REPORT ON SUPERCONDUCTING MATERIALS AND POSSIBLE APPLICATIONS

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Contents

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I. Introduction

The purpose of the Brookhaven 1963 Super-High-Energy Summer Study is to consider

a) the design and feasibility, as well as the possible construction, of storage rings for 30-Bev protons,

b) the design of a 1000-Bev proton accelerator.

Since both of these designs might be influenced by the use of superconductors, this report intends to present the present status of superconducting materials, so that their possible use may be included in the deliberations and considerations of the study.

It is obvious that superconductors also may be useful in the design of coils to provide large magnetic fields (e.g., 100 kgauss) for

1) Bubble chambers

2) Focusing magnets

3) Bending magnets, etc.

II. Brief History

In 1911, Onnes observed that the electrical resistance of mercury became zero when the temperature of the sample was reduced to less than 4.2^{o}K. This phenomenon is depicted in Fig. 1. It represents a most startling physical fact and was the beginning of all work in superconductivity. Soon after Onnes' discovery it was suggested that superconductors

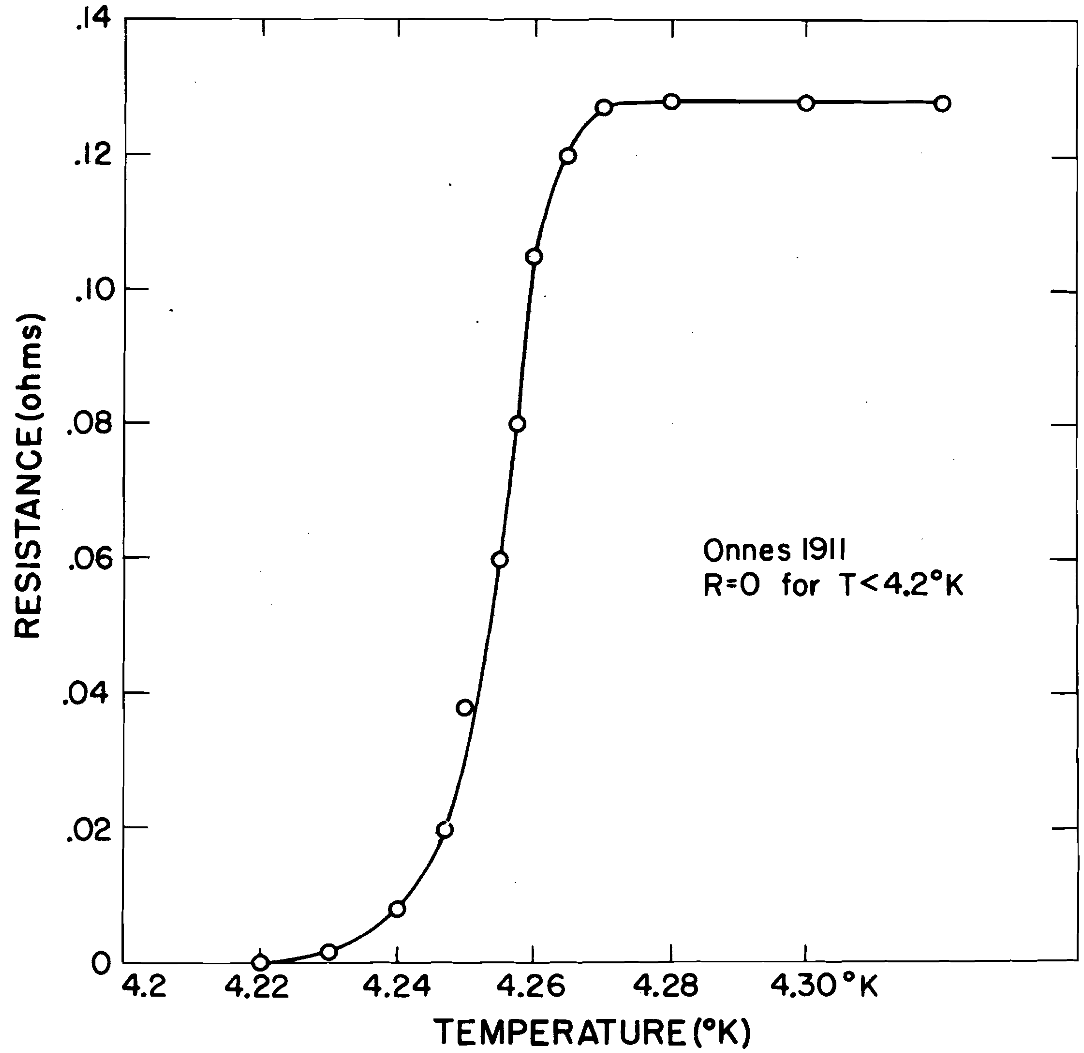
.14
.12
.10
.08
.06
.04
.02
0
RESISTANCE (ohms)
4.2
4.22
4.24
4.26
4.28
4.30°K
TEMPERATURE (°K)
Onnes 1911
R=0 for T<4.2°K

Fig. 1

might be used to wind magnetic field coils and in this way reduce the RI^2 losses to zero. This would increase the efficiency of maintaining a magnetic field from zero to 100% once it had been established by some kind of current circuit.

But then it was discovered that a fairly modest magnetic field of a few hundred gauss destroyed superconductivity in the superconductors then known. Later in 1930 it was discovered (de Haas and Voogd) that Pb-Bi retained some superconductivity in magnetic fields of at least 20 kgauss. This knowledge was not exploited[1].

This situation persisted until about two-and-one-half years ago. At that time reports[2,3,4] concerning the superconductivity of Nb-Zr, Nb_3-Sn, and V_3-Ga created new interest in the possible practical application of these "hard" superconductors to the construction of coils for large magnetic fields.

III. Experimental Procedures

A. Critical-current measurements

A common procedure for measuring the critical current (I_c amp) or the critical-current density $\left(J_c\ (\frac{\text{Amp}}{\text{cm}^2})\right)$ as a function of the magnetic field (H kgauss) is depicted in Fig. 2[5]. A sample of the superconducting material

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1. J.E. Kunzler, Revs. Modern Phys. 33, 501 (1961).
2. J.E. Kunzler et al., Phys. Rev. Letters 6, 89 (1961).
3. T.G. Berlincourt et al., Phys. Rev. Letters 6, 671 (1961).
4. F.J. Morrin et al., Phys. Rev. Letters 8, 275 (1962).
5. J.E. Kunzler, J. Appl. Phys. 33, 1042 (1962).

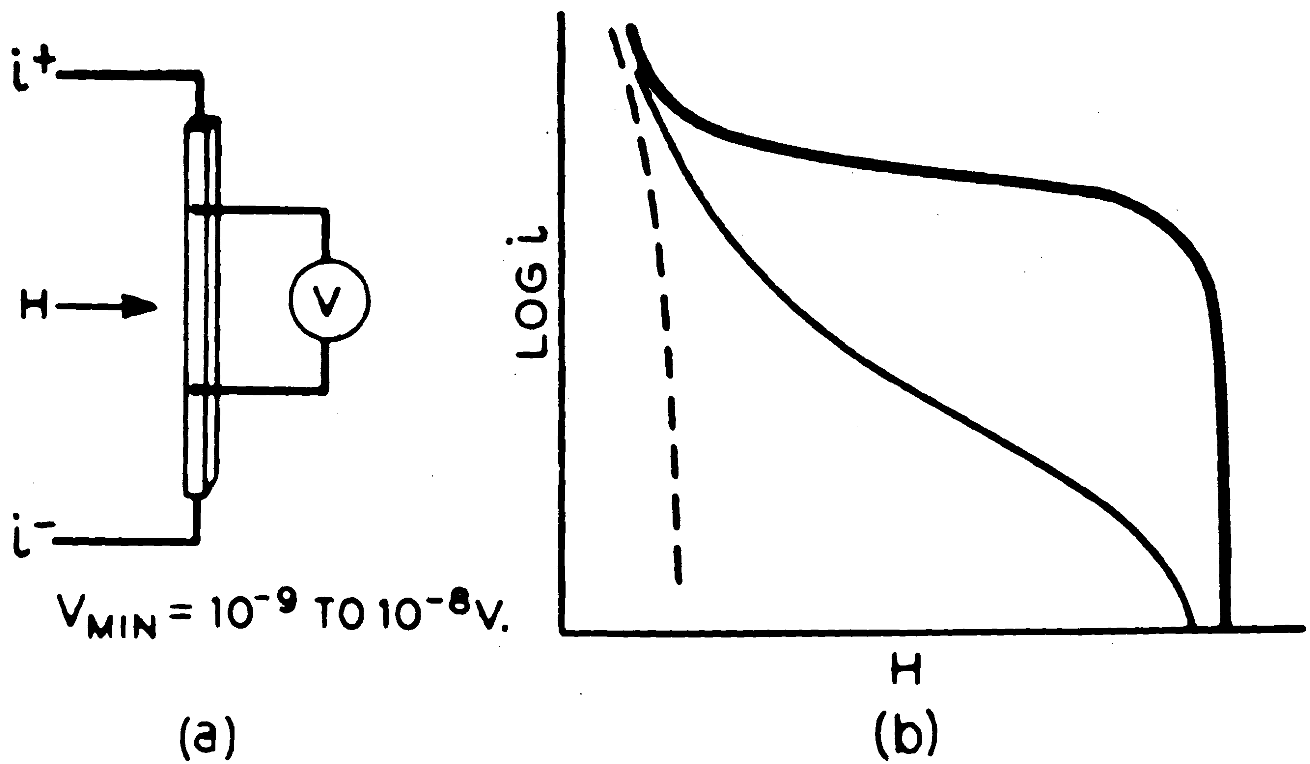

Fig. 2 - Schematic representation of (a) the experimental arrangement, and (b) an idealized representation of typical results (see Ref. 5)

is mounted in a holder so that the current through the sample is perpendicular to H. Then with H constant (e.g., at 30 kgauss), I is increased until the sample goes from the superconducting state into the normal state. This transition is indicated when a finite voltage (e.g., 10^{-6} to 10^{-9} volts) appears on the voltmeter V. During the experiment, the sample is kept at a constant temperature (e.g., 4.2°K) by immersing the sample in liquid helium and thus providing an environment similar to that which a solenoid will experience when wound of the sample material. Other experimental points are obtained by changing H to a new value (e.g., H = 70 kgauss) and repeating the procedure.

It is equally appropriate to keep I fixed and vary H if desired. Fig. 2 also shows the general shape of I_c vs H curves.

B. Magnetic-field measurements

The magnetoresistance of copper (or Bi) is a convenient property to use for measuring a magnetic field at 4.2°K. In the low-field region Bi is more sensitive than Cu, but above 20 or 30 kgauss copper has a nearly linear slope and thus is convenient.

At Brookhaven, copper magnetoresistance probes have been prepared according to the description given by Shu[6] and have been used. A typical calibration curve is shown in Fig. 3[*].

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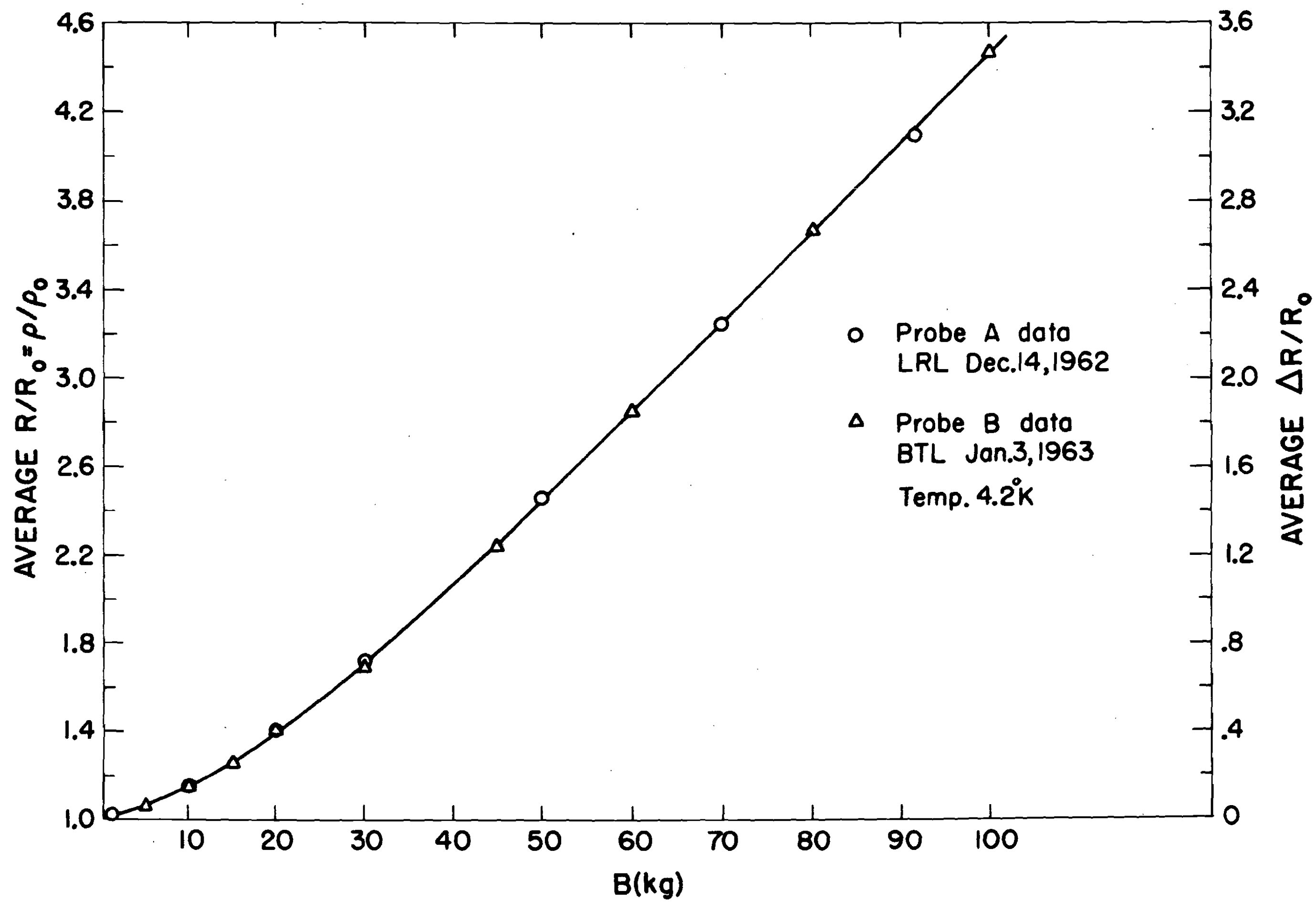
6. F.S.L. Shu and J.E. Kunzler, Rev. Sci. Instr. 34, 297 (1963).

*Much appreciation is expressed for the aid and cooperation (a) of H.C. Hitchcock and P.R. Arons at the Lawrence Radiation Laboratory in obtaining these and other experimental data, and (b) of F.S.L. Shu and J.E. Kunzler at the Bell Telephone Laboratory for similar aid.



AVERAGE R/R₀ = ρ/ρ₀
AVERAGE ΔR/R₀
B(kg)
4.6
4.2
3.8
3.4
3.0
2.6
2.2
1.8
1.4
1.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
.8
.4
0
10
20
30
40
50
60
70
80
90
100
Probe A data
LRL Dec.14,1962
Probe B data
BTL Jan.3,1963
Temp. 4.2°K

Fig. 3

Other properties[7] of some superconducting materials are given in Table I.

TABLE I

Summary of Some Superconducting Properties[7] (1963)

Substance	T_c °K	J Amp/cm^2	Possible Useful Magnetic Field
Nb_3-Sn	17.8	$\geq \sim 10^5$ at 100 kgauss	$\sim$ 180 kgauss
Nb-Zr	11.0	$\sim 10^4$ at 90 kgauss	< 90 kgauss
V_3-Ga	14.5	?	350 - 700 kgauss
V_3-Si	16.9	?	160 - 300 kgauss

At this time, H_c for V_3-Ga is not well known because of the large extrapolation necessary when going from existing data to H_c at 0°K. It is hoped that this summer (1963), when the 250-kgauss field is available at the M.I.T. National Magnet Laboratory (160,000 amps at 200 volts: 32 megawatts), the H_c vs T data for V_3-Ga may be extended so that a better estimate of H_c will be available.

Also, it would be very useful if the I_c or J_c vs H data for Nb_3-Sn were extended into the 200-kgauss region.

IV. Comparison of the Properties of Nb-Zr and Nb_3-Sn

It is pertinent to present a comparison between J_c vs H curves for Nb-Zr and Nb_3-Sn.

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7. A.M. Clogston, Phys. Rev. Letters 9, 266 (1962).

Fig. 4 gives a comparison of the J_c values for these two materials. The data for Nb_3-Sn above H = 100 kgauss are taken from pulsed-field measurements[8]. It is clear from these data that, if one wishes to construct solenoids to provide fields for $H \geq 100$ kgauss, one must use Nb_3-Sn and not Nb-Zr.

Even with the more recent data* on Nb-58%Zr presented in Fig. 5, one cannot expect to get magnetic fields of the order of 90 kgauss except at such small values of J that it is not practical. Possibly the use of Nb-Zr is limited to fields of the order of 50 or 60 kgauss.

V. Production Processes and Properties of Currently Available Nb_3-Sn

The above data represent the situation up to about a year ago when it was possible to buy Nb-Zr wire which could be wound into solenoids and required no subsequent heat treatment; previously available Nb_3-Sn needed heat treatment after winding. Since then, at least two commercial companies have developed processes for manufacturing Nb_3-Sn ribbon which does not need heat treatment after winding. These will now be described. (One other company, General Electric, has developed a new Nb_3-Sn which does need heat treatment after winding - see below.)

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8. V.D. Arp et al., Phys. Rev. Letters 6, 452 (1961).

*Some of these data were taken with the help and cooperation of H.C. Hitchcock and P.R. Arons using the Berkeley 93.5-kgauss field. Many thanks are expressed.

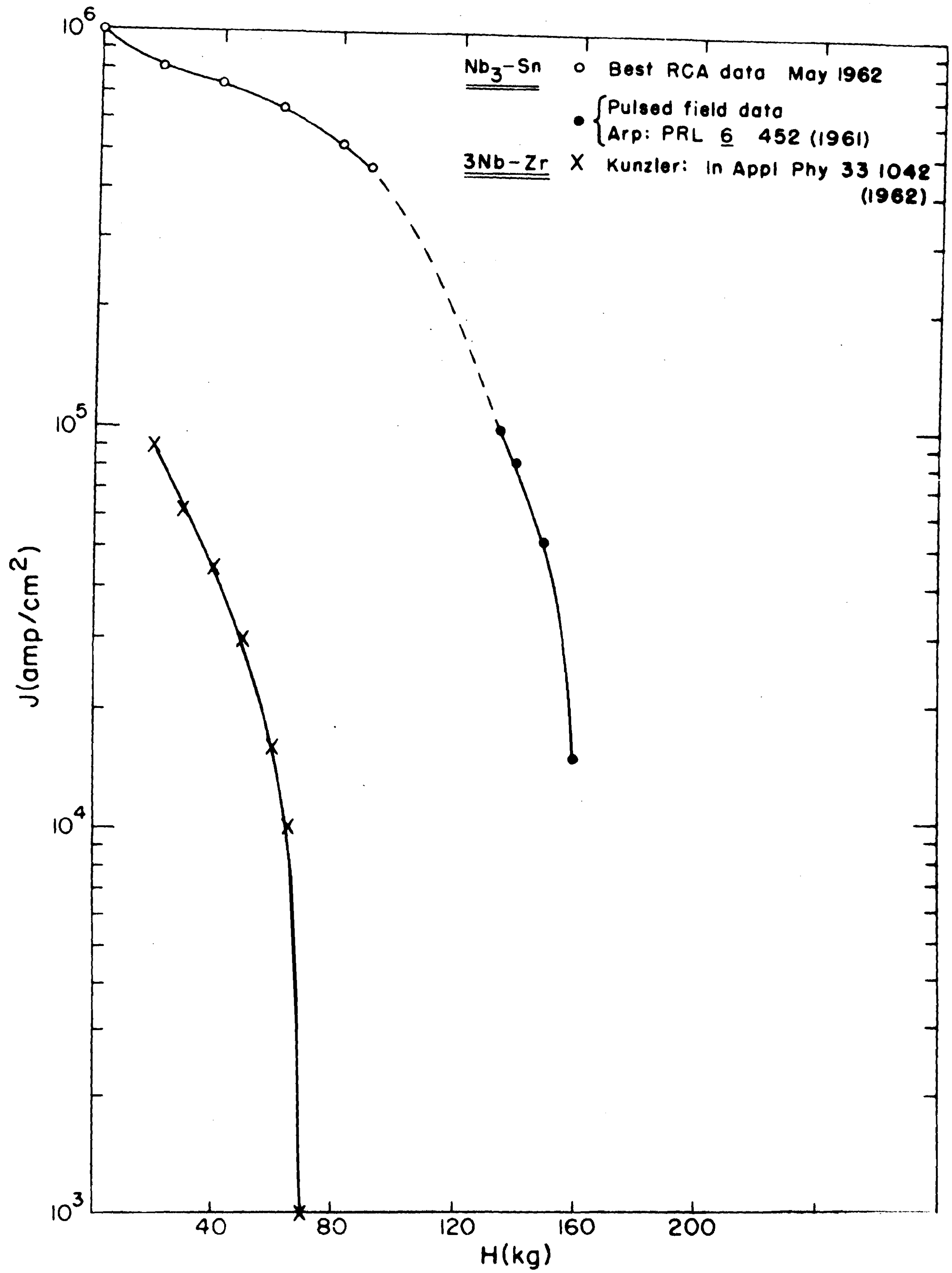
10^6
10^5
10^4
10^3
J(amp/cm^2)
40
80
120
160
200
H(kg)
Nb$_3$-Sn ○ Best RCA data May 1962
● {Pulsed field data
Arp: PRL 6 452 (1961)
3Nb-Zr X Kunzler: In Appl Phy 33 1042
(1962)

Fig. 4

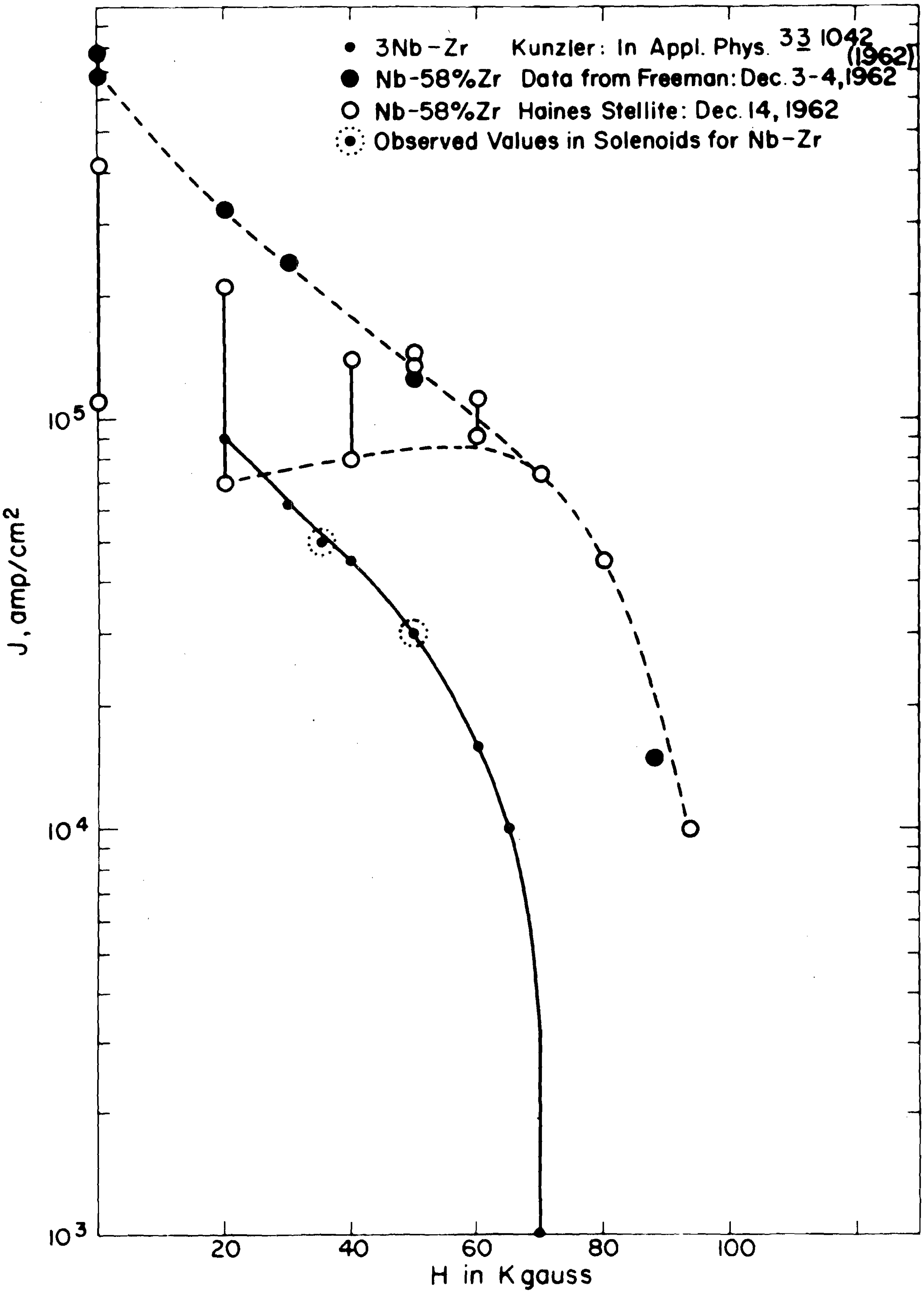
3Nb-Zr Kunzler: In Appl. Phys. 33 1042 (1962)
Nb-58%Zr Data from Freeman: Dec. 3-4, 1962
Nb-58%Zr Haines Stellite: Dec. 14, 1962
Observed Values in Solenoids for Nb-Zr
J, amp/cm2
10^5
10^4
10^3
20
40
60
80
100
H in K gauss

Fig. 5

A. RCA material

The process used by RCA is one in which $NbCl_5$ is reacted with $SnCl_2$ and H_2 to form Nb_3-Sn in the temperature range of 1000 to 1200°C and deposited on a ribbon of Hastelloy, according to the reaction

$$NbCl_5 + SnCl_2 + H_2 \longrightarrow Nb_3\text{-}Sn + HCl \ .$$

See reference 9 for further details.

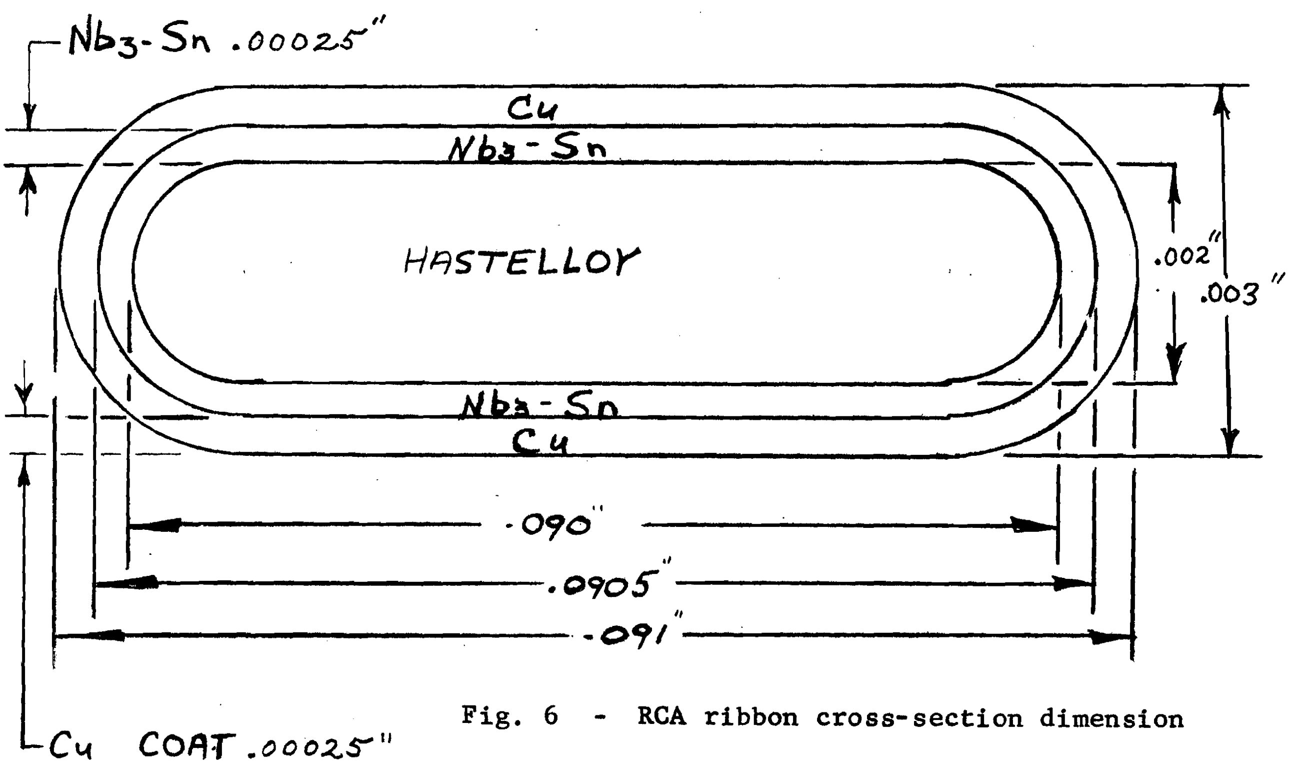

Fig. 6 - RCA ribbon cross-section dimension

Fig. 6 shows a sketch of the cross section of the Nb_3-Sn ribbon available at this time.

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9. J.J. Hanak, RCA Report "Vapor Deposition of Nb_3-Sn", August 1962; also Technical Conference on Advanced Electronic Materials, August 1962.

Other pertinent data are:

1) ΔA (cross-section area of Nb_3-Sn) = 3×10^{-4} cm^2.

2) A (total cross-section area of ribbon, including 1/4 mil mylar layer-to-layer insulation) = 1.9×10^{-3} cm^2.

3) N (number of turns per cm^2 of coil winding) calculated = 520 turns/cm^2.

4) N (observed in coil winding at Brookhaven) = 490 turns/cm^2.

5) R (radius of coil winding) $\geq$ ½ in.

6) See Fig. 8 for J_c vs H characteristic curve for short-sample data.

7) Exhibited large "training" effect until copper coated.

8) I_c (observed at Brookhaven in solenoid at 20 kgauss) = 45 amps.

9) J_c (observed at Brookhaven in solenoid at 20 kgauss) $\cong 1.5 \times 10^5$ amp/cm^2.

10) Straight-section performance not observed in Brookhaven solenoid.

Additional comments or data pertaining to the RCA ribbon:

a) A few months ago, the RCA ribbon was not copper coated and at that time exhibited a pronounced training effect such as is seen in Fig. 5 for the Nb-58%Zr but apparently the copper coating has removed this training effect and also improved the current density (see Fig. 7).

b) Fig. 8 presents consolidated data, obtained by using short samples of RCA copper-coated strip, as it is known at this time.

In addition there is a point at 20 kgauss and $J = 1.5 \times 10^5$ amp/cm^2 (I = 45 amp) which represents the operating conditions for the Brookhaven solenoid at this time. Note that this operating point is about five times

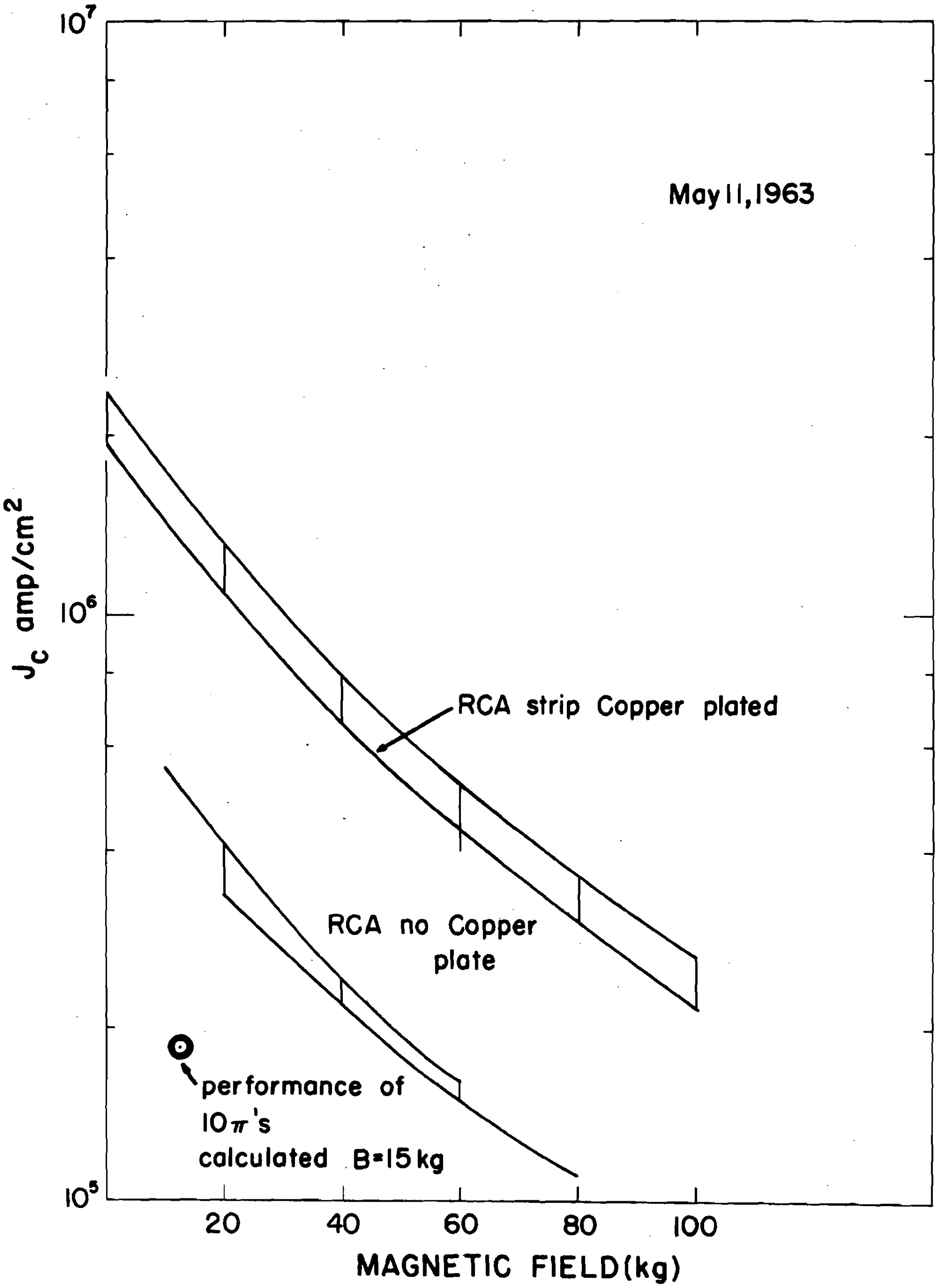
10^7
10^6
10^5
J_c amp/cm^2
May 11, 1963
RCA strip Copper plated
RCA no Copper plate
performance of 10π's calculated B=15 kg
20
40
60
80
100
MAGNETIC FIELD(kg)

Fig. 7

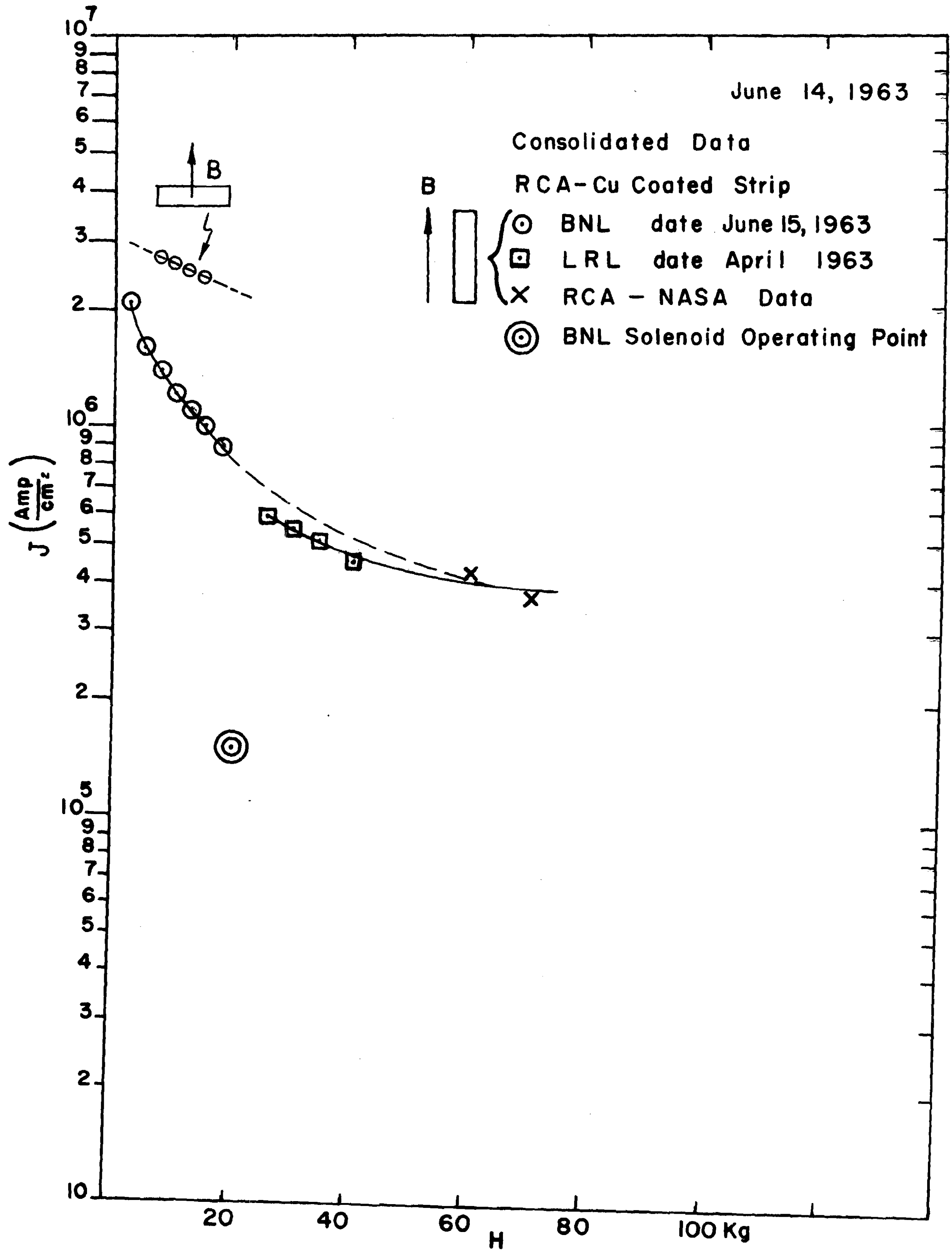
June 14, 1963
Consolidated Data
RCA-Cu Coated Strip
B
BNL date June 15, 1963
LRL date April 1963
RCA - NASA Data
BNL Solenoid Operating Point
J (Amp/cm²)
H
20
40
60
80
100 Kg

Fig. 8

lower than the J value obtained from short straight samples of the same material. The reason for this is not known.

c) The data represented by the lower curve in Fig. 8 were taken with the field parallel to the flat side of the ribbon.

d) Other data represented by the higher J values were taken with the field perpendicular to the flat side of the ribbon.

The geometry represented by item (c) is more typical of what might be expected in a solenoid than that in item (d).

B. National Research Corporation (NRC) material

In principle the NRC process for producing Nb_3-Sn strip seems simpler than the RCA process and basically consists of coating pure Nb metal with a thin uniform layer of tin so that the tin wets the surface and then, after winding on a spool (for convenient handling only), heat treating at 1000 to 1200°C. After heat treating the strip may be unwound and used to wind solenoids in the usual way and needs no further heat treatment. The strip is coated on both sides and may have the typical dimensions shown in Fig. 9.

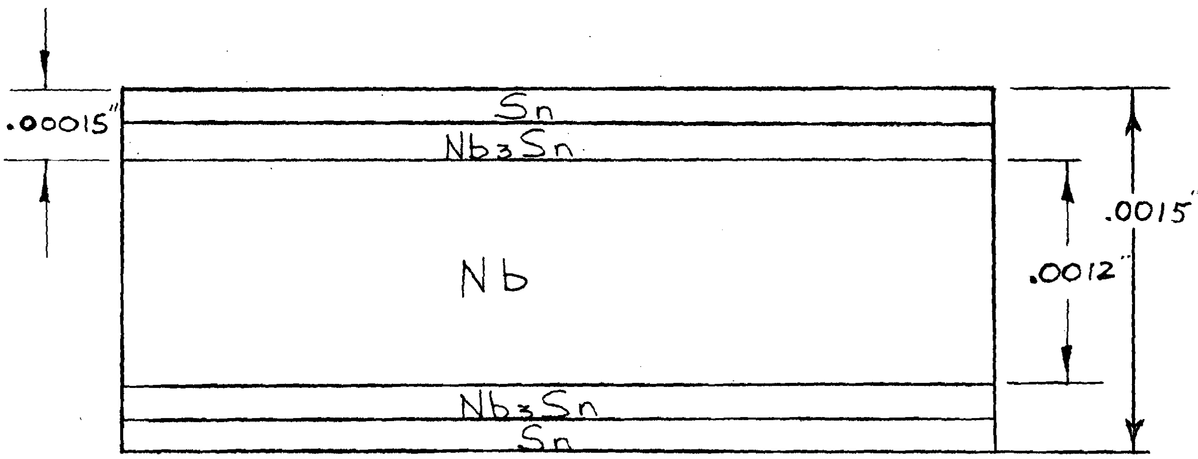

Fig. 9 - NRC ribbon cross-section dimension

Other pertinent data are:

1) $\Delta A = 2.85 \times 10^{-4}\ cm^2$.

2) $A = 1.47 \times 10^{-3}\ cm^2$.

3) $N = 800\ turns/cm^2$ (calculated).

4) $R \geq 3/16$ in.

5) No data for J_c vs H curves are available for this double-coated strip but data taken in February 1963 at the Lawrence Radiation Laboratory indicate, for small straight sections, that J is about $1.5 \times 10^5\ amp/cm^2$ at H = 93.5 kgauss.

6) As observed by using small coils (200 to 600 turns), approximate straight-section performance may be expected in solenoids. This needs further testing by experiments which are planned at Brookhaven.

7) No training has been observed so far.

8) Strips one-inch wide are available now and two-inches wide (or even wider if desired) may be available soon.

9) The material seems easier to manufacture and appears to be less fragile than the RCA material.

10) It may be that the unreacted coat of Sn left on the NRC material after heat treatment plays a role similar to the Cu coat put onto the RCA material after manufacture.

(Note: Brookhaven intends to wind a solenoid using the NRC material so that coil performance can be compared with the RCA coil now partially completed and tested.)

C. General Electric Company material

Recently,[10] the General Electric Company announced that a solenoid using Nb_3-Sn had produced a self field of 101 kgauss at 1.8°K. This corresponds to $J = 7.2 \times 10^4$ amp/cm^2 and agrees approximately with small-coil and straight-section performance (see Fig. 10). At 4.2°K and $J = 8 \times 10^4$ amp/cm^2 (note that J here refers to the average current density in the wire and not to J in the Nb_3-Sn as in the above curves) the coil produced 62 kgauss; the corresponding point at 100 kgauss and 4.2°K would have a $J \cong 4.7 \times 10^4$ amp/cm^2. Achievement of 100 kgauss under these conditions, therefore, would necessitate the winding of some additional turns on the coil.

Additional coil data:

I.D. = 0.32 in.

O.D. = 2.21 in.

Length = 1.8 in.

I = 266 amps at 1.8°K (or 175 amps at 4.2°K)

Diameter of wire = 0.027 in.

Ceramic insulation thickness = .003 in.

Diameter of wire, ceramic insulated = .033 in.

$N \simeq 145$ turns/cm^2

$NI \sim 3.9 \times 10^4$ amp turns/cm^2.

Additional comments:

a) In Fig. 10, the band of J values representing "small-coil performance" is a result of tests on about 200 small coils with several

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10. Cryogenics, June 1963.

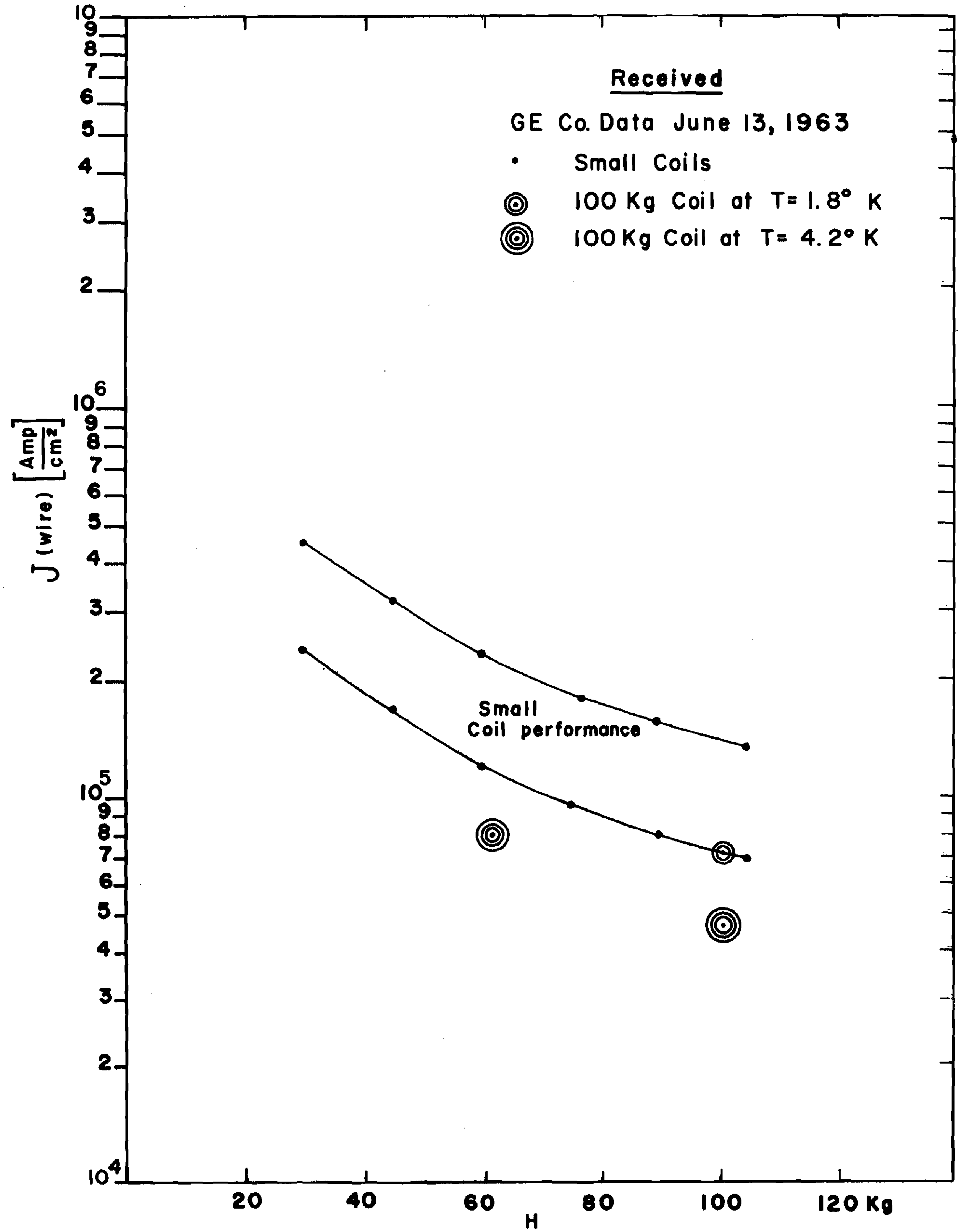

Received
GE Co. Data June 13, 1963
Small Coils
100 Kg Coil at T= 1.8° K
100 Kg Coil at T= 4.2° K
Small
Coil performance
J (wire) [Amp/cm²]
H
20
40
60
80
100
120 Kg

Fig. 10

hundred turns each. These data represent material from numerous melts and thus give somewhat different J values. The 100-kgauss coil material was different from that used to accumulate the data in the band of points.

b) No information is at hand concerning the fraction of the total cross-sectional area of the wire which is Nb_3-Sn, except that it represents a "major fraction".

c) No cost or price information is available.

d) No Nb_3-Sn strip has been made but it is believed by the General Electric Company that no technical difficulties would be encountered.

e) Wire larger in diameter than 0.027 in. seems feasible.

f) No samples are available.

g) Superconducting joints seem feasible.

h) No training has been reported.

It is important to note that approximate straight-sample performance has been achieved in this solenoid.

VI. Relative Figure of Merit and Current Cost Comparison

The value of NI (the number of amp turns/cm^2 of coil winding) will be taken as a "figure of merit" for a superconductor. On this basis and choosing values of I, from the J vs H (or I vs H) curves, which are not too optimistic, the data for a relative comparison of these materials are presented in Table II. It is observed that, for magnetic fields of the order of 100 kgauss the NRC material seems to be best at this time and (see above) has an NI about the same as the GE material. However, it must be noted that, if the RCA material were deposited on a thinner substrate, its "figure of merit" would improve. Also it should be noted

TABLE II

Comparative (Relative) Values of NI Amp Turns/cm^2

Material	Nb-58%Zr Haines Stellite 790 turns/cm^2		Nb_3-Sn RCA 480 turns/cm^2		Nb_3-Sn NRC 800 turns/cm^2	
H (kgauss)	I (amp)	NI	I (amp)	NI	I (amp)	NI
30	38	3.0×10^4	79	3.8×10^4	174	14.0×10^4
40	42	3.3×10^4	73	3.5×10^4	134	11.0×10^4
50	44	3.5×10^4	62	3.0×10^4	100	8.0×10^4
60	45	3.5×10^4	56	2.7×10^4	82	6.6×10^4
70	36	2.8×10^4	51	2.4×10^4	66	5.3×10^4
80	22	1.7×10^4	51	2.4×10^4	58	4.6×10^4
90	5	0.4×10^4	45	2.2×10^4	50	4.0×10^4

N for Nb-58%Zr includes insulation and spacing.

N for Nb_3-Sn (RCA) includes insulation and copper plate.

N for Nb_3-Sn (NRC) includes insulation and spacing for double-coated strip .125 in. × .0015 in.

that NI at 20 kgauss for the present Brookhaven coil, made of RCA material, is about 2.2×10^4 amp turns/cm^2, whereas on the basis of the data in Table II, one would have expected it to be much larger (i.e., approximately twice as large). It remains to be seen whether or not the figure of merit gets worse as the Brookhaven coil goes to larger values of H as more turns are added. It also remains to be seen if the NRC material will maintain its approximate short-section performance when high-field solenoids are made with it.

Table III gives a cost comparison for RCA and NRC material based on costs as known at this time. Currently these costs are high because the materials are new and are just becoming available. It may not be unreasonable to expect the price to be reduced to one-half or one-quarter of the current price when the manufacturing processes are stabilized; the demand for Nb_3-Sn increases and competition becomes more keen. However, a minimum price, which might be expected in the next few years, might be something like $200.00 per lb since it is understood that Nb metal costs approximately $40.00 per lb at the present time.

TABLE III

Cost Comparison Estimates for Nb_3-Sn

	RCA	NRC (double coated)
Cross-section area	1.47×10^{-3} cm^2	1.21×10^{-3} cm^2
Volume per 1 cm length	1.47×10^{-3} cm^3	1.21×10^{-3} cm^3
Mass per 1 cm length	1.295×10^{-2} gms	1.06×10^{-2} gms
Grams per meter	1.295 gms	1.06 gms
Cost (estimated)	$5.00/meter	$1.00/ft
Cost per gram	$3.86/gram	$3.08/gram
Cost per lb	$1750/lb	$1400/lb

No cost data are available for the General Electric Co. material.

VII. Brookhaven Coil Construction and Test Program: Results

This program was initiated in the fall of 1962 by the writer* and since February 1, 1963 has been continued by Dr. W.B. Sampson and Mr. Frank Abbatiello of the Brookhaven Accelerator Department staff. The program was initiated because of the common interest of the writer and the Brookhaven staff in these matters and to gain knowledge about superconductors, including the technique of handling and building physical equipment with them.

The RCA material (Nb_3-Sn) was chosen as the material with which to wind the first Brookhaven coil because it was the only material of its kind commercially available at that time. Two sections of a coil with the following geometry and characteristics have been wound and tested to date.

Brookhaven coil data:

Dimensions: I.D. = 4 cm

O.D. (of 2 sections wound) = 5.82 cm

O.D. (of 6 sections of coil when finished) ≅ 9.8 cm

Length of coil = 6.43 cm

N (number of turns/cm^2) = 490 turns/cm^2

I (for 2 sections: observed) = 45 amps

NI (for 2 sections: observed) = 2.2×10^4 amp turns/cm^2

As noted above, this coil (two-section) now produces 20 kgauss with a current of 45 amperes in the windings, and when completed should produce

*P.G. Kruger, on Sabbatical Leave from the University of Illinois, I Semester 1962-63.

about 50 kgauss if it is possible to operate at the same 45-ampere current. In this coil the RCA material has not exhibited the characteristic found for small straight sections (see Fig. 8). The calculated inductance for the first two sections is 0.17 h as compared to the measured value of 0.165 h.

At present this coil is being used for:

a) testing properties of the coil and performance of the RCA material when wound into a solenoid,

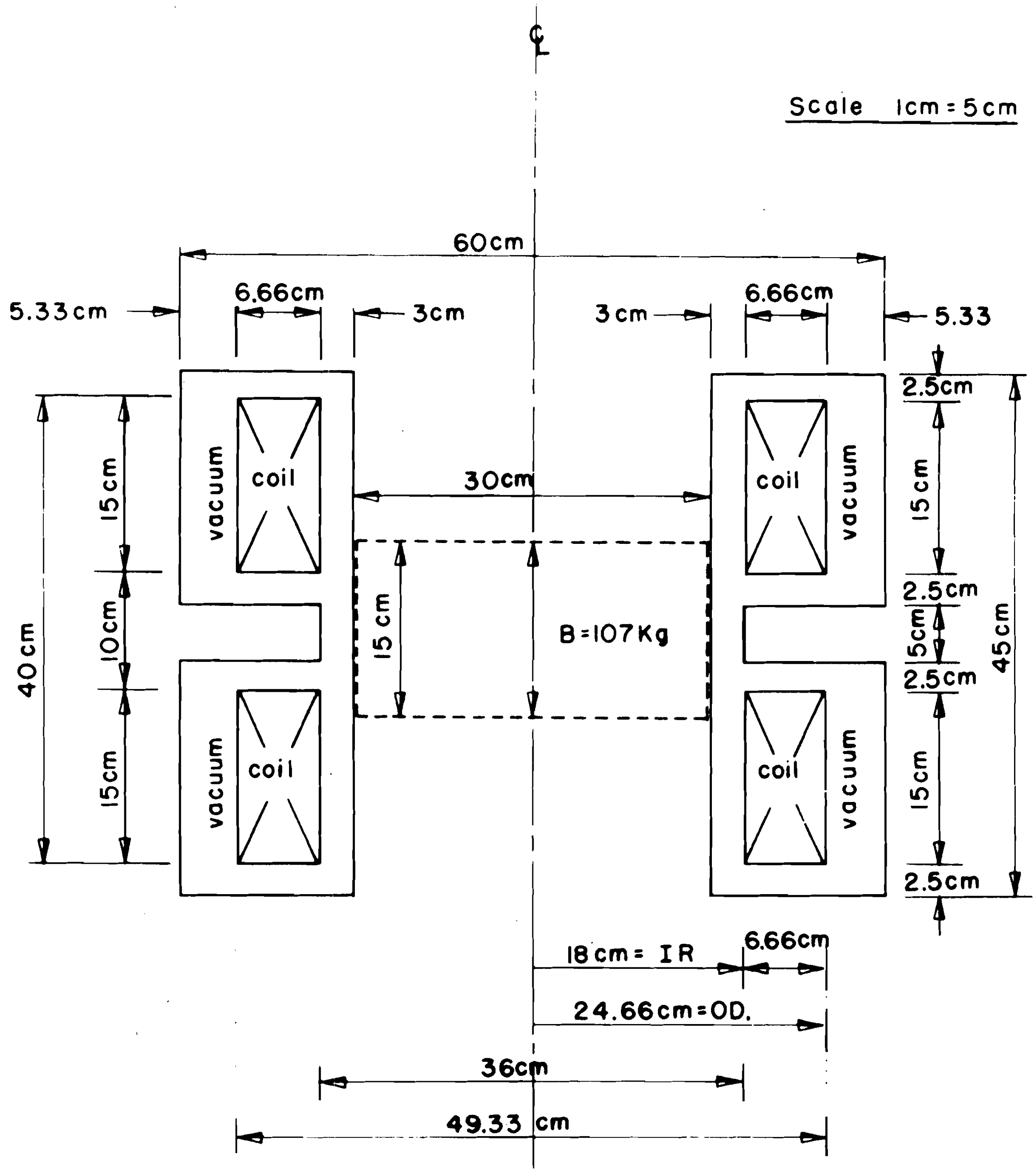
b) a laboratory facility for testing the characteristics (i.e., J vs H) of small straight sections (see Fig. 8).

It is planned to test the double-coated NRC material, in straight-section form, and when wound in a solenoid, as soon as time and material are available. It is most important to determine experimentally whether this NRC material exhibits straight-section performance in high-field solenoids, as might be expected from earlier data. Ultimately it is hoped that from these tests sufficient experience will be gained to allow the construction of a coil for a small bubble chamber with a field of approximately 100 kgauss.

VIII. Suggested Geometry for a Small Bubble Chamber Coil

From Tables II and III one may estimate that a "reasonable" NI at this time is approximately 2.8×10^4 amp turns/cm^2. This has been used to make an estimate of a possible geometry for a pair of coils with a 100-kgauss field for a small bubble chamber. Fig. 11 shows this suggested geometry.

The field at the center of a coil, and on the axis, which may be expected for this geometry, may be calculated by using the equation



The dotted rectangle represents the bubble chamber 12" dia(30cm) x 6" high.

Fig. 11

$$B_o = \left(\frac{4\pi}{10}\right) b\,(NI)\,\ln \frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{1 + \beta^2}} \quad \text{(gauss)}$$

where b = half length of the coil (cm)

$$\alpha = \frac{\text{outer radius}}{\text{inner radius}} = \frac{a_2}{a_1}$$

$$\beta = \frac{b}{\text{inner radius}} = \frac{b}{a_1}$$

To calculate the field as a function of distance from the center of the coil and along the axis one may use the equation

$$B = \left(\frac{2\pi}{10}\right) I\, \Sigma\, (N \sin\alpha + N \sin\beta) \quad \text{(gauss)}$$

where now N = number of turns per cm length of the solenoid

I = the current in amperes in the windings

and α and β are the angles shown in Fig. 12.

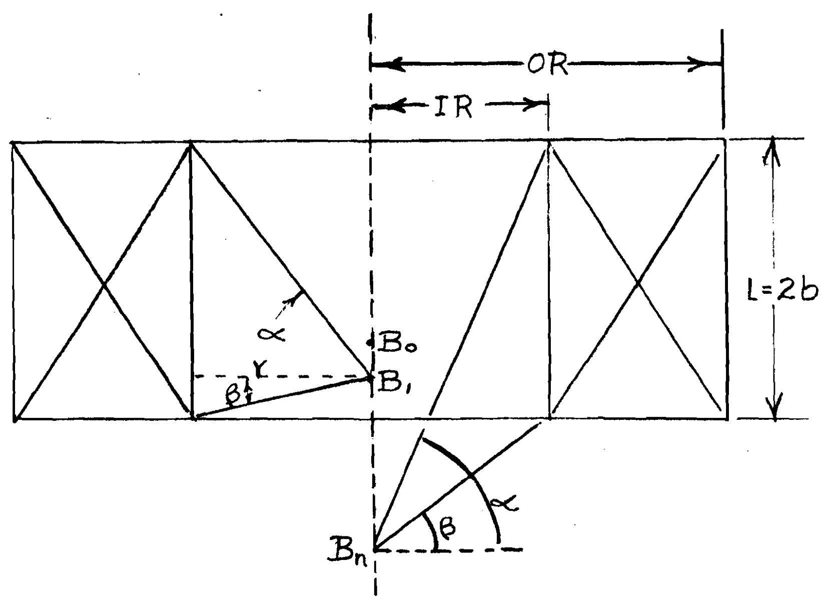


Fig. 12

Fig. 13 shows the field calculated in this way for the coil geometry shown in Fig. 11. Based on this geometry, the weight of Nb_3-Sn needed for two coils is estimated to be about 540 lbs, and the cost, at $1500/lb, would be $810,000. However, this cost, as noted above, in a year or so might be reduced to approximately $300,000.

IX. Radiation Damage

Little is known about the effect of radiation (i.e., n, p, π, etc.) on the superconducting properties of Nb_3-Sn or Nb-Zr. One report[11] indicates that no effect was observed when a Westinghouse coil (Nb-Zr) was irradiated with a total flux of 8×10^{11} protons/cm^2 at a kinetic energy of 400 Mev. This is probably an inadequate test and a total flux of 10^{17} particles/cm^2 might be necessary to give a definitive answer. Also, neutron irradiation might be more destructive than proton irradiation because then head-on collisions would be more probable and dislocations might be more numerous. The general concensus of solid-state physicists seems to be that one should not expect serious damage to superconducting properties but definitive experiments need to be done before large expenditures are made for the construction of expensive superconducting equipment.

It is strongly to be urged that such experiments be initiated at Brookhaven or Argonne or both.

X. Rf or Pulsed Current Effects

Again, on this subject little is known, especially about Nb_3-Sn. Fairbanks and Wilson at Stanford have done work relating to the use of Pb in rf cavities, and Hitchcock at Berkeley has made some measurements on

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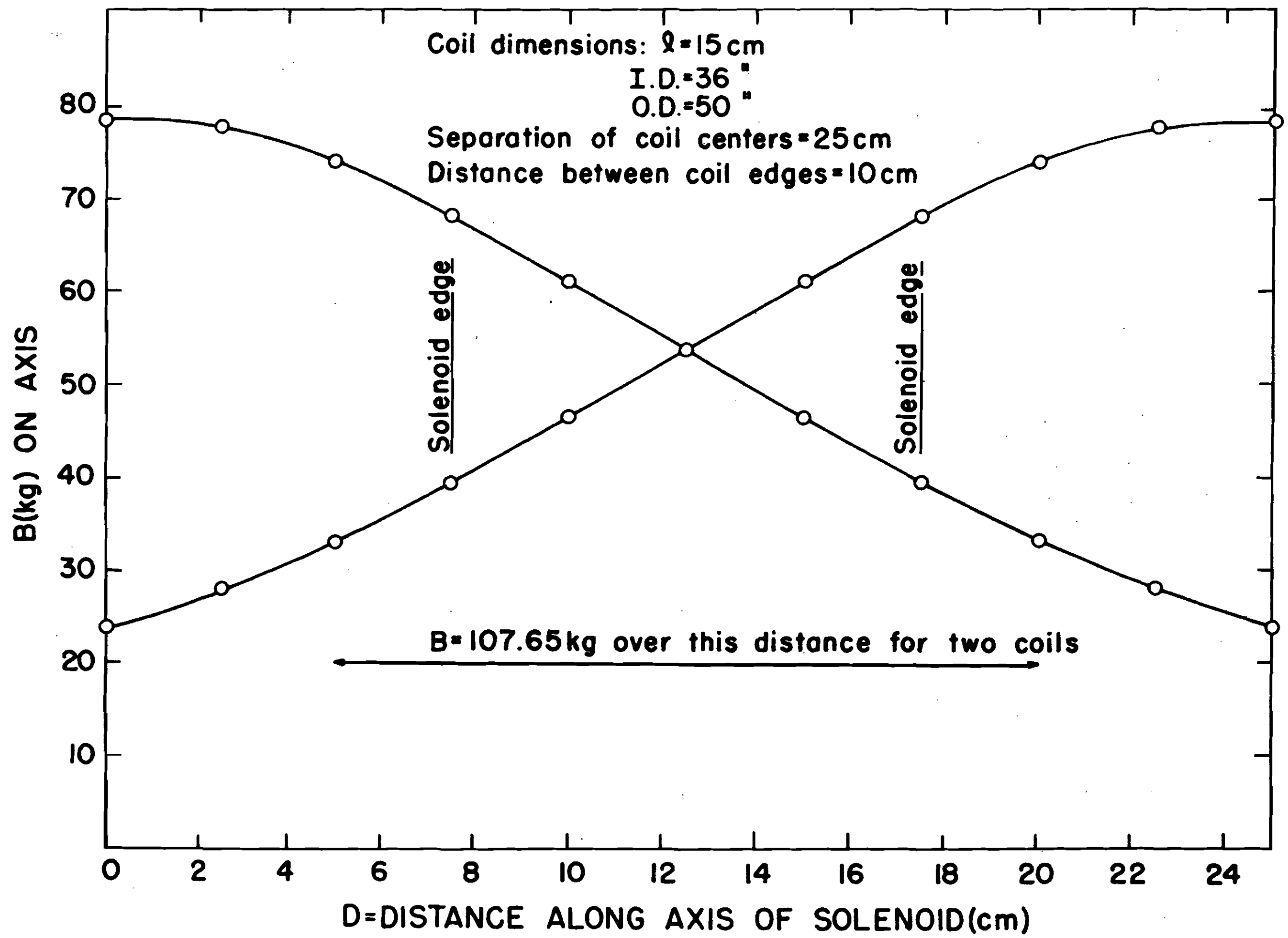
11. R. Babcock et al., Appl. Phys. Letters 1, 43 (1962).



Coil dimensions: ℓ=15cm
I.D.=36 "
O.D.=50 "
Separation of coil centers=25cm
Distance between coil edges=10cm
Solenoid edge
Solenoid edge
B=107.65kg over this distance for two coils
B(kg) ON AXIS
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
20
22
24
D=DISTANCE ALONG AXIS OF SOLENOID(cm)

Fig. 13

the effects of pulsed currents in Nb-Zr with no observed effect up to 10^3 or 10^4 sec^{-1}. These tell nothing, however, about possible effects in Nb_3-Sn and so experimental data are badly needed. Appropriate experiments should be initiated at once.

XI. Concluding Remarks and Suggestions

From the data presented herein it is obvious that, at least in the immediate future, the superconductor Nb_3-Sn is the only one available which may be used to construct physical apparatus wherein fields of 100 kgauss may be expected. The cost is somewhat high at present but not excessively so and it is important to gain more experience in constructing such physical equipment. One may expect the cost to be lower as the use and production of Nb_3-Sn increases. Perhaps the future will provide even more exciting superconductors such as V_3-Ga and V_3-Si.

It is not too soon to consider the construction of small bubble chamber coils or even fixed-field storage rings using Nb_3-Sn. However, before building a storage-ring structure, although planning and preliminary design may well start now, it will be necessary to do the experiments suggested in the two preceding sections. Model work also could and probably should be initiated now.

It is not obvious at this time that a storage ring for 30-Bev protons, using Nb_3-Sn, can be constructed in the next 2 to 5 years. But it is clear that it will not be done unless detailed plans and considerations for this possibility are initiated soon, i.e., preferably in this 1963 summer study.

The desirability of constructing a storage ring for 30-Bev protons (or even a 1000-Bev accelerator) using Nb_3-Sn depends on many rather obvious factors and considerations, some of which are listed below:

1) The radius of curvature of a 30-Bev proton in a 100-kgauss field is about 10 meters. Thus, if one includes the necessary straight sections, space for focusing magnets, etc., the final ring structure might have a circumference of about 180 meters. Does this small circumference adversely affect the possibility of doing good experiments with colliding beams in such a storage ring?

2) Even a crude preliminary estimate of storage-ring size, the amount of Nb_3-Sn needed, the cost of construction and the cost of refrigeration would be useful.

3) The same kind of cost estimates for a conventional (non-superconducting) storage ring would then allow a preliminary economic judgement to be made. This should include power costs per year.

4) One should examine the commercial capability for the production of Nb_3-Sn in 2 to 5 years so that some judgement can be made regarding the adequacy of supply.

5) One should prosecute diligently the necessary tests and model work so that decisions can be made with reasonable confidence in a year or two.

6) Since the necessary vacuum in a storage ring is considered to be of the order of 10^{-10} to 10^{-11} mm Hg, the cryogenic system might be designed to cool to 4.2°K the vacuum chamber as well as the superconducting coils. The addition of cryogenic pumping might greatly simplify the vacuum problem.

7) If a storage ring for 30 Bev were built using a superconductor like Nb_3-Sn, the experience gained during that design and construction period might pay big dividends when considering the final design and construction of the 1000-Bev accelerator.

Discussion

D.C. Rahm (BNL): Would you please comment on the impregnation of Vycor or "thirsty glass" with metals to make superconductors?

P.G. Kruger: This is indeed true. One can under high pressure force mercury to flow into the small canals in Vycor and this material will then exhibit superconducting properties. This phenomenon supports the picture of filamentary conduction and is particularly pertinent to the Nb-Zr system. There is evidence, however, to indicate that Nb_3-Sn does not have a conducting state similar to Nb-Zr. The present samples made with Vycor are about 4 or 5 mm long and about 1 mm thick and hence are not suited for winding coils.

D.C. Rahm: Do these samples remain superconducting in high magnetic fields?

P.G. Kruger: I think that they do, possibly to 100 kgauss, but I am not sure.

J.P. Blewett (BNL): Is there any evidence of long-term deterioration in the properties of superconductors which might make them less desirable in a large accelerator?

P.G. Kruger: It is really too early to say. As far as radiation effects are concerned, insufficient experiments have been performed.