FORMATION OF A CURRENT CHANNEL IN A GAS DISCHARGE IN A WEAK MAGNETIC FIELD

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The configuration of a strong-current toroidal discharge in a weak magnetic field is experimentally investigated for a magnetic flux uniform over the liner cross section, and for both constant and variable longitudinal field on the discharge periphery. It is shown that the experimentally observed formation of a current channel outwardly reminiscent of the pinch effect can be described, for both constant and variable external magnetic fields, by a stationary force-free discharge model.

In order to study certain features of a strong-current discharge, we have carried out experiments with a toroidal chamber having a thick-wall aluminum case with diameters 750 and 250 mm. Inside the case was mounted a discharge chamber (liner) 160 mm in diameter. In one series of experiments the liner was assembled of 16 aluminum sections (wall thickness 4 mm), insulated from each other with teflon gaskets; in the second series, an analogous sectionalized liner was made of nonmagnetic steel 0.1 mm thick. The steel liner was placed in a supplementary coil to introduce a variable longitudinal magnetic field into the plasma. The discharge current and voltage were measured. The distribution of the magnetic fields in the discharge was determined with magnetic probes.

In experiments with the aluminum liner, the amplitude of the discharge current reached 50 kiloamp at an initial loop voltage 1.1 kv, duration of first half wave 600 μsec, initial magnetic field up to 1000 oe, and hydrogen pressure $10^{-2} - 10^{-3}$ mm Hg. The conductivity of the plasma, calculated at the current maximum, was 6×10^{14} cgs esu on the chamber axis.

When the steel liner was used and the supplementary coil turned on, the amplitude of the discharge current reached 35 kiloamp and the conductivity did not exceed 8×10^{13} cgs esu, other conditions being equal. An appreciable change took place in the configuration of the magnetic field in the discharge region: in the first case the distribution of the azimuthal component of the magnetic field indicates that a current channel, "detached" from the walls, was formed; in the second case the current has practically constant density over the entire section of the liner (Fig. 1). It must be noted that in both cases the configuration of the discharge is completely determined by the initial magnetic field and by the current flowing in the plasma at the given instant of time, regardless of the discharge phase at which this current is reached.

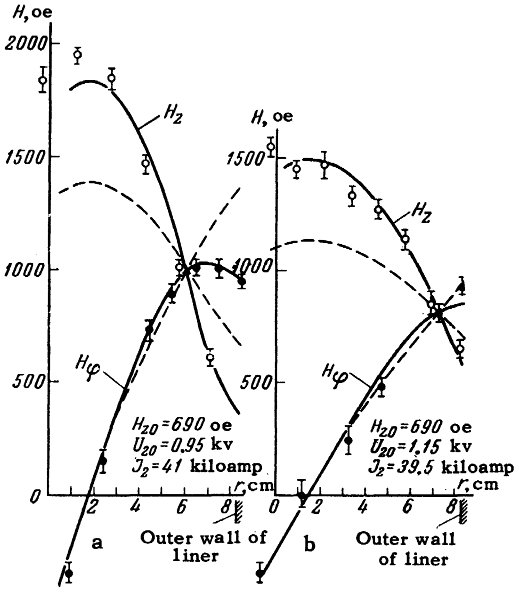

FIG. 1. Distribution of the longitudinal (H_z) and azimuthal (H_ϕ) components of the magnetic field in the discharge: a – thick-wall aluminum liner; b – thin-wall liner made of nonmagnetic steel. Solid curves – force-free model, dashed – paramagnetic model.

For a further study of the character of the discharge, alternating current was passed through the supplementary winding at approximately four times the fundamental frequency of the process. (The influence of an alternating magnetic field on the discharge configuration was investigated by Ivanov and Kirillov.[1]) The amplitude, sign, and instant of application of the supplementary field could be varied. In some experiments the field was introduced simultaneously with the start of the discharge, and its first half wave amplified the initial field. Up to the time t_1 (Fig. 2) the longitudinal field on the edge changes in phase with the field in the central region of the discharge, but beyond this instant the field in the central region remains constant, or even decreases somewhat, whereas the field on the edge decreases with the current in the exciting coil. Within 2–4 μsec after t_2 the longitudinal field inside the plasma reverses direction. The value of the field before the instant t_2 is proportional to the discharge current.

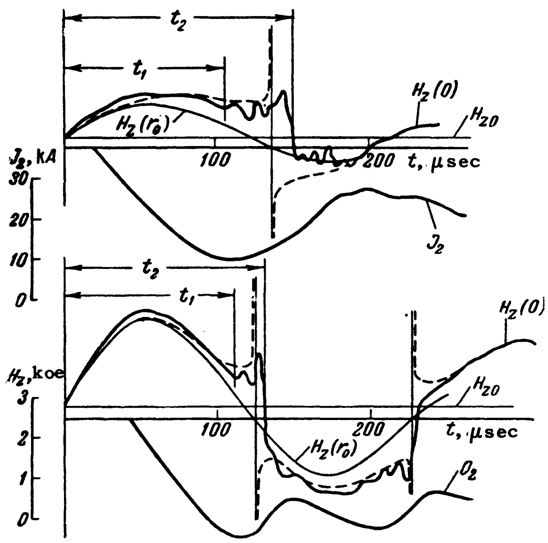

FIG. 2. Oscillograms of discharge current J_z and longitudinal magnetic field $H_z(0)$ at the center of the chamber upon application of an alternating magnetic field (r_0 – radius of liner). The dashed curve is calculated in force-free model.

From an examination of all the oscillograms obtained it follows that t_1 practically coincides with the time when the longitudinal component of the magnetic field on the edge of the liner becomes equal to the azimuthal component, and t_2 coincides with the instant when the external longitudinal field passes through zero.

Measurements of the azimuthal component of the field show that a current channel exists in the discharge between the instant t_1 and t_2, with a radius that decreases gradually to about half the initial radius at the instant t_2. A comparison of the results of different experiments shows that in this case, too, the configuration of the discharge is determined by the external magnetic field on the edge of the liner and by the discharge current flowing at the given instant of time, and is practically independent of the rate of change of the external field. The quantities also determine the times t_1 and t_2. Accordingly, for a given discharge current, the time $t_2 - t_1$ was found to be, inversely proportional to the rate of decrease of the external magnetic field.

The low conductivity of the plasma in the experiments described should cause the diffusion time of the magnetic field in the gas-discharge column to be much less than the periods of variation of the external fields, and in the first approximation there should be no "frozen-in" magnetic field in the plasma. Yet a pronounced formation of a current channel is observed, along with an increase in the longitudinal magnetic field in the central region of the discharge (only outwardly reminiscent of the "pinch"). These phenomena can be reconciled with the stationary discharge theory[2] by imposing as an additional requirement the vanishing of the current density perpendicular to the magnetic field. This leads to the force-free discharge model, which is natural for a low-temperature plasma.

The discharge configuration calculated by this theory agrees with experiment (Fig. 1). The different behavior of the discharges in aluminum and steel liners is explained by the fact that in the former case the magnetic flux is constant over the cross section of the liner during the discharge, while in the latter the magnetic field intensity is maintained practically constant on the edge of the liner. An account of this difference permits a correct interpretation of both cases.

The jump-like change in the longitudinal field inside the plasma also has a natural explanation. The direction of the current helix in the discharge is determined by the sign of the external longitudinal magnetic field. At the instant when this field passes through zero, the helix direction should reverse and cause a corresponding jump-like change in the magnetic field. It is seen from the oscillograms that the change in the sign of the longitudinal field in the plasma actually occurs somewhat later than the passage of the field on the periphery of the discharge through zero. It would be incorrect to attribute this phenomenon entirely to the finite diffusion time of the magnetic field in the plasma, since the delay in the reversal of the sign of the field at the center of the plasma relative to the periphery (Fig. 2) depends on the rate of change of the external magnetic field, although the plasma conductivity is the same in these experiments. We propose that this phenomenon is connected both with the insignificant frozen-in magnetic field in the plasma and with the toroidal geometry of the discharge and the existence of magnetic-field inhomogeneities.

The absence of a perpendicular current-density component can be explained by using the mechanism of convective instability (B. B. Kadomtsev, private communication).

In other installations of similar type[3-6] the conductivity and the ratio of the characteristic geometrical dimensions to the duration of the process differ somewhat from those given above. This raises the hope that the stationary force-free model can be employed to explain a large number of experimental facts. This model was successfully used by Lees and Rusbridge[7] to calculate the distribution of the magnetic fields in the "Zeta".

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