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**A Superconducting Solenoid Designed
for 400 kJ at 25 kA Under Conditions of
Fast Discharge and Field Reversal**

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A SUPERCONDUCTING SOLENOID
DESIGNED FOR 400 kJ AT 25 kA
UNDER CONDITIONS OF FAST DISCHARGE AND FIELD REVERSAL

by

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ABSTRACT

A 1.26-mH superconducting solenoid made of NbTi and Cu-CuNi mixed matrix superconductor was designed and fabricated by Westinghouse Electric Corporation for the Los Alamos National Laboratory as part of the pulsed energy storage coil program. The coil was designed to store 400 kJ at a current of 25 kA and has been operated to currents of 20 kA. Development of high current cables and low-loss superconductors are both necessary undertakings for future fusion devices. The first tests of the coil involved a very slow charge of the coil followed by a rapid discharge in 1.07 ms with a capacitor bank and a normal-conductor load coil in a resonant L-C-L circuit. The second test consisted of a slow charge followed by a discharge and recharge on a time scale of a few seconds. This latter cycle resembles that expected in a tokamak induction coil. Loss measurements were made by an electrical method during the second series of tests.

I. INTRODUCTION

The superconducting, ohmic-heating coil of large tokamak machines now being proposed^{1,2} will store about 1 GJ of energy with a peak field in the range of 6 to 8 T. During start-up of the tokamak, the field in the ohmic-heating coil will be brought to zero or even partially reversed in times as short as 6 s. Currents in the range of 25 to 50 kA are considered for the ohmic-heating coil cable. These requirements for tokamaks have spurred interest in the technology of low-loss, high-current, superconducting cables.

A Cu-CuNi mixed matrix surrounding NbTi produces a low-loss superconducting wire and permits the use of a larger diameter wire as the basic building unit of the cable. This simplifies the cable construction when high currents are also required. Experience with pulsed superconducting coils is limited,

and experience with mixed matrix pulsed coils is even less, primarily because of difficulties in producing wire and cable. Pulsed superconducting coils can have applications as energy-storage devices. The coil whose performance is described here was designed to serve as a prototype energy-storage coil for a proposed theta-pinch experiment.³ Used as a theta-pinch, energy-storage device, the coil would be discharged in a few milliseconds. Because the wire, cable, and coil designs are relevant to the design and construction of tokamak poloidal field coils, the coil was also tested using a simulated ohmic-heating waveform. Table I gives a brief summary of the coil parameters. Figure 1 shows the coil suspended above the dewar.

The basic superconducting strand contains 198 superconducting filaments of 14.4 μm diameter, each surrounded by a hexagon of copper measuring 21.7 μm across the parallel sides. A 90-10 CuNi web 1.5 μm thick separates the copper hexagons, and a CuNi sheath surrounds the filament bundle. The coil was designed to operate at 25 kA and the peak field on the winding at that current would have been 2.5 T. The first level cable was made by wrapping six insulated, mixed-matrix, superconducting strands around a CuNi core wire. Seven of the first-level cables were then wrapped around glass fiber roving core, and twelve of these second-level cables were wrapped around an insulated stainless steel strap. The strands were insulated with a polyamide-imide insulation.

TABLE I
PARAMETERS OF ENERGY STORAGE COILS

<u>Parameter</u>	<u>400 kJ</u>	<u>300 kJ</u>
Inductance, mH	1.26	6.05
Resistance at 20° C, Ω	0.087	0.165
Design current, kA	25	10
Stored energy at design current, kJ	400	302
Winding length, cm	67.3	79.1
Mean radius, cm	27.9	25.5
Winding thickness, cm	10.3	4.74
Number of turns	64.75	159.5
Number of layers	3	4
Peak center line field at design current, T	2.31	2.13
Conductor support method	toothed form	toothed form
Overall CuNi:Cu:NbTi	1:1.5:1	0:2.5:1
Strand diameter, mm	0.381	0.813
Filament diameter, μm	14.4	18
Filaments/strand	198	529
Wire twist pitch, cm^{-1}	3.15	1.42
Number of active wires in cable	504	72 ^a
Cable width, cm	2.48	1.68
Cable height, cm	1.91	0.84

^aTotal number including inactive strands is 84.

Fig. 1. The 400-kJ coil suspended above the test dewar.

A coil designed to operate at 10 kA and store 300 kJ was tested several years ago.⁴⁻⁶ Parameters of this coil are also listed in Table I for comparison with the 400-kJ coil. Performance of the 300 kJ-coil exceeded specifications. The coil was operated at over 14 kA with a stored energy of 0.54 MJ. Because of difficulty in obtaining a mixed matrix superconductor, a copper matrix was used, and the copper ratio was also higher than that used for the 400-kJ coil. These two factors increased the losses in the 300-kJ coil.

II. TEST FACILITY

Two separate series of tests were performed. In the first series the coil was charged over a period of 0.5 to 3 min and discharged in 1.07 ms using an L-C-L resonant circuit. In the second series the coil was charged in 0.5 to 3 min, discharged in 4 to 10 s by inserting resistors into the circuit, and finally charged in the reverse direction over a period of 2 to 15 s. Losses were measured during the second series using the electrical method first proposed by Wilson.⁷ The basic idea of this method is to plot the coil current against the time-integrated voltage across the coil. For the usual case in which the initial and final currents in the coil are zero, the area inside the closed curve swept out by this process is the energy lost in the coil. Because most of the voltage across the coil is inductive, the total amplitude of the integrated voltage signal can be reduced many orders of magnitude by subtracting a signal from a pickup coil coupled to the coil being tested. The

subtraction need not be exact but a large residual inductive voltage means that the linear range of the integrator has to be greater and that the loop becomes narrow and difficult to measure. Hysteresis losses for one direction and bipolar current swings were also measured.

During the first series of tests, a quench detector monitored the time rate of change of current through the coil with a Rogowski loop on the busbar. If the rate of change was negative, indicating a quench, the energy transfer sequence was automatically started to remove current from the coil. During the second series, the coil current was manually dumped into a resistor if the boil-off from the dewar increased.

A. Fast Discharge Tests

The circuit used for the fast discharge tests is shown in Fig. 2. The purpose of this circuit was to charge the test coil L_C , and then transfer the current rapidly to the load coil L_L , through the transfer-capacitor bank C . The hybrid switch O_1 - O_2 and V_1 - V_2 connects the charging power supply to the coil L_C . This switchgear must carry the slow charging ramp, interrupt the current, and withstand the system recovery voltage of about 36 kV after opening. To meet these requirements this switchgear consists of a combination of two series-connected vacuum interrupters V_1 - V_2 with high dielectric recovery rate, and two series-connected oil switches O_1 - O_2 with high current rating, connected in parallel to form a hybrid switch. During the charging cycle, the oil switches O_1 - O_2 carry 92% of the current, and the vacuum switches V_1 - V_2 carry 8%. To disconnect the charging power supply, the oil switch O_1 is opened first, transferring its current to V_1 - V_2 . Some arcing occurs in this switch which contaminates the oil and renders it incapable of withstanding high voltages. O_2 and V_1 - V_2 are then opened in quick succession to isolate the charging power supply. O_2 is able to withstand the system recovery voltage because it opened at zero current without arcing in oil. V_1 - V_2 , likewise, will be able to withstand the system recovery voltage after arcing because of the high dielectric recovery rate of vacuum.

Fig. 2. Circuit for fast discharge testing of the coil. Current is transferred from superconducting coil L_C to load coil L_L using transfer capacitor C . After the transfer, current is crowbarred with ignitrons I_{CB} . Switches O_1 , O_2 , V_1 , and V_2 isolate the power supply, and the transfer is initiated by opening and counterpulsing vacuum breakers V_3 and V_4 . The loss measurement makes use of L_p and R_p .

The current is first brought to the required value in the coil L_C , with the hybrid switch O_1-O_2 and V_1-V_2 closed, and the two series-connected vacuum breakers V_3-V_4 open. The transfer cycle is started by closing the vacuum breakers V_3-V_4 and opening the hybrid switch O_1-O_2 and V_1-V_2 in the sequence described above. The arc drop across V_1-V_2 would force the current through V_3-V_4 . The vacuum switches V_3-V_4 are then opened, and the arc across them is quenched by injecting a current through them in the opposite direction. This is accomplished by discharging the precharged capacitor bank C through the ignitron I_C . Current now transfers from L_C to L_L with C serving as a transfer capacitance. After the current is transferred, the crowbar switches I_{CB} are closed, and the energy in L_L is dissipated in resistor R_L .

Components L_p and R_p are part of the loss measurement apparatus. R_s is a low-inductance shunt for current measurement, and L_s is a saturable reactor for shaping the rate of change of current when the switches V_3-V_4 are counterpulsed.

Time to transfer current from the coil was 1.07 ms, and the peak voltage with an initial coil current of 20 kA was 36.4 kV. Peak voltage occurred 0.53 ms after start of the transfer.

B. Current Reversal Tests

The circuit used for the current reversal tests is shown in Fig. 3. Current is put into the superconducting coil L_C with reversing switches S_3 and S_4 open and all others closed. Current splits equally through A_1 and A_2 because of the small bus resistances R_B in series with A_1 and A_2 . Resistor R_3 ranges from 0.4 to 1.8 m Ω and resistor R_2 is 10 m Ω . To start the current reversal cycle, air-magnetic breakers A_1 and A_2 are opened to divert the current through R_3 . The current decays with a characteristic time L_C/R_3 . Switches S_1 and S_2 are opened, and switches S_3 , S_4 , A_1 , and A_2 are closed, reconnecting the power supply with opposite polarity to recharge the coil. Finally, switches A_1 and A_2 are reopened to discharge the coil. Switch A_3 and resistor R_3 , rated at 10 m Ω , provide coil protection in the event of a quench.

Fig. 3. Circuit for current reversal testing of the coil. Current is charged into the superconducting coil with reversing switches S_3 and S_4 open and all others closed. Switches A_1 and A_2 are opened to cause the current to decay through resistor R_3 . Reversing switches S_1 and S_2 are then opened, and switches S_3 , S_4 , A_1 , and A_2 closed to reverse current in the coil. Switch A_3 and resistor R_2 are part of a dump circuit for coil protection.

Fig. 4. Current in the 400-kA coil as a function of time taken from a chart record for a current reversal test.

Openings A_1 , A_2 , and A_3 simultaneously divert the current through R_3 to decay with a 100-ms decay constant. Fig. 4 shows a chart recorder trace of coil current as a function of time for a typical test.

III. RESULTS

Energy losses measured during the fast discharge tests of the 300-kJ coil are shown in Fig. 5 plotted against the peak field in the winding. Because of an equipment failure, losses in the 400-kJ coil were not recorded during the fast discharge tests. However, hysteretic losses for a cycle in which the field was slowly ramped from zero to a maximum value and then back to zero are plotted in Fig. 5 for both coils. The measured hysteresis losses of the 400-kJ coil are slightly above those of the 300-kJ coil. Predictions based on the filament diameter and mass of NbTi in each coil would place the 400-kJ losses below the 300-kJ coil losses. The dashed line in Fig. 5 shows the predicted losses in the 400-kJ coil based on fast discharge, short sample, loss measurements. Fig. 6 shows the short sample losses for the superconductor of both coils as a function of inverse decay time for the magnetic field. From these curves, the fast discharge losses for the 300-kJ coil are expected to be about a factor of 10 above the hysteresis losses, and the fast discharge for the 400-kJ coil about a factor of 2 above hysteresis losses.

Fig. 5. Energy loss in the 300-kJ coil for fast discharge tests as a function of the maximum field on the winding (squares). Hysteresis losses for slow charge and discharge of the coils are also shown. The open circles refer to the hysteretic losses in the 400-kJ coil and the closed circles refer to the 300-kJ coil. The dashed line gives the predicted fast discharge losses for the 400-kJ coil.

Fig. 7 shows energy losses in the 300-kJ coil for a cycle in which the current in the coil was brought to zero and reversed in a period of a few seconds. Several different circuits were used to reverse the current in the 300-kJ coil, and this caused some spread in the losses because of asymmetric current waveforms and different reversal times. The time for complete current reversal in the 300-kJ coil ranged from 2.9 to 5 s. Fig. 8 shows similar results for the 400-kJ coil. The time for reversing current in the 400-kJ coil also varied because of different resistors (R_2) and different power supply voltages for recharging the coil. For both coils, the measured losses were only slightly larger than the hysteretic losses.

The maximum current achieved in the coil was only 20 kA, considerably below the design operating current of 25 kA. Voltage taps attached to the joints between the coil and the current leads indicated losses of only 0.1 W at 10 kA. Variation in the quench current was small; the coil usually quenched

Fig. 6. Short sample losses normalized to the volume of NbTi for an exponential decay of the background field from 2.2 T. Losses are plotted against the inverse time constant for the decay. Each cycle consists of a slow increase of the field to maximum and then a rapid decrease to zero with time constant τ .

between 19 and 20 kA. The measured losses were higher than expected, but a systematic error in the method cannot be disallowed because no calorimetric check measurements were performed as was done with the 300-kJ coil. The superconducting wire used in the coil had a flaw in that a radial crack occurred in three of the five billets during drawing. In some wires the radial cracks extended from the surface to the center of the wire and ran for extended lengths along the wire. The cracks appeared to follow the Cu-Ni matrix hexagonal interfaces. A number of short-sample, critical-current measurements were made at Los Alamos on the superconducting wire. These results indicated that the critical current was not affected by the crack. Because of fiscal and scheduling constraints and a requirement to bring the program to a conclusion, the wire with the cracks was used to make the cable for the coil. After the fabrication of the coil, small amounts of wire remained in the form of single strands, subcables, and final cable. Critical current measurements will be performed on this material in the hope that some understanding can be obtained of the low quench current.

Fig. 7. Energy loss in the 300-kJ coil for current reversal tests as a function of the maximum field on the winding. Hysteresis losses for bipolar current swings are also shown. The circles represent hysteresis losses, the squares refer to an oscillation against a dc generator in which the generator rotor is initially stationary and the half period is 3.4 s. The triangles refer to an oscillation in which the rotor is initially rotating. The diamonds refer to a 2-s reversal obtained by dumping the coil into a resistor and then recharging it from the generator.

Fig. 8. Energy losses in the 400-kJ coil for current reversal tests as a function of the maximum field on the winding. The open circles refer to hysteresis losses. The solid circles refer to a 12-to 20-s current-reversal-time and a 7-s discharge. The crosses correspond to a slightly faster, 4.8-s-discharge time. The triangles refer to a 6-to 7-s reversal time with a 3.6-s-discharge time.

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REFERENCES

1. INTOR Group, "International Tokamak Reactor; Executive Summary of the IAEA Workshop, 1979," Nuclear Fusion, 20, 349 (March 1980).
2. R. L. Reid, W. R. Becraft, T. G. Brown, Y-K. M. Peng, C. Sardella, T. E. Shannon, D. Steiner, W. M. Wells, and G. W. Wiseman, "Oak Ridge TNS Program: System Description Manual," Oak Ridge National Laboratory report ORNL/TM-6721 (May 1979).
3. Keith I. Thomassen, Compiler, "Conceptual Design Study of a Scyllac Fusion Test Reactor," Los Alamos Scientific Laboratory report LA-6024 (January 1976).
4. J. D. Rogers, D. J. Blevins, J. D. G. Lindsay, G. A. Miranda, C. E. Swannack, D. M. Weldon, J. J. Wollan, C. J. Mole, E. Mullan, P. W. Eckels, H. E. Haller, M. A. Janocko, S. A. Karpathy, D. C. Litz, P. Reichner, Z. N. Sanjana, and M. S. Walker, "0.54-MJ Superconducting Magnetic Energy Transfer and Storage," Advances in Cryogenic Engineering, 23, 48 (1978).
5. C. J. Mole, D. W. Deis, P. W. Eckels, H. E. Haller, M. A. Janocko, W. A. Karpathy, D. C. Litz, E. Mullan, P. Reichner, Z. N. Sanjana, and M. S. Walker, "A Superconducting 0.54-MJ Pulsed Energy Storage Coil," Advances in Cryogenic Engineering, 23, 57 (1978).
6. P. Thullen, J. D. G. Lindsay, D. M. Weldon, and H. F. Vogel, "Superconducting Ohmic-heating Coil Simulation," IEEE Trans. on Mag. MAG-15, 538 (1979).
7. M. N. Wilson, "An Improved Technique for Measuring Hysteresis Loss in Superconducting Magnets," Cryogenics 13, 361-363 (1973).