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FAST RAMP SUPERCONDUCTOR FOR OHMIC HEATING COILS

M. S. Walker and B. A. Zeitlin, Intermagnetics General Corporation, Guilderland, New York
R. E. Schwall, Oak Ridge National Laboratory, Oak Ridge, Tennessee

INTRODUCTION AND SUMMARY

The present study[1] was conducted to consider practical 10,000 ampere conductor designs to meet the operating constraints for the ohmic heating coils of TNS and experimental Tokamak reactors.[2] The conductor must simultaneously meet the requirements for mechanical support, cryostabilization, high overall winding current density, low mechanical and electrical losses, and mechanical and electrical integrity for cyclic pulsed operation from -7 T to +7 T in one second.

Our suggested winding is a set of nested tubes, each made up of a stack of pancake-wound bobbins. Each pancake is co-wound of a flat open superconductor braid, steel tape, and Kapton insulation. The strands of the braid consist of sectored copper regions separated by copper-nickel and surrounding a mixed-matrix copper, copper-nickel, and NbTi multifilament core. Strands 1.5 mm in diameter provide conservative cryostabilization at overall winding current densities adequate for the OH winding of an EPR-1 or TNS sized coil (~1500 amperes/cm^2). Eddy current and coupling losses are at acceptable levels, and hysteresis losses can be reduced within acceptable limits with 10 μ diameter filaments, providing the winding is graded, tube to tube. The basic conductor and winding concept can be extended to provide conductors of higher currents.

A 2000 ampere model conductor has been fabricated from 0.94 mm diameter strands, and tested in a reinforced pancake configuration. The measured maximum recovery current corresponds to a current density of 3500 amperes/cm^2 over the entire coil cross section.

THE SUGGESTED TNS-SCALE 10,000 AMPERE CONDUCTOR AND WINDING DESIGN

Suggested Winding Scheme

To retain the advantages of the pancake winding, yet allow grading of the conductor and a partitioning of any accumulated radial forces, a hybrid multilayer stacking of pancake-wound coils is suggested as the preferred coil design for this application. The suggested winding scheme is shown in Figure 1. The ohmic heating coil (left side of the Figure) consists of a fiberglass and epoxy central column, which is surrounded successively by thinner concentric epoxy-fiberglass shells, as shown in Inset A.

Each shell has stacked upon it to the full height of the column a set of pancake-wound coils on fiberglass and epoxy bobbins, where the outside diameter of the coil flanges fit snugly inside of the inside diameter of the succeeding shell. The pancake flanges are notched, perforated, grooved or shaped as necessary to allow axial helium movement, radial helium access and a shrouding of helium gas to the larger open areas at the outside diameter of each layer. Pancakes can be wound in pairs and joints between pairs at the outside diameter can be eliminated if necessary by using appropriate spooling and winding schemes.

The pancakes will be co-wound of a flat braid interleaved with stainless steel and Kapton tape as shown in Inset B.

Suggested Conductor Configuration

The recommended conductor is a flat braid like the 97 strand braid developed at Brookhaven National Laboratory,[3] except that the strands will be 1-2 mm in diameter, much larger than those utilized at Brookhaven, and the strands will be individually insulated. The flat braid consists of a weave of strands over a "herringbone" skeleton, shown schematically at the top of Figure 2. The ribs are strands which move from the center of the conductor at an angle of about 30° to the vertical (for a flat-wound solenoid). Two layers of strands weave in an over-two, under-two, over-two sequence which is shown at the bottom of the Figure for the three axial positions corresponding to sections AA, BB, and CC in the inset. Alternate strands in each of the two side layers of strands cross each other between each pair of ribs. The layer strands at the center of the conductor become ribs and move to the outside where they join the layers again so that along the axial length of the conductor every strand occupies the location of every other strand and is completely transposed. Rigid mechanical support is provided against radial compression where the ribs support the two layers of strands, to the extent that the strands resist plastic deformation at the crossing points. A slight precompaction, assuming a tough insulation, will expand the point contact to an area contact at the strand crossing points so that substantial pressures can be withstood. An examination of deformation for crushing forces on various types of conductors at 90° crossing angles has been performed at IGC.[4]

Support of the braid is particularly good against flat surfaces on either side of the braid. The steel therefore serves a triple purpose: (1) integral support of the winding against hoop stresses, (2) tightening of the winding onto the formers due to differential compaction on cool-down,[5] and (3) rigid transmission of radial compression through the winding.

The braid configuration is excellent for cooling and heat transfer. All strand surfaces have free access to unconfined helium, excepting those small areas which are in physical contact where the strands cross or are in line contact with the steel and Kapton interturn spacers. Clear channels one strand diameter thick and effectively several strand diameters wide, run beside the ribs from the center of the braid to the upper and lower edges, where with a slight jog, but without constriction they exit from the conductor.

Good stability has been demonstrated in the Brookhaven dipoles with 12 mil diameter strands and even with porous solder filling,[3] although these dipoles are not conservatively cryostable in the context discussed here.[6] To achieve cryostability, larger strand diameters, the order of one to 2 millimeters, are needed to produce channel widths adequate for gas clearing.[5,7] However, the increase in strand size will result in some sacrifice, because of the reduction in strand surface to volume ratio, of the transient stability which has been demonstrated at Brookhaven. Because of the mechanical hysteresis losses generated in unfilled and unpotted cables of these strands,[3] larger, stiffer strands, and accordingly, fewer winding layers are recommended. Once cryostability rather than transient stability is chosen, then from a stability point of view the design becomes more conservative as the strand size increases and large channel sizes are established.

Other constraints suggest that the strands should still be made as small as is permissible, however. Electrical losses and the quantity, and therefore the cost, of strand material that is required are both reduced by reduction in strand size. Without presuming to optimize for the TNS coil, we have selected a 1-1/2 millimeter diameter strand size for reference calculations.

Suggested Strand Configuration

In consideration of the need for low hysteresis losses and on the basis of state-of-the-art fabrication capabilities, an approximately 10 μ diameter filament is suggested for the superconductor strands. To reduce coupling losses and retain an adequate intrastrand heat transfer capability, it is suggested that these filaments be placed in a mixed-matrix configuration incorporating comparable amounts of copper and NbTi in copper-clad filaments within a copper-10% nickel resistive matrix. An established 1.5:2:1 CuNi:Cu:SC mixed-matrix conductor is suggested. However, for cryostabilization additional copper is required.

A strand configuration that has been devised for low loss superconductor windings for the Air Force[9] is well suited to the present application. The configuration is shown in Figure 3. The mixed-matrix core can be surrounded with copper, providing that a resistive barrier, in this case CuNi, separates the core from the copper to prevent the leakage of coupling currents through the low resistivity copper. The resistive fins provide a barrier to currents that do enter the copper, and they also break up the copper regions to reduce eddy current losses.

REFERENCE DESIGN FOR THE 10,000 AMPERE CONDUCTOR FOR THE PEAK FIELD, 7 T, FIRST LAYER

The inside layer experiences the peak 7 T field of the winding. Calculations of the current density, losses, and cooling requirements for the conductor in this layer have been made and used as a conservative guide to estimating the overall requirements and properties for the device, although it has been necessary to calculate possible hysteresis losses assuming a graded winding as well. The results of the calculations are presented in the sections which follow.

Allowed Cryostable Heating Per Strand

We have taken a conservative posture with respect to the requirements for cryostability. The current density which can be achieved in the winding is governed by two aspects of heat transfer: (1) the cold-end recovery criteria for heat transfer to the helium must be satisfied[6] and (2) an adequate helium channeling must be provided to remove the heat which is transferred.[7] We have assumed: (1) that the braid conductor will be cooled through vertical grooves in the stainless steel adjacent to both braid surfaces as well as the channels within the braid itself, (2) that the braid interior will be as effective for removing heat as a continuous annular channel 0.15 cm wide, (3) that the steel tapes will have 0.15 cm wide channels facing the conductor on both sides, each effective over 50% of the surface facing the braid and (4) that the vertical height of these channels will be 7.5 cm. Over 0.70 watts can accordingly be extracted from each cm of height of the braid using Wilson's data; 0.0525 watts can be removed per strand, about 0.11 W/cm^2 of strand surface. Even with a 50% surface occlusion on each strand, this is conservatively below the 0.27 W/cm^2 limit for cold-end recovery in each strand were film-boiling initiated.[7]

Optimization of Strand Parameters and Current Density

By equating normal state joule heating and heat transfer from the strand, an optimal relationship between the relative fractions of the various strand components can be made and a maximum strand current can be calculated. The relative optimized fractions of components are listed in Table 1. Sixty-six strands are required for 10,000 amperes and the width of the braid (axial height in the wound geometry) is about 5 cm. The original assumption of a 7.5 cm channel height is accordingly conservative, and an iteration of this calculation assuming heat transfer for a 5 cm channel should allow higher current densities per strand, and a smaller number of strands. Alternatively, one can accept the 15% margin in cooling that the first calculation provides.

The overall current density for the braid and interstitial helium is 4.44x10^7 amperes/m^2. If the winding is designed for 1.5x10^7 amperes/m^2 as is the OH coil for the ORNL EPR-1 Reference Design, then 34% of the winding will be for the conductor and enclosed helium, leaving 66% of the volume between the inside diameter of the inside conductor layer and the outside diameter of the outermost pancake flanges for non-metallic structure, steel, Kapton, and additional helium. The latter percentage is less than was originally suggested, but still allows a reasonable fraction for each component.

Losses in the Conductor

Since the Reference Design has been guided by conservative heat transfer and cryostability considerations where the creation of adequate helium channeling has been the critical constraint, the conductor strand size is relatively large. As a consequence, eddy current and hysteresis losses have been pushed towards the target specification of matching the losses estimated for the Ohmic Heating Coil in the Oak Ridge EPR-1 Reference Design. Although the losses that are encountered will depend upon grading of the conductor, a conservative projection of the magnitude of the losses can be achieved by analyzing losses in the conductor elements which are designed to operate in the peak field region.

The loss per cycle, Q_1, which is summarized in Table 2, has been determined assuming that the 7 T reference design conductor is wound throughout the coil. The total loss calculated on this basis is clearly within the target specification.

With grading of the NbTi and a tighter twist pitch length, the losses can be reduced to meet the specifications as shown in the second estimate, Q_2. The hysteresis loss for Q_1 was calculated using the instantaneous loss equation given below for cylindrical filaments carrying transport current,[10]

$$(P/V)_{sc} = \frac{2\bar{\dot{B}} j_c d}{3\pi} g\left(\frac{I}{I_c}\right) \qquad (1)$$

assuming that the filaments are 10 microns in diameter, d, that the filament current is well below the transport current on average throughout the winding, making g=1.5, that the average peak field, B, seen in the winding is 3.5 T, and that the average filament critical current density $\bar{j}_c$ is 3x10^3 amperes/m^2. The graded estimate was made assuming an infinite solenoid with every filament reaching 0.9 j_c at maximum current.

The coupling losses were calculated in two ways for Q_1 assuming in each case that the twist pitch length is 1.5 cm, ten strand diameters. In the first case, the overall fractions of superconductor copper and copper-nickel which are given in Table 1, were assumed to be uniformly distributed throughout the strand in a mixed-matrix configuration. This calculation gave losses approximately triple the coupling for Q_1 in Table 2, which was calculated on the basis of the configuration shown in Figure 3. Although the conductor design was not graded, an average B^2 was utilized for the coil.

It may also be possible, because the sectored arrangement concentrates the filaments within r_c at about half the strand radius, to more tightly twist this composite without damage to the filaments or significant loss of effective current density due to geometric effects.[11] The coupling loss for Q_2 was accordingly calculated for L=5, rather than ten strand diameters, reducing the loss by a factor of four.

STABILITY MEASUREMENTS

The pivotal assumption in this coil design is that one can obtain bubble clearing in the channels adjacent to the braid rib. Accordingly, a small scale stability measurement was performed to determine the heat transfer characteristics of such a conductor.

A braid incorporating 21 insulated strands each 0.94 mm in diameter was fabricated.* Each strand contained 187 filaments with an overall copper to superconductor ratio of 5.8:1. No attempt was made to fabricate a low ac loss strand. The braid was compacted into a 0.28 cm x 1.09 cm rectangle by passing through a Turks head. This process yields a conductor of 50% metal density with essentially no deformation of the individual strands.

A bifilar pancake, shown in Figure 4, with an inside diameter of 12.5 cm and a radial build of 3 cm was wound from approximately 4 meters of conductor. 0.027 cm thick stainless steel ribbon was co-wound with the braid. Stability was measured by driving an extended portion of the sample normal with a co-wound heater and then observing sample voltage after the heater is turned off. A plot of recovery velocity as a function of sample current in a background field of 4 T is given in Figure 5. The maximum recovery current is approximately 1450 amperes and the full recovery current is 1000 amperes.

The maximum recovery current corresponds to a heat flux of approximately 0.121 W/cm^2 over the entire strand surface which is reasonable considering that only a fraction of the strand is actually available for heat transfer. Although the strands and channels for bubble-clearing in this test braid are smaller than those in the 10,000 ampere reference conductor design, this measured recovery heat flux is larger than the 0.11 W/cm^2 estimated for the reference design, indicating that the design may be somewhat conservative.

Further experiments are in progress to determine the effect on stability of cable compaction, and of different types of spaces between the pancakes.

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*This braid was fabricated by the Airco Central Laboratory, Murray Hill, New Jersey.

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Table 1

REFERENCE DESIGN PARAMETERS FOR THE
10,000 AMPERE CONDUCTOR FOR THE PEAK FIELD, 7 T, WINDING LAYER

Strand	
Filament	NbTi
Filament diameter, d	10×10^{-6} m
Filament J_c @ 7 T, 4.2 K	1.2×10^{9} amperes/m^2
360° Twist Length, L	0.75 cm or 1.5 cm
Configuration	Sectored Copper around Mixed Matrix Core (Figure 3)
Core Configuration	Cu Clad NbTi in CuNi
Core CuNi:Cu:NbTi	1.5:2:1
Core Radius, r_c	.668 mm
Fraction NbTi, λ_{sc}	0.079
Fraction Copper, λ_{Cu}	.704
Fraction Cu-10% Ni, λ_{CN}	.217
ρ_{Cu} (7 T)	4.25×10^{-10} Ω m
ρ_{CN}	16×10^{-8} Ω m
$\rho_{\perp}$ Core	3.2×10^{-8} Ω m
Number of CuNi Fins, n	n = 6
Fin and Ring Thickness, t	.038 mm
Strand Radius, r_s	0.75 mm
Strand Insulation	Film
Average Normal Heat Flux, x	1100 Watts/m^2
Strand Current @ 10,000 amperes	151 amperes
$\bar{\rho}_{Cu}$ (0 - 7 T)	3.2×10^{-10} Ω m
Conductor	
Number of Strands, N	67 (including rib strands)
Configuration	Flat Braid
Thickness	4.5 mm
Width	5.0 cm
Packing Factor	52%
Operating Current @ 7 T	10,000 amperes
Current Density @ 10,000 amperes	4.44×10^{7} amperes/m^2
Critical Current @ 7 T	11,111 amperes

Table 2

LOSSES FOR THE -7 T TO +7 T 2-SECOND PULSE CYCLE+
(Ungraded Winding, Conservative Cooling)

Loss Source	$\overline{P/V}$ (10^4 Watts/m^3)	Effective V (m^3)	Q_1+ (10^5 Joules)	Q_2+ (10^5 Joules)
Hysteresis Loss (10 μ filaments)	6.69***	3.69	1.85	<1.16*
Coupling Loss	0.174	8.73	0.31	0.08**
Copper Eddy Current	0.090	6.09	0.11	0.11
Steel Eddy Current+++	-	-	-	-
Mechanical Hysteresis+++	-	-	-	-
TOTAL	-	-	2.27	<1.35
ALLOWED LOSS++,+	-	-	3.17	3.17

+ Based upon the full cycle for the ORNL EPR-1 Reference Design ohmic heating coil(4)

++ Includes losses in stainless steel conduit

+++ Not Calculated. Determination of the mechanical loss is necessary to establish the validity of this design.

* Continuous grading scheme for 12 meters of an infinite, 7 T, solenoid

** For a twist length of 5 rather than 10 strand diameters

*** For the 7 T/sec. part of the cycle

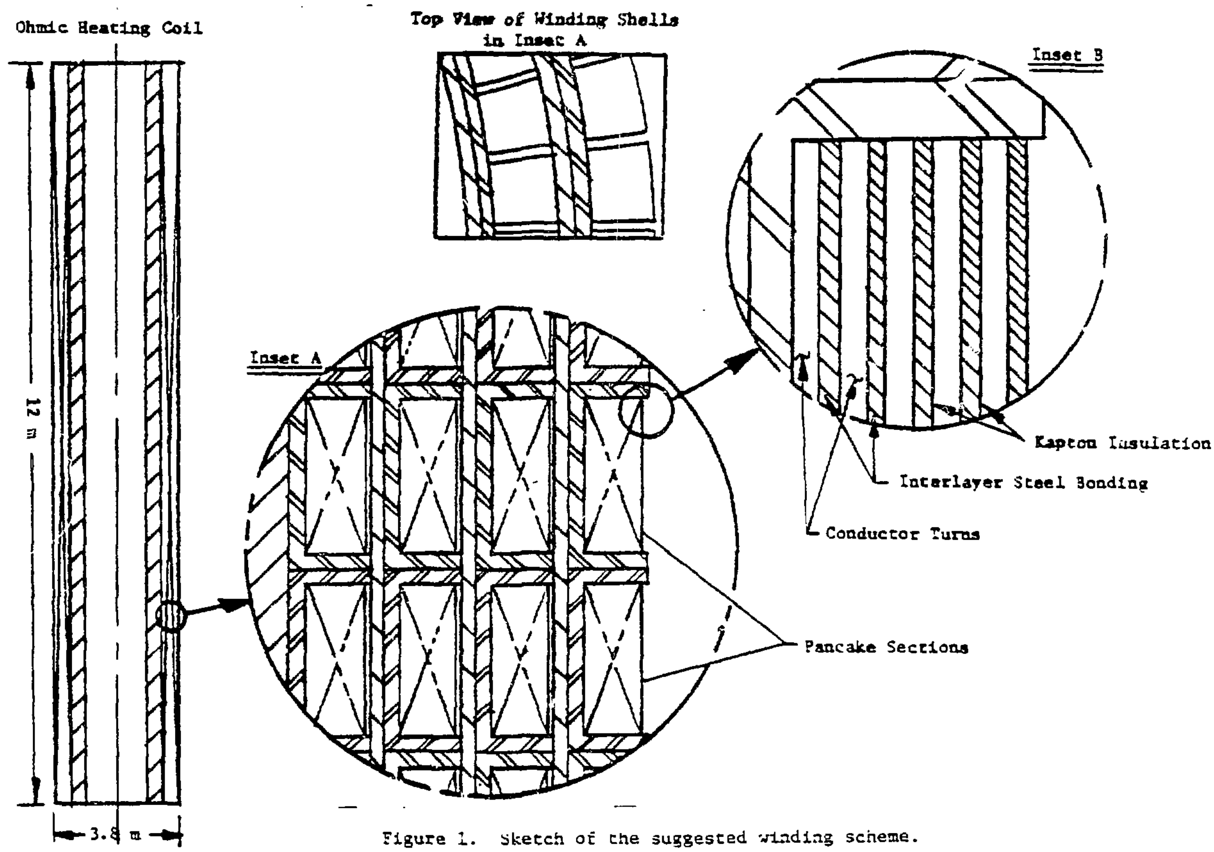

Figure 1. Sketch of the suggested winding scheme.

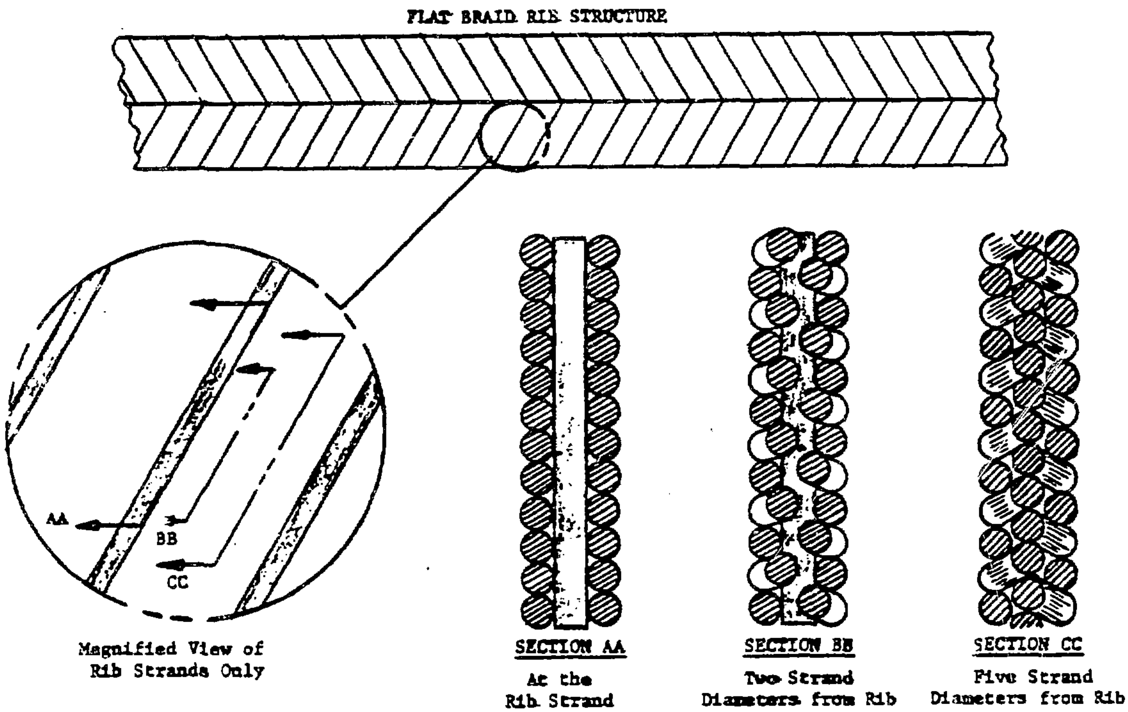

Figure 2. Slanted cross sections of the flat braid at several axial positions.

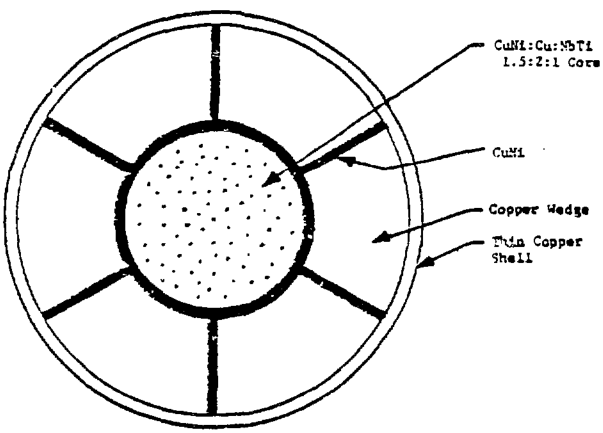

Figure 3. Layout for segmented copper-clad conductor.

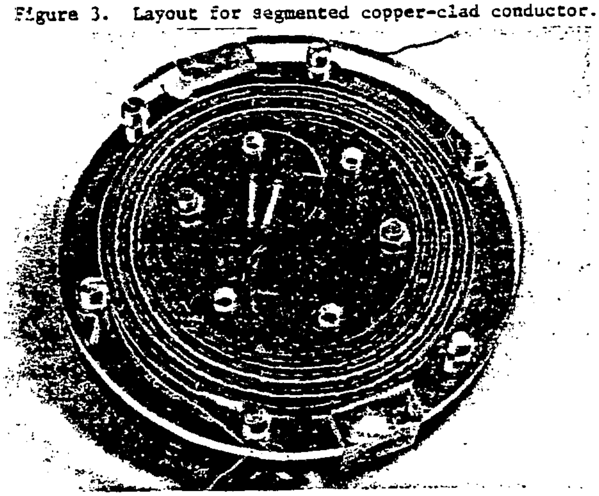

Figure 4. Bifilar pancake.

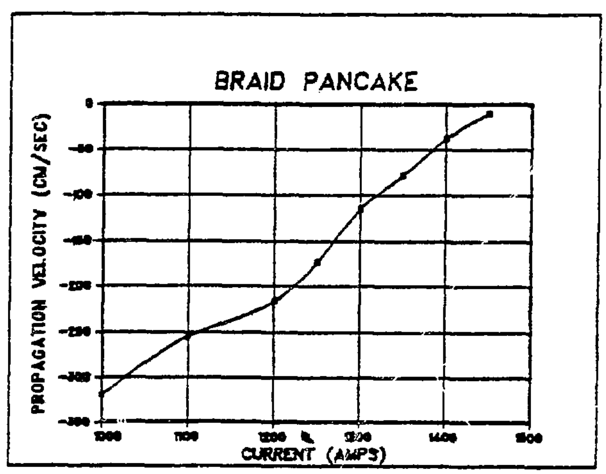

Figure 5. Recovery velocity as a function of sample current in a background field of 4 T.