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Conductivity of capacitive radiofrequency discharge, placed in a radial magnetic field

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The work examines the transport of electrons between the electrodes in a capacitive radio -frequency discharge, ignited in the plasma source having the geometry of a stationary plasma thruster. Comparisons of the discharge impedance, determined on the basis of experimental volt-ampere characteristics, with calculations made in the assumption of the applicability of classical conductivity across the magnetic field, showed a significant divergence of the results.

Keywords: capacitive, radio-frequency, discharge, magnetic field, impedance.

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A stationary plasma thruster (SPT) is currently one of the most widely used types of electric jet engines. Its key advantages are the simplicity of design and performance reliability. The operation of such thrusters relies on a DC discharge (DCD) in a magnetic field with a dominant radial component. In parallel with the practical application of SPTs, fundamental research into this DCD is ongoing in laboratories around the world. The determination of cathode–anode current transport mechanism, which cannot be characterized with the use of the classical mechanism of plasma conductivity across a magnetic field, remains a relevant topic in discharge physics. Models of near-wall conductivity and models examining the excitation of oscillations and waves in a discharge at various frequencies (from 10 kHz to 1 GHz) [1] are used at present to characterize the anomalous electron transport in a discharge.

An SPT operating based on a capacitive radio-frequency discharge (CRFD) has been discussed in [2]. The presence of near-electrode potential sheaths in a CRFD (similar to those in a DCD) made this design feasible. Instead of a constant voltage, radio-frequency (from 2 to 13.56 MHz) voltage was applied to an anode (the electrode under load) in order to produce a CRFD in a plasma source with the SPT geometry. The SPT body served as the second (grounded) electrode. A cathode was not used. The data obtained in studies into this discharge were published in, e.g., [2], where the dependences of integral and local plasma characteristics on external parameters were presented. Specifically, it was found in measurements that a CRFD provides an opportunity to produce flows of accelerated ions of inert gases and air with an energy of $70-400$ eV (depending on the discharge circuit). These results may help optimize the discharge and construct an efficient spacecraft engine. However, the fundamental issue of electron conductivity across a magnetic field in a device based on a radio-frequency (RF) discharge has not been examined yet. The present study is focused on analyzing the applicability of the classical conductivity model to electron transport in a CRFD in an external magnetic field with a dominant radial component.

Volt–ampere discharge characteristics $I_{\mathrm{RF}}(V_{\mathrm{RF}})$ and phase shift $d\varphi(V_{\mathrm{RF}})$ between RF current and RF voltage were measured in order to examine the electron transport between CRFD electrodes. A plasma source with the geometry of an SPT-70 engine was used in these experiments. The data obtained with electrodes (across which the RF voltage is applied) being closed-loop in DC were used. The electrode under load was grounded through a choke (a coil with a high inductance of $150\,\mu$H) for this purpose. Positive or negative bias V_{dc} was applied to the electrode under load in certain experiments.

The measured values of $I_{\mathrm{RF}}(V_{\mathrm{RF}})$ and $d\varphi(V_{\mathrm{RF}})$ were used to calculate the real and imaginary parts of impedance of the discharge gap. The obtained results were compared to the impedance calculated within the classical model of plasma conductivity in a transverse magnetic field.

The equivalent CRFD circuit presented in Fig. 1 was used to calculate the discharge impedance numerically. The discharge circuit incorporates capacitances C_{sh1} and C_{sh2} of near-electrode layers; resistance R_p, which specifies the resistance of a discharge with an azimuthal electron drift; and reactive component C_p, which is induced by the imaginary part of plasma conductivity. In the case of closed-loop electrodes in DC, a choke, which is represented as inductance $L = 150\,\mu$H, was connected in parallel to the discharge gap. The presence of parasitic capacitances, which are represented as C_2 and C_4, was also taken into account.

Discharge impedance Z was calculated using the formulae for the impedance of the plasma part of a one-dimensional plasma capacitor with small length d_c [3]:

$$Z_p(\omega) = R_p(\omega) + i\frac{1}{\omega C_p(\omega)},$$

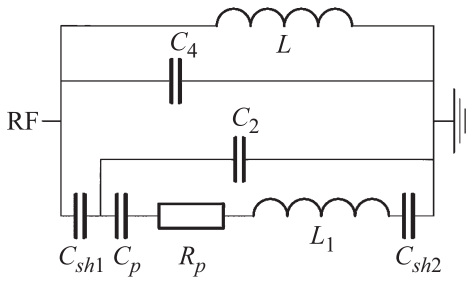

Figure 1. Equivalent circuit of a CRFD with an external radial magnetic field.

$$R_p = \frac{1}{\omega C_0} d_c^{-1} \int_0^{d_c} \frac{\varepsilon''_{zz} dz}{(\varepsilon'_{zz})^2 + (\varepsilon''_{zz})^2},$$

$$\frac{1}{C_p(\omega)} = \frac{1}{C_0} d_c^{-1} \int_0^{d_c} \frac{\varepsilon'_{zz} dz}{(\varepsilon'_{zz})^2 + (\varepsilon''_{zz})^2},$$

where $C_0 = \frac{S}{4\pi d_c}$, ε'_{zz}, ε''_{zz} — are the real and imaginary parts of permittivity, and $S = \frac{\pi d^2_{outer}}{4} - \frac{\pi d^2_{inner}}{4}$ is the cross-section area of the volume enclosed between coaxial cylinders with diameters d_{outer} and d_{inner}.

These formulae are applicable under the assumption that the conductivity of plasma along magnetic lines of force is infinite.

The permittivity was presented in the following form:

$$\varepsilon'_\perp = 1 - \frac{\omega^2_{Le}}{\omega^2 - \Omega^2_e},$$

$$\varepsilon''_\perp = \frac{\omega^2_{Le}(\omega^2 + \Omega^2_e)\nu_e}{\omega(\omega^2 - \Omega^2_e)^2},$$

where ω_{Le}, Ω_e, and ω are Langmuir, Larmor, and operating frequencies and ν_e is the collision rate.

Figure 2 shows the dependences of the real part of impedance (Re) on DC current I_{dc} flowing in the circuit between the electrodes. It was assumed that current I_{dc} is proportional to the plasma concentration. It can be seen that the dependence of the real part of impedance on the DC current flowing in the external discharge circuit (plasma concentration) saturates with increasing I_{dc} if $V_{dc} = 0$. With a negative bias applied to the electrode under load, the domain of currents I_{dc} contracts from above, and no saturation of the $\mathrm{Re}(I_{dc})$ dependence is seen. In contrast, the $\mathrm{Re}(I_{dc})$ dependence becomes non-monotonic when a positive bias is applied to the electrode under load, and its maximum shifts toward lower values of current I_{dc}. Specifically, the real part reaches its maximum at 0.3–0.4 A in the discharge regime with 100 V applied to the electrode under load. With V_{dc} increasing to 200 V, the curve shifts to the left, and the maximum is reached at 0.25–0.3 A. At $V_{dc} = 300$ V, the maximum apparently lies outside of the examined I_{dc} region.

Examining the frequency dependence of the real part of impedance at $V_{dc} = 0$ V (Fig. 2, *b*), one may note that the saturation region lies outside of the discharge current range at all the examined frequencies. However, the assumed position of the maximum shifts with frequency. Specifically, the maximum of the real part of impedance at a frequency of 13.56 MHz lies in the region of high discharge currents (on the right). This maximum shifts toward weaker DC currents I_{dc} (i.e., lower plasma concentrations) as the frequency decreases. The absolute value of resistance, which reached a maximum on the order of 1000 Ω at a frequency of 2 MHz, increases in the process.

The most intriguing results were obtained when the variation of $\mathrm{Re}(I_{dc})$ with the external magnetic field density was examined. It was found (curves *2* and *3* in Fig. 2, *a*) that the magnetic field density has almost no effect on the real and imaginary parts of discharge impedance at all the examined frequencies.

Mathematically calculated dependences of the real part of impedance on the plasma concentration corresponding

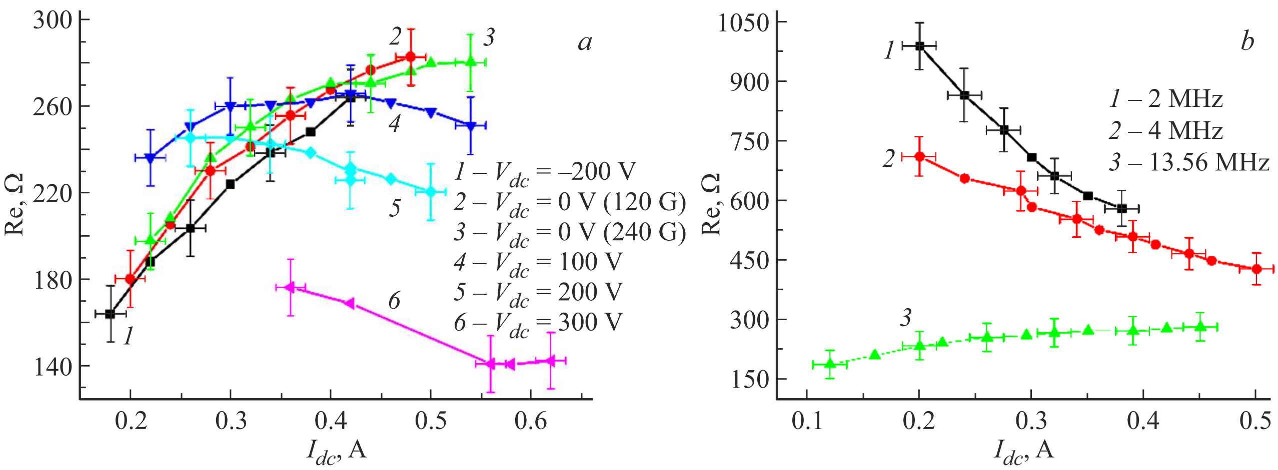

Figure 2. Dependences of the real part of impedance on I_{dc} corresponding to different constant voltages (*a*) and RF generator frequencies (*b*).

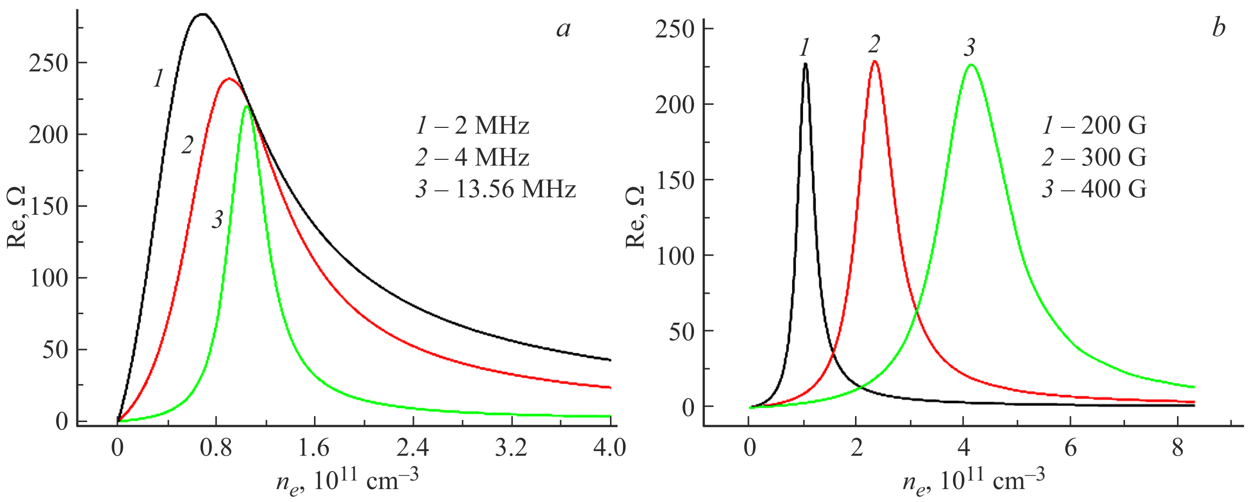

Figure 3. Calculated dependences of the real part of impedance on the plasma concentration corresponding to different RF generator frequencies (*a*) and magnetic field densities at a frequency of 13.56 MHz (*b*). $C_{sh1} = 20$ pF, $C_{sh2} = 1000$ pF, $C_2 = 20$ pF, $C_4 = 40$ pF, $B = 200-400$ G, $P = 10^{-3}$ Torr.

to different RF generator frequencies and magnetic field densities are shown in Fig. 3. It may be noted that the curves are non-monotonic; the same is true for experimental data. When the frequency increases, the real part of impedance decreases and the peak shifts toward higher concentrations (Fig. 3, *a*).

The capacitance values and the magnetic field density also affect the position of the maximum and its width. Specifically, the peak shifts toward higher concentrations and broadens (see Fig. 3, *b*) as the magnetic field density grows.

Having compared the experimental and calculated data, one may conclude that the classical conductivity model provides only a partial qualitative description of the variation of impedance. Specifically, the frequency dependence provides an explanation for the shift of the maximum of the real part of impedance toward lower concentrations. The model also indicates that the absolute values of impedance increase at lower frequencies. However, the classical conductivity model implies that variations of the magnetic field should induce a strong shift of the impedance maxima, which is not observed in actual experiments. This suggests that, just as in a DCD, classical conductivity does not provide a correct description of the interelectrode electron transport in the examined discharge.

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Conflict of interest

The authors declare that they have no conflict of interest.

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