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DESIGN "MARGIN" AND THE EFFECT OF DIFFERENT COPPER-TO-SUPERCONDUCTOR RATIOS ON B_O OF SSC DIPOLES

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A simple calculation is given of the design "margin" of an SSC dipole implied by certain assumptions of superconductor quality (J_c), Cu/SC ratios of the inner cable, operating temperature and maximum field at the conductor. (The inner layer is the critical layer in present SSC dipole designs.) The definition of "margin" is discussed.

The following assumptions are made:

J_c (strand) = 2750 A/mm^2 at 4.22 K, 5 T

I_o = 6600 A at B_o = 6.6 T, T = 4.35 K; B_o/I_o = constant = 1.0 T/kA

B_{max} = kB_o where k = 1.046 for the inner layer (k varies only slightly with specific coil cross section designs)

A convenient J_c - T - B correlation [1] is used.

With these assumptions, the magnet critical current (sometimes called the magnet "short sample" current) is determined graphically as illustrated in Fig. 1, or analytically[2]; Fig. 1 illustrates the two definitions of margin used here.

Keep in mind that design "margin" as used here is not just a "safety factor", but includes many real effects that are difficult to determine quantitatively, and which will conspire to degrade magnet performance. These effects include:

Cable degradation

Temperature fluctuations

Uncertainty in property measurements

Statistical variation of properties along cable length

dB/dt effects

Stability margin

Coil manufacturing errors, etc.

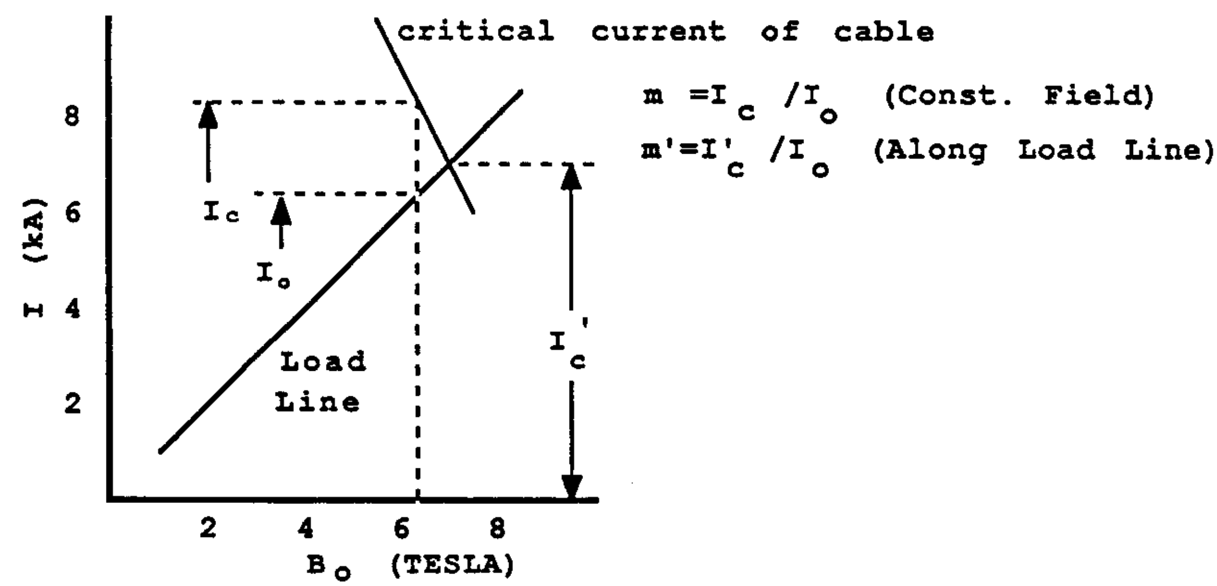

Figure 1

Note that m (constant field) is much larger than m' (along load line).

Case I - Constant $B_0 = 6.6$ T, $I_0 = 6600$ A, T = 4.35 K, Cu/SC and "margin" varies. The result is shown in Table I (for the inner cable); the design "margin", m = I_c/I_0 (at $B = B_0$) = 1.246 for Cu/SC = 1.3, and decreases as shown as Cu/SC ratio increases.

TABLE I.

Cu/SC Ratio	I_o Amp	I_c Amp	I_c' Amp	m = I_c/I_o	m' = I_c'/I_o
1.3	6600	8228	7021	1.246	1.064
1.5	6600	7563	6866	1.146	1.040
1.8	6600	6752	6646	1.023	1.007

Case II - Assume a constant design "margin", m = I_c/I_0 = 1.246 and vary Cu/Sc ratio. The operating current decreases as Cu/SC increases as shown in Table II.

TABLE II.

Cu/SC Ratio	I_o Amp	B_o Tesla	I_c Amp	I_c' Amp	m = I_c/I_o	m' = I'_c/I_o
1.3	6600	6.600	8228	7021	1.246	1.064
1.4	6514	6.514	8113	6943	1.246	1.066
1.5	6430	6.430	8009	6866	1.246	1.068
1.6	6349	6.349	7907	6791	1.246	1.070
1.7	6269	6.269	7808	6717	1.246	1.072
1.8	6191	6.191	7711	6646	1.246	1.073

Similar tables could be made with more exact assumptions including: transfer function slightly different from $B_o/I_o = 1.0$ T/kA, the newer cable specification with minimum critical current defined at 7 T - inner, and 5.6 T - outer, and different algorithms could be used for scaling of J_c with B and T. However, the basic features will be similar and the variation of margin with Cu/SC, or of B_o with constant margin, will be essentially unchanged.

Case III - Use the new <u>strand</u> specification.

The inner strand specification [4] is 328 A minimum critical current at 7 T, 4.22 K (1600 A/mm^2, Cu/SC = 1.5) which implies a strand-to-cable degradition of 5.0%. Using the strand spec., the margin (now including strand-to-cable degradation) at 6.6 T is:

$$m = I_c/I_o = 7276/6600 = 1.102 \text{ (constant field)}$$

$$m' = I_c'/I_o = 6792/6600 = 1.029 \text{ (along load line)}$$

Case IV - Use the new cable specification.

The latest inner cable specification [3] is 7167 A minimum critical current at 7 T, 4.22 K for Cu/Superconductor ratio of 1.5 ± 0.1. For the same assumptions as used before, but using this cable spec., the margin at 6.6 T is:

$$m_{cable} = I_c/I_o = 6922/6600 \text{ (constant field)} = 1.047$$

$$m'_{cable} = I_c'/I_o = 6692/6600 = 1.014 \text{(along load line)}$$

(Note that, unlike the previous definition, "margin" here does not include strand-to-cable degradation.)

These design margin values, as calculated for the new strand or cable specifications in Cases III and IV, are too low, in the opinion of the author; if superconductor cross-section is reduced by increasing Cu/SC ratio to 1.5, the design field of the SSC should be accordingly reduced to about 6.4 T. Alternatively, the operating temperature could be decreased to preserve the present margin; for example, based on the assumptions on page 1, if T is reduced to 4.185 K as Cu/SC is increased to 1.5, the operating "margin" of m = 1.246, based on J_c of the superconductor, is preserved. (Reduction of heat capacity with temperature may require somewhat lower temperature for equivalent stability.) Additional Cu will, in general, improve stability; however, we have no convincing evidence that the small increase in Cu area achieved by increasing Cu/SC from 1.3 to 1.5 (A_{Cu} increases by 6.2% from 6.661 mm^2 to 7.071 mm^2) will result in a significant increase in stability behavior of the magnets. However, if it is decided to increase Cu/Sc to 1.5, we should concurrently officially reduce the target operating field to about 6.4 T or reduce the maximum operating temperature to about 4.15 K. A "margin" at least as large as the present "margin" is needed to allow for the several types of effect listed above.

REFERENCES

(1) $$J_c(T,B) = J_c(T_o,B_o)\left(1 - \frac{P_2(T-T_o) + P_3(T-T_o)^2 + P_4(T-T_o)^3}{1 + P_5(B-B_o)}\right)[1 + P_6(B-B_o)].$$

$P_2 = -0.35424$, $P_3 = -0.023346$, $P_4 = 0.0061392$, $P_5 = -0.15335$, $P_6 = -0.19757$

G. Morgan, "Analytic Forms for Critical Current Data," BNL, SSC-MD-84 (12/11/84).

(2) In this case, the solutions are determined quickly using the "solve" function on an HP15C hand calculator.

(3) "NbTi Superconductor Cable for SSC Dipole Magnets," SSC-MAG-M-402 (6/9/87).

(4) "NbTi Wire for SSC Dipole Magnets," SSC-MAG-M-401 (6/9/87).