DEVELOPMENT OF HTS MAGNETS

Kichiji Hatanaka*, Mitsuhiro Fukuda, Keita Kamakura, Hiroshi Ueda,
Tetsuhiko Yorita, Takane Saito, Yuusuke Yasuda
Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka, 567-0047
Takeo Kawaguchi
KT-Science, 1470-1-803, Fujie, Akashi, Hyogo, 673-0044

Abstract

We have been developing magnets utilizing high-temperature superconducting (HTS) wires for this decade. We built three model magnets, a mirror coil for an ECR ion source, a set of coils for a scanning magnet and a super-ferric dipole magnet to generate magnetic field of 3 T. They were excited with AC/pulse currents as well as DC currents. Recently we fabricated a cylindrical magnet for a practical use which polarizes ultracold neutrons (UCN). The field strength at the center is higher than 3.5 T which is required to fully polarize 210 neV neutrons. The magnet was used to polarized UCN generated by the RCNP-KEK superthermal UCN source. One dipole magnet is under fabrication, which is used as a switching magnet after the RCNP ring cyclotron and is planned to be excited by pulse currents. It becomes possible to deliver beams to two experimental halls by time sharing.

INTRODUCTION

High-temperature superconductor (HTS) materials were discovered in 1986 [1] for the first time. Significant efforts have been continued for the development of new and improved conductor materials [2] and it became possible to manufacture relatively long HTS wires of the first generation [3]. Today, many researches are ongoing to establish a reliable production process of the second generation HTS wires and their applications. Although many prototype devices using HTS wires have been developed, so far these applications have been rather limited in accelerators and beam line facilities [4].

At the Research Center for Nuclear Physics (RCNP) of Osaka University, we have investigated the performance of HTS wires applied for magnets excited by alternating current (AC) as well as direct current (DC) for ten years. We have fabricated four types of magnets. They are a cylindrical magnet [5], a scanning magnet with race-track shape coils [6], a super-ferric dipole magnet [7] and a solenoid like magnet consisting of double pan cakes [8]. The coil of the dipole magnet has a negative curvature and the magnet successfully generated the field higher than 3 T at operating temperature of 20 K. First three magnets are toy models, but the last one is actually used to polarize ultracold neutron (UCN). Based on the successful application, we are now constructing a HTS switching magnet to make a time sharing of beams from the RCNP ring cyclotron. We selected a commercially available first-generation HTS wire supplied by Sumitom Electric Industries, Ltd [9].

*hatanaka@rcnp.osaka-u.ac.jp

Designs and preliminary results of performance tests of fabricated magnets are summarized in this paper.

SCANNING MAGNET

A two-dimensional scanning magnet was fabricated to model a compact beam scanning system. The size of the irradiation field is 200 mm by 200 mm for 230 MeV protons at the distance of 1.25 m from the magnet center. The required magnetic field length is 0.185Tm. The scanning magnet consists of two sets of two racetrack-type coils. Each coil is built by stacking three double pancakes. The design parameters are summarized in Table 1. Figure 1 shows a photograph of one coil.

Table 1: Design Parameters of the HTS Scanning Magnet

Coils	Iner size	B_x: 150mm x 300mm.
		B_y: 150mm x 380mm
	Separation	70mm
	Maximum Field	0.6T
	# of tturns	420 x 2 for each B_x and B_y
	Winding	3 Double pancakes/coil
	Inductance/coil	B_x: 75mH, B_y: 92mH
	Temperature	20K
	Rated current	200A
Cryostat	Cooling power	45W at 20K, 53W at 80K

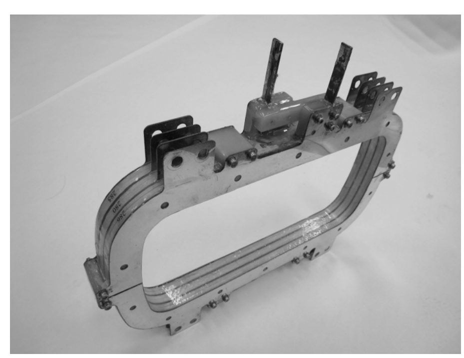

Figure 1: Single assembled B_x coil

Two sets of single-stage GM (Gifford-McMahon) refrigerators were used to cool the coils and the thermal shields. The critical current (Ic) of the HTS conductor depends on the operating temperature and the magnetic field at its surface. From the numerical estimation of the

ISBN 978-3-95450-168-7

magnetic field, the Ic value was estimated to be 260A at 20K. The rated current of the coil was designed to be 200A to generate the field length of 0.185Tm. After performance tests of the design parameters with DC currents, AC loss was measured for a pair of B_x cols onnected in series. There are several AC loss components in HTS magnets [10,11]; (1) hysteretic magnetization losses in the superconductor material, (2) dynamic resistance losses generated by a flux motion in the conductor, (3) coupling losses through the matrix, (4) eddy current losses in the matrix and metallic structures including cooling plates, and (5) Ohmic losses at exciting currents above the critical current. Each AC loss shows a different dependence on the frequencies (f), the amplitude of the external magnetic field (B) and the transport current (I_t). AC losses due to phenomena (1), (2) and (3) are independent of the frequency. On the other hand, losses (3) and (4) depend linearly on the frequency.

Figure 2 shows the measured AC power losses. of the two B_x oils in series. Full symbols show the total power losses on the left side scale. Open symbols present losses per cycle on the right side scale. The dashed curve in Fig. 3 presents the result of the finite element model analysis by T. King [12], in which the predicted power was dominated by the losses due to eddy currents in the metallic materials. In contrast, the observed dissipated power per cycle is almost independent of the frequency of the transport current as seen in Fig. 2. The solid curve in the figure shows the theoretical Q_{hys} which is normalized to the measured value at 45A and 15Hz. At 20K, J_c of the present HTS wire is about 5 x 10^8A/m^2. The theory is found to reproduce the scaling law well as a function of the transport current, if we take account the temperature dependence of the critical current density of the conductors [11].

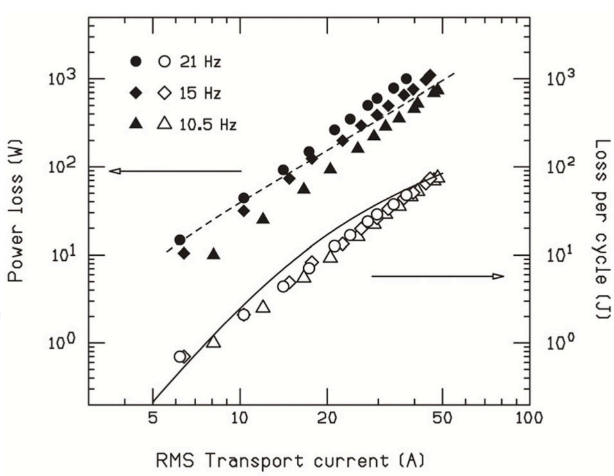

Figure 2: Measured AC losses at 20K of the B_x coils in series. Details are described in the text.

DIPOLE MAGNET

A dipole magnet was fabricated to investigate potential application of HTS coils to synchrotron magnets. It is a super-ferric magnet with race-track coils which have a negative curvature inside. The specification of the magnet is summarized in Table 2. Ic values of double pancakes were measured to be 60-70 A at 77 K. After stacking, they were 47 A and 51 A for the upper and lower coil, respectively. There were no damages observed in wire winding process. Stacked pancakes are sandwiched by ion plates to reduce magnetic fields on the wire surface, since the Ic is lowered by fields on surface. Figure 3 shows the assembled cold mass consisting of poles and coils. Coils are fixed to poles to withstand the radial electro-magnetic expansion force. Poles are fabricated by stacking 2.3 mm thick carbon steel plates. Plates were bent before stacking, welded to form a pole and finally annealed to remove the stress. The weight of the total cold mass is 250 kg. The magnet was successfully excited with the DC current of 300 A. The magnetic fields were measured in the median plane and were consistent with design values. Coil was also excited with pulsed current with the ramping speed of 100 A/s corresponding to 1 T/s.

Table 2: Design Parameters of the HTS Dipole Magnet

Magnet	Bending radius	400 mm
	Bending angle	60 deg.
	Pole gap	30 mm
Coils	Number of turns	600 x 2
	Winding	3 Double pancakes/coil
	Temperature	20 K
	Rated current	300 A

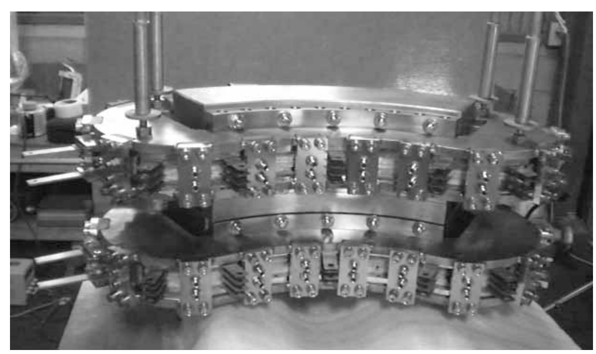

Figure 3: Lower coil of the dipole magnet.

UCN POLARIZER MAGNET

A cylindrical HTS magnet was constructed to polarize ultra cold neutrons with energies lower than 210 neV. The neutron magnetic potential is 60 neV/T. Then the magnetic field is required to be larger than 3.5 T in order to fully polarize UCNs. The magnet was built by stacking ten double pancakes and fixing them on a bobbin made of stainless steel. The design parameters are summarized in Table 3. The total length of HTS wire is 1530 m. Magnetic fields on axis were measured using Hall probe. A warm bore was installed for the measurement. Figure 4 shows the inside of the cryostat and the field distribution along the axis is shown in Fig. 5. The field is higher than 3.5 T. The UCN polarization was measured with the RCNP-KEK superthermal UCN source [13] by passing neutrons through the magnet and observed to be higher than 95 %.

Table 3: Design Parameters of the UCN Polarizer Magnet

Coil	Inner diameter	131.5 mm
	Outer diameter	213 mm
	Length	105 mm
	Number of DP	10
	Number of turns	2800
	Total length of wire	1530 m
	Inductance	1 H
	Weight	30 kg
Magnet	Operating Temperature	20 K
	Rated current	200 A
	Field at the center	3.5 T
Cryostat	Cooling power	35 W at 45 K 0.9 W at 4 K
	Temperature of the shield	60 K

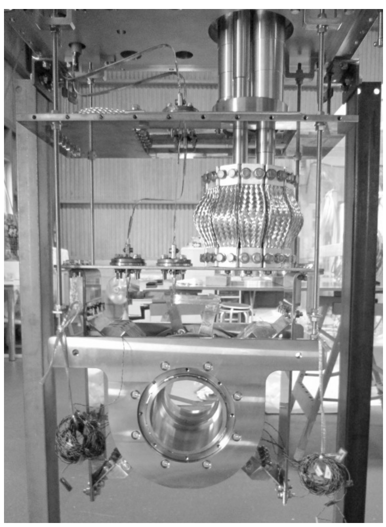

Figure 4: Coils hanged from the top flange.

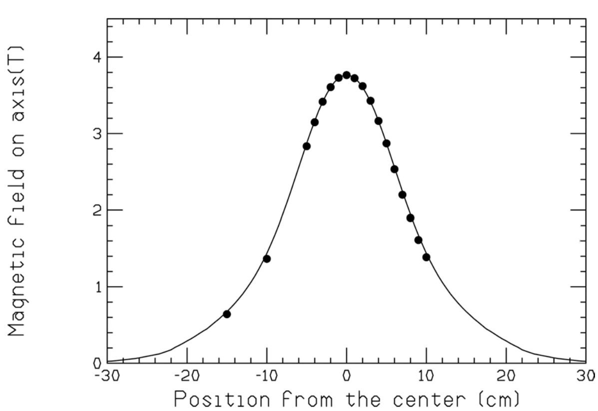

Figure 5: Field distribution along the axis. The solid line shows results of the simulation by TOSCA.

SWITCHING MAGNET

At the RCNP cyclotron facility, there are more beam time requests than available. We propose to make a beam sharing between two target positions, for example at the UCN and muon production targets. For this purpose, an existing normal conducting magnet is replaced by a pulsed magnet. We decide to apply the HTS wire for the magnet owing to our successful result of the model dipole magnet described above. Table 4 summarizes coil design parameters. The size of the race-track coil is 1,142 mm long and 580 mm wide. It is much larger than the model magnet. The magnet is currently under fabrication and the performance test gives us information on the mechanical and thermal stabilities of HTS coil in large scale.

Table 4: Design Parameters of the Coil

Coil size (inner)	1,142 mm x 580 mm
Number of turns	256 x 2
Winding	2 Double pancakes/coil
Temperature	20 K
Rated current	200 A
Ramping speed	20 A/s
Magnetic field	1.5 T

REFERENCES

[1] J. G. Bednorz and K. A. Müler, Physical B **64** (1986) 189

[2] K. Sato, K. Hayashi, K. Ohkura, K. Ohmatsu, Proc. of MT-15, Beijing (1997) 24-29

[3] L. J. Masur, J. Kellers, F. Li, S. Fleshler, E. R. Podtburg, Proc. of MT-17, Geneva (2001) 1-5

[4] D. M. Pooke, J. L. Tallon, R. G. Buckley, S. S. Kalsi, G. Snitchler, H. Picard, R. E. Schwall, R. Neale, B. MacKinnon, Proc. of CIMTEC'98, Italy (1998)

[5] K. Hatanaka, S. Ninomiya, Y. Sakemi, T. Wakasa, T. Kawaguchi, N. Takahashi, Nucl. Instr. Meth. in Phys. Res. A **571** (2007) 583-587

[6] K. Hatanaka, J. Nakagawa, M. Fukuda, T. Yorita T..Saito, Y. Sakemi, T. Kawaguchi, K. Noda, Nucl. Instr. Meth. in Phys. Res. A **616** (2010) 16-20

[7] K. Hatanaka, *et al.*, Proc. of IPAC 2012, New Orleans, the USA (2012) TUOAC02

[8] K. Hatanaka, *et al.*, Proc. of IPAC 2013, Shanghai, China (2013) THPME007

[9] http://www.sei.co.jp/super/hts/index.html

[10] C. M. Friend, "AC Losses of HTS Tapes and Wires", Studies of High Temperature Superconductors, A. V. Narlikar, Ed. New York: Nova Science Publishers, 2000, vol. 32, pp. 1-61

[11] E. H. Brandt and M. Indenbom, Phys. Rev. B **48** (1993) 12893-12906

[12] T. King, private communication

[13] Y. Masuda, K. Hatanaka, Sun-Chan Jeong, S. Kawasaki, R. Matsumiya, K. Matsuta, M. Mihara, Y. Watanabe, Phys. Rev. Lett. 108 (2012) 134801.

ISBN 978-3-95450-168-7