STUDY OF FACTORS WHICH AFFECT TRAINING IN ISABELLE R&D MAGNETS*

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Summary

Five R&D dipole magnets have been assembled with different levels of tangential prestress applied to the windings. Four magnets have trained beyond the ISABELLE 5T operating field. Three have trained to the short sample limit of the superconducting braid. The two magnets with the highest level of tangential prestress required the fewest training quenches to reach 5T. The training history of these R&D magnets is better than that of the eleven industrial magnets. Two of the industrial magnets were trained beyond 4.5T; the others reached fields in the range 3.8T to 4.2T. The industrial magnets had generally lower levels of prestress than the R&D magnets and differed in other important respects as well. These changes were designed to reduce the heat generated by conductor motion due to Lorentz forces. Construction of magnets with the present design has eliminated the largest part of the training quenches seen in the industrial series of magnets.

Introduction

The ISABELLE design calls for 720 dipole magnets with an operating field of 5T, an effective length of 4.75 m, and a field accuracy $\Delta B/B = 1.7 \times 10^{-4}$ over the $\pm$ 3 cm good field region. The coil configuration for the ISABELLE dipole magnets is a single layer six-block approximation to a cosine current distribution, wound from a high aspect ratio (0.61 mm x 1.64 mm) non-keystoned braided conductor (Fig. 1). The current density variation is obtained by an appropriate distribution of non-superconducting turns made from braided copper or copper-nickel wire. The magnets are to be self-protecting, have adequate electrical insulation and train to the operating field quickly. The effects of eddy currents on field shape and ramp rate are to be acceptably small. The initial focus of the renewed ISABELLE magnet R&D program has been on peak field and training; results of this work are reported here. Much work is also under way to insure that the other requirements, particularly those related to eddy current effects, will be met.

The magnets reported here were built to test the hypothesis that a principal cause of the slow training behavior seen in the series of industrial coils was heat generated by inelastic motion of the conductor under the action of the Lorentz force produced by current in the magnet.[1] The forces of the two-dimensional cross section of the coil have been calculated at BNL and at MIT, with consistent results. The average force on each of the current blocks is shown in Fig. 1. The radial force on each block is outward. It is transmitted to the iron core, which has an outer radius of 22.9 cm and which absorbs the load with negligible deformation. The tangential forces, which are listed in Table I, press each of the conductor blocks toward the midplane. These foces are additive, reaching a maximum of about 57 MPa (8200 psi) on the conductor block nearest the midplane.

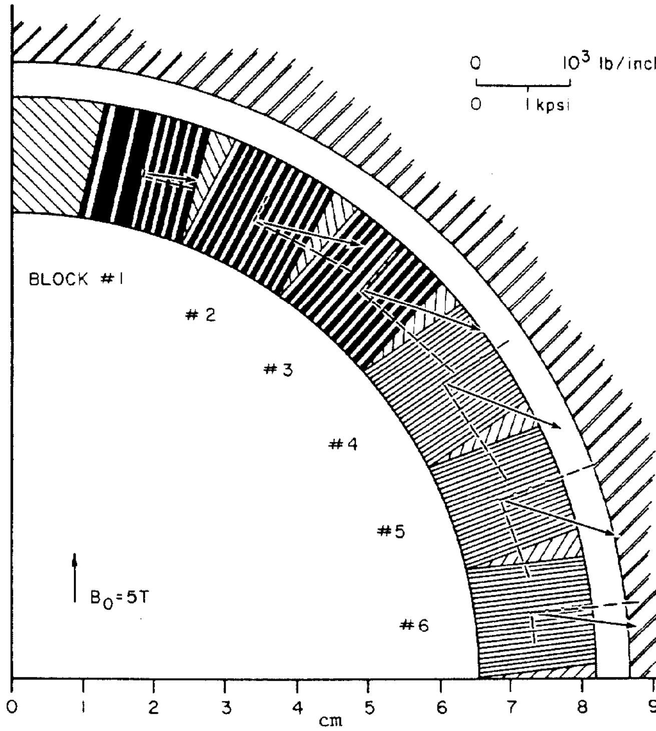

Fig. 1. Cross section of half a dipole coil. Lorentz forces at 5.0T central field are shown for each coil block. Non-superconducting spacer turns are shown in black.

TABLE I
Lorentz Force and Coil Motion for a Central Field of 5T. (Block #6 is nearest to the midplane.)

Block #	Tangential Force(psi)	Cumulative Tangential Force(psi)	Coil motion (0.001 inch) without prestress	with 4000 psi prestress
1	871	871	9.0	0.7
2	1743	2614	8.7	1.8
3	1988	4602	7.7	2.4
4	1808	6410	6.1	2.3
5	1333	7743	3.9	1.6
6	462	8205	1.4	0.6

The motion of the conductor blocks under the action of the Lorentz force is also given in Table I. (For this calculation, the elastic modulus was 2 x 10^6 psi, or 14 GPa a typical value.[2]) If the coils are not under tangential compression, conductor blocks #1-3 move the farthest and a gap is left between the center post and the conductor if the tensile strength of the epoxy bond is exceeded. A number of magnets in the industrial series had quenches predominantly in the blocks near the center post, where the conductor motion is largest. In one

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R&D magnet built about the same time, MK XVI, the quenches originated in the conductor nearest the center post. These observations support the hypothesis that conductor motion, the breaking of epoxy bonds, and training are related.

Construction of R&D Magnets

For the current R&D magnets, the design aimed at the reduction of coil motion and the reduction of heat generated at the superconductor by such motion. These changes may be grouped into three classes.

(1) The conductor motion was reduced by compressing the coils in the tangential direction when they were inserted into the iron core. Great emphasis has been placed on controlling the amount of tangential stress imposed through a radial interference between the coils and iron. The interference is obtained by making the coil bands larger than the iron core and then cooling the banded coils to 77K for insertion into the iron. A reference value is 28 MPa (4000 psi), the prestress necessary to prevent the conductor from separating from the center post under the action of the maximum Lorentz force at 5.0T (Table I). This amount of tangential stress also reduces the maximum conductor motion by a factor of three.

The industrial series of coils were assembled with very little or no prestress. For two magnets reported here (Mark 23 and Mark 25), the coils were banded with epoxy-fiberglass and inserted into the iron core with a tangential prestress of approximately 3.5 MPa (500 psi). For the other three magnets aluminum bands were used to compress the coils prior to the insertion of the coils into the iron core. With these bands a tangential prestress of 21 MPa - 28 MPa (3000 psi - 4000 psi) was obtained.

Before banding with fiberglass-epoxy or aluminum, the coils are compressed several times with metal clamps. This procedure has been adopted because the coils exhibit inelastic behavior during their first compression cycle. If they were not subjected to this procedure, the tangential compression obtainable with a fixed radial interference fit would be lower.[2]

The coils are assembled on a bore which comes into contact with the coils only at the ends. This prevents the coils from transmitting the radial compression to the bore tube and reducing the tangential compression.

(2) In order to reduce the heat generated by the remaining coil motion, there is no bond between the center post and the conductor. Also, when the coils are banded together with epoxy-fiberglass bands, mylar is placed under the bands so that the bands do not bond to the coils.

(3) In order to increase the stability of the blocks nearest the center post against quenches, copper spacer turns, instead of copper-nickel spacer turns, have been used. Also, the turn nearest the center post is copper, instead of superconductor.[3] Additional modifications to the industrial design, unrelated to our present study, have also been made. The number of superconducting turns was increased from 92 to 96. Other changes are reported elsewhere.[4]

Performance of R&D Magnets

The training of four magnets is shown in Fig. 2 and Fig. 3.[5] For comparison, the performance range of three of the industrial magnets is also shown. The results for the five new magnets are presented in Table II.

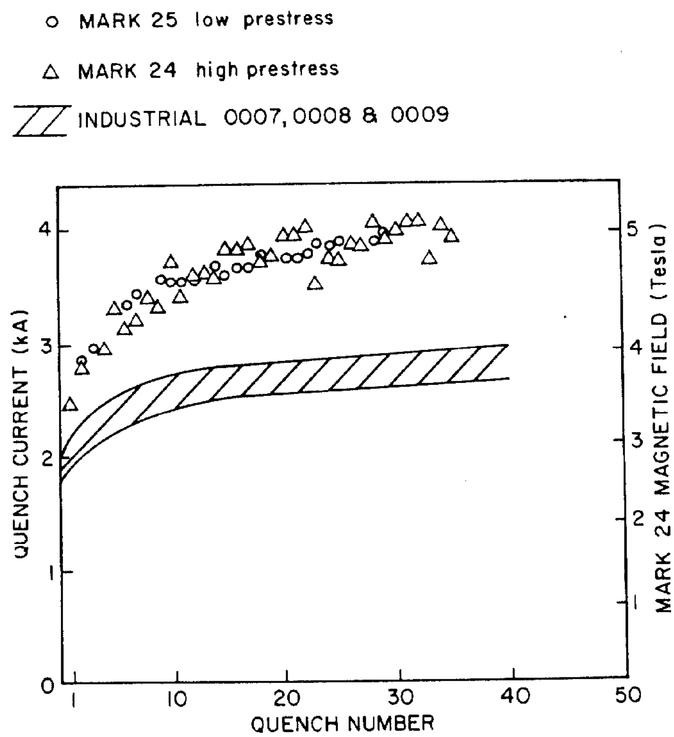

Fig. 2. Quench current and magnetic field versus quench number for magnets with 42 cm diameter cores. (For fields above 4T, the transfer function, $B/\dot{I}$, is about 3% lower for Mark 25 than for Mark 24.)

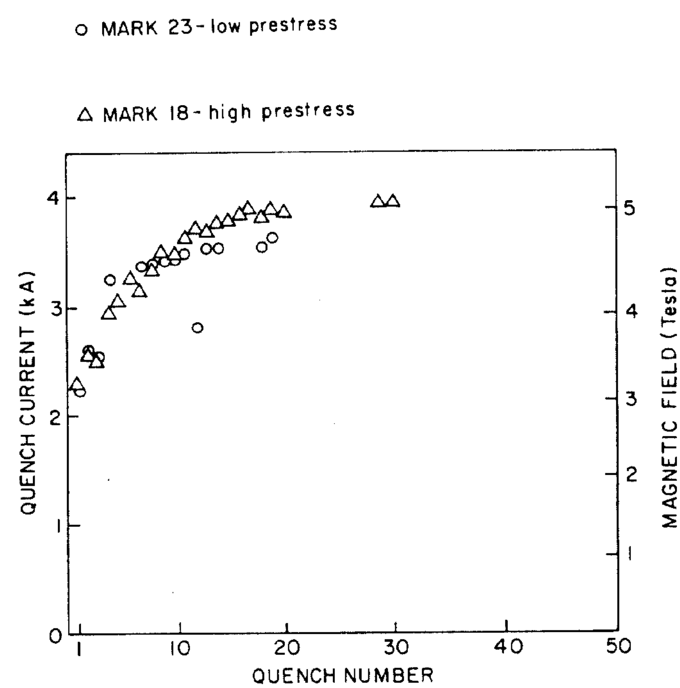

Fig. 3. Quench current and magnetic field versus quench number for magnets with 46 cm diameter iron cores. (The ISABELLE design calls for 46 cm cores.)

TABLE II
Characteristics and training of R&D dipoles tested in Tangential Prestress Experiment.

(The magnets were tested at 4.5K in liquid helium.
ISABELLE operation will be at 3.8K with super-critical forced flow.)

Magnet	Tangential Prestress	Training	I_{max} (kA)	B_{max} (T)	(4.5K) I_{ss} (kA)*	(4.5K) I/I_{ss} *
MK 23	≈ 3.5 MPa (≈ 500 psi)	4.8T in 17 quenches; 5T in 34 additional quenches after rebanding**	3.90	5.02	3.93	0.99
MK 25	≈ 3.5 MPa (≈ 500 psi)	4.9T in 29 quenches; 5T in 10 additional quenches after thermal cycle	4.21	5.12	4.08	1.03§
MK 18	23±5 MPa (3400±700 psi)	5T in 16 quenches	4.08	5.19	3.87	1.05§
MK 24	28±6 MPa (4000±800 psi)	5T in 20 quenches	4.15	5.18	3.97	1.05§
MK 31	23+4/-8 MPa (3400+500/-1200 psi)	4.8T in 28 quenches	3.67	4.83	3.84	0.96

* The short sample limit of the magnet is calculated from measurements of the braid in a constant 5T field oriented normal to the wide surface, extrapolated to the magnet load line.

** The training after rebanding reproduced all but the first three quenches of the original training curve.

§ The performance of these magnets at the short-sample limit of the conductor was verified by raising the helium temperatures and observing the reduction in quench current. The random error in the calculation of the short-sample limit is ≈1%. The observed values indicate the systematic accuracy of the present method of prediction.

Four R&D magnets achieved 5T and performed better than any of the industrial series of magnets. Three trained to the short-sample limit of the superconductor. Comparison of the two low-prestress magnets with the first two high-prestress magnets is complicated somewhat by the different sizes of the iron cores; the magnets with the larger cores require 100A less to reach 5T. Nonetheless, the following conclusions emerge. Each of the four magnets first quenches at a current near 2.3 kA, trains rapidly for about 7 quenches, and then trains more slowly. Beyond this point there is a difference in the performance of the high prestress and the low prestress magnets, with the high prestress magnets attaining about 200A more at the same quench number. Because of the slow rate of training, this 5% difference in current allows the high prestress magnets to reach 5T in about half to two-thirds the number of quenchs required by the low prestress magnets.

Two of the magnets have absorbed their own stored energy. The others have not yet been tested for self protection. However, computer simulation of quenches, based on data derived from tests of the magnets, indicate that all magnets in this series are self-protecting. Magnet suitable for ISABELLE will use braid with a higher interstrand resistivity (to reduce eddy current effects) and have a different winding sequence (for correct field shape). These changes are expected to increase quench propagation time and it will be necessary to test self-protection in these new magnets. The first test of a dipole wound with high resistance braid is expected to take place this month. (A quadrupole constructed with this braid has recently been tested and found to have substantially lower eddy currents.[6])

Several problems associated with training still remain to be solved. A few quenchs in the magnets occur at currents several hundred amps below the currents of preceeding or subsequent quenches. The first quench after a thermal cycle is at a current several hundred amps below the current of the last quench before the thermal cycle. A third aluminum-banded magnet, MK 31, has been recently tested.[7] It trained only to 4.8T, below the short-sample limit of the braid. We are currently analyzing data from this magnet.

Three R&D quadrupoles have been made and tested. All three reached the required gradient of 0.61 T/cm.

References

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