Particle Accelerators, 1970, Vol. 1, pp. 255–263

THE DESIGN OF THE SUPERCONDUCTING MAGNET FOR THE 'OMEGA' PROJECT

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The design of a large superconducting magnet (the 'Omega' magnet) cooled by forced circulation of supercritical helium is discussed.
Details are given on the coil construction, on the hollow conductor and on the helium flow diagram.
Some design problems, typical of forced circulation cooling, are considered.

1. GENERAL

The Omega project consists essentially of a large spark chamber detector associated with an analysing magnet. In the following sections, the design of the magnet (a pictorial view of which is shown in Fig. 1) will be discussed.

The magnet will be energized by two superconducting coils wound with hollow composite superconductor, and it will be cooled by a forced flow of supercritical helium. Tests made to prove the feasibility of this cooling technique and to gain experience with it have been reported elsewhere.[1]

The magnet will have an iron yoke which will serve the double purpose of enhancing the field in the central region and of reducing the external stray field.

The main characteristics of the Omega magnet will be:

Field at the centre	18 kG
Coil inner diameter	3 m
Free distance between coils	1.5 m
Free distance between poles	2 m
Over-all weight	1400 tons
Nominal current	5000 A
Number of turns	408 turns/coil
Stored energy	50 MJ.

The orders for the four main items (i.e. iron yoke, hollow conductor, coil fabrication, and refrigerator) into which the magnet has been subdivided were placed with industry in December 1969. The iron yoke will be made by the firm Schneider-Creusot (France); Oerlikon M.F.O. (Switzerland) will fabricate the hollow superconductor and the coils; Sulzer Brothers (Switzerland) will be in charge of the refrigerator. The magnet is expected to be in operation by the end of 1971.

The cost of the complete magnet, including the iron yoke, conductor, coil fabrication, refrigerator, power supply, vacuum equipment, controls, foundation, and installation will be approximately M Sw.F 9.5.

2. MAGNET DESCRIPTION

2.1. *Magnetic circuit*

The magnetic circuit is of conventional design, and its general layout is given in Fig. 2. Approximately 1300 tons of low carbon cast steel will be required for the construction.

The side yokes will be built with modular steel slabs which can be easily displaced according to the particular geometry of each experiment.

The top and bottom pole-pieces will be removable.

Four forged steel pillars will support the attracting forces (approximately 4000 tons) between the two horizontal yokes.

2.2. *Coils*

2.2.1. *General description.* A coil, the cross section of which is shown in Fig. 3, will be built up of six identical double pancakes, each having 68 turns and requiring approximately 1 km of hollow conductor. The six pancakes will be electrically connected in series, the electrical connections being made by mechanically clamping and indium-soldering two lengths of conductor. The ohmic resistance of one joint will be $< 10^{-9}\ \Omega$. The two coils (each one having two current leads) will be connected in series by an external (warm) busbar.

The conductor insulation will be obtained by wrapping it over its entire length with two layers of half-overlapped glass tape. The pancakes will be subsequently impregnated in vacuum with epoxy resin.

For cooling, the coils will be connected to the refrigerator through special insulating joints. The joints (Fig. 4) are built by fitting together a number

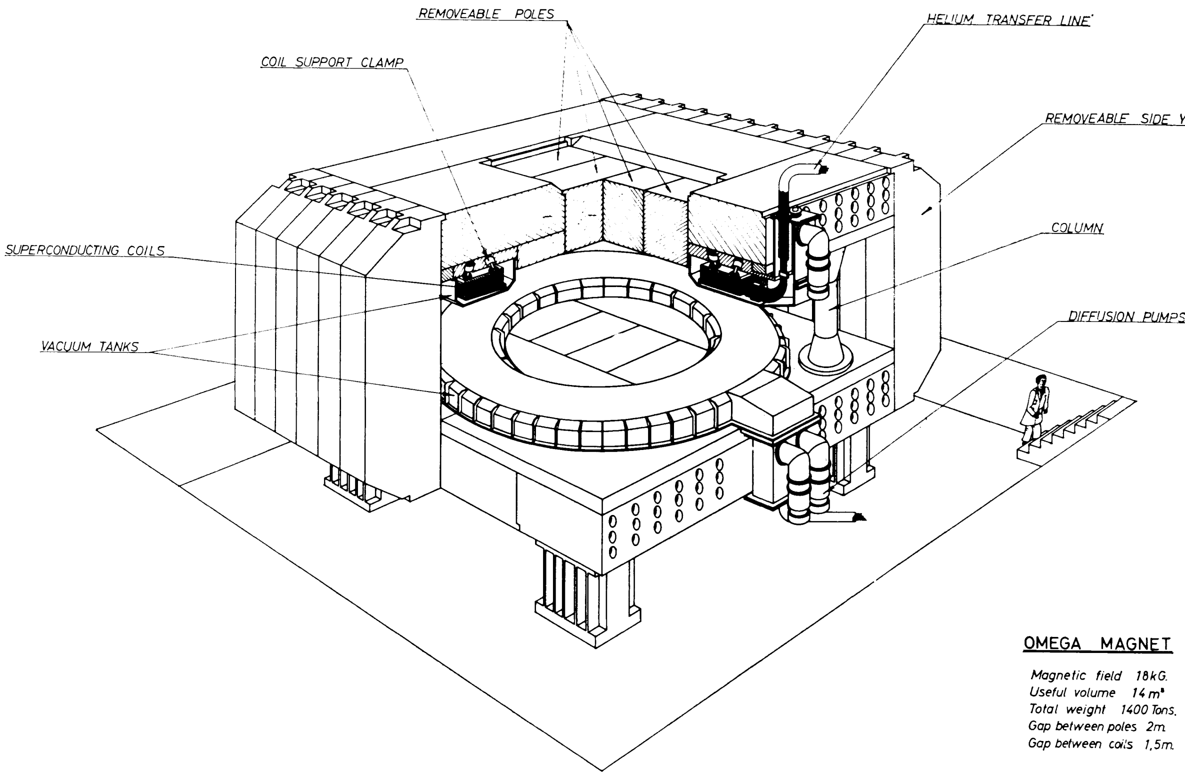

FIG. 1. General view of the 'Omega' magnet.

of oxidized aluminium bushings. The joints are vacuum-tight at liquid-helium temperature, and can withstand a test voltage of 4000 V and an internal pressure over 300 atm.

To make sure that the radiation heat losses and the heat input through the coil supports will not raise the temperature of the superconductor, the entire coil will be protected by a copper shield which will be maintained at 4.5 °K by circulating a mixture of vapour and liquid helium in a cooling loop.

Each coil will be contained into a toroidal stainless-steel vacuum tank, the thermal insulation being provided by four centimetres of multi-layer superinsulation. The radiation losses will be below 1 W per square metre of coil surface. Two oil diffusion pumps for each coil, with a total pumping speed of 8000 liters/sec, will maintain the vacuum below 10^{-5} Torr.

2.2.2. *Coil stresses.* Coil stresses will be caused by the electromagnetic forces on the conductor, and by the thermal contractions during the cooling-down period.

In both cases the stresses have been calculated assuming that an impregnated pancake could be considered as a solid disc. The hole in the conductor and the presence of the insulating material have been taken into account by using, in the calculations, a conveniently modified modulus instead of the copper elasticity modulus.

To calculate the electromagnetic radial stresses, a field map through the coil cross-section has been computed. The maximum electromagnetic radial stress is $\simeq 9$ kg/mm^2. This value is below the yield limit of copper with 5 per cent cold work as used for the conductor.

To calculate the thermal stresses, it is necessary to know the temperature distribution in the coil during the cooling-down period.

The heat exchange between the two layers of a double pancake is fairly good. Therefore, during the cooling-down process, the cold helium entering the pancake will warm up, will reach the highest temperature at the pancake inner radius, and will cool down again when circulating in the second layer of the pancake. The conductor temperatures will be approximately the same at both the pancakes inlet and outlet, and the cooling down will be only

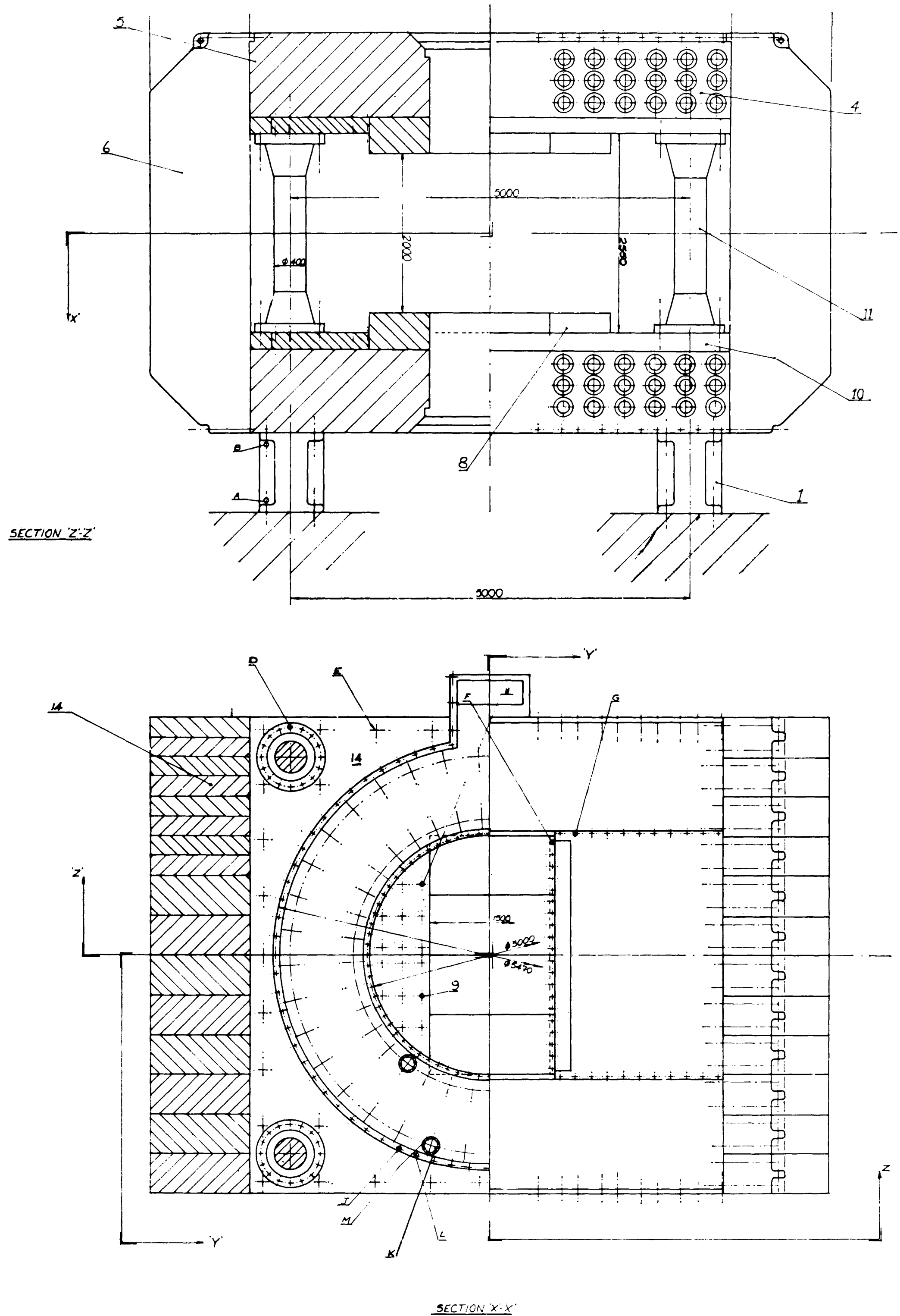

FIG. 2. Iron core.

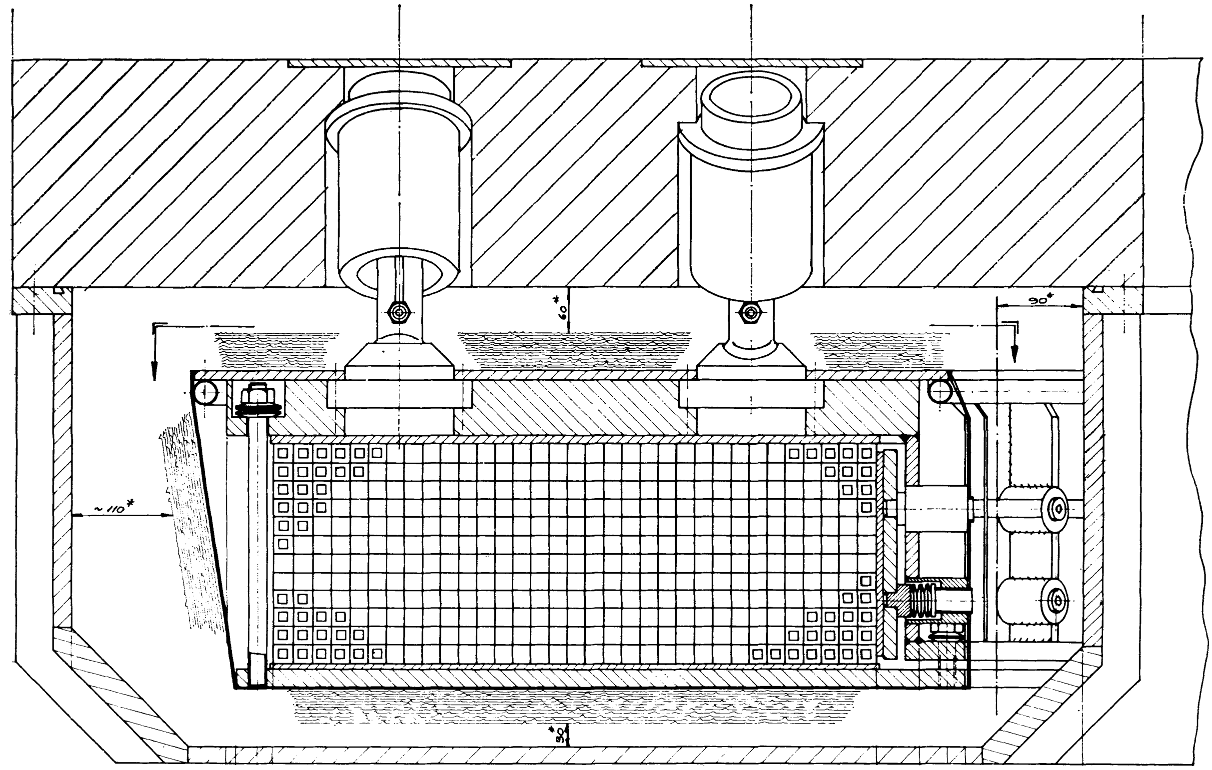

FIG. 3. Coil cross section.

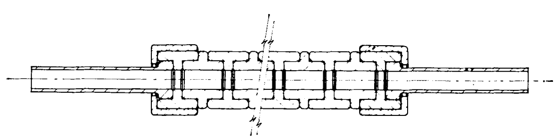

FIG. 4. Insulating joint.

due to the radial heat transmission, as in the case of a disc (without internal helium circulation), the outer edge of which is kept at low temperature.

The thermal stresses will be a function of the cooling-down velocity, which in turn will depend on the difference between the temperatures at the inner and outer coil radii. If this difference is lower than 50 °K, the copper stress will be < 6 kg/mm^2.

2.2.3. *Coil supporting system.* The two coils will be supported (each one independently of the other) by the iron yoke. This has been done in order to provide the maximum accessibility to the central field region between the coils. The coil supporting system must fulfil the following conflicting requirements:

It must

(a) introduce heat losses that are as small as possible;

(b) support axial forces, which will tend to push the coil against the magnet yoke, of the order of 2000 tons;

(c) support horizontal forces of the order of 150 tons;

(d) allow the free thermal contraction of the coil whilst still maintaining the coil centre in a fixed position.

The vertical force on the coil has been calculated by using the field map, and it has also been measured on a reduced scale (1/10) full field magnet model. By reason of the magnet symmetry, the horizontal forces on the coil should be zero. However, as a certain tolerance on the coil positioning must be accepted, and as the magnet symmetry can be destroyed by steel elements in the neighbourhood (e.g. bending magnet, quadrupole lenses, etc.), it is necessary that the supporting system is able to withstand nonnegligible horizontal forces.

The coil supporting system is schematically illustrated in Fig. 5.

The six coil pancakes will be secured to a stainless-steel spool, which will also be at low temperature

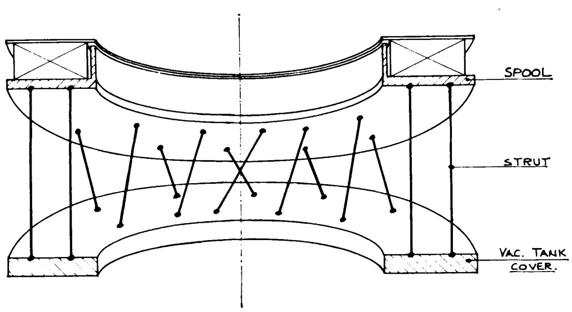

FIG. 5. Coil supporting system.

(4.5 °K). The spool will be supported from the warm vacuum tank cover-plate through 72 compressed struts, 36 struts supporting the outer and the inner coil edges, respectively. A detail of the struts, which will be machined out of a titanium alloy, is shown in Fig. 6. The struts will have spherical joints at both ends which will allow a small angular displacement. The struts supporting the inner and the outer edges will be mounted with opposite inclinations with respect to the coil axes. With this geometry the thermal contraction of the coil will be permitted whilst still maintaining the coil centre in a fixed position.

One point of the strut will be kept at 80 °K by circulating liquid nitrogen in a cooling loop. The heat input to the coil will be approximately 1.2 W per strut. Each strut will require a refrigerating power of $\simeq$ 20 W at 80 °K.

3. THE HOLLOW COMPOSITE SUPERCONDUCTOR

The coils will be wound with a hollow superconductor of square cross section of 18×18 mm^2, and with a hole of 9×9 mm^2.

The conductor (Fig. 7) will consist of a central copper tube on which two layers of copper wires ($\phi = 1.5$ mm) will be cabled with a pitch of approximately 20 cm. Four Nb–Ti filaments (with a diameter of 0.25 mm) will be embedded in each of 30 copper wires of the first layer. The second layer, made of plain copper wires, will be a mechanical protection for the first one. The conductor will be impregnated with a silver soldering alloy. It will carry a critical current of 6350 A at 5 °K in a transversal magnetic field of 35 kG.

Samples of conductor have undergone the following test:

(a) Critical current. The critical current was measured on samples bent on a diameter of 30 cm and stressed by a force of 2.5 tons.

(b) Bonding quality. The bonding quality was deduced by the slope of the voltage versus current curve for currents above the critical value.

(c) Substrate resistivity. The substrate resistivity was $\simeq 1.5 \times 10^{-8}$ Ω/cm with the sample in a field of 35 kG.

(d) Mechanical tests. The yield limit and the tensile force were measured at nitrogen temperature and were found to be higher than 3000 and 6000 kg, respectively.

4. THE REFRIGERATOR

4.1. *Refrigerator duties*

The refrigerator will have to cool down the coils from room temperature to 4.5 °K, and to maintain them at that temperature during normal operation.

The main heat losses from the two coils have been estimated as follows:

Heat input through the coil supports	180 W
Radiation losses	80 W
Miscellaneous losses	40 W
Total	300 W

Furthermore, 1.5 g/sec of liquid helium will be needed for the four current leads, and approximately 3000 W of refrigerating power at 80 °K will be required by the cooling loops of the supporting struts.

Taking into account an adequate safety factor, it has been specified that the Omega refrigerator will have to provide, simultaneously, 500 W at 4.5 °K, 2.5 g/sec of liquid helium, and 4000 W at 80 °K.

4.2. *Helium flow diagram*

The helium flow diagram is shown in Fig. 8. During normal operation, the cold valves V2, V3, V4, V5, V8, V9, V10, V11, and V15 will be closed. Valve V16 will be open. The helium, issuing at high pressure and at a low temperature from the last refrigerator heat exchanger ($\simeq$ 50 g/sec), will divide into four identical circuits connected in

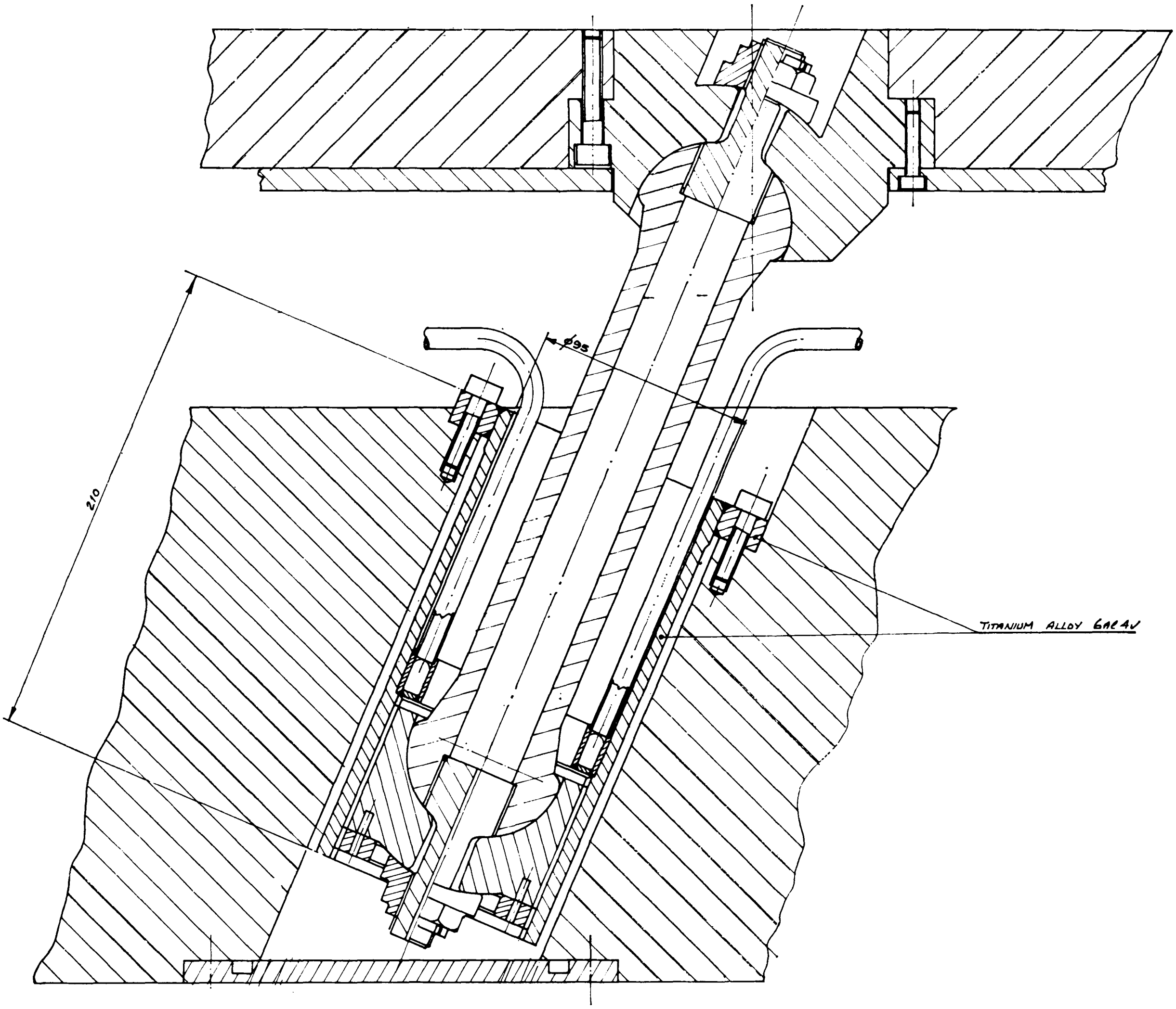

FIG. 6. Detail of the supporting strut.

parallel. At first the helium will expand in the valves V1, V6, V7, and V12, and then will flow through four heat exchangers (which are immersed in the auxiliary cryostat AC) and the four coil circuits. Each of the four coil circuits is composed of three double pancakes connected in series. After each double pancake, the helium is recirculated in a heat exchanger immersed in the auxiliary cryostat. These intermediate heat exchangers are necessary, even if there is no external heat input to the coils in order to cool the helium after its isenthalpic expansion through the coil. The temperature rise due to the isenthalpic expansion in one double pancake will be $\simeq 0.30\,°K$. In the two Joule–Thompson valves V13 and V14, the helium will expand down to 1.2 atm. The resulting mixture of gas and liquid helium will pass through the loops S_1 and S_2, and will then be collected in the auxiliary cryostat AC. S_1 and S_2 will cool the support plates of the coils. The largest fraction of the helium vapour from AC will counter-flow in the last refrigerator heat exchanger. A small fraction of the cold vapour will be used to cool the coil current leads, and will be returned to the refrigerator at room temperature.

Typical values of pressure and temperature calculated at various points of the circuit are as follows (see Fig. 8):

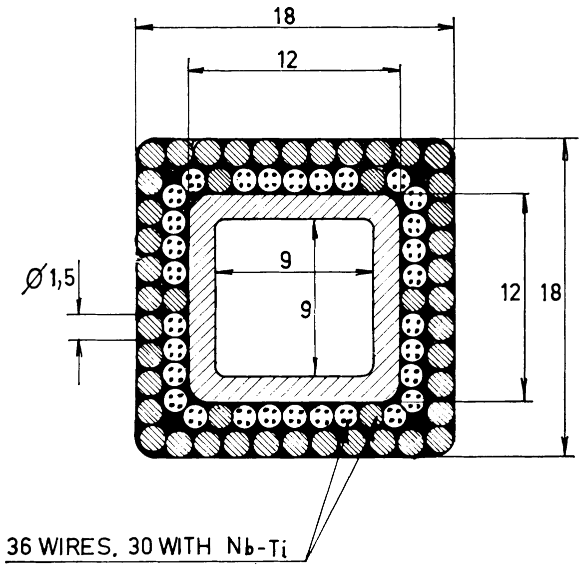

FIG. 7. Conductor cross section.

	Pressure (atm)	Temperature (°K)
Point A	12	4.5
Point B	10	4.8
Point C	10	4.4
Point D	5	4.6
Point E	1.2	4.4

4.3. *Cooling down of the coils*

The weight of the copper and stainless steel which must be cooled down from room temperature to 4.5 °K is approximately 50 tons. The corresponding enthalpy variation is ≈ 4000 MJ.

When starting the coil cooling, the mode of operation will be as follows: valves V1 to V15 will be opened (see Fig. 8). V16 will be closed. Therefore the helium will circulate in 12 parallel circuits (6 per coil), and the auxiliary cryostat will be bypassed. During cooling down, valves V1 to V14 will have to be progressively throttled to maintain the helium flow within the limits of the compressor capacity and to avoid overpressure in the auxiliary cryostat. When the coil temperature will be sufficiently low (below 7 °K) the auxiliary cryostat bypass will be suppressed (i.e. V16 will be opened and V15 will be closed) and the cryostat will be filled with liquid helium. Then valves V2, V3, V4, V5, V8, V9, V10, and V11 will be closed and the final conditions of operation will be reached.

The cooling-down time (from room temperature to operating conditions) will be approximately 200 hours, the limiting factor in the cooling velocity being the need to avoid excessive thermal stress in the coil, rather than the refrigerator capacity.

5. SPECIAL DESIGN PROBLEMS

Some design problems are common to the Omega magnet and to all the other cryogenic coils; some are specific of the forced circulation cooling system.

5.1. *Stability criteria*

The stability criteria in the case of forced cooling are not the same as in the case of a bath-cooled conductor.[2] In the second case (contrary to the first one), the temperature of the cooling medium will be independent of the power dissipated in the normal zone of the conductor. Stekly's stability criterion will be valid in the case of forced cooling, only if the length of conductor, which has become normal, is very short and produces a negligible helium heating.

The general question whether the hollow conductor will recover or not after a length of conductor has received a heating pulse and has become normal, can be answered by solving the system (1) of differential equations, which gives the conditions of thermal equilibrium for a conductor element.

$$\left.\begin{aligned} K\frac{\partial \theta_1}{\partial x^2} - C_1\frac{\partial \theta_1}{\partial t} + G + P - Q &= 0 \\ C_2 V\frac{\partial \theta_2}{\partial x} + C_2\frac{\partial \theta_2}{\partial \tau} - Q &= 0 \end{aligned}\right\} \qquad (1)$$

where θ_1 = conductor temperature
θ_2 = helium temperature
K = thermal conductivity per unit length of conductor
C_1 = specific heat per unit length
C_2 = specific heat of the helium per unit length
V = helium velocity
$G = G(\theta_1)$ = ohmic power dissipated per unit length
$P = P(x, t)$ = external power input per unit length
$Q = Q(\theta_1, \theta_2)$ = power flow per unit length from the conductor to the helium.

In the case of the Omega conductor, we have solved numerically the system of equations (1), assuming

(a) the conductor (i.e. the cooling circuit) has a very great length;

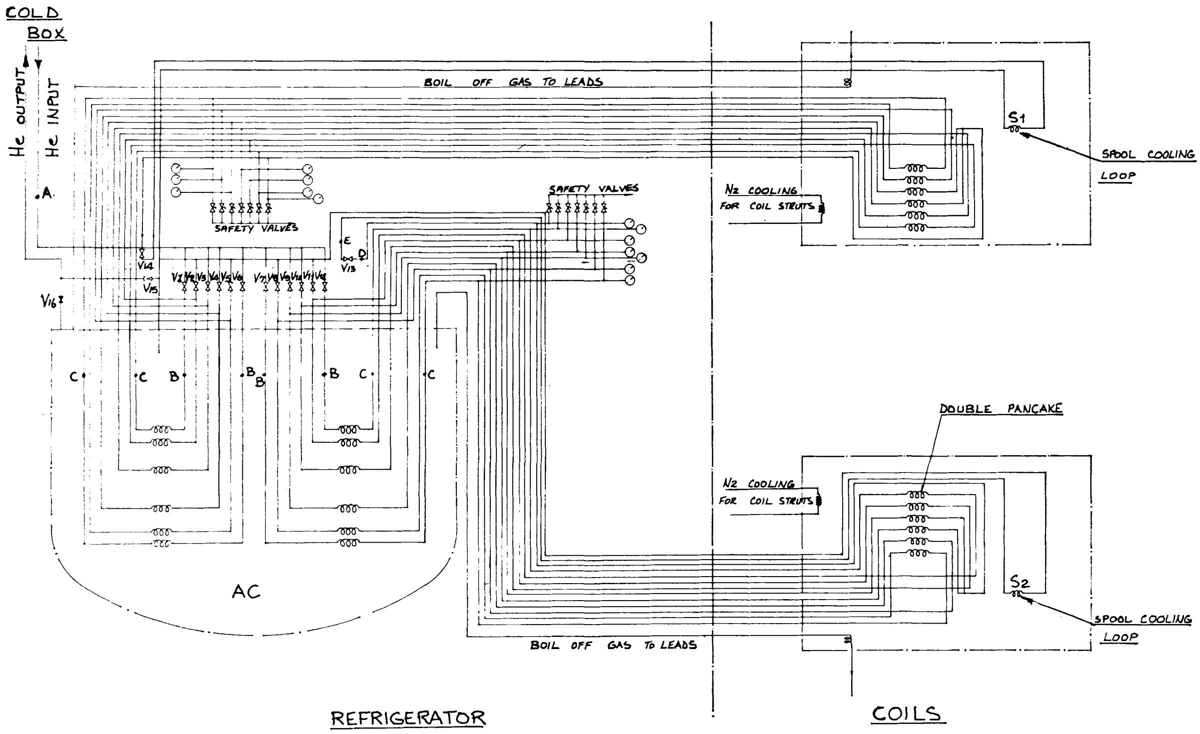

FIG. 8. Helium flow diagram.

(b) at the initial time $t = 0$, the conductor and the helium have everywhere the same temperature θ_0;

(c) at the time $t = 0$ a central section of conductor, of length L, receives a heat pulse of power P during a time τ;

(d) $Q = \alpha \cdot h(\theta_1 - \theta_2)$ (α = heat transfer coefficient; h = perimeter of the conductor hole);

(e) $G = 0$ for $\theta_1 < \theta_1'$, $G = I^2R(\theta_1'' - \theta_1)/(\theta_1'' - \theta_1')$ for $\theta_1' < \theta_1 < \theta_1''$, $G = I^2R$ for $\theta_1 > \theta_1''$.

A typical solution of Eq. (1) which shows how the normal zone propagates along the conductor is given in Fig. 9. The results of the computation are summarized in Fig. 10, where for each length L the maximum power P is plotted for which the conductor will still recover. To recover means that the normal conductor zone produced by the heat pulse will be cleared away, and that after some time the entire conductor will return superconducting.

An interesting case is that in which the conductor receives a heat pulse over its entire length ($L = \infty$). Therefore

$$\frac{\partial^2\theta_1}{\partial x^2} = \frac{\partial\theta_1}{\partial x} = \frac{\partial\theta_2}{\partial x} = 0,$$

and the system of Eq. (1) (for $t > \tau$) can be reduced to the single equation

$$\frac{d\theta_1}{d\theta_2} = \left(\frac{G}{Q} - 1\right)\frac{C_2}{C_1}. \quad (2)$$

The conductor will recover if the function $\theta_1 = \theta_1(\theta_2)$, the solution of Eq. (2), crosses the straight line $\theta_1 = \theta_2$.

5.2. *Heat transfer between conductor surface and helium*

In our calculations we have assumed that the constant heat transfer coefficient α is given by the standard correlation valid for turbulent flow:

$$\alpha = 0.024\ \mathrm{Re}^{0.8}\ \mathrm{Pr}^{0.4}\ \lambda/d, \quad (3)$$

where Re = Reynolds number
Pr = Prandtl number
λ = helium heat conductivity
d = hydraulic diameter of the pipe.

The value of α for the Omega conductor is $\simeq 0.16\ \mathrm{W/cm^2 \cdot {}^\circ K}$. Experimentally measured values of α correspond fairly well to values calculated by fitting in Eq. (3) the helium characteristics available in the literature.[3]

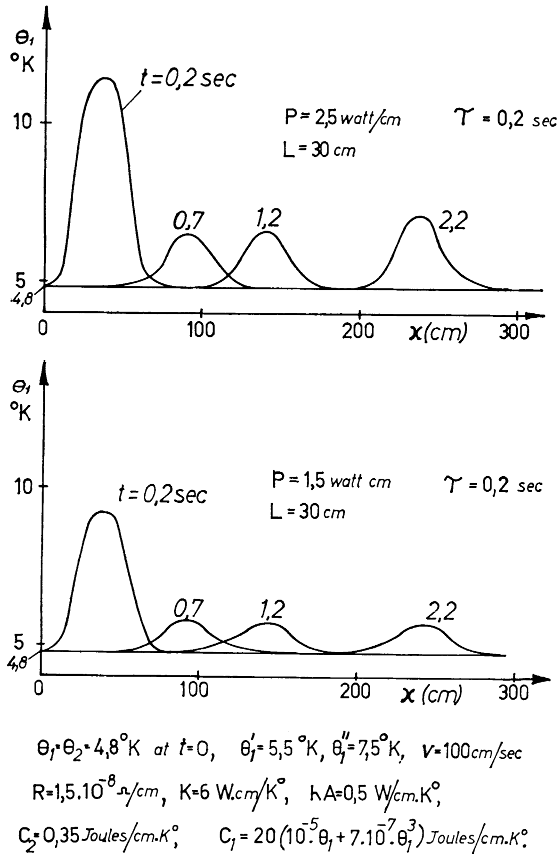

FIG. 9. Propagation of the normal zone along the conductor.

5.3. *Pressure drop in the conductor*

The maximum permissible pressure drop in the conductor will depend on the pressure at the output of the refrigerator cold box, and on the acceptable temperature rise due to helium isenthalpic expansion through the coil.

In the Omega magnet, the pressure will drop in the coil from 10 to 5 atm. The pressure drop in the

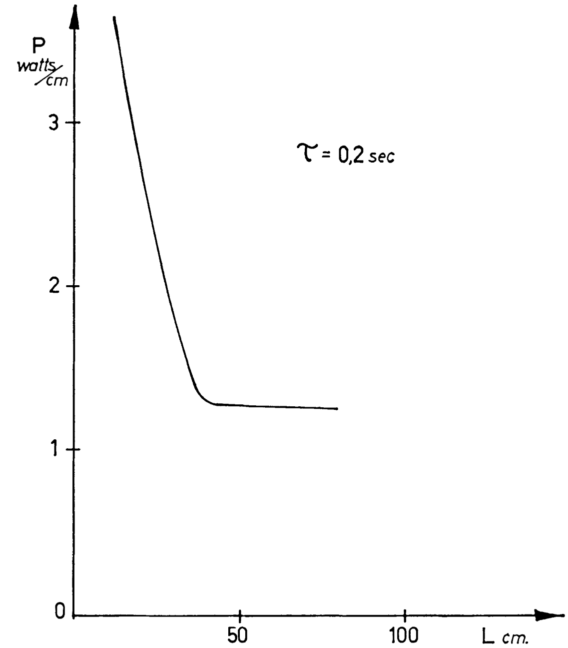

FIG. 10. Power versus critical length (for $\tau = 0.2$ sec.

conductor is given by the equation

$$\Delta p = 0.31 \frac{\delta V^2}{2} l/d \, (\mathrm{Re})^{-1/4}$$

δ = helium density l = conductor length.

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Received 20 April 1970