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SUPERCONDUCTING MAGNET MODELS FOR ISABELLE*

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Abstract

The development program for the superconducting magnets of the Intersecting Storage Accelerators is described. The dipole magnet design is of the cos θ type and employs wide ribbon conductor. Magnetic measurements are compared with calculations which include the effects of conductor magnetization and iron saturation. Calculations of the harmonics due to the magnet ends will also be presented along with estimates of the effect of the shape of the outer boundary of the iron shield on the field and the degree of interaction between the magnets in the two rings. The conductor is a metal-filled braid woven from 186 wires each containing 400 filaments. A precision molding technique has been developed which assures accurate placement of the turns and could be used for semi-mass production. The iron cores are laminated and assembled in a special way to eliminate the axial differential expansion between the coil and the core. Correction coils for the 3θ and 5θ terms are built into the bore tubes. These coils are necessary to correct the small (10^{-3}) harmonics produced by conductor magnetization at low field and iron saturation at high fields.

I. Introduction

This paper describes the superconducting magnet development program for the Intersecting Storage Accelerators (ISA or ISABELLE). The current magnet design is based on a research program which has been in existence for a number of years. The first magnets of this type were two quadrupoles built in 1967.[1] In the intervening years sufficient improvement has been made in the design of such magnets that it is now possible to consider the construction of large accelerators based on superconducting technology.

II. Test Program

A number of dipoles are being constructed which are approximately full-scale in cross section (bore 8 cm) and about 1 m long (the design of the ISA calls for 3 m long magnets). The purpose of these magnets is to demonstrate the following points:

1. Magnetic Field Precision

While recent advances in superconducting material fabrication and magnet construction techniques have made it possible to achieve short sample performance in pulsed superconducting magnets,[2,3] none of the dipoles built to date has had the precision of field required for a storage ring. One of the objects of the test program is to show that high field magnets of the desired field quality can be manufactured in the semi-mass-production manner in which accelerator magnets are usually produced.

2. Reproducibility

At the present time very little is known about the reproducibility of superconducting magnets since no attempt has yet been made to produce a series of magnets with the same characteristics. As part of the development program at least two identical magnets will be built to establish the magnet-to-magnet reproducibility.

3. Reliability

The reliability of pulsed superconducting magnets is also in question since none have been subjected to the large number of pulses that a magnet in a machine would experience. To test the long-term stability of such magnets, two dipoles will be pulsed continuously for two months while mounted in a horizontal cryostat. By using a pulsing sequence in which the magnets are operated with a very short flat-top during the day and run at full field at night it is possible to approach the total number of cycles that a device such as the ISA would see in its total lifetime, in this relatively short time.

4. Cryogenic Experience

The long-term test mentioned above will be performed in a horizontal cryostat with room-temperature aperture and a closed cycle refrigeration system so that much valuable experience can be obtained concerning the problems of continuous operation of cryogenic equipment for accelerator magnets.

At the present time the first model magnet has been partially tested and a second "identical" magnet is nearing completion.

III. Magnet Design

The magnets are of the cos θ type and many smaller versions have been built and tested.[3] The main coils are wound from wide braided conductor which is formed into six sections or "blocks" and the current distribution is provided by a spacer braid of stainless-steel wires. Careful positioning of the current elements eliminates the lower order harmonics as described in Sec. IV. The coils are surrounded by a laminated iron shield as shown in Fig. 1.

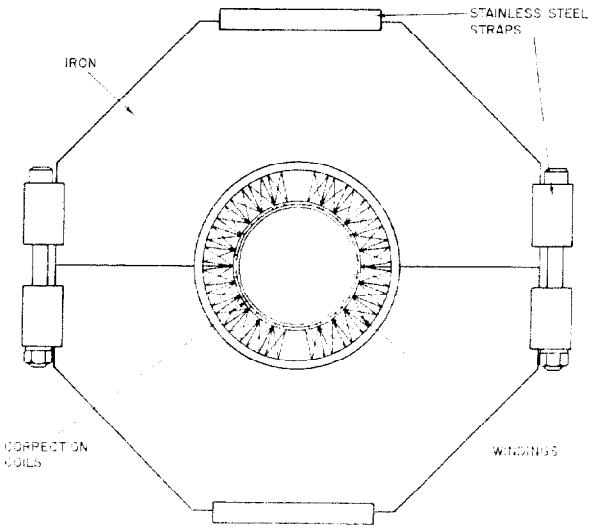


Fig. 1. Cross section of ISA prototype superconducting dipole.

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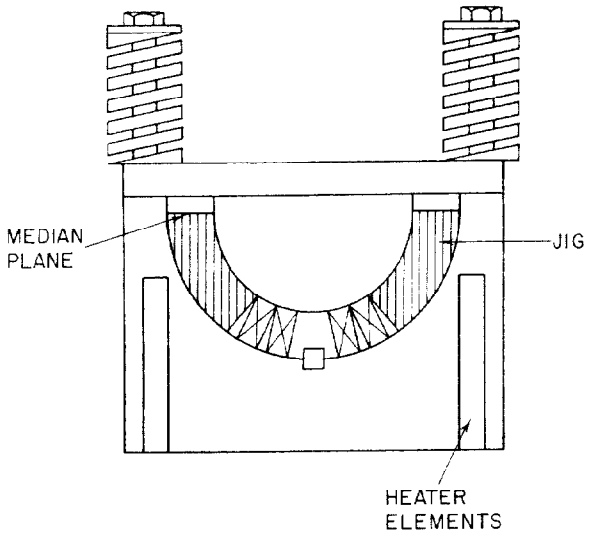


Fig. 2. Molding technique used to form main magnet coils. The die springs compress the coil blocks while the coil is hot and hold it in position during curing.

1. Construction Technique

Because of the very high precision of placement required for the conductors a novel technique of construction has been developed. This is illustrated in Fig. 2. The braided conductor (see Sec. III) is wrapped with an insulation of fiberglass tape and impregnated with a thermally activated (B-stage) epoxy. To form one of the main coils this conductor is wound on the central pole piece in the mold along with any stainless braid spacers which may be required to form the first "block." This block is then formed by the appropriate aluminum jig pieces which are referenced to the median plane. These jigs are pressed into place by the die springs while the mold is hot and are maintained in place until the epoxy is cured. The next block is then formed in the same way with the appropriate jigs and the coil built up until a half magnet is completed. In this technique the tolerance is determined by the tooling and it has been possible to hold very close tolerances (0.03 mm) from coil to coil. When completed the coil is a monolithic structure made from a single length of braid. Two such coils form a dipole.

2. Correction Coils

Special correction windings are provided to cancel out the small sextupole and decapole components introduced by conductor magnetization at low field and iron saturation at high fields. These windings are situated in slots in the bore tube which is stainless-steel coated with fiberglass epoxy. The windings are held in place by fiberglass epoxy bands which also form cooling channels for the inner surface of the main coils. The material used in the correction windings is the same as that used to form the braid. There are seven 0.2 mm insulated multifilament wires twisted into a cable which is connected at the terminals to form a seven-turn coil. These correction windings are shown in Fig. 1.

3. Iron Core

The iron core is split along the median plane. It is made from M-36 silicon steel laminations 0.06 mm thick which are tied together with stainless-steel straps. In order to match the longitudinal coefficient of thermal expansion the lamination stack is compressed in a hydraulic fixture to a predetermined pressure and then the stainless straps welded in place. By adjusting the area of the laminations and straps and the amount of preloading, it is possible to produce any effective coefficient of thermal expansion in the range between that of the M-36 steel and stainless steel.[4] This technique has been used to match the thermal expansion of the core to that of the main coil structure. The radial differential thermal expansion is taken up by preloading the coil structure with the core by assembling the coil, cooled to liquid nitrogen temperature, in a warm core. In this way the coil is kept under a compressive load by the core at all temperatures.

4. Expansion Coefficients

In order to preserve the high precision of the molding technique down to low temperatures, it is imperative that the various components of the coils have very closely matched coefficients of thermal expansion. In Table I the total integrated coefficient of expansion to 77 K for the various components of the main coils are presented. The measurements were made on blocks of conductor of the same size and shape as those in the coil. The sand-alumina-epoxy mixture is used to fill in the coil ends and support the leads.

TABLE I

Material	Length $\Delta L/L \times 10^3$	Width $\Delta w/w \times 10^3$	Thickness $\Delta t/t \times 10^3$
Superconducting braid	2.3	2.7	2.2
Stainless-steel braid	2.3	2.8	2.5
G-10 post and wedges	1.8	2.4	5.2
Sand-alumina-epoxy	2.9	2.9	2.9
M-36 silicon steel	1.9	1.9	1.9

As is evident from Table I the various components are matched very well except for the thickness coefficient of the G-10 components. The high value in this direction is due to the excess epoxy between the layers of glass. This large coefficient leads to a potential azimuthal gap of 0.1 mm which is compensated for by the precompression of the coil in the iron core. A complete magnet is shown in Fig. 3 with the top half of the core removed.

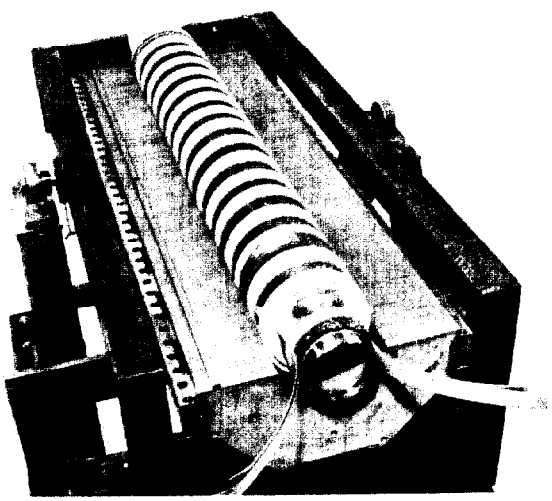


Fig. 3. Photograph of ISA model magnet with the top half of the iron core removed to show the coils.

TABLE II

(No correction coils are provided in the present models for 7θ and 9θ components.)

Field	3θ (10^{-3}/in.^{2}) (0.23×10^{-3} due to random errors)				5θ (10^{-3}/in.^{4}) (0.11×10^{-3} due to random errors)				7θ (10^{-3}/in.^{6}) (0.05×10^{-3} due to random errors)			9θ (10^{-3}/in.^{8}) (0.02×10^{-3} due to random errors)		
(kG)	Mag.	Sat.	Total	Corr. Curr.(A)	Mag.	Sat.	Total	Corr. Curr.(A)	Mag.	Sat.	Total	Mag.	Sat.	Total
5 (Injection)	-1.85	0.00	-1.85	-5.5	0.06	0.00	0.06	0.26	0.05	0.00	0.05	0.01	0.00	0.01
10	-0.78	0.00	-0.78	-4.6	0.03	0.00	0.03	0.26	0.03	0.00	0.03	0.01	0.00	0.01
20	-0.25	0.01	-0.24	-2.7	0.01	0.00	0.01	0.17	0.02	0.00	0.02	0.01	0.00	0.01
30	-0.10	0.34	0.24	4.3	0.01	-0.08	-0.07	-1.79	0.01	0.00	0.01	0.00	0.00	0.00
40	-0.03	2.40	2.37	56.5	0.00	-0.33	-0.33	-11.2	0.01	-0.04	-0.03	0.00	0.00	0.00

IV. Conductor

As mentioned previously the conductor used is a wide braid formed from 186 wires each 0.2 mm in diameter. These wires contain 367 filaments of NbTi in a copper matrix and are axially twisted with a pitch of six per inch. The copper to superconductor ratio is 1.25:1. After braiding the conductor is heat treated to form a bronze layer around each wire and then filled with a mixture of indium and thallium.[5] The filled conductor is rolled to its final dimensions, 0.53 mm thick and 1.905 cm wide, and then spiral-wrapped with 0.65 cm wide fiberglass tape 0.08 mm thick. A "B-stage" epoxy (Bondmaster E645) is applied and the conductor is ready for use in the mold. Figure 4 is a microphotograph of a conductor block showing the individual turns and insulation. In addition to this conductor one magnet will be made with fully insulated braid using the self-bonding coating "Polybondex 180."

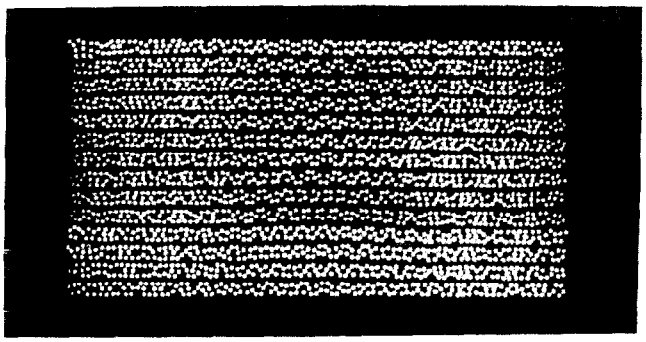


Fig. 4. Microphotograph of conductors in one magnet block. The stainless braid is more sharply defined because of the etch used to bring out detail.

V. Magnetic Field Calculations

1. Two-Dimensional Calculations

The positions of the active turns in the blocks which give the best possible field distribution are determined by a three-step process using the computer program MAGFLD.[6] First the number of turns which will fit in the highest current density block (i.e., the one at the median plane) is determined; then the program is used to calculate the current density in the other five blocks which will eliminate the lowest order harmonics. The next step is to choose the nearest integral number of turns to this "ideal" value and then use the program

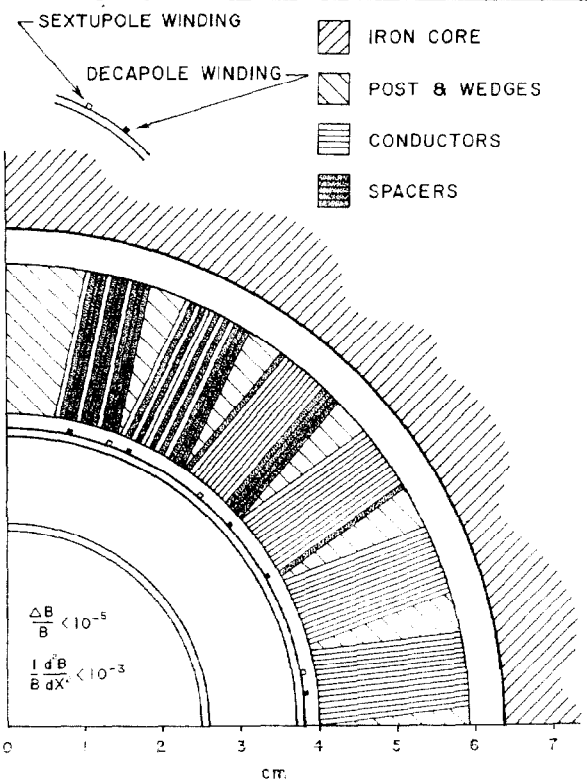


Fig. 5. The distribution of conductors in the main magnet coils. The field tolerances given are calculated for an "ideal" magnet without magnetization effects.

to determine the azimuthal shifts of the current blocks which will eliminate the six lowest order unwanted harmonics. The program does this by forming a matrix of the dependence of each component on block position and then inverting the matrix to give ideal block positions. The end results of these calculations is a distribution of real turns that gives a field which is free of undesired harmonics up to the 30th pole term. The final distribution is shown in Fig. 5.

After the distribution has been determined in this way the effect of conductor magnetization and iron saturation is calculated using the program GRACY.[7] Table II shows the calculated values of the first four harmonics due to these effects.[8] The correction current required is also shown for the components which have correction coils (3θ and 5θ). The harmonic content expected due to random errors in construction is also given in Table II.

These values were obtained by assuming a random error of up to 0.05 mm for both radial and azimuthal placement of the current blocks.

2. End Calculations

The harmonic components introduced into the total field integral by the end configuration of the coils can be computed using a technique due to Mills and Morgan.[9] Using a matrix inversion similar to that used in the two-dimensional calculation it is possible to calculate axial spacings of the blocks at the ends which will eliminate the lower order harmonics. The solutions are not, however, always physically realizable and a compromise solution which reduces the harmonics may be used. In Table III the calculated harmonic contribution of the ends is presented for both the uncorrected case and for a partially corrected situation with reasonable end dimensions.

TABLE III.

Harmonic	Uncorrected (10^{-3}/in.$^{-(n-1)}$)	Partially Corrected (10^{-3}/in.$^{-(n-1)}$)
3θ	-4.8	0.0
5θ	-1.8	-0.65
7θ	-0.019	0.13
9θ	-0.038	-0.026

3. Miscellaneous Calculations

The proposed ISA has two accelerator rings with the magnets of one ring sitting above the magnets of the other ring. At 40 kG the magnetic field of one magnet can penetrate the iron core and affect the field of the other magnets. The most important aspect of this interaction is the introduction of a small quadrupole component in the field which may have to be compensated with an additional coil.

The effect of the noncircular outer boundary of the iron core was studied using the computer program GRACY. It was found that the multipoles produced by the shape of the present core were smaller than those due to the iron saturation so that the net effect is to change somewhat the correction coil currents required to eliminate the multipoles introduced by iron saturation at high fields.

VI. Magnetic Measurements

The multipole content of the first test dipole was measured using a harmonic coil arrangement which has been previously described.[10] In this case the measuring setup consisted of two complete sets of harmonic coils at 5.08 cm and 6.89 cm diameter, respectively. Each set contained two dipole coils and one quadrupole, sextupole, decapole, fourteen-pole, and eighteen-pole coil. The experimental results are summarized in Table IV which is presented in the same form as Table II so that calculation and experiment can be compared directly.

Thermal runaway of the high current leads prevented operation above 3250 A (38.7 kG). Up to this current there was no indication of "training" or other unusual behavior. Modification of the leads should allow operation up to the limit of the magnet's potential (~ 45 kG).

The results in Table IV show good agreement with the calculated values (Table II) although the magnetization effects seem to be somewhat larger than expected. This is probably due to underestimating the critical current at low fields. In general the harmonic coefficients agree with the values expected for a random positional error at 0.05 mm. At the present time this error is almost all due to the dimensional tolerances of the G-10 wedges used in the coils. These wedges were machined with a tolerance of ± 0.08 mm. A better method of wedge forming such as molding could be expected to produce even better magnets. Table IV shows the small correction currents required even with coils of only seven turns. These currents were determined by adjusting the correction until the harmonic in question was smaller than the resolution of the measuring coils (0.05×10^{-3}/in.^{2} for 3θ and 0.03×10^{-3}/in.^{4} for 5θ).

The current, field relationship for the magnet is shown in Fig. 6 along with some short sample curves for the conductor. The short sample curves are shown for various effective resistivities since the transition to the normal state is not well defined for this type of conductor.[11] As shown in Fig. 6, the field is almost exactly linear in current for this magnet. The difference from linearity is less than 1% at 38 kG.

VII. Summary

Preliminary magnetic measurements have been performed on a precision superconducting dipole and the results indicate that fields of very high quality can be produced. The questions of magnet to magnet reproducibility and reliability will not be answered until the test program has been completed.

TABLE IV

Magnetic Field (kG)	3θ (10^{-3}/in.^{2})		5θ (10^{-3}/in.^{4})		7θ (10^{-3}/in.^{6})	9θ (10^{-3}/in.^{8})
	No Correction	Corrected Current	No Correction	Corrected Current		
5	-2.73	-8.35	-0.20	-0.87	-0.04	0.04
10	-2.28	-12.9	-0.14	-1.21	-0.03	0.04
20	-2.25	-23.4	-0.14	-2.38	-0.03	0.03
30	-1.58	-30.9	-0.26	-6.7	-0.05	0.02
35	0.39	7.7	-0.29	-8.5	-0.06	0.02

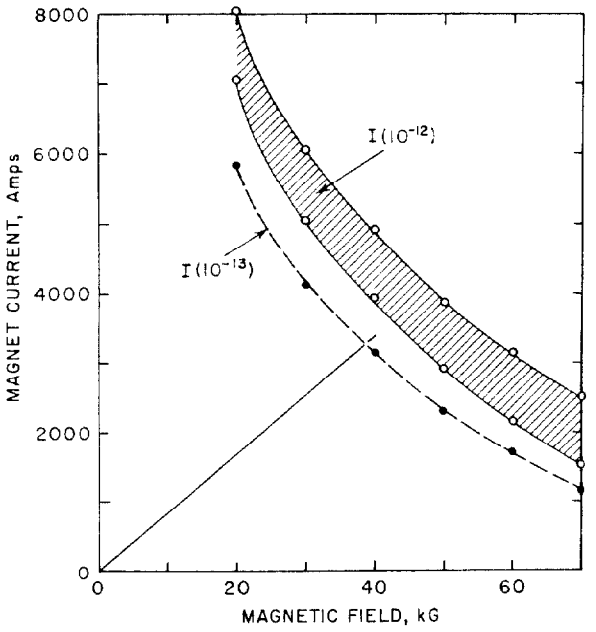


Fig. 6. The current field characteristics of the prototype magnet. The cross-hatched area represents the range of values for short sample currents at an effective resistivity of 10^{-12} Ω·cm. The curve marked $I(10^{-13})$ is the lower limit of the short sample at a resistivity of 10^{-13} Ω·cm for the wires used to make up the braid.

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