DEVELOPMENTS OF HTS MAGNETS

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Abstract

We have been developing mgnets utilizing high-temperature superconducting (HTS) wires for a decade. We have investigated the performance of HTS wires excited by alternating currents as well as direct currents. A scanning magnet was designed, fabricated, and tested for its suitability as a beam scanner. After successful cooling tests, the magnet performance was investigated in AC mode. The magnet was operated at frequencies of 10-20Hz and 20K. The power loss dissipated in the coils was measured and compared with the model calculations. In order to check feasibilities of pulse magnet using HTS wire, we have fabricated a super-ferric dipole magnet to be operated by lumping currents. Preliminary performance is described.

INTRODUCTION

More than a quarter of a century has passed since the discovery of high-temperature superconductor (HTS) materials in 1986 [1]. Significant effort went into the development of new and improved conductor materials [2] and it became possible to manufacture relatively long HTS wires of the first generation [3]. 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].

We stated to investigate the performance of HTS wires applied for magnets excited by alternating current (AC) as well as direct current (DC) ten years ago. Our previous study demonstrated a possibility to excite HTS magnets with AC currents [5]. Since HTS systems can be operated at temperatures higher than systems using low-temperature superconductors (LTS), the cryogenic components for cooling are simpler and the cooling power of refrigerators is much larger than at 4K. The temperature range for superconductivity is wider for HTS systems than for LTS systems. Then a high-frequency AC mode operation should be possible in spite of heating loads due to AC losses in coils.

In order to investigate the performance of HTS magnet in AC operation, a two-dimensional scanning magnet was designed and built to model a compact system for such applications as ion implantation or particle cancer treatment. A dipole magnet was also fabricated as a model of synchrotron magnets which is excited in a pulse mode. It is a super-ferric magnet and the coil has a negative curvature. Design and preliminary results of performance tests of these magnets are described in this paper.

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SCANNING MAGNET

Design and Fabrication

A two-dimensional scanning magnet was designed to model a compact beam scanning system. The size of the irradiation field is 200mm by 200mm for 230MeV protons at the distance of 1.25m from the magnet center. The schematic layout of the coils is shown in Fig. 1. The required magnetic field length is 0.185Tm. We selected the high temperature superconductor Bi-2223 [6] that is commercially available as the first-generation wire in lengths longer than 1000m. The HTS wire consists of a flexible composite of Bi-2223 filaments in a silver alloy matrix with a thin stainless steel lamination that provides mechanical stability and transient thermal conductivity. The wire, High Strength Wire, was supplied by American Superconductor Corporation [7] and is in thin tape-form approximately 4.2mm wide and 0.26mm thick.

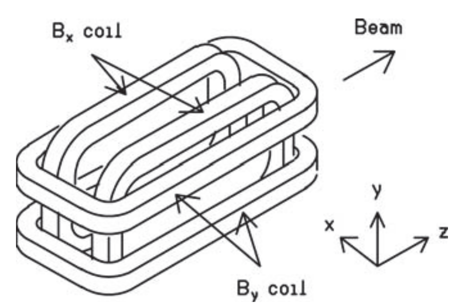

Figure 1: A schematic layout of the scanning magnet coils is shown. They generate the horizontal (B_x) and vertical (B_y) magnetic fields.

Table 1: Design Parameters of the HTS Scanning Magnet

Coils	Inner size	B_x: 150mm x 300mm
		B_y: 150mm x 380mm
	Separation	70mm
	Maximum Field	0.6T
	# of turns	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

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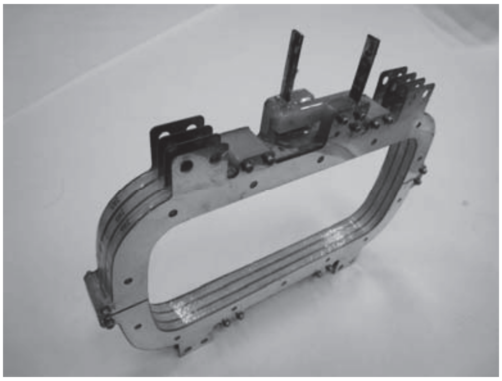

Figure 2: Photograph of single assembled B_x coil.

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 2 shows a photograph of one 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. The magnetic field perpendicular to the conductor has larger effects on Ic than the horizontal component. Before winding, the Ic of the wire over the full length was measured at 77K in a 10m pitch and found to be between 125 and 140A corresponding to an electric field amplitude of 1μV/cm. The Ic values of the coils were estimated from the Ic ($B_\perp$) characteristics of the tape conductor and a magnetic field analysis using the finite element code TOSCA. The load line of the coil was found to cross the Ic ($B_\perp$) curve at 0.195T and a current of 39A corresponding to an Ic at 77K. In the present design, the maximum field was 0.6T in the center along the axis of the magnet and the required magneto-motive force is 8.4 x 10^4AT for each coil. The maximum field perpendicular to the tape surface is estimated to be 1T. From the specification of the temperature dependence of the I($B_\perp$) characteristics, 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.

AC Operation

After performance tests of the design parameters with DC currents, the magnet was operated with AC current to investigate the dissipated losses in the coils. Owing to the good thermal performance we can expect a large thermal operating range for the present coils. Such a large range suggests the possibility to excite the magnet in the AC mode while maintaining superconductivity as long as the AC loss in the HTS tape is acceptable. Several AC loss components are observed in both LTS and HTS magnets [8, 9]. They are (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, and (4) eddy current losses in the matrix and metallic structures including cooling plates. For HTS magnets, there are Ohmic losses at exciting currents above the critical current as well. 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 the first two phenomena (1) and (2) are independent of the frequency. On the other hand, losses (3) and (4) depend linearly on the frequency.

In AC loss measurements, two B_x coils were connected in series in the cryostat and cooled down below 20K [10]. The power dissipated in the coils was measured at three frequencies, 10.5Hz, 15Hz and 21Hz. Measurements were performed using an electrical method where the voltage across coils was measured in-phase with the transport current using an oscilloscope. The system consisted of an inverter, an induction motor and a generator that was employed to convert the line frequency of 60Hz to the resonance frequencies. The inductance of a single B_x coil was measured to be 70mH at 77K. The total inductance of two coils in series was estimated to be 170mH. Coils and condensers formed a series resonance circuit. The capacitances of condensers in series were 1200μF, 600μF and 300μF. The resonance frequencies were roughly estimated to 10, 15 and 20Hz, respectively.

Figure 3 shows the measured AC power losses of the two B_x oils in series. The losses are roughly proportional to the 2.4th power of the transport current instead of the third power observed at 77K. The dashed curve in Fig. 3 presents the result of the finite element model analysis by T. King [10]. It was found that the predicted power was dominated by the losses due to eddy currents in the metallic materials. Consequently, the modelled losses were roughly proportional to the quadratic power of the transport current and the losses per cycle were linearly dependent on the frequency. In contrast, the observed dissipated power per cycle is almost independent of the frequency of the transport current as seen in Fig. 3.

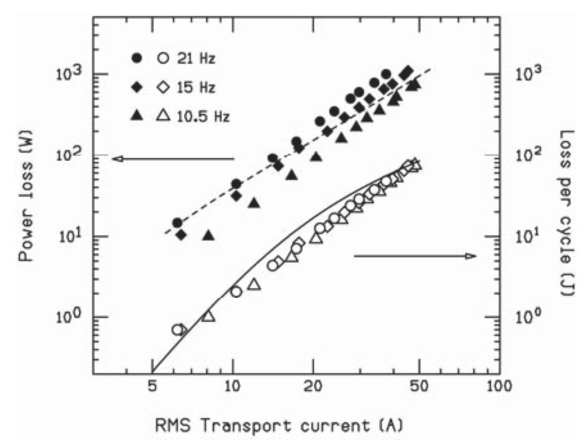

Figure 3: Measured AC losses at 20K of the B_x coils in series. Full symbols show the total power losses on the left side scale. Open symbols present losses per cycle on the right side scale. The dashed curve shows the model calculation by King [11]. The solid curve is a theoretical prediction normalized to the measured data.

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 [9].

DIPOLE MAGNET

In order to investigate feasibilities of synchrotron magnets using HTS wire, we have built a super-ferric dipole magnet to be operated by lumping currents. The specification of the magnet is summarized in Table 2.

Table 2: Design Parameters of the 3T HTS Dipole Magnet

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

We selected DI-BSCCO Type HT wire provided by Sumitomo Electric Industries, Ltd. [12]. It has the similar dimension as AMSC's wire. Upper and lower coils consist of 3 double pancakes of 200 turns which are shown in Fig. 4. Critical currents Ic of wire measured at 77K and self-field was higher than 160A. Ic values of double pancakes were 60-70A at 77K. After stacking, they were 47A and 51A for the upper and lower coil, respectively. There were no damages in wire during winding process with negative curvatures as shown in Fig. 4. Figure 5 shows the assembled cold mass consisting of poles and coils. Coils are fixed to poles to bear the radial electro-magnetic expansion force of 100,000N/m. Poles are fabricated by stacking 2.3mm thick carbon steel plates. Plates were bent before stacking, welded to form a pole and finally annealed to remove the stress. The weight of coils, poles and the total cold mass is 56, 90 and 250kg, respectively.

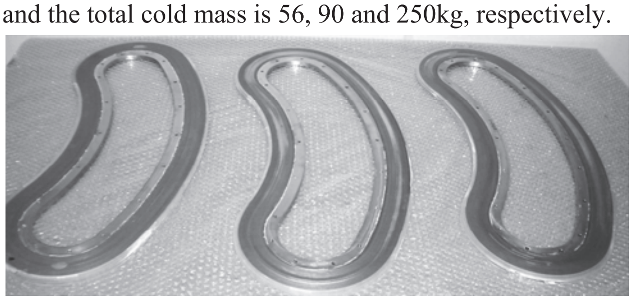

Figure 4: Photograph of double pancakes.

Cooling tests were successfully performed and the Ic values were measured to be 280A at 20K. Magnetic field was measured with three hall probes in the median plane and was consistent with design value. The magnet was excited by pulse current up to the rate of 200A/s without quenching.

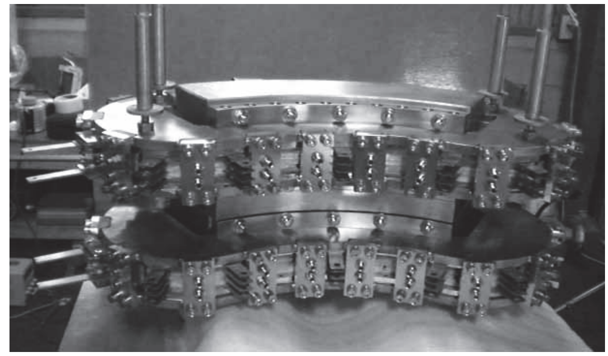

Figure 5: Assembled 3T dipole magnet.

SUMMARY

We have been developing HTS magnets using first-generation wires for a decade and investigated their performances in AC and pulse mode operations. Hysteretic magnetization losses were found to be large and wires having low AC losses are strongly demanded. Second generation wires of YBCO is expected to have better performance but is still under development. In order to extend our studies, we have proposed a new injector cyclotron at RCNP utilizing HTS wires [13]. As an application, a 3.5 T solenoid magnet is now under construction to polarize ultra cold neutrons (UCN) used in neutron electric dipole moment (EDM) measurements.

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