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Abstract

A simple method of indirect cooling of superconducting coils is described. Intrinsically stabilized conductors have been successfully operated while being cooled by heat conduction over a distance of twentysix centimeters between conductor and heat exchanger.

A. Introduction

Superconducting coils are normally operated at temperatures below 5 K. The adjustment and maintenance of the operation temperatures is established by liquid or gaseous helium.

At the present time two cooling methods are generally used. The most important of these is bath cooling with the liquid boiling under equilibrium vapor pressure. In this case the coil is immersed in liquid helium which covers the surface of the conductor almost completely. The liquid is boiling under constant pressure, so that the temperature of the conductor can easily be controlled. With suitably designed conductors (superconducting filaments in a copper matrix) and coils a stabilizing effect can be obtained. If small parts of superconducting filaments become normally resistive, the current will pass through the copper matrix. The heat which is then created within the copper will be removed by the helium.

This coil design has several disadvantages: due to the complicated geometry of helium paths the positioning of the coil can hardly be changed for a special design. On the other hand mechanical constructions become rather complicated.

Another possibility of cooling superconducting coils is to apply a hollow conductor [1), 2)]. The coolant is forced through a central bore. Since the conductors are comparatively long, one obtains high flow resistances within the cooling system. Therefore one can use only supercritical helium as a coolant. Supercritical helium is helium at a temperature below the critical temperature and at a pressure above the critical pressure.

In this thermodynamical state of helium, temperature is no longer a function of pressure alone. Heat input does not happen at constant temperature, but causes directly a temperature rise. Another disadvantage is the complicated cooling system. Due to the low flow speed of the coolant in larger magnets with long conductors one has to expect rather long decay times of temperature peaks.

In these two cooling methods the coolant is touching the conductor along its whole length. This was necessary for the conductor types used exclusively until about two years ago. In these composite conductors one had to care for normal going regions during any changes of current and magnetic field. These "quenches" have been mainly introduced by temperature rises due to flux jumps. In a fully stabilized conductor the copper matrix is able to carry the full operating current. In order to avoid an enlargement of the normal region the current heat generated in the copper has to be removed immediately from the conductor into the helium through the surface of the conductor. This is the reason why these conductors must be completely covered by the cooling medium.

In intrinsically stabilized conductors the temperature rise caused by flux jumps is so tiny that the critical temperature is not reached. Another source of instability, i.e. mechanical heat generated by deformation and friction during the movement of single parts of the conductor in the magnetic field, can be eliminated by using suitable potting or glueing techniques.

Once it is certain that no local temperature peaks are generated inside a coil at stationary or dynamical operation it is obvious that it is useful to replace the principle of direct cooling by a system of indirect cooling. In this case the cooling of the conductor as well as the removal of heat generated by the magnetic field in the superconducting filaments during field changes is performed by heat conduction. It is not necessary to bring each single part of the conductor into touch with the coolant.

B. Experimental Problems

The following problems are to be considered in the design of such a coil:

I. One has to decide between supercritical helium (one phase) and a saturated vapor liquid mixture (two phase) as cooling medium.

II. The mutual positions of the conductor and cooling systems have to be chosen very carefully taking the following points into consideration:

a) The coolant should flow through rather simple systems of tubes or channels. Flow resistance should be minimized retaining a sufficient surface area for heat exchange.

b) The contact between superconductor and cooling system should be as close as possible. This can be realized in the following ways:

1. A cooling tube is wound around the coil and then potted to it[3] (Fig. 1).
2. The conductor is wound on a coil former of a material with good heat conduction properties (copper or pure aluminum). This coil former can be cooled by tubes, heat exchangers or by holes or channels directly machined into the body. These channels can be placed at one or several regions of the coil body (Fig. 2).
3. Several copper sheets (heat drains) are placed between the windings. Their ends are attached to the cooling system.

c) The mutual positions of conductor, cooling system and mechanical mountings are of special importance. All pieces which connect the cold parts of the system with the room temperature vacuum jacket will carry a steady current of heat to the cold parts of the system. This heat current has to be guided directly into the cooling system without passing through any part of the coil. Heat conducting connections between the cold conductor and the vacuum jacket (including electrical current leads and also every kind of measuring leads) have to be attached to a directly cooled part of the cooling system (Figs. 3 and 5).

d) The influence of heat radiation has to be minimized. Heat radiation is distributed almost equally over the complete surface of the coil. Calculations of the temperature rise due to a given density of heat flux as a function of heat conductivity and of the dimensions of the coil body are given in the appendix for cylindrical coils which are cooled from the ends of the cylinder. The temperature rise of the conductor can be neglected if the application of a nitrogen cooled radiation shield and superinsulation is possible.

   For certain applications with sophisticated coil geometries an additional nitrogen shield might be too complicated and should be avoided. In such cases one has to choose materials with good heat conductivity, such as copper or pure aluminum as material for the coil carrier.

   If one has to use materials with low thermal conductivity for mechanical reasons one can surround the coil by a shield with high thermal conductivity being connected directly to the helium system. The application of such a radiation shield which does not touch the coil itself might often be simpler than a nitrogen shield with a separate cooling circuit.

e) Current leads have to be cooled directly in such a way that the region of the solder between copper and superconductor is covered by liquid. A simple way to do this would be to put this connection into the helium backflow to the refrigerator. One has also to remove from this point the quantity of gas necessary for cooling the current leads (Figs. 3; 5b; 6 and 7).

C. Experimental results

The principle of indirect cooling has been tested at DESY by means of a number of model coils of different sizes, geometries and conductor types. In order to have a cooling system as simple as possible we decided to start with the equilibrium mixture of vapor and liquid coolant. This cooling medium is very easily available at the low pressure end of the Joule-Thomson valve of an ordinary helium refrigerator. The coils have been wound - with one exception - on a coil former machined of copper. One end of the coil carrier was attached either to a simple tube or to a block of copper with cooling channels.

A summary of the test coils and of the results is given in table 1. Fig. 4 gives the maximum currents and flux densities in comparison with the short sample characteristics given by the manufacturers.

Coils 1 to 4 were primarely used to test glueing techniques and to develop a cooling system for current leads independent from the heat exchanger of the coil. In these cases about 80-90% of the short sample characteristics could be achieved. The coils could be operated in vacuum. They have been shielded only by several layers of superinsulation.

Coil no. 7 (Fig. 5) was operated under the same cooling conditions at a peak field of 5.3 T. The quenching current was 69% of the short sample critical current.

Coil no. 6 was cooled from one end by means of a copper block with a cooling channel. After having reached only 62% of the short sample characteristics another test was performed applying a bath cooling. During this test the room between the coil and the cylindrical radiation shield was filled with liquid helium (Fig. 7). The result was exactly the same as in the case of indirect cooling. In a third test the radiation shield was completely removed, the result was even better. (The higher quenching current in this test can probably be explained by mechanical positionchanges of conductorparts due to several temperature cycles.)

The most important difference between the three operating modes of coil no. 6 was in the time t_r for reestablishment of the superconducting state after a quench. This time was 35.5 sec. in the case of bath cooling, 176 sec. at indirect cooling with radiation shield and about 300 sec. at indirect cooling without radiation shield.

Coil no. 5 was wound on a coil former machined of a commercial aluminum alloy and potted under vacuum with wax. The dimensions of the coil body are the same as those of coil no. 6, but only 1/3 of the total length was covered by the superconducting coil. The coil former was cooled by a heat exchanger attached to the far end with respect to the coil. So the maximum distance between heat exchanger and superconductor was the same as at coil number 6. A cylindrical radiation shield was fixed to the cooling block. The room between shield and coil was filled with wax. During a second test the radiation shield was additionally cooled by a helical tube soldered to the surface of the radiation cylinder. Again no difference in the performance of these two modes of operation could be detected.

Conclusions

From the experiments described above we conclude that it is possible to cool intrinsically stable superconducting coils of small and medium sizes indirectly by heat conduction.

The maximum size of coils depends mainly on the distance between cooling channels as well as on the area and thermal conductivity of the materials used as coil carriers. For very large coils one has to consider that it might be difficult to remove, in the case of a quench, all stored energy from the coil. The remaining fraction of the energy dissipated in the magnet should not cause an excessive rise in temperature.

Provided that all the heat coming in locally can be removed directly by the cooling system a residual heat load for the coil remains which is due to equally distributed radiation and convection. Furthermore there will be a certain amount of electrical heat during fieldchanges, which is produced by eddy-currents in the copper and by minimal flux jumps in the superconductor. These two heat sources are approximately equally distributed over the whole coil and can be added to the heat of radiation. The formulas of the appendix show that temperature rises with the second power of the distance from the cooled end. Therefore it is preferable to cool cylindrical coils from both ends.

During our experiments a cylindrical coil of 26 cm length, cooled only from one end, could be powered to a maximum field of 2.5 Tesla. Under similar conditions it should be possible to operate a coil of about 1 m length if it is cooled simultaneously from both ends. The diameter could certainly be increased above 5 cm since the temperature difference T (Eqs. 12 and 13) does not depend on the diameter.

The cooling method using an equilibrium vapor liquid mixture at about 4.3 K has been proven to be extremely simple. Using a normal refrigerator the J.T. valve expands the gas directly into a transfer line connected to the cooling circuit of the magnet. A diagram of the cooling system is shown in fig. 7. It should be mentioned that our cooling system has the advantage that the coil itself is not operated inside a complicated cryostat. We only need a container evacuated to 10^{-4} to 10^{-6} Torr, at which pressure a good performance of the superinsulation is established.

The application of the principles of design mentioned above is by no means restricted to cylindrical coils. Dipoles and quadrupoles as well as more complicated magnets can be built and operated in the same way.

Acknowledgements

We are greatly indebted to Professor M.W. Teucher for his steady support of these investigations. We also thank all technicians of the DESY bubble chamber group for their help in fabricating and operating the coils.

A p p e n d i x

Influence of Heat Radiation

We consider a hollow cylinder of diameter r, wall thickness d ($d \ll r$) and of length l (Fig. 8). A heat flux $\dot{Q}$ which flows in the x-direction parallel to the axis of the cylinder will cause a temperature gradient.

$$\frac{dT}{dx} = - \frac{\dot{Q}}{2\pi r d \lambda} \qquad (1)$$

λ = thermal conductivity of the cylinder wall

Due to thermal radiation which we assume to be uniformly distributed over the surface of the cylinder, we have a heat input

$$d\dot{Q}_r = 2\pi r \dot{q} dx \qquad (2)$$

per cylinder element of length dx.

$\dot{q}$ = heat input per unit of cylinder surface

In a stationary case $\frac{d\dot{Q}_r}{dx}$ from equ. 2 must be equal to $\frac{d\dot{Q}}{dx}$ from equ. 1, which leads to

$$\frac{d\dot{Q}_r}{dx} = 2\pi \; r\dot{q} = \frac{d\dot{Q}}{dx} = - 2\pi r \lambda d \cdot \frac{d^2T}{dx^2}$$

or

$$\frac{d^2T}{dx^2} = - \frac{\dot{q}}{\lambda d} \qquad (3)$$

The solution of (3) is

$$T(x) = a_o + a_1 x - \frac{\dot{q}}{2\lambda d} x^2 \qquad (4)$$

and for the temperature gradient

$$\frac{dT}{dx}(x) = a_1 - \frac{\dot{q}}{\lambda d} x \qquad (5)$$

In the case of cooling from one end only the conditions

$$T = T_o$$

for $$x = x_o$$

give

$$a_o = T_o \qquad (6)$$

Furthermore the integral load of radiation heat into the total surface of the cylinder is according to Equ. 2,

$$\dot{Q}_r = 2\pi r \dot{q} l \qquad (7)$$

in the case that radiation enters only from the outer surface. If the coil has a room temperature access to the inner volume, the same current of heat enters from the inner surface which enlarges $\dot{q}$ by a factor of two.

With $\dot{Q}$ (0) from Equ. 1 we find the heat flux into the heat exchanger

$$\dot{Q}\ (0) = - \lambda \cdot 2\pi rd \frac{dT}{dx}\ (0) \qquad (8)$$

Since $\dot{Q}$ (0) is to the total heat flux leaving the cylinder, $\dot{Q}$ (0) must be equal to $- \dot{Q}_r$. Using Eqs. 5, 7 and 8 we get

$$- 2\pi r \lambda d \cdot a_1 = - 2\pi r \dot{q} l$$

$$a_1 = \frac{\dot{q} l}{\lambda d} \qquad (9)$$

and finally the temperature distribution along the cylinder

$$T_1(x) = T_o + \frac{\dot{q}}{\lambda d} \left(lx - \frac{x^2}{2}\right) \qquad (10)$$

Considering also the inner warm hole Equ. 10 has to be modified into

$$T_1'(x) = T_o + \frac{2\dot{q}}{\lambda d} \left(lx - \frac{x^2}{2}\right) \qquad (10a)$$

For a cylinder cooled from both ends we have

$$T(0) = T_o = T(l)$$

which gives another distribution

$$T_2(x) = T_o + \frac{\dot{q}}{2\lambda d} \left(lx - x^2\right) \qquad (11)$$

or

$$T_2' (x) = T_o + \frac{\dot{q}}{\lambda d} (lx - x^2) \qquad (11a)$$

The maximum temperature rises $\Delta T = T_{max} - T_o$ are

$$\Delta T_1 = \frac{\dot{q}\, l^2}{2 \lambda d} \qquad (12)$$

$$\Delta T_1' = \frac{\dot{q}\, l^2}{\lambda d} \qquad (12a)$$

$$\Delta T_2 = \frac{\dot{q}\, l^2}{8 \lambda d} \qquad (13)$$

$$\Delta T_2' = \frac{\dot{q}\, l^2}{4 \lambda d} \qquad (13a)$$

The maximum temperature in a cylinder due to heat sources uniformly distributed over the surface (radiation, residual gas convection, eddy currents, flux movements) is proportional to the second power of the distance from the heat sink and inversely proportional to the thermal conductivity of the material.

As an example, coil no. 5 with a coil body of an aluminum alloy was operated primarily without radiation shield and with a warm cylinder in the middle. Application of Equ. 12a gives, with

$$\dot{q} \approx 2 \cdot 10^{-4}\ W \cdot cm^{-2}$$

$$l = 26\ cm$$

$$d = 0,4\ cm$$

$$\lambda_{Al} \approx 4 \cdot 10^{-2}\ W\ cm^{-1}\ K^{-1}$$

$$\Delta T_{Al} \approx 8,45\ K$$

Since the temperature of this coil was larger than the critical temperature it could not be operated at all.

Coil no. 6, machined of electrolytical copper ($\lambda_{Cu} = 3\ W \cdot cm^{-1} K^{-1}$ d=0,4 cm) was operated without inner access tube. In this case Equ. 12 has to be applied with the result of

$$\Delta T_{Cu} = 5{,}5 \cdot 10^{-2}\ K$$

In our geometry the heat of radiation is absorbed at the surface of the conductor. The flux has to pass radially through the compound of conductor and epoxy resin before it enters the copper cylinder. Due to the thermal resistivity of the composite the temperature of the conductor surface is raised by

$$\Delta T_s = \frac{\dot{q} \cdot d'}{\lambda'} \qquad (14)$$

d' = thickness and λ' = thermal conductivity of the conductor compound[3]. With a value $\lambda' \approx 2 \cdot 10^{-3}\ W \cdot cm^{-1}K^{-1}$ (Lit.), d' = 0,3 cm one calculates

$$\Delta T_s \approx 3\ 10^{-2}\ K$$

Thus the total temperature rise of coil no. 6 without radiation shield was $(5{,}5 + 3) \cdot 10^{-2} = 8{,}5 \cdot 10^{-2} K$.

R e f e r e n c e s

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2) M. Morpurgo — Proc. of the 1968 Summer Study on Superconducting Devices and Accelerators, Part III BNL 50155 p. 953 (1968)

3) M.A. Green — UCRL - 20172 (1971)

4) W. Witzeling and V.A. Zhukov — CERN / D.Ph. II/LTL/70-1 (1970

Table 1

Assembly of Test Data

Coil/Test Number		1	2	3	4	5/a	5/b	6/a	6/b	6/c	7
Material of Coil Former		Cu	Cu	Cu	Cu	*	*	Cu	Cu	Cu	Cu
Cooling Method		II	II	II	II	II+III	II+IV	I	II+IV	II	II
Inner Diameter of Winding	cm	6.2	4.5	2.0	2.0	4.6	4.6	6.2	6.2	6.2	1.1
Outer Diameter of Winding	cm	6.56	6.0	3.3	3.85	5.2	5.2	6.7	6.7	6.7	3.9
Length of Winding	cm	0.9	0.9	0.9	0.9	4.9	4.9	26	26	26	4.9
Total Number of Turns		84	320	297	414	700	700	3380	3380	3380	3220
Number of Turns per Centimeter	cm^{-1}	93	356	330	460	143	143	130	130	130	644

* Commercial Aluminum Alloy

I Bath Cooling

II Cooling Channel at One End of Coil

III Helium Cooled Radiation Shield

IV Radiation Shield Cooled from One End by Heat Conduction

Table 1 (Continued)

Coil/Test Number		1	2	3	4	5a	5b	6a	6b	6c	7
Type of Conductor		a	b	b	b	a	a	b	b	b	b
Diameter of Conductor	mm	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Copper Superconductor Ratio		1.35	1.26	1.26	1.26	1.35	1.35	1.26	1.26	1.26	1.26
Number of Filaments		61	61	61	61	61	61	61	61	61	61
Diameter of Filaments	μm	34	35	35	35	34	34	35	35	35	35
Quench Current	A	168	156	154	138	100	101	138.5	140	155	72.2
Maximum Induction at the Conductor	T+)	1.05	2.88	3.19	3.60	1.42	1.44	2.25	2.27	2.52	5.29
Maximum Mean Current Density in the Conductor	Acm^{-2}	134×10^3	124×10^3	122×10^3	110×10^3	79×10^3	80×10^3	110×10^3	111×10^3	123×10^3	$57{,}7 \times 10^3$
Maximum Mean Current Density in the Coil	Acm^{-2}	87×10^3	80×10^3	78×10^3	69×10^3	47.6×10^3	48.1×10^3	72×10^3	73×10^3	81×10^3	34×10^3
Quench Current/Short Sample Critical Current		0.93	0.80	0.86	0.84	0.60	0.61	0.62	0.63	0.73	0.69
Maximum Charging Speed	As^{-1}	24		24	24						2
Recovery Time after Quench	s							35.5	176	300	

+) $1\ T = 1\ Tesla = 1\ Vs \cdot m^{-2} = 10^4$ Gauss

a IMI Niomax FM A 61/40

b VAC Vacryflux 5001 F 61/40

Figure Captions

Fig. 1 Superconducting Coil Cooled by a Helical Tube Potted Together with the Conductor

1 He-Input
2 He-Outlet
3 Superconductor
4 Cooling Tube
5 Potting Material
6 Coil Former

Fig. 2 Superconducting Coil Cooled from One End by a Cooling Channel

1 Cooling Medium
2 Heat Drains
3 Superconductor
4 Coil Former

Fig. 3 Arrangement of an Indirectly Cooled Superconducting Coil

1 He-Input
2 He-Output
3 Current Leads
4 Ends of Superconducting Winding
5 Joints Between Superconductor and Current Leads
6 Coil Former
7 Radiation Shield
8 Mechanical Supports
9 Superinsulation
10 Superconducting Winding
11 Vacuum Container

Fig. 4 Currents and Magnetic Fields of the Coils at Quench in Comparison with Short Sample Critical Data of the Conductors

a IMI Niomax FM A 61/40

b VAC Vacryflux 5001 F 61/0,4

(The numbers of the measuring points refer to the numbers of Coils and Tests in Table 1.)

Fig. 5 Experimental Arrangement for Small Coils

a Photograph with Coil No. 7
b Schematic Drawing
1 Coil Former
2 Superconductor
3 Superconducting Current Leads
4 Normal Conducting Current Leads
5 Joints Between Leads of Copper and Superconductor
6 Measuring Leads
7 He-Input
8 Cold He-Outlet
9 Cooling of Current Leads
10 Liquid Helium
11 Cooling Region

Fig. 6 Schematic Drawing of Coil No. 6

1 He-Input
2 Cold He-Outlet
3 Current Leads
4 Cooling of Current Leads
5 Heat Exchanger
6 Superconducting Ends of the Coil
7 Coil Former
8 Superconductor
9 Radiation Shield

Fig. 7 Cryogenic Flow Diagram

a Indirect Cooling
b Direct Cooling
1 Cold End of Refrigerator
2 Joule-Thomson Valve
3 Heat Exchanger
4 Liquid Helium
5 Cold Gas Backflow
6 Warm Gas Backflow (from Cooling of Current Leads)
7 Current Leads
8 Joints Between Superconductor and Normal Conducting Current Leads
9 Superconducting Winding
10 Coil Former
11 Copper Cylinder Used Either as Radiation Shield (Case a) or as Liquid Container (Case b)
12 Vacuum

Fig. 8 Definition of Coordinate System Used in the Appendix

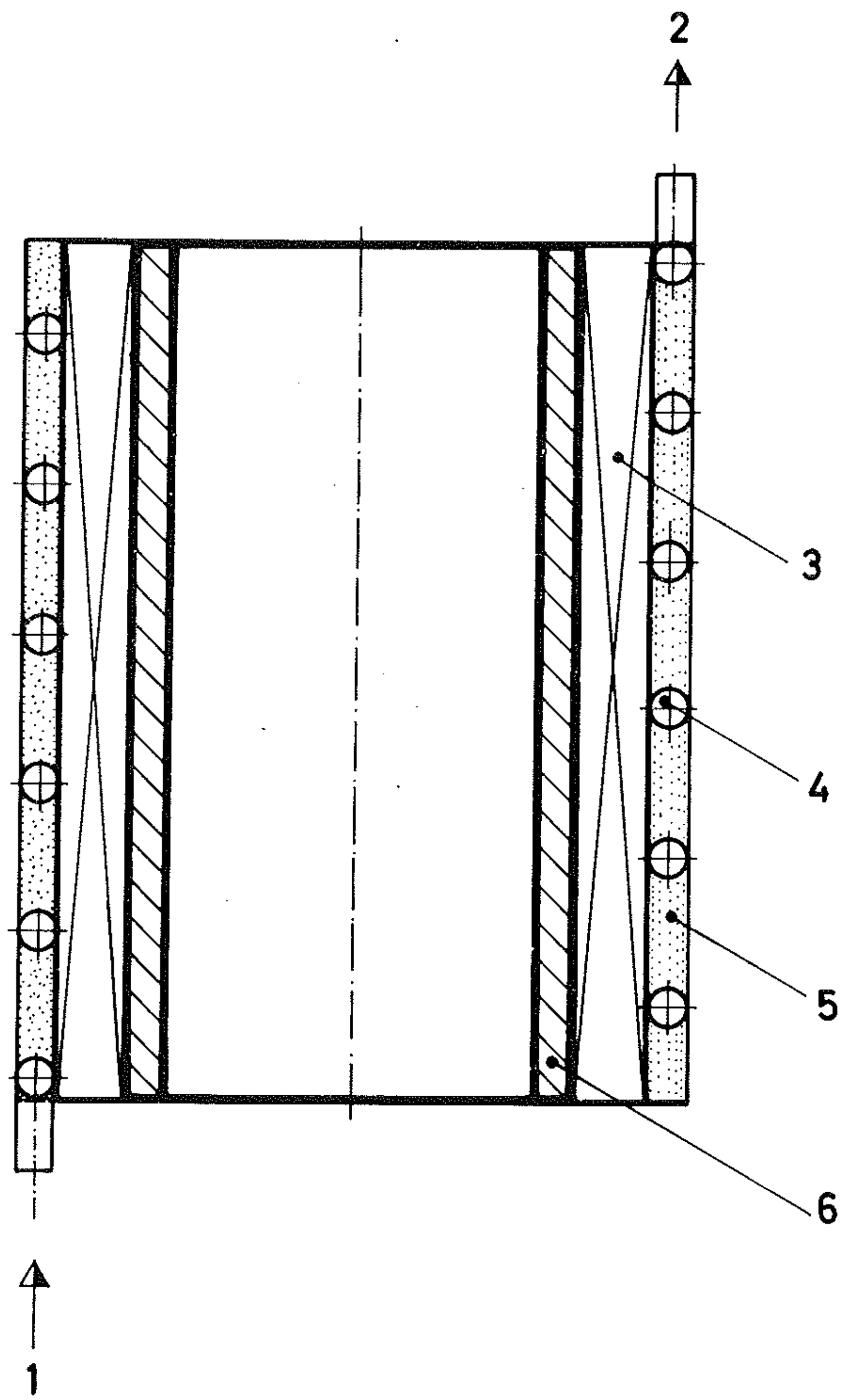


Fig. 1

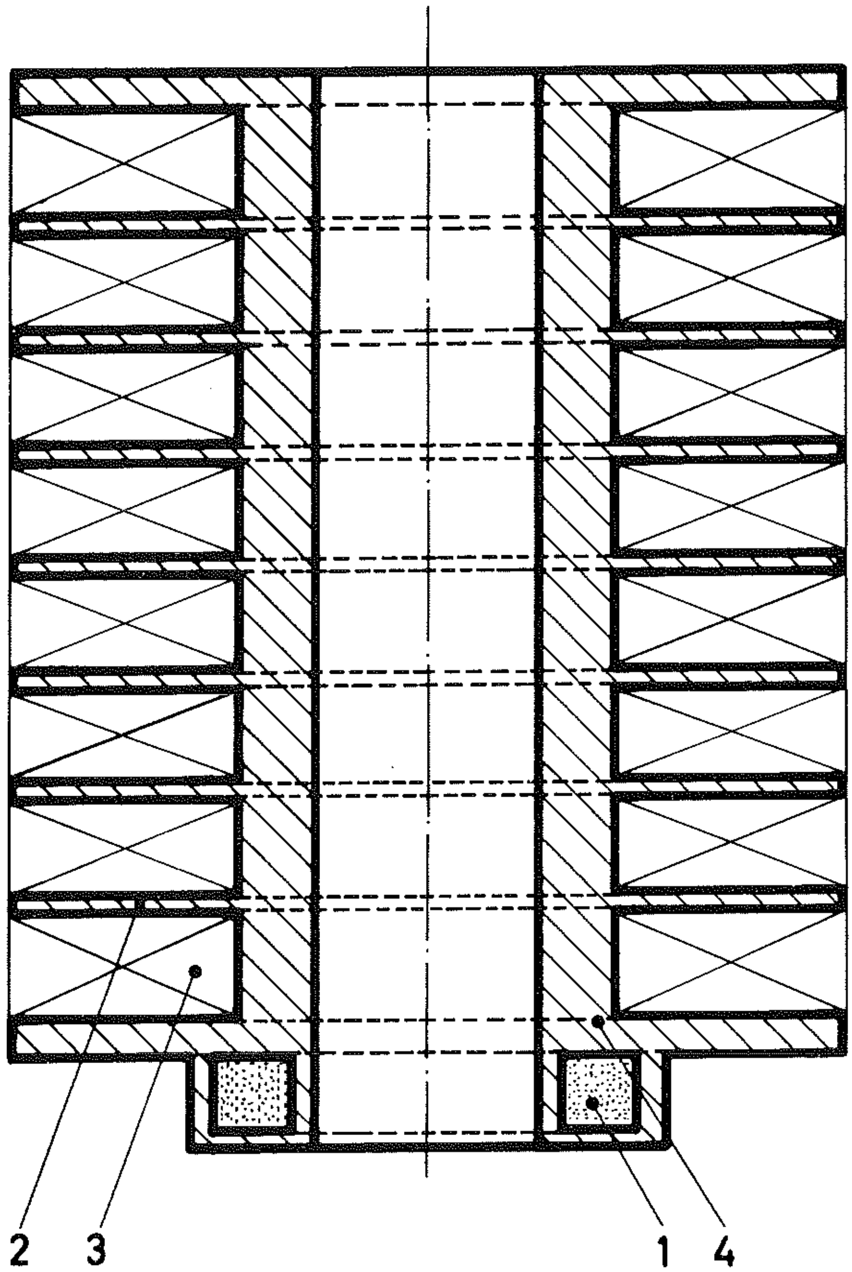
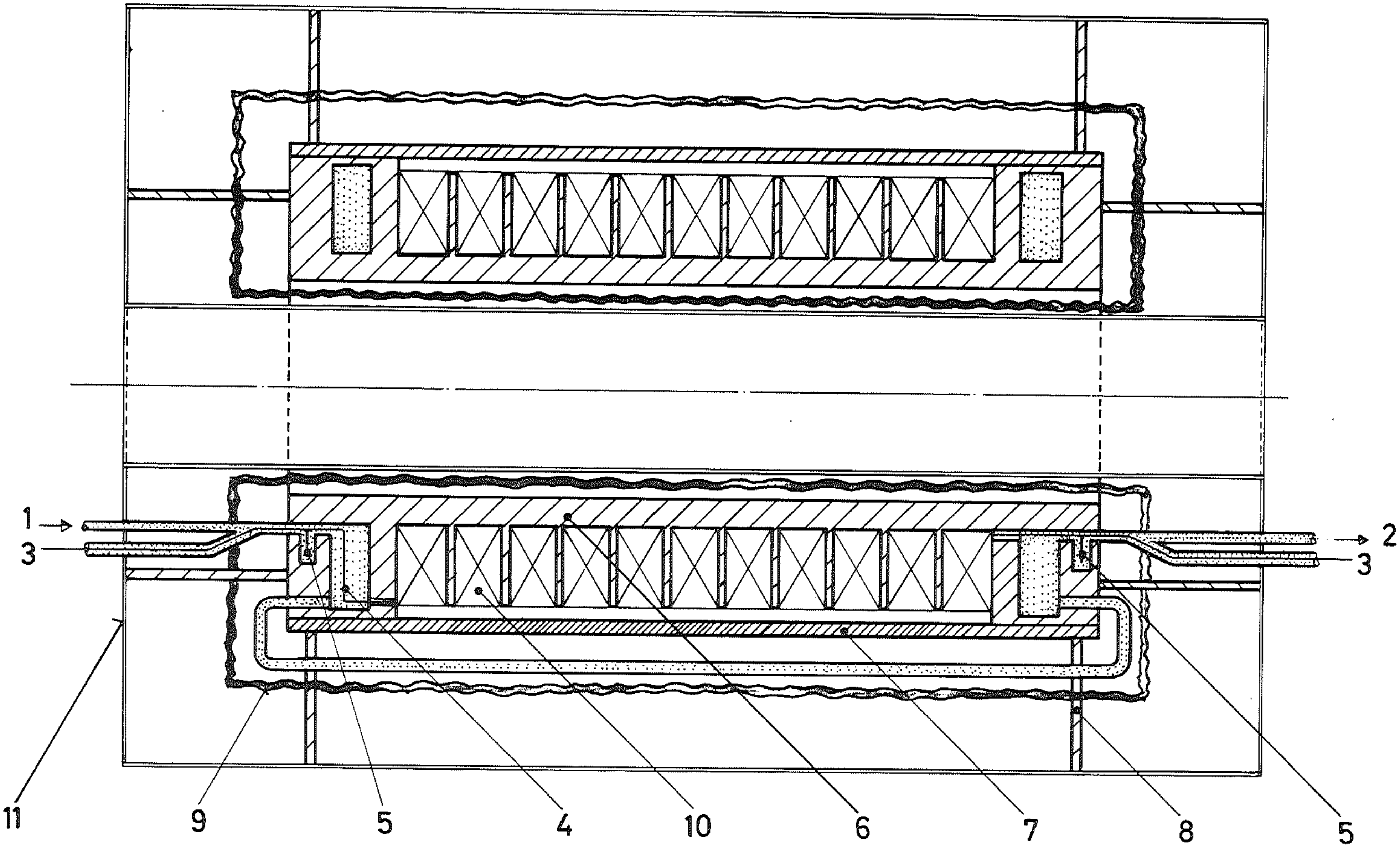
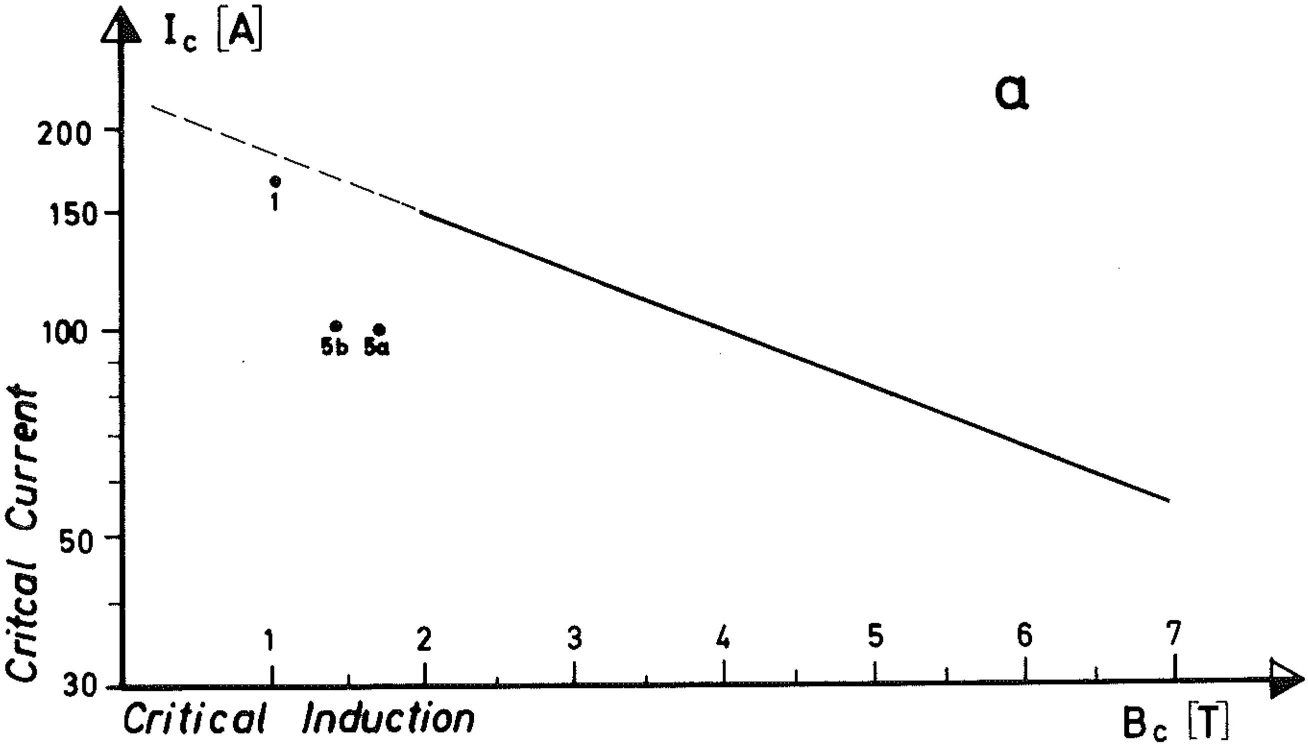


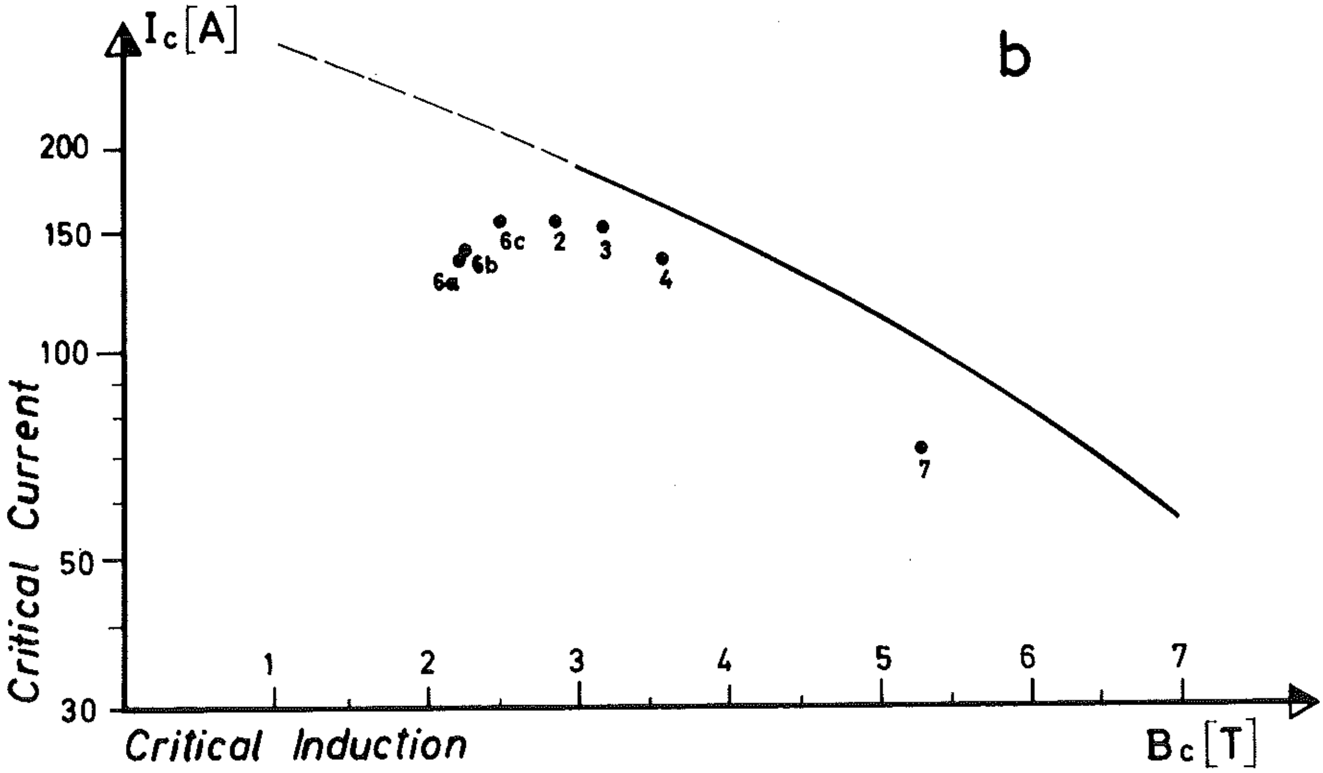
Fig. 2

Fig. 3





I_c [A]
a
200
150
100
50
30
Critical Current
1
5b
5a
1
2
3
4
5
6
7
Critical Induction
B_c [T]



I_c [A]
b
200
150
100
50
30
Critical Current
6c
2
3
6b
6a
4
7
1
2
3
4
5
6
7
Critical Induction
B_c [T]

Fig. 4

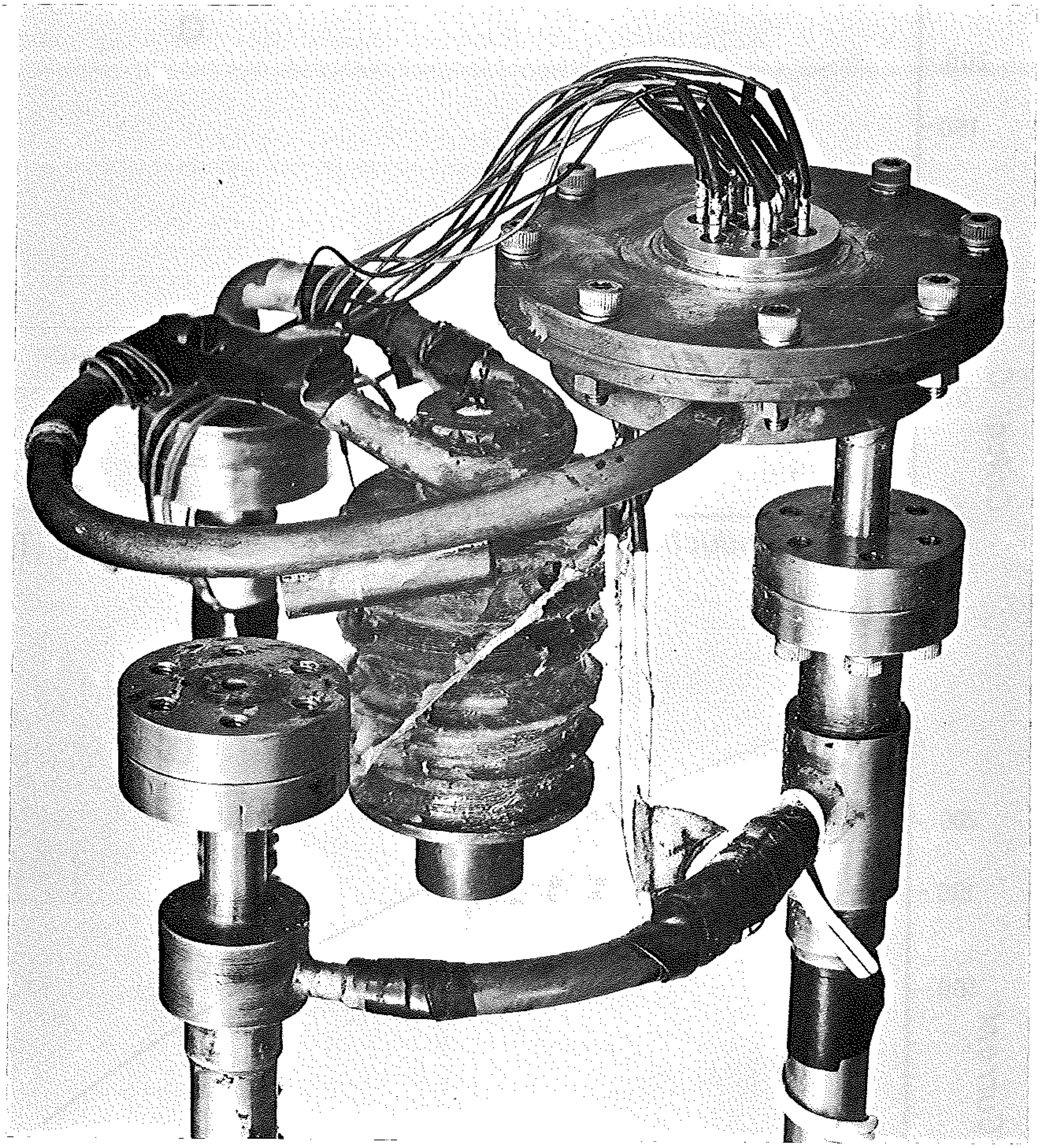


Fig. 5a

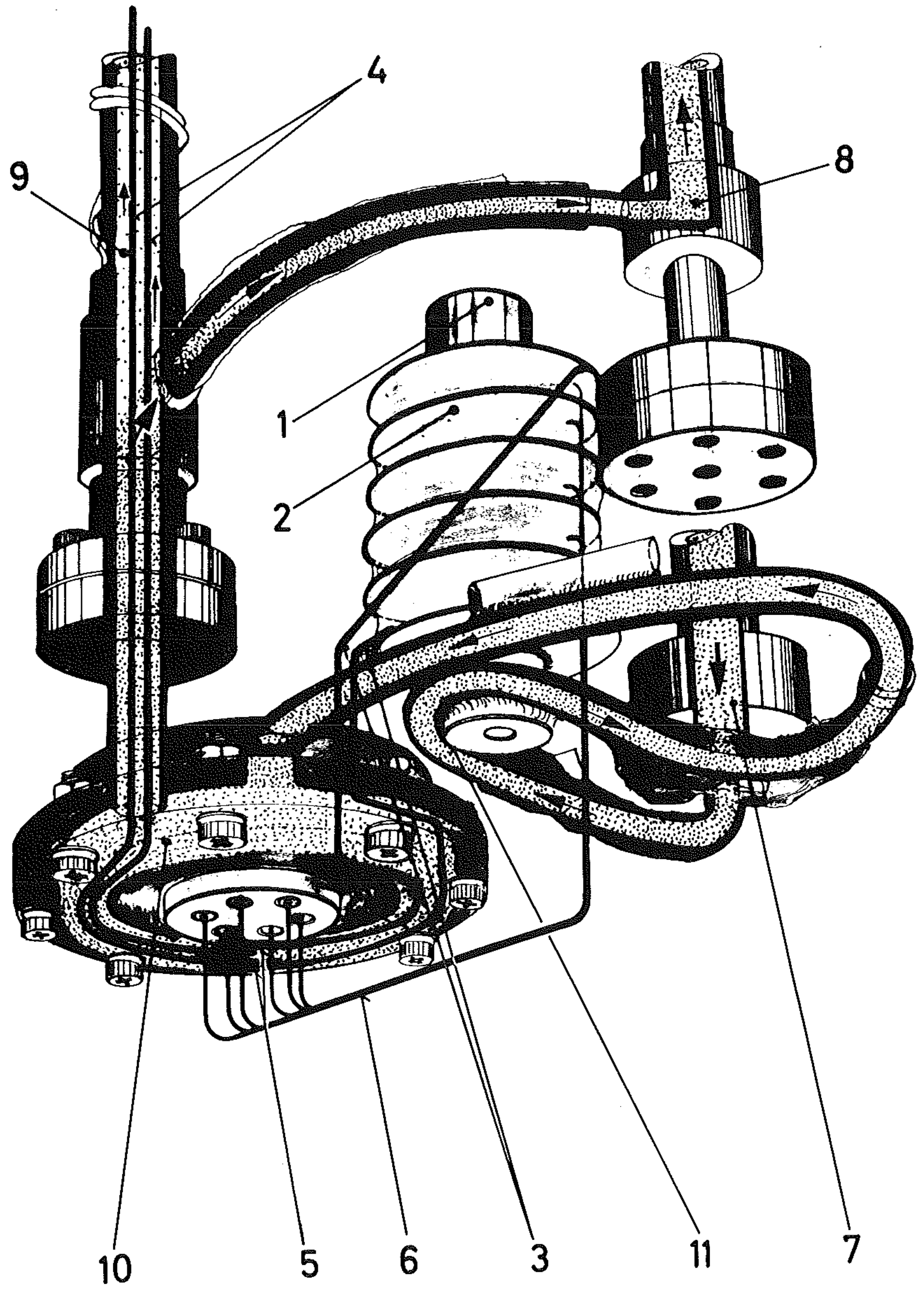


Fig. 5b

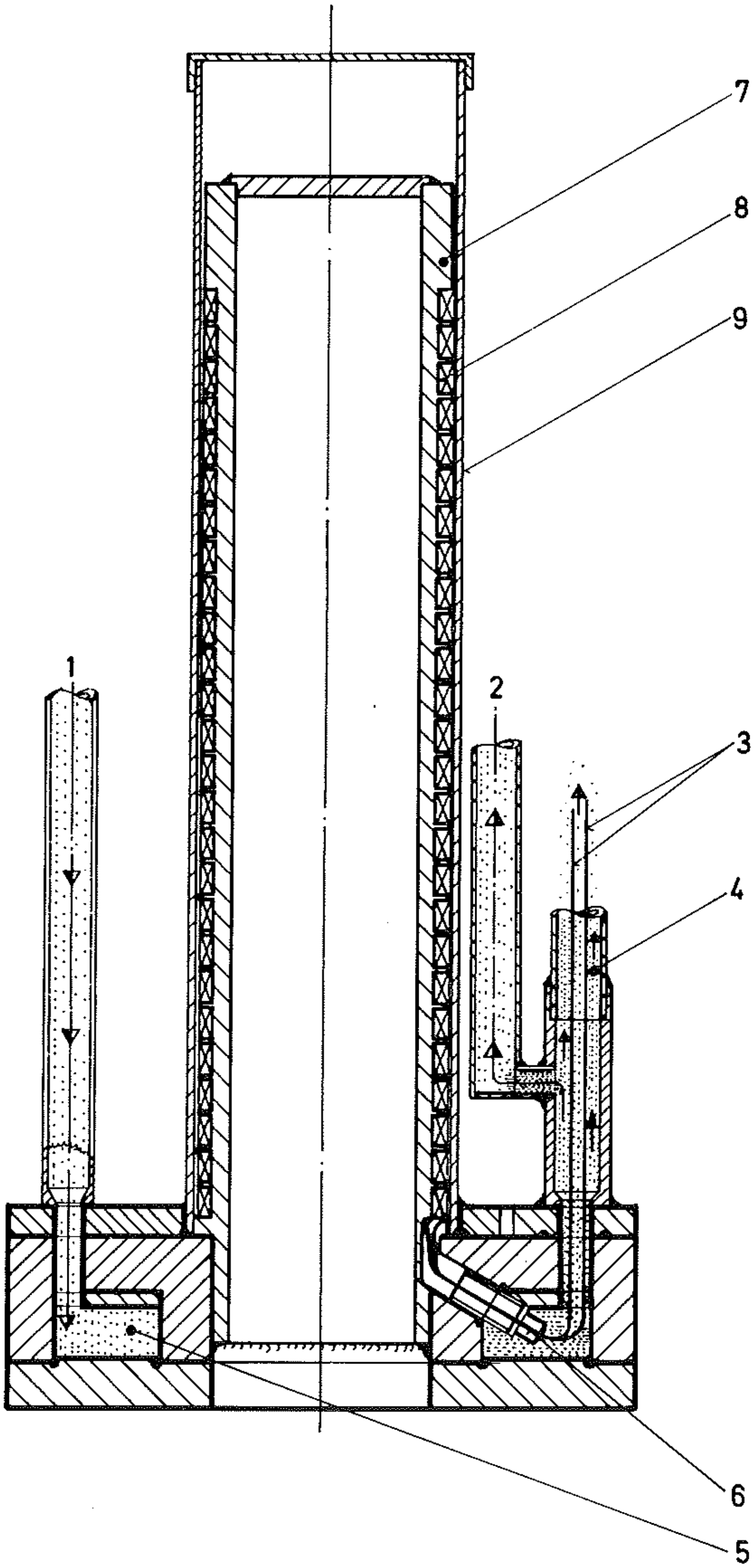


Fig. 6

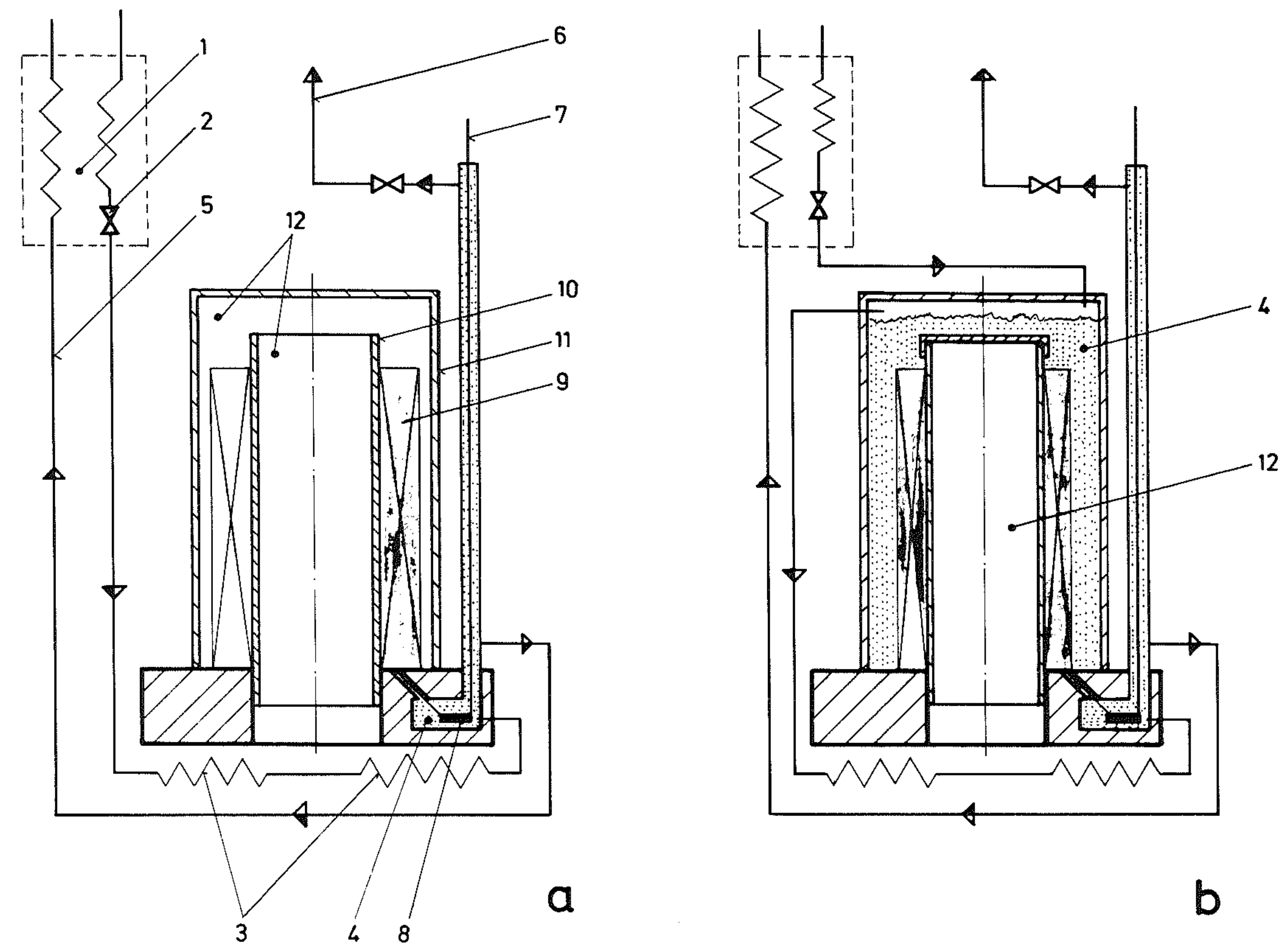


Fig. 7

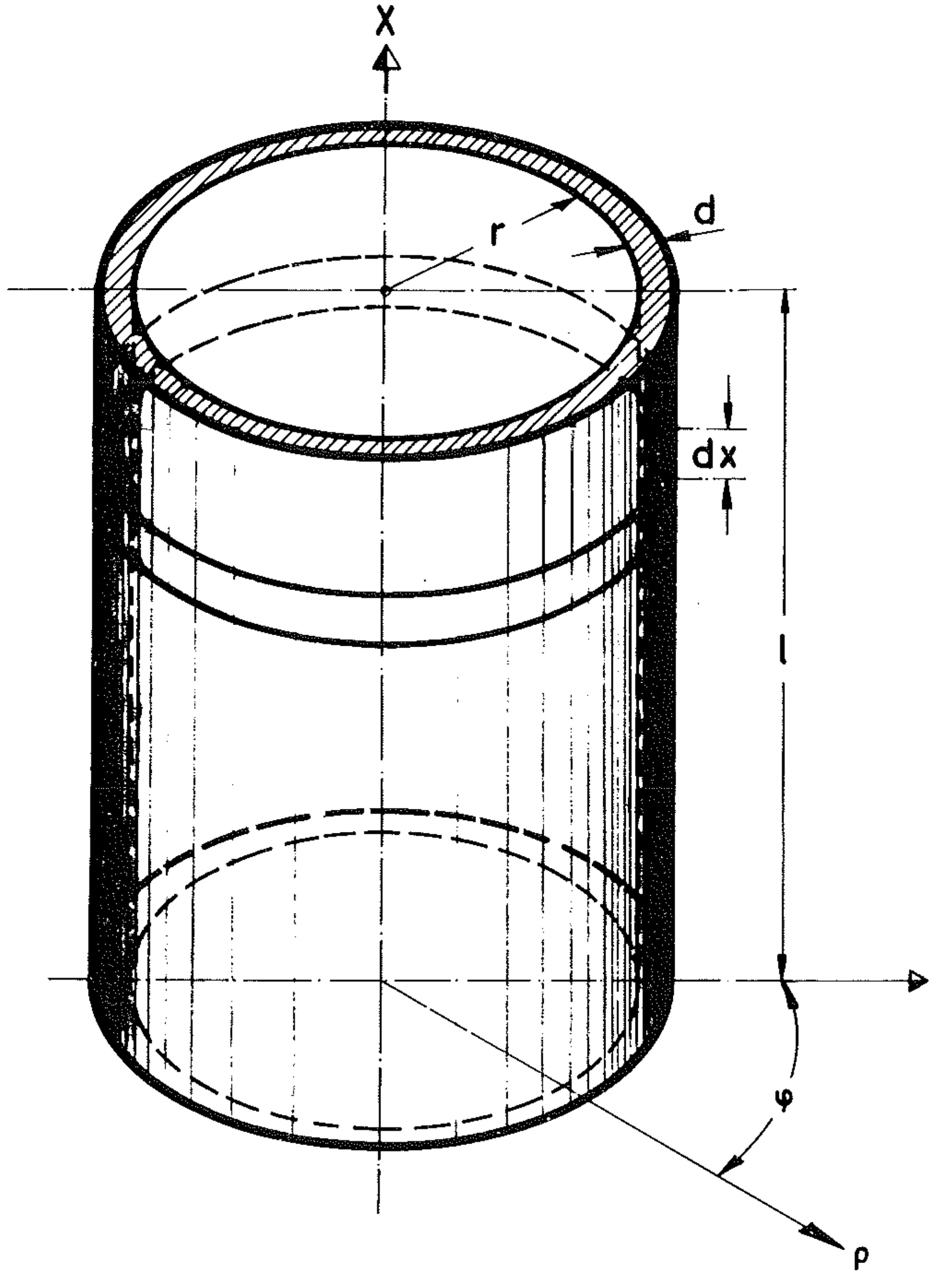


Fig. 8