

SUPERCONDUCTING TWO TESLA BENDING MAGNET†

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A superconducting 2 tesla dipole model magnet has been designed, fabricated, and tested at the National Accelerator Laboratory. The magnet is of a type called 'superferric' since it consists of an iron yoke and superconducting coil. The magnet provided a 4 cm × 10 cm free aperture and generated a magnetic field uniform to ±0.1 per cent or less within a full horizontal aperture of 5.3 cm. The current density in the conductor at 2 T was 36 kA/cm², the stored energy was 8000 J and the magnet could be charged to 2 T in about 5 minutes. The iron was refrigerated to 4.2 °K, and about 75 liters of LHe were required for cooldown from 80 °K. The cryostat heat leak was 3 liters/h. A 3 m long prototype 2 T superferric magnet is under construction.

1. INTRODUCTION

A superconducting 2 tesla dipole model magnet has been designed, fabricated, and tested at the National Accelerator Laboratory. The magnet is of a type called 'superferric' since it consists of an iron yoke and superconducting coil. Field uniformity is provided by iron surfaces machined to tight tolerances. Magnets of this type have been constructed⁽¹⁾ but dipoles suitable for particle beam bending magnets have not been built. Preliminary design studies have been made by Wilson⁽²⁾ and Teng and Lari.⁽³⁾ Potential power savings coupled with low initial cost make this type of magnet attractive. At the present moment we are considering dc magnets only.

2. DESIGN FEATURES

Figure 1 shows the assembled magnet and cryostat and Table I gives the design parameters. The magnet was designed to provide a clear aperture of

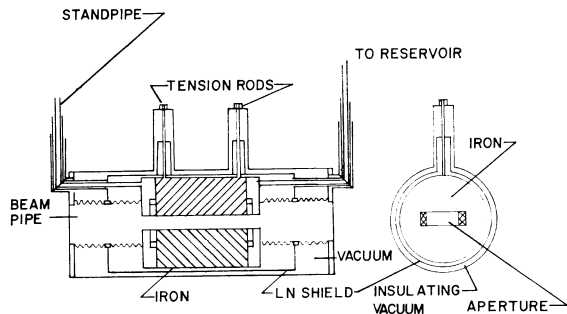


FIG. 1. Two tesla superferric bending magnet.

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TABLE I

Design/construction parameters

<i>Magnet</i>	
Type:	Picture-frame iron with superconducting coil, iron at 4.2 °K
Clear aperture:	4 cm full gap × 10 cm full width × 76.2 cm long
Mid-plane design field:	2 T
Mid-plane field uniformity (2 T):	±0.1 per cent over 5.0 cm full aperture
Total gap excitation (2 T):	72 463 A-turns
Total turns:	552
Packing factor (area of conductors/area of coil window):	54 per cent
<i>Conductor</i>	
Manufacturer:	Airco
Material:	Nb-Ti
No. S.C. strands:	121
Twist:	1 turn/cm
Cu/S.C. ratio:	3 to 1
Insulation:	Ebanol C and Glyptal
<i>Cryostat</i>	
Type:	Horizontal, liquid nitrogen shielded, cold bore
Overall dimensions:	Vacuum vessel diameter: 33 cm
Cryostat volume above coil:	0.6 liter
Reservoir volume:	15 liters

approximately 4 × 10 cm. The iron was refrigerated to 4.2 °K, thus minimizing the excitation required and allowing direct support of the lateral magnetic forces. The beam tube was therefore at 4.2 °K inside the magnet. The coil and iron geometries were selected using the computer code TRIM. Mid-plane and ground-plane insulation spacers were chosen to give good low field uniformity. No attempt was made to optimize the iron end shape.

The cryostat was designed to be small in overall diameter, with minimum vacuum space between surfaces at different temperatures. The liquid

helium volume in the cryostat is quite small so an additional integral storage reservoir was used to allow for protracted operation.

3. CONSTRUCTION—MAGNET IRON

The magnet iron was procured as a half-round forging of AISI Type 1018 low carbon steel. The magnet is not laminated since only dc operation is contemplated. The outside was turned to the final diameter and the window milled to size. When assembled the gap is constant to within ± 0.076 mm over the entire aperture. Because the iron is very brittle at liquid helium temperatures, nothing was welded to the iron and the iron supported only the magnetic forces. The dead weight of the iron was about 340 kg.

4. CONSTRUCTION—COIL

The coil form, consisting of mid- and ground-plane spacers and beam tube, was fabricated as an integrated box structure of AISI Type 304 stainless steel. The spacers were perforated to allow liquid helium circulation. The coil was wound in the vertical plane, with 18 mesh plastic-fiberglass screen 0.36 mm thick between layers. A cross section view of the coil is shown in Fig. 2. The ends were bent after the coil was assembled into the iron. When completed the coil was free of all turn-to-turn, layer-to-layer, and conductor-to-coil form shorts. The current leads, cooled by the boil-off gas, were bifilar spiral wound on a single phenolic rod.

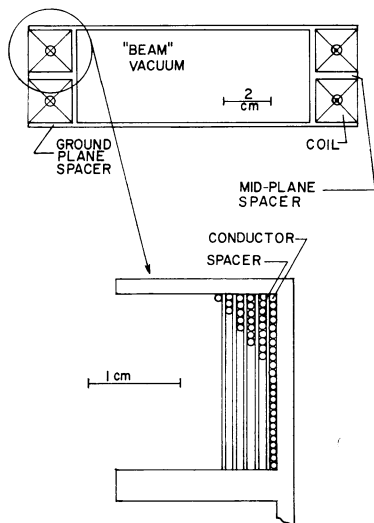


FIG. 2. Cross section of coil.

4. CONSTRUCTION—CRYOSTAT

The cryostat was fabricated entirely of AISI Type 304 stainless steel, except for the brass liquid nitrogen shield. The rectangular beam pipe/coil box interfaced at the end of the helium vessel and emerged from the cryostat as a 10 cm tube. Bellows in the beam tube allowed contraction and provided a long thermal path to room temperature. The dead weight of the iron was supported by two 4.76 mm stainless steel rods in tension. No multi-layer insulation was used in the vacuum spaces. The 15 liter reservoir was a commercial item, modified and mounted on one end of the cryostat. A vacuum insulated standpipe of similar height allowed the opposite end to vent. The entire assembly was welded together.

5. INSTRUMENTATION

Voltage taps were provided across each half of the coil and across the copper-superconductor joints at the current leads. Thermocouples were located on the iron and on the tension rods. Reservoir ullage pressure could be measured as well as gas flow rates out of the system.

6. IMMERSION TEST

Prior to assembly of the coil into the iron, the coil was tested by immersing it into a dewar of liquid helium. Aluminum plates on the sides of the coil held by tie bolts reacted the forces and restricted liquid helium penetration into the coil. The coil reached a maximum current of 260 A, corresponding to a field of about 1 T in the center of the loop. This was considered satisfactory performance and the coil was incorporated into the iron. The coil and iron together were not tested in this fashion.

7. OPERATING EXPERIENCE

The assembled magnet and cryostat were operated many times. The cryogenic data are summarized in Table II. Cooling the system became routine and could be accomplished in six hours from room temperature or in two hours from 100°K. The modest cool-down requirements were achieved by introducing the LHe at the reservoir and venting the boil-off gas from the standpipe at the opposite end. The observed steady-state heat leak of about 3 liters/h agrees with the predicted value to within 20 per cent. The heat leak due to the current leads

at 163 A, using all the boil-off gas, was about 10 per cent of the total.

The magnet was energized almost every day for

TABLE II
Operating parameters

<i>Magnetic</i>	
Coil inductance:	0.6 H
Operating current (2 T):	163 A
Stored energy (2 T):	8000 J
Mid-plane field uniformity:	± 0.1 per cent over 5.3 cm full aperture
Current density over coil window (2 T, 163 A):	19.4 kA/cm ²
Current density in conductor (2 T, 163 A):	35.8 kA/cm ²
Charge time to 2 T:	approximately 5 minutes
Maximum quench current:	200 A
Quench central field:	2.25 T
Fraction of short sample current (2.25 T):	80 per cent
Quench current density over coil window:	24 kA/cm ²
Quench current density in conductor:	44.4 kA/cm ²
<i>Cryogenic</i>	
Cooldown requirements (77 °K to 4.2 °K):	~75 liters; 0.22 liter/kg
Cooldown time (77 °K to 4.2 °K):	2 to 3 hours
Steady-state heat leak (zero current):	2.9 liters/h (observed)
Steady-state heat leak (2 T, 163 A):	3.2 liters/h (observed)

several weeks. Operating data are summarized in Table II and Fig. 3. It is highly desirable to be able to change the magnetic field in bending magnets in a few minutes. This coil is short-free, of low inductance, and can be charged and discharged quickly. Figure 4 shows that 2 T can be reached at charge rates up to about 2.3 A/sec (about 282 G/sec average).

Preliminary magnetic field data were obtained with a F. W. Bell gaussmeter with a Hall element compensated for use at cryogenic temperatures.

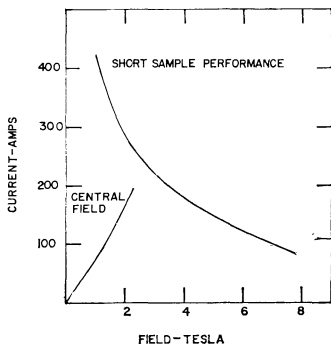


FIG. 3. Short-sample performance of conductor; magnet load lines.

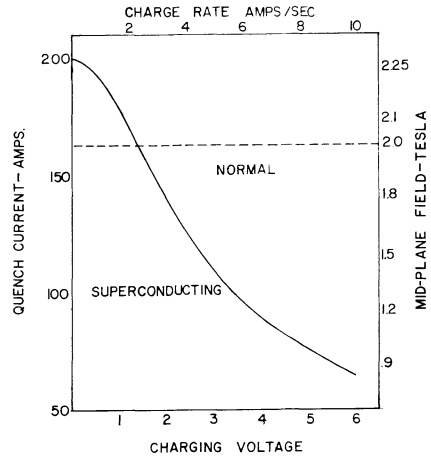


FIG. 4. Charge rate sensitivity of magnet.

The absolute accuracy of the field measurements was about ± 0.1 per cent and long-term stability of ± 0.05 per cent was observed. Measured transverse uniformity of the vertical field component at 1 T and 2 T agrees with the TRIM predictions for uniformities of less than ± 0.1 per cent. Figure 5 shows the transverse field uniformity at central fields of 1, 2, and 2.2 T. The longitudinal dependence of the vertical component was studied to investigate end effects. Figure 6 shows the on axis end effect for 1 T and 2 T.

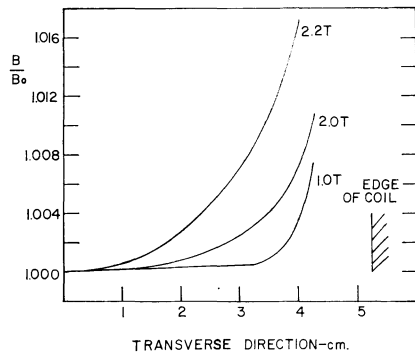


FIG. 5. Measured vertical field uniformity across aperture at several values of central field.

The coil was repeatedly quenched at various fields between 1.7 and 2 T with no subsequent degradation of performance. During a quench at 2.25 T an arc occurred between the winding and the coil form, causing a short in the winding. The magnet was subsequently operated to 2 T with slower charge rates. Computer analysis⁽⁴⁾ in-

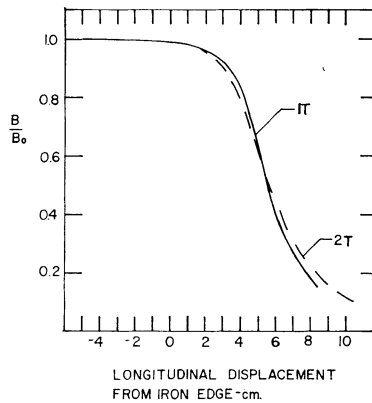


FIG. 6. Vertical field uniformity measured longitudinally, showing end effects at 1 tesla and 2 tesla.

indicates that voltages up to 200 volts can be developed during a quench at this field. Hi-pot tests on the wire insulation indicated a breakdown potential between conductor and ground of 150 to 200 V. The arc probably occurred at a weak point in the insulation.

8. FUTURE DEVELOPMENT

The success of this 0.76 m model has led us to consider a 3 m prototype. The prototype would

use a lower current density to further reduce the threat of arcing and burn-out in the event of a quench. The prototype would also include improved liquid helium irrigation into the coil and an LHe reservoir of 50 to 100 liters. The design of this magnet is in the final stages.

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