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Plasma Parameters in a Dual-Camera Low-Power Inductive RF Discharge with an External Magnetic Field

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Abstract—The results from studying a dual-camera inductive radio-frequency (RF) discharge that was placed in an external magnetic field are presented. The operating conditions were as follows: an argon pressure of 5×10^{-5}–6×10^{-2} Torr, an external magnetic field strength of 0–60 G, and an RF generator power supply of 25–300 W. During the experiment the resonant RF power consumption and the correspondence between the local power-consumption maxima and spatial maxima of the plasma concentration as a function of the external magnetic field were observed. The comparison of the experimental results with the results of the mathematical simulation indicates that the resonant character of the discharge is associated with the excitation of helicons and Trivelpiece–Gould waves.

Keywords: plasma, helicon, Trivelpiece–Gould wave, inductive, RF.

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INTRODUCTION

At present in the literature [1–7] much attention is paid to studying inductive RF discharge that is placed in an external magnetic field. The great interest in studying this discharge is caused, first, by the possibility of obtaining dense plasma at low power inputs, which is needed in a large number of practical applications, and, secondly, the variety of physical processes that occur in the discharge. The first experimental work that demonstrated a resonant increase in the plasma density in an inductive discharge in the presence of an external magnetic field was published by R.W. Boswell [1] in 1970. By studying the structure and propagation of waves in plasma in the frequency range of 7–10 MHz, R.W. Boswell et al. [8–11] managed to obtain plasma with a concentration on the order of 10^{13} cm^{-3} on the axis of a source with a diameter of 10 cm at a RF power not exceeding 1 kW. The magnetic field was on the order of 1 kG. The high plasma concentration that was obtained at relatively low RF powers stimulated the problem of the mechanism of the RF power consumption by plasma. The search for the solution to this problem is ongoing. A considerable contribution to the theoretical analysis of the problem was made by F.F. Chen [2]. He showed that running waves—helicons can be excited in plasma. F.F. Chen assumed [2] that as a result of the wave–particle interaction a group resonant electrons arises in plasma, whose speed is close to the phase speed of waves. In plasma sources with sizes that are typical of experiments the speed of resonant electrons is higher than the average thermal speed. This increases the efficiency of the ionization of atoms and decreases the energy inputs on the formation of an electron–ion pair, which makes it possible to explain Boswell's experimental data.

The work of F.F. Chen [2] and the mechanism of the RF power consumption that was proposed in it served as an impetus for many experimental works [12] that were devoted to the search for fast electrons in helicon plasma. The results can be separated in two groups. The authors of the first group of works confirmed the hypothesis of the generation of fast electrons in helicon plasma on the basis of direct or indirect data [12–19]. The authors of the second group of works [20–22] did not find differences between the energy distribution of electrons and the Maxwellian distribution function. It should be noted that the second group of works is distinguished by thorough preparation of the experiments and allowances for many factors that could lead to systematic errors in the experimental techniques of the works of the first group. In [21] F.F. Chen stated that the mechanism of the consumption of helicon waves that he proposed had not been confirmed experimentally and he considered that the causal link between fast electrons that was found in [22] and helicon waves was not proven. Nevertheless, works on the search for the group of fast electrons and the discussion of their role in the RF power absorption by helicon plasma are continuing [23, 24].

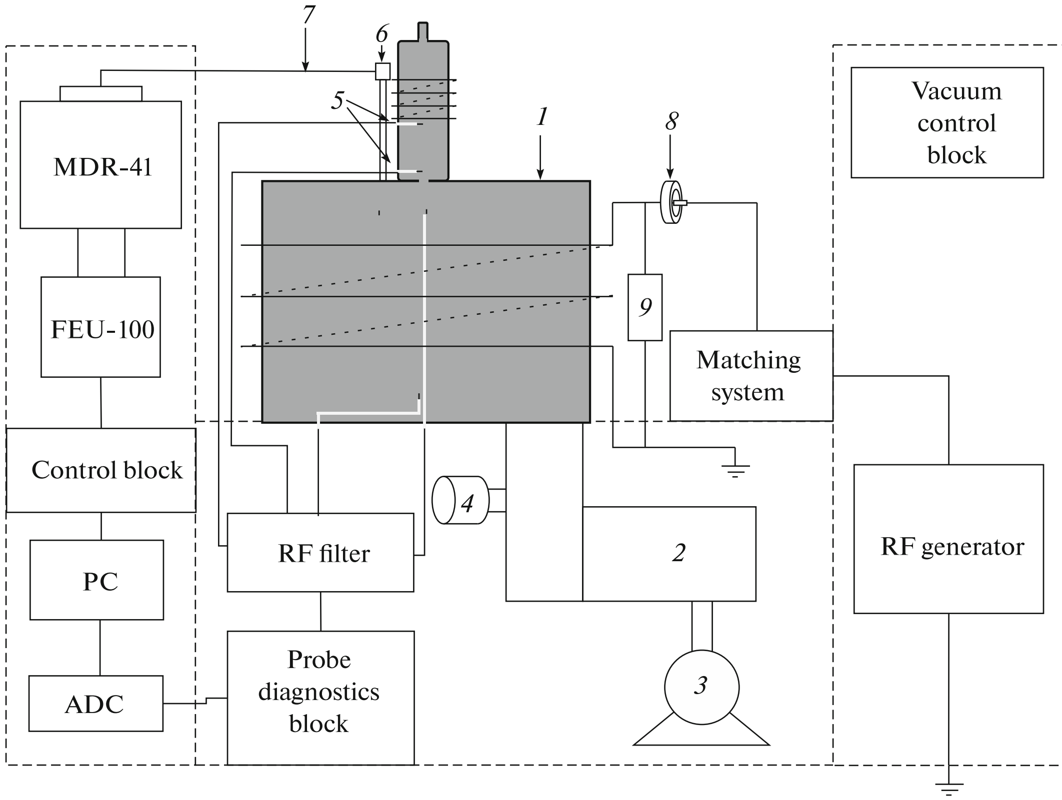

Fig. 1. The scheme of the experimental device: *1*, vacuum chamber; *2*, turbomolecular pump; *3*, rough vacuum pump; *4*, WRG-S-NW25 S/S broadband transducer of pressure measurement; *5*, Langmuir probes; *6*, a line with holes for the fixation of the optical waveguide; *7*, optical waveguide; *8*, Rogowski coil; *9*, capacitive divider.

A fundamentally different approach to the problem of the RF power consumption by helicon plasma was proposed in the mid-1990s in [7, 25, 26]. It was shown that in limited plasma sources two interconnected waves are excited, namely, helicons and Trivelpiece–Gould waves. The numerical calculations [27] made it possible to separate three regions of the existence of the discharge at low pressures that differing in the character of the excited waves. At low electron concentrations (as a rule, less than 10^{10} cm^{-3}) the RF fields of a Trivelpiece–Gould wave penetrate the plasma volume, while the helicon is a surface wave. When the plasma density increases, the RF fields of both waves penetrate inside the plasma. In the first and second cases the RF power consumption by the plasma discharge is determined by the collisionless dissipation of the energy of the Trivelpiece–Gould wave. Finally, at high plasma concentrations that are higher than 10^{12} cm^{-3}, when electron–ion collisions are included, the Trivelpiece–Gould wave becomes a surface wave, while the helicon RF fields penetrate in the plasma volume. In the latter case the role of Trivelpiece–Gould waves in the plasma absorption decreases.

The majority of the research that is reported in the literature corresponds to high values of the RF power and external magnetic field induction, at which the role of Trivelpiece–Gould waves is decreased [2, 17, 28–31]. However, the solution of a series of practical problems on the elaboration of technological plasma sources requires discharge at relatively low values of the RF power and the magnetic field induction. In this region of parameters the properties of an inductive RF discharge that is placed in an external magnetic field have been studied far from completely.

With respect to the above, in this work the efficiency of the RF power consumption and the spatial distribution of the plasma concentration in the dual-camera plasma source in the region of low values of the RF power of the generator and magnetic fields of 0–60 G were studied experimentally. The construction of the dual-camera plasma source was chosen close to that used in [32–37] in experiments with higher values of RF power and external magnetic-field induction.

1. EXPERIMENTAL DEVICE

The scheme of the experimental device is shown in Fig. 1. The device was described in detail in [38, 39]. The inductive RF discharge was ignited in a plasma source consisting of two cylindrical chambers of different diameters. The upper part of the plasma source, which was made of glass, had a diameter of 8 cm and a height of 25 cm. The lower part of the source, which was made of quartz, had a diameter of 46 cm and a height of 30 cm.

The RF power was input using a helical antenna, which was placed on the lateral surface of the upper part of the plasma source at a distance of 12–16 cm from its upper butt-end. The antenna ends were connected to the output of the automated matching system, which in turn was switched to an AE Cesar 1310 RF generator with a working frequency of 13.56 MHz and an output power of 0–1000 W. A Rogowski coil was used for measurement of the current in the antenna.

Two electromagnets that made it possible to create a homogeneous within 7% magnetic field with an induction of 0–6 mT in the lower chamber were placed in the upper and lower parts of the vacuum chamber.

2. MEASUREMENT TECHNIQUES

2.1. The Technique of the Measurement of the Equivalent Resistance

The method that was described in detail in [40] was used for the measurement of the actual RF power that is absorbed by the plasma.

The determination of P_{pl}, viz., the power that is absorbed by plasma, was based on the formula that relates the RF power of the generator, P_{Gen}, to the current in the antenna, I, the active resistance of the external circuit, R_{ant}, and the equivalent plasma resistance, R_{pl}

$$P_{\mathrm{Gen}} = \frac{1}{2}(R_{\mathrm{ant}} + R_{\mathrm{pl}})I^2.$$

During the experiments the active resistance of the external circuit was determined first according to the formula:

$$R_{\mathrm{ant}} = 2P_{\mathrm{Gen}}/I_o^2,$$

where P_{Gen} is the power of the RF generator input in the external circuit and I_o is the current through the antenna without the discharge. The values of the antenna current were then measured at definite conditions of the experiments and the P_{pl} values were calculated according to the formula:

$$P_{\mathrm{pl}} = (P_{\mathrm{Gen}}/I^2 - \frac{1}{2}R_{\mathrm{ant}})I^2.$$

The Rogowski coil was used to measure the current, I, through the antenna. The construction features of the Rogowski coil used in this work were as follows: the teflon ring with the size (D32xd17xH8) with winding of 50 turns of the copper wing with the diameter of 0.3 mm with a "reverse ring" located parallel to the measured current for the compensation of the magnetic flux. In order to decrease the capacitive coupling with external circuits this construction is placed in a copper frame. The resistance ($R = 12\ \Omega$) that loads the copper wire is selected with allowance for the fulfillment the inequality:

$$r + R \ll L\omega,$$

where r, L is the resistance and inductance of winding and ω is the frequency. The voltage that is generated at the output of the Rogowski coil is proportional to the amplitude of the RF current.

2.2. The Technique of the Probe Measurements

To control plasma parameters, the measurements were performed using Langmuir probes. The probes were a glass-coated tungsten wire with a diameter of 0.3 mm that were free from the glass on the end at a distance of 5 mm. Two probes were welded in the lateral surface of the upper part of the plasma source. Two more probes were installed at different heights over the axis in the lower part of the plasma source. Langmuir probes were placed on the axis of the plasma source at distances of 8, 18, 36 and 53 cm from the upper butt-end of the plasma source, respectively. The reference probe for the performance of the probe measurements was near the upper butt-end of the plasma source.

The standard technique of measurements was used in probe measurements [41, 42]. To suppress the RF components of the probe current from distorting the measured curve, resonance filters were used that had high resistance at the first and second harmonics of the working frequency. Signals that are proportional to the probe current and the difference of the potentials between the probe and the reference electrode came to the input of the ADC that was built into the computer.

It is known that the presence of the external magnetic field can lead to the distortion of the probe characteristics. However in this work during probe measurements we used magnetic fields of less than 6 mT. At such fields the Larmor radius is much larger than the Debye radius, which made it possible to use the standard technique of processing the results of the experiments.

2.3. The Technique of the Spectral Measurements

To measure the intensity of the plasma luminescence, its radiation using the optical waveguide was directed to the input slit of a MDR-23 monochromator, whose input- and output-slit width was 50 μm. A FEU-100 photoelectron multiplier was installed at the output of the monochromator. The signal from the output of the photomultiplier was detected using an ADC plate that was built into the computer. The spectrum was scanned in the range of 4000–6000 Å.

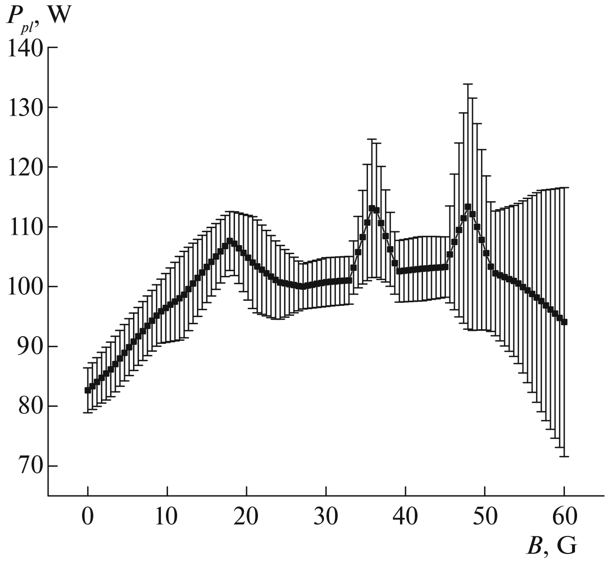

Fig. 2. The dependence of the input power on the magnetic field value. The power of the RF generator was 150 W; the argon pressure was 2.7×10^{-4} Torr.

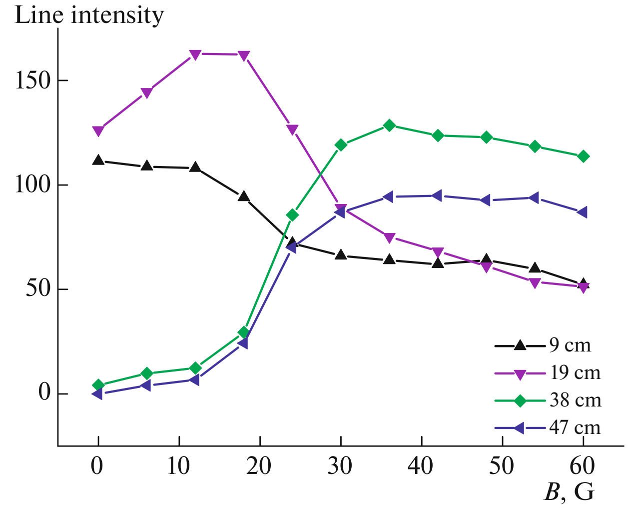

Fig. 3. The dependence of the intensity of the argon plasma luminescence ($\lambda = 4200$ Å) measured at different distances from the butt-end of the upper chamber on the value of the external magnetic field. The power of the RF generator was 150 W; the argon pressure was 2.5×10^{-4} Torr.

The intensity of the plasma luminescence that was measured directly in our version of the experiment is determined by the expression:

$$I(z) = C\int n_e(r,z)\, n_0 \int f(\varepsilon, r, z)\, q(\varepsilon)\sqrt{\varepsilon}\, d\varepsilon\, dr, \qquad (1)$$

where the integration over r corresponds to the fact that we measure the intensity averaged over the line of sight (in this case over the radius of the plasma source). It follows from (1) that under the condition of the constancy of the concentration of atoms and the energy distribution of electrons in the volume of the plasma source the axial dependence of the intensity of the plasma luminescence is the axial dependence of the plasma density averaged over the source radius.

3. RESULTS

As noted above, the aim of this work was to study the parameters of the inductive RF plasma source at low values of the input RF power, when the main contribution to its absorption is provided by the Trivelpiece–Gould wave that is excited in spatially limited plasma sources simultaneously with the helicon. It is known that the RF discharge that is excited by the inductor is ignited in the capacitive mode; then, with an increase in the RF generator power, it transfers to the inductive mode. The estimate from below the value of the generator power P_{Gen}, at which the inductive mode of the RF discharge occurs, the dependence of the intensity of the plasma luminescence on P_{Gen} was measured. The measurements showed that the RF discharge transfers in the inductive mode at P_{Gen} values > 80 BT. In this respect in this work all of the measurements were performed at RF generator powers that exceeded 100 W.

Figure 2 shows the dependence of the RF power input in plasma on the value of the external magnetic field. Measurements showed that the function $P_{pl}(B)$ is nonmonotonic and has a strongly expressed resonance character that leads to excitation under the conditions of experiments on helicons and Trivelpiece–Gould waves.

Experiments that were performed at an argon pressure below 1 mTorr and P_{Gen} > 100 W showed that the application of the external magnetic field leads to considerable changes of the discharge length. In the absence of the magnetic field the discharge is concentrated in the upper gas-discharge chamber. With the increase in the magnetic field induction the discharge begins to penetrate the lower part of the plasma source, the length of the intensely glowing part of the discharge in the lower chamber starts to increase, and, finally, at $B > 20$ G the discharge is closed on the lower flange forming an extended plasma column. The diameter of the plasma column is approximately equal to the diameter of the upper part of the plasma source. This is illustrated in Fig. 3, where the dependence of the intensity of the luminescence of the argon plasma line ($\lambda = 4200$ Å) measured at different distances from the butt-end surface of the upper part of the plasma source on the external magnetic field induction is shown. It can be seen that at $B < 20$ G the intensity of the plasma luminescence at the upper part of the plasma source ($z < 25$ cm) considerably exceeds the same characteristic for the lower part of the plasma source ($z > 25$ cm). It is necessary to note that at

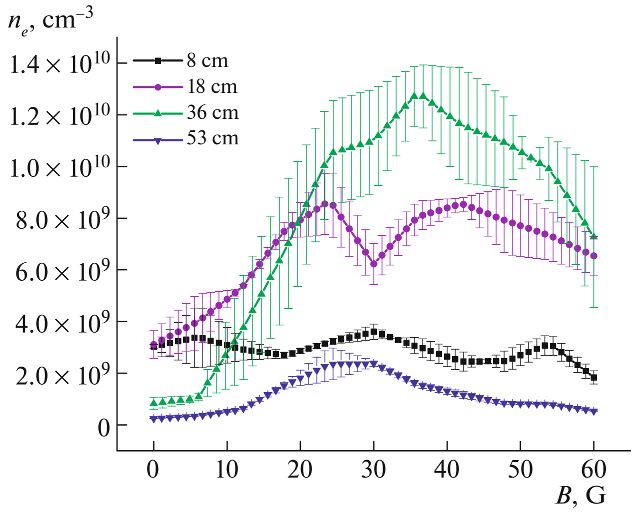

Fig. 4. Distribution of the plasma concentration as a function of the external magnetic field value. The power of the RF generator was 150 W; the argon pressure was 2.7×10^{-4} Torr.

$B > 30$ G the intensity of the discharge luminescence in the lower part of the source is nearly two times higher than that at $z < 25$ cm.

Figure 4 shows the distributions of the concentration of electrons measured on the axis of the plasma source at different distances from the upper butt-end of the source as a function of the external magnetic field value. It can be seen that the results that were obtained by the probe method coincide qualitatively with the results of the measurements of the intensity of the plasma luminescence. At a magnetic field induction of 10 G the highest values of the electron concentration are observed in the upper part of the plasma source; however, at magnetic fields higher than 20 G, when the discharge is closed on the lower flange, the electron concentration in the lower part of the plasma source becomes considerably higher than that in the upper part. In all of the considered points on the axis of the plasma source the dependence of the electron concentration on the magnetic field has a nonmonotonic character; however, the positions of the local maxima, n_e, in different regions of the column do not coincide.

We will consider the dependence of the electron current on the probe on the probe potential with respect to the reference electrode, which is the source of information about the energy distribution function of electrons, in more detail. It was established during the experiments that near the potential of the space the electron current on the probe $I_e(U)$, as presented using a semi-logarithmic scale, can be approximated by a straight line within the experimental error, which indicates the closeness of the energy distribution function of slow electrons to the Maxwellian distribution (Fig. 5a).

It should be noted that at an external magnetic-field induction that is higher than 40 G at $z = 18$ and 36 cm in the region of high values of the probe potential on the dependence $\ln(I_e)$ on U, a second slope occurs, which may indicate the presence of a group of fast electrons (Fig. 5b). The "temperature" of the fast electrons, T_{ef}, that was found from the second slope of the curve $\ln(I_e)$ for $z = 18$ cm is close to the value that was obtained for $z = 36$ cm and is from 20 to 35 eV for different magnetic field values. It is necessary to note that at $z = 8$ cm and 53 cm the second slope $\ln(I_e)$ was not found at all of the considered magnetic field values. In addition, it should be noted that the second slope, $\ln(I_e)$, occurs in the region of the floating probe potential, where the accuracy of the determination of the electron current decreases considerably.

Figure 6 shows the dependence of the temperature of slow electrons on the external magnetic-field

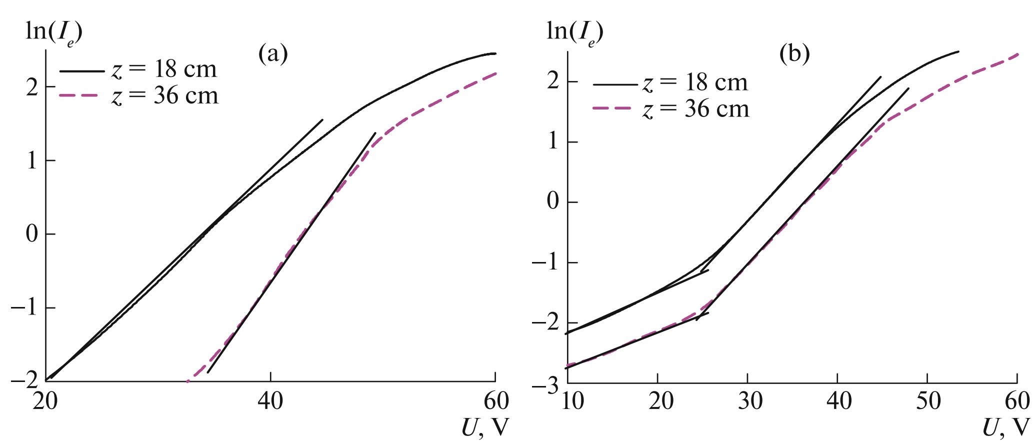

Fig. 5. The dependences of the electron current on the probe potential: a, for the case of the Maxwellian energy distribution of the electrons; b, with a non-Maxwellian "fast" group of electrons. The parameters were the same as in Fig. 4.

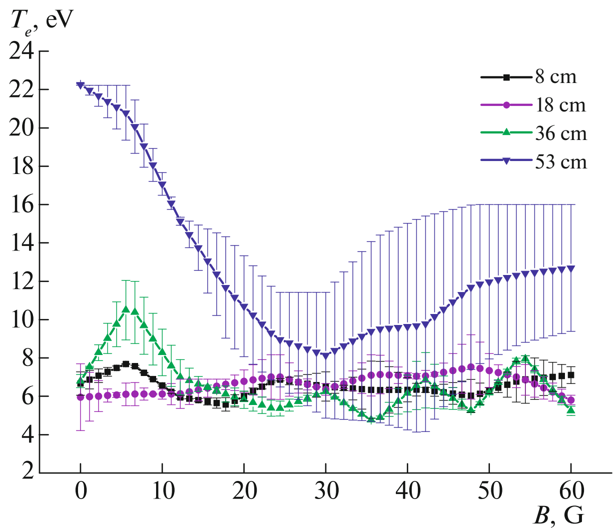

Fig. 6. The electron temperature calculated using Langmuir probes. The parameters were the same as in Fig. 4.

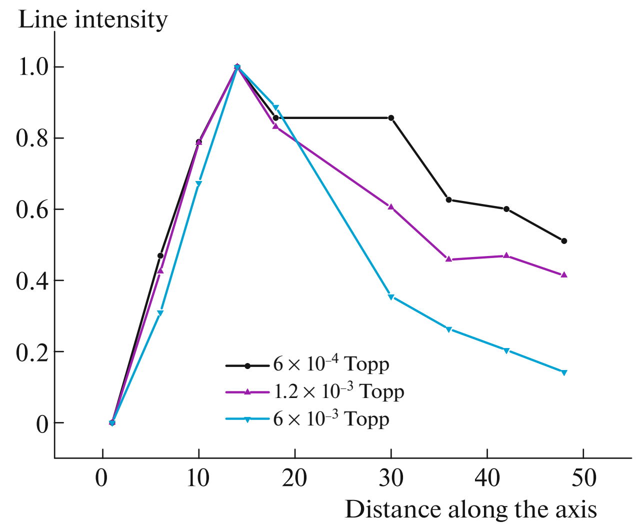

Fig. 7. The dependence of the intensity of the argon spectral line of 4200 Å on the distance along the axis of the source. The power of the RF generator was 150 W.

induction at different points on the axis of the plasma source. One should note that under conditions of the formation of the plasma column the electron temperature is level along the axis of the plasma source.

The results that were presented above were obtained at pressures of less than 1 mTorr. An increase in the pressure to 1 mTorr or higher showed that the formation of the extended plasma column does not take place, even at the highest of the considered magnetic fields, and the length of the brightly glowing part of the discharge decreases with the increase in the pressure. Figure 7 shows the dependence of the intensity of the argon spectral line of 4200 Å on the distance along the axis of the source for different values of the working body flow in the presence of the external magnetic field of 50 G.

4. DISCUSSION

In the considered ranges of the external magnetic field induction and powers of the RF generator the inequality holds:

$$\omega_{Li} \ll \omega \ll \Omega_e \ll \omega_{Le}, \quad (2)$$

where ω_{Li}, ω, Ω_e, ω_{Le} are the ion Langmuir, circular working, electron cyclotron and Langmuir frequencies. In this case, the resonant excitation of interrelated helicon and Trivelpiece–Gould waves is possible. In the low-frequency limit ($\omega \ll \Omega_e$) the spectrum of the Trivelpiece–Gould wave is known [43]:

$$\omega \simeq \frac{k_z\omega_{Le}}{\sqrt{k^2 + k_\perp^2\omega_{Le}^2/\Omega_e^2}},$$

In the limit of dense plasma ($\omega_{Le}^2 \gg \Omega_e^2$) this formula takes the form [43]:

$$\omega^2 = \frac{k_z^2}{k_\perp^2}\Omega_e^2.$$

The helicon is a transverse wave; in the low-frequency limit it has the form [43]:

$$\omega = \frac{k_z^2c^2\Omega_e}{\omega_{Le}^2}.$$

Plasma that is placed in an external magnetic field is an anisotropic medium; it is possible to speak about the longitudinal and transverse waves only in the limit of low phase speeds of waves. If plasma is limited, such waves are coupled and they can be "entangled" only in long systems, when the transverse size is much less than the transverse size of the system.

In [44, 45] theoretical and numerical models of a limited cylindrical plasma source were built in which the conditions of keeping the discharge follow the inequality (2). It was found that the high-frequency fields in the plasma are a linear combination of two solutions. Numerical calculations showed that at the frequency of 13.56 MHz and magnetic fields of higher than 20 G the azimuthal electric field of the first solution is considerably lower than the radial and axial ones, while the electric longitudinal field of the second solution is vanishingly small. This indicates that one can relate the first solution to a quasi-longitudinal Trivelpiece–Gould wave, and the second solution to a quasi-transverse one, viz., a helicon.

Figure 9 shows the results of the calculation of RF fields that were excited in a cylindrical plasma source with a diameter of 10 and a length of 50 cm by the azi-

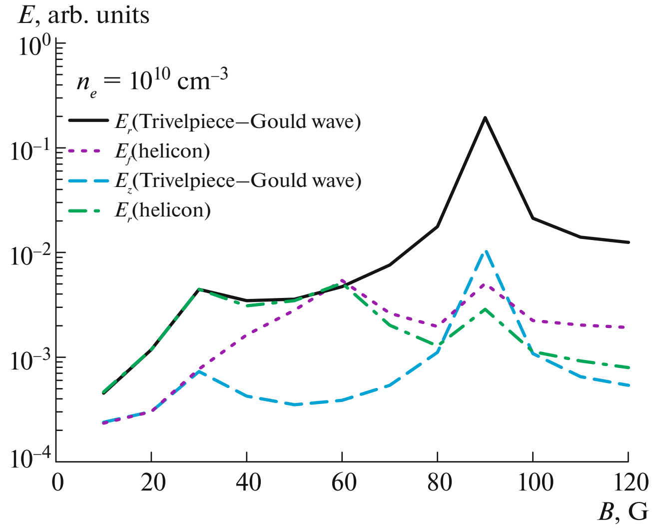

Fig. 8. The dependence of the electric field on the magnetic field for Trivelpiece–Gould and helicon waves.

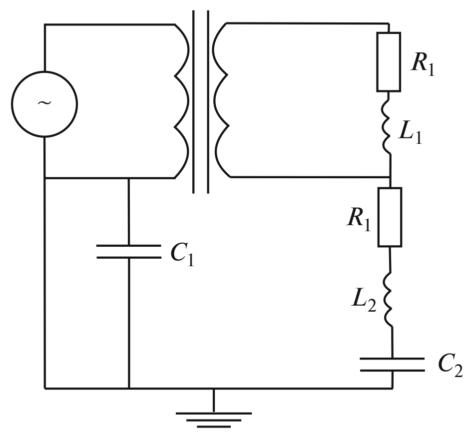

Fig. 9. An equivalent scheme of the discharge.

muthal current over the lateral surface of the plasma source. The fields were calculated using the program in [46] for the plasma concentration of 10^{10} cm^{-3} average over the volume. It can be seen that the RF radial fields, E_r, reach the largest values under the conditions of the experiment and at magnetic fields of less than 60 G the E_r values of the helicon and the Trivelpiece–Gould wave are similar. At $B > 60$ G the fields of the Trivelpiece–Gould wave become dominant. The comparison of the numerical simulation results with the experimental data shows their good qualitative agreement. This indicates that in the studied experiment the resonant excitation of the helicon and Trivelpiece–Gould wave occurs, which is reflected in the resonant character of the RF power consumption.

It is reasonable to relate the resonant character of the RF power consumption to the dependence of the electron concentration, n_e, on the magnetic field value (Fig. 4). In all of the considered regions the nonmonotonic dependence of the plasma density on the magnetic field is observed on the axis of the plasma column. However, the positions of the local maxima, n_e, in different regions of the column do not coincide. In the upper part of the flask local maxima are observed at relatively low magnetic field values. At z = 18 and 36 cm the concentration maxima are expressed more vividly and are observed at larger B values. These results indicate that the excitation of different spatial modes of waves occur during the variation of the external magnetic-field value. The variation of the magnetic field leads to the variation of the localization of the region of the power input in plasma and, as a consequence, to the nonmonotonic variation of the electron concentration in different points of the plasma column. A similar result was obtained in [47].

It was noted in Section 3 that at magnetic fields of 40 G and higher, i.e., under conditions where at z = 18 and 36 cm, local maxima of the electron concentration are observed on the probe curves that are given in the semi-logarithmic scale; "a second slope" occurs, indicating the appearance of a group of fast electrons in the discharge. An analogous result was observed in the case of the higher plasma concentration that was observed in [24]. Unfortunately, these experimental data are not sufficient to unambiguously relate the appearance of a group of fast electrons in the discharge to the generation of waves. The origin of the presence of fast electrons in the plasma source could also be spurious capacitive coupling between the antenna and grounded electrodes and the antenna and plasma.

In conclusion, we qualitatively considered the physical processes that lead to the formation of a column in a plasma source at magnetic fields higher than 20 G. The current in the antenna excites a discharge. In the absence of a magnetic field, electrons are mainly created in the volume of the upper part of the source, where the RF fields are maximal. The electrons perish on the walls of the upper and lower parts of the source, where they occur due to the chaoticity of their motion. In the presence of an external magnetic field the electrons are magnetized and begin to move along the force lines. Under the condition that the length of the free path of electrons is larger than the height of the plasma source, the electrons leave the upper part of the source and reach the lower flange of the plasma source almost without collisions. The motion of the electrons across the magnetic field is hampered, therefore the loss of electrons on the walls of the plasma source decreases, and a plasma column that is sharply contoured in the radial direction is observed. The increase in the pressure is accompanied by a decrease in the free path of electrons and a decrease in the energy of the electrons and the intensity of the plasma luminescence with distance from the antenna. The excitation of waves in the plasma column leads to the variation of the position of region of the localization of the RF power input.

The above considerations allow us to present the discharge in the form of the equivalent electric scheme that is shown in Fig. 9. The discharge in the upper part of the plasma source is presented in the form of the transformer model that was proposed in [48–50]. The discharge can be closed on the lower grounded flange; therefore, the equivalent scheme includes a branch that consists of the active resistance, R_2, inductance, L_2, and the capacities, C_1 and C_2. The capacity C_1 in the equivalent scheme occurs due to the presence of the capacity between the turns of the antenna and grounded flange, while the capacity C_2 occurs owing to the existence of the layer between plasma and the metal flange.

In the absence of the magnetic field and high argon pressures the impedance of the lower branch of the discharge is large and, as a result, the current is closed via the upper part of the equivalent scheme. The presence of an external magnetic field increases the electron concentration in the lower part of the plasma source, which leads to a decrease in the impedance of the lower branch of the discharge and an increase in the current that is closed via the lower part of the scheme.

5. CONCLUSIONS

1. As a result of experimental studies of the properties of an inductive RF discharge with an external homogeneous magnetic field that were performed with a plasma source with a complex geometry, we found a considerable redistribution of plasma parameters as a function of the working pressure and the value of the external magnetic field induction: At pressures less than 1 mTorr and the magnetic induction values of higher than 20 G (which corresponds to the conditions where electrons are magnetized and the length of the free path of electrons in the direction parallel to the magnetic field is larger than the characteristic sizes of the plasma source) the discharge takes the shape of a plasma column, whose radius approximately corresponds to the least of the radii of the parts of the plasma source. The pressure increase led to the concentration of the discharge in the upper part of the plasma source.

2. Resonant regions of RF power consumption are observed during the change of the homogeneous magnetic-field induction value. The presence of such resonant regions is in agreement with the results of the mathematical simulation and corresponds to the resonant excitation of helicons and Trivelpiece–Gould waves.

3. A nonmonotonic dependence of the plasma density on the magnetic field with displaced positions of maxima is observed during the variation of the value of the external magnetic-field induction in the regions of the location of Langmuir probes. The origin of this phenomenon is thought to be the excitation of different spatial modes of helicons and Trivelpiece–Gould waves that depend on the value of the magnetic field, which leads to a change of the localization of the region of the power input in the plasma. A group of fast electrons was observed at magnetic fields higher than 40 G.

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