Low-Field Superconducting Magnet with Nb-Ti Wire

Hisao YAGI*, Masasi INOUE*, Toshiaki TATSUKAWA*,
Susumu KATO*, Osami YAEGUCHI*

(Received Oct. 5, 1970)

A low-field square ended superconducting magnet has been constructed with Nb-Ti alloy as a coil, which is to be used for the nuclear magnetic resonance experiment at helium temperatures. The wire is wound around a brass bobbin (the inner diameter 10 mm and the length 60 mm). To operate the magnet in a persistent mode, a persistent current switch with the same wire is attached. The magnetic field strength at the exciting current 20 A is about 12kG, which is measured by a Bi-sensor. No decay of the persistent current is observed with time. The field strength vs. the current and the field distribution in the magnet are measured, which are in good agreement with the calculated values.

1 Introduction

Recently remarkable progress of a superconducting magnet has been achieved both in fundamental and technological aspects.[1] In the design of the superconducting magnet, one has to take account of the critical-field and critical-current of the material used. For a high-field magnet more than 50kG, superconducting materials such as Nb-Ti and Nb_3Sn are commonly used, while for a low-field magnet Nb-Zr is known to be stable material. And to reduce the degradation and training effects caused by flux jump, a copper-coated wire is exclusively employed.

In a previous paper,[2] we have reported some of the electrical properties of Nb-Ti wire which is used as a level indicator-sensor, with and without magnetic field. There we found "hysteresis" phenomena of supercoductivity. In the present paper, the experimental results of the superconducting magnet designed for a nuclear magnetic resonance experiment are described. Some of the experiments have already been reported on the same application of the superconducting coils.[3)-5)] Results for NMR will be published later.

2 Experimental

A. Design of the Superconducting Magnet

Although a stable coil material for a low field magnet is known to be usually Nb-Zr wire, our wire available was Nb-Ti alloy wire[2] and its length on hand was limited, say, 200m. The superconducting magnet is intended to be used for a nuclear magnetic

* Department of Applied Physics.

resonance experiment at low temperatures. In spite of this limited length of the wire, we had to design the magnet having high homogeneity and the field strength of about 10 kG through a simple power source such as a storage battery (6V–12V).

In accordance with the well-known formula as follows,[6] we have determined several parameters for a square ended magnet, as shown in Fig. 1. The field strength at the center of the magnet is written by

$$H_0=\frac{a_1F(\alpha,\beta)}{S}I[Gauss], F(\alpha,\beta)=\frac{4\pi}{10}\beta\ln\frac{\alpha+\sqrt{\alpha^2+\beta^2}}{1+\sqrt{1+\beta^2}} \quad \cdots\cdots\cdots(1)$$

$$\alpha=a_2/a_1, \beta=b/a_1,$$

where S and I are the cross-sectional area per unit turn and the current in ampere, respectively. The wire length l is given by

$$l=\frac{2\pi a_1^3(\alpha^2-1)\beta}{S}[cm], \quad \cdots\cdots\cdots(2)$$

The field strength H_z at z (cm) from the center along the center line is given by

$$\frac{H_Z}{H_0}=\frac{2\pi}{10F(\alpha,\beta)}\left[(\beta-x)\ln\frac{\alpha+\sqrt{\alpha^2+(\beta-x)^2}}{1+\sqrt{1+(\beta-x)^2}}+(\beta+x)\ln\frac{\alpha+\sqrt{\alpha^2+(\beta+x)^2}}{1+\sqrt{1+(\beta+x)^2}}\right]. \quad \cdots\cdots\cdots(3)$$

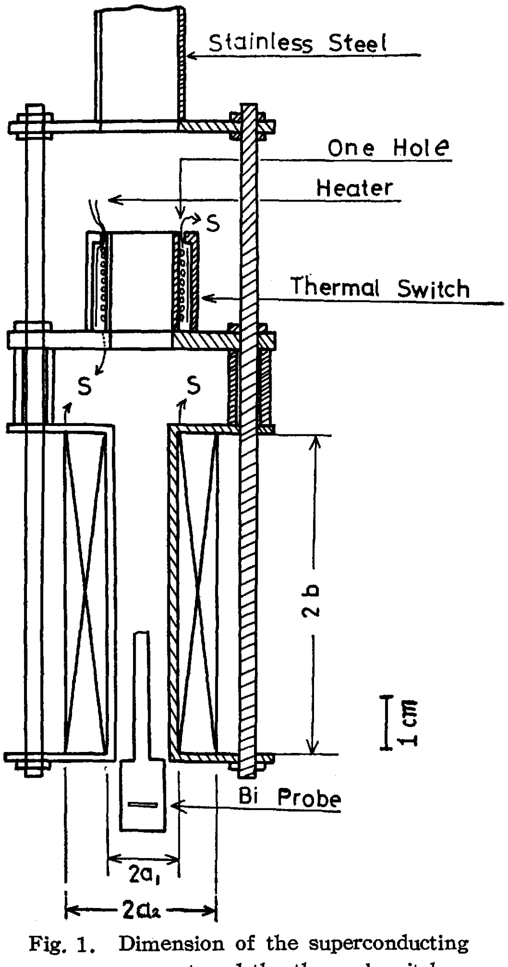

Fig. 1. Dimension of the superconducting magnet and the thermal switch.

The inductance L of the coil for $\beta>(\alpha-1)/2$ is written by

$$L=a_1^5\left[\frac{\beta(\alpha-1)}{S}\right]^2(\alpha+1)\left[\theta-\lambda\frac{\alpha-1}{\beta}\right]\times 10^{-6}[Henry], \quad \cdots\cdots\cdots(4)$$

where θ and λ are the tabulated values as functions of α and β. For the present we have selected the following values; $2a_1$=1.25cm, 2b=6.0cm. And the resultant values are;

N(total number of turns)=3420, l=203m, $S=1.15\times10^{-3}$cm^2 ,$2a_2$=2.50cm.

By using these values with eqs (1), (3), and (4) we have the calculated values; H_0= 6.47 $\times 10^3$ Gauss at I=10A, L=4. 14×10^{-2} Henry (λ=0.01219, θ=0.01084), and H_z/H_0=0.982 at z=1 cm. The coil bobbin of the magnet was made of brass, around which a thin layer of photographic film was attached for insulation. Being counted the number of turns by a mechanical counter, the Formvar-coated Nb-Ti wire was carefully wound without a spacer between the layers.

The superconducting magnet can be normally operated in a regulated mode or in a persistent mode. We have cited here the latter method, since no Joule's heat is produced and it has stable operation with no ripple of the current. For this purpose, a persistent current switch (thereafter referred to as the thermal switch) was constructed with the same wire. At first the bobbin for the switch was made of glass, simply because of transparency, but it was so fragile that we replaced it with a bakelite bobbin. The Nb-Ti wire of about 10Ω at room temperature, whose coated-copper had been removed by HNO_3 solution, was first wound around the bobbin neatly and fixed with araldite, as shown in Fig.1. Then an insulated manganin wire of 40Ω was wound on it as a heater in an induction-less way. Finally they were sealed by a bakelite cap. On the top of the cap a small hole of about 0.8mm diameter was opened for evaporation of liquid helium, when the heater is put on. When the heater is put off, liquid He will flow into the inner dead space to cool the wire, whose volume is about 0.5cm^3.

The electrical contacts between the superconducting wires or between the wire and the copper lead (1mm diameter) for an exciting current source were made by simply pressing the two leads which were sandwiched by high-purity In metal ribbon with two copper blocks. When the contacts are not so good, there occurs a decay of the persistent current, as noted later. Fig. 2 shows the constructed magnet.

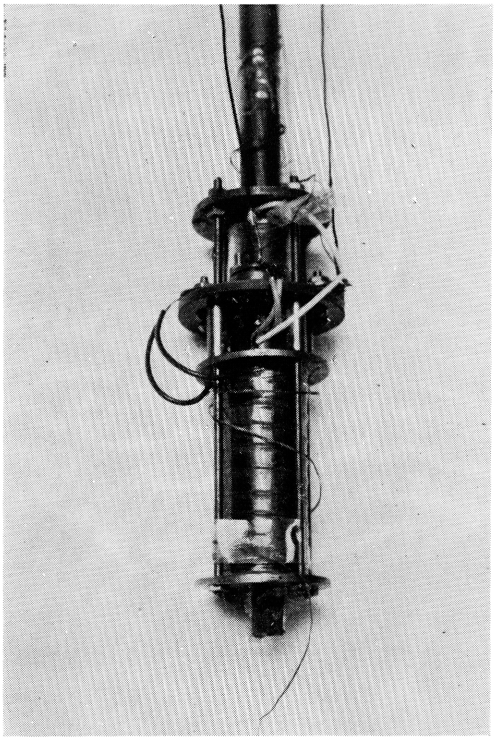

Fig. 2. The constructed magnet.

B. Field Sensor

In order to measure the magnetic field strength in the magnet, two kinds of probes have been used, InSb and Bi. As will be shown later, the n-type InSb samples available on hand was less field-sensitive than Bi, so Bi was exclusively used. The Bi-sensor was produced by melting a small amount of bulk Bi (99.99%) in a soft glass tube at elevated temperature and extending them to a small capillary shape. Then outer glass was dissolved by hydrofluoric acid and rinsed carefully. The Bi specimen formed in this way is not single crystalline but poly-crystalline, typically of $0.2\sim0.4\phi \times 5\sim7$ mm. Ohmic contacts to both ends of the rod were attained by soldering a Wood's metal. Such a small rod was so feeble that the specimen was supported on a mica sheet with a paste to keep mechanical strength. The InSb-sensor ($0.9\times0.8\times8$ mm) was soldered with In metal.

C. Apparatus

A schematic circuit of the magnet is shown in Fig. 3. After the thermal switch is put

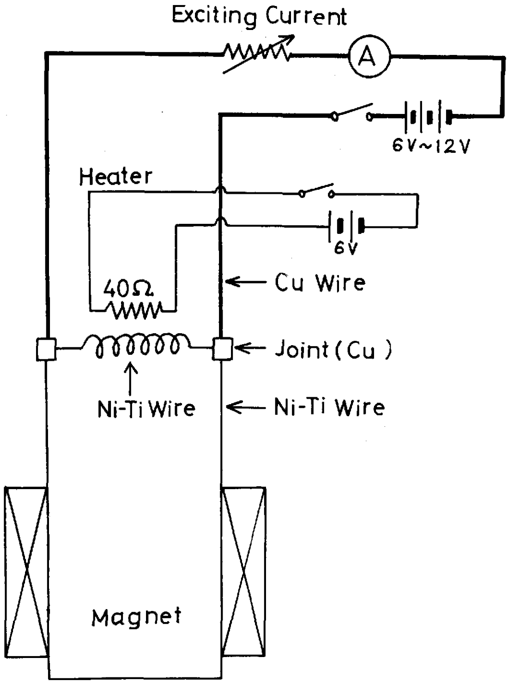

Fig. 3. Schematic diagram for the exciting current and the heater.

on, resulting in evaporation of liquid He in the bobbin case and raise of temperature of Nb-Ti wire to destroy the superconducting state, the regulated dc current is supplied through a battery (6V–12V) to the magnet. Then the thermal switch is put off, and liquid He flows into the bobbin case to cool the wire to the superconducting state again. However it takes just 11 sec for our thermal switch to recover it in the superconducting state. Soon after that, the exciting current is put off and thus the magnet works in a persistent mode. To minimize consumption of liquid these procedures must be fast enough.

Low temperature arrangement is shown in Fig. 4. At presnt, we have done at 4.2^0 K, and to reduce the temperature, liquid He will be evacuated by a rotary pump. The magnet is supported by a stainless steel tube to minimize mechanical

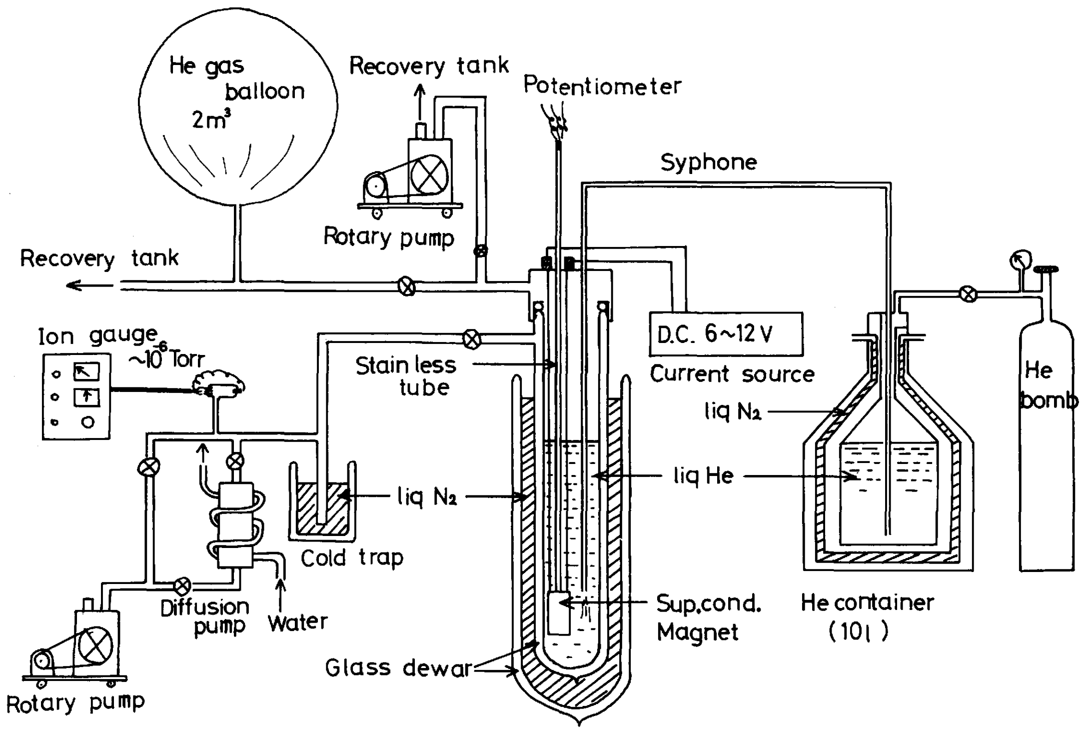

Fig. 4. Low temperature apparatus.

vibration due to bubbling of liquid.

The magnetic field strength in the magnet was detected by using the magnetoresistance effect of Bi with a usual potentiometric method. The effect was calibrated by other electromagnet, up to 22kG, in another dewar as a function of the field.

3 Experimental Results and Discussion

Transverse magnetoresistance $\Delta\rho/\rho(0)$ for Bi and n-InSb at 4.2°K are shown in Fig. 5 as a function of the magnetic field H of the regulated electromagnet. It is seen that this InSb-sensor (carrier concentration; 2.8×10^{14} cm^{-3} at room temperature) is less sensitive than the Bi-sensor. Magnetoresistance of Bi is not, however, simply dependent on the field H as $\Delta\rho/\rho(0)\propto H^2$, and the curve is rather convex at higher fields. The Bi-sensor is polycrystalline and impure, which give rise to such a deviation. Perhaps at more higher fields $\Delta\rho/\rho(0)$ may be proportional to H^2. Once we calibrate $\Delta\rho/\rho(0)$ vs. H for Bi, we can use it as a field sensor of the superconducting magnet. Fig. 6 shows $\Delta\rho/\rho(0)$ vs. the exciting current I (A) at 4.2°K, where the sensor is at the center of the magnet and measured in a persistent mode. From Figs. 5 and 6, we can plot the field strength H of the magnet as a function of the current as shown in Fig. 7. Within the experimental errors, a linear relation is well established and the observed field

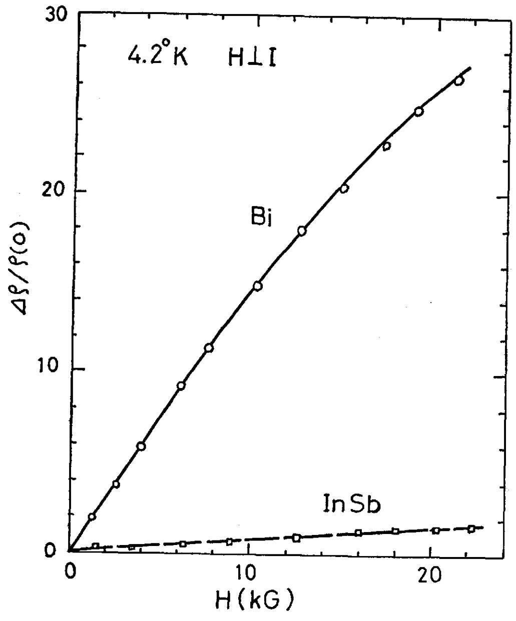

Fig. 5. Transverse magnetoresistance for Bi and n-InSb ($n=2.8\times10^{14}cm^{-3}$) against the magnetic field of an electromagnet.

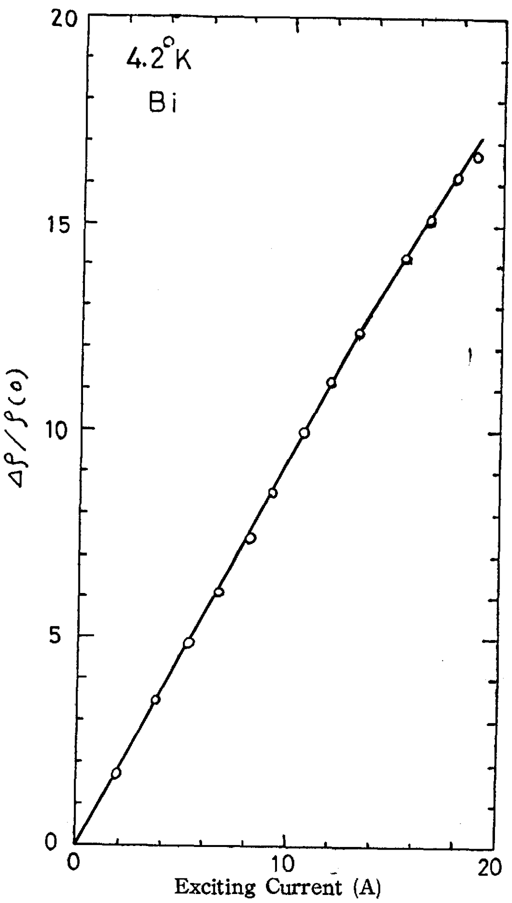

Fig. 6. Magnetoresistance for Bi located at the center of the superconducting magnet as a function of the exciting current.

strength is in good agreement with the calculated value by eq. (1).

The field distribution in the magnet was also measured in a persistent mode (I=17.05 A), as shown in Fig. 8, which shows the plots of $\Delta\rho/\rho(0)$ against the position of the sensor. Homogeneities can be estimated by the ratio of $\Delta\rho/\rho(0)$ at $z=1$ cm to that at the center, which is 13.7/14.1=0.972 and in reasonable agreement with the calculated value by eq. (3). Nevertheless, more higher homogeneities may be required to perform nuclear magnetic resonance, if the sample is more than 2 cm long. At the same time, a ripple of the field is one of the important factors for the resonance experiment. Within the present experimental accuracy it can not be detected. No residual magnetic field was found in our low-field magnet, although it is generally observed for a high-field magnet after the demagnetization, which is caused by a trapped flux.

As for the thermal switch, almost instantaneously the heater destroyed the superconducting state of Nb-Ti wire, while it took just 11 sec to recover the wire. It is desirable for the dead space of the bobbin for the switch to be as small as possible.

On the other hand, it was found that when the terminal contacts are good the persistent current does not decay. We experienced about one hour duration without measurable decay. However if the contacts are not good, the current decreases with time. Fig. 9 shows one of the examples,

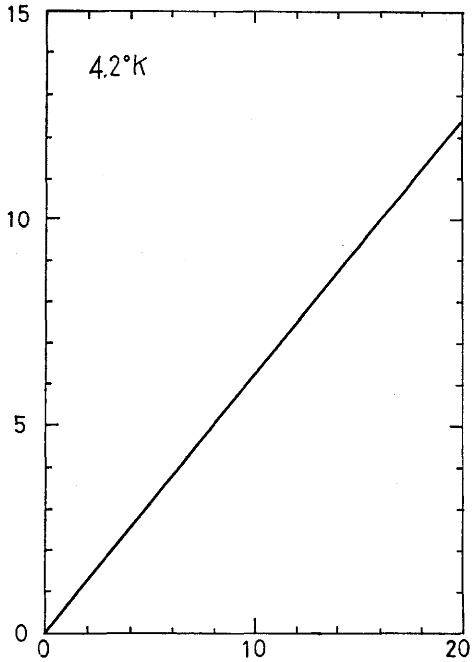

Fig. 7. Magnetic field vs. exciting current for the constructed magnet.

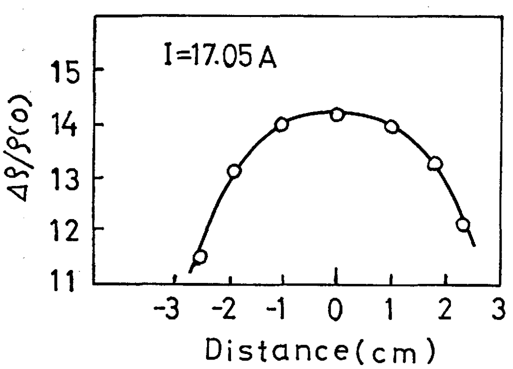

Fig. 8. Distribution of the magnetic field in the magnet, where magnetoresistance for Bi-sensor is indicated. Persistent current is 17.05 A.

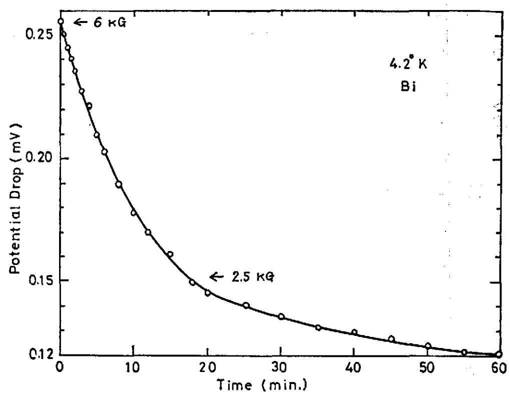

Fig. 9. Decay of the persistent current when the terminal contacts are not good, where the potential drop is read by a potentiometer, arrows indicating the corresponding magnetic field.

where the potential drop of the Bi-senser is observed by a potentiometer with time after the persistent current is supplied. The current may be dissipated at the contacts through Joule's heat.

This small-type magnet does not accomodate any safety devices, such as the resistors and diodes as usually used, to protect the instantaneous evaporation of liquid He. The dc voltages between the two terminals of the magnet, induced on the cut-off of the current, were measured as the exciting current was varied. The induced voltages were found linear with the current; about dc 10 V was induced when the current was 10A. If we use the calculated inductance $L=4.1\times10^{-2}$ Henry, the decay time is about 40 m sec.

4 Summary

By using a limited length of Nb-Ti alloy wire on hand (~200m), we have constructed a low-field square ended superconducting magnet, which is to be used for the nuclear magnetic resonance. Around a brass bobbin of inner diameter 1.0 cm and length 6.0 cm was the wire wound manually. The persistent current switch was also constructed with the same wire of 10Ω and bakelite, which operated very effectively. Bi and n-InSb specimens were used for the field sensor, but the latter was insensitive. The magnetic field strength vs. the exciting current and homogeneities in the magnet were measured, which were in reasonable agreement with the calculated values. With this magnet we are now preparing for the nuclear magnetic resonance experiment. These will be reported later.

Acknowledgement

The authors would like to thank S. Arai and K. Yoshino of Matsushita Elec. Ind., Co., Osaka, for the supply of InSb single crystals, and Prof. M. Satake for Bi samples. We also thank Vacuum Metallugical Co., Tokyo, for the supply of Nb-Ti wire and K. Tsubokawa for his assistance of constructing the magnet. A part of the expenditure of the present study has been defrayed from the Scientific Research Funds of the Ministry of Education.

Refernce :

1) V. L. Newhouse ; *Superconductivity* ed. by R. D. Parks (Marcel Dekker, Inc., New York, 1969), Vol. 2, p. 1283.

2) H. Yagi, M. Inoue, and T. Tatsukawa ; Memoirs Fac. Eng. Fukui Univ., **18** (1970) 205.

3) J. M. Younsel and N. G. Einspruch ; Proc. IEEE **52** (1964) 1238.

4) H. L. Marshall and H. E. Weaver ; J. appl. Phys. **34** (1964) 3175.

5) S. Foner ; Rev. Sci. Instr. **34** (1963) 293.

6) A. Kono ; Shinku **11** (1968) 424. [in Japanese].