THE AXICELL MFTF-B SUPERCONDUCTING MAGNET SYSTEM*

S. T. Wang, R. Bulmer, C. Hanson, R. Hinkle, T. Kozman, D. Shimer, and J. VanSant,
Lawrence Livermore National Laboratory, University of California,
Livermore, CA, U.S.A., 94550

R. Tatro, J. Wohlwend
General Dynamics, Convair Division, San Diego, CA, U.S.A., 92138.

The Axicell MFTF-B magnet system will provide the field environment necessary for tandem mirror plasma physics investigation with thermal barriers. The performance of the device will stimulate DT to achieve energy break-even plasma conditions. Operation will be with deuterium only. There will be 24 superconducting coils consisting of 2 sets of yin-yang pairs, 14 central-cell solenoids, 2 sets of axicell mirror-coil pairs, and 2 transition coils between the axicell mirror coil-pairs and the yin-yang coils. This paper describes the progress in the design and construction of MFTF-B Superconducting Magnet System.

FUNCTIONAL REQUIREMENTS AND COIL CHARACTERISTICS

Axicell MFTF-B magnet configuration is chosen over A-Cell MFTF-B [1] configuration because, in axicell, it has higher Q (defined as the ratio of fusion output energy to plasma input heating energy), lower capital cost, and reduced radial transport. The axicell magnets have better geometry in the end-plug region and looks better as a fusion reactor magnet system.

The magnet coil configurations, as shown in Fig. 1, were determined based on the field requirements over the plasma region and on other requirements, such as the penetration access for the plasma heating beams and the diagnostics and space for cryopumping. The magnet array and the profiles of on-axis field are shown in Fig. 1. Table 1 lists the important coil parameters and magnet characteristics. The configuration will accommodate a plasma column at central cell with a 30-cm plasma radius plus allowance for a 15-cm-thick plasma halo. The anchor cells will be a yin-yang pair with a mirror ratio of 3.0, instead of the 2.1 ratio in the original MFTF design. The mirror field will be 3.0 T. The field at the mirror center will be 1.0 T and the mirror-to-mirror length will be 5.1 m. The midplane-to-midplane distance from the east yin-yang pair to the west yin-yang pair will be 40 m.

The axicell plug coils (A1 and A2) will generate a 6-T mirror at the inboard and a 12-T mirror at the outboard, with a 4-T field-well between them. The center cell will consist of 14 solenoids spaced 1.25 m apart. These solenoids will produce a uniform axial field, variable up to 1.6 T.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Table 1. Coil parameters and magnet characteristics.

Parameters	Coil designations					
	P1 and P2	T1	A20	A21	A1	S1 to S7
Mean Radius (m)	2.50/0.76 ^b	2.00/1.5 ^b	0.76	---	0.95	7.50
Coil cross section (cm ²)	32.0 x 22.4	36 x 36	80 x 40	---	80 x 40	16.3 x 22.6
Current density (A/cm ²)	2100	2075	2316	4516	2516	3140
Ampere turns (KA)	5.67	3.96	7.50	2.06	8.05	1.72
Central field (T)	1.0	1.0	12.0	12.0	6.0	1.6
Conductor length (m)	24.8	18.0	6.80	---	9.84	0.42
Peak field (T)	3.07	4.0	7.6	12.8	9.1	3.2
Operating current (A)	5077	5700	5270	---	5001	2866
Inductance (L)	11.5	5.0	1.0	---	2.2	7.2
Stored energy/coil (MJ)	0	0.5	26	1.6	30.0	30.0
1% heat leak/coil (W)	520	120	0	---	0	60

^a Represents mean major radius.

^b Represents mean minor radius.

^c 50 = 5.0 T.

^d Excludes total nuclear heating (20 kW).

SUPERCONDUCTING COIL DESIGN

(a) Steady-State Cryostability

MFTF-B superconducting magnet system is the largest now under construction. To assure reliable operation, the design of these magnets is based on successfully demonstrated designs within state-of-the-art superconducting magnet technology. To minimize disruptions, the design of all coils is based on the steady-state cryostability criterion, employing the condition of 4.5 K pool-boiling helium over wetted surface area. In addition, a minimum stability margin is designed in both the field (at the operating current) and the current (at the operating field). Figure 2 shows the I-H curves specified and measured for all MFTF-B conductors (except A₂₁ coil). The important conductor-parameters designed for the MFTF-B magnets are tabulated in Table 2.

Table 2. Conductor parameters.

Field grading	MFTF type conductor		Solenoid conductor
	Grade I	Grade II	
Specifications	11.1A, 12.5 T, 4.2 K	7.2 M, 15.1 T, 4.5 K	2800 A, 12.1 T, 4.5 K
Conductor	Nb, 66% Ti	Nb, 66% Ti	Nb, 66% Ti
Composite size (mm)	6.5 x 6.5	6.5 x 6.5	1.000 x 3.072
Composite RRR	150	150	110
Filament diameter (mm)	0.20	0.20	0.22
Twist pitch (mm)	120	180	110
Conductor size (mm)	12.4 x 12.4	12.4 x 12.4	12.40 x 5.0
Stabilizer RRR	220	220	110
Overall Cu/NbTi ratio	6.2	18.7	32.0

4.5 K Operating points:

P1 and P2	5077 A, 5.2 T	---	---
T1	---	5700 A, 4.8 T	---
A ₂₀	5270 A, 7.6 T	5270 A, 5.0 T	---
A1	5001 A, 9.1 T	5002 A, 5.0 T	---
S1 to S7	---	---	2866 A, 3.2 T

(b) Yin-Yang Magnet M1 and M2

The yin-yang magnet constructed for the original MFTF was a yin-yang pair with a mirror-field ratio of 2.1 and a central field (minimum B) of 2.0 T. The maximum field at conductor was 7.68 T. The operating current was 5775 A. Detail design and fabrication has been described by C. Henning, et al. [2]. The magnet was tested successfully up to its design current and field. Detail of the testing is described by T. Kozman, et al. [3].

In the AxiCell MFTF-B magnet, the yin-yang coils will be separated by an additional 1.7 m to generate a mirror ratio of 3.0 and a central field of 1.0 T. The operating current will be 4077 A and the spreading forces of the lobe are about 45 MN, instead of a 98 MN spreading force in the original MFTF design. To limit the deflection of each coil, an intercoil box-beam is proposed to connect the coils and to provide additional mutual support for both coils (see Fig. 6). In order to reach the other coil, a 1.7-m horizontal outward extension is required to the existing reinforced structure at the lobe.

(c) Transition Coil T1

Two transition coils transform the plasma between the yin-yang coil from an elliptical shape into the circular shape necessary for the central cell. The transition coils and the yin-yang coil are the only C-type coils in the system. These coils are oriented at 45° to the gravitational field to promote uniform convective cooling of the superconductor in a liquid helium bath.

Figure 7 shows the coil structures. The coil peak field is 4.8 T at a operating current of 5700 A. The conductor and the coil structure adopted is of the yin-yang type. The turn-to-turn insulation consists of 1.14-mm-thick octagonal G-10 CR fiberglass buttons. These buttons are attached to one another by a dacron string. The layer-to-layer insulation consists of 1.6-mm-thick G-10 CR, 50% slotted for helium ventilation. The ground plane insulation of the coil is designed for 2000 V from coil to ground in a 300 k helium-gas environment. The coil insulation, the helium space, and the clearest assembly are identical to yin-yang coil fabrication. The transition coil will be wound on an "I"-shaped bobbin consisting of a 4.45-cm-thick 304 LN stainless steel coil form. The coil winding will be similar to the yin-yang coil. The coil spreading loads will be supported by a 304 LN stainless steel superstructure. The superstructure will be actively cooled during rapid cooldown in order to meet the 120 hours cooldown time requirement.

(d) The Second Axial Mirror Coil A2

The coil A2 (Fig. 4), together with the rest of AxiCell MFTF-B magnet system, will generate a 12-T on-axis peak field. As shown in Fig. 4, the coil consists of a 12-T outer coil, A20, and a Nb₃Sn coil insert, A21. Each subcoil will have a separate helium vessel. This will allow parallel progress in the design, the construction, and the test for both subcoils. In addition, the Nb₃Sn subcoil could be removed or replaced if necessary, and the leading conductors for both subcoils could be handled individually. Above all, if the Nb₃Sn coil should quench, it will not trigger a quench of the outer NbTi coil.

The subcoil A20 will be operated at an operating current of 5270 A and a peak field of 8 T at 4.5 K. It will be layer-wound, employing the G-10 CR turn insulation and G-10 CR layer blanket of A-cell magnets. The hoop load will be taken up by the conductor and the coil helium shell. The coil form will be made of 304 LN stainless steel. It will be insulated in an identical manner as the transition coil.

The subcoil A21, designed at a conservative current density of 4500 A/cm², will have a peak field of about 12.8 T. It is proposed to use a steady state, cryostable Nb₃Sn conductor. A magnet [4] of this bore size and a similar peak-field level

was successfully built to full design field without employing cryostability criteria. Figure 4 shows the proposed coil cross section and the Nb_3Sn pancake structure. Stainless steel ribbons are co-wound with the Nb_3Sn conductor to contain hoop stress within 0.2% strain. A G-10 strip is punched in a first-turn pattern and is proposed for turn-to-turn insulation. Alternatively, the stabilizer copper could be perforated with grooves and then soldered to the Nb_3Sn conductor. These approaches will provide enough face-cooling for magnet stability. Perforated G-10 CR blankets are used for insulation between pancakes. Sufficient winding space is available if lower current density is necessary to assure cryostability.

(e) The First Mirror Coil (A1)

Together, the first mirror coil, A1, and the central-cell solenoid magnets generate a 6-T on-axis peak field. The coil cross section and coil structure is identical to that of coil A20. The peak field on A1 coil conductor will be 8.1 T. The operating current for A1 will be 5092 A. Similar to coil A20, the hoop load of coil A1 will be supported by both the conductor itself and the coil outer shell.

(f) Central-cell Solenoids (S1-S7)

To expedite assembly and installation, central-cell solenoids are designed to be modular in pairs (except for S7). Each coil is welded into a two-coil module with four intercoil box beams, equally spaced. Figure 5 shows the simple monolithic NbTi conductor for solenoids. The conductor is fabricated from 1/4-hard OFHC copper having a yield stress of 159 MN/m^2 ($23 \times 10^3 \text{ psi}$). The peak field of solenoids is tabulated in Table 1. The turn insulation is 1.5-mm-thick G-10 CR buttons, which provide 70% wetted area on the broad face of the conductor. The turn layer insulation is also a 1.5-mm-thick G-10 CR blanket slotted 60% for edge cooling. Each solenoid will have 25 turns per layer. The coil form is a "U"-shaped bobbin made from 2.5-cm-thick 304 LN stainless steel plates. The side wall is insulated with solid G-10 CR, Kapton films, and slotted G-10 sheets and is identical to the yin-yang coil insulation. The plenum space is filled with multilayers of G-10 CR sheets slotted for helium ventilation. These G-10 sheets will also provide the radial force support by transmitting the hoop load to the coil outer shell.

STRUCTURAL SUPPORT SYSTEM

Total axial magnetic coil forces on each coil, in two operating conditions, were computed and listed in Table 3. Based on the axial force pattern, coils are paired into modules with intercoil struts to minimize the resultant axial load. However, to minimize the axial thermal stresses, the length of each interconnected section should not be too great. All support rods will be designed for both normal and fault conditions. Total loads will include the weight of the coil, the central cell axial magnet loads, the thermal stresses, and the earthquake loads. All of these loads will be carried by the vacuum vessel through transverse and axial struts. Figure 6 shows the concept for the magnet support system in axicell configuration. Two center-cell solenoid modules will be connected by mutual axial load transfer struts. The combined axial load will be transferred to the vessel structure by a set of four axial struts. Two vertical struts and one horizontal strut will provide vertical and transverse support, respectively, to each module and to solenoid S7. As in the A-cell MTF-B design, a temporary vertical strut is planned to provide each module with support during assembly.

The axicell plug coils, A1 and A2, will become a module and will be connected by axial load transfer struts. This module will be supported by three vertical, two transverse, and two axial struts. The transition coil will be adjacent to the yin-yang coil but will be independently supported. Two vertical and two horizontal struts will provide support in the x-y plane, while four struts will be connected to the A1-A2 module to provide axial support. The yin-yang pair will be supported by three vertical, two transverse, and two axial struts.

Table 3. Axial magnetic forces in operating condition.

Coils	Kelley mode ^a		Axicell mode ^b	
	(x 10 ³ N)	(x 10 ³ lb)	(x 10 ³ N)	(x 10 ³ lb)
M2	-5249 ^c	-1180	-5213	-1173
M1	- 308	-69.2	- 408	-91.7
T1	- 765	- 172	-1214	- 273
A2	-4528	-1018	-4724	-1062
A1	+4248 ^d	+ 955	+1206	+ 271
S7	- 574	- 129	-4969	-1117
S6	+ 166	+ 37.3	-1307	- 294
S5	+ 173	+ 38.9	- 308	-69.2
S4	+ 140	+ 31.6	+ 74	+16.6
S3	+ 70	+ 15.7	+ 43	+ 9.7
S2	+ 43	+ 9.6	+ 42	+ 9.5
S2	+ 9	+ 2.1	+ 18	+ 4.1

^a In Kelley mode, central field of S1 to S7 is 1.6 T.

^b In Axicell mode, central field of S1 to S7 is 1.0 T.

^c All negative forces point toward machine center.

^d All positive forces point away from machine center.

POWER SUPPLY AND COIL PROTECTION

The total stored energy in the axicell MFTF-B magnet system is about 1150 MJ for a central cell field of 1.6 T. To avoid possible coupling, which might induce higher coil currents and forces that could damage the coils, it is proposed to discharge all coils together in situations requiring a discharge of energy. The fast discharge constant will be ~120 s, corresponding to a discharge voltage of ~500 V across each of the yin-yang coils or ~250 V to the grounding center tap.

The MFTF-B magnet system will be energized to full field in 4 hours. Separate power supply systems are envisioned for each pair of yin-yang coils, each transition coil, and the axicell plug-coil module. These supplies will have an output rating of 0 to 10 V and 0 to 6000 A. The 14 solenoid coils at the central cell will be supplied as a group, and the supply will be rated at 0 to 50 V and 0 to 3000 A. However, 14 smaller trim supplies are provided for individual coil current control. Each power supply will have a closed-loop regulator that will control each coil current to within ±0.5%. Each magnet will have a detection system for normal-zone and an air-cooled energy discharge resistor permanently connected across the terminals of the magnet-current leads. This assures that no more than one coil will be damaged in the event of an open circuit. The helium level and pressure in the helium dewars, the voltages across vapor-cooled leads, and the lead temperature will be monitored to control the magnet-coil energy discharge.

Each power supply will have one or two circuit breakers. During energy discharge, all circuit breakers will be open, and the magnet energy will discharge through its own discharge resistor. A soft-grounding resistor will be connected to the center of the series coil string to fix the coil voltage and to lower voltage to ground by a factor of 2.

HEAT LOAD

Each magnet will be cooled by natural convection flow of liquid helium (LHe) through the coils. Elevated dewars will supply LHe to the bottom of each magnet, and LHe return flow will be from the top of each magnet (for example, see coil M2 in Fig. 6). Maximum supply temperature will be 4.5 K within the coil. The liquid quality will be 0% gas at the magnet bottom surface and no more than 10% gas helium by volume at the return flow from each magnet.

Liquid nitrogen-cooled shields will be installed to shield the magnet's cold mass and its support-structure surface. The total heat load to the nitrogen shield is 150 kW. Heat conduction inflow from room temperature sources will be intercepted by liquid nitrogen-cooled intercepts on support struts. The total heat load to all MFTF-B magnets cold mass is estimated at 2300 W (excluding neutronic heating), tabulated according to each magnet (see Table 1). In addition to this heat load, there will be a 0.11-g/s/kA/pair gaseous helium flow through any vapor-cooled lead, yielding a total flow of 9.0 g/s.

CONSTRUCTION STATUS

The first pair of yin-yang coils (EM1 and EM2) were successfully tested in February 1982 at Lawrence Livermore National Laboratory. The coil-cases of these coils will be modified to accommodate the new requirement of an additional 1.7-m separation to produce a mirror ratio of 3 in the yin-yang coils. Winding of the first coil (W#1) in the second yin-yang coil pair will be completed in June 1982. Figure 7 shows the coil winding of Layer No. 48 and the use of an end-winding clamp to hold down the coil layers at the coil-end region.

The central-cell solenoids will be manufactured at General Dynamics, Convair Division, Harbor Drive Facility in San Diego, California. Two spider-like winding fixtures are being set up for solenoid coil winding. Winding practice will be in June 1982, and actual winding will start in July 1982. Figure 8 shows the schematics both for truing the coil form and for coil compaction.

ACKNOWLEDGMENTS

The authors wish to thank G.T. Yamaguchi and Yun Chang for their efforts in field and force calculation and E. Owen for his analysis of coil quench.

REFERENCES

- 1 Van Sant, J. H., et al., "The Mirror Fusion Test Facility Magnet System," 9th Symposium on Engineering Problems of Fusion Research (1981), pp. 1996-1999.
- 2 Henning, C. O., et al., Mirror Fusion Test Facility Magnet System - Final Design Report, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52955 (1980).
- 3 Kozman, T. A., et al., "The Testing of the MFTF Magnets," paper JD-2, this conference.
- 4 Ballou, J. K., et al., "Design and Testing of a Dual 2-T 380-mm/12-T 220-mm Split Superconducting Solenoid for ORNL," vol. Mag-17, No. 5 (1981), pp. 2238-2241.

Fig. 1 MFTF-B axicell magnet arrays and axis-field profile

Fig. 2 MFTF-B conductors I-H characteristics

Fig. 3 Transition coil and superstructure

Fig. 4 A2 coil structure

Fig. 5 Solenoid coil structure

Fig. 6 Support system (elevation view)

Fig. 7 Coil winding of West M1 showing coil end region

Fig. 8 Winding schematics for central cell solenoids