Role of Insulations in a Superconducting Magnet

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journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	15
page range	297-303
year	1963
URL	http://hdl.handle.net/10097/27138

Rôle of Insulations in a Superconducting Magnet*

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(Received February 5, 1964)

Synopsis

Two types of the superconducting magnets, whose insulating layers inserted between every successive superconducting winding layer consist of the usual insulator named Mylar sheets in the one and of the metallic copper foils in the other, were examined.

The former gives a comparatively definite magnetic field with regard to the exciting current but is liable to be damaged. The latter shows a large magnetic hysteresis owing to the intra-and inter-layer persistent eddy currents between successive layers of windings, but is not damaged by the super- to normal-phase transition.

I. Introduction

Of a number of applications of the superconducting phenomenon, the superconducting magnet is one of the most remarkable applications in these days. It is the final aim of the present investigation to get a strong magnetic field by consuming the least possible energy by means of the solenoid made by winding the wire of a suitable material which is capable of supporting a large current without destroying the superconducting state.

Two types of superconducting magnets with respect to the insulating materials inserted between the successive layers of windings were manufactured. The first type called provisionally the type "A" is the one whose insulating layers consist of a true insulator called Mylar sheet of 6μ in thickness, the superconducting wire itself being coated with nylon to the thickness of 0.02 mm. The second type, called here the type "B", is that whose insulating layers consist of thin sheets of copper foil of 0.02 mm in thickness, and the superconducting wire itself has no particular insulation except a superficial thin oxide layer which was brought about during the wire drawing process. Metallic copper, of course, remains to be a normal conductor down to the lowest temperature, so that it only plays the role of insulator so far as the conducting windings are retaining the superconducting state.

II. Constructions of magnets and their experimental results

(1) Type "A" magnet

A Nb–25 per cent Zr alloy wire of 0.25 mm in diameter, coated with nylon to

* The 1101st report of the Research Institute for Iron, Steel and Other Metals. Reported at the Spring Meeting of the Society of Applied Physics in Japan, held on April 2, 1963 in Tokyo.

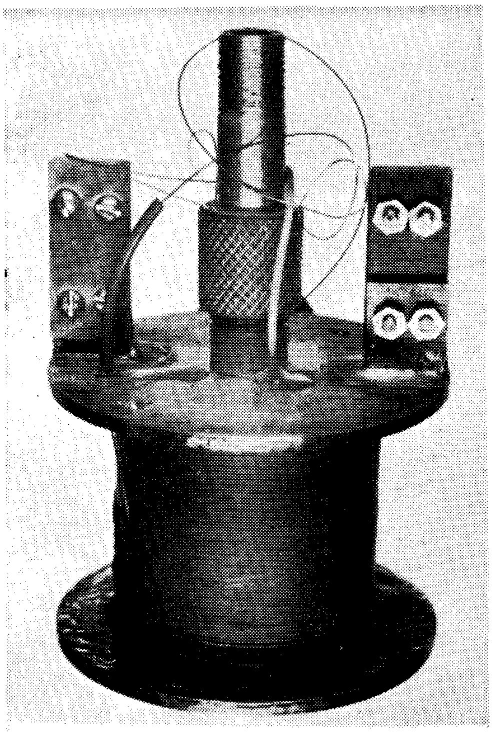

Fig. 1 Superconducting Magnet: Type "A".
Type "B" has an almost similar shape however.

0.02 mm in thickness, viz., 0.29 mm in an overall diameter and 660 m in total length, was wound on a titanium bobbin 6 mm i.d., 8 mm e.d., 34 mm long. As depicted in Fig. 1, the solenoid thus obtained has the following size: 8 mm in internal diameter, 46 mm in external diameter, 34 mm in length; the total number of windings is 7,221, the number of layer is 67, and every layer is insulated by inserting a Mylar sheet of 6μ in thickness. This alloy wire can keep, in the state of a short single piece, a superconducting state even when a direct current of 45A is passed, i.e. at a current density of $9\times10^4 A/cm^2$, at 4.2°K in a magnetic field of 9000 Oe. Both terminals of the above mentioned solenoid were connected to a pair of copper wires of 2mm in diameter by dint of two small copper buckles plated with indium metal. These copper wires were led out of a dewar vessel and connected to a battery of 6V, 200Ah in capacity via a slide rheostat. When the solenoid was cooled down to 4.2°K, it sustained a definite small current determined by the resistance of the lead wire and the slide rheostat. Then the magnetic field strength was measured as a function of the exciting current in the stage of increasing current by decreasing the external resistance slowly and smoothly until the superconducting state of the solenoid was converted into the normal conducting state. In this way, the threshold current value and the strength of a critical magnetic field could also be determined. The usual potentiometric method was used to measure the exciting current, and the strength of the magnetic field was read by measuring the resistance of an antimony single crystal of 1 mm wide

0.5 mm thick and 4 mm long, which was placed transversally in the center of the solenoid. The transverse magnetoresistance of this antimony probe was previously measured in a magnetic field up to 80 kOe at 4.2°K and a good linearity was ascertained as shown in Fig. 2.

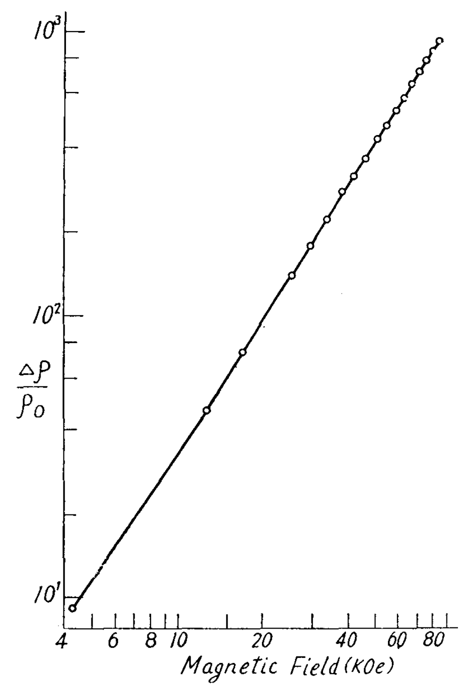

Fig. 2. Magnetoresistance of an antimony probe as a function of the magnetic field.

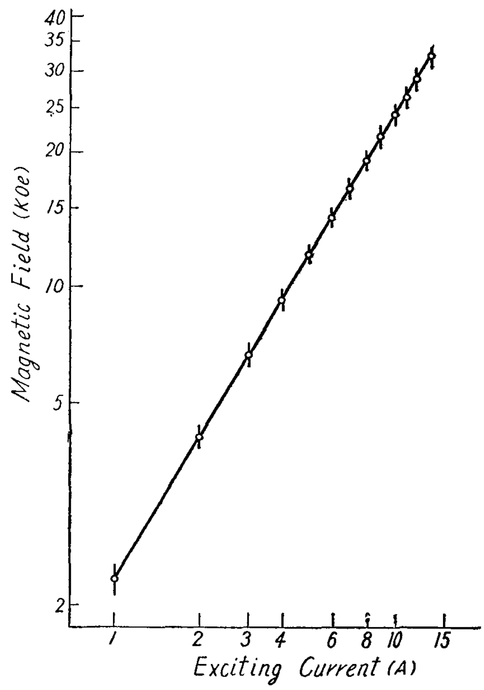

Fig. 3. Strength of magnetic field as a function of the exciting current in the type "A" magnet.

In the type "A" magnet, though starting from a very small value of exciting current, the superconduction was destroyed suddenly at 7.6A, the corresponding field being 16400 Oe, and the resistance of a few thousand ohms appeared, causing the current drop to a very small value. In this occasion, liquid helium in the dewar vessel abruptly boiled with a noise and the nylon insulation was frequently damaged by the heat evolution due to an s-n phase transition. However, in this case, the interruption of superconduction was not permanent, so that after a few minutes, by decreasing again the external resistance, the current could be increased above the former value up to 10.9A, until the superconduction was again destroyed the current dropped suddenly, the corresponding field being 26500 Oe. The temporary interruption of superconduction as above is frequently observed in a hard superconductor, and such a phenomenon is usually called a "training effect." But by decreasing again the external resistance, the exciting current could be increased up to 13.9 A., i.e. 2.9×10^4A/cm^2 in the current density, and 34000 Oe was the measured magnetic field. This field was the maximum one in the present case by the type "A" solenoid. Eventually the relationship was obtained between the current and the magnetic field as reproduced in Fig. 3. The length of the vertical extent of each point in the figure stands for the range of measured values of the magnetic field, when the current was varied cyclically between zero and the maximum value. The magnetic field, therefore, is almost proportional to the current within 1 per cent of the maximum field. Here, it is to be remarked that the maximum current density of $2.9\times10^4 A/cm^2$ in the type 'A" magnet is less than one third of the value obtained in the case of a single wire.

(2) Type "B" magnet

The magnet of the second type was manufactured by winding an uninsulated 3Nb-Zr wire. In this case too, the diameter of the wire was 0.25 mm and the total length was 660 m. The wire was wound on a stainless steel bobbin 8mm i.d., 10 mm e.d., 34 mm long, the resultant size of the solenoid was 10 mm in inner diameter, 42.4 mm in external diameter and 34 mm in length. The total number of windings was 7313, the number of layers was 58 and every layer is insulated by copper foil of 0.02 mm thick. The lead-out copper wires and other accessories were all the same as in the case of type "A" magnet. By increasing the exciting current the field attained to 2000 Oe for the current of 3A, 5000 Oe for 4A, 12000 Oe for 6A, 19000 Oe for 9A and at the field of 27000 Oe for 12.5A the superconduction of the solenoid was destroyed, giving rise to the abrupt boiling of liquid helium. In this occasion, however, the residual magnetic field of about 1200 Oe, the amount of which diminished a few per cent after an hour, was observed at the center of the solenoid owing to the local eddy current between the windings. Notwithstanding a farther decrease in the external resistance, the magnetic field in the center could not be increased noticeably.

Fig. 4 represents the relationship between the current in type "B" manget and the strength of the magnetic field in the center. But after two days, on recooling the same magnet down to 4.2°K and increasing the current, the maximum magnetic field of 32000 Oe could be observed for the current of 14.8A, that is to say, the maximum current density of $3\times10^4 A/cm^2$ which is a little higher than the value obtained in the case of type "A" manget, viz. $2.9\times10^4 A/cm^2$.

In a remarkable contrast to the type "A" magnet, the type "B" magnet gives the magnetic field which is not proportional to the current but gives an appreciably low field until 20,000 Oe is reached. However, the increasing trend of the magnetic field higher than 20000 Oe as a function of exciting current nearly coincides with the result calculated from the value of current as will be described later.

Fig. 5 shows the hysteresis curves of the magnetic field in the center of solenoid when the exciting current was changed cyclically. The residual magnetic field, when the current was annulled, was about 7500 Oe and remained almost constant within $1\sim2$ per cent after an hour standing.

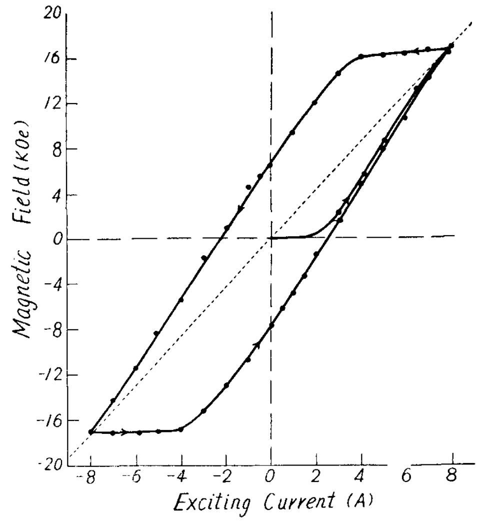

Fig. 4. Strength of magnetic field as a function of the exciting current in the type "B" magnet

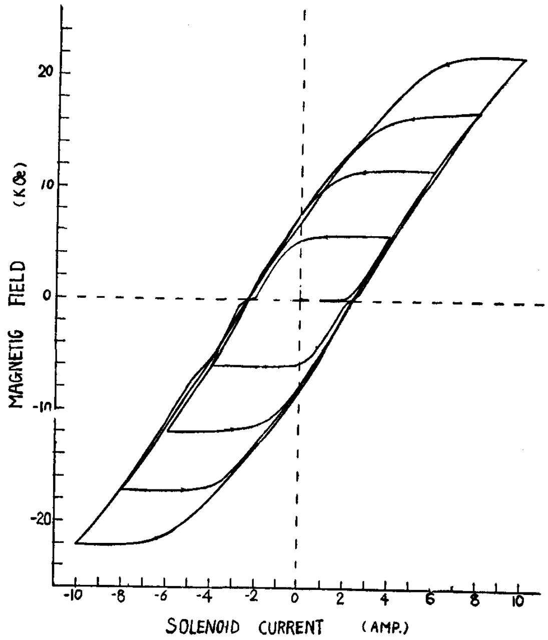

Fig. 5. Magnetic hysteresis loops observed when the exciting current was varied cyclically

It is a matter of course that because of there being no insulation except copper foils in the case of type "B" manget the destruction of insulation as in the case of type "A" magnet does not take place.

III. Considerations on the experimental results

(1) Relation between the axial field H produced at the center of a solenoid and the current density i in the winding is given by many authors[(1)] as follows:

$$H = G i \lambda \sqrt{\frac{2\pi b (a_2^2 - a_1^2)}{a_1}} = K i \lambda a_1 , \tag{1}$$

where

$$K = G \sqrt{\frac{V}{\lambda a_1^3}} = \frac{4\pi}{10} \beta \ln \frac{\alpha + \sqrt{\beta^2 + \alpha^2}}{1 + \sqrt{\beta^2 + 1}} , \tag{2}$$

in which λ is the space factor (conductor volume/total winding volume), and $\alpha = a_2/a_1$, $\beta = b/a_1$: $2a_1$, $2a_2$, $2b$ are the internal diameter, the external diameter and the length of the solenoid, respectively.

By using the dimensional values of the type "A" magnet we get $K=4.70$ by Eq. (2). The linear increase of H with i as shown in Fig. 3 is evinced by Eq. (1).

(1) Cf. M. Wood, Cryogenics, **2** (1962), 297.

For instance, the critical field H_{max} is given as 3.43×10^4 Oe by using $i_{max}=2.9\times10^4$ A/cm^2, $\lambda=0.63$, and $a_1=0.4$ cm, while the experimental result is 3.4×10^4 Oe.

In the case of type "B" magnet, a remarkable deviation from the linear relationship between H and i was observed in the range of H below 2×10^4 Oe, but the trend of the field higher than 2×10^4 Oe is almost coincide with that given by Eqs. (1) and (2). For instance, the maximum field is given as 3.17×10^4 Oe by using $K=3.23$, $i_{max}=3.0\times10^4$A/cm^2, $\lambda=0.65$ and $a_1=0.5$ cm, while the experimental result is 3.2×10^4 Oe. The experimental behaviour of type "B" magnet may be interpreted as follows: Although the surface of the wire is coated with an oxide layer and a grease film due to the wire drawing process, the electrical insulation between the contiguous windings in a layer may be imperfect, so that the effective number of turns may be considerably smaller than the geometrical one. However, as the increase of exciting current the superconducting state of the surface of wires would be destroyed, the result of which brings about the improvement of the insulation between adjacent wires and thereby the effective number of turns would approach the actual one.

(2) The hysteresis phenomenon in type "B" magnet

As the origins of such a remarkable hysteresis and marked frozen-in fluxes, there may be three factors to be considered.

(a) A persistent current is generated in an individual layer, as there is no insulation between adjacent wires.

(b) A persistent current is generated between successive layers, owing to the imperfect insulation between layers.

(c) Even if the insulations between successive layers and adjacent wires are perfect, an eddy current will flow through copper foils between the layers. If this is the case, an energy loss in copper foils will give rise to the damping of the eddy current with time (t) as $i/i_0=\exp(-Rt/L)$. Here i_0, R, L denote the initial current strength, the resistance and the inductance along the current loop, respectively. And if $L\gg R$, the damping of the eddy current would be very slow.

Taking into consideration the fact that the actual residual field in type "B" magnet is 7.5 kOe as in Fig. 5, the residual field will be due to the resultant effect of these factors.

Summary

(1) Two extreme cases with regard to the insulation between the windings were adopted in manufacturing the superconducting magnets.

(2) Type "A" magnet was wound of a nylon coated 3Nb-Zr wire and a Mylar sheet was used as an inter-layer insulation.

(3) Type "B" magnet was made of an uninsulated 3Nb-Zr wire and a copper foil was used as an inter-layer insulation.

(4) Type "A" magnet gave a magnetic field proportional to the exciting current.

A marked training effect, i.e. a temporary destruction of superconduction, was observed. But a destruction of the insulation frequently occurred owing to the heat evolution resulting from an s-n phase transition.

(5) Type "B" magnet did not show the destruction of an insulating layer, but showed a marked hysteresis phenomenon when the exciting current was cyclically changed, so that the magnetic field was not proportional to the exciting current.

Aknowledgements — Thanks are due to the Department of Education for the grant needed for executing the research and also to Mr. Mitsuru Hongo for the help in the course of experiments.