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FULL-SCALE ISA DIPOLES*

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I. Summary

After the life test of the two 8-cm (diameter) aperture one-meter long magnets (ISA I and II) had been satisfactorily concluded, the next logical step is the construction of a full-scale (12-cm aperture 4.25-meter long)dipole. The 12-cm magnet is essentially a larger version of ISA I and II with the exceptions of conductor and structural material refinements that have evolved in the 5 and 8-cm aperture model magnet series and comparable programs in other laboratories. The magnet windings will have a 23% higher packing density than ISA I and II. The rate of magnetic field sweep at which the magnetization of the magnet doubles, is an order of magnitude faster, due to improved conductor geometry. The peak magnetic field is approximately 5% greater than the central field 'B(0,0)' in the new design which has 85% usable aperture (≈ 67% actually required). The design field 'B(0,0)' is 4.0 T at 4.5 °K. The coil parameters are ID = 12.05 cm, OD = 15.538 cm, length = 427 cm and 80 turns/pole. The magnet is presently under construction and only prototype data and computed characteristics are presently available.

II. Introduction

This paper describes the construction of a full-sized ISA magnet. The magnet parameters as calculated are presented including chromaticity and quench characteristics. The relevant results from the 8-cm aperture 1-meter long model coil (ISA IV) that incorporates most of the conductor changes of the 4.25 meter magnet are presented as well.

III. Calculations

The operational characteristics and harmonic content of the magnet have been calculated. The results can be conveniently divided into the following sections.

A. Infinite μ Results

The turns distribution for the coil consists of 6 blocks which contain 19, 18, 16, 13, 9 and 5 turns respectively per block from the midplane to pole. The spaces in each of the blocks,not occupied by conductor, contain stainless steel braided conductor. This type of structure is described in earlier reports.[1]

A coil quadrant is illustrated in Fig. 1. The harmonic coefficients for the first six odd terms are zero with the designed distribution. There are 80 active turns, each 0.762-mm thick and 1.7-cm wide (including insulation). The midpoint of the base of each conductor is located on a 12.051-cm diameter circle.

The magnet's infinite μ load line given as calculated by MAGFLD is 12.437 G/A at 4.2 °K (i.e. 4.0 T at 3218 A).

B. Finite μ Results

The finite μ case as calculated by GFUN[2] using a low temperature μ table for low carbon steel predicts 3380 A/turn required for the magnet at 4.0 T. At low values, the field remains constant within 0.1% inside a circle 10.1-cm diameter (85% of the aperture). The peak field point is 5% higher than the central at low fields. This will change a percent or so as the magnet iron becomes saturated.

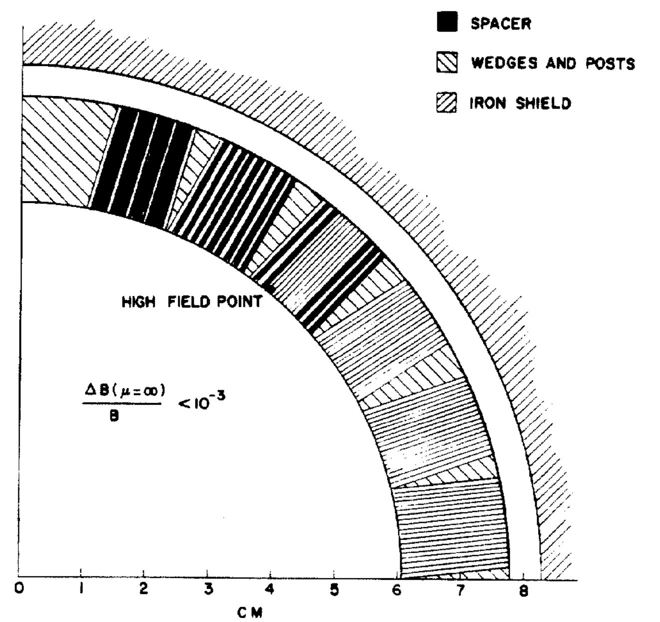

Fig. 1. The turns distribution for the full-scale ISA magnet.

It is possible to introduce a quadrupole term of 2.5×10^{-4} cm^{-1} with a displacement of 25 microns of the coil with respect to the iron shield. GFUN (SLAC) calculations utilizing a low carbon steel μ table predict a leakage field of 266 gauss at the pole and 701 gauss on the midplane, both at a 21.6-cm radius. The harmonic content of the field is listed in Table I.

TABLE I
$C(N) \times 10^4$
Field Quality Calculated for Uncorrected ISA 12-cm diam 4.25-m Long Prototype

$$\frac{B(R,\theta)}{B(0,0)} = \sum C(N) \left[\frac{R}{R(\text{inside radius of coil})}\right]^{(N-1)} \cos(N\theta)$$

$R_{IR} = 6.0025$ cm

B(0,0) Tesla	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
C(3)	0.06	0.13	0.33	0.7	7.3	32.2	81.0	167
C(5)	-0.012	-0.018	-0.012	-0.61	-4.9	-27.9	-70.4	-68.9

If the C(N)s from Table I are used at a 4 T field, the sextupole term in a 4-cm radius circle is 289 gauss or 0.5%, and the decapole term is 51.7 gauss or 0.1%. The magnetic forces on the magnet are 10.54 kg/cm horizontal outward force and 1 003 kg/cm attractive force on the iron (the attractive force between the coils is 500 kg/cm).

C. Quench Characteristics

The quench properties of the magnet are investigated by utilizing the Rutherford Quench Code,[3] and measured thermal conductivity data[4] presented in an internal

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report.[5] The results are summarized in Table II.

TABLE II
Quench Parameters for ISA Size Magnet
[Metrosil Resistor ≡ $R = R_o(I/I_o)^{0.75}$]
Total Energy 315 kJ

Protection Resistor Value (Ω)	0.4	Metro. 0.4	Metro. 0.21	0.01
The Bore Field (T) B(0,0)	4.0	4.0	4.0	4.0
Current/turn (A)	3380	3380	3380	3380
Start Temp. °K	4.2	4.6	4.6	4.2
% Energy Dumped in He	7.4	6.5	17.0	92.0
Maximum Internal Voltage (V)	76.0	95.0	175.0	390.0
Time Constant (s)	0.12	0.09	0.15	0.35
Maximum Coil Temp. °K	41.0	37.0	45.0	74.7
Maximum External Voltage (kV)	1.380	1.38	0.71	0.034

Therefore, at the design current of the magnet there appears to be no problem with respect to the quench characteristics; even higher operating currents appear to pose no problem.

IV. Construction

The cross section of the 4.25-meter dipole is shown in Fig. 2. The coil blocks contain nominally 19 turns. Each of the turns are composed of ninety-seven 0.305-mm diameter wires. The wire material is #310 stainless steel for the inert turns and a Cu-Ni-jacketed Nb-Ti and Cu composite for the active turns. The description of the composite is given in Table III.

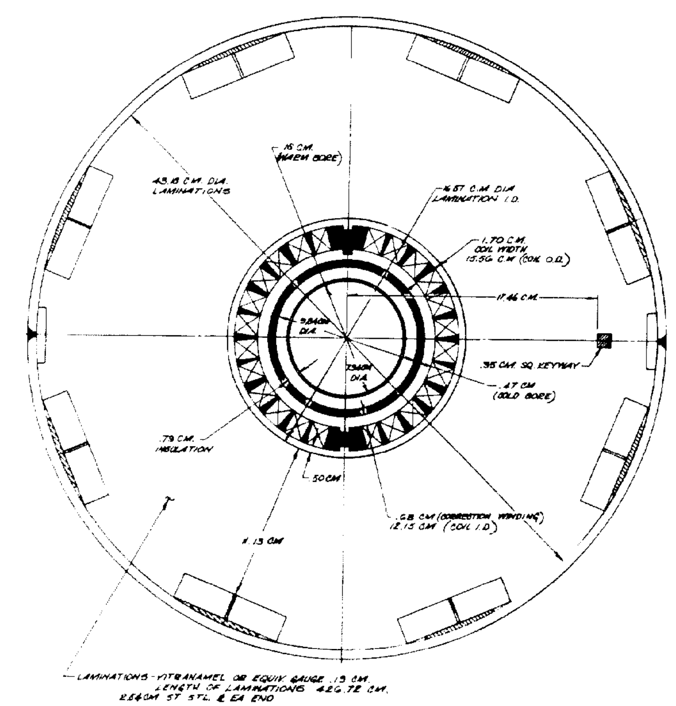

Fig. 2. The overall cross section of the 12-cm dipole (shield and coils).

TABLE III
Properties of the NbTi and Cu Composite Superconductor

Diameter	0.03048 cm
Surface Sheath Thickness	0.00102 cm
Surface Sheath Material	90% Cu:10% Ni
NbTi Filaments	517
Cu:NbTi	1.25/1
Matrix/Superconductor	1.58/1
I_c(4T, 4.2 °K) $\rho = 10^{-12}$ Ω-cm	55 A
Twist	1.2/cm
Filament Diameter	10 microns

The braid parameters are given in Table IV.

TABLE IV
Braid Parameters

No. of Wires in Braid	97
Length of Active SC Braid/Pole	756 m
Active Braid Filler	In (7% Pb)
Inactive Filler	Sn (6% Ag)
Compaction (% Volume Wire)	71 %
Insulation (Glass and B' stage epoxy)	0.064 mm
Bare Braid Dimensions	16.86 mm x 0.061 mm
Braid Transposition Pitch	11.4 cm

A photomicrograph of the prototype coil block (midplane) is shown in Fig. 3. The wedges of the coil are molded from a silica-flour-filled epoxy XD580 first developed at Rutherford,[6] which has very similar shrinkage properties to the coil block. The posts are fabricated from a Mykroy (Glass Bonded Mica) material which has similar properties to the iron shield. The typical integrated shrinkage for the material utilized in the coil structure are given in Table V.

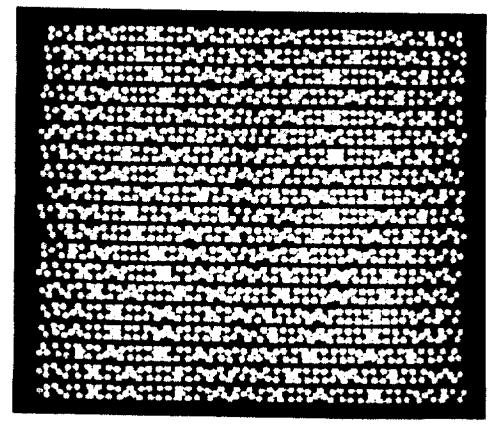

Fig. 3. Photomicrograph of the midplane current block. This is a prototype and only contains 93 wires, while the coil will have 97 wires/braid. 5X

TABLE V
$$\frac{L(300\ ^\circ K) - L(77\ ^\circ K)}{L(300\ ^\circ K)} \times 10^3$$

	Length ΔL/L	Width ΔW/W	Thickness Δt/t
Superconducting (SC) Braid w In(Pb)	2.2 ± 0.2	3.0 ± 0.3	3.1 ± 0.3
Stainless Steel (SS)	2.5 ± 0.2	2.8 ± 0.3	3.3 ± 0.3
Mykroy (Glass Bonded Mica)	1.9 ± 0.1	1.9 ± 0.1	1.9 ± 0.1
XD 580	2.8 ± 0.1	2.8 ± 0.1	2.8 ± 0.1
Sand Epoxy Filler (Ends, etc.) Alumina	2.9 ± 0.2	2.9 ± 0.2	2.9 ± 0.2
Vitrenamel (Shield)	1.9	1.9	1.9
Fibreglass Epoxy Bands	2.2 ± 0.2	2.2 ± 0.2	2.9 ± 0.2
Coil Package as Whole	2.5	2.8 ± 0.2	2.9 ± 0.2

The photomicrograph in Fig. 4 shows the turn-to-turn packing relative to the glass fiber insulation and the epoxy.

Fig. 4. An enlargement of the interlayer space to show the high glass fiber content. 300x

Typical stress/strain numbers for the current blocks (midplane) at points where the curves are linear are: a stress of 1 200 kg/cm^2 produced a strain of 10^{-3} horizontally (direction of current flow) and 8×10^{-3} vertically with the force applied layer-to-layer (azimuthally in the coil). The average Poisson's ratio was 0.11. A stress of 2 400 kg produced a strain of 1.7×10^{-3} transverse, and 2.75×10^{-3} longitudinally (direction of current flow) with the force applied across the width (radially in the coil). The average Poisson's ratio was 0.5. The total weight of the coil will be 90 kg.

The 4.25-m dipole iron shield is a laminated structure built in two halves (see Fig. 2) with the split at the median plane. The complete magnet core is 425-cm long, 44-cm outer diameter, 16.57-cm inner diameter and weighs 3 730 kg. The two halves are keyed and held together by 1.3 x 5 cm stainless steel girth bands on 25-cm centers. These girth bands are also fabricated in halves and are welded together after insertion of the coil in the assembly. The individual magnet halves are fabricated by stacking and compressing the laminations [Vitrenamel (low carbon steel)] in a suitable fixture and then welding longitudinal tie rods to heavy end plates (304 SS) before releasing the pressure on the laminations. The purpose is twofold: first integrity and second is to match the axial contraction coefficient. For a clamping pressure of 28 kg/cm^2 on the laminations and a tie rod area that is 8.3% of the lamination area, the effective axial modulus is 53×10^3 kg/cm^2 and the integrated shrinkage coefficient to 4.5 °K is 2.74×10^{-3}. The maximum stress in the SS tie rods occurs at 4.5 °K and is 881 kg/cm^2.

The mechanical stability of the magnet assembly is obtained by designing the coil and iron shield to have a modest interference fit (0.12 → 0.015 mm) at 4.5 °K. This requires a 0.5 → 0.4 mm interference between the coil structure and the iron at 300 °K. The assembly is done with the coil structure at 77 °K and the iron shield at 300 °K. The girth bands are welded under these conditions and upon reaching 300 °K for the entire structure, are stressed to 1 340 kg/cm^2.

The assembled magnet and dewar are shown in a cut-away drawing in Fig. 5. The testing will employ a refrigerator and the bath temperature will be 4.6 °K.

V. Prototype ISA IV

A fourth one-meter long, 8-cm ID, prototype of the ISA I and II series[7] has been tested. This magnet, ISA IV, is similar to the 4.25-m magnet, the major difference is that the braid contains only 93 superconducting wires instead of 97. It is a 54 turn/pole dipole with 6 current blocks containing 3, 6, 9, 11, 12, and 13 active turns from pole to midplane respectively. The iron shield was Vitrenamel (low carbon steel). The performance of ISA IV is shown in Fig. 6. The operational characteristics of ISA IV are given in Table VI.

TABLE VI
ISA IV Operation

Current in braid	4200 A
Current in wire	~ 45.4 A
Current density SC	165 kA/cm^2
Current density braid	39 kA/cm^2
Current density incl. insulation	32 kA/cm^2
Critical current density (SC) 4.8 °K and 4.2 T	≈ 165 kA/cm^2
Temperature reserve (≈ 2.5% per 0.1 °K)	0.5 °K
First quench 4.5 °K	3700 A (4.0 T)
Highest quench 4.2°K Bore B(0,0)	4.54 T
Highest quench 4.2°K Peak	4.80 T

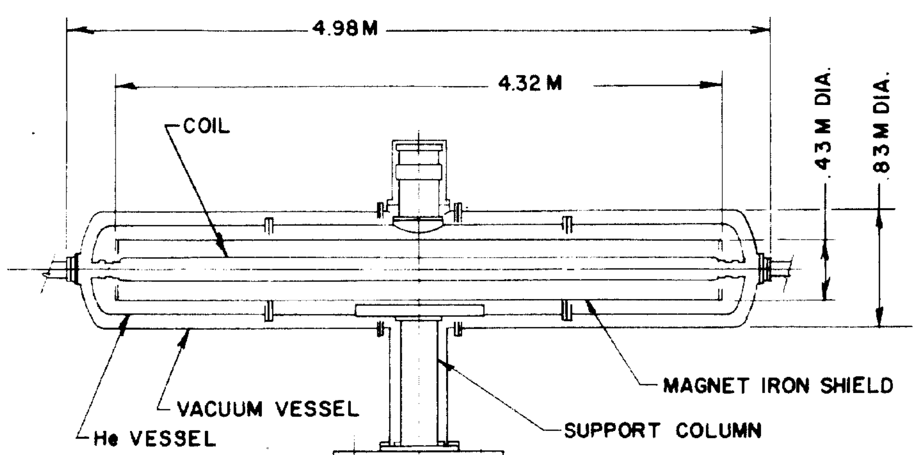

Fig. 5. The ISA size 4.25-meter magnet and dewar assembly.

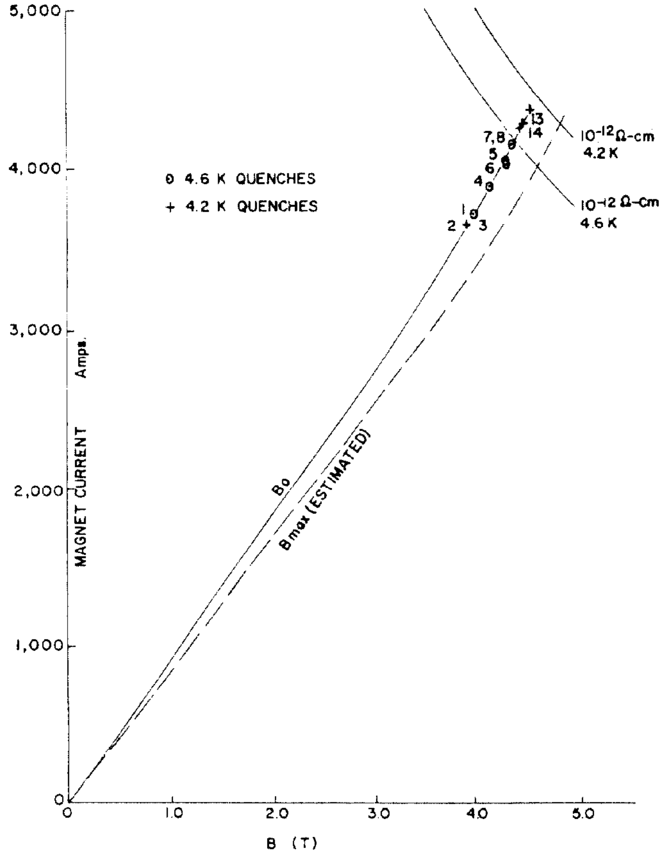

Fig. 6. This is a graph (I vs B) in which the load line of ISA IV is plotted with quench points indicated. The curves for the 10^{-12} Ω-cm equivalent resistivity for the wire used in the magnet are included as well.

Objectives for 4.25-Meter Magnet

The operational characteristics of the magnet, both cryogenic and magnetic, will be investigated. The mechanical stability and tolerances are probably the most interesting aspects to be studied in this coil. The 4.25-meter magnet should become operational in July 1975.

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