SLAC-PUB-2241
December 1978
(I)

OBSERVATIONS ON FLUX JUMPING IN TUBULAR Nb_3Sn SAMPLES IN TRANSVERSE FIELDS*

David J. Frankel

Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94305 USA

ABSTRACT

The flux jumping behavior of tubular samples of vapor-deposited Nb_3Sn has been observed at 4.2 and 1.9 K. Measurements of field profiles along the axis of the sample tubes provided information on the extent of the flux jumps and the nature of the field structure remaining after the jumps. Measurements of the field inside the tube as a function of the applied field provided information on the frequency and field dependence of the flux jumping. At low fields numerous partial flux jumps occurred, while above a critical field level of 5-10 kG samples were stable. The tubes were less stable at the lower temperature, although some improvement in stability was obtained by electroplating one of the samples with copper. The observations were compared with predictions based on the adiabatic stability criteria. Agreement was obtained between the observed temperature and field dependencies of the instabilities and the predictions of the theory.

(Submitted to Cryogenics)

*Supported by the Department of Energy, Contract No. EY-76-C-03-0515.

The flux trapping and shielding process can be used to trap or shield fields of practical interest.[1,2,3,4] A study of this process indicates that flux trapping and shielding is often limited by the occurrence of instabilities.[3,4] In general, an exact analysis of the flux jump process is a formidable problem. However, when the magnetic field changes occur on a time scale which is short compared to the time scale for thermal changes, a relatively simple expression can be derived which describes the conditions under which a small field or temperature perturbation will lead to a runaway situation. This note describes in more detail the flux jumping behavior of tubular vapor-deposited Nb_3Sn tubes, and compares it to predictions based on the adiabatic stability criteria.

THEORY

A number of authors[5,6,7,8] have derived expressions for the adiabatic stability criteria for cases of superconducting slabs or cylinders in parallel fields. These expressions generally predict that the field structure within the material will be unstable with respect to small field or temperature perturbations if the difference between the applied field and the field in the interior of the sample is greater than a critical level, H_{fj}, given by

$$H_{fj} = \left[10^7 \pi A C J_c \left(\frac{dJ_c}{dT}\right)^{-1}\right]^{\frac{1}{2}} = \left[10^7 \pi A C T_d\right]^{\frac{1}{2}} , \qquad (1)$$

where $T_d = \left(\frac{1}{J_c}\frac{dJ_c}{dT}\right)^{-1}$,

A = numerical factor with a value close to 10, which depends on the details of the particular derivation.

The applicability of this adiabatic stability criterion to Nb_3Sn can be verified by comparing estimates of the thermal and magnetic diffusivities

$$D_{th} = K/C , \qquad D_m = \frac{10^9}{4\pi} \rho .$$

The heat capacity, C, of Nn_3Sn at 4.2K is in the 1.4–1.8 mJ/cm^3-K range,[9,10] and the thermal conductivity, K, of Nb_3Sn is very low, 0.4mW/cm-K at 4.2K.[11] As a result D_{th} is less than 1 cm^2/sec. The low temperature normal state electrical resistivity of Nb_3Sn, ρ_n, is of the order of 10$\mu\Omega$-cm,[11] so D_m should be of the order of 1000 cm^2/sec. However, there can be large variations in ρ_n among different samples, and the relationship between ρ_n and the effective resistivity of the superconductor during a flux jump is somewhat uncertain. Although the effective resistivity is often approximated by simply using ρ_n, or by using a resistivity equal to the flux flow resistivity $\rho_f = \rho_n (H/H_{c2})$, neither procedure has been clearly demonstrated. In any case, Nb_3Sn should approach the adiabatic limit since the calculation given here results in a D_m approximately 1000 times larger than D_{th}.

The flux jump field for Nb_3Sn can be estimated by using appropriate values for T_d and C in Eq. (1). Experimental data on $J_c(T)$ of Nb_3Sn prepared in several different manners[12,13,14,15] are generally well fitted by the function

$$J_c(T) = J_c(0) \left[1 - (T/T_0)^2\right],$$

with the parameter T_0 1-2K less than T_c. This form of $J_c(T)$ implies

$$T_d = \left[1 - (T/T_0)^2\right] T_0^2/2T .$$

With $T_0 = 16.6$K, and C(4.2) = 1.6 mJ/cm^3-K, $T_d(4.2)$ is equal to 30, and $H_{fj}(4.2)$ is equal to 3670 Oe. Although there is little detailed data available on C(T) below 4.2K, H_{fj} at 1.9K can be estimated by assuming that the T^3 dependence of C(T) above 4.2K continues at the lower temperatures. If C(1.9) = 0.15 mJ/cm^3-K, and $T_d(1.9) = 72$K, then $H_{fj}(4.2)/H_{fj}(1.9)$ is equal to 2.12, and $H_{fj}(1.9)$ is equal to 1730 Oe.

EXPERIMENT

The experimental apparatus and procedure were similar to those described in Ref. 16. The samples were fabricated by vapor-depositing alternate layers of Nb_3Sn and Nb-Sn alloy, or Nb_3Sn and yttrium, onto 0.64 cm diameter, 7.56 cm long Hastelloy tubes.[14,15] Measurements were carried out inside a glass dewar inserted into a large, water-cooled, 20 kG magnet. The samples were oriented so that the uniform applied field was directed perpendicularly to the sample axis. The magnetic field was measured by a Hall effect probe with an active area 0.10 cm × 0.20 cm.[17] The probe could be translated along the axis of the hollow samples, while its position was monitored by a potentiometer coupled to the driving mechanism located on the top of the dewar cap. During the experiments, the steady increase or decrease of the applied field could be periodically halted, and a field profile obtained by moving the Hall probe along the axis of the sample. Alternatively, the probe could be held in a fixed position inside the hollow sample as the applied field was varied. All data were taken with the samples immersed in liquid helium. Temperatures below 4.2 K were obtained by pumping on the helium.

RESULTS

Uniform fields of approximately 1200-1600 G were generally trapped or shielded by the tubes, and differences of more than 2000 G between the fields inside the samples and the applied transverse field were observed. In the latter cases the field inside the tubes was nonuniform. Flux jumping limited flux trapping and shielding ability in most cases. The field profile measurements showed that the flux jumps were partial in nearly all cases, usually affecting less than half of the sample tube at a time. Even in regions affected by the flux jumps, the field measured after the jumps was nonuniform, and generally not equal to the field applied at the time of the flux jump. This indicated that at most only small regions of the sample were driven normal during the flux jumps. Curves generated with the Hall probe held in a fixed position inside the tubes while the applied field was varied (Fig. 1) show that at low fields, field changes occurred only through flux jumps, while above a critical field level (on the order of 5000 Oe) flux jumps no longer occurred and the internal field changed smoothly with changes in the applied field. The curves also show the effect of reducing the sample temperature from 4.2 to 1.9 K. At the lower temperature the samples are less stable, with flux jumping occurring more frequently and persisting to higher fields. A comparison of field profiles measured at 4.2 and 1.9 K (Fig. 2) showed a change in the nature of the field profiles as well. Relatively steep gradients in the field near the ends of the sample tubes were observed at 4.2 K, while only relatively flat profiles were observed at 1.9 K.

Additional tests were made after one of the sample tubes (74-72) was electroplated with copper. Several features associated with an increase in overall stability were observed. At 4.2 K, the region of stability was increased, as flux jumps occurred only below $H_a = 2400$ Oe. At 1.9 K, the trapping and shielding ability of the coated sample were superior to those of the uncoated material, and the appearance of the field profiles reverted to the form typical of profiles obtained at 4.2 K. The B vs H_a curves obtained at 1.9 K now consisted of a succession of very small flux jumps, with $\Delta H_a = \Delta B \simeq 50$ G. The small jumps occurred when field differences between the internal field and the applied field were slightly less than the corresponding differences obtained at 4.2 K, but generally larger than obtained with the uncoated tube at 1.9 K. No large flux jumps were observed at 1.9 K with the coated tube.

Table I summarizes the results obtained with the various Nb_3Sn samples. All samples were produced by vapor-depositing alternate layers of Nb_3Sn and a barrier material on Hastelloy tubes. Variations in critical currents among the tubes are due to variations in the growth morphology of the Nb_3Sn produced by the differences in layer thickness, barrier material, and substrate temperature.[14,15] The measurements showed that tubes with higher current densities tended to be less stable. In these samples flux jumps occurred more frequently and persisted to higher fields. As a result, the trapping and shielding ability of the higher J_c tubes was actually poorer than the lower J_c samples.

The flux trapping and shielding abilities of these samples were compared with predictions based on a critical current model.[18] The model adequately described the shape of typical shielding and trapping profiles, and gave critical current values of $3 - 4 \times 10^6$ A/cm^2, in agreement with values measured in axial fields by Howard.[14,15] The model indicated that most flux jumps took place at field differences of roughly 50-100% of the maximum possible for the thickness and critical current density of the material.

DISCUSSION

The behavior of the Nb_3Sn coated tubes was interesting in several respects. At both 1.9 and 4.2 K they exhibited flux jumps at low fields but were stable at higher fields. At 1.9 K the unstable region extended to higher fields than at 4.2 K. The potential trapping and shielding ability is approximately given by the product of the critical current and the wall thickness of the sample:

$$H_d = 1.257 J_c x .$$

The samples with higher values of H_d were somewhat more unstable than the lower H_d samples. The results suggest that the change in stability was related both to changes in H_d, and to changes in a property such as the heat capacity which varies rapidly in the 1.9 - 4.2K range.

The samples tested here became unstable at fields somewhat lower than the estimates of H_{fj} derived from Eq. (1). However, the general features of the theory can still be tested by choosing a more reasonable value for H_{fj} and comparing the resulting predictions of sample behavior to the experimental observations. A value $H_{fj}(4.2) = 1900$ Oe is close to the maximum values of $|H_a - H_i|$ observed in the more stable samples (74-72, 74-87) and accounts fairly well for the behavior of the other samples as well (Table II). This value is not inconsistent with the predicted value of H_{fj}, since the demagnetization factor can account for a reduction in the theoretical value of 3700 Oe by a factor of 1.5 to 2400 Oe.

Most of the flux jumping behavior in these samples is reasonably well explained by the simple adiabatic stability model if it is assumed that a sample will become unstable and exhibit flux jumps only if it is possible for a field difference greater than H_{fj} to be present across the sample wall. For example, sample 74-87 has a Nb_3Sn thickness of 6.33×10^{-4} cm. In order to maintain a field difference of 1900 G or more and therefore be potentially unstable at 4.2K, the average critical currents must be greater than a threshold value given by

$$J > \frac{1900}{1.257 \times 6.33 \times 10^{-4}} = 2.39 \times 10^6 \ \mathrm{A/cm^2} .$$

The Kim model can be used to approximate the field dependence of J_c: [19]

$$J_c(B) = 3.9 \times 10^6/(1 + B/5000) .$$

The expression indicates that critical currents greater than the threshold value flow only in fields below 3200 G. At 1.9 K the adiabatic theory predicts that H_{fj} should be reduced by a factor of 2.12 to 900 Oe. Therefore, at 1.9 K flux jumps should occur only when $J > 1.13 \times 10^6$ A/cm^2, and this occurs only when the ambient field is less than 13400 G.[20] Table II presents a comparison of experimental results with predictions based on the adiabatic model. While the model accounts for the gross variations in stability between samples, there are significant deviations between experiment and theory, and the simple theory does not account for all the details of the flux jumping behavior. For instance, the model does not indicate why there are variations in the size and frequency of flux jumps among the samples, although it seems clear that the samples with higher values of H_d tend to undergo more and smaller flux jumps. The model also fails to explain in detail why the slope of the $B_x(z)$ curves is reduced at 1.9 K. However, the reduced slope is generally in accord with the concepts of the theory, since the measured field profiles reflect the state of the sample when flux jumps are brought to a halt, and at the lower temperatures the propagation of the flux jump is more favored, since the heat capacity is decreased and J_c is increased. The effect of the copper coating in reducing the size of flux jumps at 1.9 K, and in allowing steeper profiles, is consistent with the general features of the dynamic stability criterion.[8]

CONCLUSIONS

Instabilities were observed to limit the flux trapping and shielding ability of several tubular Nb_3Sn samples. The flux jumps affected limited portions of the tubes at a time and did not result in a total breakdown of the trapping and shielding action in the affected regions. The flux jumping was more severe in samples with greater values of the parameter H_d, and at lower temperatures and fields. Flux jumps ceased to occur above a critical field level which depended on both the temperature and the sample properties. The variations in this critical field among the samples, and with temperature, were fairly well accounted for with an adiabatic analysis. In the analysis it was assumed that the sample would be unstable if a field difference greater than the predicted flux jump field, H_{fj}, could be maintained across the sample wall. This criterion is equivalent to a limitation on the maximum linear current density (A/cm) in the material. However, there were some discrepancies between the theory and experiment, and the simple theory does not fully account for all aspects of the flux jumping behavior. The experiments do show that the simple adiabatic analysis is useful in predicting qualitative behavior of Nb_3Sn samples, but that a more detailed theory is required to fully account for flux jumping behavior.

REFERENCES

1. Rabinowitz, M., Garwin, E.L., Frankel, D.J. Nuovo Cimento Lett. 7, No. 1 (1973) 1.
2. Garwin, E.L., Rabinowitz, M., Frankel, D.J. Appl. Phys. Lett. 22 (1973) 599.
3. Frankel, D.J., Garwin, E.L. IEEE Trans. Magn. MAG-13, No. 1 (1977) 205.
4. Frankel, D.J. Ph.D. Dissertation, Stanford University (1978).
5. Hancox, R. Phys. Lett. 16, No. 3 (1965) 208.
6. Wipf, S.L. Phys. Rev. 161, No. 2 (1967) 404.
7. Swartz, P.S., Bean, C.P. J. Appl. Phys. 39, No. 11 (1968) 1991.
8. Wilson, M.N., Walters, C.R., Lewin, J.D., Smith, F.F. J. Phys. D 3 (1970) 1517.
9. Vieland, L.J., Wicklund, A.W. Phys. Rev. 166, No. 2 (1968) 424.
10. Harper, J.M.E. Ph.D. Dissertation, Stanford University (1975).
11. Weger, M., Goldberg, I.B. Solid State Phys. 28 (1973) 1.

12. Bussiere, J. F., Garber, M., Shen, S. Appl. Phys. Lett. 25, No. 12 (1974) 756.

13. Schwall, R. F., Howard, R. E., Zubeck, R. B. IEEE Trans. Magn. MAG-11, No. 2 (1975) 397.

14. Howard, R. E. Ph. D. Dissertation, Stanford University (1976).

15. Howard, R. E., King, C. N., Norton, R. H., Zubeck, R. B., Barbee, T. W., Hammond, R. H. Advan. Cryog. Eng. 22 (1976) 332.

16. Frankel, D. J., to be published.

17. Bell FH-301-040, F. W. Bell Inc., Columbus, Ohio.

18. Frankel, D. J., to be published.

19. Howard has measured $J_c(B=0) = 3.9 \times 10^6$ and found that many of his samples follow the Kim model with B_0 on the order of 5000 G.

20. $J_c(B, 1.9K) = J_c(B=0, 1.9K)/(1 + B/5000)$, and $J_c(T) = J_c(0)[1-(T/T_0)^2]$ with $T_0 = 15.4K$ have been assumed.

TABLE I

Results of Measurements with .64 cm diam Nb_3Sn-coated Tubes

Sample	Maximum Uniform Field Trapped and Shielded (G)	$\lvert H_a - H_i \rvert_{max}$ (Oe)	Applied Field at which Last Flux Jump Occurs: increasing fields 4.2K (Oe)	increasing fields 1.9K (Oe)	decreasing fields 4.2K (Oe)	decreasing fields 1.9K (Oe)	$J_c(4.2)$ (Howard) (A/cm^2)
74-72							
uncoated	1500-1600	2300	3000-5000	>7000	2600-4500	>7000	-
coated	1600-1750	2100	2300-2400	>7000	1100-1200	>7000	-
74-87	1500	1800	3300-3500	13000	3100-4100	13200	3.9×10^6
74-92	1600	-	7000	14400	2300	10300	4.4×10^6
75-94	1300-1400	1400	7300-8000	-	5500-5800	-	4.2×10^6

TABLE II

Comparison of Flux Jumping Behavior of Nb_3Sn Samples to Predictions Based on the Adiabatic Stability Criterion

Sample	$J_c(4.2)$	Thickness of Nb_3Sn	H_d	Maximum Field for Instabilities			
				Calculated		Observed	
				4.2K	1.9K	4.2K	1.9K
	(A/cm^2)	(cm)	(Oe)	(Oe)	(Oe)	(Oe)	(Oe)
74-72	3.0×10^6	6.60×10^{-4}	2500	1550	9800	2600-5000	>7000
74-87	3.9×10^6	6.33×10^{-4}	3100	3200	13400	3100-4100	13100
74-92	4.4×10^6	6.33×10^{-4}	3500	4200	15700	2300-7000	10300-14400
75-94	4.2×10^6	6.90×10^{-4}	3600	4600	16700	5500-8000	-

FIGURE CAPTIONS

1. Transverse field inside sample 74-87 as a function of the applied field at 4.2 and 1.9 K.
2. Field profiles along the axis of sample 74-87 obtained during shielding tests at 4.2 and 1.9 K.

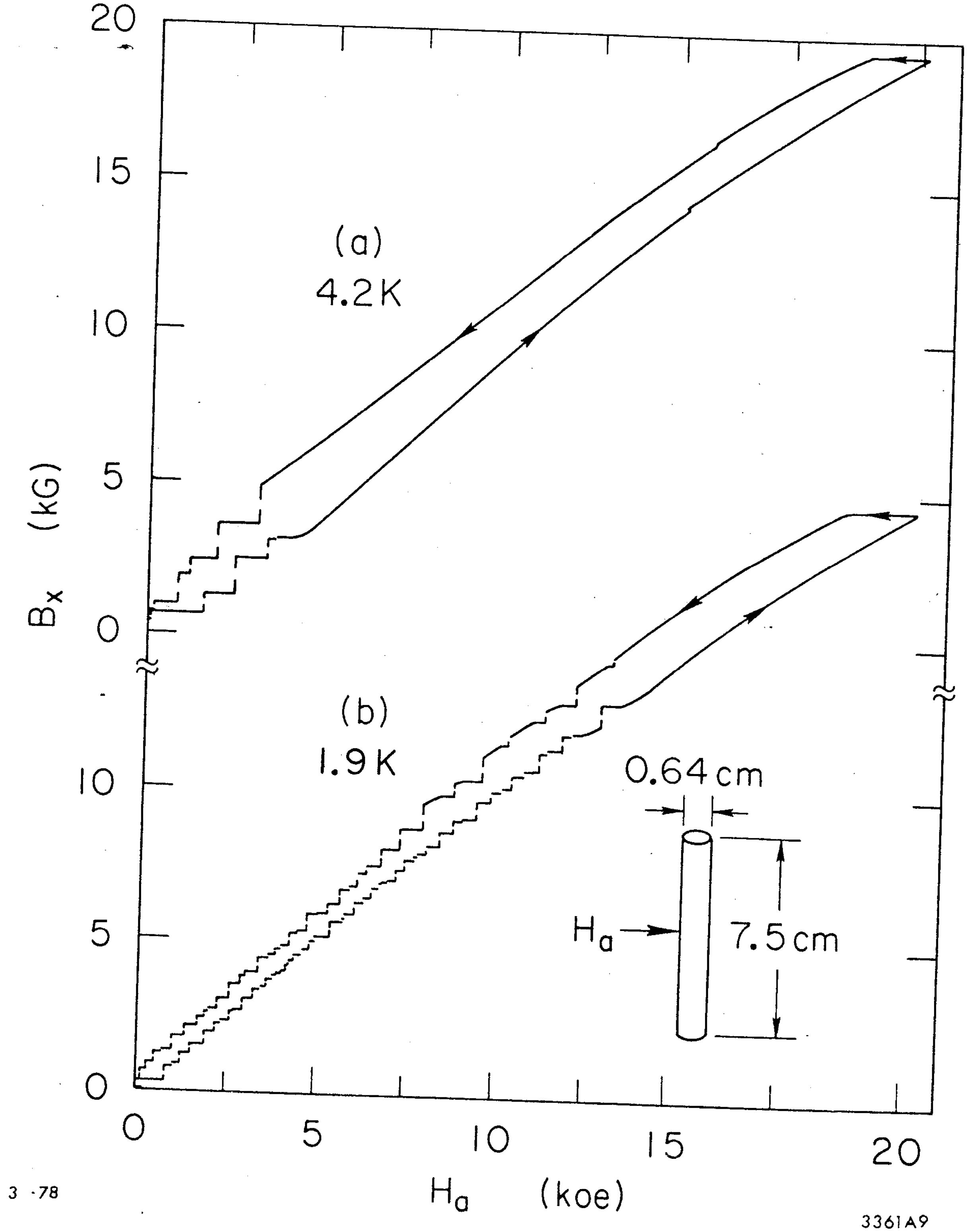
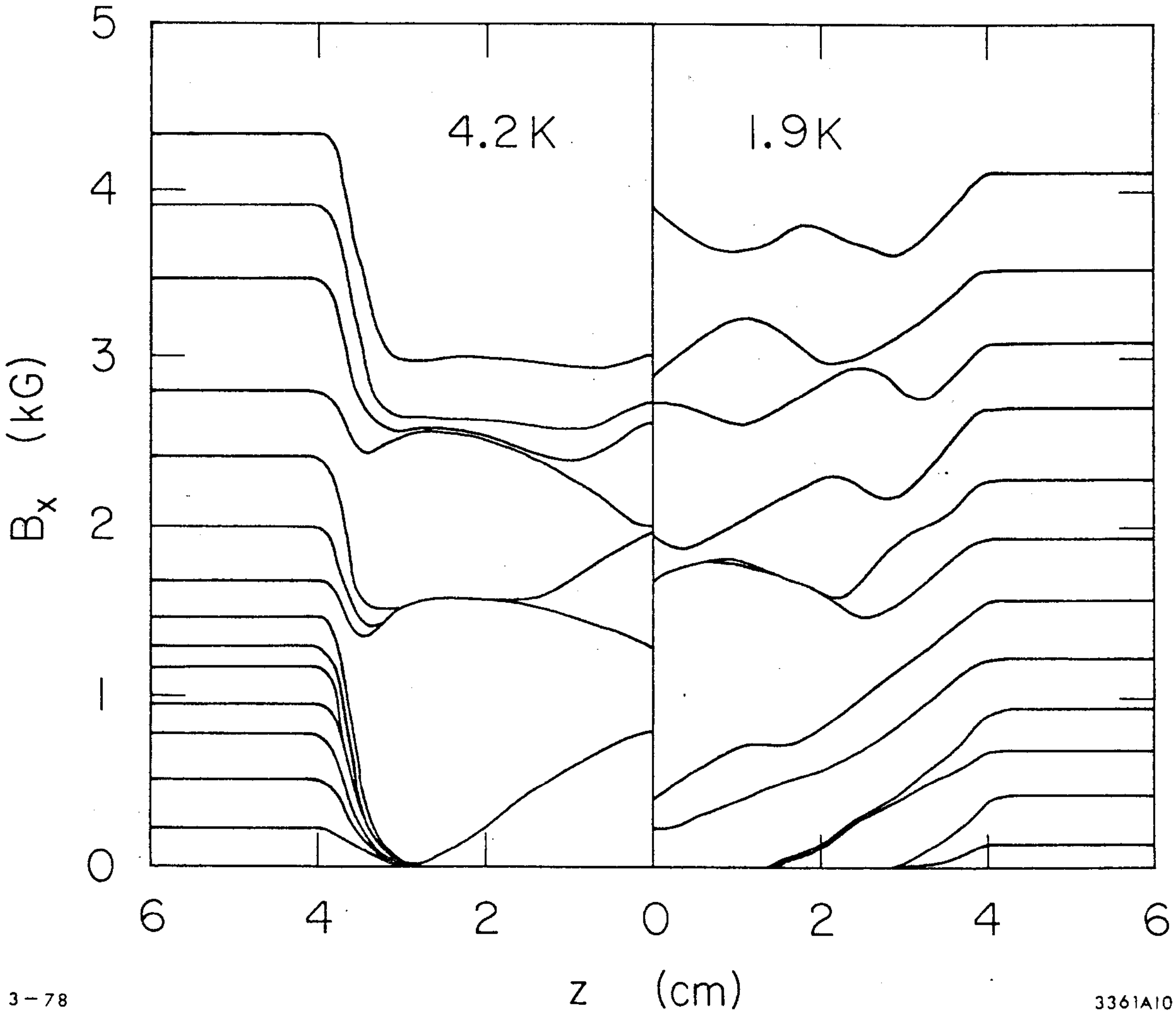

20
15
10
5
0
(a)
4.2K
(b)
1.9K
10
5
0
0.64 cm
7.5 cm
H_a
B_x (kG)
0
5
10
15
20
H_a (koe)
3 -78
3361A9

Fig. 1



3-78

3361A10

Fig. 2