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Design of Superconducting Magnets for the SSC*

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Abstract
In order for a superconducting magnet to operate reliably at a given field the design should have sufficient superconductor to allow operation at currents significantly less than the cable critical current. In addition sufficient copper should be included in the cable to give stability. Such considerations, their basis, and their application to the design of the new 5 cm bore diameter SSC dipoles, are discussed.

I. INTRODUCTION

As is well known, many superconducting magnets are observed to "train." Such magnets when initially powered will quench, *i.e.*become non-superconducting, at a current less than that expected from the behavior of a well supported short sample of the same conductor in the same magnetic field. When the magnet is powered on subsequent occasions quenches occur at progressively higher currents until the short sample limit is reached. A very poor magnet may in fact never reach the limit, but instead reach a somewhat less stable plateau below the calculated limit.

It is assumed that the premature quenches are produced by heat generated after sudden motion of parts of the magnet. The motion would be driven by the Lorentz force, but initially constrained by friction. When, as the current and field increase, the force exceeds the friction at a particular location, then that part moves causing the quench. After the quench the current is removed, because of the friction, the part that had moved does not move back. On the subsequent powering, that particular part of the magnet does not again cause a quench, and so the current and field can rise to a higher value until another part constrained by greater friction can move and again cause a quench.

What is not known is what part of a magnet is involved in this quench causing motion. One hypothesis would be that it is the motion of individual strands of the cable, in which case the motion and heating would be confined to a region with dimensions of the order of the strand radius (approx 0.4 mm in the SSC case). Another mechanism would involve the motion of an entire cable or block of cables, in which case the heating would be distributed over areas comparable at least to the cable half width (approximately 6 mm in the SSC case). In this paper we will study both possibilities, and address the choice of the ratio of copper to superconductor within the strands.

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II. EXPERIMENTAL DATA ON TRAINING AND COPPER/SUPERCONDUCTOR RATIO

Experience has long indicated that if too low a ratio of copper is used then magnets train badly, but it is not clear what the optimum value is. Since almost every magnet has many differences it is hard to quantify the experience of magnet construction. In fact there is substantial disagreement between different experts on what the best ratio should be.

The only clearly statistically significant data[1] is from the averages of observed training in cable samples clamped in pairs at 10 k psi perpendicular to a 6 Tesla field. In this orientation significant training is observed with the number of quenches to reach a plateau rising sharply as the copper ratio is reduced. Above 1.6:1 almost no training is observed, at 1.4:1 about 5 quenches are needed, and for 1.2:1 about 20 quenches are required. For ratios less than 1.1:1 it was in general not possible to reach a plateau current.

In order to study the trade off of margin with training one can plot the average current at the first quench versus the copper to superconductor ratio (Fig. 1). It is seen that the highest initial quench current is obtained for samples with a copper to superconductor ratio chosen to provide an almost negligible margin.

The dashed errors on the data points in Fig. 1 indicate the rms variation of the initial currents from individual tests. One may note from these that the difference in quench current between 1.3:1 and 1.5:1 would not be significant given single tests. It follows that it is even less possible to observe a significant difference in initial quench currents in real magnets for which there are many other sources of variation.

III. THEORETICAL ASSUMPTIONS

Attempts to fit the above cable training data have not been fully successful. It can reasonably be assumed that the source of a quench in these cable samples is individual strand motion and that the sources are thus small. It has become conventional therefore to consider the case of point heating. Locally the strand will initially be driven normal and become, by ohmic heating, a source of heat. Conduction away from the point will propagate the normal region, but thermal conduction and cooling to the helium will also cool and thus slow or stop the propagation. Calculations (Ref. 2) have sought to determine the minimum amounts of point heating that will just continue to propagate (the minimum propagating zone). But none of these calculations have indicated a maximum stability so near the maximum copper to superconductor ratio, and are thus unable to fit the above data.

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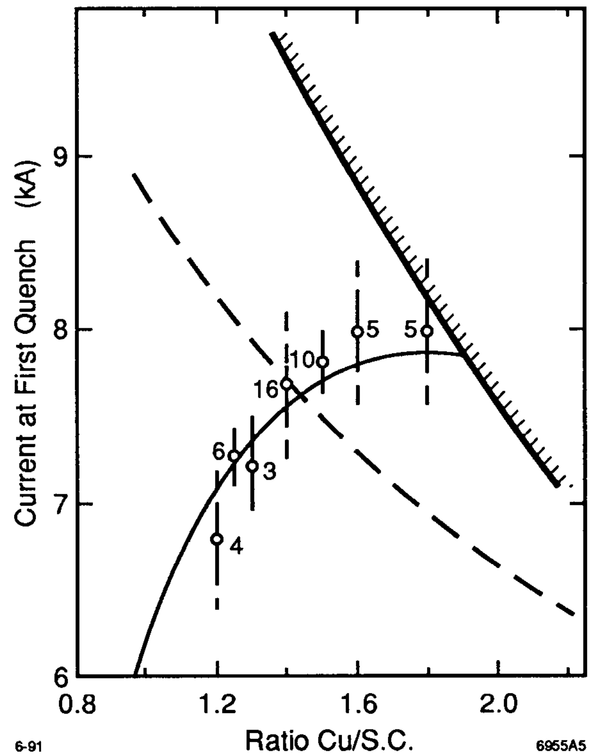

Figure 1. Average currents at the first quench of cable samples plotted as a function of the copper to superconductor ratio in the strands. The hatched boundary represents the critical current of the cables. The continuous line is the calculated quench current for a fixed energy deposition if a) the source is local within an rms radius of 0.3 mm (continuous line), and b) if the source has an rms length of 3 mm and is spread across the cable (dashed line).

In the analysis presented here we have made the following conventional assumptions.

1. Heat is introduced with a Gaussian distribution along the length of a single strand, with an rms width of 0.3 mm.
2. The axial thermal conductivity is dominated by the copper in each strand, excluding that part of the copper within the fine matrix of superconducting filaments. the copper to superconductor ratio within this matrix is taken to be 0.5:1.
3. The thermal conductivity of copper is :

$$\kappa = 0.5\ R\ T \quad (watts\ m^{-1})$$

where R is the electrical resistance ratio and T is the temperature in degrees Kelvin.

4. The electrical resistance of the copper is:

$$\rho_{Cu} = 1.7\ 10^{-8}\ (0.0032\ B + 1/R) \quad (\Omega\ m)$$

5. The specific heats of the copper and superconductor are:

$$S_{Cu} = 1600\ (T/4.2)^4 \quad (J\ m^{-3}\ deg)$$
$$S_{SC} = 6800\ (T/4.2)^4 \quad (J\ m^{-3}\ deg)$$

6. The critical current density in the superconductor (taken to be that density for which the resistance is $10^{-14}(\Omega\ m)$) is:

$$j_c = \frac{T_o - T}{T_o}\ 0.85^{(B-B_t)}\ j_o \quad (A\ m^{-2})$$

where B is the magnetic field (Tesla), T is the temperature (Kelvin), the critical temperature at that field is

$$T_o = 9.2\ (1 - 0.069\ B)^{.59} \quad (K^o)$$

and the critical current at the same field, expressed as a function of a test current density $j_t = 2750\ 10^6 (A\ m^{-2})$ at a test field $B_t = 5 Tesla$ and temperature $T_t = 4.3^o$, is

$$j_o = 0.95\ j_t\ \frac{T_{ot}}{T_{ot} - T_t}$$

where $T_{ot} = 9.2\ (1\ -\ 0.069\ B_t)^{.59} \quad (K^o)$.

7. The differential equation for the variation of temperature T as a function of time t and distance z along the direction of the stands is:

$$J\ A + j\ A\ \left(\frac{A_{sc}}{\rho_{sc}} + \frac{A_{Cu}}{\rho_{Cu}}\right)^{-1} = A\,(\chi_{sc}\ S_{sc} + \chi_{Cu}\ S_{Cu})\ \frac{dT}{dt} + \kappa\ \frac{d}{dz}\ (A \frac{dT}{dz}) + A\ \frac{2}{r}\ k(t)\ T$$

where J is the external heating per unit volume, j is the average strand current density, χ_{sc} and χ_{Cu} are the fractions of strand cross sectional areas of superconductor and copper, κ is the copper thermal conductivity, s is the exposed circumference of the strand, and $k(T,t)$ is the cooling coefficient to the helium.

In addition we have made the following assumptions not made in previous analyses, but which we believe are entirely reasonable:

1. The electrical resistance of the superconductor is:

$$\rho_{SC} = 10^{-14}\ (j/j_c)^{20} \quad (\Omega\ m)$$

where j is the current density (A/m^2) and j_c is the critical current as defined above. This relationship (see Fig. 2) is known to be correct over several decades at low resistance values, and it is not unreasonable to assume that it is true over a wider range. If so then the resistance of the superconductor does not approach that of copper until a current density

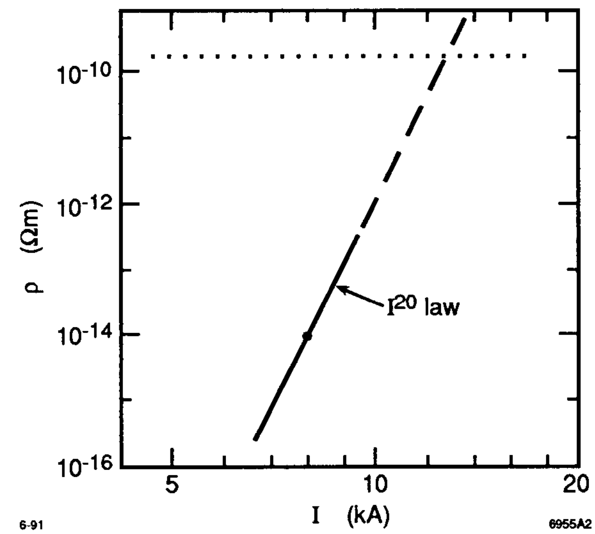

Figure 2. Typical resistance of a superconducting strand as a function of the current in a cable. The continuous line indicates the approximate region over which the dependence is known. The dotted line indicates the assumed extrapolation.

approximately 1.6 times the critical value: a result very different from that assumed in earlier papers.

2. The heat exchange to the helium is assumed to be dominated by a thermal diffusion into supercritical helium, *i.e.*

$$k(t) = \left(\frac{\kappa_{He}\, S_{He}}{t}\right)^{1/2}$$

where the thermal conductivity and specific heat of the helium are:

$$\kappa_{He} = 0.02 \quad (W\ m^{-1})$$

$$S_{He} = 700,000 \quad (J\ m^{-3}\ deg)$$

This assumption gives a good fit to the observed transient cooling to supercritical helium (Ref. 3), and are shown in the same reference to be relevant for two phase helium in small volumes.

3. Allowance is made for a transverse thermal conductivity to other strands within the cable by redefining the A in the differential equation by :

$$A = \pi r^2\ [1 + \frac{z\sqrt{K}}{r}]$$

where r is the strand radius, z is the distance along the cable from the origin, and K_{trans} is the ratio of a transverse conductivity to the longitudinal conductivity. This substitution yields an approximate expression that is exact for $z >> r$ and for $K_{trans} << 1$, and is a reasonable approximation for all values.

4. It is assumed that the very thin layers of helium between the strands would act as thermal welds between the conductors with negligible thermal resistance. The transverse thermal conductivity is thus assumed to be controlled by the cross section of copper outside the superconductor/copper matrix. Examination of typical strand cross sections determined the fractional cross section of copper outside the matrix to be given by:

$$R_{layer} = R_{Cu} - 0.5\ \frac{R_{Cu}}{1-R_{Cu}}$$

and the ratio of transverse to longitudinal conductivity was then given approximately by:

$$K = 0.81\ \frac{1-(1-R_{layer})^{1/2}}{R_{layer}}$$

IV. Results of Calculations

Using the above assumptions a computer program was used to simulate the time and one dimensional spatial development of a quench. In these calculations, two assumptions about the source area have been made:

a) that the energy is deposited in a two dimensional Gaussian distribution with a sigma of 0.3 mm at the edge of a cable;

b) that the energy is deposited in a strip across the cable with a Gaussian distribution along the length with a sigma of 3 mm.

For comparison with Sampson's training data we should assume the source of heating to be from the motion of individual strands and thus assumption (a) is appropriate. With this assumption we have calculated the minimum cable currents at which a given energy deposition will cause a quench for various ratios of copper to superconductor. The energy is then found that best fits the distribution of initial quench currents observed by Sampson. The resulting curve is plotted in Fig. 1 (continuous line). A good agreement is seen.

For comparison calculations have also been made with assumption (b). The result is also plotted on Fig. 1 and is seen not to agree at all with the data.

V. Design Considerations for SSC 5 cm Dipoles

When the decision was taken in the fall of 1989 to change the dipole magnet bore from 4 cm to 5 cm, it was taken on the basis of required dynamic aperture in the Collider. But examination of the typical training of 4 cm magnets showed some basis for concern. The typical operating field margin (the difference between the maximum field attainable and the required operating field) was small : of the order of 4% in practice and essentially zero at the lower limit of specifications. This might be acceptable if all magnets operated at their maximum fields, but even short magnets showed significant training, *i.e.*their first quench

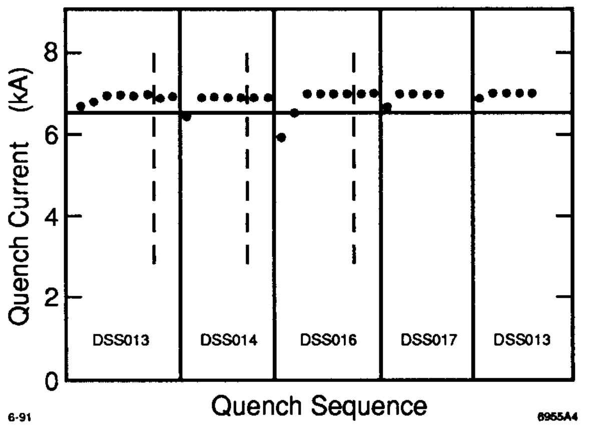

Figure 3. Initial quench sequence of recent 4 cm short (1.8 m) SSC dipole magnets.

was bellow the maximum, and thus often bellow the required operating field (see Fig. 3). In addition long magnets often exhibited training again after subsequent thermal cycles to room temperature and back.

Thus, in designing the new 5 cm dipole magnets, it was desirable to improve both the margin and, if possible, the training. To raise the margin, the area of superconductor must be raised. But if this were done at the expense of copper then, as we have seen above, the training may get so bad that the initial quench current is actually lowered. It was therefore essential to widen the cable and thus be able to increase both the amount of superconductor and the copper ratio.

The specifications chosen were:

		4 cm	5 cm
inner cable	strand diameter (mm)	0.808	0.808
	number of strands	23	30
	Cu/SC ratio	1.3:1	1.5:1
outer cable	strand diameter (mm)	0.648	0.648
	number of strands	30	36
	Cu/SC ratio	1.8:1	1.8:1

VI. COMPARISON OF QUENCH STABILITY FOR 4 AND 5 CM SSC DIPOLE DESIGN

Using the above method we have calculated the minimum energy deposition that will cause a quench in a 4 cm or 5 cm SSC magnet, for various ratios of copper to superconductor. The results for the inner coil are plotted in Fig. 4 for both a) local heat deposition (plotted as continuous lines) and b) heat distributed across the cable (plotted as dashed lines); the 4 cm calculations are plotted as fine lines and the 5 cm as heavy lines. It is seen that :

1. For local heating, there is a considerable improvement in stability as the copper to superconductor ratio is increased, but
2. For wide heating there is an improvement in stability for lower copper to superconductor ratios, but

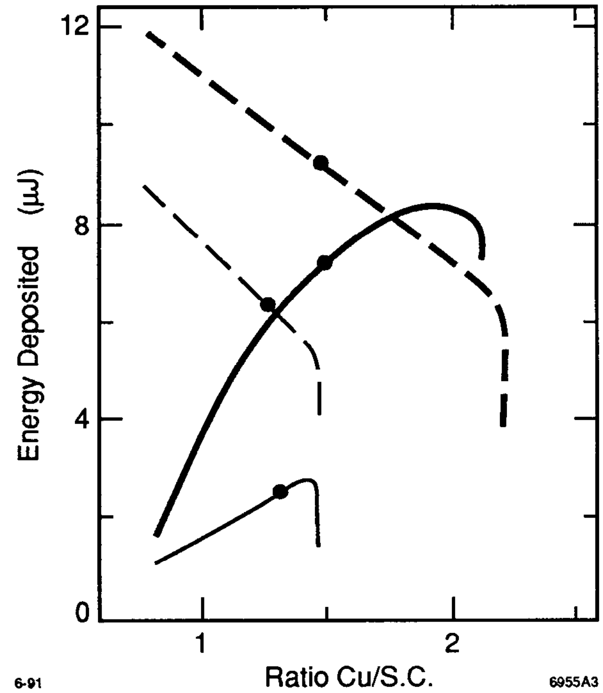

Figure 4. Minimum energy depositions to cause a quench in cables as a function of the ratio of copper to superconductor. Fine lines represent cables from 4 cm magnets, and heavy lines 5 cm magnets. Continuous lines are for local heat deposition with sigma z and y of 0.3 mm, dashed lines are for heating over +/- 3 mm over the full width of the cable.

3. In either case the wider cable in the 5 cm bore design provides a significantly greater stability than in the older 4 cm design.

The results for the outer cable are similar but with generally greater stability.

The critical energies are found to be:

magnet	source	inner	outer	factor
4 cm	local	2.5	6.5	2.6
	wide	5.7	7.7	1.4
5 cm	local	6.6	9.8	1.5
	wide	9.2	8.8	0.9

These results are interesting. For the 4 cm magnets, they predict, as is observed, that the inner coil is less stable, and should thus have more training, than the outer coil. But for the 5 cm magnets the relative stabilities of the coils depends on the source size assumed. For local heating the inner coil is still the less stable, but for wider heating the reverse is predicted. In as far as the early 5 cm magnets do indicate more training quenches of the inner coil, this can be taken as evidence that the cause of such training is local strand movement.

It would be our expectation that as a result of the greater stability, the training of the 5 cm magnets should be significantly better than that in the 4 cm magnets. This expectation has been borne out in the training behavior of

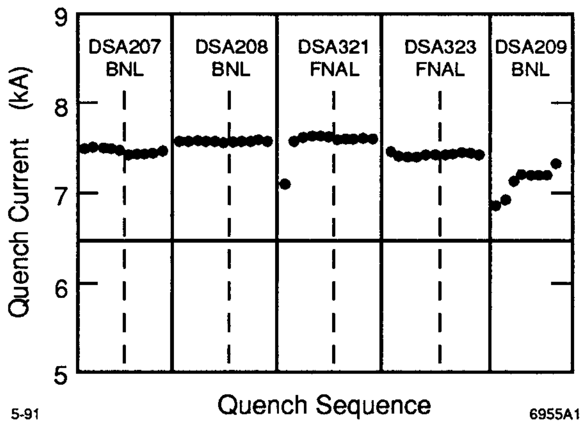

Figure 5. Initial quench sequence of the first five 5 cm short (1.8 m) SSC dipole magnets built to the new design.

the first 5 short 5 cm test dipoles (see Fig. 5). The margin is now seen to have been increased to about 13%, and no initial training is seen in 3 of the five magnets. This is a significant improvement.

Conclusion

It has been shown that if the sources of heating are local and small then stability of a cable is improved if the copper to superconductor ratio is increased, even though, as a result, the margin is reduced. But that the reverse is true for sources of heat that are wider.

It remains to devise a diagnostic to clearly distinguish the two cases in real magnets. There is some evidence from the relative amount of training in the inner and outer layers to suggest that local heating is the more significant, at least in well constructed magnets.

Failing better information one can only conclude that it is best to assume both local and wide sources of heat and design for a significant margin (5-10%) *and* use a relatively high copper to superconductor ratio.

References

[1.] W. B. Sampson, private communication

[2.] K. Y. Ng, Proc. 1989 Part. Acc. Conf., Chicago, Ill., p. 506.

[3.] C. Schmidt, Cryogenics, Vol. 28, p. 585 (1988).