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LOW-TEMPERATURE PLASMA

Properties of a Low-Pressure Inductive RF Discharge II: Mathematical Simulations

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Abstract—Self-consistent numerical simulations of a low-pressure inductive RF discharge have been carried out. It is shown that, on the one hand, the plasma parameters are determined by the RF power absorbed in the plasma and, on the other, they themselves govern the power absorption. This results in a nonmonotonic dependence of the plasma parameters on the magnetic field, as well as in discharge disruptions, similar to those observed experimentally in such discharges. An inductive RF discharge with a capacitive component is simulated. The experimentally observed characteristic properties of the discharges are explained based on the regular features of the absorption of RF power in the plasma. Traditional inductive plasma sources (both without and with a magnetic field) are considered.

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1. INTRODUCTION

The present paper is devoted to analyzing the properties of low-pressure inductive RF discharges. In our earlier paper [1], it was shown experimentally that a low-pressure inductive RF discharge in an external magnetic field exhibits the following characteristic features: a nonmonotonic dependence of the electron density and the power absorbed in the plasma on the magnetic field, disruptions at a certain critical magnetic field, a redistribution of the plasma parameters over the source volume, and a hysteresis effect in the dependence of the plasma parameters on the magnetic field and RF generator power. With a capacitive channel for RF power input into an inductive discharge, variations in the plasma parameters with varying magnetic field and RF generator power become more gradual, the discharge becomes stable, and the hysteresis in the dependence of the plasma parameters on the magnetic field and RF power disappears.

In what follows, we compare the results of computer simulations based on a self-consistent model of an inductive RF discharge [2] with the experimental data. We consider both a purely inductive discharge and an inductive discharge with a capacitive component.

2. SELF-CONSISTENT DISCHARGE MODEL

In order to construct a self-consistent model of discharges in RF sources of plasma or ions, it is, first of all, necessary to determine the relationship between the plasma parameters and the power input into the plasma. This was done in [2] by using a simple physical model of a low-pressure inductive RF discharge.

2.1. Simple Physical Discharge Model

In [2], the relationship between the power absorbed in the plasma, $P_{\rm pl}$, and the plasma parameters of a low-pressure (such that the mean free path is larger than the dimension of the plasma source) purely inductive discharge was determined from a set of equations consisting of the balance equations for the numbers of ions, electrons, and neutrals, averaged over the plasma volume,

$$Vn_0n_eZ_{\rm ion} = 0.4n_iS\sqrt{\frac{2kT_e}{M}}, \tag{1}$$

$$Vn_0n_eZ_{\rm ion} = 0.25n_eS_e\sqrt{\frac{8kT_e}{\pi m}}\exp\left(-\frac{e\phi}{kT_e}\right), \tag{2}$$

$$N' = 0.4n_iS_i\sqrt{\frac{2kT_e}{M}} + 0.25n_0S_a\sqrt{\frac{2kT_g}{\pi M}}; \tag{3}$$

the power balance equation

$$P_{\rm pl} = 0.4en_iS\sqrt{\frac{2kT_e}{M}}S\left(\phi + \frac{2kT_e}{e} + U_i(1 + W(kT_e))\right); \tag{4}$$

and the quasineutrality condition

$$n_e = n_i. \tag{5}$$

Here, n_0, n_e, and n_i are the densities of neutrals, electrons, and ions; V, S, and S_e are the volume, the total area of the source, and the area of the wall surface on which the electrons can be lost; k is Boltzmann's constant; N' is the number of neutral gas particles supplied into the gas-discharge chamber per unit time; T_e and T_g are the temperatures of electrons and gas atoms; M is the mass of a heavy particle; m is the mass of an electron; ϕ is the plasma potential relative to the wall; U_i is the ionization potential; and $W(kT_e)$ is the fraction of power lost by radiation from the atoms. The methods and results of calculating the ionization rate and radiative losses were described in [3].

In order to adapt the set of Eqs. (1)–(5) to a description of an inductive discharge with a capacitive component, we recall that, at low pressures ($p < 10^{-2}$ Torr), a capacitive discharge usually occurs in the so-called γ mode, which is characterized by the presence of electrode sheaths with a high potential drop V_s across them and intense electron emission from the electrode surfaces [4]. To simplify the problem, we assume that the space-charge electrode sheaths are thin and ignore the power spent on the generation of electron beams in the electrode sheaths. In other words, we assume that, in a capacitive discharge, the input RF power goes only into the heating of the plasma electrons. Under these assumptions, we can obtain an upper estimate for the plasma density and can be quite justified in using Eqs. (1)–(5) to describe the plasma in a low-pressure RF discharge with an inductive and a capacitive component.

The main difference between the sets of equations for a discharge with a capacitive component and for a purely inductive discharge is in the power balance equation, which implies that the power input into the discharge is equal to the sum of plasma power losses. The total power losses are the sum of the power carried by the ions and electrons to the wall of the discharge chamber of the plasma source and the power lost through ionization and radiation within the source volume (see Eq. (4)). In an inductive discharge, the power carried by the ions to the source wall is determined by the ion current density j_i and the plasma potential ϕ relative to the wall. As a rule, the potential ϕ does not exceed 50 V. In a capacitive discharge, the power carried by the ions to those sites of the gas-discharge chamber wall that are not screened by the electrodes is again equal to $j_i\phi$, but the power carried by them to the sites behind the electrodes (the capacitor plates) is proportional to V_s. Recall that, in the γ mode of a capacitive discharge, the potential drop across the sheaths can be much higher than ϕ [4]. Accordingly, the power loss in a capacitive discharge can substantially exceed that in an inductive discharge. With the aforesaid in mind, we write the power balance equation as

$$P_{\mathrm{pl}} = 0.4en_iS\sqrt{\frac{2kT_e}{M}}S\left(\phi\frac{S-S_s}{S} + V_s\frac{S_s}{S} + \frac{2kT_e}{e} + U_i(1+W(kT_e))\right), \qquad (6)$$

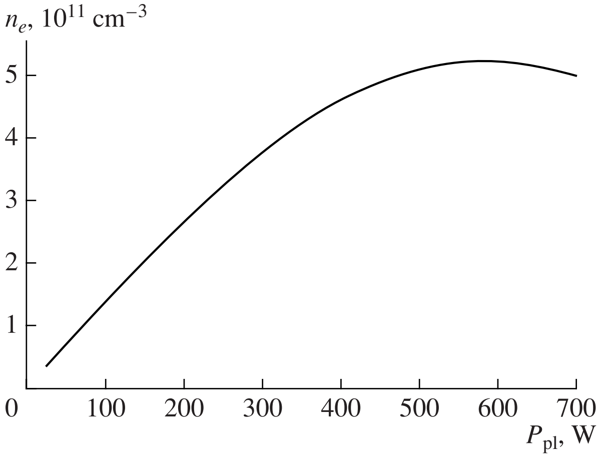

Fig. 1. Electron density vs. RF power deposited in the plasma.

where S_s is the area of the discharge chamber wall that is screened by the capacitor plates and U_i is the ionization potential.

Figure 1 displays a representative solution to the set of Eqs. (1)–(3), (5) and (6) that shows how the plasma parameters of an RF discharge depend on the power deposited in the plasma. Note again that the obtained values of the plasma density should be regarded as an upper estimate because, in the balance equations, we ignore the power lost in generating electron beams and in maintaining the charged particle density in the electrode sheaths. From Fig. 1 we can see that the electron density n_e increases in proportion to the input power, reaches a saturation value, and then decreases with increasing input power. Calculations show that, in the range where the electron density depends linearly on the input power, the electron temperature is essentially constant. The electron density ceases to increase linearly with the RF power in the range where it becomes close to the density of neutral particles and the electron temperature increases sharply. Like in [2], we restrict our analysis to a linear dependence of the electron density on the power input into the plasma and set

$$n_e = \alpha P_{\mathrm{pl}}. \qquad (7)$$

We continue to formulate the self-consistent problem by finding a relationship between the power absorbed in the plasma and the RF generator power. To do this, we must take into account the power lost in the external circuit during the inductive excitation of a discharge.

2.2. Purely Inductive Discharge

In order to give a clearer insight into the way of constructing a self-consistent model of a purely inductive RF discharge, we turn to its equivalent circuit shown in Fig. 2. The load, consisting of an antenna and a plasma coupled to it, is supplied by the RF power from a gen-

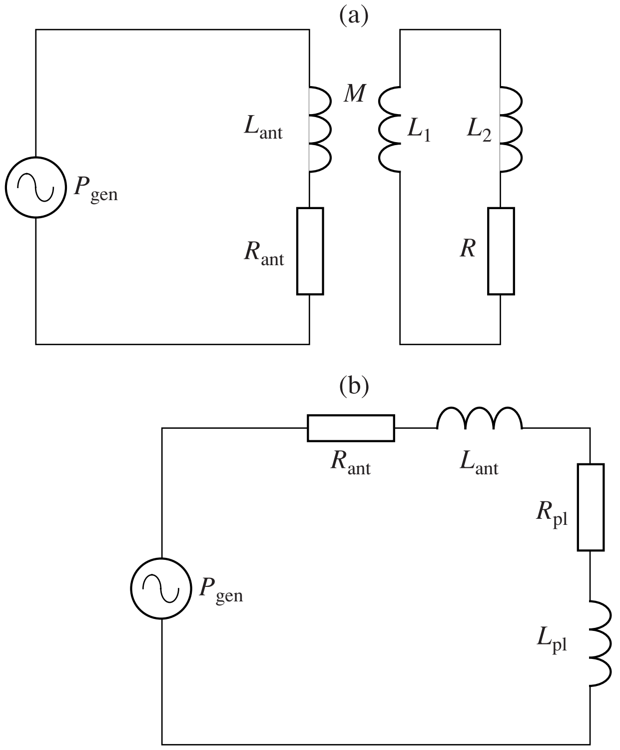

Fig. 2. Equivalent circuit of a purely inductive discharge.

erator through a matching device, which, in turn, serves to optimize the power supply from the generator to the load. When the load is matched to the generator, the generator power P is related to the antenna power $P_{\rm ant}$ and to the power $P_{\rm pl}$ deposited in the plasma through the expression

$$P_{\rm gen} = P_{\rm ant} + P_{\rm pl}. \qquad (8)$$

According to [2], for an inductively excited RF discharge, we have

$$P_{\rm pl} = 0.5R_{\rm pl}I^2. \qquad (9)$$

We thus can see that the power $P_{\rm pl}$ deposited in the plasma is determined by the antenna current I and the equivalent active plasma resistance $R_{\rm pl}$, whose relationship to the plasma parameters was considered in [2, 5].

We rewrite expression (8) in the form

$$P_{\rm gen} = 0.5I^2(R_{\rm ant} + R_{\rm pl}), \qquad (10)$$

where $R_{\rm ant}$ is the antenna resistance. With allowance for the fact that the equivalent plasma resistance depends on the discharge parameters [2, 5], we can see that the power deposited in the plasma, $I^2R_{\rm pl}$, is a complicated nonlinear function of the plasma parameters.

The self-consistent model of an inductive RF discharge should include the set of Eqs. (1)–(5), Eq. (10) (which relates the RF generator power lost in the external circuit to the equivalent plasma resistance), and the equation relating the equivalent resistance of the plasma to its parameters. In the general case, the solution to this set of equations is very difficulty to obtain. However, under condition (7), the set of equations can be substantially simplified. In this case, we can write the equation

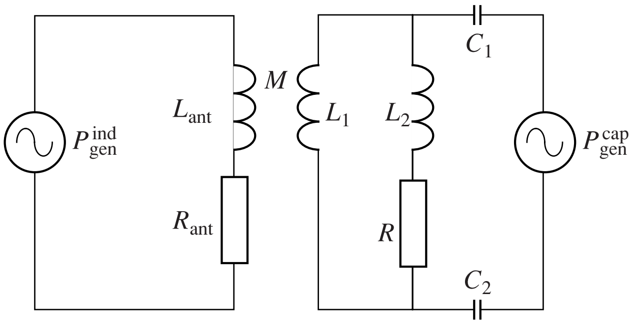

Fig. 3. Equivalent circuit of an RF discharge powered through independent inductive and capacitive channels.

$$I^2R_{\rm pl}(n_e, T_e, P, B, R, L) = \alpha^{-1}n_e$$
$$\equiv 0.4en_iS\sqrt{\frac{2kT_e}{M}}\left(\phi + \frac{2kT_e}{e} + U_i(1 + W(kT_e))\right). \qquad (11)$$

This equation, supplemented with expression (10) and the expression for $R_{\rm pl}$ corresponding to specific experimental conditions (see [2, 5]), makes it possible to find a self-consistent solution to the problem.

2.3. Discharge with Independent Inductive and Capacitive Channels

We consider a plasma source on whose external surface there are a spiral antenna and capacitor plates (see [1], Fig. 2b) and assume that the inductive and capacitive discharge channels are supplied by power from two independent RF generators. An equivalent schematic of the discharge is shown in Fig. 3. The plasma is connected into both the inductive and capacitive circuits of the discharge as an active (R) and a reactive (L) load. The RF power from the first generator goes into heating the antenna and plasma by induced currents. The RF power from the second generator goes into heating the plasma by the current flowing in a circuit consisting of capacitances C_1 and C_2 and plasma resistance R. Capacitances C_1 and C_2 are determined by the area of the capacitor plates and the distance from them to the plasma, as well as by the distance between the plasma and the discharge chamber wall.

The plasma absorbs the power fed through both the inductive and capacitive channels, $P_{\rm pl}^{\rm ind}$ and $P_{\rm pl}^{\rm cap}$,

$$P_{\rm pl} = P_{\rm pl}^{\rm cap} + P_{\rm pl}^{\rm ind}. \qquad (12)$$

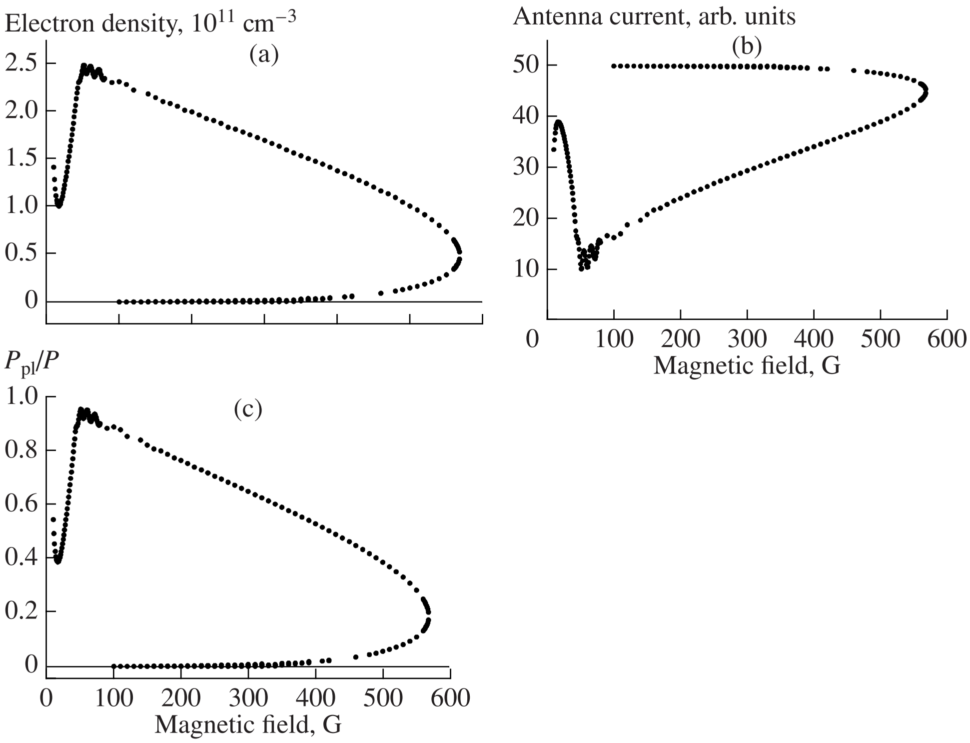

Fig. 4. Dependence of (a) the plasma density, (b) the antenna current, and (c) the efficiency of RF power deposition in the plasma on the magnetic field in a 5-cm-radius 15-cm-long plasma source for a generator power of 500 W and an antenna resistance of 0.2 Ω.

We assume that the power supplied from the generator feeding the capacitive channel is completely (without losses) deposited into the capacitive mode of the discharges,

$$P_{gen}^{cap} = P_{pl}^{cap}. \qquad (13)$$

As for the power fed through the inductive channel, we describe its absorption by the same expression as that for a purely inductive discharge,

$$P_{gen}^{ind} = I^2(R_{ant} + R_{pl}), \qquad (14)$$

where R_{ant} is the antenna resistance, R_{pl} is the equivalent plasma resistance, and I is the antenna current. We emphasize that the model of a inductive discharge with a capacitive component differs significantly from the model of a purely inductive discharge in that, in the former, the plasma parameters are determined by the total power fed into the plasma through both of the channels. Accordingly, the equivalent plasma resistance depends not only on the power fed through the inductive channel but also on the power fed through the capacitive channel.

Restricting our analysis to the range of deposited powers P_{pl} for which condition (7) is satisfied, we arrive at the following modified expression, which relates the RF power from both of the generators to the equivalent resistance R_{pl} of the plasma and its density:

$$\begin{aligned} P_{pl} &= P_{pl}^{cap} + P_{pl}^{ind} = P_{pl}^{cap} + I^2 R_{pl} \\ &= 0.4 e n_i S \sqrt{\frac{2kT_e}{M}} S\left(\phi\frac{S-S_s}{S} + V_s\frac{S_s}{S} + \frac{2kT_e}{e}\right. \\ &\quad \left. + U_i(1+W(kT_e))\right) = \alpha^{-1} n_e. \end{aligned} \qquad (11a)$$

3. RESULTS OF NUMERICAL SIMULATIONS

3.1. Purely Inductive Discharge

3.1.1. RF power absorption and discharge disruptions. Let us consider in more detail what happens in a purely inductive plasma source when the magnetic field increases. Figure 4 shows the dependence of the electron density, the antenna current, and the efficiency of power deposition in the plasma on the magnetic field B at a fixed RF generator power. As in the experiment, an increase in the magnetic field is initially accompanied by a decrease in the antenna current. At magnetic fields stronger than B_{max}, the antenna current begins to increase to approach its level before the discharge. The power fed into the plasma and the electron density both increase with magnetic field and, after the maximum value B_{max} is reached, they begin to decrease. For mag-

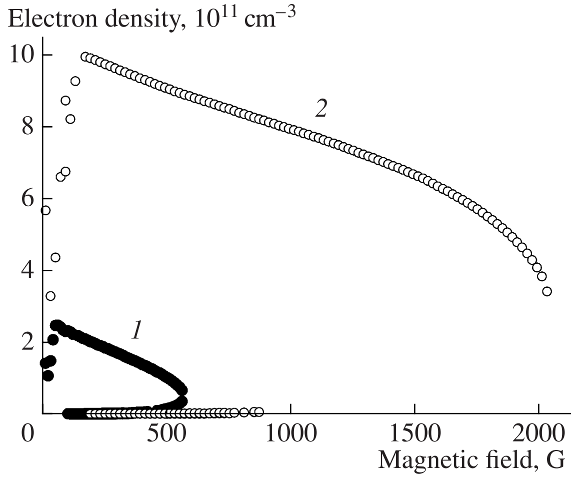

Fig. 5. Electron density as a function of the magnetic field in a 5-cm-radius 15-cm-long plasma source for an antenna resistance of 0.2 Ω and generator powers of (*1*) 500 and (*2*) 2000 W.

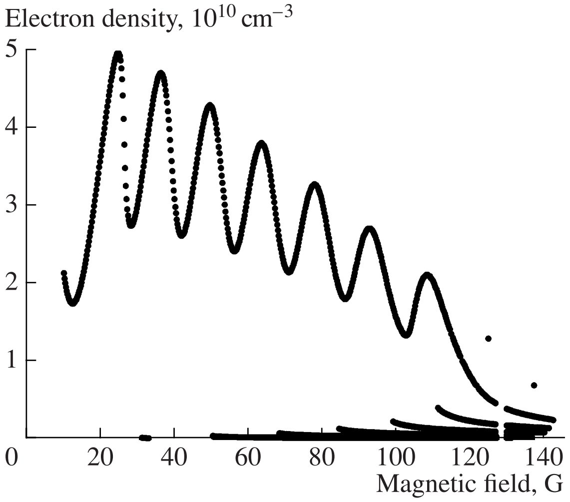

Fig. 6. Electron density as a function of the magnetic field in a 5-cm-radius 15-cm-long plasma source for a generator power of 100 W and an antenna resistance of 0.2 Ω.

netic fields exceeding the critical value B_{cr}, the set of equations describing the discharge has no solution. Physically, this indicates that the discharge cannot exist. The reason why there are no solutions for strong magnetic fields is a substantial drop in the equivalent plasma resistance and a reduction in the deposited power to a level insufficient to maintain the discharge. As the RF generator power increases, which is accompanied by an increase in the plasma density and equivalent plasma resistance, and as the plasma pressure grows, which is sometimes accompanied by an increase in the equivalent resistance at strong magnetic fields, the right boundary of the range where the solutions can exist is displaced toward stronger fields B (see Fig. 5). Similar effects were observed experimentally (see [1], Figs. 4–8).

In [2], it was shown that, for relatively long plasma sources having a relatively large radius, the dependence of R_{pl} on B characteristically has several local maxima associated with the resonant values of the magnetic field at which helicons and Trivelpiece–Gould (TG) waves are excited. Beyond the resonance region given by the inequality

$$\omega = \frac{\pi^2 c^2 \Omega_e}{L^2 \omega_{Le}^2} \ll \Omega_e,$$

the equivalent plasma resistance, the deposited power, and, accordingly, the plasma density all decrease abruptly. In turn, the decrease in the plasma density reduces both the equivalent plasma resistance and deposited power. In the range of magnetic fields where the resistance R_{pl} falls off abruptly, the plasma density decreases in a jumplike manner with increasing magnetic field. Figure 6 shows how the plasma density depends on the external magnetic field at a relatively low RF generator power. The dependence exhibits a series of local peaks whose right slopes reflect sharp decreases in the plasma density and even occasional discharge disruptions. A comparison of the results presented in Fig. 6 with the experimental data of [1] allows us to conclude that the experimentally observed jumps in the plasma density are associated with the resonances at which helicons and TG waves are excited, with the resulting sharp variations in the ability of the plasma to absorb RF power.

On the whole, a comparison of numerical results with the experimental data indicates that, in an inductive RF discharge, the characteristic features of the variation in the plasma density with varying external discharge parameters are governed by the characteristic features of the redistribution of RF power between the plasma and the external circuit. The fraction of power absorbed by the plasma is determined by its equivalent resistance, which in turn depends on the plasma parameters, the conditions for maintaining the discharge, and the mechanism for RF power absorption [2, 5].

3.1.2. Spatial redistribution of the plasma parameters. In [2], it was shown that variation in the magnetic field in the range where helicons and TG waves are excited leads to a redistribution of the regions of most intense RF power absorption over the radius of the plasma source. Estimates made for magnetic fields stronger than 1 mT show that the gyroradius of the bulk plasma electrons (those with energies lower than 10 eV) is less than 1 cm. We can therefore suggest that the RF power fed into the plasma is deposited in local radial regions. In this case, the spatial distribution of the plasma parameters should correlate with that of the RF power deposition regions.

Let us compare the numerical results with the experimental data obtained in [1]. Figure 7 shows radial pro-

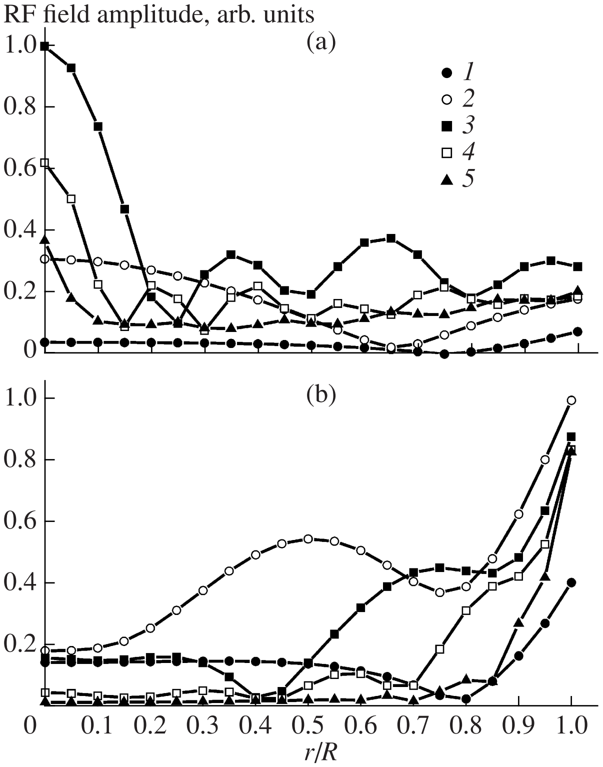

Fig. 7. Calculated radial profiles of the RF field amplitude in plasma sources with the radius $R = 7.5$ cm and lengths of (a) 15 and (b) 10 cm for different magnetic fields B = (*1*) 1, (*2*) 2.5, (*3*) 3.5, (*4*) 5, and (*5*) 10 mT.

files of the RF electric fields calculated for different values of the external magnetic field. We can see that, at magnetic fields close to the field $B_{\max}$ (which corresponds to the maximum electron density), the electric field of the waves penetrates into the plasma, whereas, at magnetic fields far stronger and far weaker than $B_{\max}$, the waves in question are surface waves. These results refer to relatively long sources. As for short plasma sources, simulations and experiments show that the RF electric field penetrates differently into them and that its amplitude is maximum near the source wall. Hence, the calculations are seen to agree qualitatively with experiment. This conclusion explains the experimentally observed spatial redistribution of the plasma density [1] as being due to the spatial redistribution of the RF electric fields with variation in the external magnetic field.

3.1.3. Hysteresis. Let us again turn to Fig. 4a, which shows how the plasma density in an inductive source depends on the external magnetic field. We can see that, for the same magnetic induction B, as well as for the same RF generator power P_{gen}, there sometimes exist several branches of the solution, i.e., several electron densities for which the set of equations describing the discharge has a solution. The above analysis refers to the branch of the solution for high electron densities. However, for magnetic fields below a certain value B^*, there exists a second equilibrium solution for which the plasma density is approximately one order of magnitude lower than that for the first branch. That there are several stable electron densities for the same value of B and of P_{gen} indicates that the system can exhibit hysteresis in response to an increase and a decrease in the external magnetic field.

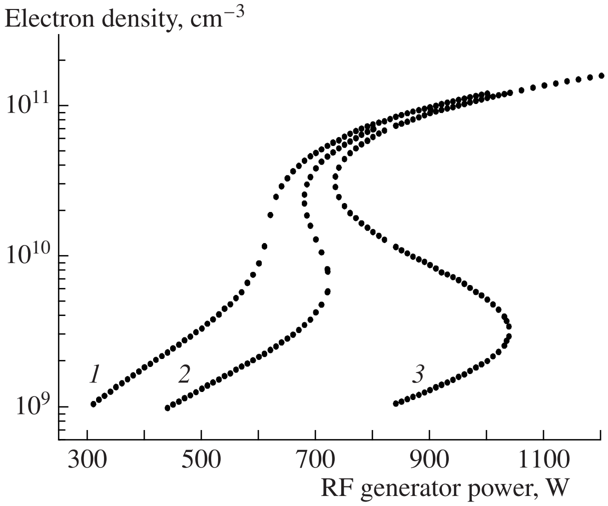

Fig. 8. Electron density as a function of the RF generator power according to the solution to the self-consistent problem for different neutral gas pressures: (*1*) 0.3, (*2*) 0.2, and (*3*) 0.1 mTorr.

Let us now analyze how the electron density depends on the RF generator power. We first consider a discharge in the absence of a magnetic field. Figure 8 shows the solutions to the self-consistent problem that were obtained for a disk-shaped inductive RF plasma source at different neutral gas pressures. The equivalent plasma resistance was calculated in accordance with the results obtained in [5].

Calculations show that the set of equations describing the discharge has solutions for RF generator powers higher than a certain critical value, which depends on both the antenna resistance and plasma parameters. The reasons for this effect were considered in [6]. It is also seen that the solutions obtained for certain conditions are non-single-valued. In order to analyze why the solution becomes non-single-valued, we perform simple algebraic manipulations to reduce the set of Eqs. (10) and (11) to a single equation,

$$\alpha n_e(1 + R_{\text{ant}}/R_{\text{pl}})/P_{\text{gen}} = 1. \qquad (15)$$

Under the condition $R_{\text{pl}} \gg R_{\text{ant}}$, the generator power is totally deposited in the plasma, so the electron density increases in proportion to it. Note that, in this case, the electron density n_e is uniquely related to the generator power P_{gen}. Under the opposite condition $R_{\text{pl}} < R_{\text{ant}}$, the problem also can have a solution; there may even be several solutions, provided that, for $R_{\text{pl}} < R_{\text{ant}}$, the

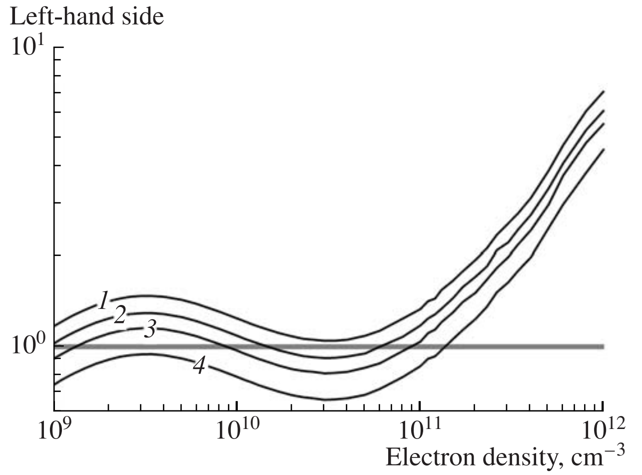

Fig. 9. Dependence of the left-hand side of Eq. (15) on the electron density for different RF generator powers: (*1*) 700, (*2*) 800, (*3*) 900, and (*4*) 1100 W.

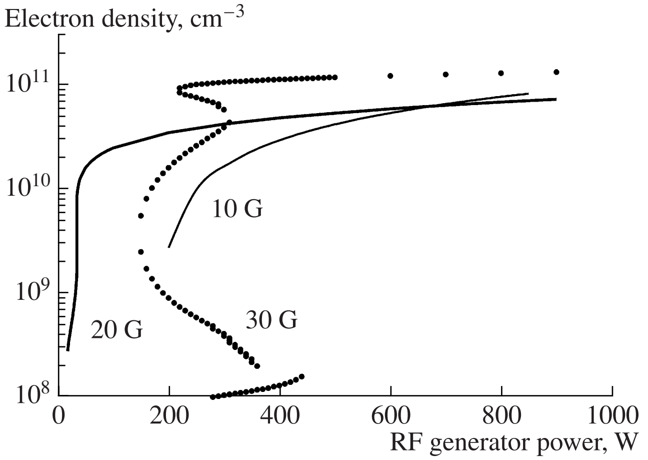

Fig. 10. Electron density vs. RF generator power for different magnetic field strengths.

deposited power $R_{\rm pl}$ depends nonlinearity on the electron density.

Figure 9 shows the left-hand side of Eq. (15) calculated for a low-pressure inductive discharge in the absence of a magnetic field. We can see that, for an RF generator power of 700 W, the left-hand side of Eq. (15) (curve *1*) is greater than unity over the entire range of electron densities under consideration. This implies that, for such generator powers, there is no solution and an inductive RF discharge is impossible. For an RF generator power in the range 800–900 W, an inductive RF discharge can exist, but the equivalent plasma resistance corresponding to the highest possible electron density is low in comparison with the antenna resistance and depends nonmonotonically on the density (see [5]). This is why the left-hand side of Eq. (15) is a nonmonotonic function of n_e and, for an RF generator power of 800–900 W, the set of equation describing the discharge can have two or three solutions. For higher powers, the solution is again single-valued, so the set of Eqs. (10) and (11) is satisfied by only one value of the plasma density (see curve *5*).

The above solutions to the self-consistent problem for an inductive RF discharge with no magnetic field present show that the discharge can exist in two modes—at a high and at a low electron density—and that a transition from one mode to another is accompanied by a jumplike increase (decrease) in the plasma density, i.e., hysteresis takes place. The hysteresis effect occurs when the equivalent plasma resistance, first, is low in comparison with the antenna resistance and, second, depends nonlinearity on the plasma density. Hence, the experimentally observed plasma density jumps and hysteresis effect can be explained in terms of the inductive discharge mechanism without allowance for the capacitive mode of the discharge. Note again that, because of a decrease in the antenna resistance and an increase in the equivalent plasma resistance with increasing neutral gas pressure and plasma source radius, the solution becomes single-valued and a transition from the discharge mode with a low electron density to the one with a high density is relatively gradual (in what follows, these discharge modes will be referred to as low and high modes, respectively).

Numerical simulations of an inductive RF discharge in an external magnetic field also reveal interesting properties of the solution. Like a discharge in the absence of a magnetic field, an inductive discharge can exist only at generator powers exceeding a threshold value $P_{\rm min}$; moreover, calculations show that the threshold power $P_{\rm min}$ depends not only on the factors mentioned above but also on the magnetic field B. This result is confirmed by Fig. 10.

We see from Fig. 10 that, in the range of low magnetic fields, $B \leq 2$ mT, for which the set of equations describing the discharge can have a solution, an increase in the RF generator power leads to a sharp increase in the electron density (and, accordingly, initiates a transition to the high discharge mode); moreover, in this case, the plasma density is uniquely related to the RF power. As the external magnetic field increases, the situation changes. In the field range where the plasma density increases abruptly, a second solution arises that corresponds to the low discharge mode. For stronger magnetic fields B, the solution becomes non-single-valued and the range of RF generator powers in which several discharge modes are possible widens. That there are non-single-valued solutions is attributed to a nonmonotonic dependence of the equivalent plasma resistance on the electron density; this dependence in turn is a consequence of the resonant nature of the excitation of helicons and TG waves in the discharge (see [2]).

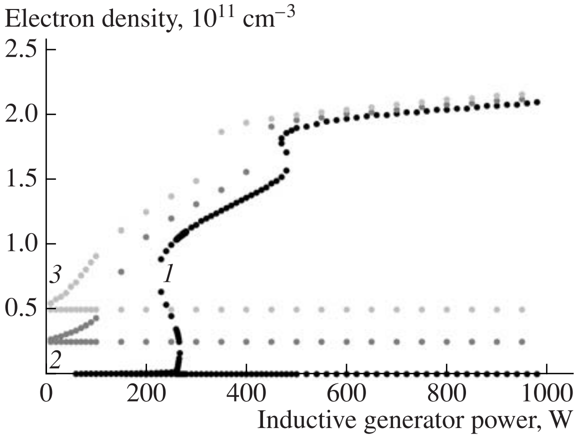

Fig. 11. Dependence of the electron density on the inductive RF generator power for the magnetic field $B = 40$ G and different capacitive RF generator powers: (*1*) 0 (without a capacitive mode), (*2*) 50, and (*3*) 100 W.

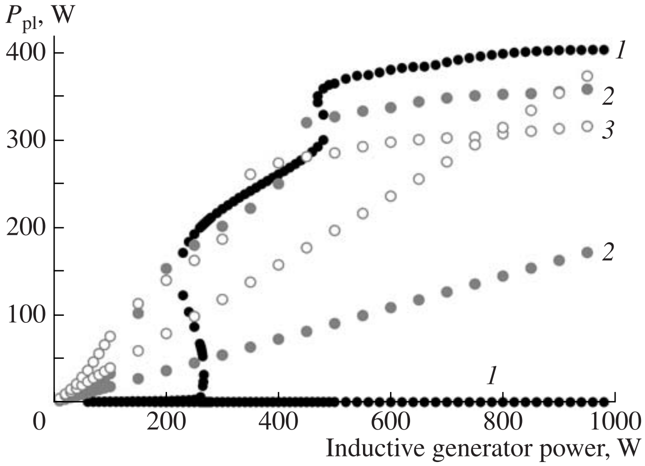

Fig. 12. Dependence of the deposited inductive power on the inductive RF generator power for the magnetic field $B = 40$ G and different capacitive RF generator powers: (*1*) 0 (without a capacitive mode), (*2*) 50, and (*3*) 100 W.

3.2. Discharge Powered through Independent Inductive and Capacitive Channels

3.2.1. Effect of the capacitive channel on the power input through the inductive channel. Figure 11 shows how the plasma density n_e depends on the RF generator power P_{gen}^{ind} in a purely inductive RF discharge maintained through the inductive channel and also in an inductive discharge additionally powered through the capacitive channel. We can see that, with the capacitive channel, the discharge can exist in modes with very different plasma densities. In the high mode, most of the power of an RF generator maintaining the discharge through the inductive channel is deposited in the plasma. In the low mode, the power from an inductive generator goes almost completely into heating the antenna and the plasma density is determined by the deposited capacitive power. Which of the discharge modes is to occur in experiments is presumably determined by the matching system, because the active and reactive components of the plasma impedance in the high and low discharge modes are markedly different. This is confirmed by the results of [7], where it was shown experimentally that the discharge mode can be changed by varying the parameters of the matching system.

Figure 12 shows how the deposited inductive power depends on the power P_{gen}^{ind} for different values of the power P_{gen}^{cap}. We can see that the deposited inductive power depends on the deposited capacitive power. For low values of P_{gen}^{ind}, the deposited inductive power P^{ind} increases with P_{gen}^{cap} to reach a level close to that corresponding to a purely inductive discharge and then decreases to a level lower than that in a purely inductive discharge. The higher the power deposited through the capacitive channel, the larger the amount by which the power P^{ind} decreases in the range of high powers P_{gen}^{ind}.

Let us qualitatively analyze the mutual influence of the two channels through which the RF power is input. To do this, we turn to the equivalent scheme shown in Fig. 3. First, we consider the case of low powers P_{gen}^{ind} and low plasma densities. From the literature [4, 6] and from numerical simulations, it is known that, over a broad range of conditions, the discharge can operate in the capacitive mode at lower RF generator powers than in the inductive mode; in this case, a certain electron density n_e^* is established in the discharge. Recall that the antenna is connected to the generator feeding the inductive channel. The onset of the plasma indicates that the external circuit of the inductive generator begins to be influenced by an equivalent resistance whose magnitude is determined by the density n_e^*, i.e., in fact, by the RF power deposited through the capacitive channel. When the electron density governed by the power deposited through the capacitive channel is higher than the density n_e^{ind} in a purely inductive plasma source, the power deposited through the inductive channel exceeds that in a purely inductive discharge. This is seen from the solutions presented in Fig. 12. Let us now consider the range of high plasma densities. An additional power deposited through the capacitive channel increases the electron density, but at high electron densities, the equivalent plasma resistance reaches its maximum and then decreases [2, 5] (see Fig. 13). The physical reason for this is that it becomes more difficult for the RF power to penetrate into the plasma as its density increases. The position of the maximum in the equivalent plasma resistance as a

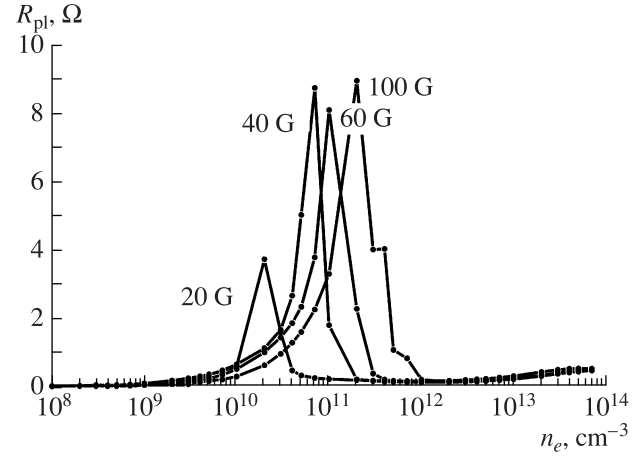

Fig. 13. Equivalent plasma resistance vs. electron density for different magnetic fields at an argon pressure of 1 mTorr in a 10-cm-radius 20-cm-long plasma source.

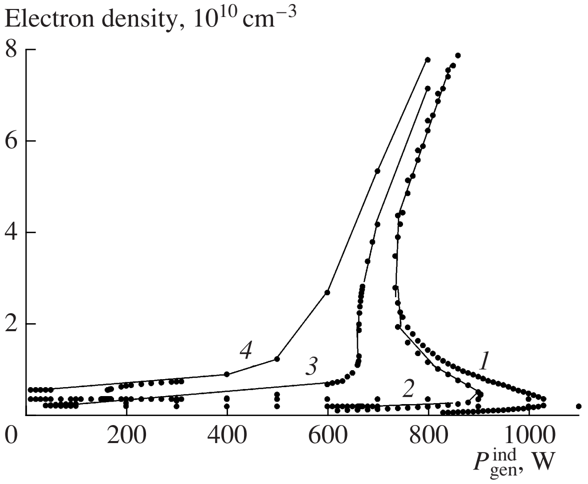

Fig. 14. Electron density vs. inductive RF generator power $P_{\mathrm{gen}}^{\mathrm{ind}}$ for different powers $P_{\mathrm{gen}}^{\mathrm{cap}}$ deposited through the capacitive channel: $P_{\mathrm{gen}}^{\mathrm{cap}}$ = (*1*) 0, (*2*) 1, (*3*) 5, and (*4*) 10 W.

function of the electron density depends sensitively on the magnetic field, so the range of powers $P_{\mathrm{gen}}^{\mathrm{ind}}$ where the power deposited through the inductive channel begins to decrease depends on B (see Fig. 13).

A decrease in the RF power deposited through the inductive channel reduces the total power input to the plasma. In this case, as the RF power deposited through the inductive channel increases, the total deposited power approaches the power deposited through the inductive channel in a purely inductive discharge. It is therefore not surprising that the plasma parameters observed experimentally in the high mode of a purely inductive discharge and in an inductive discharge with a capacitive component [1] were close to one another.

3.2.2. Hysteresis. Here, we again consider the range of relatively low powers $P_{\mathrm{gen}}^{\mathrm{ind}}$ at which the discharge evolves from the low into the high mode. From Fig. 14 we can see that, for $P_{\mathrm{gen}}^{\mathrm{cap}} = 0$, the dependence $n_e(P_{\mathrm{gen}}^{\mathrm{ind}})$ in a transition from the low to the high mode characteristically shows several solutions, which are usually attributed to hysteresis. However, as the power $P_{\mathrm{gen}}^{\mathrm{cap}}$ increases, the range of inductive generator powers where the solution is non-single-valued narrows to zero and, at the same time, the threshold power at which the discharge evolves from the low to the high mode decreases. Hence, the capacitive channel eliminates hysteresis in the dependence $n_e(P_{\mathrm{gen}}^{\mathrm{ind}})$. This result stems from an increase in the equivalent plasma resistance in the range of low electron densities when n_e is determined by the power deposited through the capacitive channel. Recall that the disappearance of hysteresis in an inductive discharge with a capacitive component was experimentally observed in [1].

Summarizing the results obtained, we can conclude that the inductive channel is responsible for a jumplike transition of a discharge from the high mode (that with a high electron density) to the low mode (that with a low electron density). The capacitive channel reduces the threshold power for the transition and makes the transition more gradual. For a discharge in an external magnetic field, the situation is qualitatively the same.

3.2.3 Effect of the capacitive channel on discharge disruptions. Here, we consider how the capacitive component of the discharge influences the dependence of the plasma density on the magnetic field for a fixed RF power fed through the inductive and capacitive channels. The relevant numerical results are presented in Fig. 15. We can see that, with the capacitive channel, the discharge can exist in modes with markedly different plasma densities. We consider in more detail the mode with a high electron density. Figure 15 shows that, when there is no capacitive channel, the discharge is disrupted at a magnetic field of about 80 G. The capacitive channel prevents the disruption. In this case, the problem has solutions in the range of magnetic fields where a purely inductive discharge is impossible. It should be noted that, at magnetic fields stronger than 80 G, the presence of the capacitive power raises the power deposited through the inductive channel; in this case, the power P^{ind} increases with $P_{\mathrm{gen}}^{\mathrm{cap}}$ (see Fig. 16). At low pressures, the equivalent plasma resistance exhibits an oscillating dependence on the magnetic field. This oscillating dependence results in a nonmonotonic dependence of the plasma density on the magnetic field B because the power deposited through the inductive channel depends nonmonotonically on the field. However, at magnetic fields stronger than 80 G, the discharge can be maintained and the plasma

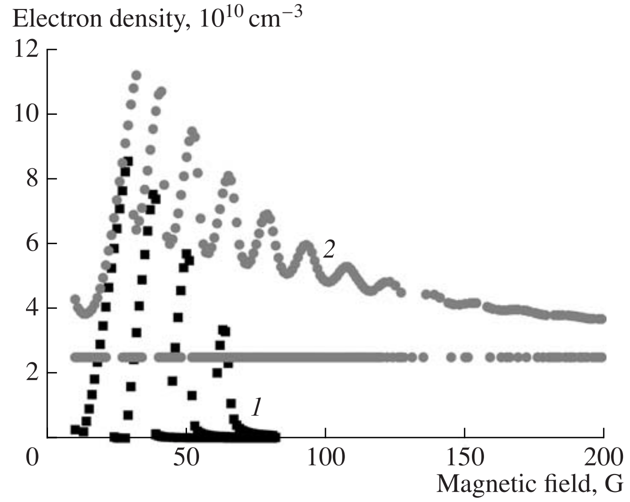

Fig. 15. Electron density as a function of the magnetic field for an inductive RF generator with a fixed power of 200 W and a capacitive RF generator with the power $P_{\rm gen}^{\rm cap}$ = (*1*) 0 and (*2*) 50 W.

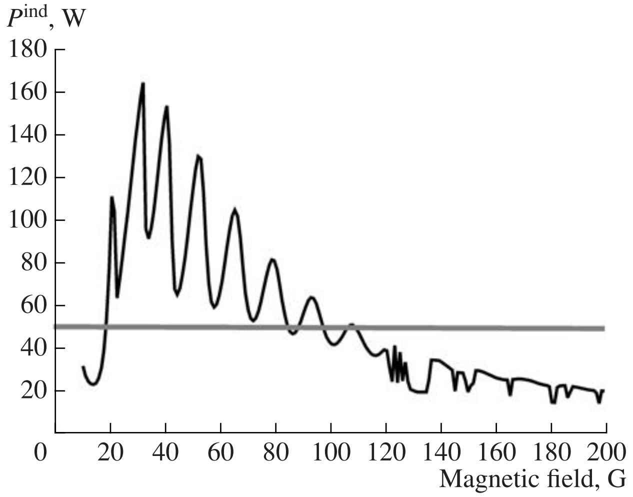

Fig. 16. Dependence of the power deposited in the plasma through the inductive channel on the magnetic field for the fixed power of the inductive RF generator, $P_{\rm gen}^{\rm ind}$ = 200 W, and the capacitive RF generator power $P_{\rm gen}^{\rm cap}$ = 50 W.

can absorb the power deposited through the inductive channel only when there is a capacitive channel for RF power input.

3.3. Hybrid Discharge

Finally, we give a qualitative description of a hybrid discharge, i.e., that initiated by the inductive and capacitive channels supplied from the same RF generator (see [1], Fig. 4b). This case models an actual discharge in which the capacitive channel occurs due to stray capacitances between the antenna and the plasma.

Being aware that representing a discharge as an equivalent circuit is just conditional, we nevertheless display such an equivalent circuit in Fig. 17. The plasma is modeled as active R and reactive L loads connected into both the inductive and capacitive circuits of the discharge. The RF generator power goes into heating the antenna, as well as into heating the plasma by the induced current and by the current flowing through the circuit consisting of capacitances C_1 and C_2 and resistance R, which is determined by the plasma ohmic resistance. Capacitances C_1 and C_2 are determined by the area of the capacitor plates and the distance from them to the plasma (the sum of the wall thickness and the thickness of the layer between the plasma and the wall of the discharge chamber). In constructing the circuit, we assumed for simplicity that the RF power is partially supplied through the capacitor; in an actual discharge circuit, this corresponds to a capacitance between the antenna surface and the plasma.

In the general case, the self-consistent model of a hybrid discharge is difficult to develop. In fact, in a hybrid discharge, variations in the RF generator power lead to a self-consistent variations not only in the plasma parameters but also in the fractions of power deposited in the plasma through the capacitive and inductive channels. We can, however, qualitatively estimate the mutual influence of the two channels.

At low RF generator powers, when a purely inductive discharge mode is impossible, the discharge can operate only in a capacitive mode. The power deposited in the plasma through the capacitive channel is equal to the RF generator power minus the power lost in heating the antenna. As a result of this power loss, a nonzero equivalent resistance arises in the inductive circuit and the power is now deposited in the plasma not only through the capacitive but also through the inductive channel. It should be stressed that the amount of power deposited through the inductive channel is determined by the power deposited through the capacitive channel. The plasma density depends on the total power depos-

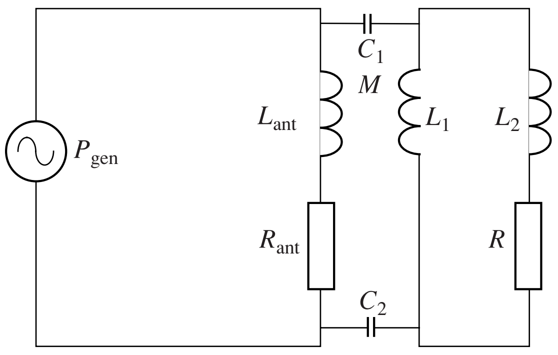

Fig. 17. Equivalent circuit of an inductive discharge with a capacitive component.

ited in the plasma through both of the channels. In this case, it is obvious that there are no physical reasons to consider the low discharge mode as purely capacitive because the total power is deposited in the plasma through both the capacitive and inductive channels.

At higher RF generator powers, when the electron density is determined by the fraction of power deposited through the inductive channel, the behavior of the hybrid discharge is qualitatively similar to that of the discharge maintained by the RF power supplied through two independent channels. For high electron densities at which the equivalent plasma resistance begins to decrease with increasing n_e, the capacitive discharge mode begins to play an important role. Hence, we can conclude that the mode of an inductive discharge with a high electron density is not purely inductive. The capacitive mode has a substantial influence on the power deposited in the plasma through the inductive channel.

4. CONCLUSIONS

We have shown both experimentally and numerically that variations in the external magnetic field change the ability of the plasma to absorb RF power and also lead to a spatial redistribution of the plasma parameters and change their values. The plasma absorbs the RF generator power only partially. On the one hand, the plasma parameters are determined by the absorbed power, and, on the other hand, they themselves govern this power. As a result, the discharge is self-consistent in nature. The self-consistent nature of the discharge is most obvious from the highly nonmonotonic dependence of the plasma parameters on the magnetic field, as well as from discharge disruptions. A significant power loss in the external circuit and the nonlinear dependence of the power absorbing ability of the plasma on the electron density give rise to hysteresis in the dependence of the plasma parameters on the RF generator power and external magnetic field.

The presence of the capacitive component changes the power deposited in the plasma through the inductive channel. As a result, a transition of the discharge from the low to the high mode occurs at a lower RF generator power. In this transition, the presence of the capacitive channel leads to a gradual variation in the plasma density with increasing generator power and to the disappearance of hysteresis. As the electron density deposited through the capacitive channel increases to a level above that at which the equivalent plasma resistance is maximum, the RF power deposited through the inductive channel decreases.

There are no physical reasons to relate the modes of an inductive RF discharge at low and high electron densities to the capacitive and inductive modes, because the presence of one channel for RF power input into the discharge plasma changes the power deposited in the plasma through the other channel.

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