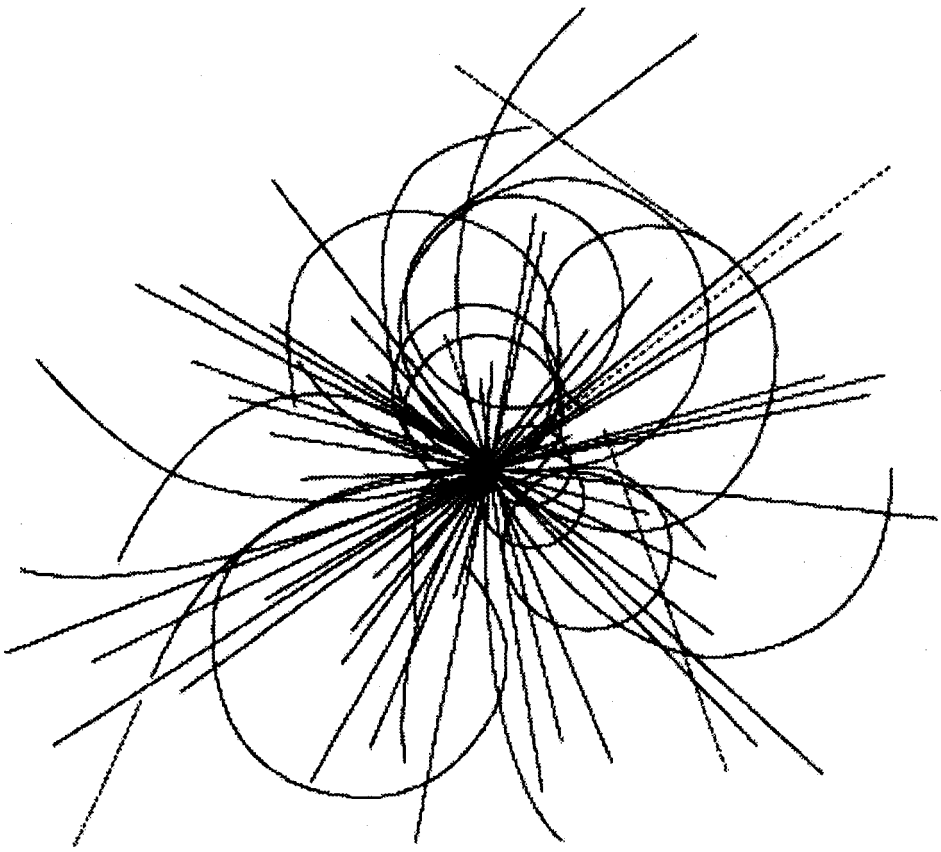
SSCL-Preprint-500

SSCL-Preprint-500
September 1993
Distribution Category: 414

R. Schermer

Status of Superconducting Magnets for the Superconducting Super Collider



Superconducting Super Collider Laboratory

SSCL-Preprint-500

Status of Superconducting Magnets for the Superconducting Super Collider*

R. Schermer

Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
Dallas, TX 75237

September 1993

*Presented at the Magnet Technology XIII Conference in Victoria, British Columbia on September 20–24, 1993.
†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

Status of Superconducting Magnets for the Superconducting Super Collider

Robert I. Schermer
Superconducting Super Collider Laboratory*
Dallas, TX 75237

***Abstract*—The arc sections of the High Energy Booster and the two Collider Rings will need more than 10,000, very large, superconducting dipole and quadrupole magnets. Development work on these magnets was carried out at US/DOE laboratories in a program that began in the mid 1980's. In 1991–92, the technology was transferred to industry and twenty, full-length, Collider dipoles were successfully fabricated and tested. This program, along with HERA and Tevatron experience, has provided industry a data base to use in formulating detailed designs for the prototypes of the accelerator magnets, with an eye to reducing cost and enhancing producibility. Several model magnets from this latest phase of the industrial program have already been tested. The excessive ramp-rate sensitivity of the magnets is understood and solutions are under investigation.**

I. HISTORY

The Superconducting Super Collider (SSC) is a chain of five accelerators. This paper will discuss the magnets for the final two stages, which are the only machines that use superconducting magnets. The penultimate stage, the High Energy Booster (HEB) accelerates protons from 0.2 TeV to 2.0 TeV and serves as an injector for the final stage, the Collider. In the Collider, protons in two counter-rotating rings are accelerated to 20 TeV and stored for 24 hours while collisions occur at several interaction points. Table I lists magnet performance parameters for these last two stages.

TABLE I
Comparison Between Heb and Collider Dipole Requirements

REQUIREMENT	HEB	COLLIDER
Number Required	512	8340*
Slot length (m)	13.17	15.82
Integrated Field (T-m)	81.37	101.36
Max. Operating Current (A)	6650	6715
Radius (m); sagitta (mm)	1001; 18	10187; 1.8
Operating mode	8 bipolar cycles	one unipolar cycle
Ramp rate (A/s)	62	4
Max. dynamic heat load to 4 K (W)	11.68	2.4
Max. He pressure drop (Pa)	106	69
Max. outlet temperature (K)	4.25	4.25
Design margin (K)	0.6	0.6

*Includes 396 dipoles, 13.32 m long.

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.
Manuscript received September 20, 1993.

As there are many common elements between the magnets for the HEB and Collider, only a single, undifferentiated, 40 mm bore dipole was developed during the initial phase of the project. This development work was carried out at Brookhaven National Laboratory (BNL) and Fermi National Accelerator Laboratory (FNAL), while Lawrence Berkeley Laboratory (LBL) was given the task of developing a 40 mm-bore quadrupole. An important step was reached when testing of full length dipoles began in early 1987. Although these early magnets trained excessively, three years of intense effort, involving production and testing of numerous short and long model magnets, culminated, in mid-1991, in the production of six, nominally identical, 17-m-long, dipoles at BNL. The construction features [1] and testing [2]–[3] of these dipoles have been extensively described.

Meanwhile, in late 1990, it had been decided that a much more satisfactory collider would result if the dipole bore were increased to 50 mm. Although the 40 mm dipoles met or exceeded their field quality requirements, computer simulations over the intervening years indicated that these requirements were not strict enough to provide adequate aperture during the one-hour injection period. Increasing the magnet aperture automatically improves field quality, as it moves the conductors further from the beam, and fabrication errors would be expected to remain constant, at worst, as the size increases. Further, an increase in aperture provided room to increase the volume of superconductor in the magnet and, hence, the margin between the magnet operating current and the critical surface. The 40 mm dipoles operated at 96% of critical current, as measured along the loadline. Even with the excellent performance attained at the end of the 40 mm program, it was unlikely that the Collider would reach operating current without a number of training quenches. By contrast, the present 50 mm dipoles operate with over 10% margin, and it is specified that the magnets may not quench below operating current.

Initially, technical guidance for the SSC was provided by the Central Design Group, which had existed since the mid-1980s at LBL. This group provided the staff nucleus for the Magnet Systems Division (MSD) when the SSC Laboratory (SSCL) was formed and moved to Dallas, Texas, in mid-1990. Almost immediately, SSCL initiated a competitive bid process that led to the selection of industrial subcontractors for development, prototyping and low-rate production of three (out of four) of the major magnet

subsystems. Contracts are of a "leader/follower" type, intended to assure that there will be two responsive bidders when contracts are awarded for full production.

a) For the Collider dipole magnets (CDM), the leader is General Dynamics Space Systems (GDSS), with Westinghouse Electric Corporation (WEC) as the follower.
b) For the HEB dipole magnets (HDM), the leader is WEC, with B&W as the follower.
c) For the Collider quadrupole magnets (CQM), the leader is a collaboration between B&W and Siemens, with GDSS selected as the follower.

The quadrupole magnets for the HEB (HQM) are being designed by CEN/Saclay; the production contract will be awarded, by competitive bid, to a small, disadvantaged business.

An important milestone was set for the new laboratory and its new industrial partners-performance of the Accelerator System String Test (ASST) by October 1, 1992. Detailed descriptions of this test have already been published [4]. Besides being a successful demonstration of magnet technology, ASST also represented the first extensive participation of industry in SSC magnet fabrication. The dipoles actually used in ASST were fabricated at FNAL, using FNAL tooling, by GDSS technicians and supervisors. A backup set of dipoles was constructed at BNL, using BNL tooling, by WEC technicians and supervisors.

The ASST program and the preceding 40 mm program provided an extensive technology base for the industrial subcontractors to draw upon. With the exception of the HQM, the subcontractors are not required to build a particular design "to print." Rather, they are encouraged to pick and choose among the options presented by the preceding development program to best satisfy the requirements of their particular magnet subsystem, to enhance producibility, and to reduce cost. This paper will discuss the choices made by the various vendors and the early results and consequences of those choices.

II. ASST MAGNET PERFORMANCE

A. *Quench Performance*

A total of 20 dipole magnets were constructed during the ASST program, 13 at FNAL, including 7 by GDSS, and 7 at BNL, including 5 by WEC. Fig. 1 shows a cross section of the FNAL design. All the FNAL magnets used vertically split yokes, while the BNL magnets used a horizontal split. There were also differences in the design of ends and splices, and innumerable small differences in construction procedure; alternate cable insulation systems were investigated in the last 4 FNAL magnets and the last 2 BNL

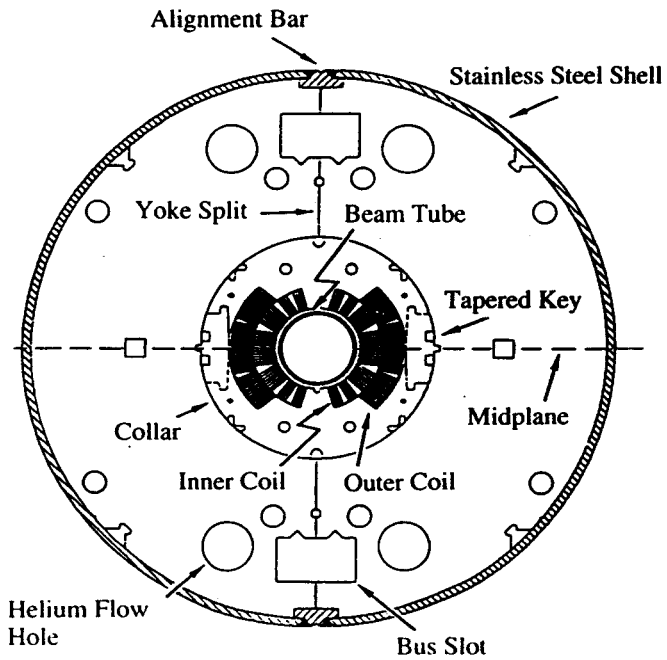


Fig. 1. Cross section of cold mass of 50 mm ASST dipole, FNAL design.

magnets. Nah [5] has presented an extensive discussion of the quench performance of the ASST magnets. Results for FNAL magnets are shown in Fig. 2; results for BNL magnets are even better. The magnets show little training, either on the initial thermal cycle or on subsequent cycles. The few low quench currents seen in Fig. 2 are due to an incorrect ramp splice design on the earliest magnets, or to ramp-rate sensitivity. The performance is particularly impressive as these magnets represent the result of a direct scaleup from the 40 mm program, with no intervening development work.

B. *Magnetic Field Quality*

Magnetic field quality is specified by the multipole expansion which, for a dipole, has the form

$$B_y + iB_x = 10^{-4} B_0 \sum_{n=0} (b_n + ia_n) \left(\frac{x+iy}{R_0} \right)^n \qquad (1)$$

where B_0 is the dipole field strength, b_n and a_n are the normal and skew multipole coefficients, respectively, and R_0 is the reference radius, which is equal to 10 mm for the SSC. In (1), n = 0 is the dipole term, n = 1 the quadrupole term, etc. Each multipole coefficient represents a superposition of terms due to the transport current in the magnet, persistent magnetization currents in the superconductor, eddy currents in the magnet structure, and

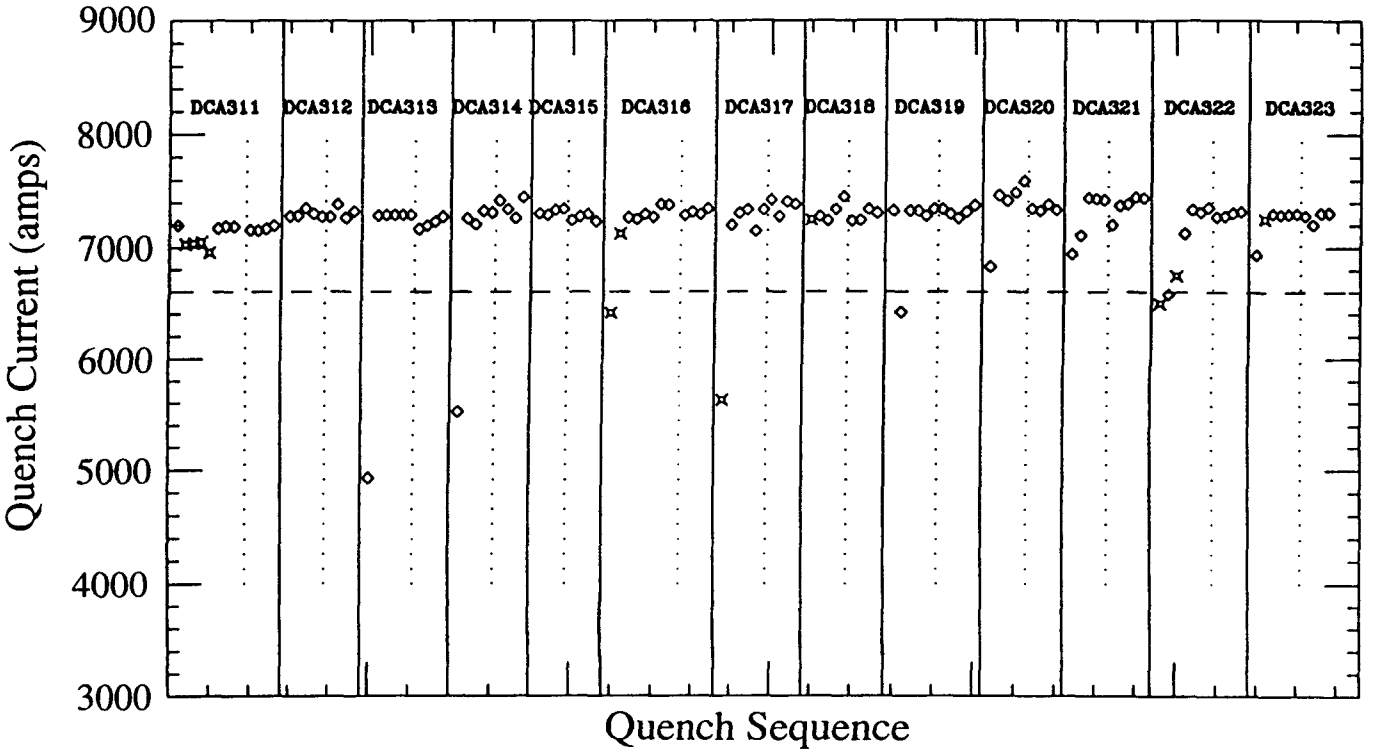


Fig. 2. Quench performance at 4.35 K of FNAL-design, ASST dipoles.

the presence of magnetic materials. Zhao [6] has described how these various terms may be deduced from a study of the current dependence of the multipole coefficients.

The coefficients produced by the passage of DC transport current through the geometric configuration of conductor and magnetic materials are called "geometric multipoles." For a perfectly constructed dipole, all geometric terms except b_n, n = even, are exactly zero by symmetry. Further, in an SSC dipole, b_2 through b_8 are designed to be zero by proper choice of collar and wedge shape in Fig. 1. The magnet fabricator is required to control the average value of each multipole coefficient over the ensemble of magnets, as well as the magnet-to-magnet variation. Tolerance values range from 1 part in 10^4 for small values of the index n, to less than 1 part in 10^5 for large values of n. If we consider any nominally identical subset of ASST magnets—the first 9 FNAL magnets, for instance—we find that the magnet fabricators exercised excellent control over processes and material tolerances. As an example, for the first 9 FNAL magnets, the standard deviation of each multipole coefficient is compared to its specified tolerance in Fig. 3.

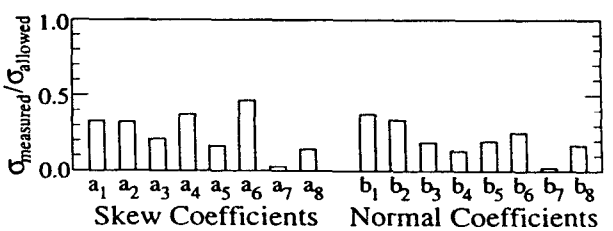


Fig. 3. Multipole statistics for 9, nominally identical, ASST dipoles built at FNAL. For each coefficient, the vertical axis gives the ratio of observed standard deviation to that allowed.

C. *Quenches During Ramping*

The quench current of the ASST magnets is significantly degraded as the ramp rate is increased [5]. This unanticipated effect is illustrated in Fig. 4 for the FNAL magnets; results from BNL are qualitatively similar. Ramp rate measurements routinely made on the 40 mm short magnets revealed insignificant degradation—typically, a quench current decrease of several hundred amperes at a ramp rate of 200–300 A/s. The experiment was performed only on one full length 40 mm magnet, with similar results. The effect was not evident until late in the 50 mm short magnet program, but has appeared in all long 50 mm magnets.

During the period when the accelerator field is being increased from its injection value to its final value, each magnet is required to reach its operating current without quenching, while producing a magnetic field with specified multipole characteristics. All magnets indeed attain operating current at the Collider ramp rate, while very few can be ramped at the HEB rate without quenching. Eddy

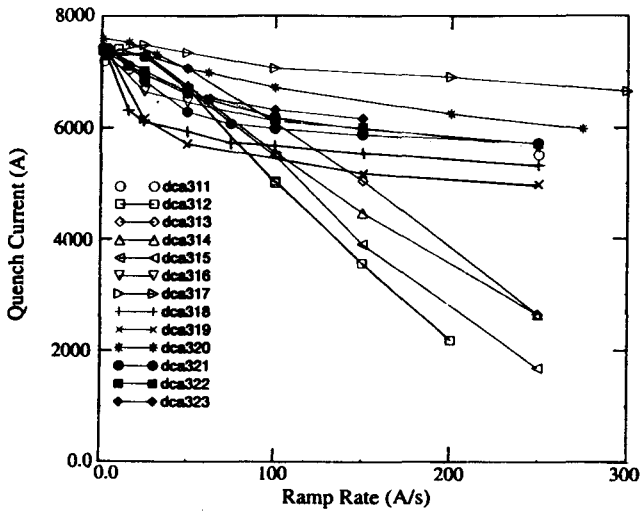


Fig. 4. Ramp rate sensitivity of FNAL design, ASST dipoles.

currents during ramping produce multipole fields [6] that may be tolerable on average in the Collider, insofar as they appear to vary in sign and magnitude down the length of the magnet, but that may not be tolerable for the HEB. On a positive note, all magnets meet the requirement that they not quench during emergency shutdown, when the ramp rate is –200 A/s.

A model for this behavior has been formulated through a combination of theoretical and experimental studies, as described in Section (III). The principal feature of the model is the occasional, unintended presence of crossover resistances in the cable that have especially low values. These lead to large eddy currents during ramping and, eventually, to premature quenching. The choice of cable insulation has a serious impact on the problem, as discussed in Section (IV).

III. RAMP RATE EFFECTS

When the current in a superconducting magnet is changed, heat is generated by hysteresis in the superconductor and in the iron yoke, and eddy currents are generated that flow from strand to strand in the cable conductor, as well as within individual strands and within any conducting materials in the magnet structure. What is the scale of the perturbations needed to explain the fact that a typical magnet in Fig. 4 quenches at 6000 A, at a ramp rate of 100 A/s? First, let us assume that the effect is due directly to the eddy currents, because the sum of transport current plus eddy current in a strand must be less than the critical current. In this case, we find that one strand of the 30-strand inner layer cable must carry an excess current of 200 A. Alternatively, if the effect is due entirely to heating, the temperature rise must be about 1.1 K. (In practice, the quench current will be depressed by a superposition of these two effects.) Let us assume, *a priori*, that such large effects can only be produced by interstrand eddy current, and support this assumption by further experimental evidence, to be introduced below. Interstrand eddy current is the only phenomenon in the list that might be expected to vary widely magnet-to-magnet.

There is an immediate problem with any simple model, however. An examination of Fig. 4 seems to indicate that the magnets can be arranged in two classes. "Type A" magnets have a quench current that decreases with ramp rate, with ever-increasing slope. Originally, it was thought that this behavior might be explained by a simple superposition of direct heating and eddy current effects. By contrast, "Type B" magnets have a quench current that falls rapidly at first but then becomes almost constant. This behavior was completely new to us and could not be readily explained.

Are the required values of temperature rise and current unbalance reasonable? Answering this question has proven to be quite difficult. The eddy currents may extend over the entire volume of the magnet, or may be concentrated in a local region, and may involve the entire cable or just a few strands. The associated heating will have some complex spatial distribution. The effect may not be directly due to the currents, but to an instability triggered by their presence. Fig. 4 does not contain enough information to distinguish these possibilities; different kinds of experiments were required. Further, it was necessary to develop a number of computational tools to perform a quantitative analysis of the results.

The conductor used in the inner layer of all SSC dipoles to the present time is a flat "Rutherford" cable, formed of 30 bare strands and slightly keystoned. Each strand crosses over each of the 29 other strands twice per cable pitch. During coil fabrication, the cable is subjected to high pressure at elevated temperature, which can lead to strand crossovers with relatively large area and low resistance unless the processing parameters are carefully chosen. A network model of the system can be formulated [7]–[8] to describe the response of the cable to changing magnetic field, and the problem can be solved at various levels of complexity.

Fig. 5(a) shows an example of the simplest case: the geometry is the same at every cross section, the cable extends to infinity in the axial direction, $\pm z$, and the crossover resistance has the same value at each node. In the straight section of a real magnet, the rate of flux change will not vary along the z direction, and will have a variation in the (r,Θ) directions that can be computed. If this flux variation is inserted into the network model, a realistic value can be computed for the eddy current and the resultant power generation in each turn of the magnet. The only free parameter is the crossover resistance, which may be obtained experimentally from a measurement of "AC loss" on a magnet [9]. This measurement, which yields the energy loss in a magnet as it is powered cyclically at various

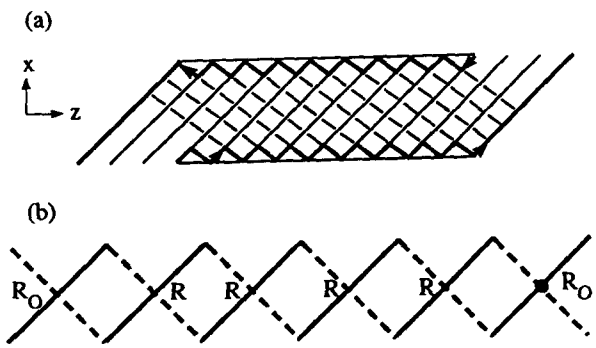


Fig. 5. Two network models for studying AC effects in cables. (a) Resistance and flux density are constant with respect to axial coordinate z but may vary across cable width. Heavy lines show net eddy current pattern. (b) Two strands with uniform crossover resistance R, except at locations marked R0.

ramp rates, has been performed on all but a few of the ASST magnets and on several short 50 mm models. An electrical technique was used that yielded precise, reproducible results.

With the power generation per conductor known, it is possible to calculate the conductor temperature, using a detailed, two-dimensional, transient, Finite Element thermal model of the magnet cross section [10]. Computation shows that the combined effect of heating and eddy currents, due only to the average value of crossover resistance, is not sufficient to account for the results shown in Fig. 4 even for Type A magnets, and is an order of magnitude too small for Type B magnets.

Any model for ramp-rate sensitivity must also account for experimental observations of quench location. Because the magnets are provided with voltage taps that monitor several turns nearest the poles of the inner coil layer, it has been known for some time that quenches at low ramp rate occur in the inner coil pole turn—the region of highest field. Further, the quenches occur at the cryogenic return end of the magnet, where the temperature is slightly higher due to heat leaks and to energy deposition during ramping. At higher ramp rates the quenches move out of the region monitored by the voltage taps, and could not be further localized until the development of the "quench antenna" [11]. We find that quenches at any given ramp rate always occur at a particular location, but the location changes as the ramp rate changes. Azimuthally, quenches are located near—but not necessarily at—the coil midplane. Axially, quenches are as likely to occur at the cryogenic inlet end as at the return end. This last fact indicates that heating is not a major contributor to the process. Rather, the results implicate strand-to-strand eddy currents, which are greatest at the midplane where the magnetic field is normal to the wide face of the cable. Also, there must be local variations in interstrand resistance that affect the exact location of the quench.

Turn-to-turn variations in interstrand resistance have been measured [8] by analyzing the unallowed multipoles exhibited during ramping of the four, lossiest, type A magnets in Fig. 4. Thus, for instance, DCA312 has a crossover resistance of 6 $\mu\Omega$, averaged over the entire magnet, but one turn with an average resistance of only 2 $\mu\Omega$. The resultant azimuthally non-uniform heating and eddy currents are still too small, according to a Finite Element thermal computation, to explain Fig. 4.

A more interesting network model is shown in Fig. 5(b). Here, two strands are linked by a uniform crossover resistance R except at two, widely separated locations, where the resistance R_0 is unusually small. The eddy current generated in this case is proportional to the net magnetic flux enclosed by the two strands. The flux is small if the strands are adjacent, and reaches a maximum when the strands are separated by 14 other strands. For the case of maximum separation, the emf of one net loop at 100 A/s is 3 μV; a current of 150 A will be generated if $R_0 = 0.1\ \mu\Omega$. This is the order of magnitude of R_0 that would be expected for a cold weld between two strands. Recently, it has been pointed out that this very low resistance requirement may be relaxed somewhat [12]. Two strands will not usually be perfectly transposed, due to accidents of magnet construction at the ends, and may easily be linked by several net flux "diamonds."

If we assume that quenching occurs when the local heating at R_0 reaches some critical value, the "strand loop" model of Fig. 5(b) accounts for most of the experimental facts regarding ramp-rate sensitivity. In particular, as will be described below, our eddy current effects can show very long time constants, usually in the range 10-100 seconds, but sometimes as long as an hour. This implies that the underlying physical process is described by a diffusion equation. In fact, both networks in Fig. 5 exhibit diffusive behavior, but on a greatly different time scale. In Fig. 5a, the eddy current loops at the edges of the cable are different from all other loops. With a resistance of 1 $\mu\Omega$, the longest time constant is about 1.0 sec. By contrast, in Fig. 5b, a very long time constant can result if the two low resistance points are widely separated in the magnet. The thermal model gives two time constants of order 3 sec and 120 sec, but these values would be the same for all magnets, in disagreement with observations.

In order to measure the system time constants a number of "special ramps" were invented: a magnet at current I_0 is ramped to current I_1 at rate r_1, the current is held constant for time t_1, the current is then ramped to I_2 at rate r_2, and so on until quench. The simplest version of this is the "delayed ramp," the results of which are shown in Fig. 6 for DCA312 at 100 A/s. This magnet quenches at 5000 A when ramped from zero current at 100 A/s without pause. If, instead, the magnet is ramped to 4800 A and held for a dwell time before continuing, the magnet attains a higher quench current. The solid curve shown in Fig. 6 is a two-term

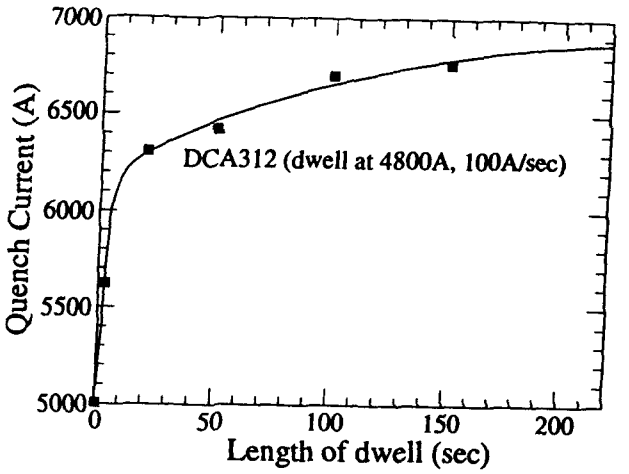


Fig. 6. Results of a "delayed ramp" experiment (see text) on DCA312. The solid line is a 2-term exponential fit to the data.

exponential fit, with time constants of 2.7 and 103 s. Although these values are close to the thermal time constants, the relative magnitude of the short time constant term is a factor of 3 too large to be attributed to heating.

Fig. 7 illustrates the effect of a three-part, "V-ramp" experiment on DCA323. In (a), the magnet is found to quench at 6320 A when ramped from zero current at 100 A/s. In part (b), the magnet is ramped to 6320 at 4 A/s, followed by a 600 s wait to allow any heating to dissipate. Then, the magnet is ramped at 100 A/s, quenching at 6970 A. In part (c) of the experiment, the magnet is ramped to 6970 A at 4 A/s and allowed to stabilize for 600 sec. Finally, it is ramped down at 100 A/s to 6320 A and then,

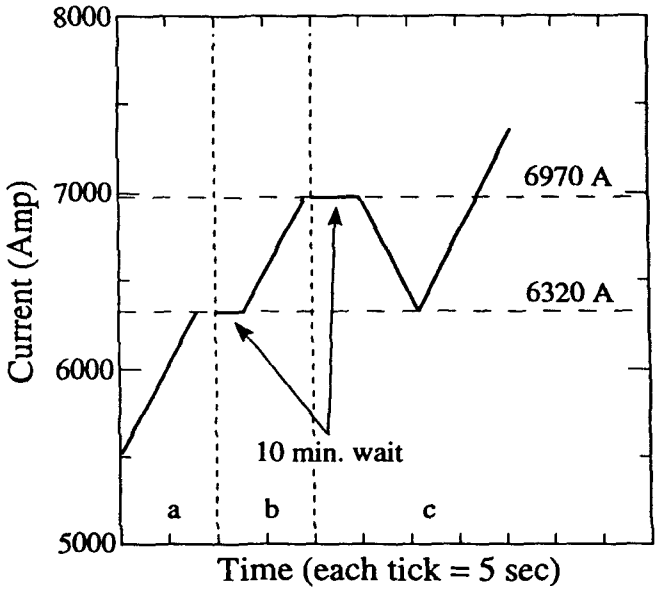


Fig. 7. Results of a "V-ramp" experiment (see text) on DCA323.

without a pause, is ramped up at 100 A/s, reaching 7350 A before it quenches.

Suppose the ramp rate quenches were due to heat. Then, in Fig. 7c, the magnet at 6320 A would be warmer than it was in Fig. 7b and would quench below 6970 A, not higher. (For magnet DCA312, in which heating dominates, this is what happens.) Instead, suppose that the effect is due to eddy currents. When the magnet is ramped down in Fig. 7c, eddy currents are generated in the opposite sense from those generated on the subsequent upramp. The magnet returns to 6970 A amps with a smaller eddy current than in Fig. 7b, and can attain a higher current before quenching. Further reflection reveals that this argument depends on the decay time constant of the eddy currents; the effect will not occur if the currents decay in a time short compared to the 13.0 seconds required to cycle between 6970 A and 6320 A.

Control of Interstrand Resistance

Why should the 50 mm magnets exhibit so much greater ramp rate sensitivity than did the 40 mm magnets? The cable used in the 50 mm magnets is wider and has more strands, so that the magnitude of eddy currents is about 50% larger at the same crossover resistance, but this is not sufficient to explain the difference. One hypothesis is that changes in strand processing, particularly use of higher purity copper combined with a changed annealing schedule, has produced very soft copper that occasionally forms cold welds. A program is underway in which interstrand resistances are measured on samples cut from magnets. Thus far, numerous examples of resistances in the 1–5 μΩ range have been found. Very recently, resistances of order 0.1 μΩ have been detected in a short section of coil cut from the region of DCA312 that quenched at 150 A/s [13].

The best solution to the problem would be one that involved a small change in a processing step. A less desirable solution would be to apply a coating to the strand; even a thin solder layer would keep the crossover resistance above the 1 μΩ level. For instance, we expect that the use of "Zebra cable," as in the Tevatron magnets, would yield magnets that met the quenching and multipole specifications for the HEB, although the AC heat load would be 50% larger than the specified value.

IV. CABLE INSULATION SYSTEMS

The industrial contractors were permitted to choose from among several insulation systems. It is not possible to make this choice in a completely analytical way, as the necessary data does not exist. Each system has its own virtues and liabilities, and each choice creates problems that the subcontractor must overcome.

For most of the ASST magnets, the cable insulation consists of a 25-μm-thick layer of polyimide film, wrapped

with a 50% overlap, topped with a 125-μm-thick layer of epoxy-impregnated fiberglass, wrapped with a 0.5-mm gap. Except for small variations in film thickness and overlap, the system is identical to that used in Tevatron, HERA, and virtually all preceding SSC magnets. In the last two BNL magnets, the fiberglass layer was replace by a second layer of polyimide, and a polyimide thermoplastic adhesive was used. The last 4 FNAL magnets also used polyimide rather than fiberglass, and several thermoset adhesives were tried.

The principal virtue of the "old" system is that many successful coils have been fabricated using it, and there is a large amount of experience in dealing with the problems it creates. Detractors point out three principal flaws, all due to the fiberglass layer.

a) In the early SSC program there was a history of turn-to turn shorts traceable, in part, to degradation of the polyimide film by the fiberglass. Laboratory tests indicated that the all-polyimide systems would have higher punch-through resistance and, indeed, magnets fabricated with these systems have been almost short free. On the other hand, very few shorts occurred in the ASST program, with the "old" insulation, indicating that the problem may be manageable with proper fabrication tooling and technique.
b) The film degradation creates some risk of turn-to-turn voltage breakdown under very conservative assumptions regarding voltages, temperatures and pressures. It would seem that the assumptions must be overly restrictive, as many magnets *do* function with this insulation. My opinion is that the problem has not been analyzed in sufficient depth.
c) One year ago, when the industrial subcontractors selected their baseline insulations, it was suspected that the epoxy system then used would not meet the SSC radiation requirements. Subsequent tests have verified this, but have also shown that there are acceptable materials that should be "drop in" replacements.

Choice of insulation affects the size of the cured coil and, thereby, the field quality of the assembled magnet. The ASST magnets did not produce the desired average value of zero for the allowed harmonics, but the coil size was well determined and it was known what wedge variations should be made to improve the results. By contrast, coils made with alternative insulations are at the very beginning of this iterative process. The ASST coils with all-polyimide insulation were quite far from nominal size. The next step would be to produce additional coils with different film thickness and, perhaps, different overlap pattern. Finally, the curing process parameters will have to be stabilized before an iteration can proceed.

Choice of insulation also impacts the ramp rate behavior of the magnets. The ASST insulation was cured at 135°C and the temperature was not critical because the adhesive is a thermoset. By contrast, polyimide adhesive must be raised above its softening temperature of 225°C. Curing temperatures of other candidate systems lie in between these extremes. In general, we find that a higher curing temperature leads to increased difficulty with ramp rate effects.

V. PRESENT STATUS

GDSS implemented three potential improvements in its first four 1-m-long models: redesign of the inner-to-outer coil "ramp splice"; use of molded end spacers; use of all-polyimide insulation.

a) An attempt to simplify fabrication of the ramp splice led to a significant number of quenches in this area. This is not surprising; all through the history of dipole development, until the ASST program, we had difficulty in this region.
b) An attempt to reduce cost by using molded end spacers, rather than machined ones, led to quenching in the magnet ends. Poor fit of these molded parts is believed to be the principal cause of the problem. Fit will be improved in future magnets, and alternative materials will be investigated.
c) Use of an all-polyimide insulation system that cures at 225°C led to inordinate ramp rate sensitivity. Excessive temperature and pressure during coil molding is believed to be the principal cause of the problem. The last two BNL/ASST magnets demonstrate that this insulation system should be viable with proper control of process parameters.

WEC produced three successful short models, using an alternative cross section provided by SSCL, and ASST insulation. Training of these magnets is shown in Fig. 8 and ramp rate performance is shown in Fig. 9. Magnet DSB703 was particularly interesting, as it employed cable all of whose strands were coated with ebonol. Such a magnet represents a limit of the network in Fig. 5b, with high interstrand resistance except at the joints. As predicted, this magnet showed very clear "Type-B" behavior.

For their baseline, WEC plans [12] to use the same cross section as GDSS, but will use neither the ASST insulation

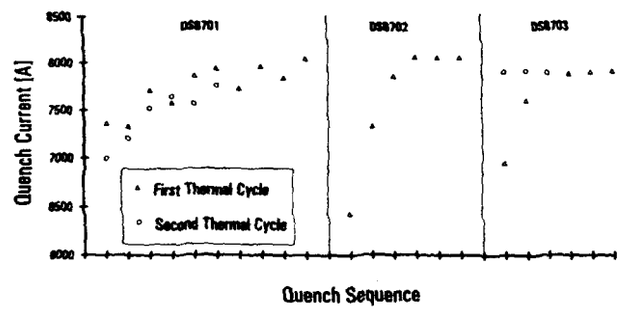


Fig. 8. Training quenches at 4.25 K of 1 m HDM model dipoles built by WEC.

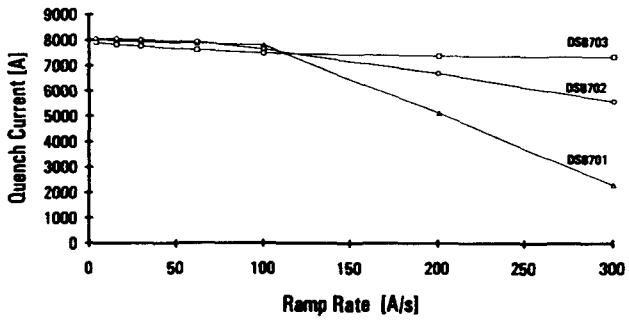


Fig. 9. Ramp rate performance of 1 m HDM model dipoles built by WEC.

nor the high temperature cure insulation chosen by GDSS. The principle challenge for WEC is improving ramp rate performance, presumably by controlling transverse resistivity. Various options for coating the strands are under active investigation.

B&W/Siemens produced three successful, short, 40 mm quadrupoles, using the LBL cross section, polyimide/ fiberglass insulation, and several construction techniques adopted from HERA [14]. B&W has also produced a conceptual study for a 50 mm quadrupole, in response to an initiative at SSCL to increase the CQM bore. Unfortunately, the cross section cannot simply be scaled to 50 mm, as it produces insufficient gradient. Several new cross section options were investigated, some of which involve a change of insulation or of cable keystone; magnet fabrication has not yet begun.

SSCL is concentrating on the special magnets that form the interaction regions, many of which have unique features or requirements. Each individual magnet type presumably will need to go through its own development process. A few short 50 mm quadrupoles have been successfully tested, and fabrication of a 15 m prototype quadrupole has begun.

VI. CONCLUSIONS

The ASST program, as planned, produced a 50 mm dipole and a 40 mm quadrupole that could be used in the Collider. If these magnets were also to be used for the HEB dipoles, ramp rate sensitivity would have to be reduced, either by an alteration in processing of the strand, cable or coil, or by adding a coating to the strands. A 50 mm quadrupole will require a modified cross section. In each program, there is an effort to make the magnet more amenable to mass production, and to lower the cost. Thus, the industrial subcontractors will not simply launch into production of ASST magnets. Rather, in the coming year, there will be a development effort at each vendor, including additional short magnet construction, before we can expect to see successful production prototypes of long magnets.

ACKNOWLEDGMENT

The work reported here distills the efforts of hundreds of colleagues at the DOE Laboratories and the industrial subcontractors. I hope they are not offended that I was not able, in general, to credit their individual contributions.

REFERENCES

[1] A. Devred, *et al.*, "Status of 4-cm aperture, 17-m-long SSC dipole magnet R&D program at BNL part I: magnet assembly," *Supercollider III*, J. Nonte, Ed. New York: Plenum, 1991, pp. 549–576.

[2] J. Kuzminski, *et al.*, "Test results of BNL built 40 mm aperture, 17-m-long SSC Collider dipole magnets," *IEEE Trans. Magn.*, Vol. 28, pp. 311–314, January, 1992.

[3] P. Wanderer, *et al.*, "Results of magnetic field measurements of 40 mm aperture, 17-m-long SSC Collider dipole magnets," *IEEE Trans. Magn.*, Vol. 28, pp. 311–314, January, 1992.

[4] T. Dombeck, "Accelerator Systems String Test objectives, problems and results," *Supercollider V*, J. Nonte, Ed. New York: Plenum, 1993, in press.

[5] W. Nah, *et al.*, "Quench characteristics of 5-cm aperture, 15-m-long, SSC dipole magnet prototypes," IEEE *Trans. on Appl. Supercon.*, vol. 3, pp. 658–661, March, 1993.

[6] Y. Zhao, *et al.*, "Current dependence of harmonic field coefficients of 5-cm aperture, 15-m-long, SSC dipole magnet prototypes," IEEE *Trans. on Appl. Supercon.*, vol. 3, pp. 674–677, March, 1993.

[7] G. H. Morgan, "Eddy currents in flat, metal-filled, superconducting braids," *J. Appl. Phys.* 44, 1973, pp. 3319–3322.

[8] T. Ogitsu, unpublished.

[9] J. P. Ozelis, *et al.*, "AC loss measurements of model and full size 50 mm SSC Collider dipole magnets at Fermilab," *IEEE Trans. on Appl. Supercon.*, vol. 3, pp. 678–681, March, 1993.

[10] G. Snitchler, D. Capone, V. Kovachev, R. Schermer, "Heat generation and cooling in SSC magnets at high ramp rate," *KEK Proc. 92-14*, pp. 15–18, December, 1992.

[11] A. Devred, *et al.*, "A method of quench localization for production phase of SSC magnets," this conference.

[12] T. Butler, *et al.*, "Status of the design, development, and test of the dipole magnets for the high energy booster," paper presented at the 1993 CEC/ICMC Conference, Albuquerque, NM, July, 1993, in press.

[13] V. Kovachev, SSCL, Dallas, TX, private communication.

[14] C. Rey, *et al.*, "A summary of the quench behavior of 1 m collider quadrupole magnets," paper presented at the 1993 CEC/ICMC Conference, Albuquerque, NM, July, 1993, in press.