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Methodological Notes

DEMONSTRATION APPARATUS FOR MICROWAVE PLASMA DIAGNOSTICS

F. Kh. BAĬBULATOV

Novosibirsk State University

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AMONG the presently employed experimental methods of plasma study, a predominent place is occupied by microwave methods based on the interaction between microwaves and plasma, particularly the sounding of a plasma by radio waves. Such sounding makes it possible to obtain comprehensive information on the electronic component of the plasma—the electron density, the frequency of the electron collisions with other particles, etc.[1,2].

In an unbounded plasma, the wave-propagation constant is determined by the complex dielectric constant of the plasma ϵ. If the frequency ν of the collisions between the electrons and other particles is small compared with the frequency ω of the sounded wave ($\nu^2/\omega^2 \ll 1$), then the dispersion equation for ϵ is given by

$$\varepsilon=\varepsilon_r+i\varepsilon_{im}\equiv[1-(\omega_0^2/\omega^2)]+i\,(\omega_0^2\nu/\omega^3),$$

where the "plasma frequency" is $\omega_0^2 = 4\pi ne^2/m$, e and m are the charge and mass of the electron, and n is the electron concentration. The solutions of the wave equation for complex amplitude are proportional to $\exp(i\omega\sqrt{\epsilon_r}x/c)\exp(-\omega\epsilon_{im}x/2c\sqrt{\epsilon_r})$; the first factor determines the phase velocity of wave propagation, and the second the damping of the waves in the plasma along the x direction. By measuring the phase shift of a wave passing through the plasma relative to the phase of a reference wave, and by measuring the attenuation of the transmitted wave, it is possible to calculate the values of n and ν.

For a bounded plasma, the phenomenon remains qualitatively the same, but it is necessary to solve the boundary-value problem. An exhaustive solution of the problem of the plasma waveguide includes a simultaneous solution of the dispersion equation and of the determinantal equation obtained when certain boundary conditions are imposed on the sought field[3].

To demonstrate one of the sounding methods, based on the passage of waves through a plasma waveguide[2], we have developed a simple radio interferometer, which makes it possible to perform both qualitative observations of the interaction between radio waves in the plasma, and quantitative measurements of the electron concentration.

Figure 1 shows an overall view of the radio interferometer, and Fig. 2 shows the construction and the power supply for the discharge tube. The quartz discharge tube has an outside diameter 27 mm and an inside diameter 22 mm. It consists of three parts (1, 2, 3) connected together by epoxy resin through duraluminum waveguide-tubes 4 and 5, which simultaneously serve also as electrodes. The ends of tube 1 are covered with glass windows 6 and 7, mounted at the Brewster angle to eliminate reflection of the radio waves from the windows. The ends 1 and 3 of the tube are inserted in smooth rectangular-to-circular waveguide junctions. These junctions transform the TE_{01} modes in the rectangular waveguide into TE_{11} modes in the round waveguide. Practically the entire length of the central part of tube 2 is placed in a metallic waveguide-jacket 10 made of copper foil. The air is evacuated from the discharge tube by a forevacuum pump through a fitting that is screwed into the electrode 5. The discharge tube is fed through an RC network, making it possible to produce a relaxation discharge of the capacitor with frequency up to 10–15 Hz, by varying the voltage applied frrom the UPU-1m rectifier.

Each capacitor discharge fills the tube section 2 with plasma. The plasma boundaries then diffuse beyond the limits of the electrodes 4 and 5 at the ends 1 and 3, and become smeared out. This feature of the discharge tube, in conjunction with the method of mounting the windows 6 and 7 and the use of junctions 8 and 9, ensures good matching of the volume of the plasma with the receiving and radiating elements of the interferometer, a necessary condition for normal functioning of the interferometer.

After the discharge, the air at the working pressure 0.01–0.1 mm Hg has a large afterglow time and deionization time, so that the next discharge is started under conditions when the gas retains an appreciable electric conductivity due to the preceding discharge. Because of this, the start of the phenomenon stretches out in time, thus facilitating its observation. To obtain oscillograms of the current pulses, a bifilar shunt is provided in the capacitor circuit (see Fig. 2).

Radio waves from a klystron (K-27) proceed through the waveguide (see Fig. 1) to a splitting device[4] and are split into two beams that follow different paths. The first beam passes through a rectangular waveguide an an absorption attenuator, while the second passes through a round waveguide containing the discharge tube. The radio waves of both beams are mixed in a second splitting device and are fed to a detector (DK-I2m), whose output is observed on the screen of an oscilloscope ("Duoskop" or ÉO-58). The optical length of the interferometer arm containing the attenuator remains constant in time. In the second arm of the interferometer, the microscopic parameters and the complex dielectric constant of the plasma vary in time, after each discharge, producing a change in the optical length and in the absorptivity of the plasma column in the waveguide. As a result of wave interference of

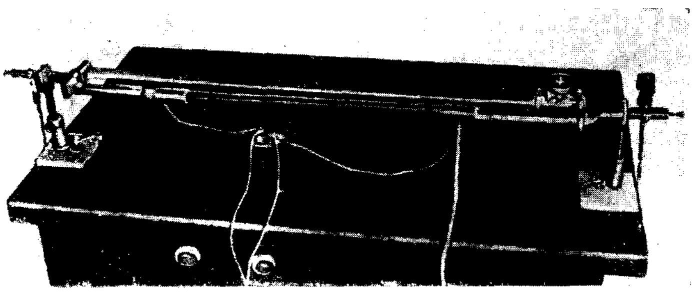

FIG. 1

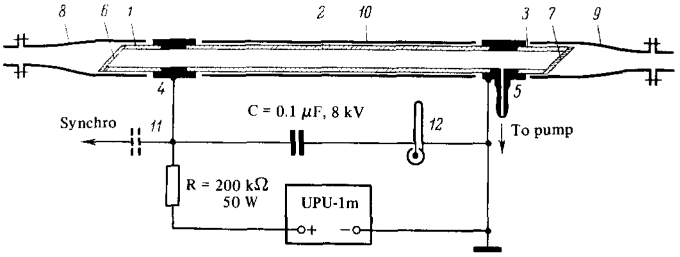

FIG. 2

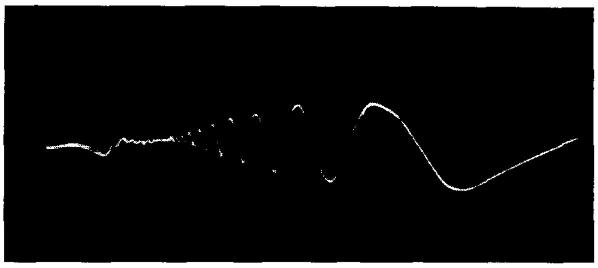

FIG. 3

these two beams—reference and sounding—the detector voltage output amplitude becomes a function of the phase difference and amplitudes of the interfering waves.

Figure 3 shows an interference pattern of the phenomenon. Each period of variation of the signal corresponds to a change in the absolute value of the phase of the sounded wave by 2π. Thus, according to Fig. 3, the total phase advance during the growth of the electron corresponds to approximately $+20\pi$, followed by resonance characterized by a maximum absorption, and a subsequent decay of the plasma, accompanied by a reverse change of the phase by -20π.

When the interferometer is adjusted, the supply voltage is applied to the Klystron (see[4]), a strong coupling is established between the exciting post of the klystron and the waveguide line, and the positions of the short-circuiting plungers of the klystron and of the detector are set for maximum-detector signal. The tube is evacuated to the required pressure and a voltage is applied to the tube electrodes from the UPU-1m rectifier, with a value such that the relaxation frequency of the discharge is about 1 Hz. The oscilloscope, which operates in the driven-sweep mode with triggering from an external signal, is synchronized by applying a voltage from the high-voltage electrode of the tube through a small capacitor. By observing the oscilloscope screen, one regulates the absorption attenuator so as to obtain the sharpest and most reproducible interference pattern. In the case of good tuning, this interference pattern should remain sharp also when the discharge repetition frequency is increased to 10–15 Hz. For example, the interference pattern shown in Fig. 3 was obtained by photographing four or five successive oscillograms on a single frame.

The demonstration is best carried out during the course of evacuation of the discharge tube. In this case it is clearly seen that the amplitude of the interference pattern increases as the gas pressure in the tube is decreased, since the number of neutral particles decreases with increasing vacuum and as a result the electron collision frequency ν decreases. The interference pattern in Fig. 3 shows clearly the dependence of the wave attenuation in the plasma on the constant electric field in the plasma. Thus, an increase of the electron concentration (positive phase advance) occurs in the presence of a large potential difference between the electrodes of the discharge tube, i.e., in the presence of a sufficiently strong longitudinal electric field in the plasma. On the other hand, a decrease of the electron density occurs under conditions when the longitudinal electric field is close to zero. Obviously, the presence of a constant electric field should cause an intensified drift of charged particles, and consequently a large number of collisions of these charged particles both with one another and with the neutrons. Therefore the absorption of the waves by the plasma is very strong during this period, as is confirmed in Fig. 3.

Under the experimental conditions, the maximum absorption of the signal occurs at the so-called resonance, when the concentration of the electrons reaches a value[3]

$$n^* = n_c/(1 + \varepsilon_{dt}),$$

where n_c is the critical concentration of the electrons, corresponding to the condition $\epsilon_r = 0$ for the solid-signal frequency ω, and ϵ_{dt} is the dielectric constant of the material of the discharge tube. Since $\omega = 5.89 \times 10^{10}\ \mathrm{sec}^{-1}$ (the wavelength in free space is 3.2 cm), it follows that $n_c = 1.09 \times 10^{12}\ \mathrm{cm}^{-3}$. Substituting the value $\epsilon_{dt} = 3.8$, we find after calculations that the electron density $n^* = 2.27 \times 10^{11}\ \mathrm{cm}^{-3}$ sets in within 24–25 μsec after the start of the discharge. The total duration of the interference pattern is 110 μsec. By exciting standing waves in the tube with the metallic jacket, but without a plasma, we determined the wavelength in such a complicated waveguide; it turned out to be approximately 3.6 cm. The length of the plasma subtended (at n = 0) 18–19 wavelengths. Since the total phase advance in the experiments with the plasma amounts to about ten periods, corresponding to a "drawing out" of thin wavelengths from the waveguide, it follows that during the period of time close to resonance the phase velocity of the wave in the plasma waveguide is approximately 2.5 times larger than the velocity of light in vacuum.

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