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METHODOLOGICAL NOTES

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On measuring the Debye radius in an unstable gas discharge plasma

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Abstract. **It is shown that at low concentrations of charged particles conditions can be realized in a magnetized unstable-to-drift plasma for which concentration perturbations are comparable to the concentration itself. The electron temperature is then determined by potential fluctuations, and the drift oscillation wavelength is of the order of the Debye length.**

The Debye radius is an important characteristic of any plasma. It represents the minimal size of the ionization region, starting with which gas can conditionally be considered as a quasi-neutral plasma. The Debye radius is determined from the condition that the thermal kinetic energy of charged particles is equal to the potential energy of their interaction when the charges are completely separated in the region in question.

In an anisothermic gas discharge plasma the Debye radius is

$$r_{\mathrm{D}} = \left(\frac{\varepsilon_0 k T_{\mathrm{e}}}{e^2 n_0}\right)^{1/2} = 6.9\left(\frac{T_{\mathrm{e}}}{n_0}\right)^{1/2}, \tag{1}$$

where k is the Boltzmann constant, T_{e} is the electron temperature, n_0 is the charged particle number density, and e is the electron charge. With formula (1) the Debye radius can be calculated using the measured electron temperature and plasma density.

The question is whether a direct experimental determination of the Debye radius is possible? The answer is that it can be measured directly in an unstable plasma with potential drift waves (see, for example, Refs [1, 2]).

In the laboratory the drift waves are generated and studied with an apparatus in the form of an elongated cylinder, the length of which exceeds its diameter by one or two orders in magnitude. The magnetic field is produced by coaxial coils and is parallel to the axis of the cylinder. Figure 1 shows a typical experimental installation used to measure oscillations of gas discharged plasma in a magnetic field.

To study an unstable plasma with potential drift waves we shall lean upon the Poisson equation

$$\nabla^2 \varphi = \frac{1}{\varepsilon_0}\, e\Delta n\,, \tag{2}$$

where φ is the electric potential. Equation (2) establishes a relationship between the fluctuations of density and potential

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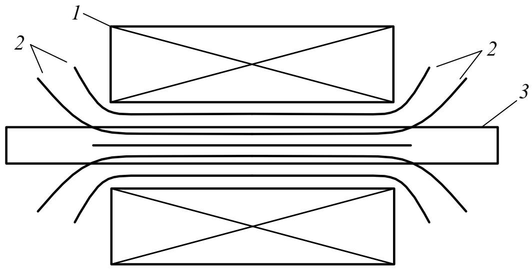

Figure 1. Experimental installation: *1* — solenoid; *2* — magnetic field lines; *3* — discharge tube.

in the wave:

$$\varphi_1 = \frac{1}{\varepsilon_0}\frac{e\Delta n_1}{K^2}\,. \tag{3}$$

Here φ_1 is the potential fluctuation, $K = 2\pi/\lambda$ is the wave number, and $\Delta n_1 = n_{1\mathrm{e}} - n_{1\mathrm{i}}$, where $n_{1\mathrm{e}}$ and $n_{1\mathrm{i}}$ are the electron and ion density fluctuations, respectively. Formula (3) relates the potential fluctuation φ_1 to the discharge perturbation Δn_1 in the wave. The fluctuations for the non-quasi-neutrality Δn_1 and electric charge $e\Delta n_1$ in the wave can be calculated by measuring the value of φ_1 in the unstable plasma. In this case the wavelength can be easily established experimentally [1, 2].

Figure 2 shows the experimental dependence of φ_1 on the plasma number density n_0 (it was obtained using an electric

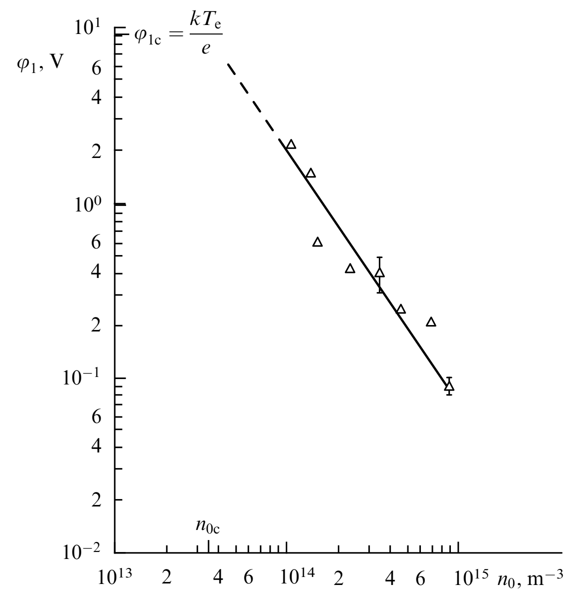

Figure 2. Dependence of the potential fluctuation φ_1 on the plasma number density n_0.

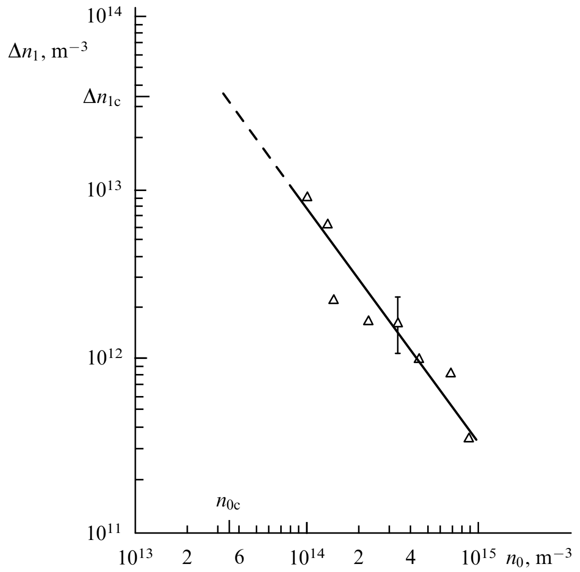

Figure 3. Dependence of the density perturbation for charged particles Δn_1 on the plasma density n_0.

probe). Figure 3 presents the dependence of Δn_1 on n_0, which was calculated by means of formula (3). As evident from their respective plots, both the quantities φ_1 and Δn_1 increase with decreasing n_0. The charge disturbances in drift waves continue to grow to the point where Δn_1 becomes equal to n_0. As is seen from Fig. 3, the equality $n_0 = \Delta n_1$ occurs at a critical number density $n_{0c} = n_0$. For $\Delta n_1 = \Delta n_{1c}$, the charges experience the maximum disturbance in the waves.

For $n_0 = n_{0c}$, the potential fluctuation ends up as

$$\varphi_{1c} = \frac{kT_e}{e} \,. \tag{4}$$

The value $\varphi_1 = \varphi_{1c}$ constitutes the greatest possible value for the potential fluctuations and depends on the electron temperature. In measuring φ_{1c} for $n_{0c} = \Delta n_{1c}$, we measure the electron temperature T_e. The temperature T_e, thus determined, coincides within the scatter of the measurement with the temperature found by other methods, for example, with the use of Langmuir probes [3] or by microwave diagnostics [4].

Notice that it is not an unexpected result that condition (4) is met in the case of the drift-dissipative instability because in the drift waves electrons are distributed according to the Boltzmann law

$$\frac{e\varphi_{1c}}{kT_e} = \frac{\Delta n_{1c}}{n_{0c}} \,. \tag{5}$$

The drift waves with frequencies much less than the rate of collisions between electrons and neutral particles owe their existence to this very electron distribution. In this case the mean macroscopic electron velocity is zero and the friction vanishes along with it [5].

For $n_0 = n_{0c}$, the charges are completely separated in oscillations over the wavelength provided that $\Delta n_{1c} = n_{0c}$. Substituting (4) into (3) yields an expression for the oscillation wavelength

$$\lambda = 2\pi \left(\frac{\varepsilon_0 k T_e}{e^2 n_{0c}} \right)^{1/2} . \tag{6}$$

This quantity has meaning of the Debye radius but exceeds 2π times the value of r_D computed from (1).

Thus, the experimentally found potential fluctuations in a magnetized plasma with drift instability enable us to determine the oscillation nonquasi-neutrality and electric charge fluctuations in a wave. The electron temperature can be determined directly from the potential fluctuations when the charged particles have a low number density and the density disturbance approaches the unperturbed density. In this case the drift oscillation wavelength has the same order of magnitude as the Debye radius, and thus the Debye radius can be measured by a direct experiment.

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