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ISABELLE FULL-SCALE DIPOLES*

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SUMMARY

Data are presented on the various cosine θ type magnet models constructed at BNL in the development of ring magnets for ISABELLE, a pair of intersecting 200 GeV proton accelerating storage rings. The rings are to be filled with 30 GeV protons from the AGS and then accelerated to 200 GeV. The acceleration period is a 120 sec ramp from ~ 0.5 T to 4 T. The two series of magnets for which data are currently available are: a) 8 cm i.d., 1 m long dipoles, and b) 12.05 cm i.d., 4.25 m long full-scale dipoles. There was an earlier series of magnets which were 5 cm i.d. 40 cm long 4 block dipoles. Data on the 5 cm and 8 cm series have been presented previously.[1-5] The effect of mechanical precompression on training was studied by varying the interference fit between the coil (ISA IV) and its iron shield. The results were used to optimize the mechanical design of the full-size magnet models. The paper deals primarily with data obtained from the tests performed on the first full-scale ISABELLE magnet, and their consequences in the design and construction of the next ISA prototype (4.25)-II.

The design parameters of the full-scale model magnet are presented elsewhere.[6] The results obtained from testing the first magnet are summarized below:

1. Accomplishments of the magnet.

   a. The uncorrected harmonics measured in this magnet reflected a mean tolerance of conductor placement of less than 50 microns and were of ISABELLE quality (correctable).

   b. The unallowed harmonics were significantly lower than those observed in previous magnets.

   c. The magnet was wound, assembled and tested in 4 weeks, thus demonstrating the relative simplicity of the construction technique.

   d. The results indicate that with slight modifications the magnets will be capable of dissipating their own stored energy in the event of a failure of the magnet protection system.

   e. The "rate dependence" of the harmonics, i.e. $C(N) = f(\dot{B})$ was greatly reduced relative to the 8 cm dipoles and is of the order needed for ISABELLE.

2. The shortcomings of the magnet.

   a. The peak field reached after 13 quenches was 3.6 T instead of the 4.0 T design field.

   b. The quench velocity in the pole region was too slow resulting in undesirable heating of some turns during quenching.

   c. The leads were poorly arranged and were magnetically unstable.

INTRODUCTION

This paper describes the design, construction, and testing of a full-scale ISA 4.25 m long 12.05 cm i.d. dipole. Data on the effect of mechanical constraints on training, obtained with smaller magnets is also included.

The Design Calculations and Results of the Full-Scale ISABELLE Magnet

The operational characteristics and harmonic content in two dimensions of the 4.25 m long dipole were calculated and are compared with the magnet performance. The design and operational characteristics may be subdivided as follows.

A. Infinite μ Two-Dimensional Design ($B_{meas} < 2.0$ T)

The turns distribution per coil quadrant consisted of 80 turns distributed in 6 blocks, each block containing 19, 18, 16, 13, 9 and 5 turns respectively from midplane to pole. Spaces in the block not occupied by conductors were filled with "310" stainless steel braid. Each turn was 0.762 mm thick and 1.7 cm wide and the midpoint of the conductor base was located on a 12.051 cm diameter circle. The magnet infinite μ load line was calculated by MAGFLD[7] to be 12.437 G/A at 4.2 K (3216 A → 4.0 T). The solid line in Fig. 1 is a plot of the infinite μ load line. All of the data points that were taken with ISA (4.25)-I lie on this line. In fact, there is very little indication that the magnet is off the infinite μ load line at 3.5 T.

B. Finite μ Calculations and Results

The finite μ case as calculated by GFUN[8] using a low temperature μ table for low carbon steel predicts 3380 A per turn would be required for 4.0 T (it is plotted with a dashed line on Fig. 1). This prediction may be pessimistic in light of the data taken on ISA (4.25)-I; it appears that 3300 A would be more accurate. The magnet was designed at low field ≤ 3.0 T to have the field constant to 0.1% inside a circle 10.1 cm in diameter (85% of the aperture). The measured field was constant to within 0.1% inside a circle 9.4 cm in diameter (78%) up to 3.4 T. A 25 micron systematic displacement of the coil with respect to the iron shield would result in $C(2) = 1.5 \times 10^{-3}$, and as shown in Table I the observed errors were about 1/3 this value.

If the C(N)'s from Table I are used at a 4.0 T central field, the sextupole component of the field on a 4 cm radius circle is 289 G or 0.5%, and the decapole term is 51.7 G or 0.1%.

C. Quench Characteristics

The quench properties of the magnet ISA (4.25)-I were investigated using the Rutherford Quench Code[9] and measured thermal conductivity data.[10] Initial calculations assumed that the quench was initiated in the high current density region (see Fig. 2) at the high field point. The first few observed quenches, however, seemed to start in the leads, therefore, the quench was initiated at the midplane. The calculations give a maximum coil temperature of 75 K for the high field point initiation and 50 K for the midplane initiation. However, the last few quenches or possibly only the last quench was initiated in the low current density region due to cracking of the 'Mikroy'† post piece. After careful checking of the coil data and then returning to the computer model, it was found that the magnet quenches in the longitudinal direction (along the current path) and

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

†Glass-mica.

not azimuthal (turn to turn, as is the case in the high current density sections) if the quench originates in a turn next to the pole. The reason for this difference, is the extra layersof insulation that the heat must travel through (the inert turns) to reach the next active turn causing a reduction of 10^6 in the ratio of azimuthal to longitudinal heat flow. The quench code revealed a possible temperature of ≥ 1000 K in the worst case. The actual temperature reached during quench is estimated to be between 400 K and 500 K, which was verified with subsequent coil data. Although the coil was electrically sound such high temperatures are clearly to be avoided. The remedy for such an undesirable characteristic is simple, and consists of metallurgically bonding the spacer to the active turns, therefore eliminating the additional thermal barriers. The two different winding arrangements are shown in Fig. 3. This shunt arrangement lowers the power density by an order of magnitude and reduces the layers of insulation to one, thus increasing the rate of heat flow azimuthally in this block by a factor of 10^4.

Construction of the ISA (4.25 m)-I Prototype

The construction parameters of the ISA (4.25 m)-I are given in great detail in reference 6. Figures 4 through 7 are photographs of the magnet at various stages of construction and assembly. The only two important material changes made for ISA (4.25)-II are replacement of the Mykroy post with molded XD 580* posts, thereby removing the large mismatch in shrinkage coefficients between the conductor and the post which caused the cracking mentioned previously. Copper braid inert turns are used in place of stainless steel to improve the shunting capabilities. The number of clamping bands on the iron shield has been doubled to ensure a more uniform loading of the coil structure.

Research and Development Magnets

ISA IV is a magnet (8 cm i.d., 1 m long) that utilizes the same basic strand Cu-NbTi composite, but not the same braid configuration (23% lower packing). The magnet's performance is well defined from 4.2 K to 4.6 K. At the present time the 8 cm i.d. 1 m long dipoles have a coil iron shield interferance fit criterion which has resulted in magnets that train less than 5 → 10%, normally starting at the equivalent strand resistance $\rho_{eq} = 10^{-12}$ Ω-cm for the 1st quench. This interference is a sufficient condition for the metal-filled coils but probably not necessary (interference load too high).

In order to determine the minimum necessary interference fit required to inhibit training in the full-scale magnets a series of tests were performed using different degrees of compressive force on one of the smaller models (ISA IV 8 cm bore 1 m length). This was accomplished by grinding the fiberglass bands on the outside of the magnet in successive steps to give different effective interference fits at low temperature. In addition, the bore of the iron shield was "honed" to a smooth finish to more uniformly load and to more accurately specify the true interference fit. In Table II the parameters used, are listed and the effect on the magnet performance given as the ratio of the current achieved to the short sample potential of the strands ρ_{eq} 10^{-12} Ω-cm measured along the load line. It is clear from Table II that the coil must be loaded to minimize training. Apparently the more uniform loading of a honed bore results in better performance for the same degree of interference. (See Fig. 8.)

As of the last test of the ISA IV it is possible to say that a residual interference load of 0.165 mm at helium temperature is sufficient to inhibit training, but may still be higher than necessary.

Future Magnets

ISA V should be ready for testing shortly. ISA V is an 8.5 cm i.d. magnet which is 94 cm long and uses an unfilled version of the ISA (4.25)-I & II conductor. The ISA (4.25)-I braided conductor is filled with In(Pb). ISA V is an experiment to see how fast a wide braid conductor can be pulsed before the C(3) term has a time dependent component of the same order of magnitude as the dc term. ISA (4.25)-II is a revised version of the ISA (4.25)-I that incorporates the design changes needed for acceptable performance and contains a 3θ correction coil to enable a system study on correction tracking. Data from the ends should enable an end correction system to be modeled.

Acknowledgments

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References

1. W.B. Sampson, P.F. Dahl, A.D. McInturff, and G.H. Morgan. "Magnetic Measurements of Superconducting Synchrotron Magnets." Proc. 4th Intern. Conf. on Magnet Technology, Brookhaven, 1972, 752.

2. W.B. Sampson, R.B. Britton, P.F. Dahl, A.D. McInturff, G.H. Morgan, and K.E. Robins, Particle Accelerators I, 173 (1970).

3. W.B. Sampson, P.F. Dahl, A.D. McInturff, and K.E. Robins, IEEE Trans. Nucl. Sci. NS-18, No. 3, 584, (1971).

4. P.F. Dahl, R. Damm, D.D. Jacobus, C. Lasky, A.D. McInturff, G.H. Morgan, G. Parzen, and W.B. Sampson, IEEE Trans. Nucl. Sci. NS-20, No. 3, 688 (1973).

5. W.B. Sampson, P.F. Dahl, A.D. McInturff, K.E. Robins, IXth Intern. Conf. High Energy Accelerators SLAC, Stanford, California, Calif. 1974, CONF 740522, 170.

6. A.D. McInturff, P.F. Dahl, R. Damm, C. Lasky, K.E. Robins and W.B. Sampson, IEEE Trans. Nucl. Sci. NS-22, No. 3, 1133 (1975).

7. G.H. Morgan, "MAGFLD - A Computer Program for a 2-Dimensional Magnetic Field for a Rectangular Current Block." BNL Informal Rept. AADD 145 (1968); "Optimization of 2-D Magnet Shapes Using MAGFLD." BNL Informal Rept. AADD 145-A (1969); "MAGFLD with Iron." BNL Informal Rept. AADD 145-B (1970).

8. M.J. Newman, C.W. Trowbridge, L.R. Turner, Proc. 4th Intern. Conf. 4th Intern. Conf. on Magnet Technology, Brookhaven 1972, 617; M.J. Newman, J. Simkin, C.W. Trowbridge, L.R. Turner, "'GFUN' User's Guide. A Users Guide to Interactive Graphics Program for Computer Design of Magnets."Rutherford

*filled epoxy.

Lab Rept. RHEL/R244 (1973).

9. M.N. Wilson, "Computer Simulation of the Quenching of a Superconducting Magnet." Rutherford Lab. Rept. RHEL/M151 (1968); Modified by M.J. Newman to calculate propagation speed for various different material parameters.

10. B. DeVito and J.E. Jensen, "Thermal Conductivity of Braided Superconductor Systems." BNL Informal Rept. CRISP 71-11 (1971).

TABLE I

$C(N) \times 10^4$

Field quality calculated and measured for an uncorrected ISA (4.25 m)-I dipole magnet (12.051 cm i.d., 4.27 cm long)

$$\frac{B(R_1\theta)}{B(0_1 0)} = C(N) \left[\frac{R}{R(\text{inside radius of coil})}\right]^{N-1} \cos(N\theta)$$

$R_{IR} = 6.0025$ cm

$B(0_1 0)$/Tesla	Random Error Cal.	0.622 Meas.	0.622 Cal.	1.244 Meas.	1.244 Cal.	1.865 Meas.	1.865 Cal.	2.486 Meas.	2.486 Cal.	3.108 Meas.	3.108 Cal.	3.4 Meas.	3.4 Cal.	4.0 Meas.	4.0 Cal.
C(2)	3.3	5.4	---	5.4	---	5.4	---	5.4	---	5.4	---	5.4	---	---	---
C(3)	3.6	-16.6	0.06	-16.5	0.14	-16.0	0.6	-16.6	7.0	- 5.0	42.0	16.0	71.0	---	167
C(4)	4.75	2.16	---	2.16	---	2.16	---	2.16	---	2.16	---	---	---	---	---
C(5)	5.2	- 5.2	-0.02	- 5.2	-0.02	- 5.2	-3	- 5.2	-4.8	---	-36.4	---	-61.9	---	- 69
C(7)	-4.7	-19.6	-4.7	-19.6	-4.7	-19.6	-4.7	-19.6	-4.7	-19.6	- 4.7	-19.6	- 4.7	---	-4.7
C(9)	-1.68	-33.7	-3.37	-33.7	-3.37	-33.7	-3.37	-33.7	-3.37	-33.7	- 3.37	---	---	---	---

TABLE II

Interference Loads for Cosine θ Magnets
Training Results

Magnet Designation diam(i.d.); length	o.d. (Band Incl.) (cm)	Room Temp. Interference (mm)	$\int_{room}^{4.2} \frac{\Delta L}{L}_{mag} - \frac{\Delta L}{L}_{Fe\ Shield}$	4.2 K Interference (mm)	Training Behavior*	Ultimate Performance (%)
I & II	12.738	0.381	1.2×10^{-3} (not honed)	0.229 ± 0.127		100
(a) IV 8 cm; 94 cm	12.738	0.381	1.1×10^{-3} (not honed)	0.241 ± 0.127	93% → 5 → 105	105
(b) IV 8 cm; 94 cm	12.738	0.381	$3.1 \rightarrow 2.9 \times 10^{-3}$ difference glass to epoxy ratio band (not honed)	0.000 ± 0.127	78% → 5 → 105	105
(c) IV 8 cm; 94 cm	12.791	0.381	1.1×10^{-3} honed bore	0.241 ± 0.0254	105 → 105	105
(d) IV 8 cm; 94 cm	12.784	0.305	1.1×10^{-3} honed	0.165 ± 0.0254	100 → 101†	101

*1st quench. % of potential load line intercept with short sample strand characteristics ($\rho_{eq} = 10^{-12}$ Ω-cm).

†This was done at a lower temperature, therefore, requiring a higher field.

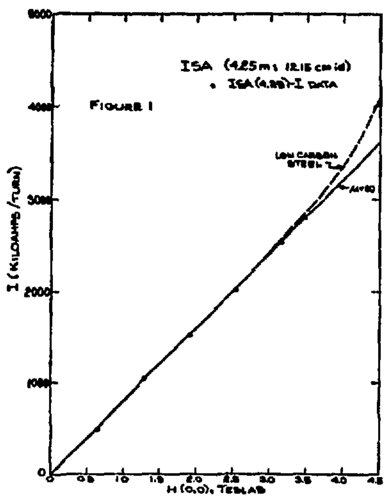

Fig. 1. ISA (4.25)'s current per turn vs central magnetic field.

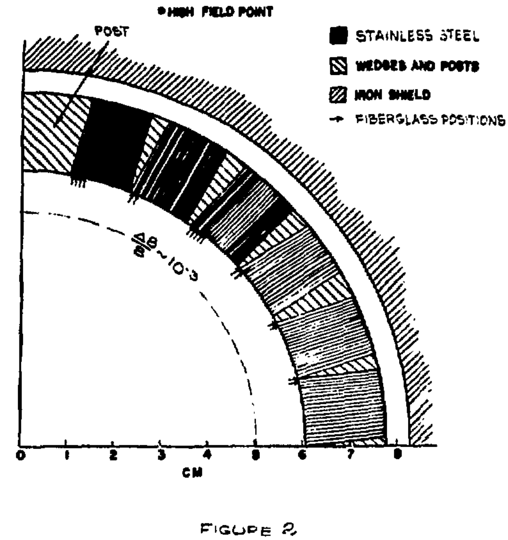

Fig. 2. The quadrant turn distribution in the ISA (4.25)-I.

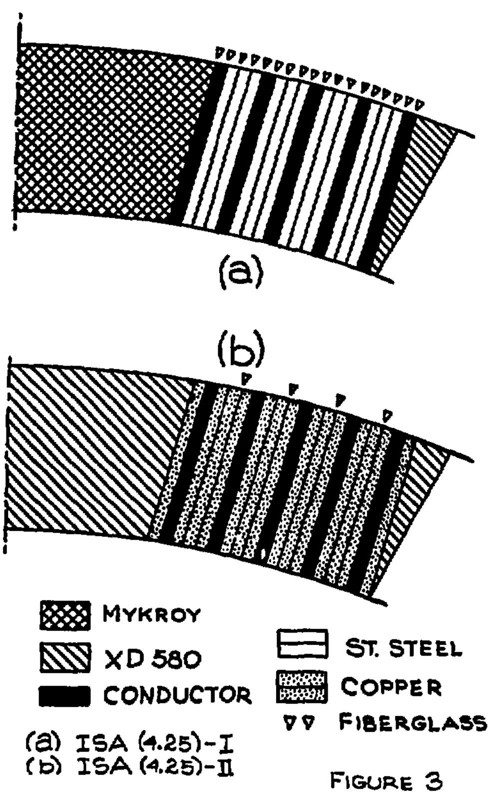

Fig. 3. The turn distribution in the 1st block for both ISA (4.25)-I and ISA (4.25)-II.

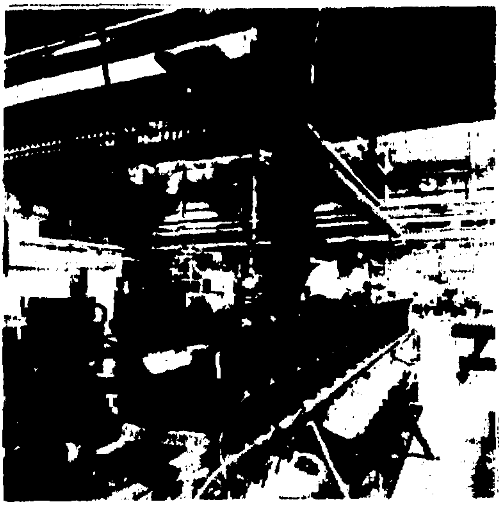

Fig. 4. The ISA (4.25) winding fixture with one of the ISA (4.25)-I's poles overhead.

Fig. 5. The assembly of ISA (4.25)-I on the bore tube.

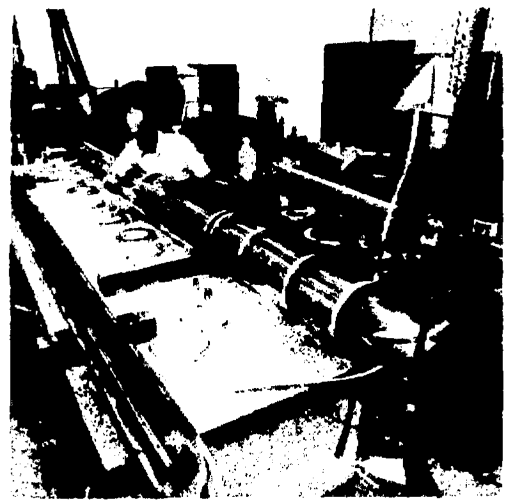

Fig. 6. ISA (4.25)-I being clamped prior to banding.

Fig. 7. ISA (4.25)-I installed in the center spool of the dewar being electrically wired.

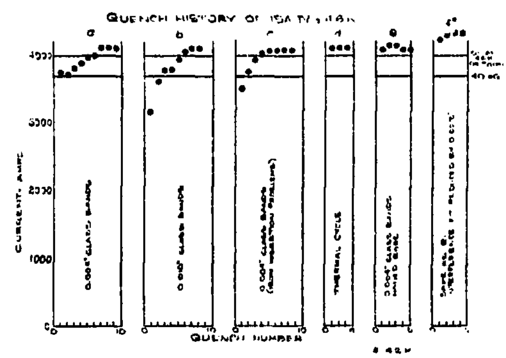

Fig. 8. Quench history of ISA IV.