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ABSTRACT

This paper summarizes critical current measurements of the Nb-Zr alloys, a Nb-Ti alloy, Ta-Ti alloys, and Nb_3Sn cored wire in steady fields up to 93.5 kG. The construction and performance of six experimental superconducting coils are described. Critical currents of 25 A have been obtained in two coils, each wound with 0.010-in.-diam Nb-25 a/o Zr wire more than 8,000 ft long.

SUPERCONDUCTING CRITICAL CURRENTS IN WIRE SAMPLES AND SOME EXPERIMENTAL COILS*†

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INTRODUCTION

For a given hard superconductor the transition boundary between the superconducting and the normal state is known to be a function of many variables. Three primary variables are the temperature, the magnetic field, and the current density. Two additional variables are the orientation of the current relative to the magnetic field and the history of the sample since it became superconducting. In short wire samples which have been cooled in zero magnetic field and are held in a fixed orientation with respect to the field, a fairly well-defined transition boundary can be determined which depends only upon the temperature, the magnetic field strength, and the amount of current passed through the wire. When the wire from which the sample was taken is wound in a coil, the conditions are apparently the same as for the short-sample measurement. The coil and sample are both cooled in liquid helium in zero magnetic field and the field generated by the coil is in the same transverse orientation to the current. One would expect to find that transition from the superconducting state occurs at the same value of current passed through the wire. In fact the transition occurs at some much lower value of current. Evidently the expected conditions are not realized in the local wire environment in the coil. Perhaps the temperature of the wire has somehow been raised. Perhaps the particular history of the wire during the rise of current and field has resulted in eddy currents that raise the current density to the critical value for low values of input current. Or there may be undiscovered variables. This paper can only present experimental results to more completely describe the problem.

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K. D. Timmerhaus, ed.

WIRE-SAMPLE MEASUREMENTS

Critical currents in wire samples were measured in the steady field of a copper magnet (as described by Aron and Hitchcock).[1] The samples are 6 cm long and are immersed in liquid helium. Figure 1 shows the critical current densities as a function of transverse applied magnetic field. The current densities are based on total area of cross section of the bare wire. The level of the critical current varies considerably with the purity and with heat treatment in the manufacturing process.

The upper curve for 25% Zr is for wire with optimized heat treatment. The lower 25% Zr curve is appropriate to the larger quantities of wire recently supplied to the Laboratory. The other zirconium alloy data represent several test samples, but each alloy of a given composition was from a single original length of wire.

The Nb_3Sn curve is the measured current density for Bell-type powder-core wire with a single niobium sheath. Steady-field measurements by Babiskin show there is no sudden drop in critical current up to fields of 150 kG for the Nb_3Sn wire.[2] The critical current based on core cross section only is 0.75×10^5 A/cm^2 at 90 kG.

Data are shown for one sample of niobium-titanium alloy. We have not tested this material sufficiently to optimize the degree of cold work or heat treatment. It may have some useful applications because it is a readily fabricated ductile alloy.

Three tantalum-titanium alloys were tested and found to have about the same critical currents as the niobium-titanium, but with lower critical fields (Fig. 2).

COIL PERFORMANCE

The performance of the experimental coils (except Coil V) is summarized on Fig. 3, where critical current is plotted against the maximum field generated by the coil. The critical current for short samples of the wire used to wind these coils is represented by the shaded stripe. These coils are wound of Nb-25 a/o Zr alloy wire 10 mils in diameter. All the coils have been carefully wound in regular layers to minimize shifting of the wire under magnetic stress and to minimize voltage gradients when the coil goes normal. The ends of each length of wire were brought out of the coil, ultrasonically tinned, and soldered to individual terminals for connection to copper leads. The coils were protected against damage from the collapsing field during transition to the normal state by diodes connected across the terminals of each length of wire. Further protection of the larger-diameter Coils II, IV, and VI was provided by spools of high conductivity or by copper secondary windings. All the coils are closely wound, with a space factor of about 50%.

Different means of insulating the coils have been used. In all the coils, except Coil II, wire was coated with Formvar, and Mylar tape was put between each layer. In addition, in Coil IV insulating varnish was applied to each layer of wire as a potting material as the coil was wound. In Coil VI 0.8 mil of copper has been electroplated onto the wire. Coil II was wound with thin copper sheet between layers and without any insulation except for a thin film of drawing lubricant (MoS_2) which was left on the wire. This coil has a rise time of about 20 minutes.

Coil IV, which carries a critical current of only 10 amperes, is our largest coil to date. It is wound with 41,500 feet of wire in 13 lengths and has an inside diameter of 4.5 inches. Each of the 13 lengths when energized separately carries currents of 21 amperes or more in the appropriate self-generated field. There has been no indication that the low critical current observed when all are connected in series has been caused by damage to the wire. Coils IV and VI have been nested to form a magnet system (Figs. 4 and 5). With the present incomplete windings the system produces 37 kG in the 2.5-inch clear hole with 9 A in the outer section and 20 A in the inner section. It is expected to produce 50 kG when the windings are completed.

Coil V was made of Nb-57 a/o Ti alloy, 10-mil-diameter wire, and carried a critical current of 6 A. The corresponding sample wire at the generated field carried 13 A (Fig. 6).

We have applied alternating currents of audio frequency to one of the coils (Coil III) and found very low critical values of alternating current, as shown on Fig. 7 (see Fig. 8 for circuit). The dc critical current for this coil was 18 A. At 60 cps the critical alternating current is 1/5 A, and decreases with increasing frequency. The low critical alternating current is thought to be caused by resistive eddy currents in the wire, which raise the temperature to the transition boundary. This is the heating that has been discussed by Jones and Schenk.[3]

DISCUSSION

Coils II and VI are the only coils that have some metal wound intimately into the coil in addition to the superconductor. The copper foil between the layers of Coil II and the copper plating of the wire of Coil VI have good thermal contact with the superconducting wire. The copper provides a heat sink equal to 8% of the heat capacity of the wire itself. Possible beneficial action of the copper as a heat sink or as an eddy-current shield against sudden penetration of magnetic flux into the wire connot be evaluated without testing a control coil. Discontinous penetration of magnetic flux into hard superconductors has been observed by several experimenters.[4] It is reasonable to expect that flux jumps induce resistive eddy currents, as do the ac fields. We are now working on a small coil to be wound with niobium-zirconium wire clad with 2 mils of cadmium to provide an appreciable heat sink.[5] The heat sink in the coil will help compensate for the poorer thermal coupling between the liquid helium and the wire in the coil than in the short-sample environment. Cadmium has high thermal and electrical conductivity at the low temperature.

APPENDIX

Procedure for Coil ac Critical Current Measurement

A. The frequency of the generator was adjusted to the resonant frequency of the series LC circuit, resonance being determined by observing the null meter.

B. The current was raised in 5-mA steps. After each step thermal equilibrium was established and the generator frequency was readjusted to indicate resonance on the null meter. The frequency was then determined by the frequency meter.

C. At some current the coil would go normal, as indicated by a sharp rise in null voltage and drop in drive current. These end points were then plotted in Fig. 4.

REFERENCES

1. P. Aron, and H. Hitchcock, J. Appl. Phys. 33, 2242 (1962).
2. J. Babiskin, Critical Transition Properties of Nb_3Sn and Nb-25 a/o Zr, Naval Research Laboratory, private communication.
3. C. H. Jones and H. L. Schnek, "AC Losses in Hard Superconductors," in Advances of Cryogenic Engineering 8 (Proceedings of Cryogenic Engineering Conference, UCLA, 1962), to be published.
4. P. S. Swartz and C. H. Rosner, J. Appl. Phys. 33, 2292 (1962).
5. Paul Aron, Lawrence Radiation Laboratory Physics Memorandum 415, Aug. 1962.

Table 1. Coil Data[a]

Coil number	I	II	III	IV	V	VI
Wire material	Nb-25 Zr	Nb-25 Zr	Nb-25 Zr	Nb-25 Zr	Nb-57 Ti	Nb-25 Zr
Central field/coil current(G/A)	2500	1130	2500	2200	2610	871
Maximum magnetic field at inside diameter of coil (kG)	43	36.5	40.8	24.2	15	22.3
Central magnetic field (kG)	42.5	26.7	39.4	22	15	21.8
Critical current, I_c (A)	16.3	24	16	10	5.9	24.5
Length of wire (ft)	8,520	8,250	3,726	41,500	6,710	10,180
Insulation on wire	Formvar	MoS_2 [b]	Formvar	Formvar	Formvar	Formvar [c]
Insulation between layers	Mylar	copper	Mylar	Mylar [d]	Mylar	Mylar
Space factor [e] (%)	50	48	60	48	51	45
Spool material	304 St. St.	copper	Micarta	304 St. St.	Micarta	alum. al.
Inductance, calculated (H)	3.63	7.95	1.46	65.5	2.47	6.41
Field energy, $1/2\ LI_c^2$ (J)	482	2,290	187	3,280	43	2,005
Coil i.d. (in.)	0.56	2.75	0.50	4.65	0.50	2.75
Coil o.d. (in.)	2.25	4.29	2.32	6.24	2.29	3.44
Coil length (in.)	4.5	1.91	1.44	5.96	3.19	6.03
Number of turns	23,622	8,934	9,994	29,148	18,429	11,848
Protective secondary	none	spool	none	at i.d.	none	at o.d.

[a] all wire is 0.010-in. diam
[b] film of drawing lubricant
[c] wire electroplated with 0.0008-in.-thick copper
[d] layers painted with General Electric insulating varnish
[e] (volume of bare wire)/(winding volume of coil)

Table 2. Wire Sample Data

Material	LRL Designation	Diam.(in.)	Manufacturer	Notes
Nb-10 a/o Zr	KD-45	0.015	Kawecki	
Nb-25 a/o Zr	WC-5K	0.010	Wah Chang	600°C H. T.
Nb-33 a/o Zr	WC-38	0.010	Wah Chang	
Nb-50 a/o Zr	WH-59	0.010	Westinghouse	Heat VAM 62-2
Nb-57 a/o Ti	WC-100	0.010	Wah Chang	
Nb_3Sn in Nb Sheath	WC-28	0.021	Wah Chang	Core diam. 0.0102 in.
Ta-20wt/o Ti	WC-109	0.010	Wah Chang	Sample #6
Ta-25wt/o Ti	WC-110	0.010	Wah Chang	Sample #8
Ta-30wt/o Ti	WC-111	0.010	Wah Chang	Sample #7

LEGENDS

Fig. 1. Critical current densities for Nb-Zr alloys, Nb-57 a/o Ti, and Nb_3Sn composite wire based on total cross section of the bare wire for 6-cm-long samples at 4.2°K.

Fig. 2. Critical current density for Ta-Ti alloys based on total cross section of the bare wire for 6-cm-long samples at 4.2°K.

Fig. 3. Critical current for coils wound with .010-in.-diam Nb-25 a/o Zr wire at 4.2°K.

Fig. 4. Superconducting magnet system as wound July 1962.

Fig. 5. Left: Photograph of Coil I; 42 kG; I_c = 16 A; outside diameter of winding, 2-1/4 in.

Right: Photograph of Coil IV; 22 kG; I_c = 10 A; outside diameter of winding 6-1/4 in.

Fig. 6. Critical current for Coil V wound with .010-in.-diam Nb-57 a/o Ti wire at 4.2°K.

Fig. 7. Critical alternating current for Coil III at 4.2°K.

Fig. 8. Circuit used to measure coil critical alternating current.

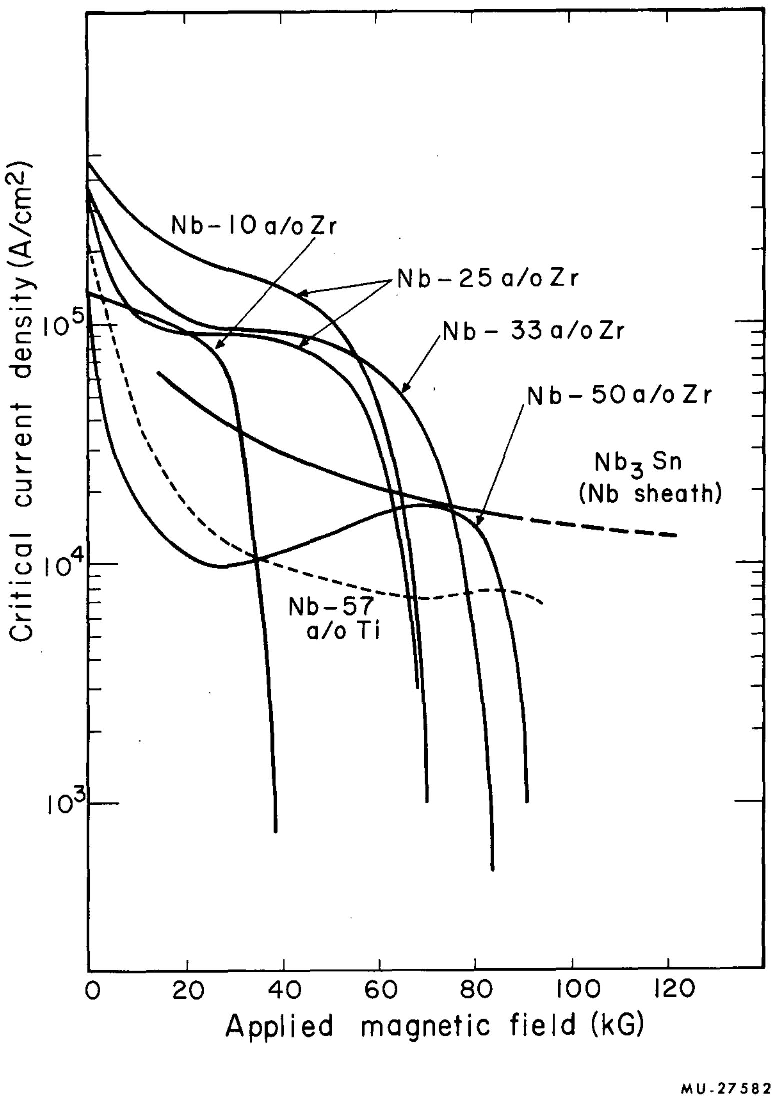

Critical current density (A/cm2)
Applied magnetic field (kG)
Nb-10 a/o Zr
Nb-25 a/o Zr
Nb - 33 a/o Zr
Nb-50 a/o Zr
Nb3 Sn
(Nb sheath)
Nb-57
a/o Ti
10^5
10^4
10^3
0
20
40
60
80
100
120
MU-27582

Fig. 1

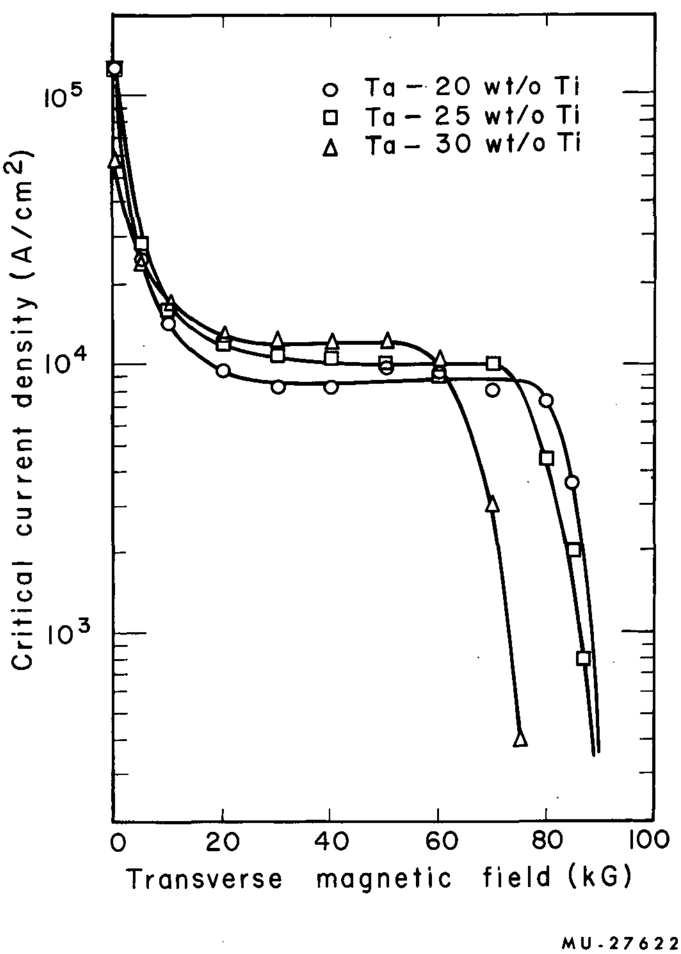
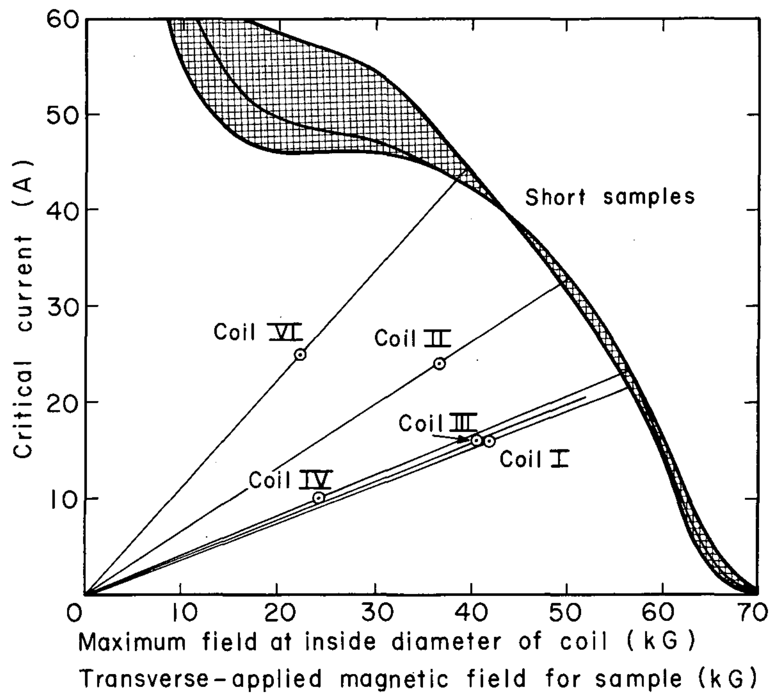
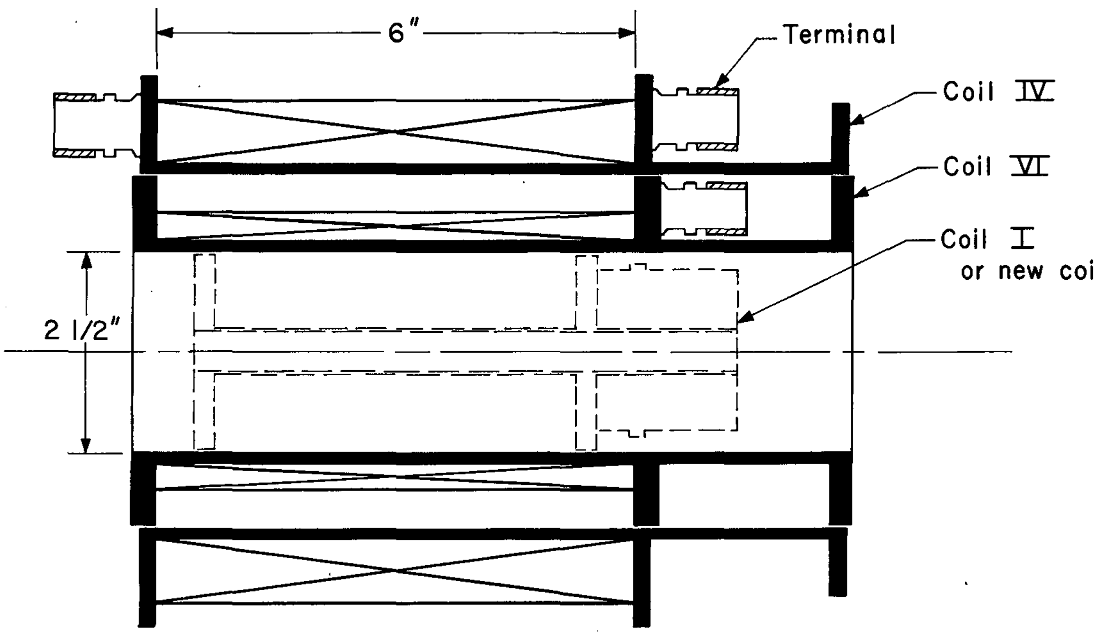

Ta – 20 wt/o Ti
Ta – 25 wt/o Ti
Ta – 30 wt/o Ti
10^5
10^4
10^3
Critical current density (A/cm^2)
0
20
40
60
80
100
Transverse magnetic field (kG)
MU-27622

Fig. 2



60
50
40
30
20
10
Critical current (A)
Short samples
Coil VI
Coil II
Coil III
Coil I
Coil IV
0
10
20
30
40
50
60
70
Maximum field at inside diameter of coil (kG)
Transverse-applied magnetic field for sample (kG)
MU-27583

Fig. 3

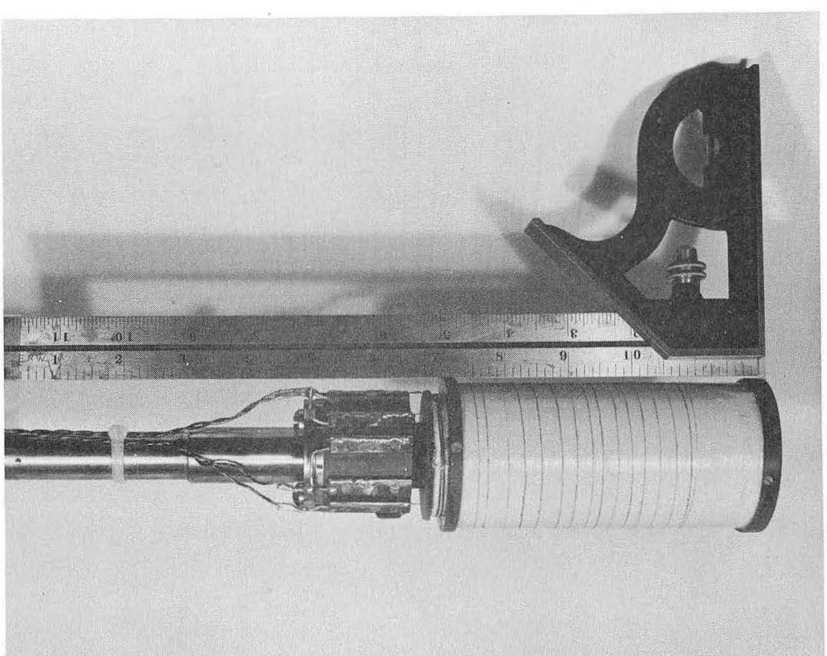


Superconducting Magnet System

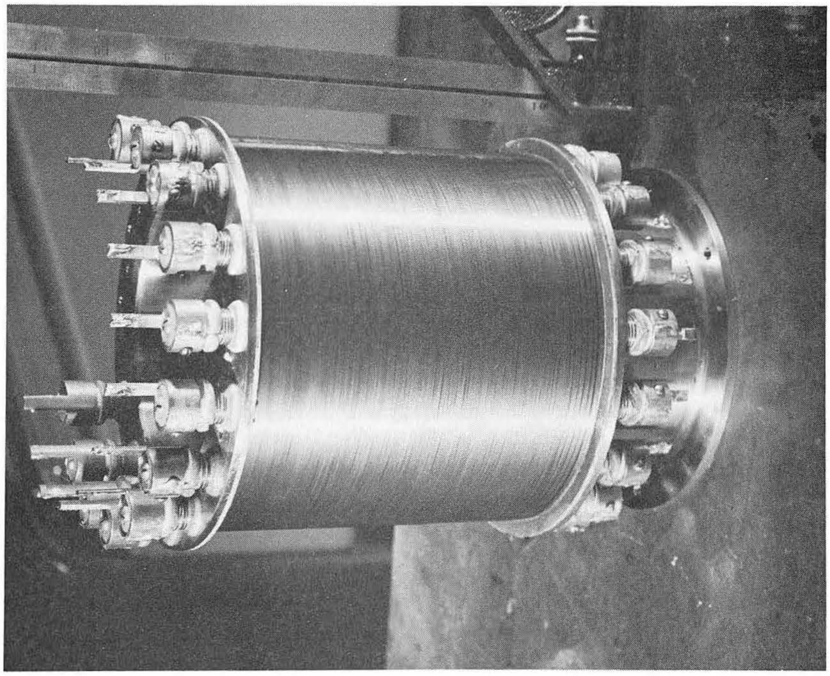
as wound July 1962 with 15-lb Nb-25 a/o Zr wire

MU-27584

Fig. 4



ZN-3220



ZN-3221

Fig. 5

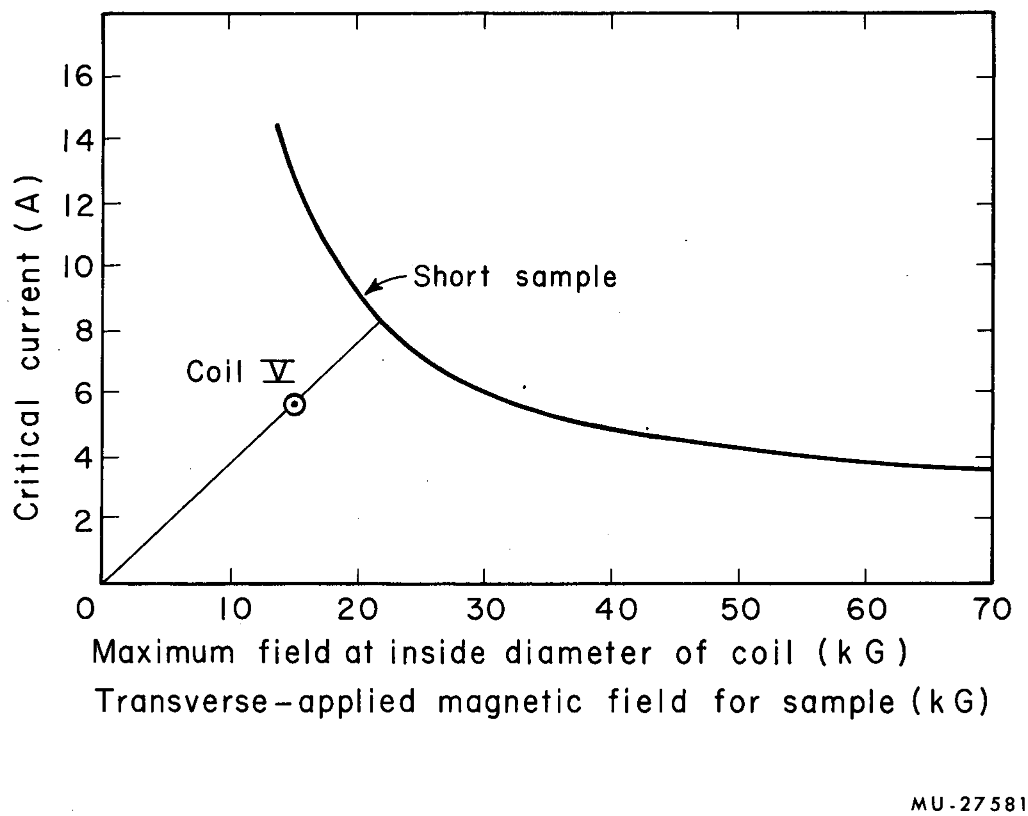
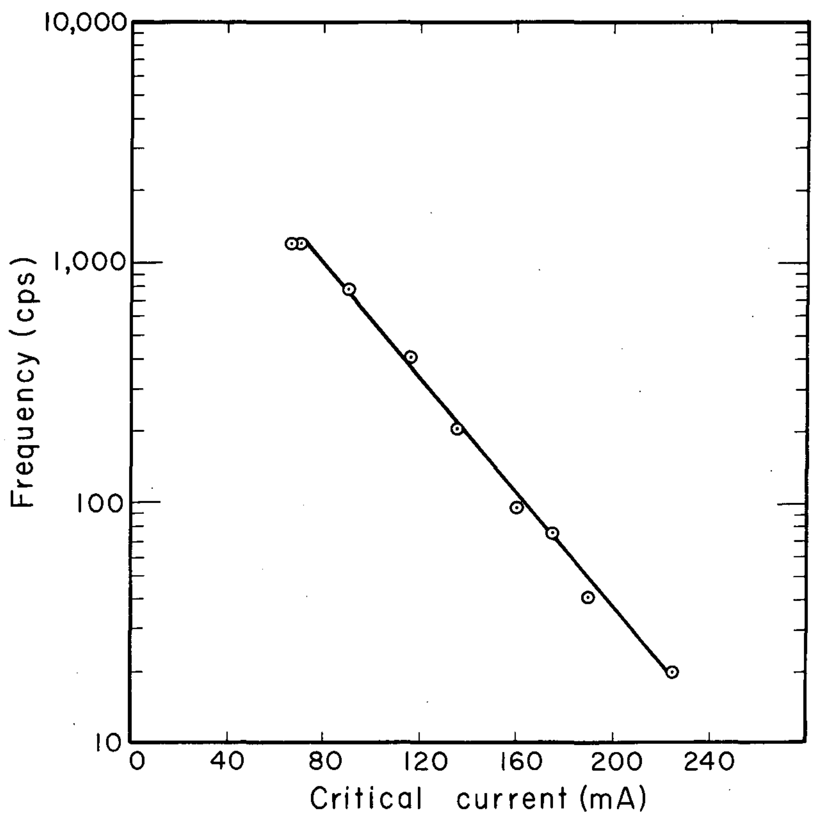

16
14
12
10
8
6
4
2
Critical current (A)
Short sample
Coil V
0
10
20
30
40
50
60
70
Maximum field at inside diameter of coil (k G)
Transverse-applied magnetic field for sample (k G)
MU-27581

Fig. 6



MU-27588

Fig. 7

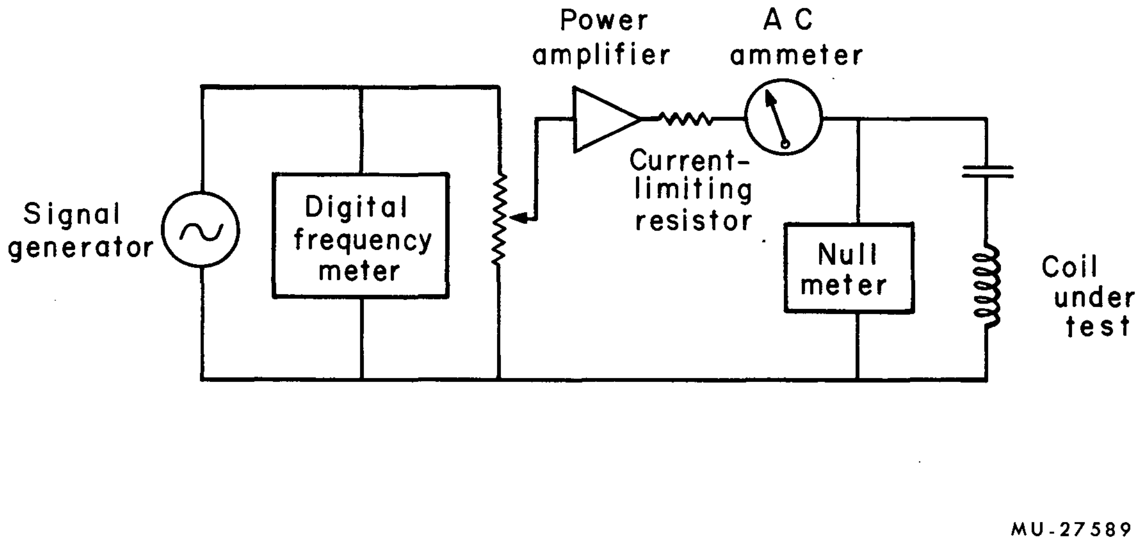

Power
amplifier
A C
ammeter
Current-
limiting
resistor
Signal
generator
Digital
frequency
meter
Null
meter
Coil
under
test
MU-27589

Fig. 8