SOVIET PHYSICS JETP VOLUME 31, NUMBER 1 JULY, 1970

PLASMA INSTABILITY IN A STRONG ALTERNATING ELECTRIC FIELD

L. I. GRIGOR'EVA, B. I. SMERDOV, K. N. STEPANOV, and V. V. CHECHKIN

Physico-technical Institute, Ukrainian Academy of Sciences, SSR

Submitted July 2, 1969

Zh. Eksp. Teor. Fiz. 58, 45–50 (January, 1970)

The frequency spectrum of the high-frequency small-scale hydrodynamic instability excited in plasma by a large-amplitude fast magnetosonic wave, which was reported previously, has now been obtained. The dependence of the noise amplitude on the wave field strength has been investigated and it was found that the dependence had a threshold.

PLASMA placed in a strong alternating electric field which is perpendicular to an external constant magnetic field is known to be unstable against the excitation of small-scale high-frequency longitudinal oscillations if the relative drift velocity $u_\perp$ of electrons and ions at right-angles to the magnetic field is sufficiently high. Depending on the ratio of $u_\perp$ and the thermal velocities v_{Te} and v_{Ti} of the electrons and ions, different types of oscillation can be excited[1-4]. In particular, hydrodynamic oscillations with a frequency of the order of $\omega_{He}\sqrt{m_e/m_i}$ should be excited if $v_{Ti} \ll u_\perp \lesssim v_{Te}$, where ω_{He} is the electron cyclotron frequency[2]. These oscillations propagate almost at right angles to the resultant magnetic field ($\cos^2\theta \ll 1$) and the growth rate is of the order of the frequency.

In our previous paper[5] we reported the discovery of small-scale high-frequency oscillations in hydrogen plasma traversed by a large-amplitude fast magnetosonic wave. These oscillations were identified with the hydrodynamic current instability noted above.

In this paper we report the results of an investigation of this instability. We have now obtained the noise spectrum and have measured the noise amplitude as a function of the amplitude of the fast magnetosonic wave. It is found that the excitation of small-scale oscillations has a threshold. The observed frequencies and threshold velocities are consistent with the theory of hydrodynamic instability.

A detailed description of the apparatus used in this investigation is given in[6]. The plasma was produced in a pulsed Penning discharge in hydrogen at a pressure of the order of 5×10^{-4} Torr. The internal diameter of the glass discharge tube was 6.6 cm and the distance between the cathodes was 88 cm. The alternating field in the plasma was produced by a coil consisting of eight sections connected in pairs and in antiphase. The coil acted as the inductance of the shock circuit operating at $\Omega/2\pi = 7 \times 10^6$ Hz. The amplitude of the longitudinal magnetic field in the plasma along the axis of the system could reach 500 Oe. The axial wavelength of the fast magnetosonic wave excited in the plasma was determined by the distance between the coil sections and amounted to $\Lambda \approx 20$ cm.

The average density of plasma electrons (over the cross section of the discharge tube) was determined with the aid of a microwave interferometer. The local plasma density was estimated with the aid of a double Langmuir probe with a floating potential and oriented along the constant magnetic field. The same probe was used to determine the electron temperature.

The alternating magnetic field was measured in the plasma by a high-frequency electrostatically screened magnetic probe. The probe was insulated from the plasma by a glass tube 5 mm in diameter. The absolute calibration of the probe was carried out as described in[7].

The electric-field oscillations in the plasma were recorded by a symmetric probe at a floating potential. Contact with the plasma was achieved through two prongs of copper wire 0.3 mm in diameter and 3 mm long, separated by a distance of $l = 2$ mm. To screen them from electrical interference, all the conducting leads were placed in a copper tube which, in turn, was insulated from the plasma by a glass tube of 5 mm outer diameter.

A block diagram of the noise-recording apparatus is shown in Fig. 1. In addition to the probe, the system incorporates a choke, a transformer, a broadband amplifier and a fast oscillograph. The choke was in the form of a section of a coaxial cable wound on a ferrite core. The screen and the central conductor of this cable were connected to the leads of the electric probe at one end and to the primary coil of a center-tapped transformer at the other. In this way, the choke effectively suppressed all undesirable electrical signals which were induced in phase in both prongs of the probe and would be transmitted (in the absence of the choke) through the capacitance between the primary and secondary coils of the transformer. At the same time, the useful signal, which is the difference between the potentials induced in the probe prongs, passes through the choke without hindrance.

The frequency characteristic of the entire system is shown in Fig. 1 under the block diagram. It is clear that in the most interesting frequency region (20–80 MHz) the ratio of output to input voltages U_{out}/U_{in} is not very different from unity. The sensitivity of the entire system is about 0.03–0.05 V.

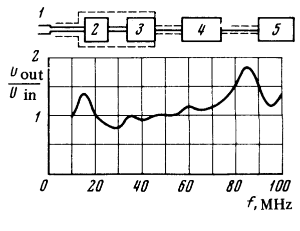

FIG. 1. Block diagram of the noise-recording system and its frequency characteristic. 1 – Electrical probe, 2 – choke, 3 – center-tapped transformer, 4 – broadband amplifier, 5 – fast oscillograph.

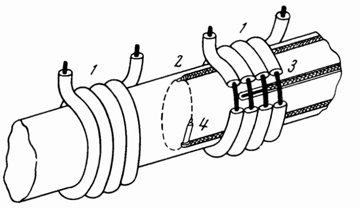

FIG. 2

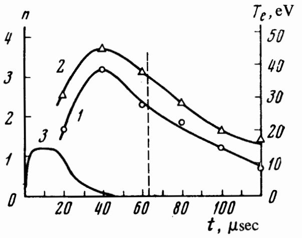

FIG. 3

FIG. 2. Disposition of probes. 1 – Coil sections, 2 – electrical probe, 3 – magnetic probe, 4 – Langmuir probe.

FIG. 3. Plasma density (in units of 10^{12} cm^{-2}) (curve 1) and electron temperature (curve 2) as functions of time. Curve 3 – discharge current (arbitrary units). The dashed line indicates the instant at which the alternating field was switched on.

As noted above, we were interested, in the first instance, in the relation between the amplitude of the observed noise and the strength of the alternating field excited in the plasma. Knowing the strength of this field, it is possible to estimate the drift velocity of the plasma particles at some preselected point, and compare this with the noise amplitude at the same point.

When the oscillations were excited by the azimuthal axially-periodic surface current, as described above, a standing wave with all the six electromagnetic field components appeared in the plasma[8]. The simplest relation between the current density (and, consequently, streaming velocity) and the alternating magnetic field in the plasma occurred under these conditions for the radial current density component. In fact, we have

$$j_r \approx en_0(r)u_r \approx -\frac{c}{4\pi}\frac{\partial H_\varphi}{\partial z}, \tag{1}$$

where n_0 is the undisturbed plasma density. Since the field distribution along the z axis is nearly sinusoidal, we can write $H_\varphi(r, z) = H_{\varphi 0}(r)\sin K_{\|}z$, where $H_{\varphi 0}$ is the maximum value of H_φ, which occurs under the coil section[8], and $K_{\|} = 2\pi/\Lambda$ is the longitudinal wave number. The radial streaming velocity will then assume the

$$u_r(r,z) = \frac{K_{\|}c}{4\pi n_0 e} H_{\varphi 0}(r)\cos K_{\|}z \tag{2}$$

maximum value $u_{r0}(r) = (K_{\|}c/4\pi n_0 e)H_{\varphi 0}(r)$ half-way between two neighboring coil sections.

The azimuthal components of the current density and streaming velocity are proportional to $\sin K_{\|}z$ and are, therefore, zero in this cross section. To estimate the total streaming velocity, which in the above cross section of the plasma column is equal to the radial component, it is sufficient to determine the plasma electron density in the given cross section at a particular radial distance, and the component H_φ of the magnetic field of the wave at the same radial distance in the cross section under the coil section. The streaming velocity obtained in this way is conveniently related to the radial component of the noise electric field in the cross section half-way between the coil sections and at the same radial distance at which the plasma density is measured.

In view of the foregoing, the radially-oriented electric probe was placed half-way between two neighboring sections of the coil. The magnetic probe which was oriented so as to determine H_φ was placed under the coil section at the same radial distance (2.7 cm). The double Langmuir probe was used to determine the plasma density and electron temperature was placed in the same cross section and at the same radial distance as the electrical probe. The disposition of all the probes is shown in Fig. 2.

The constant magnetic field in all the experiments was 940 Oe. The plasma density and electron temperature at the location of the probes varied with time as shown in Fig. 3, and amounted to 2.2×10^{12} cm^{-3} and 34 eV, respectively, when the alternating field was switched-on. This value of the density is in good agreement with microwave interferometer measurements averaged over the cross section, and the density in the axial region obtained from microwave transmission on the assumption that the radial density distribution is triangular. The validity of this assumption for a discharge of this kind was established experimentally in[9]. High-intensity noise with characteristic frequencies of the order of a few tens of MHz was recorded by the electrical probe when an alternating field of sufficiently large amplitude was switched-on. Figure 4 shows a typical oscillogram of such noise together with the oscillogram of the magnetic field H_φ, whose amplitude in the first half-period was 40 Oe. The noise spectrum in the frequency range 20–80 MHz was obtained as a result of computer analysis of oscillograms similar to those shown in Figs. 4 and 5.

The dependence of the noise amplitude on the amplitude of the field H_φ is shown in Fig. 6. It is clear that the noise amplitude decreases monotonically with decreasing H_φ and, consequently, with decreasing streaming velocity. However, at low values of the wave field strength the noise level falls to zero before H_φ. There is, therefore, a threshold value of the streaming veloc-

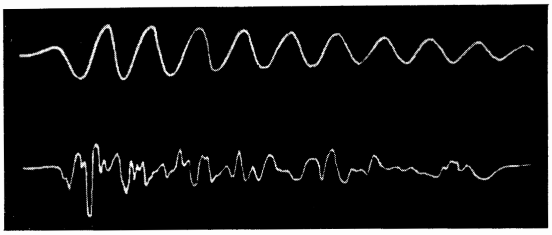

FIG. 4. Oscillograms of plasma noise and the field H_φ at large wave field strengths.

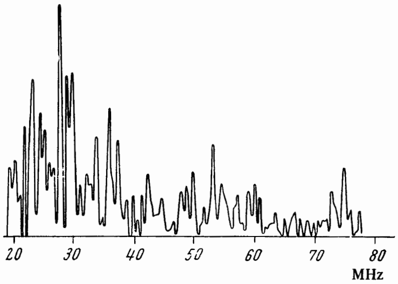

FIG. 5. Noise spectrum at large field strengths.

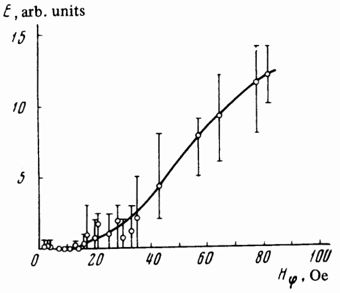

FIG. 6. Noise amplitude as a function of the amplitude of the field H_φ.

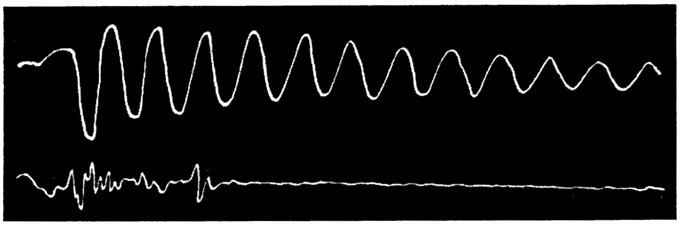

FIG. 7. Oscillograms of noise and the field H_φ in plasma with H_φ just above the threshold value.

ity (corresponding to $H_\varphi \approx 15$ Oe in Fig. 6) above which the instability is observed. Figure 7 shows an oscillogram of the signal from the electrical probe together with the H_φ oscillogram at an H_φ amplitude somewhat greater than the threshold value.

The streaming velocity estimated from Eq. (2) under the conditions of Fig. 7 with $H_\varphi \approx 15$ Oe is 10^7 cm/sec. It is interesting to compare this velocity with other velocities characteristic for plasma. The plasma ion temperature was not measured in the present investigation but we can use the results reported in[10] for a completely analogous discharge, where the ion temperature estimated from the Doppler broadening of the H_β line was approximately 2 eV after 20 μsec following the termination of the current, which corresponded to $v_{Ti} \approx 2 \times 10^6$ cm/sec. The ion sound velocity under the conditions of the experiment was $v_s = \sqrt{T_e/m_i} \approx 6 \times 10^6$ cm/sec.

In conclusion, let us briefly review our results.

When the instability sets in, the noise amplitude $E = -\nabla\varphi$ increases exponentially with time:

$$\varphi = \varphi_0 \exp\left\{\int \gamma\, dt\right\}, \tag{3}$$

where φ_0 is the thermal noise amplitude. In this expression $k_\parallel \approx k_r \cos\theta$ is the axial wave number of the longitudinal oscillations and $\gamma = \operatorname{Im}\omega$ is the growth rate given by the dispersion relation[2]

$$\frac{1}{\omega_{He}^2} - \frac{\cos^2\theta}{\omega^2} - \frac{m_e}{m_i(\omega - k_r u_r)^2} = 0. \tag{4}$$

This equation is valid if $\omega/k_\parallel v_{Te} > 1$. Hence we find that, when all the above conditions are satisfied, the maximum growth rate is $\gamma \sim \omega \sim \sqrt{\omega_{He}\omega_{Hi}} \sim ku$. This corresponds to $\cos^2\theta \sim m_e/m_i$.

Assuming that the electrical probe has maximum sensitivity for oscillations whose wavelength is of the order of twice the distance between the probe prongs, we can write $k_r = \pi/l = 16\ \text{cm}^{-1}$. In accordance with the above theoretical estimates, we then have $\varphi_0 \lesssim 0.01$ V and $\gamma \sim \omega \sim 10^8$–$10^9\ \text{sec}^{-1}$. The observed frequencies and growth rates lie in this range.[1]

Under linear conditions the oscillation potential reaches its maximum value of the order of

$$\varphi_m \sim \varphi_0 \exp\{\eta k_r u_r/\Omega\}, \tag{5}$$

where $\eta \sim 1$. Near the threshold $k_r u_r/\Omega \sim 3$–4, which ensures that the noise amplitude increases above the level of thermal fluctuations by a factor of 10–100, i.e., up to a level exceeding the probe sensitivity. The threshold character of the noise is due to the fast (exponential) dependence of the noise amplitude on the streaming velocity amplitude, i.e. on the amplitude of the fast magnetosonic wave, given by Eq. (5).

We are grateful to A. V. Longinov for valuable discussions and help in the construction and adjustment of the measuring systems, and to V. T. Pilipenko for assistance in the measurements.

[1] V. I. Kurilko and V. I. Miroshnichenko, in: Fizika plazmy i problemy upravlyaemogo termoyadernogo sinteza (Physics of Plasma and the Problem of Controlled Thermonuclear Fusion), Vol. 3, AN UkrSSR, 1963.

[2] K. N. Stepanov, Zh. Tekh. Fiz. 34, 2146 (1964) [Sov. Phys.-Tech. Phys. 9, 1653 (1965)].

[3] M. V. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, L. I. Rudakov, V. A. Skoryupin, and G. V. Sholin, Zh. Eksp. Teor. Fiz. 46, 511 (1964) [Sov. Phys.-JETP 19, 349 (1964)].

[4] V. L. Sizonenko and K. N. Stepanov, Nuclear Fusion 7, 131 (1967).

[5] L. I. Grigor'eva, B. I. Smerdov, K. N. Stepanov, B. A. Fetisov, and V. V. Chechkin, ZhETF Pis. Red. 8, 616 (1968) [JETP Lett. 8, 379 (1968)].

[6] M. P. Vasil'ev, L. I. Grigor'eva, A. V. Longinov, B. I. Smerdov, and V. V. Chechkin, Zh. Eksp. Teor. Fiz. 54, 1646 (1968) [Sov. Phys.-JETP 27, 882 (1968)].

[7] I. G. Brown and V. Shepherd, Plasma Physics 9, 741 (1967).

[8] M. P. Vasil'ev, L. I. Grigor'eva, V. V. Dolgopolov, B. I. Smerdov, K. N. Stepanov and V. V. Chechkin, Zh. Tekh. Fiz. 34, 974 (1964) [Sov. Phys.-Tech. Phys. 9, 755 (1964)].

[9] L. A. Lushin, V. I. Kononenko and A. I. Skibepko, in: Fizika plazmy i problemy upravlyaemogo termoyadernogo sinteza (Physics of Plasma and the Problem of Controlled Thermonuclear Fusion), Vol. 2, AN UkrSSR, 1963.

[10] M. P. Vasil'ev, L. I. Grigor'eva, V. V. Dolgopolov, B. I. Smerdov, K. N. Stepanov, and V. V. Chechkin, Zh. Tekh. Fiz. 34, 984 (1964) [Sov. Phys.-Tech. Phys. 9, 702 (1964)].

[11] V. I. Aref'ev, A. V. Gordeev, and L. I. Rudakov, Plasma Physics and Controlled Nuclear Fusion Research, Conference Proceedings, Novosibirsk, 1–7 August 1968, Vol. II, IAEA, Vienna, 1969, p. 165.

Translated by S. Chomet
6

---

[1] We note that in the above frequency range the azimuthal current density component j_φ can also excite "whistler"-type instabilities [11]. However, the wavelength of these oscillations is $ƛ \sim c/\omega_{pi} \gtrsim 10$ cm, which appreciably exceeds not only the linear dimensions of the probe but also the radius of the plasma cylinder and, therefore, the potential difference between the probe prongs ($l = 2$ mm) due to the "whistler" is negligible. This large-scale instability can be detected with magnetic probes, but we have not carried out such measurements.