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Abstract

Full Text

PHYSICS

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THE EFFECT OF A TRANSVERSE MAGNETIC FIELD ON A TOROIDAL DISCHARGE

In studying pulsed discharges with large current in toroidal chambers with a stabilizing longitudinal magnetic field on installations of the "Tokamak" series, it was found (^{1}) that in regimes where the highest conductivity and plasma temperature are ordinarily attained, the oscillogram of the discharge current during the first half-period of the voltage has the form shown in Fig. 1. The reason for this two-humped form of the current oscillogram was initially unclear. At the present time it may be regarded as established that the indicated form of the discharge pulse is directly connected with radial motions of the plasma column, during which its major radius R changes (Fig. 2).

In the chambers of our experimental installations there are limiting diaphragms, which determine the maximum cross-sectional area of the annular plasma column. If the amplitude of the radial displacements of the plasma column during the discharge proves sufficiently large, then at certain instants of time intense interaction of the plasma with the diaphragms may occur. At these instants the outer layers of the plasma column are cut off by the edge of the diaphragm and, in addition, a large quantity of impurities enters the plasma. This, naturally, should be reflected in the magnitude of the discharge current. Therefore, in order to explain the form of the discharge pulse, it is necessary to know the mechanism of the radial motions of the plasma column. The position of the column in the chamber is determined by the condition of equilibrium of the forces acting on it. In the ideal case, when the external sources of electric power create magnetic fields having only one azimuthal component, parallel to the plasma current, the position of the plasma column in a chamber with conducting walls is determined by the following equation, derived by V. D. Shafranov (^{2}):

Fig. 1. Oscillograms of the discharge current $I(t)$ and of the intensity of the

Fig. 2. Schematic cross section of the apparatus chamber. $R_0 = 62.5$ cm, $a = 10$ cm, $b = 25$ cm

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vortex electric field $E(t)$ on the axis of the discharge chamber. $B_0 = 5600$ oersted, $p_{D_2} = 6.9 \cdot 10^{-4}$ mm Hg.

$$\delta = \frac{b^2}{2R}\left[\ln\frac{b}{a} + \left(1 - \frac{a^2}{b^2}\right)\left(\frac{8\pi\bar{p}}{B_a^2} - \frac{1}{4}\right)\right]. \tag{1}$$

Here a is the radius of the cross section of the plasma loop, b is the radius of the cross section of the conducting shell, $\overline{p}$ is the mean plasma pressure, and B_a is the magnetic field of the plasma current at the boundary of the column. The quantity δ denotes the displacement of the plasma column relative to the line passing through the centers of the transverse sections of the toroidal shell (the axial line of the chamber).

Formula (1) applies to the case in which the current is uniformly distributed over the cross section of the column.

Under the actual experimental conditions, the external sources of electric power produce not only an azimuthal component of the magnetic field, but also a small field component B_z, perpendicular to the plane of the plasma loop, and its magnitude varies during the discharge. The interaction of the current with the component B_z produces an additional radial force, changing the magnitude of the equilibrium displacement δ. In order to take the action of this force into account in formula (1), it is necessary to add to the expression on the right-hand side the quantity $\frac{B_z}{B_b}b$, where B_b is the magnetic field of the plasma current at the boundary of the copper shell.

Fig. 2. Schematic cross section of the apparatus chamber.
$R_0 = 62.5$ cm, $a = 10$ cm, $b = 25$ cm

The sources of the occurrence of B_z are:

1. The current flowing in the metallic inner shell of the chamber (the “liner”). Owing to the toroidal geometry, such a current inevitably produces a component directed parallel to the z axis.
2. The current flowing in the primary winding of the transformer that generates the discharge voltage. Despite the presence of a conducting shell shielding the vacuum chamber against penetration of stray magnetic fields, during the discharge pulse a small component of the stray field remains inside the chamber, parallel to the z axis.

3. The winding that produces the longitudinal magnetic field also makes its contribution to the component B_z. The current flowing through the turns of this winding has a small azimuthal component. The presence of this component is equivalent to the flow around the toroidal surface of the chamber of a longitudinal current, which will produce a field component in the direction of the z axis.

4. The component B_z is also produced by the "return turn," which is connected in series with the winding of the longitudinal magnetic field and serves to eliminate coupling between the discharge circuit and the longitudinal magnetic-field circuit. The return turn runs along the equator of the chamber on its outer side. Inside the chamber the magnetic field of the current flowing in the return turn is, in order of magnitude, comparable with the component B_z produced by the longitudinal-field winding, but their signs are opposite.

The contribution to the magnitude of the component B_z from the sources indicated in items 1, 2, and 4 can be determined experimentally. The component along the Z axis produced by the longitudinal-field coil is difficult to measure, since it is very small in comparison with the main azimuthal component of the field. However, the contribution to B_z from the longitudinal-field coil can be estimated by calculation. Knowing the total value of B_z (which under typical conditions reaches 10 G, i.e. only $\sim 0.2\%$ of the magnitude of B_0) and the value of the ratio p/I, which is determined on the basis of radiointerferometric measurements of n_e and determination of T_e from the mean conductivity, one can, using formula (1), construct the curve of variation of δ during the dis—

series. This curve for typical conditions is shown in Fig. 3 together with the current oscillogram.

The accuracy in determining δ should not be overestimated. Formula (1) was derived under idealized assumptions, which in carrying out the experiments are fulfilled only in a very rough approximation (owing to the azimuthal nonuniformity of the longitudinal magnetic field, the complex geometry of the stray field of the transformer primary winding, and the presence of gaps in the metallic shell of the chamber, which weaken its stabilizing action). Therefore, the curve of the change in δ shown in Fig. 3 should be regarded more as a qualitative than as a quantitative characteristic of the radial motions of the plasma cord. Nevertheless, Fig. 3 shows with sufficient clarity the connection between the motion of the cord and the change in the magnitude of the discharge current. At the beginning of the process the axis of the cord is displaced outward, as a result of which at a certain moment an intense interaction of the plasma with the diaphragms installed in the chamber begins. The holes in the diaphragms are displaced somewhat toward the outer wall of the chamber, but this displacement proves insufficient to prevent contact between the expanding plasma cord and the edges of the diaphragm. Interaction with the diaphragm leads to a decrease in the diameter of the plasma cord and to cooling of the plasma. Therefore the current falls. The secondary rise of the current occurs because, starting from

Fig. 3. Discharge current $I(t)$ and displacement of the axis of the plasma cord $\delta(t)$ relative to the axis of the discharge chamber. (The dashed line shows the deviation from the calculated value of δ when B_z is changed by ±1 G)

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a certain moment, the value of δ decreases, i.e., the cord moves inward. During this motion contact with the diaphragm ceases, the plasma again begins to heat up, and the diameter of the cord increases (with a substantially reduced concentration of particles in the cord).

Fig. 3. Discharge current $I(t)$ and displacement of the axis of the plasma cord $\delta(t)$ relative to the axis of the discharge chamber. (The dashed line shows the deviation from the calculated value of δ when B_z is changed by ±1 G.)

The validity of such an interpretation of the process can be verified by means of a very simple experiment. If the return turn is disconnected, the value of δ changes in such a way that the outward displacement of the plasma cord should increase considerably (under the experimental conditions to which Fig. 3 pertains, the current in the return turn is directed opposite to the current in the plasma and repels the plasma cord). Therefore the interaction of the cord with the diaphragm will increase and the conductivity of the plasma will fall. Fig. 4 gives an oscillogram of the discharge current for this case. It shows that disconnecting the return turn is associated with a sharp decrease in the current in the plasma. The same result is produced by changing the direction of the current in the longitudinal-field winding while the direction of the discharge current is fixed.

Thus, it turns out that the discharge process is very sensitive to such manipulations as can affect a small component of the total magnetic field along the z-axis.

Hence, among other things, it follows that one may count on a considerable improvement in the conditions for heating the plasma in toroidal chambers when using systems specially intended to create program-

···of the measured values of B_z (such a system may, for example, consist of conductors placed between the liner and the outer shell of the chamber).

Fig. 4. Oscillograms of the discharge current $I(t)$ with the return turn disconnected and of the intensity of the vortex electric field $E(t)$ on the axis of the discharge chamber.
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