UCRL--15409

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DESIGN FEATURES OF THE SOLENOID MAGNETS FOR THE CENTRAL CELL OF THE MFTF-B

General Dynamics

October 23, 1981

Lawrence
Livermore
Laboratory

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by

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SUMMARY

The 14 superconducting solenoid magnets which form the central cell of the MFTF-B are being designed and fabricated by General Dynamics for the Lawrence Livermore National Laboratory. Each solenoid coil has a mean diameter of five meters and contains 600 turns of a proven conductor type.

Structural loading resulting from credible fault events, cooldown and warmup requirements, and manufacturing processes consistent with other MFTF-B magnets have been considered in the selection of 304 LN as the structural material for the magnet. The solenoid magnets are connected by 24 intercoil beams and 20 solid struts which resist the longitudinal seismic and electromagnetic attractive forces and by 24 hanger/side supports which react magnet dead weight and seismic loads. A modular arrangement of two solenoid coils within a vacuum vessel segment allow for sequential checkout and installation.

The underlying philosophy behind the design, analysis, and fabrication of the central cell solenoid magnets has been the selection and application of techniques, features, and manufacturing processes which have been proven on the MFTF Yin-Yang magnets.

1. MIRROR FUSION TEST FACILITY

The upgraded Mirror Fusion Test Facility (MFTF-B) at Lawrence Livermore National Laboratory (LLNL) will be a Tandem Mirror Plasma confinement system that will be used to address physics issues that cannot be addressed in smaller scale machines such as TMX. The MFTF-B facility will use 22 superconducting coils shown in Figure 1 to provide the Tandem Mirror confinement field. Two Yin-Yang magnet pairs (one of which was recently completed by LLNL) 40M apart, provide the end plugs for the plasma confinement region. Transition coils transform the elliptical flux tube (plasma fan) exiting each Yin-Yang pair into a circular flux tube entering the central cell region where fourteen solenoids provide the required uniform field. A C-coil at each end of the system provides the required field distribution through the additional A-cell barrier region. The MFTF-B coils are identified in Figure 1. The magnet system is divided into east and west segments and coils are numbered consecutively starting at the center of the system. The physical parameters for the solenoid coils (S1-S7), transition coils (T1), Yin-Yang Magnets (M1, M2), and A-cell magnets (M3) are shown in Table 1.

2. DESIGN REQUIREMENTS

The major design requirements for the MFTF-B solenoid magnets are summarized in Table 2. Essentially, the magnets are required to produce a maximum one Tesla central field (uniform within ± 1% at the plasma surface) within the restrictions imposed by LLNL space allocations, power supply and cryogenic system limitations, and magnet stability requirements. In addition, the potential MFTF-B operating modes may require that the currents between adjacent solenoids be varied up to 15% through the use of trimming power supplies to provide a gradual ramping of the field in the central cell. Therefore, the coils and their structures are designed for operation in any steady-state mode within the limitations of the current levels required for the 1 Tesla condition and the 15% adjustment capability. The system is required to be designed for 1,000 magnetic cycles spread over a ten-year operating life.

The coils are required to have a minimum 25% margin of safety on both critical current and cryostable current at their normal operating current levels. The stability margins accommodate current peaking during fast dumps of adjacent magnet groups (T1) (M1, M2) and (M3). The coil insulation systems are required to be designed for 1,000 VDC between the coil and ground to provide additional safety margin over the maximum predicted value of 400 volts.

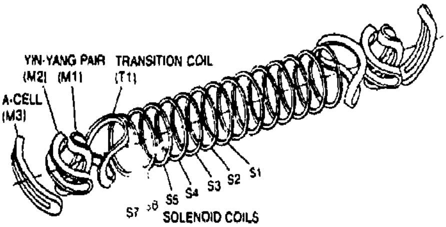

Figure 1. General Dynamics is responsible for the design and fabrication of 18 of the 22 new MFTF-B coils

Table 1. . FTF-B magnet parameters.

Coil	Quantity	Major Radius (M)	Minor Radius (M)	Sweep Angle (Deg)	Amp Turns (MA)	Peak Field (Tesla)	Coil Cross-section (M × M)
A-cell	2	8.25	0.49	27.5	8.67	8.07	0.709 × 0.44
Transition coil	2	2.50	1.50	65.0	3.67	4.49	0.538 × 0.204
Solenoid coil	14	5.0	NA	NA	1.38-1.64	2.95	0.183 × 0.336
Yin-Yang	4	2.5	0.7	75	7.25	7.02	0.824 × 0.328

Table 2. Solenoid magnet requirements.

- **Configuration**
  - 5M diameter, 2m spacing
- **Performance**
  - On-axis self field = 0.403T
  - Max current requirement = 1.6 X 10^8 amp-turns
  - Max variation between coils of 15%
  - 1,000V DC between terminals & from coil to ground (for insulation design only)
  - 25% minimum stability margin at operating current
  - Cooldown/warmup < 120 hr
  - Charging rate < 4 hr
  - 1,000 thermal & electrical cycles
- **Constraints**
  - Stay-in zone (including shields) = 0.40M axial X 0.70M radial
  - Maximum module weight = 60,000 lb
  - Maximum total cryogenic heat load for S1-S8 = 300 watts
  - Design stress = 2/3 yield
  - 200K deg adiabatic temperature rise
  - 1,000V across dump resistor
  - No quench for fast dump of a single group

The requirements for neutral beams, beam dumps, diagnostics, cryogenic systems, and radiation shields limit the space allowed for the solenoid, coils, and intercoil structures. The maximum allowable width of the coils, which are spaced at two-meter intervals, is 0.25M (9.84 in.). The space available for intercoil structure is approximately a (0.4 × 0.3M) box at 90-deg intervals around the coil. In addition, the maximum module weight is limited to 60,000 lb.

3. SOLENOID DESIGN CONFIGURATION

Three different solenoid coils are contained in MFTF-B. All three configurations are layer-wound coils with 25 turns per layer. However, variations in total required current result in different numbers of layers. Solenoids S1-S5, east and west, have 24 layers (600 turns); S6 has 25 layers (625 turns); and S7 currently has 21 layers (525 turns). Figure 2 shows a typical S1-S5 coil cross-section. This figure is consistent with the S6 and S7 coil designs with the exception of the number of turns and case height.

3.1 Conductor and Insulation

Key technical data for the conductor which is used in all solenoids is shown in Table 3. The conductor consists of a small (3.02 × 1.83 mm)

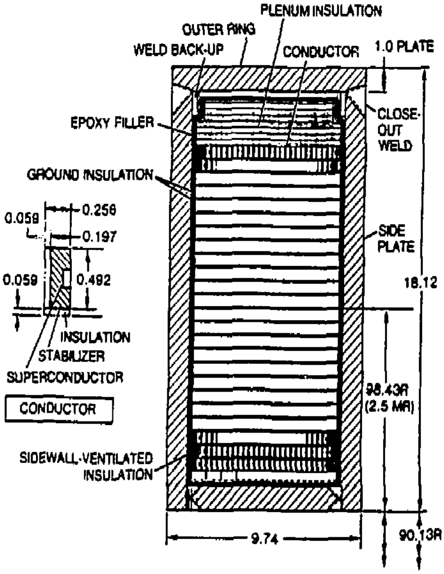

Figure 2. Solenoid coils use proven design concepts.

Table 3. Solenoid conductor data.

Operating current	Amps	2,666
S/C current density	Amps/cm sq	137,000
Pack current density	Amps/cm sq	3,054
Critical current	Amps	3,400 at 4.5K
Length	km	9.42/magnet
Superconducting material	—	NB TI
CU: non-CU ratio	—	28.8
Cross-sectional area	cm sq	0.625
Cond packing factor	—	0.684
HE vol to cond vol	—	0.25
Stabilizer heat flux (design)	W/cm sq	0.22
Stabilizer material	—	OFHC cu
RRR stabilizer	—	110
Solder material	—	50%PB/50%SN

copper/NbTi monolith soldered into a copper stabilizer. The stabilizer has an aspect ration of 2.5:1 and is fabricated from 1/4 hard OFHC copper. The conductor configuration was selected because it has good structural integrity, is easy to splice, and because its similarity with previously successful conductors, combined with conservative design, allowed us to avoid complex heat transfer testing. The conductor is layer wound with the long sides parallel to the radial direction to improve heat-transfer capability.

The layer insulation is 1.5 mm G-10 CR. 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 1.5-mm thick G-10 CR and provides 70% wetted area on the sides of the conductor. Against each sidewall, a 6.3 mm thick (1/4 in.) turn-to-turn type insulation is used to enhance ventilation and to reduce the effect of the walls on the conductor heat transfer capability. The thick insulation also reduces 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 9.5-mm (3/8 in.) thick with 6.3-mm (1/4 in.) slots machined into one side to provide additional helium ventilation in the high-field region.

The space between the outer layer of conductor and the outer ring of the case is filled with slotted G-10 CR. The slots provide ventilation during operation and allow helium to flow near the outer ring during cooldown. This insulation provides support for the coil pack and limits coil displacements during operation.

Solid G-10 CR and Kapton tape are used to provide electrical insulation between the coil and the case. Two layers of 1.5 mm (0.060 in.) G-10 CR combined with 6 layers of 0.12 mm (0.005 in.) Kapton tape provide a minimum double-ground insulation barrier at all points.

3.2 Coil Winding

The coils are layer wound with 25 turns/layer. At the end of every layer, approximately 6.3 mm (1/4 in.) of shim material is installed between the last conductor turn and the sidewall ventilated insulation. The last turn is then ramped over to the sidewall and up to the start of the next layer. Because each conductor length is two layers (785M or 2,570 ft.) long, splices occur at the end of every other layer and always at the same side of the conductor pack. A typical conductor splice is shown in Figure 3. The stabilizer is cold welded together and the superconducting inserts are overlapped. A splice bar is soldered over the entire length of the splice to increase the splice strength and provide enhanced cryostability.

The entering lead which connects to the first layer is routed into the coil through a machined pocket in the case sidewall (Figure 4). A larger copper stabilizer (7.6 cm × 0.64 cm) is used in the transition between the external leads and the first-layer conductor. The stabilizer of the basic conductor is soldered into the large stabilizer and then terminated. The superconductor is continuous and is routed through the larger stabilizer to the external splice. The larger stabilizer reacts conductor tension loads and accommodates the radial movement of the external leads.

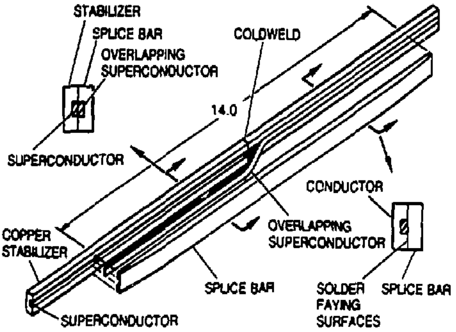

Figure 3. Solenoid splice provides structural and electrical continuity.

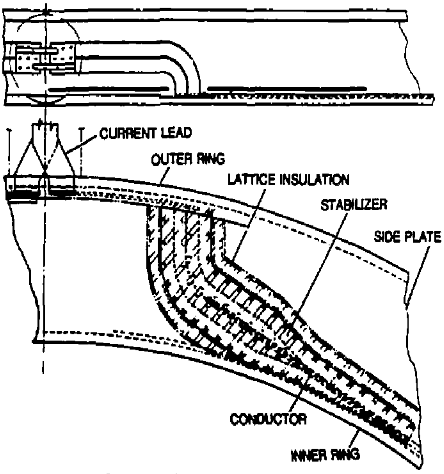

Figure 4. Solenoid coil entering lead has a large stabilizer.

Coil Structure — The solenoid cases are all-welded 304 LN stainless steel structures. Each case is assembled in three subassemblies: The winding bobbin comprised of the inner ring and side plates and two 180-deg outer ring segments. The S1-S6 case material is one-inch thick and the S7 case is 1.5 inches thick.

The "U" coil bobbin was chosen to simplify case assembly and to provide good lateral support during winding. Closeout welds are minimized and are located where there is reduced possibility of damage to the coils.

Each coil, except for the S7 solenoids, is welded into a two coil module (Figure 5) to facilitate assembly and installation of the MFTF-B systems. The current plan is to completely install each solenoid module and its associated shields and cryogenic lines into a short vessel module. The completed vessel modules will then be assembled to form the MFTF-B central cell.

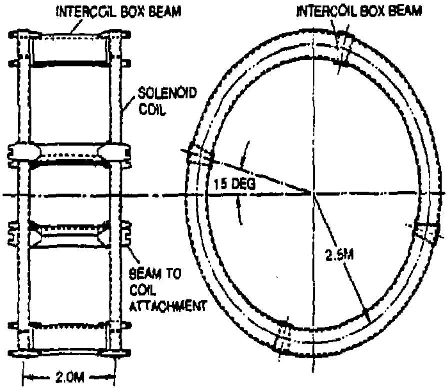

Figure 5. Solenoid coils are welded into two coil modules.

3.3 Solenoid Support Structure

Figure 6 illustrates the solenoid coil mechanical grouping. Individual coils (S1-S6) are welded into modules as previously discussed. These coil modules are supported vertically and laterally from the vessel and connected to adjacent modules by adjustable pin-ended struts that allow for precise alignment of the coils. The vertical and lateral loads on each module are transmitted directly to the vessel through four struts. The axial loads are transfered between coils through the intercoil struts and box beams and eventually reacted through axial struts into the vacuum vessel. The twelve solenoids were split into three separate groups to minimize the longitudinal motion of the coils caused by contraction of the coils at 4K. The net axial loads on each set of four coils are transmitted to the vessel through four axial struts. The end solenoids (S7) are hung independently from the other magnets for two reasons: The magnets are in the vessel transition region and cannot be installed as part of a vessel module and, by supporting S7 axially from the Transition/Yin-Yang magnet complex, the magnetic loads on the supports for the middle twelve solenoids are reduced.

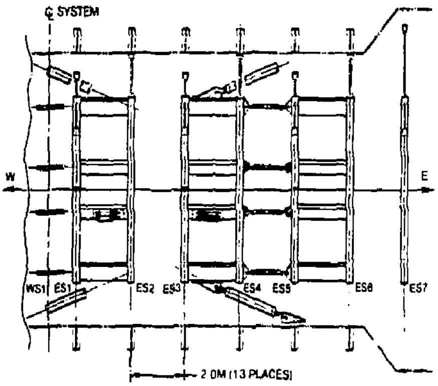

Figure 6. Solenoid mechanical groups isolate electromagnetic loads.

3.4 Vapor-Cooled Leads

The helium supply lines and return lines for the middle twelve solenoids are manifolded in pairs so that there are single inlet and exit ports for each coil module. The current leads, however, exit the vessel through separate stacks at the top of each coil

Figure 7 illustrates a preliminary design of a typical current lead routing from the magnet to the external current bus connection. The lead and bus assemblies must be capable of operating uncooled for ten minutes, must have a maximum helium flow through the leads during normal operation of 0.14g/s/KA, and must accommodate up to 7.5 mm vertical and 12.7 mm horizontal motion between the magnets and the vessel. The assembly between the magnet and the bottom of the vapor-cooled leads consists of large, copper-stabilized Nb_3Sn leads supported within an eight-inch diameter stainless steel duct. The entering and exiting leads are isolated from one another and supported by G-10 CR fiberglass plates which, in turn, are supported by the current lead duct. The duct has several bellows to provide sufficient flexibility to accommodate the magnet deflections.

The vapor cooled leads are based on the LLNL lead design for the MFTF Yin-Yang magnet.[1,2] In the case of the solenoid magnets, each lead consists of 26 stainless steel jacketed copper tubes brazed into copper terminal blocks at each end. Helium vapor flows through the tubes from bottom to top and exists into a helium return line at the top of the lead. The helium flow rate through the leads is regulated in the helium return system. The swagged stainless steel jacket on each of the lead tubes provides thermal mass to meet the requirement for ten minutes of uncooled operation.

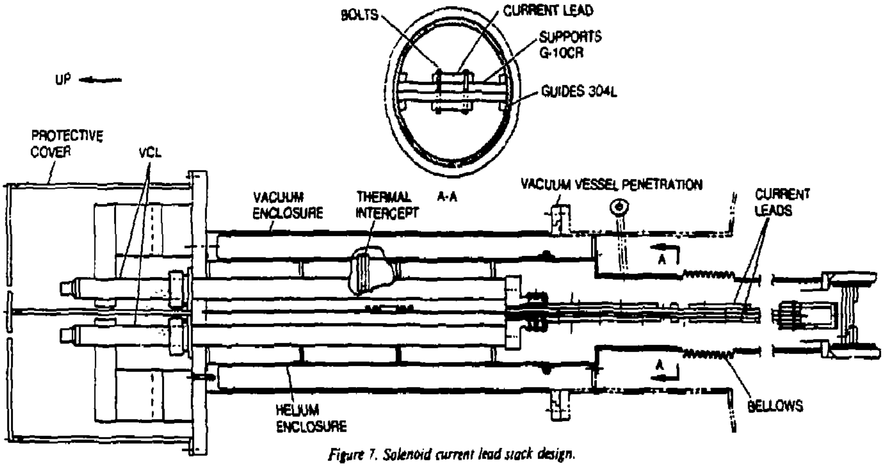

Figure 7. Solenoid current lead stack design.

4. COIL ANALYSIS

4.1 Structural Analyses

Up-to-date finite-element techniques, fracture analyses methods, and hand calculations are used to verify the magnet strength and reliability requirements. Three different finite-element models form the basis for the solenoid coil case stress analysis. A detailed quarter-symmetric model (Figure 8) is used to analyze all electromagnetic effects. A simpler beam-element model of a full-coil module is used to address the asymmetric seismic inertia conditions. The effects of cooldown temperature gradients are addressed by a half-symmetric model of a coil module. The maximum case stresses are less than 25 ksi.

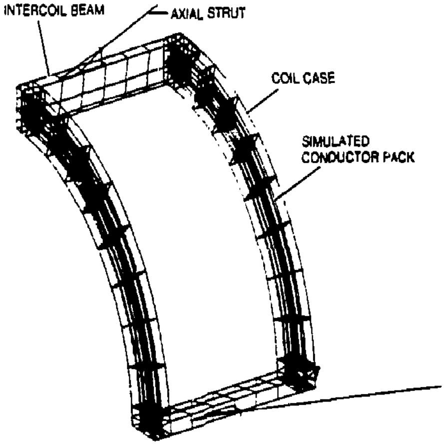

Figure 8. Finite element methods are utilized for structural analyses.

Solenoid coil pack analyses are performed using the STANSOL[3] computer code developed at Oak Ridge National Laboratory (ORNL). The code has been used to analyze stresses and deflections for all normal operating modes and to assess the impact of winding gaps and coil sponginess on these stresses and deflections. The maximum anticipated gap between the inner bobbin and the first winding layer is 0.10 inch. This corresponds to a maximum conductor stress of 23 ksi. Our analyses also indicate that there will be less than 25% variation in stresses and deflections across any given layer. Loads development for the solenoid magnets, and for all of the MFTF-B magnets, was a significant task due to the multitude of possible operating and fault modes. To generate loads in a timely and useful manner, a matrix of detailed EFFI[4] loads was developed by LLNL. Coil self loads, and interactive loads with every other coil, were calculated for each coil. These loads were then combined using a special GD post-processing program to produce the critical loads on each coil.

4.2 Thermodynamic Analysis

Extensive thermodynamic analyses have been used to verify that the coils meet the MFTF-B design requirements. A detailed analysis model of one half of a solenoid coil was built to assess the temperature behavior of the coil pack and case during cooldown. The analysis indicates that the coil and case cool to 5.4K in less than 120 hours with maximum 100K top-to-bottom and 15K transverse temperature gradients. Analyses have shown, however, that we need augmented cooling on the intercoil box beams.

Cryostability analyses have shown that the solenoid conductor has a 25% margin on cryostable current at its 2668A operating current. Heat transfer data was obtained from the literature and from our previous tests on the General Dynamics Large Coil Program (LCP) Conductor and Cask Magnet Program System (CMPS) conductor. When this data is correlated in terms of conductor orientation and insulation gap, it indicates that the MFTF-B solenoid conductor will have a minimum film boiling recovery flux of 0.22 W/cm^2 for a 1.5 mm insulation gap. The joule heating in the solenoid conductor for the 2668A operating current is 0.13 W/cm^2. Joule heating calculations include a 20% increase in resistivity due to radiation degradation over the 10-year lifetime of the magnets.

Heat load calculations show that the solenoid coils meet the 600 W steady state maximum refrigeration load established by LLNL for the S1-S6 coils. The maximum calculated heat loads on S1-S6 include 201W for radiation; 100W for conduction through the supports; 53W for the vapor cooled leads; and 113W for neutron heating. LN$_2$ intercepts on supports and radiation shielding on all structures are used to minimize the heat loads.

The quench vent and emergency pressure relief system for the MFTF-B central solenoids is combined into a large, 18-in. quench manifold with the rest of the MFTF-B magnets. The system can vent worst-case quench heating and expel helium from any of the west C-coil or central solenoid magnet groups and maintain magnet pressures below five atmospheres and not blow the burst disks. The extremely remote possibility of simultaneous worst-case quench venting of all the magnets commonly vented to the 18-inch quench manifold can produce magnet pressures of about seven atmospheres. The solenoids are designed for this worst-case 7 atmospheric pressure.

4.3 Electrical Analysis

The electrical analysis of the MFTF-B solenoids predicted the current voltage and temperature behavior of the coils during magnet fast dump and quench conditions. The possibility of fast dumping or quenching different groups of MFTF-B magnets necessitated the calculation of the current/time behavior in all magnets in order to select critical loading conditions. Several different magnet electrical groupings were analyzed in an attempt to minimize the induced currents and fault loads. Currents were calculated for each magnet for various fast dump and quench conditions using a commercial circuit analysis computer code called SYSCAP[5]. For the current magnet electrical grouping (EM3) (EM2, EM1) (ET1) (ES7-WS7) (WT1) (WM1, WM2) (WM3) the maximum induced current in the S7 coil is 600 amps and occurs when the transition coil is fast dumped. The maximum induced currents in the middle twelve solenoids are all less than 130 amp. The required 25% stability margin at normal operating current provides adequate margin for current peaking in the middle twelve solenoids (Ioper = 2668A). Additional stability margin has been provided in the S7 solenoids to account for the added current peaking in those magnets (Ioper = 2365A).

Conductor quench temperature calculations were based on the assumption of adiabatic behavior. Our analysis has shown that for a maximum lead-to-lead voltage of 160 volts, the maximum conductor temperature is 156K. The current LLNL electrical circuit has a maximum of five solenoids connected in series with one dump resistor. The maximum voltage across the dump resistor is 800 volts and the maximum coil-to-ground voltage is 400 volts. However, the quench analysis is being refined in an effort to lower the dump voltage.

5. REFERENCES

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