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FIELD ENHANCEMENT OF A 12.5-T MAGNET USING HOLMIUM POLES

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Abstract

Unlike conventional ferromagnetic materials such as iron and Supermendur, which produce saturation magnetization fields of approximately 2 T, several of the rare-earth elements (holmium, terbium, erbium, gadolinium, and dysprosium) yield saturated fields of nearly 4 T. This property makes these rare-earth metals particularly attractive as flux concentrators for use in superconducting magnets. This report concerns the use of holmium inserts to enhance the peak useful field of the nominally 12.5-T, 5-cm-bore tape magnet manufactured by the Intermagnetics General Corporation (IGC). Nonlinear magnetostatic analysis indicates that this field increases to nearly 16 T with the rare-earth poles inserted within the bore on both sides of the coil's split-plane radial access gap. This paper focuses on computer modeling methods and experimental results.

Introduction

Ferromagnetic materials can play an important role in increasing the maximum usable magnetic field in research-laboratory small superconducting

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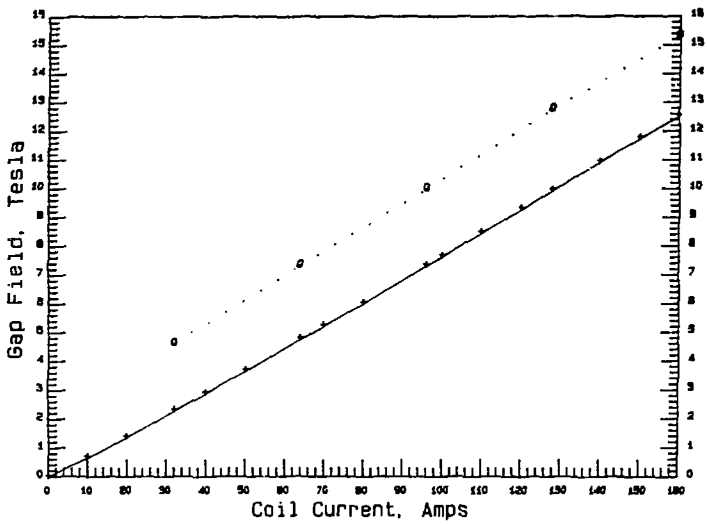
magnets. In the past these coils have been found to be invaluable in several areas, ranging from nuclear magnetic resonance (NMR) materials measurements to the qualifying and development of superconducting conductors for use in magnetic fusion coils. However, the maximum permissible fields that can be generated by commercially available superconductors of Nb-Ti and Nb_3Sn peak at about 8 and 13 T, respectively, for coils designed to operate at 4.2 K--limits imposed by the fundamental material properties (J_c, T_c, and H_{c2}) of these two superconductors. There are only four methods of obtaining higher fields: superfluid He-II with coil operation at 1.8 K, copper-resistive-coil inserts, new superconducting compounds and alloys, and ferromagnetic flux concentrators that increase the coil field. For laboratory magnets (with inner bore diameters of less than 10 cm), the latter approach seems to be the least expensive and easiest to implement. In this case the limiting field is determined by the saturation properties of available ferromagnetics.

Figure 1 shows the a computer fit to magnetization and permeability data for holmium metal, as measured by Schauer et al.[1] and first applied by Rupp.[2] The peak saturation field for this metal is 3.9 T--almost twice as high as that of iron and Supermendur ferromagnetic materials. Its relative permeability exceeds 1.0 even at applied field strengths greater than 20 T, making holmium an excellent material for enhancing the fields of small superconducting magnets. Our calculations and experiments confirmed the usefulness of holmium in small superconducting coils.

Two right-cylindrical poles of holmium were placed within the 5-cm-diam bore of a commercially available 12.5-T tape magnet composed of Nb-Ti and Nb_3Sn. The holmium poles completely filled the magnet bore tube except for a 1.1-cm axial space located at the coil midplane that serves as the split-plane radial-access gap. Figure 2 shows the placement of these holmium cylinders within the coil.

R. W. Hoard - Figure 5



Because tape magnets are designed to be non-cryostatically stable (with coil-pack current densities approaching 20,000 a/cm^2), it appeared that the enhanced fringing fields surrounding the holmium would exceed the allowable peak field on the Nb_3Sn tape (13 T) at the magnet midplane and/or that the radial field components at the axial ends of the coil would also increase sufficiently over the original magnet design specifications, resulting in a quench of the magnet. Radial increases in the fringing fields were alleviated by making the holmium cylinders slightly (2.0 cm) longer than the axial length of the winding pack.

The authors calculated the case of two ferromagnetic cylinders immersed in a uniform magnetic field and separated by a gap distance g (Fig. 3). If the field strength is sufficiently strong and uniform, the material achieves a constant magnetization value M_s. Then the central resultant field H_c can be determined from

$$H_C = M_S\left(\cos\left\{\tan^{-1}[2R/(g+2L)]\right\} - \cos[\tan^{-1}(2R/g)]\right) + H_b \qquad (1)$$

in which R and L are the radius and length, respectively, of each cylinder depicted in Fig. 3 and H_b is the applied background field.[3] Using values of 3.9 T, 2.5 cm, 11.0 cm, and 1.1 cm for M_s, R, L, and g, respectively, implies that the original central field of a 12.5-T magnet will be increased to 15.47 T.

However, a more detailed analysis was needed to determine the off-axis and non-central field values. The authors used the two-dimensional non-linear, magnetostatics program JASON to determine the field profiles shown in Fig. 2, which model the tape magnet as several pancake layers with different coil pack current densities J_{pack}. (The exact variation of J_{pack} with pancake location is a proprietary trade secret to IGC[4]). Then they plotted the uniformity of the axial field component H_z across the gap as a function of radial distance from the center of the holmium poles. Figure 4 compares both the calculated results from JASON and the experimentally measured points, indicating that the expected field enhancement would yield a field uniformity of better than 5% across the 2.0-cm-diam region between the poles. The JASON program predicted a 0.1-T increase in the peak field on the innermost Nb_3Sn tape turns adjacent to either side of the radial-access gap whereas the radial component of the fringing fields at the axial ends of the coil was calculated to increase only by 0.01 T. These calculations were later shown to be approximately 1% higher than the actual experimental results.

Experimental Results

The central field between the holmium poles was measured using two cryogenic hall probes and a small 1.1-cm o.d. search-coil (connected to an electronic integrator).[5] These were mounted on a long, epoxy, G-10 probe that was inserted during ambient conditions down into the cryostat and through the magnet's radial-access gap. Measurements were made by centering each device between the holmium poles at selected fractional values of the magnet's full current. All three instruments agreed within 1% and yielded a final gap field of 15.3 T at the full-rated coil current of 160 A. The field enhancement resulting from the holmium poles as a function of current excitation is depicted in Fig. 5. Specifically, a separate magnetoresistive probe, located adjacent to the innermost Nb_3Sn tape turns at the midplane, indicated that the peak field on the conductor decreased by 0.1 from its original design value of 13.0 T.

Conclusions

Because the central field predicted by Eq. (1) was relatively close to that actually measured, its validity is established. Furthermore, differences between the calculated and experimental results are within the experimental error of 1%. Thus, calculational ease of designing these holmium flux concentrators clearly establishes this as a simple and effective method of enhancing the field strength of laboratory-sized superconducting magnets. The current market price of the 99+% purity holmium used in this study is approximately $1872/kg; although this price limits application to small-sized solenoids, these coils can be used to test and develop the advanced high-field conductors needed in fusion magnets.

Acknowledgments

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Figure Captions

Fig. 1. Comparison of the magnetization curve (solid line) for rare earth element holmium to its relative permeability (dotted line).

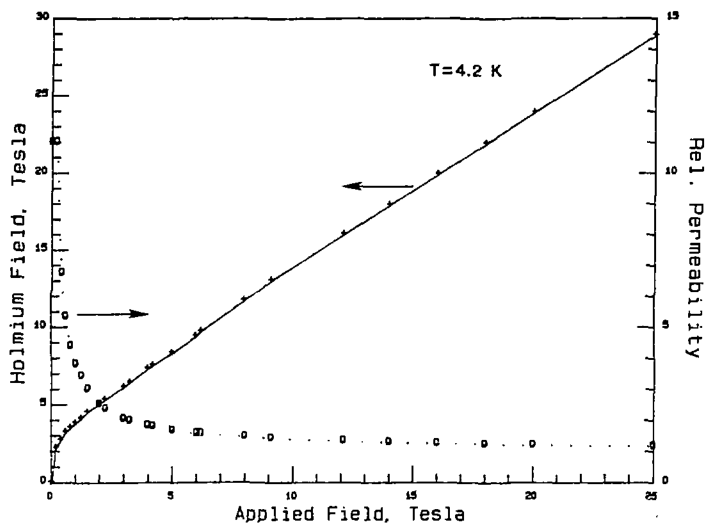
Fig. 2. Field contours of a commercially available tape magnet with holmium pole inserts.

Fig. 3. Geometry of the two holmium cylinders. Note that R is radius, L is length, and g is gap.

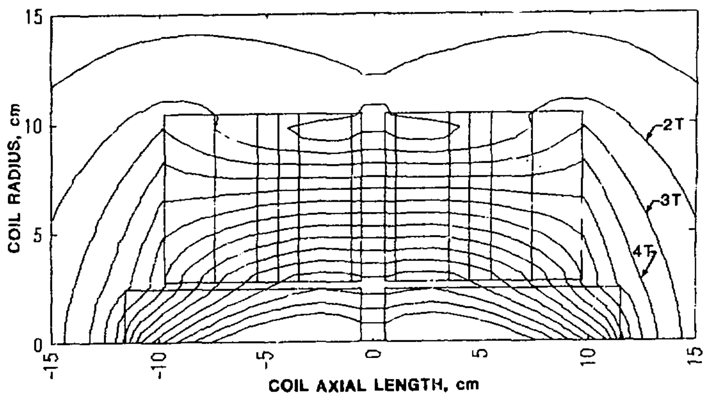
Fig. 4. Calculated axial field uniformity (solid line) vs experimental measurements (dotted line).

Fig. 5. Comparison of magnetic field vs current of the typical tape magnet (solid line) to the magnet with holmium poles (dotted line).

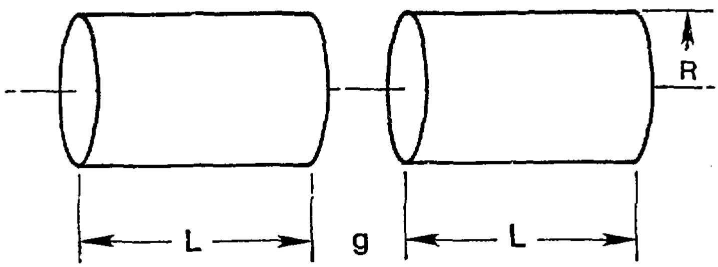
R. W. Hoard - Figure 1



R. W. Hoard - Figure 2



HOLMIUM POLES



R. W. Hoard - Figure 4