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An inorganically insulated 30-kG 2-in. -bore Nb-25% Zr solenoid for operation at 1° K is described. The thickness of the copper plating and the thermal environment prevented serious current degradation at 1° K. The insulation was sufficient to allow for a high charge rate with low heat input to the 1° K bath.

Introduction

Recent work has shown that coils can be constructed from Nb Zr conductors of enhanced current-carrying capacity with little or no degradation in current-carrying capacity of the superconductor.[1,2] This stabilization requires good cooling and a large proportion of high-conductivity "normal" conductor.

It has also been demonstrated that all-metal coils with less of the normal conductor are capable of producing high current densities with little degradation of the current capacity of the wire at temperatures of 4.2° K and less.[3]

It has been reported that coil operation below 4.2° K resulted in further degradation in conductor current-carrying capacity when organic insulated copper-coated Nb Zr wire was used in coils. This degradation at low temperatures is caused by the increased severity of flux jumping. The degradation could be reduced or eliminated if the conductor was well cooled, adequately shunted along its length, and fixed in position.[3]

Design Requirements

The solenoid was required for use in a 1° K liquid helium II bath, where it was to be used for adiabatic demagnetization refrigeration (Fig. 1.) The heat input to the bath was to be less than 30 mW as the coil was discharged from 30 A to zero current in 5 min. An approximately linear fall in current with time was required during the discharge. The magnetic field needed was 25 kG at the center of a solenoid of length 10 in., i. d. 2 in., and o. d. 3 in.

Because of space restrictions, a minimum current density of 20 000 A/cm^2 was required.

The present design was tried because existing methods of coil construction would not meet all the above requirements.

Coil Construction

A radial thickness of 0.0015 in. of electroplated copper was coated on the 0.010-in. -diam Supercon Nb 25% Zr wire. Normal practice at the time this coil was conceived had been to use a radial coating thickness of 0.001 in. The increased amount of normal conductor used in this coil results in less degradation of the current-carrying capacity of the wire for a given temperature rise caused by flux movement.

When the copper thickness is increased much beyond 0.0015 in., the loss in packing factor may not be compensated by the increase of conductor current-carrying capacity.

Organic insulation was rejected because of its thickness and its poor heat-transfer characteristics.

Turn-to-turn insulation was obtained by chemically oxidizing the copper electroplate until it turned black. This semiconducting layer is about 0.0001 in. thick. The insulation is sufficient to reduce heat produced by turn-to-turn shunting to a negligible amount during routine operation. When the coil goes normal, the semiconducting properties of copper oxide permit the current to shunt between turns and thereby inhibit the buildup of large voltages.

Good heat transfer through the thin oxide coating causes the normal region to propagate rapidly during a transition. Consequently the stored energy in the coil is safely distributed over a large fraction of the winding.

Complete insulation between layers is essential to limit shunt-current heating and to permit a high charge rate without the coil's going normal prematurely. Tightly woven Fiberglass cloth 0.004 in. thick was used as the interlayer insulation, and was given higher strength by being impregnated with thinned, clear varnish. It was thought that this porous interlayer material would permit helium II to permeate the winding. It was hoped that the remarkable heat conductivity of helium II would provide a good thermal environment for the wire.

The coil was wound and tested twice. Occasional asperities on the copper electroplate caused some interlayer shorts on the first wind so that 1 hour was required to energize the coil to full current. Subsequently the wire was run through fine sandpaper.

The Nb Zr conductor snapped during the first unwind. The two portions of the conductor were joined by forming a lap joint for 30 ft and indium-soldering them together. The presence of this splice in the finished coil did not affect its current-carrying capacity.

Lead losses were reduced on the original solenoid (Fig. 2) by eliminating the copper connection between the vapor-cooled phosphor-copper input lead and the coil for 2 in. The normal conductor was replaced by a 2-in. length of RCA Nb_3Sn ribbon soldered to a 1/4-in. -wide stainless steel strip over this distance.

A compact joint was made on the present solenoid (Fig. 3) between the Nb Zr wire and the lead by winding the wire around a plug at the end of the lead and soldering the wire to the lead length.

Coil Performance

The coil operated at 38 A (35 kG) at 4.2° K, and at 32.5 A (30 kG) at 1° K. The short-sample characteristics for the conductor used in the coil were 70 A at 30 kG and 62 A at 35 kG at 4.2° K. The design has resulted in degradation in conductor performance at 4.2° K and further degradation at 1° K. The degradation between the performance at 4.2° K and 1° K is less than that measured in superconducting coils of more conventional construction. Further efforts are necessary to improve the performance in this type of solenoid while meeting the necessary design specifications.

The average current density in the coil was 30 000 A/cm^2 at 4.2° K with a packing factor of 38%. When the magnet was discharged from 30 A to zero current in 2.5 min. 30 mW of heat energy was dissipated in the helium bath at 4.2° K. It was estimated that this discharge was made up of 12 mW due to ohmic losses in the power lead, 6 mW due to eddy-current losses in the phosphor-copper spool, and 12 mW due to current shunting and magnetization losses.

At 4.2° K the maximum current was affected by the charge rate and to a lesser extent by training. At 1° K these effects were not important. However, flux jumping at the lower temperature is far more severe (Fig. 4).

When 80% of the winding was above the liquid level, the current-carrying capacity of the wire was degraded at 4.2° K, but it was not degraded at 1° K. This performance indicates that the helium II at 1° K permeates the winding.

Full-wave voltage ripple from a simple single-phase diode supply did not reduce the current-carrying capacity of the coil.

Adiabatic demagnetization refrigeration requires a smooth discharge of the magnet. It was found that the current decayed almost linearly when the power supply was turned off and the current was allowed to circulate through the silicon diodes. The magnet discharged from 30 A to zero current in 3 min for the supply currently used. A much longer decay was obtained when the power leads were shorted above the Dewar with a knife switch. The current then dropped exponentially from 30 to 1 A in 50 minutes.

Coil Protection

The copper coating around the superconductor and the oxide insulation were adequate in themselves to protect the coil.

The time constant for transition (τ) of 150 msec compared favorably with the 110 msec calculated through use of the analysis developed by Z. J. J. Stekly.[4,5] For coils of similar construction the τ is proportional to the area of the copper electroplate (A), the coil inductance (L), and the current at transition (I) according to

$$\tau \propto A\, L^{1/4}/I^{3/4}.$$

For this coil τ = 150 msec with $A = 0.542 \times 10^{-4}$ in.^{2}, L = 5.5 henry, and I = 36 A (Fig. 5).

For the observed 150-msec time constant it was calculated that the wire temperature should not exceed 60° K. (As an example of the effect of τ on wire temperature, a time constant of 1 sec would have resulted in a wire temperature of about 200° C for this particular wire and a transition current of 36 A.)

On several occasions the coil has been allowed to go normal with the power supply left on afterwards. The coil recovered in 20 sec and then attained a current of at least as much as the first transition.

Coil Parameters

Wire

Manufacturer	Supercon
Diameter of Nb 25% Zr	0.010 in.
Thickness of copper electroplate	0.0015 in.
Thickness of copper oxide	≈0.0001 in.
Total diameter	0.013 in.
Length in coil	13 500 ft
Resistance of wire at 20° C	0.162 ohm/ft
Resistance ratio, 20° C to 77° K	7.2
Resistance ratio, 20° C to 11° K	102

Short sample data:

Magnetic field (kG)	10	20	30	40
Critical current (A)	100	77	70	55

Coil Dimensions

Spool i. d.	2-3/32 in.
Coil i. d.	2-7/32 in.
Coil o. d.	3-1/32 in.
Coil length	10 in.
Coil thickness	13/32 in.

Spool material - hard drawn phos-copper tube with 1/2-in. -thick brass flanges

Winding Specifications

Number of layers	26
Number of turns/layer	763
Total number of turns	19 800
Layer-to-layer insulation	0.004 in. glass cloth
Thickness of one layer	0.0156 in.
Compressed thickness of glass cloth	0.0026 in.
Fraction of winding space occupied by superconductor	38%
Number of turns/in.^{2}	4 870
Current density for winding space at 38 A	1.9×10^5 A/in.^{2}

Coil Characteristics

kG/A	0.92
Inductance	5.5 henry
Maximum field at 1° K (32.5 A)	30 kG
Maximum field at 4.2° K (38 A)	35 kG
Stored energy at 38 A	4 000 joules
Charging voltage for 38 A	3.5 volt-min
Flux at 38 A	0.01 weber

Coil Resistance

	20° C	77° K	11° K
Resistance of coil (ohm)	1 623	267	≈ 26
Resistance of wire (ohm)	2 300	320	≈ 23
R_{coil}/R_{wire}	71%	83%	≈ 100%

Transition-Time Constant (τ)

Current at transition (A)	9	18	27	36
Transition-time constant (sec) ($I_\tau = I_0/e$)	0.4	0.3	0.23	0.15

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Footnote and References

*Work done under the auspices of the U. S. Atomic Energy Commission.

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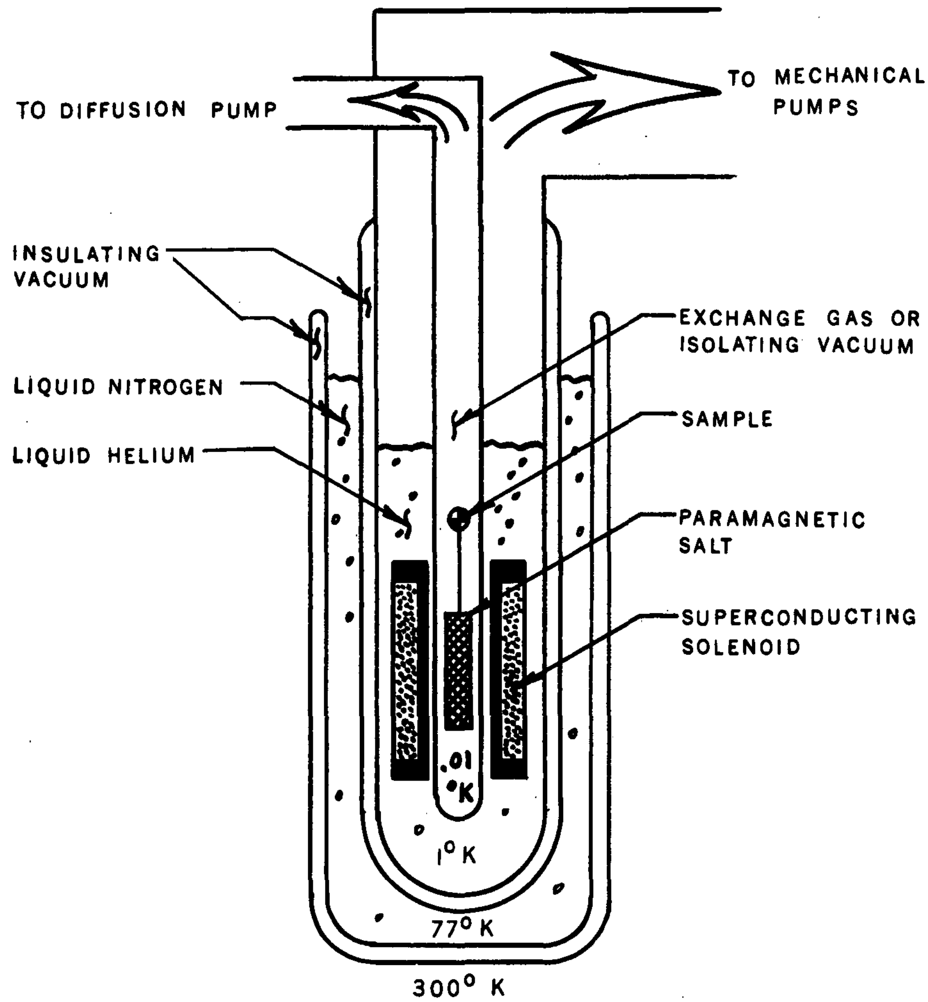
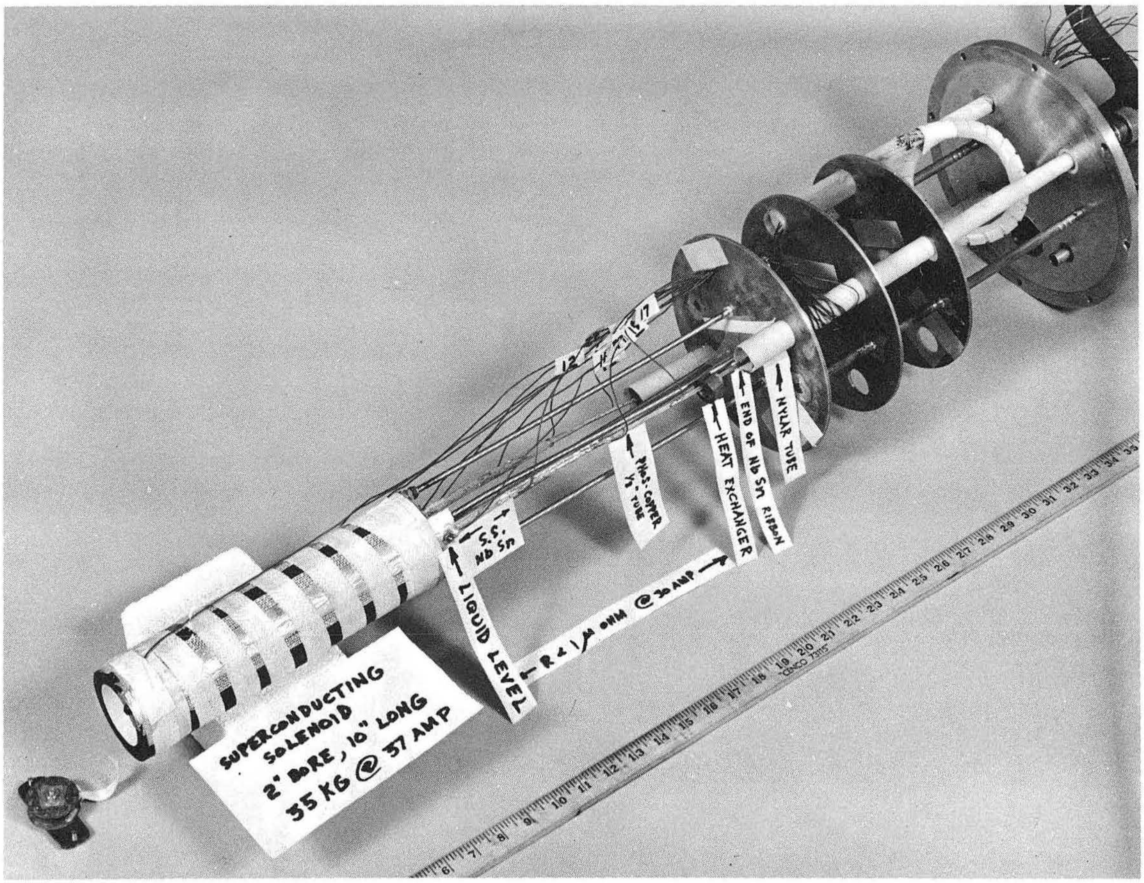


MUB-7673

Fig. 1. Schematic representation of adiabatic demagnetization refrigeration apparatus.



ZN-5174

Fig. 2. Original solenoid. Leads have 2-in. sections of stainless steel strip with Nb_3Sn ribbon soldered to them.

ZN-5102

Fig. 3. Present solenoid. Leads are phos-copper tubes with Nb 25% Zr wire soldered to them.

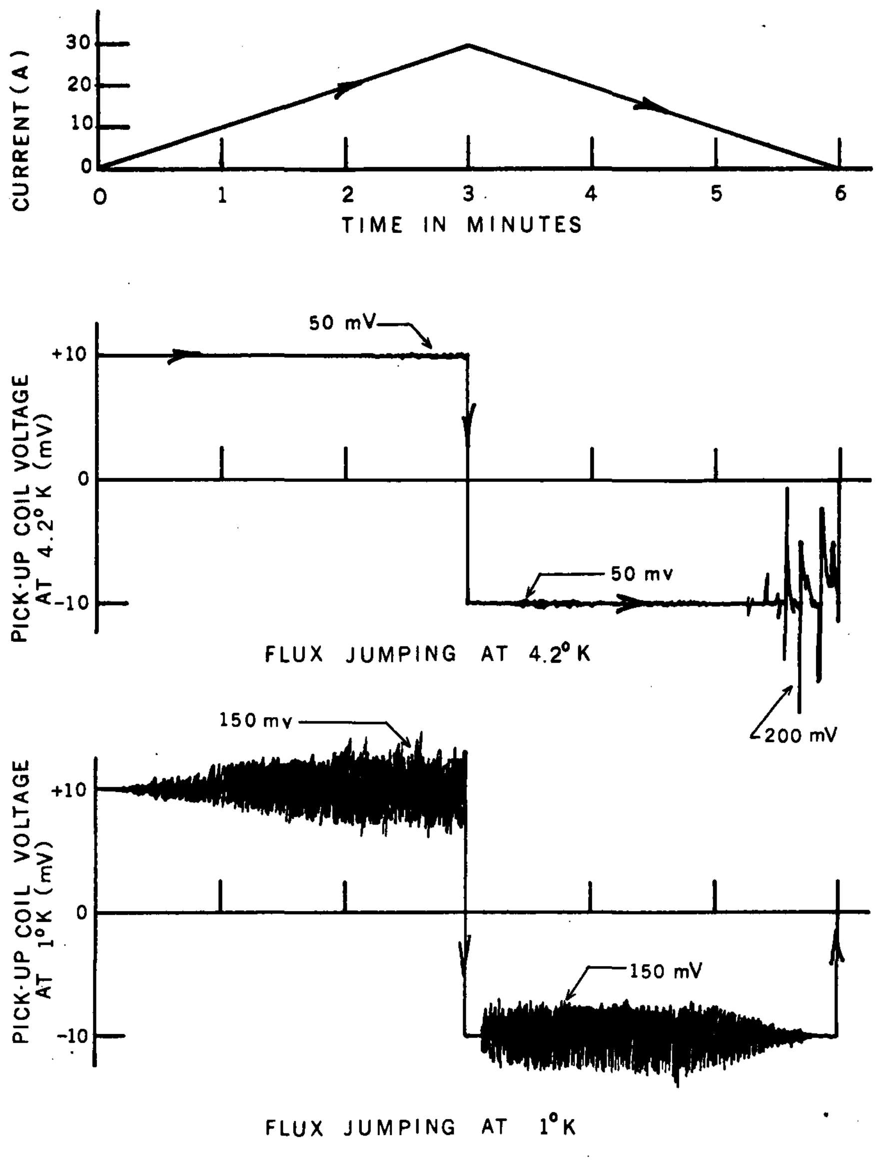


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Fig. 4. Flux jumping during charge and discharge as observed with an X-Y plotter. A 0.132-henry pickup coil was placed in the center of the solenoid. (The response time of the X-Y plotter was not fast enough to record the full magnitude of the flux jumps. The approximate sizes of the jumps observed with an oscilloscope are indicated.)

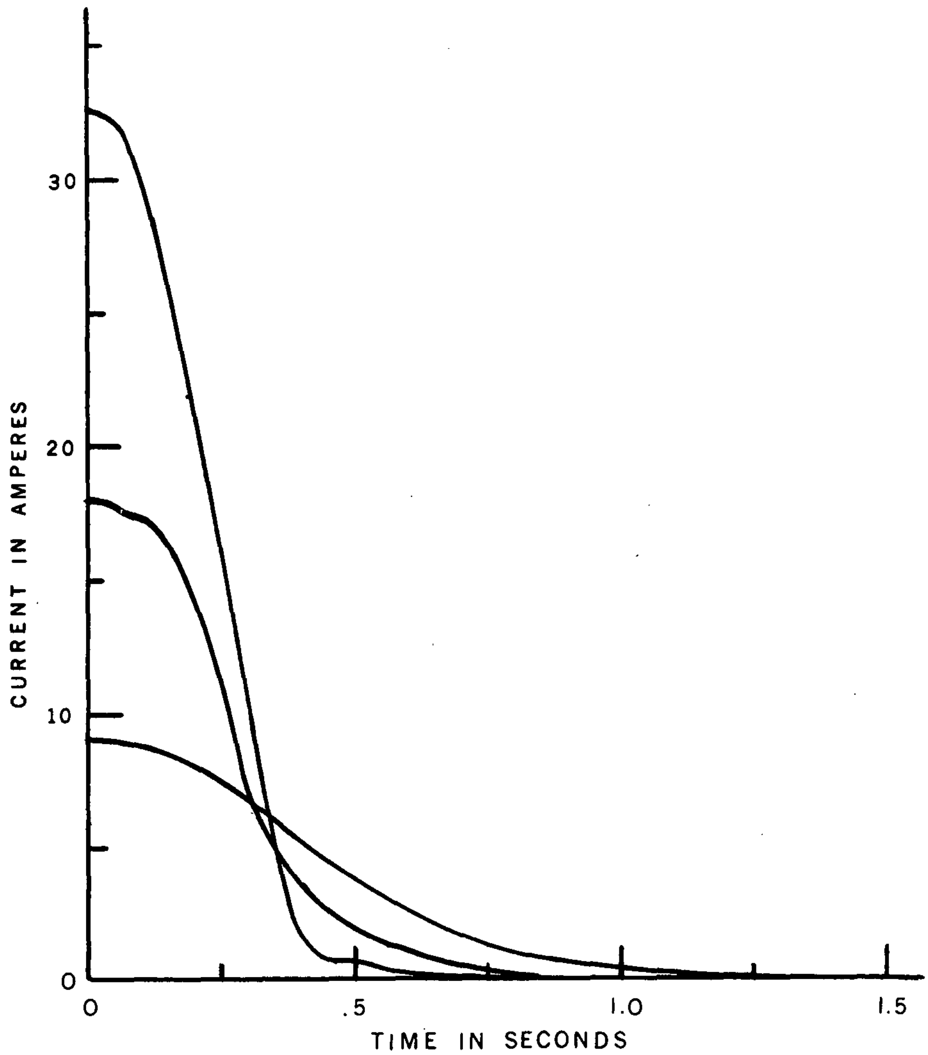

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Fig. 5. Current decay when the solenoid makes the transition from the superconducting state to the normal state. Transition currents of 32.5, 18, and 9 A are represented.