FINAL REPORT

on

FLUX PINNING AND STABILIZER STUDIES

U.S. Department of Energy, Division of High Energy Physics
Contract No. DE-AC02-86ER40296
(8/28/86 to 11/31/92)

to the

Advanced Technology Research and Development Branch
Division of High Energy Physics
U.S. Department of Energy
Washington, DC 20585

by

E.W. Collings
Principal Investigator

BATTELLE
505 King Avenue
Columbus, OH 43201
November 29, 1994

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
DISCLAIMER

 Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
A synopsis of the results of the flux-pinning and stabilizer studies that form the central theme of the subject contract is followed by a list of papers that were published during its time period -- 8/28/86 to 11/31/92.

**FLUX-PINNING RELATED STUDIES IN NbTi**

*Physical and Superconducting Properties of NbTi and NbTiMn*: Transport measurements of residual electrical resistivity, $\rho_n$, and superconducting transition temperature, $T_c$, have been made on a series of NbTi alloys both with and without the addition of 0.5 wt% Mn. Wires that had already experienced cold drawing followed by a single precipitation heat treatment were measured after further cold drawing (CW), again after a second precipitation heat treatment (CW+PHT), then again after further cold drawing (CW+PHT+CW). $\rho_n$ measurements were also made on samples taken from ingots that had been quenched from the bcc phase ($\beta$Q).

*Resistivity*: From $\beta$Q (ingot) to CW (wire) a decrease in $\rho_n$ was noted; this was followed by a further decrease from CW to CW+PHT; subsequent CW then raised $\rho_n$. The results of PHT could be interpreted in terms of $\alpha$-phase precipitation and the concentrations of Nb and Mn solutes within those precipitates.

*Superconducting Transition Temperature*: For reference the $T_c$s of calorimetrically measured $\beta$Q ingots were noted. From $\beta$Q to CW an increase in $T_c$ was observed; this was followed by a further increase in $T_c$ from CW to CW+PHT; subsequent CW then
decreased $T_c$. **Beta-Stabilizing Strength of Mn:** Using a simple model calculation for the resistivity of a two-phase alloy we interpreted the difference between the concentration dependences of $\rho_n$ of the NbTi and NbTiMn series in terms of differences in $\alpha$-phase precipitate concentration. It was concluded that as a stabilizer of the $\beta$ phase (suppressor of $\alpha$-phase precipitation) Mn is 4-6 times stronger than Nb, in agreement with earlier results.

**PROPERTIES OF THE MATRIX (STABILIZER)**

Filament Surface effects: Although the effect of surface superconductivity on hysteresis losses in longitudinal orientations have been studied extensively, not so in the transverse case. For bulk superconductors, surface superconductivity has a negligible influence on the hysteretic loss. However, in fine filament materials, since the surface comprises a rather large portion of the superconductor this will no longer be the case. Magnetic hysteresis measurements have been made on fine multifilamentary NbTi/Cu and NbTi/CuMn composites, both as constructed and with the matrix etched away. Hysteresis loss comparisons have been made for both transverse and longitudinal orientations, and for a range of filament diameters.

**PROXIMITY EFFECT**

Position and Amplitude of Proximity Effect Peaks: High resolution magnetization studies of low-field proximity-effect enhanced magnetization of NbTi/Cu composites have been made. Particular emphasis was placed on the displacement $\Delta H$, of the proximity effect peak from the origin. A previously observed dependence of $\Delta H$ on the field-sweep amplitude, $H_M$, has been more thoroughly investigated. The $H_M$ dependence of $\Delta M$ can be described in three different regimes: (1) below the $H_{C1}$ of the filaments, (2) $H_{C1} < H < 2H^*$, and (3) $H > 2H^*$ where $H^*$ is the field at which full penetration occurs. In region 1, $\Delta M$ is characteristic of a type II superconductor with weak pinning. In regions 2 and 3 the $H_M$ dependence of $\Delta M$ can be explained in terms of demagnetization effects and their role in creating a local minimum in the interfilamentary field. Such Field minima occur when, after full field penetration (i.e. $H > H^*$), the applied field is reduced to near zero. The proximity effect, being highly field dependant, becomes greatest at this B field minimum. In region 2 the magnetization of the NbTi is a rapidly varying function of $H_M$ in the region of the minimum, and thus so is $\Delta H$. In region 3 $\Delta H$ has saturated, since full penetration has been reached and the NbTi magnetization is slowly varying in the region of the proximity peak. A model for the $H_M$ dependence of $\Delta H$ has been developed.
PROXIMITY EFFECT AND STRAND DESIGN

Advanced Strand Design: Nonsuperconducting saddle magnets can in principle be designed to produce an undistorted dipolar magnetic field. But if the coils are wound from superconducting strands, residual magnetization, $M_R$, resident in the strand material itself is responsible for multipolar distortions of the desired field. It is well known that the height of the $M(H)$ hysteresis loop, viz. $\Delta M(H) \equiv (M_{R+} - M_{R-})$, where the signs refer to the trapping (paramagnetic) and shielding (diamagnetic) branches of $M(H)$, respectively, is proportional to the product of filament diameter, $d$, and critical current density, $J_c(H)$. Thus in an attempt to reduce strand magnetization (in the presence of high $J_c$) and the attendant field distortion, a strong effort has been under way to produce, on a commercial scale, multifilamentary strands with smaller and smaller filaments. In order to preserve filament quality in small filaments (i.e. to prevent thickness undulations, or “sausaging”), it has been suggested necessary to confine the ratio of filament spacing $(s)$ to filament diameter $(d)$ to $s/d \leq 0.15\pm0.02$. The combination of small $d$ with low $s/d$ results in interfilamentary spacings sufficiently close to proximity-effect couple the filaments. For example, at an $s/d$ of 0.15, Cu-matrix filaments that have been reduced to 5-1/2 $\mu$m in diameter are beginning to exhibit coupling; and the coupling becomes worse as $d$ is still further reduced. But if the interfilamentary matrix is alloyed with ~0.5 wt.% Mn, coupling is barely perceptible even with 1 $\mu$m diameter filaments. Next, having disposed of an excess magnetization due to proximity-effect coupling one is still faced with the inherent magnetization of the NbTi filaments themselves. During the operating cycle (field-increasing) of the SSC magnet, this magnetization is diamagnetic; accordingly it can be neutralized by including in the superconducting strand a material with a large positive magnetization, such as Ni. To be sure, Ni barriers have been incorporated into multifilamentary strands to eliminate proximity-effect interfilamentary coupling, and bulk Ni inserts have been recommended for magnetization compensation in SSC dipoles, but the idea of associating Ni directly with the strand for local magnetization compensation is relatively new. It may turn out to be convenient to add the Ni as an electroplated layer on the outside of the strand, or to include it within the strand in the form of replacement- or extra filaments. In this work some strand designs have been recommended and developed.

MULTIFILAMENTARY STRAND DESIGN

Magnetically Compensated Strands: Nonsuperconducting saddle magnets can in principle be designed to produce an undistorted dipolar magnetic field, but if they are wound from superconducting strands, residual magnetization, $M_R$, (i.e. "persistent current") resident in the filaments causes a multipolar distortion of the desired field. Numerous ways of reducing this magnetization or its effect, at both the strand-design and magnet-design levels, have been proposed. Central to the various possible "magnetization-compensation" approaches is the fact that during the
operating (field-increasing or “shielding”) branch of the SSC magnet’s excitation cycle, $M_R$ is mostly diamagnetic. Such a negative magnetization can obviously be neutralized by the inclusion within the magnet of strategically placed ferromagnetic-Ni elements. Early studies have suggested that magnetization compensation could be achieved through the insertion of bulk Ni into the dipole “wedge”. But in this work we have ascertained that the Ni can be associated with the composite strand itself, either in the form of replacement filaments or as an electroplated coating on the outside surface.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
RESEARCH PUBLICATIONS
FOR THE PERIOD
8/28/86 TO 11/31/92


AC LOSS MEASUREMENTS OF TWO MULTIFILAMENTARY NbTi COMPOSITE STRANDS,

MAGNETIC STUDIES OF PROXIMITY-EFFECT COUPLING IN VERY CLOSELY SPACED FINE-FILAMENT NbTi/CuMn COMPOSITES,

CRITICAL FIELD ENHANCEMENT DUE TO FIELD PENETRATION IN FINE-FILAMENT SUPERCONDUCTORS,

THEORY OF FLUX PENETRATION EFFECTS BELOW $H_{c1}$ IN MULTIFILAMENTARY SUPERCONDUCTORS,

DESIGN OF COUPLED OR UNCOUPLED MULTIFILAMENTARY SSC-TYPE STRANDS WITH ALMOST ZERO RETAINED MAGNETIZATION AT FIELDS NEAR 0.3 T,

MAGNETIZATION STUDIES OF MULTIFILAMENTARY STRANDS FOR SUPERCONDUCTING SUPERCOLLIDER (SSC) APPLICATIONS -- METHODS OF CONTROLLING PROXIMITY-EFFECT COUPLING AND RESIDUAL MAGNETIZATION

DESIGN OF MULTIFILAMENTARY STRANDS FOR SSC DIPOLE MAGNETS

INTERFILAMENT AND INTRAFILAMENT MAGNETIZATIONS IN FINE-FILAMENTARY COMPOSITE STRANDS FOR PRECISION-DIPOLE MAGNET APPLICATIONS
DESIGN, FABRICATION, AND PROPERTIES OF MAGNETICALLY COMPENSATED SSC STRANDS

POSITION AND AMPLITUDE OF PROXIMITY EFFECT PEAKS IN THE MAGNETIZATION CURVES OF NbTi/Cu AND NbTi/CuMn MULTIFILAMENTARY STRANDS

HYSTERETIC SURFACE EFFECTS IN MULTIFILAMENTARY NbTi WIRES EXPOSED TO TRANSVERSE APPLIED FIELDS

EDDY-CURRENT EFFECTS IN TWISTED AND WOUND SSC STRANDS

FERROMAGNETIC MATERIAL IN THE SUPERCONDUCTOR AND ITS EFFECT ON THE MAGNETIZATION SEXTUPOLE AND DECAPOLE IN THE SSC DIPOLES AT INJECTION

EFFECT OF TWIST PITCH, SAMPLE LENGTH, AND FIELD ORIENTATION ON THE PROXIMITY EFFECT ENHANCED MAGNETIZATION IN FINE FILAMENTARY MULTIFILAMENTARY STRANDS

TEMPERATURE AND FIELD DEPENDENCE OF SHORT TERM DECAY AND LOSS IN MULTIFILAMENTARY SUPERCONDUCTORS
MAGNETIZATION DECAY OF SSC-TYPE STRANDS IN VARIOUS SHORT TEST SAMPLE CONFIGURATIONS  
K. R. MARKEN, M. D. SUMPTION, E. W. COLLINGS, AND R. M. SCANLAN,  

METALLURGICAL, PHYSICAL, AND SUPERCONDUCTIVE PROPERTIES OF A SERIES OF NbTi AND NbTiMn ALLOYS  

ADVANCED STRAND DESIGN FOR PRECISION DC-FIELD AND RAMP-FIELD MAGNETS  

EXPERIMENTS TO IMPROVE MATERIALS FOR SSC MAGNETS  

AC LOSS AND TRANSVERSE RESISTIVITY IN MULTIFILAMENTARY STRANDS WITH MATRICES OF Cu AND CuMn  