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# PEAK OPERATING FIELD FOR DIPOLE MAGNETS

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## Summary

An operating central field of 6.4 tesla for designs A and D, 5.5 tesla for design B and 3 T for C are suggested for the purpose of scaling cost on a comparable basis.

## Introduction

At the time of the Reference Designs Study (May 1984) a Nb-Ti current density of 2400 A/mm$^2$ (5T, 4.2K, $10^{-12}$ ohm-cm) was selected as a "design goal" for the strand used in the cable for design A. The comparable value for strand used in the Tevatron magnets was about 1850 A/mm$^2$ over an extended production period. However, at that time (early 1984) the possible potential for improving the $J_c$ was realized based on multiple heat treatments (instead of a single heat treatment) using a more homogeneous NbTi alloy. This had been verified on a small laboratory specimen but not yet tested in production. Cable for design A(84) had not yet been produced commercially in its final configuration and model magnets had not yet been tested. In the absence of directly applicable experience reasonable allowances were made for degradation caused by cabling and a design field of 6.5T was chosen for design A(84). This design was a 2-in-1 design with a close-fitting cold iron yoke. In contrast, designs A and D have a 15 mm collar between the windings and the cold iron. This effect decreases the field that can be attained.

## Design A and D

At present, we can base the magnet operating field on experimental results from 4.5-m BNL models and 1-m LBL models. Production cable with strand $J_c$

(4.2, 5T, $10^{-12}$ ohm-cm) of 2500 A/mm$^2$ results in magnets with a critical field of 6.6T or greater that is achieved with reasonably little training. Figures 1 & 2 show training curves. With improved $J_c$ that we anticipate, we can expect higher critical fields. Strand $J_c$ of at least 2700 A/mm$^2$ has been delivered routinely in recent procurements (LBL and TAC) and the latest strands from a 12" billet has 2950 A/mm$^2$ (LBL-Supercon). We have assumed that strands with a minimum $J_c$ of 2750 A/mm$^2$ can conservatively be provided in large quantities in the future.

To be conservative, we reduce the operating field to a value substantially less than the expected critical field to allow for effects such as occasional radiation heating due to beam spill. Thus we suggest 6.4T as the nominal operating field for design D; at this field the strand $J_c$ at 4.5 K is about 25% higher than the operating current density. We believe that this is a prudent safety margin to use at present, even though we expect each magnet to have a maximum field at least 0.4 tesla higher.

Figure 3 shows J strand vs. $B_0$ for Design D; $J_c$ of the strand, taken at the maximum field at the value of 1.045 x $B_0$, is plotted for two different classes of superconductor; one, labeled $J_c$ = 2500, is representative of cable used in present models and the other, labeled $J_c$ = 2750, is what we expect for future procurements based upon material now being delivered. Also showing is J vs. $B_0$ for the Design D magnet. (a) is the representative model operating point, (b) is the design critical field limit and, (c) is the assumed design operating point.

Design B

With the same 25% operating margin ($j_{crit}/j_{op}$ = 1.25), $B_0$ = 5.5 tesla for design B.

Table I gives the operating condition for the models and the assumed operating conditions for Designs D and B.

Design C

In contrast to the cosine theta magnets, the peak field of the C design is limited by the properties of iron. This less well defined limit manifests itself as a deterioration of field quality as the field rises. Measurements and calculations to date (see the final report of the Technical Magnet Review Panel) indicate that rapid change of the field shape begins in the neighborhood of 3T. Consequently this value was used as the peak operating field of the C design for the purposes of the cost estimate.

Table I

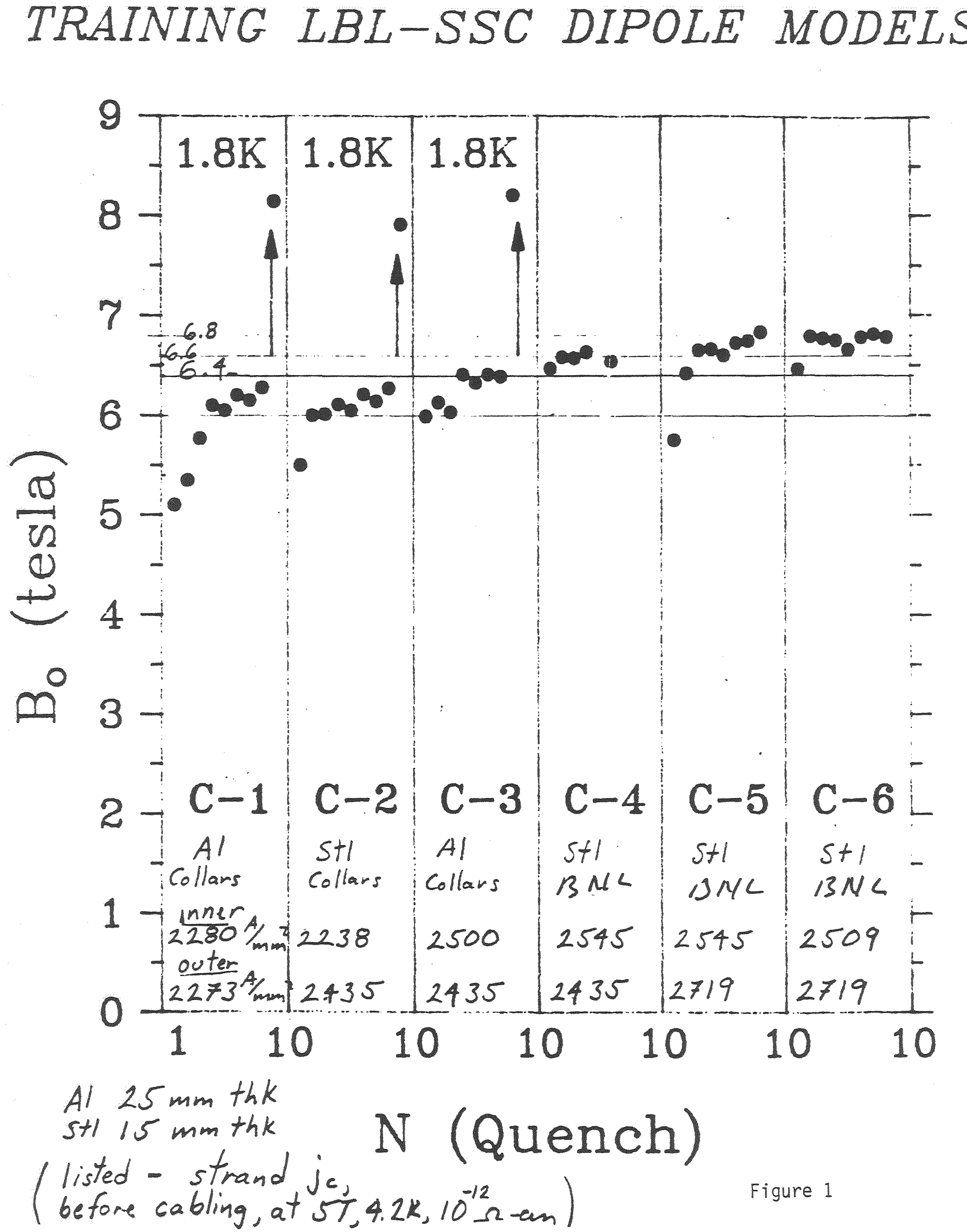
| | $B_0$ tesla | Operating j A/mm$^2$ | $j_c$ strand 4.2 K, 5T A/mm$^2$ | $J_c$ strand 4.5 K B = 1.045 $B_0$ | $j_c/j_0$ |
|---|---|---|---|---|---|
| Models Design D | 6.6 Measured | 1277 | 2500 Measured | 1311 | 1.03 |
| Production Design D | 6.40 | 1238 | 2750 Specified | 1546 | 1.25 |
| Production Design B | 5.50 | 1627 | 2750 Specified | 1988 | 1.25 |

Design D

$B_0/I$ = 1.009 T/kA at 6.4T
inner cable: 23 str x .0318"
cu/superconductor: 1.3
Exptl critical $B_0$ = 6.6T with
$J_c$ of strand = 2500 A/mm$^2$ (4.2K, 5T)

Design B

$B_0/I$ = 0.841T/kA at 5.5T
inner cable: 25 str x .0298"
cu/superconductor = 1.8



TRAINING LBL–SSC DIPOLE MODELS
1.8K
1.8K
1.8K
6.8
6.6
6.4
$B_o$ (tesla)
C–1
Al Collars
inner 2280 A/mm²
outer 2273 A/mm²
C–2
Stl Collars
2238
2435
C–3
Al Collars
2500
2435
C–4
Stl BNL
2545
2435
C–5
Stl BNL
2545
2719
C–6
Stl BNL
2509
2719
N (Quench)
Al 25 mm thk
Stl 15 mm thk
(listed - strand jc, before cabling, at 5T, 4.2K, $10^{-12}$ Ω-cm)


Figure 1

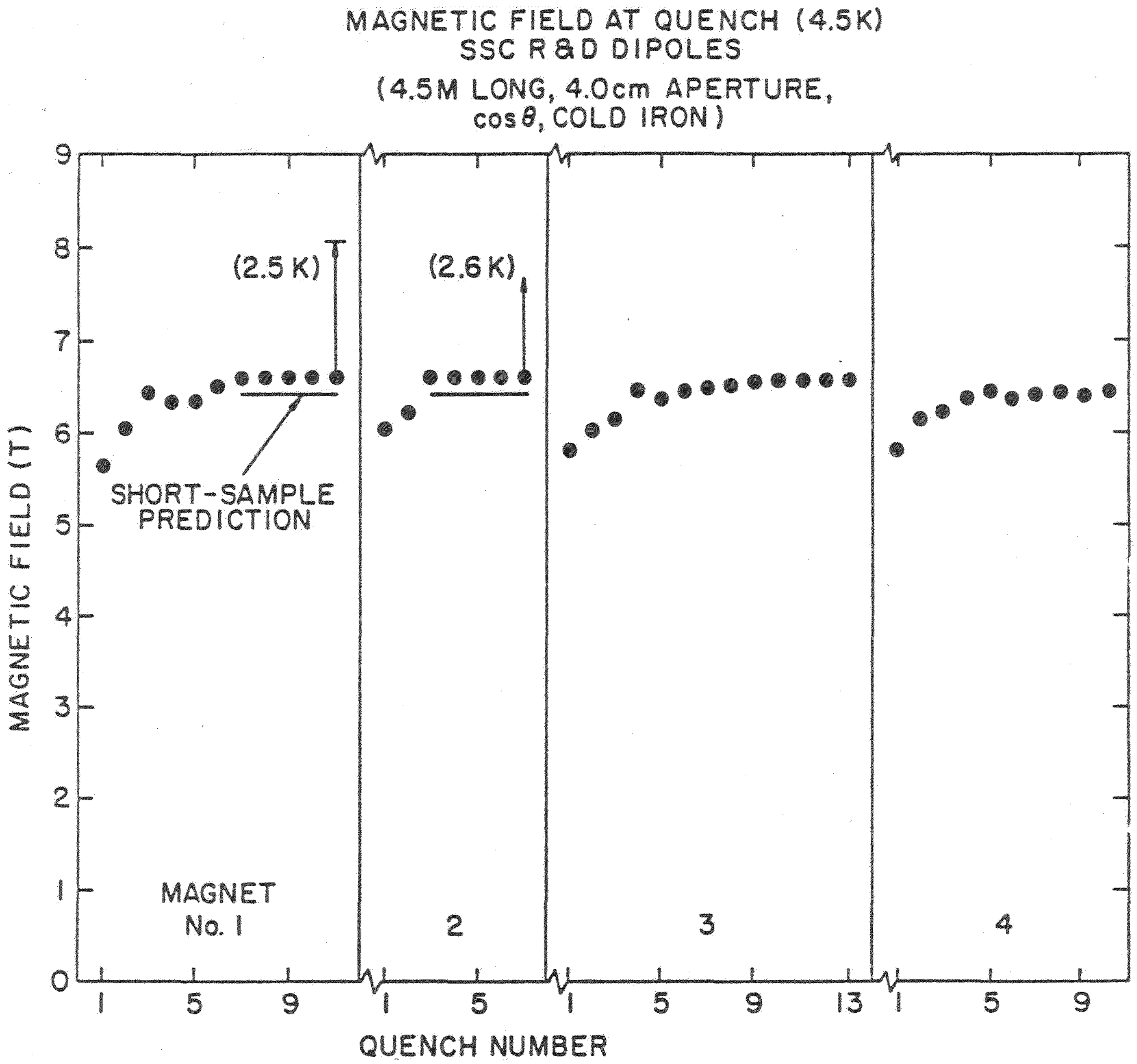

MAGNETIC FIELD AT QUENCH (4.5K)
SSC R&D DIPOLES
(4.5M LONG, 4.0cm APERTURE,
cos θ, COLD IRON)
MAGNETIC FIELD (T)
0
1
2
3
4
5
6
7
8
9
(2.5 K)
(2.6 K)
SHORT-SAMPLE
PREDICTION
MAGNET
No. 1
2
3
4
1
5
9
1
5
1
5
9
13
1
5
9
QUENCH NUMBER

Figure 2

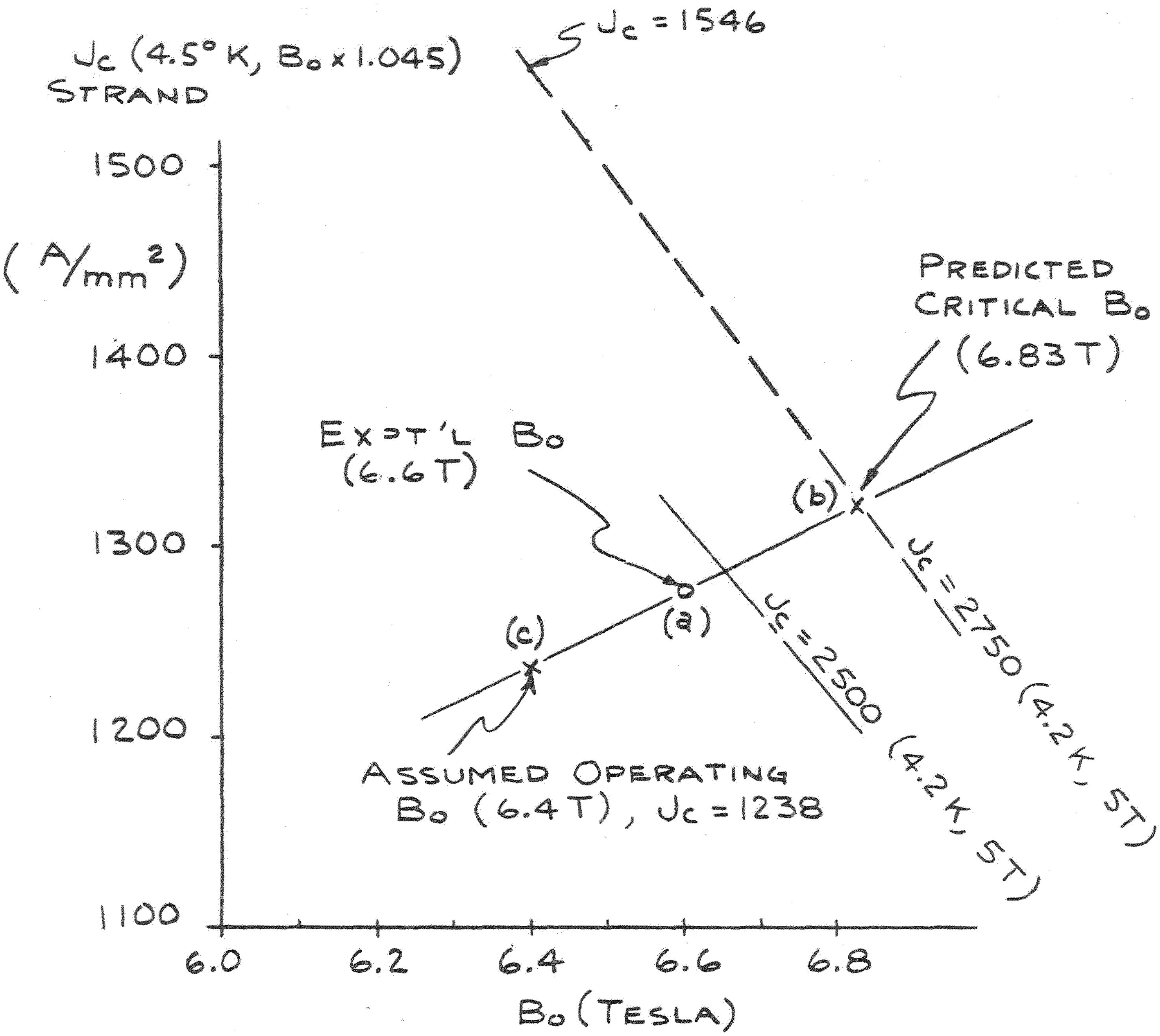



Fig. 3 Strand $J_c$ vs. $B_0$ for
(a) Model magnets with $J_c$ (4.2 K, 5T) = 2500 A/mm$^2$,
(b) Predicted critical $B_0$ for $J_c$ (4.2, 5T) = 2750 A/mm$^2$,
(c) Assumed $B_0$ for design D,

(Operating "margin" = 0.38 T) at $\frac{J_c \text{ strand}}{j_{\text{operating}}} = 1.25$

## Appendix A
## Scaling $J_c$ of Nb-46.5% Ti with B and T

$J_c$ of this alloy, made with high-homogeneity rod, has been measured by Larbalestier[1] as a function of field. It is well known that in similar alloys with differing $J_c$'s, that $J_c$ will scale with B and T in an identical manner. A scaling relationship[2] that fits data well over the range of B and T of interest is:

$$J_c = P_1\left(1-\frac{T-4.2}{P_2-BP_3}\right)\left(\frac{1+P_4B}{1+P_5B+P_6B^2}\right) \qquad (1)$$

where T in K, B in tesla, $J_c$ and $P_1$ in A/mm$^2$

$P_2$ = 4.996
$P_3$ = - .465
$P_4$ = - .10263
$P_5$ = .31525
$P_6$ = - .030335

and $P_1$ is determined from measured $J_c$.

Comparison with measured data at 4.2K is shown in Table II below.

Table II

| B | $J_c$ A/mm$^2$ Measured | $J_c$ A/mm$^2$ Calculated From (1) |
|---|---|---|
| 8 | 967 | 988 |
| 7 | 1429 | 1429 |
| 6 | 1892 | 1864 |
| 5 | 2339 | 2339 |
| 4 | 2844 | 2899 |

$P_1$ = 8734 to normalize calculation and data at 5 T.

In the field range of interest, B = 6-7T, agreement is excellent, and is very good over a wide range. Scaling with temperature is well understood. At 6 T, the above equation predicts that $J_c$ at 4.2K/$J_c$ at 4.5 K = 1.126.

(1) Larbalestier, IEEE Trans. on Nuc. Sci., NS-30, No. 4, p. 3299 ff.
(2) G. Morgan, SSC-MD-84, BNL.

An example of measured data at 6 T (see Fig. 4) shows a scaling:

$$J(T_2) = J(T_1) \bullet \left( \frac{7 - T_2}{7 - T_1} \right) \quad \text{giving } J_c(4.2K)/J_c(4.5K) = 1.120$$

agreement is excellent; the equation given a slightly convervative value of $J_c$ at 4.5K. Using the equation the following values of $J_c$ at 4.5K are predicted for material with

$J_c$ = 2500 at 5 T, 4.2K and

$J_c$ = 2750 at 5 T, 4.2K

| B | $J_c$ = 2500 at 5T, 4.2 | $J_c$ = 2750 at 5T, 4.2 |
|---|---|---|
| 3 | 3541 | 3895 |
| 4 | 2803 | 3083 |
| 5 | 2219 | 2441 |
| 6 | 1722 | 1895 |
| 7 | 1265 | 1391 |

These values are used in Table II to determine operating J for designs D and B.

1025S

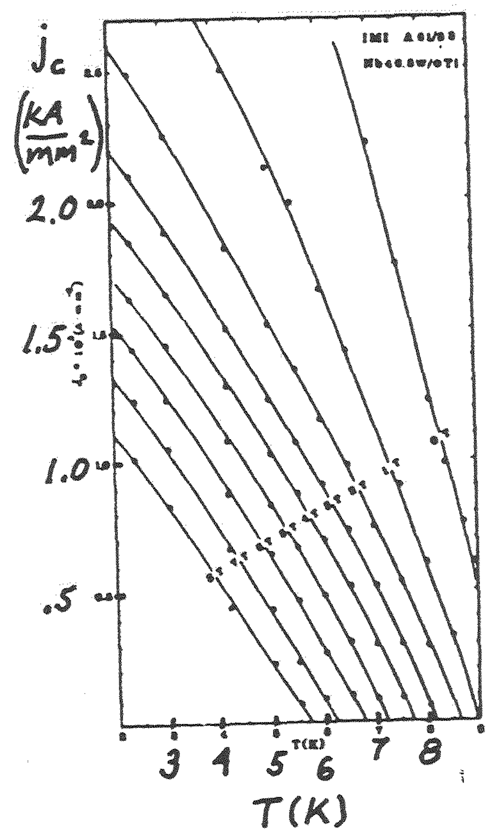



Fig. 4

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EVALUATION OF THE TEMPERATURE AND MAGNETIC FIELD DEPENDENCE OF CRITICAL CURRENT DENSITIES OF MULTIFILAMENTARY SUPERCONDUCTING COMPOSITES

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