. KONAKH., TVT, 2, 493, 1964.

10. Yu. A. TARASOV i V. ABRAMOV. Paris Conf. on Ionization Events in Gases, Paris, 1963.

11. Yu. M. VOLKOV, TVT 4, 3, 1965.

VOLT TECHNICAL CORPORATION
1145, 19th ST. NW,
WASHINGTON D. C. 20036.
Telephones: 223-6700
223-4930

Translated by ANDRE L. BRICHANT

ON 4 AND 5 MARCH 1967

Job No.GB-802