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DESIGN AND FABRICATION OF THE SUPERCONDUCTING-MAGNET SYSTEM FOR THE MIRROR FUSION TEST FACILITY (MFTF-B)

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Lawrence Livermore Laboratory

DESIGN AND FABRICATION OF THE SUPERCONDUCTING-MAGNET SYSTEM FOR THE MIRROR FUSION TEST FACILITY (MFTF-B)[1]

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ABSTRACT

The superconducting magnet system for the Mirror Fusion Test Facility (MFTF-B) consists of 24 magnets; i.e. two pairs of C-shaped Yin-Yang coils, four C-shaped transition coils, four solenoidal axicell coils, and a 12-solenoid central cell. General Dynamics Convair Division has designed all the coils and is responsible for fabricating 20 coils. The two Yin-Yang pairs (four coils) are being fabricated by the Lawrence Livermore National Laboratory.

Since MFTF-B is not a magnet development program, but rather a major physics experiment critical to the mirror fusion program, the basic philosophy has been to use proven materials and analytical techniques wherever possible. The transition and axicell coils are currently being analyzed and designed, while fabrication is under way on the solenoid magnets.

1. INTRODUCTION

The initial MFTF-B design, incorporating a massive A-cell and superstructure, shown in fig. 1, was approved by the Department of Energy (DOE) in early 1980. At that time, senior DOE review panels encouraged efforts to achieve a more nearly axisymmetric design that would enhance Q and directly relate to a mirror fusion reactor. This would allow the experimental reactor studies and planning programs to focus on a single mirror concept during the next few years. The current configuration, shown in fig. 2, allows several different operating modes:

1. This work performed under LLNL Contract 9590309.

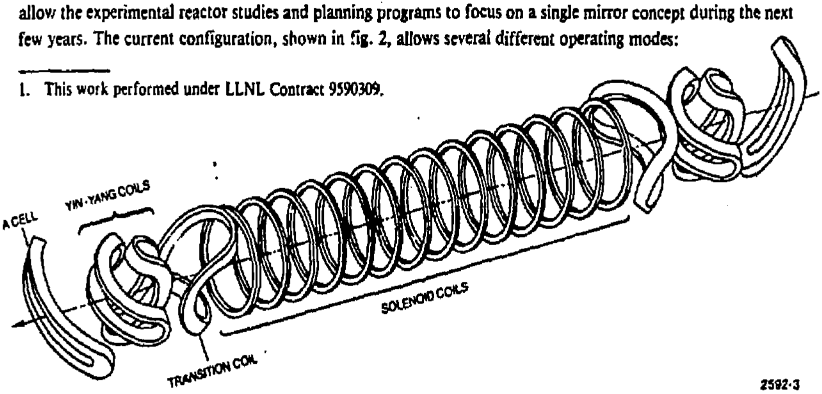

Figure 1. Initial MFTF-B magnet configuration used 14 solenoids and two large A-cell coils.

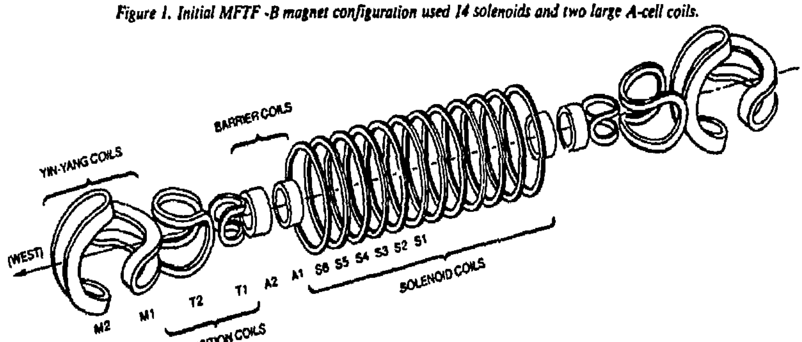

Figure 2. General Dynamics is responsible for the design and fabrication of 22 of the 26 magnets for the MFTF-B axicell system.

- Reference case (MARS), using the axicell thermal barrier
- TMX upgrade mode
- TDF (Kelley) mode

A potential fourth mode (like TARA) could be achieved by reversing the two axicells so that thermal and potential barriers are created in the axicells. While this mode is not currently considered desirable due to unstable trapped particles, magnet analysis and design are such as to allow for the changes to the magnet configuration.

It is the objective of the MFTF program offices, both at Lawrence Livermore National Laboratory (LLNL) and General Dynamics, to make maximum use of components designed and/or fabricated during the preceding A cell configuration phase /1/. This includes structural plate, superconductor, insulation, current leads, and structural supports.

Incorporation of an Nb_3Sn insert coil into the outer axicell involves the only use of advanced technology in the magnet system. Development of this superconductor by LLNL is aided by the ongoing Nb_3Sn development at LLNL to support their High Field Test Facility (HFTF).

2. DESIGN REQUIREMENTS

LLNL magnet design requirements /2/ and the basic ground rule that proven analytical procedures, materials, and manufacturing processes be used as extensively as possible, have resulted in what we believe to be a conservative design. General Dynamics has enhanced the approach by adapting materials and manufacturing approaches used by LLNL and CBI in the Yin-Yang, which successfully demonstrated its design, fabrication, and performance in February 1982.

The entire magnet system is designed for a 10-year life. During this period, it can be exercised through 100 cooldown and warmup cycles, 1,000 electrical cycles, and three seismic events. The magnet system must be capable of being cooled down or warmed up between ambient and operating temperatures in 120 hours (five days) and be capable of being charged from zero to full operating current in four hours. Each magnet has separate current leads and is designed to be adjustable from zero to full design current and a maximum working voltage of 1,000 vdc. Each magnet is also designed to be unconditionally stable, with the stability margins shown in table I, to preclude quenching due to increases in transient currents induced by a fast dump of any adjacent coils.

The general geometric dimensions associated with the present magnetic configuration (fig. 2) are shown in fig. 3. Specific data will be displayed in the discussion relating to each coil type. The on-axis magnetic field is shown in fig. 4 for the operating modes and includes the contribution from each coil.

To ensure that the MFTF-B magnets will operate reliably over the system lifetime, LLNL has imposed additional requirements relating to reliability, maintenance, and availability. The magnet availability goal of 0.999 is specified for the basic structures [mean time between failure (MTBF) = 10^6 hours]. Mechanical and electrical joints will have an availability factor of 0.995 (10^5 hours MTBF). Within these constraints and guidelines from LLNL, General Dynamics has established the transition, axicell, and solenoid coil configurations.

Table I. Minimum coil stability margins.

Coil	ΔI/I (%)	ΔB/B (%)
S1-S6	10	10
A1	15	10
A20	15	10
A21	75	7.5
T1	10	10
T2	10	10

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Table II. Characteristics of axicell MFTF magnets (MARS mode)[4].

Coil	Conductor Type	Coil Weight (Tons)	Amp Turns (10^6 AT)	Operating Current (A)	Peak Field (Tesla)	Avg. Current Density (A/cm²)
M2	1	187.5	6.14	4,410	5.9	2,274
M1	1	187.5	5.32	3,822	5.2	1,971
T2	1	~50	3.64	6,066	4.9	3,170
T1	1	~20	2.70	5,625	5.7	2,961
A2I	2	NA	4.40	1,000	12.7	1,934
A20	1	~25	9.75	4,543	7.7	2,380
A1	1	~25	8.02	3,737	8.0	1,956
S6	3	~15	1.08	1,800	2.2	1,971
S5	3	~15	1.08	1,800	2.2	1,971
S4	3	~15	1.03	1,717	2.1	1,889
S3	3	~15	1.03	1,717	2.1	1,889
S2	3	~15	1.02	1,704	2.1	1,867
S1	3	~15	1.02	1,704	2.1	1,867

1. Yin Yang type NbTi conductor
2. Nb_3Sn conductor
3. Solenoid-type NbTi conductor
4. Kelley mode operation will result in higher solenoid currents & fields

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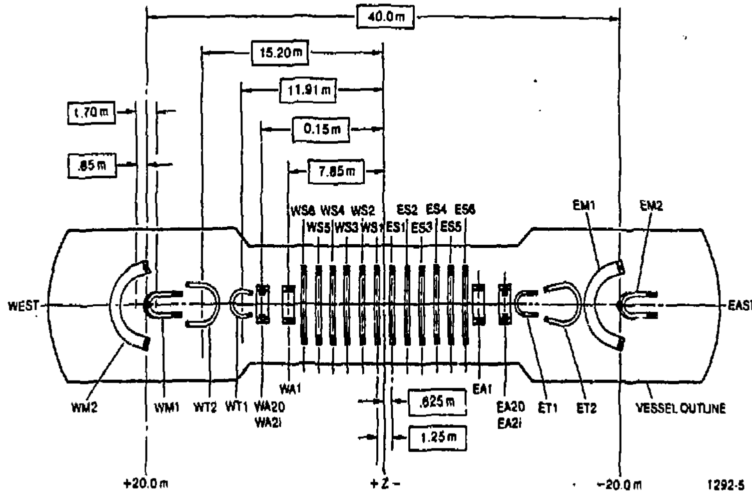

Figure 3. MFTF-B axicell magnet locations are determined by physics requirements.

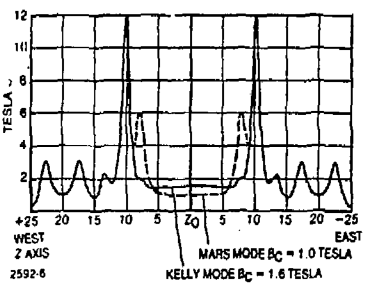

Figure 4. MFTF-B magnets provide the capability of different field distributions.

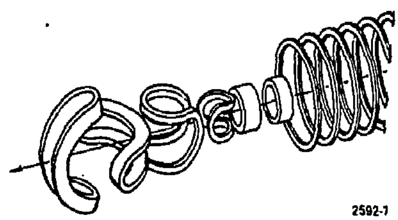

Figure 5. MFTF-B magnet designs must meet stringent space constraints.

3. TRANSITION COILS

The basic geometry and relative locations of the two transition coils, T1 and T2, are illustrated in fig. 5. These C-shaped coils are similar to those analyzed and designed by General Dynamics for the original MFTF-B configuration (fig. 1). These coils will be wound on 1.75-inch (4.45 cm) thick L-shaped coil forms and then closed out with the mating "L" sections. We anticipate that additional restraint structures will be required around the coils to react the coil magnetic spreading loads. Nitrogen-controlled 304LN stainless steel, with a minimum 4K yield strength of 100 ksi (690 MN/m^2) will be used as the structural material. The coil internal features are shown in fig. 6. Magnet supports will be designed to provide adjustment capability for coil alignment.

3.1 Conductor and Insulation

The Yin-Yang type pool boiling conductor, procured for the original A-cell and transition coils, will be used. The 1.247-cm-square conductor consists of a 0.65 by 0.65-cm NbTi monolithic core surrounded by a ventilated copper jacket. This conductor was originally developed by LLNL for the Yin-Yang magnets /3/ and has been extensively tested. This eliminates the need to demonstrate its cryostability performance, thus reducing program costs while still ensuring reliability. Fig. 7 shows the conductor and insulation. The T1 coil consists of 480 turns (15 turns in each of 32 layers) and is operated at 5,625 amperes to achieve the required magnet field. Coil T2 consists of 600 turns (25 turns in each of 24 layers) and is operated at 6,066 amperes.

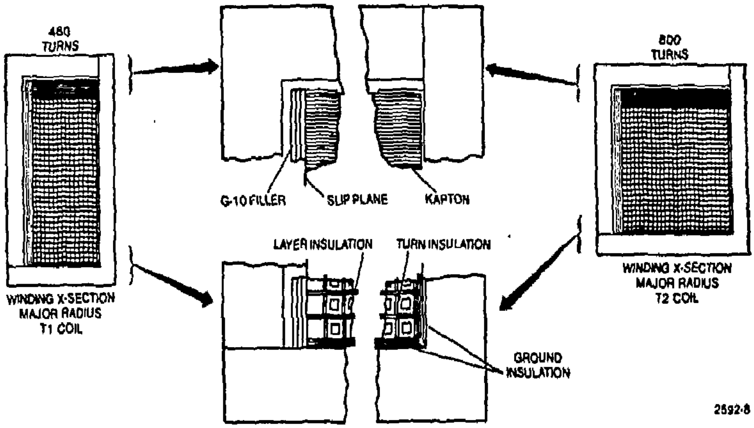

Figure 6. Transition coils have similar designs.

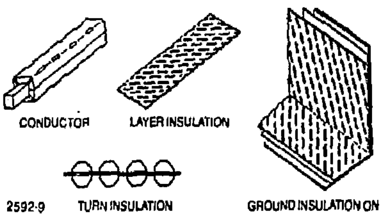

Figure 7. Transition and barrier coils use Yin-Yang type conductor and insulation.

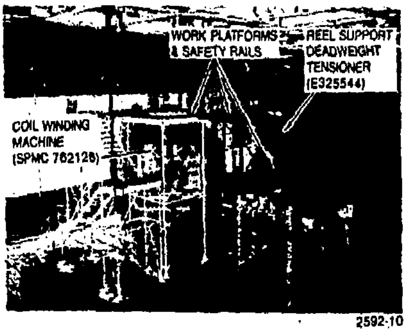

Figure 8. Winder intended for use on MFTF-B A-cell magnets will be used for the T2 coils.

Insulation concepts previously used by the Yin-Yang magnets were adapted to and procured for the original A-cell and transition coils and are now being adapted to coils T1 and T2. The turn-to-turn insulation consists of 0.114-cm-thick, octagonal, G-10CR fiberglass buttons spaced at 1.84-cm intervals on a Dacron string. The layer-to-layer insulation is 0.160-cm-thick G-10CR slotted sheets that provide the proper bearing area and helium ventilation for the conductor. Conductor pack-to-ground insulation is critical to magnet reliability. Techniques used on the Yin-Yang and other General Dynamics magnets will be used. The ground insulation on the coil form base and side consists of two sheets of 0.160-cm solid G-10CR, six layers of 0.0127 cm (0.005 inch) Kapton film, and one sheet of 0.160-cm slotted G-10CR. The slots provide 50% open area and are oriented to allow layer-to-layer helium flow. The outboard side insulation consists of a double layer of Mylar adjacent to the G-10CR glue blocks, which bear against the winding. Outboard of the Mylar, six layers of 0.0127-cm (0.005-inch) Kapton film complete the enclosure of the winding pack. The remaining space between the coil winding pack and the L-shaped coil cover is filled with G-10CR sheet and is epoxy-trowelled to provide a tight fit with the coil covers.

3.2 Coil Winding

Both transition coils, T1 and T2, will be layer-wound on L-shaped bobbins. T2 will be wound at General Dynamics on the two-axis winding machine similar to that being used by LLNL to wind the Yin-Yang coils (fig. 8). A tight conductor pack is ensured through the use of compaction tools and a winding tension of 600 pounds. Clamping fixtures are used extensively to maintain tightness during the winding operation. The outer ends of the odd-numbered layers are spliced to the outer ends of the even-numbered layers and, as such, the winding direction is reversed for each layer.

4. AXICELL COILS

The basic geometry and relative positions of axicells A1 and A2 are shown in fig. 5. Coil A2 consists of an NbTi outer coil (A20) and an Nb_3Sn insert coil (A2I). Each coil has its own helium jacket, thereby allowing design, fabrication, and test of the coils to be conducted in parallel. The inner coil A2I can also be removed and replaced as necessary. Coils A1 and A20 have the same dimensions. Structural material will be 5.0-cm (2-inch) nitrogen controlled 304LN, with a 4K yield strength of 100 ksi. Adjustable supports will link the two coils to one another and to the vacuum vessel. Inner features of coils A1 and A20 are shown in fig. 9.

4.1 Conductor and Insulation

The same Yin-Yang type conductor previously described for the transition coils will be used in coils A1 and A20. Both coils consist of 2,146 turns (74 turns in each of 29 layers). A1 is operated at a maximum of 3,737 amperes. Coil A20 is operated at 4,543 amperes. The Nb_3Sn conductor for coil A2I (not yet selected for development by LLNL) will be incorporated into the coil design and fabrication by General Dynamics. The stability margins are such that a quench in the Nb_3Sn coil will not initiate a quench in the outer N_bTi coil /4/.

4.2 Coil Winding

Coils A1 and A20 will be wound on the weld positioners at General Dynamics used to wind the solenoid coils. The solenoids will be completed in time to allow this equipment to be used. It is anticipated that these coils will be layer-wound onto the U-shaped bobbin, using tools and techniques currently being employed on the solenoid coils and on other successful General Dynamics magnet programs (PMS and EBT).

The winding approach to be used on coils A2I has not been firmly established at this time, but maximum application of LLNL experience with the High Field Test Facility (HFTF) Nb_3Sn coils will be made. All equipment currently being used by LLNL to wind the HFTF coils (fig. 10) will be made available to General Dynamics for winding the A2I coils.

5. SOLENOID COILS

The basic geometry and relative location of the solenoid coils are illustrated in fig. 5. The 5 m mean diameter coils are spaced 1.25 m apart (center-to-center). Two solenoid coils, their intercoil beams, support struts, and vapor-cooled leads will be installed into a segment of the external vacuum vessel, thus forming a module. This module will then be checked (vacuum, cryogenic, electrically) before being installed in the total system. Nitrogen-controlled 304 LN is also the structural material for the solenoids. The solenoid structure consists of a 2.54-cm-thick U-channel and an outer ring. The coil features are shown in fig. 11.

5.1 Conductor and Insulation

The solenoid conductor is a variation of such previous successful conductors as the CERN bubble chamber and ANL U-25 MHD magnet. The 1.23 by 0.49-cm (0.492 by 0.197-inch), ¼-hard copper stabilizer has a slot on one side into which a 0.302 by 0.183-cm (0.12 by 0.72-inch) NbTi monolith is soldered. Fig. 11 shows the conductor and insulation. Each solenoid consists of 600 turns (25 turns in each of 24 layers) and is operated at a maximum current of 1,800 amperes for the normal mode (MARS).

The layer insulation is 0.15-cm G-10CR. It is punched with a chevron slot pattern (60% open) to encourage helium flow away from the side walls toward the center of the coil pack. The turn insulation is also 0.15-cm-thick G-10CR and provides 70% wetted area on the sides of the conductor. Against each sidewall, 0.63-cm-thick (0.25-inch) machined post type insulation is used to enhance ventilation and to reduce the effect of the walls on conductor heat transfer capability. The thick insulation eliminates the possibility that an end turn in a layer might slip past the layer insulation.

Thick insulation is also provided against the inner bobbin. This insulation is 0.95-cm (0.37-inch) thick with 0.63-cm (0.25-inch) slots machined into one side to provided additional helium ventilation in the high-field region.

5.2 Coil Winding

Coil winding consists of coil preparation (leak check, true-up, and ground insulation), coil winding (conductor, insulation, and splice), coil in-process testing (electrical, splice, layer/turn dimensions), and coil closeout.

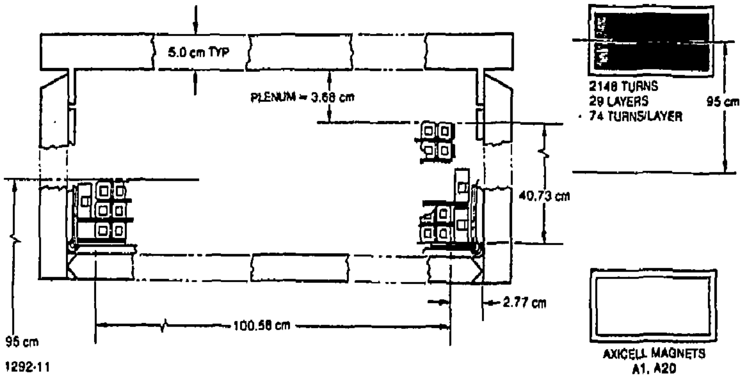

Figure 9. Axicell magnet construction uses Yin-Yang construction.

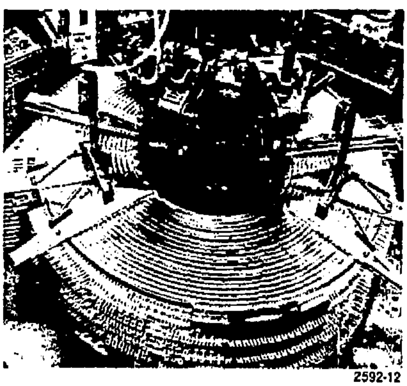

Figure 10. MFTF coil winding experience will be used on the MFTF-B Nb_3Sn coil.

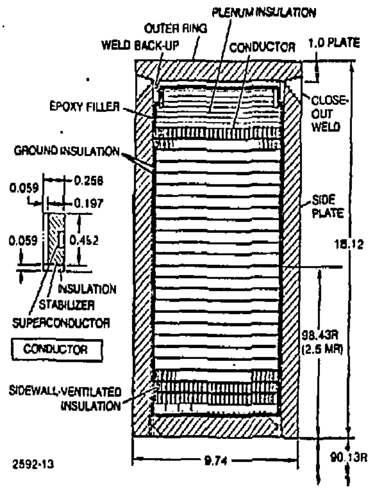

Figure 11. Solenoid coils use proven design concepts.

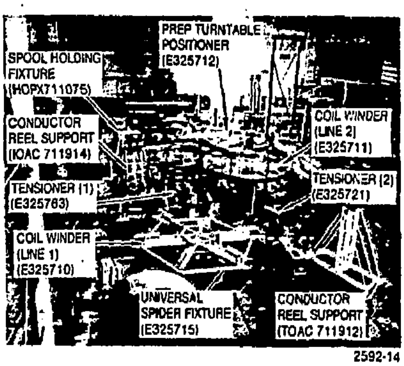

Figure 12. Two winding lines have been established for the solenoid coils.

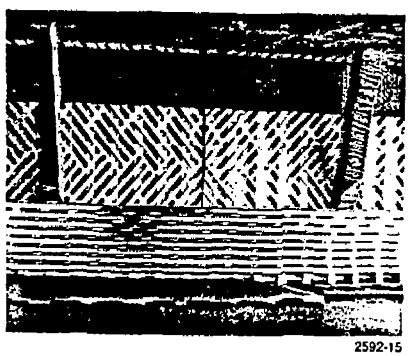

Figure 13. Solenoid conductor is layer-wound onto a U-coil bobbin.