LA-UR-80-2774

TITLE: A HIGH-FIELD BIPOLAR LOSS MEASUREMENT APPARATUS

AUTHOR(S): P. Thullen, D. Weldon, and J. Wollan

SUBMITTED TO: Applied Superconductivity Conference,
Santa Fe, NM, September 29-October 3, 1980

DISCLAIMER

This document contains information that was prepared by and for the U.S. Government. It is the property of the U.S. Government and is loaned to you. It and its contents are not to be distributed outside your agency without the express written approval of the U.S. Government. The U.S. Government makes no warranty, expressed or implied, for the use of the information contained herein. The U.S. Government assumes no responsibility for any damages, including consequential, actual or expected, that may result from the use of the information contained herein. This disclaimer applies to all copies of this document, including those made by microfilm, microfiche, or other means. The U.S. Government makes no representation as to the accuracy or completeness of the information contained herein. The U.S. Government makes no representation as to the accuracy or completeness of the information contained herein. The U.S. Government makes no representation as to the accuracy or completeness of the information contained herein.

MASTER

By acceptance of this article, the publisher recognizes that the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos Scientific Laboratory requests that the publisher identify this article as work performed under the auspices of the Department of Energy.

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

A HIGH-FIELD BIPOLAR LOSS MEASUREMENT APPARATUS*

P. Thullen, D. Weldon, and J. Wollan
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

Summary

An apparatus has been constructed to measure dissipation in superconducting wire in high alternating fields. The apparatus will be used to make measurements on conductors which must operate in fields up to 7.0 T and rates of field change up to 15 T/s. The magnet for this facility is wound of uninsulated, 15 strand Rutherford cable in which the strand is a 0.812 mm diameter, fully mixed matrix, Cu plus CuNi, multifilament NbTi conductor. The coil is wound in a bath cooled configuration with an overall current density of 7.8 kA/cm². The circuit incorporates a pair of locomotive traction motors as the capacitive circuit element for the bipolar swing. The design, construction and operating characteristics of the field coil and the associated circuitry are described.

Introduction

Most experimental evaluations of losses in superconductors, particularly dynamic losses, have been performed in relatively low magnetic fields. As requirements of various programs call for higher fields in magnets of ever increasing size, accurate calculation for minimization of losses has become increasingly important. Past estimates of the losses in such systems have been purely theoretical or theoretical extrapolations of low field experimental data. It is desirable to determine more accurately the losses in conductors for systems for which hysteretic and dynamic losses under high field conditions have important economic consequences. To make such determination, a loss measurement facility has been built with a peak field of 7 T. The field can be swept from +7 T to -7 T at rates from 4 to 15 T/s. The design and construction of the cable, magnet, circuit, and results of tests of the system are addressed in this paper. The paper does not discuss loss measurements, nor the loss measurement system which is essentially identical to a system already discussed in the literature.¹

The circuit is a unique feature of this system. It uses a pair of diesel-electric-locomotive traction motors which function as capacitors forming a resonant circuit with the coil. A similar circuit was used for low field tests of the Los Alamos Scientific Laboratory (LASL) 300 kJ pulsed coil.² Characteristics of the motors have also been reported.¹ In this application the traction motors are initially rotating so that 100% reversal of the current can be accomplished.

Magnet Design

The magnet is shown in Fig. 1. The magnet and conductor parameters are listed in Table I. The magnet design was constrained by a number of factors. A minimum bore size was set by the dimensions of the loss measurement apparatus. A limited amount of conductor was available, which forced a design with a high current density. The coil had to meet the bipolar field sweep requirements without quenching. Finally, the magnet had to operate at a specific current level so that the traction motors would operate over an acceptable range of armature and field current, terminal voltage, and rotational speed.

Fig. 1. Completed 7 T pulsed magnet.

Conductor Configuration

The superconducting strand is a mixed-matrix, Cu, CuNi multifilamentary NbTi conductor. The material was available as excess wire from another program and had very low losses required for a pulsed magnet. Because of manufacturing difficulties, the final cable was actually made up of two slightly different strands, as indicated in Table I. The majority of the magnet winding, about 400 m, was made from strand A, the remaining 100 m was made from strand B. Cold, welded joints in individual strands were used to join the pieces of cable.

The cable configuration was determined by optimizing the coil design to match the traction motors. The individual strands were uninsulated so the heat transfer and stability would be better. To lessen difficulty of winding the small bore magnet, the cable was not solder filled.

Coil Configuration

The winding is in the form of an axial helix, which produces a layer wound coil. This simple structure requires elementary winding equipment.

*Work performed under the auspices of the United States Department of Energy.

TABLE I
COIL AND CONDUCTOR DIMENSIONS

<u>Coil</u>			
Bobbin inner diameter, cm			5.20
Bobbin outer diameter, cm			5.99
Winding inner diameter, cm			6.20
Winding outer diameter, cm			23.00
Winding length, cm			24.00
Number of turns			1163
Number of layers			35
Inter-turn spacer diameter, cm			0.10
Inter-layer spacer thickness, cm			0.08
Percent cable coverage, %	35 to 50		
Average current density, kA/cm ²			7.79
Operating current, A			1350
Operating field, T			7
Percent along load line, %			90
Inductance, H			0.062
<u>Cable</u>			
Cable dimensions $\ell \times w$, cm		0.632 $\times$ 0.152	
Number of strands			15
Twist pitch length, cm			6
<u>Strand</u>			
Diameter, cm	A	B	
	0.0813	0.0813	
Number of filaments			156
Filament diameter, μ m			31
Matrix ratio, CuNi:Cu:NbTi	1.5:2:1	1:1.5:1	
Twist pitch length, cm	---		0.62
Resistivity ratio			52
J_c at 10^{-12} Ω cm and 7 T, kA/cm ²			96
I_c at 10^{-12} Ω cm and 7 T, A			110

Because the conductor is uninsulated, the individual turns are separated from one another by insulating spacers, and the bobbin is made of non-conducting material. The inter-layer spacers and bobbin are of G-10 fiber reinforced plastic. The turn-to-turn spacer is round, 0.1 cm diameter Teflon monofilament line co-wound with the conductor. The fabric plies of the inter layer spacers and the bobbin were oriented to lie in directions which yield an increase in tension as a result of differential thermal contraction from cooldown. The final winding is open and well ventilated, and adequately insulated turn-to-turn and layer-to-layer. This configuration further simplifies winding because all components including spacers are quite large and easily handled.

Cable Elastic Characteristics

When a magnet has a bore diameter which is less than two-thirds of the outside diameter, there exists a potential for the layers of the coil to separate radially. Under the action of the Lorentz forces, the inner layers will have their spacing increased, tending to separate, and those near the outside will have their separation decreased. The presumption is that actual loss of contact between layers is detrimental to the performance of a pulsed solenoid. To overcome this effect, thick walled pulsed solenoids must be wound under tension.

The stress analysis computer code STANSOL II⁴ was used to determine the pretension required to prevent coil separation.

⁴DuPont tradename.

This code assumes the coil to be a two dimensional axi-symmetric structure composed of many orthotropic cylinders. In addition to the coil geometry, the code requires as input, both radial and tangential elastic constants for all layers. Table II lists the elastic constants of the three components of this coil.

The bobbin properties are uniform in the tangential and radial directions because the bobbin is constructed of a number of washers cut from G-10 plate, glued into a cylindrical stack. The largest thermal contraction of the bobbin is in the axial direction. This construction prevents the bobbin from contracting away from the winding when it is cooled and provides the maximum strength in the plane of greatest load.

The inter-layer spacers are also made of G-10. They are cut from the edge of a plate and installed so that the glass filaments run radially and axially. This gives high radial strength and modulus with low radial thermal contraction. If this were not done, the combined thermal contraction of 35 layers of spacers would result in loss of radial pressure during cooldown unless excessively high winding pretension was used.

The tensile properties of the cable were determined in a simple tensile test using an Instron machine. A sample exceeding one strand transposition in length was employed. The first major failure of the unfilled cable occurred when it buckled from a rectangular configuration to a nearly round cross section. A slight increase in load caused the wires to begin breaking singly. The buckling load and the wire breaking loads are remarkably close and are similar to the load computed from tests on a single strand. A solder filled cable was prepared and tested. It did not buckle but failed at a load of the same magnitude as the unfilled cable. The tensile tests showed that the unfilled cable could withstand tensile loads considerably higher than those anticipated during coil winding or operation.

Values of buckling and ultimate stress are listed in Table III. These values were computed on the basis

TABLE II
COIL ELASTIC CONSTANTS

	E , psi	ν	αT
<u>Bobbin (G-10)</u>			
Radial	5.2×10^6	0.211	0.0027
Tangential	5.2×10^6	0.211	0.0027
<u>Spacer (G-10)</u>			
Radial	5.2×10^6	0	0.0027
Tangential	0	0	0.0032
<u>Conductor</u>			
Radial	8.5×10^6	0.3	0.0032
Tangential	6.0×10^6	0.3	0.0032

TABLE III
TENSILE TEST RESULTS

Test No.	Buckling Stress psi	Failure Stress psi	Modulus psi	Comment
1	74×10^3		7.8×10^6	Unwelded
2	75×10^3	77×10^3	6.7×10^6	Unwelded
3	72×10^3	74×10^3		Unwelded
4		52×10^3	5.2×10^6	Unwelded
5		76×10^3	4.3×10^6	Soldered
6		71×10^3		Single Wire

of experimental load and the average cable area which includes wire and some voids.

The tensile tests were performed on defect free, relatively short samples of cable. During winding, long sections containing cabling or wire defects were found to buckle under a much lower load.

Values of the tensile modulus are also shown in Table III. These were determined during the tensile tests. Reasons for the wide variation in values are unknown. An average value was used for computation.

The cable is unfilled; and, when a longitudinal compressive load is applied, the cable simply expands across the broad dimension. This results in a very low longitudinal modulus of elasticity in compression, the measured value being 0.3×10^6 psi. Because of the thickness of the build and the use of pretension to prevent separation of the winding layers, the inner turns of the coil are in hoop compression following winding. In this magnet design, the cable is not free to deform under hoop compression. It is constrained by clamping action of the inter layer spacers. The average pressure acting on these spacers is 600 psi under operating conditions. This pressure and the associated frictional forces prevent the cable from spreading across the broad dimension.

A simple test was devised to determine the effectiveness of this clamping action in restraining the spread of the cable. A clamp fixture was constructed to apply lateral pressure while the longitudinal compressive modulus of a sample was measured in the Instron machine. The sample and test fixture are shown in Fig. 2, and a plot of the resulting modulus values is shown in Fig. 3.

The sample was installed in the clamp fixture using spacers typical of the final construction. Three and five spacers were used over the 2.75 in. gage length with no apparent effect on the results. The clamp fixture plattens were lubricated during two of three tests as noted on Fig. 3.

Fig. 2. Axial compression cable sample and side pressure fixture.

Fig. 3. Axial compressive modulus variation with lateral pressure and platten conditions.

There is no apparent reason why lubricating the platens should lead to an increase in apparent modulus nor is there any explanation for the slight maximum at 450 psi. These tests make clear that lateral restraint gives the cable a compressive modulus equal to or greater than the tensile modulus.

The assumption of a constant cable modulus allows the coil to be analyzed using STANSOL II, which does not consider properties which are discontinuous with load. It also means that a reasonable pretension on the outer layers of the coil will not cause excessive deformation of the inner layer.

The radial moduli of the spacers and cable were estimated from tabulated material properties with allowance made for actual contact areas. A sensitivity study showed that the maximum hoop stress is relatively insensitive to the values chosen for the various radial moduli. The possibility of coil separation increases as the overall radial modulus decreases and must be considered when choosing the winding pretension.

Stress Analysis

Figure 4 shows the radial and hoop stresses in the bobbin and winding when the magnet is warm, cold, and carrying rated current. These curves were generated for a constant 30 pound winding pretension. Fig. 4 shows that this value prevents separation of the layers and results in modest hoop stress levels under operating conditions. In actual practice a pretension of 50 pounds was used to allow some margin for creep and other unknowns which would undoubtedly be present and reduce the final radial pressure.

This pretension yields a coil in which most of the turns on the midplane reach the same stress level under the maximum stress conditions. The inner turns cycle over the largest stress range. The radial stress increases when the coil is cooled to operating temperature. When it is energized, the radial stress at the coil bobbin interface is reduced a great deal. With insufficient pretension the coil bobbin interface would be the location of first separation.

Fig. 4. Radial and hoop stress variation in bobbin and winding as function of operating conditions and radial position.

Circuit Design and Operation

The circuit configuration is shown in Fig. 5. The magnet is initially energized using two solid state 10 V, 1000A power supplies connected in parallel. At the same time the traction motors are self-motored to a predetermined speed. The traction motor fields are continuously energized. Breakers between the coil and motors are initially open. The field reversal is initiated by opening the breakers between the power supplies and coil, allowing the coil to discharge into resistors R_1 and R_3 . Part way through this resistive discharge, the traction motors are disconnected from the spin-up supply and connected to the coil. The motors, acting as electromechanical capacitors, recharge the magnet with opposite polarity. The energy then oscillates between the coil and motors or is dissipated in R_1 if S_2 is opened. The reversal time is controlled by the length of the resistive discharge, which is determined by the values of R_1 and R_3 , the switching time, and the equivalent capacitance of the traction motors, which is set by the shunt field current. The capacitance of each traction motor can be varied from 0.25 to 15 F, which places an upper limit on the field reversal time of about 4 μ s. The maximum switch standoff voltage of 600 V places a lower limit on the reversal time of about 0.5 μ s.

Because the coil is not cryostable and its behavior in case of a quench is undetermined, a quench detector was installed. It operates by comparing the voltage measured between a center tap and one terminal with the output of a resistive voltage divider connected across the coil. When an abnormal signal is detected, all switches are opened and the magnet is discharged into resistor R_1 .

Fig. 5. Test circuit.

During normal field reversals, the elastic deformation of the magnet causes a spurious signal to the quench detector. For this reason the detector is disconnected for a period of 1 to 2 s during current reversal.

System Testing

The dc performance of the coil was checked first and found to be excellent. It reached the design current of 1350 A in 100 A increments with only one quench at 1230 A. Current ramp rates for these tests were 10 to 20 A/s. Upon reaching maximum current for each test the coil was discharged in 1 to 2 s either into the discharge resistor or the traction motors.

Following these preliminary tests, the magnet was given a visual inspection. Some of the outside turns had slipped over the Teflon interturn spacers as a result of axial Lorentz forces. No other damage was evident. The turns were moved to their original locations, and the number of outside braces was increased from 4, as shown in Fig. 1, to 12 to prevent a recurrence of this problem.

The complete system was then tested to evaluate coil and motor performance for a full bipolar swing. A typical trace of the magnet current versus time is shown in Fig. 6.

In Fig. 6 operation of many circuit elements can be detected from discontinuities in the current trace. A slow ramp charge to 11 kA is followed by a region of almost constant current. During this time, S_1 and S_4 are open and all other switches are closed. The discharge cycle is initiated by opening S_1 and allowing the current to decay to a low value, in this instance about 80 A. During this time period, S_5 and S_6 are opened and the traction motors allowed to coast. When

Fig. 6. Current waveform from typical pulsed test of 7 T magnet.

the current reaches a desired low value, switches S_3 and S_4 are closed, and the current is quickly brought to -1065 A. The recharge current waveform is a damped sinusoid, and the oscillations will continue until the energy is dissipated in R_1 and R_3 . In this experiment, S_2 was opened before all of the energy was dissipated in the oscillatory circuit resulting in a resistive decay at the end of the waveform.

A series of tests were run using increasing magnet currents to determine appropriate circuit parameters for full reversal. The system performed very well. The maximum swing obtained so far was from 1280 A to -1220 A in 1.8 s, which corresponds to a maximum field of 6.6 T and an average field sweep rate of 7.2 T/s.

Conclusions

Careful attention to the mechanical characteristics of the conductor in conjunction with detailed analysis of the mechanical design of the coil have produced a magnet which has performed to 100% of design. The field reversal system also performed as designed. The operating parameters for all possible combinations of field and sweep rate values remain to be mapped, and the loss measurement portion of the system is to be made operational.

Acknowledgements

The authors wish to acknowledge J. Hand, who wound the solenoid, and D. Trudell, who built the control circuitry for this experiment. Their patience and care helped make the facility successful from the beginning.

References

1. J. J. Wollan, "Energy Losses in Mixed Matrix Superconducting Wires Under Fast Pulsed Conditions," IEEE Trans. on Magnetics, Mag. 13, No. 1, 544-547 (1977).
2. P. Thullen, J. D. G. Lindsay, D. M. Weldon and H. F. Vogel, "Superconducting Ohmic-Heating Coil Simulation," IEEE Trans. on Magnetics Mag. 15, No. 1, 538-541 (1979).
3. P. Thullen and D. M. Weldon, "Commutator DC Machines Used as Mechanical Capacitors in a Series Resonant Ohmic-Heating Circuit Simulation," Proc. 8th Symp. on Engineering Problems of Fusion Research, Vol. 11, San Francisco, Nov. 13-16, 1979, IEEE Pub. No. 79CH1441-SNPS pp. 729-733.
4. N. E. Johnson, W. H. Gray, and R. A. Weed, "Stress Analysis of Non Homogeneous Transversely Isotropic Superconducting Solenoids," Proc. 6th Symp. on Engineering Problems of Fusion Research, San Diego, Nov. 18-21, 1975, IEEE Pub. No. 75CH1097-SNPS, pp. 243-247.