HTS MAGNETS FOR ACCELERATOR APPLICATIONS

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Abstract

We have fabricated several magnets utilizing the first generation HTS wires and analyzed their characteristics for this decade. HTS materials have advantages over LTS materials. Magnets can be operated at 20 K or higher temperature and cooled by cryo-coolers. The cooling structure becomes simpler and the cooling power of a cooler is higher. Owing to a large margin in operating temperature, it is possible to excite HTS magnets by AC or pulsed currents without quenching. After successful tests of proto type models, two magnets have been fabricated for practical use. The hysteresis losses of HTS wire were measured by the electric or calorimetric method. They were a few tens Joule/cycle.

INTRODUCTION

High critical temperature superconductor (HTS) materials were discovered in 1986 [1] and new materials have been developed to achieve higher critical temperature so far. Among them, two kinds of wires are commercially available having length over several kilo meters. They are based on Bi-2223 (the first generation wire) and REBCO (the second generation wire). Since HTS wires have several advantages over low critical temperature superconducting (LTS) wires, application studies of HTS wires have been intensively investigated in the accelerator field and others. We also have been developing magnets by applying the first generation wires for more than 10 years at the Research Center for Nuclear Physics (RCNP) of Osaka University.

Three model magnets were fabricated to speculate a feasibility to apply HTS wires in the accelerator technology; a mirror coil for an ECR ion source [2], two sets of race track coils for a scanning magnet [3], and a 3T superferric dipole magnet having a negative curvature [4]. They were excited with AC or pulse currents as well as DC currents and their thermal and electromagnetic characteristics were measured. After successful performance tests of proto type models, two magnets have been fabricated for practical use. A cylindrical magnet generates a magnetic field higher than 3.5 T at the center to polarized 210 neV ultra cold neutrons [5]. A beam line switching dipole magnet is excited by pulse currents in order to deliver accelerated beams to two target stations by time sharing.

MODEL MAGNETS

Air core magnets were fabricated and electrically measured AC losses were compared to simulations. A two-dimensional scanning magnet was designed to model a compact system for the cancer treatment [3]. The magnet was designed to deflect 230 MeV protons by 80 mrad in both the horizontal (x) and vertical (y) directions. The iso center is at 1.25 m from the magnet and the designed irradiation field is 200 mm by 200 mm. The magnet consists of two sets of two racetrack shaped coils. Specifications of coils are summarized in table 1. Three double pancakes are stacked to form one coil. 0.9 mm thick brass cooling plates are inserted between pancakes. Figure 1 shows one of assembled coils. Detailed structure of coil is described in ref. [3].

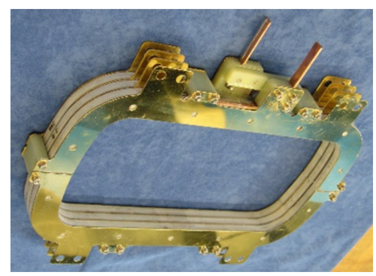

Figure 1: Assembled B_x coil.

The Ic of the tape was measured at 77 K in a 10 m pitch before winding and was between 125 and 140 A corresponding to an electric field amplitude of 1 μV/cm. The Ic of the each pancake and stacked coil were measured in a liquid N_2 bath and were 56-62 and 40-43 A, respectively. Two single-stage GM refrigerators are used to cool coils and thermal shields separately. An AL330 of CRYOMECH, Inc. is used to cool coils and it has a cooling capacity of 45 W at the desined operating temperature of 20 K. From the temperature dependence of the Ic ($B_\perp$) characteristics of the tape, Ic is estimated to be 260 A. at 20 K

A pair of coils are electrically connected in series and used as a scanning magnet excited by AC or pulsed cur-

Table 1: Specifications of Coils of the Scanning Magnet

Inner size	B_x: 150 mm x 300 mm B_y: 150 mm x 380 mm
Cross-section	30 mm x 30 mm
Separation	70 mm
Maximum field at the center	0.6 T
HTS tape length/coil	B_x: 420 m, B_y: 460 m
Number of turns/coil	420 turns
Stacking/coil	3 Double pancakes
Inductance/coil	B_x: 75 mH, B_y: 92 mH

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rents. AC loss was measured by electrical method at 77 and 20 K [3]. There are several AC loss components observe in both LTS and HTS magnet [6, 7]. They are (1) hysteresis losses in the superconducting material, (2) dynamic resistance losses generated by a flux motion in the conductor, (3) coupling losses through the matrix and (4) eddy current losses in the matrix and metallic components including cooling plates. In addition, there are (5) Ohmic losses at exciting currents above the critical current for HTS magnets. Each component shows a specific dependence on the frequency (*f*), the amplitude of the external magnetic field (*B*), and the transport current (*I*). In the critical state medel (CSM), the hysteresis loss per cycle is analytically formulated by Brant st al. [7] as follows,

$$Q_{hys} \propto 2\ln[\cosh(x)] - x\tanh(x) \quad (1)$$

where $x=B/B_{c0}$ and $B_{c0}=\mu_0 J_c d/\pi$. J_c is the critical current density and d thickness of the conductor tape. Figure 2 shows AC losses of a pair of B_x coils in series measured at 20 K. Upper points are total losses scaled (left axis) and lower ones are losses per cycle (the right axis). The observed dissipated power per cycle is almost independent of the frequency of the transport current and the current dependence is well described by the formula (1).The hysteresis losses are around several tens Joule/cycle.

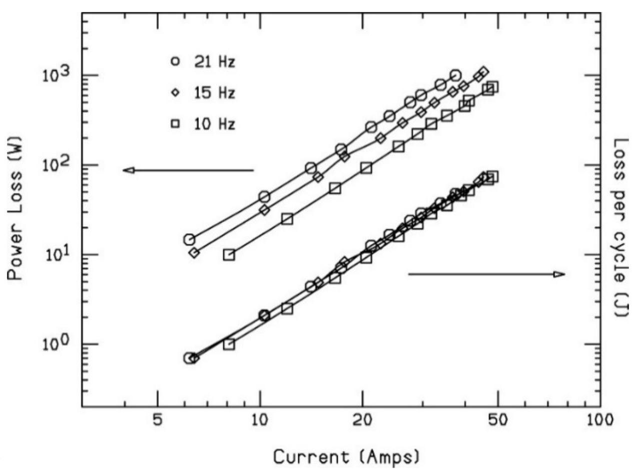

Figure 2: Measured AC losses at 20 K of the B_x coils in series. Data points at the same frequency are connected by line. Details are described in the text.

A dipole magnet was fabricated to investigate a potential application of HTS coils to synchrotron magnets [4]. 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. The HTS tape is from Sumitomo Electric Industries, Ltd. Ic values of tape, double pancakes and stacked coils were measured at 77 K to be 160-189, 60-70 and 47-51 A, respectively. There were no damages observed during tape winding process. Figure 3 shows the upper coil during the stacking process. Coils are fixed to poles to withstand the radial electro-magnetic expansion force. Poles are laminated with 2.3 mm thick carbon steel plates to excite the magnet by pulse currents. Plates were bent before stacking, welded to form a pole and finally annealed to remove the stress. Poles and coils were installed in the cryostat and cooled together. The weight of the total cold mass is 250 kg. The magnet was excited with the DC current of 300 A to generate the field of 3 T at the center. Coil was also excited with pulsed current with the ramping speed of 100 A/s corresponding to 1 T/s.

Table 2**:** Specifications of the Model Dipole Magnet

Magnet	Central bending radius	400 mm
	Bending angle	60 degrees
	Pole gap	30 mm
	Maximum field at the center	3 T
	Cold mass	250 kg
Coil	Number of turns/coil	300 turns

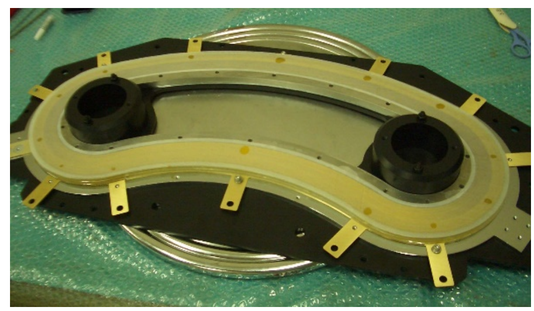

Figure 3: Photograph of the upper coil in assembling.

BEAM LINE SWITCHING MAGNET

To provide more beam to RCNP cyclotron users, beam sharing between two target rooms are planned. To put it into practice, a conventional normal conducting magnet will be replaced by a pulsed magnet [8]. The magnet consists of a laminated yoke and two cryostats. B-2223 wire with reinforcing copper alloy (DI-BSCCO type HT-CA from Sumitomo Electric Industries, Ltd.) and insulation tape are wound into double pancake coil and are conduction cooled by 10 K GM cryocoolers (SRDK-408S2 from Sumitomo Heavy Industries, Ltd.). The typical cooling power of the 2nd stage is 16 W at 20 K and 2 W at 7.5 K. Figure 4 shows the structure of a cryostat. Each cryostat contains a radiation shield thermally connected to the 1st stage of the cryo-cooler.

It takes 50 hours to cool the whole magnet down to operational temperature. For time sharing of a beam, rapid

Table 3: Design Parameters of the HTS Dipole Magnet

Coil	Inner size	1,142 mm x 580 mm
	Number of DP	2
	Numbers of turns	256 x 2
	Inductance	2.5 H
Magnet	Temperature	< 20 K
	Rated current	200 A
	Field at center	1.6 T

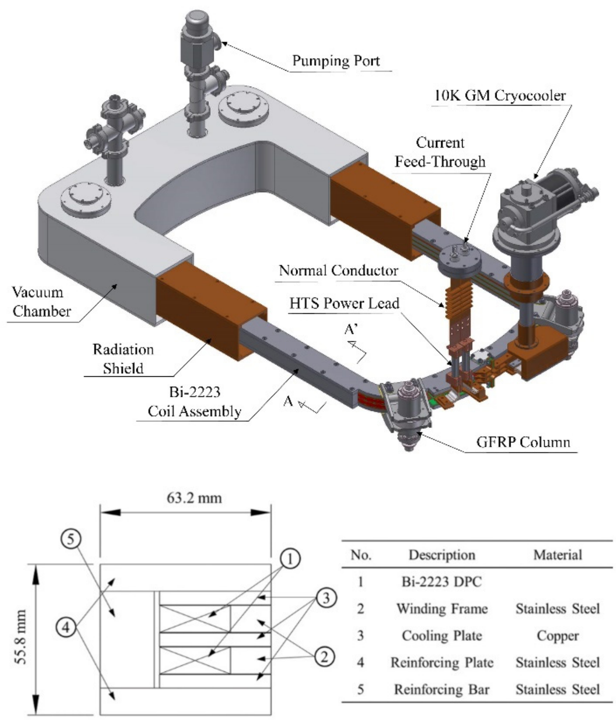

Figure 4: Structure of a cryostat (upper panel) and A-A' cross sectional view of and major component list of the coil assembly (lower panel).

excitation is required. The magnet's iron core is laminated and the power supply is designed to perform 20 A/s ramping with 2.5 H of the coil's inductance. A temperature history during a pattern operation is shown in Figure 5. Coil temperature stays in the operating temperature with a large margin during 30-second exciting and 60-second degaussing pattern. The saturated temperature after two hours of operation is lower than 8.5 K. The result confirmed the thermal design. To provide precise beam switching, the highly stable field strength is required.

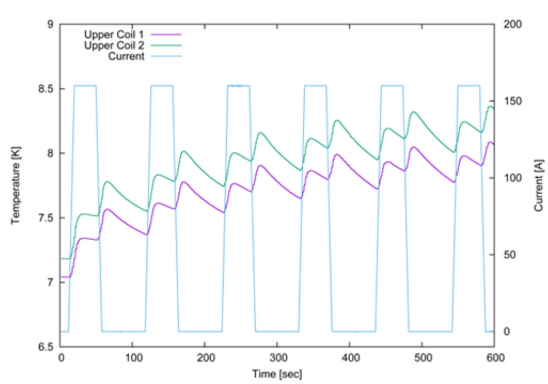

Figure 5: Temperature of upper coil in pattern operation.

We have measured time-varying magnetic field losses with triangular wave excitations [9]. Measurements were performed by the calorimetric method. The hysteresis loss of the HTS coil was about 18 Joule/cycle. Eddy current losses of the metric components were estimated using an electromagnetic finite element analysis software JMAG. This value is in the same order as the hysteresis loss of the scanning magnet described in the previous section. We are performing systematic measurements of the magnetic fields to find the optimum conditions to obtain the stable field. Drift of the magnetic field was compared with and without the current sweep reversal (cycling). Figure 6 shows the time structure of the cycling. With cycling, the field drift was reduced to 1.1 x 10^{-5} mT/s from 1.1 x 10^{-4} mT/s without cycling.

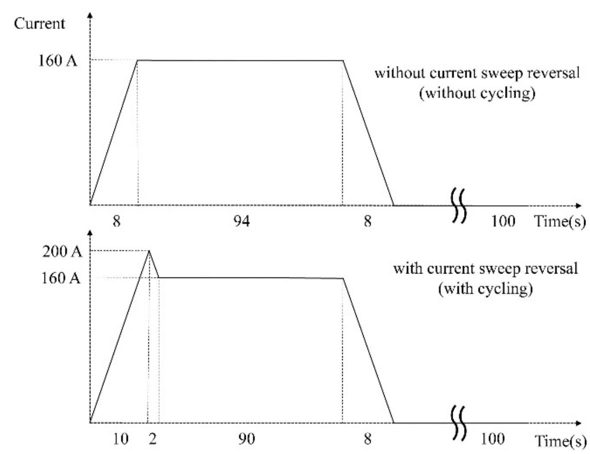

Figure 6: Structure of the exciting currents.

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