EXCITATION OF AN INDUCTIVE HF DISCHARGE

E. T. Protasevich

UDC 537.521.7

Use of an hf discharge in science and technology is connected to the relative ease with which a stable nonequilibrium plasma can be produced over a wide range of pressures. The excitation winding for an inductive hf discharge is usually a coil containing several (sometimes 3-5) turns of conductor. However, for some applications [1] this "loose" winding must be replaced by a dense one compressed into a roll which surrounds the cylindrical discharge chamber. The goal of the present study is experimental production of a gas discharge plasma with homogeneous electron concentration distribution along the discharge chamber axis.

It is known that in an inductive hf discharge the parameters of the excitation winding and the plasma generated are related by an expression [2] which is valid for high electron temperature T_e:

$$\int_0^{T_m} \sigma(T)\,\lambda(T)\,dT = \frac{c^2 H_0^2}{64\pi} = \left(\frac{I_0 n}{2}\right)^2, \quad (1)$$

where $\sigma(T)$ and $\lambda(T)$ are the electrical and thermal conductivities of the plasma, H_0 is the amplitude of the magnetic component, and $I_0 n$ is in A-turns.

Figures 1 and 2 show a diagram and the equivalent circuit of the winding under consideration. For convenience in calculation we choose the equivalent circuit in the form shown in Fig. 2b. Considering the coil to be "thin" ($r_c - r_{min} \ll r_{min}$ and $\ell^2/4 \gg r^2$). We write the current flowing through an elementary ring of width $d\ell$: $di = j d\ell = j dx$ ($j = I_0/\ell = \text{const}$) and the magnetic field dH created by this current at the center of the coil: $dH = [r^2_c/2(r^2_c + x^2)^{3/2}]di$. We then sum up the magnetic field of the entire winding

$$H = j\frac{r_c^2}{c} n \int_{-l/2}^{l/2} \frac{dx}{(r_c^2 + x^2)^{3/2}} \simeq \frac{i}{l} n. \quad (2)$$

A simplification has been introduced in Eq. (2) in accordance with the assumption that $\ell^2/4 \gg r^2_c$. Using known relationships between inductance L and the magnetic induction, and assuming that the areas of individual turns are approximately the same, we define the winding inductance $L = \pi\mu_0(r_c^2/\ell)n^2$ (where n is the number of turns).

Considering two adjacent turns as a cylindrical capacitor, we find the interturn capacitance of the coil $C_k = 4\pi\varepsilon\varepsilon_0\ell/[\ln(r_2/r_1)]$, where r_1 and r_2 are the radii of the adjacent turns. Inasmuch as $r_2 - r_1 = \delta$ and $\ln(r_2/r_1) \simeq \ln(1 + \delta/r_c) \simeq \delta/r_c$, then, considering $C_1 \simeq C_2 \simeq \ldots C_k$, we obtain $C = 4\pi\varepsilon\varepsilon_0\ell r_c/(n\delta)$.

We will define the active resistance R and the loss resistance in the coil dielectric R_{cd}. It can easily be shown that these values are equal respectively to $R = 2\pi\rho r_c n/(\ell\Delta)$, and $R_{cd} = \rho_d\delta n/(2\pi\ell r_c)$ (where ρ and ρ_d are the resistivities of the coil material and dielectric).

Substituting the values obtained for L and C in the expression for the resonant frequency of the circuit we find $f = \frac{c}{4\pi^2}\sqrt{\frac{\delta}{n r_c^3 \varepsilon}}$ (where c is the speed of light).

It is evident from Fig. 2b that such an excitation winding compressed into a roll is a parallel tank circuit for the hf generator in which one finds current resonance, i.e., the tank circuit current exceeds the current in the external circuit by a factor of Q times. It follows from Eq. (1) that this fact has a significant effect on the amplitude of the magnetic component of the hf field and the plasma parameters.

Tomsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 13-15, September-October, 1988. Original article submitted June 16, 1987.

 0021-8944/88/2905-0612$12.50

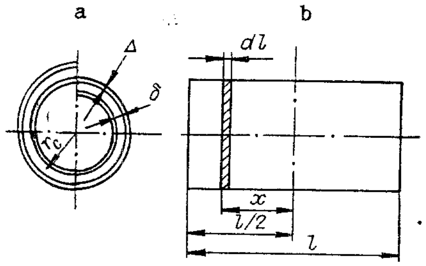

Fig. 1

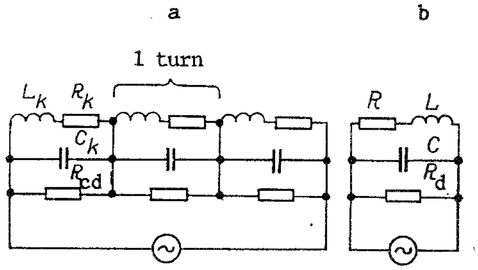

Fig. 2

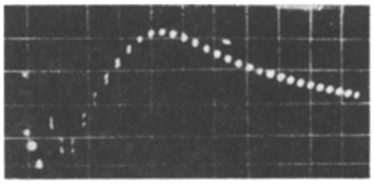

Fig. 3

The resonant resistance of the tank circuit $R_{0e} = Q^2R$ is determined by the quality factor of the excitation winding

$$Q = \frac{\Delta}{4\pi\rho}\sqrt{\frac{\mu_0 \delta n}{r_c \varepsilon \varepsilon_0}}. \qquad (3)$$

It follows from Eq. (3) that to obtain Q_{max} it is necessary that $\delta \to \delta_{max}$ and $\varepsilon \to \varepsilon_{min}$. Since for the majority of solid dielectrics ε = 3-5, the optimal resonance case will be that in which ordinary air serves as the insulation between layers ($\varepsilon \simeq 1$).

Efficiency of operation of such a winding for excitation of an hf inductive discharge was tested using a generator (f = 36-37 MHz, P = 40-60 kW, τ = 10-60 msec, F = 1-5 Hz) at pressures from fractions to thousands of Pa using a quartz tube as the discharge chamber ($\sim 9 \cdot 10^{-2}$ m, $\ell \sim 1$ m). A comparison was made with an hf capacitive discharge produced under the same experimental conditions. The plasma concentration was measured by an shf-interferometer ($\lambda \sim 3 \cdot 10^{-2}$ and $8 \cdot 10^{-3}$ m). A typical interferogram is shown in Fig. 3 (time markers every 20 μsec).

For the capacitive discharge and for two pairs of external ring electrodes made in the form of plates 0.1 m wide [3], the average electron concentration in the plasma n_e at the ends and in the middle of the distance between the electrodes differs by not less than an order of magnitude, while for the three-turn winding considered here the concentration gradient did not exceed the measurement accuracy, i.e., 15-20%. Thus, in the second case the plasma distribution along the discharge chamber proves to be more uniform, which may be of practical use [1].

As for the other plasma characteristics (temperature, collision frequency, etc.), within the limits of measurement accuracy (~20%) they were practically identical in the capacitive and inductive discharges. Thus, in particular, for a pressure of the order of $\sim 10^5$ Pa $n_e \gtrsim 10^{19}$-10^{20} m^{-3} while $T_e \sim 1$ eV.

LITERATURE CITED

1. A. N. Didenko, E. T. Protasevich, and V. V. Tikhomirov, "Passage of high-current electron beams through plasma at low pressure," Pis'ma Zh. Tekh. Fiz., 1, No. 15 (1975).
2. R. V. Mitin and V. S. Valuzhin, "Capacitive high-frequency gas discharge threshold regime," Teplofiz. Vys. Temp., 22, No. 1, (1984).
3. E. T. Protasevich, "Low-pressure nonequilibrium plasma source," Prib. Tekh. Éksp., No. 5 (1986).