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SOLENOID PRODUCING A MAGNETIC FIELD UP TO 30 kOe IN A VOLUME OF 5 LITERS AND CONSUMING 500 kW

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1. GENERAL DESCRIPTION OF THE APPARATUS

IN an investigation of certain properties of plasma, we constructed a solenoid having the parameters indicated in the title to obtain a constant magnetic field. Inasmuch as the solenoid operates well and reliably, and the design of its winding and cooling system incorporates certain original ideas, we present here a brief description of the entire apparatus and of the construction of the solenoid, and present the appropriate calculations.

The construction of the solenoid is shown in Fig. 1, and the diagram of the entire setup is shown in Fig. 2. The solenoid winding consists of wafer-type coils, arranged six on each side symmetrically with respect to the central cross section, and in the center there is free gap of 3 cm, which makes it possible to carry out the observations in the transverse magnetic field. The solenoid has an iron armature, which increases the homogeneity and intensity of the magnetic field inside the solenoid, and decreases the stray field on the outside. The solenoid is fed from a 500 V dc generator rated 500 kW (Fig. 3). The current in the solenoid is controlled by varying the excitation of the generator, which is stabilized by the current itself.

The main design problem that had to be solved is connected with the winding of the solenoid itself. As is well known, the winding must satisfy the following requirements: first, it must have a high copper filling factor; second, it must be effectively cooled; third, it must be strong enough to withstand, at the attained magnetic field, the forces arising in the winding as the result of the interaction between the current and the field.

We used a ribbon-type winding consisting of a number of series-connected wafers. A similar type of winding was already used in the construction of the solenoid described by S. P. Kapitza[1]. The winding is cooled by a liquid flowing radially between the wafers; instead of oil we used distilled water, which in the case of turbulent flow produces a much more effective cooling than laminar flow of oil. The use of pure water for cooling has now become much simpler and more reliable, owing to the use of ion-exchange filters. As shown in Fig. 2, part of the cooling water is diverted and passes through the ion filter; it is thus continuously purified and its electric conductivity is maintained at a very low level (less than 10^{-7} Ohm-cm). In spite of the fact that the outer edge of the ribbon in the wafer has no insulation and is directly immersed in the water, the parasitic current through the water is practically nil.

The entire cooling system, through which pure water circulates, is made of copper or stainless steel. The circulating pumps are also made of stainless steel. The circulating cooling system is shown in Fig. 2. Attention must be called to the fact that a very important factor in the cooling system chosen by us is the absence of an insulating layer on the outer surface of the wafers, for this ensures effective transfer of heat from the copper

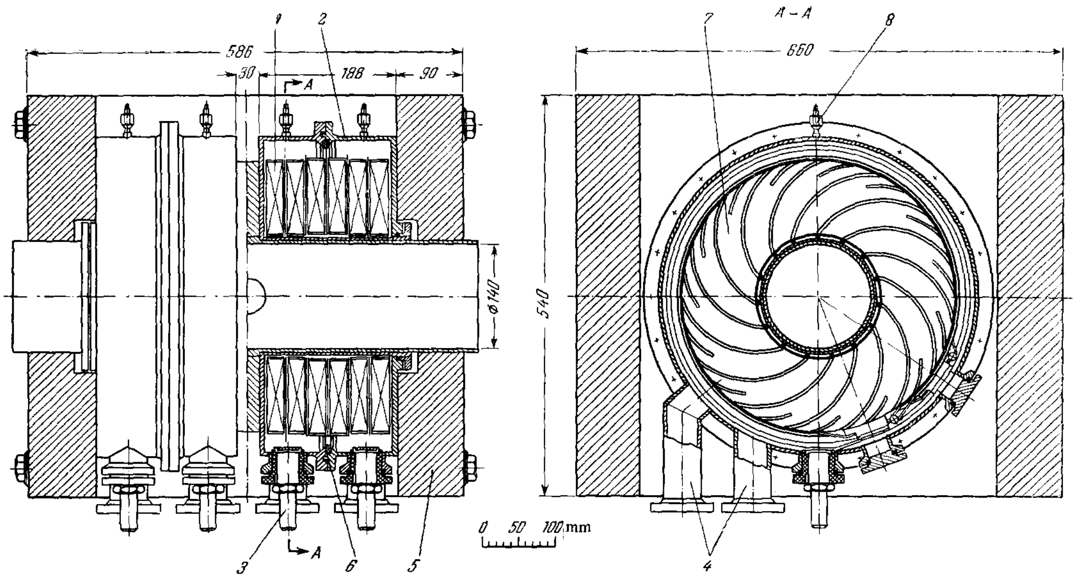

FIG. 1. Design diagram of the solenoid. 1 – wafer; 2 – jacket; 3 – current lead; 4 – tubes for inflow and outflow of water; 5 – armature; 6 – partition separating the water streams; 7 – spacer with spirals guiding the water stream; 8 – hole for dumping the water.

to water. In such an insulation system, the winding must be carefully protected against over-voltages that arise when the power supply is too rapidly disconnected. As a precaution, therefore, the winding is connected to the generator without a switch, and to stop the current flow it is necessary to stop the generator.

2. WINDING CALCULATIONS

We use the following notation: ribbon width 2b, inside wafer radius R_0, outside radius R_1, number of wafers 2n, total length of solenoid L, power supply W, current I, voltage V. It our solenoid $R_0 = 8.0$ cm, $R_1 = 18.0$ cm, L = 40.6 cm, n = 6, W = 5×10^5 W, and I = 10^3 A.

The calculation formulas for the winding are readily derived from Ohm's law and from geometrical conditions, and we present them here only in final form.

The end-surface area of the wafer is

$$S = \pi (R_1^2 - R_0^2); \tag{1}$$

the volume of the entire winding is

$$O = 4nbS; \tag{2}$$

the per-unit thermal load of the winding is

$$w = \frac{W}{O} \tag{3}$$

(in our solenoid w = 20.5 W/cm^3); the ribbon cross section area is

$$C = I \sqrt{\frac{\mu}{w}}, \tag{4}$$

where

$$\mu = \frac{\mu_0}{\eta} \tag{5}$$

is the resistivity of the ribbon, η is the coefficient of filling the wafer with copper, and μ_0 is the resistivity of the copper at the working temperature T_1. This temperature is determined by the cooling conditions and will be calculated in the next section (see formula (24)). In our solenoid $T_1 = 40-50°$ and $\eta = 0.9$, so that we used in the calculations $\mu = 2 \times 10^{-6}$ Ohm/cm. The thickness of the ribbon with the insulating liner is

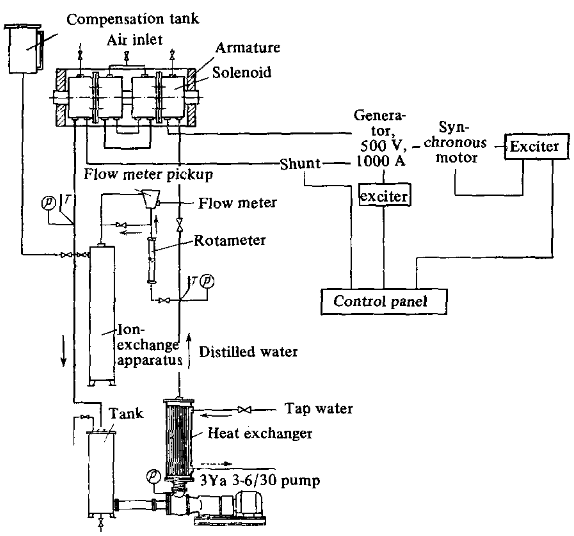

FIG. 2. Diagram of setup

$$d = \frac{C}{2b}. \tag{6}$$

An advantage of the winding employed by us is that it can be made of several layers of thin ribbons. A multilayer winding is not only easier to wind, but is also much more reliable and it is simpler to add new pieces of ribbon, since this can be done without noticeably disturbing the cross section of the ribbon. The wafers were wound on a frame in a special machine, which ensured even ribbon tension so that the coils obtained were dense and with level end surfaces. Each wafer was individually banded.

We chose two parallel ribbons, each with 25 × 0.6 mm cross section; the insulation was a lavsan polyester ribbon 0.14 mm thick and of the same width as the copper ribbon. The number of turns in each wafer was

$$N = \frac{R_1 - R_0}{d}; \tag{7}$$

the length of the ribbon in each wafer was

$$\mathscr{L} = \pi N (R_1 + R_0); \tag{8}$$

in our solenoid N = 73 and L = 60 meters.

3. COOLING AND THERMAL CONDITIONS OF THE WINDING

The cooling was by water flowing over the end surfaces of the wafers. The temperature gradient was the sum of two temperature drops, ΔT_1 (temperature drop in the copper) and ΔT_2 (temperature drop between the cooled water and the end surface of the wafers). The temperature drop from the central cross section to the ends is determined by the following expression:

$$\Delta T_1 = \frac{1}{2} \frac{b^2}{4.18 k_{Cu}} w, \tag{9}$$

where k_{Cu} is the thermal conductivity of the copper, which we assumed to be 0.96 cal/cm-sec. In our solenoid, at the load w = 20.5 W/cm^3 in the copper and at 2b = 2.5 cm, the temperature drop in the copper was only 4°.

The main temperature drop was between the water and the end surfaces of the wafers. Calculations show that to realize this temperature drop it is necessary to have an intense flow of liquid. The flow must be turbulent and the rate of flow of the water should be sufficiently large, since the heat transfer increases with the velocity. In the case of radial flow of the water between the wafers, the flow velocity must decrease on approaching the periphery of the winding. To ensure uniform heat exchange over the entire surface of the wafers, it

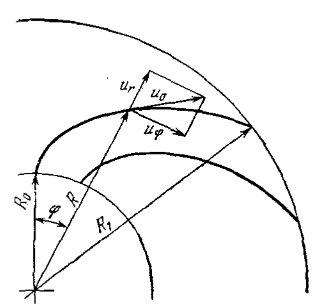

FIG. 3. Illustrating the calculation of the liner profile

is necessary to maintain the rate of water flow over the surface constant, this being effected with the aid of spacers placed in the gap between the wafers and diverting the stream of the water. This is done as follows: a thin glass-bakelite disc is inserted in the center of the gap between the wafers; on each side of the disc are fastened narrow teflon strips bent into a spiral (see Figs. 1 and 7); these strips not only direct the stream of liquid in such a way as to cause it to flow over the end surface with equal velocity, but also serve as spacers that are compressed between the wafers and ensure strength of the entire winding.

Let us calculate the curve into which the spacers must be bent to ensure a constant velocity of water flow. We denote the average water velocity in the gap by u_0. The coordinates R and φ determine the profile of the spiral liner between the coils, along which u_0 = const. Figure 3 shows the profiles of the liners and the resolution of the velocity intercomponents u_r and u_φ.

To maintain constant water flow it is necessary that the following relation be satisfied between the radial and tangential components of the velocity:

$$u_r R = u_0 R_0, \quad u_0 = \text{const}, \quad u_r^2 + u_\varphi^2 = u_0^2, \tag{10}$$

from which we get

$$u_\varphi = u_r \left(\frac{R^2}{R_0^2} - 1\right)^{1/2}. \tag{11}$$

The equation of the profile of the spiral is

$$R\frac{d\varphi}{dR} = \frac{u_\varphi}{u_r} = \left(\frac{R^2}{R_0^2} - 1\right)^{1/2}. \tag{12}$$

integrating this equation under the condition $u_\varphi = 0$ ($R = R_0$), we obtain the equation of the spiral curve of the spacers in the form

$$\varphi = \left(\frac{R^2}{R_0^2} - 1\right)^{1/2} - \arccos\frac{R_0}{R}. \tag{13}$$

For the calculations it is convenient to express this equation in parametric form, namely:

$$\frac{R_0}{R} = \cos x, \quad \varphi = \mathrm{tg}\, x - x. \tag{14}$$

The length of the stream is

$$D = \int_{R_0}^{R} \sqrt{dR^2 + R^2 d\varphi^2} = \frac{R_0}{2}\left(\frac{R_1^2}{R_0^2} - 1\right). \tag{15}$$

Figure 1 shows the section of the solenoid; we see that the number of the guiding spacers is larger at the outer edge of the wafer. This is due to structural considerations: first, for increased strength; second, to decrease the distance between spacers, so as to direct the stream of water effectively along the spiral. It is also seen from Fig. 4 that in the three outermost wafers the water flows from the periphery to the center, and in the three other wafers in the opposite directions. These streams are made continuous in the gaps between the

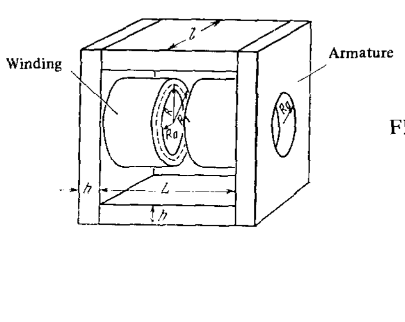

FIG. 4. Armature of solenoid

openings in the wafers and the internal tube, on which the winding is placed. The glass-bakelite disc spacers are placed in the gaps between the wafers and extend beyond the winding; this is done in order to increase the possible path of stray currents through the water in those places where there is an appreciable potential difference between neighboring wafers. The jacket is coated with enamel to prevent leakage of current through the water to the internal surface of the jacket.*

The temperature drop ΔT_2 between the water and the wall of the wafer is calculated by the usual method[2]. We need the following constants, which determine the properties of the water at 20°C: viscosity of water $\psi = 0.01$ poise, specific heat $c_0 = 1$ cal/g, density $= 1$ g/cm^3, thermal conductivity $k_0 = 1.5 \times 10^{-3}$ cal-cm/sec, kinematic viscosity $\nu = \psi/\rho = 0.01$, and Prandtl number $\mathrm{Pr} = \nu\rho c_0/k_0 = 6.6$. The average velocity of the stream of water between the wafers is

$$u_0 = \frac{Q}{4\pi n R_0 a}, \tag{16}$$

where Q is the quantity of water flowing, n is the half the number of wafers, and a is the height of the gap between the wafers, in which the water flows. The Reynolds number is equal to

$$\mathrm{Re} = \frac{d_e u_0}{\nu}, \tag{17}$$

where

$$d_e = 2a \tag{18}$$

is the equivalent diameter for a gap of height a. Then

$$\mathrm{Re} = \frac{Q}{2\pi n \nu R_0}. \tag{19}$$

to ensure turbulent flow of the liquid it is necessary to satisfy the condition $\mathrm{Re} > 2500$; this determines the lower limit for the water flow Q. Q determines the temperature difference ΔT_3 between the incoming and outgoing distilled water, which is used to cool the solenoid winding. From the heat balance we have

$$\Delta T_3 = \frac{W}{4.18 C\rho Q}. \tag{20}$$

In our solenoid, at full power and at a flow $Q = 1.2 \times 10^4$ cm^3/sec, the temperature drop ΔT_3 was 10°. This yielded Re = 8000, and ensured turbulence of the stream. To determine the drop T_2, we calculate the heat exchange between the copper and the water. To this end, we determined the heat-transfer number (see[2]), which is given by

$$K_0 = 0.04\,\mathrm{Re}^{-0.25}\,\mathrm{Pr}^{-0.6}. \tag{21}$$

The heat transfer coefficient between the copper and the liquid is

$$\alpha = c_0 \rho K_0 u_0, \tag{22}$$

From which we get the temperature drop between the water and surface of the wafers in the form

*Since the jacket was made of stainless steel, it was impossible to coat it with enamel in the usual manner. We are grateful to the Chemical Machinery Research Institute in Kharkov and to A. I. Matyash, the Director of the Laboratory, for this work, which was performed specially for us.

$$\Delta T_2 = \frac{bw}{4.18\alpha} = \frac{bw}{4{,}18 c_0 \rho K_0 u_0}. \quad (23)$$

This temperature drop between the wafers and the water makes very exact demands on the cooling system. In practice, it is not desirable to make the drop ΔT_2 larger than 20–30°. Therefore, given a ribbon width 2b and a specific thermal load of the winding w, taking into account the weak dependence of the heat-transfer number K_0 on the velocity, the only way to decrease ΔT_1 is to increase the flow velocity u_0. In our case u_0 lies in the range 2.5–3 m/sec. We find thus that the average copper temperature T_1 in the solenoid winding exceeds the temperature of the water entering the solenoid T_0, and equals

$$T_1 = T_0 + \frac{2}{3}\Delta T_1 + \Delta T_2 + \frac{1}{2}\Delta T_3. \quad (24)$$

As already indicated, in our solenoid $\Delta T_3 \approx 10°$; the temperature of the water coming from the heat exchanger is 20–30°C, and the temperature of the copper T_1 reaches 45–55°C, in accordance with which we calculate the average Ohmic resistance of the winding.

The pressure drop Δp necessary for the water circulation is calculated in the usual manner (see[2]) and equals

$$\Delta p = 8\cdot 10^{-8}\rho \frac{u_0^2}{a} \mathrm{Re}^{-0.25} D \text{ atm}, \quad (25)$$

where D, the length of the spirals, is determined by (15). The value of Δp calculated in this manner is too low, since it does not take into account the roughness of the wall and the appreciable input and output resistances. In our solenoid, the total pressure drop between the input and the output of the liquid was Δp = 1.3 atm at Q = 12 1/sec, a = 0.15 cm, and D = 16.3 cm.

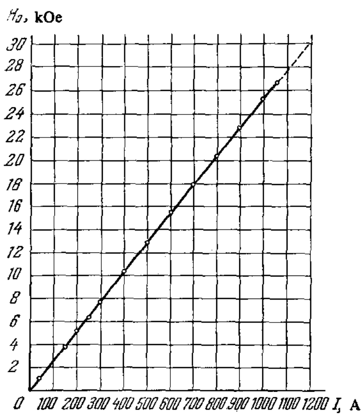

FIG 5. Dependence of the field H_0 at the center of the solenoid on the current I.

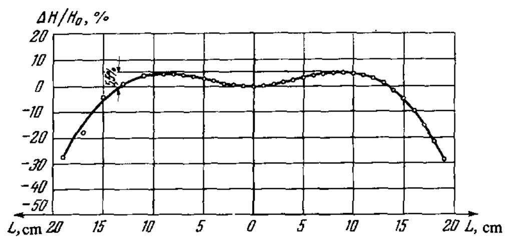

FIG. 6. Distribution of the field along the axis of the solenoid at H_0 = 255 Oe.

4. CALCULATION OF THE ARMATURE AND OF THE FIELD AT THE CENTER OF THE SOLENOID

In the case of an ideally short-circuiting armature, the field at the center of the solenoid, with allowance for the apertures at the ends of the winding, is given by the formula

$$H_0 = 0.4\pi \frac{A}{L}\left(1 - 2\frac{R_0^2}{L^2}\right), \quad (26)$$

where

$$A = 2\pi N I \quad (27)$$

are the ampere-turns of the solenoid. In our solenoid $A = 9 \times 10^5$ and $H_0 = 29.5 \times 10^3$.

The shape of the armature is shown in Fig. 4. To determine the dimensions of the armature it is necessary to calculate the magnetic flux Φ in the armature. It can be regarded as the sum of two fluxes:

$$\Phi = \Phi_0 + \Phi_1. \quad (28)$$

The flux Φ_0 is produced by the magnetic field flux through the aperture of the solenoid. With an approximation sufficient for our purposes, we assume that

$$\Phi_0 = \pi R_0^2 H_0. \quad (29)$$

The flux Φ_1 is produced by the magnetic field linking with the winding of the solenoid. To calculate the flux Φ_1 we introduce the coordinates

$$x = R - R_0, \quad x_0 = R_1 - R_0. \quad (30)$$

The field H in the winding at $R_0 < R < R_1$ and the field H_0 on the boundary of the armature and the winding of the solenoid is then given by

$$H = 4\pi j (x_0 - x), \quad H_0 = 4\pi j x_0, \quad (31)$$

where j is the average current density in the winding. We get

$$\Phi_1 = \int_0^{x_0} 2\pi H (R_0 + x)\, dx. \quad (32)$$

Substituting the field H from the preceding formula and integrating, we get

$$\Phi_1 = \pi H_0 \left(R_0 + \frac{1}{3}x_0\right) x_0. \quad (33)$$

From (28), (29), and (33) we obtain the total flux through the armature:

$$\Phi = \frac{\pi}{3} R_0^2 H_0 \left[1 + \frac{R_1}{R_0} + \left(\frac{R_1}{R_0}\right)^2\right]. \quad (34)$$

The calculation of the armature reduces to the requirement that its cross section must not offer a noticeable magnetic reluctance when the external magnetic

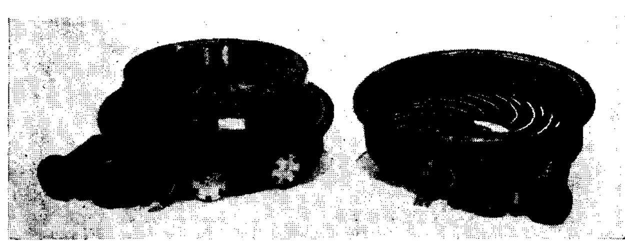

FIG. 7. Photograph of the solenoid winding.

circuit is closed. This will be the case if the magnetic induction B is much lower throughout the armature than the iron-saturation induction. In our calculations we assume that we should have $B < 17$ kG. As seen from Fig. 4, the armature is made up of plates of thickness h; they are cut of sheets of low-carbon steel. The thickness h should be sufficient to prevent saturation of the iron in the armature at the ends of the winding. To this end, it is necessary to satisfy the two conditions

$$h > \frac{\Phi_0}{2\pi R_0 B} \quad \text{и} \quad h > \frac{\Phi}{2\pi R_1 B}. \tag{35}$$

The plate width l is determined from the formula

$$l = \frac{\Phi}{2hB}. \tag{36}$$

In our solenoid h = 9 cm and l = 55 cm. The weight of the armature turned out to be 800 kg and the weight of the winding 210 kg, so that the total solenoid weighed somewhat more than one ton.

CONCLUSION

The solenoid calculations presented here are approximate but, as demonstrated by its tests, these calculations give results that are sufficiently close to reality (within 5—10%). The final parameters of the solenoids should be determined experimentally.

The experimentally determined dependence of the field H_0 in the center of our solenoid on the current I is shown in Fig. 5. The field distribution along the solenoid axis is shown in Fig. 6. These curves were obtained with a magnetometer operating at nuclear resonance in water. The thermal conditions were also in sufficiently good agreement with the calculations.

On the basis of the presented calculation method it can be shown that a solenoid of such a design can be realized also for powers much higher than 500 kW.

The detailed designs of the solenoid and of the heat exchangers were developed by designers A. I. Degal'tsev and Yu. E. Saprykin, to whom we are grateful. The apparatus was constructed at the machine shop at the Institute of Physics Problems of the USSR Academy of Sciences.

[1] S. P. Kapitza, in: Elektronika bol'shikh moshchnostei (High-power Electronics), No. 2, AN SSSR, 1963, p. 107.

[2] P. L. Kapitza, Dokl. Akad. Nauk SSSR 55 (7), 595 (1947).

Translated by J. G. Adashko