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UPGRADED COIL CONFIGURATION FOR ISABELLE MAGNETS

H. Hahn, P.F. Dahl, J.E. Kaugerts, and A.G. Prodell

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Abstract - Achievement of the design field of 5 T in the ISABELLE dipole magnets is turning out to be more arduous than expected and several avenues of improvement are being pursued. One possibility for improving training and peak field performance is discussed in this paper. It has been recognized that the inert spacers with their adjacent active turns in the cosine magnet windings can be replaced by a double thickness braid operating at approximately half-current density in 46 of the 190 turns. Since the high-field region occurs in the low current density turns near the poles, a performance improvement can be expected. It has been verified that the proposed coil configuration satisfies the field requirements and details thereof are given. Results from an experimental magnet in which superconducting spacer turns are used to simulate half-current density windings are presented. Construction of thick braid coils is being planned and the status of these magnets is reviewed.

INTRODUCTION

A proton-proton colliding beam facility ISABELLE is under construction at Brookhaven National Laboratory [1]. The two rings are each almost 4 km in circumference and will require a total of over 1000 superconducting magnets. The dipoles are 4-3/4 m long, have a coil aperture of about 13 cm, and must operate at 5 T in order to achieve the design energy of 400 GeV per ring. The major requirements for the magnets, in addition to operational field strength, can be summarized under acceptable training, static and dynamic field quality, reproducibility from magnet to magnet, ramp losses, self-protection during quenching, absence of electrical shorts, and manufacturability within a limited budget. The development of superconducting dipoles is turning out to be more arduous than expected. Experience with developmental magnets has shown that the above requirements have been met individually on particular magnets; however, they have not as yet been achieved consistently in a series of magnets. The most visible difficulty in the present dipole magnet is the large number of training quenches required to reach design field, although all magnets seem to reach short-sample current if trained long enough. A substantial R&D program has been mounted to develop an adequate understanding of the limitations and to improve the performance of the ISABELLE magnets [2]. In spite of considerable progress which has been made so far it seems advisable to investigate solutions which depart from the original design concepts. In this paper a proposal for improving training and peak field performance of the dipoles involving only substitutional changes is discussed.

UPGRADED COIL CONFIGURATION

The coil configurations for dipole and quadrupole magnets are single layer multiple block approximations to cosine current distributions, wound from a high aspect ratio non-keystoned braided conductor. The azimuthal current density variation is obtained by an appropriate distribution of braided inert spacer turns. The cross section of recent test magnets is shown in Fig. 1. The coil is shrink-fitted into a cold iron core which is assembled from unsplit laminations held in a heavy wall stainless steel tube.

It has been recognized that the spacers with their adjacent active turns can be replaced by a double thickness braid operating at approximately half the current density [3]. Since the high-field region occurs in the low current density turns near the poles, a performance improvement can be expected.

Graded conductor has been used in the past to reduce cost by operating at approximately constant product of current density times local field. The proposed scheme on the contrary has the objective of packing the maximum possible amount of superconductor into a given cross section. In our particular case, about a 28% addition of NbTi in the entire coil is achieved. The cross section of the proposed dipole coil is shown in Fig. 2. The configuration uses a five-block 45 turn per quadrant solution with the upper two blocks containing the 23 double thickness turns [4]. Incorporating a single thick metal wedge between block 3 and 4 satisfies the field shape requirements. It must be emphasized that the overall coil geometry remains unchanged and thus all improvements in assembling and shrink fitting the coils developed for the standard coil will be applicable. While the arguments are developed in this paper for the dipole case, they apply also to the quadrupole although modifications are here less pressing.

The use of thick braid is expected to improve the performance in several ways:

i) The two blocks operating at half-current density will have an increased stability margin against quenching, thus reducing the number of training quenches required. The enthalpy reserve of a thick braid is almost an order of magnitude larger than for the thin braid at equal current and field [5]. Making plausible assumptions on the quench inducing disturbances, one can expect that no training quenches will occur in the thick braid region. In order to obtain an estimate of the likely reduction in training, the quench origin has been located in four recent magnets (MK-18, 23, 24, 25). From Fig. 3 it can be seen that in the average 40% (7 of the first 18) quenches originate in multifilar turns and presumably could be eliminated

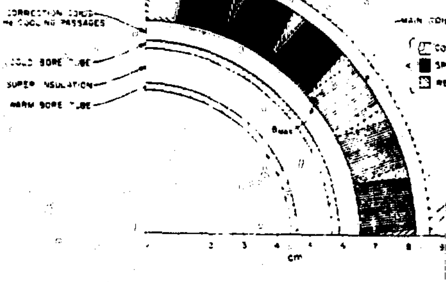

Fig. 1. Cross section of R&D dipoles.

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by adopting the thick braid solution.

ii) The top field performance of a trained magnet is ultimately limited by the short sample characteristics of the braid at the point of highest local magnetic field, B_{max}. Considering the example of the coil in Fig. 2, with bifilar (i.e. thin superconductor plus spacer turns) instead of the thick braid one finds a two-dimensional field enhancement of 7.7% and in the ends 11%. In the proposed solution the limiting field, B'_{max}, occurs in the monofilar turns and the respective values are 2.4% and 6%. It follows that the proposed solution has its short sample performance improved by about 4%.

iii) The field in the braid of the upper blocks near the pole is more or less constant with radius and parallel to the braid, whereas in the lower blocks the field diminishes along the radius and is primarily perpendicular to the braid. The monofilar turns at the location of the limiting field B'_{max} are in a nonuniform field. In fact, the field here changes by about 30% over the braid width which suggests that the local enthalpy reserve and stability against quenching is enhanced. Counteracting this gain is the anisotropy of the critical current in the braid, which is about 10% lower for B perpendicular to the braid (i.e. the usual test condition). It is conceivable that the magnet remains stable in the current-sharing state, but operation in this mode is not recommended.

iv) Incidental to this solution, but nevertheless of considerable practical importance, is the possibility of using preinsulated braid thereby eliminating the need for handwrapping of multifilar turns, and making possible prewinding insulation tests of the full length of conductor.

CONDUCTOR DEVELOPMENT

The upgraded coil configuration requires, in addition to the standard braid, a conductor essentially of twice thickness, that is 1.47 instead of 0.71 mm. It is intended to produce the new conductor in the form of a 59 strand braid with the nominal cross section of 16.5 × 1.5 mm including insulation. A comparison of the braid parameters is given in Table 1.

The development of thick braid has been undertaken in collaboration with industry (AIRCO, Murray Hill, New Jersey) and first test pieces have been produced and used to establish mechanical and electrical properties of thick braid blocks.

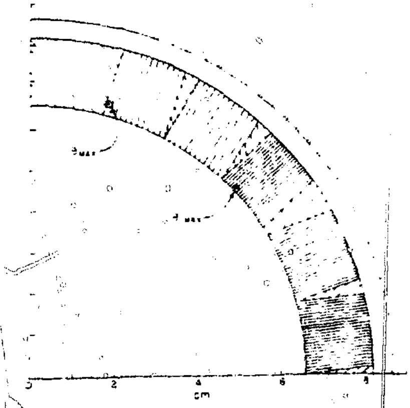

Fig. 2. Cross section of upgraded dipole coil incorporating thick braid.

Table 1. Braid Parameters

	Standard	Thick Braid	unit
Braid dimensions	16.3 × 0.7	16.3 × 1.5	mm²
No. of strands	97	59	
Wire diameter	0.30	0.57	mm
Filament diameter	9	17	μ
No. filaments/wire	500	500	
Ratio matrix/SC	1.5	1.6	
I_c/wire @ 5 T & 4.2 K	55	200	A
I_c/braid @ 5 T & 4.2 K	4.6	12	kA
Transposition length	30	40	cm
Interstrand resistance*	5	0.3	μΩ
Elastic modulus	25	14	GPa

*Filled with staybrite (SnAg) but without high resistance heat treatment.

Parenthetically it should be remarked that it is, of course, possible to increase the matrix/SC ratio somewhat in order to reduce the additional cost incurred from using more superconductor. This would retain the winding simplifications, but may come at the expense of the full stability gain. In the case of quadrupoles such a modified thick braid would certainly be acceptable.

COIL DESIGN CONSIDERATIONS

Whereas it can be expected that the thick braid will lead to an improved training and peak field performance, it is necessary to investigate other aspects entering the coil design, such as quench propagation, magnetization, B-dot effects, insulation, ends, joint of thick/thin braid, etc.

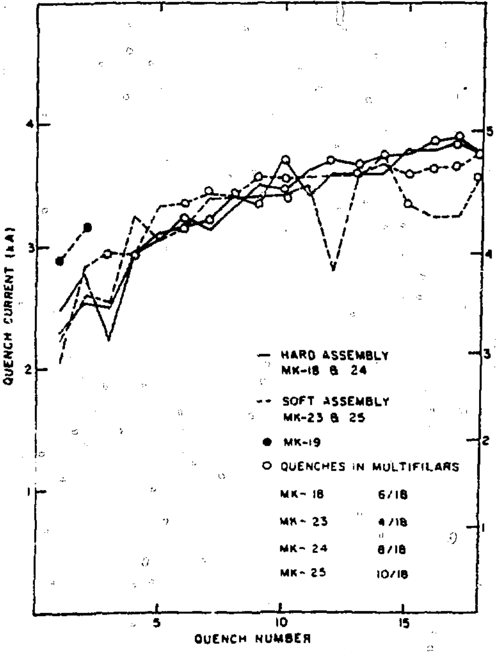

Fig. 3. Training curves of recent test dipoles. Open circles represent quenches originating in multifilar turns.

Of primary concern here is azimuthal quench propagation velocity which, to a large extent, determines magnet self-protection during a quench. The maximum temperature reached in the coil during a quench is related to the $\int I^2 dt$ integral and depends inversely on azimuthal quench velocity. An upper limit on this integral is about 3.5 kA^2 sec in the monofilar turns [5], which in the design according to Fig. 1 is the critical region. The tolerance to heating of a thick braid is larger by a factor of 4 whereas the turn-to-turn azimuthal quench propagation time has been estimated [7] to increase only by a factor 2.8. These scaling arguments indicate that the monofilar turns remain the critical region in the thick braid design of Fig. 2. Experiments on propagation through thick metal wedges indicated that their delay is equivalent to 3 to 4 monofilar turns [8]. Results of more detailed calculations [9] of maximum temperatures in the proposed design are shown in Fig. 4, suggesting that the magnet will be self-protecting during a quench provided that the nominal monofilar turn-to-turn transit time is less than about 2 msec. With proper fabrication techniques this requirement can be satisfied. It has been observed that azimuthal quench propagation depends strongly (up to factor 10 variation) on

- the presence of helium within the winding, i.e. the coil porosity, and
- good contact between turns which is helped by pressure during the coil winding process and assembly.

Eddy currents induced in the superconducting braid while the magnet current is being ramped can produce substantial field distortions and power losses. The total power dissipation per unit length of the dipole is given by [10]

$$P = \frac{n^2 w^2 \ell N}{360} \frac{\dot{B}^2}{R}$$

where n, w, ℓ are number of wires, width and transposition length of braid respectively, R the interstrand resistance, N the total number of turns, and $\dot{B}$ the ramp rate. Induced field harmonics are minimized by an exponential ramp rate, with $\dot{B}/B = 5.4 \times 10^{-3}$ sec^{-1} during the 8 min ramp time from 0.37 to 5 T. Under these conditions, the standard braid exhibits a maximum power loss of 60 W/m, which is unacceptable. Heat treatment and mechanical cracking of braid filler is expected to produce the desired high resistance braid with an order of magnitude increased interstrand resistance [11]. This treatment would also have to be applied to the thick braid. The incremental power loss due to the application of thick braid can be estimated to be

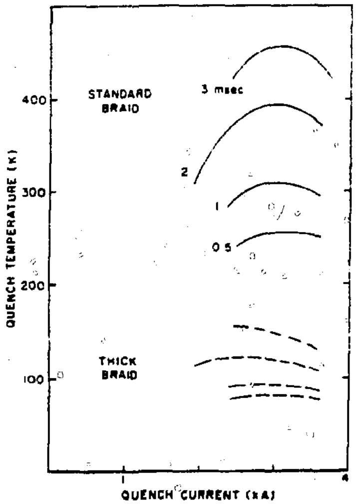

Fig. 4. Calculated maximum temperature during a quench which starts at the pole. Parameter is the nominal turn-to-turn transit time at 3.1 kA.

$$\frac{\Delta P}{P} = W_P \left(\frac{n_{th}^2 \ell_{th} N_{th} R}{n^2 \ell N R_{th}} - 1 \right)$$

where the index "th" refers to the thick braid values and the geometrical weighting factor is given by

$$W_P = \int_{\phi}^{\pi/2} \cos^3\theta \, d\theta \Big/ \int_{0}^{\pi/2} \cos^3\theta \, d\theta = 0.08$$

with $\phi = \arccos (N_{th}/N)$. Using the numbers of Table 1 one finds a 15% increase of the loss. Similar expressions, but with changed weighting factors apply to the induced field harmonic coefficients. We conclude that reducing the interstrand resistance is the prevailing concern, whereas the use of thick braid by itself causes only minimal changes.

Induced SC magnetization currents in the filaments are the cause of power losses and field changes at injection. An upper-limit estimate of the increase in the field coefficients is given by

$$\frac{\Delta b_n}{b_n} = W_n \left(\frac{d_{th}^3 n_{th} I_{th}}{d^3 n I} - 1 \right)$$

where d, n, I are the filament diameter, total number of filaments, and the critical current of the braid respectively. In the worst case, the dipole term, $W_o = 0.35$ neglecting the azimuthal field variation in the coil. One finds that the dipole error due to magnetization increases by less (presumably by much less) than a factor 3, which would seem acceptable. Note that magnetization effects could be reduced by going to more filaments of smaller diameter.

The upgraded coil configuration is substitutional for the standard coil and few changes in fabrication technique are expected. The thick braid will be insulated in the same way as the standard braid with B-stage epoxy-impregnated fiberglass tape 50μm thick. Consideration is given to adding a single 25μm kapton layer if better insulation is judged necessary. The necessary overlap joint between thick and standard braid will be located at one end, and made by routine practice. The higher stiffness of the thick braid requires additional tooling to form the ends, but no serious complication is expected.

TEST MAGNETS

In order to verify the increased stability arguments, two full-size test magnets (MK-19 and 20) were built in which the inert spacers were replaced by superconducting turns. SC spacers were used in earlier short magnets [12] and more recently in Nb_3Sn magnets [13] to increase the current stability of the turns near the pole. The winding scheme for the test magnets is shown in Fig. 3 (with MK-19 being insignificantly different) and the important parameters are listed in Table 2. Both magnets were soft assembled with MK-20 directly comparable to MK-23 and 25. MK-19 in contrast, was assembled like MK-5 (the best performing dipole) with stress relieved fiberglass bands, masking tape between coil and bands, and the bore tube supporting the coil. MK-19 was wound with natural ends, MK-20 with end spacers.

Table 2. Full Size Test Magnets

	MK-19	MK-20	unit
No. of turns	192	192	
Transfer Function	1.423	1.415	T/kA
Built in b_2	- 29	+ 15	$10^{-6}cm^{-2}$
b_4	- 41	6.8	$10^{-7}cm^{-4}$
b_6	- 29	- 44	$10^{-8}cm^{-6}$
b_8	- 1.1	0.34	$10^{-9}cm^{-8}$
Lamination o.d.	43.7	41.9	cm
I_c @ 5 T, 4.2 K	4.25 & 4.35	4.15 & 4.55	kA
Elastic Modulus	10	13	GPa
Prestress Estimate*	4	5	MPa

*Full prestress preventing coil motion at the pole would require about 30 MPa.

The particular arrangement with superconducting inert turns is subject to substantial eddy current effects during ramping and the magnets are effectively dc magnets only. The maximum induced current is, in steady state ramping, estimated to be

$$I_{eddy} = \frac{\pi^2}{8}\frac{w}{\mu_o}\left(\frac{B}{I}\right)\tau\dot{I}$$

with τ the time constant, w the braid width and B/I the transfer function. The observed time constant is on the order of one hour resulting in 800 A induced current in the braid at the ramp rate of 0.01 A/sec. The induced currents are additive to the transport current and the critical current is easily exceeded during ramping. Interchanging active and spacer turns would have resulted in a subtraction of the eddy current and a substantial improvement of performance. The time constant depends quadratically on the spacer turn length; cutting the spacer length would practically eliminate the eddy current effects.

The effectiveness of the superconducting turns in suppressing training quenches depends on the time required to switch the current locally from the active into the superconducting spacer turn (the current diffusivity is about 10^3 m^2/sec). It has been estimated that a minimum propagating zone can be bypassed within a few milliseconds, which may well be marginal at top field. At lower fields quench recovery has been observed.

The test magnet MK-19 underwent about 40 low field quenches at fast ramp rates until the eddy current effect was correctly diagnosed. MK-19 had then its first training quench at 39.8 kG (2.895 kA) and trained in one step to 42.5 kG when ramped at 0.01 A/sec. Training was stopped due to magnet damage caused by a failure of the quench protection circuit. Testing of MK-20 is forthcoming.

A noninductive simulation coil, 50 cm long, was wound with thick braid in order to test training behavior and quench velocities. No training quenches were observed at 5.5 T up to the magnet design current of 4 kA. [8].

CONCLUSION

It is, in our opinion, justified to discount the eddy current quenches observed on MK-19. Under this assumption, its performance would seem to be superior to all other standard dipoles tested recently (Fig. 3). However, it is not possible, without further work, to attribute it to the presence of superconducting spacer turns rather than some other aspects of the magnets, such as the particular asembly technique applied to MK-19. The results are in any case sufficiently encouraging to pursue the thick braid solution with vigor.

Thick braid has been delivered by industry to this laboratory in quantities adequate for construction of a dipole and several quadrupoles. In view of its greater simplicity, the construction of a full size quadrupole, 1.5 m long, is under consideration (Fig. 5). The primary purpose of this test magnet is to gain fabrication experience and to verify the training behavior of magnets containing thick braid. It is expected that this first step will lead to the construction of full-size dipole magnets.

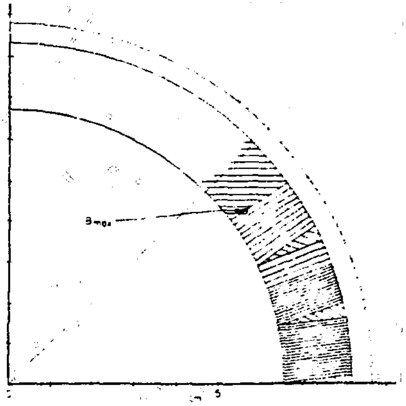

Fig. 5. Cross section of thick braid quadrupole.

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REFERENCES

[1] H. Hahn, IEEE Trans. MAG-17, 702 (1981).
[2] E.J. Bleser, "Construction of Superconducting Magnets at Brookhaven National Laboratory" these proceedings.
[3] H. Hahn, "A Semiflexible Coil with Graded Current Density for ISABELLE Magnets", to be published in Proc. Superconducting Magnet Workshop, Brookhaven (1980)
[4] P.F. Dahl and H. Hahn, IEEE Trans. MAG-17, 168 (1981).
[5] S.L. Wipf, "Stability and Degradation of Superconducting Current-Carrying Devices", Los Alamos Scientific Report, LA7275 (unpublished 1978).
[6] M. Garber and W.B. Sampson, IEEE Trans. MAG-17, 77 (1981).
[7] J.D. Jackson, "Theory of Transverse Quench Propagation", ISABELLE Technical Note 234 (unpublished 1980).
[8] W.B. Sampson, private communication (1981).
[9] A.J. Stevens, private communication (1981).
[10] E.D. Courant, "Eddy Currents in Superconducting Braid", ISABELLE Technical Note 168 (unpublished 1980).
[11] T. Luhman, "Metallurgical Characterization of NbTi Braid", ISABELLE Technical Note No. 274 (unpublished 1980).
[12] W.B. Sampson, P.F. Dahl, A.D. McInturff, G.H. Morgan, Proc. 4th Intern. Conf. Magnet Technology, Brookhaven 1972 (NTIS Springfield, VA) p. 752.
[13] W.B. Sampson, S. Kiss, K.E. Robins, A.D. McInturff, IEEE Trans. MAG-15, 117 (1979).

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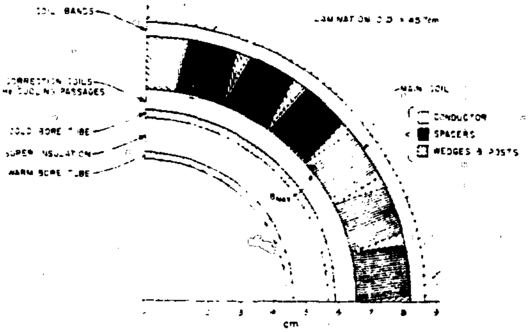

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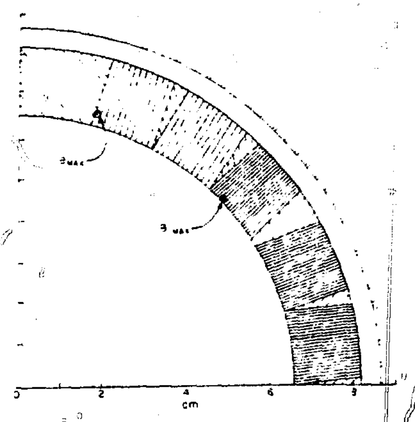

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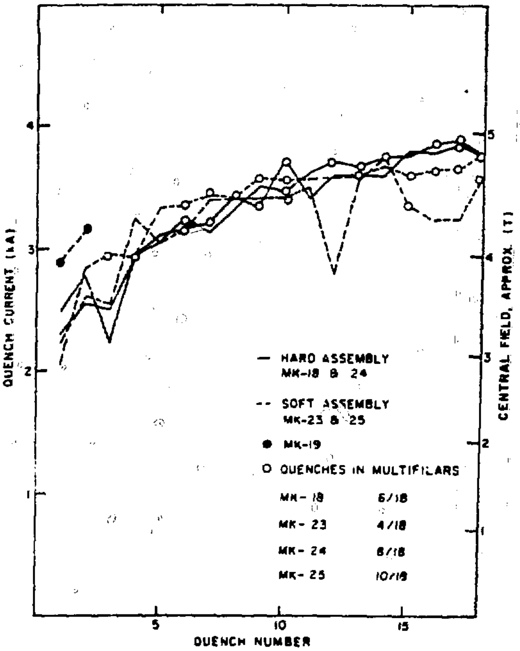

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- the presence of helium within the winding, i.e. the coil porosity, and
- good contact between turns which is helped by pressure during the coil winding process and assembly.

Eddy currents induced in the superconducting braid while the magnet current is being ramped can produce substantial field distortions and power losses. The total power dissipation per unit length of the dipole is given by [10]

$$P = \frac{n^2 w^2 \ell N}{360} \frac{\dot{B}^2}{R}$$

where n, w, ℓ are number of wires, width and transposition length of braid respectively, R the interstrand resistance, N the total number of turns, and $\dot{B}$ the ramp rate. Induced field harmonics are minimized by an exponential ramp rate, with $\dot{B}/B = 5.4 \times 10^{-3}$ sec^{-1} during the 8 min ramp time from 0.37 to 5 T. Under these conditions, the standard braid exhibits a maximum power loss of 60 W/m, which is unacceptable. Heat treatment and mechanical cracking of braid filler is expected to produce the desired high resistance braid with an order of magnitude increased interstrand resistance [11]. This treatment would also have to be applied to the thick braid. The incremental power loss due to the application of thick braid can be estimated to be

$$\frac{\Delta P}{P} = W_P \left(\frac{n_{th}^2 \ell_{th} N_{th} R}{n^2 \ell N R_{th}} - 1 \right)$$

where the index "th" refers to the thick braid values and the geometrical weighting factor is given by

$$W_P = \int_{\beta}^{\pi/2} \cos^3\theta \, d\theta \Big/ \int_0^{\pi/2} \cos^3\theta \, d\theta = 0.08$$

with β = arc cos (N_{th}/N). Using the numbers of Table 1 one finds a 15% increase of the loss. Similar expressions, but with changed weighting factors apply to the induced field harmonic coefficients. We conclude that reducing the interstrand resistance is the prevailing concern, whereas the use of thick braid by itself causes only minimal changes.

Induced SC magnetization currents in the filaments are the cause of power losses and field changes at injection. An upper-limit estimate of the increase in the field coefficients is given by

$$\frac{\Delta b_n}{b_n} = W_n \left(\frac{d_{th}^3 n_{th} I_{th}}{d^3 n I} - 1 \right)$$

where d, n, I are the filament diameter, total number of filaments, and the critical current of the braid respectively. In the worst case, the dipole term, $W = 0.35$ neglecting the azimuthal field variation in the coil. One finds that the dipole error due to magnetization increases by less (presumably by much less) than a factor 3, which would seem acceptable. Note that magnetization effects could be reduced by going to more filaments of smaller diameter.

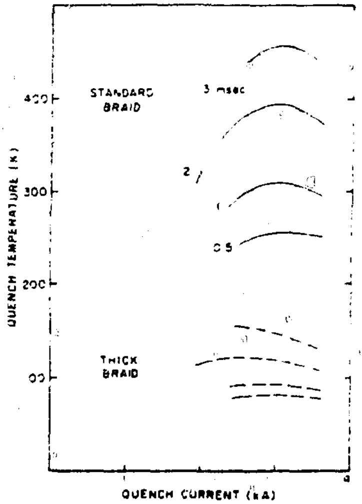

Fig. 4. Calculated maximum temperature during a quench which starts at the pole. Parameter is the nominal turn-to-turn transit time at 3.1 kA.

The upgraded coil configuration is substitutional for the standard coil and few changes in fabrication technique are expected. The thick braid will be insulated in the same way as the standard braid with B-stage epoxy-impregnated fiberglass tape 50 μm thick. Consideration is given to adding a single 25μm kapton layer if better insulation is judged necessary. The necessary overlap joint between thick and standard braid will be located at one end, and made by routine practice. The higher stiffness of the thick braid requires additional tooling to form the ends, but no serious complication is expected.

TEST MAGNETS

In order to verify the increased stability arguments, two full-size test magnets (MK-19 and 20) were built in which the inert spacers were replaced by superconducting turns. SC spacers were used in earlier short magnets [12] and more recently in Nb_3Sn magnets [13] to increase the current stability of the turns near the pole. The winding scheme for the test magnets is shown in Fig. 1 (with MK-19 being insignificantly different) and the important parameters are listed in Table 2. Both magnets were soft assembled with MK-20 directly comparable to MK-23 and 25. MK-19 in contrast, was assembled like MK-5 (the best performing dipole) with stress relieved fiberglass bands, masking tape between coil and bands, and the bore tube supporting the coil. MK-19 was wound with natural ends, MK-20 with end spacers.

Table 2. Full Size Test Magnets

	MK-19	MK-20	unit
No. of turns	192	192	
Transfer Function	1.423	1.415	T/kA
Built in b_2	- 29	+ 15	$10^{-6}cm^{-2}$
b_4	- 41	6.8	$10^{-7}cm^{-4}$
b_6	- 29	- 44	$10^{-8}cm^{-6}$
b_8	- 1.1	0.34	$10^{-9}cm^{-8}$
Lamination o.d.	+5.7	+1.9	μm
I_c @ 5 T, 4.2 K	4.25 & 4.35	4.15 & 4.55	kA
Elastic Modulus	10	13	GPa
Prestress Estimate*	4	5	MPa

*Full prestress preventing coil motion at the pole would require about 30 MPa.

The particular arrangement with superconducting inert turns is subject to substantial eddy current effects during ramping and the magnets are effectively dc magnets only. The maximum induced current is, in steady state ramping, estimated to be

$$i_{eddy} = \frac{\pi^2}{9}\,\frac{w}{c}\left(\frac{B}{I}\right)\tau\,\dot{I}$$

with τ the time constant, w the braid width and B/I the transfer function. The observed time constant is on the order of one hour resulting in 800 A induced current in the braid at the ramp rate of 0.01 A/sec. The induced currents are additive to the transport current and the critical current is easily exceeded during ramping. Interchanging active and spacer turns would have resulted in a subtraction of the eddy current and a substantial improvement of performance. The time constant depends quadratically on the spacer turn length; cutting the spacer length would practically eliminate the eddy current effects.

The effectiveness of the superconducting turns in suppressing training quenches depends on the time required to switch the current locally from the active into the superconducting spacer turn (the current diffusivity is about 10^3 m^2/sec). It has been estimated that a minimum propagating zone can be bypassed within a few milliseconds, which may well be marginal at top field. At lower fields quench recovery has been observed.

The test magnet MK-19 underwent about 40 low field quenches at fast ramp rates until the eddy current effect was correctly diagnosed. MK-19 had then its first training quench at 39.3 kG (2.896 kA) and trained in one step to 42.5 kG when ramped at 0.01 A/sec. Training was stopped due to magnet damage caused by a failure of the quench protection circuit. Testing of MK-20 is forthcoming.

A noninductive simulation coil, 50 cm long, was wound with thick braid in order to test training behavior and quench velocities. No training quenches were observed at 5.5 T up to the magnet design current of 4 kA. [8].

CONCLUSION

It is, in our opinion, justified to discount the eddy current quenches observed on MK-19. Under this assumption, its performance would seem to be superior to all other standard dipoles tested recently (Fig. 3). However, it is not possible, without further work, to attribute it to the presence of superconducting spacer turns rather than some other aspects of the magnets, such as the particular asembly technique applied to MK-19. The results are in any case sufficiently encouraging to pursue the thick braid solution with vigor.

Thick braid has been delivered by industry to this laboratory in quantities adequate for construction of a dipole and several quadrupoles. In view of its greater simplicity, the construction of a full size quadrupole, 1.5 m long, is under consideration (Fig. 5). The primary purpose of this test magnet is to gain fabrication experience and to verify the training behavior of magnets containing thick braid. It is expected that this first step will lead to the construction of full-size dipole magnets.

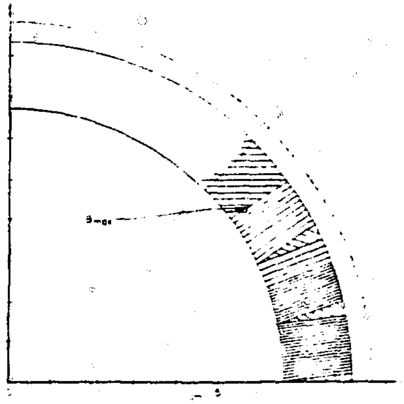

Fig. 5. Cross section of thick braid quadrupole.

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REFERENCES

[1] H. Hahn. IEEE Trans. MAG-17, 702 (1981).

[2] E.J. Bleser, "Construction of Superconducting Magnets at Brookhaven National Laboratory" these proceedings.

[3] H. Hahn, "A Semiflexible Coil with Graded Current Density for ISABELLE Magnets", to be published in Proc. Superconducting Magnet Workshop, Brookhaven (1980)

[4] P.F. Dahl and H. Hahn, IEEE Trans. MAG-17, 168 (1981).

[5] S.L. Wipf, "Stability and Degradation of Superconducting Current-Carrying Devices", Los Alamos Scientific Report, LA7275 (unpublished 1978).

[6] M. Garber and W.B. Sampson, IEEE Trans. MAG-17, 77 (1981).

[7] J.D. Jackson, "Theory of Transverse Quench Propagation", ISABELLE Technical Note 234 (unpublished 1980).

[8] W.B. Sampson, private communication (1981).

[9] A.J. Stevens, private communication (1981).

[10] E.D. Courant, "Eddy Currents in Superconducting Braid", ISABELLE Technical Note 168 (unpublished 1980).

[11] T. Luhman, "Metallurgical Characterization of NbTi Braid", ISABELLE Technical Note No. 274 (unpublished 1980).

[12] W.B. Sampson, P.F. Dahl, A.D. McInturff, G.H. Morgan, Proc. 4th Intern. Conf. Magnet Technology, Brookhaven 1972 (NTIS Springfield, VA) p. 552.

[13] W.B. Sampson, S. Kiss, K.E. Robins, A.D. McInturff, IEEE Trans. MAG-15, 117 (1979).