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Abstract

Full Text

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STUDIES OF PLASMA IN AN APPARATUS WITH A TRAVELING WAVE

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The apparatus is intended for studying the possibility of confining hydrogen plasma by a high-frequency traveling magnetic field (^{1}) and for investigating the physical phenomena arising in the interaction of plasma with high-frequency fields. The device is a high-frequency three-phase traveling-wave self-oscillator operating at a frequency of 2.5 MHz. The electromagnetic wave propagates along a delay line closed into a ring, with a phase velocity of $5 \cdot 10^7$ cm/sec. The inductive elements of the line embrace a toroidal discharge chamber made of quartz glass, with a major torus diameter of 70 cm and a minor diameter of 8 cm. Along the line there are laid 12 wavelengths. The installed pulse power of the generator tubes is 60 MW. The pulse duration is 300–600 μsec. A specially developed self-oscillator circuit ensures a weak dependence of the high-frequency voltage on the resonant system on the plasma parameters and uniquely fixes the direction of propagation of the traveling wave. The gas is ionized by the electric field of the traveling wave. The amplitude of the magnetic field H_z in this system, in any cross section of the torus, increases from the axis to the periphery, which ensures fulfillment of the conditions for magnetohydrodynamic stability (^{1}). The generator power of 20 MW achieved at the first stage made it possible to carry out studies at a high-frequency field amplitude of up to 350 Oe. The measurements were performed in the range of initial hydrogen pressures $3 \cdot 10^{-3} \div 10^{-1}$ mm Hg, with an ultimate

Fig. 1. Dependence of the azimuthal current I_z on the voltage across the circuit at various initial pressures p_0

Figure 2 and Figure 3: distributions of magnetic field amplitude and phase across the discharge chamber.

Figure 2: Figure 2 and Figure 3: distributions of magnetic field amplitude and phase across the discharge chamber.

vacuum in the chamber of $2 \cdot 10^{-6}$ mm.

The results of the studies make it possible to draw certain conclusions. The interaction of the traveling electromagnetic wave with the plasma is determined by essentially nonlinear effects. In the very first experiments with a traveling wave, a quasi-steady electron flow in the direction of wave propagation was discovered in the plasma ($^{2-4}$). In our apparatus this current I_z was measured at

using a Rogowski belt. Figure 1 shows the measured values of the current I_z in various regimes.

The nonlinearity of the process is manifested not only in the appearance of a directed electron drift. It was found that, at sufficiently high values of the ionization coefficient and of the magnetic-field amplitude, the plasma consumes considerably more power than would be expected from an estimate of the conductivity determined from the electron temperature and the degree of ionization. Measurements with a double Langmuir probe placed at the center of the discharge chamber, where the high-frequency field is small, showed that in all regimes the electron concentration exceeds $1 \cdot 10^{14}$ cm^{-3}, while the electron temperature increases with increasing field amplitude and power supplied to the discharge. At 250 oersted and an initial pressure of $5 \cdot 10^{-3}$ mm, the electron temperature reaches 10 eV and the electron concentration is $1.7 \cdot 10^{14}$ cm^{-3}, which corresponds to an ionization coefficient of 50%. The obtained

Fig. 2. Typical distribution of the magnetic field H_z over the cross section of the discharge chamber. $p_0 = 5 \cdot 10^{-3}$ mm. Crosses—without plasma; circles—with plasma

Fig. 3. Nonmonotonic distribution of the amplitude and phase of the magnetic field H_z over the cross section of the discharge chamber. $p_0 = 10^{-2}$ mm

value of the temperature is confirmed by spectral measurements. In the discharge spectra taken under the same conditions with an ISP-51 spectrograph, a large number of OII and NII lines are present, the excitation potentials of which are 25-30 eV. As the magnetic-field strength increases, the intensity of impurity lines (especially CII 4267 Å) rises rapidly, while the intensity of the hydrogen lines falls. The plasma conductivity at the obtained values of the electron temperature and concentration should be $4 \cdot 10^{14}$ CGSE units. At the same time, the power consumed by the plasma and the amplitude of the magnetic field, measured under the same conditions, correspond to an effective conductivity $\sigma_{\text{eff}} = 2.5 \cdot 10^{13}$ CGSE units. As can be seen, the conductivity values differ by more than an order of magnitude.

The low value of the effective conductivity is confirmed by the observed distribution of the magnetic field H_z in the cross section of the discharge chamber (Fig. 2). The measured depth of field penetration is 0.5–0.6 cm, which also corresponds to an effective conductivity of 2-3 $\cdot 10^{13}$ CGSE units. The non-monotonic character of the amplitude and phase distribution of the field over the chamber cross section (Fig. 3), observed under certain conditions, indicates that phenomena occur in the experiments which differ substantially from the usual picture of high-frequency-field penetration into a conductor.

The discovered effect of anomalously large absorption by the plasma of the energy of a traveling electromagnetic wave and the low value of the effective conductivity opens up the possibility of heating the plasma to high temperatures.

The low value of the effective conductivity can be explained by the magnetization of the plasma associated with the directed drift of the electrons. A rigorous solution of the self-consistent problem of the interaction of the high-frequency field of a traveling wave with the plasma is connected with enormous difficulties. Therefore it is meaningful to give a qualitative consideration of the question, which can be carried out on the basis of Maxwell' s equations and the generalized Ohm' s law, valid within the framework of the magnetohydrodynamic approximation.

It can be shown that the instantaneous values of the density of the azimuthal current j_z and of the high-frequency current j_φ are determined by the relations:

$$j_\varphi = -neV_\varphi \frac{\left(\frac{eH_r}{mc}\tau\right)}{\left(1 + \frac{eH_r}{mc}\tau\right)^2}, \tag{1}$$

$$j_z = -neV_\varphi \frac{\left(\frac{eH_r}{mc}\tau\right)^2}{1 + \left(\frac{eH_r}{mc}\tau\right)^2}, \tag{2}$$

where V_φ is the phase velocity of the wave; H_r is the component of the magnetic field normal to the surface; τ is the time between collisions of an electron with an ion or atom; n is the electron concentration.

Assuming that $H_r = H_{rm} \cos \chi(V_\varphi t - z)$, where χ is the propagation coefficient, after expanding (1) and (2) in a Fourier series one can obtain an expression for the constant component of the azimuthal current

$$j_{z0} = -neV_{\varphi}\left(1 - \frac{1}{\sqrt{1 + \left(\frac{eH_{rm}}{mc}\tau\right)^2}}\right) \tag{3}$$

and for the effective conductivity of the plasma for the first harmonic of the current

$$\sigma_{\text{eff}} = \sigma\frac{2}{\left(\frac{eH_{rm}}{mc}\tau\right)^2}\left(1 - \frac{1}{\sqrt{1 + \left(\frac{eH_{rm}}{mc}\tau\right)^2}}\right), \tag{4}$$

where

$$\sigma = \frac{ne^2}{m}\tau$$

is the ordinary conductivity of the plasma.

When the parameter $\frac{eH_{rm}}{mc}\tau \to 0$, then $\sigma_{\text{eff}} \to \sigma$, and $j_z \to 0$. As this quantity increases, σ_{eff} decreases, and j_z tends to the value

$$j_{z\,\text{max}} = -neV_{\varphi}.$$

This is consistent with the observed increase in the azimuthal current I_z when the initial pressure is decreased (Fig. 1).

From (1) and (2) it is evident that the directed velocity of the electrons cannot exceed V_{φ}. Since under our conditions the phase velocity of the wave is much less than the thermal velocity of the electrons, the constant and high-frequency components of the currents cannot lead to the appearance of kinetic instabilities of the electron component.

A strong increase in the drift current I_z may, generally speaking, lead to the appearance of magnetohydrodynamic instability. However, it can be shown that, under the assumption of an exponential skin layer, the relation

of the constant and high-frequency fields is such that the conditions for magnetohydrodynamic stability are satisfied. Indeed, in all operating regimes of the device the inequality

$$\frac{H_{\equiv}^2}{8\pi} < \frac{H_{\sim}^2}{16\pi}.$$

is fulfilled.

In this case no instabilities of the magnetohydrodynamic type were detected. Instabilities similar to those described in ([3]) were not observed. Nor was any possible "entrainment" of the plasma as a whole by the field of the traveling wave detected. The presence of entrainment was to be established from the Doppler shift of the spectral line by means of an ISP-51 A spectrograph. As a result of repeated experiments on the lines H_α (6565 Å, linear dispersion 11 Å/mm) and CII (4267 Å, linear dispersion 3.5 Å/mm), no line shift is seen. The velocity of entrainment of the plasma, if it exists at all, in any case does not exceed $3.5 \cdot 10^5$ cm/sec, i.e., 1% of V_ϕ.

At present, studies are being carried out on the device at considerably higher power levels (up to 50 MW), with magnetic-field strengths up to 500 oersteds. Effects are being studied that are caused by detachment of the plasma from the chamber walls at the point where, owing to the toroidality, the magnetic-field strength is greatest. This occurs at low initial hydrogen pressures ($2 \cdot 10^{-3}$ mm) and is manifested especially clearly in a discharge in air at a pressure of $5 \cdot 10^{-4}$ mm. The presence of detachment is determined by means of magnetic probes, a microwave interferometer with wavelength 8 mm, and high-speed photographs of the discharge.

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Note: Figure translations are in progress. See original paper for figures.