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Abstract

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ON THE PROBLEM OF RECORDING LOSSES OF ENERGY BY A PLASMA

(Presented by Academician L. A. Artsimovich on 10 V 1960)

To estimate the effectiveness of thermal insulation of a plasma in a toroidal chamber with a strong magnetic field (^{1}), a radiation detector was used which could measure the fraction of the energy falling on the chamber wall. The detector consisted of platinum foil $6\,\mu$ thick, heated to 1500°K by direct current. The radiation of the foil was directed through a light guide onto an FEU-22 photomultiplier, whose photocathode has maximum sensitivity in the region of 9000 Å. The signal from the photomultiplier was fed through an amplifier to an oscilloscope. To obtain an absolute calibration of the detector, a capacitor of several tens of microfarads was discharged through the foil. Knowing the energy released in the foil from the beginning of the process to a given instant of time, one can find the relation between the energy put into the foil and the magnitude of the current pulse from the photomultiplier.

The detector could operate in the time interval from $0.2\,\mu$sec to several tens of milliseconds. The lower limit is determined by the thermal conductivity of the platinum foil, the upper one by its cooling due to radiative emission. The minimum energy that could be recorded is about $2 \cdot 10^{-3}$ J/cm^2. The sensitivity of such a detector can be made greater by improving the properties of the light guide and increasing the working surface of the foil (in our case it was 0.3 cm^2). The sensitivity limit of the radiation detector is determined by the intrinsic noise of the photomultiplier. Since the measuring apparatus of the radiation detector (photomultiplier, amplifier, oscilloscope) has no galvanic contact with the plasma and can be placed several meters from the operating installation, such an energy-recording system is interference-resistant. In addition, such a detector can be used in chambers with a high initial vacuum; to obtain this vacuum the chamber walls are degassed by preliminary heating to a high temperature ($\sim$ 400°). The radiation detector was placed in the chamber of the torus in such a way that the plane of the foil coincided with the wall of the gas-discharge chamber.

Figure 1 gives the curves of: the current in the gas I_g; the total voltage around the circuit V_{circ}; the derivative of the current $\dot{I}$; the current to the diaphragm* I_d; the pulse from the radiation detector $I_{\phi u}$; I_g is shown averaged, since the oscillogram is very irregular. On the $I_{\phi u}$ curve, bursts are visible which are

Fig. 1

Figure 1: Fig. 1

determined by the noise of the photomultiplier. On the W_1 curve are plotted the errors caused only by the noise of the photomultiplier. I_d is not observed at $H_0 = 3.2\,\text{kOe}$.

The dashed line shows the curve of the energy W_1 released on $1\,\text{cm}^2$ of the wall surface, calculated from the pulse curve of the radiation detector at a longitudinal magnetic-field strength H_0 equal to 3.2 and 0.53 kOe. A detailed description of the installation and of the method for measuring its electrical parameters is given in (1). As was shown in (2), the gas loop is stable when

$$K = \frac{ca^2}{2R}\frac{H_0}{I_r} > 1$$

(K is the Kruskal-Shafranov stability criterion), where a is the radius of the plasma loop and R is the major radius of the torus. When this condition was satisfied, no current to the diaphragm was observed (which corresponds to magnetic-field values $H_0 > 3$ kOe).

From oscillograms of the photomultiplier current obtained at various values of H_0 (from 7.8 to 0.53 kOe), it is seen that energy begins to be released to the wall of the torus chamber both in weak and in strong magnetic fields. But as the value of H_0 is decreased, the energy is released to the wall more intensely and its recording begins at an earlier time (200 μsec at $H_0 = 0.53$ kOe and 400 μsec* at $H_0 = 7.8$ kOe). The curve of energy release to the chamber wall has a smooth character, and no bursts were detected on it from the beginning to the end of the process in the gas.

Fig. 1

In Fig. 2 are shown the curves of the energy W_0 put into the gas, referred to 1 cm^2 of the surface of the toroidal-chamber wall, and the energy W_1 absorbed by 1 cm^2 of the wall. The energy W_0 was calculated from the formula

$$\int_0^t I_r U_r \, dt/S,$$

where U_r is the ohmic voltage drop, determined from

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* Two diaphragms were inserted into the toroidal chamber, whose internal diameter of 30 cm determined the cross section of the gas turn.

Fig. 2

Figure 2: Fig. 2

$$U_r = V_{\text{obs}} - L\,dI_r/dt,$$

$L = 0.65$ μH is the inductance of the gas loop*, and $S = 5.8 \cdot 10^4$ cm^2 is the surface area of the chamber walls. The errors plotted on the W_1 curve are due to photomultiplier noise and to the inaccuracy of graphical integration of the current during calibration of the sensor foil. The energy supplied to 1 cm^2 of the sensor foil during calibration was determined from the formula

$$W_1 = \int_0^t I_{\text{cal}}^2 R_{\text{foil}}\,dt/S_{\text{foil}}.$$

Processing of the results shows that by the time when the current in the gas becomes close to zero and the supply of energy from the capacitor bank into the gas ceases, the curves of the energy put into the gas and the energy recorded by the radiation detector do not quite coincide. Such a discrepancy may be explained either by a systematic error in the calibration of the detector or, more probably, by the fact that different amounts of energy fall on different parts of the chamber and especially on the diaphragms. Nevertheless, it is of some interest to consider the difference ΔW between the energy W_0 put into the gas and the energy W_1 recorded by the detector.

Fig. 2

This difference approximately represents the energy put into the plasma up to the given moment of time. Since it is a small difference of two large quantities, it is difficult to determine it accurately because of the reasons mentioned above and because of errors caused by photomultiplier noise. However, the fraction of energy put into the plasma can nevertheless be estimated, at least for the initial instants of time. From consideration of this difference one may conclude that at large values of H_0 ($K > 1$) energy begins to be released to the wall of the gas-discharge chamber when the plasma temperature reaches tens of electron-volts. The fact that the energy is appreciably released on a wall element at large H_0, when no current to the diaphragm is observed and the discharge, according to the available data, is stable ([1,2]), indicates that, apparently, the energy is carried to the walls by electromagnetic radiation. When the apparatus operates with weak magnetic fields ($K < 1$), the curves W_1 and W_0 almost merge, and ΔW is appreciably smaller than in the regimes where $K > 1$. In these

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* The inductance was measured on an installation modeling the torus.

regimes the moment at which the radiation detector begins to record energy approximately coincides with the beginning of the current to the diaphragm. Apparently, for $K < 1$ the role of particles in carrying energy out of the plasma becomes significant.

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