1-LB-I2/SCC 2011

Submitted 30 November 2011

**Research and development of fundamental technologies for accelerator magnets
using high T_c superconductors**

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Abstract

The progress of a project on the research and development of fundamental technologies for accelerator magnets using high T_c superconductors (HTS) is reported. The aim of the project is to establish technologies for cryo-cooler-cooled HTS accelerator magnets wound with coated conductors. At the first stage of the project, the conceptual design study of accelerators was carried out, and the coils of the HTS magnets which are compatible with these accelerators were designed successfully. The required winding technologies were clarified through designing the coils, and the R&D of winding technologies for coils with three-dimensional shape and those with negative bend are in progress. The influence of the tape magnetization, that is, the shielding current on the wide face of coated conductor, on the field quality of magnets was studied.

Keywords for subject index: accelerator; coated conductor; magnet; magnetization;
winding

Highlights:

- 1) We designed accelerator magnets using coated conductors which are compatible with accelerator designs.
- 2) A three-dimensional coil and a negative-bend coil were fabricated and were tested in LN₂ to show good voltage-current characteristics.
- 3) The influence of tape magnetization on field quality was evaluated by numerical electromagnetic field analyses.

PACS code: 84.71.Ba, 84.71.Mn, 29.20.-c, 87.56.bd

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1. Introduction

The applications of high T_c superconductors (HTS) to accelerator magnets are attractive from the following viewpoints.

- 1) Reduction of power consumption, as compared to copper magnets
- 2) Easy operation and less governmental regulation because of applicability of cryo-cooler, as compared to low T_c superconductor (LTS) magnets
- 3) Potential good thermal stability, when operated at a high temperature where the specific heats of materials are large
- 4) Generation of a very high magnetic field, if the magnets operated at a low temperature, because of high critical current densities even in high magnetic fields

From these viewpoints, several groups have been studying the applications of HTS to accelerator magnets [1–11]. Most of these previous studies used Bi-2212 round wires and/or focused on high magnetic field generation at 4.2 K, though the use of coated conductors and the use of cryo-coolers should be particularly attractive from the viewpoints of 1) through 3).

A research and development project is in progress in Japan on the fundamental technologies for accelerator magnets using high T_c superconductor tapes, mainly coated conductors, and cooled by cryo-coolers. In this paper, the overview of the project and the results at this moment are presented.

2. Overview of the project

The name of the project is *Research and development of the fundamental technologies for accelerator magnets using high T_c superconductors*, and it is funded by Japan Science and Technology Agency under its Strategic Promotion of Innovative Research and Development Program. The aim of the project is to establish the fundamental technologies to realize cryo-cooler-cooled HTS accelerator magnets. Future applications of such magnets include the accelerator system for carbon cancer therapy and accelerator driven sub-critical reactor (ADSR). The entire period of the project is 10 years, and its first stage is from January 2010 through March 2012. The participating institutions are Kyoto University (Department of Electrical Engineering and Research Reactor Institute), Toshiba Corporation, High Energy Accelerator Research Organization, National Institute of Radiological Sciences, and Japan Atomic Energy Agency.

Among various HTS, RE-123 coated conductors are focused on. As compared to Bi-2212 round wire or Bi-2223 tape, RE-123 coated conductors show better performance in magnetic fields, and their performance has been being improved rapidly and continuously through competition among many manufacturers.

At the first stage of the project, the conceptual design study of accelerators is carried out, and the coils of the HTS magnets which are compatible with these accelerators are designed. Through designing the coils, the required winding technologies can be clarified, and the development of these technologies is started. Besides winding technologies, the study on the

influence of the tape magnetization on the field quality and neutron radiation tests [12] are carried out in the first stage.

The outline and an example of the conceptual design study of accelerators are presented in section 3. Those of the design study of magnets are presented in section 4. The development of the winding technologies is described in section 5. The influence of the tape magnetization (shielding current on the wide face of coated conductor) on the field quality of magnets is described in section 6.

3. Conceptual designs of accelerators

At the first stage of the project, the conceptual design study was carried out for the following accelerators.

- 1) Radial sector FFAG accelerator for carbon cancer therapy
- 2) Spiral sector FFAG accelerator for ADSR
- 3) Beam transport line of carbon cancer therapy facility
- 4) Spiral sector FFAG accelerator for carbon cancer therapy

With respect to the main ring of accelerator, we focused on the FFAG (Fixed Field Alternating Gradient) accelerator [13, 14], because the strong focusing (alternating-gradient focusing) is possible by use of dc magnetic field (fixed magnetic field). High power beams, which are obtained by the strong focusing, expand applications to various areas, such as energy frontier, nuclear science, etc. Meanwhile, the dc magnetic field is advantageous from the viewpoint of the compatibility with superconductor magnets. The radial magnetic field distribution in magnets for FFAG accelerators is as follows.

$$B(r) = B_0 \left(\frac{r}{R_0} \right)^k, \quad (1)$$

where r is distance from the center of the accelerator, and k is referred to as k value [13–15]. This nonlinear magnetic field distribution contributes to beam bending as well as beam focusing / defocusing.

Among 1) through 4), the detailed design is shown for 1) the radial sector FFAG accelerator for carbon cancer therapy. The beam orbit and an outline of the designed accelerator are shown in Fig. 1 and Table 1, respectively. The accelerator consists of 8 magnet cell, and each magnet cell is a FDF triplet consisting of a focusing magnet (F magnet), a defocusing magnet (D magnet), and another focusing magnet (F magnet). The diameter of the accelerator is around 10 m, which is almost half of that of the standard synchrotron using copper magnets for carbon cancer therapy.

4. Coil designs of HTS accelerator magnets

For the designed accelerators 1) through 4) in section 3, HTS magnets were designed. In general, accelerator magnets can be classified from the viewpoint of defining precise magnetic fields: coil-dominated magnets in which the magnetic field is defined by the coil shape; iron-dominated magnets in which it is defined by the iron pole shape [16]. The coil-dominated magnets were designed for the accelerators 1) and 4), and the iron-dominated magnets were designed for the accelerators 2) and 3).

Here, we show the designs of the coils of the coil-dominated magnets for

1) the radial sector FFAG accelerator for carbon cancer therapy. The details of the method as well as constraints and assumptions should be referred to [17]. The coils were wound with 5 mm-wide and 0.2 mm-thick coated conductors.

First, the cross-sectional design (two-dimensional design) was carried out. Eq. (1) can be expressed with the combination of multi-pole magnetic field components as

$$B_0 (r / R_0)^k = B_0 \{(R_0 + x) / R_0\}^k = B_0 \sum_{n=1}^{\infty} r_0^{n-1} \frac{k!}{R_0^{n-1} (n-1)! \{k - (n-1)\}!} \left(\frac{x}{r_0}\right)^{n-1}, \quad (2)$$

where B_0 is magnetic field at magnet center, R_0 is distance between accelerator center and magnet center, x is displacement from magnet center, and r_0 is the reference radius [15]. Each multi-pole magnetic field component in Eq. (2) can be generated by the cylindrical sheet current as

$$i(\theta) = B_0 \sum_{n=1}^{\infty} \frac{2R_c^n}{\mu_0} \frac{k!}{R_0^{n-1} (n-1)! \{k - (n-1)\}!} \cos(n\theta), \quad (3)$$

where R_c is the radius of the sheet current, and θ is the angle [18]. The magnetic field given by Eq. (2) can be generated by the combined sheet currents given by Eq. (3). From this combined sheet currents, the azimuthal positions of conductors in the cross-section of the magnet can be determined. The effect of the iron yoke was considered by the image-current method. Outlines and cross-sections of the designed magnets are shown in Table 2 and Fig. 2, respectively. The design with elliptical cross-section was made to decrease the leakage magnetic field from the coil ends. Fig. 3 shows the

histogram of the magnetic field to which conductors are exposed.

Second, the three-dimensional design was carried out. The coil ends were designed and were connected to the straight section, which was designed in the same manner as the cross-sectional design. When designing the coil-end shape, we applied the differential geometry [17, 19, 20]. At the coil ends, we allowed the edge-wise bending of coated conductors so as to fit them to the bore tube. The effect of the iron yoke was considered by the image-current method. The conductor positions were optimized iteratively to reduce the field error. Outlines of the designed magnets and a bird's-eye view of the designed F magnet are shown in Table 3 and Fig. 4, respectively. The minimum generalized flat-wise bending radius [17] was 50.3 mm, and the maximum edge-wise bending strain was 0.272%.

5. Winding technologies

Through design study of coils, the requirements for winding technologies were clarified. For the coil-dominated magnets, the three-dimensional winding technology is required, and for the magnets of spiral sector FFAG accelerators, the technology to wind coils with negative bend is required. Both types of coil should be impregnated with epoxy for conduction cooling [22].

Fig. 5 shows a one-turn three-dimensional coil, which simulates the inner-most turn of the designed coil in Fig. 4. The voltage – current characteristic was measured in liquid nitrogen. The coil did not show any

degradation in its voltage – current characteristic.

Fig. 6 shows another test coil with negative bend, which is similar to a coil for the superferric magnet of spiral sector FFAG accelerators. This coil was also tested in liquid nitrogen and showed a good voltage – current characteristic without any degradation [23].

The winding technologies for epoxy-impregnated coils without any degradation are essential to build high current density magnets by using coated conductors. In this sense, the obtained results are milestone to realize HTS accelerator magnets with very high current density.

6. Influence of tape magnetization on field quality of magnets

One of the concerns in accelerator magnets wound with coated conductors is the tape magnetization [7]. The tape magnetization, that is, the shielding current on the wide face of coated conductor, generates an additional magnetic field, which is not considered usually when designing a magnet [23–26]. This additional magnetic field can deteriorate the field quality of magnets.

First, the cross-sectional designs of two types of dipole magnet were made [23]: a cosine-theta magnet, in which Rutherford cables in usual cosine-theta magnet is replaced with coated conductors; a magnet consisting of stack of racetrack coils. The specifications of magnets are listed in Table 4, and their cross-sections are shown in Fig. 7. For these magnets, numerical electromagnetic field analyses were made to calculate the current

distribution in each coated conductor. Then, the generated magnetic field can be calculated considering the tape magnetization (the shielding current on the wide face of coated conductor). The numerical method is same as one in [23]. Based on the measured transport characteristics of a coated conductor, the E - J (electric field – current density) characteristic of the coated conductor, which depends on the amplitude and the direction of magnetic field as well as the temperature, was formulated with the percolation depinning model [27–29]. Fig. 8 shows the measured critical currents and the critical currents obtained from the formulated E - J characteristic. This formulated E - J characteristic was used for the numerical electromagnetic field analyses.

In Fig. 7, the current distributions in coated conductors are shown with colors. The observed non-uniform current distributions are caused by the shielding currents. In Figs. 9 and 10, multi-pole components of the magnetic field generated in the cosine-theta magnet and in the stacked racetrack magnets are shown. In both dipole magnets, higher harmonics are less than around 10^{-4} if uniform current distributions are assumed. Non-uniform current distributions caused by the shielding current (tape magnetization) increase higher harmonics in both magnets. However, in the cosine-theta magnet, higher harmonics are less than 10^{-3} even if the tape magnetization is considered. In the cosine-theta magnet, in which tape wide faces align radially, the shielding current changes the current distribution radially, rather than azimuthally. This is the reason why the shielding current (tape

magnetization) less affect the field quality in the cosine-theta magnet.

7. Summary

A research and development project is in progress in Japan on the fundamental technologies for accelerator magnets using high T_c superconductor tapes, mainly coated conductors, and cooled by cryo-coolers. In the first stage of the project, we successfully designed coil-dominated HTS magnets which are compatible to accelerator designs. Requirements to winding technology were clarified through design study of magnets, and the developments of winding technologies for coils with three-dimensional shape and those with negative bend are in progress. Numerical electromagnetic field analyses suggest that cosine-theta coils might be preferred to racetrack coils from the viewpoint of the influence of tape magnetization on the field quality of magnets.

Acknowledgement

This work was supported by Japan Science and Technology Agency under Strategic Promotion of Innovative Research and Development Program.

References

- [1] R. Gupta, M. Anerella, J. Cozzolino, J. Escallier, G. Ganetis, A. Ghosh, M. Harrison, A. Jain, A. Marone, J. Muratore, B. Parker, W. Sampson, P. Wanderer, IEEE Trans. Appl. Supercond. 12 (2002) 75.
- [2] R. Gupta, M. Anerella, J. Cozzolino, J. Escallier, G. Ganetis, A. Ghosh, M. Harrison, A. Marone, J. Muratore, J. Schmalzle, W. Sampson, P. Wanderer, IEEE Trans. Appl. Supercond. 14 (2004) 1198.
- [3] R. Gupta, M. Anerella, A. Ghosh, J. Schmalzle, W. Sampson, IEEE Trans. Appl. Supercond. 18 (2008) 236.
- [4] R. Gupta, M. Anerella, G. Ganetis, A. Ghosh, H. Kirk, R. Palmer, S. Plate, W. Sampson, Y. Shiroyanagi, P. Wanderer, B. Brandt, D. Cline, A. Garren, J. Kolonko, R. Scanlan, R. Weggel, IEEE Trans. Appl. Supercond. 21 (2011) 1884.
- [5] S. Ninomiya, K. Hatanaka, Y. Sakemi, T. Kawaguchi, N. Takahashi, Proc. Asian Particle Accelerator Conference 2004 (2004) 507.
- [6] K. Hatanaka, S. Ninomiya, Y. Sakemi, T. Wakasa, T. Kawaguchi, N. Takahashi, Nucl. Instr. Meth. in Phys. Res. Section A 571 (2007) 583.
- [7] N. Amemiya, K. Takahashi, N. Okada, T. Nakamura, T. Ogitsu, T. Kurusu, M. Ono, M. Kodaira, K. Noda, IEEE Trans. Appl. Supercond. 20 (2010) 364.
- [8] K. Takahashi, N. Amemiya, T. Nakamura, T. Ogitsu, T. Kurusu, T. Yoshiyuki, K. Noda, S. Awaji, IEEE Trans. Appl. Supercond. 21 (2011) 1833.

- [9] X. Wang, S. Caspi, D. W. Cheng, D. R. Dietderich, H. Felice, P. Ferracin, A. Godeke, J. M. Joseph, J. Lizarazo, S. O. Prestemon, G. Sabbi, IEEE Trans. Appl. Supercond. 20 (2010) 368.
- [10] T. Aoki, H. Ueda, A. Ishiyama, N. Miyahara, N. Kashima, S. Nagaya, IEEE Trans. Appl. Supercond. 21 (2011) 3200.
- [11] Y. Kanbayashi, T. Aoki, X.Wang, A. Ishiyama, H. Ueda, N. Miyahara, N. Kashima, S. Nagaya, “Influence of neutron irradiation on mechanical properties of high temperature superconductors” presented at EUCAS 2011 and submitted to Physics Procedia Trans. Appl. Supercond.
- [12] M. Yoshida, T. Nakamoto, T. Ogitsu, Q. Xu, T. Itahashi, Y. Kuno, Y. Kuriyama, Y. Mori, B. Qin, A. Sato, K. Sato, and T. Yoshiie, “Low-temperature neutron irradiation tests of superconducting magnet materials using reactor neutrons at KUR”, presented at CEC/ICMC and accepted for publication in Advances in Cryogenic Engineering (Materials)
- [13] K. R. Symon, D. W. Kerst, L. W. Jones, L. J. Laslett, K. M. Terwilliger, Phys. Rev. 103 (1956) 1837.
- [14] S. Machida, Y. Mori, R. Ueno, Proc. of European Particle Accelerator Conference 2000 (2000) 557.
- [15] T. Obana, T. Ogitsu, T. Nakamoto, K. Sasaki, A. Yamamoto, T. Orikasa, M. Yoshimoto, Y. Mori, IEEE Trans. Appl. Supercond. 15 (2005) 1185.
- [16] S. Russenschuck, Field computation for accelerator magnets. Weinheim, WILEY-VCH, 2010, pp. 14–15.

- [17] K. Takahashi, N. Amemiya, T. Nakamura, Y. Mori, T. Ogitsu, M. Yoshimoto, I. Watanabe, T. Yoshiyuki, “Magnetic field design of coil-dominated magnets wound With coated conductors” presented at MT-22 and submitted to IEEE Trans. Appl. Supercond.
- [18] S. Russenschuck, Field computation for accelerator magnets. Weinheim, WILEY-VCH, 2010, pp. 293–326.
- [19] S. Russenschuck, Field computation for accelerator magnets. Weinheim, WILEY-VCH, 2010, pp. 609–636.
- [20] B. Auchmann, S. Russenschuck, IEEE Trans. Magn. 40 (2004) 1208.
- [21] H. Miyazaki, S. Iwai, T. Tosaka, K. Tasaki, S. Hanai, M. Urata, S. Ioka, Y. Ishii, IEEE Trans. Appl. Supercond. 21 (2011) 2453.
- [22] K. Koyanagi, T. Tosaka, K. Tasaki, T. Kurusu, T. Yoshiyuki, N. Amemiya, T. Ogitsu, “Fabrication of YBCO small test coils for accelerator magnet development” presented at MT-22 and accepted for publication in IEEE Trans. Appl. Supercond.
- [23] N. Amemiya, K. Akachi, Supercond. Sci. Technol., 21 (2008) 095001.
- [24] M. C. Ahn, T. Yagai, S. Hahn, R. Ando, J. Bascunan, Y. Iwasa, IEEE Trans. Appl. Supercond. 19 (2009) 2269.
- [25] Y. Yanagisawa, Y. Kominato, H. Nakagome, R. Hu, T. Takematsu, T. Takao, D. Uglietti, T. Kiyoshi, M. Takahashi, H. Maeda, IEEE Trans. Appl. Supercond. 21 (2011) 1640.
- [26] A. Otsuka, Y. Yanagisawa, T. Kiyoshi, H. Maeda, H. Nakagome, M. Takeda, IEEE Trans. Appl. Supercond. 21 (2011) 2076.

- [27] T. Kiss, M. Inoue, S. Nishimura, T. Kuga, T. Matsushita, Y. Iijima, K. Kakimoto, T. Saitoh, S. Awaji, K. Watanabe, Y. Shiohara, *Physica C* 378-381 (2002) 1113.
- [28] T. Kiss, M. Inoue, T. Kuga, M. Ishimaru, S. Egashira, S. Irie, T. Ohta, K. Imamura, M. Yasunaga, M. Takeo, T. Matsushita, Y. Iijima, K. Kakimoto, T. Saitoh, S. Awaji, K. Watanabe, Y. Shiohara, *Physica C* 392-396 (2003) 1053.
- [29] K. Higashikawa, T. Kiss, M. Inoue, S. Awaji, K. Watanabe, H. Fukushima, Y. Yamada, Y. Shiohara, *Physica C* 469 (2009) 1776.

Table 1 Outline of designed radial sector FFAG accelerator for carbon cancer therapy

Magnet cell	FDF triplet	
Packing factor	0.535	
k value	4.2	
Number of cells	8	
Accelerated particle (Energy)	C^{6+} (20 MeV/u – 400 MeV/u)	
Orbit radius	3.56 m– 5.02 m	
Type of magnet	Focusing (F) magnet	Defocusing (D) magnet
Integrated field at $r=4.29$ m		
per magnet	1.83 T·m	1.57 T·m
Opening angle per magnet	8.59 degrees	6.88 degrees

Table 2 Outlines of cross-sectional designs of magnets

Cross-sectional shape	Circle	Ellipse
Radius of mandrel	1.2 m	1.4 m / 0.8 m
Inner radius of iron yoke	1.4 m	1.6 m
Distance between center of magnet and center of accelerator	4.29 m	4.29 m
Good field region	± 0.73 m	± 0.73 m
Operation current per conductor	391 A	423 A
Magnetic field at center of magnet	2.85 T	2.85 T
Peak field	10.8 T	11.0 T
Number of turns	2488×10	2466×10
Number of layers of coil	14	14

Table 3 Outlines of three-dimensional designs of magnets

Type of magnet	F magnet	D magnet
Radius of mandrel	1.2 m	1.2 m
Inner radius of iron yoke	1.4 m	1.4 m
Distance between center of magnet and center of accelerator	4.29 m	4.29 m
Good field region	± 0.73 m	± 0.73 m
Operation current per conductor	467 A	479 A
Magnetic field at center of magnet	1.22 T	1.06 T
Integrated field at $r=4.35$ m per magnet	1.83 T·m	1.57 T·m
Number of turns	2514×10	2836×10
Number of layers	14	16
Length of conductors per magnet	101 km	104 km

Table 4 Outlines of designed dipole magnets for numerical electromagnetic field analyses to evaluate the influence of tape magnetization

Type of magnet	Cosine-theta	Stacked racetrack
Radius of mandrel	60 mm	60 mm
Inner radius of iron yoke	120 mm	120 mm
Reference radius	30 mm	30 mm
Magnetic field at magnet center	3.26 T	3.10 T
Operation current per tape	200 A	200 A
Number of turns	2800	2680

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Fig. 10