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A THERMONUCLEAR REACTOR WITH A PLASMA FILAMENT FREELY FLOATING IN A HIGH FREQUENCY FIELD[1)]

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The problem is considered of the possibility of utilizing the plasma of a high frequency discharge freely floating in deuterium for the realization of a controlled thermonuclear reactor. Methods of calculation are developed and the dimensions of the reactor are determined for which the neutron emission attains a power sufficient to make up the power expended in maintaining the discharge. A design for a thermonuclear reactor is developed. An indication is given of those scientific problems which still require investigation in order to realize this type of a thermonuclear reactor.

1. INTRODUCTION

In a previous paper[1] (which is cited below as I) a description was given of our observation of a freely floating discharge in a resonator with a high frequency field ($\omega = 10^{10}$). If the resonator was filled with deuterium the discharge had a filamentary form. Its position in the resonator was stabilized by the rotation of the gas and it existed for an indefinitely long time. The power which was absorbed by the discharge attained a value of up to 20 kW. The properties of the plasma in such a filament were investigated in detail primarily by spectrographic methods. These investigations and their theoretical interpretation were presented in the cited paper I.

The most interesting property of such a filamentary discharge turned out to be the high electron temperature of the plasma which in the interior region of the discharge is of the order of 100 eV. Such a high temperature can exist due to the thermal insulating properties of a double layer, since the electrons in the course of their thermal motion are reflected from it elastically.

In the present paper we investigate the problem of the possibility of utilizing the plasma of such a filamentary discharge in order to realize a controlled thermonuclear reactor and we make a calculation of the dimensions which a reactor must have in order to be a source of useful electrical energy.

The possibility of realizing a high power reactor is based on the following: the power generated in the reactor will be proportional to the volume of the filament, while its thermal losses are proportional to its surface, and, therefore, by increasing the dimensions of the filament it is possible to attain a situation in which the generated power completely compensates for the power losses. A reactor of this kind can be said to be "closed." It is evident that only a reactor of dimensions greater than those of a closed one can produce useful energy.

From subsequent discussion it will be seen that the information presently available on the plasma in the filament is already sufficient in order to carry out a design of such a reactor.

Theoretical and experimental investigations of the plasma filament in I have shown that due to the good thermal insulation properties of a double boundary layer even in the case of a high electron density their temperature can be greater than a million degrees. This removes one of the principal difficulties of realizing a controlled thermonuclear reaction—the loss of heat from the plasma due to the thermal conductivity of the electrons. Another difficulty is raising to a high temperature the deuterium ions themselves. We consider that this can be overcome by the thermal insulation of the hot ions by a strong magnetic field; these questions were discussed in I Sec. 7. Since the heat transfer from the electrons to the ions occurs due to the Coulomb interaction, and at a high temperature this

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is small, then energy must be supplied to the ions in order to heat them. As was shown in I (Sec. 8), this can be attained, for example, by exciting radial magnetoacoustic oscillations in the filament. In this case we assume that a sufficiently large fraction of the acoustic energy goes into heating the ions.

Thus, the thermonuclear reactor under consideration will consist of a high frequency filamentary discharge situated in a constant longitudinal magnetic field. Radial magnetoacoustic oscillations will be excited in it. We must take into account that the design of such a reactor is based on the extrapolation of data obtained by us in I. The volume of the filament in these investigations so far was not greater than 10 cm^3, while the plasma processes occurring in it will now be extrapolated to a plasma volume of several cubic metres. Such a great extrapolation is associated with a reduction in the reliability of the results obtained, but at the present stage of the work this is inevitable.

2. THE DESIGN OF A "CLOSED" REACTOR

We divide our calculations into two parts. At first we consider the energy balance of a thermonuclear reaction and establish the dimensions of the filamentary discharge and the temperature of its plasma. This is carried out with a sufficient degree of reliability.

We then consider the problem of the practicability of realizing the thermal insulation of a filamentary discharge of dimensions required by us. Although we already have sufficient data to solve this problem, it is just here that we have to employ a great degree of extrapolation, the limited reliability of which we have already mentioned. We present our calculations not in order to seek the optimum variant, but in order to exhibit the method of making such calculations. The final aim of these calculations is to determine the dimensions of a "closed" arrangement for which the energy obtained from the nuclear reaction will be sufficiently great in order to compensate for all the energy losses required to maintain the filamentary discharge.

For the sake of simplicity and reliability of these calculations we shall carry out an extrapolation for processes occurring in an apparatus similar to the one which we use for the experimental study of the plasma in a filament. This apparatus was described in I (Sec. 2), Fig. 2.1. A design drawing of such an apparatus of increased dimensions designed for a closed thermonuclear reaction is shown in Fig. 1. The filamentary discharge 1 of length $2l$ and of an external diameter 2a is situated in the middle of the cylindrical container of the reactor 2 which is filled with deuterium at a pressure p heated to a temperature T_D. As before, in order to stabilize the position of the filament within the container the deuterium undergoes rotational motion. This is achieved by the fact that deuterium enters the container from the ends through inclined nozzles 3 and leaves the container through a number of openings made in the central section of the container. We denote the temperature of the electrons in the plasma filament by T_e and that of the ions by T_i; we assume the latter is sufficiently high so that the thermonuclear reaction which arises would generate heat with a power

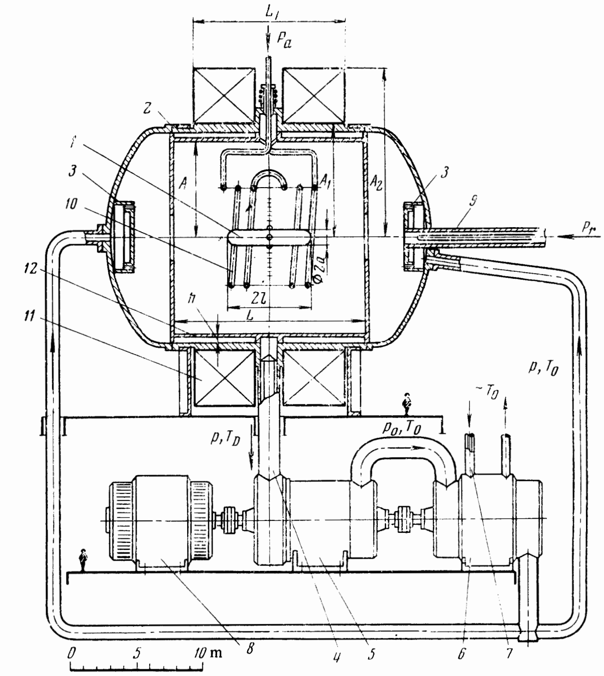

FIG. 1. Drawing of the construction of a thermonuclear reactor operating on a closed cycle. 1 – filamentary discharge, 2 – cylindrical container of the reactor, 3 – inclined nozzles, 4 – pipe connecting the container of the reactor with the gas turbine, 5 – gas turbine, 6 – isothermal compressor, 7 – cooling water, 8 – generator, 9 – coaxial waveguide, 10 – coil for the alternating magnetic field, 11 – solenoid, 12 – copper wall of the resonator, L – length of the resonator, L_1 – length of the solenoid, P_a – power of magnetoacoustic oscillations, P_r – high-frequency power, A – radius of the resonator, A_1 – internal radius of the winding, A_2 – external radius of the winding, $2l$ – length of the filamentary discharge, 2a – diameter of the filamentary discharge, h – distance between the wall of the container and the resonator.

P_T. This power goes entirely into heating the deuterium, since, as can be shown, with the high deuterium pressure utilized by us (30 atm) the dimensions of the container are sufficiently great so that the neutrons emitted by the filament do not leave the container and give up the greatest part of their energy to the molecules of the gas surrounding the filament. The deuterium enters through the pipe 4 into the gas turbine 5 where it expands adiabatically to a pressure p_0 and a temperature T_0 close to the temperature of the cooling water. Then the gas enters the isothermal compressor 6 cooled by the water 7 and again at a pressure p, but now at a temperature close to T_0, enters the reactor container. The power of the turbine 5 after subtraction of the power utilized by the compressor 6 is equal to P_p; it appears in the generator 8 and is directed into the electrical grid for utilization. In order to maintain the temperature of the plasma in the discharge we have the high frequency generator of power P_r fed by a coaxial waveguide 9. Moreover, the discharge is also supplied by the power P_a generated in it by magnetoacoustic oscillations which are excited in the filament by a variable magnetic field from the coil 10. The constant axial magnetic field H is produced by the solenoid 11 which utilizes the power P_H.

The container made of austenite steel has walls of

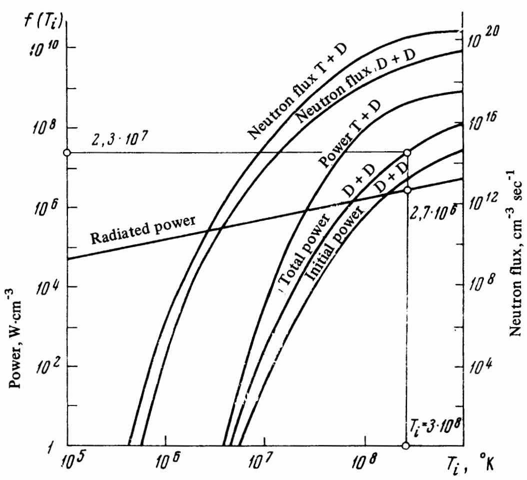

FIG. 2. Theoretical curves for the calculation of the power of a thermonuclear reactor. The ion density is $N_i = 10^{18}$ cm^{-3}.

thickness d_k which is determined by the allowable stresses at a gas pressure p. Within the container at a distance h from the walls there is placed the copper wall of the resonator 12 which guarantees the electrical conductivity of the internal surface of the container. The distance h is so chosen as to create a sufficiently good thermal insulation and so that the walls of the container would be at a temperature close to normal.

For the energy calculations in thermonuclear processes we utilize the curves given in the paper by Thompson[2]. They are reproduced in Fig. 2. These curves have been calculated for a plasma with an ion density of $N_i = 10^{18}$ cm^{-3}.

The power W obtained from 1 cm^2 of plasma depends not only on the temperature T_i, but also on the square of the pressure. It is equal to

$$W = \frac{N_i^2}{10^{36}} f(T_i) \ \mathrm{W/cm^3} \tag{1}$$

where $f(T_i)$ is the function shown in the graph of Fig. 2 and determined by the given temperature T_i. In the plasma the number of ions N_i is equal to the number of electrons N_e and is determined by the expression

$$N_i = N_e = \frac{N_n T_n}{T_i + T_e} \frac{p}{p_n}. \tag{2}$$

Assuming the normal values $N_n = 2.7 \times 10^{19}$ at $T_n = 273°$ and $p_n = 1$ atm, we obtain from (1)

$$W = \frac{5.4 \cdot 10^7}{(T_i + T_e)^2} f(T_i) p^2 \mathrm{W/cm^3} \tag{3}$$

From the curve shown in Fig. 2 it can be seen that in an equilibrium plasma when the electron temperature T_e differs but little from the ion temperature T_i (in spite of an increase of $f(T_i)$ with temperature) due to the quadratic term in the denominator the power W has a maximum near $T_i = 10^8$ deg. For energetic processes this temperature would be optimal if there were no power losses due to bremsstrahlung W_{rad} which are also shown on the graph and are equal to

$$W_{rad} = 8.2 \cdot 10^9 \frac{\sqrt{T}}{(T_i + T_e)^2} p^2 \ \mathrm{W/cm^3} \tag{4}$$

Obviously in order to obtain useful power from a thermonuclear reaction it is necessary that the losses W_{rad} would amount to only a small fraction of the generated power W. Denoting this fraction by ϵ we obtain

$$\varepsilon = \frac{W_{rad}}{W} = 1.51 \cdot 10^2 \frac{\sqrt{T_e}}{f(T_i)}. \tag{5}$$

From this expression it can be seen that ϵ becomes small when $T_e < T_i$, i.e., this is exactly opposite to what usually takes place in our filaments. At the given stage of our investigations the choice of the ratio of the temperatures is a somewhat arbitrary factor in the calculations. One of the factors which can turn out to be decisive in the choice of this ratio is the collective interaction between the ions and the electrons. As is well known, such an interaction has been experimentally established, but, as yet, we do not know how to take it into account quantitatively. If this interaction is great, then in order to avoid large losses of ion energy one must assume, as we shall do in future, that T_e and T_i are the same. We assume for ϵ the value 0.1. From the graph of Fig. 2 it can be seen that the ion temperature will then be close to $T_i = 3 \times 10^8$ deg, which has been assumed in our calculations. Then, from the graph we find $f(T_i) = 2.3 \times 10^7$ W/cm^3. In order to simplify the calculations we shall treat the filament as a cylinder of length $2l$, of radius b (b is the radius of the hot plasma in the filament).

If at an ion temperature T_i the radius of the Larmor orbit is equal to r_i, then one should take into account the fact that only the ions which are situated at a depth $2r_i$ below the surface of the filament will have a temperature not lower than T_i and will participate in the nuclear reaction. Then for the total thermonuclear power generated by the filament we have

$$P_T = 5.4 \cdot 10^7 \frac{(1 - 4r_i/b)}{(T_i + T_e)^2} f(T_i) p^2 \cdot 2\pi l b^2 \ \mathrm{W}, \tag{6}$$

with the Larmor radius determined in accordance with formula I (7.3) by the expression

$$r_i = (2kT_i m_0 c^2 / e^2 H^2)^{1/2}, \tag{7}$$

where k is the Boltzmann constant, and e and m_0 are the charge and the mass of the deuteron. Evidently, in order for the orbits to be contained within the filament we must have $r_i \ll b$. In order to maintain the temperature of the plasma filament it is necessary first of all to compensate for the power P_{rad} of bremsstrahlung radiation which will be emitted by the electrons over the whole volume of the filament. It will be equal to

$$P_{rad} = 8.2 \cdot 10^9 \frac{\sqrt{T_e}}{(T_i + T_e)^2} p^2 \cdot 2\pi l b^2 \ \mathrm{W}. \tag{8}$$

Evidently, this power can be compensated at the expense of the energy supplied to the electrons. Secondly, one must compensate for the losses P_k due to the thermal conductivity which was investigated in I Sec. 6. According to our experiments the thermal conductivity depends but little on the pressure and is proportional to the length of the filament. For deuterium according to these data we assume

$$P_k = \frac{2.6 \cdot 10^3 \cdot 2l}{\lg(l/a)} \ \mathrm{W}. \tag{9}$$

We calculate the useful power P_p which can be obtained from the gas turbine. If within the container the gas temperature is equal to T_0 then the useful power will be equal to

$$P_p = \eta_0 \frac{T_D - T_0}{T_D} [P_T + P_{rad} + P_k], \quad (10)$$

where η_0 is the total hydromechanical efficiency of the turbogenerator installation, $(T_D - T_0)/T_D$ is the thermodynamic efficiency.

The power supplied by the plasma in the filament to the surrounding gas will be compensated for by the high frequency power P_r and by the power of the magnetoacoustic oscillations P_a, so that

$$P_{rad} + P_k = P_r + P_a. \quad (11)$$

Moreover, it is also necessary to take into account the power P_H which will be expended in order to maintain within the reactor the magnetic field H. The value of this power depends on the volume of the solenoid winding, and is, therefore, to a certain extent arbitrary. We estimate it for the most advantageous case when the field is related to the height of the winding by the following expression:

$$H = 0.4\pi (A_2 - A_1) I \text{ Oe} \quad (12)$$

where A_2 and A_1 are respectively the external and the internal radii of the winding in cm, I is the current density in amperes. This formula corresponds to a solenoid of infinite length. In practice, conditions close to this can be realized in a solenoid which has an iron yoke providing a closed path for the magnetic flux similarly to the manner described in[3]. In the same manner one determines the power in the case of a toroidal resonator. The power utilized by the solenoid will be given by

$$P_H = \mu_c \varphi^{-1} \pi (A_2^2 - A_1^2) L_1 I^2, \quad (13)$$

where μ_c is the specific resistance of the metal of the winding (copper or aluminum) at the working temperature of the solenoid, L_i is the length of the solenoid, while φ is the filling coefficient of the winding. We denote the ratio of the radii by $(A_2/A_1) = \kappa$. Then from the preceding expressions we obtain

$$P_H = 2 \frac{\mu_c}{\varphi} \frac{\varkappa + 1}{\varkappa - 1} L_1 H^2. \quad (14)$$

Thus, for a constant ratio κ the power per unit length of the winding of the solenoid is independent of the transverse dimensions of the volume in which the magnetic field is created. But the weight of the metal in t the solenoid increases rapidly with its volume; it is equal to

$$F_H = \varphi \rho_0 \pi A_1^2 (\varkappa^2 - 1) L_1, \quad (15)$$

where ρ is the density of the metal of the winding.

On the basis of formula (6) it can be seen that for given values of T_i and T_e the generated thermonuclear power P_T increases in proportion to the square of the pressure and to the cube of the linear dimensions of the filament.

According to formula (4) the losses due to radiation increase in the same manner, but the other losses - those due to the creation of the magnetic field and due to thermal conductivity - increase only linearly with the dimensions of the filament. We determine what must be the dimensions of the filament in order that the obtained useful power P_p could compensate for the losses. In other words, the useful power P_p must be equal to the power expended. We take

$$P_p = P_H + \eta_a^{-1} P_a + \eta_r^{-1} P_r, \quad (16)$$

where η_r and η_a are respectively the efficiency of the high frequency generator supplying power in order to maintain the filamentary discharge, and of the generator of magnetoacoustic oscillations. Below we assume for the relative radiation losses (5) the value $\epsilon \approx 0.1$. The ion temperature, as has been already indicated, is taken equal to $T_i = 3 \times 10^8$ deg and coincident with the electron temperature T_e. If the magnetic field H = 10,000 Oe, then according to (7) the radius r_i of the Larmor orbits will be equal to 3.3 cm.

A very important index for the determination of the dimensions of the reactor is the quantity γ-the ratio of the semilength l to the filament radius b:

$$\gamma = l / b \quad (17)$$

(cf. I (6.28)). At the end of I (Sec. 6) it was pointed out that the length of the filament $2l$ attains its limiting value when

$$l = \lambda_0 / 4, \quad (18)$$

where λ_0 is the wavelength in the high frequency resonator supplying the power. A further increase in the power supplied leads to an increase in the diameter of the filament. The degree of increase in the filament diameter was determined on the one hand, (as has been indicated in I (Sec. 6) by the heat losses and, consequently, by the degree of perfection in the circulation of the gas, and, on the other hand, by the dimensions of the region within the resonator where power is supplied to the filament. In order that γ could be as small as possible it is necessary that the ratio $2\lambda/\lambda_0$ (I Sec. 5) should be as close as possible to unity. In our first experiments we had $\gamma = 25$, but we have now attained the value $\gamma = 10$ and there is a basis for assuming that one can attain the value $\gamma = 5$, which is the value that we have assumed in the present calculations. Evidently, the smaller is γ, the more fully will the volume of the resonator be utilized. Utilizing formulas I (5.1)–(5.3) and (13) we obtain for the radius of the resonator A and for its length L

$$A = \frac{l}{1.3} \frac{1}{\sqrt{1 - (2l/L)^2}} \qquad L = n\Lambda, \quad (19)$$

where Λ is the wavelength in the resonator.

According to (17)–(19) we choose the following values for the dimensions of the filament in the resonator: $2l$ = 650 cm, b = 65 cm. If the gas pressure in the container is p = 30 atm, then from formulas (6), (8) and (13) we obtain the following values for the power:

$$P_T = 21 \text{ MW} \quad P_{rad} = 4.0 \text{ MW} \quad P_H = 2.0 \text{ MW}$$

Assuming the wavelength of the high frequency generator to be ~13 m, on the basis of the expressions given in I (Sec. 5) we determine the length of the resonator and its radius: L = 1500 cm, A = 700 cm. For the interior radius of the solenoid winding we obtain A_1 = 730 cm, and, taking the ratio of the radii to be $\kappa = 1.5$ with a filling coefficient $\varphi = 0.85$, the specific resistivity of copper equal to 1.7×10^{-6} ohm/cm, and the length of the solenoid equal to $L_1 = 1{,}000$ cm, we obtain from formula (13) $P_H = 2$ MW. Setting the temperature of the gas in the container $T_D = 600°K$, the temperature of the cooling water $T_0 = 300°K$ and the coefficient $\eta_0 = 0.75$ in accordance with (10) we obtain for the generated useful power the value $P_p = 0.0$ MW. The power used to maintain the discharge with an efficiency of the high frequency generators being given by η_r and $\eta_a = 0.75$, according to (16) will be equal to $P_p = 2 + (4 + 1.3)/0.75 = 9$ MW. From this we see that the generated useful power will be sufficient to compensate for the power losses. Thus, a thermonuclear installation of dimensions chosen by us can operate without utilizing external energy and is therefore "closed."

The other parameters for this installation are calculated in the usual manner. Thus, the pressure after the turbine will be

$$p_e = p\left(\frac{T_0}{T_r}\right)^{n/(n-1)}. \quad (20)$$

For deuterium the ratio of specific heats is $n = 1.4$, whence we obtain $P_0 = 3$ atm. Also, we can show that at a pressure of $p = 30$ atm the consumption of deuterium circulated through the turbine will be 3 m^3/sec. The thickness of the walls of the container with a load of 30 kg/mm^2 permissible for alloy steel will be $d_k = 7$ cm. The weight of the container is approximately 1,000 T, while the weight of the copper winding for the solenoid according to formulas (10)—(15) for $A_1 = 730$ cm will be approximately $F_H = 17{,}000$ T.

The reactor is shown to scale in Fig. 1. From the diagram it can be seen that this "closed" installation has, although quite large, but still realizable dimensions.

We make an estimate of the reliability of the calculations carried out above. First of all we estimate the sufficiency of thermal insulation in the magnetic field of the ions in the plasma. We assume the temperature of the ions to be $T_i = 3 \times 10^8$ and the magnetoacoustic power supplied to the filament to be equal to 3–4 kW per centimetre of its length. We assume that in the plasma turbulent heat removal from the ions will occur. According to I (7.25) within the limits of accuracy of the calculation we find that the thermal insulation for the ions may be sufficient.

These conclusions are obtained on the assumption that a significant fraction of the magnetoacoustic energy goes into heating the ions. As has been pointed out already, this assumption, although quite probable, still has not been experimentally checked to date.

In our calculations we assume that the transfer of the power to the ions occurs uniformly over the volume of the plasma. It would be more correct to assume that in the case of radial oscillations more energy will be liberated at the centre of the filament; then the thermal insulation will be considerably improved and, consequently, the temperature of the ions will be increased. In our calculations, as has been pointed out already, we do not take into account the collective interaction between the ions and the electrons. We also do not take into account thermal losses of ions from the ends of the filamentary discharge. These losses are absent if the resonator is of toroidal shape. Taking all these circumstances into account one should regard our calculations as a first approximation.

3. INCREASE IN THE EFFICIENCY OF THE REACTOR

In the calculations given above we did not set ourselves the aim of obtaining the optimum design of a thermonuclear reactor. Our goal was only to show that the available theoretical and experimental data are sufficient in order to carry out a calculation of the dimensions of a reactor and to determine its energetic indices.

It is possible to improve the efficiency of the design considered above by a number of methods. The first is to raise the ion temperature T_i above the electron temperature T_e. Theoretically this is entirely possible. If we assume that at high temperatures the energy exchange between ions and electrons is practically absent, then there are no obstacles to them having different temperatures. The supply of power to the electrons comes from the high frequency source independently of the supply to the ions of energy from the magnetoacoustic oscillations of the plasma. Power losses due to bremsstrahlung will occur only at the expense of the electron energy. These factors may give the possibility of obtaining an electron temperature T_e lower than the ion temperature T_i which will considerably increase the efficiency of the thermonuclear reaction. Firstly, because losses due to bremsstrahlung from electrons will be diminished (cf., expression (4)). Secondly, for the same density N_i and for the same pressure the temperature of the ions will be increased, and this, in accordance with (3) will increase the thermonuclear power. All this can be realized only under the condition that, indeed, a significant fraction of the power from magnetoacoustic oscillations will go into heating the ions.

Further, it is evident that an increase in efficiency can be attained by utilizing a superconducting solenoid instead of an ordinary one. Then with a lower energy expenditure one can obtain a magnetic field greater by a factor of 3–4 and correspondingly increase the thermal insulation of the ions, to improve the conditions for supplying the power to the ions, and to increase the pressure in the reactor. All this will significantly reduce its dimensions.

Finally, the efficiency of a thermonuclear reactor will be significantly increased if its resonator is made in the shape of a toroid. This will not only lead to a more complete utilization of the volume of the reactor and of the magnetic field, but will also remove end losses of heat from the filament. As we have indicated already in I, experimentally a closed ring filament of plasma can have a stable existence. In I (Figs. 1-4), a photograph was given of such a filament obtained in a resonator with H_{01} oscillations. We have already realized a toroidal resonator in which we obtained an almost closed ring discharge. We have not continued these experiments, since experience has shown that such a type of apparatus of small dimensions does not make it possible to produce rotation of the gas in order to obtain a sufficiently quiet filamentary discharge and, consequently, to study its properties. Nevertheless, these experiments have shown that in a toroid the cross section of the filament continues to increase with increasing supply of power and, in spite of a strong snaking of the discharge, retains its stability.

In order to obtain useful power it is necessary to increase the dimensions of the reactor compared to the dimensions of a reactor working on a closed cycle. Since as the reactor is made larger the losses grow as the square of its linear dimensions, while the power developed grows as the cube of its linear dimensions, energy available for utilization will appear. It is possible to obtain useful power not only by increasing the dimensions of the installation, but also by simultaneously increasing the deuterium pressure and the intensity of the magnetic field.

4. CONCLUSION

The calculations given above give us a basis for assuming that an actual possibility is not excluded of realizing a thermonuclear reactor of appreciable power on the basis of a filamentary discharge. It is possible to establish the practical value of this direction of experimentation only by means of a further development of theoretical and experimental investigations of the filamentary discharge. The basis problems of such investigations are, firstly, to establish experimentally the validity of the expression adopted by us in I (7.25) for the thermal insulation of ions in a magnetic field and, secondly, to establish experimentally the efficiency of the heating of the ions by a magnetoacoustic oscillation (cf. 1, Sec. 8).

The dimensions of the reactor shown in Fig. 1 do not appear to be unrealizable. Moreover, as can be seen, the approximations which we have made in carrying out the calculations lead to an overestimate of the dimensions.

Finally, one should take into account that the method considered by us for utilizing a filamentary discharge for a thermonuclear reactor is not the only possible one. For example, the possibility is not excluded of producing heating of the ions in the plasma not by means of acoustic waves, but by the ordinary pinch of the filament, as is done in pulsed reactors, by a rapid application of an intense magnetic field. But, of course, one should begin by considering simpler arrangements as has has been done in the present paper.

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45