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MHD

SCMS-1 SUPERCONDUCTING MAGNET SYSTEM FOR AN MHD GENERATOR

U.S.-U.S.S.R. COOPERATIVE PROGRAM IN MHD POWER GENERATION

April 13-21, 1977
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MASTER

U.S. Department of Energy
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Superconducting Magnet System
for an MHD Generator (SCMS-1)

V.B. Zenkevich, I.A. Kirenin, V.A. Tovma

Institute for High Temperatures
Academy of Sciences U.S.S.R.

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The progress towards building efficiently operating MHD power plants is determined to a great extent by the success in the development of superconducting magnet systems (SCMS) for MHD generators.

The research and development effort connected with the building of the superconducting magnet systems for MHD generators at the Institute for High Temperatures of the U.S.S.R. Academy of Sciences included the designing, fabrication and testing of the superconducting magnet system for an MHD generator (SCMS-1), producing a magnetic field up to 4 Tesla in a warm bore tube 300 mm in diameter and 1000 mm long (the nonuniformity of the magnetic field in the warm bore did not exceed ± 5%) [1,2].

Because of the requirements for the magnetic system of an MHD generator the design selected consisted of a dipole, saddle-form coil, wound around a tube. Such a system has the following advantages:

a) it provides an adequate uniformity of high magnetic field in the channel;

b) the fabrication of the bore tube, which carries the mechanical stress of the coil, is technically simple;

c) the mechanical stress of the coil is transmitted to the bore tube thus reducing the need for heavy banding between coil layers. This simplifies the fabrication technology of the system and does not greatly increase the weight and the dimensions of the magnetic system, as would the heavy external banding, if it were used.

The cooling of the coils is of the external type with helium access to each layer of the winding.

For winding of the superconducting magnet system a 49-strand cable was used consisting of 42 composition conductors, having a diameter of 0.3 mm each, containing six superconducting strands with a niobium-titanium alloy base (the superconducting strands were 70 microns in diameter), and seven copper conductors of the same diameter as the composite conductors. The cable is made monolithic with high purity indium and insulated with lavsan fiber. The cable diameter with insulation is 3.5 mm.

The fabrication and support of the complex coil configuration is facilitated by aluminum supports of two types: the "central," around which layers of winding are wound, and "end supports," which were inserted between single layers of the winding. The supports (4 mm thick) were made of sheet aluminum of the AD-1M brand. Each half of the dipole winding contained up to 29 layers with the number of coils varying, depending on the distance from the axis of the system, between 61 coils on the internal layer and up to 97 coils on the external layer.

Figure 1 shows the assembly of the supports forming the coils.

The winding of the superconducting magnet system was made of ten separate pieces of cable with welding seams between the pieces of cable located on the ends of the coils. The seams were made using copper bars with 10 x 12 mm section; the ends of the connected cable pieces were placed into grooves 6 mm in width and 3.5 mm in depth and coated with high purity indium.

Portions of the winding made of a continuous piece of cable, represent discrete sections of the winding, each one attached to a current leadout –

a piece of copper pipe 10 x 1.5 mm. The current leadouts were brazed to copper plates by means of a silver brazing compound PS -45. Thus, winding was connected by twelve current leadouts: two of them were attached to the ends of the winding and served to feed transport current, and ten were connected to the points of sequential connection of sections to provide parallel connection of each section of the winding to the protective 0.15 Ohm resistance located beyond the cryostat. The sequentially connected gating resistors were provided, in case the winding should go into normal state.

The superconducting cable was placed between the supports determining its shape, and each layer of the winding was coated with a special dielectric compound ED-6 with epoxy base. This was done in order to avoid degradation of the current in the winding, that could occur if the coils were to shift under the effect of electrodynamic stresses.

Figure 2 shows one of the layers of the winding.

The tangential and radial stresses in the coils were compensated by 1 mm wire stainless steel (OKH18N10T) banding between layers. The wire was placed in bands equidistant from each other in 1 mm deep and 50 mm wide grooves cut in the supports; the distance between the banding strips was 70 mm. To protect the insulation of the superconducting cable from damage by banding wire stainless steel bands 0.1 mm thick were placed between the layers of the winding and the wire.

The axial stresses on the butt ends of the winding were assumed by two stainless steel flanges (KH18N10T) 20 mm thick, fastened to the bore tube by means of eight bolts and interconnected across the external diameter by twelve lengthwise 2 x 20 mm section strips, welded to the flanges.

The winding was cooled between the layers by means of 1 x 10 mm longitudinal channels cut in the supports and the channels formed by the banding strips. The entry of helium into the channels occured through the butt surfaces of the winding and through the openings in the supports of the points where the channels were located. The preliminary tests of SCMS-1 were carried out in a vertical helium bath cryostat 700 mm in diameter.

Figure 3 shows the cross-section of the vertical cryostat (the overall view is shown in figure 4) with the magnetic system placed inside the liquid nitrogen cooled cryostat. It consists of two vessels with a high vacuum insulation. The helium vessel consists of two cylindrical containers [2] and [3] with elliptical bottoms. To reduce the heat flux to the liquid helium, the external coating of cylindrical container [2] has a layer of aluminum-coated lavsan film. The nitrogen vessel also consists of two cylindrical containers with elliptical bottoms [4] and [5]; to reduce the thermal fluxes to the liquid nitrogen the external surface of cylinder [4] has a multi-layer insulating screen consisting of alternating layers of aluminum-coated lavsan and fiberglass paper.

The superconducting magnet system is suspended in the helium cryostat by suspending it from flange [6] by means of three stainless steel pipes.

To reduce the thermal fluxes to the helium, produced by convection heat distribution and heat conductivity of the gas column and the cryostat throat, the upper portion of the helium cryostat is plugged with a stopper [10] made of eight plastic foam circles. To reduce the amount of liquid helium necessary for filling the system, the internal volume of the coils is also filled with plastic foam. To cool the superconducting magnet system coils and fill the helium vessel with liquid helium, two pipes (7) and (8), have been installed, made of two concentrically placed, thin walled stainless steel pipes, with vacuum space between the walls. The pipe (8) was inserted under the coils of the superconducting magnet system and is used for the cooldown of the system (to 4.2 K); the pipe (7) was terminated above the system and served for filling the cryostat with liquid helium and for maintaining the liquid helium level.

To ensure the safety of SCMS-1 cooldown in the entire temperature range (from 300 to 4.2 K) two safety valves were provided, that could be regulated in the .07 - 2 kg standard/cm^2 range.

To ensure the safe transition of the winding from the superconductor to the normal state provisions were made for lifting the flange (6) supporting the suspended SCMS-1 winding, in order to dump the rapidly evaporating helium. The flange can be lifted along 18 directional pins to a height of 80 mm limited by retaining nuts.

The amount of liquid helium necessary for the cooling of a large superconducting magnet system, is determined to a great extent by the cooling system selected. We used a three-stage cooldown of the SCMS-1 winding. Figure 5 shows the diagram of the cryogenic system.

The cooldown of SCMS-1 from 293 to 80 K was achieved by means of liquid nitrogen poured into the helium vessel of the cryostat (6) from the nitrogen tank (5) (TRZhK-3M).

The monitoring of the feed rate of liquid nitrogen to the SCMS and the temperature changes of various sections of the vessel was performed by measuring resistances of separate sections during the cooldown. During the cooling process the difference in temperatures of the internal and external walls did not exceed 5 K, which guaranteed an absence of excessive temperature stresses in the winding.

The second stage of the cooldown consisted of reducing the coil temperature from 80 to about 65 K; this was accomplished by pumping out the nitrogen vapor to a residual pressure of $P \sim 0.17$ Ata. using a vacuum pump of the VN-1MG type. The reduction of coil temperature to $T \approx 65$ K made it possible to reduce the amount of helium required for cooling the winding by about 5%.

Prior to the last stage of cooldown (filling with liquid helium) the liquid nitrogen was removed and the coils and helium vessel were carefully purged with gaseous helium.

The liquid helium from vessel (8) of the RS-100 and RS-2500 type having a capacity of 100 and 500 litres, respectively, was transferred through a siphon into the lower portion of the cryostat. The transfer siphon at its exit has a collector with twelve pipes designed to provide a uniform distribution of helium around the perimeter of the winding. The evaporating helium passed through the channels in the winding and the circular millimeter gap of ~ 547 mm between the helium cylinder and the winding. The cooling capacity of the vented helium vapors was used to cool two primary current leads, which during the charging of the magnetic system were transmitting current, as well as the 10 auxilliary current leads connecting the winding sections with the protective resistance and the cryostat throat.

The distribution of gas flow along the main and the auxilliary current leads and the cryostat throat was maintained by means of valves located upstream of the rotameters R_1, R_2 and R_3. The flow distribution is regulated to maintain approximately equal temperature at the three exits from the cryostat. The measurement of the flow temperature was by means of carbon resistor thermometers T_1, T_2 and T_3 located directly in the pipeline at the exit from the cryostat.

Each of the three flows exiting from the cryostat was heated to the ambient temperature (15 - 20 C) in electrical heaters (4) (the output of each was regulated between 0 and 4.5 kW depending on the amount of helium and its temperature at the exit from the heater) and passing the rotameters (3) was collected into a 100 m^3 soft bag. The gaseous helium from the gas bag was pumped by three compressors (2) of the IVUV-45/150 type into 1500 m (normal) cylinder banks (1).

During the cooldown of the SCMS-1 from 65 to 4.2 K the rate of liquid helium flow between the vessels and the cryostat was regulated in the 50 l/hr range during the initial cooling period (in the temperature range indicated above) to 150 l/hr towards the end of the cooldown, i.e., when the winding was practically down to operating temperature. The helium transfer rate was monitored by measuring the electrical resistance changes in the winding sections and the gas temperature at the exit from the cryostat. The gas temperature at the cryostat exit was no lower than 238 K.

The process of system cooldown with subsequent helium refilling to the operating level took about 8 hours: 6 for the cooldown and 2 for refilling of the cryostat to operating level. The filling of the SCMS-1 and the helium bath of the cryostat used up 410 l of liquid helium. The filling to the operating level (200 mm above the top of the system) required 230 l of liquid helium.

For liquifaction and accumulation of helium the "Air Liquid" made (9) facility was used, having an output of 30 l/hr with the subsequent transfer of liquid helium into Dewars (8) of the RS-500 and RS-100 type, and also into the fixed container with V = 3000 liters, made of a modified cryostat with a helium volume of 1300 mm.

The preliminary testing of the SCMS was made in a vertical cryostat. The electrical schematic is shown in figure 5. The feed source is based on a low voltage motor generator of the AND-5000/2500 type. Current is regulated through excitation coils of the generator with voltage fed from the electrical machinery amplifier of the EMU-3P type. In turn, the windings of the EMU-3P are fed from rectifiers. The regulation of the current feed to the SCMS may be done both manually (by the operator) and automatically (by means of an appropriate automation control unit). The feed source provided current up to 5000 Amperes with the output voltage up to 6 V, the current stability was no less than ± 0.5% from the assigned current value.

Since the superconducting cable used in the winding was partially stabilized (the ratio of section of normal metal with high electrical conductivity, Cu and In, to the section of the superconductor equals 7, and only ~ 20% of the cable surface is in contact with the liquid helium), special attention was directed at protecting the winding against the possible transition to normal state. The protection was first of all the gating of the section. The external resistance, gating each section, should a normal zone appear in that section of the winding, dissipated a significant portion of the energy accumulated in the winding. In addition, protective functions were performed by the aluminum support, particularly the central supports. If the system should begin operating in normal state (such a transition is inevitably accompanied by a drop of current in the system and consequently a change in the magnetic flow penetrating the supports) the supports would experience swirl currents, which would play the role of the secondary transformer windings (the primary transformer winding in this case would be the winding of the SCMS). At that point the supports would dissipate part of the energy connected with the magnetic flow penetrating the support.

Should the normal zone appear in the winding made of partially stabilized cable, it would be best to extract the energy rapidly from the magnetic system. One of the possible methods of doing this is to discharge the winding into active resistance. It is known that a portion of the energy produced for active resistance during a discharge is proportionate to the value of this resistance, while the value of the resistance is limited by the value of breakdown voltage through the cable insulation. The preliminary tests of the cable insulation demonstrated that it can support voltages up to 1000 V. On the basis of this the value of discharge resistance during tests of the SCMS was set at 0.4 Ohm. The power circuit was decoupled using an air contactor with an arc extinguishing chamber.

The current in the winding was measured by means of a measuring resistance R = 0.0001 Ohm and a digital voltmeter of the TR-6555 type equipped with a printing device.

The measurement of the magnetic field strength was conducted using a calibrated Hall sensor located in the center of the magnetic system. The Hall sensor was powered from a "Deviz" type battery; the monitoring of the measuring current and the measuring of the electromotive Hall force were performed by a digital voltmeter of the "Solatron" type.

The voltage at the ends of the winding during the increase and decrease of current was monitored by means of a digital voltage of the TR-65 type.

The SCMS winding was tested at different rates of current increase in the range from 0 to 0.3 Amps/sec with numerous current increases to 500 Amps. The discharge of the SCMS winding was carried out both in the slow and the rapid operating mode by discharging to the discharge resistance. The time constant for the current extinction was ~ 40 seconds.

The critical SCMS current was I_{cr} = 589 Amps, the rate of current density was 3.77 x 10^3 Amps/cm^2. At critical current the magnetic field B_o in the center of the system equaled 3.8 Tesla and the maximum rate of magnetic field on the coils, 60 kE. At critical current the coil of the system accumulated energy approximately equal to ~2.254 megaJoule. The value of the critical current of SCMS proved to be ~ 15% less than the average value of critical current in short samples of the superconducting cable used to fabricate the system. Figure 7 shows the dependence of critical currents in the cables on the value of the magnetic field and the line dependence of maximum field in the winding on the value of current feeding the winding. When assembling the SCMS coils in the horizontal cryostat, measures were taken to guarantee good cooling of the contact plats, connecting the coil segments.

Main characteristics of the SCMS-1 winding

Diameter, mm	
internal	400
external	690
Length, mm	1790
Weight, kg	1800
Inductance, Gn	13
Critical current, Amperes	589

Rate of current density, Amps/cm^2	3.77 x 10
Magnetic field in the center of the system, kE	38
Accumulated energy, megaJoule	2.25
Length of uniform field zone (± 5%), mm	1000

Horizontal Cryostat with winding SCMS-1

After testing in the vertical cryostat, SCMS-1 was placed in a horizontal cryostat.

Figure 8 shows the diagram of the cross-section of the horizontal cryostat with SCMS-1 winding and figure 9 shows the overall view of the horizontal cryostat.

The cryostat consists of a horizontal, eccentrically located vessel system with a high vacuum, multi-layer insulation. The internal room temperature bore of 300 mm serves to accommodate an MHD generator channel. The special feature of this cryostat design is that the internal cylinder of the helium vessel is also the supporting bore tube of the SCMS-1 coils with flat bottoms welded on to it. This design makes it possible not only to have a maximum dimension for the room temperature zone, but also to decrease the horizontal dimension of the cryostat itself.

The helium bath (12) is attached with four suspension supports (8) to the nitrogen bath (2).

To compensate for axial stresses, occuring in operation as a result of interaction of magnetic field with plasma, and also during the transport of the cryostat, the helium vessel through supports (6) transmits mechanical stresses to the nitrogen vessel. The external housing through four supports (10) bears the weight of both the nitrogen and the helium vessels. The orientation of the nitrogen vessel is controlled by four struts (3).

Between the bottoms of the external housing and the butt ends of the helium vessel are located shields (9), attached to the nitrogen vessel and having a temperature close to T = 77 K.

To decrease the amount of liquid helium placed into the cryostat, the space between the winding of the SCMS and the external helium vessel wall is filled with plastic foam filler. The evaporating helium is removed from the cryostat along six current leads (5) made of 16 x 1.5 diameter copper pipes with perforated 3.5 mm section openings with a 25 mm pitch. Of the six pipes four are used as current leads and two as intermediate current leads connecting sections of SCMS-1 winding with a protective system which transits from the superconductor to the normal state.

The design of the cryostat makes it possible to feed liquid helium into the helium vessel from the bottom and the top of the SCMS-1 coils. The liquid helium level is monitored by means of "feelers" connected to appropriate instrumentation and to a sonic and light signaling system.

To ensure safety during the period when SCMS-1 shifts from superconducting to normal state, the helium vessel of the cryostat is provided with a safety valve and a rupture membrane.

Technical characteristics of the cryostat

Dimensions, mm	
length	2500
external diameter	1700
height	2400
Diameter of warm bore, mm	300
Weight of cryostat with SCMS-1 coils without cooling agents, kg	6000

Amount of liquid helium contained in the helium vessel up to the working level, l	600
Time for helium operating to the minimum permissible level, hours	
without current	15
with current	5
Amount of liquid helium for cooling SCMS-1 and helium vessel of the cryostat from 80 to 4.2, l	700
Evaporation of helium at I = 600 Amps, kg/hr	6
Evaporation of liquid nitrogen, kg/hr	1.4

BIBLIOGRAPHY

1. The Most Important Results of Scientific and Research Projects of 1975. Moscow, Nauka, 74 - 77, 1976.
2. V.A. Al'tov, et al. Saddle Coil Superconducting Magnetic System of an MHD Generator. Electrotekhnika, No.8, 2 - 4, 1976.

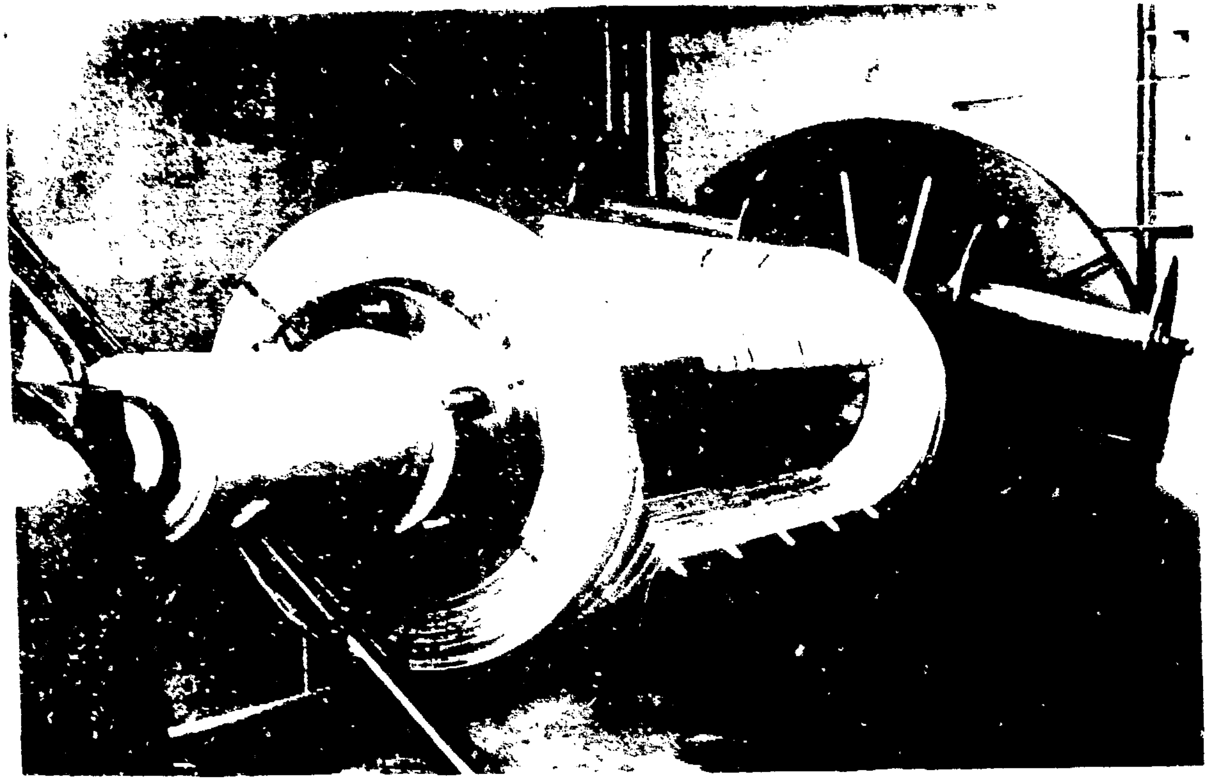


Fig. [illegible]. Assembly of supports for magnet coils.

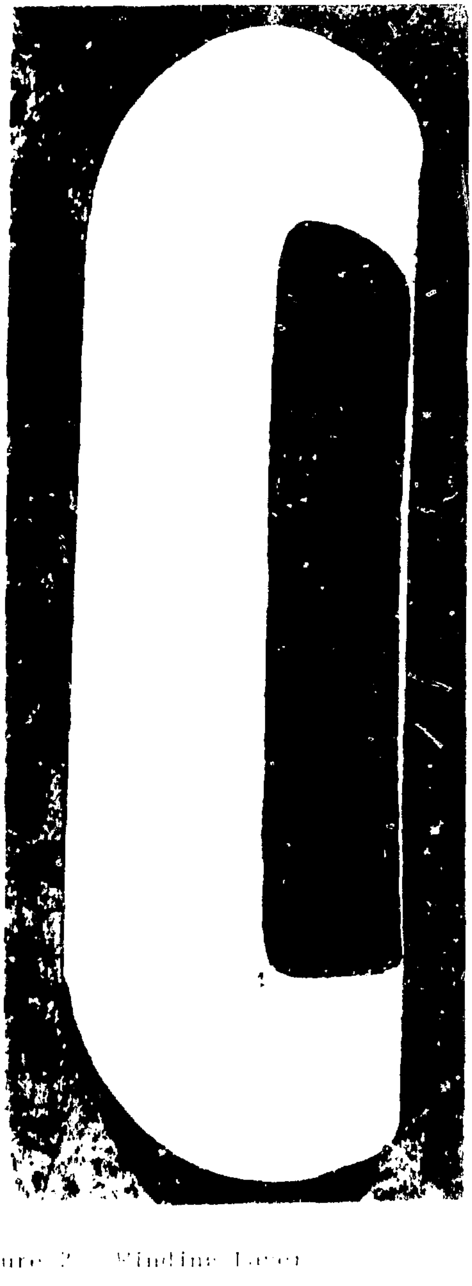


Figure 2 Winding Layer

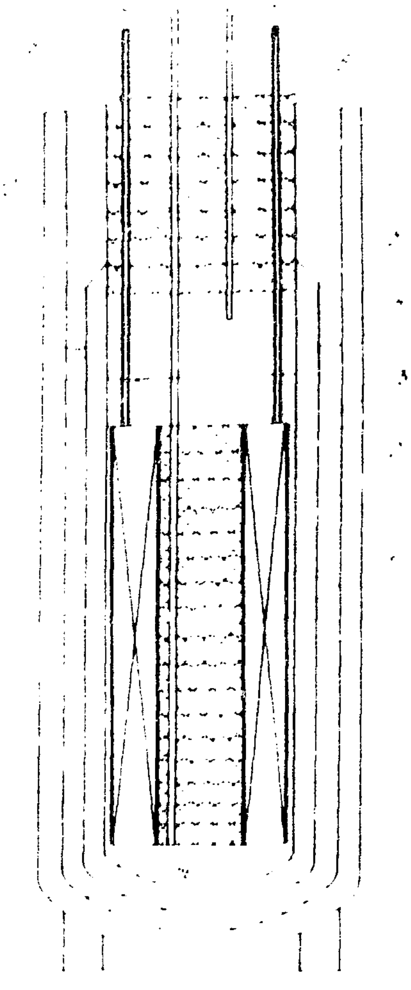
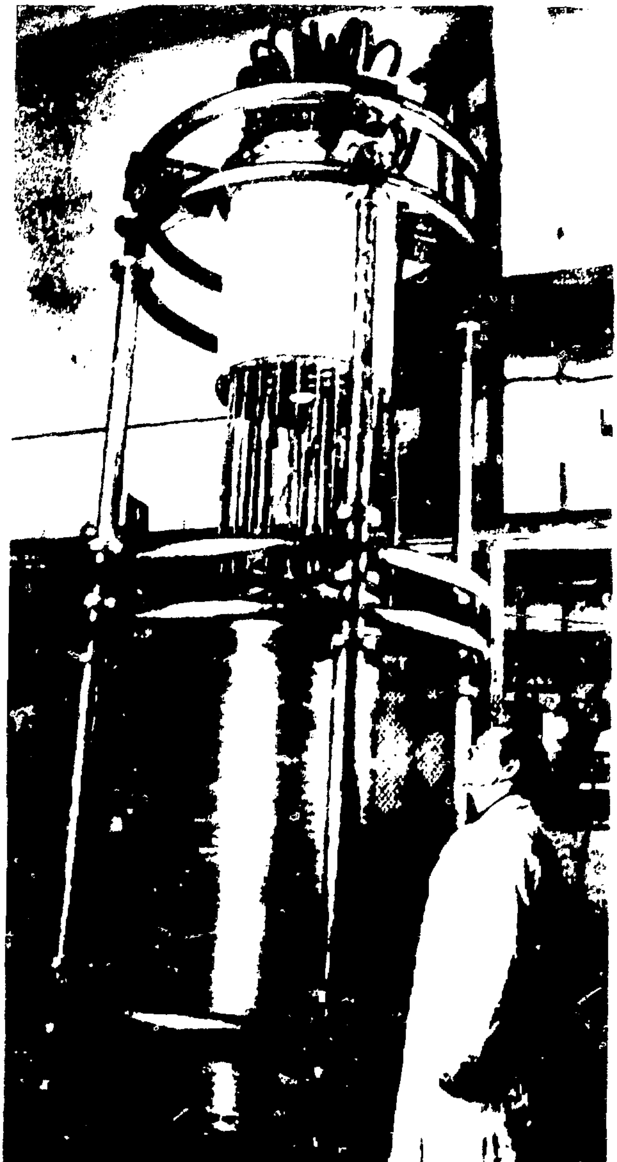
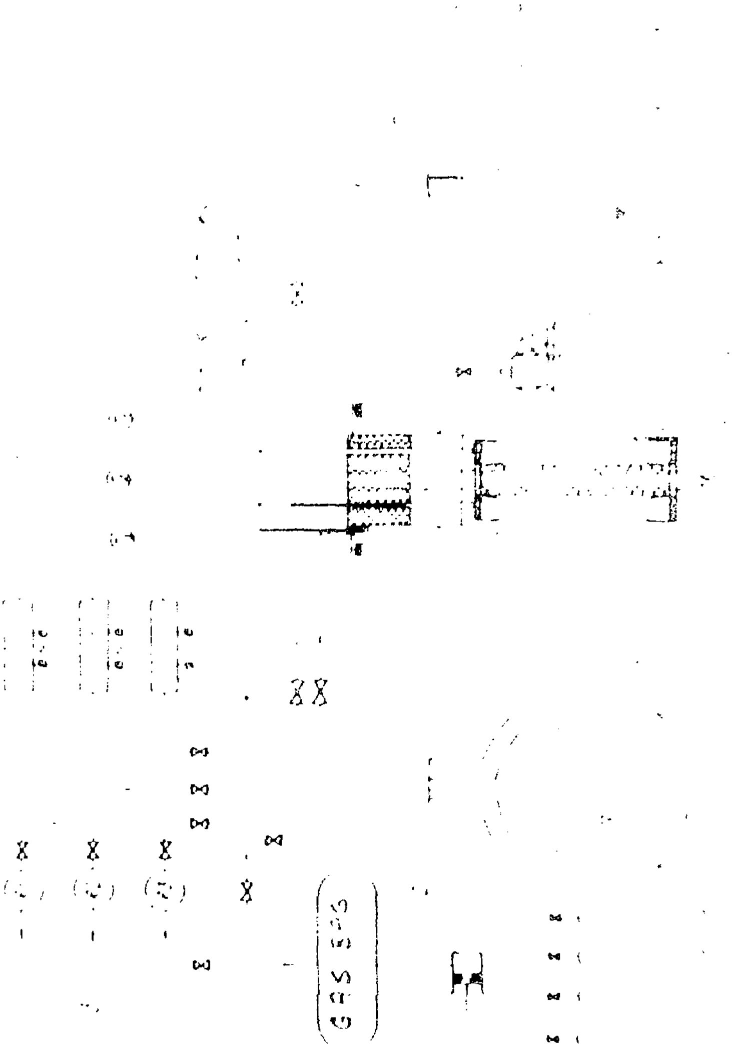


Figure 3. Cross-section diagram of winding and cryostat.

1 winding; 2 helium cylinder;
3,4 nitrogen vessel cylinder;
5 external housing; 6 cryostat lid;
7,8 filling pipes; 9 current leads;
10 plastic foam stopper.





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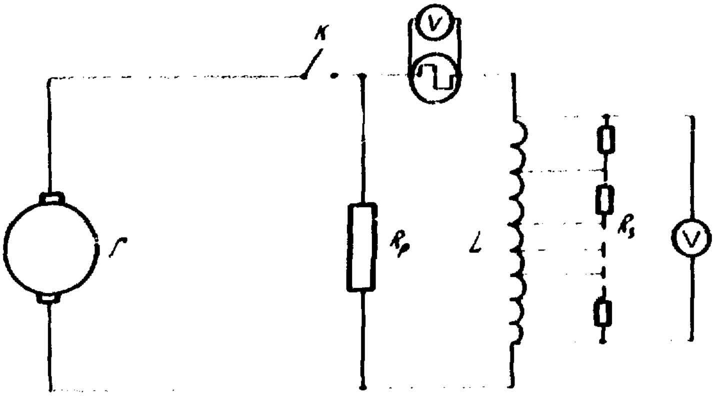

Figure 6. Electric circuit schematic.

- feed power source
- gating device
- superconducting coils
- protective resistance
- protective resistances for individual sections

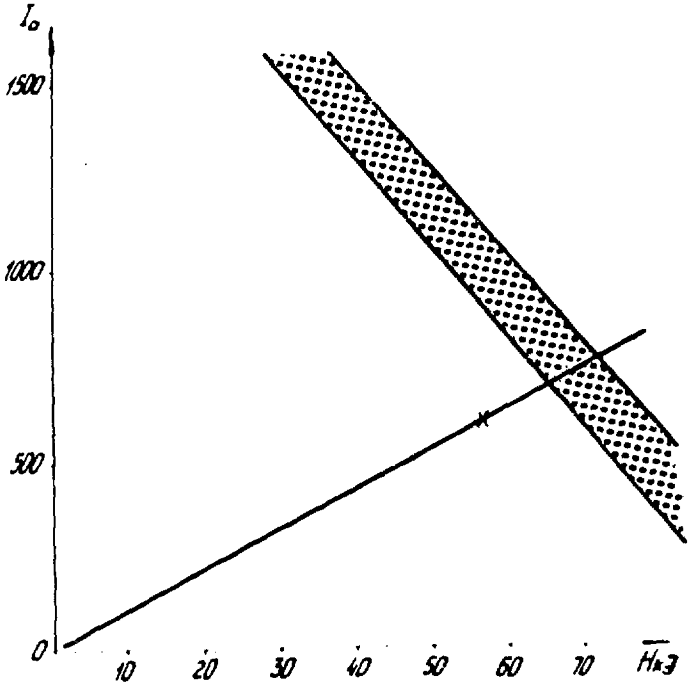

Figure 7. Dependence of superconducting cable critical current on magnetic field strength.

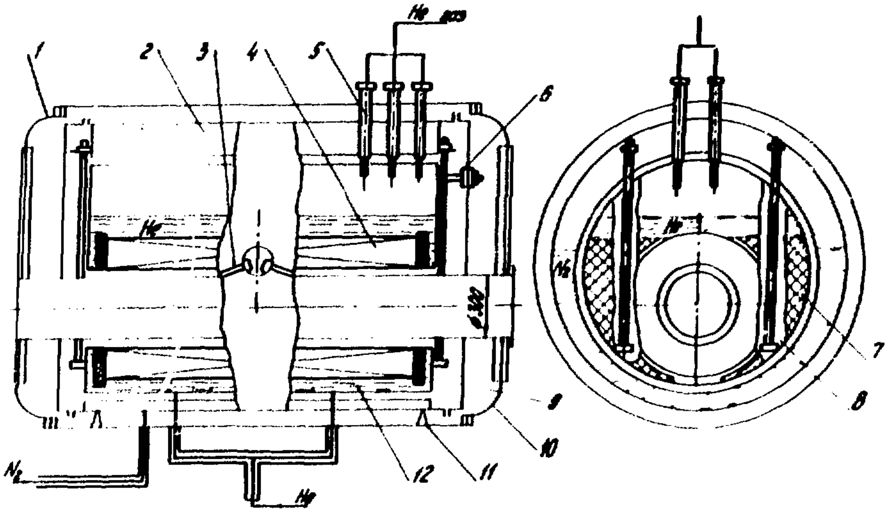

Figure 8. Cross section diagram of a SCMS cryostat.

1 - cryostat housing; 2 - nitrogen vessel; 3 - tension rods; 4 - coil; 5 - current leads; 6 - supports; 7 - plastic foam; 8 - suspension; 9 - shield; 10 - housing; 11 - supports; 12 - helium vessel.

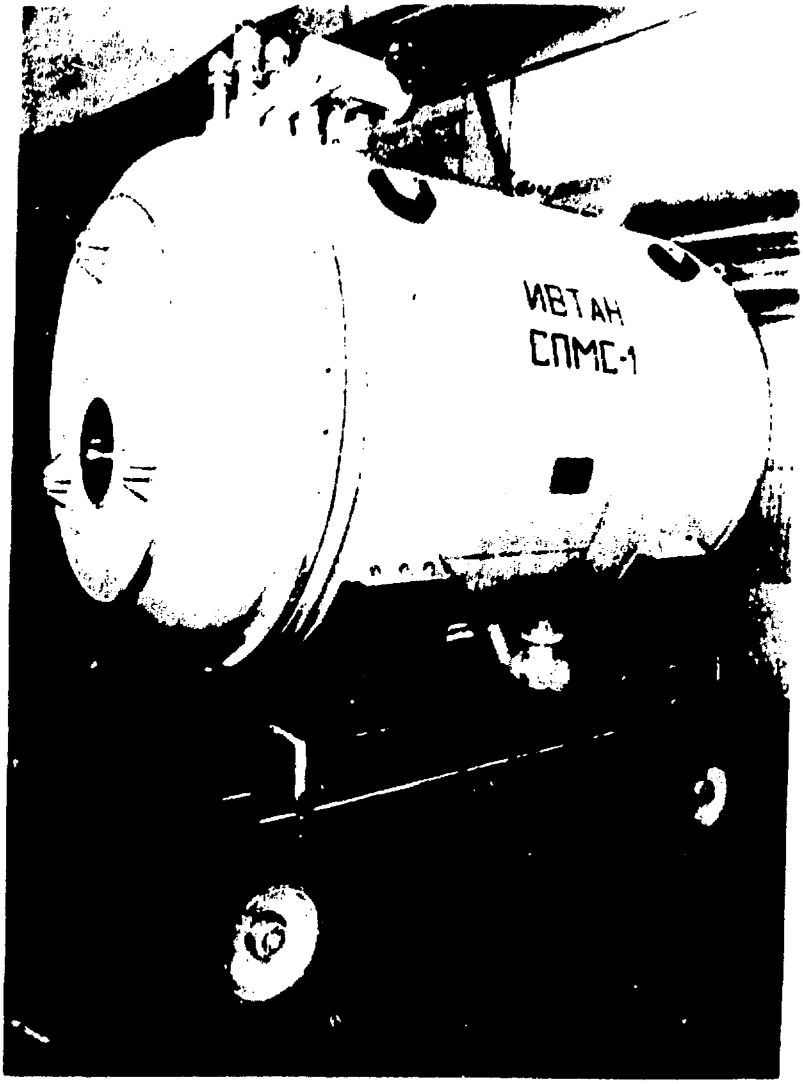

Figure 9. Horizontal cryostat.