THE STUDY OF HIGH MAGNETIC FIELD AND AC OPERATION OF HIGH TEMPERATURE SUPERCONDUCTING MAGNET

S. Ninomiya, K. Hatanaka and Y. Sakemi, RCNP, Osaka Univ., Osaka 567-0047, Japan
T. Kawaguchi and N. Takahashi, KT Science Ltd, Hyogo 673-0044, Japan

Abstract

A high-temperature superconducting solenoid magnet was designed and fabricated. A DC operation produced a 0.21 T mirror magnetic field for a 2.45 GHz ECR ion source was successfully carried out. A magnetic field of 2.04 T was obtained with a 197 A DC operation by installing iron poles and return yokes. The magnet was also operated with 0.14-1.73 T magnetic fields in 0.05 Hz frequency. The present results show HTS magnets have many possible applications in the accelerator field.

INTRODUCTION

The technology of high-temperature superconductor (HTS) has been utilized such as current leads for low-temperature superconducting (LTS) magnets[1]. There have been, however, only a few magnets using HTS coils in the accelerator field.

A HTS magnet has some advantages in principle in comparison with a LTS magnet. Since HTS systems have higher operating temperatures than LTS systems, simpler cryogenic systems can be used for cooling. In addition, as the temperature range to keep superconductivity is wider than that of LTS systems, a larger thermal margin is expected. Therefore, an AC mode operation can be possible in spite of heating loads due to the AC loss in coils.

HTS coils have some engineering difficulties, one of which is wire manufacturing of the HTS materials. Recently, it has become possible to obtain HTS wires larger than 100m length[2].

In this study, two solenoid coils using a HTS wire was designed and fabricated to show a new application possibility of a HTS magnet in the accelerator field. Some performance tests were carried out. This system will be used as mirror coils of a 2.45 GHz ECR ion source in future.

DESIGN

An air-core HTS Solenoid Magnet

Cross sectional view of the air-core HTS solenoid magnet is shown in fig.1. The HTS coils are mounted on a bobbin made of SUS316. The coils are supported by four titanium-alloy rods which are 4 mm in diameter. A thermal shield is connected to the 80 K first stage of a G-M refrigerator. Twenty layers super-insulations are set between the thermal shield and the wall of the cryostat. Current leads are made of electric copper. In order to reduce power losses, HTS tapes are soldered on the leads between the thermal anchors and the HTS coils.

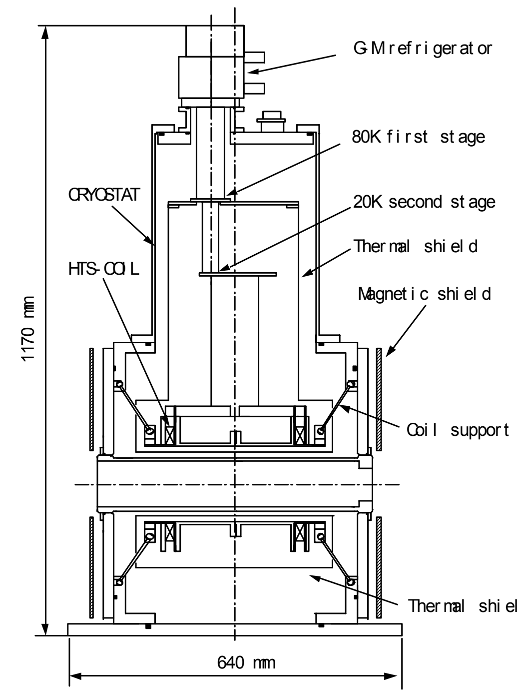

Figure 1: Cross sectional view of the HTS solenoid magnet.

Specifications of the design parameters of the present solenoid coils are summarized in Table 1. The HTS wire consists of filaments of $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi2223) , in a silver matrix. The tape is 4.2 mm wide and 0.21 mm thick. The critical temperature (T_c) of the material is about 110 K. Each coil consists of two double-pancakes and their inner and outer diameter is 156 and 225 mm, respectively. Each pancake has 146 turns of windings and is 9 mm in height.

The critical current (I_c) strongly depends on the coil temperature and on the magnetic field at the coil position. The critical current for the solenoid coil is expected to be about 30 A (1 μV/cm, self-field) at 77K. The rated current was designed to be 90 A at the operating temperature of 30 K.

A two-stage G-M refrigerator is used to cool the coils and thermal shields. The cooling power is 18 W and 9 W at the first (80K) and the second (20K) stage, respectively. Power losses at current leads are estimated to be 10 W and 2 W at the high- and low-temperature stages at the operation with a 90 A, respectively. The total heat load is estimated to be 18 W and 3 W at the first and the second stage of the refrigerator, respectively.

Table1: Design parameters of the HTS-magnet

HTS-coils	Superconductor	Bi 2223/ Ag tape Total length 360 m
	No. of turns	292 x 2 coils
	Winding construction	4 pancakes / coil
	Critical current expected at 77 K	30 A
	Rated current	90 A at 30K
	Max. magnetic field in the coil at the rated current	5.2 kG in parallel to tape 3.6 kG in normal to tape
Cryostat	Cooling method	Conduction cooling by a G-M refrigerator
	Thermal insulation	Vacuum isolation, 80K shield and super-insulation
	Cooling power of the G-M refrigerator	9 W at 20 K, and 18 W at 80K

A magnetic-core HTS dipole magnet

The HTS solenoid magnet can be converted into a high-magnetic-field dipole magnet, with only installing iron poles and a return yoke. A magnetic-core HTS dipole magnet for scanning is designed in order to investigate perspective of a HTS magnet. Figure 2 shows a 3D model of the iron poles and a return yoke with the HTS solenoid coils which locate the same position in fig.1. Two iron poles are installed both from right and left sides in fig. 1.

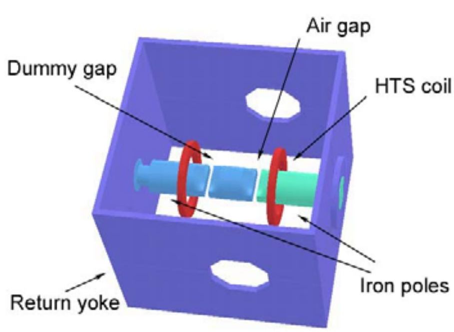

Figure 2: A 3D model of iron poles and return yokes. The positions of the HTS coils are also shown.

Since a distance between the HTS coils is relatively long (250 mm), an air gap is set at an eccentric position in order to obtain intense magnetic field. Another dummy gap is set to the opposite position because of reduction of motive force to the coils. Distances of both the air gap and the dummy gap are the same, 14 mm. A thin return yoke (thickness: 15 mm) is also installed. The magnetic field in gap was designed to be 1.64 T with a 90 A operation.

PERFORMANCE

A Magnetic-Mirror-Field Test

All design values in table 1 were found to be achieved after fabrication. The critical current was measured in the liquid nitrogen to be 36 and 39 A, respectively, which is even higher than expected. The values of I_c did not change after three heat cycles.

The solenoid coils were mounted on the bobbin, electrically connected in series and assembled in a cryostat. Cooling tests were performed with measuring an ohmic resistance, which is shown in fig. 3. After about 25 hours cooling time, a transition to superconductor was observed around 105 K which is consistent with the specification, 110 K. Coils and the thermal shields were cooled down to about 10 K and 83 K, respectively. The critical current is estimated to be higher than 200 A at 10 K.

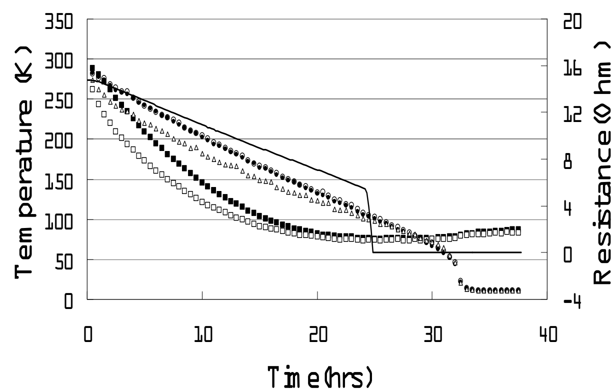

Figure 3: Temperatures and coil resistance as a function of a cooling time. Open and solid circles show temperatures of each coil. Temperatures of the second stage of the G-M refrigerator are shown in open triangles. Temperatures of a thermal shield(solid square) and the first stage of the refrigerator(open square) are also shown. Total resistance of two coils is shown by solid line.

Coils were excited with 100 A DC current, which is 10 A higher than the designed value. Figure 4 shows longitudinal magnetic field distributions along the central axis of the air-core HTS magnet. Measured magnetic fields agreed quite well with calculations by the program code TOSCA. Maximum magnetic field was 2.1 kG, which is consistent with that expected for a 2.45 GHz ECR ion source.

During one-hour coil excitation of 100 A, the temperature of the coils kept almost constant. The temperature of the first stage, however, increased by 3 degree because of the heat load at current leads. An intermittent 197 A operation was successfully performed. This shows that I_c is larger than 197 A at 10 K as expected. A precise I_c value is, however, not obtained because current intensity at a current lead is limited.

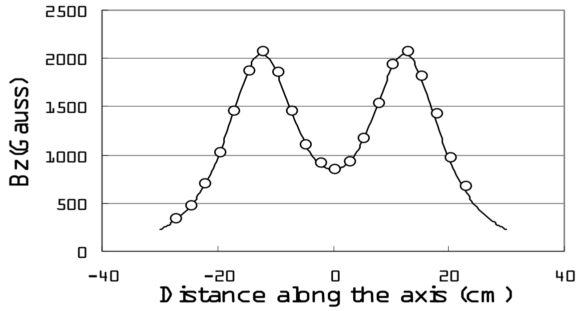

Figure 4: Longitudinal magnetic field B_z distribution along the central axis(points). The coil current is 100 A. Calculated magnetic fields are also shown(line).

An AC Operation Test with High Magnetic Fields

The magnetic field measured and calculated by TOSCA code is shown in fig. 5 for the magnetic-core HTS dipole magnet as a function of a coil current. The magnetic field is saturated more than 50 A. With 197 A coil current, the magnetic field of 2.04 T was obtained. Measured magnetic fields were in good agreement with those calculated. It should be noted that an adequate HTS coil design for high magnetic field allows more intense field with the same magnetomotive force of this HTS magnet.

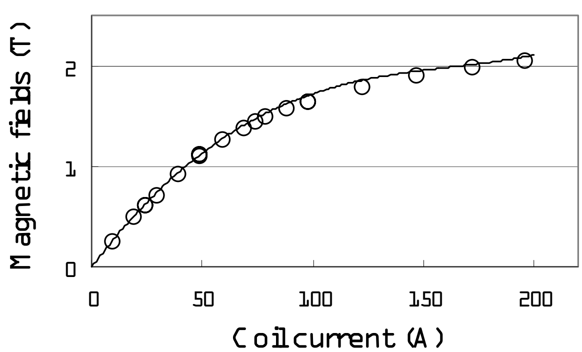

Figure 5:Magnetic fields B_z at the center of the air gap as a function of coil current(circle). Calculated magnetic fields are also shown(line).

Figure 6 shows the magnetic fields with coil current on an AC operation. Coils were excited by a homo-pole DC power supply in 0.05 Hz. The coil current was controlled from 4 to 115 A with a triangle waveform. The magnetic field ranges from 0.14 to 1.73 T and reproducibility was quite well. No linear correlation of the observed magnetic fields to the coil current is due to saturation of the magnetic field shown in fig. 5. Since the magnetic field well followed up to the current, no significant effects from eddy current were found. Coil temperature increased less than 2 K after 5 minutes operation.

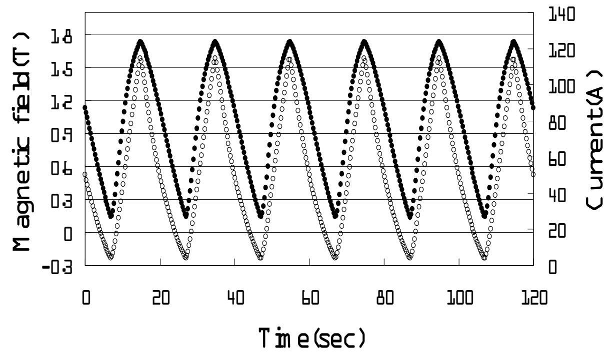

Figure 6: Observed magnetic fields on an AC operation(solid circle). The frequency is 0.05 Hz. Coil current measured at the current lead by a DCCT is also shown(open circle).

More rapid cycling tests were also performed. Ramp rate of the magnetic field was observed about 0.5 T/sec at maximum in a 0.25 Hz operation.

Present results clearly show that a large applicability of HTS wires to AC magnets, such as scanning magnets for the cancer therapy and high duty synchrotrons, etc. Beam scanning test with this HTS magnet will be carried out this April.

SUMMARY

A solenoid magnet was fabricated with the Bi2223 HTS wire. A two-stage G-M refrigerator could cool the HTS magnet to about 10 K.

The magnetic field of the HTS air-core magnet is 0.21 T at maximum, which is suitable for a 2.45 GHz ECR ion source. After conversion into the high-magnetic-field dipole magnet by installing iron cores and a return yoke, the magnetic field of 2.04 T was obtained with a 197 A DC operation. For an AC operation, 0.14-1.73 T magnetic fields can generate in 0.05 Hz frequency. A maximum ramp rate of the magnetic field was about 0.5 T/sec in 0.25 Hz operation. The present results indicate a HTS magnet has many possible applications in the accelerator field, especially for scanning magnet.

REFERENCES

[1] e.g. L. Tkachenko *et al.*, Proc. Of EPAC 2002, Paris (2002) 2454-2456
[2] LJ. Masur *et al.*, Proc. of MT-17, Geneva (2001) 1-5.