A HTS SCANNING MAGNET AND AC OPRRATION *

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Abstract

A scanning magnet using high-temperature superconductor (HTS) wire was designed, fabricated, and tested for its suitability as beam scanner. After successful cooling tests, the magnet performance was studied using DC and AC currents. In AC mode, the magnet was operated at frequencies of 30-59 Hz and a temperature of 77 K as well as 10-20 Hz and 20K. The power loss dissipated in the coils was measured and compared with the model calculations. The observed loss per cycle was independent of the frequency and the scaling law of the excitation current was consistent with theoretical predictions for hysteretic losses in HTS wires.

INTRODUCTION

More than two decades have 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, these applications are presently rather limited in accelerator and beam line facilities [4].

Our previous study demonstrated a possibility to excite HTS magnets with alternating currents (AC) [5]. Since HTS systems have higher operating temperatures than low-temperature superconductor (LTS) systems, the cryogenic components for cooling are simpler and the cooling power of refrigerators is much larger than at 4K. Because the temperature range for superconductivity is wider than for LTS systems, a larger range pf operating temperatures is available. A high-frequency AC mode operation should be possible in spite of heating loads due to AC losses in the coils.

A two-dimensional scanning magnet was designed and built to model a compact system for such applications as ion implantation or particle cancer treatment. Two sets of single-stage GM (Gifford-McMahon) refrigerators were used to cool the coils and the thermal shields. After performance tests of the design parameters with direct currents (DC), the magnet was operated with AC current to investigate the dissipated losses in the coils. Observed AC losses are compared with theoretical predictions and model calculations.

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MAGNET

The two-dimensional scanning magnet was designed to model a compact 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 schematic layout of the magnet coils is shown in Fig. 1. Both the B_x and B_y coils are centered at the same position along the beam axis. The required magnetic field length is 0.185 Tm. We selected the high temperature superconductor Bi-2223 [6] that is commercially available in lengths longer than 1000 m. 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 4.2 mm wide and 0.26 mm thick.

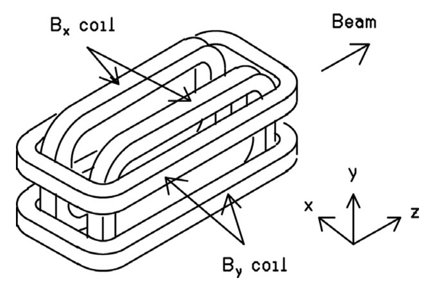

Figure 1: A schematic layout of the scanning magnet coils is shown. They generate the horizontal (B_x) and vertical (B_y) magnetic fields.

Table 1: Design parameters of the HTS scanning magnet.

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

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 an as

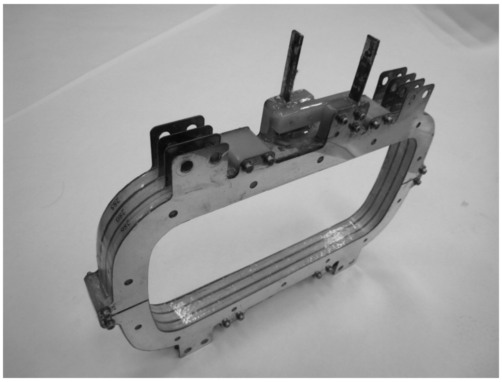

Figure 2: Photograph of single assembled B_x coil.

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 77 K in a 10 m pitch and found to be between 125 and 140 A corresponding to an electric field amplitude of 1 μV/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 0.195 T and a current of 39 A corresponding to an Ic at 77 K. In the present design, the maximum field was 0.6 T in the center along the axis of the magnet and the required magneto-motive force is 8.4 x 10^4 AT for each coil. The maximum field perpendicular to the tape surface is estimated to be 1 T. From the specification of the temperature dependence of the I($B_\perp$) characteristics, the Ic value was estimated to be 260 A at 20 K. The rated current of the coil was designed to be 200 A to generate the field length of 0.185 Tm.

DC PERFORMANCE TEST

The Ic value of each pancake was measured in a liquid nitrogen bath. They were 56-62 A for all pancakes. After stacking three pancakes to form a coil, the self-field Ic of the B_x and B_y coils was measured separately. The Ic values were 40-43 A and consistent with the design value of 39 A described in the previous section. This demonstrated that the HTS wire was not damaged by the winding procedure and that we can expect operating currents larger than 200 A at 20 K.

After the installation of the magnet, the cryostat was evacuated by a turbo-molecular pump with a pumping rate of 300 l/sec. Coil resistances and temperatures on the coil surfaces and shields were measured during the cooling procedure. HTS coils became superconducting at 105 K after 10 hours of cooling. The final temperature below 20 K was achieved after one day of cooling. The temperature of the coils was measured by silicon diode sensors DT-670 of Lake Shore Cryotronics Inc. at several locations. The temperature of the thermal shields was measured by thermocouples. The equilibrium temperature was about 100 K at the farthest point from the cold head of the refrigerator.

The Ic values measured at 20 K were 257 A and 282 A for the B_x and B_y coils, respectively. They were consistent with the design values. The magnetic field distribution along the central axis (z) was measured at 100 A using a Hall probe. The measured B_y values are shown in Fig. 3 together with calculated results with the code TOSCA. The measurements and calculations agree very well.

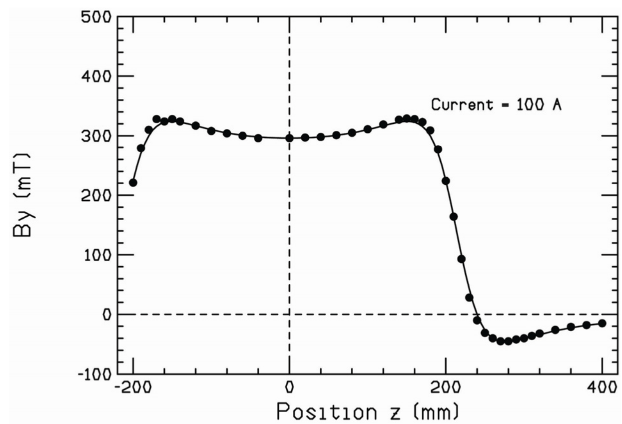

Figure 3: Dark points represent measured B_y fields along the central axis at 100 A. The solid curve shows the calculated magnetic field.

AC OPERATION

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). The power dissipation per cycle for each loss (1) - (4) listed above scales as

$$2\ln[\cosh x] - x\tanh x \tag{1}$$

$$BI^2 \tag{2}$$

$$fB^2 \tag{3}$$

$$fB^2 \tag{4}$$

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. For such a geometry as discussed in the present study, the external magnetic fields are also generated by the transport current. In this case, the magnetic field amplitude can be expected roughly proportional to the transport current. 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 20 K [10]. The power dissipated in the coils was measured at three frequencies, 10.5 Hz, 15 Hz and 21 Hz. Measurements were performed using an electrical method where the voltage across coils was measured in-phase with the transport current using an oscilloscope. The schematic set-up of the measurement is shown in Fig. 4. Coils and condensers formed a series resonance circuit. The system consisted of an inverter, an induction motor and a generator that was employed to convert the line frequency of 60 Hz to the resonance frequencies. The inductance of a single B_x coil was measured to be 70 mH at 77 K. The total inductance of two coils in series was estimated to be 170 mH. The capacitances of condensers in series were 1200 μF, 600 μF and 300 μF. The resonance frequencies were roughly estimated to 10, 15 and 20 Hz, respectively.

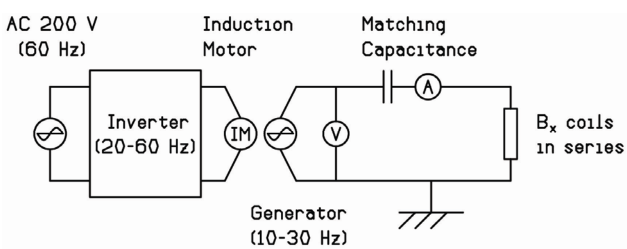

Figure 4: Schematic measurement set-up of AC losses of the B_x coils at 20 K. Details are described in the text.

Figure 5 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 77 K. The dashed curve in Fig. 5 presents the result of the finite element model analysis by T. King [10]. A close inspection of the result showed that the hysteretic and normal resistance losses were all reduced compared to calculations at 77 K, but the eddy current losses in the silver alloy matrix and the brass cooling plates resulted in an overall increase of the losses. 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 again almost independent of the frequency of the transport current as seen in Fig. 5. The solid curve in the figure shows the theoretical Q_{hys} which is normalized to the measured value at 45 A and 15 Hz. At 20 K, J_c of the present HTS wire is about 5 x 10^8 A/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.

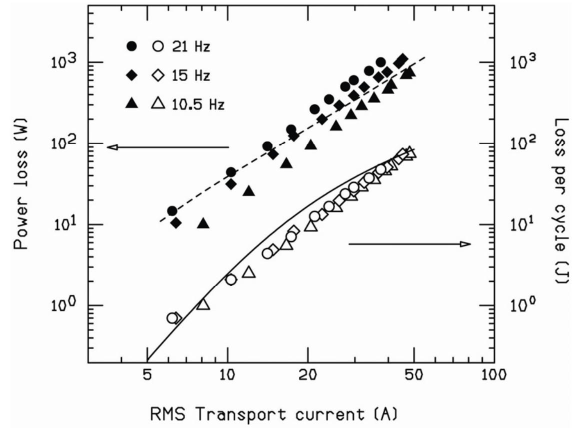

Figure 5: Measured AC losses at 20 K of the B_x coils in series. Full symbols show the total power losses on the left side scale. Open symbols present losses per cycle on the right side scale. The dashed curve shows the model calculation by King [11]. The solid curve is a theoretical prediction normalized to the measured data.

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