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[54] **COOLING DEVICE FOR SUPERCONDUCTING COILS**

[75] Inventors: **Gaston Bronca,** Fontenay-aux-Roses; **Christian Lefrancois,** Orsay, both of France; **Ivan Hlasnik,** Bratislavia, Czechoslovakia; **Jean-Paul Pouillange,** Bagneux, France

[73] Assignee: **Commissariat a L'Energie Atomique,** Paris, France

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[58] **Field of Search** 335/216; 174/DIG. 6

[56] **References Cited**

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Primary Examiner—George Harris
Attorney—Cameron, Kerkam & Sutton

[57] **ABSTRACT**

A cooling device for a superconducting element which is wound in continuous turns to form a coil. The device comprises an assembly of thin metallic filaments which is mounted between the different turns of the coil. The filaments are electrically insulated from each other and in thermal contact with the turns of the winding and with a bath of liquefied gas.

7 Claims, 3 Drawing Figures

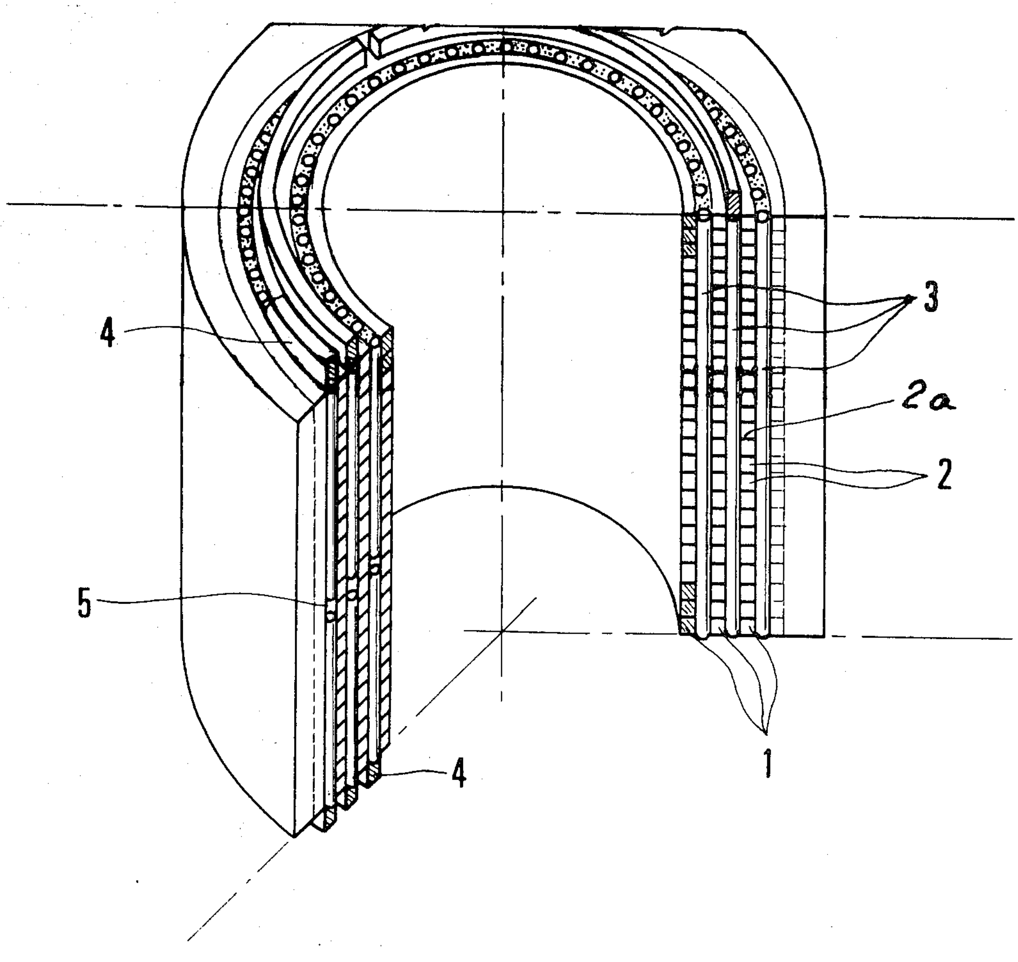


Fig. 1

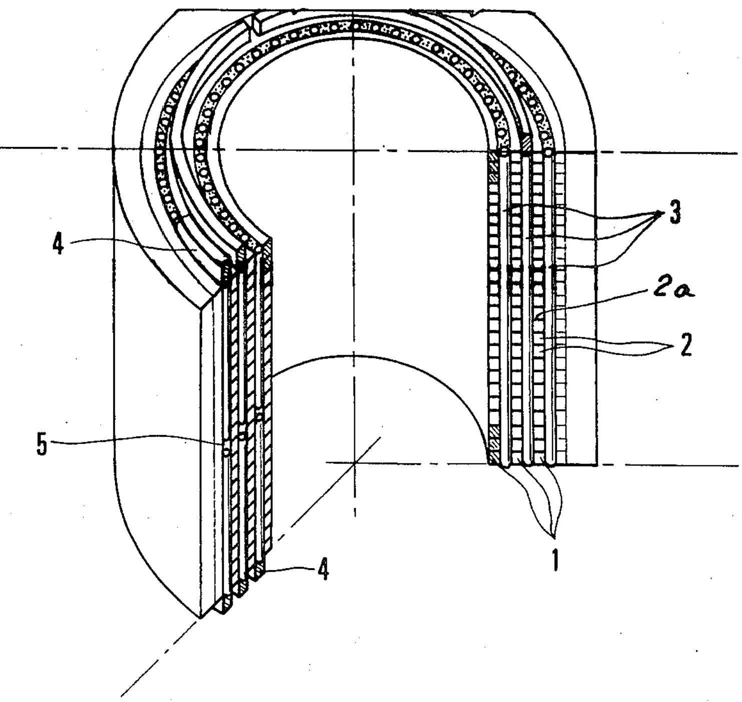


Fig. 2

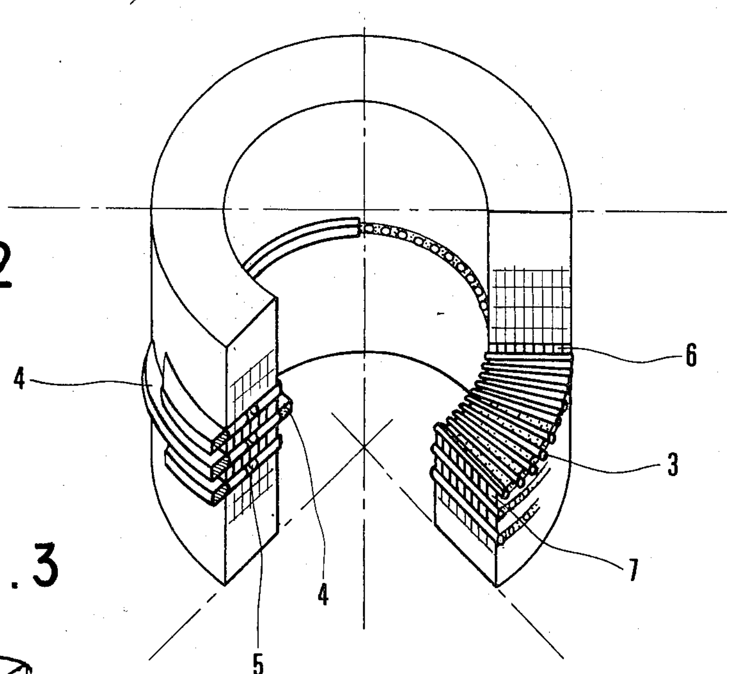
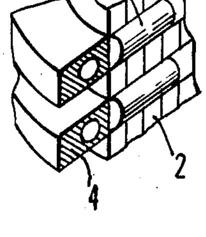


Fig. 3



COOLING DEVICE FOR SUPERCONDUCTING COILS

This invention relates to a cooling device for superconducting coils which are primarily intended to operate in the presence of variable magnetic fields.

It is in fact known that, under these conditions, energy losses develop in the form of heat within the turns of superconducting coils ; the origin of these losses is either electromagnetic (variation of the magnetic flux within a superconducting element) or mechanical (friction of conductors under the action of electromagnetic forces). It is also known that, in order to reduce the level of electromagnetic losses, it is an advantage to employ very thin superconducting wires or lengths of wire which can be supplied with current in parallel provided that they are suitably transposed.

The heat build-up which accompanies said losses brings about a reduction in the critical current density within the superconducting turns and consequently in the performances of coils which is more marked as the critical temperature of the material which forms said turns in respect of the maximum field considered is of lower value. This reduction in critical density J_c can be represented approximately by

$$\Delta J_c = (\Delta T / T_{cB} - _{To}) J_{co}$$

wherein T_o represents the temperature of a bath of liquefied gas which maintains the material of the turns of the coil below its critical temperature,

T_{cB} represents the critical temperature of the material at the value of induction B considered,

ΔT represents the temperature rise of the material with respect to the bath,

J_{co} represents the critical density of superconducting current at a temperature T_o and at a value of induction B.

It is closely an advantage from this point of view to choose a material in which the value T_{cB} is of a high order such as Nb_3Sn, for example. However, the technique of fabrication of thin niobium-titanium filaments still appears to be preferable. At an induction of 5 to 6 Teslas, T_{cB} is in the vicinity of 6° K in the case of niobium-titanium. A temperature rise of 0.2° K therefore corresponds to a reduction of J_c of the order of 10 percent. Moreover, the losses per cubic centimeter and per cycle in the case of niobium-titanium filaments having a diameter of 10 microns and subjected to a pulsed induction having an amplitude of 6 Teslas are of the order of 6×10^{-2} joules.

The foregoing considerations thus emphasize the advantage of effective cooling of the turns of superconducting coils. At the present time, reliance is placed on the conductivity of the coil, whether this latter is impregnated or not, in order to supply to the bath of liquefied gas the heat which is produced within the coil as a result of losses; alternatively, the cooling is improved by providing ducts for circulating the liquefied gas within the interior of the coil itself.

The first method which permits construction of compact coils having good mechanical strength gives rise at the present time to excessive values of heat build-up as a result of insufficient apparent thermal conductivity of the coil. In regard to heat build-up, the second method produces good results insofar as the system of ducts actually permits the circulation of the liquefied gas, which presupposes either a thermo-siphon effect entailing the

need for a system of ducts which are oriented in a direction in the vicinity of the vertical or a forced circulation of gas. However, the practical application of a method of this type is liable to involve heavy capital expenditure.

In practice, the thickness of the ducts must be greater than a few tenths of a millimeter, thereby substantially reducing the coefficient of filling of the coil with the turns of superconducting material. Moreover, this method is not conductive to mechanical strength of the coil.

At the time of construction of direct-current superconducting coils, metallic sheets are sometimes inserted between the turns or layers of turns. This arrangement is employed for the purpose of improving the stability, on the one hand by increasing the thermal conductivity of the coil and on the other hand by slowing-down the penetration of the magnetic flux into the superconducting material at the time of a flux jump by means of the eddy currents which develop within the conductive sheets. However, this method is not directly applicable to windings which operate in a variable magnetic flux regime since the level of losses associated with the eddy currents which would develop within said metallic sheets would be too high.

This invention relates to a cooling device which is designed and arranged to increase the apparent thermal conductivity of a superconducting coil to a considerable extent while circumventing the disadvantages of arrangements of the prior art. More specifically, the invention applies to a superconducting coil which is subjected to a variable magnetic field and constituted by a multi-turn winding of a superconducting element and in which a thermal contact is established between all the turns of the coil and a bath of liquefied gas which surrounds said coil.

To this end, the device under consideration essentially comprises an assembly of thin metallic filaments which is mounted between the different turns of the coil, said filaments being electrically insulated from each other and in thermal contact on the one hand with the turns of the winding and on the other hand with a bath of liquefied gas.

The establishment of a thermal contact between the turns and the liquefied gas by means by filaments which are electrically insulated from each other has the effect of reducing to a considerable extent the level of losses associted with the eddy currents which develop within the solid metallic elements in a variable magnetic regime. A metal which has high purity and has been annealed after conversion to filaments will be employed for these latter in order to benefit by high thermal conductivity at very low temperature. However, any other metal having good thermal conductivity could be employed.

In order to reduce the temperature difference between the superconductor and the filaments, it is recommended to carry out an impregnation with electric insulating material having high thermal conductivity. In fact, the layers of ambient gas which constitute thermal insulators are removed by impregnating the coil. It is possible to improve the conductivity of this impregnation by adding either metallic powders such as copper, for example, or silica powders.

Calculations show that the heat transfer between the filaments and the liquefied gas constitutes a difficult problem. If it is in fact desired to ensure that the temperature difference between the gas bath and the filament surface which is in contact with this latter is of the order of 0.1° K, the heat flux exchanged per cm^2 should be lower than 10^{-2} watts. In order to produce this result, it is possible :

either to allow the filaments to project from the coil over a given distance,

or to make use only of the transverse cross-section of the filaments as a surface for heat transfer with the liquefied gas. This transverse cross-section is bared after impregnation by grinding the external surface of the coil,

or to connect the the ends of the filaments which are placed between two turns or sets of turns by means of a metallic bead which is applied against an end turn of one of said sets. After impregnation of the coil, the bead is bared by grinding. If the filaments are connected by means of a bead at both ends, the heat-transfer surface will accordingly be doubled and it is then necessary to cut the filaments in order to prevent the formation of closed conductive loops,

or to produce a forced circulation of liquefied gas within a duct having good thermal contact with the filaments.

A better understanding of the invention will be gained from the following description in connection with two exemplified embodiments which are given by way of indication without any limitation being implied, reference being made to the accompanying drawings, wherein :

FIG. 1 shows a multi-layer superconducting coil provided with a cooling device in accordance with the invention ;

FIG. 2 shows a wafer-type superconducting coil which constitutes an alternative form of construction;

FIG. 3 is an enlarged detail of a part of FIG. 2 showing gas circulation ducts in the beads.

The coil which is illustrated in FIG. 1 is made up of a plurality of layers 1 of consecutive turns formed of superconducting wires or strips 2 and especially of niobium-titanium. Each layer 1 of wires is separated from the adjacent layer by metallic filaments 3 having high thermal conductivity and formed, for example, of annealed copper having a very high degree of purity. Said metallic filaments 3 have small transverse dimensions of the order of 100 microns and are electrically insulated by means of a material *2a* such as polyester, polyvinylacetal or epoxy varnish filled with heat conducting powders.

The wires 2 may have a flattened shape in order to improve the thermal contact with the filaments which can also have a flattened shape.

One or both ends of the filaments 3 which are associated with each layer and stripped of their electric insulation are embedded in a metallic bead 4 which is immersed in a bath of liquefied gas, especially external liquid helium. In the case in which a bead is formed at each end, the filaments 3 are cut at 5 in order to prevent formation of closed conductive loops.

The device of FIG. 2 is an alternative embodiment in which the same reference numerals are employed to designate the corresponding elements for the sake of enhanced clarity.

In the coil which is illustrated in this figure, the turns constitute wafers such as those which are designated by the reference numerals 6 and 7, said wafers being separated by metallic filaments 3 which are insulated but disposed radially. The outer extremities of these filaments 3 are also embedded in a metallic bead 4.

The inner extremity of each filament can also be joined to a second bead if the internal diameter of the coil so permits, in which case the filaments are cut at 5.

The method of cooling superconducting coils which are subjected to a variable magnetic regime reconciles the advantages of the two methods at present in use (impregnation of the winding and system of ducts). These advantages lie in compactness of the coil, good mechanical strength and a high value of occupation by the superconductor, good cooling of the coil and simplification of the cryostat.

What we claim is :

1. A cooling device for a superconducting coil constituted by a winding of continuous turns of a superconducting element, wherein said device comprises an assembly of thin metallic filaments which is mounted between the different turns of the coil, said filaments being electrically insulated from each other and in thermal contact with the turns of the winding and with a bath of liquefied gas.

2. A device according to claim **1**, wherein the surface which provides heat transfer between the metallic filaments and the bath of liquefied gas is defined by metallic beads in which the ends of said filaments are embedded after said ends have previously been stripped of insulation.

3. A device according to claim **2**, wherein the ends of the metallic filaments which have been stripped of insulation are immersed in the bath of liquefied gas.

4. A device according to claim **2**, wherein the ends of the metallic filaments are in thermal contact with the bath of liquefied gas by means of the transverse section of said filaments.

5. A device according to claim **1**, wherein the thermal contact between the filaments and the liquefied gas is established within ducts for the circulation of said gas.

6. A device according to claim **1**, wherein the thermal contact between the turns of the coil and the filaments is established by impregnating the turns with electric insulating material which is filled with heat-conducting powders.

7. A device according to claim **1**, wherein the metallic filaments are a metal having high purity selected from the group consisting of silver, aluminum and copper annealed after fabrication of said filaments.

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