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DESIGN FEATURES OF THE A-CELL AND TRANSITION COILS OF MFTF-B

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SUMMARY

The MFTF-B A-cell and transition coil magnets combine with the Yin-Yang magnet pair to form the end mirrors in the MFTF-B tandem mirror magnet array. General Dynamics is using technology proven in the design and construction of the Yin-Yang magnets at Lawrence Livermore National Laboratory (LLNL) in the design of these critical MFTF-B magnets.

The MFTF-B transition coil and A-cell magnet designs use variations of the copper-stabilized NbTi conductor developed by LLNL for the MFTF Yin-Yang magnets. This conductor will be wound on one inch thick (12.7 mm) stainless steel coil forms using a two-axis winding machine similar to the existing LLNL Yin-Yang winding machine. After winding, covers will be placed over the coil and welded to the coil form to form a helium-tight jacket around the conductor. These jacketed coils are then enclosed in thick structural cases that react the large Lorentz forces on the magnets.

The space between the coil jacket and case will be filled by a stainless steel bladder that will be injected with urethane. The injection bladder will provide cooling passages during cooldown as well as transmitting the Lorentz forces between the jacket and the case. The large self-equilibrating lobe-spreading forces on the magnets (29.10^6 lb, 127.0 MN) for the A-cell are reacted primarily through the thick 304 LN case into the external superstructure. The net Lorentz forces and the inertial forces on the magnet are reacted through support systems into the LLNL vacuum vessel structure.

INTRODUCTION

As magnetic fusion research progresses toward the ultimate goal of commercial power generation, increasingly larger machines are needed to address the various physics issues of fusion. Lawrence Livermore National Laboratory (LLNL) is currently developing the largest tandem mirror facility to date: the upgraded Mirror Fusion Test Facility (MFTF-B). Eighteen of the 22 superconducting magnets for this ambitious program will be supplied to LLNL by General Dynamics Convair Division. This paper presents the design status of two types of MFTF-B end region C-shaped coils: the A-cell and transition coils. These two magnets differ in geometry, but both use the basic design approaches successfully employed in the manufacture of the original MFTF-A Yin-Yang magnets.

BACKGROUND

For MFTF-B, the tandem mirror magnetic field is developed by the 22 superconducting magnets illustrated in Figure 1. At this time, one Yin-Yang pair, designed by GDC and manufactured by the LLNL/Chicago Bridge and Iron (CBI) team, has been installed in a stub vacuum vessel for verification testing. Components for the other Yin-Yang pair have been ordered. The LLNL/General Dynamics Convair Division/CBI team is currently in the final phase of the engineering design of the remaining 18 magnets.

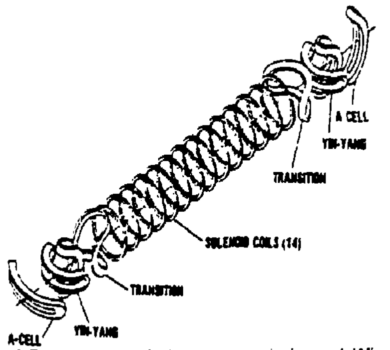

Figure 1. Twenty-two superconducting magnets comprise the upgraded Mirror Fusion Test Facility.

An elliptical plasma fan exits the Yin-Yang which then passes through the transition coil for shaping into the basic circular flux tube of the central cell region. The central region field is maintained by 14 solenoids at 2m (6.6 ft.) spacing. At the extreme ends of the facility are the A-cell magnets, which provide the additional barrier fields for the end regions. The A-cell and transition coils perform different functions and are of different geometry, but both use the same design principles.

1. DESIGN REQUIREMENT

Of utmost importance in establishing requirements and design guidelines for the MFTF-B magnets the ground rule that the magnets shall utilize proven and reliable concepts. MFTF-B is a physics experiment, not a magnet development program. With this thought in mind, LLNL evolved basic magnet performance parameters to ensure a conservative design approach. General Dynamics Convair Division has enhanced this position by adapting proven materials and manufacturing approaches used by LLNL/CBI for the Yin-Yang. This includes maintaining the guard vacuum concept, using the same type of pool boiling conductor, and using the same structural materials/welding processes.

Major design requirements for the A-cell and transition coil are presented in Table 1 as specified by LLNL (Ref. 1). It is evident in Table 1 that the peak field for the two magnets are considerably different. As would be expected then, the A-cell poses the greater engineering challenges.

MFTF-B is currently assigned a 10-year operating life. Within this time span, we are required to design for a multitude of occurrences such as 1,000 cooldown/warmup cycles, 1,000 charging cycles (with fast dumps of coil groups), quench events, seismic events, and electromagnetic fault conditions.

Unconditional cryostability of the A-cell and transition coil conductors is required, and must include a 10% margin of safety on normal operating current and normal operation magnetic field to preclude quenching when increases in transient current are induced by fast dumps of adjacent magnets.

Table 1 displays basic structural design safety factors and include rules such as yield allowable = 2/3 fty, ultimate allowable = 1/2 ftu, and lifetimes = 4. Geometry limitations are imposed by LLNL. Basically, the expected coil shape and "stayout" zones are defined. Requirements for neutral beams, beam dumps, diagnostics, cryogenic systems, and radiation shields limit the space available for coil structure.

Due to the necessity of the MFTF-B magnets to operate in a reliable manner over the lifetime of the system, LLNL has imposed specific requirements for reliability, availability, and maintenance. For

Table 1. A-cell and transition magnet requirements.

	A-cell	Transition
Configuration		
Major radius (M)	6.25	2.50
Minor radius (M)	0.49	0.75
Performance		
Central field (T)	6.5	N.A.
Peak field (T)	8.07	4.49
Amp turns (MA)	8.67	3.67
Design voltage (V) (terminal to ground)	1,000	1,000
Stability margin ($I_{cr}/I_0 - 1$)	0.10	0.10
Cooldown/warmup time (hr)	<120	<120
Charging time (hr)	<4	<4
Thermal, electrical cycles	1,000	1,000
Constraints		
Total helium heat load (W)	310	190 (incl. 37)
Design stress	$\frac{2}{3} F_{ty}$ $\frac{1}{2} F_{tu}$	$\frac{2}{3} F_{ty}$ $\frac{1}{2} F_{tu}$
Max quench temperature (K)	200	200
Max dump voltage (V)	1,000	1,000
No quench for dump of a single group	Yes	Yes

the magnets, an availability goal of 0.999 is specified for the basic structures mean time between failures (MTBF) ≈ 10^6 hours. Mechanical and electrical joints will have an availability factor of 0.995 (10^5 hours MTBF). To support these requirements, a comprehensive reliability program plan has been devised by General Dynamics for the MFTF-B magnets.

Within the constraints and design ground rules specified by LLNL, we have established the A-cell and transition coil configurations.

2. TRANSITION COIL DESIGN CONFIGURATION

The geometry for the transition coil is more straightforward than the A-cell and will be summarized first. Figure 2 depicts the shape and major components for the transition magnet. Electromagnetic forces tend to open the magnet, but these are partially reacted by a superstructure which contacts the major radius at mid span.

All steel structural components (for transition coil and A-cell) are manufactured from nitrogen-controlled 304 LN stainless steel with a minimum 4K yield strength of 690 MN/m^2 (100 ksi). The major internal features are shown in Figure 3. The magnet is wound on, and then closed out, with relatively thin L-shaped forms. Next, an inflatable SS bladder is installed and the main structural case is slipped over the completed component with an intentional 1.90-cm (0.75 in.) gap maintained all around the interface. The bladder is then filled with urethane. As mentioned previously, this approach was successfully used on the original Yin-Yang pair, and extrapolation to the transition coil should prove to be a relatively simple matter.

The transition coil is supported by mounting the coil directly onto the Yin-Yang. In addition, the end solenoid coil is linked axially to the transition coil. Alignment capability is built into support points via adjustable brackets and turnbuckle struts.

2.1 Conductor and Insulation

A key feature of the transition coil design is use of the Yin-Yang type pool boiling conductor, with the amount of NbTi reduced to be compatible with the 4.5 Tesla peak field. Figure 4 depicts a typical conductor bundle. This well-known Yin-Yang type conductor consists of a NbTi monolithic core surrounded by a ventilated annealed copper jacket. Use of this previously developed conductor eliminates the need for verification testing for cryostability performance and eliminates the need and time to develop a new conductor production line. These items both increase reliability and decrease cost.

The conductor is operated at 6431 amp and requires 570 (15 turns/38 layers) turns to meet field requirements.

Another advantage to using the Yin-Yang conductor is the availability of a proven insulation system. Turn-to-turn spacers consist of octagonal G-10CR fiberglass buttons (0.114-cm thick) attached to one another by a dacron carrier string. Layer insulation consists of 0.160-cm thick G-10CR slotted sheets which provide for helium ventilation and for the proper bearing area on the conductor.

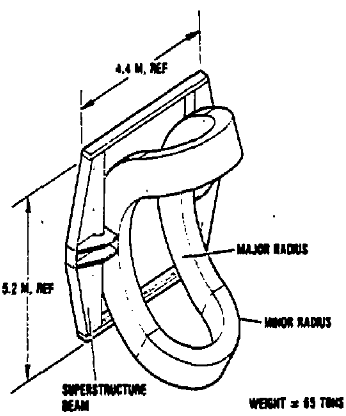

Figure 2. Transition coil and superstructure beam.

Conductor pack to coil form ground insulation is vital to magnet reliability, and we have thus adapted a technique employed on Yin-Yang, as well as on other General Dynamics superconducting magnets. The ground insulation on the coil base and inboard side consists of two sheets of 0.063 solid G-10CR, five layers of 0.005 Kapton film, and one sheet of 0.063 slotted G-10CR. Slots provide 50% open area and are oriented to allow for layer-to-layer flow. The outboard side insulation consists of a double layer of Mylar adjacent to the G-10CR glu-blocks (which bear against the winding). Outboard of the Mylar, five layers of

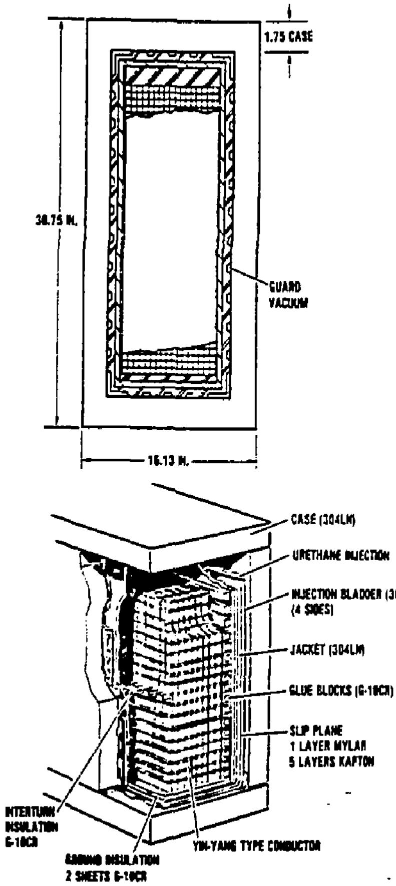

Figure 3. Transition coil uses proven design concepts.

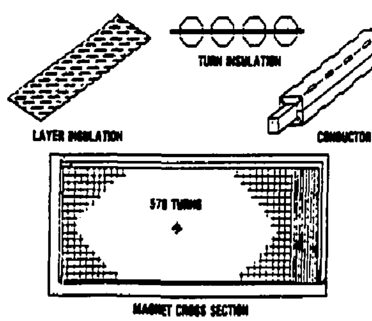

Figure 4. Transition coil conductor and insulation configurations.

0.005 Kapton enclose the coil pack. The remaining space between the coil pack and coil cover is filled with G-10CR sheet and is epoxy-trowelled to provide a fit to the covers.

2.2 Coil Winding

The transition coil is wound on a stainless steel "L"-shaped bobbin by means of a two-axis winding machine similar to the winding machine used for the Yin-Yang coil (Figure 5). A tight conductor pack is ensured by a combination of a winding tension of 600 psi and use of compaction tools. Clamping fixtures are extensively used to maintain tightness during the entire winding operation.

Winding direction for each alternate layer is opposite to the previously wound layer by the nature of the C-shaped winding form. Outer ends of odd-numbered layers are spliced to the outer ends of even-numbered layers by means of a joint developed for Yin-Yang.

Prior to closeout welding of the mating "L" section jacket, epoxy shimming is used to eliminate gaps between the pack and closeout member.

2.3 Structural Case

As was shown in Figure 3, the completed transition coil pack/coil form assembly is fitted within the primary structural case. Electromagnetic loads are reacted by the 304 LN stainless steel magnet case. Assembly of the case is accomplished by placing two mating L-shaped sections of the 4.45-cm (1.75 in.) thick case around the winding pack/coil form assembly. This minimizes closeout welding and allows for good weld positioning. An intentional 1.9-cm (0.75 in.) gap between coil form and magnet case is filled by injecting the SS bladders with urethane.

2.4 Superstructure Beam

An electromagnetic spreading load of 19.6 MN (4.4 10^6 lbs) is partially reacted by the superstructure shown previously in Figure 2. This beam is essentially an I-section tapered along the length for clearance purposes, and made of 4.45-cm (1.75 in.) 304 LN plates. Tapered gussets welded at mid span transmit load from the magnet case into the beam web.

2.5 Stack Design

A current lead duct is installed between the coil case and a penetration in the vacuum vessel. This duct serves to enclose the conductor leads in helium coolant, support the conductor leads, and provide a return passage for helium coolant from the windings.

Bellows on the current lead duct accommodate triaxial movement from the combined effects of thermal excursion (at cooldown), seismic deflections, and electromagnetic-induced deflections. Axial movement presents the greatest challenge: a 3.8-cm (1.50 in.) translation due to thermal excursion must be accommodated.

3. A-CELL COIL DESIGN CONFIGURATION

The configuration of the A-cell is somewhat analogous to the transition coil, but significant differences do exist. In Figure 6, it is clear that the minor radius portion of the A-cell is much smaller than other C-shaped coils in MFTF-B. Note also the presence of a minor radius superstructure.

A typical cross-section of the A-cell is configured the same as the transition coil, as was shown in Figure 3. The Yin-Yang type conductor is also used for A-cell, but additional turns are required. Wall thicknesses for the magnet case are also different. One of the most noteworthy differences is that the conductor pack in the minor radius

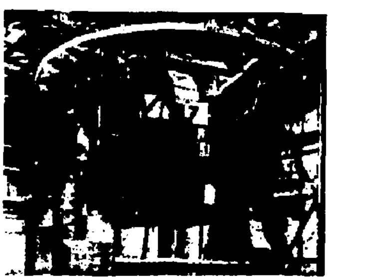

Figure 5. The LLNL Yin-Yang type winder is our choice for transition coil winding.

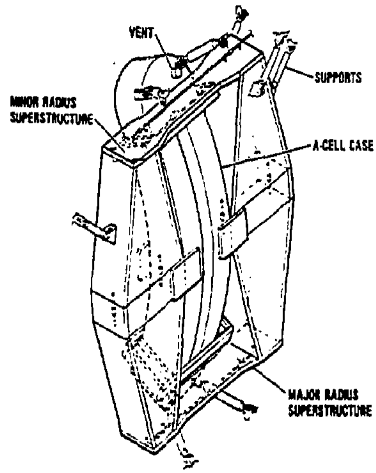

Figure 6. A-cell structural assembly.

of the A-cell is comprised of spread segments (Figure 7) to accommodate field shaping.

3.1 Conductor and Insulation

The Yin-Yang type conductor, with increased NbTi, is used for the inner 16 turns of the A-cell (grade I), while the outerturns use the Yin-Yang type conductor (grade II) with reduced NbTi. The grade I and II conductors are identical in outward appearance (see Figure 5), and use the same insulation system described previously. For the A-cell, the turn-to-turn buttons are more closely spaced in the peak load areas. The total turns are 1,600 (32 turns/50 layers) operating at 5,416 amps.

3.2 Coil Winding

The winding procedures described for the transition coil are directly applicable to the A-cell except the conductor is spread in the minor radius area.

3.3 Structural Case

A typical cross-section for the A-cell major radius is shown in Figure 8. The magnet case is considerably thicker than the transition coil; note the 14.0-cm (5.50 in.) thick outside plate.

3.4 Superstructure Beam

For the A-cell, the spreading load is 127MN (28.6 10^6 lb: six and one half times the transition coil load). To react a significant portion of this load has required a double-web beam with 12.7-cm (5.0 in.) thick flanges.

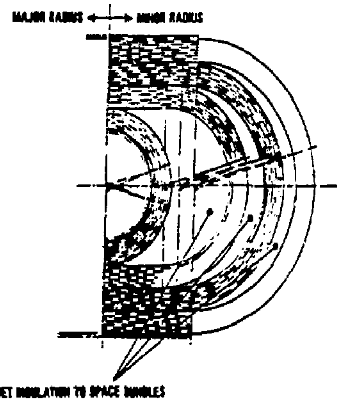

Figure 7. Conductors are separated in the minor radius.

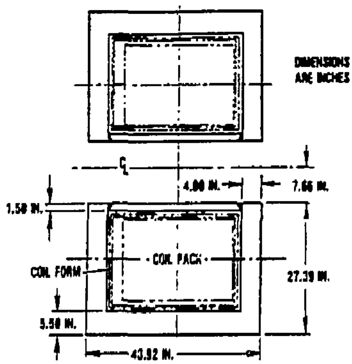

Figure 8. A thick magnet case is needed to react A-cell electromagnetic loads.

4. ENGINEERING ANALYSIS

Tradeoffs which best satisfied the competing analytical disciplines (structural, electrical, thermodynamic) were performed for the A-cell and transition coil. Satisfying the structural requirements for the A-cell presented the greatest challenge.

4.1 Structural Analysis

For MFTF-B, we are applying the analytical tools of finite-element analysis, fracture mechanics procedures, and hand calculations to satisfy design and reliability requirements. Only a brief overview is provided here.

Large, three-dimensional finite-element models form the basis for most stress analysis. The A-cell MSC/NASTRAN (Ref. 2) model is depicted in Figure 9 and is used to identify overall stresses and deflections. Hand analysis is used to expand and refine the model data.

An innovative approach has been devised to generate electromagnetic loads for input to the finite-element models. A concern with MFTF-B loading conditions was that a multitude of conditions can exist depending upon the status of various magnet groups. To best accommodate this, detailed EFFI (Ref. 3) loads were generated by LLNL for General Dynamics use. The coil self loads and the background loads from each coil were compiled into a massive data base. The individual EFFI model was constructed to be compatible with the finite-element structural models of the various coils. Thus a loads postprocesing program was developed to first plot total running electromagnetic forces from EFFI for easy visual identification of worst-load conditions for various combinations of active/inactive magnets. The program will next generate an input file consisting of nodal loads for direct use in the appropriate finite-element model for the chosen load cases.

The major problem encountered in the A-cell involved high stresses in the minor radius region of the coil caused by the spreading load. Structural problems in this region were solved through use of coil clamps (Figure 6) and a large stiffener welded to the magnet case.

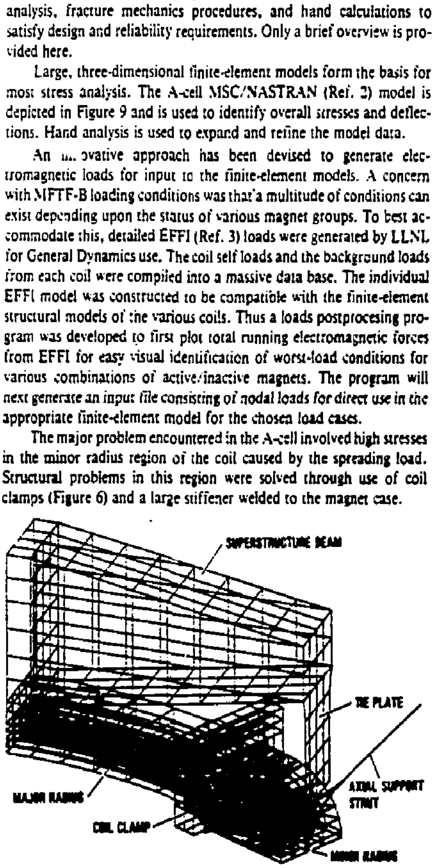

Figure 9. A-cell structural analysis requires a complex finite-element model to evaluate electromagnetic force effects.

4.2 Thermodynamic Analysis

Primary thermal analysis tasks consist of cooldown/warmup evaluation, cryostability analysis, vapor-cooled leads analysis, quench pressure studies, and heat-leak determination. A brief overview of A-cell and transition coil results is presented here.

Cooldown/warmup is achieved in the specified 120-hr allowable time period. Preliminary assessment of thermal gradients has shown acceptable stress levels (below 35 ksi). Careful orificing and valving have been shown to properly condition coolant flow to the magnets.

Unconditional conductor cryostability has been demonstrated by analysis and previous bundle tests for the conditions of:

- Current and field = 110% of normal operation
- Neutron radiation degradation of resistivity
- Helium cooling based on a horizontal bundle orientation ($\dot{q}$ = 0.19 W/cm^2

Vapor-cooled leads provide an analytical challenge, and required a detailed thermal model. Iterations were performed to assess sensitivity to coolant flow rates, time of uncooled operation, geometry parameters, etc. The design must tolerate ten minutes of uncooled operation without an excessive temperature rise.

Total helium heat loads during operation were calculated as 510 watts and are lower than the specified design goals. The A-cell poses the greatest losses, with the superstructure and LN_2 shields the major contributor. Note also that the A-cell is mounted from warm structure (vacuum vessel) and hence has heat loads induced via support struts. Special features such as LN_2 intercepts and aluminum foil boots are incorporated to minimize strut heat loads.

To protect the magnets from excessive internal pressure during quench, a vent valve opens at two atmospheres to begin relieving pressure. Continued pressure buildup beyond two atmospheres would eventually blow a burst disk (designed for five atmospheres). Due to sharing of the feed line into the recuperator by other magnets, an actual design pressure of seven atmospheres is needed for the A-cell and transition coil. A fault condition associated with failure of the burst disk to blow suggests the magnets should be structurally adequate to accommodate 10 atmospheres.

4.3 Electrical Analysis

Primary tasks associated with MFTF-B electrical evaluation include magnet electrical grouping analysis, induced currents during fast dumps, preparation of conductor specification, and quench protection.

Of particular interest for MFTF-B are induced current effects for fast dumps of coils or coil groups. General Dynamics and LLNL have agreed upon the coils to be included in each electrical group based upon a criteria of minimization of induced currents. Evaluation of the transient response of various magnets during fast dumps has been accomplished with the circuit analysis code SYSCAP (Ref. 4). For the A-cell, the induced current is only 2.7% above the normal operation current of 5,416 amp. For the transition coil it is 7.1%.

For quench protection, we use the standard adiabatic assumptions which have been programmed into a code for ease of usage. The A-cell and transition coil are designed to dump at an initial voltage of 1,000 VDC. Peak local conductor temperatures are 190K for the A-cell and 90K for the transition coil. The analysis included mutual induction effects.

5. REFERENCES

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