THE FINAL DESIGN OF A SUPERCONDUCTING MHD MAGNET
FOR
THE COAL-FIRED FLOW FACILITY AT THE UNIVERSITY OF TENNESSEE SPACE INSTITUTE

by

S.-T Wang, L. R. Turner, L. Genens,
W. Pelczarski, J. Hoffman, J. Gonczy, H. Ludwig,
R. C. Niemann, K. Mataya, and E. Kraft

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INTRODUCTION

The superconducting magnet system (SCMS) consists of the superconducting magnet, magnet cryostat, a helium refrigerator/liquefier facility, a helium gas-handling system, apparatus for cryogenic transfer and storage, a magnet power supply, a integrated instrumentation and control system including a computer for magnet operation, data acquisition, system status and diagnosis, and magnet protection. The complete system will be tested at Argonne and installed at the Coal-Fired Flow Facility (CFFF) at the University of Tennessee Space Institute (UTSI) in 1981. The cryogenic aspects are described in paper KD-4 while the magnet safety is analyzed in paper KD-5.

The MHD warm bore, the magnet cryostat layout and the axial field profile, are shown in Fig. 1. Significant magnet system parameters are listed in Table I.

It is recognized that the UTSI SCMS must serve as a model with the design scalable to future large MHD magnets as the Engineering Test Facility (ETF) and in the full-size base load systems. The successful experiences gained in designing and fabricating the UTSI SCMS will definitely advance the state-of-the-art of large MHD magnets and will provide a significant technological data base for future large MHD superconducting magnets.

For a given conductor design, cooling provisions and given coil structure, one can compute the minimum propagating energy and perform verification experiments. Nevertheless, because of the complex mechanical nature of a given coil and the lacking of acceptable criteria for the size of disturbance against which the conductor should be stable, therefore, the UTSI SCMS conductor is designed to be absolutely or unconditionally cryostable. Despite the absolute stability, an achieved average current density of about 2000 A/cm^2 over the coil cross section is adequate so that the economy of the total ampere-turns needed is quite good.

The coil configuration is the U.S. SCMS type circular saddle¹. The coil will be assembled on the magnet bore tube with spiral banding. The bore tube will be about 6.3 cm thick (in the thickest section) and the banding will be strong enough for coil assembly but too weak to transmit the 30,180 kgf/cm maximum burst force to the bore tube. Fifteen (15) ring girders will be used as the superstructure to contain the force. The decentering force of about 0.2177×10^6 kgf will be taken up by end flanges and bore tube.

COIL CONFIGURATIONS

As shown in Fig. 2, the magnet is circular saddle wound, with fourteen layers. The outer thirteen layers are each 4.88 m long; the inner layer consists of two subcoils: No. 1A, 2.04 m long; and No. 1B, 2.87 m long. This coil spacing provides the required field profile. This coil cross section is chosen so that it is efficient in producing magnetic field and keeps the azimuthal force build-up in each layer to an acceptable level. Layers two through nine all subtend to angle of 53° , ensuring that the radial force from each layer is supported by the next.

CONDUCTOR DESIGN

To reduce conductor costs, three grades of conductor, A, B, and C, designed for fields up to 7.5 T, 6.5 T, and 4.5 T, respectively, will be used. The critical current is 4500 A at 4.2 K.

Grade A will be used at fields up to the peak field; grade B, up to 6.0 T; and grade C, up to 4.0 T. Layer 1, containing only 42 turns, will consist of grade A. Layers 2 through 4 will have both grade A and B. Layers 5 through 8 will have all three grades; and the remaining six layers, grades B and C. For the inner layers, the field where the layer begins to turn over at the high field end determines the turn at which grades must be changed; for the outer layers, it is the field at the high field end.

As shown in Fig. 3, the selected conductor will be 3.10 cm high with conductor thickness varying according to the field grades. The superconducting insert shall be a soldered cable of multiple wires of Nb-48% Ti superconducting composites transposed around a copper strip. The stabilizer shall be an integrated piece with a longitudinal groove. The superconducting cable shall be bonded by 50-50 noncorrosive soft-solder to the longitudinal groove of OFHC copper stabilizer. The depth of the longitudinal groove shall be such that the surface of the superconducting cable strips will be 0.76 mm below the front face of the copper stabilizer.

COIL STRUCTURE

The structure of turn-to-turn and layer-to-layer is shown in Fig. 4. The turn-to-turn insulation will be provided by a pultruded fiberglass strip with keystone cross section. The keystone feature eliminates the tedious labor of inserting angle-correcting wedges during coil winding. The pultruded fiberglass strip will be made in a fishbone-like pattern so that vapor-locking will be avoided and that about 30% of broad face will be cooled. The conductor designed with this face cooling and 50% edge cooling, will be cryostable with a steady state heat transfer of about 0.14 W/cm^2 to the liquid helium. This low heat flux assures the unconditional stability for the conductor.

The CFFF SCMS will consist of 14 coil layers. Except for coils in Layer 1 which will be banded to the bore tube by 321 stainless steel, each coil layer, having two circular saddle coils, will be assembled onto the bore tube by pultruded fiberglass banding of 1.85 cm inch width by 0.71 cm in thickness. The pitch length is 3.7 cm at straight coil region and 2.78 cm at coil end regions. The pitch length is reduced at coil end region because the conductors in the coil end are at places nearly parallel to the spiral banding. Thus, about 50% of the conductor edges will be cooled in the straight coil region

while about 30% of the conductor edges will be cooled in the coil end region.

A micarta coil form, similar to the one used in the U.S. SCMS, will be employed to wind the CFFF SCMS saddle coil. The coil form will be made of 3.084 cm thick linen base phenolic laminate. It will be slotted to allow it to conform to the cylindrical saddle shape. The slots will be filled with glass fillers and shell 828-Versamid 140 epoxy to sustain the curved shaped.

The bore tube will be insulated by bore tube insulating sleeves which are made of wetted wound fiberglass cylinder of about 0.635 cm in thickness. The cylinder will be machined with cooling grooves 1.428 cm wide by 0.476 cm in depth.

A layer of 0.635 cm thick G-10 coil blanket will be placed over the insulating sleeve cylinder to provide 50% edge cooling and coil support at the coil end region. Similar coil blankets of 0.655 cm in. thickness are used to insulate the stainless steel banding by placing the coil blankets above and beneath the stainless steel banding of coil Layer 1.

CRYOSTABILITY

Calculated recovery currents for the three grades of conductor are 3780 A at 7 T for grade A, 3860 A at 6 T for grade B, and 4300 A at 4T for grade C. The calculation is based on a heat transfer coefficient of 0.15 W/cm^2 . All these recovery currents are above the design operating current of 3675 A. Special attention must be paid to the cryostability of the end regions, for the three reasons. First, the peak fields in grades B and C (but not A) conductors occur there. Second, there is less edge cooling, because the banding pitch is tighter. Third, there may be lengths of conductor, up to 33 cm (13 in.) long, covered by the banding in a region where the banding and conductor run parallel.

ELECTROMAGNETIC FORCES AND PRESSURE

The conductor in the high-field (6.0 T) cross section A-A Fig. 2 exerts a burst force of 30,180 kgf/cm outward on the girders; a clamping force of 24287 kgf/cm pushes the two halves of the magnet together.

In Fig. 5, the radial magnetic pressure due to the radial and azimuthal components for force for each 5° azimuthal increment is shown, totaled over all fourteen layers to give the net pressure and also totaled to the layer which gives the peak pressure. The radial pressure shown in Fig. 5 includes the radial pressure due to the azimuthal forces; the combined pressure gives the burst force of 30,180 kgf/cm.

Figure 5 also shows the accumulated pressure for each layer, calculated in the high field cross section. The number of turns per layer were chosen to limit this average pressure to prevent yielding in the copper stabilizer of the conductor.

The coil ends contribute axial forces as well as burst and clamping force; the forces are also shown in Fig. 5.

The decentering forces on each coil are especially bothersome for a dipole magnet with a tapered field. These forces result from the asymmetric field distribution. Each layer experiences a different field at the two ends, and consequently different and non-cancelling forces. The 219,500 kgf is distributed nearly uniformly over the outer thirteen layers.

STRUCTURAL SUPPORT AND STRESS ANALYSIS

The bore tube is the main structural support for the cold mass and magnetic forces. Made up of two end flanges and a cylindrical section, the assembly will weigh 13,152 kg. The bore tube details and dimensions are shown in Fig. 6.

The decentering magnetic force is supported by the flange at the high

field end and by a step in the tube. In addition to the magnet forces, the bore tube assembly is designed for a 3.4 atm (50 psi) pressure in the helium vessel.

The end flanges are annular plates of 2.34 m diameter supported at the inner boundary by the bore tube. The outer boundary attaches to the outer helium shell. Bending moments transferred by the end flanges to the bore tube are supported by gussets on the tube section outboard to the flanges. A total of 32 (including four support link gussets) are provided on the high field flange and 16 (including four support link gussets) on the low field flange. All gussets have a minimum thickness of 2.54 cm except the 10.16 cm thick gussets at the cold mass support link locations. The flanges will be cast from ASTM A 351-75 Grade CF8M modified. This material contains a maximum of 0.04% carbon and is the cast alloy of wrought 316-L. Cast stainless properties and soundness are enhanced with an increase of ferrite. Since the increased permeability associated with ferrite is not detrimental to the design, ferrite in the range of 5% to 15% has been specified. The yield stress of the flange material will be at least 517 MN/m^2 (75 kpsi) at 4.2 K. The maximum calculated stress 339 MN/m^2 occurs at the inner corner where the high field end flange joins the cylindrical tube. To minimize the flange moments transferred to the bore tube, a 22.86 cm (9 in.) stub of tube will be cast as an integral part of the flange. This positions the weld in a location where the moments have essentially died out.

Fabrication of the tubular section of the assembly will be from rolled and welded annealed, and pickled, corrosion-resisting chromium nickel steel plate type 316-L, as per ASTM A240-75. The 4.547 m long tube will be made from four rolled sections solution annealed prior to welding together. This method of fabrication results in one longitudinal and five circumferential welds.

The stress value at various high stress points are indicated in Fig. 6.

The eleven main girder rings are 30.48 cm wide, spaced 2.54 cm apart, and symmetrically located over the 300 cm effective field region. Each ring consists of two 130° cast stainless steel segments pinned to six (three-per-side) aluminum ties plates as shown in Fig. 7.

The cross section of the main girder segments is an "I"-beam with a solid center portion. These segments will be cast from ASTM A 351-75 Grade CF8M (type 316 stainless steel).

Selection of aluminum tie bars in the main girder rings was made to minimize the weight and to assure the girders will be tight against the fiberglass bands after cooldown. Three 5.08 cm x 20.32 cm x 165.6 cm long plates per side of 2219-T87 aluminum has been selected because of its good ductibility and high yield strength.

The pin selected for the finger arrangement shown in Fig. 7 is 6.67 cm diameter and is solution treated and aged A-286 ST. STL. with an estimated yield of 896 MN/m^2 (130,000 psi) at 4.2 K.

The conductors at each coil end will be supported by two end ring girders made of 90° segments of 2219 T87 aluminum alloy. The girder located closest to the high field plane will have a radial thickness of 30.48 cm whereas the outer girder will be 20.32 cm thick. The segments will be cut from a 5.08 cm thick plate stock. The maximum tensile stress in the body of the 20.48 cm ring girder is 193 MN/m^2 . The maximum tensile stress in girder at pin holes is 234.4 MN/m^2 .

POWER SUPPLY, INSTRUMENTATION AND MAGNET PROTECTION

The power supply will have an output characteristic of 20 V - 5000 A. 0.05 Ω dump resistor submerged in a water tank will be used to safely

discharge the magnet in the event of emergency. The magnet could be energized in 70 minutes and discharged in 7 minutes. The maximum discharge terminal voltage will be 100 V with respect to the grounding center tap of the dump resistor.

A total of 95 strain gauges are distributed among high stress points. Thermocouples made of copper-constantan, silicone diode, and Au-Fe are used within coil winding, helium vessel, bore tube, ring girder, cold mass support and the nitrogen shield system. Potential taps will be needed for monitoring charging voltages and the unbalanced voltage. Conductor motion will be monitored by an accelerometer and microphones in addition to the potential taps. Hall probes will be used to measure the MHD channel field and the peak field in the winding. Finally, the liquid helium level and the liquid nitrogen level will be measured by an NbTi probe and oxygen bellow assembly, respectively.

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TABLE I

MAGNET SYSTEM PARAMETERS FOR CFFF SCMS

1. <u>MHD Warm Working Bore Size</u>	Inlet 80 cm, End of Effective Field 100 cm
2. <u>MHD On-Axis Field</u>	Inlet at 4.8 T, Peak at 6 T, Outlet at 4.8 T
3. <u>MHD Effective Magnetic Length</u>	3.0 m
4. <u>Field Ripple, Uniformity and Field Tapper</u>	
Ripple Along Field Taper	+ 2.5% of on Axis Field
Cross-sectional Field Uniformity	+ 5% of on Axis Field
Field Taper	0.2 T/m
5. <u>Magnetic Coil Characteristics</u>	
Coil Winding Bore (Minimum)	119 cm
Bore Tube Thickness (Maximum)	~ 6.3 cm
Winding Type	Circular Saddle with Intermediate Crossovers
Operation Current	3675 A
Peak Field	6.9 T
Winding Build	0.53 m
Average Current Density	~ 2890 A/cm ² in Copper; ~ 2000 A/cm ² in Winding
Cryostability	0.142 W/cm ²
Stored Energy	~ 168 MJ
Inductance	21 H
Max. Transverse Force	30180 kgf/cm
6. <u>Coil Force Support</u>	Partially support from bore tube and major support from external ring girders
7. <u>Support Against External Forces During Operating and Shipping</u>	3 g vertically down, 1 g vertically up, + 2 g axial and + 1 g lateral
8. <u>Cryostat</u>	
4.2 K Cold Mass Weight	1.32×10^5 kg
4.2 K Cold Mass Dimensions	~ 3.16 m dia x 5.05 m long
Liquid Helium Inventory	8962 L
Heat Leak to LHe ⁴	14.0 watts (= 20 L/hr)
Vacuum Vessel, Support & LN ₂ Shield Weight	~ 4.06×10^4 kg
Vacuum Vessel Dimension	~ 3.6 m dia ₅ x 6.4 m long
Total Magnet Weight	~ 1.73×10^5 kg
9. <u>Refrigerator/Liquefier Facility</u>	Closed cycle refrigeration capable of system cooldown in 4 weeks and liquid helium production of 50 liquid liters per hour. Other components are liquid helium storage dewars, helium gas recovery.

FIGURE CAPTIONS

- Figure 1 MHD Warm Bore, Cryostat Layout and Field Profile.
- Figure 2 Coil Configuration of Circular Saddle Coil
- Figure 3 CFFF SCMS Conductor
- Figure 4 Coil Structure of Turn-to-Turn and Layer-to-Layer
- Figure 5 Magnetic Forces and Pressure
- Figure 6 Bore Tube, End Flange, and Stresses
- Figure 7 Main Ring Girder and End Ring Girder

SECTION A-A

TOP VIEW

SECTION B-B

TWENTY 1.02 mm. DIA.
SC WIRES-TWIST
FILAMENT DIA. = 80 μ
STRAND PITCH = 0.2 TURN/CM.

TWENTY 0.89 mm. DIA.
SC WIRES-TWIST
FILAMENT DIA. = 70 μ
STRAND PITCH = 0.2 TURN/CM.

SEVENTEEN 0.79 mm. DIA.
SC WIRES-TWIST
FILAMENT DIA. = 60 μ
STRAND PITCH = 0.2 TURN/CM.

PARTIAL VIEW OF SADDLE COIL
(NOT TO SCALE)

PULTRUDED FIBERGLASS
BANDING-SPIRAL WOUND

END TURN REGION

STRAIGHT REGION

LAYER-TO-LAYER STRUCTURE

TURN-TO-TURN STRUCTURE

LOADING	A	B	D
VERTICAL ($\frac{MN}{m^2}$)	210	186	172
AXIAL ($\frac{MN}{m^2}$)	252	223	207

SHIPPING

LOADING	G	H	I	K	M
AXIAL ($\frac{MN}{m^2}$)	—	339	-250	88	140
AZIMUTHAL ($\frac{MN}{m^2}$)	33	147	29.6	14	62

MAGNETIC LOADING
PLUS HELIUM PRESSURE

BORE TUBE & END FLANGES

TYPICAL JOINT

UNDERSIDE VIEW

MAIN RING GIRDER

TYPICAL JOINT

TOP VIEW

END RING GIRDER