DEVELOPMENT OF A PULSED CABLE TEST FACILITY
FOR
SUPERCONDUCTING OHMIC HEATING COILS

MASTER

by

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Prepared for
Applied Superconductivity Conference
Santa Fe, New Mexico
September 29, 1980 - October 3, 1980

and

IEEE Transactions on Magnetics

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ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Operated under Contract W-31-109-Eng-38 for the
U. S. DEPARTMENT OF ENERGY

DEVELOPMENT OF A PULSED CABLE TEST FACILITY FOR SUPERCONDUCTING OHMIC HEATING COILS*

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Abstract

This paper describes a Pulsed Cable Test Facility (PCTF) under development at Argonne National Laboratory (ANL). Its essential part is a pulsed superconducting split coil. The inner and outer diameters of the coil will be 45.1 cm and 88.3 cm, respectively, with an adjustable gap between the two halves of the coil. At a peak current of 11 kA, the coil will store an energy of 3.5 MJ and produce a magnetic field of 6.4 T. Using a 7 MW pulsed (2.9 MW rms) power supply, the PCTF coil will produce field change of 6 T/s. With the addition of a solid state switch to the system, dB/dt values of up to 24 T/s can be obtained. Pancake coils, wound with developmental cables, will be placed in the adjustable gap of the PCTF coil and be tested at up to 50 kA furnished by a separate power supply. The PCTF cryogenic facilities include a non-metallic cryostat and a helium liquefier.

Introduction

Near term tokamaks such as the Engineering Test Facility (ETF) will need pulsed superconducting coils for ohmic heating of the plasma. Such ohmic heating coils will require high current (50 - 100 kA) operation and may require pulsing rates of 10 - 15 T/s. Superconducting cables for these coils must be cryostable with relatively low ac losses and be mechanically stable under cyclic stress conditions encountered during pulsing of the coils. Such cables must be developed in a cost effective manner to meet the near term goals of ETF. At present, there are no facilities to fully test such superconducting cables.

Currently ANL is developing a PCTF. Its purpose is to minimize the time and cost for developing superconducting cables. The PCTF features a split superconducting coil that produces pulsed fields, in which superconducting cables can be tested. These cables will have the form of single or double pancake coils. While under test they will carry dc or ac currents.

The split coil of the PCTF will also serve other important purposes: the test of the split coil itself will be a test of the PCTF 11 kA model cable which can be scaled up to a 50-kA cable; it will be used as a matching coil to the existing ANL 1.5-MJ coil for the study of energy storage and transfer using a high current (5 - 10 kA) thyristor bridge network; it will be used for the study of parallel operations of the two halves of the split coil.

Cable fabrication for the PCTF coil is complete, and the construction of the coil and a non-metallic cryostat is expected to be complete by the end of 1980.

Design and Fabrication of the 11 kA Cable

Design of the cable for the PCTF split coil is illustrated in Fig. 1. The cable has been fabricated by the New England Electric Wire Corp. of Lisbon, NH, according to ANL specifications. A closeup of the cable cross section is shown in Fig. 2. The overall structure of the cable is similar to that of the ANL

1.5-MJ coil. The cable consists of twenty-four 19-strand concentric subcables twisted in a left-hand direction around an insulated stainless steel strip with a twist pitch length of 20 cm.

Each 19-strand concentric subcable consists of six superconducting strands and 13 copper conductors. The six superconducting strands are twisted around a copper center conductor in a right-hand direction with a twist pitch length of 1.27 cm. The finished strand is compacted by drawing through a 0.145-cm carbide die. Then 12 additional copper conductors are twisted around the compacted strand in a left-hand direction with a twist pitch length of 2.54 cm, and the assembly is run through a 0.241-cm compacting die. Prior to the cabling, the diameters of the copper and superconducting strands were 0.051 cm and the surfaces of the strands were tinned with Stabrite. Each superconducting strand contains 2041, 6- μ m filaments with a twist pitch length of 0.64 cm and has a copper-to-superconducting ratio of 1.8:1.

To ensure stable current sharing within the 19-strand subcable, spaces within the 19-strand subcable are partially filled with Sn - 50% Pb soft-solder. The soldering also improves the mechanical rigidity of the completed cable so that the PCTF coil can be wound without additional axial support. The soldered 19-strand subcable is wrapped with a pressure sensitive polyester tape of thickness of 0.005 cm so that approximately 40% of the cable surface is covered. The resulting incomplete electrical insulation between neighboring 19-strand subcables allows adequate cooling while reducing coupling losses among the subcables.

Fig. 1 Structure of the Cable for the PCTF Coil

*Work supported by the U.S. Department of Energy

Fig. 2 Cross Section of the PCTF Cable

During the final cabling, the cable was compacted using a Turk-head to ensure mechanical rigidity of the cable. The compression of the cable, however, has not damaged the insulation between the stainless steel strip and the 19-strand subcable. The stainless steel strip is 2.54 cm wide and 0.08 cm thick with 0.025-cm thick insulation of polyester tape. The electrical contacts between neighboring 19-strand subcables are mostly on the edge of the cable because of their deformations during the compacting process. The electrical contacts in the broad sides of the cable are rather weak and randomly distributed. The dimensions of the finished cable are 3.05 cm x 0.65 cm. The total cable length fabricated for the coil is approximately 900 m.

The Pulsed Superconducting Split Coil

The split coil is composed of two helically wound solenoids each with 22 layers and nine turns per layer. Table I lists the basic parameters of the split coil. The inner and outer diameters of the coil are 45.1 cm and 88.3 cm, respectively, with an axial length of 31.1 cm for each half of the coil. The insulation between the turn of the windings is two layers of 0.02-cm thick glass cloth tape and 0.01-cm thick polyester tape, each with a width of 1.59 cm. The winding layers are separated by 0.32-cm thick and 0.95-cm wide epoxy fiberglass laminated (G-10 CR) strips. Spaces between the strips provide 0.95-cm wide cooling channels in the vertical direction. The cross section of a unit cell in the coil is 3.05 cm². Fractions of the conductor, stainless steel strip, non-metallic materials, and voids in the unit cell are 0.355, 0.065, 0.26, and 0.32 respectively.

A pancake coil wound from an experimental cable can be inserted between the two halves of the split coil for testing as shown in Fig. 3. The gap of the split coil is adjustable to permit testing of pancake coils of different thickness. The load line of the split coil without the gap is shown in Fig. 4. The short sample critical current is obtained by multiplying 24 times the value of the 19-strand subcable. The measured critical current of a short sample of the 19-strand cable is 470 A at 7 T.

When the coil is fully charged, the maximum axial pressure in the cable will be 18.5 MPa. The rigidity of the cable will allow the axial pressure to be supported by the cable itself. The average hoop stress in the cable will be 72.5 MPa. Part of the stress can be sustained by the stainless steel and the conductor

Table I
Coil Parameters of the Pulsed Cable Test Facility

Central Field at 11 kA, T	5.8
Maximum Field at 11 kA, T	6.4
Inner Diameter, cm	45.1
Outer Diameter, cm	88.3
Axial Length, cm	63.5 cm + Gap
Inductance, mH	56
Number of Turns	396
Stored Energy at 11 kA, MJ	3.5
Overall Current Density, A/cm ²	3600
Cable Dimensions, cm	3.05 x 0.64
Cable Length, m	840
Ampere-Meter, A-m	9.35×10^6
Cu/NbTi Ratio	7.9
dB/dt, T/s	6-20
Hysteresis Losses (kJ/Cycle)	~ 0.4
Eddy Current Losses at 10 T/s (kJ/cycle)	~ 5.0
Coil Weight, kg	1200

itself. The excess hoop stress will be supported by the outer bands made from wet layup epoxy fiberglass.

The ac losses of the split coil, estimated from the test results of the ANL 1.5-MJ coil and Equation (2) in Ref. (1), are approximately 5 kJ/cycle at 10 T/s. The coupling time constant of the 19-strand subcable was also measured for fields up to 2 T.^{4,5}

Fig. 3 The Split Coil Assembled in the Non-Metallic Cryostat

Fig. 4 Load line of the coil and short sample current

From the measured coupling time constant of 1.7 ms, the ac losses of the coil is extrapolated to be 4.9 kJ/cycle at 10 T/s. This value does not include the additional loss due to the coupling among the 19-strand sub-cables. The losses of 5 kJ/cycle corresponds to the boil-off of less than 3% of the liquid helium in the void spaces of the coil.

Experimental Arrangement for the Facility

Figure 3 shows the split coil assembled in a non-metallic cryostat. The cryostat consists of two fiberglass reinforced polyester resin tanks, manufactured by the Hasbrouch Plastics Inc., Hamburg, NY.³ The inner helium tank has an inner diameter of 101.6 cm, a depth of 228.6 cm, and a wall thickness of 0.95 cm.

A pair of 11 kA vapor cooled current leads will be connected to the split coil. Another two pairs of leads rated 30 kA, will be used for the test of the pancake coils. A liquid helium level of 60 cm above the top of the coil allows 200 pulses of the coil when the helium is not refilled continuously. Liquid helium necessary for the initial cooldown and test is approximately 2000 l.

Nine thermocouples and 22 potential taps will be installed for the test of the split coil. Another six thermocouples and five helium level sensors will be installed in the cryostat.

A pulsed power supply 7 MW at its peak (2.9 MW rms) charges the PCTF coil to 6.4 T (11 kA) in 1 s. It can discharge the coil in about the same time (6.4 T/s). A solid state switch will be added to this power supply, as shown in Fig. 5, to force an exponential decay of the field at $\dot{B} \leq 24$ T/s. In the circuit of Fig. 5 the power supply charges the inductor through thyristor assembly TH₁. When the current has reached a preset value of 11 kA, thyristors TH₂ are turned on and current begins to flow through resistor

R₂. A signal from pulse transformer, CT₁, triggers turn-off thyristor TH₁, which applies the back-bias voltage on capacitor C_x across thyristors TH₁. This causes TH₁ to turn off within 25 μ s and the current in the superconducting coil L transfers to resistor R₁. This resistor is adjustable to force a voltage of 2.5 kV across the superconducting coil. The signal from CT₁ is also used to initiate turn-off of the 2.9 MW power supply by means of rectifier phase control. Thyristors TH₂ provide a discharge path for the energy stored in the current equalizing reactors L_g.

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3. The explicit reference to a particular product or service does not imply that other vendors might not be able to supply equivalent products or services.
4. S. S. Shen and R. E. Schwall, "Losses and Transient Field Effect in Superconducting Cables for PF and TF Coils," *Proc. of 7th Symposium on Eng. Problems of Fusion Research*, Knoxville, TN, October 25-28, 1977, p. 1293.
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Fig. 5 Pulsed Power Supply with Solid State Switch